



Letter

First measurement of polarized spin-density matrix elements and differential cross sections $d\sigma/dt$ in ω photoproduction off the proton for $2.7 < E_\gamma < 5.2$ GeV using CLAS at Jefferson Lab

T. Hu^a, Z. Akbar^a, V. Crede^{a,*}, J. M. Laget^b, V. Mathieu^{c,d}, M. J. Amarian^e, W. R. Armstrong^f, H. Atac^g, N. A. Baltzell^{h,b}, L. Barionⁱ, M. Battaglieri^j, I. Bedlinskiy^k, B. Benkel^l, F. Benmokhtar^m, A. Bianconi^{n,o}, L. Biondo^{j,p,q}, A. Biselli^r, M. Bondi^j, F. Bossù^s, S. Boiarinov^b, W. J. Briscoe^t, S. Bueltmann^e, D. Bulumulla^e, V. D. Burkert^b, R. Capobianco^u, D. S. Carman^b, J. C. Carvajal^v, A. Celentano^j, T. Chetry^w, G. Ciullo^{x,i}, G. Clash^y, P. L. Cole^z, M. Contalbrigoⁱ, G. Costantini^{n,o}, A. D'Angelo^{aa,ab}, N. Dashyan^{ac}, R. De Vita^j, M. Defurne^s, A. Deur^b, S. Diehl^{u,ad}, C. Djalali^{ae,h}, R. Dupre^{af}, H. Egiyan^{ag,b}, A. El Alaoui^l, L. El Fassi^{f,w}, L. Elouadrhiri^b, P. Eugenio^a, S. Fegan^y, A. Filippi^{ah}, G. Gavalian^{e,b}, Y. Ghandilyan^{ac}, G. P. Gilfoyle^{ai}, F. X. Girod^b, A. A. Golubenko^{aj}, G. Gosta^{n,o}, R. W. Gothe^h, K. A. Griffioen^{ak}, M. Guidal^{af}, K. Hafidi^f, H. Hakobyan^{l,ac}, M. Hattawy^e, T. B. Hayward^u, D. Heddle^{al,b}, A. Hobart^{af}, M. Holtrop^{ag}, Y. Ilieva^{t,h}, D. G. Ireland^{am}, E. L. Isupov^{aj}, D. Jenkins^{an}, H. S. Jo^{ao}, K. Joo^u, S. Joosten^f, D. Keller^{ap}, A. Khanal^v, M. Khandaker^{aq}, A. Kim^u, W. Kim^{ao}, F. J. Klein^{ar}, V. Klimenko^u, A. Kripko^{ad}, V. Kubarovsky^{as,b}, V. Lagerquist^e, L. Lanza^{aa}, M. Leali^{n,o}, P. Lenisa^{x,i}, K. Livingston^{am}, I. J. D. MacGregor^{am}, D. Marchand^{af}, L. Marsicano^j, V. Mascagna^{n,o}, M. E. McCracken^{at}, B. McKinnon^{am}, Z. E. Meziani^f, S. Migliorati^{n,o}, R. G. Milner^{au}, T. Mineeva^{u,l}, M. Mirazita^{av}, V. Mokeev^b, C. Munoz Camacho^{af}, P. Nadel-Turonski^b, K. Neupane^h, J. Newton^b, S. Niccolai^{af}, M. Nicol^y, G. Niculescu^{aw}, M. Osipenko^j, A. I. Ostrovidov^a, P. Pandey^e, M. Paolone^{ax}, L. L. Pappalardo^{x,i}, R. Paremuzyan^b, E. Pasyuk^b, S. J. Paul^{ay}, W. Phelps^{al}, N. Pilleux^{af}, O. Pogorelko^k, J. W. Price^{az}, Y. Prok^{e,ap}, B. A. Raue^v, T. Reed^v, M. Ripani^j, J. Ritman^{ba}, A. Rizzo^{aa,ab}, G. Rosner^{am}, F. Sabatié^s, C. Salgado^{aq}, S. Schadmand^{ba}, A. Schmidt^t, R. A. Schumacher^{at}, E. V. Shirokov^{aj}, U. Shrestha^u, P. Sommerling^u, D. Sokhan^{s,am}, N. Sparveris^g, S. Stepanyan^b, I. I. Strakovsky^t, S. Strauch^h, R. Tyson^{am}, M. Ungaro^{u,b}, L. Venturelli^{n,o}, H. Voskanyan^{ac}, A. Vossen^{bb,b}, E. Voutier^{af}, D. P. Watts^y, X. Wei^b, M. H. Wood^{bc,h}, B. Yale^{ak}, M. Yurov^{ao}, N. Zachariou^y, J. Zhang^{e,ap}, The CLAS Collaboration at Jefferson Laboratory

^a Florida State University, Tallahassee, Florida, 32306, USA

^b Thomas Jefferson National Accelerator Facility, Newport News, Virginia, 23606, USA

^c Departamento de Física Teórica, Universidad Complutense de Madrid and IPARCOS, Madrid, E-28040, Spain

^d Departament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos, Universitat de Barcelona, E-08028, Spain

^e Old Dominion University, Norfolk, Virginia, 23529, USA

^f Argonne National Laboratory, Argonne, Illinois, 60439, USA

^g Temple University, Philadelphia, PA, 19122, USA

^h University of South Carolina, Columbia, South Carolina, 29208, USA

ⁱ INFN, Sezione di Ferrara, Ferrara, 44100, Italy

* Corresponding author.

