

Measurement of the helicity asymmetry $\mathbb{E}$ for the $\vec{\gamma}p \rightarrow p\pi^0$
reaction in the resonance region

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(Dated: May 15, 2023)

The double-spin-polarization observable $\mathbb{E}$ for $\vec{\gamma}\vec{p} \rightarrow p\pi^0$ has been measured with the CEBAF Large Acceptance Spectrometer (CLAS) at photon beam energies E_γ from 0.367 to 2.173 GeV (corresponding to center-of-mass energies from 1.240 to 2.200 GeV) for pion center-of-mass angles, $\cos\theta_{\pi^0}^{c.m.}$, between -0.86 and 0.82. These new CLAS measurements cover a broader energy range and have smaller uncertainties compared to previous CBELSA data and provide an important independent check on systematics. These measurements are compared to predictions as well as new global fits from The George Washington University, Mainz, and Bonn-Gatchina groups. Their inclusion in multipole analyses will refine our understanding of the single-pion production contribution to the Gerasimov-Drell-Hearn sum rule and improve the determination of resonance properties.

I. INTRODUCTION

The determination of resonance properties for all accessible baryon states is a central objective in nuclear physics. The extracted resonance parameters provide a crucial body of information for understanding the nucleon excitation spectrum and for testing models of the nucleon inspired by quantum chromodynamics (QCD) and, more recently, lattice QCD calculations. The spectra of N^* and Δ^* baryon resonances have been extensively studied through meson-nucleon scattering and meson photoproduction experiments. Properties of the known resonances continue to become better determined as experiments involving polarized beams, targets, and recoil measurements are expanded and refined [1, 2]. Extracted quantities include resonance masses, widths, branching fractions, pole positions, and associated residues, as well as photon decay amplitudes [3]. The helicity 1/2 and 3/2 photon decay ampli-

tudes ($N^* \rightarrow p\gamma$) can be extracted from a combination of resonance contributions to meson-nucleon scattering and photoproduction analyses.

New states have also been found, mainly through multichannel analyses that are sensitive to states having a relatively weak coupling to the πN decay channel [4–6]. A comprehensive overview of the available data is presented in Ref. [7]. For the reaction of interest, experimental data on the differential cross section, beam-spin asymmetry, recoil polarization, beam-target polarization observables and others have been established for a wide range in energies and angles [7]. Data on the double polarization observable $\mathbb{G}$ for the same reaction have also been recently published by the CLAS Collaboration [8]. This analysis builds from previously published work (see Ref. [8] and Ref. [9]) using the same experiment and employing similar analysis procedures. Similar approaches were also employed by the CLAS Collaboration for the determination of the beam helicity asymmetry measurements using polarized neutrons [1, 10, 11].

Here, we have extracted the beam-target ($\mathbb{E}$) observable for neutral pion photoproduction from data taken with the CLAS FROzen Spin Target (FROST) [12]. This observable is valuable both in multipole analysis and in providing a contribution to the Gerasimov-Drell-Hearn (GDH) and related sum rules [13]. Our extraction uses a different beam and polarized target apparatus as well as reaction identification methodology from the single previous measurement (see Ref. [14]). Where the data over-

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lap with the previous measurement it provides an impor-
tant independent check on systematics in the extraction
of double-polarization observable $\mathbb{E}$, while improving the
statistical quality of the world dataset. The new data also
provide first information for energies $W < 1.42$ GeV.

As described below, the observable $\mathbb{E}$ is measured using
a longitudinally polarized target and a circularly polar-
ized photon beam. The difference of cross sections for
helicity states $3/2$ and $1/2$, that is,

$$\Delta(d\sigma/d\Omega) = (d\sigma_{3/2}/d\Omega - d\sigma_{1/2}/d\Omega),$$

for $\vec{\gamma}\vec{N} \rightarrow N\pi$, is given in terms of helicity amplitudes:

$$\frac{d\sigma_{3/2}}{d\Omega} = \frac{q}{k} (|H_1|^2 + |H_3|^2), \quad (1)$$

$$\frac{d\sigma_{1/2}}{d\Omega} = \frac{q}{k} (|H_2|^2 + |H_4|^2), \quad (2)$$

where q and k are the pion and photon center-of-mass
momenta, respectively. Helicity amplitudes are labeled
following Ref. [15] with H_1 and H_3 having initial helicity
 $3/2$ and final helicities $1/2$ and $-1/2$, respectively; H_2
and H_4 have initial helicity $1/2$ and final helicities $1/2$
and $-1/2$, respectively. An integral involving $\Delta(d\sigma/d\Omega)$
gives the single-pion production part of the GDH sum-
rule [13]. The sum and difference of the helicity $1/2$ and
 $3/2$ components can then be used to construct the beam-
target polarization quantity $\mathbb{E}$ [16, 17] as

$$\mathbb{E} = \frac{|H_2|^2 + |H_4|^2 - |H_1|^2 - |H_3|^2}{|H_2|^2 + |H_4|^2 + |H_1|^2 + |H_3|^2}. \quad (3)$$

In order to extract the four helicity amplitudes, given
that they are complex quantities, we need more than
the cross section and $\mathbb{E}$. There are 16 possible experi-
ments involving polarized beams, targets, and recoil par-
ticles, not all of which are independent [16, 18]. How-
ever, the moduli of the helicity amplitudes can be deter-
mined with two additional double-polarization measure-
ments (beam-recoil and target-recoil). A complete so-
lution for these amplitudes is phrased as the “complete
experiment” problem, a topic that continues to be stud-
ied [19]. The helicity amplitudes are constructed from an
infinite sum of multipoles, and these are quantities that
provide information on the existence and properties of
resonances. This leads to the search for an appropriately
truncated set of multipoles—a problem different from
pursuing a complete experiment [20–22]. In this discus-
sion, it should be remembered that these rules for find-
ing multipoles are only guiding principles, as they ignore
the influence of experimental uncertainties. In practice,
all new experiments that improve the quality of exist-
ing measurements, or add information from new sources,
are important to the program of multipole and resonance
analysis. The advantage of the new CLAS FROST data
presented here relative to previous CBELSA measure-
ments [14] is the extended energy range covering lower
energies with smaller uncertainties.

The paper is organized in the following manner. We
give a brief background of the experimental conditions for
this study in Sec. II. An overview of the method used to
extract the double-polarized asymmetry results is given
in Sec. III and the uncertainty estimates for the data ob-
tained are given in Sec. IV. The resulting data are sum-
marized and compared to various predictions in Sec. V
and a new partial wave analysis (PWA), where we com-
pare multipoles obtained with and without including the
present dataset is presented in Sec. V A. A summary and
outlook are presented in Sec. VI.

