Update on E12-10-002: Precision measurements of the F_2 structure function at large x in the resonance region and beyond

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E12-10-002 has been approved by PAC35 to measure $H(e,e')$ and $D(e,e')$ inclusive cross sections in the resonance region and beyond for a precise extraction of the F_2 structure function at large Bjorken x, up to 0.99, and intermediate four-momentum transferred squared Q^2, up to about 17 GeV^2. These measurements will be used for detailed studies of the perturbative and nonperturbative mechanisms underpinning the valence quark dynamics at large x. With the advance of these studies the data could then be utilized to constrain PDFs at large x. The approved experiment will require an 11 GeV unpolarized electron beam, the standard Hall C cryogenic targets, hydrogen and deuterium, and an aluminum target for background measurements. For detection we will use the existing HMS and the new SHMS which are part of the standard package for the 12 GeV upgrade in Hall C. Our total beamtime request adds up to 314 hours or 13 days.

I. MOTIVATION

This section is structured in two subsections. The first subsection will summarize the physics motivation of E12-10-002 which has been discussed in detail in the proposal PR12-10-002. The second subsection will present the new developments since the approval of E12-10-002 that highlight the need for precise measurements of the proton and deuteron F_2 structure functions at large x and intermediate Q^2.

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A. Physics Motivation: Summary

The distribution of up and down quarks in the nucleon is one of the fundamental characterizations of the structure of the ground state in QCD. In spite of the fact that the building blocks of matter, quarks and gluons, are not observables, several decades of accumulated data from a variety of hard scattering processes together with sophisticated QCD analyses lead to a detailed mapping of the nucleon's parton distribution functions (PDFs) over a wide range of kinematics [1].

Lepton-nucleon deep inelastic scattering (DIS) processes played a dominant role in obtaining information on the behavior of the quark PDFs as well as on the gluon distribution but the kinematic coverage of many DIS experiments is limited in Bjorken x and so our knowledge of PDFs is not uniform over the entire x range, lacking especially at large x. As x approaches 1 at fixed Q^2, the invariant mass of the produced hadronic system, W, approaches values in the nucleon resonance region where non-perturbative effects are non-negligible. In order to stay in a region of high W but access high values of x, one must go to increased values of Q^2. Presently this avenue has limitations imposed by the available beam energy.

A detailed mapping of the large-x region is important for a number of reasons. The large-x region provides a laboratory for studying the flavor and spin dynamics of quarks. The behavior of parton distribution functions with x is of interest in itself, to e.g. experimentally support (or not) the Drell-Yan-West relation postulate which links the x dependence of the structure function as x approaches 1 and the Q^2 dependence of the electromagnetic form factor. Moreover, the d/u ratio at large x is very sensitive to different mechanisms of spin-flavor symmetry breaking in the nucleon [2]. The large-x region contributes significantly to the moments of unpolarized (and polarized) structure functions, especially for the higher moments. The lower moments can be calculated from first principles in QCD on the lattice [3] in terms of matrix elements of local operators. In addition, knowledge of PDFs at large x is essential for determining high-energy cross sections at collider energies such as in search of new physics beyond the Standard Model, where structure information at large x feeds down through perturbative Q^2 evolution to lower x and higher values of Q^2.

A fully quantitative description of the nucleon structure in terms of PDFs relies, however, on our ability to unravel the Q^2 and x-dependence of the data in detail. In particular it is important to obtain more quantitative information on the boundary or "transition" regions of x and Q^2 where perturbative QCD (pQCD) evolution regulated by the Q^2-evolution equations can no longer be the only mechanism responsible for the Q^2-dependence of the data. Explicitly, from a theoretical standpoint, the large-x region requires the inclusion not only of leading twist PDFs, but also of contributions suppressed by at least one power of Q^2, which include target mass and higher twist contributions. Moreover, if a nuclear target is used one must include nuclear corrections which account for the difference between the PDFs in free nucleons and those in nucleons bound in a nucleus. Several exploratory studies have been performed following this avenue in an attempt to improve our knowledge of PDFs at large x [1, 4].

