Spin Physics Program in TJNAF Hall C

Oscar Antonio Rondon

Institute of Nuclear and Particle Physics - University of Virginia
Charlottesville, VA 22901, U.S.A.
e-mail: or@virginia.edu

Received 20 October 2003;
final version 31 December 2003

The spin physics program in Thomas Jefferson National Accelerator Facility's (TJNAF) Hall C concentrates on precision studies of the nucleon spin structure functions that can be extracted with inclusive polarized scattering experiments. Experiment 01-006 (Resonances Spin Structure - *RSS*) to measure the nucleon spin structure functions in the region of the nucleon resonances at an average four-momentum transfer $Q^2 = 1.3[\mathrm{GeV/c}]^2$ has been completed. Another experiment, to measure the proton SSF's in in the Bjorken scaling variable range $0.3 \leq x \leq 0.8$ for $2.5\ [\mathrm{GeV/c}]^2 \leq Q^2 \leq 6.5\ [\mathrm{GeV/c}]^2$ has recently been approved by TJNAF's Physics Advisory Committee (PAC), as E03-109. This new "Spin Asymmetries on the Nucleon Experiment" (SANE) will cover a significant part of the experimentally hard to reach region $0.6 \leq x \leq 1$. An extension of the inclusive program to carry out semi-inclusive measurements has been proposed, too. These experiments will be reviewed in some detail.

PACS: 13.88.+e, 21.10.Hw, 13.60 Hb
Key words: nucleon spin, nucleon resonances, polarized electron scattering,

1 Introduction

The Hall C program on spin physics concentrates on the study of the nucleon spin structure functions (SSF's). Started in 2002, the program consists of inclusive polarized scattering experiments that have been completed or are in the planning stage.

The first experiment to measure the proton and deuteron SSF's in the region of the nucleon resonances has been completed (TJNAF E01-006 *RSS*). At the May 2003 PAC meeting, another experiment to measure the proton SSF's in the deep inelastic scattering (DIS) and nucleon resonances regions for $x > 0.3$ "Spin Asymmetries on the Nucleon Experiment" (SANE), was approved as E03-109. In addition, a proposal to measure semi-inclusive hadronic spin asymmetries has been submitted for consideration.

The spin physics program in Hall C takes advantage of the extensive capabilities of Jefferson Lab for polarized scattering:

- The CEBAF polarized electron beam.
- Solid polarized targets jointly operated by the Unversity of Virginia and TJNAF.
- The High Momentum spectrometer (HMS).

– The proposed Big Electron Telescope Array (BETA) non-magnetic detector.

Descriptions of the completed and approved experiments, and a brief summary of the proposed semi-inclusive measurement follow.

2 Resonances Spin Structure - *RSS* (TJNAF E-01-006).

This experiment[1]) was designed to make high precision and high resolution measurements of the spin structure of the proton and deuteron in the region of final state mass $W \leq 2$ GeV that corresponds to the prominent nucleon resonances, at four-momentum transfer $Q^2 \sim 1.3$ [GeV/c]^2. The physics goal was to explore fundamental properties of the nucleon and QCD in this kinematic region, with adequate precision to obtain conclusive information. The neutron spin asymmetries will be extracted from the measured proton and deuteron asymmetries.

For $Q^2 \leq 5$[GeV/c]^2, the $Q^2 - x$ kinematic plane is dominated by the nucleon resonances which, until recently, had barely been studied in polarized scattering. The limited resolution in W that can be achieved at the high energy physics labs where spin physics research has been done in the past, is one of the main reasons for the dearth of polarized resonances data. The Hall C HMS is capable of $\Delta W \leq$ 30 MeV, which combined with CEBAF's 6 GeV beam energy, make it possible to carry out precision measurements of spin structure.