II. EXPERIMENT

The CLAS E-03-105 experiment [23] (FROST or g9
run period) ran from December 2007 to February 2008
using the Continuous Electron Beam Accelerator Facil-
ity (CEBAF) [24] at Jefferson Lab in Newport News,
Virginia. Data were collected using the CEBAF Large
Acceptance Spectrometer (CLAS) [25] housed in Hall B.
This magnetic spectrometer allowed the efficient re-
construction of charged particles with polar angles be-
tween 8° and 140° over a large azimuthal acceptance
($\sim 83\%$). The spectrometer was constructed around a
toroidal magnetic field and was comprised of drift cham-
bers [26] for charged particle momentum determination,
time-of-flight scintillators [27] for particle identification,
electromagnetic calorimeters [28] for neutral particle re-
construction, and a start counter [29] that allowed the
event start-time determination in photoproduction ex-
periments. Hall B also housed the tagger spectrome-
ter [30] that allowed the identification of the photon that
initiated the reaction detected in CLAS, with energy res-
olution of $\Delta E \sim 0.2\%$.

In this experiment, a circularly polarized tagged
bremsstrahlung photon beam was incident on a longi-
tudinally polarized proton target [12] located near the
center of the CLAS detector [25]. The CEBAF electron
beam was supplied at two different energies, 1.645 and
2.478 GeV. The electrons were delivered at currents be-
tween 33 and 45 nA in beam bunches separated by about
2 ns. The electron beam helicity (and thus the photon he-
licity) was flipped at a rate of 30 Hz. The electron beam
was incident on a 10^{-4} radiation-length thick gold foil ra-
diator to produce the bremsstrahlung photon beam. The
dipole magnet of the Hall B photon tagger deflected the
electron beam and post-bremsstrahlung electrons in order
to tag photons produced with energies between $\sim 20\%$
and $\sim 95\%$ of the incident electron beam energy [30]. The
degree of photon polarization varied between 20% and
85% depending on the incident electron beam energy and
the bremsstrahlung photon energy. This was determined
on an event-by-event basis using the Olsen and Maximon
formula [31]

$$P_\odot = P_e \frac{4x - x^2}{4 - 4x + 3x^2}, \quad (4)$$

where x is the ratio of photon to electron energy $x = \frac{E_\gamma}{E_e}$ and P_e is the electron polarization. The electron polarization was measured throughout the run period using the Hall B Møller polarimeter [32], and the average was established to be $P_e = 0.835 \pm 0.035$.

The experiment utilized a FROzen Spin Target (FROST), made up of frozen butanol beads (C_4H_9OH), in which the protons in the hydrogen atoms were dynamically polarized. Butanol's covalently bonded protons in hydrogen atoms are polarizable using a technique called Dynamic Nuclear Polarization (DNP), in which spin polarization is simply transferred from the electrons to the nucleons. Details of the target polarization procedure can be found in Ref. [12].

The dynamically polarized target resulted in polarization of the free protons within the butanol of over 90%, with the polarization degrading over time – typically about 1% per day. Because of this, the target was repolarized periodically. The degree of polarization of the free protons was determined on a run-by-run basis using Nuclear Magnetic Resonance (NMR) measurements. The orientation of the spin of the free protons in the butanol target was also flipped regularly, enabling systematic checks.

Additional targets, carbon and polyethylene (CH_2), were placed downstream of the butanol target, which allows a detailed study of contributions from bound and unpolarized nucleons to our reaction yields. In practice, however, a free-proton signal was evident from the carbon target region, which was produced from hydrogen contamination (ice built up downstream of the target) and complicated this approach significantly. In this work, like in other FROST analyses [9, 34–38], we report a result based on an analysis of the butanol target data alone. The secondary targets were only used to establish the systematic uncertainties related to contributions from unpolarized bound nucleons within the butanol target, as discussed in Sec. III A.

A. Double Polarization Observable $\mathbb{E}$

This analysis is focused on the determination of the $\mathbb{E}$ observable, which manifests itself in the differential cross section in polarized beam - target experiments. In general, the differential cross section of polarized beam-target experiments for meson photoproduction reactions is given by [7]

$$\begin{aligned} \frac{d\sigma}{d\Omega}(E_\gamma, \cos \theta_{\pi_0}^{c.m.}, \phi) = & \sigma_0 [1 - P_L \Sigma \cos(2\phi) \\ & + P_x (-P_L \mathbb{H} \sin(2\phi) + P_\odot \mathbb{F}) \\ & - P_y (-\mathbb{T} + P_L \mathbb{P} \cos(2\phi)) \\ & - P_z (-P_L \mathbb{G} \sin(2\phi) + P_\odot \mathbb{E})], \end{aligned}$$

where P_L and $P_\odot$ correspond to the photon's degree of linear and circular polarization, and P_x , P_y , and P_z correspond to the degree of target polarization along the x ,

y , and z axes, respectively. Here, the z axis points along the photon direction, and the y axis is along the vertical direction in the lab frame. The azimuthal angle ϕ corresponds to the angle between the photon polarization vector (when the photon beam is linearly polarized) and the reaction plane defined by the incident photon and the outgoing pion directions. The observables Σ , $\mathbb{G}$, $\mathbb{H}$, $\mathbb{T}$, $\mathbb{F}$, $\mathbb{P}$, and $\mathbb{E}$ all depend on the kinematic variables E_γ (the laboratory frame photon energy) and $\cos \theta_{\pi_0}^{c.m.}$ (the center-of-mass, *c.m.*, polar angle of the meson in the final state). For a circularly polarized beam ($P_L = 0$ and $P_\odot \neq 0$) and target polarized along the z direction ($P_x = 0$ and $P_y = 0$), the cross section equation reduces to

$$\frac{d\sigma}{d\Omega}(E_\gamma, \cos \theta_{\pi_0}^{c.m.}) = \sigma_0 [1 - P_z P_\odot \mathbb{E}]. \quad (5)$$

Therefore, the observable $\mathbb{E}$ can be extracted from the unpolarized differential cross section σ_0 and the values of target and circular photon polarization P_z and $P_\odot$, respectively. Alternatively, the observable $\mathbb{E}$ can be extracted from asymmetries utilizing various orientations of the target-photon polarization. Collecting data with both photon helicities and target polarizations along the $+z$ and $-z$ directions allows the cancellation of the detector acceptance and efficiency needed for the determination of the unpolarized cross section. Denoting the total helicity state (photon-target) with $1/2$ for the case where the photon helicity is anti-parallel (also denoted as $\uparrow\downarrow$) to the target polarization and $3/2$ for the case where the photon helicity is parallel to the target polarization (also denoted as $\uparrow\uparrow$ ¹), one can determine the observable $\mathbb{E}$ from

$$\mathbb{E} = \frac{1}{P_z P_\odot} \frac{\sigma^{1/2} - \sigma^{3/2}}{\sigma^{1/2} + \sigma^{3/2}}, \quad (6)$$

where σ denotes the cross section of events obtained with the corresponding photon-target helicity. Assuming the detector efficiency, acceptance, and luminosity are constant throughout the experiment², the observable $\mathbb{E}$ can be directly extracted from the event yields (N) for each photon-target helicity configuration (the cross section is directly proportional to the event yield):

$$\mathbb{E} = \frac{1}{P_z P_\odot} \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}, \quad (7)$$

where the detector and experimental effects listed above cancel out. It is evident from Eq. (7) that a detailed determination of the target polarization P_z and photon

¹ The notations $\uparrow\downarrow$ and $\uparrow\uparrow$ represent the orientation of the target polarization relative to the photon helicity, with $\uparrow\downarrow$ and $\downarrow\downarrow$ being equivalent (same for $\uparrow\uparrow$ and $\downarrow\downarrow$).

