# (A proposal to Jefferson Lab PAC48) Polarization Transfer in Wide-Angle Charged Pion Photoproduction

J. Arrington (spokesperson)

Argonne National Laboratory, Lemont, IL 23606

A.J.R. Puckett (spokesperson), P. Datta, E. Fuchey, S. Seeds

University of Connecticut, Storrs, CT 06269

A.S. Tadepalli (spokesperson), B. Wojtsekhowski (spokesperson), S. Barcus, A. Camsonne,
J.P. Chen, D. Gaskell, J.-O. Hansen, W. Henry, D. Higinbotham, D. Flay, M. Jones,
C. Keppel, D. Mack, S. Malace, D. Meekins, R. Michaels, B. Sawatzky, G. Smith,
H. Szumila-Vance, S. Wood

Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

S. Alsalmi

King Saud University, Riyadh 11451, Saudi Arabia

H. Bhatt, D. Bhetuwal, B. Devkota, J. Dunne, D. Dutta, C. Ayerbe Gayoso, L. El-Fassi, A. Karki

Mississippi State University, Mississippi State, MS 39762

V. Bellini, C. Sutera

Istituto Nazionale di Fisica Nucleare, I-95123 Catania, Italy

G. Cates, K. Gnanvo, N. Liyanage, V. Nelyubin

University of Virginia, Charlottesville, VA 232904

E. Cisbani, F. Meddi, G.M. Urciuoli

Istituto Nazionale di Fisica Nucleare - Sezione di Roma, P.le Aldo Moro, 2 - 00185 Roma, Italy

J.C. Cornejo<sup>\*</sup>, B. Quinn

Carnegie Mellon University, Pittsburgh, PA 15213

R. Gilman

Rutgers, The State University of New Jersey, New Brunswick, NJ 08854

D. Hamilton, R. Montgomery

SUPA School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK

F. Hauenstein

Old Dominion University, Norfolk, VA 23529 Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, US

P. Markowitz

Florida International University, Miami, FL 33199

P. Monaghan

Christopher Newport University, Newport News, VA 23606

A. Schmidt

The George Washington University, Washington, DC 20052, USA

A. Shahinyan

AANL, 2 Alikhanian Brothers Street, 0036, Yerevan, Armenia

J. Bernauer

Stony Brook University, Stony Brook, NY 11794, US Riken BNL Research Center, Upton, NY 11973, US

E. Cline

Stony Brook University, Stony Brook, NY 11794, US

T. Averett

College of William and Mary, Williamsburg, VA 23185, US

D. Nguyen

Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, US

W. Tireman

Northern Michigan University, Marquette, Michigan 49855, US

M.E. Christy, T. Gautam

Hampton University, Hampton, Virginia 23669, USA

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#### Abstract

Single pion photoproduction from a nucleon is the simplest inelastic hadronic process. Its physics mechanism needs to be understood in terms of QCD, and the cross section should be understood from first principles. Almost fifty years ago, measurements of differential cross sections were performed at SLAC in the wide angle regime [1], where the Mandelstam variables s, -t, -u are much larger than  $\Lambda^2_{QCD}$ . Surprisingly, until recently, theoretical calculations underestimated the observed cross sections by **almost two orders of magnitude**. A discrepancy of this scale shows that the amplitude of the process used in these calculations is missing the main contribution.

The problem was theoretically solved just three years ago by P. Kroll and K. Passek-Kumericki, whose GPD-based theory includes both twist-2 and twist-3 amplitudes [2]. The expected range of applicability of the calculations is  $s, -t, -u \gg \Lambda_{QCD}^2$ . The signatures of the twist-3 amplitude are the cross sections and also the predicted double polarization observables  $K_{LL}$  and  $A_{LL}$ . The sign of  $K_{LL}$  is opposite to that of  $A_{LL}$  if the twist-3 amplitude is the dominant contribution, as in the GPD-based calculations. An experimental check of the prediction would provide valuable information on the validity of the handbag mechanism in the GPD framework in the accessible energy range.

The proposed experiment will be performed in Hall A at Jefferson Lab. The experiment will use the 6.6 GeV CEBAF electron beam to impinge photons in the energy range  $E_{\gamma} \geq 4.0$  GeV on a deuterium target. The produced  $\pi^{\pm}$  will be detected by the BigBite spectrometer and the recoil nucleon polarization will be measured by the polarimeter in the Super Bigbite Spectrometer. The experimental setup is identical to the GEn-RP (E12-17-004) experimental setup with the Big-Bite/SuperBigbite angles at  $\theta_{BB}/\theta_{SBS} = 41.9^{\circ}/24.7^{\circ}$ .

This experiment aims to measure helicity correlation observables that have not been measured before for wide angle pion photoproduction. Such a pioneering measurement will help to uncover the nature of the interaction mechanism that underlies exclusive single pion photoproduction from the nucleon in the wide angle regime.

# 1 Introduction

Understanding of the mechanism of meson photoproduction from the nucleon, the simplest inelastic process, is an important task of hadron physics. Observables in the wide angle regime are expected to be particularly sensitive to details of the reaction mechanism. Many calculations fall short of explaining the observed cross sections in this kinematical region, and worldwide experimental and theoretical efforts are underway to solve the problem which has been a puzzle for almost fifty years now.

## 1.1 The Field of Meson Photoproduction

The field of meson photo- and electroproduction has been an area of active research for many decades. Pioneering experiments were conducted at Stanford, where the ratios of electron-induced and photon-induced pion processes were measured at different incident beam energies in an attempt to understand the observed pion cross sections [3]. Many experiments have been performed in the resonance region. The cross section and all polarization observables have been investigated carefully for photon energies below 2-3 GeV, see the data base [4]. Partial-wave analvses based on these data can be found on SAID and MAID web pages [5, 6]. The s, -t, -u values in those experiments are too low for applicability of currently known leading twist calculations. For the resonance region, the Regge model of Ref. [7] was used to fit the data from SLAC and other labs. At JLab, several measurements of the cross sections of neutral and charged pions were performed for energy up to 5.5 GeV [8, 9]. The energy range for linearly polarized photon asymmetry E up to 2.3 GeV [10] and the polarization transfer asymmetry  $K_{LL}$  at 3.5 GeV [11] and 5.5 GeV [12].



Figure 1: Differential cross section  $d\sigma/dt$  for the process  $\gamma p \to \pi^+ N$  at 90° versus s. The solid line shows  $s^{-7}$  for reference. The figure is taken from [1].

#### 1.2 Scaling in Meson Photoproduction

Measurements of exclusive photoproduction processes for a variety of reactions were conducted at large values of t and u from 4 to 7.5 GeV beam energies at SLAC [1]. Scaled cross sections as a function of |t| and scattering angle  $\theta^*$  were studied in detail for these reactions. For example, Fig. 1 shows the differential cross section  $d\sigma/dt$  for the process  $\gamma p \to \pi^+ N$  at 90° cm. angle versus s along with the  $s^{-7}$  for reference. Surprisingly good scaling behavior was observed at fixed center of mass angles in these measurements. At the same time, calculations missed the observed cross sections by **two orders of magnitude!** 

The constituent counting rule (CCR) predicts the differential cross section at fixed center of mass angles for an exclusive two-body reaction at high energy and large momentum transfer as:

$$\frac{d\sigma}{dt} \sim \frac{f(\theta_{cm})}{s^{n-2}} \tag{1}$$

where s and t are the Mandelstam variables,  $\theta_{cm}$  is the center of mass frame angle,  $f(\theta_{cm})$  depends on the dynamics of the process and n is the number of active "elementary" fields in the initial and final states that are participating in the reaction. In the case of a process like  $\gamma p \to \pi^+ n$ , the CCR predicts an  $s^{-(3+2+3+1-2)} = s^{-7}$  dependence. This model based on dimensional analysis proposed by Gunion, Brodsky, and Blankenbecler [13] attempts to connect the observed cross section to the number of "elementary fields" participating in the reaction. Although this model is a fairly good representation of the scaling features, it falls short of explaining the absolute cross sections. A very good question, which a full theory should be able to answer, is: Why does the scaling prediction work so well?

## **1.3** Charged Pion Photoproduction Experiments

Differential cross section measurements of charged pions in the reactions  $\gamma n \rightarrow \pi^- p$ and  $\gamma p \rightarrow \pi^+ n$  were conducted in Hall A at Jefferson Lab [9]. The cross sections were measured over a wide range of photon energies from 1.1 to 5.5 GeV with pion center of mass angles ranging from  $\theta_{\rm cm} =$ 50° to 110°.

