# UPDATE to E12-09-002; Charge Symmetry Violating Quark Distributions via Precise Measurement of $\pi^+/\pi^-$ Ratios in Semi–inclusive Deep Inelastic Scattering.

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## I. ABSTRACT

We propose to measure precision ratios of charged pion electroproduction in Semi–Inclusive Deep Inelastic Scattering from deuterium. This data will be used to test the validity of charge symmetry in the valence quark distributions.

This experiment will use the SHMS and HMS in Hall C to measure electrons and charged pions in coincidence. In this case, the SHMS will be used as the electron arm, and the HMS as the hadron arm. The experiment will measure semi–inclusive production of charged pions at three different values of $Q^2$=4.0, 5.0, and 6.1 GeV$^2$ at large $x$. A range of $x$ and $z$ values is required to fully constrain charge symmetry violating contributions in both the quark distributions and fragmentation functions. Efficient detection of both signs of charged pions is important, and while absolute yields and cross sections will be measured, uncertainties due to the overall normalization cancel in the measured ratio.

Charge symmetry is routinely assumed in parton distribution functions, however, surprisingly there are no direct measurements of contributions from charge symmetry violation. Measurement of a nonzero effect would have profound consequences regarding our assumptions about quark distributions at large $x$. In addition, violation of charge symmetry in quark distributions has consequences reaching beyond QCD and would impact, for example, the recent extraction of the Weinberg angle from neutrino DIS.

This experiment, run alone, requires $\sim$ 22 days to complete in Hall C assuming a maximum of 50 $\mu$A beam current and a beam energy of 11 GeV. However, it can run together with E12-09-017 and E12-06-104 which have some overlap in the kinematic settings. The common running running time is $\sim$ 1 day including overhead. In addition it would also share the same setup and checkout time with these experiments.

## II. PHYSICS MOTIVATION

Symmetries are the key to understanding and classifying the structure of matter and the fundamental forces. Their study leads to better understanding of the underlying physics. With the advances in experimental and theoretical tools, symmetries other than those of space-time were introduced in physics. Isospin (IS) and charge (CS) symmetries are examples. Charge symmetry is related to the invariance of the QCD Hamiltonian under rotations about the 2-axis in isospin space, turning $u$ quarks to $d$ and protons to neutrons. For details we refer the reader to comprehensive reviews by Miller, Nefkens and Slaus [1], and Henley and Miller [2]. At the quark level CS implies the invariance of a system under the interchange of up and down quarks while simultaneously interchanging protons and neutrons, *i.e.*

$$\begin{aligned} u^p(x,Q^2) &= d^n(x,Q^2) \\ d^p(x,Q^2) &= u^n(x,Q^2). \end{aligned} \tag{1}$$

At the quark level, CS is badly broken by the $u-d$ mass difference, but this is hidden by other dynamical effects. Quantum Chromo-Dynamics (QCD) provides a clear formulation of the origin of charge symmetry violation (CSV). In QCD, the only sources of CSV are electromagnetic interactions and the mass difference $\delta m = m_d - m_u$ between down and up quarks. Electromagnetic interactions should play a minor role at high energies. Thus, the light quark mass difference is the interesting feature of the QCD view of CSV [3].

In this experiment, we are interested in CSV of valence quark distributions. At present, there are no direct measurements that reveal the presence of CSV in parton distribution functions. We have only upper limits on the magnitude of CSV. These limits arise from comparing the structure function $F_2^\nu$ measured in neutrino induced charged current reactions, and the structure function $F_2^\gamma$ for charged lepton DIS, both measurements on isoscalar targets [4]. The most precise neutrino measurements were obtained by the CCFR collaboration [5], who extracted the $F_2^\nu$ structure function for neutrino and anti-neutrino interactions on iron at FNAL. The NMC collaboration performed the most precise measurements of $F_2^\gamma$ structure functions using muon interactions on deuterium at $\mathrm{E}_\mu =$ 90 and 280 GeV. In the region of $0.1 \leq x \leq 0.4$, an upper limit of 9% was set for CSV effects.