² The effective acceptance for each configuration (*i.e.* $\uparrow\downarrow$ and $\uparrow\uparrow$) is the same due to the high beam-helicity flip rate of 30 Hz.

polarization $P_\odot$ is needed for the precise determination of $\mathbb{E}$ (see Eq. (4)). It is worth noting here that Eq. (7) is valid when no contribution from unpolarized nucleons or background is present. We discuss the effect such contributions have on the determined observable and the need to determine a dilution factor in Sec. III A.

III. REACTION RECONSTRUCTION

Events with one positively charged track were retained for further analysis. We applied a set of selection cuts to the data to identify the $\vec{\gamma}\vec{p} \rightarrow p\pi^0$ reaction. The identification of final state protons from the sample of positively charged particles was performed by comparing a particle's speed, determined from time-of-flight ($\beta_m = \frac{\text{distance}}{\text{time}}$) and start counter information, to the particle's momentum, as determined from track curvature in the toroidal magnetic field. For a given momentum, p , the expected proton speed is given by $\beta_c = \frac{p}{\sqrt{p^2 + m^2}}$, where m is the proton mass. Charged particles with $\Delta\beta = \beta_m - \beta_c$ around zero correspond to protons.

The CLAS reconstruction algorithms also allow the determination of the reaction vertex by extrapolating the particle's reconstructed track to the target region and evaluating the distance of closest approach with the incident beam position. The determined distance and time between the reaction vertex and the hit on the time-of-flight system allowed us to determine the vertex time of the event. Timing information from the tagger hodoscope also allowed us to determine the timing of each bremsstrahlung photon at the reaction vertex. Comparison between these two times allowed the unambiguous determination of the photon that initiated the reaction detected in CLAS.

Proton four-vectors were corrected for the expected energy loss sustained while exiting the target cell as well as for misalignments in the drift chambers and inaccuracies in the magnetic field maps (the latter corrections were established using the fully constrained reaction $\vec{\gamma}\vec{p} \rightarrow p\pi^+\pi^-$).

With this information, the reaction $\vec{\gamma}\vec{p} \rightarrow p\pi^0$ was fully reconstructed using the missing-mass technique. Figure 1 shows the square of the missing mass of $\gamma p \rightarrow pX$ (labeled as $M_{\gamma p \rightarrow pX}^2$) for four kinematic bins. The clear peak around the squared mass of the neutral pion corresponds to the events of interest (photoproduction of π^0 off polarized protons). This peak sits on top of a smooth background. This is primarily caused by contributions from the photoproduction of π^0 off unpolarized and bound protons, which results in a wider missing-mass distribution due to the Fermi motion of the bound nucleon. Background from double pion photoproduction reactions was determined to have only a small contribution (1-3%) using independent studies [39].

NMR measurements [33] allowed us to accurately determine the degree of proton polarization on a run-by-run basis. This reflects the polarization of events that

originated from the free protons within the butanol target. The effective target polarization P_z^{eff} allows us to account for events that originate from unpolarized material within the target cell. The determination of the effective target polarization was based on the relative yield between free- and bound-proton events. Contributions from bound nucleons dilute or reduce the effective target polarization, with the dilution factor, D_F , determined from the missing-mass distribution, as described below.

A. Contributions from Bound Protons

The contributions from unpolarized bound protons within the target cell material (butanol) were accounted for in the analysis by the determination of the dilution factor. Considering the reaction $\vec{\gamma}\vec{p} \rightarrow p\pi^0$ originating from both free polarized and bound unpolarized protons, the yields obtained from these are given by:

$$\begin{aligned} N_{free}^{\uparrow\uparrow} &= N_0(1 - P_z P_\odot \mathbb{E}), \\ N_{free}^{\uparrow\downarrow} &= N_0(1 + P_z P_\odot \mathbb{E}), \\ N_{bound}^{\uparrow\uparrow} &= N'_0, \\ N_{bound}^{\uparrow\downarrow} &= N'_0, \end{aligned}$$

where the experimental yield is given by

$$N_{exp}^{\uparrow\uparrow} = N_{free}^{\uparrow\uparrow} + N_{bound}^{\uparrow\uparrow},$$

and

$$N_{exp}^{\uparrow\downarrow} = N_{free}^{\uparrow\downarrow} + N_{bound}^{\uparrow\downarrow}.$$

From this, the experimental asymmetry results in the following:

$$\frac{N_{exp}^{\uparrow\downarrow} - N_{exp}^{\uparrow\uparrow}}{N_{exp}^{\uparrow\downarrow} + N_{exp}^{\uparrow\uparrow}} = D_F P_z P_\odot \mathbb{E}, \quad (8)$$

where $D_F = \frac{N_0}{N_0 + N'_0}$ is the dilution factor, and the product $D_F P_z$ is the effective target polarization P_z^{eff} .

In this analysis, the dilution factor was determined experimentally from the missing-mass distribution $\gamma p \rightarrow pX$, with N_0 representing the total yield of events from a free-proton target, and N'_0 the yield of events from bound protons. Specifically, we exploited the fact that reactions originating from bound protons results in a wider missing-mass distribution due to the Fermi motion of the target nucleon, to determine the ratio between free protons to our total yield. A carbon target upstream of the butanol target allowed us to establish the expected probability distribution function (PDF) that describes the missing mass from bound-nucleon events. The bound-nucleon PDF and a Gaussian to describe the free-proton events were fitted to the missing-mass distribution of events originating from the butanol target. The dilution factor was then determined by integrating the bound-nucleon PDF in the $\mu \pm 3\sigma$ range established from the

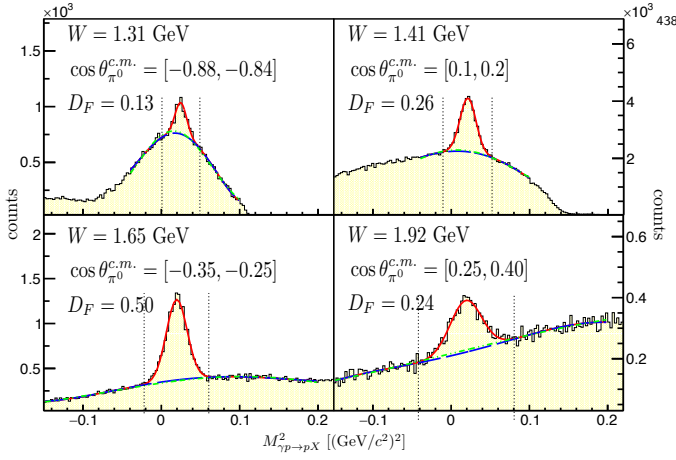


FIG. 1. Missing mass squared distribution of $\gamma p \rightarrow pX$ for four kinematic bins. Two PDFs were used to determine the bound-nucleon contribution as shown with the blue dashed and green dash-dotted lines (red solid line shows the full fit). The vertical black dotted lines indicate the $\mu \pm 3\sigma$ cuts applied to calculate the dilution factor and the reaction yields.

