Designing a Tritium Target for the MARATHON Experiment

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1. Abstract

Designing the Tritium Target for the MARATHON Experiment. NICK LUBINSKY (Rensselaer Polytechnic Institute at Troy, New York, 12179) PATRICIA SOLVIGNON (Thomas Jefferson National Accelerator Facility, Newport News, VA 23606).

All interactions in the physical world can be broken down to four different forces; the strong force, gravity, electromagnetic force, and the weak force. The strong force is mediated by gluons acting upon quarks, antiquarks, and gluons themselves. Previously, data was obtained on the quark distribution ratio using hydrogen and deuterium. Therefore, the extraction of the neutron structure function from deuterium data depends heavily on nuclear corrections embedded in the deuteron wavefunction. Subsequently, assuming nuclear corrections are dependent only on the atomic mass, there are no better candidates for testing than mirror nuclei. This allows us to have a scattering ratio between protons and neutrons and by extension their constituent quarks, since the only difference between a neutron and proton is the interchange of an up to a down quark. Three different theoretical predictions exist from Special Unitary 6 Symmetry (SU(6)), SU(6) breaking, and perturbative quantum chromodynamics (pQCD) (the explanation of these theories are beyond the scope of this paper). The focus of this study is to devise an experiment capable of determining the distribution of quarks inside the nucleus, as well as support or refute towards one of these three predictions. Simulations were created of the tritium target with the simulation program Geant4. Specifically, collimators were designed over the target windows to minimize contamination emanating from the aluminum container, as well as to evaluate the heat deposited in the crucial elements of the target system. It was found that tungsten rectangular block collimators with a cylindrical section removed asymmetrically was particularly effective at this event biasing. Extensive work is being done on this simulation. It is shown that tungsten collimators can be just as effective at event biasing as other methods, such as magnetic displacement. This result will aid in the attainment of Jefferson Lab target safety requirements thereby allowing the next stage of target development.

2. Introduction:

In the past, experiments have been run to try to determine the quark distribution ratio between protons and neutrons. Previously, this distribution was obtained using hydrogen and deuterium targets. However, due to this deuteron, large nuclear corrections had to be made on the acquired data. Also, there are three plausible predictions arising from several independent theories. These theories are Special Unitary Group 6 Symmetry (SU(6)), SU(6) breaking, and Perturbative Quantum Chromodynamics (pQCD). Each of these theories predict very different outcomes at Bjorken x = 1. To clarify the situation, this experiment will use light mirror nuclei for which nuclear corrections are comparable. Consequently, mirror nuclei necessitate the assumption that the quark distribution is only dependent on the atomic mass of particles. Therefore, the experiment was chosen to run using a tritium and helium-3 target, and then compare the ratio. As such, the safety requirements of the tritium target had to be ascertained. To meet these requirements, collimators were designed and tested over a range of vital angles. Vital angles, which were 20 to 30 degrees from the detector, were critical in this simulation because at these angles, the downstream collimator has the greatest probability to interfere with unadulterated tritium scattering. By isolating just the scattering from the aluminum, it is possible to calculate the efficacy of the target window collimators, even more so for the isolated tritium.

This experiment relies heavily upon Electron-Nucleon Deep Inelastic Scattering (DIS), which is closely related to soft sphere scattering. Essentially, during an inelastic collision between an electron and a nucleon, such as a proton or neutron in this experiment, a virtual photon is emitted. One of the nucleon's quarks then absorbs this virtual photon and subsequently the nucleon breaks apart into several other hadrons, as can be seen by this Feynman diagram (see Figure 1).

For this DIS scattering, the nucleon structure functions F_1 and F_2 are as follows:

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x)$$

$$F_2(x) = x\sum_i e_i^2 q_i(x)$$

These structure functions are based on the Quark-Parton Model (QPM) in terms of quark probability distributions $q_i(x)$[1].

