Photoproduction of π^0 on Hydrogen Target with CLAS

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Abstract

We report first high precision measurement of exclusive π^0 photoproduction cross section in Dalitz decay and conversion mode on hydrogen target in a wide kinematic range with CLAS setup at Thomas Jefferson National Accelerator Facility. Measurement is performed in the reaction $\gamma p \to pe^+e^-X(\gamma)$ using tagged photon beam spanning in energy interval, covered "resonance" and "Regge" regimes, $E = 1.25 - 5.55$ GeV. In the final state of the reaction, the particles pe^+e^- are detected while the photon is not detected. π^0 is identified in the missing mass of proton. This new data are quadrupled the world bremsstrahlung database above E = 2 GeV. Our data appear to favor Regge pole model while disfavor handbag one.

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Introduction: In elementary particle physics involving energies less than 2.5 GeV in the c.m. total energy W ("resonance" regime), the study of lightest mesons (π^0 and η) in photoproduction has always been a complementary tool to elastic πN scattering. At high energies single pion photoproduction can be used to test predictions of Regge theory, in which recent calculations [**?**] have shown to describe the presented data well. Furthermore, these measurements have shown that the differential cross section for single pion photoproduction at fixed c.m. angles, $\theta_{c.m.}$, of 70°, 90° and 110° seem to scale as $\frac{d\sigma}{dt} \sim s^{2-n} f(\theta_{c.m.})$, where s and t are the Mandelstam variables and n is the total number of interacting elementary fields in the initial and final state of the reaction. This is predicted by the constituent counting rule [15, 16] and exclusive measurements in pp and $\bar{p}p$ elastic scattering [17, 18], meson-baryon Mp reactions [18], and photoproduction γN [19–26] agree well with this rule. This experiment is a unique opportunity to bridge resonance and high-energy, in particular, "Regge", regimes and increases available database above resonance range by significant amount.

The Regge pole amplitudes rely on already known Regge trajectories and coupling constants. The unitary cut amplitudes count on the independent description of the elementary photoproduction and meson re-scattering on-shell amplitudes. This approach is "parameter free". There is little degree of freedom left. One possibility is the relative sign between amplitudes.These 3 sentences has grammatical errors. The first sentence has no definitive subject, therefore ambiguous. The second sentence is not linked to any other sentence and therefore an incomplete sentence. The third sentence does not define the relation of "Possibility" The phase between the poles and the elastic neutral pion re-scattering is fixed by unitarity (for the absorptive part and consequently for the real part), but the relative phase of the amplitudes in the inelastic cuts is not determined by the cross section of the corresponding elementary reactions. A second possibility is a more accurate description of these elementary cross sections, but this is second order. The Regge pole and cut model for near forward higher energies above resonance regime π^0 photoproduction have been developed by Ader, Capdeville, and Salin [1], Goldstein and Owens [2], Laget [3], Mathieu, Fox, and Szczepaniak [4], Donnachie and Kalashnikova [5], and many others.

The introduction of the handbag mechanism, developed by Kroll *et al.* [6], has provided complimentary possibilities for the interpretation of hard exclusive reactions. In this approach, the reaction is factorized into two parts, one quark from the incoming and one from the outgoing nucleon participate in the hard sub-process, which is calculable using pQCD. While the soft part consists of all the other partons that are spectators and can be described in terms of GPDs [7]. This approach was developed to understand the nature of the observation which the HERMES Collaboration made [8].

Previous bremsstrahlung measurements for $2 \leq E \leq 18$ GeV (1964 – 1979) gave 451 $d\sigma/d\Omega$s data points for $\gamma p \to p\pi^0$ [9]. While recent tagged CLAS $g1c$ measurement contribution for $2 \leq E \leq 2.9$ GeV is limited to 164 $d\sigma/d\Omega$s [11] data points. Meanwhile, existing bremsstrahlung world data on photoproduction of neutral pions on proton target have very large systematic uncertaintes and do not have sufficient accuracy to perform comprehensive phenomenological analyses.

In this work, we provide a large set of cross sections from E = 1.275–5.425 MeV in laboratory photon energy, corresponding to a c.m. energy W range of 1.81–3.33 GeV. In this paper, we have therefore tried to confront the Regge pole and handbag phenomenology with the new CLAS experimental information on the $d\sigma/d\Omega(|t|)$ for the $\gamma p \to \pi^0 p$ above "resonance" regime. As will be seen, this data set (it quadrupled the world bremsstrahlung database above E = 2 GeV) and previous CLAS $g1c$ tagged measurements [11] greatly constrains the high energy phenomenology.