Gaussian fit (where μ and σ are the mean and standard deviation of the free-proton peak). An example of such fits in four kinematic bins is shown in Fig. 1. Different bound-nucleon PDFs were utilized to systematically study the effect these have on the determination of the dilution factor, as described below.

B. Yield Determination

As mentioned before, the polarization observable $\mathbb{E}$ was determined using the asymmetry of yields from the two photon-target polarization configurations (parallel and anti-parallel), as shown in Eq. (8). The yields correspond to the total number of events with a z -vertex cut between -3 cm and 3 cm that enabled us to select events that originated within the butanol target and within a missing-mass range that was dependent on the kinematic bin. The missing-mass range was the same as the range used in the dilution factor determination, established from fits to the missing-mass with a Gaussian to describe the free-proton contributions and a bound-nucleon PDF (either a second Gaussian or a polynomial). The range was then established to be at $\mu \pm 3\sigma$ for each kinematic bin.

IV. UNCERTAINTIES

The statistical uncertainties of $\mathbb{E}$ were determined using error propagation from the two yields, and accounting for the statistical uncertainty associated with the dilution factor determination. The latter was determined using the covariance matrix of the bound-nucleon fit parameters, as well as the integral and its uncertainty of the fit

to the butanol missing-mass distribution.

Source	σ^{sys}
Particle identification	0.002
Reaction reconstruction / m_X cut	0.008
Photon selection	0.015
Vertex cuts	0.006
Fiducial cuts	0.002
Dilution factor	0.014
Point-to-point D_F	0.0–0.3
Total Point-by-point (absolute) Syst.	0.023–0.301
Photon polarization	4%
Target polarization	6%
Global Scale (relative) Syst.	7.2%

TABLE I. Summary of systematic uncertainties related to the determination of the double-polarization observable $\mathbb{E}$.

A thorough assessment of systematic effects in the determined observable was carried out, including effects related to particle identification and reaction reconstruction. Uncertainties in the photon and target polarization were also evaluated and included as a global scale systematic effect. Systematic uncertainties related to the dilution factor determination were also evaluated in detail. A total dilution factor systematic uncertainty of $\sim 4\%$ was established by studying the effect different PDFs had on describing the bound-nucleon contributions. The dilution factor is expected to have a smooth dependence on the kinematic variables. A point-to-point dilution factor systematic uncertainty was also included to account for differences in the dilution factor from this smooth variation. This point-to-point systematic uncertainty was established using interpolation of the dilution values from adjacent bins and the determined value of the bin in question.

A summary of the systematic uncertainties is given in Table I. The uncertainties are split into a point-by-point (absolute) uncertainty that was applied to all points³, and a relative uncertainty (associated with the target and photon polarizations) that was applied as a scale systematic affecting all points in a correlated way.

V. RESULTS AND DISCUSSION

The current work enabled the determination of $\mathbb{E}$ between center-of-mass ($c.m.$) energies $W = 1.25$ GeV and $W = 2.23$ GeV for a wide angular coverage of the π^0 . These results extend the kinematic reach of the world

³ The point-by-point uncertainty was added to each point's statistical uncertainty in quadrature and it was treated independently for each point.

dataset for the $\mathbb{E}$ observable to lower energies, while significantly improving the statistical precision in all energy bins. The newly obtained values agree well with previously published data from CBELSA [14], as shown in Fig. 2. Specifically, Fig. 2 shows the CLAS results on $\mathbb{E}$ (black open circles) for four *c.m.* energy bins and how they compare to CBELSA (red open squares) results. The figure also provides predictions (*i.e.* PWA solutions) from the SAID (solid blue line), the MAID (magenta dashed-dotted line), and the Bonn-Gatchina (green dashed line) PWA solutions. It is evident that at lower energies, where a plethora of other data exist [7], the PWAs predict well the precise measurement of $\mathbb{E}$ from CLAS. At higher energies, significant deviations between the solutions and data are evident. Overall, the SAID and Bonn-Gatchina PWA solutions agree well, especially at larger π^0 angles in the *c.m.* frame, whereas deviations in all angles are observed between the MAID PWA solutions and our data.

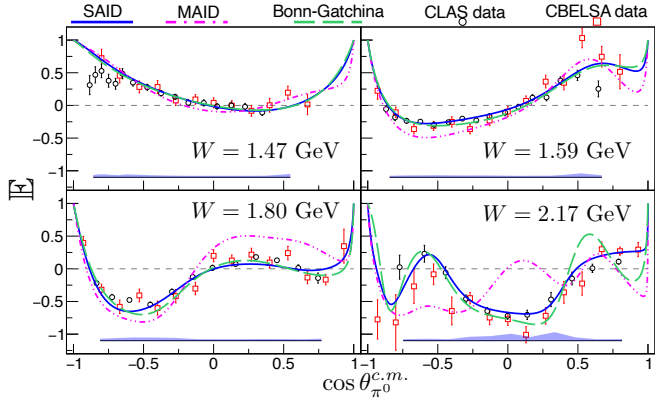


FIG. 2. Results from CLAS (black open circles) for $\mathbb{E}$ as compared to published data from CBELSA [14] (red open squares) for four kinematic bins. Statistical and point-to-point systematic uncertainties are combined in quadrature. Systematic uncertainties for CLAS results are indicated by the shaded regions at the bottom of each plot. PWA predictions for Scattering Analysis Interactive Database (SAID) SM22 [40], MAID PIONMAID-2021 [41], and Bonn-Gatchina BnGa-2022-02 [42] are shown in solid blue, magenta dashed-dotted, and green dashed curves, respectively. The CBELSA data were included in the SAID, MAID, and Bonn-Gatchina fits.

The full kinematic coverage of the CLAS dataset is illustrated in Fig. 3 (CBELSA results are omitted in these plots). The new results were included in the world database and PWA fits were performed in all three frameworks. Specifically, the new PWA solutions for SAID (blue solid line), MAID (magenta dashed-dotted line), and Bonn-Gatchina (green dashed line) that account for the CLAS $\mathbb{E}$ results (in addition to the other world data) are shown in Fig. 3. These new fits describe well the $\mathbb{E}$ data, with the exception of the MAID solution at energies $W > 2.10$ GeV. More details on the PWA fits and

their findings are provided below.

