CAA proposal on single charged pion $\gamma n \rightarrow \pi^- p$ photoproduction from deuterium

W. Chen, D. Dutta (Co-spokesperson), H. Gao (Spokesperson/Contact person), K. Kramer, W. Xu
Triangle Universities Nuclear Laboratory and Department of Physics, Duke University, Durham, NC 27708

E. De Sanctis, M. Mirazita, F. Ronchetti, P. Rossi (Co-spokesperson)
INFN, Laboratori Nazionali di Frascati

R. Schumacher
Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213

R.A. Arndt, W.J. Briscoe, Y. Ilieva, I.I. Strakovsky, R.L. Workman
Center for Nuclear Studies and Data Analysis Center
George Washington University, Wasington, DC 20052

K. Hicks, T. Mibe
Department of Physics and Astronomy, Ohio University, Athen, OH 45701

P. Stoler
Department of Physics, Rensselaer Polytech Institute, Troy, NY 12181

S.J. Brodsky
SLAC, Stanford University, Stanford, CA 94309

G.F. de Téramond
University de Costa Rica, San José, Costa Rica

H.G. Juengst
Department of Physics, *Old Dominion University, Norfolk, VA 23529*

L.Y. Zhu
Department of Physics, University of Illinois, Urbana, IL 61801

Abstract

The $\gamma n \rightarrow \pi^- p$ and $\gamma p \rightarrow \pi^+ n$ reactions are essential probes of the transition from meson-nucleon degrees of freedom to quark-gluon degrees of freedom in exclusive processes. The cross sections of these processes are also advantageous, for investigation of the oscillatory behavior around the quark counting prediction, since they decrease relatively slower with energy compared with other photon-induced processes. Recent data from JLab experiment E94-104 show dramatic change in the scaled differential cross-section from the $\gamma n \rightarrow \pi^- p$ and $\gamma p \rightarrow \pi^+ n$ processes in the center of mass energy between 1.8 GeV to about 2.4 GeV. We propose to carry out a CLAS approved analysis of the g10 data on the $\gamma n \rightarrow \pi^- p$ to investigate this dramatic behavior in much finer photon energy bins. Furthermore, the angular dependence of the scaling behavior for this process will also be studied in detail. We also propose to analyze the g2 data on the $\gamma n \rightarrow \pi^- p$ process up to a center-of-mass energy of 2.5 Gev as a function of the pion center-of-mass angle.

I. INTRODUCTION AND MOTIVATION

The $\gamma n \to \pi^- p$, $\gamma p \to \pi^+ n$ and $\gamma p \to \pi^0 p$ reactions are essential probes of the transition from meson-nucleon degrees of freedom to quark-gluon degrees of freedom in exclusive processes. The differential cross-section for many exclusive reactions [1], at high energy and large momentum transfer, appear to obey the quark counting rule. These rules were first obtained based on dimensional analysis [2] but later they were confirmed in the short-distance pQCD framework [3]. In the last few years, an all-orders demonstration of counting rules for hard exclusive processes has been shown arising from the correspondence between the anti-de Sitter space and the conformal field theory [4] which connects superstring theory to conformal gauge theory. In recent years, a similar trend, i.e. global scaling behavior, has been observed in deuteron photo-disintegration experiments at SLAC and JLab [5]- [9], in fact the onset of scaling is observed at a surprisingly low transverse momentum value above about 1.1 (GeV/c) [7,9]. In addition to the early onset of scaling, some exclusive processes such as pp and πp elastic scattering, show a striking oscillation in the scaled differential cross-section about the predicted quark counting rule behavior (s^{-10} for pp elastic scattering). One explanation [10] for these oscillations and the striking spin-correlation [11] in pp elastic scattering involves the interference between short-distance and long-distance (Landshoff [12]) amplitudes. This QCD process is analogous to the QED effect of Coulomb-nuclear interference observed in low energy charged particle scattering. Another explanation [13] interprets the oscillations in terms of opening of new charm resonance states ($uuduudc\bar{c}$). One may also explain the enhancement in polarized pp elastic scattering data in terms of a threshold effect (almost bound state) since the “free” case (outside nuclear matter) does not seem to have enough attraction to form a bound state [14,15]. With a quite modest value for the scattering length $a_s = -0.2\ fm$ extracted from charmonium-nucleon scattering, de Teramond *et al.* [16] have shown that the anomalous spin-spin behavior in pp elastic scattering may be well accounted for.

Deviations (oscillations) from the pQCD counting rule above the resonance region has recently been shown in a model of a composite system with two spinless charged constituents [17], employing the so-called concept of “restricted locality” of quark-hadron duality [18]. Ji, Ma and Yuan [19] derived a generalized counting rule for exclusive processes at fixed angles involving parton orbital angular momentum and hadron helicity flip. In this formalism the deviation from the quark counting rule [2] would be related to the orbital angular momentum. Recently, a non-perturbative derivation of generalized counting rules including the orbital angular momentum was also obtained by Brodsky and de Teramond [20].

The photo-pion production reactions are well suited for investigation of the scaling behavior ($\frac{ds}{dt} \propto s^{-7}$) and also for studying oscillatory behavior around the quark counting rule prediction, because the cross section of these processes decrease relatively slower with energy compared with other photon-induced processes. The relatively higher rates for these processes will also allow angular scans to investigate the momentum transfer (t) and transverse momentum (p_T) dependence of the scaling behavior in addition to the usual energy scan looking at the center-of-mass energy ($W = \sqrt{s}$) dependence. Recent results from deuteron photo-disintegration [7,9] suggest an angular dependent scaling onset.

II. JEFFERSON LAB EXPERIMENT E94-104

Experiment E94-104 was carried out in Hall A [21] at the Thomas Jefferson National Accelerator Facility (JLab). The continuous electron beam, at a current around 30 μA and energies from 1.1 to 5.5 GeV, impinged on a 6% copper radiator and generated an untagged bremsstrahlung photon beam. The production data were taken with the 15 cm cryogenic liquid hydrogen (LH2) target for singles $p(\gamma, \pi^+)n$ measurement, or with the liquid deuterium (LD2) target for coincidence $d(\gamma, \pi^- p)p$ measurement. The two High Resolution Spectrometers (HRS) in Hall A were used to detect the outgoing pions and recoil protons. Two new aerogel Čerenkov detectors in the left spectrometer were constructed for this experiment to provide particle identification for positive particles, mainly pions and protons, since the time-of-flight technique fails at high momentum. Details of the Hall A spectrometers can be found in Ref [21].

Based on two-body kinematics, the incident photon energy was reconstructed from final states, i.e. the momentum and angle of the π^+ in the singles measurement, and the momenta and angles of the π^- and p in the coincidence measurement. A 100 MeV bin with the center of the bin 75 MeV from the beam energy, was chosen for the data analysis, where the multi-pion contribution was negligible. The data after background subtraction, with cuts on trigger type, coincidence timing, particle identification, acceptance and photon energy, were compared to a Monte Carlo simulation code modified for this experiment based on MCEEP [22] with the same cuts on acceptance and photon energy. The raw cross section was extracted by comparing data and simulation. The distributions of acceptance, reconstructed momentum and photon energy were in good agreement with results obtained from simulations. Details on the simulation and the bremsstrahlung photon flux calculation can be found in Ref [23].

Important correction factors were applied to deduce the final cross section such as the nuclear transparency factor in the deuteron due to the final state interaction, material absorption of pions and protons, pion decay loss, detection efficiency, etc.. Analysis details can be found in Refs [23,24]. The total errors were dominated by systematic errors and were estimated to be 10% for the cross section, while point-to-point uncertainties for the three kinematics at 3.3, 4.2 and 5.5 GeV were estimated to be 5%. The statistical errors were approximately 2%. The results [25], as shown in Figure 1 and Figure 2, agree with the world data within uncertainties in the overlapping region. The data at $\theta_{cm} = 70°, 90°$ exhibit a global scaling behavior predicted by the constituent counting rule in π^- channel, similar to what was observed in the π^+ channel at similar center-of-mass angles. The data at $\theta_{cm} = 50°$ do not display scaling behavior and may require higher photon energies for the observation of the onset of the scaling behavior. The data suggest that a transverse momentum of around 1.2 GeV/c might be the scale governing the onset of scaling for the photo-pion production, which is consistent with what has been observed in deuteron photodisintegration [7,9].

