# Photoproduction of $\pi^0$ on Hydrogen Target with CLAS


Michael C. Kunkel,[1] Moskov J. Amaryan,[1,*] Igor I. Strakovsky,[2] James Ritman,[3] and Gary R. Goldstein[4]

[1] *Old Dominion University, Norfolk, VA 23529, USA*

[2] *The George Washington University, Washington, DC 20052*

[3] *Institut fr Kernphysik, Forschungszentrum Jülich 52424, Jülich, Germany; JARA-FAME (Forces and Matter Experiments), Forschungszentrum Jülich and RWTH Aachen University, 52056 Aachen, Germany*

[4] *Tufts University, Medford, MA 02155, USA*


## Abstract


We report first high precision measurement of $\pi^0$ photoproduction cross section in Dalitz decay 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, $E = 1.275 - 5.425$ GeV. In the final state of the reaction, photon is missing and $pe^+e^-$ are detected. $\pi^0$ is identified in the missing mass of proton and background is negligible in our case. These new data are quadrupled the world bremsstrahlung database above E = 2 GeV. Our data appear to favor the Regge pole model and quark counting rule while disfavor handbag model.



PACS numbers: 12.38.Aw, 13.60.Rj, 14.20.-c, 25.20.Lj


**Introduction:** The rich $\pi + N$ resonance spectrum for c.m. energies up to 2.5 GeV provides insights and challenges concerning the workings of the strong interaction through partial wave expansions, exchange potentials, non-relativistic quark models and QCD. The $\pi^0$ and $\eta$ photoproduction has always been a complementary tool to investigate and constrain the various models and lead to further insights. At the interface between the crowded low energy resonance cross section and the smooth higher energy behavior, traditionally described by Regge poles [1], lies a region in which hadronic duality provides an interpolation description of the cross section behavior. Exclusive $\pi$ photoproduction and $\pi$ nucleon elastic scattering show this duality in a semi-local sense through Finite Energy Sum Rules (FESR) [2]. The connection to QCD is more tenuous for on-shell photoproduction of pions at small scattering angles, but the quark content can become manifest through fixed angle dimensional counting rules [3] as well as being evident in semi-inclusive or exclusive electroproduction of pions (described through TMDs and GPDs).

This experiment is a unique opportunity to bridge resonance and high-energy, in particular, “Regge”, regimes and increases the available database above the resonance range by a significant amount.

**Regge Pole Model:** The Regge pole description of photoproduction amplitudes relies on already known Regge trajectories and coupling constants. The unitary cut amplitudes in meson photoproduction are interpreted as rescattering of on-shell meson-nucleon amplitudes. The phases between the poles and the elastic neutral pion re-scattering are critical in determining the polarizations and the constructive or destructive interferences that appear in the resonance spectrum.

The Regge pole and cut model for higher energies above the resonance regime for $\pi^0$ and $\eta$ photoproduction developed by Goldstein and Owens [4] has the exchange of leading Regge trajectories with appropriate t-channel quantum numbers along with Regge cuts generated via final state rescattering through Pomeron exchange. There are two allowed t-channel $J^{PC}$ quantum numbers series, the odd-signature $1^{--}$ and the $1^{+-}$, corresponding to the $\rho^0$, $\omega$, and the $b_1^0$, $h_1$ Reggeons, respectively. The Regge couplings to the nucleon were fixed by reference to electromagnetic form factors, $SU(3)_{flavor}$, and low energy nucleon-nucleon meson exchange potentials. The Primakoff effect is not included in the parameterization. Similar approaches to some extent were developed by Laget [5], Mathieu, Fox, and Szczepaniak [6], and recently, Donnachie and Kalashnikova [7]. The model of Laget is presumably valid within the full angular range ($\theta = 0° - 180°$) [5] while the others are good for different ranges of the forward direction (from $|t| = -t_{min}$ at $\theta = 0$ to $\theta = \pi/2$) [4, 6, 7]. Here, we examine how Regge phenomenology works for the full CLAS energy range, say E > 2.8 GeV.