The cross section for the collisions is calculated as well. The differential cross section

$$\frac{d\sigma}{d\Omega \mathrm{dE}'} = \frac{\alpha^2}{4E^2\sin^4\left(\frac{\theta}{2}\right)}\left[\frac{F_2}{v}\cos^2\left(\frac{\theta}{2}\right) + \frac{2F_1}{M}\sin^2\left(\frac{\theta}{2}\right)\right]$$

where $v = E - E'$, E is the initial energy, E' is the energy after the collision, and M is the mass. From this, we can surmise then that the probability of reflection R is

$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_2 M}{F_1 v}\left(1 + \frac{v^2}{Q^2}\right) - 1$$

where $Q^2 = 4EE'\sin^2(\frac{\theta}{2})$. The Bjorken x, or fraction of the nucleon momentum carried by the struck quark, is given as $x = \frac{Q^2}{2Mv}$.[1]

Now, the QPM has the initial assumption that isospin symmetry is in effect. Isospin symmetry implies that the number of up quarks within the proton is equivalent to the number of down quarks in the neutron, the number of down quarks in the proton is equivalent to the number of up quarks in the neutron. Subsequently, the structure functions for the proton and neutron are $F_2^p = x\left[\frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}) + \frac{1}{9}(s+\bar{s})\right]$ and $F_2^n = x\left[\frac{4}{9}(d+\bar{d}) + \frac{1}{9}(u+\bar{u}) + \frac{1}{9}(s+\bar{s})\right]$, respectively. Therefore, this satisfies the Nachtmann inequality of $\frac{1}{4} \leq \frac{F_2^n}{F_2^p} \leq 4$. Applying the limit at Bjorken x approaching 0, F_2^n/F_2^p approaches 1.[1] However, as x approaches 1, F_2^n/F_2^p approaches ¼. This implies that the high momentum partons within the proton are up quarks and those within the neutron are down quarks. As such, without much loss of generality, the ratio becomes $\frac{F_2^n}{F_2^p} = \frac{\left[1+4\left(\frac{d}{u}\right)\right]}{\left[4+\left(\frac{d}{u}\right)\right]}$

where d and u denote the quark plus anti-quark distributions.[1]

The F_2^n/F_2^p ratio was so vastly different at large Bjorken x due to not fully understood binding and EMC effects (where the EMC effect is where nucleons inside a nucleus have a different distribution of momentum among their component quarks) in the deuteron. The deuteron structure function convolution, in terms of free nucleon structure functions as calculated in a covariant framework, is:

$$F_2^d(x,Q^2) = \int f(y)\left[F_2^p(x,Q^2) + F_2^n(x,Q^2)\right]dy$$

where the spectral function f(y) accounts for Fermi motion and the binding effects, and y is the fraction of the nucleus momentum carried by the struck nucleon.[1] Furthermore, the EMC effect for deuteron scales with nuclear density, similar to heavy nuclei. Subsequently, all these effects coalesce into a giant margin of error, as Figure 6 illustrates. As a direct consequence of this, the projected experiment has a wide array of projected data due to the large uncertainty arising from a deuterium target, as can be seen in Figure 7.[1]

Since using deuterium carries a large uncertainty in the extraction of the neutron and subsequently the quark distribution, tritium and helium-3 will be used. As such, the structure functions for tritium and helium-3 are

$$F_2^{\,^3H} = f_n \otimes F_2^p + 2f_p \otimes F_2^n \text{ and } F_2^{\,^3He} = 2f_p \otimes F_2^p + f_n \otimes F_2^n$$

respectively. (The symbol $\otimes$ means the direct product.) Here, isospin symmetry implies that

$$f_{n/\,^3H} = f_{p/\,^3He} \equiv f_p \text{ and } f_{p/\,^3H} = f_{n/\,^3He} \equiv f_n$$

Again, f_p and f_n are the spectral functions, or functions portraying generalized density of states, for the proton and neutron, respectively ($f_{p/\,^3He}$ is the spectral function for the proton within the tritium, etc.). [1]

The SU(6) theory depicts some interesting predictions. The ratio F_2^n/F_2^p approaches 2/3 while d/u approaches ½. [1]

Of the predictions, the Broken SU(6) Quark Model, relying on Regge Theory, considers a diquark spectator configuration. For this configuration, spin one is suppressed relative to spin zero within the nucleon wavefunction [1]. Therefore, F_2^n/F_2^p approaches ¼ and d/u approaches zero.