Another interesting feature of the data is an apparent enhancement in the scaled differential cross section at center-of-mass angle of 90° below the scaling region, at a center-of-mass energy ranging approximately from 1.8 GeV to 2.5 GeV, in both channels of the charged pion photoproduction, as shown in Fig. 3 and Fig. 4. This effect has been observed in existing neutral pion photoproduction [26,27] data as well as in the preliminary CLAS results on the $\gamma p \to \pi^+ n$ and the $\gamma p \to \pi^0 p$ channels shown in Fig. 5 [31] and Fig. 6 [32]. Without any conclusive statements at present, some speculations might be made. The observed enhancement around 2.2 GeV might relate to some unknown baryon resonances, as some of the well known baryon resonances (Δ, N*'s around 1.5 GeV and 1.7 GeV) are clearly seen in the scaled cross section below 2.2 GeV. Several baryon resonances are predicted to be in this energy region by the constituent quark model [33], but have not been seen experimentally, i.e. the so called 'missing resonances'. The observed enhancement might be associated with the strangeness production threshold.

III. PROPOSED CAA

Recently, the CLAS Collaboration has completed the g10 data taking with the goal of high statistics search for pentaquark Θ^+ state. The data was taken on a 24-cm liquid deuterium target, with two settings of the torus magnet current (I=3375 and I=2250) and with two charged particle triggers. The incident electron beam energy was 3.767 GeV, which corresponded to a maximum $\sqrt{s}$ of 2.8 GeV. This data set is therefore ideal for the detailed investigation of the scaled differential cross-section $s^7\frac{d\sigma}{dt}$ as a function of $\sqrt{s}$ for the $\gamma n \to \pi^- p$ channel up to 2.7 GeV. Detailed study of the angular dependence of the scaling behavior will also be carried out. Furthermore, we also propose to carry out similar studies of the g2 data, which allow a maximum center of mass energy value of 2.5 GeV for the $\gamma n \to \pi^- p$ process.

For the process of interest, the $\gamma n \to \pi^- p$ quasifree process from the deuteron, only events with two charged particles will be analyzed. Using the two-body kinematics, the photon energy as well as the spectator proton can be reconstructed by detecting the π^- and the proton in coincidence. The incident photon energy is known from the photon tagger. The redundancy in photon energy determination from the reconstructed photon energy based on the two-body process provides crosscheck. This study will allow the detailed mapping of the dramatic transition region suggested by the Hall A E94-104 data [24], and also will help to elucidate the discrepancy between the Bonn data [28] and the Hall A data [24]. Furthermore, the angular dependence of this rather interesting transition behavior will be also studied in great details.

Fig. 7 shows sample spectra from analyzing the $\gamma n \to \pi^- p$ process from deuterium at the quasielastic kinematics by detecting the proton and the π^- particles in the final state from a small subset of the g10 data. The upper left panel shows that the maximum center-of-mass energy from the g10 data is 2.8 GeV for the $\gamma n \to \pi^- p$ process. The upper right panel shows the center-of-mass angle distribution for the π^- particle from the $\gamma n \to \pi^- p$ process. As one can see that the CLAS g10 data set covers a broad angular range for the reaction of interest, therefore allows for a detailed study of the angular dependence of the scaling behavior. The lower left panel shows the reconstructed missing momentum of the spectator proton, which should be compared with the fermi momentum of the nucleon inside the deuteron for the quasifree $\gamma n \to \pi^- p$ process. The lower right panel shows the reconstructed spectator proton mass squared distribution from the measured momentum and angle of the π^- and proton. The mass resolution is around

30 MeV (FWHM). Fig. 8 shows similar spectra from g10 except for the upper right panel in which a cut is applied requiring the missing particle be the spectator proton. One can see that there are dips in the π^- center-of-mass angular distribution. Fig. 9 and Fig. 10 show the π^- and the proton angular distribution in the lab with (right panel) and without (left panel) the missing mass cut on the spectator proton. One sees similar dips in the π^- angular distribution in the lab, which is likely caused by the detection inefficiency. The detection efficiency is currently being studied. Fig. 11 shows the two dimensional plot of the π^- (right) and proton (left) momentum and angle in the lab frame, respectively. The pion and proton momentum and angular distributions were obtained with the spectator proton being reconstructed.

In addition to the quasifree $\gamma n \rightarrow \pi^- p$ process discussed previously, we plan to study the exclusive $\gamma d \rightarrow \pi^- pp$ process by detecting the 3-charged particles in the final state. Fig. 12 shows sample spectra from analyzing the 3-charged particle final state. The upper left panel shows the coverage of the center-of-mass energy for the γd system and the maximum value is above 4.0 GeV. The momentum and angular acceptance for the three-charged particles are shown individually in the upper right, lower left and left right panels, respectively.

IV. ANTICIPATED RESULTS

Preliminary CLAS results shown in Fig. 5 on the $\gamma p \rightarrow \pi^+ n$ process from g1c analysis is based on an integrated luminosity of 1.1 $\times 10^6$ μb^{-1} [1]. For the g10 running, there are two torus field settings and the integrated luminosity for each torus field setting is 25 pb^{-1}. Fig. 13 shows the projected results from the proposed analysis on the $\gamma n \rightarrow \pi^- p$ process at the 90° based on the CLAS acceptance, the preliminary analysis of the g10 data, and the statistical errors of the preliminary $\gamma p \rightarrow \pi^+ n$ results from g1c (Fig. 5). Also shown in the same figure are the Hall A E94-104 results [24] with statistical uncertainties, together with all other existing data on this reaction. The projected statistical errors correspond to an integrated luminosity of 50 pb^{-1}. The average proton detection efficiency is 90%, evaluated using GSim as a function of the azimuthal angle ϕ. The detection efficiency for π^- is around 70% obtained from a study of the g10 data set on the $\gamma d \rightarrow \pi^- pp$ process and the $\gamma d \rightarrow ppX$ process with X being π^- from reconstruction. Fig. 14 shows the pion detection efficiency as a function of π^- angle in the lab frame from this study. The center-of-mass angle coverage for the $\gamma n \rightarrow \pi^- p$ process for the g10 data is from 40° to 150° for the π^- particle. The expected statistical uncertainties for other center-of-mass angles are similar to those of the 90°.

In summary, we propose to analyze the g2 and the g10 data sets to extract the differential cross-section $\frac{d\sigma}{dt}$ from the $\gamma n \rightarrow \pi^- p$ process as functions of the center-of-mass angle and the center-of-mass energy. This will allow detailed investigation of the

---

[1] The total integrated luminosity for g1c is 2.5 pb^{-1} for photon energies between 1.8 and 2.3 GeV and 4 pb^{-1} till $\sim$ 3 GeV

dramatic scaling behavior observed by the 90° data from experiment E94-104 [24] in the center-of-mass energy region of $\sim$ 2.0 - 2.5 GeV. Furthermore, the angular dependence of the scaling behavior will be studied in detail. We will also study the scaling behavior of the $\gamma d \to \pi^- pp$ process as a function of the center-of-mass energy and its angular dependence. The results from the proposed analysis will be published as articles in peer reviewed journals.

V. COLLABORATION

Members of the collaboration have extensive experience in carrying out photopion production experiments both in Hall A and Hall B. The proposed g10 analysis on the $\gamma n \to \pi^- p$ process as a function of center-of-mass energy and center-of-mass angle will comprise the majority of the Ph.D. thesis work of Wei Chen, a graduate student from Duke University. The expertise and manpower of this collaboration is adequate to carry out the proposed analysis. The collaboration also has very strong theoretical support.