A. Multipole analysis

In the SAID multipole analysis of these data, an energy-dependent parametrization, based on the Chew-Mandelstam K -matrix approach, has been used. The Chew-Mandelstam parametrization (CM) for a hadronic T matrix, described in Ref. [43], was used in a previous coupled-channel fit of πN elastic scattering and $\pi N \rightarrow N\eta$ reaction data. The parametrization form used in that fit was given as

$$T_{\alpha\beta} = \sum_{\sigma} [1 - \bar{K}C]_{\alpha\sigma}^{-1} \bar{K}_{\sigma\beta}, \quad (9)$$

where the notation $\bar{K}$ was used to distinguish this from the Heitler K -matrix [44] and α, β , and σ are indices that label the channels, πN , $\pi\Delta$, ρN , and ηN . The parameter C corresponds to the Chew-Mandelstam function described in Ref. [45]. Given the success of this approach in the hadronic two-body sector, the fit formalism was extended to pion photoproduction [46].

The Chew-Mandelstam form of Eq. (9) has been extended to include the electromagnetic channel as:

$$T_{\alpha\gamma} = \sum_{\sigma} [1 - \bar{K}C]_{\alpha\sigma}^{-1} \bar{K}_{\sigma\gamma}. \quad (10)$$

Here, γ denotes the electromagnetic channel, γn , and σ denotes the hadronic channels that appear in the parametrization of the hadronic rescattering matrix,

$$[1 - \bar{K}C]^{-1}.$$

By sharing this common factor, which qualitatively encodes the hadronic channel coupling (or rescattering) effects, Eqs. (9) and (10) constitute a unified approach to the problem of parametrizing the hadronic scattering and photoproduction amplitudes.

The existing hadronic elements of Eq. (9) were not varied in the fits of the photoproduction data. For this reason, the photoproduction fits have a resonance structure identical to that found in Ref. [43]. The electromagnetic CM K -matrix elements contain polynomials in energy with the correct threshold behavior. The order of these polynomials was increased until the fit's χ^2 value was not significantly improved. At this level, increasing the order no longer produced significant improvements to the fit. While the initial fit from SAID to the present set of data delivered a good overall description, some systematic deviations were noticed at back angles and at the highest energies.

PionMAID-2021 is an updated version of the unitarity isobar model MAID2007 [47]. It has been developed to analyze the world data of neutral- and charged-pion photoproduction. The model contains a resonance part, parameterized by a Breit-Wigner shape, and a background

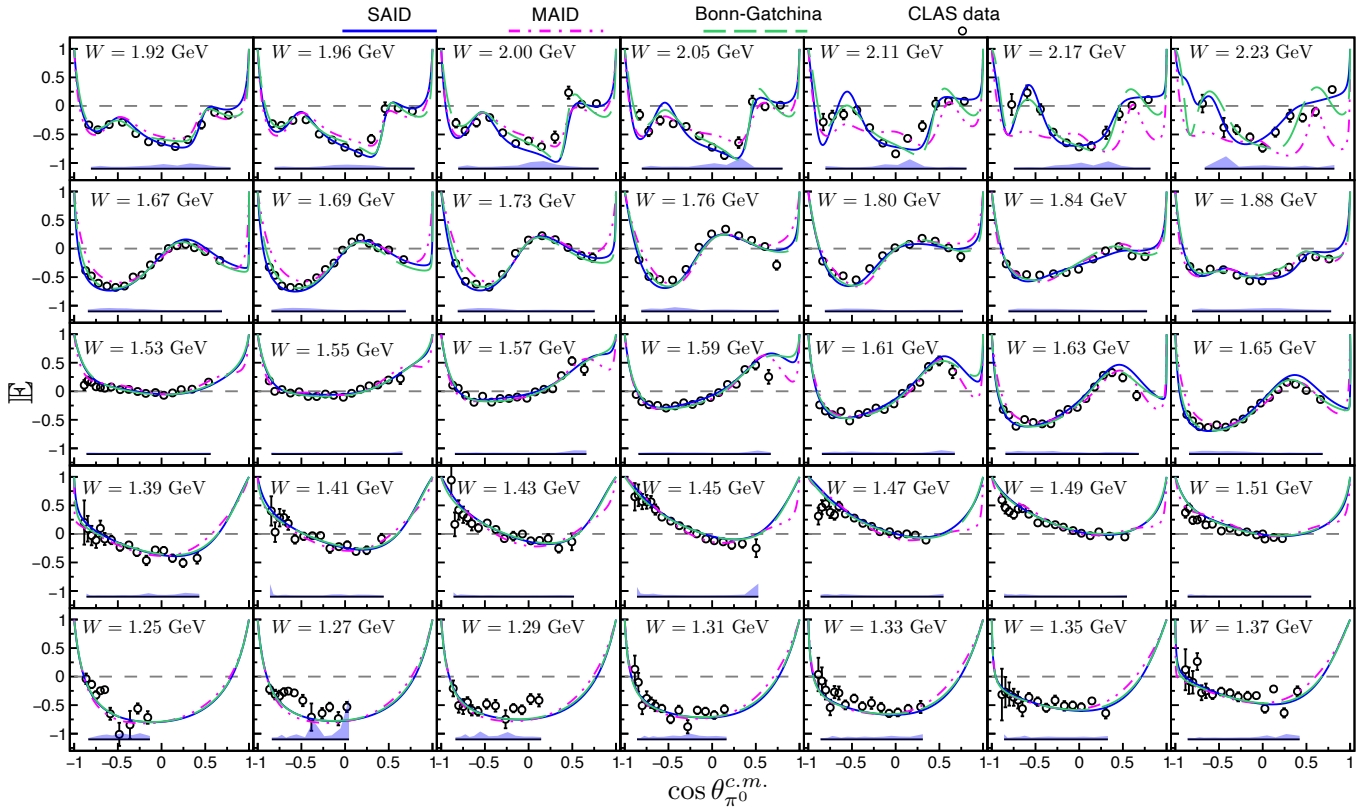


FIG. 3. Double-polarization observable E (black open circles) from this work as a function of the pion angle in the $c.m.$ frame. The different panels denote bins in $c.m.$ energy W . The new SAID KI22 (blue solid curves), the Bonn-Gatchina (green dashed curves), and MAID (magenta dashed-dotted curves) solutions are also indicated in the panels. Statistical and point-to-point systematic uncertainties are combined in quadrature. Systematic uncertainties are indicated in the shaded regions at the bottom of each plot.

with Born terms in the resonance region. Regge phenomenology was applied at energies above the resonance region [41] for neutral and for charged pion photoproduction [48, 49]. The model describes experimental data up to photon energies of 18 GeV and is well adapted for predictions at higher energies.

The Bonn-Gatchina model was developed for the partial wave analysis of reactions with multi-particle final states. The particle interaction vertices are described in the framework of the covariant tensor formalism and the energy-dependent part of the partial wave amplitudes satisfies unitarity and analyticity conditions. The description of the method can be found in Ref. [50]. The present solution describes 201 datasets, which includes the pion- and photon-induced reactions with one or two pseudoscalar mesons in the final state, as well as photon-induced reactions with production of the ω meson.

