The EMC Effect for Tritium and Helium-3 from JLab's MARATHON Experiment using DIS.

Jason Bane

University of Tennessee

jbane1@vols.utk.edu

Thomas Jefferson National Accelerator Facility is a U.S. Department of Energy Office of Science national laboratory.

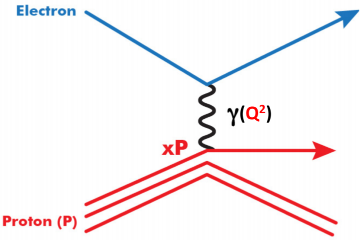
Jefferson Lab's unique and exciting mission is to expand humankind's knowledge of the universe by **studying the fundamental building blocks of matter** within the nucleus: subatomic particles known as **quarks and gluons**.

More than 1,500 nuclear physicists worldwide come to Jefferson Lab to conduct and collaborate on research.

Outline

1. Deep Inelastic Scattering
2. The EMC Effect
3. The MARATHON Experiment
4. Data Analysis
5. EMC Effect of A=3

Deep Inelastic Scattering (DIS)



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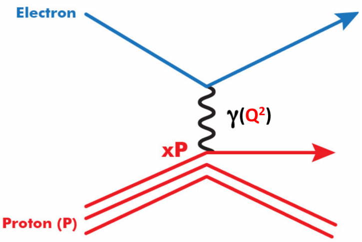

- $Q^2 \equiv 4EE' sin^2 \frac{\theta}{2}$

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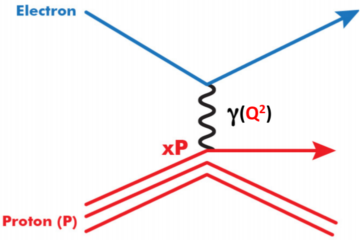

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- $\nu \equiv$ E-E′

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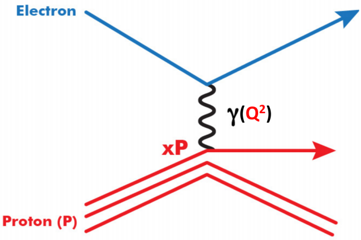

- $Q^2 \equiv 4EE' sin^2 \frac{\theta}{2}$
- $\nu \equiv$ E-E$'$
- $X_{Bj} = \frac{Q^2}{2\nu M}$

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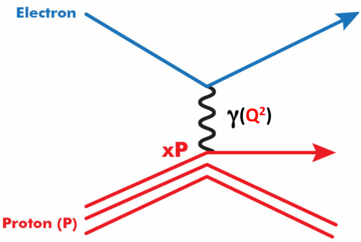
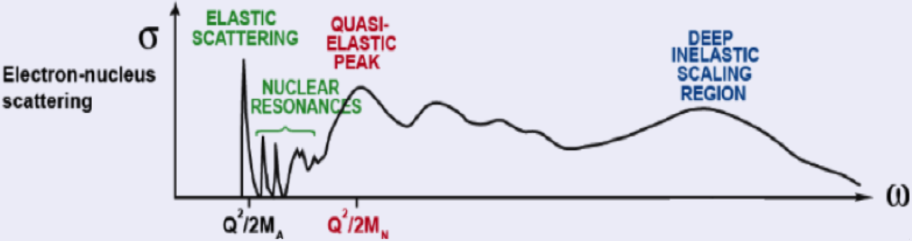
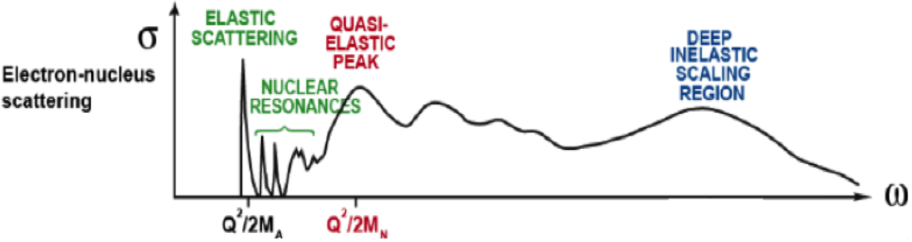


- $Q^2 \equiv 4EE' sin^2 \frac{\theta}{2}$
- $\nu \equiv$ E-E$'$
- $X_{Bj} = \frac{Q^2}{2\nu M}$
- $W^2 = 2M\nu + M^2 - Q^2$

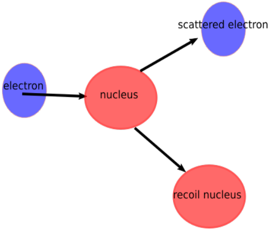
DIS ??????