VI. ACKNOWLEDGEMENT

We thank M. Dugger and B. Ritchie for providing data on the $\gamma p \to \pi^0 p$ process.

REFERENCES

[1] R. L. Anderson *et al.*, Phys. Rev. D **14**, 679 (1976); G. White *et al.*, Phys. Rev. D **49**, 58 (1994).

[2] S. J. Brodsky and G. R. Farrar, Phys. Rev. Lett. **31**, 1153 (1973); Phys. Rev. D **11**, 1309 (1975); V. Matveev *et al.*, Nuovo Cimento Lett. **7**, 719 (1973).

[3] G.P. Lepage, and S.J. Brodsky, Phys. Rev. D **22**, 2157 (1980).

[4] J. Polchinski and M.J. Strassler, Phys. Rev. Lett. **88**, 031601 (2002); R.C. Brower and C.I. Tan, Nucl. Phys. B **662**, 393 (2003); O. Andreev, Phys. Rev. D **67**, 046001 (2003); S.J. Brodsky, hep-ph/0408069; S. J. Brodsky and G. F. de Teramond, Phys. Lett. **B582**, 211 (2004); S. J. Brodsky *et al.*, Phys. Rev. D **69**, 076001 (2004).

[5] J. Napolitano *et al.*, Phys. Rev. Lett. **61**, 2530 (1988); S.J. Freedman *et al.*, Phys. Rev. C **48**, 1864 (1993); J.E. Belz *et al.*, Phys. Rev. Lett. **74**, 646 (1995).

[6] C. Bochna *et al.*, Phys. Rev. Lett. **81**, 4576 (1998).

[7] E. C. Schulte *et al.*, Phys. Rev. Lett. **87**, 102302 (2001)

[8] M. Mirazita *et al.*, Phys. Rev. C **70**, 014005 (2004).

[9] P. Rossi *et al.*, Phys. Rev. Lett. **94**, 012301 (2005).

[10] S.J. Brodsky, C.E. Carlson, and H. Lipkin, Phys. Rev. D **20**, 2278 (1979); J.P. Ralston and B. Pire, Phys. Rev. Lett. **61**, 1823 (1988); C.E. Carlson, M. Chachkhunashvili, and F. Myhrer, Phys. Rev. D **46**, 2891 (1992).

[11] D. G. Crabb *et al.*, Phys. Rev. Lett. **41**, 1257 (1978).

[12] P. V. Landshoff, Phys. Rev. D **10**, 1024 (1974).

[13] S. J. Brodsky, and G. F. de Teramond, Phys. Rev. Lett. **60**, 1924 (1988).

[14] S.J. Brodsky, I.A. Schmidt, G.F. de Teramond, Phys. Rev. Lett. **64**, 1011 (1990).

[15] M.E. Luke, A.V. Manohar, M.J. Savage, Phys.Lett. **B288**, 355 (1992).

[16] G. F. de Teramond, R. Espinoza and M. Ortega-Rodriguez, Phys. Rev. D **58**, 034012 (1998).

[17] N. Isgur, S. Jeschonnek, W. Melnitchouk, and J.W. Van Orden, Phys. Rev. D **64**, 054005 (2001); F.E. Close and N. Isgur, Phys. Lett. **B 509**, 81 (2001); S. Jeschonnek and J.W. Van Orden, Phys. Rev. D **65**, 094038 (2002); F.E. Close and Q. Zhao, Phys. Rev. D **66**, 054001 (2002).

[18] Q. Zhao and F. Close, Phys. Rev. Lett. **91**, 022004 (2003).

[19] X. Ji, J.-P. Ma, F. Yuan, Phys. Rev. Letts. **90**, 241601 (2003).

[20] S.J. Brodsky, G.F. de Teramond, Phys.Lett.B **582**, 211 (2004), also hep-th/0310227.

[21] J. Alcorn *et al.*, Nucl. Instrum. Methods A522, 294 (2004).

[22] P. Ulmer *et al.*, http://www.physics.odu.edu/∼ulmer/mceep/mceep.html.

[23] L.Y. Zhu, Ph.D. thesis, February, 2004, Massachusetts Institute of Technology (unpublished).

[24] L.Y. Zhu *et al.*, Phys. Rev. Lett. **91**, 022003 (2003).

[25] L.Y. Zhu *et al.*, nucl-ex/0409018, accepted by Phys. Rev. C.

[26] H. Genzel, P. Joos, and W. Pfeil, Photoproduction of Elementary Particles (Springer-Verlag, Berlin, 1973), Group I Volume 8 of Numerical Data and Functional Relationships in Science and Technology, edited by K.-H. Hellwege.

[27] O. Bartholomy *et al.*, Phys. Rev. Lett. **94**,012003 (2005).

[28] H.-J. Besch *et al.*, Z. Phys. C **16**, 1 (1982).
[29] I. I. Strakovsky (private communication); R. A. Arndt *et al.*, Phys. Rev. **C66**, 055213 (2002); nucl-th/0205067; http://gwdac.phys.gwu.edu/.
[30] I. I. Strakovsky (private communication); S. S. Kamalov, *et al.*, Phys. Rev. C **64**, 032201 (2001)(A dynamical model); D. Drechsel, *et al.*, Nucl. Phys. A **645**, 145 (1999)(a unitary isobar model); http://www.kph.uni-mainz.de/MAID/. MAID2001 refers to the Nov. 2001 version of the MAID solution from S. S. Kamalov.
[31] R. Schumacher, private communication.
[32] M. Dugger, B. Ritchie, private communication; The Bonn data from CB-ELSA is from O. Bartholomy *et al.*, Phys. Rev. Lett **94**, 012003 (2005)
[33] S. Capstick, Phys. Rev. D **46**, 2864 (1992); S. Capstick and W. Roberts, Phys. Rev. D **49**, 4570 (1994).
[34] "Photoproduction of Elementary Particles", edited by H. Genzel, P. Joos and W. Pfeil pp16-268, (1973); M. A. Shupe *et al.*, Phys. Rev. D. **19**, 1921 (1979).

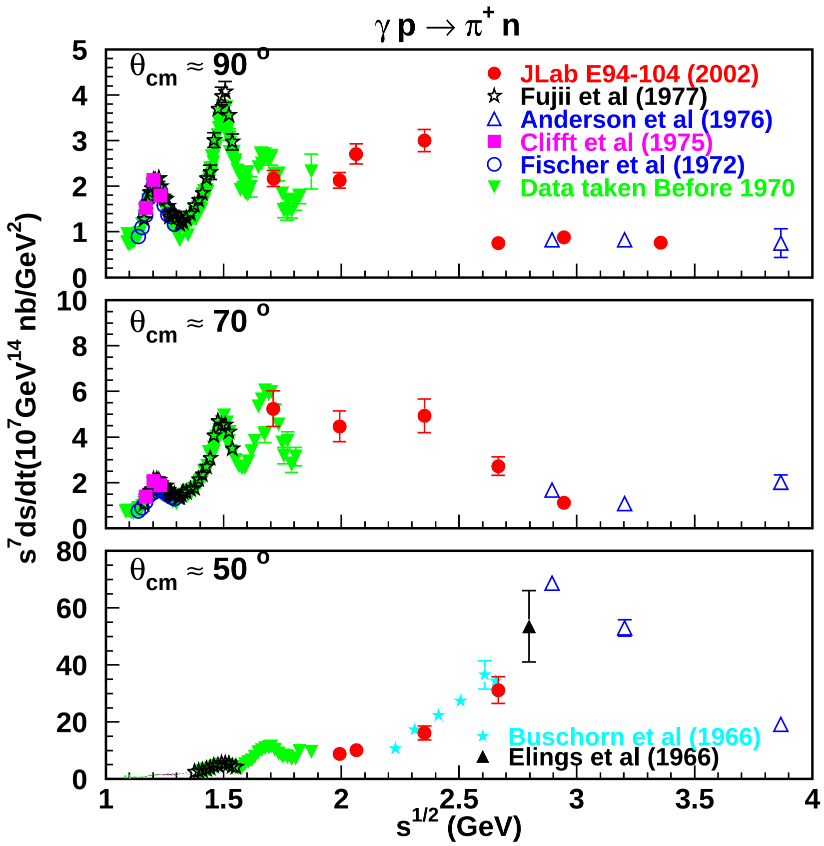

FIG. 1. The scaled differential cross section $s^7\frac{d\sigma}{dt}$ versus center-of-mass energy for the $\gamma p \rightarrow \pi^+ n$ at $\theta_{cm} = 90°, 70°, 50°$.

