

Update of Experiment E12-06-104

Measurement of the Ratio $R = \sigma_L/\sigma_T$ in Semi-Inclusive Deep-Inelastic Scattering July 01, 2010

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Executive Summary

E12-06-104 seeks to perform measurements of the ratio $R = \sigma_L/\sigma_T$ of longitudinal to transverse cross sections in pion electroproduction. The emphasis will be on measurements in the so-called semi-inclusive deep inelastic scattering region, where essentially no information exists on the value of R , with extensions into the exclusive region.

Whereas inclusive scattering cannot distinguish between the quark flavor, there is great promise in flavor decompositions of regular parton distributions through semi-inclusive deep inelastic scattering and of generalized parton distributions through deep exclusive scattering. For the latter, the ratio $R = \sigma_L/\sigma_T$ asymptotically scales like Q^2 , the four-momentum transfer squared, at fixed Bjorken x . For the former, the ratio R is assumed to be similar to that of deep inelastic scattering.

Surprisingly, the latter assumption has never been thoroughly checked. Obviously, with less and less energy available to produce mesons, as is the case close to the exclusive limit (where the elasticity $z \rightarrow 1$), this assumption must locally fail. In fact, the ratio R for semi-inclusive pion electroproduction may at low energies very well depend both on z and p_T , the transverse pion momentum, beyond the well-known dependence on x and Q^2 of R in deep inelastic scattering. To measure this behavior, for the first time, is the subject of this proposal, for which we request 40 days of beam time.

The proposed measurements are both of fundamental and of practical value: Fundamental since the ratio R in semi-inclusive deep inelastic scattering has never been properly measured; Practical because many semi-inclusive deep inelastic scattering experiments at a 12-GeV JLab (and other low-energy facilities) requiring knowledge on the ratio R as input. Beyond this, the new data will allow further study of the inclusive-exclusive connection in pion (and kaon) electroproduction, and the onset of factorization in terms of a quark scattering process followed by a quark-hadron fragmentation proceed.

We will detect charged pions (π^\pm) in coincidence with scattered electrons from the semi-inclusive ($e, e'\pi$) reaction on 10 cm extended LH2 and LD2 targets at beam energies of 6.6, 8.8 and 11.0 GeV, and beam currents of up to 50 μA . The Hall C HMS spectrometer and the projected SHMS with its first-generation detector package will be used for electron and pion detection.

Members of this collaboration have spearheaded the now-flourishing semi-inclusive deep inelastic scattering physics at Jefferson Lab, and play leading roles in the construction of detector systems for the SHMS base equipment, with the following responsibilities: Hampton - wire chambers, James Madison - scintillators, Regina - C4F8O Cherenkov, Yerevan - Electromagnetic Calorimeter. We note that the first two systems are funded by an NSF/MRI grant, the third by an NSERC grant, and the fourth system is (partly) based on the ex-HERMES calorimeter, and gifted by NIKHEF/Netherlands and Yerevan.

Recently, members of this collaboration (Catholic, Florida International, Mississippi State, Yerevan) have been actively pursuing a kaon identification system, consisting of a pair of aerogel detectors, to be inserted for dedicated experiments such as E12-06-104 to the SHMS detector stack. This would allow simultaneous accumulation of kaon data, albeit with about a factor of ten reduced statistics, even if electroproduced pions are the focus of the E12-06-104 experiment.

I. INTRODUCTION

Considerable information on nucleon structure has been extracted over the past few decades from separations of inclusive lepton-nucleon cross sections, at high four-momentum transfer squared Q^2 and high excitation energy ν (corresponding to large missing mass W), into longitudinal and transverse structure functions. Measurements of the structure function F_2 were shown to be related to the momentum distribution of the quarks inside the nucleon in terms of parton distribution functions. The experimental observation of the smallness of the ratio $R = \sigma_L/\sigma_T$ provided the first evidence of the spin-1/2 nature of the partons.

It has been long realized that more stringent tests of the quark-parton model arise from inclusive hadron production experiments. There is great similarity with the inclusive process described above, but the tagging of the type of coincident hadron gives access to the flavor of the struck quark via the correlation in flavor of the quark and the hadron. Thus, in semi-inclusive DIS (SIDIS) not only the sum, but also the individual parton distributions can be accessed. In SIDIS there exists also extra kinematical degree of freedom associated with the momentum of the hadron detected. With the positive z -axis in the direction of the electromagnetic current, further variables can be chosen to characterize the problem: z , p_T and ϕ . Now there will be four structure functions for the $(e, e'h)$ process, the usual longitudinal and transverse structure functions and two interference structure functions.

