(Letter Of Intent to Jefferson Lab PAC-24)

# $\vec{e}$ – <sup>2</sup>H Parity Violating Deep Inelastic Scattering at CEBAF 6 GeV

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#### Abstract

We propose to perform a measurement of the parity violation asymmetry  $A_d$  of  $\vec{e} - {}^2$ H deep inelastic scattering (DIS) at  $Q^2 = 2.0$  (GeV/c)<sup>2</sup>. The ultimate goal is to extract the weak mixing angle  $\sin^2 \theta_W$  and to determine the effective coupling constants  $(2C_{2u} - C_{2d})$ . The result of  $(2C_{2u} - C_{2d})$  will improve the current knowledge of this quantity by about an order of magnitude. Such data will provide crucial information on the test of the Standard Model via parity violation DIS processes.

We plan to use a 15-cm liquid deuterium target in Hall A and 140- $\mu$ A, 6.0-GeV polarized beam. A minor upgrade is needed for the Compton polarimeter and a fast counting data acquisition system is to be built for the proposed measurement. Assuming a 80% beam polarization, we need 60 days of beam time to reach a  $\pm 0.69\%$ (stat.)  $\pm 0.74\%$ (syst.) uncertainty on  $\sin^2 \theta_W$  at  $Q^2 = 2.0$  (GeV/c)<sup>2</sup>. The uncertainty on the extracted effective weak couplings will be  $\Delta (2C_{2u} - C_{2d}) = 0.026$ .

The proposed measurement is the first step of a DIS-parity program at JLab. If the result shows a large deviation from the Standard Model predication, then furthur measurements at larger  $Q^2$  and with better precision are needed to unravel possible sources of the deviation and help to reveal new physics beyond the Standard Model. This can be done using an upgraded spectrometer (e.g., MAD) and JLab 12-GeV beam.

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# 1 Introduction

We propose to perform a measurement of the parity violation asymmetry  $A_d$  of  $\vec{e} - {}^2\text{H}$  deep inelastic scattering at  $Q^2 = 2.0 \text{ (GeV/c)}^2$ . The ultimate goal is to extract the weak mixing angle  $\sin^2 \theta_W$  and to determine the effective coupling constants  $(2C_{2u} - C_{2d})$ . This will be the first precise data on the  $\sin^2 \theta_W$  at this  $Q^2$  range. By assuming the Standard Model values of  $(2C_{1u} - C_{1d})$  (this will be tested by combing the results from Cs APV and the future Qweak experiment), one can determine from  $A_d$  the weak coupling constant  $(2C_{2u} - C_{2d})$ . This quantity is currently not well known and we expect to reduce its uncertainty by about an order of magnitude.

The proposed measurement is the first step of a DIS-parity program at JLab. One of the major concern for DIS-parity experiments is QCD higher-twist effects (although two available calculations show negligible results), which may also cause part of the  $3\sigma$  deviation observed by the NuTeV collaboration. If the new data show a large deviation from the Standard Model predication, then furthur measurements are to be proposed at different  $Q^2$  and with higher precision using upgraded spectrometer (e.g., MAD) and JLab 12-GeV beam. Compared with data at different  $Q^2$ , it is possible to extract, or set limit on the higher-twist effects to a good precision, thus make DIS-parity a reliable way to test the Standard Model. On the other hand, if there are significant higher twist effects, then DIS-parity experiments can be used to study the quark-quark correlation inside the nucleon.

If the higher twist turn out to be negligible for DIS-parity, then the new data have the potential to explore new extension of, or new physics beyond the Standard Model. Being in the intermediate  $Q^2$  range and has different sensitivities to possible new physics, the proposed measurement is complementary to the existing APV and NuTeV results, the running E158 and the future Qweak experiments.

We plan to use a 15-cm liquid deuterium target in Hall A and 140- $\mu$ A, 6.0-GeV polarized beam. Assuming a 80% beam polarization, we need 60 days of beam time to reach a  $\pm 0.69\%$ (stat.)  $\pm 0.74\%$ (syst.) uncertainty on  $\sin^2 \theta_W$  at  $Q^2 = 2.0$  (GeV/c)<sup>2</sup>. The uncertainty on the extracted effective weak couplings will be  $\Delta (2C_{2u} - C_{2d}) = 0.026$ .

We first review the experimental status for  $\sin^2 \theta_W$  and  $(2C_{2u} - C_{2d})$ , present the expected results from this measurement and discuss possible new physics beyond the Standard Model (SM) that could be revealed by the new data. Experimental design of the proposed measurement will be presented, followed by a thorough analysis of the systematic uncertainties. Finally, we will summarize the expected total uncertainty and the beam time request.

# 2 Motivation

# **2.1** The Running of $\sin^2 \theta_W$ and Experimental Status

Testing the electroweak sector of the Standard Model is a major focus of nuclear and high energy physics experiments. The weak mixing angle,  $\theta_W$ , is one of the fundamental parameters of the Standard Model. The tangent of  $\theta_W$  represents the relative coupling strength of the SU(2) and U(1) groups. In the Standard Model the effective value of  $\sin^2(\theta_W)$  varies with momentum transfer  $Q^2$ , with a minimum at the Z resonance ( $Q^2 = M_Z^2$ , or the Z-pole). The variation of  $\sin^2 \theta_W$  with  $Q^2$ , referred to as the "running of  $\sin^2 \theta_W$ ", can be calculated within the Standard

Model (SM) framework [1]. Testing this prediction requires a set of precision measurements at a variety of  $Q^2$  points, with sufficiently small and well understood theoretical and experimental uncertainties associated with the extraction of  $\sin^2 \theta_W$ , such that one can interpret the results with confidence.

At the Z-pole, the value of  $\sin^2(\theta_W)$  has been well established from a number of measurements [4, 5]. Combined with measurements of the W and t quark masses from the Tevatron, the average of all existing measurements gives the remarkably precise value  $\sin^2 \theta_W(M_Z)_{\overline{MS}} =$  $0.23113 \pm 0.00015$  [15] in the Modified Minimal Subtraction ( $\overline{MS}$ ) scheme. However, careful comparison of measurements involving lepton and hadron electroweak couplings at the Zpole has recently revealed a three standard deviation inconsistency, which strongly hints at new physics beyond the Standard Model or a significant systematic error underestimate in one or more experiments [3]. Away from the Z-pole, there exists only two precision measurements. The atomic parity violation (APV) on the cesium (Cs) is in reasonably good agreement with the SM prediction at low energy [7]. However the atomic theory uncertainty associated with the extracting of  $\sin^2 \theta_W$  from Cs APV is about four times larger than the experimental error and earlier analysis claimed a two standard deviation away from the SM [8]. This reduces the possibility of searching for new physics beyond the SM from the APV results. Another measurement away from the Z-pole was performed by the NuTeV collaboration [9]. The value of  $\sin^2 \theta_W$ was extracted from the ratios of neutral current to charged current  $\nu$  and  $\bar{\nu}$  DIS cross sections on an iron target at  $Q^2 \approx 20$  (GeV/c)<sup>2</sup> and is found to be three standard deviations above the SM prediction. The NuTeV result triggered a large amount of theoretical interest. For example, as recently pointed out, the charge symmetry violation (CSV) can explain one third of this deviation [10]. If it cannot be explained completely by conventional hadronic effects, the NuTeV results would point to new physics beyond the SM. Other than APV and NuTeV measurements, the E158 experiment currently running at SLAC measured  $\sin^2 \theta_W$  via the asymmetry  $A_{LR}$  of Møller scattering at  $Q^2 = 0.03$  (GeV/c)<sup>2</sup> and the Qweak experiment planned at JLAB Hall C will measure  $\sin^2 \theta_W$  in the same  $Q^2$  range using  $\vec{e} - p$  elastic scattering.

Figure 1 gives the SM-predicted running of  $\sin^2 \theta_W$ . Also shown are the results from the existing Cs APV [7], the existing neutrino DIS (NuTeV) [9] measurement and  $Z \rightarrow \bar{b}b$  decay asymmetry measurement at the Z-pole [3], the expected uncertainty from the measurement using Parity Violating Deep Inelastic Scattering (DIS-parity, this proposal), the expected uncertainty of the approved JLAB  $Q_{\text{weak}}$  [11] and the running SLAC Møller (E158) [12] experiments. The proposed measurement will provide information on the  $\sin^2 \theta_W$  complementary to all other experiments mentioned above.

# **2.2** The Effective Couplings $C_{2u}$ , $C_{2d}$ and the Experimental Status

Among the experiments (finished or planned) aiming at the testing of Standard Model and the search for new physics, some are purely leptonic (E158) and are not sensitive to new interactions involving quarks, some are semi-leptonic (APV, Qweak) but can only access weak coupling  $C_{1q}$ . In contrast to  $C_{1q}$ 's, the weak couplings  $C_{2q}$  are poorly known. Table 1 summarizes the current knowledgement of  $C_{iq}$  [13]. From existing data we have  $2C_{2u} - C_{2d} = -0.08 \pm 0.24$  [15]. This constraint is quite loose and makes it barely possible to extract  $C_{3q}$  from CERN data. Moreover,  $C_{2q}$ 's are important because they are sensitive to possible new axial Z-u(d) quark couplings and one additional Z' (see Section 2.5) to which  $C_{1q}$ 's are not sensitive. Here  $e^{-2}$ H DIS-parity is

Figure 1: The running of  $\sin^2 \theta_W$  shown as a function of  $Q^2$  [6]. The expected total uncertainty of the proposed DIS-parity experiment is shown in red. Also shown are the existing Atomic Parity Violation (APV) cesium [7], the existing neutrino DIS (NuTeV) [9] measurements and  $Z \rightarrow \overline{b}b$  decay asymmetry measurement (Z-pole) [3], along with expected uncertainty of the approved JLAB  $Q_{\text{weak}}$  [11] and the running SLAC Møller (E158) [12] experiments.



facility	process	$< Q^2 >$	$C_{iq}$	result	SM value
		$(\text{GeV/c})^2$	combination		
SLAC	$e^-$ D DIS	1.39	$2C_{1u}-C_{1d}$	$-0.90\pm0.17$	-0.7185
SLAC	$e^-$ D DIS	1.39	$2C_{2u}-C_{2d}$	$+0.62\pm0.81$	-0.0983
CERN	$\mu^{\pm}$ C DIS	34	$0.66(2C_{2u}-C_{2d})$	$+1.80\pm0.83$	+1.4351
			$+ C_{3u} - C_{3d}$		
CERN	$\mu^{\pm}$ C DIS	66	$0.81(2C_{2u}-C_{2d})$	$+1.53\pm0.45$	+1.4204
			$+ 2C_{3u} - C_{3d}$		
Mainz	$e^-$ Be QE	0.20	$2.68C_{1u} - 0.64C_{1d}$	$-0.94\pm0.21$	-0.8544
			$+2.16C_{2u}-2.00C_{2d}$		
Bates	$e^-$ C elastic	0.0225	$C_{1u} + C_{1d}$	$0.138 \pm 0.034$	+0.1528
Bates	$e^-$ D QE	0.1	$C_{2u}-C_{2d}$	$0.015\pm0.042$	-0.0624
JLAB	$e^-p$ elastic	0.03	$2C_{1u} + C_{1d}$	approved	+0.0357
	<sup>133</sup> Cs APV	0	$-376C_{1u} - 422C_{1d}$	$-72.69\pm0.48$	-73.16
	<sup>205</sup> Tl APV	0	$-572C_{1u}-658C_{1d}$	$-116.6\pm3.7$	-116.8

Table 1: Existing data on P or C violating coefficients  $C_{iq}$  [13]. The errors are combined (in quadrature) statistical, systematic and theoretical uncertainties.

unique because it can provide precise data on  $2C_{2u} - C_{2d}$  which are not accessible through other processes. We expect to improve the uncertainty on  $2C_{2u} - C_{2d}$  by an order of magnitude.