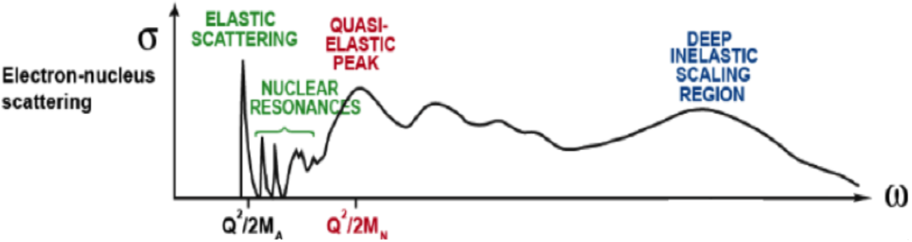


Idealized spectra of high-energy electron scattering as a function of energy transfer [G. T. Garvey, et al., 2015].

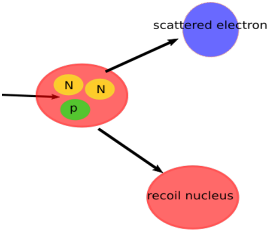


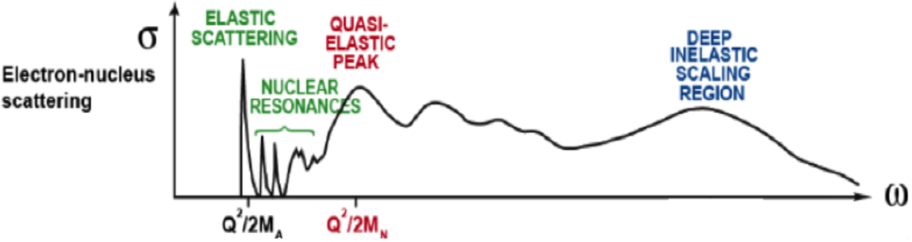
- **Elastic scattering**



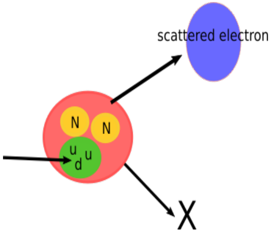


- **Quaiselastic**




σ
Electron-nucleus scattering
ELASTIC SCATTERING
QUASI-ELASTIC PEAK
NUCLEAR RESONANCES
DEEP INELASTIC SCALING REGION
ω
Q²/2M_A
Q²/2M_N

- **DIS**

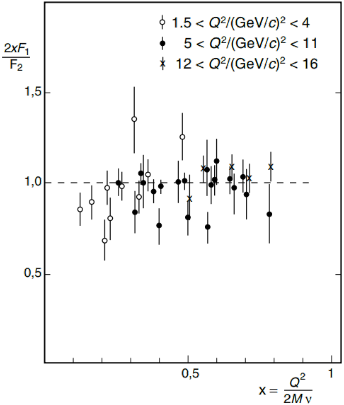

scattered electron
N
N
u
u
d
X

Why DIS?

$$\sigma_{eN} = \frac{\alpha^2}{4E^2 sin^4(\frac{\theta}{2})}[\frac{F_2(x)}{\nu} cos^2\left(\frac{\theta}{2}\right) + \frac{2F_1(x)}{M} sin^2\left(\frac{\theta}{2}\right)]$$

Quark parton model

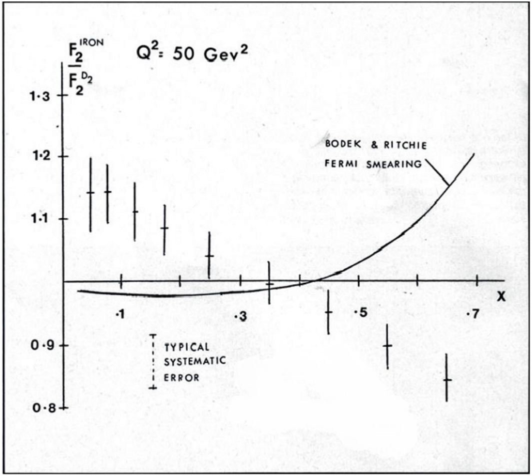
- $F_2(x) = x \cdot \sum_i z_i^2 f_i(x)$
- $F_1(x) = 1/2 \cdot \sum_i z_i^2 f_i(x)$
- **Spin 1/2 quarks**
  $F_2(x) = F_1(x) \cdot 2x$



