The BONuS Experiment: New Results and Future Plans*

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Abstract

Knowledge of both neutron and proton structure functions is necessary in order to determine the valence quark distributions in the nucleon. Measurements on the neutron typically use nuclear targets, but the results are complicated by nuclear binding and nucleon off-shell effects. In the BONuS (Barely Offshell Nucleon Structure) experiment at Jefferson Lab, 4.2 and 5.3 GeV electrons were scattered from a gaseous deuterium target. A Radial Time Projection Chamber (RTPC) was used to detect the low energy spectator protons, thus enabling a cleaner investigation of the neutron. Results for the unpolarized neutron structure function F_2^n, as well as the neutron to proton ratio F_2^n/F_2^p are presented. The range of validity of the spectator model is discussed. These results may be important for neutrino-nucleus scattering experiments in order to understand nuclear background processes. We also report on an investigation of the EMC effect in deuterium.

INTRODUCTION

The behavior of parton distribution functions at high Bjorken x is of great interest to the nuclear and particle physics communities. To focus on just one example, the ratio of d and u quark distributions d/u as $x \to 1$ depends sensitively on the mechanism by which spin-flavor symmetry is broken [1]. An understanding of both neutron and proton structure is important in order to access the underlying u and d valence quark distributions. The ratio of the unpolarized structure function F_2 for the neutron and proton is sensitive to the d/u ratio at high x via

$$\frac{F_2^n}{F_2^p} = \frac{1 + 4d/u}{4 + d/u}.$$

In order to investigate this ratio, one needs data on both proton and neutron targets. Neutron structure information is also needed for the analysis of neutrino-nucleus scattering experiments, such as MiniBooNE, MINERvA, T2K, ND280, etc.

Unfortunately our access to neutron structure functions is limited by the lack of a free neutron target. Experiments on nuclear targets are plagued by the uncertainty inherent in corrections for off-shell and binding effects, which are especially problematic at large x [2].

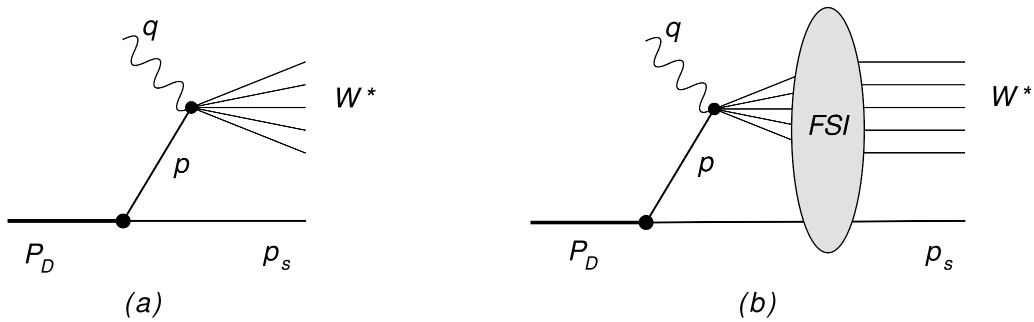

FIG. 1: Schematic of electron scattering from the deuteron, with detection of the spectator proton p_s. Final state interactions are shown in (b) [3].

BONUS EXPERIMENT

To approximate a free neutron target, the BONuS collaboration has successfully used a deuterium target and detected the low energy, recoil proton, which allows us to correct for the initial (Fermi) momentum of the neutron in the deuteron. This spectator tagging technique is illustrated in Fig. 1. Calculations have shown that Final State Interactions (FSI) can be minimized for low momentum spectator protons ($p_s < 100$ MeV/c) recoiling at angles relative to the momentum transfer from the electron, θ_{pq}, greater than 100 degrees [4]. Off-shell effects are similarly negligible for $p_s < 100$ MeV/c [5, 6].

