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Δ PRODUCTION VIA $\gamma p \to \Delta\pi$ BY LINEARLY POLARIZED PHOTONS AT 2.8 AND 4.7 GEV*

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ABSTRACT

The production of $\Delta(1236)$ by linearly polarized photons at 2.8 and 4.7 GeV was studied using a hydrogen bubble chamber. At 2.8 GeV the cross sections for $\gamma p \to \Delta^{++}\pi^-$ ($\gamma p \to \Delta^o\pi^+, \Delta^o \to p\pi^-$) were found to be 3.7 ± 0.4 μb (0.5 ± 0.2 μb); at 4.7 GeV, 1.0 ± 0.1 μb (0.16 ± 0.09 μb). Measurement of the parity asymmetry, P_σ, for Δ^{++} production with $|t| < 0.5$ GeV^2 yielded the values -0.27 ± 0.12 and -0.53 ± 0.15 at 2.8 and 4.7 GeV respectively, whereas pure one-pion exchange (OPE) would lead to $P_\sigma = -1$. The gauge invariant OPE model of Stichel and Scholz, with the inclusion of absorption corrections, accounts well for the Δ^{++} differential cross sections up to $|t| \lesssim 0.3$ GeV^2 and is in agreement with the Δ^{++} spin density matrix and P_σ for $|t| \lesssim 0.1$ GeV^2.

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Previous photoproduction experiments using bubble chambers[1,2] and the SLAC-spectrometer[3] have studied the reaction

$$\gamma p \rightarrow \Delta \pi \tag{1}$$

where Δ is the $\Delta(1236)$ nucleon resonance, and have shown that for photon energies $E_\gamma \gtrsim 2$ GeV the differential cross section $d\sigma/dt$ (t is the square of the four-momentum transfer between incoming proton and outgoing Δ) is proportional to $1/E_\gamma^2$ in common with a number of two-body photoproduction processes.[4] Such an energy dependence would be expected for processes dominated by one-pion exchange (OPE), but OPE leads to a zero cross section in the forward direction in contrast to experiment;[3] it is also not gauge invariant. These difficulties are overcome by a gauge-invariant extension of the OPE model proposed by Stichel and Scholz.[5] The angular correlations in Δ production by polarized photons provide a further check of the gauge invariant OPE model[6] and a test of relations based on vector dominance (VDM).[7]

We exposed the 82" hydrogen bubble chamber at SLAC to the linearly polarized Compton backscattered laser beam at 2.8 and 4.7 GeV, and studied Δ production in the reaction

$$\gamma p \rightarrow p\pi^+\pi^- \tag{2}$$

At the two energies, 2854 and 2910 events of reaction (2) were obtained. Details of the beam, exposure and our analysis procedure for reaction (2) have been published.[8,9]

Results. In Fig. 1 we show the $\pi^\pm p$ mass spectra for reaction (2). At both energies a clear Δ^{++} signal is found; some Δ^0 production may also be present. The shaded distributions are for events selected with $|t| < 0.4$ GeV^2 and $M_{\pi^+\pi^-} > 1.0$ GeV so as to remove most of the ρ^0 reflection and to minimize other backgrounds. Corrections for Δ^{++} production due to contamination from wide-angle electron-positron pair production and for scanning losses of events with short recoil protons (proton momenta < 0.14 GeV/c)[8] were found to be negligible from a Monte-Carlo simulation.

The solid curves in Fig. 1 were obtained from a maximum likelihood fit to the entire Dalitz plot assuming Δ^{++}, Δ^{o}, ρ^{o} production, and a phase space background. The ρ^{o} mesons were assumed to have their spin aligned along their direction of motion in the overall c.m.s.[9] and to have a dipion mass spectrum described by our previously determined parameterization[8] which gave a good fit to the data. The Soding model, which also fits the $\pi^+\pi^-$ mass distributions well,[8] was not used because the Drell terms in this model already contain contributions to Δ production. In order to state a total Δ cross section, $\sigma(\Delta\pi)$, we must choose a reasonable parameterization of the Δ production amplitude T_Δ. In place of the usual Breit-Wigner forms, e.g., those discussed by Jackson,[10] which describe the Δ shape well near resonance but fail far away,[11] we feel it is more meaningful to use a purely phenomenological form[10] derived from the experimental phase shifts δ_{33}:

$$|T_\Delta|^2 \propto \frac{\sin^2\delta_{33}}{\Gamma(M)} = \frac{1}{\Gamma(M)}\,\frac{\left(M_\Delta\Gamma(M)\right)^2}{\left(M_\Delta^2 - M^2\right)^2 + \left(M_\Delta\Gamma(M)\right)^2} \tag{3}$$

where $\Gamma(M)$ follows from $\tan\delta_{33} = M_\Delta\Gamma(M)/\left(M_\Delta^2 - M^2\right)$ and $M_\Delta = 1.236$ GeV. The values of δ_{33} have been taken from a phase shift analysis.[12] If instead the second part of Eq. (3) is used together with a conventional parameterization for $\Gamma(M)$ as was done, e.g., by Boyarski et al.,[3] one finds a value of $\sigma(\Delta\pi)$ larger by ~20%.

In Table 1 the total cross sections for production of Δ^{++} and Δ^{o} ($p\pi^-$ decay mode only) are given for the two energies. Figure 2 shows the differential cross sections $d\sigma/dt$ for Δ^{++} production obtained from an independent maximum likelihood fit as described above for each t-interval. Also shown are the measurements of Boyarski et al.[3] at E_γ=5.0 GeV. Measurements in the backward direction have been made by Anderson et al.[13]

The Δ^{++} angular distributions have been analyzed in terms of the Δ spin density matrix in the Gottfried-Jackson frame. The z axis is taken as the direction of the incident proton in the Δ rest frame; the y axis is defined as the normal to the production plane ($\hat{y} \propto \hat{\gamma} \times \hat{\pi}^-$). The electric vector ϵ of the photon makes an angle Φ with the production plane: $\cos\Phi = \hat{\gamma} \cdot (\hat{\epsilon} \times \hat{y})$, $\sin\Phi = \hat{y} \cdot \hat{\epsilon}$. The decay angles θ and ϕ are the polar and azimuthal angles of the outgoing proton in the Δ rest system: $\cos\theta = \hat{p} \cdot \hat{z}$, $\cos\phi = \hat{y} \cdot (\hat{z} \times \hat{p})/|\hat{z} \times \hat{p}|$, $\sin\phi = -(\hat{y} \times \hat{z}) \cdot (\hat{z} \times \hat{p})/|\hat{z} \times \hat{p}|$. The decay angular distribution is then given by[14]:

$$
\begin{aligned}
W(\cos\theta, \phi, \Phi) = \frac{3}{4\pi} \Big\{ & \rho^0_{33} \sin^2\theta + \left(1/2 - \rho^0_{33}\right)\left(1/3 + \cos^2\theta\right) \\
& - 2/\sqrt{3}\ \mathrm{Re}\ \rho^0_{31} \cos\phi \sin 2\theta - 2/\sqrt{3}\ \mathrm{Re}\ \rho^0_{3-1} \cos 2\phi \sin^2\theta \\
& - P_\gamma \cos 2\Phi \Big[\rho^1_{33} \sin^2\theta + \rho^1_{11} \left(1/3 + \cos^2\theta\right) \\
& - 2/\sqrt{3}\ \mathrm{Re}\ \rho^1_{31} \cos\phi \sin 2\theta - 2/\sqrt{3}\ \mathrm{Re}\ \rho^1_{3-1} \cos 2\phi \sin^2\theta \Big] \\
& - P_\gamma \sin 2\Phi \Big[2/\sqrt{3}\ \mathrm{Im}\ \rho^2_{31} \sin\phi \sin 2\theta + 2/\sqrt{3}\ \mathrm{Im}\ \rho^2_{3-1} \sin 2\phi \sin^2\theta \Big] \Big\}
\end{aligned}
\tag{4}
$$

where P_γ is the degree of linear polarization; $P_\gamma = 94\%$ at 2.8 GeV and $P_\gamma = 92\%$ at 4.7 GeV. We define the polarization asymmetry Σ by

$$
\begin{aligned}
\Sigma &= \frac{1}{P_\gamma} \frac{W(\Phi=0) - W(\Phi=\pi/2)}{W(\Phi=0) + W(\Phi=\pi/2)} \\
&= -2\left(\rho^1_{33} + \rho^1_{11}\right)
\end{aligned}
\tag{5}
$$

where $W(\Phi)$ is the Φ distribution integrated over θ and ϕ. A related quantity is the parity asymmetry, P_σ, defined in terms of the cross sections for natural and unnatural parity exchange in the t-channel, σ^N and σ^U:

$$
P_\sigma = \frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U}
\tag{6}
$$