Ratio of $2x \cdot F_1(x)$ and $F_2(x)$ vs. x. [Povh, 1995]

The EMC Effect

European Muon Collaboration



[J.J. Aubert, et al. 1981]

- X = fraction of momentum carried by quark

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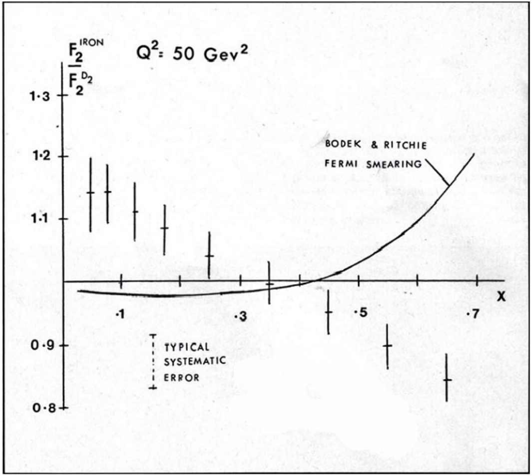

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- Expected Unity at low x

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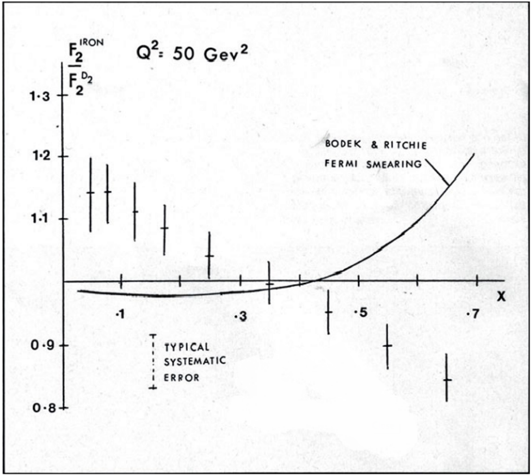

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- X = fraction of momentum carried by quark
- Expected Unity at low x
  - Binding $<$ momentum transfer
  - Free Nucleons
- $F^A = Z \cdot F^p + (A - Z) \cdot F^n$

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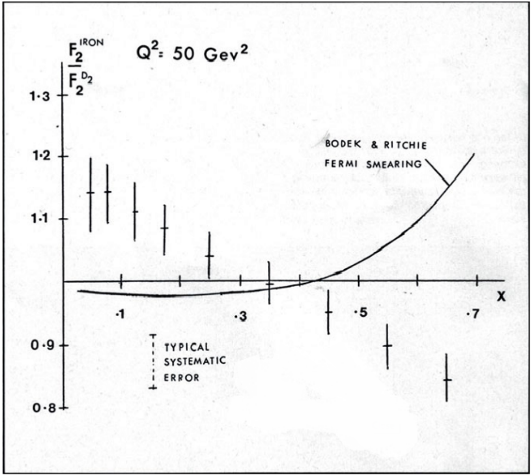

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- Unexpected Relative Decrease
- Missing high-momentum quarks in A>2

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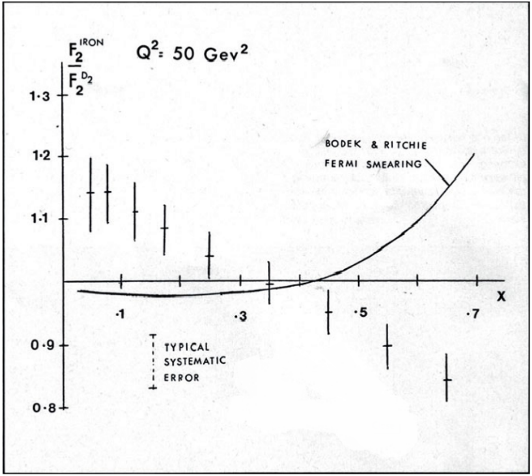

