A Comprehensive Study of Discrepancies in Photoproduction Reactions

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(Dated: Received: May 24, 2012/ Revised version:)

Facilities worldwide have accumulated data to extract meson photoproduction amplitudes. The current focus is on complete experiments which involve the determination of 16 spin-dependent observables in single- and double-polarization experiments. While only 8 well-chosen observables are needed in the mathematical problem to extract the scattering amplitude without ambiguities, an experimental approach will require a significantly larger number of observables because of unavoidable experimental uncertainties. Observables for complete experiments will also come from different facilities which use detectors optimized for different reactions and kinematical regions. The current agreement of available cross section data from different experiments is unsatisfactory above $E_\gamma = 1.5$ GeV and in the more forward and backward directions of the c.m. system. Here, we review the experimental database and present a comprehensive picture of the observed normalization issues and some discrepancies in the angular distributions in photoproduction reactions.

PACS numbers: 13.60.Le Meson production, 13.60.-r Photon and charged-lepton interactions with hadrons, 14.40.Aq π, K, and η mesons, 25.20.Lj Photoproduction reactions

I. INTRODUCTION

The spectrum of excited states has provided essential information on the nature of particles. The careful mapping of the hadron spectrum shines light on the effective degrees of freedom that give rise to excited hadrons and the nature of the nonperturbative regime of quantum chromodynamics (QCD). Symmetric quark models that attempt to describe the spectrum of baryons predict the pattern of low mass states quite well. However, the predicted baryons with masses above about 1.8 GeV/c^2 greatly outnumber the experimentally found states. Despite efforts to find physical mechanisms to account for these discrepancies, no satisfactory answer has been found. Experimentally, most known baryon resonances lie below 2 GeV/c^2 and were discovered in elastic πN scattering experiments. Work by Koniuk and Isgur [1] and later by Capstick and Roberts [2–4] have shown that many of these "missing" baryons have weak πN couplings, but strongly couple to γN. In recent years, many laboratories around the world (Jefferson Laboratory, ELSA, MAMI, GRAAL, SPring-8, etc.) have published differential and total cross sections as well as polarization observables of photoproduced final states. A nice review on baryon spectroscopy is given in [5].

The photoproduction of single-pseudoscalar mesons off the nucleon is described by four complex helicity amplitudes: two for the spin states of the photon, two for the target nucleon, and two for the recoiling baryon; parity considerations reduce these eight amplitudes to four. Experimentally, 16 observables can be determined: the unpolarized differential cross section, $d\sigma_0$, three single-spin observables, Σ (beam), T (target), P (recoil), and three sets of four asymmetries: beam-target, beam-recoil, and target-recoil. It has been shown in [6] that angular distributions of at least eight carefully chosen observables at each energy are needed for both proton and neutron to determine the full scattering amplitude without ambuguities. Such "complete" experiments are now underway at facilities worldwide. Since real experiments determine observables with sizable experimental uncertainties, more than the proposed eight experiments will be needed. Moreover, the experimental efforts are partially complementary (in terms of observable reactions, energy, and angular range) so that a complete set of observables will come from different experiments. The quoted systematic uncertainties from most experiments are on the order of 10 % and are not large enough to explain or reconcile the differences that are on the order of 40 % in some kinematic regions. The effect of these discrepancies on the interpretation of the data in terms of contributing baryon resonances, e.g. in a Partial Wave Analysis (PWA), is striking. In the case of η photoproduction, this has been discussed for example by Sibirtsev et al. [7].

The normalization discrepancies in photoproduction reactions have been recently discussed by Dey *et al.* [8]. The authors highlight the fact that differential cross sections from older SLAC/DESY/CEA data for the pseudoscalar meson channels used untagged bremsstrahlung photon beams and are roughly a factor of two larger than the more recent tagged photon experiments from the CLAS "g11a" experiment. Along with these normalization discrepancies, the authors also discuss discrepancies between CLAS and experiments at ELSA for the η and π^0 channels.

In this review, we expand the study of discrepancies in photoproduction reactions, include more data in our discussion, and present a different view of the experimental situation. The paper is structured in the following way. In Section II, we give an overview of recent and earlier photoproduction experiments which published cross section results for incoming photon energies above 1.2 GeV. Section III describes the difficulties in comparing results from different experiments. Results on a large variety of different reactions are then discussed in Section IV. We summarize and conclude in Section V.

II. PUBLISHED CROSS SECTION DATA

Data on meson photoproduction off the proton were recorded using many different detector systems. In this section, we discuss the experiments which contributed to cross section measurements above incoming photon energies of about $E_\gamma > 1.2$ GeV.

A. Photoproduction experiments using the bremsstrahlung technique

At Jefferson Laboratory (JLab), the CLAS spectrometer utilizes information from a set of drift chambers in a toroidal magnetic field and time-of-flight information to detect and reconstruct charged particles. A detailed description of the spectrometer and its various detector components is given in [9].

Three CLAS experiments are relevant for this review. The "g1" experiment accumulated data in 1998 (g1a) and in 1999 (g1c) utilizing electron beam energies of 2.49 and 2.45 GeV (3.12 GeV in a second data run), respectively. These experiments used a single-prong trigger configuration which allowed to record single-pion events. Results from the "g1a" experiment were only published for the reaction $\gamma p \to p\eta$ [10]. For the absolute normalization of the η channel, the SAID-SM02 solution [11] was used to normalize the measured relative cross sections for π^0 photoproduction. The normalization uncertainty for all photon energies below 2 GeV was estimated at 3 % [10]. The CLAS "g1c" experiment recorded data under very similar experimental conditions and allowed for an absolut normalization of the angular distributions by measuring the photon flux. Results relevant for this review can be found in [12–19].

The CLAS "g11a" experiment accumulated a high-statistics data sample in 2004 of about 20 billion triggered events. This experiment was dedicated to the search for the exotic Θ^+ pentaquark state and utilized a two-prong trigger configuration to optimize the detection of events with multiple charged tracks in the final state. The CLAS detector is divided into six azimuthally-symmetric sectors and coincidences within a time window of 150 ns between the photon tagger and two charged particles in two different sectors triggered the recording of the events. This trigger was needed for the rather specific physics motivation, but the experiment did not allow to analyze the single-pion channel. A primary electron beam of energy $E_0 = 4.023$ GeV was used to generate tagged photons with energies between 0.81 and 3.81 GeV covering center-of-mass energies up to $\sqrt{s} \approx 2.84$ GeV. Results on cross sections can be found in [20–25].

At the ELectron Stretcher Accelerator (ELSA), three very different experimental setups extracted cross section data for several photo-induced reactions. In 2001, the CB-ELSA detector recorded events to analyze the reactions $\gamma p \to p\pi^0$ [26, 27] and $\gamma p \to p\eta$ [28, 29]. The original experiment consisted of the Crystal Barrel (CB) calorimeter with its 1380 CsI(Tl) crystals covering 97.8 % of 4π [30]. The CB calorimeter had an excellent photon-detection efficiency and covered polar angles from 12° to 168°. Charged reaction products were detected in a three-layer scintillating fiber detector which surrounded the 5 cm long liquid hydrogen target. More information can be found in [27]. For the 2000/2001 data-taking, electrons were extracted in two separate experiments at energies of 1.4 and 3.2 GeV, covering tagged photon-energies from 0.3 to about 3.0 GeV, with a typical intensity of $1 - 3 \times 10^6$ tagged photons/s. The coincidence between tagger and scintillating fibre detector provided the first-level trigger of the experiment.

The experimental setup was later modified and in a series of measurements in 2002/2003, utilized a combination of the CB calorimeter and the BaF_2 TAPS detector in the forward direction. The experiment covered almost the full 4π solid angle (> 98 % coverage). The CB detector in its CBELSA/TAPS configuration consisted of 1290 CsI(Tl) crystals, which had a trapezoidal shape and were oriented toward the target, with a thickness of 16 X_R, and covered the polar angles from 30° to 168°, while TAPS consisted of 528 hexagonal BaF_2 crystals with a length of approximately 12 X_R, and covered the polar angles from 5° to 30°; both covered the full azimuthal circle. TAPS was configured as a hexagonal wall and served as the forward endcap of the CB. Forward-going protons were detected by plastic scintillators (5 mm thick) located in front of each TAPS module; the other protons were detected by the three-layer scintillating fiber detector. Results of the CBELSA/TAPS setup on single-meson cross section measurements off the proton can be found in [31–36].

It is worth emphasizing that these two recent ELSA experiments utilized entirely different experimental setups under very different trigger conditions. Moreover, the CBELSA/TAPS data provide improved angular coverage in the forward and backward direction in the c.m. system, whereas CB-ELSA and CLAS data are limited at about 30° and 40°, respectively.

The SAPHIR detector [38] was a multi-purpose magnetic spectrometer at ELSA with a large angular acceptance consisting of a tagging facility, drift chambers and a scintillator wall for triggering and time-of-flight measurements. The detector covered the full polar angular range from 0° to 180°, but the accepted solid angle is limited to approximately $0.6 \times 4\pi$ sr due to the magnet pole pieces. The photon flux was measured using the tagging system and a photon-veto counter downstream of the detector. Relevant results can be found in [39–44].