There is a connection between the DIS and resonance's regions of lepton-nucleon scattering, known as Bloom-Gilman (B-G) or local duality [1]. B-G duality can be summarized as the averaging out of the magnitude of the unpolarized structure function $\nu W_2 = F_2$ in the region of the resonances to the extrapolation of its DIS counterpart. The local character of duality is reflected in the fact that the averaging applies to individual resonances, not just to the region as a whole. Quantitatively, local duality can be expressed in terms of the equality of two integrals:

$$\frac{2M}{Q^2}\int_{\nu_a}^{\nu_b} d\nu \nu W_2(\nu, Q^2) = \int_{\omega'_a}^{\omega'_b} d\omega' F_2(\omega')$$
$$\nu_{a,b} = \frac{W_{a,b}^2 - M^2 + Q^2}{2M}, \qquad \omega'_{a,b} = 1 + \frac{W_{a,b}^2}{Q^2} \tag{1}$$

The integrand on the left is the structure function in the resonances, the one on the right is its DIS counterpart, extrapolated to the same region of final state mass $W_b - W_a$. For the unpolarized structure function $F_2^p(W, Q^2)$ this equality obtains to $\pm \sim 0.1$ or better, for each of the major resonance regions starting at $Q^2 \geq \sim 1$ [GeV/c]^2.

Unpolarized local duality has been confirmed at JLab [2] for the proton and deuteron. The earliest mention of local duality in the spin structure functions can

[1]) *RSS* Collaboration (TJNAF E-01-006): U. Basel, Florida International U., Hampton U., U. Massachusetts, U. Maryland, Mississippi S. U., North Carolina A&T U., U. of N. C. at Wilmington, Norfolk State U., Old Dominion U., S. U. New Orleans, U. of Tel-Aviv, TJNAF, U. of Virginia, Virginia P. I. & S. U., Yerevan Physics I.; O. A. Rondon-Aramayo, UVA and M. Jones, JLab, Spokesmen

be found in the original proposal of the *RSS* experiment [3]. If local duality is a reflection of some fundamental nucleon properties and not just the result of some fortuitous coincidences it should also be present for the neutron and for the polarized structure functions [4]. Although existing spin structure data [5, 6, 7, 8] hint at duality in the SSF's, a quantitative confirmation of local spin duality has yet to be done.

The spin asymmetries $A_1(\nu, Q^2)$ and $A_2(\nu, Q^2)$ extend the DIS description of the nucleon spin structure to the region of the resonances. $\nu = E - E'$ is the lepton energy loss, E and E' are the beam and final energies. In this region the nucleon spin structure can be described in terms of either the $G_1(\nu, Q^2)$ and $G_2(\nu, Q^2)$ spin structure functions (SSF's) or A_1 and A_2. The latter are constructed starting from the virtual photon absorption cross sections $\sigma^T_{1/2}$, $\sigma^T_{3/2}$, and $\sigma^{TL}_{1/2}$ for photon helicities +1, -1, 0, respectively:

$$A_1 = \frac{\sigma^T_{1/2} - \sigma^T_{3/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}} = \frac{M\nu G_1(\nu, Q^2) - Q^2 G_2(\nu, Q^2)}{W_1(\nu, Q^2)}$$
$$A_2 = \frac{\sigma^{TL}}{2\sigma^T} = \frac{\sqrt{Q^2}\big(MG_1(\nu, Q^2) + \nu G_2(\nu, Q^2)\big)}{W_1(\nu, Q^2)}, \tag{2}$$

where $2\sigma^T = \sigma^T_{3/2} + \sigma^T_{1/2}$, M is the nucleon mass and $W_1(\nu, Q^2)$ is transverse unpolarized structure function. In the scaling limit of DIS, the structure functions depend (up to logarithmic corrections) only on the scaling variable $x = Q^2/(2M\nu)$:

$$\lim_{Q^2,\nu\to\infty} M^2\nu G_1(\nu, Q^2) = g_1(x)$$
$$\lim_{Q^2,\nu\to\infty} M\nu^2 G_2(\nu, Q^2) = g_2(x)$$
$$\lim_{Q^2,\nu\to\infty} MW_1(\nu, Q^2) = F_1(x). \tag{3}$$

A_1 and A_2 are related to the measured asymmetries $A_\parallel$ and $A_\perp$ for the longitudinal and transverse configurations of the beam and target spins by

$$A_1 = \frac{C}{D}\Big(A_\parallel - dA_\perp\Big)$$
$$A_2 = \frac{C}{D}\Big(c'A_\parallel + d'A_\perp\Big), \tag{4}$$

where C, c', d, d' and D are functions of kinematic variables only (D has an additional mild dependence on the unpolarized structure function $R(\nu, Q^2) = \sigma_L/\sigma_T$).