While the primary goal of this experiment is to place constraints on charge symmetry violating quark distributions, the charged pion, semi-inclusive cross sections and ratios themselves are of interest. As noted in the PAC37 report:

> *...the cross sections are such basic tests of the understanding of SIDIS at 11 GeV kinematics that they will play a critical role in establishing the entire SIDIS program of studying the partonic structure of the nucleon. In particular they*

*complement the CLAS12 measurements in areas where the precision of spectrometer experiments is essential – in this case, precise control of the relative acceptance and efficiency for different particle charges.*

The role of this experiment in the context of the Hall C semi–inclusive program is discussed further in Appendix A.

## III. FORMALISM

Semi-inclusive pion production from lepton deep inelastic scattering on nuclear targets was suggested [6, 7] as a sensitive probe of CSV effects in nucleon valence distributions. The authors proposed measuring the quantity $R^D_{meas}(x,z)$ defined by:

$$R^D_{meas}(x,z) = \frac{4N^{D\pi^-}(x,z) - N^{D\pi^+}(x,z)}{N^{D\pi^+}(x,z) - N^{D\pi^-}(x,z)}, \tag{2}$$

where $N^{D\pi^+}$ ($N^{D\pi^-}$) is the yield of $\pi^+$ ($\pi^-$) produced in coincidence with the scattered electron from deuterium.

The charge-symmetry violating quark distributions can be extracted using the above quantity via the following "master" formula:

$$D(z)\ R(x,z) + CSV(x) = B(x,z) \tag{3}$$

where

$$\begin{aligned} D(z) &= \frac{1-\Delta(z)}{1+\Delta(z)}, \\ R(x,z) &= \frac{5}{2} + R^D_{meas}, \\ CSV(x) &= \frac{-4(\delta d - \delta u)}{3(u_v + d_v)}, \\ B(x,z) &= \frac{5}{2} + R^D_{sea\_S}(x,z) + R^D_{sea\_NS}(x). \end{aligned} \tag{4}$$

In the quantity $D(z)$, $\Delta(z)$ is the ratio of unfavored to favored fragmentation functions, $D_u^{\pi^-}(z)/D_u^{\pi^+}(z)$. The functions $R^D_{sea\_S}$ and $R^D_{sea\_NS}$ in $B(x,z)$ depend on the strange and non-strange sea quark distributions and must be calculated from PDF parametrizations. This experiment makes measurements at the largest practical values of $x$ to minimize sensitivity to this term. $CSV(x)$ contains the difference of charge–symmetry–violating quark distributions,

$\delta d - \delta u$, where

$$\delta d(x) = d^p(x) - u^n(x),$$
$$\delta u(x) = u^p(x) - d^n(x). \tag{5}$$

In this experiment, we will measure $R^D_{meas}(x, z)$ (see Eq. 2) and thus $R(x, z)$ for 16 bins in $x$ and $z$ for 3 distinct $Q^2$ bins. We will end up with 16 equations similar to Eq. (3) and 8 unknowns, which are CSV($x_1$), CSV($x_2$), CSV($x_3$), CSV($x_4$), D($z_1$), D($z_2$), D($z_3$) and D($z_4$).

For a better idea about the $B(x, z)$ term, we used the PDFs from CTEQ6L and fragmentation functions from a recent parametrization by De Florian and collaborators [8]. The non strange sea term was found to be large compared to the strange term. For $x$ values above 0.35, the strange contribution becomes negligible. Therefore, making the $B(x, z)$ independent of $z$. The $R^D_{sea\_NS}$ term can be obtained from the parton distribution function, and the uncertainties on this non strange sea term represent the main theoretical systematical uncertainties on the extracted CSV term.

## IV. FACTORIZATION AT A 12 GEV JLAB AND HADRON MASS CORRECTIONS

As in all semi-inclusive analyses, the formalism used to extract charge symmetry violating quark distributions involves the assumption of factorization, i.e., that semi-inclusive pion production can be described by two independent processes. First, the virtual photon interacts with a quark in the hadronic system - then that quark subsequently hadronizes forming a pion or other particle. Only when this picture is valid can we be confident that the formalism we are using to measure CSV effects is appropriate.