Recently, two theory groups, S. Alekhin *et al.* [4] and CTEQ6X [1], have focused on extending the PDFs extraction to larger x. The standard cuts on DIS data in traditional QCD analyses have excluded points with low W^2 (a typical example, CTEQ6 [5] used only data with $Q^2 > 4$ GeV^2 and $W^2 > 12.25$ GeV^2) which means that the PDFs have not been constrained at large x, $x > 0.7$. The analyses of S. Alekhin *et al.* [4] and CTEQ6X [1] showed that excellent fits of PDFs can result when the Q^2 and W^2 cuts on data are lowered provided that target mass corrections, higher-twist contributions, and nuclear effects for deuterium targets are all taken into account.

For example, the CTEQ6X analysis [1] has shown that with a more permissive kinematic cut ($Q^2 > 1.69$ GeV^2 and $W^2 > 3$ GeV^2) which allows more experimental constraints for PDF fits at large x, there is a substantial reduction in the uncertainties of PDFs. The errors are reduced by $10-20\%$ for $x < 0.6$ and by up to $40-60\%$ at larger x (8% of the total number of data points employed in the fit is from the lower energy Hall C run E00-116 [6]). The resulting fits from CTEQ6X also show that the leading twist u- and d-quark PDFs are stable with respect to the choices made for implementing the target mass corrections, as long as a flexible higher twist parametrization is employed. It was also found that compared to previous global analyses there is a stronger suppression of the d-quark distribution at large x. The amount of suppression, however, is sensitive to the treatment of the nuclear corrections which are an important source of uncertainty at large x and further progress needs to be made in the study of the behavior of the large-x PDFs and d/u ratio [1].

The very large x region ($x > 0.8$), however, can only be accessed presently via resonance region measurements. In this region, the contribution from nonperturbative effects is large but the results accumulated over the past decades have shown that *on average* the resonance region structure functions mimic the behavior of structure functions extracted from the DIS region [6–10]. This phenomenon termed *quark-hadron duality* has been extensively studied at JLab since it was first observed at SLAC in 1969 [7]. Increasing evidence supports the idea that *quark-hadron duality* can be used as a tool to access the very large x region and provide experimental constraints for global PDF fits. Recent *quark-hadron duality* studies on the proton, deuteron, and neutron F_2 structure functions from $Q^2 \sim 1$ to $Q^2 \sim 7$ GeV^2 by S. Malace *et al.* [6, 10] suggest that global QCD analyses as those of Alekhin *et al.* [4] and