E-mail address: crede@fsu.edu (V. Crede).

- ^j INFN, Sezione di Genova, Genova, 16146, Italy
^k National Research Centre Kurchatov Institute - ITEP, Moscow, 117259, Russia
^l Universidad Técnica Federico Santa María, Casilla 110-V Valparaíso, Chile
^m Duquesne University, 600 Forbes Avenue, Pittsburgh, PA, 15282, USA
ⁿ INFN, Sezione di Pavia, Pavia, 27100, Italy
^o Università degli Studi di Brescia, Brescia, 25123, Italy
^p INFN, Sezione di Catania, Catania, 95123, Italy
^q Università degli Studi di Messina, Messina, 98166, Italy
^r Fairfield University, Fairfield, Connecticut, 06824, USA
^s IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, F-91191, France
^t The George Washington University, Washington, DC 20052, USA
^u University of Connecticut, Storrs, Connecticut, 06269, USA
^v Florida International University, Miami, Florida, 33199, USA
^w Mississippi State University, Mississippi State, MS 39762-5167, USA
^x Università di Ferrara, Ferrara, 44121, Italy
^y University of York, York, YO10 5DD, United Kingdom
^z Lamar University, 4400 MLK Blvd, PO Box 10046, Beaumont, Texas, 77710, USA
^{aa} INFN, Sezione di Roma Tor Vergata, Rome, 00133, Italy
^{ab} Università di Roma Tor Vergata, 00133, Rome, Italy
^{ac} Yerevan Physics Institute, Yerevan, 375036, Armenia
^{ad} II Physikalisches Institut der Universität Gießen, Gießen, 35392, Germany
^{ae} Ohio University, Athens, Ohio, 45701, USA
^{af} Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, 91405, France
^{ag} University of New Hampshire, Durham, New Hampshire, 03824-3568, USA
^{ah} INFN, Sezione di Torino, Torino, 10125, Italy
^{ai} University of Richmond, Richmond, Virginia, 23173, USA
^{aj} Department of Physics and Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, 119234, Russia
^{ak} College of William and Mary, Williamsburg, Virginia, 23187-8795, USA
^{al} Christopher Newport University, Newport News, Virginia, 23606, USA
^{am} University of Glasgow, Glasgow, G12 8QQ, United Kingdom
^{an} Virginia Tech, Blacksburg, Virginia, 24061-0435, USA
^{ao} Kyungpook National University, Daegu, 41566, Republic of Korea
^{ap} University of Virginia, Charlottesville, Virginia, 22901, USA
^{aq} Norfolk State University, Norfolk, Virginia, 23504, USA
^{ar} Catholic University of America, Washington DC, 20064, USA
^{as} Rensselaer Polytechnic Institute, Troy, New York, 12180-3590, USA
^{at} Carnegie Mellon University, Pittsburgh, Pennsylvania, 15213, USA
^{au} Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139-4307, USA
^{av} INFN, Laboratori Nazionali di Frascati, Frascati, 00044, Italy
^{aw} James Madison University, Harrisonburg, Virginia, 22807, USA
^{ax} New Mexico State University, PO Box 30001, Las Cruces, NM, 88003, USA
^{ay} University of California Riverside, 900 University Avenue, Riverside, CA, 92521, USA
^{az} California State University, Dominguez Hills, Carson, California, 90747, USA
^{ba} GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, D-64291, Germany
^{bb} Duke University, Durham, North Carolina, 27708-0305, USA
^{bc} Canisius College Buffalo, New York, 14208, USA