**Handbag Model:** The introduction of the handbag mechanism, developed by Kroll *et al.* [8], 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. The soft part consists of all the other partons that are spectators and can be described in terms of GPDs [9]. This approach was developed to understand the nature of the observation which the HERMES Collaboration made [10]. The handbag model applicability requires a hard scale, which, for meson photoproduction, is only provided by large transverse momentum. That corresponds to large angle production, roughly for $-0.6 \le \cos\theta \le 0.6$. Here,


* mamaryan@odu.edu; Corresponding author.

we examined how the handbag model may extend for the $\gamma p \to p\pi^0$ case as Kroll *et al.* proposed.

**Scaling:** Binary reactions in QCD, with large momentum transfer occur via gluon and quark exchanges between colliding particles. The quark counting rule of Brodsky and Farrar [3] has a simple recipe to predict the energy dependence of the differential cross sections of two-body reactions at large angles when $t/s$ is finite and is kept constant. The lightest meson photoproduction was examined in terms of the counting rule [11–15]. As has been observed, first of all at SLAC by Anderson *et al.*, the reaction $\gamma p \to \pi^+ n$ shows agreement with constituent counting rules that predict the cross section should vary as $s^{-7}$ [11]. The agreement extends down to s = 6 GeV$^2$ where baryon resonances are still playing a role. Here, we examined how the counting rule is applicable to the $\gamma p \to \pi^0 p$ up to s = 10 GeV$^2$.

Previous bremsstrahlung measurements for $2 \leq E \leq 18$ GeV (1964 – 1979) gave 451 $d\sigma/dt(|t|)$s for $\gamma p \to p\pi^0$ [16]. Existing bremsstrahlung world data on photoproduction of neutral pions on proton target have very large systematic uncertainties and do not have sufficient accuracy to perform comprehensive phenomenological analyses. The recent tagged CLAS $g1c$ measurement has overall systematic uncertainty of 5% and its contribution for $2 \leq E \leq 2.9$ GeV is limited by 164 $d\sigma/dt(|t|)$s [17].

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. We have, therefore, tried to compare the Regge pole, the handbag, and the quark counting rule phenomenology with the new CLAS experimental information on the $d\sigma/dt(|t|)$ for the $\gamma p \to \pi^0 p$ above the "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 greatly constrain the high energy phenomenology.

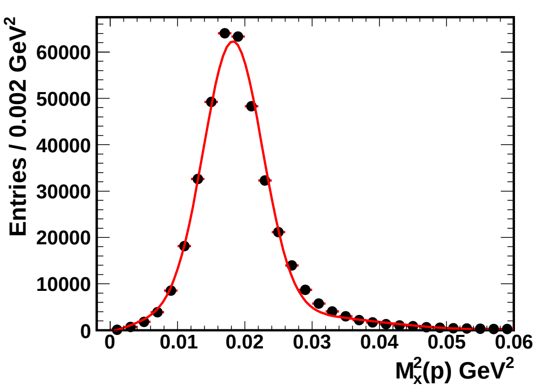


FIG. 1: (Color online) Peak of $\pi^0$ in the missing mass of proton for events with $pe^+e^-(\gamma)$ in final state.

**Experiment:** The experiment is performed with the CLAS setup at TJNAF using a tagged photon beam produced by bremsstrahlung from the 5.6 GeV electrons of CEBAF accelerator, impinged on liquid hydrogen target. The experimental details were given in many CLAS Collaboration papers - see for instance, Ref. [17]. The reaction of interest is the photoproduction of neutral pions on a hydrogen target $\gamma p \to p\pi^0$, where the neutral pions were detected via external conversion, $\pi^0 \to e^+e^-\gamma$ and subsequent Dalitz decay $\pi^0 \to \gamma^*\gamma \to e^+e^-\gamma$. Preference given to Dalitz decay mode of $\pi^0$ with very small branching ratio of 1.17% compared main decay mode $\pi^0 \to \gamma\gamma$ with branching ratio 98.82% [18] is twofold. First, we wanted to study the $M_{e+e-}$ dependence of the $\pi^0$ cross section. Then, secondly and most importantly, in the Dalitz decay mode, the final state contains three charged tracks, contrary to the $\gamma\gamma$ decay, which allows us to run the experiment with high current, and which otherwise wouldn't have been possible with a 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 final state shown in Fig. 1. The selected strategy of the analysis of $g12$ data allowed to have negligible background vs., for instance, $g1c$ results published recently [17]. 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, $\pi^+$, $\pi^-$, all particles that were $\pi^+$, $\pi^-$ were tentatively assigned to be electrons or positrons based on their charge (for details, see Ref. [19]). After particle selection, standard $g12$ calibration, fiducial cuts [20] 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 t used the $\gamma p \to p\pi^+\pi^-$ channel to filter background from double charged pion production from single $\pi^0$ production. The 1-C $t$ was used for the topology of $\gamma p \to pe^+e^-(\gamma)$ to fit to a missing final state photon. The 2-C t was used for the topology of $\gamma p \to pe^+e^-(\gamma)$ to fit to a missing nal 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 between g12 data and Monte-Carlo simulations.