It is not a foregone conclusion that semi-inclusive processes at a 12 GeV JLab will satisfy the factorization criteria described above, however there is good reason to believe that they will. Already at 6 GeV, we have seen signs that factorization may be satisfied as seen in Hall C experiment E00-108 [9] in which semi–inclusive charged pion production from hydrogen and deuterium targets was measured. In that experiment, the absolute cross sections were found to be consistent with cross section calculations performed in a leading order framework using CTEQ5M [10] parton distribution functions and a high energy parametrization of the fragmentation functions [11]. In addition, the $z$ dependence of combinations of the two charge states and targets were found to be consistent with the simple factorization assumption up to $z \approx 0.7$.

While the Hall C 6 GeV results are promising, it is important to test for factorization over a wider kinematic range, and especially at the kinematics relevant to the experiment. We plan to perform similar to tests to those performed in E00-108 to verify that factorization is satisfied at the kinematics sampled by this experiment.

Recently, Accardi, Hobbs and Melnitchouk [12] have calculated the hadron mass corrections for SIDIS. They find large mass corrections for the unfavored fragmentation function compared to the favored ones, which can be non-negligible at large $z_h$ ($\geq 0.6$). The $z_h$ coverage of this experiment spans the range 0.4 to 0.7, so the hadron mass effects should be small for much of our kinematics. In addition, although the hadron mass corrections can have significant effect for experimental cross-sections at JLab energies, this experiment aims to measure cross-section ratios so the effect of the hadron mass corrections should be minimal.

## V. EXPERIMENTAL OVERVIEW

Since the effect we are attempting to measure is potentially small, it is important that systematic errors are well controlled. In particular, magnetic, focusing spectrometers are ideal for measurements of charged pion ratios due to their identical acceptance at positive and negative polarity. In addition, small angles and large momenta are required, hence Hall C with the HMS and new SHMS are well suited to this experiment.

In this experiment we will measure the ratio of the $\pi^-$ to $\pi^+$ production yields on deuterium for different $x$ and $z$ bins:

$$R_Y(x,z) = \frac{Y^{\pi-}(x,z)}{Y^{\pi+}(x,z)}$$

We will measure semi–inclusive pion electroproduction from a 10 cm liquid deuterium target at large $x$ to map out potential charge symmetry violation in the valence quark distributions. The kinematics were chosen with the following goals:

- Measure semi–inclusive charged pion electroproduction from deuterium at three different $Q^2$ (4.0, 5.0 and 6.1 GeV$^2$). At each $Q^2$ value cover several values of $x$ and $z$ such that one can extract $R^D_{meas}(x,z)$ at each of these points and thereby extract the charge symmetry violating quark distributions and the fragmentation functions.
- At $Q^2 = 4.0$ GeV$^2$, semi-inclusive yields will be measured for $x = 0.35$, 0.4, 0.45 and 0.5. At each $x$ setting measurements will be performed at $z = 0.4$, 0.5, 0.6 and 0.7
- At $Q^2 = 5.0$ GeV$^2$, semi-inclusive yields will be measured for $x = 0.45$, 0.5, 0.55, and 0.6. At each $x$ setting measurements will be performed at $z = 0.4$, 0.5, 0.6 and 0.7
- At $Q^2 = 6.1$ GeV$^2$, semi-inclusive yields will be measured for $x =$0.5, 0.55, 0.6 and 0.65. At each $x$ setting measurements will be performed at $z = 0.4$, 0.5, 0.6 and 0.7

- At $Q^2 = 4.0$ and $5.0$ GeV$^2$, we will take additional data from liquid hydrogen. These data will be combined with the deuterium data to perform simple tests of factorization. For example, we will form target ratios (p/D) of sums and difference of charged pion yields, which should be independent of $z$ with a magnitude consistent with that predicted by PDFs if factorization holds.