Last of all the predictions, pQCD consider diquark spins. When these spins are aligned, only the exchange of longitudinal gluons is permitted. This in turn suppresses Compton scattering amplitude. Furthermore, the quark carrying nearly all the momentum of the nucleon (x~1) must have the same helicity as the nucleon. Consequently, F_2^n/F_2^p approaches 3/7 and d/u approaches 1/5 as x approaches one.[1]

The purpose of this experiment is to determine the quark distributions between the proton and neutron. The difference in the electron scattering cross section between helium-3 and tritium “directly” yields the difference in scattering between the proton and neutron. Essentially, this will be an invaluable electron scattering tool. Further possible studies continuing on this research include more deep inelastic scattering at Bjorken x>1. More in depth research possibilities such as quasi-elastic and elastic scattering are also feasible.

In regards to the experiment, several safety precautions had to be implemented. Some previous precautions included lowering the density of the tritium target and increasing the target aluminum window thickness. Another such precaution was the introduction of tungsten window collimators.[2] These collimators have the purpose of reducing the events emanating from the aluminum container and interfering with the tritium or helium-3 events. These collimators also had to be minimally intrusive, as these collimators can easily contaminate target scattering at low angles. It was determined that the worst window contamination for the kinematic settings occurred when the spectrometer is positioned at 20 and 30 degrees. Another safety precaution was to determine where energy was being deposited, and the quantity deposited. Having the insight into energy deposition allows for precautionary action. Consequently, these safety precautions would allow for adequate data collection with minimal interference.

3. Materials and Methods:

To construct a target capable of determining the quark distributions within hadrons, several biasing factors became increasingly significant. The first of which is target window event biasing. Specifically, the contamination from the end caps where the beam enters the pressure tank full of tritium is very prominent in the data. Using the software Geant4, many simulations were prepared using different designs of tungsten blocks to cut out interfering aluminum events.

First of all, energy calculations were improved upon. Code was implemented that tracked all object interactions and recorded energy deposited per material, then tallied per event. This energy deposition could then be converted into net power in watts, and then subsequently used to determine whether cryogenic cooling would be necessary.

Next, tungsten collimators were implemented. A multitude of shapes and orientations were tested for both efficiency at removing aluminum events and for minimal impact on the tritium events. At 20 and 30 degrees, the shape of the collimators were further stressed and restricted by their size. At these angles, the back end of the collimators began to interfere much more frequently.

4. Results:

Thus far several independent tungsten collimators have been run at the most forward scattering angles requested by the experiment. At these angles, the designs play a critical role. From the simulation, integrals were calculated on the events that hit the detector: one for the downstream aluminum collimator, one for the upstream aluminum collimator, and one for the tritium events. This integral was then divided by the number of total events, to provide a rate in Hertz. The data collected is tabulated within Table 1. Thus far, three shapes were designed and implemented at varying distances from the target. One of these was a simple bar of tungsten 1.75 cm by 5 cm by 5 cm. Another shape was a hemi-cylinder of 1 cm thickness, 5 cm height, and 3.75cm outer radius. Last of all that was tested was a rectangular block with a cylindrical chunk removed asymmetrically.

5. Data Analysis and Conclusion:

At this time, the initial analysis of the collimators is underway. From the data, it appears that the designs of those that were tested were overzealously thin; multiple scattering is occurring within the collimator and thereby the secondaries generated are interfering with the detector, causing an increase in rates.