Electrons of energy 2.1, 4.2 and 5.3 GeV were scattered from a 7 atm D_2 target of length 20 cm in Hall B at Jefferson Lab and detected in the CEBAF Large Acceptance Spectrometer (CLAS) [7]. The target was surrounded by a Radial Time Projection Chamber (RTPC) [8], which was designed to minimize the material through which low energy protons had to travel. A schematic of the RTPC is shown in Fig. 2. A longitudinal magnetic field of 3.5 and 4.7 Tesla was provided by a solenoid surrounding the RTPC and enabled the proton momenta to be determined from the radius of curvature of their trajectory. Ionization electrons produced by the proton drifted to the first of three layers of Gaseous Electron Multiplier (GEM) foils at a radius of 6 cm. The electrical signal was amplified in the three layers of GEM foils and then detected on readout pads, which recorded the amplitude of the signal in 114 ns bins. The maximum drift time was about 6 μs.

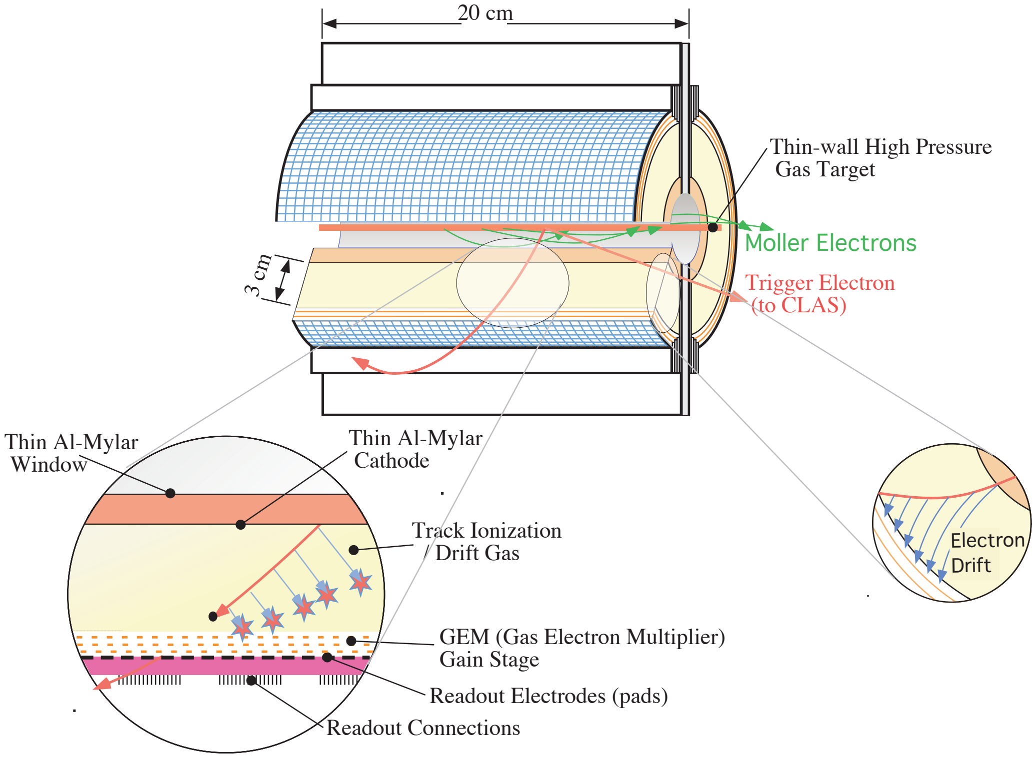

FIG. 2: Schematic of the Radial Time Projection Chamber, which includes three layers of GEM detectors [3].