At high energies $P_\sigma = 2\left(\rho^1_{33} + \rho^1_{11}\right) = -\Sigma$.[15]

To obtain the nine measurable density matrix parameters, events were selected with $M_{p\pi^+} < 1.32$ GeV and the method of moments was used with the Eberhard-Pripstein procedure[16] to remove the ρ^0 reflection: only events with

$\cos\theta_H < 0.3$ (0.7) at 2.8 GeV (4.7 GeV) were used, where θ_H is the angle in the c.m.s. of the Δ between the decay proton and the Δ line of flight in the total c.m.s. Figure 3 shows the ρ^{α}_{ik} and P_{σ} obtained this way. The values of P_{σ} averaged over $|t| < 0.5$ GeV^2 are given in Table 1. It is clear that OPE alone cannot explain the data since it would require $P_{\sigma} = -1$. Qualitatively the same result was obtained in an experiment done at low energy.[17]

Comparison with Theory. We calculated the predictions of the minimal gauge invariant extension of the OPE model (GIOPE) with absorption corrections. Gauge invariance in this model is achieved by adding to the OPE diagram the s-channel nucleon exchange, the u-channel Δ exchange and the contact graph (see Fig. 4) according to the prescription of Stichel and Scholz.[5] The decomposition of the Born amplitudes into helicity amplitudes was taken from Locher and Sandhas.[18] In contrast to these authors, following the idea of vector dominance, we applied absorption corrections in both initial and final states[19] by multiplying the helicity amplitudes for spin J by the factor[20]

$$\left\{1 - C_{in} \exp\left(-J^2/2A_{in}q^2_{in}\right)\right\}^{1/2} \left\{1 - C_{out} \exp\left(-J^2/2A_{out}q^2_{out}\right)\right\}^{1/2}$$

where q is the c.m.s. momentum, A the slope parameter, C the absorption parameter ($C = \sigma_T/4\pi A$, σ_T the total cross section for scattering of either the initial or final state particles) and the indices "in", "out" refer to the initial and final states respectively. We assumed that $A_{in} = A_{out} = A$ and $C_{in} = C_{out} = C$; A was taken from elastic πp scattering to be 8 GeV^{-2}; for C a value of 0.8 was used. The finite width of the Δ was taken into account by integrating over the $\pi^+ p$ mass range using the (3,3) elastic scattering cross section.

The solid curves in Fig. 2 show the predictions of GIOPE for $d\sigma/dt$ ($\gamma p \to \Delta^{++}\pi^-$). For comparison we also give the predictions for C=1 (dashed curves). There is good agreement for $|t| < 0.3$ GeV^2, but at larger $|t|$ too much

Δ^{++} is predicted. It is interesting to note that, for $|t| > 0.02$ GeV^2 the OPE graph alone leads to approximately the same $d\sigma/dt$.

In Fig. 3 we compare the predictions of GIOPE with the measured density matrix parameters and P_σ as calculated from these. It can be seen that the diagrams II-IV (see Fig. 4) simulate some natural parity exchange contributions in the t-channel. Although there is agreement for $|t| \lesssim 0.1$ GeV^2 in an average sense we cannot test the strong variations predicted by GIOPE for $|t| \lesssim 0.02$ GeV^2. For $|t| > 0.1$ GeV^2 some of the ρ^{α}_{ik} and P_σ are not reproduced well. The GIOPE predictions for the ρ^{α}_{ik} are essentially independent of the value of the absorption parameter C. The density matrix parameters predicted by the OPE graph alone, namely, $\rho^{1}_{11} = -1/2$, all other ρ^{α}_{ik} in Eq. (4) equal to zero, bear no resemblance to the data.