The remainder of the background was attributed to $\pi^+\pi^-$ events. To reduce the background further, a comparison 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 energy. The individual contributions came from particle efficiency, sector-to-sector..., flux determination, missing energy cut, 4-C, 2-C, and 1-C pull probability, target..., branching ratio, fiducial cut, and z-vertex cut.

**Results:** The new CLAS high statistical cross sections, obtained here, for $\gamma p \rightarrow \pi^0 p$ are compared in Figs. 2 and 3 with previous data from tagged JLab CLAS $g1c$ measurements [17], and bremsstrahlung DESY, Cambridge Electron Accelerator (CEA), and SLAC, and Electron Synchrotron at Cornell Univ. experiments [16]. The overall agreement is good, specifically with the tagged CLAS $g1c$ data.

At higher energies (above $s \sim 6$ GeV$^2$) and large angles ($\theta \geq 90°$) in c.m., the results are consistent with the $s^{-7}$ scaling expected from the quark counting rule [3]. 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. Oscillations observed at 50° and 70° up to s$\sim$10 GeV$^2$ indicate that the quark counting rule requires higher energies and higher $|t|$ to prove it.

In Figs. 3 and 4, the $d\sigma/dt(|t|)$ values are shown along with predictions from Regge pole and cut [4–7] models and the handbag [8] model.

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$. The Regge model predicts "nonsense, wrong signature zeroes" where the Regge trajectories cross negative even integers. For the dominant vector meson Regge poles, these dips should appear at approximately $-t = 0.6$, 3.0, 5.0 GeV$^2$, which agrees with the data. That is why it is 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 $\rho^0$, $\omega$ 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. [5]). 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 [4], fares in an enlarged range. Remarkably, with a lowering of the original Pomeron strength, the model fits the data fairly well up to the 90°. The description of the $\pi^0$ photoproduction cross sections at largest $|t|$ requires some improvement of the Regge model probably by including u-channel exchange.

Simultaneously, Fig. 4 shows that the new CLAS data are orders of magnitude higher than the handbag model for $\pi^0$ photoproduction below $s = 11$ GeV$^2$.

**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 cross section for $\pi^0$ 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 the Dalitz decay mode was employed for extracting the cross sections from the experimental data. Measurements are performed in the reaction $\gamma p \rightarrow p e^+ e^- X(\gamma)$ using a tagged photon beam spanning the energy interval covered by "resonance" and "Regge" regimes.

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 and quark counting rule while disfavoring the handbag approach.

**Acknowledgements:** We thank Alexander Donnachie, Peter Kroll, Jean-Marc Laget, Vincent Mathieu, and Anatoly Radyushkin for comments on the feasibility of our measurements. We would like to acknowledge the outstanding efforts of the staff of the Accelerator and the Physics Divisions at Jefferson Lab that made the experiment possible. This work was supported in part by the Italian Istituto Nazionale di Fisica Nucleare, the French Centre National de la Recherche Scientifique and Commissariat à l'Energie Atomique, the United Kingdom's Science and Technology Facilities Council (STFC), the U.S. DOE and NSF, and the Korea Science and Engineering Foundation. The Southeastern Universities Research Association (SURA) operates the Thomas Jefferson National Accelerator Facility for the US DOE under contract DEAC05–84ER40150.