In the asymptotic limit, in the model where the electro-produced pions are the fragmentation products of spin-1/2 partons, the ratio $R = \sigma_L/\sigma_T$ must disappear like $1/Q^2$, like in the inclusive case. This idea is supported by the measurement of angular distributions of hadrons in the process $e^+e^- \rightarrow h + X$, with h a hadron, for spin-1/2 partons. At high energies, the JADE experiment [1] at a center-of-mass energy of 35 GeV, and the OPAL and DELPHI experiments at the Z -pole [2,3] show a longitudinal to total cross section ratio well consistent with either JETSET [4] or a second-order QCD calculation [5]. At a lower center-of-mass energy of 7.4 GeV, this ratio, and hence R , is found to depend on z , approaching small numbers for $z \rightarrow 1$, where the observed hadrons (pions) are thought to only be emitted by spin-1/2 partons. In SIDIS, the only available data is from Cornell in the 70's [6-8]. These data are shown in Fig. 1, in combination with a sample of projected data from the E12-06-104 experiment. The precision of the Cornell data is such that the ratio R could both be consistent with what would be expected from R in DIS and with a null value. As a function of z , some hint of an increase of R at larger $z \sim 0.8$, may exist, at a 2σ level.

Historically, the effects of the interference structure functions on the measured cross sections were parameterized as *constants* describing a possible $\cos(\phi)$ and $\cos(2\phi)$ dependence, thought to disappear in the asymptotic limit. Obviously, this assumption can not be correct at lower beam energies, where these interference structure functions can depend on all kinematical variables (x, Q^2, p_T, z) . Measurements of such $\cos(\phi)$ and $\cos(2\phi)$ dependencies are now thought to possibly shed light on the transverse motion of quarks.

The SIDIS process equals a deep exclusive scattering (DES) process in the limit of $z \rightarrow 1$. In DES experiments, the flavor of the generalized parton distribution can be probed. These processes can be factorized in terms of handbag diagrams into a hard-scattering process and a soft process, and anticipate a behavior $R = \sigma_L/\sigma_T \sim Q^2$ at a constant value of Bjorken x , in the asymptotic limit. This is in sharp contrast to the anticipated $R \sim 1/Q^2$ behavior expected from SIDIS processes. This also invokes a practical complication, in terms of possible contributions of $\rho \rightarrow \pi^+\pi^-$ production to the measured $(e, e'\pi^+)$ SIDIS rates.

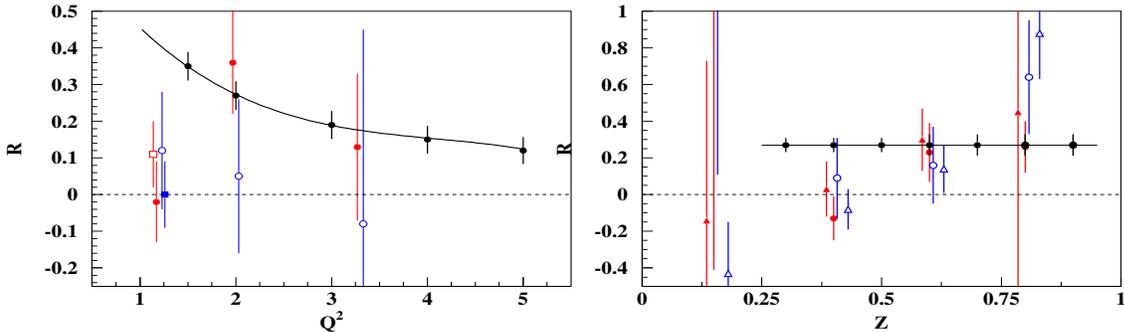


FIG. 1. The ratio $R=\sigma_L/\sigma_T$ in SIDIS as a function of Q^2 (left panel) and z (right panel) as measured at Cornell [6–8]. Different symbols reflect the data from the proton, deuteron, π^+ , and π^- data, respectively. The solid curves reflect the parameterization of R for DIS. Projected data for the E12-06-104 experiment have been added as black solid circles, for the bottom panel at $x = 0.2$ and $Q^2 = 2 \text{ GeV}^2$ (with the R parameterization also reflecting these values). Similar data as a function of z will be obtained at $x = 0.4$ and $Q^2 = 4 \text{ GeV}^2$.

Hence, to shed more light on the role of R in SIDIS seems appropriate. Knowledge on R is fundamental in its own right to better understand to what extent the electro-produced pions at 12-GeV beam energies are the direct fragmentation products of the struck partons, and has great practical implications on the analysis of SIDIS experiments.

II. THEORY AND MOTIVATION

Inclusive Scattering The inclusive cross section can be expressed in terms of σ_T and σ_L , the cross sections for the absorption of transverse and longitudinal photons, respectively. For asymptotic energies, the ratio of longitudinal to transverse cross sections $R \rightarrow 1/Q^2 \rightarrow 0$, a consequence of the scattering of (asymptotically free) spin-1/2 constituents. At lower and finite Q^2 , the ratio R becomes sensitive to indirect gluon effects and higher-twist contributions. Similarly, in the naive quark-parton model, R is related to the parton's average transverse momentum $\langle k_t^2 \rangle$: $R = 4(M^2 x^2 - \langle k_t^2 \rangle)/(Q^2 + 2\langle k_t^2 \rangle)$.