At the recently upgraded Mainz Microtron (MAMI-C), an experimental setup utilizing a combination of the NaI(Tl) Crystal Ball and BaF_2 TAPS multiphoton spectrometers recorded high-quality data on the reaction $\gamma p \to p\eta$ in the energy range from the production threshold of 707 MeV to 1.4 GeV [37]. While the NaI(Tl) crystals are arranged in two hemispheres which cover 93 % of the 4π solid angle, TAPS subtends the full azimuthal range for polar angles from 1° to 20°. Since the TAPS calorimeter was installed 1.5 m downstream of the Crystal Ball center, the resolution of TAPS in the polar angle θ was better than 1°. For an electron beam energy of 1508 MeV, a tagger channel in this experiment has a width of about 2 MeV at 1402 MeV and about 4 MeV at 707 MeV (the η-production threshold).

A summary of older experiments

A whole "industry" of photoproduction experiments recorded data in the 60's and 70's of the last century until about the discovery of the J/ψ resonance in the mid-70ties when the era of charmonium and other heavy-flavor physics began. Results were mostly published at higher energies and only few results bridge the gap to the resonance (peak-)region below $E_\gamma = 2$ GeV of more recent and current experiments.

Good angular coverage in the backward direction for some reactions, e.g. $\gamma p \to p\pi^0$ and $n\pi^+$, was provided by earlier experiments at the Bonn 2.5 GeV Synchrotron, e.g. [45–49]. The laboratory angle of the detected protons was about 2° for a π^0 c.m. angle of 175° at 1.4 GeV incoming photon energy. The protons were detected in a magnetic spectrometer system. In the forward direction, angular distributions of the differential cross sections were measured at c.m. angles between 0° and 65° in the enegy range from 1.3 to 2.2 GeV. The neutral mesons were detected by their decay photons, e.g. $\pi^0 \to \gamma\gamma$ [47]. The experiments were done with a bremsstrahlung beam produced on an internal target of the synchrotron.

At the 5 GeV electron synchrotron NINA at the Daresbury Laboratory, a linearly-polarized bremsstrahlung beam was used to extract differential cross sections for a large variety of reactions: $\gamma p \to p\eta$ [50], $p\pi^0$ [51, 52], $p\omega$ [53], and $p\phi$ [54, 55]. The incident photon intensity as a function of energy was derived from a quantameter, together with the shape of the spectrum as measured with a pair spectrometer.

Three further facilities deserve a brief discussion. At the Deutsches Elektronen-Synchrotron (DESY), a bremsstrahlung beam was produced on a tungsten target. The flux was measured with a gas-filled quantameter. Results were reported for single pseudoscalar mesons in the reactions $\gamma p \to p\pi^0$ [56–58], $\gamma p \to n\pi^+$ [59, 60], and $\gamma p \to p\eta$ [61].

Measurements at high photon energies were performed at the Stanford Linear Accelerator Center (SLAC) using a bremsstrahlung beam, e.g. $\gamma p \to KY$ with $Y = \Lambda, \Sigma$ [62, 63], $\gamma p \to n\pi^+$ [64, 65], and $\gamma p \to p\eta\,(\pi^0)$ [66]. The beam was monitored by detecting Cherenkov light of e^+e^- pairs from a converter in the beam. The Cherenkov monitor was calibrated against a precision calorimeter [64]. In [62], the overall uncertainty in normalization was estimated at 10 %; other references give smaller uncertainties, e.g. [64]. Vector meson photoproduction was studied in a bubble chamber exposed to monochromatic linearly-polarized photons from a backscattered laser beam $\vec{\gamma} p \to p\omega\,(\rho,\,\phi)$ [67]. The SLAC high-power quantameter is described in [68].

Finally, a bremsstrahlung beam from a tungsten target was used at the Cambridge Electron Accelerator (CEA) at the Massachusetts Institute of Technology (MIT). The beam was monitored with a quantameter which was calibrated against a Faraday cup and whose output was measured with a current integrator. The beam conditions gave an average beam intensity of about 0.5×10^{10} equivalent quanta per second [69]. Results were published for $n\pi^+$ [69–71], $K^+\Lambda$, $K^+\Sigma^0$ [69], $p\eta \to p\gamma\gamma$ [72], and $p\pi^0 \to p\gamma\gamma$ [73].

B. Experiments using Compton backscattering

The GRenoble Anneau Accelerateur Laser (GRAAL) facility was located at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France. For a detailed description of the facility, we refer to [75]. The tagged and polarized γ-ray beam was produced by Compton scattering of laser photons off the 6 GeV electrons circulating in the storage ring. The photon energy was provided by an internal tagging system consisting of silicon microstrips for the detection of the scattered electron and a set of plastic scintillators for Time-of-Flight (ToF) measurements [76]. A thin monitor was used to measure the beam flux (typically 10^6 γ/s). The monitor efficiency $(2.68 \pm 0.03\,\%)$ was estimated by comparing with the response of a lead/scintillating fiber calorimeter at a low rate. At larger angles, the photons from the decay of a neutral meson were detected in a BGO calorimeter made of 480 crystals. At forward angles, the photons could be detected in a lead-scintillator sandwich ToF wall, but the detector was not used in all analyses, thus limiting somewhat the forward acceptance. Results on single-meson cross section measurements were recently reported for the following final states: $p\pi^0$ [75], $p\eta$ [74, 76], and $p\omega$ [].

At the SPring-8/LEPS facility, the photon beam was produced by backward-Compton scattering of laser photons off electrons with an energy of 8 GeV, e.g. [77–79]. A liquid hydrogen target with a thickness of 16.5 cm was used. The data were accumulated with about 1.0×10^{12} photons at the target. Charged particles were detected by using the LEPS magnetic spectrometer with an angular coverage of about ±20° and ±10° in the horizontal and vertical directions, respectively.

III. METHODS OF COMPARISON

When differential cross sections are measured, the final reported values are dependent upon the choice of kinematic variables. The most common kinematic variables for a differential cross section to be binned in are either as a function of the cosine of the polar angle of the meson in the center-of-mass system ($\cos\theta^{\rm c.m.}_{\rm meson}$) or in the absolute

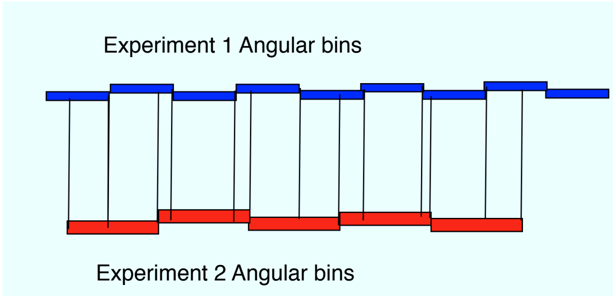

FIG. 1: (Color online) The edges of the bins in each data set are compared to find widths where one value from each experiment can be checked for a reported value. If there is a value reported for each experiment, the value times the width are added to each experiment's sum, which in turn will be used in a ratio.

value of the mandelstam t variable minus it's minimum possible value ($|t - t_{min}|$). In $\gamma p \rightarrow p\,X$ reactions, these two variables can be related to each other through the relation:

$$|t - t_{min}| \,=\, -\frac{s - m_p^2}{2m_p}\,|\,\vec{p}_{\,\rm c.m.}|\,\frac{1 - \cos\theta_{\rm meson}^{\rm c.m.}}{2}\,, \qquad (1)$$

where m_p is the mass of the proton, $\vec{p}_{\,\rm c.m.}$ is the momentem of a particle in the center of mass frame and $m_{\rm meson}$ is the mass of the photoproduced meson. When comparing two experiments in this review, all differential cross sections are converted to the $\cos\theta_{\rm meson}^{\rm c.m.}$ variables.

To calculate the comparison ratio between two experiments, the differential cross sections for equivalent energies are summed over bin by bin in a method illustrated in Figure 1. A total cross section like sum

$$Sum_{Exp\#} \,=\, \sum BinValue * width$$

is performed by considering the angular range as a series of widths defined by the edges of each bin in both data sets (illustrated in Fig. 1). For each width, only if both data sets have a reported cross section, the sum is increased. Once all the bins have been summed over, the ratio is calculated by:

$$Ratio \,=\, \frac{Sum_{Exp1}}{Sum_{Exp2}}\,.$$

This ratio should be a fair and simple comparison of the data reported at that energy. The center of the energy bin for each experiment is averaged to define the energy of the ratio. A ratio is not reported unless the bin center for each energy bin is within the energy range of the other experiment.

The problems with this ratio come when considering that each experiment does not have the same binning in either energy or angle. A ratio is not reported if the kinematic ranges for differential cross sections do not match. If the binning is shifted and the differential cross section is rapidly changing, the ratio could be shifted away from the true value. If the energy bins are shifted but are generally the same size, the ratio will also be slightly shifted. If the angular range is shifted, the ratio could be shifted due to the angular bin centers of the last bin being not equal. These effects introduce some fluctuations in the ratio distributions which will be presented in the following sections.