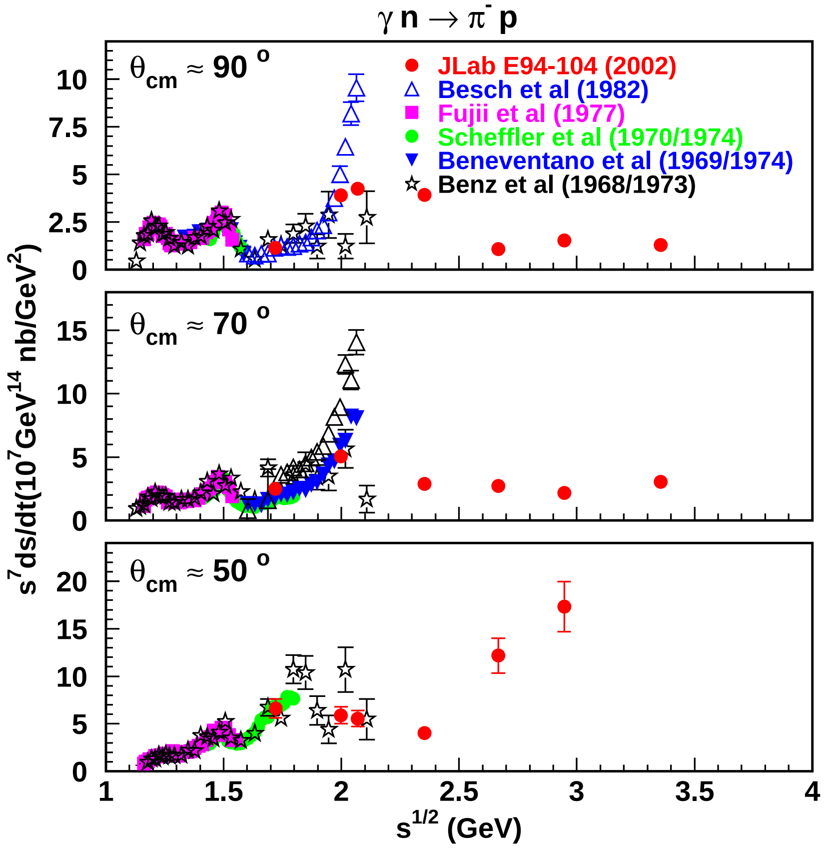

FIG. 2. The scaled differential cross section $s^7\frac{d\sigma}{dt}$ versus center-of-mass energy for the $\gamma n \rightarrow \pi^- p$ at $\theta_{cm} = 90^\circ, 70^\circ, 50^\circ$.

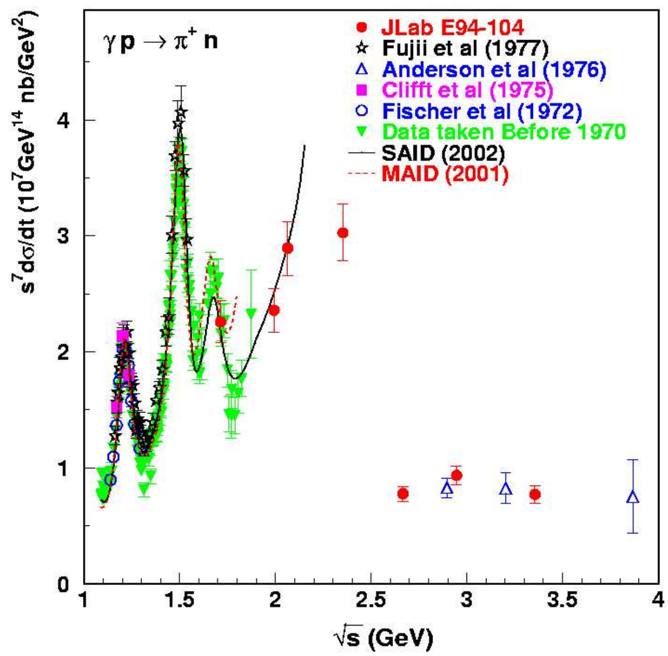

FIG. 3. The scaled differential cross section $s^7\frac{d\sigma}{dt}$ versus center-of-mass energy for the $\gamma p \to \pi^+ n$ at $\theta_{cm} = 90°$. The data from JLab E94-104 are shown as solid circles. The error bars for the new data and for the Anderson *et al.* data [1], include statistical and systematic uncertainties. Other data sets [26,27] are shown with only statistical errors. The open squares in the lower plot were averaged from data at $\theta_{cm} = 85°$ and $95°$ [28]. The solid line was obtained from the recent partial-wave analysis of single-pion photoproduction data [29] up to E_γ=2 GeV, while the dashed line from the MAID analysis [30] up to E_γ=1.25 GeV.

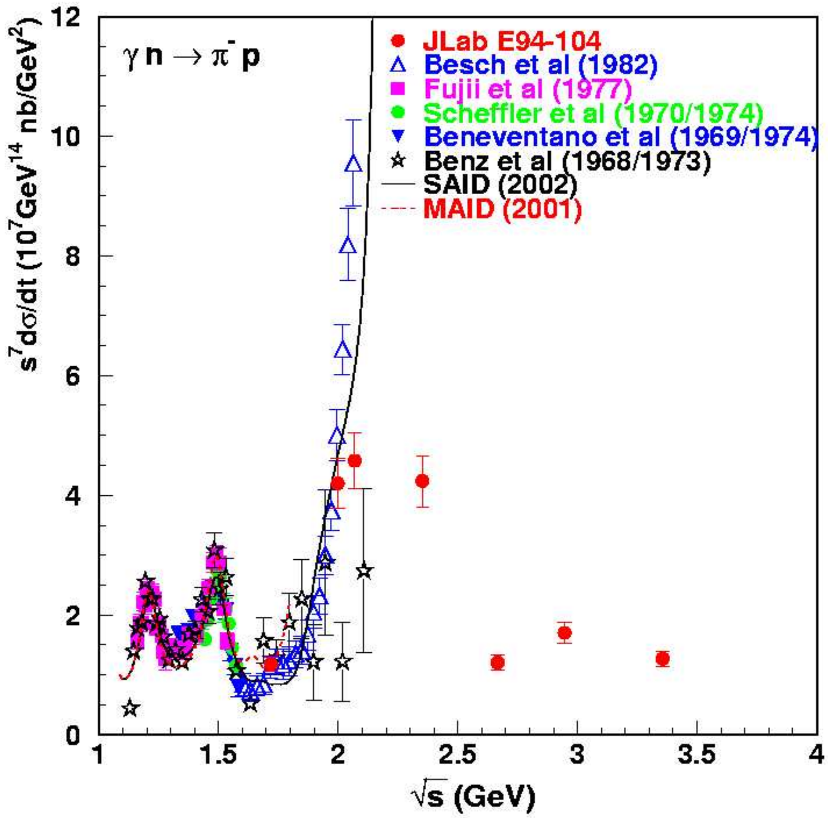

FIG. 4. The scaled differential cross section $s^7 \frac{d\sigma}{dt}$ versus center-of-mass energy for the $\gamma n \rightarrow \pi^- p$ at $\theta_{cm} = 90°$. The data from JLab E94-104 are shown as solid circles. The error bars for the new data and for the Anderson *et al.* data [1], include statistical and systematic uncertainties. Other data sets [26,27] are shown with only statistical errors. The open squares in the lower plot were averaged from data at $\theta_{cm} = 85°$ and $95°$ [28]. The solid line was obtained from the recent partial-wave analysis of single-pion photoproduction data [29] up to E_γ=2 GeV, while the dashed line from the MAID analysis [30] up to E_γ=1.25 GeV.