In Table II, χ^2 values are compared for fits in which the present data were included and those in which they were not. Figure 3 gives a more detailed view of the improved quality of the fits obtained with the SAID, MAID and Bonn-Gatchina approaches. While the overall fit is quite good, the largest discrepancies are seen at backward angles and higher energies, as illustrated in Fig. 4. Fig. 5

similarly shows that the fit is not uniformly good, with the largest χ^2 values occurring at higher energies, as one would expect.

As for variations in multipole amplitudes due to the inclusion of the new data, the Bonn-Gatchina group found changes in the helicity 1/2 and 3/2 photon decay amplitudes associated with the $N(2120)3/2^-$ and changes of the helicity 1/2 amplitude associated with the $\Delta(1940)3/2^-$. These states are not included in the SAID model and changes were seen only for amplitudes at the highest energies, which were small in magnitude. No significant resonance changes were reported in the MAID re-analysis.

PWA	No FROST	With FROST
SAID	SM22: 2.1	KI22: 1.5
MAID	pionMAID-2021: 5.2	2.7
BnGa	BnGa-2022-02: 2.7	1.8

TABLE II. Summary of $\chi^2/\text{data point}$ for the new FROST E data. PWA solutions are SAID: SM22 [40] and new KI22. MAID: PIONMAID-2021 [51]. Bonn-Gatchina: BnGa-2022-02 [42].

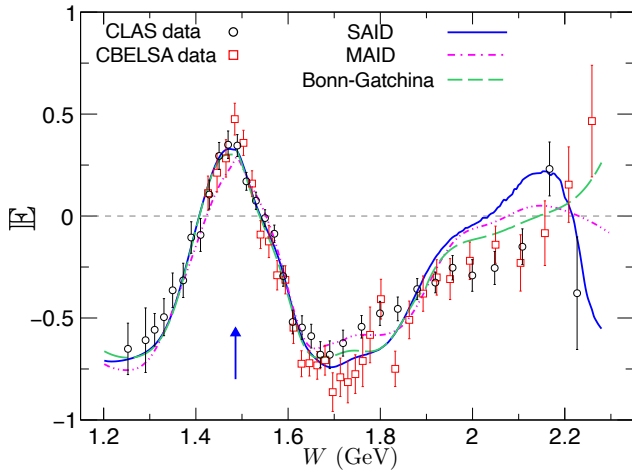


FIG. 4. Comparison of the present CLAS FROST data (black open circles) and previous CBELSA measurements [14] (red open squares) vs. present SAID KI22 (blue solid curve), MAID (magenta dashed-dotted curve), and Bonn-Gatchina (green dashed curve) solutions for the $\gamma\bar{p} \rightarrow p\pi^0$ reaction and for the double-polarization observable $\mathbb{E}$ at 120° . The new CLAS FROST $\mathbb{E}$ data are included in the fits. Statistical and point-to-point systematic uncertainties are combined in quadrature. The blue vertical arrow indicates the η production threshold.

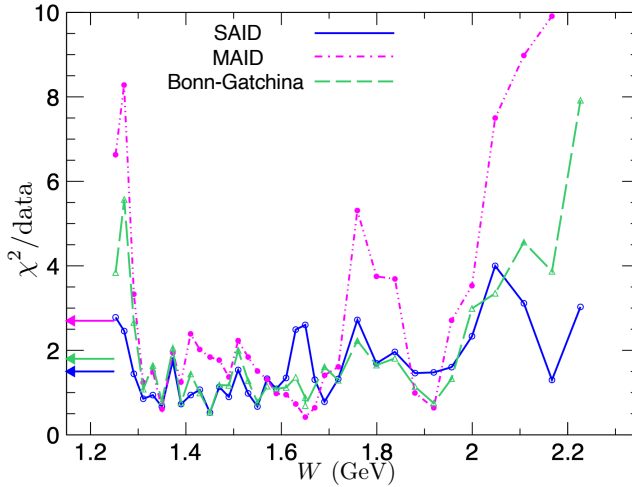


FIG. 5. Comparison of the present SAID KI22 (blue open circles and solid line), MAID (magenta filled circles and dashed-dotted line), and Bonn-Gatchina (green open triangles and dashed line) fits for the $\gamma\bar{p} \rightarrow p\pi^0$ reaction for the double-polarization observable $\mathbb{E}$. The lines connecting the points are included only to guide the eye. Shown are the fit χ^2 -per-data-point values averaged within each energy bin, where the arrows (blue for SAID, magenta for MAID, and green for Bonn-Gatchina) show the overall χ^2 per data point values from Table II.

While the inclusion of new and precise polarization measurements has led to better agreement between groups extracting multipole amplitudes [2], the prediction of new quantities, or existing quantities outside

their ranges of measurement, is generally only qualitative, as can be seen in Figs. 2 and 4. The most extensive single- and double-polarization data above photon energies of 2 GeV, come from pre-1980 Daresbury experiments with limited angular coverage. More recent measurements at Jefferson Lab, MAMI, Bonn, and SPring-8 have provided data with higher precision and broader angular range, but do not provide a database approaching a “complete experiment.” Each new measurement is particularly valuable at these higher energies. More detailed analyses from SAID [40], MAID, and Bonn-Gatchina are expected and will include these and other recent data.

VI. SUMMARY AND OUTLOOK

The CLAS E-03-105 experiment (FROST), which utilized longitudinally polarized protons and circularly polarized photons, allowed the precise determination of the beam-helicity asymmetry $\mathbb{E}$ for the $\gamma\bar{p} \rightarrow p\pi^0$ reaction. The new results provide an important independent check on the extraction of the double-polarization observable $\mathbb{E}$ with a precision improved over the past data from CBELSA, while extending the kinematical coverage at lower energies. Specifically, the newly obtained data cover *c.m.* energies between $W = 1.25$ GeV and $W = 2.23$ GeV, whereas results from CBELSA provided an energy coverage between $W = 1.42$ GeV and $W = 2.58$ GeV.

PWA fits within the SAID, MAID, and Bonn-Gatchina frameworks were performed with the inclusion of this newly obtained dataset. The Bonn-Gatchina group found changes in the helicity 1/2 and 3/2 photon decay amplitudes associated with the $N(2120)3/2^-$ and changes of the helicity 1/2 amplitude associated with the $\Delta(1940)3/2^-$, while the MAID solution did not show any significant changes. A detailed analysis from the SAID group is underway to establish the impact of this new dataset and their findings will be reported in a dedicated paper.

Numerical CLAS FROST $\mathbb{E}$ data are available in the SAID [52], CLAS [53], and University of York Pure databases [54].

VII. ACKNOWLEDGMENTS

This work was supported in part by the U. S. Department of Energy, Office of Science, Office of Nuclear Physics under Awards No. DE-SC0016583 and DE-SC0016582; by the U. K. Science and Technology Facilities Council grants, ST/P004385/2, ST/T002077/1, and ST/L00478X/2; by the EU Horizon 2020 research by innovation program, STRONG-2020 project (under grant agreement No. 824093), as well as by the Russian Science Foundation RSF22-22-00722 grant. We also acknowledge the outstanding efforts of the staff of the Acceler-

ator and Physics Divisions at Jefferson Lab that made this experiment possible. The Southeastern Universities Research Association (SURA) operated the Thomas Jefferson National Accelerator Facility for the United States Department of Energy under contract DE-AC05-06OR23177. Further support was provided by the National Science Foundation, the Italian Istituto Nazionale

di Fisica Nucleare, the Chilean Comisión Nacional de Investigación Científica y Tecnológica (CONICYT), the Chilean Agency of Research and Development (ANID), the French Centre National de la Recherche Scientifique, the French Commissariat à l’Energie Atomique, and the National Research Foundation of Korea.