Several calculations done using CCR, Hadron Helicity Conservation (HHC), and the pQCD approach fall short of the observed  $\pi^{\pm}$  cross sections, indicating a problem in the assumed interaction mechanism responsible for these observed cross sections. The experimental results indicate



Figure 2: Ratio of differential cross sections  $d\sigma(\pi^-)/d\sigma(\pi^+)$  for the process  $\gamma p \rightarrow \pi^+ n$  and  $\gamma n \rightarrow \pi^- p$  at 90° versus E, the energy of the incident photon. Data points are taken from [9]. The solid line corresponds to the handbag prediction, with uncertainties due to target mass corrections [15].

a surprising global scaling behavior at high energies and high transverse momenta, consistent with the constituent counting rule. Data also suggest an enhancement in the cross section at center of mass energies near 2.2 GeV and indicated a possible substructure around the scaling behavior.

It is important to be able to explain the observed cross sections as that sheds light on our understanding of the dynamics of interaction that operates in a particular regime. For the wide angle regime in particular, two extreme scenarios have been proposed which can be distinguished by the number of active participants in the hard scattering regime. The handbag mechanism [28, 29] involves only one active constituent, while the perturbative QCD (pQCD) mechanism involves three [13]. A depiction of the handbag mechanism is shown in Figure 3. In any given kinematic regime, quantum mechanics permits both mechanisms to contribute to the scattering amplitude. At "sufficiently high" energy the pQCD mechanism is expected to dominate, but it is not known at what s this transition takes place and how the transition to the purely pQCD mechanism emerges. Therefore, it is essential to understand the physical mechanism that is responsible for the observed cross section in the wide angle regime.

## 1.4 Handbag Approach Calculations

As discussed in the the previous section, the handbag mechanism (depicted in Figure 3) is characterized by the fact that only one quark from the incoming and one from the outgoing nucleon participate in the hard process while all others become "spectators". The calculations [14] were done in order to explain the ratio of  $\pi^+$  and  $\pi^-$  for the reactions  $\gamma n \to \pi^- p$  and  $\gamma p \to \pi^+ n$  at large center of mass angles using the handbag approach in the framework of the GPDs. The ratio of the cross sections calculated using this approach is approximately given by

$$\frac{d\sigma(\gamma n \to \pi^- p)}{d\sigma(\gamma p \to \pi^+ n)} \approx \left(\frac{e_u s + e_d u}{e_u u + e_d s}\right)^2 \qquad (2)$$



Figure 3: Schematic of the handbag mechanism, which is characterized by the fact that only one quark from the incoming and one from the outgoing nucleon participate in the hard process with all others being spectators [15].

where  $e_u$  and  $e_d$  are the charges of the up and the down quarks while s and u are the Mandelstam variables. The leading order calculation for the ratio agrees quite well with experimental data for Compton Scattering suggesting that the handbag approach accurately describes the reaction for the chosen energies and angles. Recently, the cross section of  $\pi^0$ exclusive photoproduction from the CLAS6 detector in Hall B of Jefferson Lab [8] (shown in Fig. 4) and calculations done by P.Kroll *et al.* [14] using a leading twist handbag model have disagreed in some kinematics, by **more than two orders of magnitude**.



Figure 4: Differential cross section for  $\pi^0$  photoproduction from CLAS in Hall B at Jefferson Lab. Red circles are data points from the experiment plotted along with statistical uncertainties. The systematic uncertainties are shown in the shaded blue area in the sub panel. Figure taken from [8].

Since leading twist calculations are unable to account for the observed  $\pi^0$  cross sections, Kroll *et al.* [2] calculated the wide angle photoproduction cross section of  $\pi^0$  mesons within the handbag factorization scheme. These calculations take twist-2 and twist-3 contributions into consideration in order to obtain consistent results with CLAS data [8] (shown in Figure 5-a). The twist-3 contribution dominates, while the twist-2 contribution to the cross section is almost negligible. Calculations were also performed for spin dependent observables which are the correlations between the helicities of the incoming photon (+ and -) and the longitudinal component of polarization for the initial nucleon  $(A_{LL})$  or the final nucleon  $(K_{LL})$ . These helicity correlations are defined as follows:

$$K_{LL} = \frac{d\sigma(+, \rightarrow) - d\sigma(-, \rightarrow)}{d\sigma(+, \rightarrow) + d\sigma(-, \rightarrow)}$$
(3)

Similarly,

$$A_{LL} = \frac{d\sigma(+\to) - d\sigma(-\to)}{d\sigma(+\to) + d\sigma(-\to)}$$
(4)

where the first symbol denotes the incident photon helicity and the second denotes the proton longitudinal polarization.

$$K_{LS} = \frac{d\sigma(+,\uparrow) - d\sigma(-,\uparrow)}{d\sigma(+,\uparrow) + d\sigma(-,\uparrow)}$$
(5)



Figure 5: a)  $\pi^0$  cross section data from CLAS along with calculations made by Kroll *et al.*. Dashed, solid, and dotted lines are for s = 9, 11.06 and 20 (GeV/c)<sup>2</sup>. b)  $K_{LL}$  and  $A_{LL}$  predictions for  $\pi^0$  made by Kroll *et al.* [2].

Similarly,

$$A_{LS} = \frac{d\sigma(+\uparrow) - d\sigma(-\uparrow)}{d\sigma(+\uparrow) + d\sigma(-\uparrow)},\tag{6}$$

where the first symbol denotes the incident photon helicity and the second, nucleon sideways polarization, where sideways is the direction perpendicular to longitudinal in the plane of the reaction. For twist-2 contributions, the authors estimate that:

$$A_{LL}^{twist-2} = K_{LL}^{twist-2} \tag{7}$$

and for twist-3 contribution,

$$A_{LL}^{twist-3} = -K_{LL}^{twist-3} \tag{8}$$

Calculations have been made for  $\pi^0$  photoproduction as shown in Figure 5 b). Similar calculations have been made for  $\pi^{\pm}$  photoproduction by Kroll and Passek-Kumericki [17]. In contrast to  $\pi^0$  photoproduction, the twist-2 contribution is not negligible in the forward direction whereas the twist-3 contribution dominates the backward direction. As can be seen in Fig. 6, the values of  $A_{LL}$  and  $K_{LL}$  are mostly mirror images of each other, but approach 0 for more forward angles, unlike in the  $\pi^0$  case. Such helicity correlations for  $\pi^{\pm}$  have not yet been measured at sufficiently large s, -t, and -u and as proposed, would certainly be a pioneering measurement. Such a measurement will put constraints on the contribution of twist-2 and twist-3 amplitudes to the  $\pi^{\pm}$  photoproduction cross section while potentially providing empirical support for the validity of the handbag mechanism in the framework of GPDs.



Figure 6: Predictions for helicity correlations of  $\pi^-$  photoproduction [2] and  $\pi^+$  photoproduction [17] at s = 15  $(\text{GeV}/c)^2$ . The predictions are valid only for -t and -u larger than 2.5  $(\text{GeV}/c)^2$ .

## 1.5 Wide Angle Compton Scattering (WACS)

Compton Scattering serves as another powerful tool to investigate nucleon structure. Real Compton Scattering (RCS) is a hard exclusive process that can provide complementary information to exclusive reactions such as high  $Q^2$  elastic scattering, Deeply Virtual Compton Scattering (DVCS) and high energy meson photoproduction. Taken together, they provide an independent test of the validity and/or relative importance of competing mechanisms in the wide angle regime. The GPD-based analysis of the electron-nucleon scattering form factors and WACS was updated by M. Diehl and P. Kroll for the WACS cross section and its form factors [18]. Experiments [19, 20] studied the WACS reaction in Hall A at Jefferson Lab. They measured the precise spin-averaged cross sections over the kinematic regime of  $5 \leq s \leq 11 \, (\text{GeV}/c)^2$  and  $1.5 \leq -t \leq 6.5 \, (\text{GeV}/c)^2$ . The scaling of the WACS cross section at fixed  $\theta_{CM}$  was found to be in good agreement with the predictions of the GPDs model at 90 cm. angle.

Polarization transfer to the recoil proton,  $K_{LL}$ , was also measured for WACS [19] using longitudinally polarized incident photons. The results were in excellent agreement with the GPD-based predictions and in disagreement with the pQCD predictions. These results strongly support the notion that at least in this energy range and wide angle regime, the photons interact with a single quark, contrary to the pQCD approach in which there are three "active participants". In addition, another measurement in Hall C was made at a single kinematic point [11], and the result for  $K_{LL}$  (red data point in Figure 7) was unexpectedly higher than any of the available theoretical predictions - a paradox which was resolved by a new calculation [21] with modification of the model for the axial GPD  $\tilde{H}$ .