In practice, R remains rather constant for the phase space accessible to a 12-GeV JLab, to only drop $\sim 1/Q^2$ beyond $Q^2 \sim 3 \text{ GeV}^2$ [9]. Also keep in mind that for measurements of R in DIS no distinctions are made between possible diffractive and non-diffractive contributions, all are included in the experimental determinations. Lastly, DIS measurements of R on deuterium (for $Q^2 > 1 \text{ GeV}^2$) are found to be in excellent agreement with the data on hydrogen, so to very good approximation $R^p = R^d$ for DIS.

Semi-Inclusive Scattering In the one-photon exchange approximation, the pion electroproduction cross section can be written as the product of a virtual photon flux (Γ) and a virtual photon cross section (evaluated in the laboratory frame),

$$\frac{d\sigma}{d\Omega_\pi dM_x} = \frac{d\sigma_T}{d\Omega_\pi dM_x} + \epsilon \frac{d\sigma_L}{d\Omega_\pi dM_x} + \epsilon \frac{d\sigma_{TT}}{d\Omega_\pi dM_x} \cos 2\phi_{pq} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{LT}}{d\Omega_\pi dM_x} \cos \phi_{pq}, \quad (1)$$

where ϵ describes the longitudinal polarization of the virtual photon. The interference terms (σ_{LT} and σ_{TT}) integrate to zero for complete ϕ ($= \phi_{pq}$) coverage. The cross sections can be parameterized in terms of four structure functions, W_L, W_T, W_{TT} and W_{LT} , that in general now depend on Q^2, W^2, z and p_T .

In the Bjorken limit, these formulas should simplify, and can be more intuitively expressed in a quark-parton model. From perturbative QCD, there will be factorization between the virtual photon-quark interaction and the subsequent quark hadronization,

$$\frac{\frac{d\sigma}{d\Omega_e dE_e dz dp_T^2 d\phi}}{\frac{d\sigma}{d\Omega_e dE_e}} = \frac{dN}{dz} b e^{-bp_T^2} \frac{1 + A \cos(\phi) + B \cos(2\phi)}{2\pi}, \quad (2)$$

$$\frac{dN}{dz} \sim \sum_q e_q^2 q(x, Q^2) D_{q \rightarrow \pi}(z, Q^2), \quad (3)$$

where the fragmentation function $D_{q \rightarrow \pi}(z, Q^2)$ gives the probability for a quark to evolve into a pion π detected with a fraction z of the quark (or virtual photon) energy, $z = E_\pi/\nu$. The transverse momentum p_T , z and the angle ϕ reflect the extra kinematical degree of freedom associated with the pion momentum, with b the average transverse momentum of the struck quark. The factors A and B express the dependence on the two interference structure functions, and thus could in principle depend on Q^2, W^2, z and p_T .

E00-108 measured the $^{1,2}H(e, e'\pi^\pm)X$ cross sections, predominantly at $x = 0.32$. The data conclusively showed the onset of the quark-hadron duality phenomenon in the semi-inclusive ($e, e'\pi$) process, and the relation of this to the high-energy factorization ansatz of subsequent electron-quark scattering and quark \rightarrow pion production. Agreement between data and Monte Carlo simulation, based upon CTEQ5M parton distributions [10] and BKK fragmentation functions [11], was found to be excellent for $z < 0.65$ (or $M_x^2 > 2.5 \text{ GeV}^2$: note that within the E00-108 kinematics $p_T \sim 0$, and M_x^2 is almost directly related to z , as $W'^2 \equiv M_x^2 = M_p^2 + Q^2(1/x - 1)(1 - z)$). A sample of E00-108 results are shown in Fig. 2 with closed (open) symbols reflecting the data after (before) subtraction of the diffractive ρ contributions. (PYTHIA was used to estimate the $p(e, e'\rho)p$ cross section, with modifications as implemented by the HERMES collaboration [12,13].) The ratio of favored to unfavored fragmentation functions in the high-energy limit should solely depend on z , but not on x , as confirmed. Furthermore, simple ratios are remarkably close to the near-independence of z as expected in the high-energy limit (at leading order in α_S). Apparently, above $M_x^2 = 2.5 \text{ GeV}^2$ or so, there are already sufficient resonances to render a spectrum mimicking the smooth z -dependence as expected from the factorization ansatz.

E00-108 always assumed $R_{SIDIS} = R_{DIS}$. Of course, if integrated over z, p_T, ϕ and all hadrons, this must be true. But, R_{SIDIS} may very well depend on z , and in fact **must** in the deep exclusive limit (see next subsection). Even more, at large z there are known contributions from (semi-)exclusive channels such as pions originating from ρ decay. Similarly, there is still large debate whether the events originating from diffractive ρ are, or are not, part of the semi-inclusive deep inelastic scattering formalism (whereas in deep inelastic scattering, see above, the issue does not enter).