It is also interesting to determine the ratio $R = \sigma(\gamma p \to \Delta^{++}\pi^-)/\sigma(\gamma p \to \Delta^{o}\pi^+, \Delta^{o} \to p\pi^-)$. If there is only t-channel $I^G = 1^-$ (e.g., π) exchange, then $R = 9$. Stichel and Scholz in their version of GIOPE keep only contributions equivalent to this $I^G = 1^-$ exchange in the t-channel and hence predict $R = 9$. Other versions of GIOPE[18,21] drop this restriction to $I^G = 1^-$ t-channel exchange and R becomes a function of t. If this $R \neq 9$ is then interpreted in terms of t-channel effects alone it can be taken as evidence for $I^G = 1^+$ or $I = 2$ (exotic) exchanges. Our data on R (see Table 1) are consistent with either version of GIOPE. The data of Boyarski et al.,[21] for Δ^{++}, Δ^{o}, Δ^{-} production of protons and deuterons are inconsistent with the assumption of $I = 1$ exchange alone and led to speculations on the existence of exotic exchanges.[4] We point out that these data may be understood in terms of the GIOPE model.[22]

Vector dominance (VDM) relates reaction (1) to the reactions $\pi p \to \Delta V^{o}$ where V^{o} is ρ^{o}, ω or ϕ. Gotsman[7] has fitted the latter reactions to a sum of Regge exchange amplitudes in order to perform the line reversal needed for the comparison. With $\gamma_\rho^2/4\pi = 0.5$ (γ_ρ describes the γ-ρ coupling strength), his predictions for

5 GeV are in fair agreement with our $d\sigma/dt$ for $|t| > 0.1$ GeV^2. While the predictions for some of the ρ^{α}_{ik} and for P_σ (see dashed curve in Fig. 3) are in qualitative agreement, the prediction $\rho^{0}_{33} \simeq 0$ is not supported by the data.

Conclusion. The cross sections, density matrix elements, and parity asymmetry of $\gamma p \to \Delta^{++}\pi^-$ have been measured as a function of t. In the region $0.05 \lesssim |t| \lesssim 0.3$ GeV^2 the differential cross section is described by OPE alone if absorption corrections are applied. However, the density matrix parameters and the parity asymmetry values, found for $|t| < 0.5$ GeV^2 to be $P_\sigma = -0.27 \pm 0.12$ and -0.53 ± 0.15 at 2.8 and 4.7 GeV respectively, indicate the presence of other processes. The gauge invariant OPE model with absorption corrections reproduces the differential cross sections for $|t| \lesssim 0.3$ GeV^2 and the density matrix parameters for $|t| \lesssim 0.1$ GeV^2.

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TABLE 1

Cross Sections for $\gamma p \to \Delta\pi$ and Parity Asymmetry P_σ for $\gamma p \to \Delta^{++}\pi^-$

E_γ (GeV)	$\sigma_{\Delta^{++}\pi^-}$ (μb)	$\sigma_{\Delta^0\pi^+}$, $\Delta^0 \to p\pi^-$ (μb)	P_σ $\|t\| < .5$ GeV^2
2.8	3.7 ± 0.4	0.5 ± 0.2	-0.27 ± 0.12
4.7	1.0 ± 0.1	0.16 ± 0.09	-0.53 ± 0.15

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Figure Captions

1. Reaction $\gamma p \to p\pi^+\pi^-$. Effective mass distributions for the $p\pi^+$ and $p\pi^-$ systems. The shaded histograms represent events with $|t| < 0.4$ GeV^2 and $M_{\pi^+\pi^-} > 1.0$ GeV. The curves are the result of the fits described in text.

2. Reaction $\gamma p \to \Delta^{++}\pi^-$. Differential cross sections $d\sigma/dt$ from this experiment (⧫) and from Ref. 3 for $E_\gamma = 5$ GeV (△). The shaded regions in (b), (d) are shown on an expanded scale in (a), (c). The curves are the predictions

of the gauge-invariant OPE model with absorption corrections for C = 0.8 (——) and C = 1 (- - - -).