IV. COMPARISON OF CROSS SECTION DATA

It is worth discussing briefly the experimental procedure to extract cross sections before discussing results. The experimental differential cross sections are usually determined according to:

$$\frac{{\rm d}\sigma}{{\rm d}\Omega} = \frac{N_{\rm meson\,\rightarrow\,final\ state}}{A_{\rm meson\,\rightarrow\,final\ state}}\,\frac{1}{N_\gamma\,\rho_{\rm\,t}}\,\frac{1}{\Delta\Omega}\,\frac{1}{\frac{\Gamma_{\rm decay\ mode}}{\Gamma_{\rm\,total}}}\,, \qquad (2)$$

where

$\rho_{\rm\,t}$: target area density
$\rm N_{\,meson\,\rightarrow\,X}$: number of reconstructed data events
N_γ : number of incoming beam photons
$\rm A_{\,meson\,\rightarrow\,X}$: Monte Carlo acceptance
$\Delta\Omega$: solid-angle interval, e.g. $\Delta\Omega = 2\pi\Delta\cos\,(\theta_{\rm\,c.m.})$
$\frac{\Gamma_{\rm decay\ mode}}{\Gamma_{\rm\,total}}$: decay branching fraction.

Systematic errors of the final physics results can come from many sources in the experimental analyses. The event numbers are determined in most cases from fits to mass distributions. Difficulties can arise from the treatment of background in these distributions. Moreover, the detector acceptance needs to be modeled in Monte Carlo simulations to account for the geometrical detector and hardware inefficiencies. More relevant to our review is N_γ which denotes the number of incoming photons in photoproduction reactions and is required to absolutely normalize angular distributions. In many experiments, the largest single contribution to the overall systematic error comes from this number.

A. The reaction $\gamma p \rightarrow N\pi$

The meson which is produced more than any other meson in hadronic reactions and has been studied best experimentally is the pion. Single-pion photoproduction has been fairly well understood for incoming photon energies at and below 1 GeV. Recent single- and (double-) polarization data though indicate that our current understanding is limited at higher energies [] and this has come as a surprise. In particular, the reaction $\gamma p \rightarrow p\pi^0$ has been considered well understood up to energies of about $E_\gamma = 1.7$ GeV and model predictions (e.g. SAID) were used in the past to normalize observed relative angular distributions, e.g. [26–29].

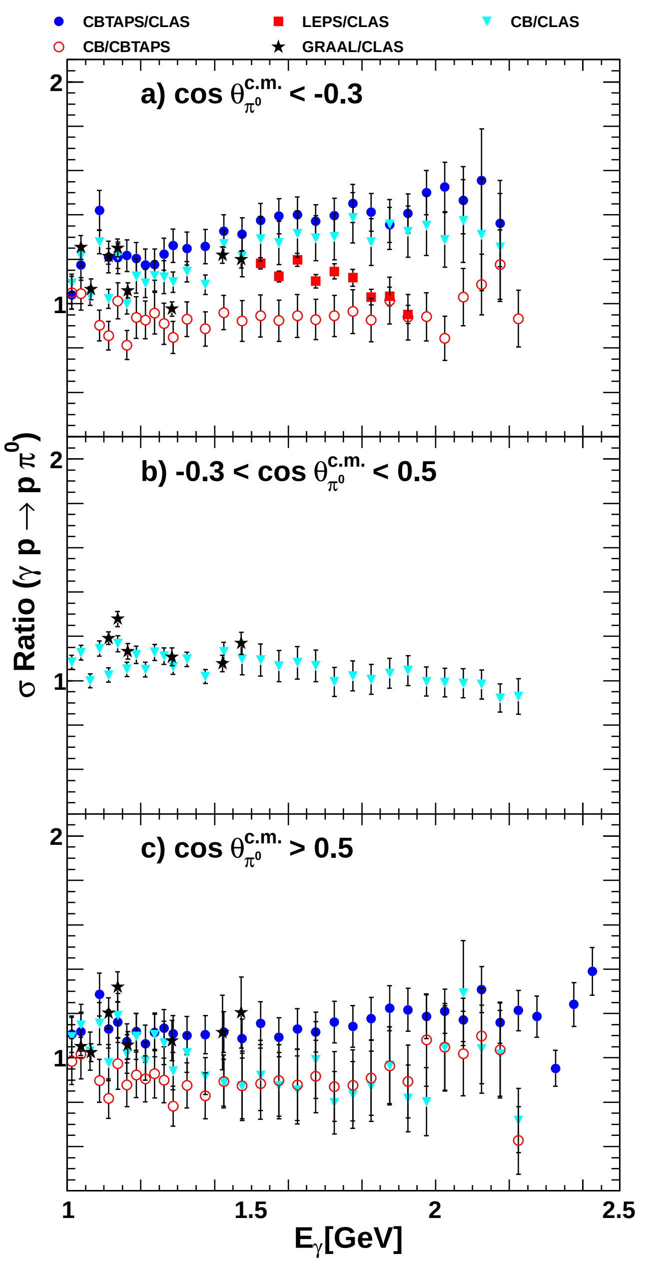

FIG. 2: (Color online) Ratios of $\gamma p \to p\pi^0$ cross section results from various experiments for three different angular ranges: CLAS [18], CB-ELSA [26, 27], CBELSA/TAPS [34], GRAAL [75], and LEPS [78]. The angular distributions have been integrated according to the method outlined in Section III.

Above 1 GeV, the $p\pi^0$ final state was recently studied at CLAS (g1c) [18], CB-ELSA [26, 27], CBELSA/TAPS [34], GRAAL [75], and LEPS [78]. Some older data are available from Bonn [45–48] and DESY [57, 58]. In Fig. 2, the differential cross sections are compared from different experiments by presenting ratios over a large energy range according to the method discussed in Section III. The experimental situation in this central region is sparse because many experiments apply more restrictive triggers to increase statistics on rare channels which does not allow to study single-pion production. The 2005 CB-ELSA and 2007 CLAS g1c data agree very nicely within about 10 % (▼). Below 1.7 GeV, the CB-ELSA results are slightly higher, but still agree with CLAS within the quoted systematic errors. While the photon flux was experimentally determined for the CLAS data, the low energy CB-ELSA data (E_γ < 1.3 GeV), were fitted to the SAID-SM02 model [11] by the χ^2 method for each energy channel. For the high-energy range (E_γ > 1.3 GeV), the comparison between SAID and the observed angular distributions only defined an overall scaling factor for the absolute normalization. The overall comparison between CLAS and the available data from GRAAL also ranges from fair to good (★). Data from CBELSA/TAPS were reported only for the forward and backward regions; data from LEPS are only reported in the backward region below $\cos\theta_{\rm c.m.} < -0.6$. For this reason, we do not use them in the discussion of the overall normalization.

The observed discrepancies in the forward and backward regions can be more likely attributed to a limited understanding of detector acceptances rather than normalization discrepancies. Below $\cos\theta_{\rm c.m.} < -0.3$, the CBELSA/TAPS data are fairly consistent with the CB-ELSA data (○) within systematic errors (Fig. 2 (a)). On average, the latter appear somewhat lower than the recent CBELSA/TAPS data, but the energy dependence is weak. Discrepancies of both ELSA results relative to the CLAS data are more striking and reach almost 40 % at the highest available energies (▼, ●). The GRAAL data tend to exhibit a similar discrepancy relative to the CLAS data above 1.3 GeV, but the available energy range is too small to draw any conclusion. We do not have an explanation for this observation. Moreover, the LEPS data do not seem to be consistent with any of the other experiments and the agreement appears energy dependent (■).

The situation is less severe in the forward direction above $\cos\theta_{\rm c.m.} > 0.5$ (Fig. 2 (c)). We observe fair consistency among the available datasets within about 20 %, the energy dependence of the discrepancies is very small. Since the CLAS data are only available in $\theta_{\rm c.m.}$ bins and the cross section is rapidly changing in this forward angular range, a small effect from the conversion to a $\cos\theta_{\rm c.m.}$ binning is possible.