In addition, for the ($e, e'\pi$) formalism, the structure functions in general depend on additional variables beyond x and Q^2 , in particular on z and p_T , and the ratio R_{SIDIS} could very well depend on the transverse momentum p_T . This has experimentally never been checked, given the sparse data available as already shown in Fig. 1. As such, it is of prime importance

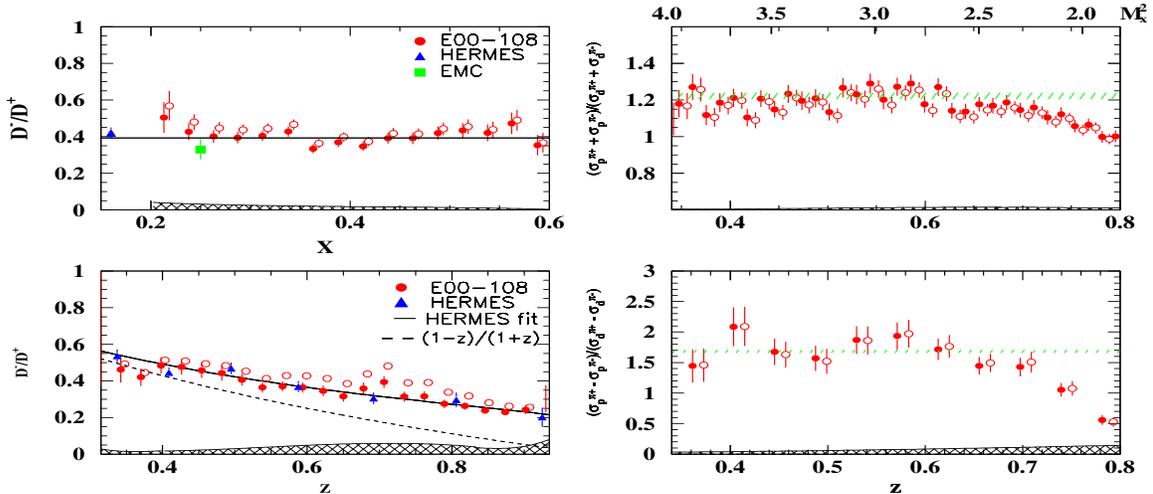


FIG. 2. *Left:* The ratio of unfavored to favored fragmentation function D^-/D^+ as a function of x at $z = 0.55$ (top panel) and as a function of z for $x = 0.32$ (bottom panel). The solid curve is the HERMES fit. *Right:* The ratio of proton to deuteron results of the sum (top) and difference (bottom) of π^+ and π^- cross sections as a function of z , at $x = 0.32$. Closed (open) symbols reflect data after (before) events from coherent ρ production are subtracted. (For details see Ref. [14]).

to also map the behavior of R_{SIDIS} versus the transverse momentum p_T . One would anticipate that at low energies, the behavior of the p_T spectrum mimics the angular distributions of the nucleon resonance decays more, whereas at large p_T one reaches the hard scattering limit again. Hence, at large p_T R_{SIDIS} must anneal to R_{DIS} for consistency reasons.

To make any progress with verifying assumptions of R_{SIDIS} as a function of p_T by necessity requires a combination of full-azimuthal angle data, such as those to be acquired with CLAS12, and longitudinal-transverse separations as performed with a pair of magnetic spectrometers, HMS and SHMS, rigidly connected to a pivot (albeit that p_T is linked to $\cos(\phi)$ in this case).

To conclude, there are similar question whether the ratio R_{SIDIS} is similar for positively- and negatively-charged pions, and similar for protons and deuterons (or neutrons). All these assumptions have never been experimentally tested. Using only the deuterium data, we also could construct the D^-/D^+ fragmentation function ratios for both positively- and negatively-charged pions, and map their longitudinal behavior. In short, many questions exist on R_{SIDIS} that warrant detailed experimental study for a successful quark flavor separation program at a 12-GeV Jefferson Lab through semi-inclusive scattering.

Deep Exclusive Scattering Over the last decade, QCD factorization theorems were derived for various deep inelastic exclusive processes [16–19], intrinsically related to the access to Generalized Parton Distributions (GPD's) [20,21]. It is still uncertain at which Q^2 value one will reach the factorization regime, where the leading-order perturbative QCD domain fully applies for meson electroproduction. However, it is expected to be between $Q^2 = 5$ and 10 (GeV/c)².

The leading-twist perturbative QCD contribution in the case of hard meson electroproduction involves an additional one-gluon exchange. This means that at asymptotic energies the behavior of R for $z < 1$ (SIDIS) has disappeared like $1/Q^2$, whereas the ratio R is very large for $z = 1$ (DES), where $R = \sigma_L/\sigma_T \sim Q^2$, at constant Bjorken x . Indeed, the ratio $R = \sigma_L/\sigma_T$ in diffractive electroproduction of ρ^0 mesons has been measured, through angular distributions, and shows a rise with Q^2 of R . On the other hand, for deep exclusive pseudoscalar meson production, no signature of an increase of σ_L/σ_T with Q^2 at fixed x has been experimentally noticed yet. This represents a major puzzle, and a series of dedicated longitudinal-transverse separation experiments planned for both deep exclusive pion and kaon electroproduction at fixed x will address this separately.