In view of the experimental and theoretical advances, a resumption of the investigation of



Figure 7: Longitudinal polarization transfer in the RCS process at an incident energy of 3.23 GeV [19]. The labels on the curves are KN for the asymmetry in the hard subprocess; GPD, shown as a gray band, for the handbag approach using GPD's [22]; CQM for the handbag approach using constituent quarks [25]; Regge for a Regge exchange mechanism [23]; and COZ and ASY for pQCD calculations [24] using the asymptotic (ASY) or Chernyak-Ogloblin-Zhitnitsky (COZ) distribution amplitudes.

wide angle meson photoproduction is timely and necessary to complement the WACS results. An independent check of the polarization transfer observables for Wide Angle Pion Photoproduction (WAPP) would provide valuable information shedding light on the validity of the handbag mechanism in the GPD framework in this energy range. This pioneering measurement will shed light on the interaction mechanism, particularly in the wide angle regime.

# **Physics Motivation**

The goal for the pioneering measurement of the polarization transfer observable  $K_{LL}$  for  $\pi^{\pm}$  photoproduction in the wide-angle regime is to address the following questions:

- What is the nature of the interaction mechanism of meson photoproduction from the nucleon at  $s, -t, -u \gg \Lambda_{QCD}$ ?
- Does the twist-3 contribution dominate the twist-2 contribution in the wide angle regime, as suggested by the cross section measurements?

# Measurement proposal

We propose to measure  $K_{LL}$  and  $K_{LS}$  for charged pion photoproduction in the wide angle regime by using the SBS as the nucleon arm and BB as the  $\pi^{\pm}$  arm. The experiment will use the 6.6 GeV CEBAF electron beam to impinge photons in the energy range 4.0 - 6 GeV on a deuterium target and run with the same setup as the GEn-RP experiment. The BB/SBS angles are the same as those in the GEn-RP setup [26], shown in Fig. 8, which are  $\theta_{BB}/\theta_{SBS} = 41.9^{\circ}/24.7^{\circ}$ .



Figure 8: Schematic of the experimental setup of GEn-RP [26]. BigBite will be the  $\pi^{\pm}$  arm and the polarimeter will be the nucleon arm.

# 2 Experimental Setup

The experimental setup will be identical to the GEn-RP setup, as shown in Figure 8. For the WAPP experiment we will use:

- CEBAF 6.6 GeV electron beam of 5  $\mu$ A current
- 15 cm long  $LD_2$  target with a 6%X0 Cu radiator in front of the target
- Electron-nucleon luminosity at ~  $4.5 \times 10^{37} \text{ cm}^{-2} \text{s}^{-1}$  (LD<sub>2</sub> target contribution, total luminosity with radiator  $6 \times 10^{37} \text{cm}^{-2} \text{ s}^{-1}$ )
- BigBite arm to detect the  $\pi^{\pm}$ . It has a dipole magnet followed by GEM trackers, GRINCH (a gas Cherenkov detector), rear GEM chamber, Pb-glass preshower, timing hodoscope, and Pb-glass shower calorimeter.
- Proton arm with a polarimeter. This arm has a 48D48 dipole magnet followed by the front GEM chambers, a steel analyzer block for proton scattering, the rear GEM chambers, and an HCAL (Hadron calorimeter) for the detection of protons and neutrons.

More detailed information about the equipment can be found in reference [26] as well as the GMn run plan. As such, this proposal covers only the essential features of the spectrometers necessary to achieve the experiment's goals.

# 2.1 The CEBAF Electron Beam

We propose to perform the measurement in Hall A of Jefferson Lab using the CW polarized 6.6 GeV electron beam from the CEBAF accelerator. Electron beam polarizations of  $\sim 85\%$  have been routinely achieved, and such a beam polarization value has been assumed in the calculations of the projected statistical precision of the proposed measurement.

# 2.2 The Liquid Deuterium Target (LD<sub>2</sub>)

The electrons will be incident on a 15 cm long liquid deuterium (LD<sub>2</sub>) target which has 100  $\mu m$  Al entrance and exit windows with thickness of ~ 0.054 g/cm<sup>2</sup> of material (compared to ~ 1.69 g/cm<sup>2</sup> LD<sub>2</sub>). The 6%X0 Cu radiator is mounted on the target ladder 10 cm upstream of the target.

# 2.3 The BigBite spectrometer - $\pi^{\pm}$ Arm

BigBite is a large-acceptance non-focusing magnetic spectrometer which subtends a solid angle of  $\sim 58$  msr when placed 1.55 m from the center of the target to the entrance of the dipole. A schematic of the BigBite arm is shown in Figure 9.

The main components of the BigBite arm are:



Figure 9: Schematic of the BigBite arm. See text for details.

## 2.3.1 The Dipole Magnet

The 20 ton dipole magnet constructed at the Budker Institute was used originally at NIKHEF and has been used in several experiments performed with the 6 GeV CEBAF electron beam. With the entrance aperture at 155 cm from the target center, the minimum central scattering angle that BigBite can reach is around 30°. The field integral along the central trajectory is 1.2 Tm. The angular resolutions of the detector are  $\delta\theta \approx 1$  mrad for  $p_{\pi} \approx 1$  GeV/c. The momentum resolution  $\delta p/p \approx 1\%$ . The vertex resolution is  $\approx 2$  mm along the direction perpendicular to the central axis of the magnet.

## 2.3.2 Front and Rear GEM chambers

In order to achieve higher usable luminosity, the MWPCs from the 6 GeV era of experiments were replaced with GEM-based tracking detectors. The front GEM detector planes will be installed immediately after the dipole magnet and before the gas Cherenkov detector called "GRINCH". For the front GEM tracker, four triple-foil GEM chambers will be installed with a total area of 40 cm x 150 cm. A rear GEM detector plane will be installed in between the GRINCH and the preshower calorimeter. For the rear GEM chamber, 4 GEM modules of 60 cm x 50 cm in area will be installed, giving a total area of 60 cm x 200 cm.

## 2.3.3 Gas Cherenkov

The gas Cherenkov detector, "GRINCH", prepared by the College of William and Mary and collaborators, contributes greatly to off-line separation of  $e^-$  and  $\pi^{\pm}$ . Light emitted from the charged particle tracks in the detector will be reflected by four cylindrical mirrors and detected in 510 9125 PMTs which have a diameter of 29 mm. The clusters of hits in adjacent PMTs will be identified by time coincidence and location correlation with the particle trajectory.

# 2.3.4 Timing Hodoscope

Precision timing of a particle will be provided by the Timing Hodoscope built by a collaboration led by Glasgow University. This hodoscope consists of 90 EJ200 plastic scintillator bars, with dimensions  $25 \ge 25 \ge 600$  mm, each read out by ET9142 29 mm PMTs. The projected time resolution of 0.15 ns allows identification of the individual RF buckets in the beam sent by the CEBAF accelerator.

# 2.3.5 Pb-Glass Calorimeter - Preshower and Shower

Preshower and shower components of the BigBite detector consist of lead glass blocks read out by PMTs which collect the Cherenkov light from relativistic charged particles, including the primary particles and secondary  $e^+/e^-$  produced in electromagnetic cascade events. The preshower blocks are 9 cm x 9 cm x 30 cm and have radiation hard lead-glass (reused from HERMES). The long axes of the preshower modules are oriented perpendicular to the pion direction while the long dimensions of the shower blocks are oriented along the pion direction. The energies deposited in the preshower and the shower modules will help distinguish between electrons and pions in the detector. Both measurements will be used in the trigger logic.

# 2.4 The Proton Arm

A schematic of the proton arm with a polarimeter is shown in Figure 10.

The components of the proton arm are the following:

# 2.4.1 48D48 Dipole Magnet

The 48D48 dipole magnet serves several purposes in this experiment.

- 1. To precess the proton spin, allowing measurement of the longitudinal component of the proton polarization (at the reaction point) as the nucleon polarimeter is sensitive only to transverse components of polarization.
- 2. For momentum analysis of charged-particle tracks.
- 3. For neutron/proton separation in the GMN/GEN-RP experiments.



Figure 10: The view of the proton arm.

4. To sweep low-momentum, charged background out of the acceptance of the polarimeter. For an integrated field strength of  $\sim 1.7$  Tm, all charged particles with momenta below  $\sim 1$  GeV/c are swept beyond the acceptance of HCAL.

## 2.4.2 GEM Charged Particle Trackers

These are the most delicate parts of the SBS apparatus. The front tracker includes two GEM planes with a size of 40 cm x 150 cm (built by INFN) and two bigger chambers of 60 cm x 200 cm (built by UVa). The rear tracker has four chambers of area 60 cm x 200 cm (built by UVa). The front tracker allows us to track the protons produced by interactions of the beam with the deuterium target, for the dual purposes of (a) reconstructing the scattered proton's kinematics, and (b) defining the trajectory of the proton incident on the analyzer for measurement of the angular distribution of secondary scattering, used for polarimetry. The rear tracker detects the protons scattered in the analyzer.