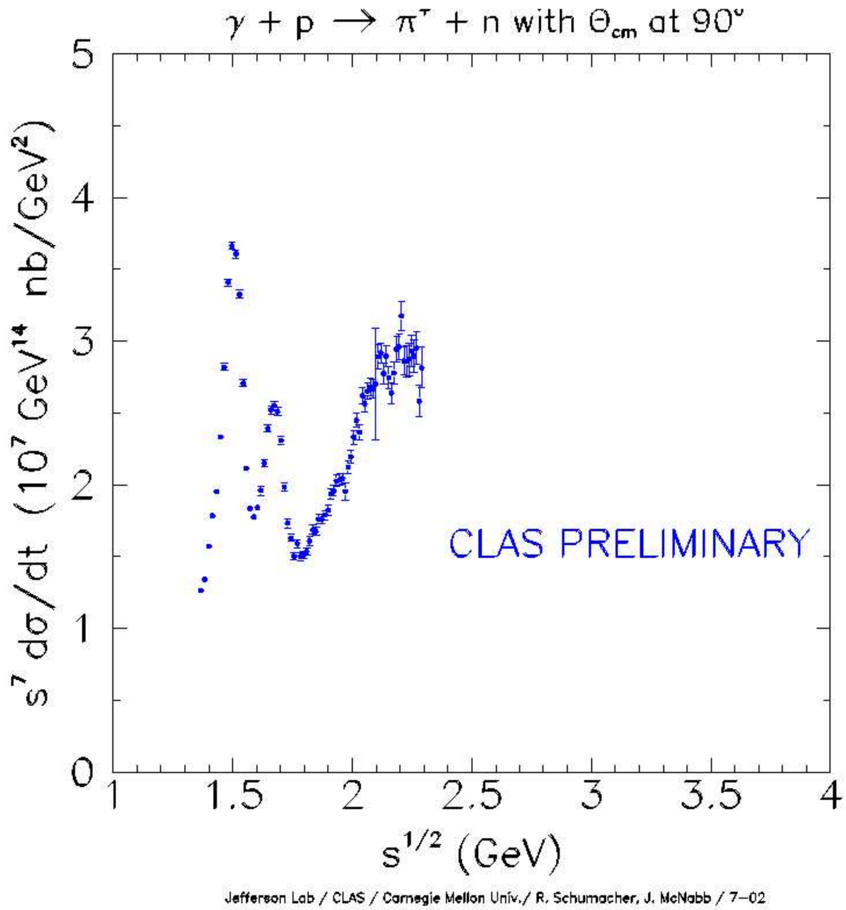

FIG. 5. Preliminary results from CLAS g1c on the scaled differential cross section $s^7\frac{d\sigma}{dt}$ versus center-of-mass energy for the $\gamma p \to \pi^+ n$ at $\theta_{cm} = 90°$. The purpose of this figure is to show the statistical uncertainties of the g1c measurement, which is used in projecting the statistical uncertainties for the proposed g10 analysis on the $\gamma n \to \pi^- p$ process (see text).

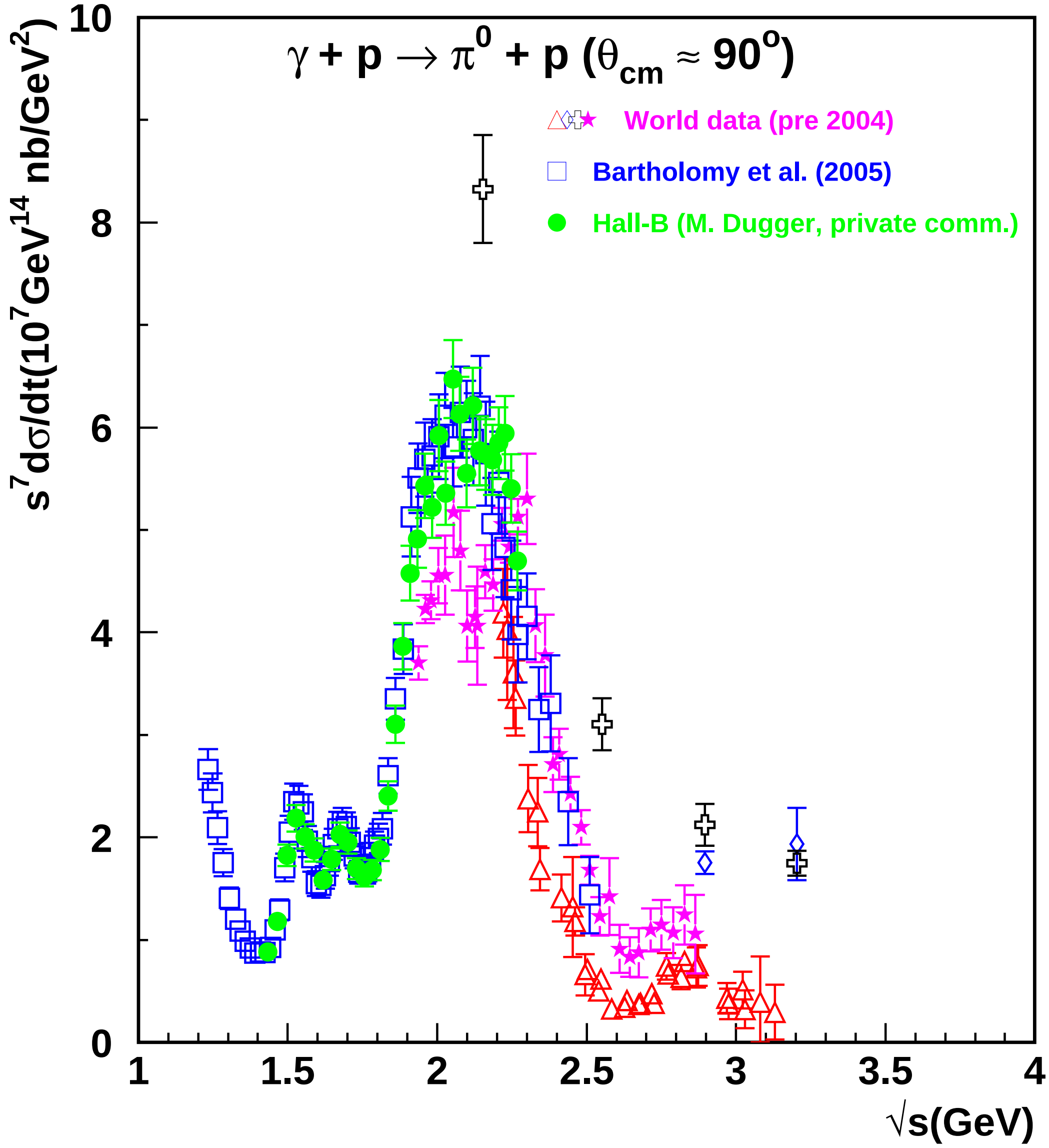

FIG. 6. Preliminary results from CLAS on the scaled differential cross section $s^7 \frac{d\sigma}{dt}$ versus center-of-mass energy for the $\gamma p \to \pi^o p$ at $\theta_{cm} = 90°$, together with world data and the Bonn data.