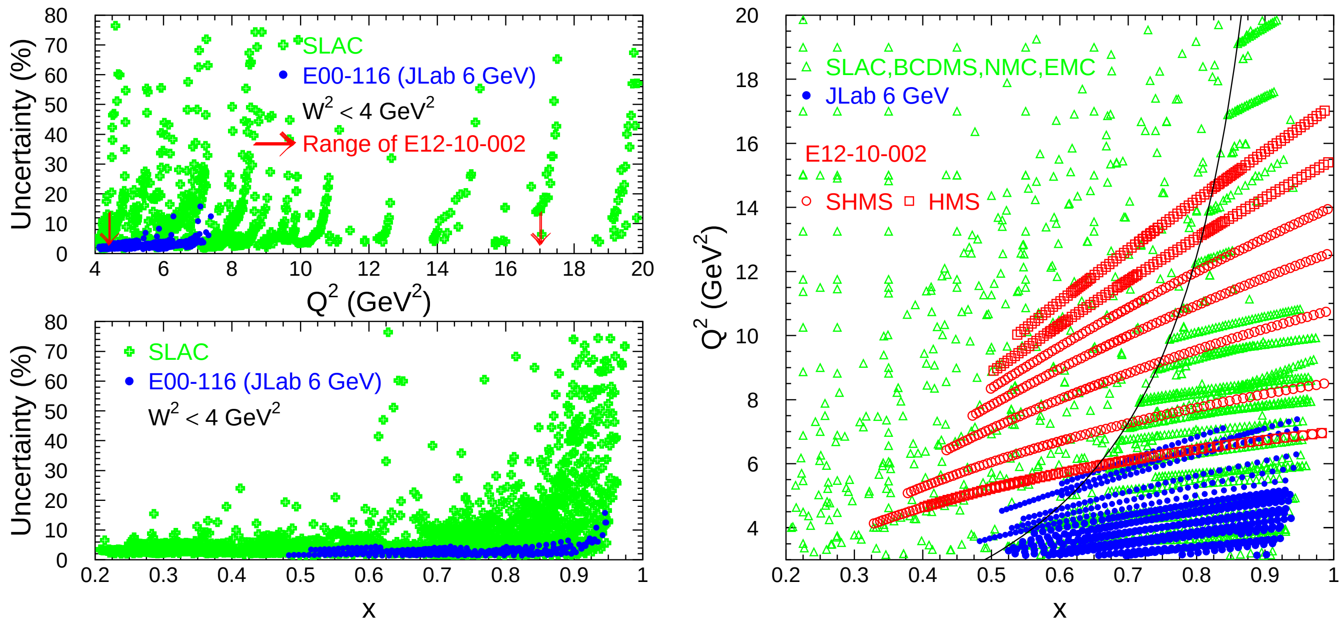

FIG. 1: **Left:** Statistical uncertainties from SLAC (green) and JLab experiment E00-116 [6] (blue) as a function of Q^2 (top panel) and x (bottom panel) in the region $W^2 < 4$ GeV^2. The arrows on the top panel indicate the Q^2 coverage of the approved experiment E12-10-002. The statistical uncertainties for the approved experiment are expected to be similar or better than those of the lower energy run E00-116 [6]. **Right:** Kinematics for the approved experiment E12-10-002 in x and Q^2. World data from SLAC, BCDMS, NMC, EMC, SLAC (green) and lower energy JLab (blue) are also shown. The solid curve indicates $W^2 = 4$ GeV^2.

CTEQ6X [1] that already implement nonperturbative effects at large x to describe low W^2 DIS data could be readily extended to the resonance region down to a W^2 of about 1.9 GeV^2 (the *quark-hadron duality* studies on the neutron F_2 structure function have been published since the approval of E12-10-002 in Physical Review Letter [10]).

Presently, there are precise measurements of the proton and deuteron F_2 structure functions at large x up to a value of about 0.9 and $Q^2 < 7$ GeV^2 with most of the statistics provided by JLab data. There are few measurements from SLAC at higher Q^2, up to 10 GeV^2, but with rather large statistical uncertainties (reaching values of 60-70% at the largest x), as shown in Fig. 1 (left). Above Q^2 of 10 GeV^2 the high x region, $x > 0.8$, is largely unexplored. The 11 GeV beam at JLab offers the unique opportunity of extending the precision measurements of the proton and deuteron F_2 structure functions to larger x and Q^2 and E12-10-002 plans to cover a kinematic region from 0.3 to 0.99 in x and from 4 GeV^2 to 17 GeV^2 in Q^2, as shown in Fig 1 (right).

B. New developments

Since the approval of E12-10-002 in January of 2010, PDF fits from S. Alekhin *et al.* [4] and CTEQ6X [1] have been published. We are in contact with both collaborations and have gained access to their computational packages of the F_2 structure function. We computed truncated moments of the proton and deuteron F_2 structure functions from both data and new theoretical parametrizations for different resonance regions and the results are displayed in Figs. 2 and 3. Although the approved experiment plans to measure proton and deuteron F_2 structure functions up to a W^2 of 9 GeV^2, here we have chosen to emphasize the very large x region thus we show results in a W^2 range from 3.9 to 1.3 GeV^2.

The truncated moments from both data and theory are computed as integrals of the F_2 structure function over x ranges corresponding to W^2 ranges delimiting different resonance regions (Figs. 2 and 3): first resonance region W^2 : $(1.3, 1.9)$ GeV^2, second resonance region W^2 : $(1.9, 2.5)$ GeV^2, third resonance region W^2 : $(2.5, 3.1)$ GeV^2 and the fourth resonance region W^2 : $(3.1, 3.9)$ GeV^2. The solid circles represent the ratio of deuteron to proton truncated moments calculated from measurements of the Hall C experiment E00-116 [6] while the solid curves show the same ratio calculated from parametrizations of S. Alekhin *et al.* [4] (blue) and CTEQ6X [1, 11] (pink, green) at the kinematics of E00-116. Two versions of the CTEQ6X parametrization are shown: CTEQ6X (standard) [1] which does not include off-shell corrections (pink) and has been recently published and CTEQ6X K-P off-shell [11]