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- [1] D. Ho *et al.* [CLAS Collaboration], “Beam-target helicity asymmetry for $\vec{\gamma} n \rightarrow \pi^- p$ in the N^* resonance region,” *Phys. Rev. Lett.* **118**, 242002 (2017).
- [2] A. V. Anisovich, R. Beck, M. Döring, M. Gottschall, J. Hartmann, V. Kashevarov, E. Klempt, U. G. Meißner, V. Nikonov, M. Ostrick *et al.* “The impact of new polarization data from Bonn, Mainz and Jefferson Laboratory on $\gamma p \rightarrow \pi N$ multipoles,” *Eur. Phys. J. A* **52**, 284 (2016).
- [3] R. L. Workman *et al.* [Particle Data Group], *Prog. Theor. Exp. Phys.* **2022**, 083C01 (2022).
- [4] D. Rönchen, M. Döring, H. Haberzettl, J. Haidenbauer, U. G. Meißner, and K. Nakayama, “Eta photoproduction in a combined analysis of pion- and photon-induced reactions,” *Eur. Phys. J. A* **51**, 70 (2015).
- [5] The Bonn-Gatchina analyses are available through the Bonn website: <http://pwa.hiskp.uni-bonn.de/>; see also E. Gutz *et al.* [CBELSA/TAPS Collaboration], “High statistics study of the reaction $\gamma p \rightarrow p\pi^0\eta$,” *Eur. Phys. J. A* **50**, 74 (2014).
- [6] H. Kamano, S. X. Nakamura, T. S. H. Lee, and T. Sato, “Nucleon resonances within a dynamical coupled-channels model of πN and γN reactions,” *Phys. Rev. C* **88**, 035209 (2013).
- [7] D. G. Ireland, E. Pasyuk, and I. Strakovsky, “Photoproduction reactions and non-strange baryon spectroscopy,” *Prog. Part. Nucl. Phys.* **111**, 103752 (2020).
- [8] N. Zachariou *et al.* [CLAS Collaboration], “Double polarization observable $\mathbb{G}$ for single pion photoproduction from the proton,” *Phys. Lett. B* **817**, 136304 (2021).
- [9] S. Strauch *et al.* [CLAS Collaboration], “First measurement of the polarization observable $\mathbb{E}$ in the $\vec{p}(\vec{\gamma}, \pi^+)n$ reaction up to 2.25 GeV,” *Phys. Lett. B* **750**, 53 (2015).
- [10] D. Ho *et al.* [CLAS Collaboration], “Beam-target helicity asymmetry $\mathbb{E}$ in $K^0\Lambda$ and $K^0\Sigma^0$ photoproduction on the neutron,” *Phys. Rev. C* **98**, 045205 (2018).
- [11] N. Zachariou *et al.* [CLAS Collaboration], “Beam-target helicity asymmetry $\mathbb{E}$ in $K^+\Sigma^-$ photoproduction on the neutron,” *Phys. Lett. B* **808**, 135662 (2020).
- [12] C. D. Keith, J. Brock, C. Carlin, S. A. Comer, D. Kashy, J. McAndrew, D. G. Meekins, E. Pasyuk, J. J. Pierce, and M. L. Seely, “The Jefferson Lab Frozen Spin Target,” *Nucl. Instrum. Meth. A* **684**, 27 (2012).
- [13] I. Strakovsky, S. Širca, W. J. Briscoe, A. Deur, A. Schmidt, and R. L. Workman, “Single-pion contribution to the Gerasimov-Drell-Hearn sum rule and related integrals,” *Phys. Rev. C* **105**, 045202 (2022).
- [14] M. Gottschall *et al.* [CBELSA/TAPS Collaboration], “First measurement of the helicity asymmetry for $\gamma p \rightarrow p\pi^0$ in the resonance region,” *Phys. Rev. Lett.* **112**, 012003 (2014).
- [15] R. Walker, “Phenomenological analysis of single pion production,” *Phys. Rev.* **182**, 1729 (1969).
- [16] I. S. Barker, A. Donnachie, and J. K. Storrow, “Complete experiments in pseudoscalar photoproduction,” *Nucl. Phys. B* **95**, 347 (1975).
- [17] R. L. Workman and R. A. Arndt, “Saturation of the Drell-Hearn-Gerasimov sum rule revisited,” *Phys. Rev. D* **45**, 1789 (1992).
- [18] W.-T. Chiang and F. Tabakin, “Completeness rules for spin observables in pseudoscalar meson photoproduction,” *Phys. Rev. C* **55**, 2054 (1997).
- [19] K. Nakayama, “On the spin-observables in pseudoscalar meson photoproduction,” *J. Phys. G* **46**, 105108 (2019).
- [20] A. Švarc, Y. Wunderlich, H. Osmanović, M. Hadžimehmedović, R. Omerović, J. Stahov, V. Kashevarov, K. Nikonov, M. Ostrick, L. Tiator *et al.* “Connection between angle-dependent phase ambiguities and the uniqueness of the partial-wave decomposition,” *Phys. Rev. C* **97**, 054611 (2018).
- [21] Y. Wunderlich, A. Švarc, R. L. Workman, L. Tiator, and R. Beck, “Toward an understanding of discrete ambiguities in truncated partial-wave analyses,” *Phys. Rev. C* **96**, 065202 (2017).
- [22] R. L. Workman, L. Tiator, Y. Wunderlich, M. Döring, and H. Haberzettl, “Amplitude reconstruction from complete photoproduction experiments and truncated partial-wave expansions,” *Phys. Rev. C* **95**, 015206 (2017).
- [23] “Pion photoproduction from a polarized target,” Spokespersons: N. Benmouna, W. J. Briscoe, G. V. O’Rielly, I. I. Strakovsky, and S. Strauch [CLAS Collaborations], JLab Proposal E-03-105, Newport News, VA, USA, 2003.
- [24] C. W. Leemann, D. R. Douglas, and G. A. Krafft, “The Continuous Electron Beam Accelerator Facility: CEBAF at the Jefferson Laboratory,” *Ann. Rev. Nucl. Part. Sci.* **51**, 413 (2001).
- [25] B. A. Mecking *et al.*, “The CEBAF Large Acceptance Spectrometer (CLAS),” *Nucl. Instrum. Meth. A* **503**, 513 (2003).
- [26] M. D. Mestayer, D. S. Carman, B. Asavapibhop, F. J. Barbosa, P. Bonneau, S. B. Christo, G. E. Dodge, T. Dooling, W. S. Duncan, S. A. Dytman *et al.* “The CLAS drift chamber system,” *Nucl. Instrum. Meth. A* **449**, 81 (2000).
- [27] E. S. Smith, T. Carstens, J. Distelbrink, M. Eckhause, H. Egiyan, L. Elouadrhiri, J. Ficenec, M. Guidal, A. D. Hancock, F. W. Hersman *et al.* “The time-of-flight system for CLAS,” *Nucl. Instrum. Meth. A* **432**, 265 (1999).
- [28] M. Amarian, G. Asrian, K. Beard, W. Brooks, V. Burkert, T. Carstens, A. Coleman, R. Demirchian, Y. Efre-