Experiment: Experiment is performed with CLAS setup at TJNAF using tagged photon beam produced by bremsstrahlung from 5.72 GeV electrons of CEBAF accelerator, impinged on liquid hydrogen target.

The reaction of interest is photoproduction of neutral pions on hydrogen target $\gamma p \to p\pi^0$, where the neutral pions were detected via external conversion, $\pi^0 \to \gamma\gamma \to e^+e^-\gamma$, and subsequent Dalitz decay, $\pi^0 \to \gamma^*\gamma \to e^+e^-\gamma$. The final state contains three charged tracks, $p; e^+; e^-$, which allows to run experiment with high current, and which otherwise wouldn't have been possible with single prong charged track, due to trigger and data acquisition limitations.

Data analysis: The missing mass of proton for events with $pe^+e^-(\gamma)$ in the final state is shown in Fig. 1. The selected strategy of the analysis of $g12$ data allowed to have negligible background. The fit (shown by red solid line) performed with Gaussian plus 3rd order polynomial function results in $M^2_{\pi^0} = 0.0182$ GeV^2 and Gaussian $\sigma = 0.0043$ GeV^2.

Lepton identification was based on conservation of mass. Once the data is skimmed for p, π^+, π^-, all particles that were π^+, π^- were tentatively assigned to be electrons or positrons based on their charge (For details see [28]). After particle selection, standard g12 calibration, fiducial cuts [27] and timing cuts were applied in the analysis.

The analysis employed three separate kinematic fitting hypotheses, 4-C, 1-C and 2-C as well as a cut on the missing energy of the detected system. The 4-C fit used the $\gamma p \to p\pi^+\pi^-$ channel to filter background from double charged pion production from single π^0 production. The 1-C fit was used for the topology of $\gamma p \to pe^+e^-(\gamma)$ to fit to a missing final state photon. The 2-C fit was used for the topology of $\gamma p \to pe^+e^-(\gamma)$ to fit to a missing final state photon but also to constrain the invariant mass of $e^+e^-(\gamma) = m^2_{\pi^0}$. The "confidence levels" for each constraint were consistent

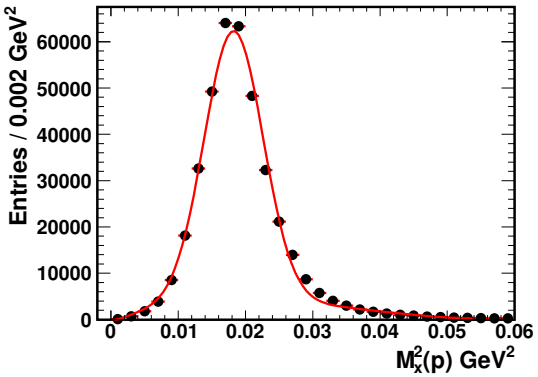

FIG. 1: (Color online) Peak of π^0 in the missing mass of proton for events with $pe^+e^-(\gamma)$ in final state.

between g12 data and simulation.

The remainder of the background was attributed to $\pi^+\pi^-$ events. To reduce the background further, a comparison of the missing mass squared off of the proton and the pe^+e^- missing energy of the system was performed. This comparison revealed that the majority of $\pi^+\pi^-$ background has missing energy less than 75 MeV. To eliminate this background all events with a missing energy less than 75 MeV were removed.

Overall, angular independent systematic uncertainty varies between 9% and 12% as a function of photon beam energy. For the individual contributions of the systematic uncertainty see Tab. I

TABLE I: Systematic error used in the $\frac{d\sigma}{d\cos\theta^{\pi^0}_{C.M.}d\phi}$ measurements.

Systematic	Error
Particle Efficiency (total)	0.005
Sector	$0.0361 + 0.0065E_\gamma$
Flux	0.057
Missing Energy Cut	0.02781
2-C Fit Pull Probability	0.0219
1-C Fit Pull Probability	$0.00216 + 0.01083E_\gamma$
4-C Fit Pull Probability	0.00031
Target	0.005
Branching Ratio	0.0037
Fiducial Cut	0.024
z-vertex Cut	0.0041
Total	$\sqrt{(6.5 + 0.52E_\gamma + 0.16E_\gamma^2)\cdot 10^{-3}}$

Results: The new CLAS high statistical cross sections, obtained here, for $\gamma p \to \pi^0 p$ are compared in Figs. 2 and 3 with previous data from tagged JLab CLAS $g1c$ [11], and bremsstrahlung DESY, Cambridge Electron Accelerator (CEA), and SLAC, and Electron Synchrotron at Cornell U [9]. The overall agreement is good, specifically with the tagged CLAS $g1c$ measurements.