Figure 2: The effective couplings  $C_{1u}$ ,  $C_{1d}$  (left),  $C_{2u}$  and  $C_{2d}$  (right). The future Qweak experiment (purple band), combined with the APV-Cs result (red band), will provide the most precise data and the best Stardard Model test on  $C_{1u}$  and  $C_{1d}$ . Assuming the SM prediction of  $2C_{1u} - C_{1d}$ , the value of  $2C_{2u} - C_{2d}$  can be determined from the proposed measurement to  $\Delta(2C_{2u} - C_{2d}) = 0.026$  (red band) which is  $\approx 10$  times better than existing world data (green band) [15].



### 2.3 Parity Violating Deep Inelastic Scattering (DIS-parity)

Historically, the observation of parity violation asymmetry in DIS played a key role in establishing the validity of the Standard Model. In the 1970's, PV DIS at SLAC confirmed the SM prediction for the structure of weak neutral current interactions [14]. These results were consistent with a value for  $\sin^2 \theta_W \approx 1/4$ , implying a tiny V(electron)×A(quark) neutral current interaction. Subsequent PV measurements performed at both very low energy scales (APV) as well as at the Z-pole have been remarkably consistent with the results of this early DIS-parity measurement.

We now briefly review the principle of the PV mechanism for e - N DIS. Detailed formalism for  $\vec{e} - {}^{2}$ H DIS-parity will be given in the next section.

We consider electron scattering on a fixed nuclear target. We denote by m the electron mass,  $k = (E, \vec{k})$  and  $k' = (E', \vec{k'})$  the initial and final electron four-momenta; the target has a mass  $M_T$  and its initial four-momentum is  $P = (E_t, \vec{P})$ ; the final state of the target is not detected. For a fixed target, one has  $P = (M_T, \vec{0})$  in the laboratory frame. Electrons can scatter off nuclear target by exchanging either a virtual photon  $(\gamma^*)$  or a virtual  $Z^0$ , as shown in Fig. 3. Until 1977, electrons had been used solely as an electromagnetic probe of the nucleon because the amplitude of weak neutral-current scattering at low energy is small. A number of facilities (JLAB, SLAC, MIT-Bates, Mainz) now can provide luminosity high enough to make feasible studies of the nucleon via its weak neutral current coupling. The weak neutral current can be accessed by measuring a parity-violating asymmetry that is proportional to the interference term between weak and electromagnetic scattering amplitudes.

Figure 3: Tree-level Feynman diagrams for electron scattering.



The scattering amplitude for the process is a product of currents for the electron and the hadron, sandwiched around the photon and the  $Z^0$  propagator  $\mathcal{M}_{\gamma}$  and  $\mathcal{M}_Z^l$ :

$$\mathcal{M}_{\gamma} = j_{\mu} \left(\frac{1}{q^2}\right) J^{\mu} ; \qquad \mathcal{M}_Z = j_{\mu} \left(\frac{1}{M_Z^2}\right) J^{\mu} . \tag{1}$$

We consider a longitudinally polarized electron beam. Because the electromagnetic interaction conserves parity, we do not need to separate right- and left-handed amplitudes. For the weak amplitude, we can write  $\mathcal{M}_Z^r$  and  $\mathcal{M}_Z^l$  for the incident right- and left-handed electrons, respectively. The cross sections for scattering right- and left-handed electrons off an unpolarized target are proportional to the square of the total amplitudes:

$$\sigma^r \propto (\mathcal{M}_\gamma + \mathcal{M}_Z^r)^2, \qquad \sigma^l \propto (\mathcal{M}_\gamma + \mathcal{M}_Z^l)^2.$$
 (2)

The parity-violating asymmetry can be written as

$$A_{LR} \equiv \frac{\sigma^r - \sigma^l}{\sigma^r + \sigma^l} = \frac{(\mathcal{M}_{\gamma} + \mathcal{M}_Z^r)^2 - (\mathcal{M}_{\gamma} + \mathcal{M}_Z^l)^2}{(\mathcal{M}_{\gamma} + \mathcal{M}_Z^r)^2 + (\mathcal{M}_{\gamma} + \mathcal{M}_Z^l)^2} \approx \frac{\mathcal{M}_Z^r - \mathcal{M}_Z^l}{\mathcal{M}_{\gamma}}.$$
 (3)

Measuring the parity-violating asymmetry allows one to access the weak neutral current in a ratio of amplitudes rather than the square of this ratio, greatly enhancing its relative contribution. We can make an estimation of the asymmetry from the ratio of the propagators:

$$A_{LR} \approx \frac{Q^2}{M_Z^2} \approx 120 \text{ ppm} \text{ at } Q^2 = 1 (\text{GeV/c})^2$$
 (4)

using  $M_Z = 91.2$  GeV [15].

# **2.4** Formalism for $\vec{e} - {}^2$ H Parity Violating DIS

The parity violating asymmetry for longitudinally polarized electrons scattering off an unpolarized deuteron target is given by [16, 17]

$$A_{d} \equiv \frac{\sigma^{r} - \sigma^{l}}{\sigma^{r} + \sigma^{l}}$$
  
=  $(\frac{3G_{F}Q^{2}}{\pi\alpha2\sqrt{2}})\frac{2C_{1u}[1 + R_{c}(x)] - C_{1d}[1 + R_{s}(x)] + Y(2C_{2u} - C_{2d})R_{v}(x)}{5 + R_{s}(x) + 4R_{c}(x)}$  (5)

where  $C_{1,2u(d)}$  are products of weak charges given approximately by

$$C_{1u} = g_A^e g_V^u = -\frac{1}{2} + \frac{4}{3} \sin^2(\theta_W)$$
 (6)

$$C_{1d} = g_A^e g_V^d = \frac{1}{2} - \frac{2}{3} \sin^2(\theta_W)$$
(7)

$$C_{2u} = g_V^e g_A^u = -\frac{1}{2} + 2\sin^2(\theta_W)$$
(8)

$$C_{2d} = g_V^e g_A^d = \frac{1}{2} - 2\sin^2(\theta_W)$$
(9)

and

$$Y = \frac{1 - (1 - y)^2}{1 + (1 - y)^2 - y^2 R / (1 + R)}$$
(10)

with  $y = \nu/E$  and  $\nu = E - E'$  is the energy loss of the incident electron. In Eq. (6)-(9),  $C_{1u(d)}$ represents the axial Z-electron coupling  $(g_A^e)$  times the vector Z-u(d) quark coupling  $(g_V^{u(d)})$ , while the  $C_{2u(d)}$  are the vector Z-electron coupling  $(g_V^e)$  times the axial Z-u(d) quark coupling  $(g_A^{u(d)})$ . Each of the  $C_{1(2)q}$  terms might be sensitive to physics beyond the SM in different ways. The ratio R is defined as  $R \equiv \sigma_L/\sigma_T$ . The ratios  $R_c$ ,  $R_s$  and  $R_v$  are given by the quark

The ratio R is defined as  $R \equiv \sigma_L/\sigma_T$ . The ratios  $R_c$ ,  $R_s$  and  $R_v$  are given by the quark distribution functions:

$$R_{c}(x) \equiv \frac{2(c(x) + \bar{c}(x))}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)}$$

$$R_{s}(x) \equiv \frac{2(s(x) + \bar{s}(x))}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)}$$
  
and  $R_{v}(x) \equiv \frac{u_{V}(x) + d_{V}(x)}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)}$  (11)

with  $u_V(x)$  and  $d_V(x)$  the valence quark distributions,  $u(x) = u_V(x) + u_{sea}(x)$ ,  $d(x) = d_V(x) + d_{sea}(x)$ , c(x),  $\bar{c}(x)$ , s(x) and  $\bar{s}(x)$  are the sea quark distributions.

Applying the Fermi weak interaction coupling constant  $G_F = 1.166 \times 10^{-5} (\text{GeV/c})^{-2}$  and Eq. (6)-(9), (10), in addition  $R_c \approx 0$ ,  $R_s \approx 0$  and  $R_v \approx 1$  at high x, one obtains for the  $\sin^2 \theta_W$ 

$$A_d = (109 \text{ ppm}) Q^2 \left[ \left( -\frac{3}{2} + \frac{10}{3} \sin^2 \theta_W \right) + Y R_v \left( -\frac{3}{2} + 6 \sin^2 \theta_W \right) \right]$$
(12)

The uncertainty in  $\sin^2 \theta_W$  due to the error in  $A_d$  is

$$\frac{\delta(\sin^2 \theta_W)}{\sin^2 \theta_W} = \frac{\delta A_d}{A_d} \left[ 1 - \frac{1}{4\sin^2 \theta_W} \left( \frac{1+Y}{\frac{5}{9}+Y} \right) \right]. \tag{13}$$

Therefore measurements at larger Y are more sensitive to  $\sin^2 \theta_W$ .

Similarly, one has for  $(2C_{2u} - C_{2d})$ 

$$\frac{\delta(2C_{2u} - C_{2d})}{(2C_{2u} - C_{2d})} = \frac{\delta A_d}{A_d} \left[ 1 - \frac{1}{Y} \frac{2C_{1u} - C_{1d}}{2C_{2u} - C_{2d}} \right].$$
(14)

One again need to have larger Y to minimize the uncertainty in  $(2C_{2u} - C_{2d})$ .

#### 2.5 Exploring New Physics Beyond the Standard Model

Although there exist a large amount of data confirming the electroweak sector of the SM at a level of a few 0.1%, there also exist strong conceptual reasons (e.g., the so-called high-energy desert from  $M_{weak} \approx 250$  GeV up to the Planck scale  $M_P \approx 2.4 \times 10^{18}$  GeV) to believe that the SM is only a piece of some larger framework [19]. On one hand, this framework should provide answers to the conceptual puzzles of the SM; on the other hand, it leaves the SU(3)<sub>C</sub> ×SU(2)<sub>L</sub>×U(1)<sub>Y</sub> symmetry of the SM intact at  $M_{weak} \approx 250$  GeV. Hence, there exists intense interest in the search for new physics. In this section we first describe how DIS-parity can explore new physics in a somewhat different way from Qweak, E158 and NuTeV. We then give a few possible models for new physics, namely the search for extra neutral gauge boson Z', leptoquark and supersymmetry.