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ABSTRACT

We report on the differential cross sections $d\sigma/dt$, the unpolarized spin-density matrix elements $\rho_{00}^0, \rho_{1-1}^0, \text{Re } \rho_{10}^0$, and the first extraction of the polarized elements $\text{Im } \rho_{10}^0, \text{Im } \rho_{1-1}^0$ for the reaction $\gamma p \rightarrow p\omega$ using the CLAS spectrometer at Jefferson Laboratory. The ω mesons were detected in their dominant charged decay mode, $\omega \rightarrow \pi^+\pi^-\pi^0$, and all t -dependent results are presented in a fine binning for incident photon energies between 2.73 and 5.16 GeV (corresponding to the center-of-mass energy range $W \in [2.45, 3.25]$ GeV). All matrix elements are first measurements for $-t > 0.6$ GeV². Moreover, differential cross sections $d\sigma/d(\cos \Theta_{\text{c.m.}}^\omega)$ and the corresponding angle-dependent unpolarized spin-density matrix elements in the Adair frame are presented for the incident photon energy range 1.56–3.80 GeV (corresponding to $W \in [1.95, 2.83]$ GeV). These new ω photoproduction data are consistent with earlier CLAS results but extend the energy range well beyond the nucleon resonance region into the Regge regime. The comparison with Regge-theory-based model predictions shows that the new data impose more stringent constraints on our understanding of ω photoproduction.

1. Introduction

The light-flavor vector mesons ρ , ω , and ϕ have the same spin, parity and charge conjugation quantum numbers, $J^{PC} = 1^{--}$, as the photon and, therefore, these mesons play an important role in photoproduction. In high-energy ω photoproduction, the non-resonant amplitude is dominated by a diffractive mechanism, whereas single- π exchange has been predicted to dominate in the nucleon resonance regime at lower energies. The contribution from nucleon excitations in ω photoproduction was recently studied by several groups [1–4]. Surprisingly, an amplitude analysis within the Bonn-Gatchina framework [5] found Pomeron-exchange to provide the largest contribution to the non-resonant background. In vector-meson photoproduction, the spin observables of the vector mesons are represented by their density matrix. Its elements, the

spin-density matrix elements (SDMEs), are the physical observables that provide information on the underlying production mechanism and the decay distribution, $W(\cos \theta, \phi)$, of the vector meson. In ref. [5], the t -channel amplitude was identified by polarized SDMEs using linear beam polarization, and additional beam- and beam-target polarization observables [6,7].

At low momentum transfer, the differential cross section exhibits the typical exponential $-t$ dependence expected from Pomeron and Reggeon exchange. This diffractive production mechanism is described by the incident photon that fluctuates into a vector meson and then elastically scatters from the target nucleon. At large momentum transfer, the cross section shows a flat behavior that can be explained in terms of QCD-inspired two-gluon exchange [8]. The impact parameter becomes small enough and prevents the two constituent gluons from forming the

exchanged Pomeron. Moreover, the light, non-strange quark composition of the ω meson allows valence quarks to be exchanged between the meson and recoil nucleon [9]. In contrast, the latter mechanism is suppressed in single- ϕ meson photoproduction by the OZI rule and two-gluon exchange dominates. At medium energies, it is important to establish factorization of Regge vertices to separate mesons from baryons. This has been discussed in a recent Regge-based study that also provides the implication of Regge-pole models on the SDMEs [10].

The low-energy regime close to threshold, where nucleon resonances dominate ω photoproduction, and the Regge regime are analytically connected. However, the scarcity of $-t$ -dependent cross sections and other spin observables has hindered our understanding of the transition from the baryon resonance regime to high-energy photoproduction. Moreover, each Reggeon exchange has a known energy behavior, whereas the dependence on the momentum exchange is initially unknown and only poorly understood in the transition and medium-energy regimes. In this Letter, we report differential cross sections and various extracted SDMEs for the center-of-mass energy range $W \in [1.95, 3.25]$ GeV for the reaction $\gamma p \rightarrow p \omega$ using circularly polarized tagged photons. The $\omega \rightarrow \pi^+ \pi^- \pi^0$ decay angular distribution W is parameterized by the density matrices ρ^α , $\alpha = 0, 1, 2, 3$. For circularly polarized incident photons with helicities $\lambda_\gamma = \pm 1$, $W^\pm(\cos \theta, \phi)$ is given by Schilling et al. [11]

$$W^\pm(\cos \theta, \phi) = W^0(\cos \theta, \phi) \pm \delta_\odot W^3(\cos \theta, \phi), \quad (1)$$

where $\delta_\odot$ denotes the degree of circular beam polarization, and θ and ϕ are the polar and azimuthal angles of the normal to the decay plane ($\hat{k}_{\pi^+} \times \hat{k}_{\pi^-}$) in the ω rest frame. In this analysis, the SDMEs were extracted from the data for each kinematic bin, $(W, \cos \Theta_{\text{c.m.}}^\omega)$ or $(W, -t)$, by performing an Extended Maximum Likelihood fit to Eq. (1) with

$$W(\theta, \phi, \rho^0) = \frac{3}{4\pi} \left(\frac{1}{2} (1 - \rho_{00}^0) + \frac{1}{2} (3\rho_{00}^0 - 1) \cos^2 \theta - \sqrt{2} \text{Re} \rho_{10}^0 \sin 2\theta \cos \phi - \rho_{1-1}^0 \sin^2 \theta \cos 2\phi \right) \quad (2)$$

$$W(\theta, \phi, \rho^3) = \frac{3}{4\pi} \left(\sqrt{2} \text{Im} \rho_{10}^3 \sin 2\theta \sin \phi + \text{Im} \rho_{1-1}^3 \sin^2 \theta \sin 2\phi \right), \quad (3)$$

where $\rho_{00}^0, \rho_{1-1}^0, \text{Re} \rho_{10}^0$ and $\text{Im} \rho_{10}^3, \text{Im} \rho_{1-1}^3$ are the unpolarized and polarized SDMEs, respectively.