3. Reaction $\gamma p \to \Delta^{++}\pi^{-}$. Density matrix parameters and parity asymmetry P_{σ}. The solid curves are the predictions of the gauge-invariant OPE model with absorption corrections for C = 0.8. The dashed curves show the VDM predictions (Ref. 7).

4. The four Feynman diagrams for $\gamma p \to \Delta\pi$ taken into account in the gauge-invariant OPE model.

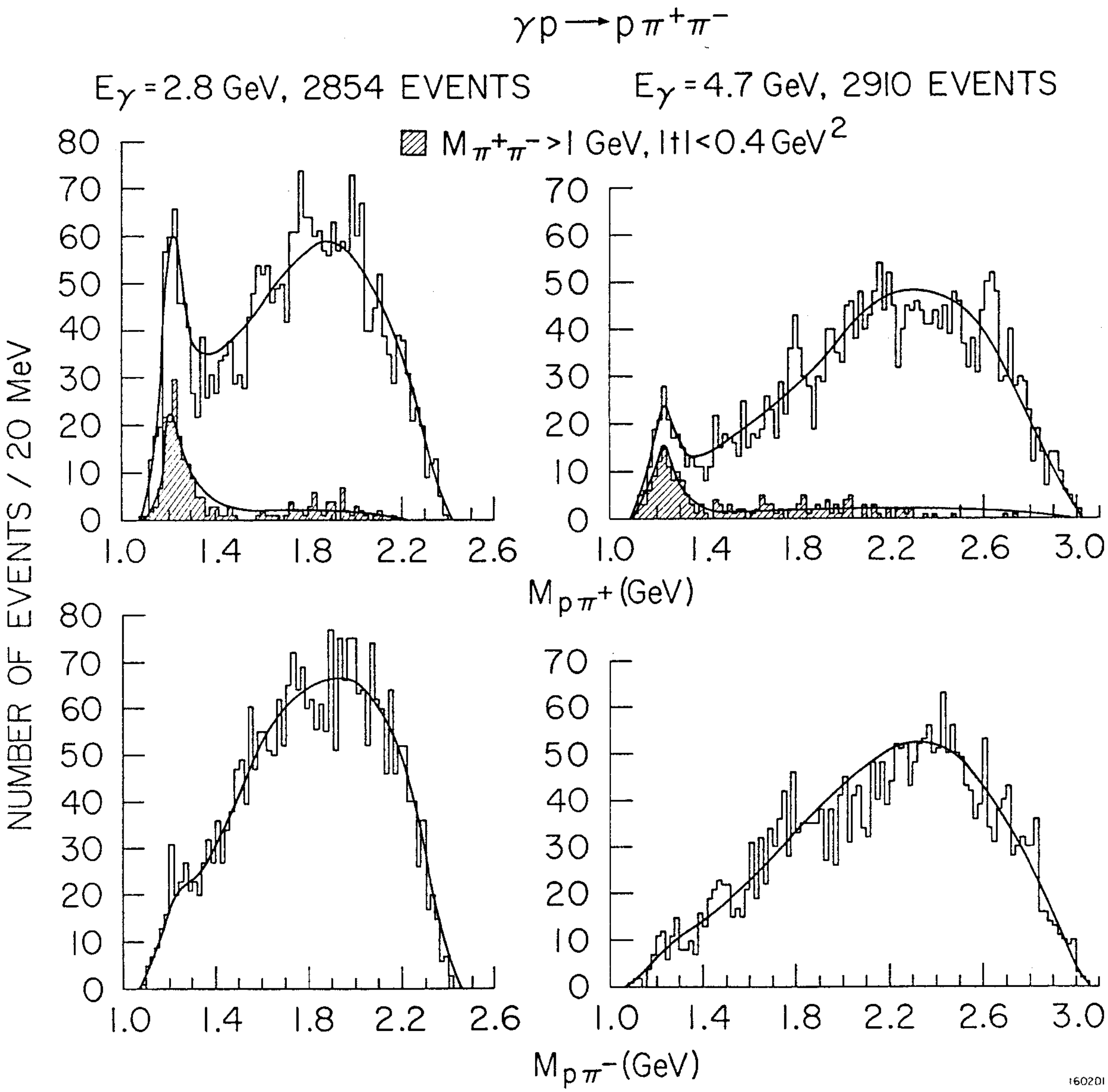
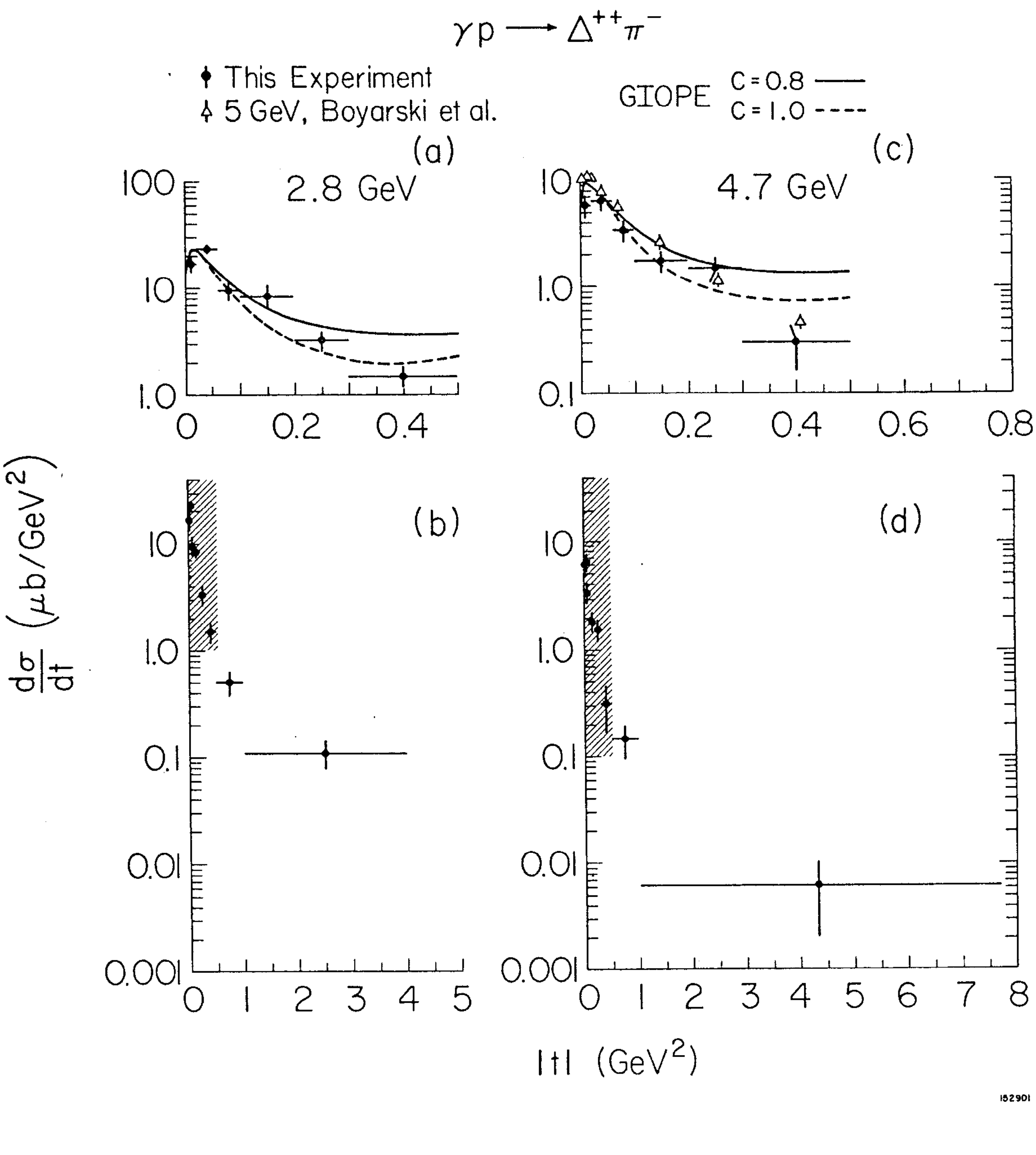
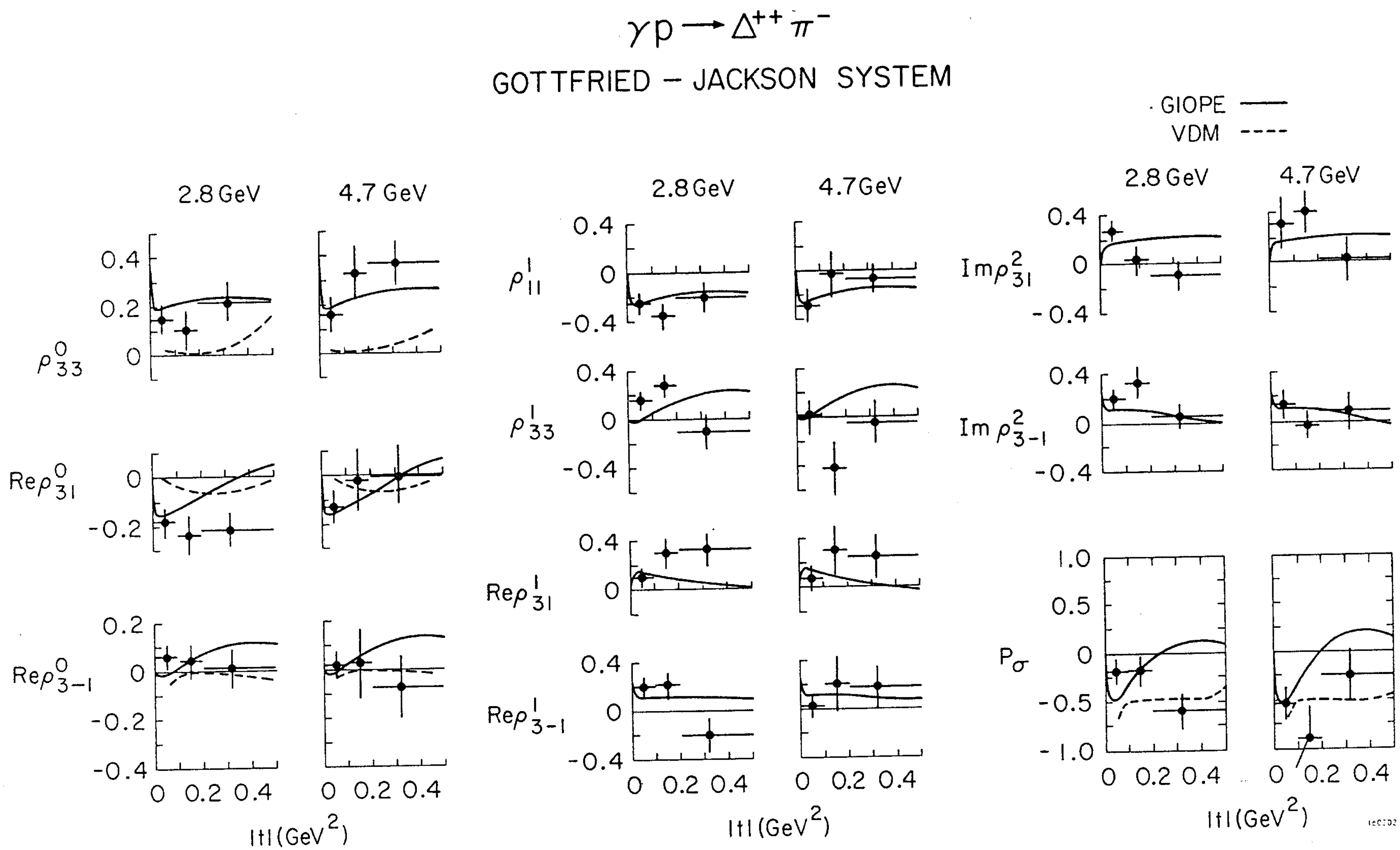