In Fig. 3, we have plotted the available data at fixed angles for a large energy range from 1.0 to 2.6 GeV. For the backward region at $\cos\theta_{\rm c.m.} = -0.85$ ($\theta_{\rm c.m.} \approx 148^\circ$), most of the experiments show a very consistent behavior (Fig. 3 (a)). However, the CLAS data are clearly lower, which is in agreement with (Fig. 2 (a)). Excellent agreement can be seen for the central region at $\cos\theta_{\rm c.m.} = 0.05$ ($\theta_{\rm c.m.} \approx 87^\circ$) (Fig. 3 (b)) and a normalization discrepancy in this channel can again be ruled out. In the more forward region at $\cos\theta_{\rm c.m.} = 0.55$ ($\theta_{\rm c.m.} \approx 57^\circ$), the agreement among datasets is somewhat shifted. While overall very good

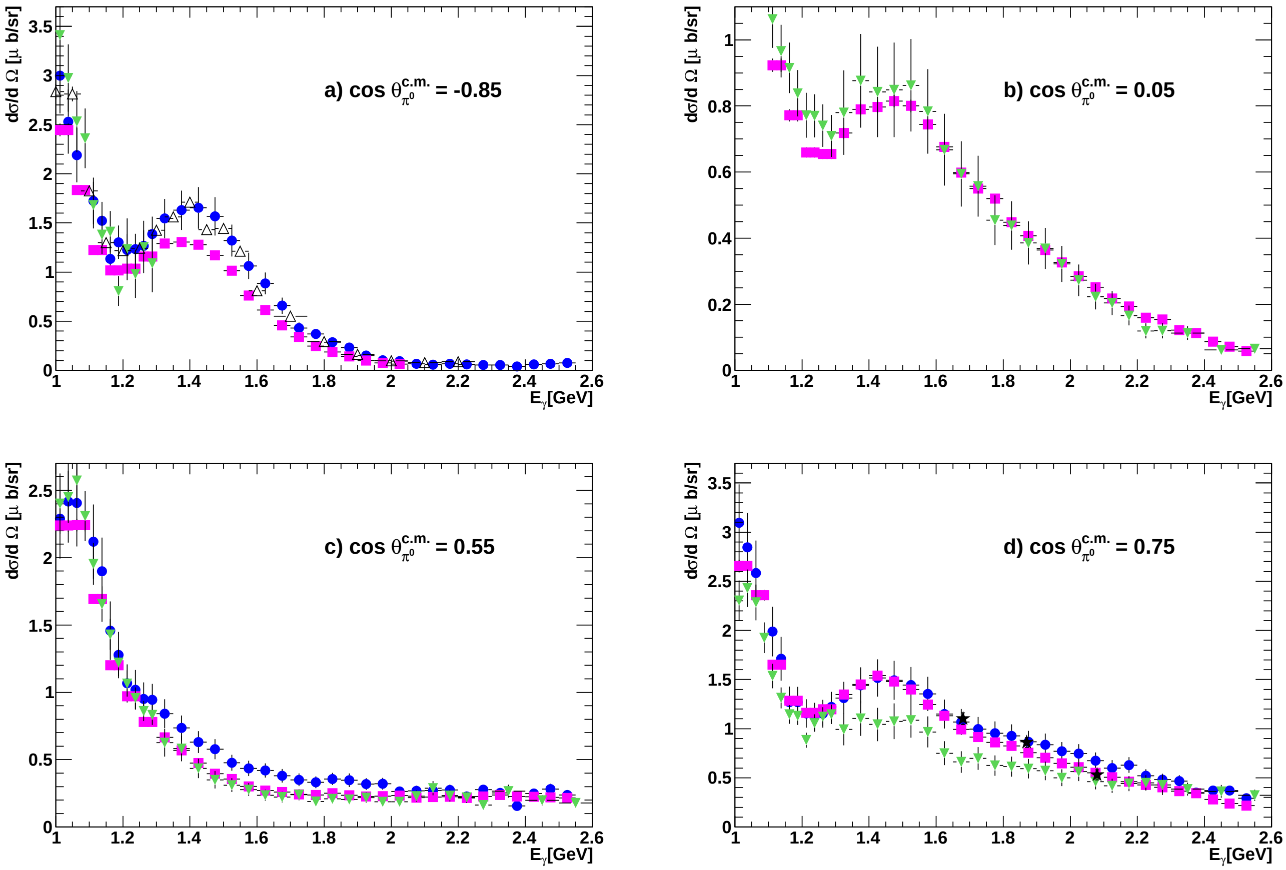

FIG. 3: (Color online) Differential cross sections for the reaction $\gamma p \to p\pi^0$ for $E_\gamma \in [1.0, 2.6]$ GeV at four different polar angles of the π^0 in the center-of-mass system: (a) $\theta \approx 148°$, (b) $\theta \approx 87°$, (c) $\theta \approx 57°$, (d) $\theta \approx 41°$. Data are taken from CLAS ■ [18], CB-ELSA ▼ [26, 27], CBELSA/TAPS ● [34], Becks *et al.* △ [45], and Brefeld *et al.* ★ [47]. Statistical and systematic errors have been added in quadrature.

consistency is observed, the CBELSA/TAPS data are slightly higher indicating a steeper slope of the forward t-channel peak in the differential cross sections for these data (Fig. 3 (c)). The last distribution at $\cos\theta_{\mathrm{c.m.}} = 0.75$ ($\theta_{\mathrm{c.m.}} \approx 41°$) shows the CB-ELSA data lower than all other datasets (Fig. 3 (d)).

The reaction $\gamma p \to n\pi^+$ has been studied more recently at JLab in the CLAS g1c experiment [19] and at the Bonn 2.5 GeV electron synchrotron [49]. The latter experiment covered the backward region of the π^+ in the c.m. system up to $\theta_{\mathrm{c.m.}} \approx 180°$ and for $E_\gamma < 2$ GeV with no kinematic overlap to the recent JLab results which were published for $\cos\theta_{\mathrm{c.m.}} \leq 125°$. Earlier results come from DESY [59, 60], SLAC [64, 65], and CEA [69–71].

We observe good agreement among all available datasets below about 2 GeV. As an example at higher energies, Fig. 4 shows the differential cross sections for the $n\pi^+$ channel for $E_\gamma = 2.63$ GeV from CLAS g1c [19] (●) and DESY [60] (■). The data span distinct angular ranges. We used the SAID model to fit these data (with identical parameters) and to determine a possible normalization discrepancy. The fits give a scaling factor of

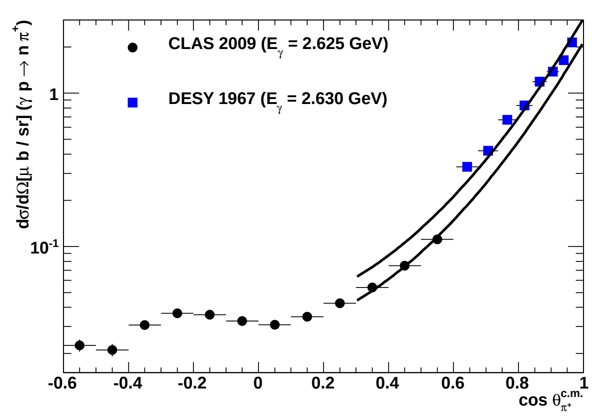

FIG. 4: (Color online) Differential cross sections for the reaction $\gamma p \to n\pi^+$ for $E_\gamma = 2.63$ GeV from CLAS g1c ● [19] and DESY ■ [60]. The "current" SAID solution has been used to fit the data, although $E_\gamma = 2.63$ GeV is outside its validity range. The two curves differ only by a scaling factor. Statistical and systematic errors have been added in quadrature.

approximately 1.43 ± 0.04 which indicates that the DESY data may be about 40 % higher. However, we emphasize this is not a direct comparison owing to the lack of kinematic overlap. The discrepancy remains only suggestive.

In summary, we do not observe a strong overall normalization discrepancy in the reactions $\gamma p \to p\pi^0$ and $n\pi^+$ among the available data for photon energies from 1.0 to about 2.5 GeV. However, weak experimental evidence is worth mentioning for a discrepancy at higher energies in the reaction $\gamma p \to n\pi^+$ between CLAS and older DESY data. For the π^0 channel, the older data from DESY are only available at higher energies ($E_\gamma \geq 4$ GeV) and we did not attempt a comparison. Any conclusion must remain speculative. A new generation of photoproduction experiments will have to bridge the energy gap and study the normalization scale above 3 GeV.

Moreover, we believe that the more recent π^0 analyses exhibit certain weaknesses in describing the detector acceptance in particular kinematic regions and overall systematic errors may be underestimated. While the CLAS g1c analysis quotes a Monte Carlo validity only for $0.9 < \cos\theta^{\pi}_{\rm c.m.} < 0.5$ and for $0.65 < E_\gamma < 1.8$ GeV [18], the CBELSA/TAPS data, though showing better acceptance in the more forward region, experience stronger contributions at $\cos\theta_{\rm c.m.} = 0.55$ from the overlap region between the forward and central detector, which may slightly underestimate the acceptance.

B. The Reaction $\gamma p \to p\eta$

The $p\eta$ final state was studied at CLAS in the g1a [10] and g11a [22] experiments, CB-ELSA [28, 29], CBELSA/TAPS [33], MAMI [37], GRAAL [76], and LEPS [79]. Older results are available from Daresbury [50], DESY [61], SLAC [66], and CEA [72]. In Fig. 5, differential cross sections from a large number of different experiments are compared to the CLAS g11a results as a reference.