2. Previous measurements

The differential cross sections $d\sigma/dt$ were initially measured in the 1970s and 1980s at the Stanford Linear Accelerator Center (SLAC) at $E_\gamma = 2.8, 4.7, 9.3$ GeV using a laser-produced polarized photon beam [12, 13] and at the Cornell Laboratory of Nuclear Studies using incident tagged-photons with energies between 7.5 GeV and 10.5 GeV [14]. At the electron synchrotron NINA, Daresbury Laboratory, measurements were made in the photon energy range 2.8 to 4.8 GeV at backward angles [15] and by the LAMP2 Group at forward angles [16]. The LAMP2 group published very wide energy bins. Therefore, these data and earlier statistically limited data from the Cambridge [17] and DESY [18] bubble chamber groups are omitted here. More recently, the CLAS Collaboration at Jefferson Laboratory reported cross section data for four different energy bins between 3.2 and 3.92 GeV [19]. Unpolarized SDMEs were extracted at SLAC [13], Cornell [14], and Daresbury [16] at the above energies for $-t < 0.6$ GeV², by CLAS [20] for $E_\gamma < 3.83$ GeV in a $(E_\gamma, \cos \Theta_{\text{c.m.}}^\omega)$ representation, and at ELSA [5] below 2.5 GeV. Our measurements are first measurements for $-t > 0.6$ GeV². Some experiments reported data on SDMEs using linear polarization [5, 13]. The polarized SDMEs presented here have been extracted from photoproduction data using circular polarization; they are also first measurements.

3. The CLAS-g12 experiment

These new results were obtained within the framework of the CLAS-g12 experiment [21], conducted at Jefferson Laboratory before the 12 GeV upgrade. CLAS-g12 used longitudinally polarized electrons with energies of $E_{e^-} = 5.715$ GeV and polarization $\sim 67.2\%$ [22] on a liquid-hydrogen target. Circularly polarized photons were obtained by transferring the polarization from the electrons to the photons in a bremsstrahlung process when the electrons scattered off an amorphous gold radiator. The degree of the photon-beam polarization, $\delta_\odot$, was given as a function of the degree of electron-beam polarization, δ_{e^-} , and the photon-beam energy E_γ as Olsen and Maximov [23]:

$$\delta_\odot = \delta_{e^-} \cdot \frac{4x - x^2}{4 - 4x + 3x^2}, \quad (4)$$

where $x = E_\gamma/E_{e^-}$.

The polarized photons were energy and time tagged with resolutions of 0.1% and 100 ps, respectively, using a photon tagging system [24].

The CLAS detector, with its six-fold symmetry about the beamline (sectors), was capable of detecting charged particles with a laboratory polar-angle coverage of $[8, 142]^\circ$ and almost 2π coverage in the azimuthal angle [25]. The final-state particles traversed several layers of sub-detectors, including drift chambers (DC) and time-of-flight (TOF) scintillators. A start counter (SC) provided the initial time information of the events. For an event to be recorded, the trigger required a scattered electron in the bremsstrahlung tagger in coincidence with either (a) (at least) three charged tracks in different sectors with no restrictions on photon energy, or (b) only two tracks in different sectors with the additional requirement of at least one tagger photon with an energy above 3.6 GeV.

3.1. Event selection

In this analysis, the ω was reconstructed from its $\pi^+ \pi^- \pi^0$ decay with a branching ratio of $(89.3 \pm 0.6)\%$ [26]. The CLAS spectrometer was designed primarily for the detection and measurement of charged particles. Nevertheless, the overconstrained event kinematics enabled the reconstruction of a single undetected neutral meson through the missing-mass technique. Candidate $\gamma p \rightarrow p \pi^+ \pi^- (\pi^0)$ events were initially selected by requiring exactly one reconstructed proton track and two reconstructed charged-pion tracks, with the π^0 identified as the missing particle. Positively and negatively charged pions were identified based on the opposite curvatures of their tracks in the CLAS toroidal magnetic field. The acceptance for π^- mesons was lower than that for π^+ mesons because negatively charged particles were bent toward the beamline, causing a significant fraction of them to escape through the forward hole of the CLAS spectrometer. The π^0 meson was subsequently identified through kinematic fitting. The selection of the $p \pi^+ \pi^- \pi^0$ sample is outlined in detail in ref. [21].