3 Experimental summary

Polarized electrons of 5.755 GeV beam energy produced by CEBAF were used. The Hall C HMS, parked at 13.15°, was used to detect the scattered electrons. Two central momentum settings were used: 4.7 GeV/c and 4.09GeV/c. The deflection of

the beam downstream of the target in the configuration to measure $A_\perp$ required a special beam pipe and helium bag. The deflection for the upstream beam line was corrected by the Hall C's two-magnet chicane.

The resulting effective kinematics for this energy and HMS angle are shown in Figure 1, which displays Q^2 plotted against the final state mass W. The overlap of the ranges of Q^2 and W covered in each of the two HMS central momentum settings is visible. The band at constant $W = 0.94\,\mathrm{GeV}$ corresponding to $e-p$ elastic scattering can also be seen. The kinematic region covered by the data connects very well with other polarized DIS experiments, for direct comparison of DIS data with data measured in the resonances to study local duality. This choice of kinematics has the additional advantage that the spin structure function $g_1(W, Q^2)$ measured in our experiment can be used to test the extended Gerasimov-Drell-Hearn [9, 10] sum rules with a minimum of interpolations or use of fits to the world data.

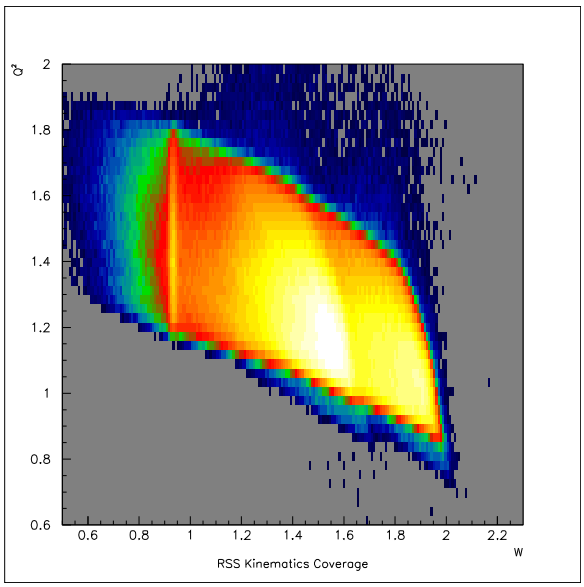

Fig. 1. Kinematics of E-01-006.

The Hall C Møller polarimeter was used to measure the beam polarization. A total of 64 measurements were done during the run. A summary of the average effective beam polarizations for the four configurations of asymmetry measurement and target material is shown in Table 1.

The Hall C beam raster system, as modified for E93-026 (*GEn01*) was used. to distribute the beam uniformly over the target cell face. To verify the actual relative positions of the beam and the target cells, an optics cell with tungsten wire cross-hairs was installed as part of the target insert.

Data were taken on 3 cm long ammonia and deuterated ammonia targets ($^{15}NH_3$

Table 1. Average beam current, beam and target polarizations.

Configuration	Target	Beam I [nA]	Beam polarization	Target polarization
$A_\perp$	NH_3	100	65.6%	69.1%
	ND_3	115	65.6%	18.3%
$A_\parallel$	NH_3	91	71.0%	66.9%
	ND_3	112	71.0%	15.1%

and $^{15}N^2H_3$). The ammonia was polarized by Dynamic Nuclear Polarization (DNP) in a 5 T magnetic field cooled to $\sim$ 1 K by a ^{4}He evaporation refrigerator. The polarization was measured by NMR. Table 1 lists the average polarizations for each species during the corresponding measurement periods.

4 Analysis and Preliminary Results

In addition to the asymmetry data, calibration data were taken for optics studies of the HMS and for background correction. For the latter, data on a C disk target and on a cell alternately empty or filled only with LHe were taken. The polarized target contains ^{15}N, ^{4}He and other materials besides the polarized hydrogen or deuterium. The dilution factor f is defined as the fraction of counts coming from the hydrogen or deuterium in the target. The C and empty target data are used to calculate the packing fraction of ammonia in the cells by comparing the measured C and He rates to model rates. A model of the ammonia target is adjusted to match the data. The same model is used to calculate the dilution factor.

Sample spectra for the ammonia, carbon and helium targets as functions of W together with the current Montecarlo (MC) simulation[2]), and the ratios of Montecarlo to data rates, are shown in Figure 2. The data correspond to a special high HMS momentum setting dedicated to dilution factor modeling. The ammonia model rates are calculated for a a nominal 50% packing fraction. Work to improve the MC/data agreement even further is ongoing . At the moment, MC and data agree to about 10% (better for the parallel configuration than for the perpendicular one).