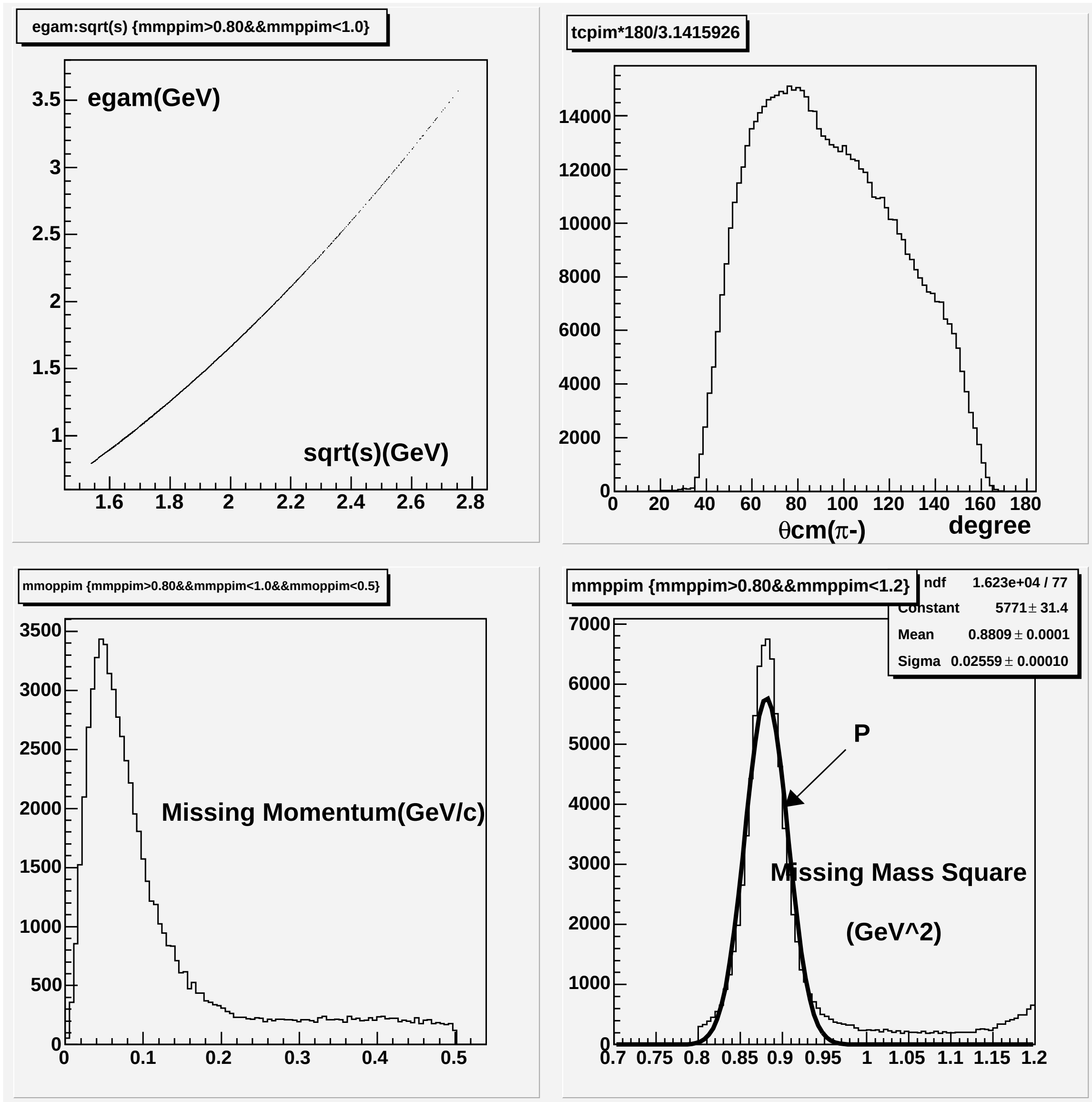

FIG. 7. Sample spectra from CLAS g10 data on the $\gamma n \rightarrow \pi^- p$ process. The upper left panel is tagged photon energy (in GeV) versus the center-of-mass energy in (GeV), and the upper right panel is the π^- center-of-mass angle distribution for the $\gamma n \rightarrow \pi^- p$ process. The lower left panel is the reconstructed nucleon momentum distribution inside the deuteron, and the right panel is the missing mass squared plot from $\gamma d \rightarrow \pi^- p X$.

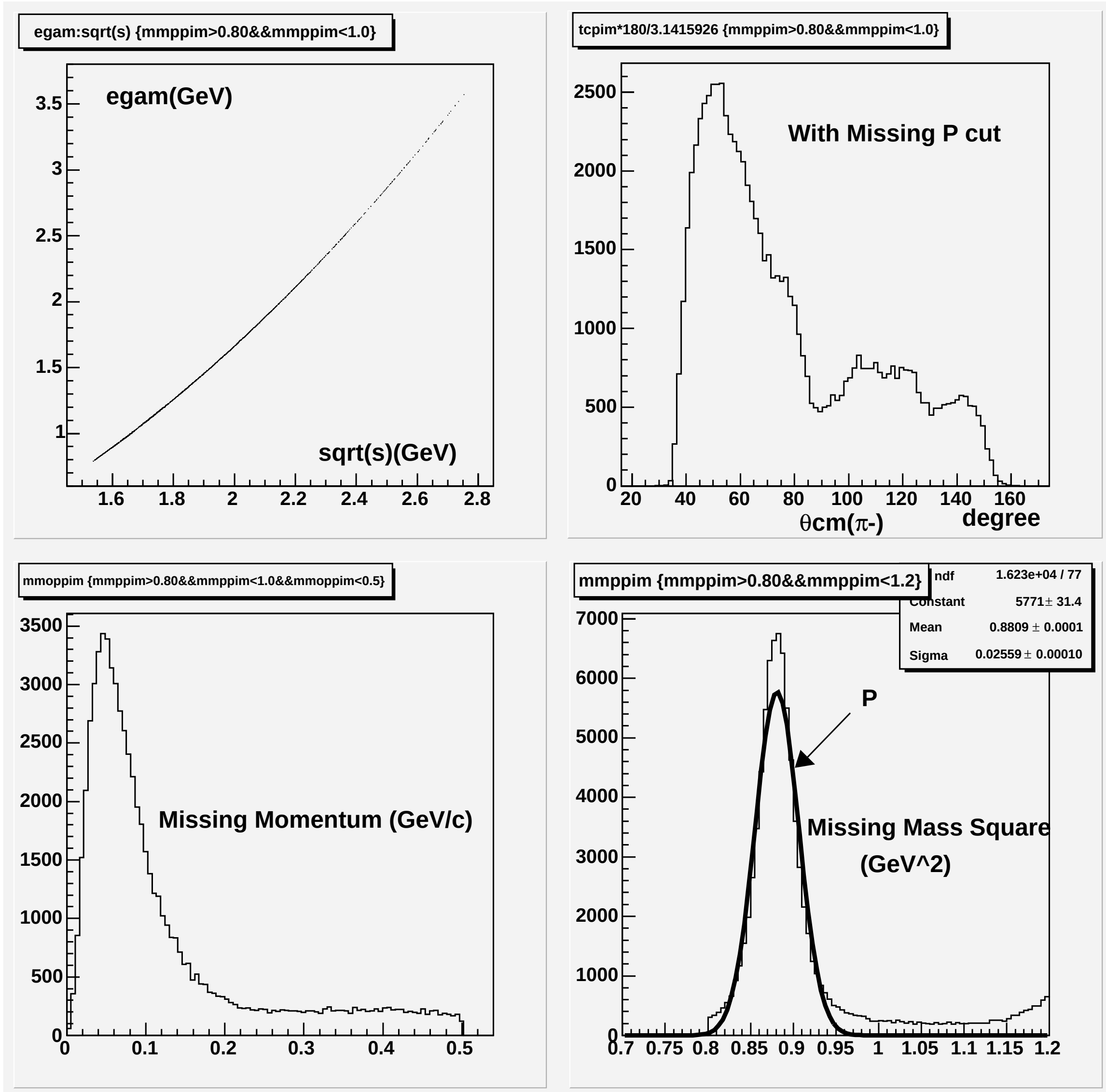

FIG. 8. Sample spectra from CLAS g10 data on the $\gamma n \rightarrow \pi^- p$ process. All panels shown here are the same as shown in Fig. 7 except for the upper right panel in which a cut is applied, requiring the missing particle be a proton.