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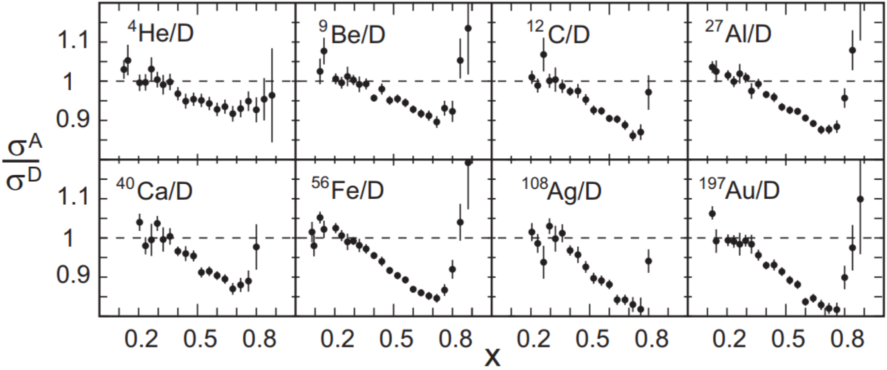
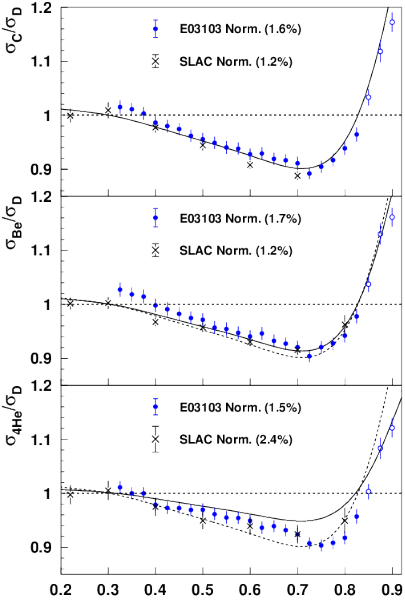
- EMC Effect ≡ structure of the A/D Ratio

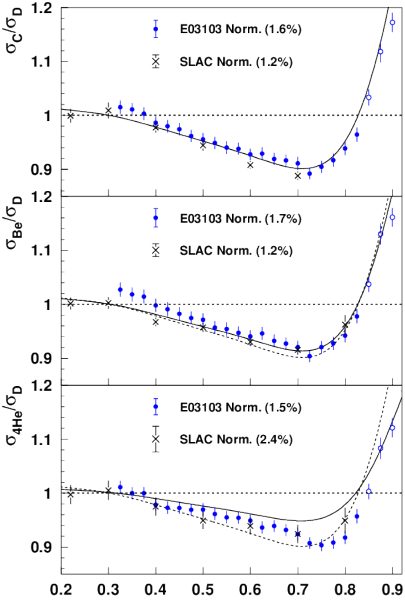
The EMC Effect

SLAC experiment E139 [J. Gomez et al., 1994] .





- JLab experiment E03103 [J.Seely, A. Daniel et al, 2009]



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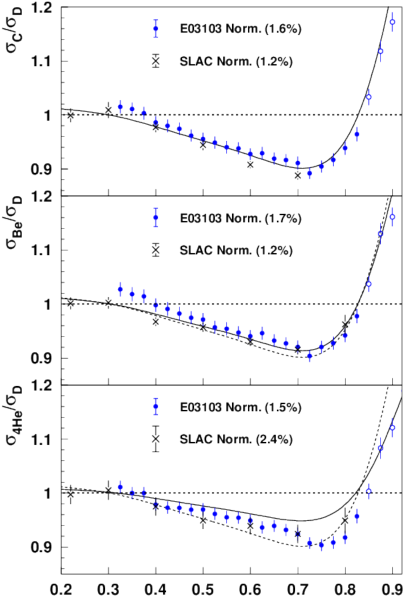

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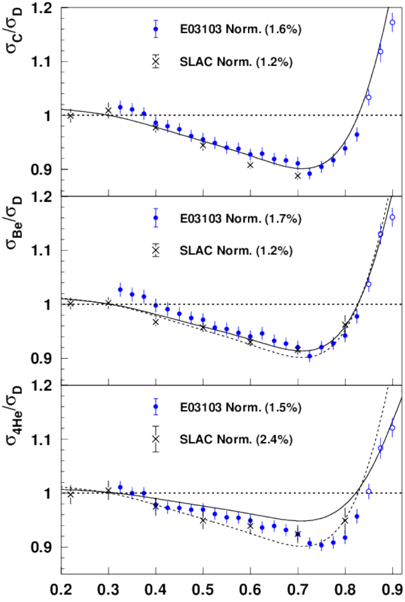