In a brief summary, events were selected to have exactly one incident-photon candidate with a timing (using the photon tagger) at the event vertex within 1 ns of the event time provided by the SC. Only those events that had exactly one proton, π^+ , and π^- were retained. To further improve the particle identification, each particle's β value was calculated separately from its measured momentum using the DC, β_{DC} , and from its measured velocity using the TOF system and the SC, β_{TOF} . Events were selected based on good agreement of β_{DC} and β_{TOF} [21]. The momenta of the final-state particles were corrected for energy losses using standard CLAS techniques.

A four-constraint (4C) kinematic fit to the exclusive $\gamma p \rightarrow p \pi^+ \pi^-$ reaction imposing energy and momentum conservation aided in tuning the full covariance matrix. The reaction $\gamma p \rightarrow p \pi^+ \pi^-$ (missing π^0) was then kinematically fit, and events with a confidence level below 0.01 were rejected, removing most of the $\pi^+ \pi^-$ background.

3.2. Background subtraction

In a final step, the remaining background beneath the ω peak was accounted for using a multivariate side-band subtraction technique [27], which determined the probability Q for an event to be a signal event (as opposed to background) on the basis of a sample of its nearest kinematic neighbors in a very small region of the multi-dimensional $\pi^+\pi^-\pi^0$ phase space around the candidate event [21,27]. The method assumes that the signal and background distributions do not vary rapidly in the selected region. The $\pi^+\pi^-\pi^0$ mass distribution of each event and its nearest kinematic neighbors was fit using a Johnson form for the signal probability function (PDF) and a second-order Chebychev polynomial for the background PDF. The value of Q was then defined as the ratio of signal, $s(m)$, to total amplitude, $s(m) + b(m)$, at the mass m of the candidate event:

$$Q = \frac{s(m)}{s(m) + b(m)}. \quad (5)$$

The Q -factor method introduces correlations among events and their nearest neighbors because a given event can contribute to the nearest-neighbor sets of multiple *seed* events. The resulting systematic uncertainty in the extracted ω yield arising from these correlations, for a given kinematic bin, is therefore calculated as

$$\sigma_{\text{corr}}^2 = \sum_{i,j} \sigma_Q^i \rho_{ij} \sigma_Q^j, \quad (6)$$

where the sum over i and j extends over all events in the bin, σ_Q^i and σ_Q^j are the fit uncertainties associated with events i and j , respectively, and ρ_{ij} denotes the correlation coefficient between the two events. The correlation coefficient is defined as the fraction of nearest-neighbor events shared by events i and j . In this analysis, the total uncertainty on the signal yield in each kinematic bin was obtained by adding the systematic uncertainty given by Eq. (6) in quadrature with the statistical uncertainty [27].

Fig. 1 demonstrates the quality of the background subtraction. Examples of signal and background distributions are shown in the invariant $\pi^+\pi^-\pi^0$ mass obtained by weighting each event with Q and $1 - Q$, respectively. Likewise, in this analysis, event yields for cross section measurements were based on sums over Q values, whereas contributions to the decay angular distribution given by Eq. (1) have been weighted event-by-event with the corresponding Q values to subtract background.

The $\gamma p \rightarrow p\omega \rightarrow p\pi^+\pi^-\pi^0$ acceptance of CLAS was evaluated in GEANT3 [28] Monte-Carlo simulations by generating events evenly distributed across the available phase space. The Monte Carlo events were then analyzed using the same reconstruction and selection criteria that were applied to the data events [21].

4. Results

The differential ω photoproduction cross section as a function of $-t$ is shown in Fig. 2 for four selected energy bins. The horizontal bars

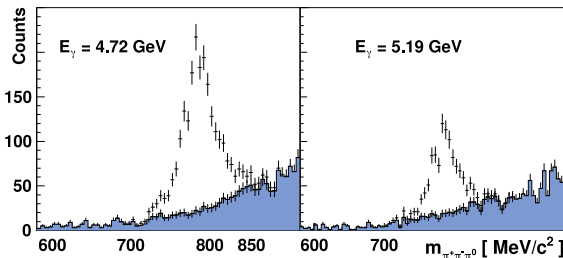


Fig. 1. Examples of signal and background mass distributions from data after applying all kinematic cuts. The invariant $\pi^+\pi^-\pi^0$ masses are shown for approximately 70-MeV-wide E_γ bins with center values of $E_\gamma = 4.72$ GeV (left) and 5.19 GeV (right). See text for details.