The overall consistency between the 2005 CB-ELSA and 2009 CBELSA/TAPS data for $E_\gamma < 2$ GeV is fair to good (★). The earlier CB-ELSA data appear slightly higher, but within systematic errors. For the CB-ELSA η data, the same photon flux normalization was used that was determined for the CB-ELSA π^0 data from fits to the SAID-SM02 model [11]. Since the CLAS g1a data were also normalized to SAID, the good agreement with the CB-ELSA data is not a surprise (this comparison is not shown in Fig. 5). We observe however striking discrepancies above $E_\gamma > 1.5$ GeV between the CBELSA/TAPS data and the CLAS g11a data of almost 60 % above 2 GeV (●). Since this observation is fairly consistent over the full angular range, we attribute this effect to a normalization discrepancy between CLAS g11a and CBELSA/TAPS. The latter data are observed at higher values. Both experiments are self-consistent concerning different decay modes of the η meson, which also hints at an overall normalization discrepancy. For

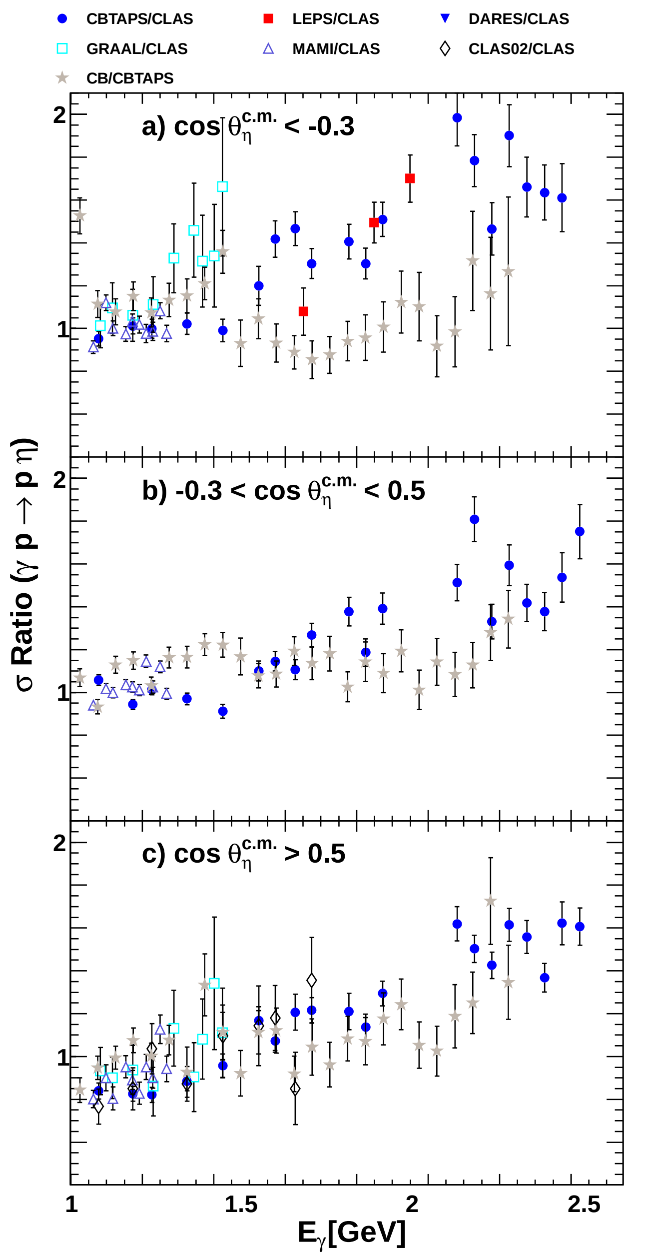

FIG. 5: (Color online) Ratios of $\gamma p \to p\eta$ cross section results from various experiments for three different angular ranges: CLAS g1a [10], g11a [22], CB-ELSA [28, 29], CBELSA/TAPS [33], MAMI [37], GRAAL [76], LEPS [79], and Daresbury [50]. The angular distributions have been integrated according to the method outlined in Section III.

the CBELSA/TAPS data, $\eta \to \gamma\gamma$ and $\eta \to \pi^0\pi^0\pi^0$ were analyzed separately and showed good agreement [33]; at CLAS, $\gamma p \to p\,X_{(\eta)}$ and $\gamma p \to p\eta \to p\pi^+\pi^-\,X_{(\pi^0)}$ were analyzed [22]. Other datasets (with some caveats, though) show a very similar overall normalization discrepancy relative to CLAS g11a, e.g. CLAS g1a (normalized to SAID), LEPS (only in the backward region), and GRAAL (for $E_\gamma < 1.5$ GeV) (Fig. 5). A further com-

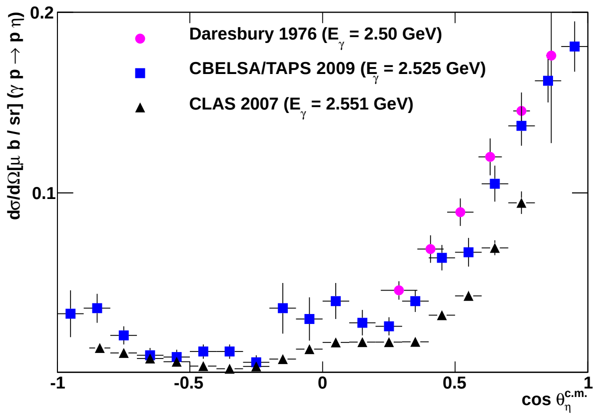

FIG. 6: (Color online) Comparison for the reaction $\gamma p \to p\eta$ between CLAS g11a [22], CBELSA/TAPS [33], and Daresbury data [50] for $\sqrt{s} \approx 2.35$ GeV. The error bars comprise statistical and systematic errors added in quadrature.

parison with older Daresbury data at a center-of-mass energy of $\sqrt{s} = 2.35$ GeV in a distribution of $d\sigma/d\Omega$ is shown in Fig. 6 and corresponds to a similar comparison discussed in [8] (Fig. [4] therein) where a distribution of $d\sigma/dt$ was chosen. Excellent agreement between the Daresbury data and CBELSA/TAPS can be observed, but a normalization discrepancy of about 40-50 % relative to the CLAS g11a data is again clearly seen. This scaling discrepancy is also observed between CLAS g11a data and older data from DESY [61] as well as LNS [80] and is discussed in more details in [8]. The authors conclude that while DESY/LNS/Daresbury agree well with each other at photon energies between 3 and 4 GeV, CLAS g11a appears sytematically lower by about a factor of two and note that none of the older experiments used a tagged photon beam.

The low-energy behavior of all the datasets is very similar and most experiments agree within systematic errors. An interesting acceptance effect is observed at very forward angles above $\cos\theta_{\rm c.m.} > 0.6$. Both the GRAAL and CLAS g11a data with somewhat limited aceptance in this angular range are observed systematically higher than the data from MAMI and CBELSA/TAPS with good acceptance at these forward angles. This pushes the ratios in Fig. 5 (c) slightly below one in this low-energy range. Figure 7 shows this effect for $E_\gamma \leq 1.4$ GeV. At higher energies, the LEPS data match the CBELSA/TAPS data and add some validity to the backward angular behavior.

In summary, we conclude that different data on η photoproduction for $E_\gamma > 1$ GeV agree fairly well. However, a normalization discrepancy is observed relative to the CLAS g11a data which increases almost linearly with energy above $E_\gamma > 1.5$ GeV. Assuming this linear trend continues, it might explain a factor of two difference between CLAS g11a and the older data at energies above 3 GeV, but we emphasize that this is speculative. However, it is quite remarkable that a large amount of older data from different facilities agree so well. The older publications clearly mention that the flux was measured (mostly by using a quantameter), which contradicts speculations that the angular distributions were normalized to each other.

We have also analyzed the results for the reaction $\gamma p \to p\eta'$, which has been mainly studied at CLAS [16, 22] and with significantly poorer statistics at some other experiments [33, 40]. Here we note that CLAS g1c and g11a results are in good agreement. Check again.

C. $\gamma p \to p\,V$ $(V = \omega,\, \phi)$ Comparisons

The photoproduction of vector mesons has been studied at CLAS in the g11a experiment in the reactions $\gamma p \to p\omega \to p\,X_{(\omega)}$ and $p\pi^+\pi^-\,X_{(\pi^0)}$ [20, 21] as well as $\gamma p \to p\phi \to pK^+K^-$ [25], CBELSA/TAPS [36] ($\gamma p \to p\omega \to p\pi^0\gamma$), SAPHIR [43] ($p\omega \to p\pi^+\pi^-\,X_{(\pi^0)}$), and LEPS [79] ($\gamma p \to p\omega$ in $\gamma p \to p\,X$). Older results come from Daresbury ($p\omega$ [53]) and SLAC ($p\omega$, $p\phi$ [67]).

We begin the discussion with a comparison between CLAS g11a and CBELSA/TAPS (Fig. 8) for both the ω (●) and η (■) channel. A very good agreement is observed for the behavior of both channels over a large energy range. The somewhat higher CLAS η results at lower energies ($E_\gamma < 1.5$ GeV) and in the forward region have been discussed in the previous section (also Fig. 7). Since the acceptances are very different for the two channels and CLAS has reported self-consistency for different ω decay modes, we conclude that the ω channel exhibits a very similar normalization discrepancy (at least between CBELSA/TAPS and CLAS) as the η channel.