To summarize, many experiments have been run to determine the quark distribution within the proton and neutron that used deuterium and hydrogen. As deuterium relies heavily on theoretical calculations, this experiment will compare the mirror nuclei of tritium and helium-3 to determine the quark distribution without the complicated and misunderstood corrections applied to deuterium. This requires safety requirements to be met, such as thick entrance and exit windows of the target, and low tritium density. As a result, it was necessary to incorporate window collimators. Preliminary analysis of the collimators is still underway. Currently, those that were tested were slightly too thin, causing multiple scattering to occur and these secondaries interfered with the detector, increasing the rates. With these collimators, the tritium events can be collected faster and with minimal contamination. Therefore, the quark distribution investigation can be pursued further. The tritium target design and the simulation will allow for the development of many more experiments looking, for example, at Bjorken $x \geq 1$ inelastic scattering, short-range correlations[3][4], and also elastic scattering.

6. Tables and Figures:

Table 1: Collimators vs. Rates and Energy Deposition

Collimator Shape	Angle	Tritium Rate (Hz)	Aluminum Window Rate (Hz)	Energy Deposited in Collimator from Window Events
No collimator	20 degrees	2009.33	4378.35	--
No Collimator	30 degrees	Still Simulating	Still Simulating	--
Bar	20 degrees	2026.85	4393.67	Still Simulating
Bar	30 degrees	257.797	792.032	19.2 TeV
Cylinder	20 degrees	Still Simulating	Still Simulating	Still Simulating
Cylinder	30 degrees	Still Simulating	Still Simulating	Still Simulating
Block with Removed Section	20 degrees	Still Simulating	Still Simulating	Still Simulating
Block with Removed Section	30 degrees	Still Simulating	Still Simulating	Still Simulating