reflect the bin size. The full set of cross sections $d\sigma/d(\cos\Theta)$ in 20-MeV-wide and 10-MeV-wide bins for the W range 1.95–2.35 GeV and 2.35–2.83 GeV, respectively, and $d\sigma/dt$ in 20-MeV-wide bins for the W range 2.45–3.25 GeV is provided as supplemental material [29]. A ratio distribution of CLAS-g11a [20] and our new CLAS-g12 results using the $d\sigma/d(\cos\Theta)$ cross sections shows a fairly Gaussian distribution, which indicates that an overall decrease of about 1.2% is observed in these new data relative to the previous CLAS data. The earlier CLAS-g6 results [19] shown in Fig. 2 are also in excellent agreement with these new results. Data from NINA at large momentum transfer [15] underestimate the new CLAS results by about 25%. In the region $-t < 1$ GeV², good agreement is observed with the previous SLAC measurements [13]. The $d\sigma/dt$ cross sections show the expected exponential Ae^{Bt} behavior for $0.1 < -t < 0.5$ GeV². We have determined $B = 4.6 \pm 0.2$ GeV⁻² and $B = 4.1 \pm 0.3$ GeV⁻² for $W = 2.48$ GeV and 2.72 GeV, respectively. These values are consistent with the CLAS measurements of ref. [19].

A major contribution to the overall systematic uncertainty comes from the background subtraction (see details in refs. [21,27]). This absolute contribution is added in quadrature to the statistical uncertainty and shown for each data point in Fig. 2. Additional scale-type systematic uncertainties originate from modeling the detector acceptance (7.1%) [21,32], kinematic fitting (1.2%), trigger efficiency correction (1.1%), liquid-hydrogen density (0.5%) [32], photon flux normalization (5.7%) [32], and the $\omega \rightarrow \pi^+\pi^-\pi^0$ branching fraction (0.6%) [26].

For each $(W, \cos\Theta_{\text{c.m.}}^\omega)$ and $(W, -t)$ bin, an event-based maximum-likelihood technique was applied to fit Eq. (1) to the two-dimensional ω decay angular distribution spanned by the two angles of the normal to the three-pion plane in the ω rest frame. The analysis was performed in both the helicity and the Adair frames. Examples of the three unpolarized SDMEs are shown in Fig. 3 (left) for two selected 20-MeV-wide W bins and $-t < 1$ GeV² to facilitate comparison with previous results.

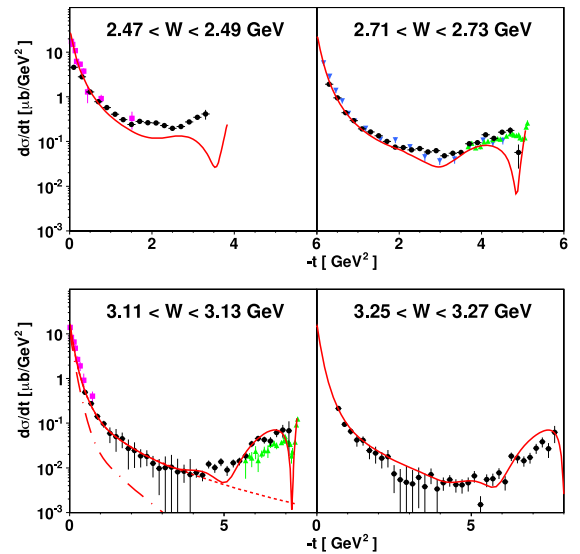


Fig. 2. Four selected examples of $d\sigma/dt$ in 20-MeV-wide center-of-mass bins. The new CLAS data are shown as the black solid circles ($\bullet$) and the uncertainties include the statistical and Q -value correlation uncertainties added in quadrature, see text for more details. The remaining energy bins for the entire W range 2.45–3.25 GeV are also available [29]. Also shown for comparison are earlier data from CLAS [19] ($\blacktriangledown$) for the energy bin $E_\gamma \in [3.38, 3.56]$ GeV, (all published data below 6 GeV from) NINA [15] ($\blacktriangle$) at $E_\gamma = 3.5$ GeV and 4.7 GeV, and SLAC [13] ($\blacksquare$) at $E_\gamma = 2.8$ GeV and 4.7 GeV. In these energy bins, $\Theta_{\text{c.m.}}^\omega = 90^\circ$ (180°) corresponds to $-t = 1.92, 2.54, 3.68, 4.08$ GeV² (3.82, 5.07, 7.37, 8.16 GeV²), respectively. The red curves denote the model predictions of ref. [30]: full solution (solid curve), only two-gluon and f_2 contributions (long dash-dotted curve), additional π exchange (dashed line).