#### 2.5.1 DIS-parity and New Physics

If free from nuclear and QCD higher-twist effects, the DIS-parity measurement can help to explore possible new physics beyond the Standard Model. DIS-parity involves exchange of  $Z^0$  between electrons and quarks and thus is sensitive to physics that might not be seen in purely leptonic observables, such as the precision  $A_{LR}$  at SLC and  $A_{FB}^l$  at LEP. There is currently a

 $3\sigma$  disagreement [3] between purely leptonic and semi-leptonic observables at the Z-pole from SLC and LEP. The recent NuTeV [9] result at low  $Q^2$  involves a particular set of semi-leptonic charged and neutral current reactions is  $3\sigma$  from the SM prediction. A precision measurement of DIS-parity will add the first clean semi-leptonic observable to the world data below the Z-pole and will provide essential clues as to the source of these discrepancies.

A precision DIS-parity measurement would also examine the Z coupling to electrons and quarks at low  $Q^2$  far below the Z-pole. This is important because DIS-parity is sensitive to particular combination of couplings and has completely different sensitivities to new physics than other semi-leptonic processes (e.g., Qweak). For example, there might be large axial quark couplings which cause the  $3\sigma$  effect in NuTeV result but cannot be seen in  $C_{1q}$ . Next, there is at least one possible Z' boson accessible only through  $C_{2q}$  but not  $C_{1q}$ . DIS-parity will significantly strengthen the constraints on possible new physics.

### 2.5.2 Z' Searches

Neutral gauge structures beyond the photon and the Z boson have long been considered as one of the best motivated extensions of the SM [20]. They are predicted in most Grand Unified Theories (GUT) and appear in superstring theories. Such a gauge boson is called a Z'. Although there may be a multitude of such states at or just below the Planck scale, there exist many models in which the Z' is located at or near the weak scale. Only the latter, the light Z' is of interest here.

Since a Z' which couples to  $Z^0$  will strongly affect the observables around the Z-pole which were measured to an remarkable precision, we only consider Z' which does not mix with  $Z^0$ . Direct searches at FNAL up to 600 GeV have ruled out any Z' with  $M_{Z'} < M_Z$  but a heavier Z' (most likely above ~ 600 GeV) is possible. Such Z' can arise in  $E_6$  [21], a rank-6 group and a possible candidate for the GUT. This  $E_6$  breaks down at the Planck scale and becomes the  $SU(3)_C \times SU(2)_L \times U(1)_Y$  symmetry of the familiar SM. The breaking of  $E_6$  to the SM will lead to extra Z's and it is possible that at least one of these is light enough to be observed. In  $E_6$  the Z' can be parameterized as

$$Z' = \cos \phi Z_{\psi} + \sin \phi Z_{\chi} . \tag{15}$$

The  $Z_{\psi}$  and  $Z_{\chi}$  arise from the breakdown  $E_6 \to SO(10) \times U(1)_{\psi}$  and  $SO(10) \to SU(5) \times U(1)_{\chi}$ . The effect of Z' in  $E_6$  can be observed in neutrino DIS, PV e-N scattering, PV Møller scattering and APV. It might explain partly the descrepancies between the NuTeV result and the SM predictions. Conversely, the results from  $\nu$ -DIS, DIS-parity and APV will set constraints on the properties of Z'. In particular, the  $Z_{\psi}$  can have only axial vector couplings to fermions (leptons and quarks) and may only be seen via  $C_2$  couplings in DIS-parity.

#### 2.5.3 Leptoquark (LQ) and Supersymmetry (SUSY)

Leptoquarks are vector or scalar particles carrying both lepton and baryon numbers. For DISparity, the presense of LQ will change the observed asymmetry by an amount proportional to  $\frac{\lambda^2}{4M_{LQ}^2}$  where  $M_{LQ}$  is the mass of LQ and  $\lambda$  is its coupling to electron and quarks. Hence a deviation of the measured  $\sin^2 \theta_W$  or  $2C_{2u} - C_{2d}$  from its SM prediction can be interpreted as caused by LQ effects and can set constraint on the LQ properties  $\lambda$  and  $M_{LQ}$ . Supersymmetry (SUSY) is a symmetry between bosons and fermions [25]. It requires a Lagrangian which is invariant under transformations which mix the fermionic and bosonic degrees of freedom. In any supersymmetric scheme, all particles fall into supermultiplets with at least one boson and one fermion having the same gauge quantum numbers. Hence, to each fermion and to each vector boson of a gauge theory there will correspond superpartners. If the symmetry were unbroken, the pairs of bosons and fermions would have the same mass – in contradiction with experimental results. Thus if they exist, one must assume heavy masses (above TeV range) because no supersymmetric particles has ever been detected.

Although no supersymmetric particle has yet been discovered, there exists strong motivation for believing that SUSY is a component of the "new" SM. For example, the existense of lowenergy SUSY is a prediction of many string theories; it offers a solution to the hierarchy problem. providing a mechanism for maintaining the stability of the electroweak scale against large radiative corrections; it results in coupling unification close to the Planck scale; and more excitingly it can be extended to gravity (the extended version including gravity is called supergravity). In light of such arguments, it is clearly of interest to determine what insight about SUSY the new PV DIS measurements might provide.

The effect of SUSY on the coupling coefficients  $C_{1,2u(d)}$  in the one-loop correction is different from that in the Standard Model. Therefore the asymmetry  $A_d$  is sensitive to possible SUSY effect in the PV scattering.

# **3** Experimental Setup

In this section we describe the experimental setup for the proposed measurement in Hall A.

### 3.1 Overview

The floor plan for Hall A is shown in Figure 4. We use  $140 - \mu$ A polarized beam and a 15cm liquid deuterium target. The scattered electrons are detected by the two standard Hall A High Resolution Spectrometers (HRS). We will describe these instrumentation in the next a few sections. A fast counting system will be added to the standard Hall A Data Acquisition (DAQ) to measure electron and pion events at rate as high as 1 MHz. A Luminosity Monitor (Lumi) is located downstream on the beam-line to monitor the helicity dependent target boiling effect and all possible false asymmetries to a  $10^{-8}$  level.





### 3.2 Beam Line

We propose to use 6.0-GeV polarized beam with a ~ 80% polarization and  $140 - \mu A$  beam current. The beam energy can be measured to a  $\Delta E/E = 2 \times 10^{-4}$  level using either ARC or eP devices [28]. We need 1% precision in the beam polarization measurement in order to achieve an acceptable systematic error on the final results. In Hall A, we plan to use a upgraded Compton polarimeter (see next paragraph) and additional information from Møller polarimeter (with possible upgrade).

The current systematic uncertainty of the Compton polarimeter is about 1.1% for 4.7-GeV beam. With 40-minutes run at 40  $\mu$ A the statistical error is 0.8%, giving 1.4% total uncertainty. The systematic uncertainty for a 6.0-GeV beam will be smaller (1.1%) and can be further reduced to 0.8% by using 300 –  $\mu$ m instead of 600 –  $\mu$ m micro-strips in the electron detector [26]. With one hour measurement one can achieve 0.6% statistical error. Therefore the total uncertainty for 6-GeV beam will be 1.0% after upgrading the microstrips. The cost estimate for this upgrade is

 $\approx$  \$ 30 K and  $\approx$  5 calendar days facility development time (beam can be on during the last 2 days).

Currently the Møller polarimeter in Hall A can provide 3% precision. Upgrades have been proposed for the Møller to reach a precision of  $\leq 1\%$  [27]. The Pb-parity proposal [27] has given a cost estimate for the Møller upgrade. We will use Møller as a cross check for the Compton polarimeter.

To reduce the heat impact on the target, the beam is circularly rastered such that the beam spot size at the target is  $\sim 4$  mm in diameter.

## 3.3 Parity DAQ (Hall A)

The parity DAQ in Hall A [31] and the beam helicity feedback system has been successfully used to control the beam helicity-dependent asymmetry for the Hall A parity experiments in the past. The asymmetry measured by the parity DAQ is sent to the polarized electron source group where the Pockel cell voltage is adjusted accordingly to minimize the beam intensity asymmetry. The beam helicity asymmetry can be controlled to  $10^{-7}$  level. The false asymmetry caused by the beam helicity asymmetry should be much smaller than this number (since it is a second order effect). This is sufficient for the proposed measurement.

### 3.4 The Liquid Deuterium Target

We will use the Hall A standard 15-cm cryogenic liquid deuterium  $(LD_2)$  target at its highest cooling power. The target density is 0.167 g/cm<sup>2</sup>. The end-caps of the cell are made of 3 mil Be. The end-cap contamination will be measured using two empty targets with different end-cap thicknesses.

### 3.4.1 Boiling Effect

The target boiling effect implies two meanings. The first one is the "local boiling effect", which is the real phase change of the liquid target. We require zero local boiling for the proposed measurement. The second meaning is usually used for parity experiments. In this case, "target boiling" is a terminology for the change in target density due to heating of the target, for example, change in density due to deviation in beam parameters, mostly spot size, and pulse-to-pulse target density fluctuation. The latter may cause a false asymmetry and will affect the measurement. We will discuss it in the next subsection. The first one will generate a noise ("boiling noise") in the signal which is equivalent to an additional statistical fluctuation.

The rate for the proposed measurement is around 86 KHz (see Section 4.2). The statistical uncertainty per beam pulse pair (33 ms H+ and 33 ms H-, hence total is 66 ms) is on the order of  $\pm 0.01$ . The noise from target boiling effect should be less than 3% of the statistical uncertainty, i.e., 300 ppm per pulse. Compared to the noise limit for the HAPPEX I (200 ppm, in 1998) and the planned HAPPEX II (7 ppm) experiments, this can be easily achieved, as will be shown in Section 3.5.

### 3.4.2 Helicity Dependent Density Fluctuation

The measured parity-violating asymmetry of  $\vec{e}^{-2}$ H scattering is expected to be ~ 100 ppm. The helicity dependent density fluctuation should be controlled under 0.05% of this value, i.e., 0.05 ppm. The Luminosity Monitor in Hall A will monitor this quantity. Taking advantage of the high rate at small angle, it is possible to monitor the false asymmetry to a 10 ppb level within each beam helicity pulse, and hence guarantee the control of the density fluctuation to an acceptable level. The luminosity monitor will be described in the next section. The target cooling system and the boiling effects will be tested during commissioning runs.

### 3.5 Luminosity Monitor

Luminosity Monitors (Lumi) were successfully used for the SAMPLE experiment at MIT-BATES, the A4 experiment at MAINZ [38], the E158 experiment at SLAC [32] and the G0 experiment in Hall C. Currently, a luminosity monitor built by the MIT group has been installed in Hall A [33] for the 2003 running period of HAPPEX II [35] and the Pb parity experiment [27]. The main feature of Lumi is to measure essentially zero asymmetry during normal running of the experiment, to a very high precision. The main effect that Lumi is supposed to monitor is the target boiling effect. Lumi is also used to monitor all other general false asymmetries.

The Hall A Lumi consists of 8 pieces of quartz at  $0.5^{\circ}$ . Each piece has  $2 \times 5 \text{ cm}^2$  effective area at 7 m from target. The rate for 6-GeV beam is  $> 10^{11}$  Hz per piece [34]. With this high rate, the false asymmetry and the target boiling effect can be monitored to a level of 20 ppm per beam pulse with one piece of quartz. Hence the requirement that the target boiling should be monitored below 180 ppm per pulse can be easily achieved.