DATA ANALYSIS

The power of the spectator tagging technique can be seen in Fig. 3, which shows the nucleon resonance region plotted as a function of the invariant mass, W, of the virtual photon plus nucleon (black symbols), which assumes a free nucleon target and is calculated entirely from the initial and scattered electron. If one uses the spectator proton kinematics in order to calculate the true neutron momentum in the deuteron, one finds an invariant mass distribution, W^* (red symbols) that is closer to that of the free proton. In this case, the Fermi momentum of the neutron in the deuteron is properly taken into account. The BONuS data were analyzed in two ways. First a set of Very Important Proton (VIP) events were defined to include protons with momenta less than 100 MeV/c and scattering angles θ_{pq} greater than 100 degrees. These VIP events are ones in which Final State Interactions and other nuclear effects are minimized, as described above. For these events the ratio of tagged to inclusive scattering events was calculated as a function of the various kinematic

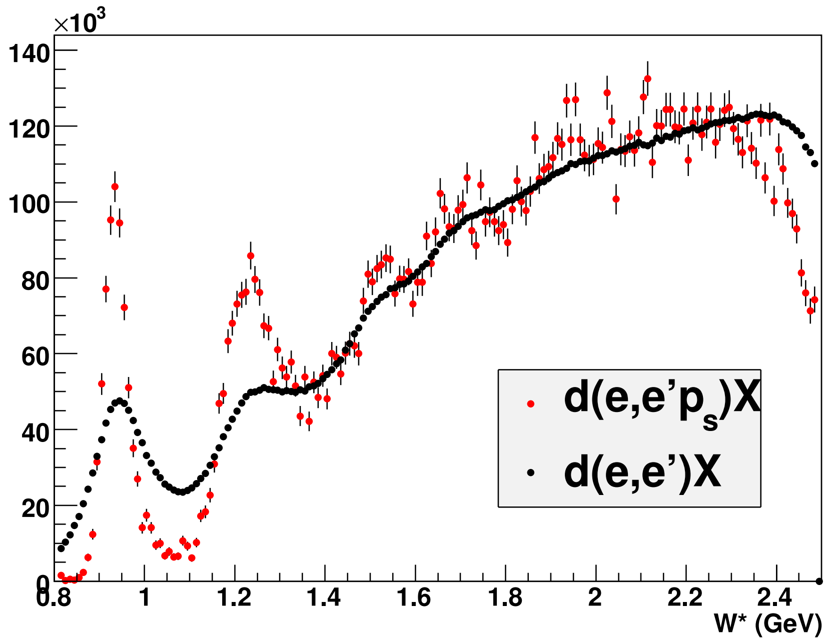

FIG. 3: W^* for inclusive electron scattering on the deuteron (black) and semi-inclusive [9].

variables. After corrections to account for background differences and a singe normalization factor determined from a new parametrization of world data by Christy *et al.* [10–12] we found F_2^n/F_2^d. Some of the 5.3 GeV data are shown in Fig. 4 in bins of momentum transfer Q^2.

A second approach was to use all tagged data (*i.e.* not only the VIP events), and divide by data simulated using the spectator model in every kinematic bin. The resulting ratio, known as $R_{D/S}$, deviates from 1 in bins where the data do not match the Monte Carlo prediction and is therefore an indication of the range of validity of the spectator model. Multiplying by the spectator model for F_2^n results in a model dependent result for the neutron structure function, called $F_2^{n,eff}$. The systematic errors in the two methods of analyzing the data are different, but the results are very similar [3]. Fig. 5 shows an example of the ratio $R_{D/S}$ as a function of θ_{pq} for various ranges in spectator momentum. In general the data are consistent with the spectator model for low proton momenta and backward angles, although there is some deviation even for the 2nd lowest momentum bin. Detailed results from the BONuS experiment can be used to test FSI calculations (see, e.g., Ref. [13]).