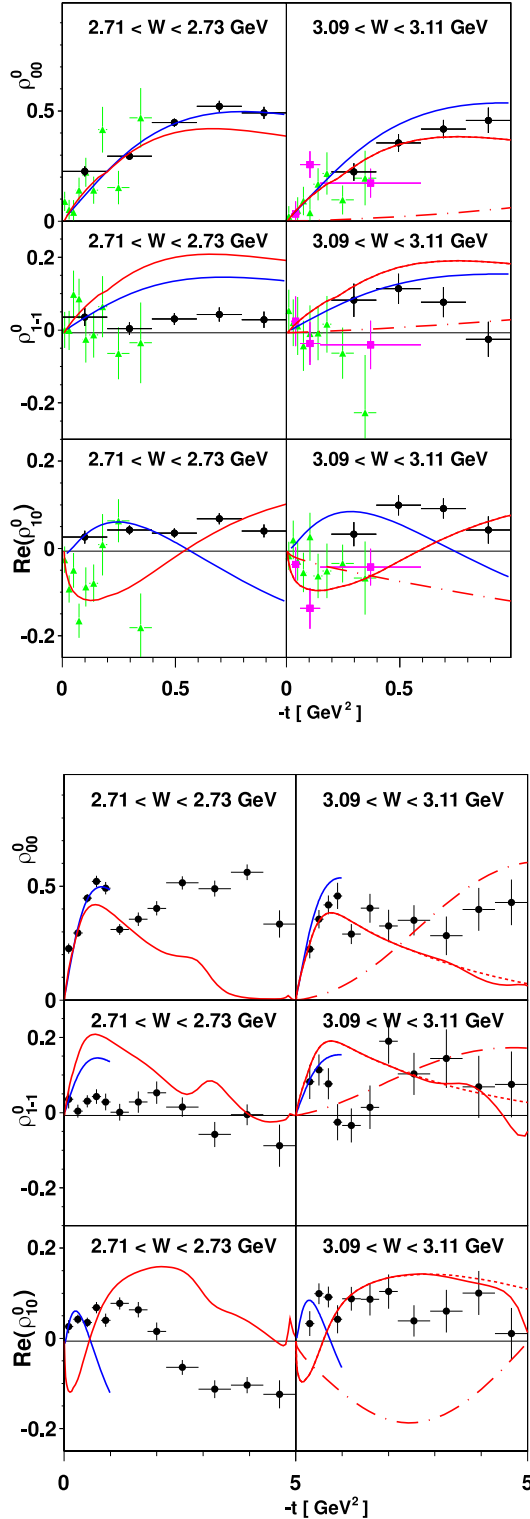


Fig. 3. Examples of the three unpolarized SDMEs ρ_{00}^0 (top), $\text{Re}(\rho_{10}^0)$ (middle), ρ_{1-1}^0 (bottom) in the Adair frame. The new CLAS data are shown as the black solid circles (●). The remaining energy bins for the entire W range 2.45–3.25 GeV are also available [31]. On the left, the three elements are shown for $0 < -t < 1 \text{ GeV}^2$ to allow for better comparison with previously published results from SLAC [13] (■) at $W \approx 3.11 \text{ GeV}$ and LAMP2 [16] (▲) at $W \approx 2.8 \text{ GeV}$ and $W \approx 3.1 \text{ GeV}$. On the right, the new results are shown for $0 < -t < 5 \text{ GeV}^2$. The blue curves denote the model prediction of ref. [10]; see caption of Fig. 2 for the red curves of ref. [30].

The full $-t$ range for these two W bins is shown in Fig. 3 (right) and for the two polarized SDMEs in Fig. 4. The full set of SDMEs from this analysis is available in ref. [31]. The observables are presented in the Adair frame to facilitate the comparison with earlier CLAS data [31]. The main advantage of this frame is that the z -axis is defined with respect to the beam direction in the overall center-of-mass (CM) frame, making the Adair frame particularly natural for studying the reaction dynamics. Systematic uncertainties were determined for all SDMEs by modifying each Q factor by its corresponding fit uncertainty σ_Q and re-extracting the observables. The absolute difference was taken as the systematic uncertainty and added in quadrature to the statistical uncertainty.

The Regge-based model of ref. [10] was developed to understand SDMEs in light vector-meson photoproduction and to study the γ - ω vertex. In the model, the Reggeon amplitude factorizes into a product of two vertices, which describe the photon and proton interactions. This factorization follows from unitarity in the t channel and allows for the study of the helicity structure at the photon vertex independently from the target. In the center-of-mass frame, the net helicity transfer between the ω meson and the photon $|\lambda_\gamma - \lambda_\omega|$ can be 0, 1, or 2, and is referred to as helicity conserving, single- and double-helicity flip, respectively. Both helicity-flip couplings have been fit to SLAC data [13] at an energy of $E_\gamma = 9.3 \text{ GeV}$ and extrapolated to lower energies. The model is shown as the blue curve in Fig. 3. In addition to natural-parity a_2 and f_2 exchanges, as well as unnatural-parity π exchange (naturalness given as $\eta = P(-1)^J$ with parity P), natural-parity Pomeron exchange has been considered. The contribution of η exchange is found to be negligible in ω photoproduction and axial-vector trajectories have been neglected in the model [10] since the pseudoscalar exchanges are sufficient to describe the unnatural components of the SDMEs. The model compares well with the unpolarized SDME ρ_{00}^0 within its valid range of about $0 < -t < 1 \text{ GeV}^2$, but overestimates the SDME ρ_{1-1}^0 and even exhibits the wrong sign for $\text{Re}(\rho_{10}^0)$ due to an overestimated contribution of unnatural π exchange relative to natural Pomeron and tensor a_2/f_2 exchanges. In the model, a reduction of π exchange would flip the sign of ρ_{10}^0 to match data.