## 2.4.3 Analyzer

A 60 cm x 200 cm x 8.9 cm block of steel has been chosen as a polarization analyzer in order to scatter the recoil protons. The trajectory change, reconstructed after forward "p-p" scattering, is used to determine the polarization of the incident proton. Iron seems to be the appropriate choice of material since it has a high number of protons per unit volume and is relatively cheap.

# 2.4.4 Hadron Calorimeter - HCAL

The Hadron Calorimeter, or simply HCAL, will be used in the detection of the protons. It consists of a 12 x 24 array of 15 x 15 x 90.8 cm calorimeter modules which are formed by alternating Fe and plastic scintillator plates. The total thickness of Fe is 50.8 cm and of the plastic scintillator 40 cm. Scintillation light will be collected by a wavelength-shifting guide and then transmitted to a PMT. The time resolution is expected to be 0.5 ns. The response to protons and neutrons will be very similar and the efficiency is expected to be  $\sim 90\%$  for the protons in the proposed measurement.

# **3** Proposed Measurements

### 3.1 Kinematics and Monte Carlo Simulations of $\vec{\gamma}n \to \pi^- \vec{p}$ in the GEn-RP setup

We propose to use the same kinematic settings as the approved GEn-RP experiment E12-17-004, with the SuperBigbite Spectrometer (SBS) at a central angle of 24.7° and with BigBite (BB) at a central angle of 41.9°. With a beam energy of 6.6 GeV, the combined acceptance of SBS and BB at these central angles is optimal for the detection of  $\pi^- p$  and, to a lesser extent,  $\pi^+ n$  photoproduction events at simultaneously large values of s, -t, and u, in the backward-angle regime. Figure 11 shows the simulated distributions of the Mandelstam



Figure 11: Distributions of s, -t, -u, and  $\cos \theta_{CM}$  within the combined BigBite-SBS acceptance, from g4sbs, the SBS GEANT4-based Monte Carlo simulation package. See text for details.

variables and the CM scattering angle  $\theta_{CM}$ , plotted as  $\cos(\theta_{CM})$ , for 4 GeV  $\leq E_{\gamma} \leq 6.6$  GeV. The distributions shown in Fig. 11 correspond to the following requirements on the signals in the detectors:

- 1. Good  $\pi^-$  track in the BigBite GEMs
- 2. Energy deposition of at least 500 MeV in the BigBite shower calorimeter

- 3. Energy deposition less than 100 MeV in the BigBite preshower calorimeter
- 4. Energy deposition of at least 80 MeV in the active material (scintillator) of HCAL
- 5. A good proton track in the front GEMs of the SBS polarimeter.

The cross-section-weighted average kinematic variables within the acceptance for events passing the above selection criteria for  $\gamma n \to \pi^- p$  are:

- $\langle s \rangle = 9.3 \text{ GeV}^2$
- $\langle -t \rangle = 4.6 \text{ GeV}^2$
- $\langle -u \rangle = 2.9 \text{ GeV}^2$
- $\langle \cos(\theta_{CM}) \rangle = -0.22$

All of the Mandelstam variables are sufficiently large that one might reasonably expect the handbag mechanism to play a dominant role in the observed cross sections and polarization observables. Figure 12 shows the distributions of the incident photon energy  $E_{\gamma}$ , and the



Figure 12: Distributions of  $E_{\gamma}$ , the incident photon energy,  $p_{\pi}$ , the  $\pi^-$  momentum in BigBite, and  $p_p$ , the proton momentum in SBS. Note that 4 GeV was the lower limit placed on  $E_{\gamma}$  for "signal" event generation.

momenta  $p_{\pi}$  and  $p_p$  of the pion and proton.

#### 3.2 Event generation, cross section model and event rate estimate

Physics signal events including  $\gamma n \to \pi^- p$  and  $\gamma p \to \pi^+ n$  on the deuterium target were generated uniformly in  $E_{\gamma}$ , the incident photon energy, -t, the momentum transfer to the outgoing nucleon, and  $\phi$ , the azimuthal angle of the  $\pi$  in the lab frame, with limits chosen to populate the full acceptance of BigBite for the chosen range of  $E_{\gamma}$ . The effects of Fermi smearing due to the initial nucleon's motion were accounted for by randomly sampling the magnitude and direction of the struck nucleon's momentum from a parametrized nucleon momentum distribution for the deuteron. The incident photon and nucleon kinematics were then boosted to the nucleon rest frame, where the calculations of the outgoing particle kinematics and the center-of-momentum scattering angle  $\theta_{CM}$  in terms of s, -t, and  $\phi$  are simpler. After calculating the outgoing particle kinematics in the nucleon rest frame, they were boosted back to the lab frame and tracked through the GEn-RP setup in g4sbs. The charged pion photoproduction cross section was estimated based on the following parametrization of SLAC  $\pi^+n$  data [1]:

$$s^{7} \frac{d\sigma}{dt} (\gamma p \to \pi^{+} n) = 0.828 \times 10^{7} (1-z)^{-5} (1+z)^{-4} (\text{nb/GeV}^{2} \cdot \text{GeV}^{14}), \qquad (9)$$

where  $z = \cos \theta_{CM}$ . The  $\gamma n \to \pi^- p$  cross section was assumed to be 1.7 times the  $\gamma p \to \pi^+ n$ cross section based on the  $\sigma(\pi^{-})/\sigma(\pi^{+})$  ratio measurements from Ref. [9]. To obtain an equivalent differential cross section per incident electron, the photoproduction cross section  $d\sigma/dt$  was then multiplied by the differential Bremsstrahlung flux per electron at the generated photon energy due to both the radiation length of the materials upstream of the generated interaction vertex and the real photon content of the electron beam, with the latter estimated using the equivalent photon approximation. The average estimated real photon flux per electron, integrated within the generated range of  $E_{\gamma}$ , including both "external" and "internal" fluxes, was approximately 4.3% for the chosen generation limits and the assumed target and radiator thickness. A weight for each Monte Carlo-generated event was then calculated as the product of the estimated differential cross section, the phase space volume for event generation, and the luminosity, divided by the total number of attempted event generations, which includes attempted event generations in kinematically forbidden corners of the phase space. No final-state particles were generated or tracked through the simulation for the small fraction of events whose attempted kinematics were forbidden, but these attempted generations had to be included in the normalization to correct for the ratio between the user-generated phase space and the kinematically allowed subset of the user-generated phase space. These event weights were then applied in generating histograms such as those shown in Figs. 11 and 12 to obtain weighted Monte Carlo event samples corresponding to expected event rates and distributions.

## 3.3 Trigger and estimated rates

### 3.3.1 BigBite Charged Pion Trigger

The standard BigBite trigger is designed to be highly efficient for electrons while suppressing charged pions and low energy particles. To facilitate the proposed measurements, a dedicated charged pion trigger is required. The design of such a trigger is complicated by the fact that lead glass is not very sensitive to charged pions, but is highly sensitive to electrons, positrons, and high-energy photons. To realize an adequately efficient trigger for  $\pi^- p$  events with a manageable rate requires a coincidence with the high-energy nucleon detected in HCAL and a modified trigger logic for BigBite to enhance the efficiency for charged pions while suppressing electrons and photons.



Figure 13: Simulated preshower and shower energy depositions by good signal  $\pi^-$ , illustrating the BigBite trigger logic for charged pions. Black circles represent the "true" energy depositions, while red squares represent the energies smeared by the calorimeter energy resolution. Top Left: shower energy deposition. The vertical lines at 0.2 GeV and 0.5 GeV represent possible thresholds. Top Right: preshower energy deposition, illustrating dominant minimumionizing peak. The vertical line illustrates the "veto" threshold above which triggers will be rejected, as they are predominantly electron and photon-induced. Bottom left: Sum of shower and preshower for good signal  $\pi^-$ . Bottom right: correlation between preshower and shower signals, smeared for detector resolution.

Figure 13 shows the response of the BigBite preshower and shower calorimeters to the  $\pi^-$  from physics signal events (high-energy, exclusive  $\pi^- p$  photoproduction). The preshower spectrum consists predominantly of the minimum-ionizing peak at around 50 MeV, with a low-level tail extending out to high energies. Approximately 80% of signal  $\pi^-$  events deposit less than 100 MeV in the preshower. The shower spectrum also exhibits a minimum-ionizing-like peak at around 300 MeV, corresponding to pions that pass through the entire thickness of the shower calorimeter without undergoing a hadronic interaction and subsequent high-energy shower. Some relatively small fraction of charged pions will also decay to muons while passing through the BigBite calorimeter. The absolute and relative positions of the minimum-ionizing peaks reflect the ratio of thicknesses of the preshower and shower blocks along the direction of particle motion. Given the larger thickness of energy in the shower calorimeter than in the preshower. For a threshold on the shower only, the efficiency for signal  $\pi^-$  is about 94% (61%) for a threshold of 200 MeV (500 MeV).