Figure 1: Feynman Diagram

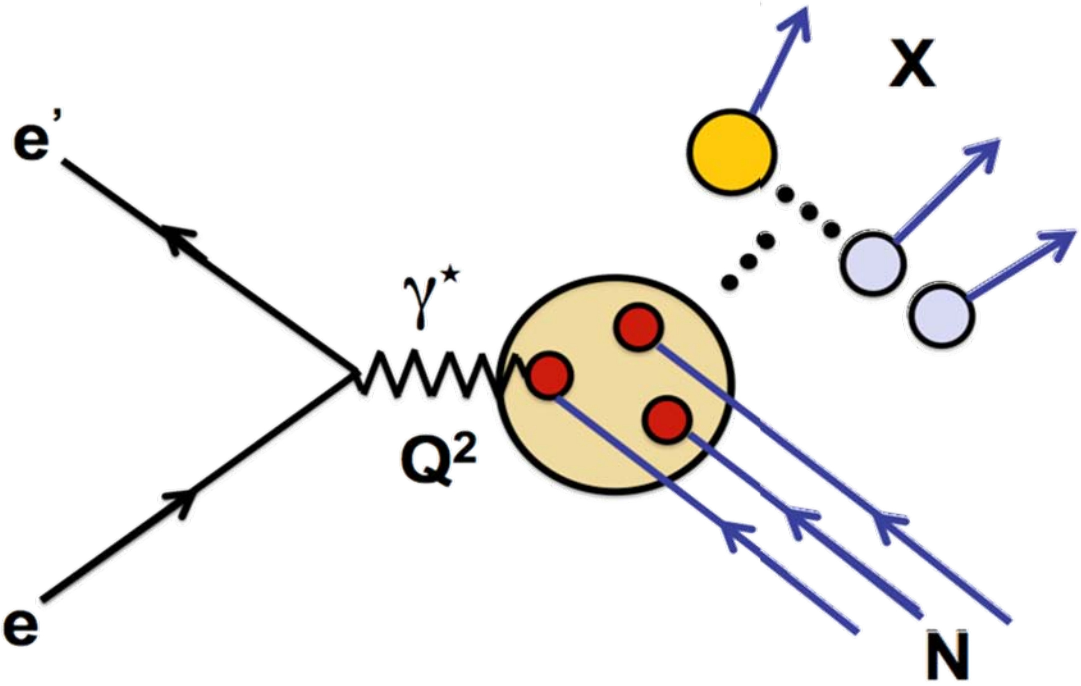


Figure 2: Spectrometer Setup

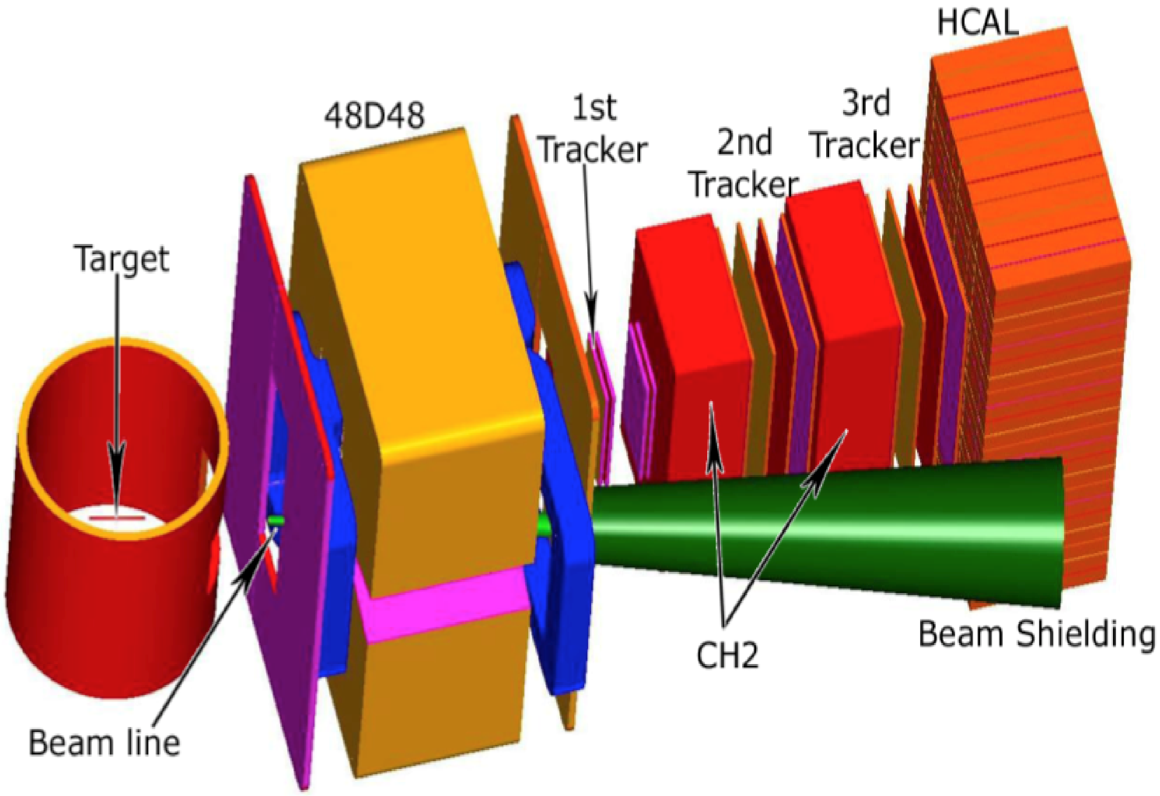