Most of the events in Lumi are elastic. The asymmetry is in general proportional to  $Q^2$ , hence the physics asymmetry detected by Lumi is very small, of the order of < 10 ppb. Therefore the false asymmetry can be monitored to  $\sim 10$  ppb. This will cause a << 0.1% systematic uncertainty to the measured asymmetry which is sufficient for the proposed measurement.

#### 3.6 Spectrometers

In Table 2 we list the major characteristics of the High Resolution Spectrometer (HRS) in Hall A.

Spectrometer	HRS (single)
Momentum range $p$	$0.3-4.0~{ m GeV/c}$
Scattering angle $\theta$	$12.5^\circ - 165^\circ$ (left)
	$12.5^{\circ} - 135^{\circ}$ (right)
Momentum Acceptance $\Delta p/p$	$\pm 4.5\%$
Solid Angle $\Delta\Omega$	$5.4 \mathrm{msr}$
(extended target, no collimator)	
Transverse Length Acceptance	$\pm 5 \text{ cm}$

Table 2: Hall A HRS general characteristics.

The central momentum of the HRS can be calculated from the dipole field magnitude and the HRS constant to  $5 \times 10^{-4}$  level [29]. The HRS central angle can be determined to  $\pm 0.2$  mrad using H(e, e'p) elastic scattering data, with careful analysis[30].

We now discuss the detector PID efficiency. For the HRS pair, a  $CO_2$  Čerenkov detector and a double-layered lead glass shower detector are used for electron identification on each spectrometer. The PID efficiency of these detectors is usually given as the pion rejection factor at a certain electron detection efficiency (e.g., 99%), which gives the ratio of number of pions that are rejected by the detector to the number of pions that are mis-identified as electrons by the detector. Based on data from the past experiments, the combined pion rejection factor of the detectors is better than  $10^4$  [36]. At high rate, a practical estimate of the PID efficiency should also take into account the effect of event pileup, detector readout deadtime and electronic noise. We simulate these effects and find that the pion rejection with the fast counting DAQ should be better than  $10^3$ .

# 3.7 Fast Counting DAQ

Our preliminary concept for the data acquisition is to use a fast counting method which makes a rapid (10 nsec) identification of electrons, pions, and associated pileups, and counts these in scalers. Since the rate is very high, approaching 1 MHz, we cannot use the standard Hall A DAQ. At the same time, because of the need to separate the pion background we must use a counting method. The counting method has been used successfully at 100 MHz by the Mainz A4 parity violation experiment [38][39]. Also relevant is the experience of the G0 collaboration in deploying a counting method [40]. Normally an integrating DAQ, in which one integrates the detected flux over the helicity pulse, is preferred for parity violation experiments because it avoids dangerous deadtime corrections. However, we believe we can control this correction as further discussed below.

The counting electronics will process signals from the existing Hall A detector set. We are considering a custom electronic design that could possibly be engineered by the JLab electronics group at a cost of approximately \$50 K for the experiment, see Figure 5. The detector signals that we will use include the ten signals from the gas Čerenkov detector and the approximately 180 signals from two layers of lead glass detectors. In addition, the 24 signals from scintillators might be useful for crude directional information. The Čerenkov signals and the two lead glass layers are summed in separate analog summing circuits and passed through discriminators resulting in logic pulses. Logical combinations of these pulses identify pions, electrons, and pileup effects. In particular, electrons are identified as events which pass above the Čerenkov cut and which deposit a sufficient total energy in the lead glass, while pions have leave no signal in the Cerenkov and small average signals in the lead glass. By using different cuts one can have different confidence level for the purity of the selected particles. The efficiency of the cuts and the cross contamination of the particle samples can be checked by comparing to the standard DAQ results at lower beam current. Both the standard DAQ modules and the new custom counting DAO modules can be read simultaneously and compared. From experience in Hall A, these efficiencies and contaminations are already known under running conditions similar to the proposed measurement; the discriminating power for electrons and pions are given in Appendix A in details.

Pileup of two particles will occur in approximately 6% of events at 100 MHz if we make no



Figure 5: PID Logic diagram for fast counting DAQ.

changes to the existing photo-tubes which have a 60 nsec resolving time. Although these effects cannot be directly studied with the standard DAQ at high rates, we can indirectly study them by an analysis in which the data of independent events are added. The pileup effects include: 1)  $e^ -e^-$ ; 2)  $e^- - \pi$ ; 3)  $\pi - \pi$ . Since electrons must only pass a threshold, electrons accompanied by a secondary particle will still be counted as electrons; however, a correction must be applied for 2 electron pileup. These can be measured using a higher threshold cut on the lead glass and counting the events that pass this higher threshold. A simulation of the pileup effects is given in Appendix A. The pileups involving pions will result in a (1.5-2.0)% loss of the pion count rate, since they tend to be moved away from the one-pion cut window. A fraction (0.5 - 1)% of two pion events will be counted erroneously as electrons. These effects from pions can be corrected with sufficient accuracy and the uncertainty is practically negligible (since the  $\pi/e$  ratio is always less than unity and the pion asymmetry will be measured precisely).

We believe we can maintain the deadtime at the 10 nsec level, resulting in an approximately 1% deadtime correction. The asymmetry corrected for a deadtime probability  $\delta$  is  $A = A_o(1-\delta)$  where  $A_o$  is the observed asymmetry. Our goal is to measure  $\delta$  to at least  $\pm 0.3\%$ . To ensure reliability it is important to measure  $\delta$  with at least two independent methods. Our preliminary ideas to measure  $\delta$  are as follows. A first method is to pulse the detector channels with a light sources whose amplitude and pulse shape is similar to those of real particles, and count how many of these signals are subsequently identified by the electronics. A second method is to introduce a deliberate programmable deadtime into the front end, most likely at the discriminators. This deadtime should be sufficiently large that it dominates the deadtime of the signal pathway thus making the deadtime of each channel understood and predictable. The path of each detector signal would be reproduced in identical copies with different deadtimes (e.g. 10, 20, and 40 nsec). Each signal passes through the three paths, and one obtains the correction by extrapolating

to zero deadtime. Although the three paths are identical circuits, we would reduce possible biases by permuting periodically the set of three programmed deadtimes. Combination of these two methods can provide a  $\pm 0.3\%$  deadtime measurement. The cost estimate is included in the \$50 K previously mentioned.

### 3.8 Data Analysis

### 3.8.1 Extracting Asymmetry A<sub>d</sub> from Data

The parity violating asymmetry of  $\vec{e} - {}^{2}H$  scattering is extracted from the measured raw asymmetry as

$$A_d = \frac{A_{raw}}{P_{beam}} + \Delta A_{EM}^{RC} + \Delta A_{HT}$$
(16)

where  $P_{beam} \sim (80\pm0.8)\%$  is the beam polarization,  $\Delta A_{EM}^{RC}$  is the electromagnetic radiative correction and  $\Delta A_{HT}$  is the higher twist correction. For the higher twist corrections we use the two available calculations given in Section 4.1.11.

# **3.8.2** Extracting $\sin^2 \theta_W$ from $A_d$

From Eq. (5), one can extract  $\sin^2 \theta_W$  from asymmetry  $A_d$  as

$$\sin^2 \theta_W = a_1 A_d + b_1 \tag{17}$$

where  $a_1$  and  $b_1$ , if the electroweak radiative corrections are not included, are given by

$$a_1 = \frac{1}{\mathcal{K}Q^2} \frac{5 + R_s + 4R_c}{\frac{10}{3} + \frac{8}{3}R_c + \frac{2}{3}R_s + 6YR_v},$$
(18)

$$b_1 = \frac{\frac{3}{2} + R_c + \frac{R_s}{2} + \frac{3}{2}YR_v}{\frac{10}{3} + \frac{8}{3}R_c + \frac{2}{3}R_s + 6YR_v}$$
(19)

with  $\mathcal{K} \equiv \frac{3G_F}{\pi \alpha^2 \sqrt{2}}$  and  $R_c$ ,  $R_s$  and  $R_v$  defined by Eq. (11). We use the MRST2002 [45] and CTEQ6M [46] PDF fits to evaluate  $R_c$ ,  $R_s$  and  $R_v$  and their uncertainties.

With electroweak radiative corrections (see Section 4.1.9), Eq. (18) and (19) become

$$a_{1} = \frac{1}{\mathcal{K}Q^{2}} \frac{5 + R_{s} + 4R_{c}}{\frac{8}{3}\kappa'\rho'(1 + R_{c}) + \frac{2}{3}\kappa'\rho'(1 + R_{s}) + 6\kappa\rho YR_{v}},$$

$$b_{1} = \frac{(\rho' - 2\lambda_{1u})(1 + R_{c}) + (\frac{1}{2}\rho' + \lambda_{1d})(1 + R_{s}) + YR_{v}(\frac{3}{2}\rho - 2\lambda_{2u} + \lambda_{1d})}{\frac{8}{3}\kappa'\rho'(1 + R_{c}) + \frac{2}{3}\kappa'\rho'(1 + R_{s}) + 6\kappa\rho YR_{v}},$$
(20)

where  $\rho$ ,  $\rho'$ ,  $\kappa$ ,  $\kappa'$  and  $\lambda_{1(2)q}$  are given in Section 4.1.9.

# **3.8.3** Extracting $2C_{2u} - C_{2d}$ from $A_d$

From Eq. (5), one can extract  $2C_{2u} - C_{2d}$  from asymmetry  $A_d$  as

$$2C_{2u} - C_{2d} = a_2 A_d + b_2 \tag{22}$$

where  $a_2$  and  $b_2$ , if the electroweak radiative corrections are not included, are given by

$$a_2 = \frac{1}{\mathcal{K}Q^2} \frac{5 + R_s + 4R_c}{YR_v},\tag{23}$$

$$b_2 = -\frac{2C_{1u}(1+R_c) - C_{1d}(1+R_s)}{YR_v}$$
(24)

with  $\mathcal{K} \equiv \frac{3G_F}{\pi \alpha^2 \sqrt{2}}$  and  $R_c$ ,  $R_s$  and  $R_v$  defined by Eq. (11). We used MRST2002 [45] and CTEQ6M [46] PDF fits to evaluate  $R_c$ ,  $R_s$  and  $R_v$  and their uncertainties. For  $C_{1q}$  we use the Standard Model values Eq. (6-7), assuming  $\sin^2 \theta_W = 0.235$  at  $Q^2 = 2$  (GeV/c)<sup>2</sup>.

With electroweak radiative corrections, Eq. (31-32) (see Section 4.1.9) need to be used for  $C_{1q}$ 's in Eq. (24).

# 4 Expected Uncertainties and Rate Estimation

In this section we first give estimations for the systematic uncertainties. The higher twist effects are estimated using available calculations. Then we calculate the statistical uncertainty and in the end give the beam time request for the proposed measurements.