The standard BigBite electron trigger is based on a simple sum of preshower and shower energies. The bottom left panel of Fig. 13 shows the sum of preshower and shower energy depositions by good "signal"  $\pi^-$  events. A very high efficiency for  $\pi^-$  could be achieved by setting the threshold on this sum at about 200 MeV. Even at 500 MeV, a threshold on the sum of shower and preshower leads to an efficiency of approximately 73%. However, the rate from other background processes using this logic at such low thresholds would overwhelm the DAQ, even at the relatively low total luminosity of this proposal. Instead, the BigBite trigger will be modified to exploit the fact that electrons and photons also tend to deposit large amounts of energy in the preshower while the energy deposition by charged pions is generally small. The dedicated charged pion trigger will require that the energy deposition in the preshower be less than 100 MeV, while the energy deposition in the shower be at least 500 MeV. This trigger logic can easily be achieved via a slight reconfiguration of the existing BigBite trigger electronics. While it would be desirable to set the shower threshold as low as 200 MeV to achieve an even higher efficiency for charged pions by including the minimumionizing peak, the higher shower threshold of 500 MeV represents an optimal compromise between adequately high efficiency for the signal events on the one hand, and manageable "unwanted" trigger rate due to background processes on the other.

## 3.3.2 HCAL trigger

The SBS single-arm trigger is based on the large energy deposition in the hadron calorimeter HCAL by the outgoing polarized nucleons from high-energy photoproduction events. Figure 14 shows the distribution of the energy deposition in the active material of HCAL by the good "signal" protons from high-energy  $\pi^- p$  photo-production events. Setting the threshold at 0.08 GeV leads to a high efficiency of about 92% for the events of interest, which are those in which the proton leaves a track in the front GEMs, undergoes a forward elastic nuclear scattering event in the analyzer, leaves a single track in the rear GEMs, and then deposits all its energy in HCAL.

#### 3.3.3 Trigger rate estimates

ROOT's built-in interface to the PYTHIA6.4 generator was used to produce "minimum bias" events in ep and en fixed target scattering at a 6.6 GeV beam energy of this proposal, for the purpose of estimating the single arm trigger rates for different thresholds and the real and accidental coincidence rates between SBS and BigBite. After simulating proton and neutron events individually in PYTHIA and then tracking them through the g4sbs simulation package, the total rates were estimated by weighting individual events by the total cross section per proton (neutron) times the number of protons (neutrons) per unit area along the beamline, including both target and radiator materials, and dividing by the total number of generated events. The total luminosity for a 5  $\mu$ A beam incident on a 6% Cu radiator and a 15-cm liquid deuterium target is approximately  $6 \times 10^{37}$  nucleons/cm<sup>2</sup>· electrons/s.



Figure 14: Energy deposition in the active material (scintillator) of HCAL by good signal protons from  $\pi^{-}p$  photoproduction events, for events in which the proton scatters elastically in the analyzer, producing a single track in both the front and rear GEMs of the polarimeter. The line at 80 MeV is the trigger threshold.

Figure 15 shows the distributions of the signal rates relevant to the trigger formation from PYTHIA. Requiring that the preshower signal be below 100 MeV, which keeps 80% of the "signal" pions, reduces the background rate in the shower by at least a factor of two for signals above the nominal threshold of 500 MeV (which gives 61% efficiency for the "signal" pions), and by an even larger fraction for signals below the minimum ionizing peak. Recall that a threshold of 200 MeV in the shower would give an efficiency of 94% for the signal pions. The minimum ionizing peak is almost absent from the distribution of events rejected by the preshower cut, indicating that this trigger has a high efficiency for charged pions and good rejection power for electrons and photons.

Table 1 shows the single arm and coincidence trigger rates (both real and accidental), estimated using the PYTHIA "minimum bias" generator, for thresholds of 200 MeV or 500 MeV, using either "Pion" or "Electron" logic. The "Pion" logic requires the preshower signal to be below 100 MeV and the shower signal to be above threshold, while the "Electron" logic requires the sum of shower and preshower signals to be above threshold. Given the large number of channels and the estimated data rates from the GEM detectors, the maximum event rate to disk that the combined BigBite/SBS DAQ is expected to be capable of handling by the time of the GMn/GEn-RP run, about one year from this writing based on current



Figure 15: Distributions of trigger-relevant quantities from PYTHIA. Left: BigBite shower energy deposition, smeared for detector resolution. Black circles show the total rate, red squares show the rate after requiring the preshower energy *less than* 100 MeV, and blue triangles show the events rejected by this cut. The vertical line at 0.5 GeV shows the nominal threshold. Middle: BigBite preshower energy deposition, smeared for detector resolution. Here again, red squares (blue triangles) represent events with shower signals above (below) the nominal threshold of 500 MeV. Right: HCAL signals.

Hall A schedule projections, is 5 kHz. These estimates show that the pion logic, with a threshold of 500 MeV, meets this requirement, with an adequately high efficiency of around 50% for the main physics signal events of interest for this proposal.

# 3.4 Selection of exclusive $\gamma n \rightarrow \pi^- p$ events

The exclusive  $\pi^- p$  photoproduction channel will be selected using the two-body kinematic correlations between the reconstructed pion and proton four-vectors, as well as the correlations between the angles and energies of the particles themselves. Because the photon beam is untagged, the photon energy has to be reconstructed from the measured particle kinematics. Figure 16 shows the distributions of the various exclusivity cut variables that can be exploited. The distributions shown include the effects of Fermi motion and detector resolution. In most cases, Fermi motion gives the dominant contribution to the resolution of the variable in question. Assuming the pion is produced on a free neutron at rest, the photon energy is related to the outgoing pion kinematics by:

$$E_{\gamma}(p_{\pi},\theta_{\pi}) = \frac{2m_n E_{\pi} + m_p^2 - m_{\pi}^2 - m_n^2}{2(m_n + p_{\pi}\cos\theta_{\pi} - E_{\pi})}$$
(10)

Under the same assumptions, a similar relation holds between the photon energy and the outgoing *proton* kinematics:

$$E_{\gamma}(p_p, \theta_p) = \frac{2m_n E_p + m_{\pi}^2 - m_p^2 - m_n^2}{2(m_n + p_p \cos \theta_p - E_p)}$$
(11)

Table 1: Estimated single arm and coincidence trigger rates from PYTHIA, assuming 5  $\mu$ A on 15-cm LD<sub>2</sub> target with 6% Cu radiator. The "Pion" logic consists of requiring the preshower signal to be *less than* 100 MeV and applying the indicated threshold on the *shower*. The "Electron" logic consists of applying the indicated threshold on the sum of preshower and shower signals. The coincidence timing window is assumed to be 30 ns wide for the accidental rate estimate.

Trigger Logic	"Pion"	"Pion"	"Electron"	"Electron"
Threshold (GeV)	0.2	0.5	0.2	0.5
"Signal" pion efficiency	75%	49%	97%	71%
BigBite singles rate (kHz)	422	91	976	289
HCAL singles rate (kHz)	416	416	416	416
Accidental coin. rate (kHz)	5.3	1.1	12.2	3.6
Real coin. rate (kHz)	6.2	2.5	14.3	6.5
Total coin. rate (kHz)	11.5	3.6	26.5	9.8
Physics signal rate ( $\gamma n \rightarrow \pi^- p$ , Hz)	16.3	10.4	23.5	17.2

Finally, when both proton and pion are detected and reconstructed, both the photon energy and the initial neutron momentum in the deuteron can be reconstructed, under the assumption of exclusive photoproduction and the assumption that the neutron is on mass shell. In this case, the photon energy is given by the following simple formula, which gives a significantly more accurate photon energy reconstruction compared to the pion or proton kinematics alone:

$$E_{\gamma} = \frac{s_{p\pi} - m_n^2}{2(E_{\pi} + E_p - p_{\pi} \cos \theta_{\pi} - p_p \cos \theta_p)},$$
(12)

$$s_{p\pi} = (E_p + E_\pi)^2 - (\mathbf{p}_p + \mathbf{p}_\pi)^2$$
 (13)

The top left panel of Fig. 16 shows the quality of the photon energy reconstruction achieved using the various methods. The reconstruction of  $E_{\gamma}$  from the pion kinematics is significantly worse than the reconstruction using the proton kinematics or the combined kinematics. This is largely owing to the large lab frame scattering angle of the  $\pi^{-}$  and its relatively low momentum around 2 GeV, making it more sensitive to the z component of the initial neutron's Fermi motion. The reconstruction from the proton kinematics is much better than from the pion, and the reconstruction of  $E_{\gamma}$  from the combined kinematics of both particles is better yet. In the real data analysis, the pion will be reconstructed first, as the occupancies of the BigBite GEMs are expected to be lower than those of the front GEMs of the SBS polarimeter, and the tracking in BigBite is strongly constrained by both the optics of the BigBite dipole magnet and the high-energy cluster in the BigBite shower calorimeter, the signals in which will be relatively clean at the proposed luminosity, based on previous experience. After reconstructing the pion angles, momentum, and interaction vertex, the proton kinematics will be predicted based on the assumption of exclusive photoproduction kinematics, and the predicted proton kinematics will be used to define a search region at the front GEMs of the SBS polarimeter for tracking. If a track is found in this search region with