The measured asymmetries are extracted from the counts asymmetries $\epsilon = (L-R)/(L+R)$, where L, R are charge normalized numbers of counts for opposite beam helicities, corrected for dead time and pion contamination. $A_\parallel$ and $A_\perp$ are related to ϵ by

$$A_{\parallel,\perp} = \frac{1}{C_N f_{RC}} \Big(\frac{\epsilon}{f P_b P_t} - C_D \Big) + A_{RC}. \tag{5}$$

[2]) Hall C's SIMC modified to include polarized target magnetic field and large beam raster. The Born cross sections are modifications of the QFS program [11]

where C_N, C_D are corrections for the small contribution of the polarized proton in ^{15}N, f_{RC}, A_{RC} are the multiplicative and additive radiation corrections, and P_b, P_t are the beam and target polarizations, respectively.

Preliminary uncorrected asymmetries $A_{\perp,\parallel}$ are shown in Figures 3 and 4. The asymmetries are shown only for the restricted kinematic region 1.1 GeV $\leq W \leq$ 1.9 GeV. Data below and above these limits are still being analyzed. Corrections for the actual packing fractions, electromagnetic radiative effects and nitrogen polarization are not included. The $A_\perp$ results are the first and only ones of their kind in the world. A clear difference between the proton and deuteron asymmetries can be seen, in particular for $A_\parallel$. A clean extraction of the neutron asymmetry is expected on this basis.

The analysis of this experiment is the dedicated work of senior physicists and UVA and JLab research associates. Final results are expected by the end of 2003.

5 SANE: *Spin Asymmetries of the Nucleon Experiment*

The unpolarized and polarized structure functions of the nucleon have been studied extensively in DIS for $x \leq\sim 0.6$. The experimentally hard to reach region $0.6 \leq x \leq 1$ has until recently remained largely unexplored. For $Q^2 \leq\sim 5$ [GeV/c]^2 this region, which is dominated by the nucleon resonances, extends to even lower values of x as Q^2 decreases. Above $Q^2 = 5$ [GeV/c]^2, the rapid decrease of the scattering cross section severely limits the counting statistics that can be accumulated in a reasonable length of data taking time.

This "high x" region is of great importance in nucleon structure studies, as a testing ground for the predictions of a broad variety of nucleon models. The approach to $x = 1$ of quantities such as the ratio of d to u quarks, the A_1 spin asymmetry, the ratios of the polarized to unpolarized quark densities $\Delta q/q$, and others, takes very different values depending on models such as helicity conservation based on perturbative QCD, the $SU(6)$ model of quarks, constituent quark models, chiral soliton models, etc. Moreover, the moments of the structure functions, which are related by the Operator Product Expansion (OPE) to quark matrix elements of increasing twist, are weighted by integer powers of x that emphasize the contributions of the high x region. Some of these matrix elements, like the twist-3 d_2, which depends on the transverse spin structure function g_2, can be calculated in lattice QCD, providing a benchmark for this method.

The SANE experiment[3]), conditionally approved by Jefferson Lab's Program Advisory Committee with A$^-$ scientific rating, was proposed to use the Hall C facilities to measure the proton SSF's in the range $0.3 \leq x \leq 0.8$ for 2.5 [GeV/c]$^2 \leq Q^2 \leq 6.5$ [GeV/c]^2. By making use of the *Big Electron Telescope Array* (BETA), a novel type of large solid angle non-magnetic detector, SANE will compensate for the reduction in scattering cross sections to attain excellent statistical precision.

The proton spin asymmetry A_1 and spin structure g_2 will be obtained from inclusive inelastic scattering of polarized electrons on polarized protons in a solid

[3]) TJNAF E03-109, G. Warren *et al.*

ammonia (NH_3) target. Asymmetries for normalized counts of the electrons scattered for opposite beam helicities will be measured for the (anti)parallel (180°) and near-perpendicular (80°) orientations of the polarized nucleon spins relative to the beam helicity, to obtain model independent determination of both structure functions.