# 4.1 Systematic Error Estimation

### 4.1.1 Experimental Systematics

We estimate the uncertainty in the beam polarization to be 1%. Other error sources include those from the beam energy  $\Delta E/E = 2 \times 10^{-4}$  [28] and the spectrometer central momentum  $\Delta E'/E' = 5 \times 10^{-4}$  [29]. The scattering angle  $\theta$  can be determined to 0.2 mrad from HRS survey and careful analysis of <sup>1</sup>H(*e*, *e'p*) scattering data using the procedure described in [30]. The four momentum transfer  $Q^2$  for each kinematic setting will be determined using low beam current and regular counting mode DAQ. The uncertainty in  $Q^2$  is thus given by the uncertainties in *E*, *E'* and  $\theta$ . It contributes uncertainties of  $\delta \sin^2 \theta_W / \sin^2 \theta_W < 0.2\%$  and  $\delta(2C_{2u} - C_{2d}) = 0.0018$ to the extracted results.

# 4.1.2 Pion Background

### **Pion rate**

The rate of pion photo-production is estimated by the Wiser fit [51]. Based on the DIS data taken in August 2000 (proton target) and June-July 2001 (<sup>3</sup>He target), the Wiser fit in general, overestimates the pion cross section by at least a factor of two. We use the Wiser fit to give a conservative estimate for the pion rate. The electron rate is calculated using world fits of R [53] and the deuteron structure function  $F_2^d$  [41]. The pion to electron ratio is less than 1 for the proposed kinematics.

# **PID efficiencies for Hall A detectors**

A CO<sub>2</sub> Čerenkov counter and a double-layered lead glass counter will be used for particle identification (PID). The PID efficiencies for the Hall A detectors are well understood. With careful detector calibration and off-line analysis, the combined pion rejection factor was found to be better than  $10^4$  for both spectrometers [36] in the regular counting DAQ mode. With the fast counting mode, signals from the Čerenkov detector, lead glass counters and scintillators are sent to the fast counting system which accumulates the electron and pion events separately. See Section 3.7 for the design of fast counting DAQ and Appendix A for a simulation of the effects of event pileup on PID efficiencies. Test runs are necessary to check the PID efficiencies with fast counting DAQ. The threshold for the PID units of the DAQ system will be set before the production running based on the test-run results. We expect the combined pion rejection factor with fast counting DAQ to be  $\approx 10^3$ .

### **Pion asymmetry**

The asymmetry of pion production in the DIS region is expected to be small. We first discuss

the possible effect from single spin asymmetry. The single beam-spin azimuthal asymmetry (beam SSA) reported recently by the HERMES collaboration [54] is consistent with zero, but with large error bars. The data from JLAB Hall B [55] show a  $A_{LU}^{\pi^+ \sin \phi} \sim 5\%$  azimuthal beam SSA for  $\pi^+$  electro-production. However, since we are doing an inclusive measurement where the out-of-plane angle  $\phi$  is being integrated, we do not expect any background from SSA [56].

The only possible background to the proposed measurement is coming from weak interactions between partons. Compared to the measured asymmetry, which comes from the interference term between electromagnetic and weak interactions, this background is suppressed by a factor of 100 - 1000. Since the measured asymmetry is about 100 ppm, the maximum background one can have is less than  $10^{-6}$ , or 1 ppm.

Experimentally, in the original SLAC experiment [14] the pion asymmetry was found to be smaller than the electron asymmetry.

Overall, we expect that the pion asymmetry to be well below  $10^{-4}$ . The combined pion rejection factor is expected to be better than  $10^3$ . Hence the asymmetry from the pion background will be less than  $10^{-7}$ . Compared to the measured electron asymmetry ~ 100 ppm, this is a  $< 10^{-3}$  effect and is taken into account in the uncertainty analysis.

Furthermore, the pion asymmetry will be measured using the fast pion counters and the pion to electron ratio will be determined using regular counting mode DAQ. The required statistics to achieve  $\delta A_{\pi^-,cont} = 0.1 \delta A_{e^-}$  is

$$N_{\pi^{-}} = \frac{1}{(\delta A_{\pi^{-}})^2} = \frac{1}{\left(\frac{0.1}{\beta}\delta A_{\pi^{-}}\right)^2} = \frac{100\beta^2}{N_{e^{-}}}$$
(25)

where  $\beta = \frac{rate_{\pi^-}}{rate_{e^-}}\eta_{pi^-}$  with  $\eta_{pi^-} = 1/\eta_{pi^-, rej.} \approx 10^{-3}$  the pion contamination factor and  $\eta_{\pi^-, rej.}$  the pion rejection factor of the PID detectors. The beam time required to reach this statistics is

$$T_{\pi^{-}} = \frac{N_{\pi^{-}}}{rate_{\pi^{-},det}} = \frac{N_{\pi^{-}}}{\beta rate_{e^{-}}} \frac{rate_{\pi^{-}}}{rate_{\pi^{-},det}} = \frac{100\beta N_{e^{-}}}{rate_{e^{-}}} \frac{rate_{\pi^{-}}}{rate_{\pi^{-},det}}$$
$$= 100\beta T_{e^{-}} \frac{rate_{\pi^{-}}}{rate_{\pi^{-},det}} = 0.1 \frac{rate_{\pi^{-}}}{rate_{e^{-}}} \frac{rate_{\pi^{-}}}{rate_{\pi^{-},det}} T_{e^{-}}$$
(26)

To ensure the purity of the pion events, we will use tight PID cuts to select pions hence the efficiency of pion scalers is  $\frac{rate_{\pi^-,det}}{rate_{\pi^-}} \approx 50\%$ . The required beam time is about 20% of that for the electron runs. Since pions can be measured simultaneously to electron, we do not need extra beam time for  $\pi$  asymmetry measurement.

#### 4.1.3 Pair Production Background

Part of the background of the proposed measurement comes from the pair production  $\gamma \rightarrow e^+ + e^-$ , where  $\gamma$  is coming from the decay of the electro- and photo-produced pions. Usually the  $e^+e^-$  pairs are assumed to be symmetric and the asymmetry of the  $e^-$  of the pair production background is the same as the positron asymmetry, while the latter can be measured by reversing

the polarity of the spectrometers. To ensure that the measurements are not affected by this background, the positron asymmetry needs to be measured to  $\alpha \delta A_{e^+} = 0.1 \delta A_{e^-}$ , where  $\alpha$  is the fraction of the electrons contributed from the pair production to the total electron yield. The statistics required is therefore

$$N_{e^+} = \frac{1}{(\delta A_{e^+})^2} = \frac{1}{\left(\frac{0.1}{\alpha}\delta A_{e^+}\right)^2} = \frac{100\alpha^2}{N_{e^-}}$$
(27)

The beam time required to reach this statistics is

$$T_{e^+} = \frac{N_{e^+}}{rate_{e^+}} = \frac{N_{e^+}}{\alpha \ rate_{e^-}} = \frac{100\alpha N_{e^-}}{rate_{e^-}} = 100\alpha T_{e^-}$$
(28)

The estimated positron to electron ratio is  $\approx 0.05\%$ , (this is an overestimated value from the Wiser fit [51]). We will measure the real rate ratio using the regular counting DAQ and determine the precision we need for the positron asymmetry. Then we will reverse the HRS polarity to measure the positron asymmetry. The request beam time is less than 5% of the total running time.

We also need to check the effect of  $\pi^+$  background on the measurement of  $e^+$  asymmetry. We need  $\eta_{pi+}\frac{rate_{\pi^+}}{rate_{e^+}}\delta A_{\pi^+} = 0.1\delta A_{e^+}$ . We assume the pion contamination is the same for  $\pi^+$  and  $\pi^-$ , i.e.,  $\eta_{pi^+} \approx 10^{-3}$ ; the  $\pi^+$  rate and asymmetry are in the same order of magnitude as  $\pi^-$ , i.e.,  $A_{\pi^+}$  well below  $10^{-4}$  and  $\frac{rate_{\pi^+}}{rate_{e^-}} < 1$ , we need

$$T_{\pi^{+}} = \frac{N_{\pi^{+}}}{rate_{\pi^{+}}} = \frac{1}{(\delta A_{\pi^{+}})^{2}rate_{\pi^{-}}} = (\eta_{pi^{+}}\frac{rate_{\pi^{+}}}{rate_{e^{+}}})^{2}\frac{1}{(0.1\delta A_{e^{+}})^{2}rate_{\pi^{-}}}$$
$$= (\eta_{pi^{-}}\frac{rate_{\pi^{-}}}{rate_{e^{-}}}\frac{rate_{e^{-}}}{rate_{e^{+}}})^{2}\frac{\alpha^{2}}{(0.01\delta A_{e^{-}})^{2}rate_{\pi^{-}}} = (100\eta_{pi^{-}})^{2}\frac{rate_{\pi^{-}}}{rate_{e^{-}}}T_{e^{-}}$$
$$\approx 0.01T_{e^{-}} < T_{e^{+}}$$
(29)

So the  $\pi^+$  asymmetry should be measured simultaneously with the  $e^+$  asymmetry but we do not need extra beam time.

#### 4.1.4 Target End Cap Contamination

The target cell end caps are made of 7 mil aluminum with 3 mil Be in the centeral region where the beam goes through. Be has density 1.848 g/cm<sup>2</sup>, the ratio of yield from endcaps to that from LD<sub>2</sub> is estimated to be  $L_{Be}/L_{LD2} \times \rho_{Be}/\rho_{LD2} = 2.64\%$  for each end cap. The real ratio should be less than this value since end caps are on the falling edges of the HRS acceptance. This ratio can be measured quickly using an empty target with the same end caps as the LD<sub>2</sub> cell. Since Be has Z = 4, N = 5, the asymmetry of  $\vec{e} - Be$  scattering is not very different from  $A_d$  and can be measured using an empty target with thick Be end caps. To control the uncertainty in  $A_d$ due to end cap contamination, and assuming the end caps of empty cell is 100 times thicker than that of the LD<sub>2</sub> cell, we need 6% of total beam time to measure the asymmetry of end caps. The uncertainty in the extracted values are  $\delta \sin^2 \theta_W / \sin^2 \theta_W < 0.05\%$  and  $\delta (2C_{2u} - C_{2d}) < 0.002$ .

#### 4.1.5 Target Purity

The liquid deuterium usually used contains [44] 1889 ppm HD, < 100 ppm H<sub>2</sub>, 4.4 ppm N<sub>2</sub>, 0.7 ppm O<sub>2</sub>, 1.5 ppm CO (carbon monoxide), < 1 ppm methane and 0.9 ppm CO<sub>2</sub> (carbon dioxide). Compared to the statistical accuracy of the measurement ( $\approx 1.1\%$  in  $A_d$ ), the only non-negligible contamination to the measured asymmetry is from the proton in HD. Since the asymmetry of the proton is given by [17]

$$A_p = \left(\frac{3G_F Q^2}{\pi \alpha 2\sqrt{2}}\right) \frac{2C_{1u}u(x) - C_{1d}[d(x) + s(x)] + Y[2C_{2u}u_v(x) - C_{2d}d_v(x)]}{4u(x) + d(x) + s(x)}$$
(30)

which is of the same order as the asymmetry of the deuteron, the proton in HD contributes < 0.1% uncertainty to the measured asymmetry. For the extracted results it causes uncertainties of  $\delta \sin^2 \theta_W / \sin^2 \theta_W < 0.05\%$  and  $\delta (2C_{2u} - C_{2d}) < 0.002$ .