Motivation Summary E12-06-104 will measure R in the SIDIS process, to

- Verify whether $R_{SIDIS} = R_{DIS}$.
- Check the z -dependence of R from the semi-inclusive to the exclusive region.
- Verify that R_{SIDIS} anneals to R_{DIS} at large p_T .
- Verify if R_{SIDIS} follows the Q^2 dependence of R_{DIS} , at two values of x .
- Verify that $R_{SIDIS}^{\pi^+} = R_{SIDIS}^{\pi^-}$ and $R_{SIDIS}^H = R_{SIDIS}^D$.
- With a factor of ten reduced statistics: map $R_{SIDIS}^{K^+}$ and $R_{SIDIS}^{K^-}$.

The physics of interest is to what extent the struck quark indeed fragments into the measured pion, even at lower beam energies. In addition, we will study the connection between pion formation in semi-inclusive kinematics and the exclusive limit. Lastly, there are great practical advantages of these measurements for the general SIDIS program at a 12-GeV JLab, e.g., for measurements of the light quark sea flavor asymmetry, a flavor decomposition of the nucleon spin at $x > 0.1$, and measurements of azimuthal asymmetries in SIDIS.

III. EXPERIMENT

Our goal will be the first thorough study of the ratio $R = \sigma_L/\sigma_T$ in SIDIS. These measurements will provide input on the relation of the electroproduced pion with the struck quark, and provide a baseline for the interpretation of SIDIS cross section measurements.

Experimental overview The experiment will use the HMS and SHMS magnetic spectrometers for coincidence measurement of scattered electrons and pions from the $(e, e'\pi^\pm)$ reaction. The role of HMS and SHMS is reversed in some kinematics, but in general the SHMS, with its most forward angle of 5.5° , will detect the pions (and kaons, see below).

It is good practice to do precision Rosenbluth separations with targets that closely mimic point-like targets for the spectrometers. Hence, all measurements will be performed on 10 cm extended (hydrogen and deuterium) targets, and similar Al “dummy” measurements for target wall subtraction. We assume a beam current of $\sim 50 \mu\text{A}$ ($40 \mu\text{A}$ for the dummy targets). The target density will be monitored by pressure and temperature measurements. At $\sim 50 \mu\text{A}$ we expect negligible, $<0.5\%$, density changes, for a raster size of $2 \times 2 \text{ mm}^2$.

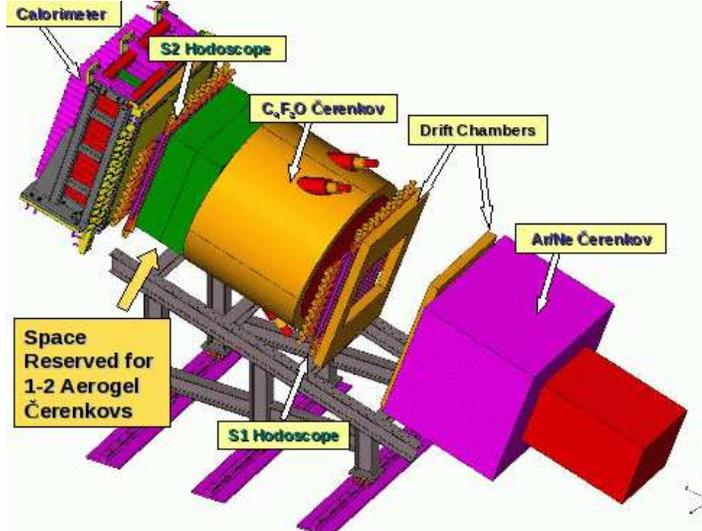


FIG. 3. Block diagram of the detector package of the SHMS. A free space of 60 cm exists for a pair of Aerogel detectors, not part of the base equipment but part of an NSF/MRI proposal submitted by collaboration members. This would allow accumulation of charged-kaon data.

The experiment will use beam energies of 6.6, 8.8, and 11.0 GeV to accomplish the Rosenbluth separations, at fixed values of (three of) x , Q^2 , z , and p_T^2 . The series of measurements will provide scans in z , up to the exclusive limit, p_T^2 , and Q^2 . The largest fraction of the beam time will be at the lowest beam energy, to provide the lowest value of the virtual photon polarization, ϵ . In general, the range of ϵ is ~ 0.5 . We will use the simultaneously measured inclusive cross sections to determine $R = \sigma_L/\sigma_T$ for inclusive $(e,e'X)$ DIS and compare with the SIDIS data. We may alternatively use these data for systematics control.

Spectrometer System and SHMS Particle Identification We will use the existing HMS and new SHMS in coincidence mode. The SHMS has a (D)QQQD design, with the first dipole a small horizontal pre-bender and the remainder a conventional QQQD vertical bend design, a close copy of the HMS design. The SHMS design is optimized to reach the highest momenta (11 GeV/c) and smallest scattering angles (down to 5.5°). The SHMS acceptance is about 4 msr, with a momentum acceptance of -10% to +20%. The detector package (see Fig. 3) resembles the HMS detector package. It contains a noble-gas Čerenkov (not used here), two SOS-type chambers for track reconstruction, an x-y scintillator hodoscope for timing/triggering, a heavy gas Čerenkov, a second x-y scintillator (one plane) and quartz Čerenkov hodoscope for timing/triggering, and a Lead-glass shower counter.