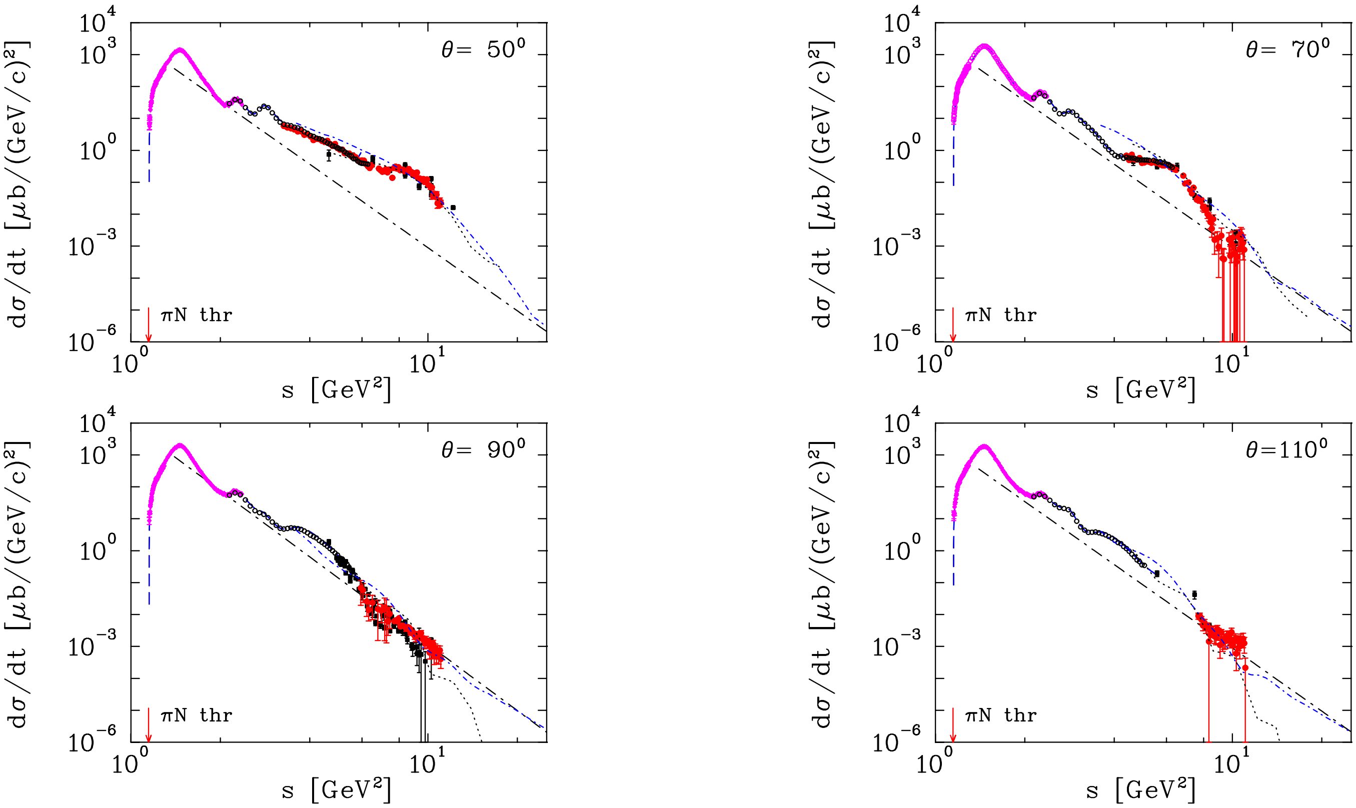


FIG. 2: (Color online) Differential cross section of $\gamma p \to \pi^0 p$ $d\sigma/dt(s)$ at 50°, 70°, 90°, and 110° in c.m. as a function of c.m. energy squared, $s$. The red filled circles are results from the current analysis of the CLAS Collaboration $g12$ data. The recent tagged data are from CLAS $g1c$ [17] (black open circles) and A2 at MAMI Collaboration [21] (magenta open diamonds with crosses). While black open filled squares are data from old bremsstrahlung measurements above E = 2 GeV [16]. The plotted points from previously published experimental data within $\Delta\theta = \pm 2^\circ$ of pion c.m. production angle, $\theta$. Plotted uncertainties are statistical. The blue dashed line corresponds to the SAID PWA DU13 solution (no new CLAS data are in the fit) [22]. Black dot-dashed lines are plotted as the best fit result for 90° case. Pion production threshold shown as a vertical red arrow. Regge results [4, 5] are given by black dotted and blue short dash-dotted, respectively.