Figure 3: Target Design

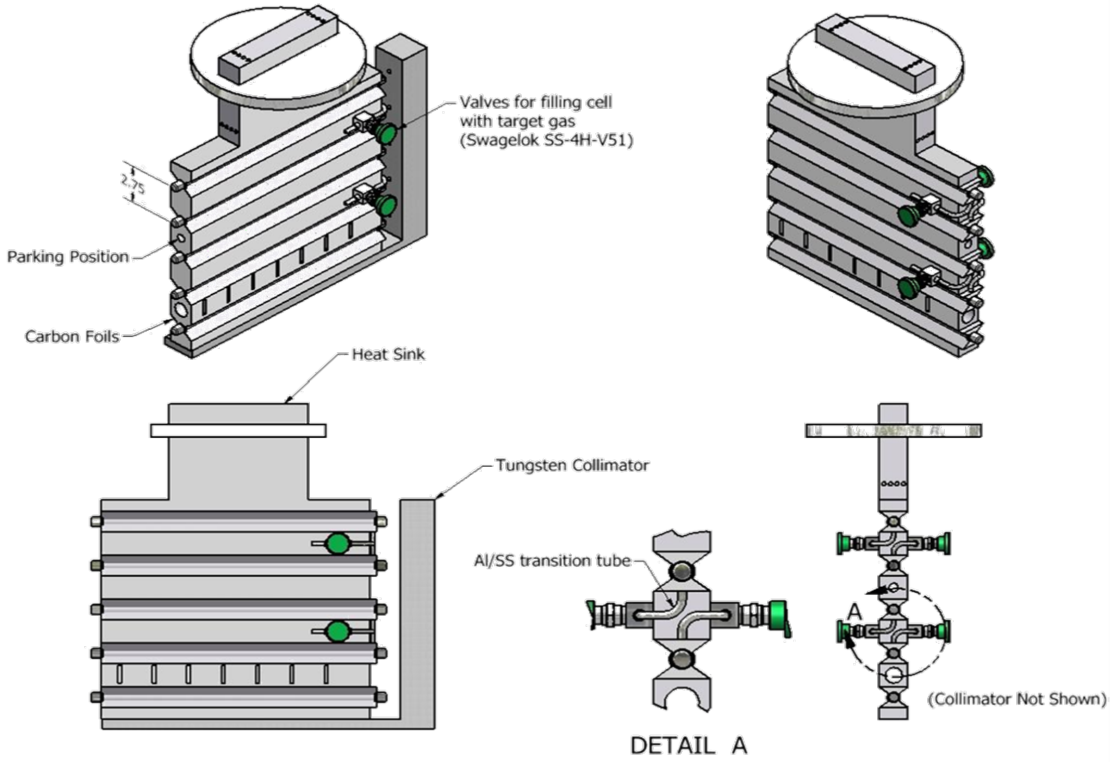


Figure 4: Geant4 Simulation of Tritium Events

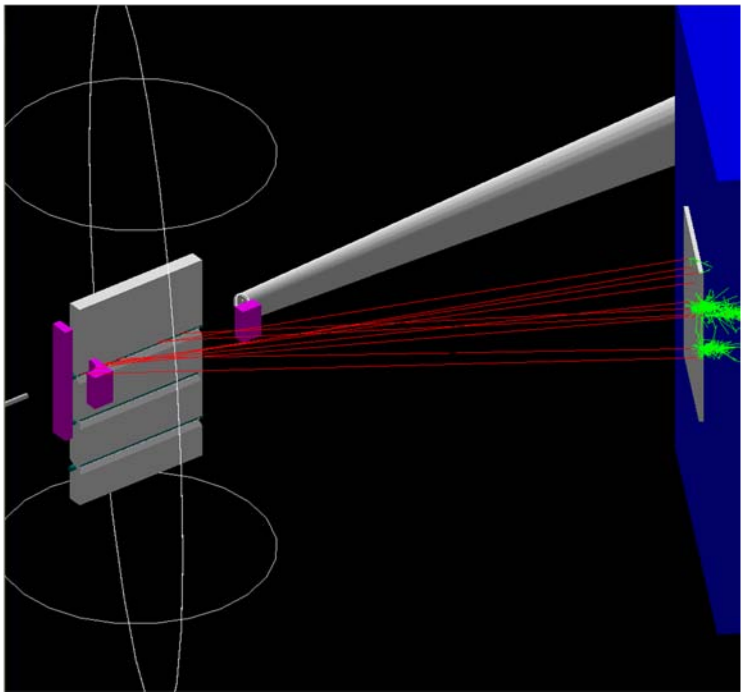