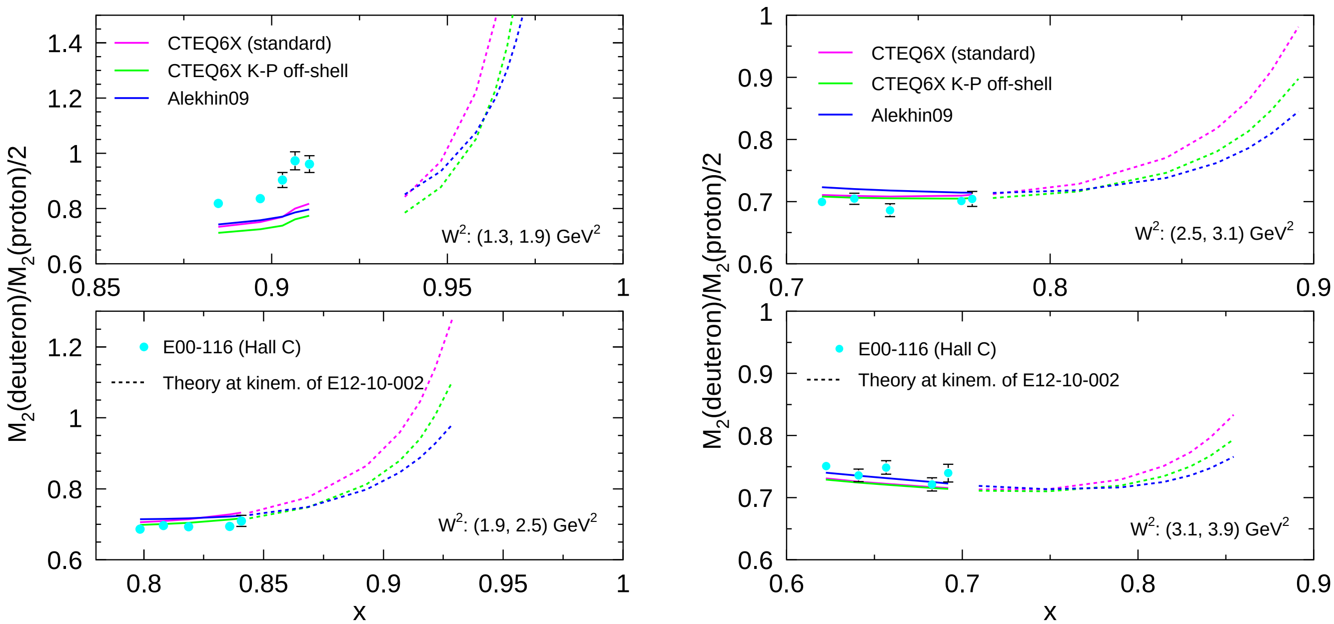

FIG. 2: Ratio of deuteron to proton truncated moments calculated from the F_2 measurements of E00-116 [6] (solid circles) and from theoretical parametrizations of F_2 by S. Alekhin *et al.* [4] and CTEQ6X [1, 11] (solid and dashed curves) as a function of x. The solid and dashed curves display the theory truncated moments computed at the kinematics of E00-116 and of the approved experiment E12-10-002, respectively. **Left:** Ratio of deuteron to proton truncated moments in the first (top) and second (bottom) resonance regions. **Right:** Ratio of deuteron to proton truncated moments in the third (top) and fourth (bottom) resonance regions.

(green) which includes off-shell corrections using the Kulagin-Petti prescription [12]. The latter of the CTEQ6X parametrizations will be submitted for publication soon. The dashed curves display the ratio of truncated moments from theory **calculated at the kinematics of the approved experiment E12-10-002**.