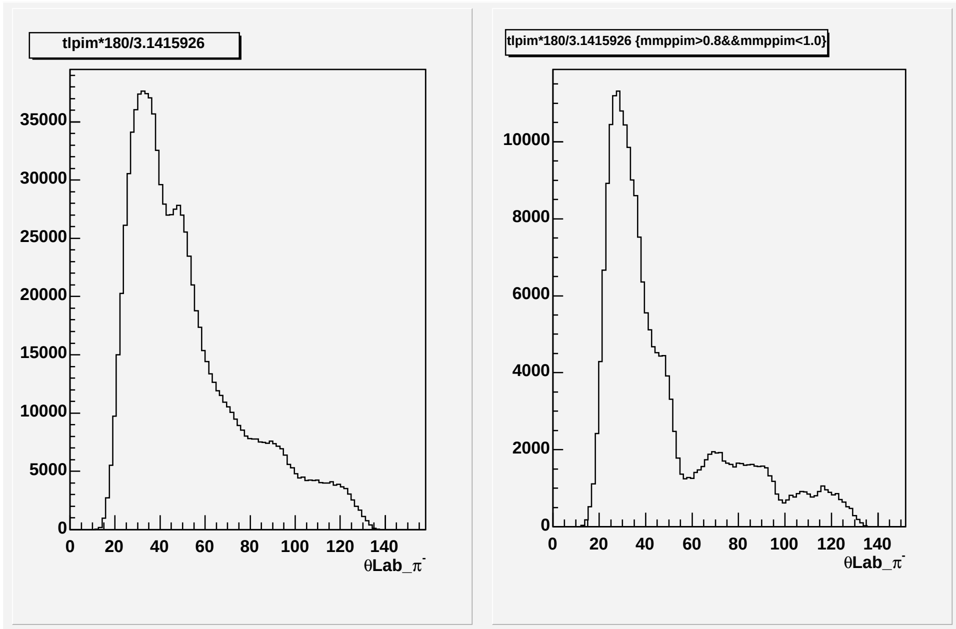

FIG. 9. The π^- angular distribution in the lab frame from CLAS g10 coincidence detection of π^-, p for the quasifree $\gamma n \to \pi^- p$ process. The left panel is without the missing particle mass cut and the right panel is with the cut (see text for details).

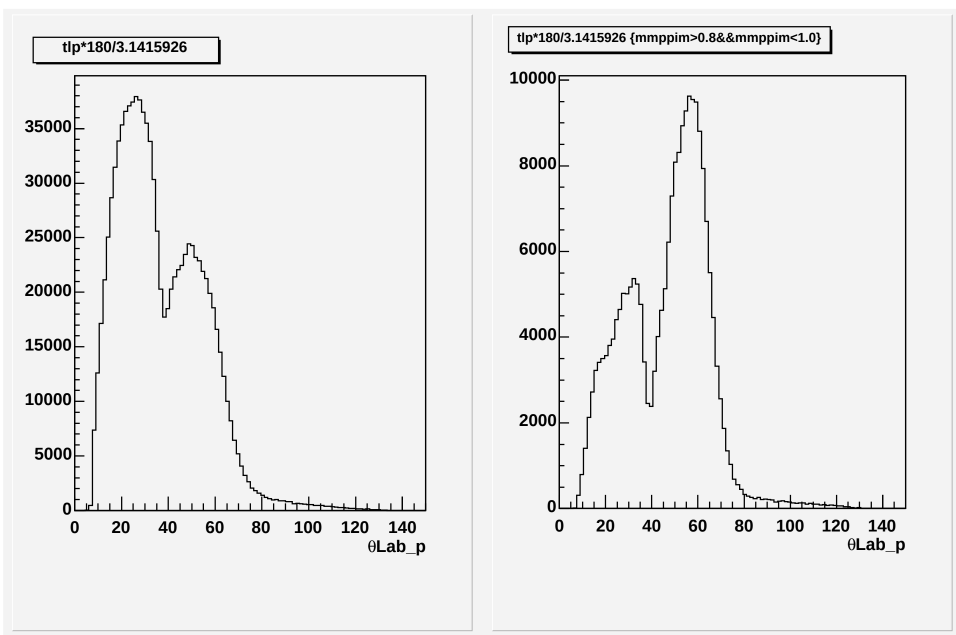

FIG. 10. The proton angular distribution in the lab frame from CLAS g10 coincidence detection of π^-, p for the quasifree $\gamma n \to \pi^- p$ process. The left panel is without the missing particle mass cut and the right panel is with the cut (see text for details).

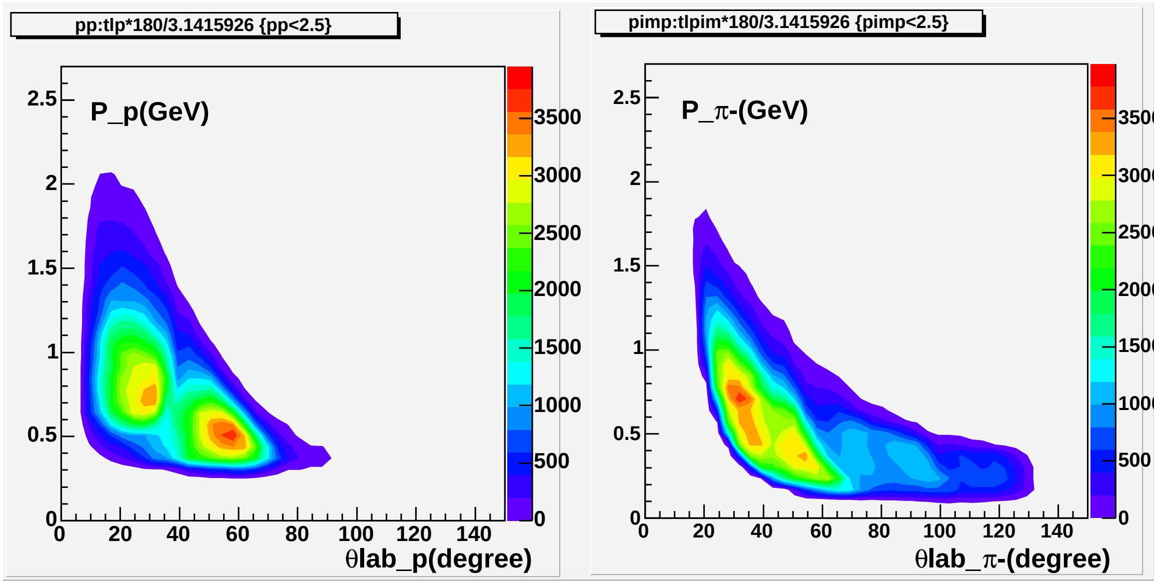

FIG. 11. The momentum and angular acceptance of the π^- and proton from CLAS g10 data for the quasifree $\gamma n \to \pi^- p$ process.