Figure 5: Geant4 Simulation of Target Window Events

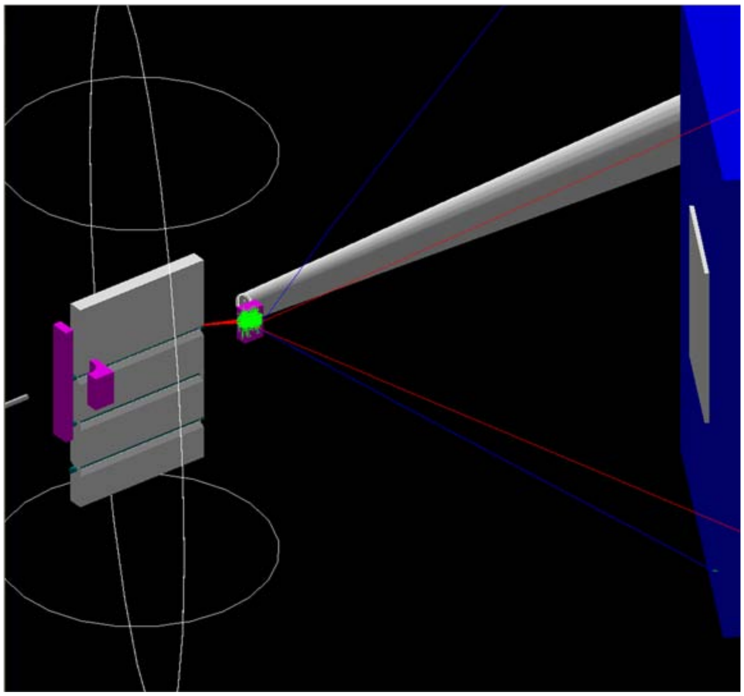


Figure 6: Deuterium F_2^n/F_2^p vs. Bjorken x (per correction)