Figure 16: Exclusivity cuts used to the select the  $\gamma n \to \pi^- p$  channel. Top left: reconstructed incident photon energy  $E_{\gamma}$ , from combined  $\pi^-$  and p measured kinematics (black circles), from measured proton kinematics (red squares), and from measured pion kinematics (blue triangles). Top middle: "Missing energy", defined as  $E_{\gamma} + M_n - E_p - E_{\pi}$ , with  $E_{\gamma}$  reconstructed from measured *proton* kinematics assuming an initial neutron at rest. Top right: component of missing momentum parallel to **q**-vector defined as the expected proton direction according to the measured pion kinematics, with incident photon energy reconstructed from the combined pion and proton kinematics. Bottom left: magnitude of missing momentum component perpendicular to **q**. Bottom middle: squared transverse momentum from reconstructed pion and proton kinematics; assuming exclusive photoproduction on an on-shell neutron, this measures the initial transverse momentum of the struck neutron. Bottom right: "Missing mass squared" defined as the invariant mass squared of the four-vector  $P_{\gamma} + P_n - P_p - P_{\pi}$ .

vertex, momentum, and scattering angles consistent with exclusive kinematics as predicted from the reconstructed pion kinematics, the photon energy will be reconstructed a second time from the proton kinematics, which will be more accurate. The vertex correlation in particular will be especially powerful at suppressing accidental coincidences.

The top middle plot in Fig. 16 shows the "missing energy" defined as  $E_{miss} = E_{\gamma}(p_p, \theta_p) + m_n - E_p - E_{\pi}$ . A cut on this quantity provides a good initial selection for exclusive events (without using circular logic). Another powerful correlation for the selection of exclusive photoproduction events is the coplanarity of the outgoing particles. Figure 17 shows the correlation between the azimuthal angles of proton and pion, the difference  $\Delta \phi = \phi_p - \phi_{\pi} - \pi$ , and the "acoplanarity" defined as  $\arccos(-\hat{n}_{\pi} \cdot \hat{n}_p)$ , where  $\hat{n}_{\pi}$  and  $\hat{n}_p$  are the unit normal vectors to the planes formed by the incident photon direction and, respectively, the outgoing momenta of pion and proton. If both  $\pi^-$  and proton tracks compatible with exclusive



Figure 17: Azimuthal angle correlations between pion and proton. The "acoplanarity" is defined as the angle between the two planes defined by the beam direction and, respectively, the pion and proton momenta.

kinematics are found, as measured by their vertex correlation, azimuthal angle correlation, and missing energy, the photon energy can be reconstructed a third time, with even higher accuracy, using equation (12). Finally, additional cuts can be placed on quantities such as missing parallel and perpendicular momenta, the squared transverse momentum, and the missing mass squared. Not all of these quantities are independent.

The main backgrounds to the  $\gamma n \to \pi^- p$  process within the interesting range of photon energies are the radiative tail events from quasi-elastic d(e, e'p) scattering, with an electron detected in BigBite and misidentified as a  $\pi^-$ , and the production of heavier mesons and/or multiple pions. The contamination from the radiative tail of quasi-elastic events is expected to be negligible for two reasons; first, as discussed above, the trigger of BigBite will be modified to be mainly sensitive to charged pions, and electrons will be suppressed at the trigger level, especially at high energies. Moreover, to the extent that any electrons sneak past the trigger, they will fire the GRINCH detector, which is insensitive to  $\pi^-$  at the momenta of interest for this proposal. The combination of exclusivity cuts at our disposal should also strongly suppress the contributions of multi-pion production and other non-exclusive processes within the photon energy range of interest.

The advantage of the  $\gamma n \to \pi^- p$  channel, as compared to  $\gamma n \to \pi^0 n$  or  $\gamma p \to \pi^0 p$ , is that with two charged particles in the final state, both detected in magnetic spectrometers with sub-percent level momentum resolution, angular resolution at the level of mrad, and vertex resolution at the level of mm, the selection of the exclusive channel is expected to be extremely clean, even with an untagged photon beam. Morever, the estimated cross section for the physics signal process is large enough that the experiment can be run at relatively low luminosity, where the events in the detectors are relatively clean and the reconstruction is far less challenging than in the high- $Q^2$  elastic form factor experiments, where cross sections are much smaller and maximal luminosity is required.

## 3.5 Polarimeter Figure-of-Merit and estimated precision on $K_{LL}$

The main emphasis of the proposed measurement is the recoil proton polarization for the  $\vec{\gamma}n \to \pi^- \vec{p}$  channel, which will be measured via secondary proton-nucleus scattering in the GEn-RP analyzer. The spin-orbit coupling in  $\vec{p} + A \to p + X$  scattering leads to an azimuthal asymmetry in the angular distribution of scattered protons. By tracking protons before and after the secondary scattering in the steel analyzer, the angular distribution will be measured directly. As  $K_{LL}$  is a double-polarization observable measuring the correlation between the incoming photon helicity and the outgoing proton's longitudinal polarization, it changes sign on reversal of the electron beam polarization. As in many previous experiments of this type (see, e.g., Ref. [31]), any false/instrumental asymmetries in the polarimeter will be canceled by the rapid beam helicity reversal. Moreover, the instrumental asymmetries of the polarimeter will also be directly measured as a byproduct of the elastic ep scattering measurements used to calibrate the polarimeter analyzing power, since the induced polarization in  $ep \to ep$  scattering is zero in the one-photon-exchange approximation and small in general. Knowledge of the polarimeter instrumental asymmetry will also provide for an ancillary measurement of the induced polarization in this process.

The momenta of the polarized recoil protons in this proposal are virtually identical to those of recoil nucleons in the approved GEn-RP proposal (E12-17-004). For this exploratory measurement, the beam polarization does not need to be known to better than a few percent, and a single measurement via the Hall A Møller polarimeter, that is already planned as part of the GEn-RP run, will suffice for the purpose of our exploratory measurement. The stability of the polarization will also be monitored via the non-invasive Compton polarimeter in Hall A. The analyzing power of the GEn-RP polarimeter in the momentum range of interest for this proposal will be directly calibrated via dedicated measurements of elastic  $\vec{e}p \rightarrow e\vec{p}$  scattering, that will be obtained as part of the GEn-RP run. The elastic *ep* reaction is self-calibrating with respect to the analyzing power, as explained in Ref. [31]. Most prior recoil polarization experiments [31] used either C or  $CH_2$  as analyzer material. Recent measurements on C, CH,  $CH_2$ , and Cu at the JINR in Dubna, Russia [30] in the momentum range of interest for this proposal found that the analyzing power for proton-nucleus scattering  $p + A \rightarrow p + X$ , was nearly independent of the analyzer material. Moreover, the authors found that the analyzing power increased by approximately 30% for forward-scattered protons when applying a high threshold on the energy deposited in a hadron calorimeter. A similar increase might be expected in the SBS/GEn-RP setup, given the essential role that the high threshold in HCAL plays in the trigger for both experiments. However, such an increase is not assumed in our projected statistical uncertainties.

Figure 18 shows the simulated polar scattering angle distribution in the polarimeter, for events passing all the trigger cuts, in which the  $\pi^-$  leaves a good track in the BigBite GEMs, the proton leaves a good track in the front GEMs of the SBS polarimeter, and a single charged track is produced in the rear GEMs. The GEn-RP polarimeter design is optimized for detection of the charge-exchange process  $\vec{n}p \rightarrow pn$ , in which an incoming high-energy neutron produces a forward-going proton that is detected in the rear GEMs. One feature



Figure 18: Polar angle distribution in the polarimeter for the protons from  $\gamma n \to \pi^- p$ . Left: "Transverse momentum"  $p_T \equiv p_p \sin \theta_{FPP}$ , where  $p_p$  is the momentum of the proton incident on the polarimeter, and  $\theta_{FPP}$  is the polar angle of scattering in the analyzer. The vertical line indicates the minimum  $p_T$  value accepted for the polarimetry analysis (the maximum is 1.2 GeV). Right: polar scattering angle  $\theta_{FPP}$ . Vertical lines indicate the approximate scattering angle range accepted for the analysis, corresponding to the  $p_T$  range shown in the left panel.

of the GEn-RP analyzer that is different compared to previous experiments using C or CH<sub>2</sub> as analyzer is that it is physically thin, but made of denser, higher-Z material with shorter radiation length. This is necessary to achieve a high efficiency for "tagging" the charge exchange process in the GEn-RP experiment, but comes at the cost of a wider multiple-Coulomb scattering peak at small angles than is typical for materials composed of lighter nuclei like C and CH<sub>2</sub>. This does not, however, pose a significant challenge to recoil proton polarimetry. As shown in Fig. 18, the wider Coulomb scattering peak in steel as compared to CH<sub>2</sub> necessitates the use of a low- $p_T$  cutoff of approximately 0.15 GeV as opposed to 0.1 GeV or 0.06 GeV that was typically used for previous recoil proton polarimeters based on CH<sub>2</sub>. This does not significantly affect the overall figure-of-merit, as the maximum of the analyzing power typically occurs around  $p_T \approx 0.4$  GeV, and the slight reduction of the useful  $p_T$  range due to increased multiple scattering is more than offset by the higher efficiency for scattering in the useful  $p_T$  range.