[1] J. P. Ader, M. Capdeville, and Ph. Salin, Nucl. Phys. **B3**, 407 (1967).

[2] H. K. Armenian, G. R. Goldstein, J. P. Rutherfoord, and D. L. Weaver, Phys. Rev. D **12**, 1278 (1975).

[3] S. J. Brodsky and G. R. Farrar, Phys. Rev. Lett. **31**, 1153 (1973).

[4] G. R. Goldstein and J. F. Owens III, Phys. Rev. D **7**, 865 (1973).

[5] J.-M. Laget, Phys. Rev. C **72**, 022202(R) (2005).

[6] V. Mathieu, G. Fox, and A. Szczepaniak, Phys. Rev. D **92**, 074013 (2015).

[7] A. Donnachie and Yu. S. Kalashnikova, Phys. Rev. C **93**, 025203 (2016).

[8] H. W. Huang and P. Kroll, Eur. Phys. J. C **17**, 423 (2000); H. W. Huang, R. Jakob, P. Kroll, and K. Passek-Kumericki, Eur. Phys. J. C **33**, 91 (2004); M. Diehl and P. Kroll, arXiv:1302.4604 [hep–ph].

[9] X. Ji, Phys. Rev. Lett. **78**, 610 (1997); Phys. Rev. D **55**, 7114 (1997); A. V. Radyushkin, Phys. Lett. B **380**, 417 (1996); Phys. Rev. D **56**, 5524 (1997); D. Muller, *et al.* Fortsch. Phys. **42**, 101 (1994).

[10] M. Amarian *et al.* (HERMES Collaboration), AIP Conf. Proc. **570**, 428 (2001), Proceedings of the *14th International Spin Physics Symposium* (SPIN 2000), Osaka, Japan, Oct. 2000, edited by K. Hatanaka, T. Nakano, K. Imai, and H. Ejiri.

[11] R. L. Anderson *et al.*, Phys. Rev. D **14**, 679 (1976).

[12] D. A. Jenkins and I. I. Strakovsky, Phys. Rev. C **52**, 3499 (1995).

[13] L. Y. Zhu *et al.* (Jefferson Lab Hall A Collaboration), Phys. Rev. Lett. **91**, 022003 (2003).

[14] W. Chen *et al.* (CLAS Collaboration), Phys. Rev. Lett. **103**, 012301 (2009).

[15] Kook-Jin Kong, Tae Keun Choi, and Byung-Geel Yu, Phys. Rev. C **94**, 025202 (2016).

[16] The Durham HEP Reaction Data Databases (UK) (Durham HepData): http://durpdg.dur.ac.uk/hepdata/reac.html .

[17] M. Dugger *et al.* (CLAS Collaboration), Phys. Rev. C **76**, 025211 (2007).