At high energies (above $s = 5.9$ GeV) and large angles (90°) in c.m the results are consistent with the s^{-7} scaling expected from the constituent counting rule [14]. The black dash-dotted line on 90° (Fig. 2) is a result of the fit of new CLAS $g12$ data only, performed with power function $\sim s^{-n}$, leading to n = 6.89±0.26.

In Figs. 3 and 4, the $d\sigma/dt(|t|)$ are shown along with predictions from Regge pole [2–5] and handbag [6] models. Two Regge models are valid up to $|t| = 1\ GeV^2$ [4, 5] while two others are valid up to $|t|$ maximum ($|t| \sim 9\ GeV^2$ for E = 5.425 GeV) [2, 3]. Meanwhile. handbag model is good for $-0.6 \leq \cos\theta \leq 0.6$.

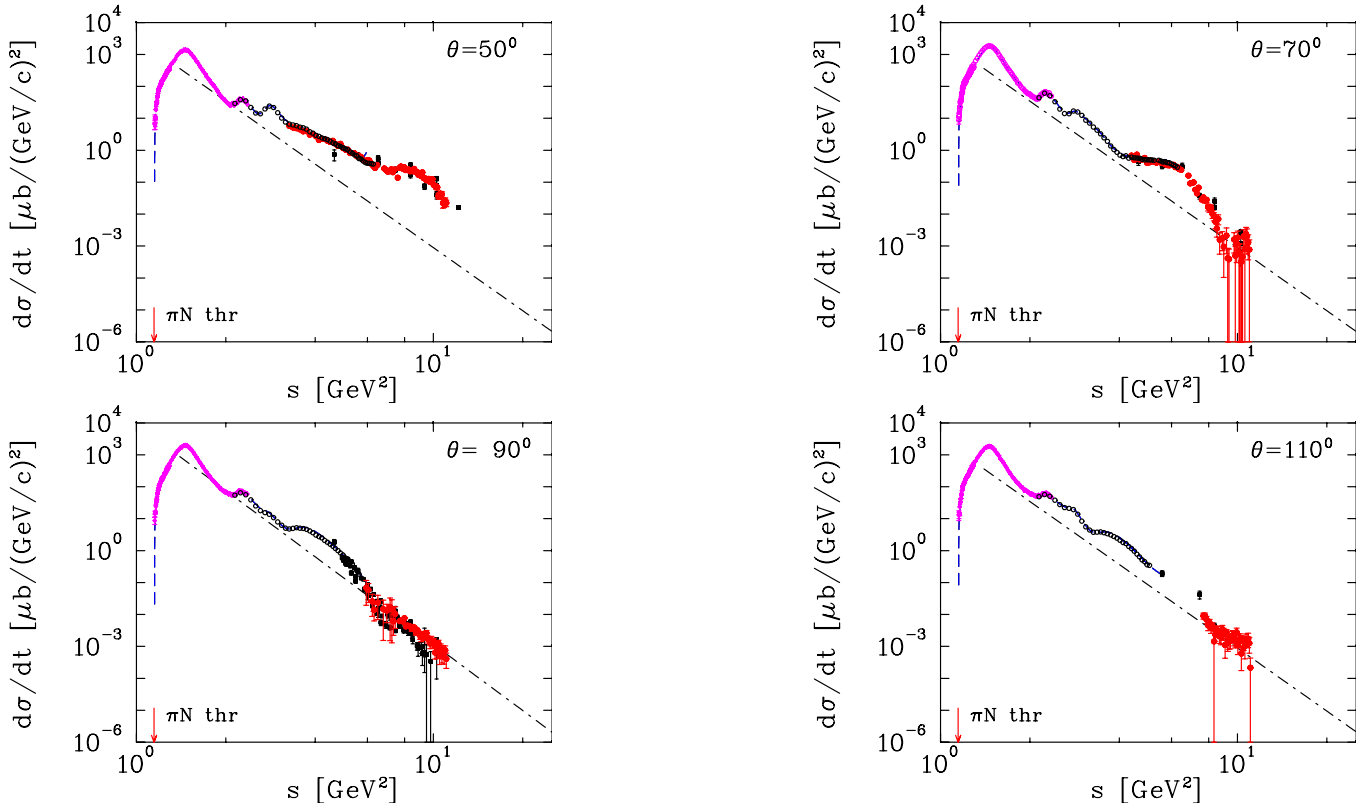

FIG. 2: (Color online) Differential cross section of $\gamma p \to \pi^0 p$ dσ/dt(s) at 50°, 70°, 90°, and 110° in c.m. as a function of c.m. energy squared, s. The red filled circles are results from the current analysis of the CLAS Collaboration $g12$ data. The recent tagged data are from CLAS $g1c$ [11] (black open circles) and A2 at MAMI Collaboration [12] (magenta open dymonds with crosses). While black open filled squares are data from old bremsstrahlung measurements above E = 2 GeV [9]. The plotted points from previously published experimental data within $\Delta\theta = \pm 2°$ of pion c.m. production angle, θ. Plotted uncertainties are statistical. The blue dashed line corresponds to the SAID PWA DU13 solution (no new CLAS data are in the fit) [13]. Black dot-dashed lines are plotted to help guide the eye except the 90° case (see text for details). Pion production threshold shown as a vertical red arrow.

Below $|t| \sim 0.6\ GeV^2$ (t is the squared four-momentum transfer), there is a small difference between different Regge approaches. Overall, the Regge approximation becomes less relevant below E = 3 GeV (Fig. 3). CLAS data make this statement more apparent. Note that some small structures start to appear around $|t| = 0.3-0.6\ GeV^2$ ($\cos\theta = 0.6-0.8$ below E = 4 GeV. The dip around $|t| = 0.9-1.2\ GeV^2$ ($\cos\theta = 0.2-0.4$) (moving with energy) agrees with presented CLAS data. This is surprising. There was no evidence found before (with the actual data) for this dip. Note that the Regge amplitudes imposes non negligible constraints for the "resonance" region. Our data show two more visible dips above E = 4 GeV and around $|t| \sim 3\ GeV^2$ and $|t| \sim 5\ GeV^2$ which are disfavor Regge model. That's why it's also important to study the high energy region, above "resonance" regime.

The Reggeon trajectories and cancellation of singularities in $|t|$ gives rise to zeroes in the various combinations of helicity amplitudes. These are seen as dips in the cross sections. Dips that occur for one Regge trajectory are filled in by the contributions from other, distinct trajectories. That is, the zeroes for the ρ^0, ω trajectories occur at different values of $|t|$ than those of the b_1^0, h_1 trajectories. Nevertheless, because the two sets have opposite naturality (parity $(-1)^J$ or $(-1)^{J+1}$), there are combinations of helicity amplitudes that will separate into "natural" and "unnatural" parity. Those would have zeroes separately. Since zeroes are not observed, but dips are, a mechanism for producing those dips is provided by final state interactions which correspond to Regge cuts (for an alternative Regge cut model see, for instance, Ref. [3]). Those were implemented in an eikonal formalism. It was expected that the appropriate range of $|t|$ was roughly $0 < |t| < 1.3\ GeV^2$. Since the newly assembled data reach all $|t|$, it is interesting to see how the old model, for instance [2], fares in an enlarged range. Remarkably, with a lowering of the original Pomeron strength (by eyeball), the model fits the data fairly well up to the 90°. The description of the π^0 photoproduction cross sections at largest $|t|$ requires some improvement of the Regge model by probably including u-channel exchange.

Simultaneously, Fig. 4 shows that new CLAS data disesteem the handbag model for π^0 photoproduction below s = 11 GeV^2.