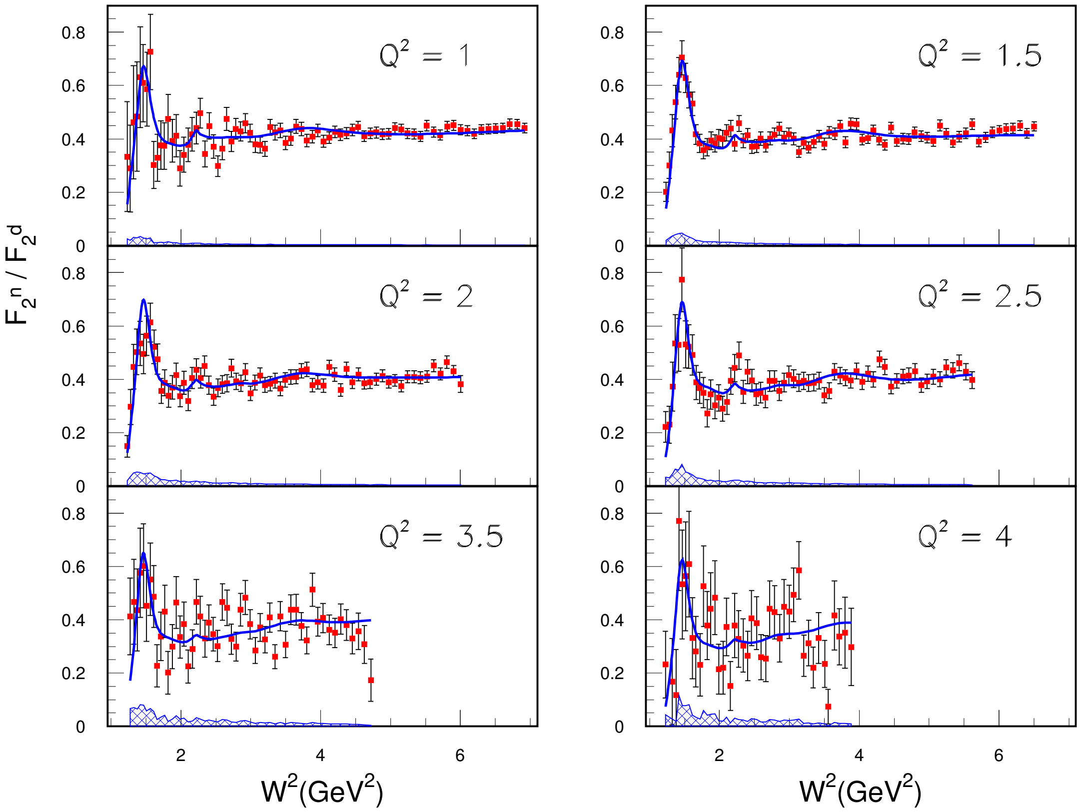

FIG. 4: Ratio of F_2^n to F_2^d for 5.3 GeV data in bins of Q^2. Results are only for VIP events (see text for details) [3]. The curve is a new parametrization of world data by Christy *et al.*, [12], which was used to normalize the data. The blue hatched band represents the point-to-point systematic uncertainty.

RESULTS

To extract the neutron structure function F_2^n we start with the ratio of tagged to untagged VIP events, as described above (see, e.g., Fig. 4). We multiply these ratios by F_2^d as determined by a new fit to world data from Christy *et al.* [12], which does not include the BONuS data. The resulting values for F_2^n are model dependent, mainly via the normalization factor that comes from the world parametrization. Fig. 6 shows the final result for both the 4.2 and 5.3 GeV data, together with the Christy fit to world data. One can see that the world data parametrization describes the data well, but that it averages out the resonances somewhat, because the fit is based on deuteron data.