### 4.1.6 Target Density Fluctuation and Other False Asymmetries

The Luminosity Monitor can make sure that this part is less than 0.1 ppm, i.e., < 0.1% uncertainty in the measured asymmetry. It will cause uncertainties of  $\delta \sin^2 \theta_W / \sin^2 \theta_W < 0.05\%$  and  $\delta (2C_{2u} - C_{2d}) < 0.002$ .

#### 4.1.7 Parton Distribution Functions and Ratio R

The uncertainty in R is estimated using a world fit [53]. The uncertainty in  $\sin^2 \theta_W$  due to PDF is less than 0.01% and the uncertainty in  $(2C_{2u} - C_{2d})$  is  $\approx 0.0001$ .

We used the unpolarized parton distribution functions (PDF) from MRST2002 [45] and CTEQ6M [46] to calculate the quark distribution ratios  $R_c$ ,  $R_s$  and  $R_v$  and the asymmetry  $A_d$ . The uncertainties of the PDF fits are used to estimate the uncertainty in the extracted  $\sin^2 \theta_W$  and the larger value from the two PDF sets is selected. The uncertainty in  $\sin^2 \theta_W$  due to PDF is less than 0.1% and the uncertainty in  $(2C_{2u} - C_{2d})$  is  $\approx 0.0007$ .

#### 4.1.8 Electromagnetic (EM) Radiative Correction

Figure 3 describes the scattering process at tree level. In reality both the incident and the scattered electrons can emit photons. Consequently when we extract cross sections and asymmetries from the measured values there are electromagnetic radiative corrections to be made. The theory for the EM radiative correction is well developed [57]. The correction can be calculated and the uncertainty in the correction is mainly due to the uncertainty of the structure functions ( $F_2$  and R for an unpolarized target) that are used in the calculation. We have calculated the ratio of the radiated (observed) cross section and asymmetry to the un-radiated (Born) ones. The uncertainty in the asymmetry correction is about relative 0.4%.

#### 4.1.9 Electroweak Radiative Correction

The products of weak charges  $C_{1,2u(d)}$  given by Eq. (6-9) are valid only in the case with no electroweak radiative correction. With this correction they are given by

$$C_{1u} = \rho' [-\frac{1}{2} + \frac{4}{3}\kappa' \sin^2(\theta_W)] + \lambda_{1u}$$
(31)

$$C_{1d} = \rho' [\frac{1}{2} - \frac{2}{3}\kappa' \sin^2(\theta_W)] + \lambda_{1d}$$
(32)

$$C_{2u} = \rho[-\frac{1}{2} + 2\kappa \sin^2(\theta_W)] + \lambda_{2u}$$
(33)

$$C_{2d} = \rho[\frac{1}{2} - 2\kappa \sin^2(\theta_W)] + \lambda_{1d}$$
(34)

The electroweak radiative correction is well determined in the Standard Model, with a weak dependence on the Higgs mass, assuming the minimal  $SU(2) \times U(1)$  model with one Higgs doublet. SM electroweak radiative corrections to  $C_{1,2u(d)}$  have been calculated [58] and are relatively small. The corrections modify the  $\rho$ ,  $\kappa$ , and  $\lambda$  parameters from their tree level values  $\rho - \rho' = \kappa = \kappa' = 1$  and  $\lambda_{1u} = \lambda_{1d} = \lambda_{2u} = \lambda_{2d} = 0$ . A recent evaluation [59] gives  $\rho' = 0.9878$ ,  $\kappa' = 1.0027$ ,  $\rho = 1.0007$ ,  $\kappa = 1.0300$ ,  $\lambda_{1d} = -2\lambda_{1u} = 3.7 \times 10^{-5}$ ,  $\lambda_{2u} = -0.0121$ ,  $\lambda_{2d} = 0.0026$ , changing the asymmetry by 2.4%, corresponding to a 1.4% correction to the value of  $\sin^2(\theta_W)$  and 20% correction to  $(2C_{2u} - C_{2d})$  extracted from a measured value of  $A_d$ . The error of this correction is estimated to be  $\approx 0.1\%$  for  $\sin^2(\theta_W)$  and  $\approx 2\%$  for  $(2C_{2u} - C_{2d})$ . The error is dominated by the uncertainty in the Higgs mass, which is expected to be reduced as new data become available. Other Higgs scenarios and/or new physics at the TeV scale will affect electroweak correction, offering the opportunity for new physics. The error on the electromagnetic coupling constant  $\alpha$  has a negligible effect on the PV DIS asymmetry.

#### 4.1.10 Charge Symmetry Violation (CSV)

Charge symmetry implies the equivalence between up (down) quark distributions in the proton and down (up) quarks in the neutron. Most low energy tests of charge symmetry find it is good to at least 1% level [60] so it is usually assumed to be justified in discussions of strong interactions. However, charge symmetry is not strictly true since the constituent mass of the d quark is ~ 4.3 MeV heavier than the u quark.

The charge symmetry violating (CSV) distributions are defined as [61]

$$\delta u(x) = u^p(x) - d^n(x) , \qquad (35)$$

$$\delta d(x) = d^p(x) - u^n(x) , \qquad (36)$$

where the superscripts p and n refer to the proton and neutron, respectively. Eq. (35) is usually referred to as the "majority" CSV term and Eq. (36) is the "minority" CSV term. The relations for CSV in anti-quark distributions are analogous. Recent precise measurements have significantly decreased the upper limits on parton CSV contributions, but also suggest CSV effects at small x. We now estimate the effect of CSV on the parity violation DIS asymmetry.

Taking into account the CSV effect, Eq. (5) becomes

$$A_d = \left(\frac{3G_F Q^2}{\pi \alpha 2\sqrt{2}}\right) \tag{37}$$

$$\frac{2C_{1u}[1+R_c(x)-R_{\delta d}]-C_{1d}[1+R_s(x)-R_{\delta u}-R_{\delta s}]+Y(2C_{2u}-C_{2d})[R_v(x)-\frac{R_{\delta uv}}{3}-\frac{2R_{\delta dv}}{3}]}{5+R_s(x)+4R_c(x)-R_{\delta u}-4R_{\delta d}-R_{\delta s}}$$

where  $R_{\delta q}$  and  $R_{\delta q_v}$  are defined as

$$R_{\delta u} = \frac{\delta u(x) + \delta \bar{u}(x)}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)}$$

$$R_{\delta d} = \frac{\delta d(x) + \delta \bar{d}(x)}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)}$$

$$R_{\delta uv} = \frac{\delta uv(x)}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)}$$

$$R_{\delta dv} = \frac{\delta dv(x)}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)}$$
(38)

CSV distributions for the valence quarks can be calculated using phenomenological parton distributions based on [63]

$$\delta d_{v}(x) = -\frac{\delta M}{M} \frac{\mathrm{d}}{\mathrm{d}x} [x d_{v}(x)] - \frac{\delta m}{M} \frac{\mathrm{d}}{\mathrm{d}x} d_{v}(x)$$
  

$$\delta u_{v}(x) = \frac{\delta M}{M} \left( -\frac{\mathrm{d}}{\mathrm{d}x} [x u_{v}(x)] + \frac{\mathrm{d}}{\mathrm{d}x} u_{v}(x) \right)$$
(39)

where  $\delta M = M_n - M_p = 1.3$  MeV is the mass difference between the neutron and proton,  $\delta m = m_d - m_u = 4.3$  MeV is the mass difference between the *down* and *up* quarks and *M* is the average nucleon mass.

We use Eq. (??) to calculate the CSV valence quark distributions using the PDF from the meson cloud MIT-bag model [63], the MRST2001 [45] and the CTEQ6M fit [46]. The meson cloud MIT-bag model is used to calculate the CSV sea quark distributions [63]. We find the CSV effect  $\delta q/q$  is < 1% for  $u_v$ , s and  $\bar{d}$ , (1 - 3)% for  $d_v$  and  $\bar{u}$  and (2 - 4)% for  $\bar{s}$ , respectively. Overall, the correction to  $\sin^2 \theta_W$  is (0.1 - 0.2)% and to  $(2C_{2u} - C_{2d}$  is 0.0067. The maximum corrections from these models is taken as the systematic uncertainties due to CSV.

#### 4.1.11 Higher-Twist Effects

Figure 3 shows only the leading twist diagrams for parity violating DIS. When  $Q^2$  is large enough, the leading twist process dominates and one can extract  $\sin^2 \theta_W$  from the measured asymmetry based on the quark-parton model, although one must take into account the electroweak radiative corrections. At lower  $Q^2$ , however, one must consider corrections due to the fact that the color interactions between the quarks become stronger. These interactions introduce a scaling violation stronger than the pQCD  $Q^2$  evolution described by the DGLAP equations, to the low  $Q^2$  region  $Q^2 < 1$  (GeV/c)<sup>2</sup>. This is usually referred to as the higher twist (HT) effect and is treated by the Operator Product Expansion (OPE). For  $\vec{e}-^2H$  scattering, HT effects start from twist-four terms which diminish as  $1/Q^2$ .

The theory for HT effects are not well established. Most of the knowledge for HT is from experimental data. We now give an estimate of the higher twist corrections for the proposed measurement based on available models or phenomenological fits.

An estimate of the twist four-corrections to asymmetry in  $\vec{e} - {}^{2}\text{H}$  scattering was carried out early in 1985 by Castorina and Mulders [65], in which the expansion of the product of electromagnetic and weak currents and the MIT bag model were used. The twist-four correction to the measured  $\vec{e} - {}^{2}\text{H}$  asymmetry is given by  $\delta \sin^{2} \theta_{W} = -0.22(4\pi\alpha_{c}B)/(M^{2}Q^{2})$ , where  $B^{1/4} = 0.145$  GeV is the bag pressure and M = 0.938 GeV is the nucleon mass. The bagmodel parameter  $\alpha_{c}$ , also referred to as the effective color coupling constant, is within the range of  $0 < \alpha_{c} < 1.0$ . Using  $\alpha_{c} = 0.5$  and  $\sin^{2} \theta_{W} \approx 0.236$ , one obtains a 0.15% correction at  $Q^{2} = 2.0$  (GeV/c)<sup>2</sup>. If we double the correction as a conservative estimate of its uncertainty, the relative uncertainty  $\delta \sin^{2} \theta_{W} / \sin^{2} \theta_{W}$  due to the higher-twist correction should be less than 0.3%.

Recently, wealth of data at low  $Q^2$  allows one to determine the HT contributions to the DIS structure functions  $F_2(x, Q^2)$ . The second approach to estimate HT correction to DIS-parity is

Figure 6: The higher twist coefficients  $C_{HT}$  as a function of x [67]. Solid circles (open squares) are for H<sub>2</sub> (D<sub>2</sub>) data. Curve is a parameterization by Virchaux and Milsztajn [69].



based on these experimental data and the assumption that the HT effects partly cancel in the numerator and the denominator of the asymmetry. The higher twist terms have been determined for the e-p and e-<sup>2</sup>H  $F_2(x, Q^2)$  [67] as  $F_2(x, Q^2) = F_2(x)(1 + C_{HT}(x)/Q^2)$  after the DGLAP evolution (up to Next-Leading-Order) is removed. Figure 6 shows the extracted higher-twist coefficient  $C_{HT}$  along with a parameterization by Virchaux and Milsztajn [69]. Data show that  $C_{HT}$  is consistent with zero for x < 0.4 and increases significantly at x > 0.45.