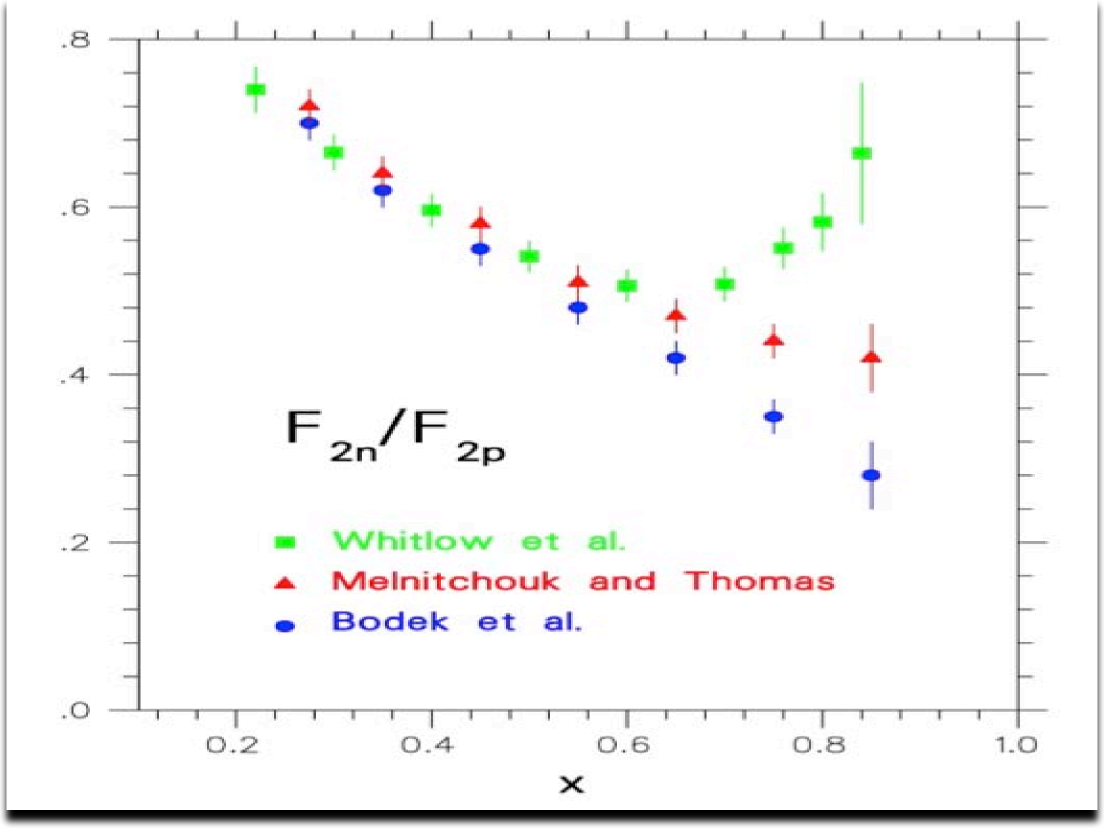
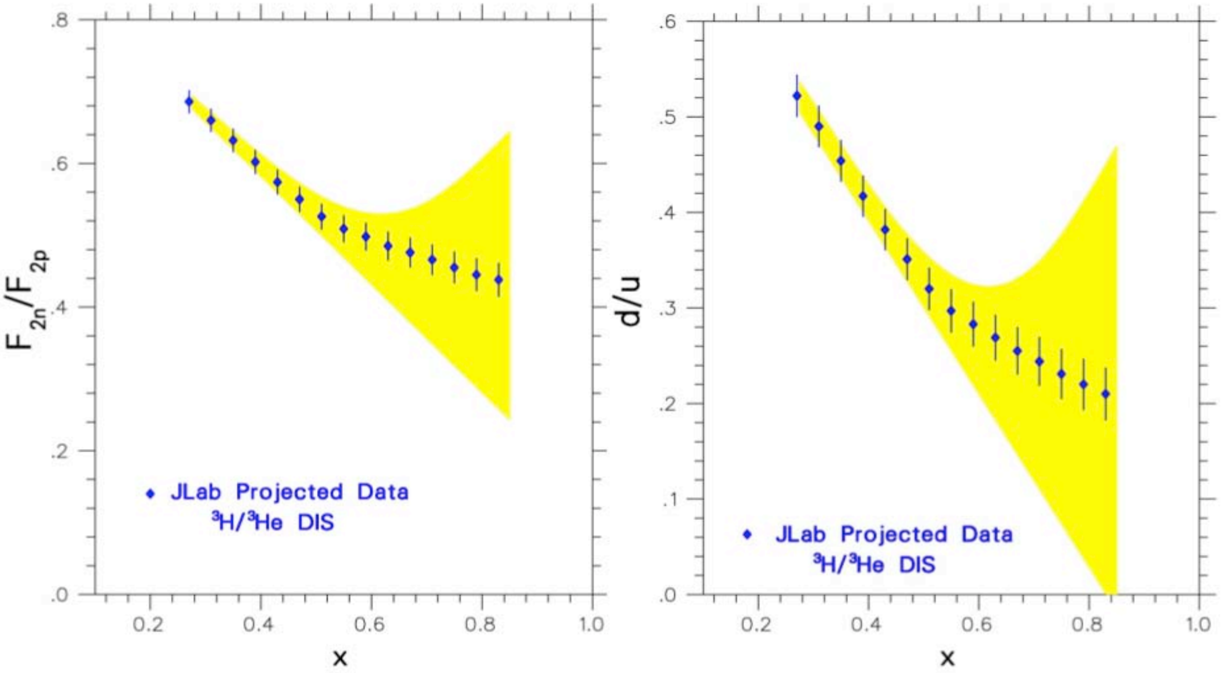


Figure 7: Projected JLab Data of tritium F_2^n/F_2^p vs. Bjorken x



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[4] P. Solvignon, J. Arrington, and D. B. Day, "Precision Measurement of the Isospin Dependence in the 2N and 3N Short Range Correlation Region," in *Hall A Collaboration*, Newport News, 2010, pp. 1-19.