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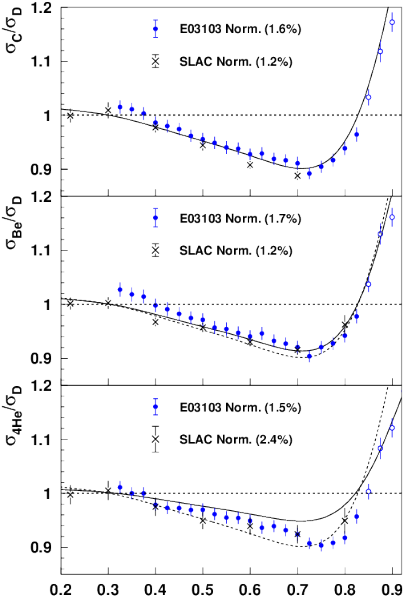

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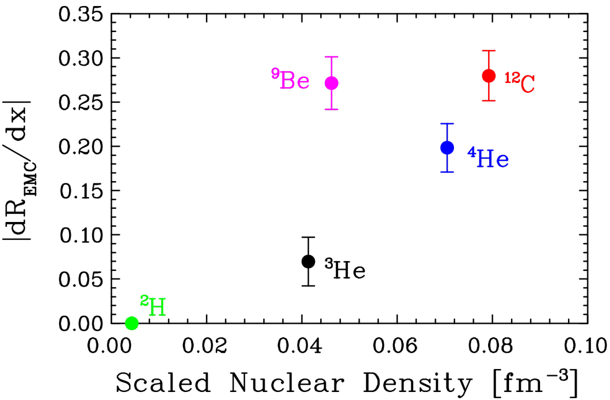
- Quantized by slope of A/D ratios from 0.3 - 0.7 in x
- Models have difficulty matching data for all criteria
- $\approx$ log dependence in A

The EMC Effect

JLab experiment E03103
[J.Seely, A. Daniel et al, 2009]



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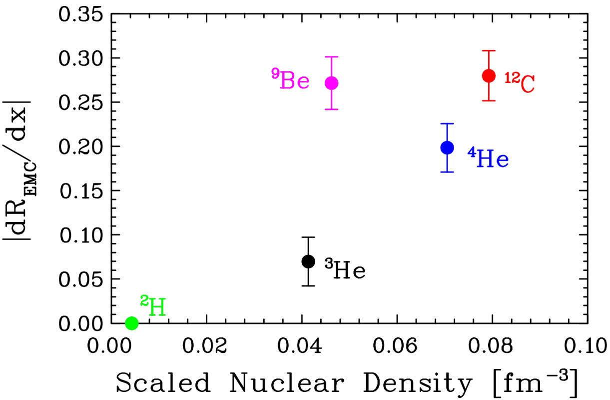
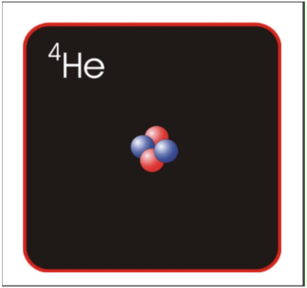
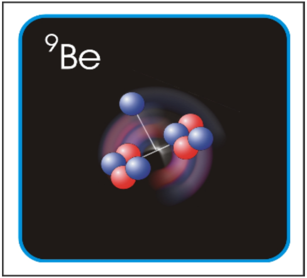


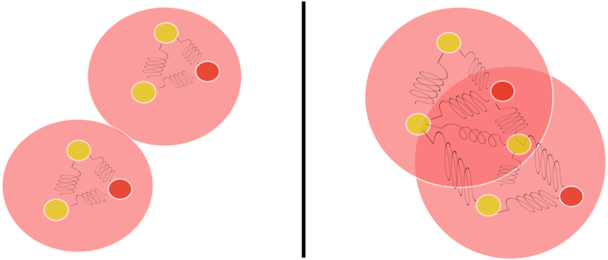




EMC Models

Multiquark Cluster

- Possible formation of color singlet quark clusters
- Clusters contain momentum of multiple nucleons
- Multiquark bag should be large compared to nucleon
  - softer momenta
  - Could explain rapid rise in EMC ratio



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Nuclear Binding

- Convolution of momentum and separation energy
  $\vec{p'} = (M + \epsilon, \vec{p})$
- Smearing in x
- Can explain the EMC effect region
- Fails to reproduce the rising around x of 0.2

EMC Models

Medium Modification

- Modification of nuclear structure
- Fields created by surrounding nucleons
- Modification of quark waveform
- Shown to describe EMC effect well for a collection of nuclear targets.