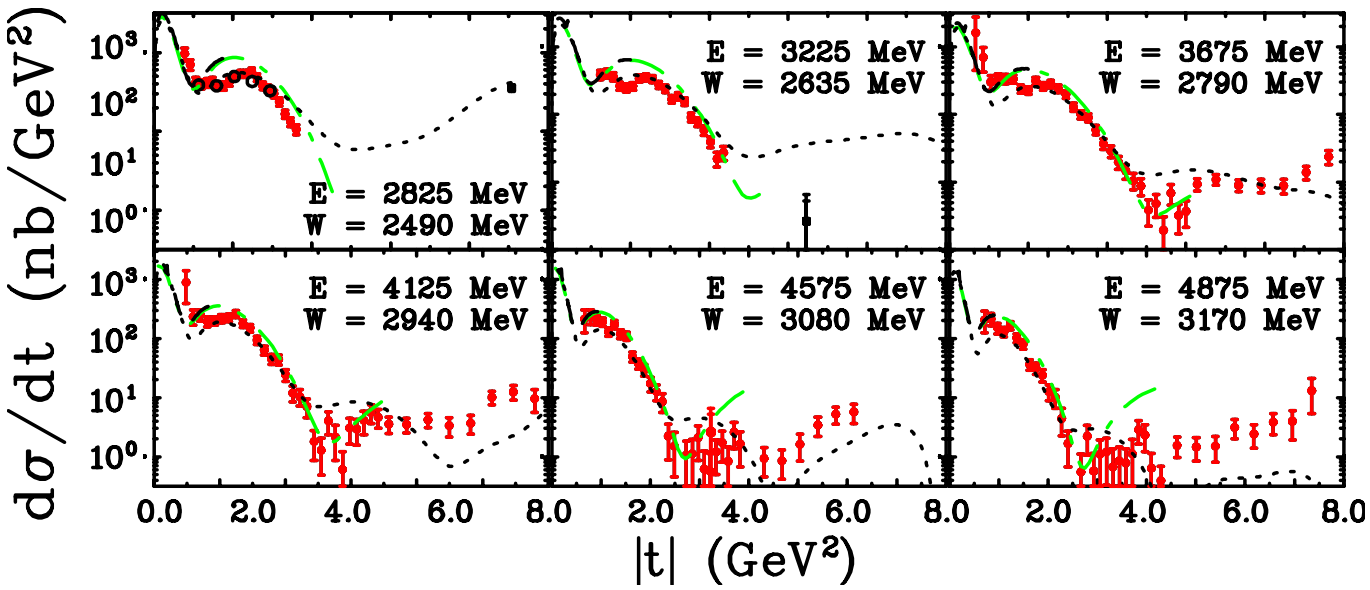

FIG. 3: (Color online) Samples of the π^0 photoproduction cross section, $d\sigma/dt(|t|)$, off the proton versus $|t|$ above "resonance" regime. Tagged experimental data are from the current CLAS $g12$ (red filled circles) and CLAS $g1c$ [11] (black open circles). The plotted points from previously published bremsstrahlung experimental data above E = 2 GeV [9] (black filled squares) are those data points within $\Delta E = \pm 3$ MeV of photon energy in laboratory system indicated on each panel. Plotted uncertainties are statistical. Regge results [2, 4, 5] are given by black dotted, green long dash-dotted, and black short dash-dotted lines, respectively.

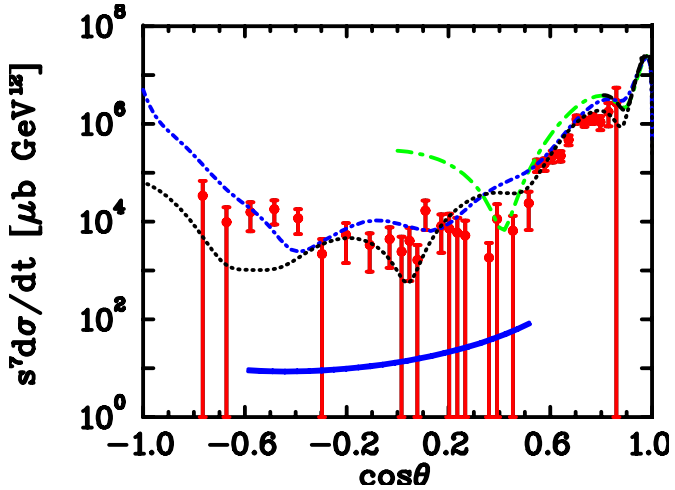

FIG. 4: (Color online) Differential cross section of π^0 photoproduction. CLAS experimental data at $s = 11$ GeV^2 are from the current $g12$ experiment (red filled circles). The theoretical curves a given for Regge fits [2–5] at $s = 11$ GeV^2 (black dotted, blue short dot-dashed, green long dash-dotted, and black short dash-dotted lines, respectively) and handbag model by Kroll *et al.* [6] at $s = 10$ GeV^2 (blue double solid line).

Conclusions: A significant increase in the comprehensiveness of the database for observables in the meson photoproduction process is critical to reaching definitive knowledge about QCD-based models of the nucleon. Studies that cover a broad range of c.m. energy W are particularly helpful in sorting out the phenomenology.

Through the experiments described above, an extensive and precise data set (2030 data points) on the differential cross section for π^0 photoproduction from the proton has been obtained over the range of $1.81 \leq W \leq 3.33$ GeV. A novel approach based on the use of Dalitz decay mode was employed for extracting the cross sections from the experimental data.

The measurements obtained here have been compared to existing data. The overall agreement is good, while the data provided here quadripleted the world bremsstrahlung database above E = 2 GeV, more precise than previous

measurements, and cover the reported energies with finer resolution. By comparing this new and greatly expanded data set to the predictions of several phenomenological models, the present data were found to favor the Regge pole model while disfavor while disfavor handbag one.

The present set of cross sections...

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