Polarized electrons of 6 and 4.8 GeV beam energy will be scattered on the polarized target. The expected $\sim 70\%$ beam polarization will be measured with the Hall C Møller polarimeter. The target protons are polarized in the same University of Virginia system that has been used in E143/E155 at SLAC and E93-026 (*GEn01*) and E01-006 (*RSS*) at Jefferson Lab. Average in beam proton polarization of $\sim 70\%$ has routinely been achieved with this target.

The scattered electrons will be detected in the BETA detector, placed at 40° relative to the beam direction. The kinematic coverage for this angle is shown in Figure 5. The final state mass resolution is better than $\Delta W \sim 120$ MeV down to $W = 1.38$ GeV. This will allow for testing polarized local duality as far as the second resonance region. The solid angle of the system is 0.194 msr after cuts. Figure 6 shows an artist's view of BETA, which consists of three main subsystems:

• A lead-glass calorimeter, consisting of 1792 elements 4 cm by 4 cm by ~ 40 cm. This calorimeter is being built for the Hall C measurement of G_E^p/G_M^p (E01-109). An energy resolution of $5\%/\sqrt{E}$(GeV) is expected.

• A 16 by 8 elements Lucite hodoscope to complement the tracking resolution of the telescope system.

• A Cherenkov detector with a 5.9 GeV/c pion threshold momentum, to reduce the pion background to the 1000:1 rejection level. This level will be achieved with collection of 17-20 photoelectrons per electron.

The target's polarizing magnetic field sweeps most of the low energy background out of the path to the detector. A calorimeter threshold setting of 900 MeV will reduce the remaining background in the near-perpendicular target configuration to less than 0.6% accidental events after off-line cuts. In addition, the HMS will be used to detect positrons from pair production processes, which constitute the main background to the electron asymmetry. The positron rates and asymmetry (if any) will be measured with this method.

Samples of the expected results are shown in Figures 7 and 8. Improvements in the statistical errors of up to 5 times smaller than the current data's are expected. The moments of g_1 and g_2 will be measured with adequate precision to reduce the error on the twist-3 quark matrix element $d_2 = \int_0^1 x^2(2g_1 + 3g_2)dx$ to one half its current value. The error in the extrapolation of A_1 to $x = 1$ will be reduced by 60% relative to its current value, in combination with data from the *eg1* experiment in Hall B.

6 Flavor Decomposition of Nucleon Spin Structure

Spin physics extends well beyond inclusive scattering. Semi-inclusive and exclusive measurements can be used to not only study parton distribution functions

other than g_1 and g_2, but also can be applied to determine the composition by quark flavor of g_1. By detecting hadrons in coincidence with the scattered leptons, individual quark flavors can be tagged by the hadron they associate with. An experiment to measure semi-inclusive spin asymmetries on protons and deuterons in polarized DIS reactions $p(e,e'h)$ and $d(e,e'h)$, where $h = \pi^{+/-}, K^{+/-}$, has been proposed in Hall C (TJNAF PR03-114[4]).

The measurement plans to cover the kinematic range $1.2 \leq Q^2 \leq 3.2$ [GeV/c]^2 and $0.12 \leq x \leq 0.43$, for hadrons carrying energy E_h in the range $0.38 \leq z(= E_h/\nu) \leq 0.71$. The goal of the experiment is to extract the Δu, Δd, Δs, and antiquark flavor composition of the nucleon spin and test factorization using the z dependence of spin dependent yield ratios. Electrons will be detected with a large solid angle non-magnetic detector based on the BETA detector described in the section on SANE (minus the Lucite hodoscope) and hadrons with the Hall C HMS. The experiment plans to use the same U. of Virginia polarized target used in the previous experiments, loaded with ammonia for protons and lithium deuteride (Li^2H) for deuterons.

The proposed technique is to form semi-inclusive asymmetries at fixed z

$$A_1^h(x,z,Q^2) = \frac{\sum_f e_f^2 \Delta q_f(x,Q^2) D_f^h(z,Q^2)}{\sum_f e_f^2 q_f(x,Q^2) D_f^h(z,Q^2)} \tag{6}$$

in terms of fragmentation function ratios $D_h^+/D_h^-, D_f^h/D_h^+$. Since the phase space will be identical for both h^+ and h^-, only ratios of the fragmentation functions are needed, greatly reducing the uncertainty contributed by the fragmentation functions. Then, a fit to all z data points at fixed x is done to determine the quark flavor helicity distributions using known parton distribution functions. Factorization could be tested studying the z dependence of combined h^+ and h^- asymmetries. Combined proton and deuteron data for both h^+, h^- which is independent of the D's adds a further check on whether factorization obtains.