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Rescaling

- Relate DIS structure functions with scaling variable
- $F_2^{Fe}(Q^2) = F_2^D(\xi Q^2)$
- Large nuclei bound in large area compared to free nucleon
- Applicable $\rightarrow 0.3 < x < 0.8$

EMC Models

Brief summary of a small subset of models.
Sources for this discussion and others

- [Cloet, and Thomas, 2006]
- [Bickerstaff and Thomas, 1989]
- [Geesaman, Saito, and Thomas, 1995]
- [Norton, 2003]
- [Smith and Miller, 2007]

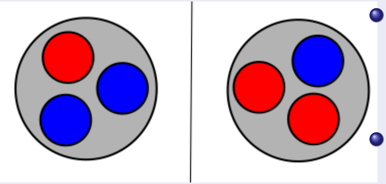
The EMC Effect

The EMC puzzle

- 3+ decades of study
- ~~Every Model is Cool(EMC)~~
- Dependence on A
- Driven by local density

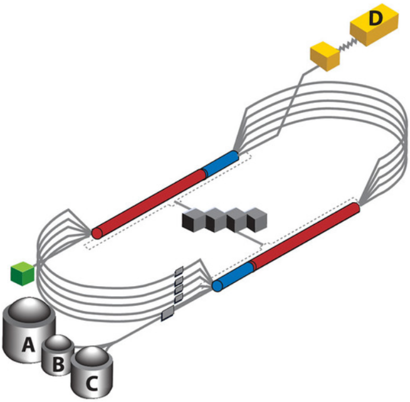
MARATHON

MeAsurement of F_2^n/F_2^p, d/u RAtios and $A=3$ EMC Effect in Deep Inelastic Electron Scattering off the Tritium and Helium MirrOr Nuclei.



- Lightest and simplest mirror system
  - Number of protons in ^3H = neutrons in ^3He
- Differences in the nuclear effects are small

The Continuous Electron Beam Accelerator Facility (CEBAF) at Thomas Jefferson Accelerator Facility.



- $\approx$ 2.2 GeV per revolution
- 12 GeV for Hall D
- Superconducting RF cavities
- RF separators split the beam to each Hall

MARATHON's proposal

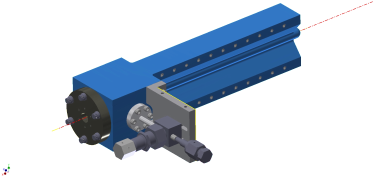
- 11 GeV Beam
- Hall A's high resolution spectrometers (HRS)
- Tritium

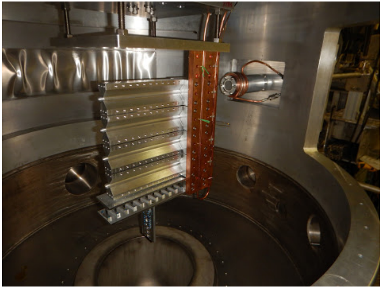
Uses of Tritium


Tritium Target Cell

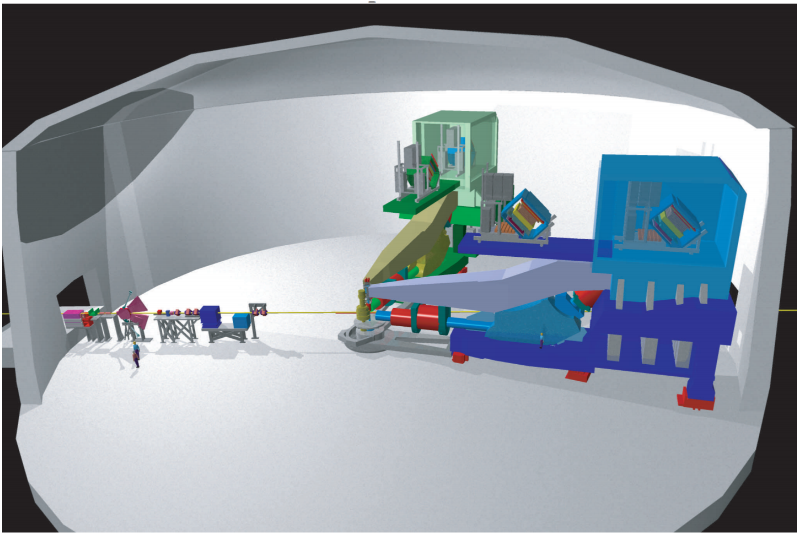
First tritium target at JLab

- Thin Al entrance and exit windows 0.01 inches
- 1090Ci of Tritium (0.1 g)
- 25 cm long
- Tritium Cell was filled in Savannah River
- 40 kelvin Helium is used to cool an attached heat sink