The overall figure of merit for the measurement of  $K_{LL}$  is determined by the photon beam polarization and the scattering efficiency and analyzing power of the polarimeter. For the range of photon energies considered in this proposal, the average circular photon polarization is estimated at approximately 90% of the longitudinal electron beam polarization. In the estimates that follow, we have assumed 85% longitudinal electron beam polarization,

Table 2: Polarimeter performance parameters for the proposed measurement.  $\varepsilon$  is the "efficiency" defined as the fraction of incident protons that undergo a "useful" scattering in the analyzer.  $\langle A_y \rangle$  is the weighted average analyzing power within the accepted  $p_T$  range.  $P_{\gamma}$  is the assumed average incident photon polarization.  $\mathcal{F}$  is the "figure of merit" defined in Eq. (14).  $\chi$  is the precession angle of the proton's spin relative to its trajectory in the SBS dipole magnet.

Polarimeter Performance Parameter	Value
$\varepsilon \equiv \frac{N_{event}}{N_{inc}}$	12.2~%
$\langle A_y  angle^{n c}$	11.4%
$P_{\gamma}$	76.5%
${\cal F}$	$9.3 \times 10^{-4}$
$\langle \sin \chi \rangle$	0.86

implying an average photon polarization of approximately 76.5%. The statistical figure of merit  $\mathcal{F}$  is defined as:

$$\mathcal{F} \equiv \frac{1}{N_{inc}} \sum_{i=1}^{N_{event}} \left( P_{\gamma} A^i_y(p^i_p, p^i_T) \right)^2, \qquad (14)$$

where  $N_{inc}$  is the number of protons incident on the polarimeter,  $P_{\gamma}$  is the photon beam polarization and  $A_y$  is the analyzing power, which depends on the incident proton momentum  $p_p$  and the transverse momentum  $p_T = p_p \sin \theta_{FPP}$ , with  $\theta_{FPP}$  the polar scattering angle in the analyzer. The sum runs over the subset  $N_{event} < N_{inc}$  of events producing a single track in the useful  $p_T$  range:  $0.15 \le p_T \le 1.2$  GeV. The polarimeter figure of merit was estimated for this proposal using a parametrization of the analyzing power for single-track events from the GEp-III data [31]. According to Ref. [30], the analyzing power is not expected to depend strongly on the target material. Using the GEp-III results for  $A_y$  actually represents a very conservative estimate, since in the Hall C polarimeter the energy of the scattered particles was not measured, only the scattering angles, and the trigger in the Hall C experiment was based on thin scintillators located *upstream* of the polarimeter. In the proposed measurements, the hadron calorimeter-based trigger will preferentially select high-energy protons that undergo forward elastic scattering in the analyzer, and the Dubna results show that these events have higher average analyzing power compared to the totally inclusive sample.

Table 2 shows the polarimeter performance parameters estimated from the g4sbs Monte Carlo simulation of the experiment. With an estimated scattering efficiency of 12.2%, and an estimated average analyzing power of 11.4%, the figure of merit is  $\mathcal{F} = 9.3 \times 10^{-4}$ . The absolute statistical uncertainty on each of the two transverse components of the proton polarization measured by the polarimeter is given by

$$\Delta P_{x,y}^{FPP} = \sqrt{\frac{2}{N_{inc}\mathcal{F}}},\tag{15}$$

where  $P_x^{FPP}$  and  $P_y^{FPP}$  are approximately related to the longitudinal  $(P_L)$  and sideways  $(P_S)$ 

components of the reaction-plane polarization components by:

$$P_y^{FPP} \approx P_S \tag{16}$$

$$P_x^{FPP} \approx -P_L \sin \chi, \tag{17}$$

where  $\chi \equiv \gamma \kappa_p \theta_{bend}$  is the precession angle of the proton's spin relative to its trajectory in the SBS dipole field. For the planned measurements, the field integral is approximately 1.7 T·m. For a proton momentum of 3.3 GeV/c, this corresponds to a trajectory bend angle of approximately 9 degrees and a precession angle  $\chi$  of approximately 59 degrees. To a good approximation, then, the absolute statistical uncertainty on  $K_{LL} = P_L$  can be estimated as

$$\Delta_{stat} (K_{LL}) \approx \frac{1}{\langle |\sin \chi| \rangle} \sqrt{\frac{2}{N_{inc} \mathcal{F}}}$$
(18)

Thus, the required number of  $\gamma n \to \pi^- p$  events, which dictates the beam time request, is given by

$$N_{inc} = \frac{2}{\mathcal{F}} \left( \Delta_{stat} \left( K_{LL} \right) \left\langle \left| \sin \chi \right| \right\rangle \right)^{-2}.$$
(19)

For a first, exploratory measurement of  $K_{LL}$  for wide-angle pion photoproduction in the kinematic regime where handbag dominance might reasonably be expected, a 4% absolute statistical precision (5% relative, based on the handbag prediction) is a reasonable, easily achievable goal, given the large predicted value of  $K_{LL}$  at our kinematics and, moreover, the large, opposite-sign prediction for  $A_{LL}$  assuming twist-3 dominance. To achieve this level of precision, according to equation (19), requires a total of 1.8M exclusive  $\pi^- p$  events. According to table 1, the signal event rate passing the coincidence trigger with a good  $\pi^-$  track in BigBite at the proposed luminosity is 10.4 Hz. As such, to achieve our 4% absolute statistical precision goal requires 48 hours of 5  $\mu$ A beam on the 15-cm LD<sub>2</sub> target, assuming the use of a 6% Cu radiator upstream of the target.

A future measurement of  $A_{LL}$  for  $\gamma \vec{n} \to \pi^- p$ , with comparable precision and at similar kinematics, can be straightforwardly accomplished in comparably small beam time using BigBite and SBS along with the polarized <sup>3</sup>He target being constructed for experiment E12-09-016, the measurement of the neutron form factor ratio  $G_E^n/G_M^n$  to  $Q^2 \approx 10 \text{ GeV}^2$ . The complementary measurement of  $A_{LL}(\gamma n \to \pi^- p)$  will be the subject of a future proposal.

## 3.6 Systematic Uncertainties

The major contributions to the systematic uncertainty of the  $K_{LL}$  measurement include the knowledge of the beam polarization and the polarimeter analyzing power, the calculation of the proton's spin precession through the SBS dipole, the contamination from accidental coincidences and backgrounds from other processes, and the nuclear effects, including the binding and Fermi motion of the initial neutron bound in a deuterium nucleus, and the effects of final state interactions. Other contributions to the systematic uncertainty, including



Figure 19: Distribution of  $\sin \chi$  within the acceptance (left), correlation between  $\sin \chi$  and the proton momentum  $p_p$  (middle), and difference (right) between "true"  $\sin \chi$  from GEANT4 spin tracking (numerical integration of the BMT equation) and simple dipole approximation from measured trajectory bend angles and momentum.

Table 3: Estimated total error budget for  $K_{LL}(\gamma n \to \pi^- p)$ .  $P_e A_y$  is the product of the electron beam polarization and the analyzing power.