Finally, we can take our result for F_2^n/F_2^d and calculate F_2^n/F_2^p using world data for F_2^d

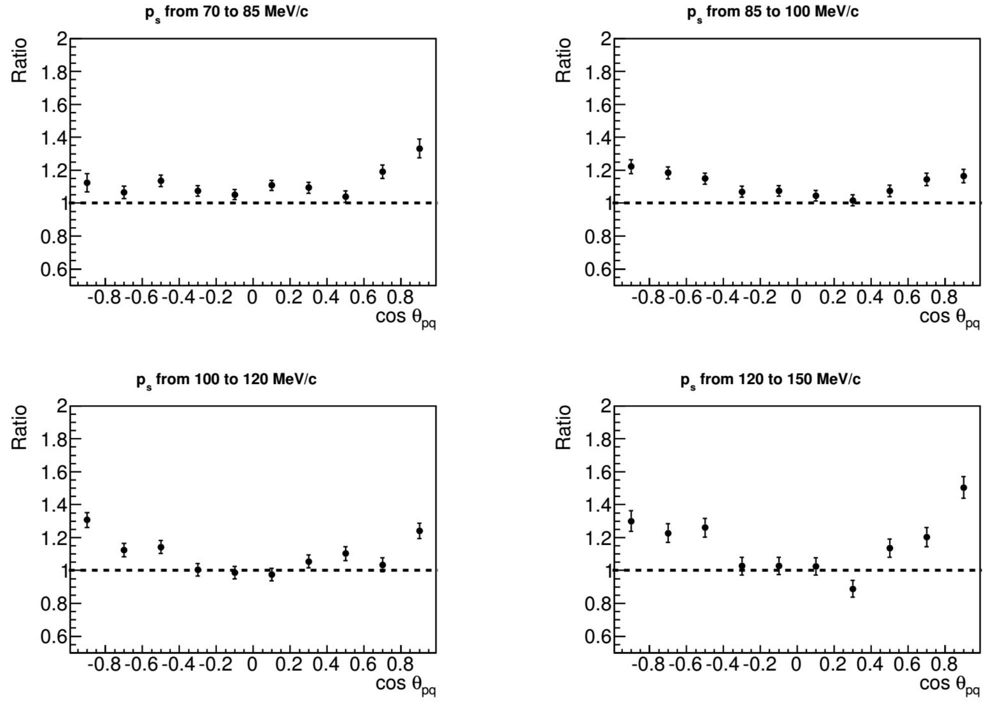

FIG. 5: Ratio of tagged events to events simulated in the spectator model as a function of θ_{pq} for various ranges of spectator proton momentum. These data are for one Q^2 bin (1.10 - 2.23 GeV^2/c^2) and one W* bin (1.35 - 1.6 GeV/c^2). Systematic uncertainties are shown by the shaded band [3].

and F_2^p in deep inelastic scattering (DIS) kinematics to investigate the behavior of u/d as x approaches 1. Our result is shown in Fig. 7. The highest x accessible to our data depends on the lower limit of W^* that is included, but for the safest integration limit our ratio only goes out to $x \approx 0.6$. Data at higher beam energy is needed, and we are now preparing a new BONuS experiment that will use the upgraded beam energy at Jefferson Lab [14].

Another interesting topic that can be investigated with the BONuS data is the possibility of measuring an EMC effect in deuterium [15]. The EMC effect refers to the deviation from 1 of the ratio of the F_2 structure function for a nucleus compared to "free" nucleons, usually taken as F_2^d. The slope of the ratio between $x = 0.3$ and 0.7 is often taken as indicative of the size of the EMC effect in a nucleus. But what about the deuteron itself? One can construct the ratio of F_2^d to the sum of F_2 for the proton and neutron, as shown in Fig. 8. There is a noticeable slope to the ratio, which is consistent with the calculation by Kulagin and Petti [16]. The EMC slope in the deuteron is consistent with the trend that relates the