To uniquely identify charged kaons, the collaboration plans to augment the SHMS detector stack with a pair of aerogel detectors in an available 60-cm space slot. The Yerevan group, together with Hall C staff, built and commissioned the HMS Aerogel detector [23], used in a series of Hall C experiments to date. A consortium, led by the Catholic University of America in collaboration with the University of South Carolina, Florida International University, Mississippi State University and Yerevan Physics Institute, recently submitted a request to the Major Research Instrumentation program of the National Science Foundation for funding for this dedicated kaon identification system, which we are eager to add.

IV. PROPOSED MEASUREMENTS

E12-06-104 seeks to perform the first complete study of $R = \sigma_L/\sigma_T$ in SIDIS, as follows:

- Map R as a function of z at $x = 0.20$ and $Q^2 = 2.00 \text{ GeV}^2$, for both hydrogen and deuterium targets. This kinematics is chosen for compatibility reasons with the expected flavor decomposition program at a 12-GeV JLab. Especially, we would like to verify in at least one case that $R_{SIDIS}^H = R_{SIDIS}^D$.
- Map R^H as a function of z at $x = 0.40$ and $Q^2 = 4.00 \text{ GeV}^2$. We keep the ratio Q^2/x fixed, and thus the virtual-photon momentum nearly fixed. The SHMS momentum acceptance allows for good overlap in z . At this Q^2 , one expects $R_{DES} > R_{SIDIS}$.
- Map R_H as a function of p_T^2 at $x = 0.30$ and $Q^2 = 3.00 \text{ GeV}^2$. This combination is chosen to allow such scan within a reasonable amount of beam time. A lower value of (x, Q^2) would preclude measurements at both sides of the virtual-photon direction.
- Add kinematics to allow a map of R^H ranging from $Q^2 = 1.5$ to 5.0 GeV^2 .

Choice of Kinematics The invariant mass W^2 is 6.88, 7.88, and 8.88 GeV^2 for most chosen kinematics, well within the typical DIS region for inclusive scattering. For the bulk of the proposed data we have used W'^2 (M_x^2) larger than 3.3 GeV^2 , within the region where the E00-108 experiment found factorization to hold in SIDIS. Given that $W'^2 \equiv M_x^2 = M_p^2 + Q^2(1/x - 1)(1 - z)$, this cut will by necessity be alleviated in the $z \rightarrow 1$ limit. The lower z range is limited to $z \sim 0.3$, where the pion momenta (for parallel kinematics) become only 1.8 GeV . This is such that $\pi^+ N$ and $\pi^- N$ scattering cross sections are mostly absorptive and roughly equal, and simple Glauber estimates should be valid.

In all cases, we have made sure that the laboratory angle of SHMS is at least 5.5° , and the laboratory angle of HMS at least 10.5° . In addition, the minimum separation angle between HMS and SHMS is always larger than 18° . The range in ϵ is optimized for the Rosenbluth separations, and is typical ~ 0.5 , with three ϵ points per separation.

We keep the three-momentum transfer roughly constant, by maintaining a fixed Q^2/x ratio. The requirements to have $M_x^2 > 3.3 \text{ GeV}^2$, an SHMS angle above 5.5° , and a large swing in $\epsilon > 0.5$, implies there is not a large range of Q^2 at fixed x . With the behavior of R in DIS well constrained and behaved as function of x and Q^2 , the choice of fixed Q^2/x seems more prudent for SIDIS. We also connect to two approved proposals for deep exclusive pion [24] and kaon [25] electroproduction, respectively, that will provide data at fixed x .

Coincidence Rate Estimates The coincidence rate estimates are based upon the CTEQ5 next-to-leading-order (NLO) parton distribution functions [10], and the fragmentation function parameterization from Binnewies *et al.* [11]. Both the D^-/D^+ ratio [26] and the b -value [12] were taken from a HERMES analysis ($b \approx 4.66$). We assumed the parameters A and B to be zero for the rate estimates, which is not a major assumption. Lastly, we assumed that the rates for $z > 0.70$ were identical to those at $z = 0.70$, to mimic the fact that the high- z cross sections were found to be underestimated in the E00-108 experiment. The coincidence rate estimates show that in most cases of kinematic settings from 5 k to 10 k SIDIS events can be collected within 1-3 hours running at beam current 25-50 μA . For electroproduced kaons, we will obtain roughly 1 k SIDIS events per setting.