Source of uncertainty	Estimated uncertainty contribution	Absolute/relative
$P_e A_y$	2%	relative
Spin precession	0.5%	absolute
Background contamination and subtraction	$\lesssim 1\%$	relative
Nuclear effects	pprox 1-2%	relative
Other	1%	absolute
Statistical	4%	absolute
Total (assuming $K_{LL} = 0.8$ )	6%	relative

the quality of the angle reconstruction in the polarimeter and the kinematic reconstruction, are relatively minor. Given the high-energy kinematics (simultaneously large s, -t, and -u), the effects of nuclear corrections on the measured polarization asymmetry are expected to be small compared to the 4% absolute statistical uncertainty goal. The calculation of the proton's spin precession in the SBS dipole is much simpler than it was for previous experiments using focusing magnetic spectrometers with multiple quadrupoles. Based on the experience from Ref. [31], the contribution of the precession calculation to the uncertainty in the longitudinal polarization transfer is at the level of a few parts per thousand (absolute). Although this calculation should be under even better control for SBS, which consists of a single, simple dipole magnet, we assign a conservative estimate of 0.5% for the precession calculation. Figure 19 illustrates the simplicity of the spin precession in the SBS dipole. The precession angle relative to the trajectory is nearly constant at about 59 degrees throughout the acceptance, because  $\chi = \gamma \kappa_p \theta_{bend}$ ,  $\gamma$  is approximately proportional to the proton momentum at large momenta, and  $\theta_{bend}$  is inversely proportional to the proton momentum for the simple dipole field. Table 3 lists the major sources of systematic uncertainty and our best estimate of their values. The proposed measurement in 48 hours of beam time would reach approximately 4.8% absolute total uncertainty, or 6% relative total uncertainty, assuming a  $K_{LL}$  value of 0.8.

# 4 Summary of Beam Time Request and Expected Results

The Wide Angle Pion Photoproduction (WAPP) is considered an interesting and a powerful test of our understanding of calculating cross sections from first principles. Several calculations fall short of explaining the observed cross sections indicating a lack of understanding of the nature of interaction mechanism for the wide angle regime. Only recently do calculations based on the handbag approach in the GPDs framework agree with the observed cross sections. Therefore, a test of the polarization observables,  $K_{LL}$  and  $A_{LL}$  in the accessible energy range is timely and necessary to test the validity of this approach.



Figure 20: Projected result of this experiment for  $K_{LL}$  (shown as a blue data point).

Here, we propose an experiment to measure the helicity correlation parameter,  $K_{LL}$  for meson photo-production in the wide angle regime. The proposed experiment will be performed in Hall A of Jefferson Lab. The total beam time required for this experiment is 48 hours plus an additional 16 hours for the beam energy change procedure (from 4.4 GeV, the planned energy for the GEN-RP measurement, to 6.6 GeV). The 6.6 GeV CEBAF electron beam will be used with a 6% Cu radiator, to produce photons in the range of energies from 4.0 - 6 GeV, incident on a 15-cm deuterium target. This radiator is already included in the plans for the GMN/GEN-RP run, to calibrate the neutron detection efficiency for HCAL. The beam current will be 5  $\mu$ A. The produced  $\pi^-$  will be detected by the BigBite spectrometer and the recoil proton, in the Super Bigbite Spectrometer where the polarization will be measured by the polarimeter. The experimental setup is identical to the GEn-RP (E12-17-004) experimental setup with the BigBite/SuperBigbite angles at  $\theta_{BB}/\theta_{SBS} = 41.9^{\circ}/24.7^{\circ}$ as in  $Q^2=3.5$  (GeV/c)<sup>2</sup> kinematics of the run plan. The trigger in BigBite will be adjusted, using the available signals, to reduce detection of the high energy photons and electrons. This measurement of  $K_{LL}$  will be the first of its kind and indeed a pioneering one. A complementary measurement of the  $A_{LL}$  observable in single  $\pi^-$  production from a polarized neutron in He-3 is also straightforward, and will be the subject of a future proposal.

This experiment aims to measure the helicity correlation observables that have not been measured before for wide angle pion photoproduction. The projected result for  $K_{LL}$  is shown in Fig. 20. Parameters of the measurement are summarized in Tab. 4. The same accuracy for  $A_{LL}$  on polarized neutron will require a measurement using the GEn-He-3 setup [32] and 96 hours of beam time (such a proposal is under development).

Proposed pioneering measurement will help to uncover the nature of the interaction mechanism in the wide angle regime that is responsible for the exclusive single pion photoproduction from a nucleon.

$E_{\gamma}$	$\langle s \rangle$	< -t >	< -u >	$K_{LL}$	$K_{LS}$
$\mathrm{GeV}$	$(\text{GeV}/c)^2$	$(\text{GeV}/c)^2$	$(\text{GeV}/c)^2$	accuracy	accuracy
4.5-5.5	9.3	4.6	2.9	$\pm 0.05$	$\pm 0.05$

Table 4: Parameters of the proposed experiment on polarization transfer in  $D(\vec{\gamma}, \pi^- \vec{p})$  process.

# References

- [1] R.L. Anderson *et al.*, *Phys. Rev.* D 14, 679 (1976)
- [2] P. Kroll, K. Passek-Kumericki, *Phys. Rev.* D 97, 074023 (2018)
- [3] W. K. H. Panofsky and W. M. Woodward, and G. B. Yodh, Phys. Rev. 102, 1392 (1956)
- [4] The Durham HEP Reaction Data Databases (UK) (Durham HepData): http:// durpdg.dur.ac.uk/hepdata/reac.html
- [5] Partial-Wave Analyses at GW, http://gwdac.phys.gwu.edu
- [6] Photo- and Electroproduction of Pions, Eta, Etaprime and Kaons on the Nucleon, https://maid.kph.uni-mainz.de.
- M. Guidal, J.-M. Laget and M. Vanderhaeghen, Nucl. Phys. A 627 (1997) 645;
   J.M. Laget, Phys. Lett. B 685 (2010) 146; J.M. Laget, Prog.Part.Nucl.Phys. 111 (2020) 103737
- [8] M.C. Kunkel *et al.*, *Phys. Rev.* C98, 015207 (2018)
- [9] L.Y. Zhu et al., Phys. Rev. Lett. 91 (2003) 022003; Phys.Rev. C71 (2005) 044603
- [10] D. Ho et al., Phys. Rev. C 98, 045205 (2018)
- [11] C. Fanelli et al., Phys. Rev. Lett. 115, 152001 (2015)
- [12] W. Luo et al., Phys. Rev. Lett. 108 (2012) 222004
- [13] J.F. Gunion, S.J. Brodsky, R. Blankenbecler, Phys. Rev. B **39** 649 (1972); S.J. Brodsky and G. Farrar, *Phys. Rev. Lett.* **31**, 1953 (1973); V. Matveev *et al.*, *Nuovo Cimento Lett.* **7**, 719 (1973); S. J. Brodsky and G. P. Lepage in *Perturbative Quantum Chromo-dynamics*, edited by A. Mueller (World Scientific, Singapore, 1989); S. J. Brodsky and G. P. Lepage, *Phys. Rev.* **D 22**, 2157 (1980)
- [14] H.W. Huang, R. Jakob, P. Kroll, K. Passek-Kumericki, Eur. Phys. J. C 33, 91 103 (2004)
- [15] H.W. Huang, P. Kroll, T. Morii, Eur. Phys. J. C 23, 301 (2002).
- [16] H. W. Huang, P. Kroll, Eur. Phys. J. C 17, 423-425 (2000).
- [17] P. Kroll, K. Passek-Kumericki, private communication (2019)
- [18] M. Diehl and P. Kroll, Eur.Phys.J. C73, 2397 (2013)
- [19] D.J. Hamilton, V.H. Mamyan *et al.*, *Phys. Rev. Lett.* **94**, 242001 (2005)

- [20] A. Danagoulian, V.H. Mamyan et al., Phys. Rev. Lett. 98, 152001 (2007)
- [21] P. Kroll, arXiv:1703.05000
- [22] M. Diehl *et al.*, *Phys. Rev.* D 67, 037502 (2003).
- [23] F. Cano and J.M. Laget, Phys. Lett. B 551, 317 (2003)
- [24] T. Brooks and L. Dixon, *Phys. Rev.* D 62 114021 (2000)
- [25] G.A. Miller, *Phys. Rev.* C 69, 052201(R) (2004)
- [26] B. Sawatzky, V. Bellini, K. Gnanvo, D. Hamilton, M. Kohl, N. Piskunov, and B. Wojtsekhowski, spokespersons, JLab experiment E12-17-004.
- [27] H.W. Huang, P. Kroll, Eur. Phys. J. C 17, 423-425 (2000)
- [28] X. Ji, Phys. Rev. D 55, 7114 (1997), Phys. Rev. Lett. 78, 610 (1997)
- [29] A.V. Radyushkin, Phys. Lett. B 380, 417 (1996), Phys. Rev. D 56, 5524 (1997)
- [30] S. N. Basilev *et al.*, Eur. Phys. Journal A 56, 26 (2020)
- [31] A. J. R. Puckett *et al.*, Phys.Rev.C **96** (2017) 5, 055203, Phys.Rev.C **98** (2018) 1, 019907 (erratum)
- [32] G. Cates, S. Riordan, and B. Wojtsekhowski, spokespersons, JLab experiment E12-09-016.