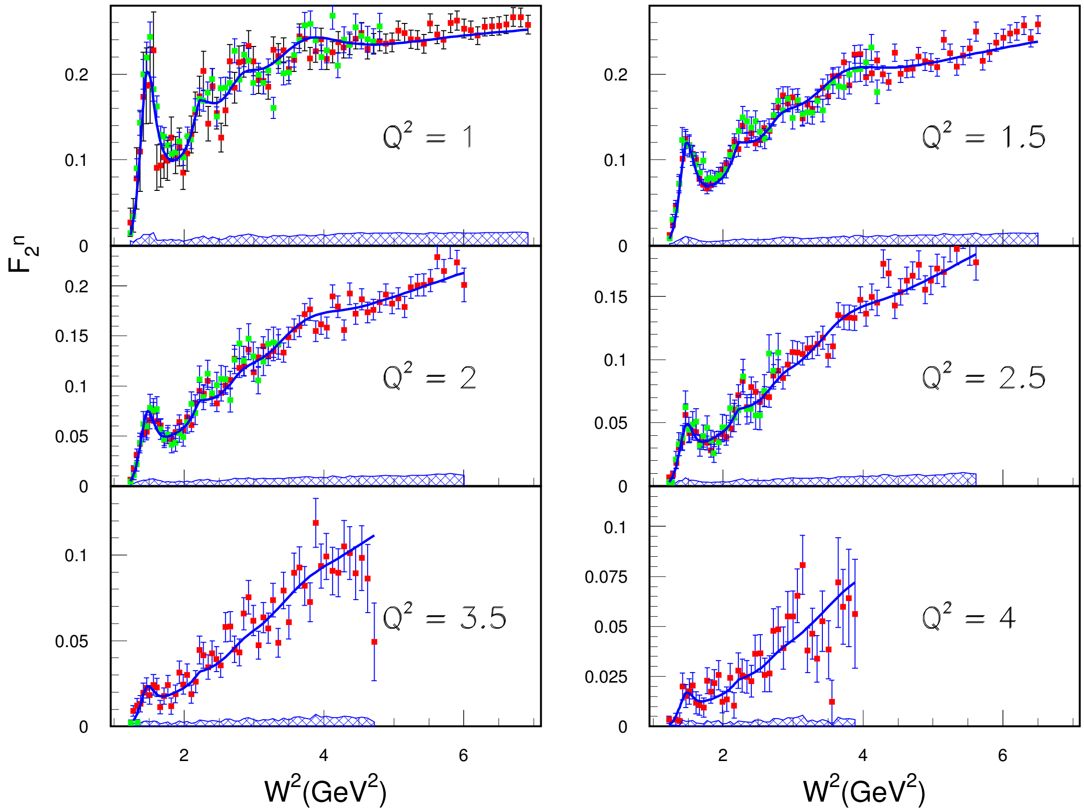

FIG. 6: BONuS result for F_2^n extracted for VIP events (see text). The curve is a new parametrization of world data by Christy *et al.*, [12], which does not include the BONuS data. Results for a beam energy of 4.2 GeV (5.3 GeV) are shown in green (red). The blue hatched band shows the systematic uncertainty for the 5.3 GeV data. The size of the systematic uncertainty for the 4.2 GeV data is similar.

size of the EMC effect to the probability of short range correlations in a nucleus [15, 17].

SUMMARY

In the BONuS experiment at Jefferson Lab 4.2 and 5.3 GeV electrons were scattered off of a gaseous deuterium target. Detection of the low energy recoiling protons in the RTPC enabled us to tag events in which the electron scattered from the neutron in the deuteron. At low spectator momenta and backward angles the events are relatively free from final state and other nuclear effects, which makes it possible to extract the structure function of the neutron F_2^n over a wide kinematic range. These results are useful for understanding