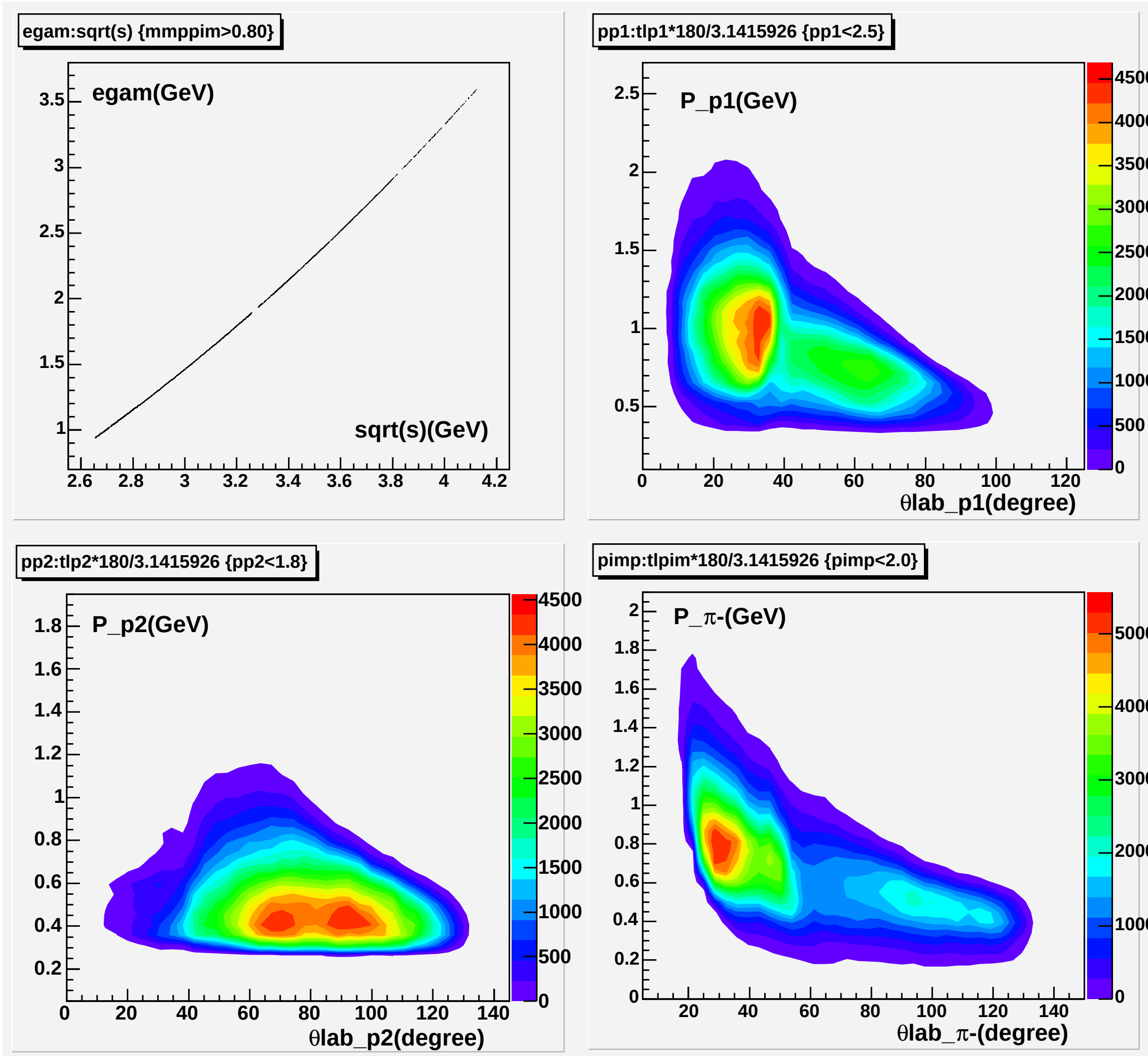

FIG. 12. Sample spectra from CLAS g10 data on the $\gamma d \to \pi^- pp$ process.

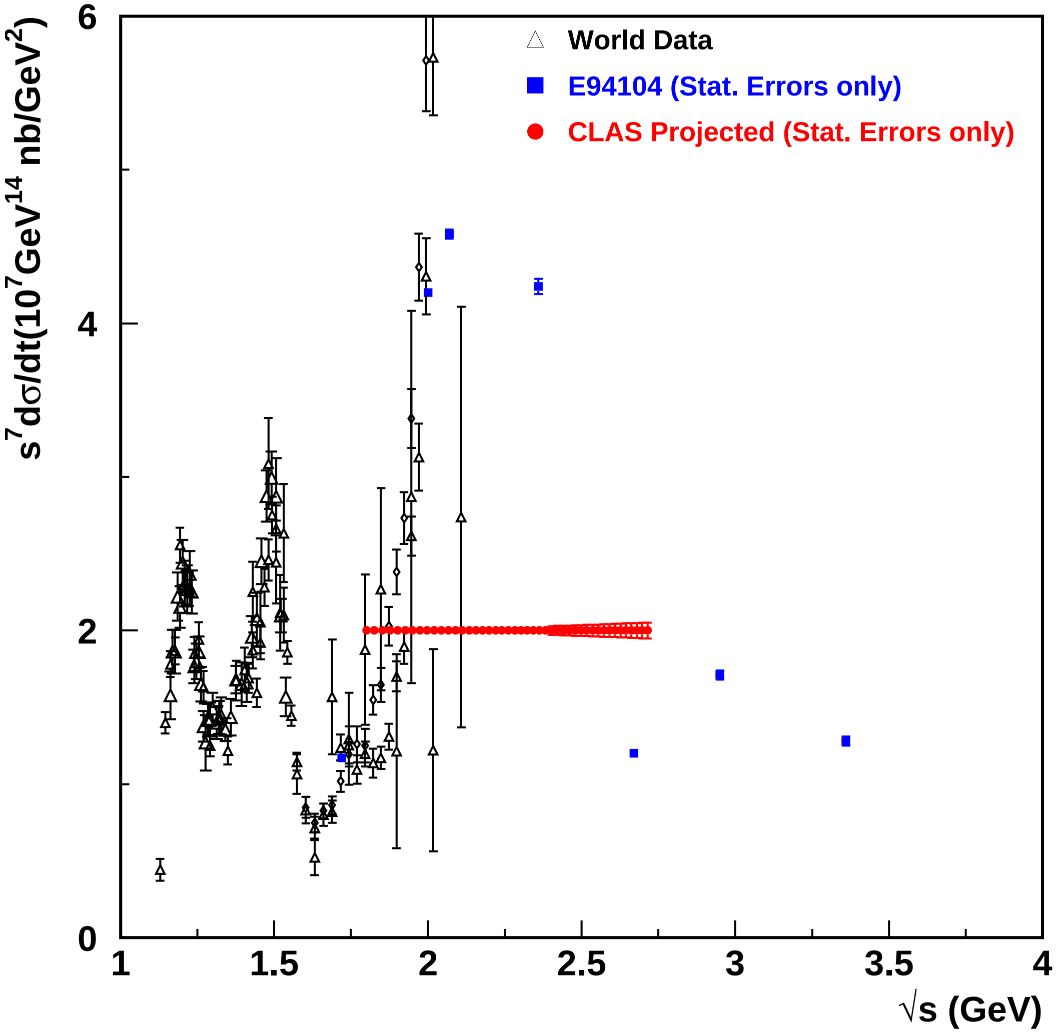

FIG. 13. Projected CLAS g10 results for the $\gamma n \to \pi^- p$ process at the 90° center-of-mass angle.

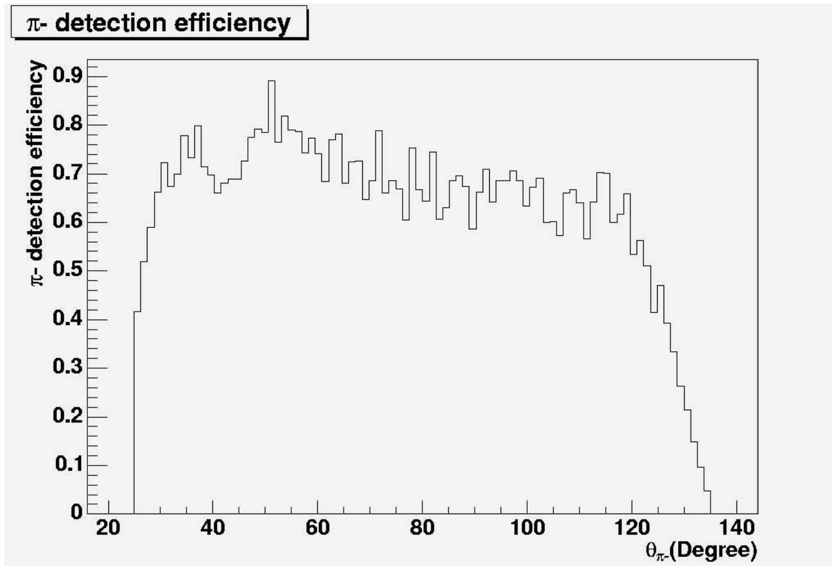

FIG. 14. The π^- detection efficiency from g10 data as a function of the π^- angle in the lab frame (see text for details).