Presumably, the higher twist dynamics is the same for the  $\gamma^*$  and  $Z_0$  exchange processes in

DIS-parity as that for  $F_2$ , hence cancel in the asymmetry. One possible effect that does not cancel comes from the different coupling strength of the EM and weak interactions in the interference term, which is proportional to the EM and weak charges, respectively. Quantitative calculations for the HT correction to  $A_d$  were performed in the QCD LO, NLO and NNLO framework [72]. The results are given below.

Figure 7 shows the higher twist correction to  $A_d$  at  $Q^2 = 2.0 (\text{GeV/c})^2$ . The calculation is performed using various phenomenological fits of the parton distributions (CTEQ, MRST and GRV) and models (LO, NLO and NNLO). The maximum correction  $(A_d^{HT} - A_d)/A_d$  at x = 0.35(the proposed kinematics) from all possible models(fits) is 0.3%, while the average value is 0.15%. Here  $A_d^{HT}$  ( $A_d$ ) is the asymmetry calculated with (without) the higher twist effects. The calculation also depend on the exact shape of the  $C_{HT}$  parameterization by Virchaux and Milsztajn [69] as shown in Figure 6. To take into account the uncertainty in this parameterization, we compare Figure 7 with Figure 6. Clearly the correction for the asymmetry is suppressed by about a factor of 20. Since  $C_{HT}$  is known to be  $(2 - 3) \pm (2 - 3)\%$  in the region 0.2 < x < 0.4, as shown by the data points in Figure 6, the correction to  $A_d$  should be  $\approx 0.15\%$ . We again make a conservative estimation and take the full correction as the uncertainty in  $A_d$  due to HT effects.

> HT Correction at  $Q^2 = 2.(GeV/c)^2$ 0.02 MRST4, NNLO, MSBAR 0.015 MRST8, NLO, MSBAR 0.01 GRV98MS NLO MSBAR 0.005 CTEQ, NLO, MSBAR 0 -0.005-0.01-0.015 -0.02 0.2 0.4 0.6 X<sub>Bi</sub>

Figure 7: The higher twist correction to  $A_d$  at  $Q^2 = 2.0$  (GeV/c)<sup>2</sup>.

Overall, we estimate the uncertainty in  $A_d$  due to HT is in the order of 0.15% at  $Q^2 = 2.0 \text{ (GeV/c)}^2$  when extracting  $\sin^2 \theta_W$  from  $A_d$ . However, if the result deviates largely from the SM prediction, one might question the HT calculations given above and furthur more, give an estimate of possible HT contribution to the  $3\sigma$  effect observed in the NuTeV result, since the HT

effects observed here is expected to be 10 times larger than that at NuTeV kinematics ( $Q^2 = 20 \text{ (GeV/c)}^2$ ). If the HT effects are indeed significant, then more measurements at different  $Q^2$  and x will be needed to unravel the HT effects for the DIS-parity experiments.

## 4.2 Rate Estimation

We used the NMC95 unpolarized DIS fit [41] to calculate the  $e^-$  rate. Pion and positron (pair production) backgrounds are estimated using the Wiser [51] fit which is a conservative estimate based on the proton and <sup>3</sup>He DIS data from Hall A in 2000 [52].

# 4.3 Kinematics Optimization

To optimize the kinematics, we use a single beam energy of 6.0 GeV and vary the scattering angle from  $9^{\circ}$  to  $50^{\circ}$ . For each angle setting, we vary the spectrometer momentum setting from 1 to 4 GeV/c and estimate the rate, pion and positron background and systematic errors. A measurement is considered to be feasible if the positron (pair production) contamination is less than 5%, the pion/electron ratio is less than 1 and if a meaningful total uncertainty can be achieved within a reasonable running time. The optimized kinematics is given in Table 3.

Kinematics	$Q^2 = 1.96 \; (\text{GeV/c})^2$
E (GeV)	6.0
E' (GeV)	3.0
heta	$19^\circ$
$W^2 ({ m GeV})^2$	4.55
$x_{Bj}$	0.348
Y	0.624
$R_c$	0.003
$R_s$	0.039
$R_v$	0.931
$A_d$ (measured, ppm)	131
$e^{-}$ rate (KHz)	86
$\pi^{-}/e^{-}$ ratio	60%
$e^+/e^-$ ratio	0.05%
total rate (KHz)	$\approx 140$
$e^-$ production time (days)	48

Table 3: Kinematics for the Proposed Measurements.

# 4.4 Error Budget

Source	$\delta \sin^2 \theta_W / \sin^2 \theta_W$	$\delta(2C_{2u}-C_{2d})$
$\Delta P_{beam} / P_{beam} = 1\%$	0.666%	0.0185
$\Delta E/E = 2  imes 10^{-4}$	0.010%	0.0003
$\Delta E'/E' = 5  imes 10^{-4}$	0.022%	0.0006
$\Delta \theta = 0.2 \mathrm{mrad}$	0.058%	0.0016
Deadtime correction	pprox 0.18%	pprox 0.0051
Target Endcap contamination	< 0.05%	< 0.0016
Target purity	< 0.05%	< 0.0016
Pion background	< 0.05%	< 0.0016
Pair production background	< 0.05%	< 0.0016
$\Delta R \equiv \sigma_L / \sigma_T$	0.004%	0.0001
Parton Distributions	0.024%	0.0007
Charge Symmetry Violation	0.241%	0.0067
Electro-weak Radiative Correction	0.2%	0.0035
Electro-magnetic radiative Correction	0.4%	0.0070
Higher Twist Effects	0.1%	0.0025
total syst.	0.739%	0.0197
statistical	0.690%	0.0172
total uncertainty	1.011%	0.0262

Table 4: Error Budget for the Proposed Measurements.

# 4.5 Beam Time Request

We need 60 days beam time for measurements of  $\sin^2 \theta_W$  at  $Q^2 = 2.0$  (GeV/c)<sup>2</sup>. Among these 60 days, 56 days are for production running, including 48 for  $e^-$  runs, 4 days for  $e^+$  runs and 4 days for measuring the asymmetry of target Be end-caps. We need three days commissioning for measuring  $Q^2$ , target end-cap contamination and checking PID performance with the regular counting DAQ as well as the fast counting DAQ.. Table 5 summarizes the details of the proposed measurements. Beam time needed for target commissioning is not listed here.

Table 5: Kinematics, estimated uncertainty and running time.

$E_b$	θ	$E_p$	$x_{Bj}$	$Q^2$	$\Delta \sin^2  heta_W / \sin^2  heta_W$	$\Delta(2C_{2u}-C_{2d})$	total beam time
(GeV)		(GeV)		$(\text{GeV/c})^2$	(total)	(total)	(days)
6.0	$19^{\circ}$	3.0	0.35	2.0	$\pm 1.00\%$	0.025	60

# 4.6 Overview of Instrumentation and Cost Estimate

Table 6: An overview of instrumentation and cost estimate for the proposed measurement.

Experimental Hall	Hall A		
Beam polarimeter	Compton upgrade (\$30 K), Møller upgrade planned for Pb-parity		
	(estimate 2 years)		
Beam line	ARC and eP		
Beam Helicity Control	Parity DAQ and helicity feedback - well developed		
Luminosity Monitor	Currently being installed, will be used for HAPPEX II and Pb- parity		
Cryogenic Target	Standard 15-cm LD2 cryogenic target		
Spectrometers	Two HRS taking data simultaneously provide additional check for data quality		
DAQ	Need to build a fast counting DAQ system (\$50 K)		
PID	A gas Čerenkov counter and a double-layered Pb glass shower counter. Pion rej. $> 10^4$ with regular DAQ and $> 10^3$ with fast counting DAQ		
Facility Development	< 1 year		
Cost Estimate	\$80 K		

**\* Red** texts indicate new instrumentation/upgrade proposed in this document.

\* Green texts indicate new instrumentation/upgrade planned for other experiments.

# 5 Summary

We propose to measure the parity violation asymmetry  $A_d$  for  $\vec{e} - {}^2\text{H}$  deep inelastic scattering at  $Q^2 = 2.0 \text{ (GeV/c)}^2$  using a 15-cm liquid deuterium target in Hall A and  $140 - \mu\text{A} 6.0$ -GeV polarized beam. The value of  $\sin^2 \theta_W$  and  $2C_{2u} - C_{2d}$  can be extracted. Assuming a 80% beam polarization, we request 60 days of beam time to reach a  $\pm 0.69\%$ (stat.)  $\pm 0.74\%$ (syst.) uncertainty for the extracted  $\sin^2 \theta_W$ . The weak couplings will be determined to  $\Delta(2C_{2u} - C_{2d}) = 0.026$  which is 10 times better than the present knowledge of this quantity ( $2C_{2u} - C_{2d} = -0.08 \pm 0.24$ , Particle Data Group).

The proposed measurement is the first step of a DIS-parity program at JLab. If the new data deviate significantly from the Standard Model predictions, then more measurements will be needed at different  $Q^2$  to find out possible sources of the deviation, especially to unravel the QCD higher-twist effects. With an upgraded spectrometer (e.g., MAD) and JLab 12 GeV beam, it is possible to pin down the higher twist effects to a good precision, hence prove that DIS-parity is a clean way to test the Standard Model.

If the higher twist effects turn out to be negligible, or can be corrected to a good precision, then DIS-parity will be a useful tool to explore new extension of the Standard Model in the intermediate  $Q^2$  range complementary to the APV data, the NuTeV results, the running E158 and the future Qweak experiments.

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# A PID Simulation for the Fast Counting DAQ

We simulate the PID signals from the gas Čerenkov and lead glass shower detectors based on the signal pattern from data. We then simulate the pileup effects on the electron(pion) efficiency and pion(electron) contamination for electron(pion) scaler with a high rate (1 MHz) and ratio  $\pi/e = 1$ .

### A.1 PID signal from data

A typical summed ADC signal for the CO<sub>2</sub> gas Čerenkov detector is given in Figure 8. The electrons are usually identified by a cut  $\sum ADC_i > 400$  and in principle pions should not trigger any signal.

Figure 8: Left: summed ADC signal of left HRS gasČerenkov detector, without cut (black), after lead glass counters' electron cut (red) and pion cut (blue). The vertical line shows a cut  $\sum ADC_i > 400$  for selecting electrons. Data are from 2001 DIS runs, the kinematics is  $x_{Bj} = 0.33$ , E' = 1.32 (GeV/c),  $Q^2 = 2.7$  (GeV/c)<sup>2</sup> and  $\pi^-/e^- \sim 1$ .



A typical 2D spectrum for the summed ADC signal from the first layer (6.0 radiation length) of the lead glass shower detector vs. that from the second layer (20.8 radiation length) for the right spectrometer is shown in Figure 9. One can clearly see two blobs, the one with higher energy deposit in both layers is for the electrons and the one with lower energy deposit in both is formed by the pions. One can thus select the electrons and pions by applying electron and pion cuts, as shown in Figure 9.