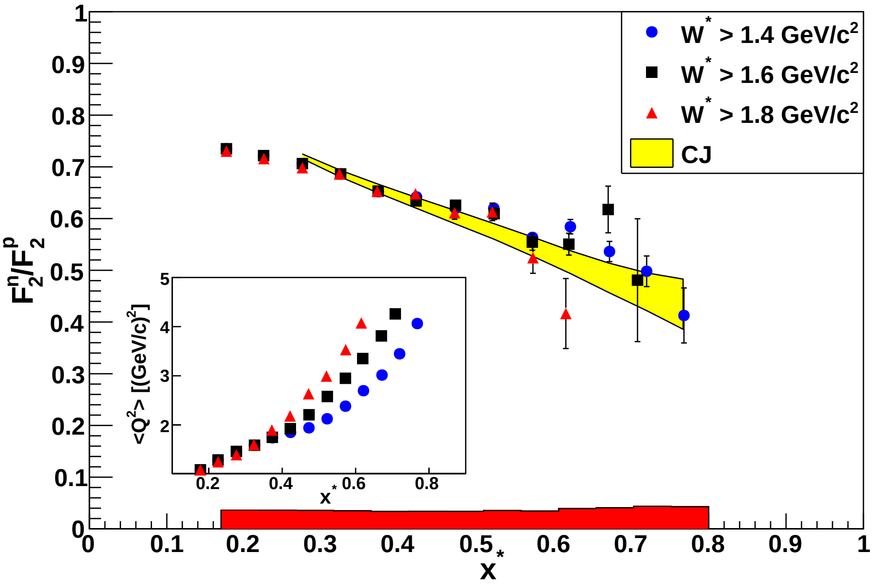

FIG. 7: Ratio of F_2^n/F_2^p as a function of Bjorken x for various integration limits in W^* [3]. The red band indicates the systematic uncertainty. The global parton distribution function fit by Accardi *et al.* [2] is shown as the yellow band.

background events in neutrino-nucleus scattering experiments, and for studying the behavior of the quark distributions d/u at large Bjorken x.

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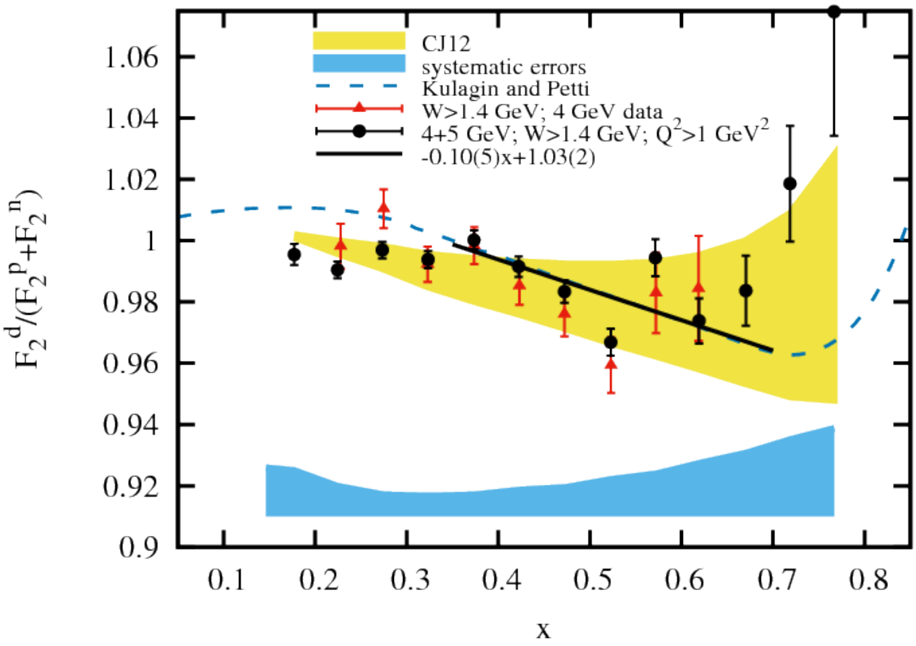

FIG. 8: Ratio of F_2^d to the sum of F_2 for the proton and neutron [15]. The black circles include the 4.2 and 5.3 GeV data. The red triangles are the 4.2 GeV data only. The systematic errors are shown by the blue band. The yellow band represents the range of predictions arising from global fits that use three different nuclear models for deuteron data [18].

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