γp → pπ⁺π⁻
Eγ = 2.8 GeV, 2854 EVENTS
Eγ = 4.7 GeV, 2910 EVENTS
M π⁺π⁻ > 1 GeV, |t| < 0.4 GeV²
NUMBER OF EVENTS / 20 MeV
M pπ⁺ (GeV)
M pπ⁻ (GeV)
160201

Fig. 1



γp ⟶ Δ⁺⁺π⁻
This Experiment
5 GeV, Boyarski et al.
GIOPE C = 0.8
C = 1.0
(a)
2.8 GeV
(c)
4.7 GeV
(b)
(d)
dσ/dt (μb/GeV²)
|t| (GeV²)
152901

Fig. 2



γp → Δ++ π−
GOTTFRIED – JACKSON SYSTEM
GIOPE
VDM
2.8 GeV
4.7 GeV
ρ⁰₃₃
Reρ⁰₃₁
Reρ⁰₃₋₁
ρ¹₁₁
ρ¹₃₃
Reρ¹₃₁
Reρ¹₃₋₁
Imρ²₃₁
Imρ²₃₋₁
Pσ
|t| (GeV²)

Fig. 3

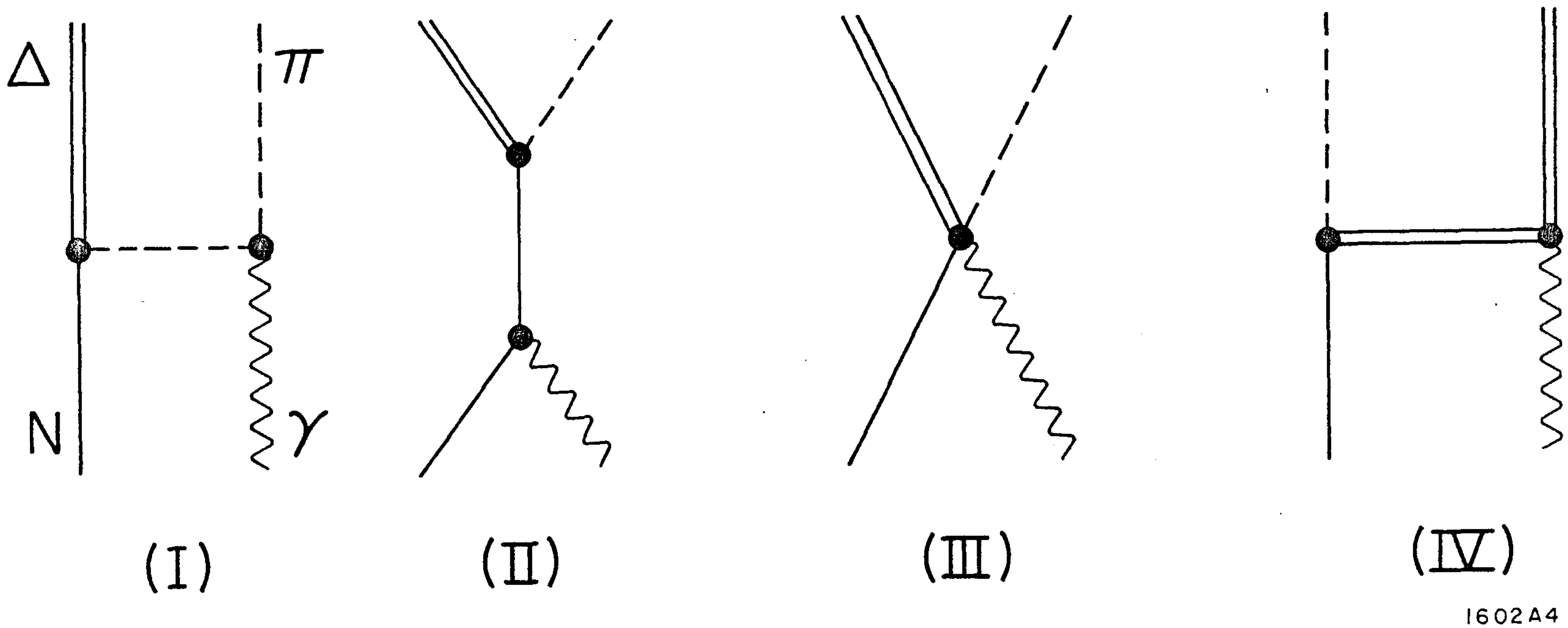


Fig. 4