- menko, H. Egiian *et al.* “The CLAS forward electro-795
magnetic calorimeter,” Nucl. Instrum. Meth. A **460**, 239796
(2001). 797
- [29] Y. G. Sharabian, M. Battaglieri, V. D. Burkert, R. De798
Vita, L. Elouadrhiri, L. Guo, D. Kashy, V. Kubarovskiy,799
G. S. Mutchler, M. Ostrick *et al.* “A new highly seg-800
mented start counter for the CLAS detector,” Nucl. In-801
strum. Meth. A **556**, 246 (2006). 802
- [30] D. I. Sober, H. Crannell, A. Longhi, S. K. Matthews,803
J. T. O’Brien, B. L. Berman, W. J. Briscoe, P. L. Cole,804
J. P. Connelly, W. R. Dodge *et al.* “The bremsstrahlung805
tagged photon beam in Hall B at JLab,” Nucl. Instrum.806
Meth. A **440**, 263 (2000). 807
- [31] H. Olsen and L. C. Maximon, “Photon and electron po-808
larization in high-energy bremsstrahlung and pair pro-809
duction with screening,” Phys. Rev. **114**, 887 (1959). 810
- [32] C. K. Sinclair, “Electron beam polarimetry,” Thomas811
Jefferson National Accelerator Facility (U. S.) (1998). 812
- [33] S. Goertz, W. Meyer, and G. Reicherz, “Polarized H, D,813
and He-3 targets for particle physics experiments,” Prog.814
Part. Nucl. Phys. **49**, 403 (2002) [erratum: Prog. Part.815
Nucl. Phys. **51**, 309 (2003)]. 816
- [34] I. Senderovich *et al.* [CLAS Collaboration], “First mea-817
surement of the helicity asymmetry $\mathbb{E}$ in η photoproduc-818
tion on the proton,” Phys. Lett. B **755**, 64 (2016). 819
- [35] Z. Akbar *et al.* [CLAS Collaboration], “Measurement of820
the helicity asymmetry $\mathbb{E}$ in $\omega \rightarrow \pi^+\pi^-\pi^0$ photoproduc-821
tion,” Phys. Rev. C **96**, 065209 (2017). 822
- [36] P. Roy *et al.* [CLAS Collaboration], “Measurement of823
the beam asymmetry Σ and the target asymmetry $\mathbb{T}$ in824
the photoproduction of ω mesons off the proton using825
CLAS at Jefferson Laboratory,” Phys. Rev. C **97**, 055202826
(2018). 827
- [37] P. Roy *et al.* [CLAS Collaboration], “First measurements828
of the double-polarization observables $\mathbb{F}$, $\mathbb{P}$, and $\mathbb{H}$ in829
 ω photoproduction off transversely polarized protons in830
the N^* resonance region,” Phys. Rev. Lett. **122**, 162301831
(2019). 832
- [38] N. Zachariou *et al.* [CLAS Collaboration], “Double po-833
larisation observable $\mathbb{G}$ for single pion photoproduction834
from the proton,” Phys. Lett. B **817**, 136304 (2021). 835
- [39] M. Dugger *et al.* [CLAS Collaboration], “Beam asymme-836
try Σ for π^+ and π^0 photoproduction on the proton for837
photon energies from 1.102 to 1.862 GeV,” Phys. Rev. C838
88, 065203 (2013). 839
- [40] W. J. Briscoe, A. Schmidt, I. Strakovsky, R. L. Workman,
and Alfred Švarc, “Extended SAID partial-wave analysis
of pion photoproduction,” in progress.
- [41] V. L. Kashevarov, M. Ostrick, and L. Tiator, “Regge phe-
nomenology in π^0 and η photoproduction,” Phys. Rev. C
96, 035207 (2017).
- [42] T. Seifen *et al.* [CBELSA/TAPS Collaboration], “Polar-
ization observables in double neutral pion photoproduc-
tion,” [arXiv:2207.01981 [nucl-ex]].
- [43] R. A. Arndt, W. J. Briscoe, I. I. Strakovsky, and
R. L. Workman, “Extended partial-wave analysis of πN
scattering data,” Phys. Rev. C **74**, 045205 (2006).
- [44] M. W. Paris and R. L. Workman, “Toward a unified
description of hadro- and photoproduction: S -wave π^-
and η^- photoproduction amplitudes,” Phys. Rev. C **82**,
035202 (2010).
- [45] R. A. Arndt, J. M. Ford, and L. D. Roper, “Pion - nu-
cleon partial wave analysis to 1100-MeV,” Phys. Rev. D
32, 1085 (1985).
- [46] R. L. Workman, R. A. Arndt, W. J. Briscoe, M. W. Paris,
and I. I. Strakovsky, “Parameterization dependence of T
matrix poles and eigenphases from a fit to πN elastic
scattering data,” Phys. Rev. C **86**, 035202 (2012).
- [47] D. Drechsel, S. S. Kamalov, and L. Tiator, “Unitary Iso-
bar Model - MAID2007,” Eur. Phys. J. A **34**, 69 (2007).
- [48] M. Guidal, J. M. Laget, and M. Vanderhaeghen, “Pion
and kaon photoproduction at high-energies: Forward and
intermediate angles,” Nucl. Phys. A **627**, 645 (1997).
- [49] J. M. Laget, “Exclusive meson photo- and electro-
production, a window on the structure of hadronic mat-
ter,” Prog. Part. Nucl. Phys. **111**, 103737 (2020).
- [50] A. V. Anisovich, V. A. Nikonov, A. V. Sarant-
sev, V. V. Anisovich, M. A. Matveev, T. O. Vulf, K. V.
Nikonov, and J. Nyiri, “Analysis of the meson-
meson data in the framework of the dispersion D -matrix
method,” Phys. Rev. D **84**, 076001 (2011).
- [51] V. L. Kashevarov and L. Tiator, private communication,
2022.
- [52] W. J. Briscoe, I. I. Strakovsky, and R. L. Work-
man, GWU CNS DAC SAID database located at
http://gwdac.phys.gwu.edu/analysis/pr_analysis.html.
- [53] CLAS Physics Database is available through the JLab
CLAS website: <http://clasweb.jlab.org/physicsdb>.
- [54] The data supporting this research is openly available
from the University of York Pure repository with DOI:
10.15124/99b659e3-e612-45f1-83f9-9122c9aa711c.