The ratio of deuteron to proton truncated moments from E00-116 data [6] agrees fairly well with the ratio extracted from the theoretical parametrizations in the fourth, third and second resonance regions. It should be noted that data with $W^2 < 3$ GeV^2 have not been included in the PDF fits of S. Alekhin *et al.* [4] and CTEQ6X [1, 11]. The agreement between data and calculations in the third resonance region is a clear indication of the onset of quark-hadron duality where theoretical parametrizations with experimental constraints from data with higher W^2, Q^2 and x up to 0.8 average to resonance region data with lower W^2, Q^2 but similar x. The second and first resonance regions lay in a kinematic range where the theoretical parametrizations are mostly extrapolated in x (more so for the first resonance region). The agreement between data and calculations is still good in the second resonance region but worsens for the first resonance region as previously acknowledged [6, 10].

As shown by the dashed curves, differences between various theoretical parametrizations grow at larger x and Q^2 and this is due to lack of experimental constraints for $x > 0.8$ and/or higher sensitivity to nuclear corrections which become increasingly important. The approved experiment E12-10-002 will provide precise experimental constraints in this kinematic region where data are presently sparse and with large uncertainties.

Another development since the approval of E12-10-002 by PAC35 is the organization of a workshop dedicated to the latest advances in the study of the nucleon structure at large x. The contact person for E12-10-002 received the *2010 JSA Postdoctoral Research Fellowship* with a \$10,000 research grant that is being used to organize this workshop. **The 3rd International Workshop on Nucleon Structure at Large Bjorken x** will be held at Jefferson Lab in Newport News, Virginia on October 13-15, 2010. Some of the topics to be addressed include: parton distributions at large x, quark-hadron duality and higher twists, transverse momentum and spin distributions, lattice QCD and low energy models, implications for new physics searches. More details can be found at http://conferences.jlab.org/HiX2010/index.html.