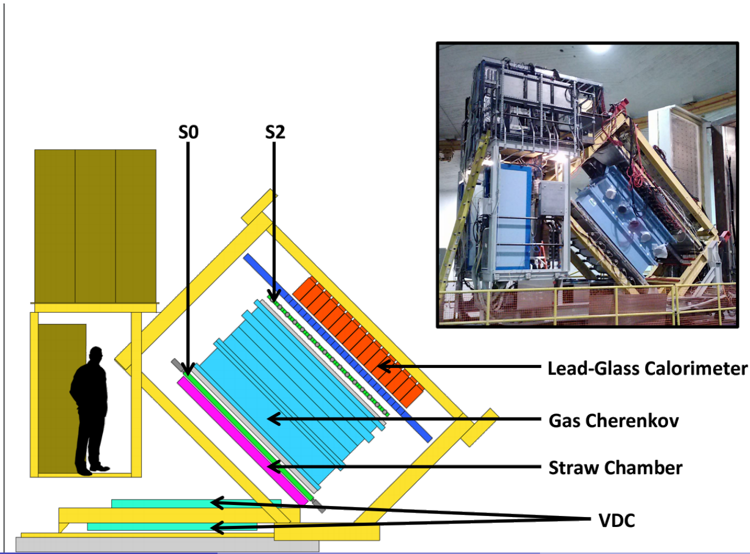




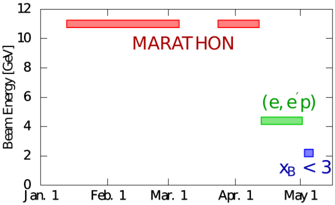
Hall A



High Resolution Spectrometers (HRSs)

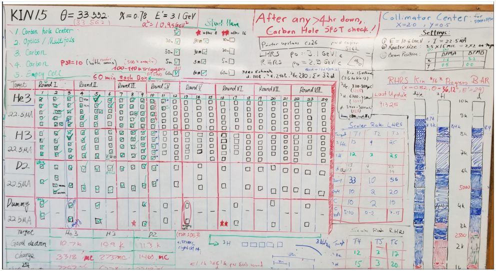


The Run Period

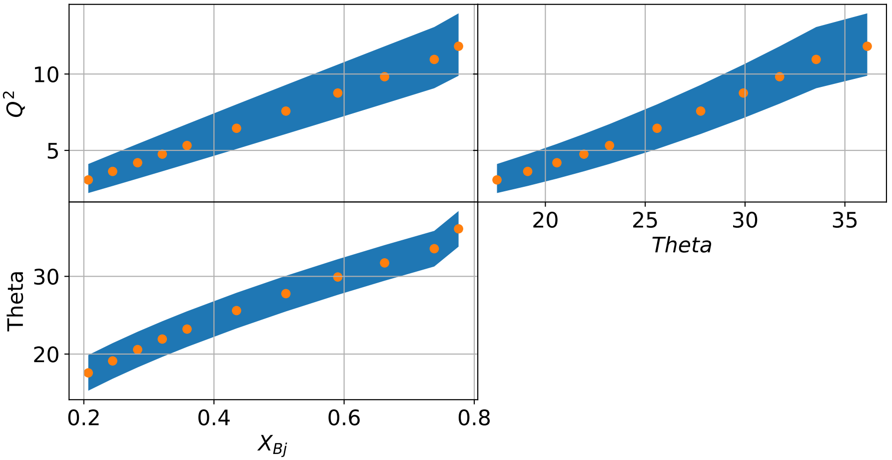


Rey Torres

- Ran from January 11th to April 12th of 2018.
- Gaseous targets - Tritium, Deuterium, Helium-3, and Hydrogen
- Rotated through targets to achieve equal statistics and reduce the impact of systematic uncertainties



Kinematic Coverage



Kinematic coverage between Q^2, x, and Theta. The band around the points represents the approximate spectrometer acceptance in the y axis.

Path to The EMC Effect

- Calibrate detectors to receive meaningful data
- Determine the yield, efficiency and background
- Calculate the cross sections and ratios
- Extract the corrected EMC effect!