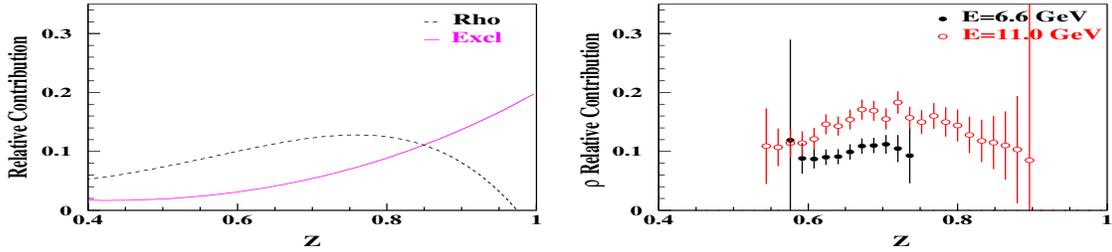


FIG. 4. *Left*: Fraction of pions from exclusive radiative tail (solid curve) and from decay of diffractive ρ mesons (dotted curve) relative to semi-inclusive production, at $Q^2 = 2.0 \text{ GeV}^2$ and $x = 0.20$. *Right*: Relative contribution of pions from diffractive ρ versus z for beam energies of 6.6 GeV (solid symbols) and 11.0 GeV (open symbols) at $Q^2=2.0 \text{ GeV}^2$ and $x=0.20$.

Beam currents for deuterium will be adjusted to render singles rates similar as for hydrogen, with about equal physics statistics. 10% of the run time is on the “dummy” target, for subtraction of end-wall purposes. Checkout and configuration time changes are included.

Systematic Uncertainties Since both the SHMS mechanical and optics design, and also the planned SHMS detector package, are essentially a clone of the HMS, we expect to achieve a similar high level of understanding of the SHMS acceptance function and detector properties. Hence, it makes sense to estimate the systematic uncertainties for the proposed measurements based upon the HMS, and/or HMS-SOS performance.

Based upon an impressive database of inclusive (e, e') Rosenbluth separations spanning the elastic, resonance and deep inelastic scattering regions, we have achieved a typical point-to-point systematic uncertainty of 1.1 to 1.6% for such measurements [27]. Indeed, the full collection of a few 100 of Hall C’s Rosenbluth Separations data of E94-110 shows a spread of data points about the linear fits which is Gaussian with a σ of 1.6%.

For coincidence measurements of the pion form factor with the HMS-SOS combination, a point-to-point systematic uncertainty of 1.9% was achieved [28]. The latter is mostly due to the relatively poor understood acceptance function of the SOS, with its difficulty to view long, extended targets. Hence, the estimate for the HMS-SHMS combination for 12-GeV pion form factor measurements is 1.6% [29].

Hence, it stands to reason to expect a systematic uncertainty of about 1.6%, comparable to the statistical precision we attempt to achieve. Nonetheless, some non-trivial contributions to the measured SIDIS ($e, e'\pi$) cross sections will enter, related with the “radiation tail” of pions from the exclusive production channel, and from the decay of diffractive ρ production (see Fig. 4). Note that the relative contribution of pions from diffractive ρ decay are expected to be about 8-10% at beam energy 6.6 GeV, and reach up to 10-15% at 11 GeV (bottom panel in Fig. 4), so partly cancel. Anticipated data from CLAS12 (ρ) and Hall C (F^π , pion CT) will further constrain these contributions. Similarly, the transverse momentum scans with full azimuthal angular dependence, as will be accumulated with the CLAS12 experiments, will shed further light on potential systematic uncertainties for R as function of p_T .

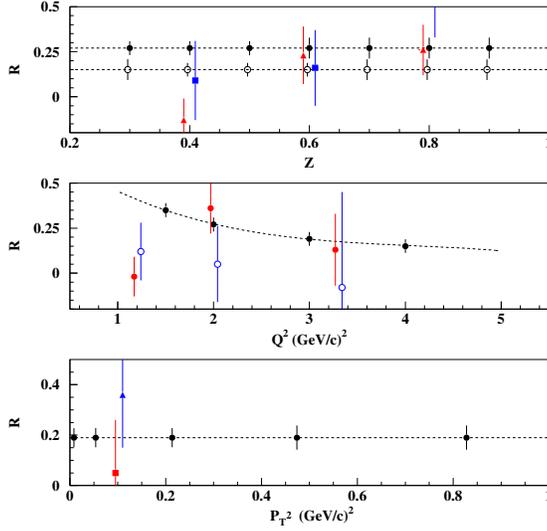


FIG. 5. The proposed measurements for the ratio of longitudinal to transverse cross sections in semi-inclusive deep inelastic pion electroproduction ($R = \sigma_L / \sigma_T$) as a function of Q^2 (top panel, both at $x=0.20$ and $x = 0.40$), z (middle panel), and p_T^2 (bottom panel). For comparison, we show the only existing data from Cornell. The dashed curves represent R for DIS.

V. EXPECTED RESULTS AND BEAM TIME REQUEST

We request a total of 40 days of beam time to measure $R = \sigma_L / \sigma_T$ in semi-inclusive deep inelastic scattering as a function of z , Q^2 , and p_T^2 , covering a region of interest to the general program of SIDIS physics at a 12-GeV JLab. Of course, these data will also provide precise new measurements of the separated cross sections σ_{SIDIS}^T and σ_{SIDIS}^L .

The itemized beam time request is given below.