In the above settings, we require the usual "DIS" kinematics such that $Q^2 > 1$ GeV$^2$ and $W^2 > 4$ GeV$^2$. Also, we will require $W'^2 = (m_p + \nu - E_\pi)^2 - |\vec{q} - \vec{p_\pi}|^2$, the mass of the unobserved final state, be larger than 2.0 GeV$^2$ ($W'$ >1.414 GeV). This last constraint is driven by the observation from E00-108 that factorization seems to hold up to $z = 0.7$, or for their kinematics, $W'^2 > 2$ GeV$^2$.

The experiment will measure $D(e, e'\pi^+)X$, and $D(e, e'\pi^-)X$ using the HMS and SHMS spectrometers in Hall C. Electrons will be detected in the SHMS and the charged pions in the HMS. Electron momenta and angles range from 4.5 to 6.7 GeV and 13.43° to 20.21° respectively, while the pion kinematics require momenta from 1.71 to 4.55 GeV and angles of 11.90° to 20.28°. These requirements are well within the capabilities of the SHMS and HMS.

This experiment has relatively modest particle identification requirements which should be easily achievable using the standard detectors in the HMS and SHMS spectrometers. In particular, the existing set of detectors in the HMS are adequate to identify charged pions at both positive and negative polarity.

## VI. UNCERTAINTIES AND PROJECTED RESULTS

At each setting, we will take enough statistics to achieve $\approx$ 1% uncertainties in the charged pion ratio, $R_D^{\pi^+/\pi^-} = Y_D(\pi^+)/Y_D(\pi^-)$. The backgrounds from random coincidences are significant at some settings, but at larger $z$ the backgrounds are smaller so will not contribute significantly to any amplification of the statistical error. For that reason, we will take 20,000 counts at each setting (and polarity) for the $z = 0.6$ and $z = 0.7$ settings, while we will take 30,000 counts at for $z = 0.4$ and $z = 0.5$ settings.

The systematic and total uncertainties are summarized in Table I. Uncertainties due to backgrounds from diffractive $\rho$ production and the radiative tail of exclusive pion production are the largest systematic uncertainties in this experiment. Many experimental systematic uncertainties, such as absolute target thickness completely cancel in the ratio of yields. Others, like pion re-scattering and absorption in the spectrometer, while potentially different

| Source | Uncertainty | Uncertainty in $R_D^{\pi^+/\pi^-}$ (per $z$ bin) |
|---|---|---|
| Statistics | 0.7% | 1.0% |
| Luminosity | 0.3% | 0.3% |
| Tracking efficiency | 0.1-1% | 0.2% |
| Dead time | <0.1% | <0.1% |
| Acceptance | 1-2% | 0.1% |
| PID efficiency | <0.5% | 0.2% |
| $\rho$ backgrounds | 0.5-3% | 0.2-0.7% (1.2%) |
| Exclusive rad. tail | 0.2-1.3% | 0.1-0.6% (1.3%) |
| Total systematic | | 0.49-1.02% (1.8%) |
| Total uncertainty | – | 1.1-1.43% (2.1%) |

TABLE I: Systematic uncertainties. The uncertainties listed are for *each* $z$ bin so can be combined in quadrature. Numbers in parentheses are for the largest $z = 0.7$ bin, where backgrounds from $\rho$ and the radiative tail from pion electroproduction are larger.

for each charge state, are expected to be small. Other notable sources of uncertainty come from the measurement of beam current and boiling effects in the liquid deuterium target. The product of target thickness and beam current can be constrained to about 1% using the beam current monitoring devices and measurements of target boiling effects. However, the relative luminosity can also be measured via electron singles yields in the SHMS. Since the inclusive electron yield should have high statistics with minimal pion backgrounds, we anticipate the overall normalization uncertainty can be as low as 0.2-0.3%.

Uncertainties due to differences in tracking efficiencies, a potentially large correction at the high single-arm rates of this experiment, will be mitigated by keeping the singles rates in the hadron arm close to identical. The rates in the electron arm will necessarily be different, but since the global rates are much lower (at most 130 kHz) uncertainties associated with tracking are much smaller.