Further ω cross section ratios for all angles are shown in Figure 9. The CLAS and SAPHIR data seem to match well in the forward region (■), but show an energy-

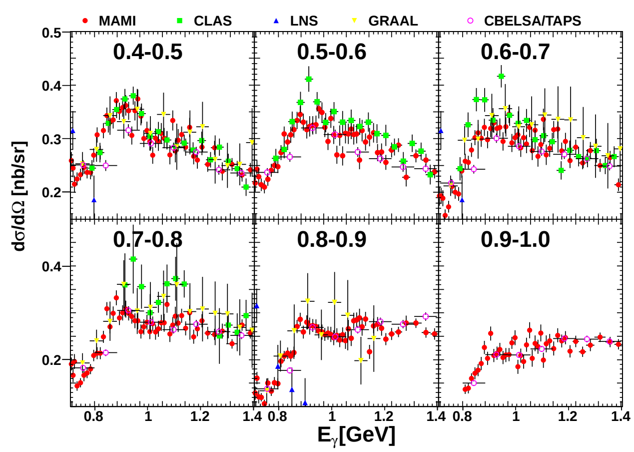

FIG. 7: (Color online) Differential cross sections for the reaction $\gamma p \to p\eta$ for $E_\gamma \in [0.8, 1.4]$ GeV and different angle bins in the forward direction. Data are taken from CLAS g11a ■ [22], CBELSA/TAPS ○ [33], MAMI ● [37], and GRAAL ▼ [76]. The error bars comprise statistical and systematic errors added in quadrature.

dependent normalization discrepancy for all other angular regions. We estimate that this discrepancy is at least 20 % above 1.7 GeV; the SAPHIR data are systematically lower than the CLAS g11a data. This is in complete disagreement with the CBELSA/TAPS data for the ω channel (●). The LEPS results appear to match the CLAS data in the backward region (○), but the agreement with LEPS data appears to be channel-dependent (e.g. very good agreement is observed with CBELSA/TAPS η results). We do not observe consistent agreement of LEPS results with another experiment for the non-strange reactions $\gamma p \to p\pi^0$, $p\eta$, and $p\omega$. These mesons are however all reconstructed by detecting the proton and using the missing-mass technique and are observed in the c.m. backward region. For the hyperon channels, $\gamma p \to K^+ Y$ with $Y = \Lambda$, Σ, LEPS published differential cross sections in the angular range from $\theta_{c.m.} = 0°$ to $60°$ of the K^+ scattering angle in the center-of-mass system (the hyperons were identified by using the missing-mass technique). We will discuss reactions involving strange mesons and baryons in the following sections.

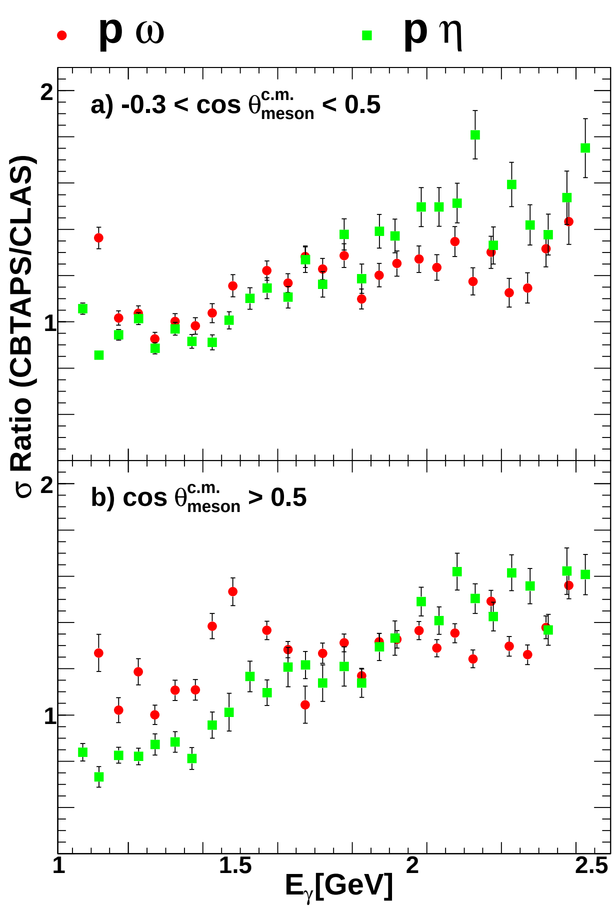

FIG. 8: (Color online) Ratios of $\gamma p \to p\omega$ and $\gamma p \to p\eta$ cross section results from CLAS g11a [20–22] and CBELSA/TAPS [33, 36]. The angular distributions have been integrated according to the method outlined in Section III.

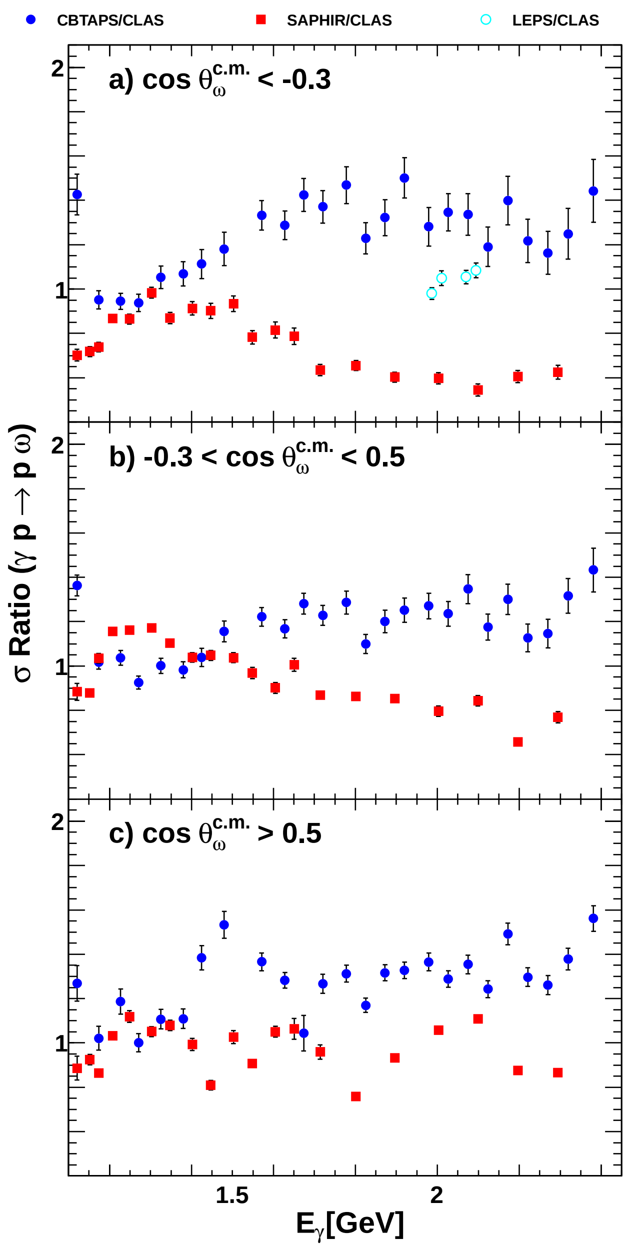

FIG. 9: (Color online) Ratios of $\gamma p \to p\omega$ cross section results from various experiments for three different angular ranges: CLAS g11a [20, 21], CBELSA/TAPS [36], SAPHIR [43], and LEPS [79]. The angular distributions have been integrated according to the method outlined in Section III.

In [8] (and Fig. 8 therein), fair agreement is claimed between CLAS g11a and older SLAC results at a c.m. energy of $\sqrt{s} = 2.475$ GeV, but our analysis reveals a difference between the two experiments at this energy (Fig. 10). Assuming an exponential behavior in the forward direction ($\cos\theta_{\rm c.m.} > 0.5$), the distributions have been fitted to $a + bx + cx^2$ using a logarithmic scale for the y-axis; the coefficients b and c are identical for both datasets. The data are well described and the ratio

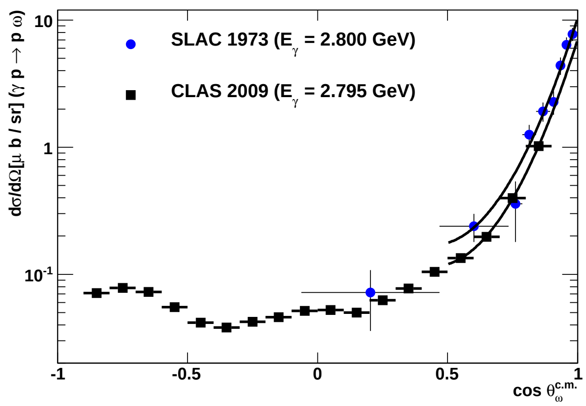

FIG. 10: (Color online) Comparison between data for the reaction $\gamma p \to p\omega$ from CLAS g11a [20, 21] and older data from SLAC [67] at a center-of-mass energy of $\sqrt{s} = 2.475$ GeV corresponding to $E_\gamma = 2.8$ GeV. The error bars comprise statistical and systematic errors added in quadrature.

of the offsets gives $a_{\rm SLAC}/a_{\rm CLAS} = 1.47 \pm 0.09$, which is consistent with the normalization discrepancy between CBELSA/TAPS and CLAS for the ω and η channel (Fig. 8). Fair agreement is observed between CLAS g11a and older Daresbury results [53] (Fig. 9 in [8]), though.