- Map $R_{SIDIS}^H + R_{SIDIS}^D$ as function of z at $x = 0.2$ and $Q^2 = 2.0 \text{ GeV}^2$ (**168 Hours**)
- Map R_{SIDIS}^H as a function of z at $x = 0.4$ and $Q^2 = 4.0 \text{ GeV}^2$ (**319 Hours**)
- Map R_{SIDIS}^H as a function of p_T^2 at $x = 0.3$ and $Q^2 = 3.0 \text{ GeV}^2$ (**311 Hours**)
- Add kinematics to map R_{SIDIS}^H for $Q^2 = 1.5\text{-}5.0 \text{ GeV}^2$ (**88 Hours**)
- Overhead (**75 Hours**)

The proposed data cover the range of $Q^2 = 1.5\text{-}2.0 \text{ GeV}^2$. Scans in z are proposed at $Q^2 = 2.0$ ($x = 0.2$) and 4.0 GeV^2 ($x = 0.4$), and should settle the behavior of σ_L / σ_T for large z . A projection of the quality of proposed data for R_{SIDIS} as compared with the only existing data, from the Cornell experiments, is shown in Fig. 5.

REFERENCES

- [1] M. Blumenstengel *et al.*, Nucl. Phys. B **517** (2001) 37.
- [2] OPAL Collaboration. R. Akers *et al.*, Z. Phys. C **68** (1995) 203.
- [3] DELPHI Collaboration. P. Abreu *et al.*, Eur. Phys. J. C **6** (1999) 19.
- [4] T. Sjöstrand. Comput. Phys. Commun. **39** (1986) 347; T. Sjöstrand, M. Bengtsson, Comput. Phys. Commun. **43** (1987) 367.
- [5] S. Bethke, J. Phys. G **26** (2000) R27, hep-ex/0004021.
- [6] C. J. Bebek *et al.*, Phys. Rev. Lett. **34** (1975) 759.
- [7] C. J. Bebek *et al.*, Phys. Rev. Lett. **37** (1976) 1525.
- [8] C. J. Bebek *et al.*, Phys. Rev. **D 15** (1977) 3085.
- [9] V. Tvaskis, M. E. Christy *et al.*, Phys. Rev.Lett. **98**, 142301 (2007); nucl-ex/0611023; E99-118 experiment, spokespersons: A. Bruell, J. Dunne, and C.E. Keppel.
- [10] H.L. Lai *et al.*, Eur. Phys. J. **C12** (2000) 375.
- [11] J. Binnewies, B. A. Kniehl, and G. Kramer, Phys. Rev. D **52** (1995) 4947.
- [12] B. Hommez, Ph.D. Dissertation, Gent University (2003), unpublished.
- [13] M. Tytgat, Ph.D. Dissertation, Gent University (2001), unpublished.
- [14] T. Navasardyan *et al.*, Phys. Rev.Lett. **98**, 022001 (2007); hep-ex/0611023; E00-108 experiment, spokespersons: R. Ent, H. Mkrtchyan, and G. Niculescu.
- [15] F.E. Close and N. Isgur, Phys. Lett. **B 509** (2001) 81.
- [16] S.J. Brodsky, L. Frankfurt, J.F. Gunion, A.H. Mueller, and M. Strikman, Phys. Rev. D **50**, 3134 (1994).
- [17] J. Collins, L. Frankfurt, and M. Strikman, Phys. Rev. D **56**, 2982 (1997).
- [18] L.L. Frankfurt, P.V. Pobylitsa, M.V. Polyakov, and M. Strikman, Phys. Rev. D **60**, 014010 (1999).
- [19] M. Diehl, T. Gousset, B. Pire, and O. Teryaev, Phys. Rev. Lett. **81**, 1782 (1998).
- [20] X. Ji, Phys. Rev. Lett. **78**, 610 (1997); Phys. Rev. D **55**, 7114 (1997).
- [21] A.V. Radyushkin, Phys. Lett. **B380**, 417 (1996); Phys. Rev. D **56**, 5524 (1997).
- [22] J.D. Bjorken and J.B. Kogut, Phys. Rev. D **8** (1973) 1341.
- [23] R. Asaturyan *et al.*, Nucl. Instr. and Meth. **A548**, 364 (2005).
- [24] *Scaling Study of the L-T Separated Pion Electroproduction Cross Section at 11 GeV*, E12-07-105 experiment, spokespersons: T. Horn and G. Huber.
- [25] *Studies of the L-T Separated Kaon Electroproduction Cross Section from 5-11 GeV*, E12-09-011 experiment, spokespersons: T. Horn, G. Huber and P. Markowitz.
- [26] P. Geiger, Ph.D. Dissertation, Heidelberg University (1998), unpublished.
- [27] Y. Liang *et al.*, nuc-ex/0410027; E94-110 experiment, spokesperson: C.E. Keppel.
- [28] T. Horn *et al.*, Phys. Rev. Lett. **97**, 192001 (2006); E01-004 experiment, spokespersons: H.P. Blok, G.M. Huber and D. Mack.
- [29] *Measurement of the Charged Pion Form Factor to High Q^2* , E12-06-101 experiment, spokespersons: G.M. Huber and D. Gaskell.