A sample of the expected results is shown in Figure 9.

7 Conclusion

A promising program of spin physics with 6 GeV beam energy has started in Jefferson Lab's Hall C. In addition to the completed and currently in preparation inclusive experiments, a semi-inclusive experiment has been proposed. There is also a preliminary program for the 12 GeV upgrade of CEBAF, which includes doing a full test of polarized local duality on protons and deuterons, extending the semi-inclusive measurements, testing effects of nuclear binding on spin structure with ^{6,7}Li and other nuclear targets, and new ideas with upgraded Hall C equipment (Super HMS, BETA upgrade).

This work was supported by Department of Energy contract DE-FG02-96ER40950 and by the Institute of Nuclear and Particle Physics of the University of Virginia.

[4]) Spokesmen: X. Jiang (Rutgers University), M. Jones (TJNAF) and D. Day (U. of Virginia)

References

[1] E.D. Bloom and F.J. Gilman, Phys. Rev. Lett. **25** (1970) 1140; Phys. Rev. D **4** (1971) 2901.

[2] I. Niculescu *et al.*, Phys. Rev. Lett. **85** (2000) 1186.

[3] O. Rondon-Aramayo, *Precision Measurement of the Nucleon Spin Structure Functions in the Region of the Nucleon Resonances*, CEBAF proposal PR95-005, and CEBAF PAC10 report.

[4] F. E. Close and N. Isgur, Phys. Lett. **B509** (2001) 18.

[5] E143 collaboration (K. Abe *et al.*), Phys. Rev. D **58** (1998) 112003 .

[6] TJNAF E94-010, Z-E. Meziani, private communication.

[7] TJNAF eg1, S. Kuhn, private communication.

[8] HERMES Collaboration (A. Airapetian *et al.*), Phys. Rev. Lett. **90** (2003) 092002-1, and A. Fantoni, private communication

[9] V.D. Burkert and B.L. Ioffe, *et al.*, Phys. Lett. B **296** (1992) 223.