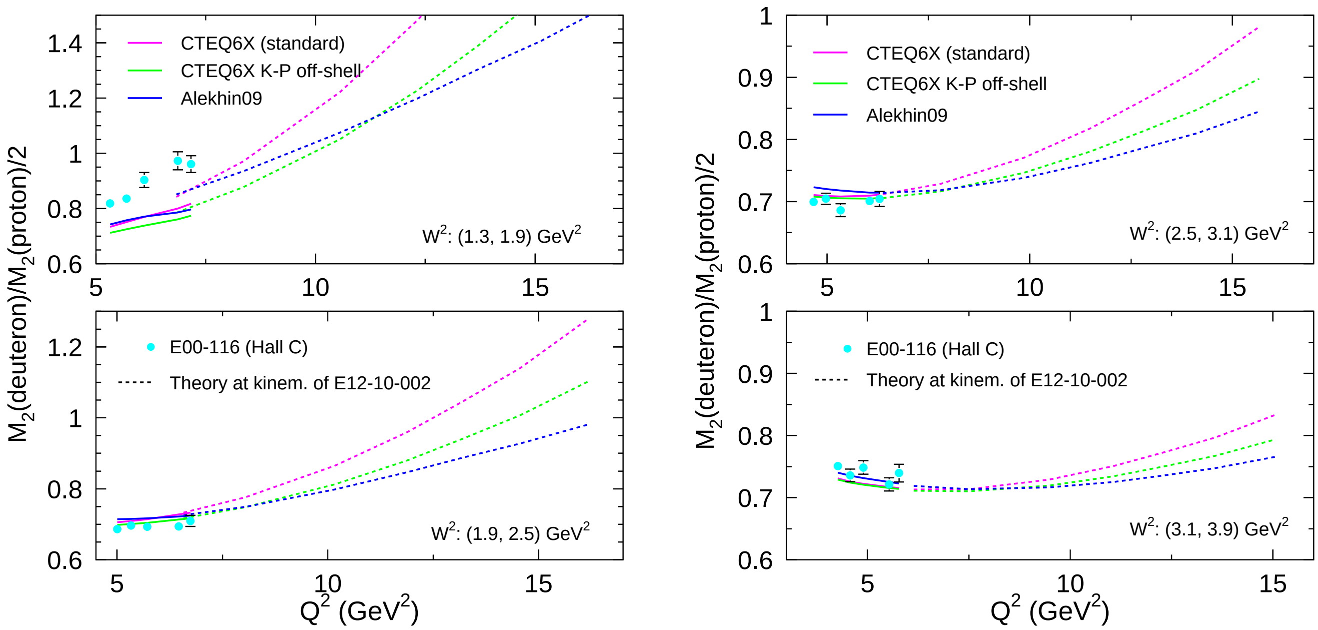

FIG. 3: Ratio of deuteron to proton truncated moments calculated from the F_2 measurements of E00-116 [6] (solid circles) and from theoretical parametrizations of F_2 by S. Alekhin *et al.* [4] and CTEQ6X [1, 11] (solid and dashed curves) as a function of Q^2. The solid and dashed curves display the theory truncated moments computed at the kinematics of E00-116 and the approved experiment E12-10-002, respectively. **Left:** Ratio of deuteron to proton truncated moments in the first (top) and second (bottom) resonance regions. **Right:** Ratio of deuteron to proton truncated moments in the third (top) and fourth (bottom) resonance regions.

II. TECHNICAL DETAILS OF E12-10-002

Since the approval of E12-10-002 at the end of January 2010 there have been no new developments regarding the technical experimental details. E12-10-002 is a straightforward extension of the lower energy run E00-116 [6, 10]. To summarize the detailed discussion given in the proposal PR12-10-002, we plan to measure the $H(e, e')$ and $D(e, e')$ cross sections in the resonance region and beyond up to a W^2 of 9 GeV^2, x of 0.99 and Q^2 of 17 GeV^2. These measurements will be performed using an 11 GeV unpolarized electron beam, the standard system of cryogenic targets in Hall C (hydrogen and deuterium), and the existing HMS and the new SHMS which is part of the standard package for the 12 GeV upgrade in Hall C.

With SHMS we plan measurements at five fixed spectrometer angles, 17^o, 20^o, 25^o, 30^o and 35^o, varying the central momentum of the scattered electron from 2.3 GeV/c to 6.01 GeV/c. This will offer a kinematic coverage in x from 0.3 to 0.97 and in Q^2 from 4 GeV^2 to 13.9 GeV^2. HMS will be used for large angle measurements, 45^o and 55^o, with central momenta of the scattered electron ranging from 1.16 GeV/c to 2.54 GeV/c. The HMS measurements will push the kinematic coverage to a Q^2 as large as 17 GeV^2. Data at 17^o will be taken in HMS as well for crosschecks of the two spectrometers (a detailed account of each kinematic setting and time estimates have been given in the proposal PR12-10-002, Table I).

In order to reduce the uncertainty in the extraction of F_2 from cross sections due to the uncertainty in $R = \sigma_L/\sigma_T$ we plan to make measurements of R at two (W^2,Q^2) points (see proposal PR12-10-002). The point (W^2,Q^2) = (3.5, 6.1) GeV^2 will provide the opportunity to crosscheck our measurement of R with those from SLAC (R from the widely used parametrization *R1998* [13]) while the point (W^2,Q^2) = (2, 6.6) GeV^2 will provide R in a region where, currently, no such measurements are available. For this we will measure cross sections at another beam energy, namely 6.6 GeV, with HMS. In addition to the ϵ points planned at 11 GeV and 6.6 GeV, the lower energy data from E00-116 at 5.5 GeV will be used to provide an additional ϵ point for this determination of R (Fig. 9 in proposal PR12-10-002). From estimates based on previous measurements of R at both smaller Q^2 (same W^2) and same Q^2 (larger W^2) we expect R to be small, $R < 0.15$, at the kinematics of E12-10-002. We estimate that our determination of R will be sufficient to reduce the R-related systematic uncertainty on F_2 to an acceptable level (i.e. $< 2\%$, which would be less than the uncertainty of the lower energy run E00-116).

For background measurement purposes we will also take data on an aluminum empty target (dummy target)

TABLE I: Beam time request for the proposed experiment.