The model described in ref. [33] was developed to analyze the cross sections of meson photo- and electroproduction channels. The red curves in Figs. 2 and 3 show the most recent predictions [30]. In the ϕ channel, the two-gluon exchange contribution reproduces the production cross section [34] and the SDME ρ_{00}^0 at high energy fairly well [35]. In ω production, this contribution is supplemented by π and f_2 exchanges at forward angles, as well as proton exchange at backward angles. While the relativistic spin-momentum dependence of the π exchange amplitude is fully taken into account, the corresponding dependence of

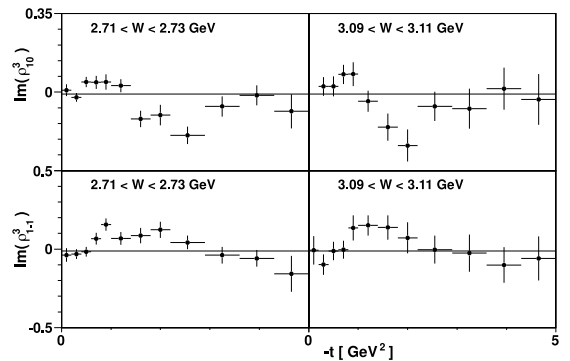


Fig. 4. Examples of the two polarized SDMEs $\text{Im}(\rho_{10}^3)$ and $\text{Im}(\rho_{1-1}^3)$ in the Adair frame for the same two energy bins presented in Fig. 3. The remaining energy bins for the entire W range 2.45–3.25 GeV are also available [31]. These results are first measurements and therefore, a model description is not yet provided.

the f_2 exchange amplitude is chosen to be the same as that for two-gluon exchange (f_2 -Pomeron equivalence) and, consequently, both conserve helicity. The only difference resides in the propagator: The two-gluon amplitude is purely imaginary (absorptive), whereas the f_2 amplitude is real and incorporates the Regge propagator with the linear trajectory of the f_2 . At intermediate angles, the use of a saturating Regge trajectory for the π meson is necessary to account for previously measured cross sections [9]. As can be seen in Fig. 2, the model agreement with the cross sections is excellent (without any adjustments), especially at the highest energies, where the data seem to indicate the predicted minimum at the most backward angles. In contrast, the new SDMEs reported here are not well described. To improve the model, it will be necessary to go beyond the Pomeron- f_2 equivalence, and take into account the actual spin-momentum structure of the f_2 exchange amplitude. This approach is not expected to change the description of the differential cross sections. Furthermore, a saturating trajectory for the f_2 can be used, at the expense of modifying that for π exchange.

5. Summary and conclusions

In summary, the first comprehensive data set of photoproduction cross sections and (un)polarized SDMEs has been presented for the reaction $\gamma p \rightarrow p\omega$ using circularly polarized tagged photons up to $W = 3.25$ GeV and the CLAS spectrometer at Jefferson Laboratory. The results are given in terms of $\cos\Theta_{\text{c.m.}}^\omega$ for $W \in [1.95, 2.83]$ GeV and in terms of $-t$ for $W \in [2.45, 3.25]$ GeV. We observe excellent agreement with predictions for the cross sections. At the highest energy, the data seem to be consistent with a downward bending at large $|-t|$ values providing a hint for the node predicted by the model in ref. [30]. Moreover, the new set of SDMEs shows fair agreement with the predictions of the JPAC model [10] for $-t < 0.5$ GeV². However, the data indicate that the model significantly overestimates the contribution of unnatural to natural π exchange, which is most obvious for $\text{Re}\rho_{10}^0$. These new measurements provide a testing ground for the improvements required in the current models. In particular, the first extraction of the polarized SDMEs $\text{Im}\rho_{10}^3$ and $\text{Im}\rho_{1-1}^3$ provides important additional information to improve our understanding of ω photoproduction in the transition from the baryon resonance regime to high-energy photoproduction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

Supplementary material

Supplementary material associated with this article can be found in the online version at [10.1016/j.physletb.2026.140845](https://doi.org/10.1016/j.physletb.2026.140845).

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