Some discussion of ϕ data. SAPHIR?

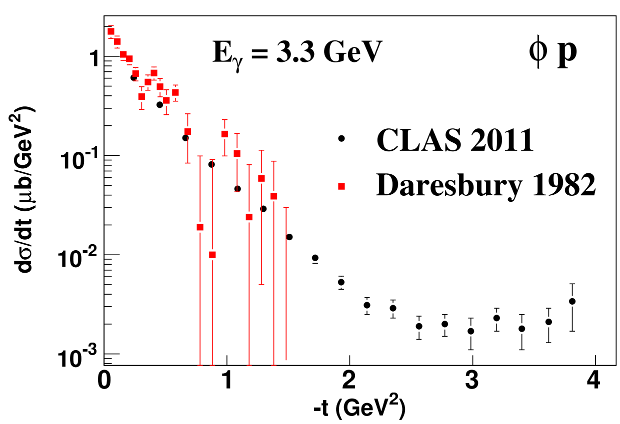

FIG. 11: (Color online) Picture taken from [8]. Comparison between data for the reaction $\gamma p \to p\phi$ from CLAS g11a [] and older data from Daresbury [54] at $E_\gamma = 3.3$ GeV. The error bars comprise statistical and systematic errors added in quadrature.

In summary, we observe a similar normalization discrepancy between the CLAS g11a and CBELSA/TAPS data for the reaction $\gamma p \to p\omega$ which has been discussed earlier for the η channel. We believe that a comparison with older data from SLAC and Daresbury is inconclusive to resolve this issue. CLAS g11a data are however in fair agreement with earlier ω results from CLAS g1c off the proton at a high momentum transfer [13]. Check again.

D. $\gamma p \to K^0\Sigma^+$ and $\gamma p \to K^{*0}\Sigma^+$ Comparisons

A large amount of data on strangeness channels is available for comparisons in attempts to further understand normalization discrepancies. The reaction $\gamma p \to K^0\Sigma^+$ has been measured recently at ELSA with the CBELSA/TAPS setup in the neutral decay of $K^0\Sigma^+$ into $(p\pi^0)(\pi^0\pi^0)$ [31, 35] and earlier with SAPHIR into $(p\pi^0)(\pi^+\pi^-)$ and $(n\pi^+)(\pi^+\pi^-)$ [44]. The latter decay modes were also studied at CLAS g1c, but published

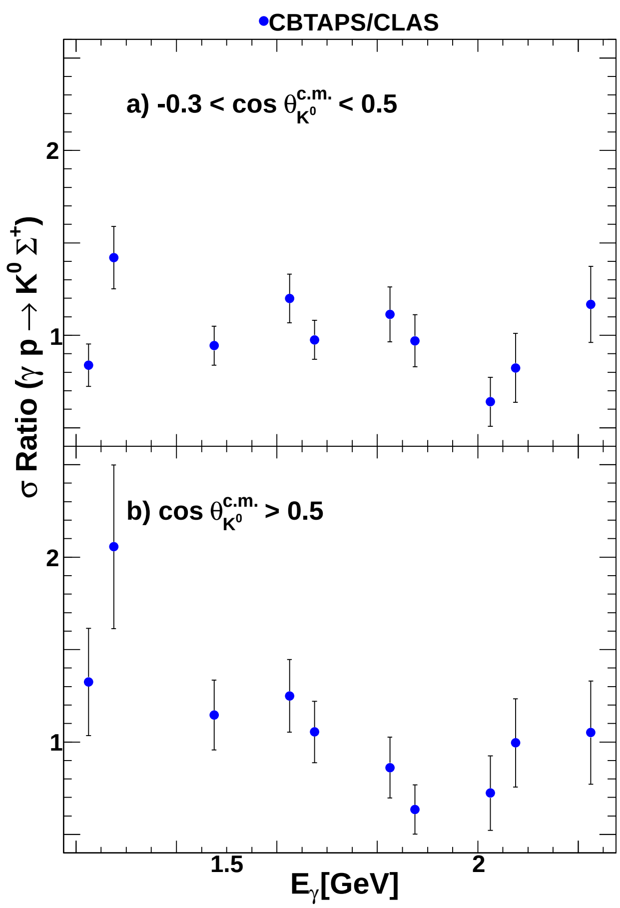

FIG. 12: (Color online) Ratios of $\gamma p \to K^0\Sigma^+$ cross section results from CLAS g1c [14] and CBELSA/TAPS [35]. The angular distributions have been integrated according to the method outlined in Section III.

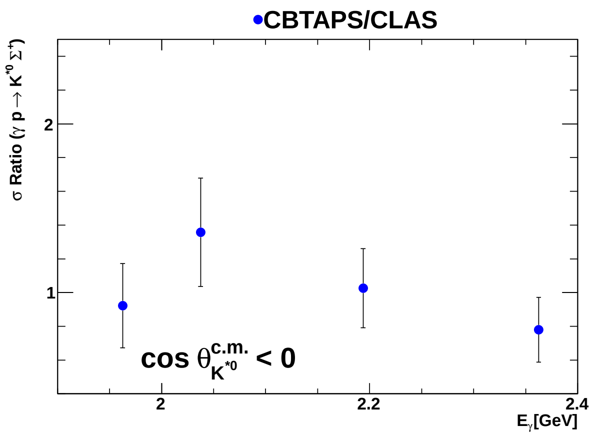

FIG. 13: (Color online) Ratios of $\gamma p \to K^{*0}\Sigma^+$ cross section results for $\cos\theta_{c.m.} < 0$ from CLAS g1c [17] and CBELSA/TAPS [32]. The angular distributions have been integrated according to the method outlined in Section III.

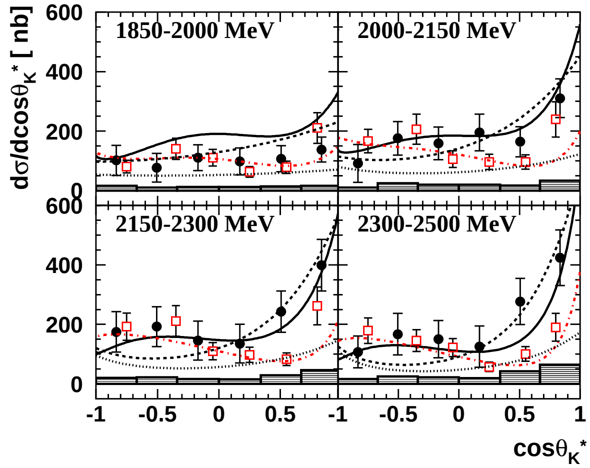

FIG. 14: (Color online) Picture taken from [32]. Results on the reaction $\gamma p \to K^{*0}\Sigma^+$. Differential cross sections from CLAS g1c □ [17] and CBELSA/TAPS ● [32].

only as a Ph.D. thesis [14]. More results are in preparation for publication in the near future. The reaction $\gamma p \to K^{*0}\Sigma^+$ was studied at CBELSA/TAPS in the decay into $(p\pi^0)(\pi^0\pi^0\pi^0)$ [32] and CLAS g1c into $(K^+\pi^-)(\Sigma^+)_{\text{miss}}$ [17].

The $K^0\Sigma^+$ cross section ratios are shown in Fig. 12. The CBELSA/TAPS data are in reasonable agreement with the CLAS g1c data for the central region (Fig. 12 (a)). An overall systematic normalization discrepancy of 30-40 % or more over a larger energy range is not observed. We do not show the backward region here because the available statistics is very limited and no conclusion can be drawn from a comparison. A small dip is observed in the ratios around $E_\gamma = 1.9$ GeV in the forward direction, which we believe is a fluctuation in the CBELSA/TAPS data. The available statistics is not good enough to draw any decisive conclusion about the detector acceptance and its influence on the differential cross sections. We note that at ELSA, the same $p\pi^0\pi^0\pi^0$ final state has been used to extract the η cross section under the same analysis conditions to provide a cross check. The η results are in very good agreement with the earlier CB-ELSA results []. Check again.

The $K^{*0}\Sigma^+$ cross section ratios between CLAS g1c [17] and CBELSA/TAPS [32] are shown in Fig. 13 for $\cos\theta_{\text{c.m.}} < 0.0$. The error bars are large and definitive conclusions about normalization discrepancies are difficult to draw. Fig. 14, which is taken from [32], shows the data points directly for four different energy bins. A clear discrepany is observed in the forward region which we believe needs to be attributed to an unknown acceptance effect. The overall normalization between the experiments appears to match well, but only about two remaining data points in the backward region for each energy bin at even somewhat different angles can be compared.

In summary, we do not observe a strong "obvious" normalization discrepancy for K^0 production between CLAS g1c and CBELSA/TAPS results, but large discrepancies owing to unknown acceptance effects. Data at higher energies for further comparisons are not available to the best of our knowledge.