Other uncertainties due to particle ID efficiency and acceptance should cancel in the ratio, but we include allowance for some small difference, perhaps due to slightly different event distributions across the spectrometer acceptance.

We estimate the total experimental systematic uncertainty in the ratio to be $\Delta R/R = 0.5 - 1.8\%$ ,varying with $z$.

Fig. 1 shows the expected uncertainties for our measurements of the CSV term which is $(\delta d - \delta u)$. Both statistical and systematical errors are included. The yellow band shows the systematic error related to the parton distribution functions; especially the non strange sea contribution. The expected precision is quite good especially for high $x$ measurements where the magnitude of the non strange sea drops dramatically, making the systematic uncertainties negligible. Since the low $x$ data takes marginally small time, we have decided to extract the CSV term for $x$ as low as 0.35 although the systematic errors due to the PDFs are large.

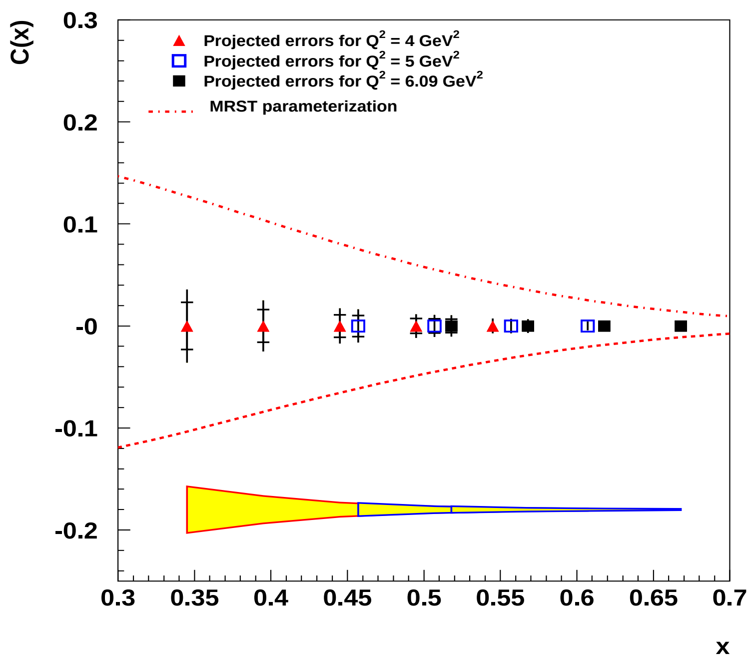


FIG. 1: Predicted uncertainties for the charge symmetry violating quark distributions, $\delta d - \delta u$. Both statistical and systematical errors are included. The internal errors are statistical uncertainties while the external ones correspond to experimental systematic errors added in quadrature. The yellow band corresponds to the systematic error related to uncertainties in the PDFs. The two curves are the upper and lower limit of CSV contribution given by MRST parametrization. The dashed curve corresponds to $\kappa = +0.65$ while the dotted-dashed one corresponds to $\kappa = -0.8$.

Using the method described in the formalism section, we will extract simultaneously the $x$-dependent term related to CSV and the $z$-dependent term connected to the fragmentation functions.

## VII. BEAM TIME REQUEST

The required production running time for this experiment is summarized in Table II. A total of 367 hours is required for data-taking on deuterium. However, about 15 hrs of this time is common with E12-09-017. In addition to production data from deuterium, we request $\approx$ 72 hours of data on liquid hydrogen to perform factorization tests at the two lowest $Q^2$ settings using the $z$-scan data. Using this hydrogen data combined with the

| Activity | Time (hours) |
| --- | --- |
| LD2 data taking | |
| $Q^2$=4 GeV$^2$ | 32.2 |
| $Q^2$=5 GeV$^2$ | 96.5 |
| $Q^2$=6.1 GeV$^2$ | 238.6 |
| LD2 Total | 367.3 |
| Al. dummy data | 36.7 |
| LH2 data | 72.1 |
| Polarity and kinematics changes | 44 |
| Total | 520.1 (21.7 days) |

TABLE II: Total beam time requested.

deuterium data that will be taken at those settings, we will perform tests similar to those done during Hall C experiment E00-108. We also request time for aluminum dummy data taking to subtract contributions from the liquid target cell walls. About 5 hrs of this time is also common with E12-09-117.