Activity	time (hours)
Hydrogen and Deuterium running	229
Empty (dummy) target running	20
Hydrogen elastics	5
Target boiling studies	8
Configuration change	10
BCM calibration	4
Beam spot monitoring	4
R measurements	10
Detector checkout	24
Total	314 ($\sim$ 13 days)

at the same kinematics as for the hydrogen and deuterium cryogenic targets. This will allow the subtraction of background coming from the electrons scattered on the aluminum walls of the cryogenic target cells. The other source of background from secondary electrons produced in the target is the production of neutral pions that decay into $\gamma\gamma$ or $e^+e^-\gamma$. The photons can further convert into e^+e^- pairs in the target materials or in the materials preceding the detectors. This background being charge-symmetric can be measured directly by changing the polarity of the spectrometers to positive and measuring the produced positrons. We used the model of P. Bosted [14] to estimate the contribution of this background and we found that the largest contribution is expected at 55^o and the lowest momentum and is estimated to be of the order of 11% for the hydrogen target and of 15% for deuterium. By 42^o the contribution drops to about 2% while for the next largest angle, namely 35^o is below 1%. This model compared well to data taken at the lower energy run E00-116 [6] but has not been thoroughly tested at the energies of E12-10-002 so we plan to measure the charge-symmetric background not only at 55^o and 42^o but also at the next two largest angle settings, namely 35^o and 30^o, even if the contribution of this background is estimated to be at the sub-percent level.

Our beamtime request to laboratory is summarized in Table I (time estimates for each kinematic setting and target were presented in Table I in the proposal PR12-10-002). The run times were calculated assuming a beam energy of 11 GeV, a current of 40μA, a 10cm target length and a 2% statistical uncertainty in a W^2 bin of 0.1 GeV^2. The total runtime for the cryogenic targets is 229 hours, including positive polarity measurements of the charge-symmetric background. The total beamtime request adds up to 314 hours or 13 days.

III. SUMMARY

E12-10-002 plans to measure $H(e,e')$ and $D(e,e')$ inclusive cross sections in the resonance region and beyond for a precise extraction of the F_2 structure function at large Bjorken x, up to 0.99, and intermediate four-momentum transferred squared Q^2, up to about 17 GeV^2. These data will provide a good coverage of the large x and intermediate Q^2 region where very few measurements exist, some with large statistical uncertainties. Our measurements will allow the study of the transition from perturbative to non-perturbative degrees of freedom, and will contribute to a precise determination of large-x quark distributions, which is one of the milestones (HP14) for the 12 GeV upgrade.

Assuming a beam energy of 11 GeV, a current of 40μA, a 10cm target length and a 2% statistical uncertainty in a W^2 bin of 0.1 GeV^2 we will need 314 hours or 13 days to complete this experiment given that the commissioning of the spectrometers has been done. The systematic uncertainty is expected to be comparable to that of the successful lower energy run E00-116 [6].

[1] A. Accardi *et al.*, Phys. Rev. D **81**, 034016 (2010).
[2] W. Melnitchouk and A.W. Thomas, Phys. Lett. B **377**, 11 (1996).
[3] D. Dolgov *et al.*, Phys. Rev. D **66**, 034506 (2002); M. Gockeler *et al.*, Nucl. Phys. Proc. Suppl. **119** 32 (2003); W. Detmold, W. Melnitchouk, A.W. Thomas, Phys. Rev. D **66**, 054501 (2002).
[4] S. Alekhin *et al.*, Phys. Rev. D **81**, 014032 (2010); S. Alekhin, Phys. Rev. D **63**, 094022 (2001); S. Alekhin, Phys. Rev. D **68**, 014002 (2003).
[5] J. Pumplin, D.R. Stump, J. Huston, H.L. Lai, P. Nadolsky, W.K. Tung, JHE P 0207:012 (2002).
[6] S.P. Malace, Phys. Rev. C **80**, 035207 (2009).
[7] E. D. Bloom and F. J. Gilman, Phys. Rev. Lett. **25**, 1140 (1970).

[8] I. Niculescu *et al.*, Phys. Rev. Lett. **85**, 1182, 1186 (2000).
[9] Y. Liang *et al.*, arXiv:nucl-ex/0410027.
[10] S.P. Malace *et al.*, Phys. Rev. Lett. **104**, 102001 (2010).
[11] A. Accardi, private communication.
[12] S.A. Kulagin and R. Petti, arXiv:1004.3062 [hep-ph].
[13] K. Abe *et al.*, Phys. Lett B **452**, 194 (1999).
[14] P. Bosted, CLAS-NOTE-2004-005 (2004, unpublished).