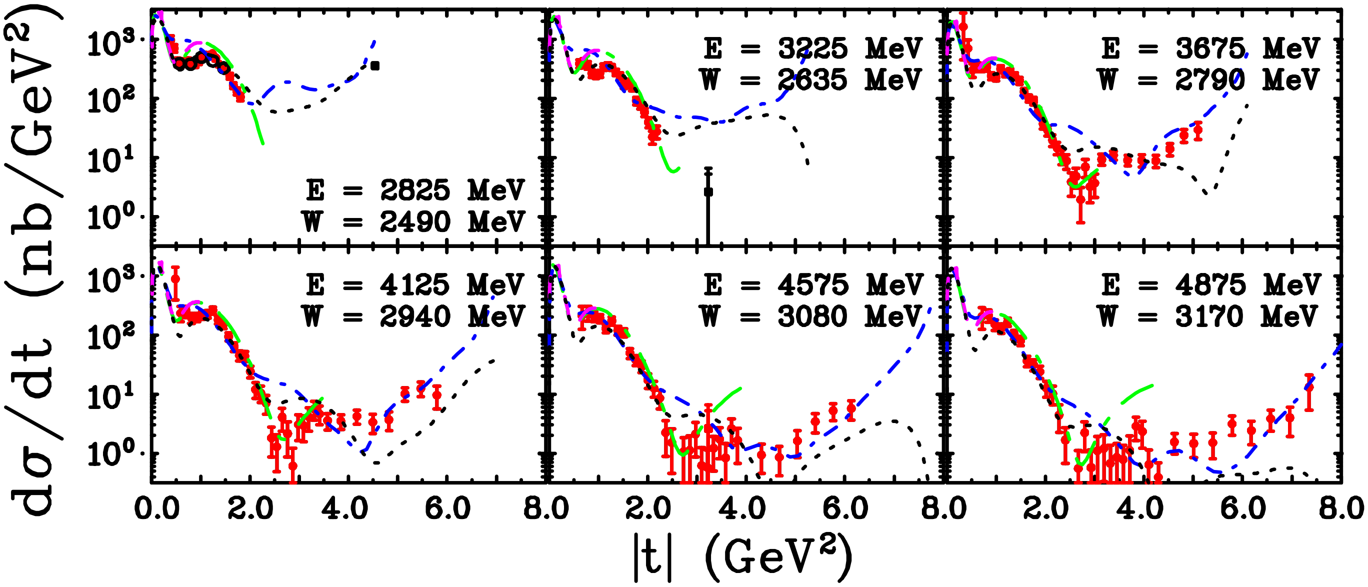


FIG. 3: (Color online) Samples of the $\pi^0$ photoproduction cross section, $d\sigma/dt(|t|)$, off the proton versus $|t|$ above "resonance" regime. Tagged experimental data are from the current CLAS $g12$ (red filled circles) and CLAS $g1c$ [17] (black open circles). The plotted points from previously published bremsstrahlung experimental data above E = 2 GeV [16] (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 [4–7] are given by black dotted, blue short dash-dotted, green long dash-dotted, and magenta long dashed lines, respectively.

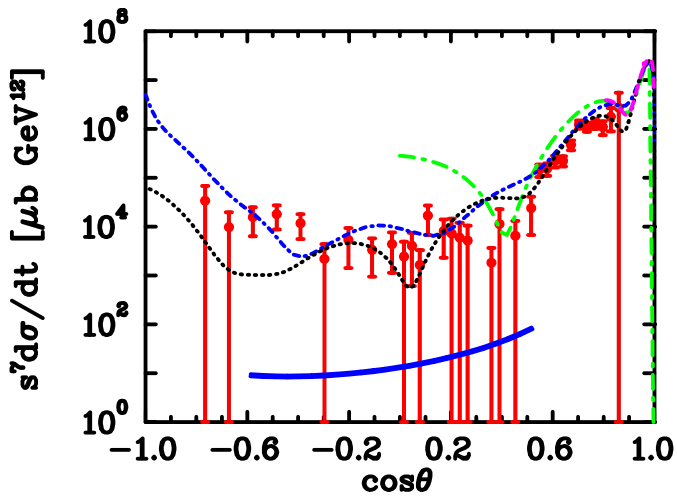


FIG. 4: (Color online) Differential cross section of $\pi^0$ photoproduction. CLAS experimental data at $s$ = 11 GeV$^2$ are from the current $g12$ experiment (red filled circles). The theoretical curves a given for Regge fits are the same as in Fig. 3 and handbag model by Kroll *et al.* [8] at $s = 10$ GeV$^2$ (blue double solid line).


[18] C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C **40**, 100001 (2016).

[19] M. C. Kunkel, Ph. D. Thesis, 2014.

[20] Z. Akbar *et al.*, CLAS Technical Note, 2016.

[21] M. Fuchs *et al.*, Phys. Lett. B **368**, 20 (1996); R. Beck *et al.*, Eur. Phys. J. A **28S1**, 173 (2006).

[22] M. Dugger *et al.* (CLAS Collaboration), Phys. Rev. C **88**, 065203 (2013).