E. $\gamma p \to K^+\Lambda$ Comparisons

The reaction $\gamma p \to K^+\Lambda$ has been recently studied at spectrometer-based experiments which are optimized for charged particles in the final states: CLAS g1c [12, 15] and g11a [23], SAPHIR [39, 41], and LEPS [77]. Some older results are available from SLAC [62, 63] at and above 5 GeV and from CEA [69] above about 3.4 GeV.

Figure 15 (left) shows the $K^+\Lambda$ cross section ratios for data from both CLAS experiments, SAPHIR, and LEPS. In the central region (Fig. 15 (b)), a normalization discrepancy at about 20 % and more is observed between CLAS and SAPHIR; the SAPHIR cross sections are observed at lower values (■). The shape of these cross section ratios exhibit a similar behavior that is also seen between CLAS and SAPHIR in the single-ω photoproduction ratios in Figure 9. A corresponding linear dependence of this discrepancy with energy is suggestive based on Fig. 9 (b) and Fig. 15 (b). In the backward region, the CLAS/SAPHIR discrepancy increases to almost 50 %, while reasonable agreement is only observed in the forward region at higher energies. This is also similar to the single-ω channel where good agreement between CLAS and SAPHIR was only seen below 1.5 GeV and in the more forward region.

We have no explanation for the CLAS/SAPHIR disagreement, but note the fair consistency of the discrepancies between the ω and $K^+\Lambda$ channels. The SAPHIR experimental setup does no longer exist, so it will be difficult to resolve this issue. Since we find no further

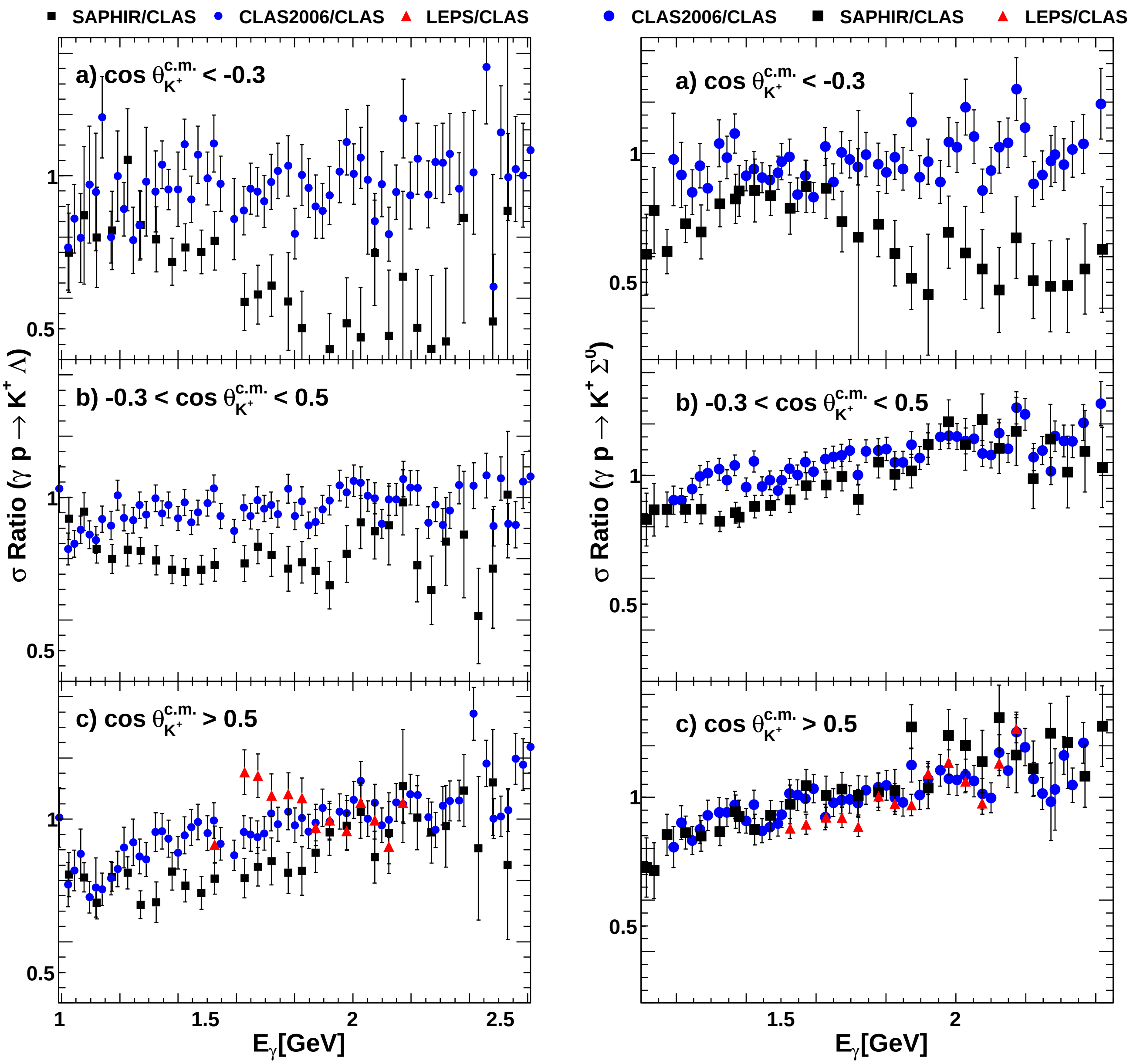

FIG. 15: (Color online) Ratios of cross section results. Left: $\gamma p \to K^+\Lambda$ from CLAS g1c [], CLAS g11a [], SAPHIR [41], and LEPS [77]. Right: $\gamma p \to K^+\Sigma^0$ from CLAS g1c [15], CLAS g11a [24], SAPHIR [39, 41], and LEPS [77]. The angular distributions have been integrated according to the method outlined in Section III.

experimental evidence that would support the SAPHIR normalization we conclude that SAPHIR possibly overestimated its flux normalization, which leads to overall lower cross section values.

The agreement between the CLAS g1c and g11a experiments is fair for the $K^+\Lambda$ channel and within about 20 % (●). However, the cross section ratios ($\sigma_{\text{g1c}}/\sigma_{\text{g11a}}$) suggest a linearly-rising behavior with energy, in particular in the forward direction (Fig. 15 (c)).

In [8] (and Fig. [1] therein) and [23], good agreement is observed between LEPS and CLAS g11a for the reaction $\gamma p \to K^+\Lambda$. Figure 15 (c) confirms the good agreement (▲), but the LEPS/CLAS g11a comparison is also consistent with the suggested linear behavior in energy between CLAS g1c and g11a. A comparison with the CEA data though reveals a normalization discrepancy of about a factor of two at energies above 3 GeV [8].

F. $\gamma p \to K^+\Sigma^0$ Comparisons

The final reaction of this review is $\gamma p \to K^+\Sigma^0$ which has been measured at CLAS at g1c [12, 15] and g11a [24], SAPHIR [39, 41], and LEPS [77]. The references for older results from SLAC [62, 63] and CEA [69] are the same as for the $K^+\Lambda$ channel. Figure 15 (right) shows a variety of cross section ratios for this reaction.

In the backward region, we observe reasonable agreement between the two CLAS experiments within systematic errors, but a discrepancy of about 40 % relative to the SAPHIR results above $E_\gamma \approx 1.8$ GeV. This observation is very similar to the one in the $K^+\Lambda$ channel and SAPHIR is again observed at lower values than CLAS. We do not have an explanation for this, but rule out a normalization issue owing to the behavior of the cross sections at other angles. In the central region overall fair agreement is observed between the three datasets within about 20 %, but the distributions are weakly suggestive of a small linear energy dependence of the CLAS 2006 (g1c) and SAPHIR results relative to the CLAS 2010 (g11a) results. This is again very similar to our observations in the $K^+\Lambda$ channel.

The suggested linear dependence is more clearly observed in the forward region where excellent agreement between CLAS g1c, SAPHIR, and LEPS is observed. Since these three experiments show an overall very similar behavior relative to the most recent CLAS g11a results, this may be indicative of a photon flux normalization for the CLAS g11a data which is overestimated toward higher energies and which pushes the cross sections to lower values for the $K^+\Sigma^0$ channel. In [8], a normalization discrepancy of roughly a factor of two is observed between scaled differential cross sections from CLAS g11a ($s^2 \times d\sigma/dt$) and SLAC. The discussion in [8] points out that the results from the two experiments agree well in shape, but that the CLAS cross sections are systematically lower. A naive extrapolation of the linear behavior in Fig. 15 (right) to the energy range above 4 GeV would be surprisingly consistent with a factor-of-two discrepancy relative to the high-energy SLAC measurements.

V. SUMMARY AND CONCLUSIONS

- Old data are amazingly consistent.
- Possible problem with normalization of CLAS g11a cross sections: $p\omega$ [21], $p\eta$ [22] and $K^+\Sigma^0$ [24]? The problem with this argument is the good agreement between the Dugger (g1c) and Williams (g11a) results on the reaction $\gamma p \to p\eta'$.
- What are further big discrepancies? Anything that needs to be addressed again experimentally?
- What do the current discrepancies mean for the partial-wave analyses?

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