[10] X. Ji, Report MIT-CTP-2288, March 1994

[11] J. Lightbody and J. O'Connell, Computers in Physics, May/June 1988, p. 57

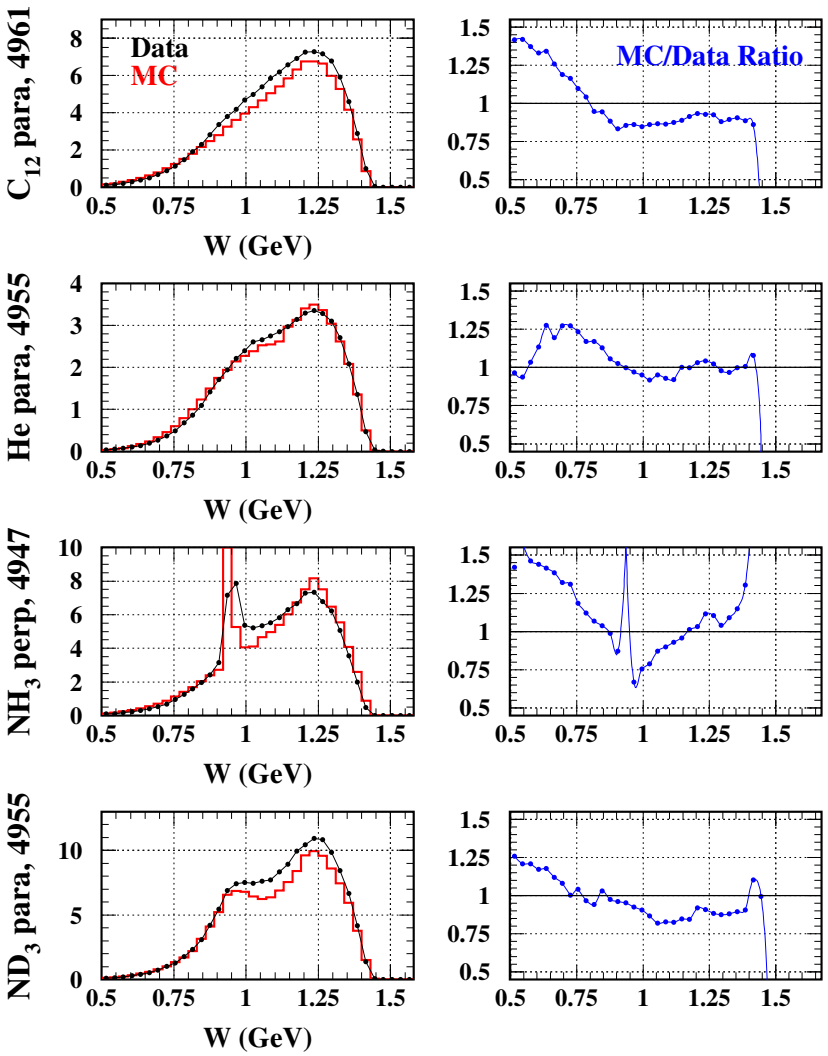

Fig. 2. Carbon, helium and ammonia spectra for the HMS high momentum setting (black circles) and Montecarlo (MC) simulation (red histograms) versus final state mass. The MC represents absolute rates calculated with a single normalization factor for C and He. The ammonia MC rates are calculated for a nominal 50% packing fraction. The ratio MC to data rates is shown in blue.

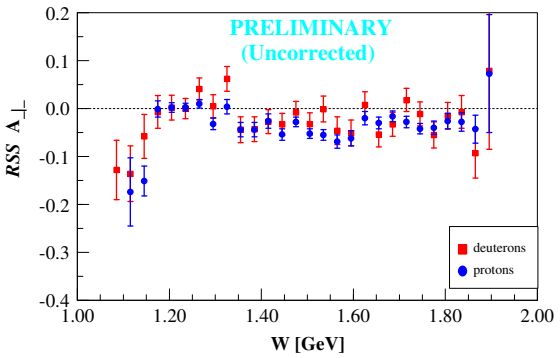

Fig. 3. Preliminary measured asymmetry for the perpendicular configuration for protons (blue circles) and deuterons (red squares), without corrections (see text for details).

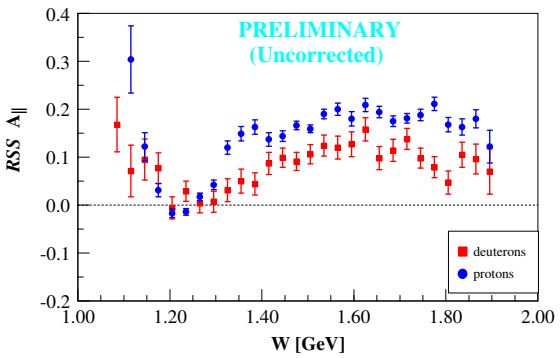

Fig. 4. Preliminary measured asymmetry for the parallel configuration for protons (blue circles) and deuterons (red squares), without corrections (see text for details).

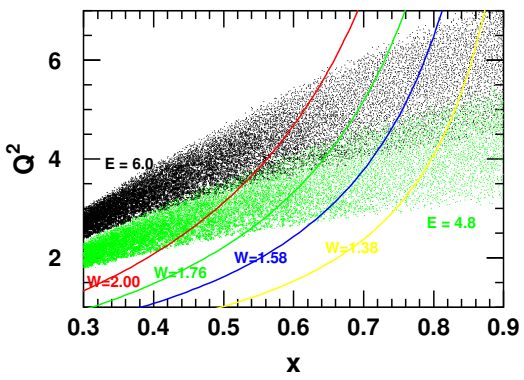

Fig. 5. Kinematics of SANE. The region covered by the 6 GeV beam energy is indicated by the black points (upper band), that covered by the 4.8 GeV energy is in green (lower band). Curves of constant final state masses are shown, too.