### A.2 Simulation of pileups

For the fast counting DAQ, the photo-tube signals will be sent directly to discriminators instead of ADCs. However the pattern should be similar to Figure 9, although there will be electronic

Figure 9: Right: two-dimensional distribution of energy deposits in the two layers of lead glass counter in the right HRS, after the gas Čerenkov ADC electron cut (red) and the pion cut (blue). Black straight lines show the boundary of the 2D cut to select electrons. Data are from 2001 DIS runs, the kinematics is  $x_{Bj} = 0.33$ , E' = 1.32 (GeV/c),  $Q^2 = 2.7$  (GeV/c)<sup>2</sup> and  $\pi^-/e^- \sim 1$ .



noise coming in. The particle identification can be done by checking the output of discriminators with different preset thresholds (or windows).

We simulate the pileup effects as follows:

- Assuming  $\pi/e$  ratio = 1, total rate = 1 MHz;
- In the event generator, assign particle type ( $\pi$  or e) to each event according to assumed  $\pi/e$  ratio;
- Assign energy deposits  $E_{psh}$  and  $E_{sh}$  to each event according to its particle type and  $E_{psh}$ ,  $E_{sh}$  pattern, here  $E_{psh}(E_{sh})$  is the energy deposit in the first(second) layer; For electrons we use correlated Gaussian distribution and for pions Landau distribution is used;
- Assign a Čerenkov signal to each event according to its particle type: We assume the single photo-electron peak of each Čerenkov PMT is aligned to channel 150. The average number of photo-electron  $n_{ph.e.} \approx 10$  from data. Therefore for each electron, we assign an output using Gaussian distribution centered at  $150 \times 10$  and standard deviation  $150 \times sqrt10$  (since Poisson distribution can be approximated by a Gaussian when  $n_{ph.e.} >> 1$ . For each pion, we assume that it either do not generate any output (zero) or generate one photo-electron in the PMT due to 4%  $\delta$ -electron effect. For  $\delta$  electrons, the output should follow Poisson distribution with  $n_{ph.e.} = 1$ .
- Simulate the time interval between two events: generate a random number t within (0,1), if  $t < t_r \times rate$ , consider it as a pileup, add  $E_{sh}$  and  $E_{psh}$  to the values of the previous event, save the sum for current event. Here  $t_r$  is the detector resolving time (a few 10nsec);
- Now export events:

- if there is no pileup, export the previous event;
- if there is pileup, do not export the previous event; in this case, if the previous event is e, change the current particle type to e no matter what was the original value, continue to the next event;
- Choose specific PID cuts, calculate the pion contamination for resolving time varying from 0 to 100 nsec;
- Some signal patterns are given in the next section. The results are summarized below:
  - 1. For lead glass shower counter:
    - The pion rejection factor drops from  $\approx 107 (t_r = 0)$  to  $\approx 100 (t_r = 60$  nsec) to  $\approx 96 (t_r = 100$  nsec). This is due to  $\pi \pi$  pileup being counted as electrons;
    - The electron detection efficiency starts to drop linearly as  $t_r$  at  $t_r > 70$  nsec. At low resolving time it fluctuates because some real electrons (but with low energy deposits hence fall below the *e* cuts) gain amplitude from pileup and can be counted as electrons. In principle the *e* efficiency will not drop at large  $t_r$ . The *e* efficiency varies from  $\approx 99.295\%$  ( $t_r = 0$  nsec) to  $\approx 99.278\%$  ( $t_r = 100$  nsec);
    - The pion detection efficiency drops linearly for  $t_r > 50$  nsec. This is because for  $\pi \pi$  pileups the signals mostly go beyond the pion cut and cannot be counted as pions. For  $e \pi$  pileups the signals fall into electron cut and are counted as electrons. For either case the pion event is lost. The pion efficiency drops from  $\approx 82.6\%$  ( $t_r = 0$ ) to  $\approx 82.1$  (60 nsec dt) to  $\approx 81.7$  (100 nsec dt).
    - The electron counts above the high cut increases linearly as  $t_r$ . It starts from  $0(t_r = 0)$  to 3% ( $t_r = 60$  nsec) to 5% ( $t_r = 100$  nsec). This is consistent with that e e pileups are proportional to  $t_r$  and two e events are counted as one. Therefore  $\eta_{e,highcut} = t_r \times (rate)/2$ .
  - 2. For Čerenkov detector:
    - The pion rejection factor drops from  $\approx 105 (t_r = 0)$  to  $\approx 101 (t_r = 60$  nsec) to  $\approx 99 (t_r = 100$  nsec). This is due to  $\pi \pi$  pileup being counted as electrons;
    - The electron detection efficiency drops as  $t_r$  increases. It changes from  $\approx$  99.07% ( $t_r = 0$  nsec) to  $\approx$  99.0% ( $t_r = 60$  nsec) to  $\approx$  98.85% ( $t_r = 100$  nsec);
    - The pion detection efficiency drops linearly. It changes from  $\approx 95.42\%$  ( $t_r = 0$ ) to  $\approx 95.26$  ( $t_r = 60$  nsec) to  $\approx 95.18$  ( $t_r = 100$  nsec).
    - The electron counts above the high cut increases linearly as  $t_r$ . It starts from  $0(t_r = 0)$  to 1.5% ( $t_r = 60$  nsec) to 2.5% ( $t_r = 100$  nsec). This is lower than the expected e e pileups ( $\eta_{e,highcut} = t_r \times (rate)/2$ ) since not all e e pileups generate a high Čerenkov signal.

# A.3 Shower Output

Figure 10: Simulation of lead glass shower outputs with  $t_r = 0$  (left) and 60 nsec(right),  $\pi/e$  ratio=1. and total rate=1 MHz. Electron (pion) events are shown in red (blue).



# A.4 Čerenkov Output

Figure 11: Simulation of Čerenkov output with  $t_r=0$ (left) and 60 nsec(right),  $\pi/e$  ratio=1. and total rate=1 MHz. Electron (pion) events are shown in red (blue).



# A.5 PID Efficiency



Figure 12: Lead glass counter PID efficiency vs. resolving time, pi/e ratio=1., total rate=1 MHz.

# A.6 Effect on the Extracted Asymmetry

We now check what is the effect of pileups on the measured asymmetry. When there is no pileup, the measured asymmetries after electron and pion cuts are:

$$A_{e \ cut} = A_{e}[1 - R_{e}^{\pi}] + A_{\pi}R_{e}^{\pi}$$
(40)

$$A_{\pi \ cut} = A_{\pi} [1 - R_{\pi}^{e}] + A_{e} R_{\pi}^{e}$$
(41)

where  $R_e^{\pi}$  ( $R_{\pi}^e$ ) is the  $\pi(e)$  to  $e(\pi)$  ratio after all electron (pion) cuts,  $A_e$  ( $A_{\pi}$ ) is the real electron (pion) asymmetry and can be extracted from the measured ones as

$$A_e = \frac{A_{e \ cut}[1 - R_{\pi}^e] - A_{\pi \ cut}R_e^{\pi}}{\{[1 - R_e^{\pi}][1 - R_{\pi}^e] - R_{\pi}^eR_e^{\pi}\}}$$
(42)

$$A_{\pi} = \frac{A_{\pi \ cut}[1 - R_e^{\pi}] - A_e \ cut R_{\pi}^{\mu}}{\{[1 - R_e^{\pi}][1 - R_e^{\pi}] - R_e^{\pi} R_{\pi}^{e}\}}$$
(43)



Figure 13: Čerenkov detector PID efficiency vs. resolving time, pi/e ratio=1., total rate=1 MHz.

The ratios  $R_e^{\pi}$  and  $R_{\pi}^e$  can be measured at low rate ( $t_r \approx 0$  equivalently). The uncertainty in asymmetry  $A_e$  due to pion contamination is

$$\frac{\Delta A_e}{A_e} = \Delta R_e^{\pi} \left( 1 + \frac{A_{\pi cut}}{A_{ecut}} \right) \tag{44}$$

To keep  $\Delta A_e/A_e < 0.1\%$ , the ratio  $R_e^{\pi}$  needs to be measured to  $\Delta R_e^{\pi} < \Delta A_e/A_e/(1 + A_{\pi cut}/A_{ecut}))$ . We have  $A_{\pi cut}/A_{ecut} \approx A_{\pi}/A_e$  and from Section 4.1.2 it has been shown that  $A_{\pi}/A_e < 1$ , therefore  $\Delta R_e^{\pi} < 0.0005$  is needed. The statistics required to reach this level is  $N_e + N_{\pi} > 4$  M. With regular DAQ the highest counting rate is 4 KHz, this means 45 minutes beam time.

When the resolving time is not zero, pileup occurs and the measured asymmetries become

$$A_{e \ cut}(t_r) = A_e \left[ 1 - R_e^{\pi} \frac{\eta_{\pi, rej}(0)}{\eta_{\pi, rej}(t_r)} \right] + A_{\pi} R_e^{\pi} \frac{\eta_{\pi, rej}(0)}{\eta_{\pi, rej}(t_r)}$$
(45)

$$A_{\pi \ cut}(t_r) = A_{\pi} \left[ 1 - R_{\pi}^e \frac{\eta_{e,rej}(0)}{\eta_{e,rej}(t_r)} \frac{\eta_{\pi}(0)}{\eta_{\pi}(t_r)} \right] + A_e R_{\pi}^e \frac{\eta_{e,rej}(0)}{\eta_{e,rej}(t_r)} \frac{\eta_{\pi}(0)}{\eta_{\pi}(t_r)}$$
(46)

where  $\eta_{\pi,rej}(t_r)$  ( $\eta_{e,rej}(t_r)$ ) is the pion (electron) rejection factor with electron (pion) cuts and detector resolving time  $t_r$ ,  $\eta_{\pi}(t_r)$  is the pion efficiency with pion cuts and detector resolving time  $t_r$ . We assume the electron efficiency does not drop as  $t_r$  increases, as shown by the simulation.

The uncertainty in asymmetry  $A_e$  due to pileup effect is thus

$$\frac{\Delta A_e}{A_e} = R_e^{\pi} \left( 1 + \frac{A_{\pi cut}}{A_{ecut}} \right) \Delta \left( \frac{\eta_{\pi, rej}(0)}{\eta_{\pi, rej}(t_r)} \right)$$
(47)

The ratio  $R_e^{\pi}$  is expected to be less than  $10^{-3}$  if both lead glass and Čerenkov counters are used. Furthermore it has been shown in the simulation that the value  $\frac{\eta_{\pi,rej}(0)}{\eta_{\pi,rej}(t_r)} - 1$  is in the order of < 10% at  $t_r = 60$  nsec, this value can also be checked by the electron scalers with high *e* cuts in the fast counting DAQ (which is in the same order of magnitude of the value  $\frac{\eta_{\pi,rej}(0)}{\eta_{\pi,rej}(t_r)} - 1$ ). therefore the uncertainty  $\frac{\Delta A_e}{A_e}$  due to pileup effects is in the order of  $10^{-4}$ .

Overall, in order to keep the effect on the asymmetry due to PID efficiencies to be less than  $\Delta A/A < 0.1\%$ , 4 M events are needed with regular DAQ and low beam current, which corresponds to  $\approx 45$  minutes beam time. The effect on the asymmetry from pile-ups is in the order of  $10^{-4}$  and can be safely neglected.

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