Finally, we allocate 44 hours for various kinematic and polarity changes. At each $x$ point, we plan to minimize systematic effects by taking the $z$-scan data at one polarity and then changing polarity immediately and completing the setting before moving on to the next $x$ setting. This results in a total of 12 polarity changes at one hour each. In addition, we allocate 20 minutes to each momentum change (48 at each polarity).

The total time required for this experiment is 22 days. We note that if E12-09-002 (this experiment) and E12-09-117 run together, the combined running time would be 1.0 day shorter than if each were run separately due to the kinematic overlap in the deuterium and hydrogen data–taking.


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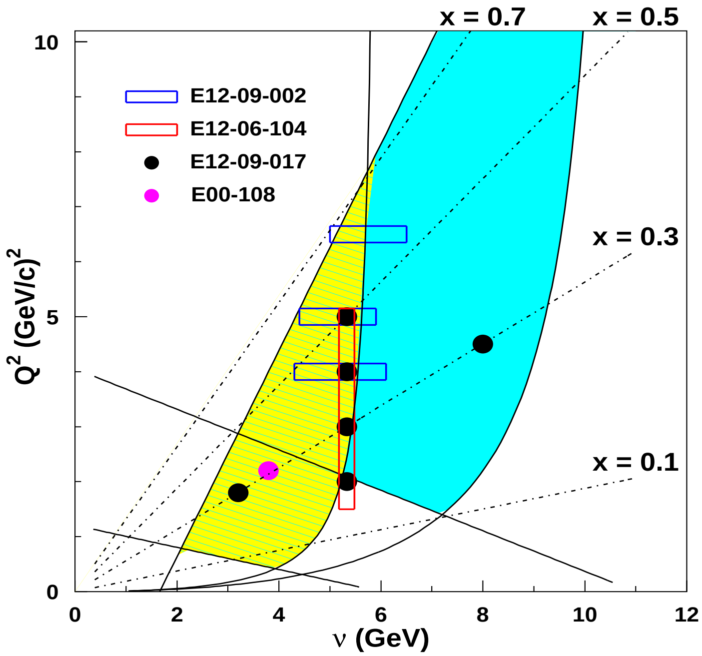


FIG. 2: $Q^2$ vs. $\nu$ for phase space accessible in Deep Exclusive reactions in Hall C after the 12 GeV Upgrade. The phase space covered by the approved Hall C semi-inclusive experiments is also shown. E12-09-002 (this experiment) is shown by the blue boxes, E12-09-017 by the large black points, E12-06-104 by the red box. For reference, the 6 GeV point from E00-108 is also shown (magenta point). Figure courtesy of Rolf Ent.

In addition to placing constraints on charge symmetry violating quark distributions, E12-09-002 will play an important role in supplementing the semi-inclusive data set provided by Hall C as part of the overall JLab semi-inclusive program. While large acceptance devices like CLAS12 and the proposed SOLID and Super-Big Bite spectrometers will provide unrivaled access to azimuthal distributions in single-spin and double-spin asymmetries, as well as large phase-space coverage to enable the multi–dimensional binning of distributions and cross sections to study dependencies, (e.g., $Q^2$ dependence at fixed $x$, etc.), Hall C will play an important role in providing precise measurements of cross sections and charge ratios in select regions of phase space.

The phase space covered by the approved Hall C semi-inclusive program is illustrated in Fig. 2. E12-06-104 will provide L–T separated cross sections for particular values of $x$ and $Q^2$, scanning over $z$ and $P_T$. E12-09-017 will measure precise $\pi^+/\pi^-$ ratios, and also measure unseparated cross sections, providing additional $z$ and $P_T$ scans while also scanning $Q^2$ at fixed $x$. Finally, this experiment (E12-09-002) will provide charged pion ratios and cross sections for a range of $x$ at three fixed values of $Q^2$ in parallel kinematics, scanning in $z$ at each point.