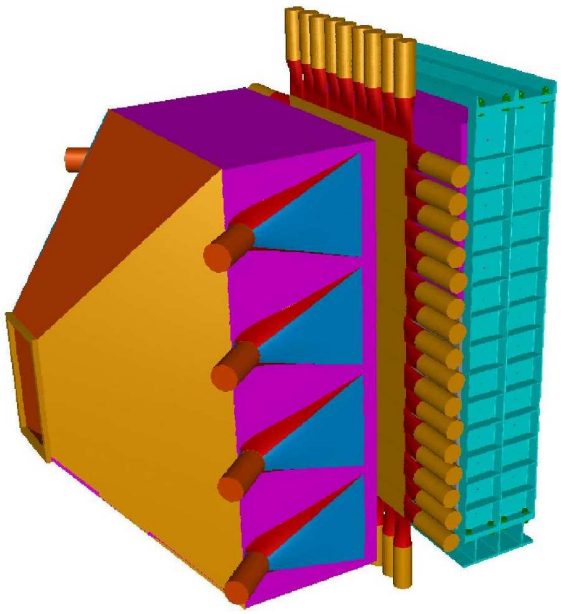

Fig. 6. Artist view of BETA. The sideways pyramid shaped object at left (orange and purple) is the Cherenkov detector, the stack of rectangular blocks on the right (blue) is the calorimeter. The Lucite detector is sandwiched in between.

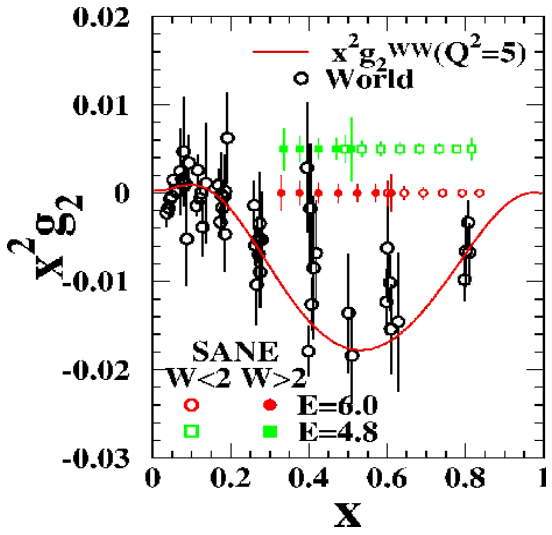

Fig. 7. Expected results for g_2 (small red and green circles) and world data (large circles).

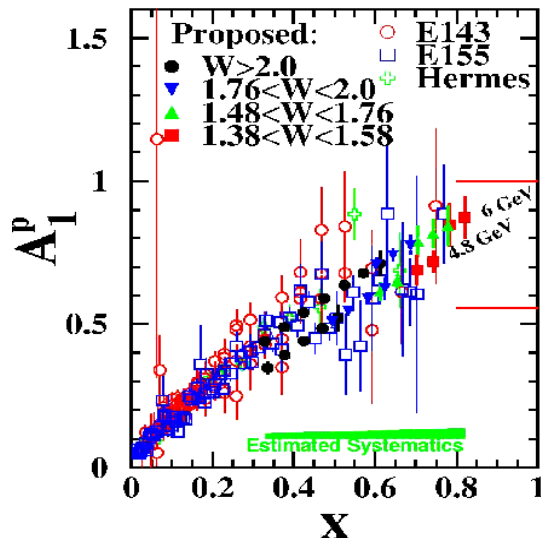

Fig. 8. Expected results for A_1^p (solid symbols) and world data (open symbols).

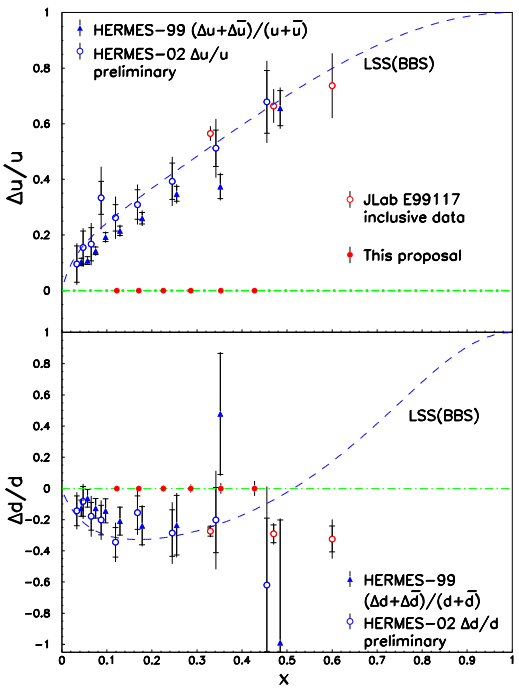

Fig. 9. Expected results for PR03-114 and world data.