Preparing Data for Analysis

Calibration

ADC calibration

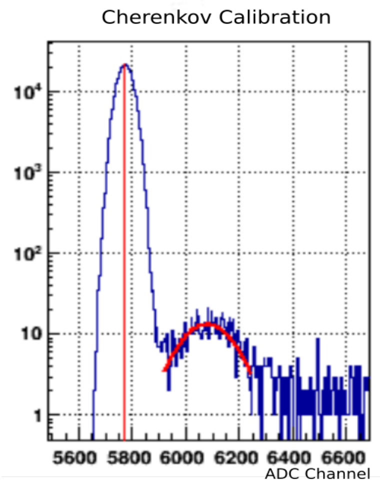
- Calorimeters, Scintillators, and **Cherenkov**

TDC calibration

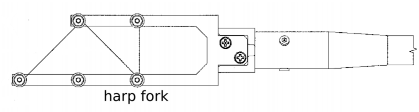
- Scintillators and VDC

Detector calibrations

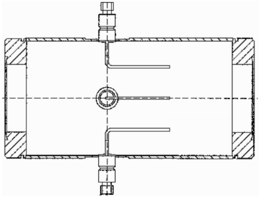
- Beam Current Monitors
- **Beam Position Monitors**



Beam Position Monitor(BPM) Calibration



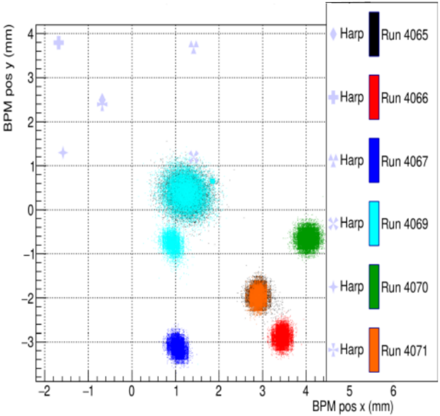
Intrusive absolute position measurement



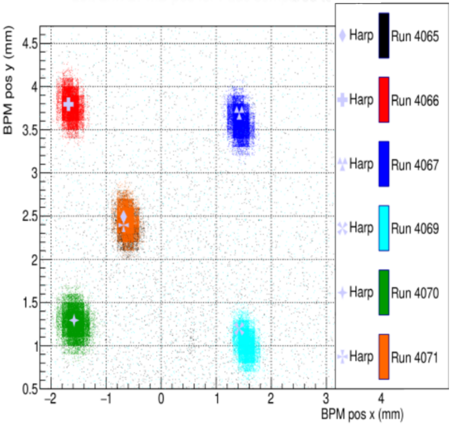
Relative position measurement

$$\begin{pmatrix} X_{position} \\ Y_{position} \end{pmatrix} = \begin{pmatrix} C(0,0) & C(0,1) \\ C(0,0) & C(0,1) \end{pmatrix} * \begin{pmatrix} X_{BPM} \\ Y_{BPM} \end{pmatrix} + \begin{pmatrix} X_{offset} \\ Y_{offset} \end{pmatrix}$$

Beam position from BPM and harp for a collection of runs



Before Calibration



After Calibration

Experimentally Measured Cross Section

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- N = Number of electrons
- L = Luminosity

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  - Density Correction

Experimentally Measured Cross Section

- N = Number of electrons
- ϵ = Efficiency
- L = Luminosity
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Experimentally Measured Cross Section

- N = Number of electrons
- BG = Background
- L = Luminosity
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- ϵ = Efficiency

Experimentally Measured Cross Section

- N = Number of electrons
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- L = Luminosity
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- ϵ = Efficiency
- $\Delta E' \Delta\Omega$= Bin Size
- $A(E', \theta)$ = Acceptance probability

Experimentally Measured Cross Section

$$\frac{d\sigma}{dE'd\Omega} = \frac{(N - BG)}{L \cdot \epsilon \cdot \Delta E' \Delta\Omega \cdot A(E', \theta)}$$

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- BG = Background
- L = Luminosity
  - Density Correction
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Calculating efficiencies

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- Use well defined samples from separate system(s)

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- Use well defined samples from separate system(s)
- Testing cherenkov $\rightarrow$ calorimeters
- Testing VDC use scintillators.

Efficiencies (ϵ)

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- Use well defined samples from separate system(s)
- Determine good event samples with cuts

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- # of events which fail the criteria $\rightarrow$ inefficiency

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  - Cherenkov
  - Calorimeters

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- Particle Identification(PID)
  - Cherenkov
  - Calorimeters
- Trigger
  - Scintillators & cherenkov
  - $\approx 99\%$

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- Tracking
  - Vertical Drift Chambers(VDCs)
  - $\approx$ 98%

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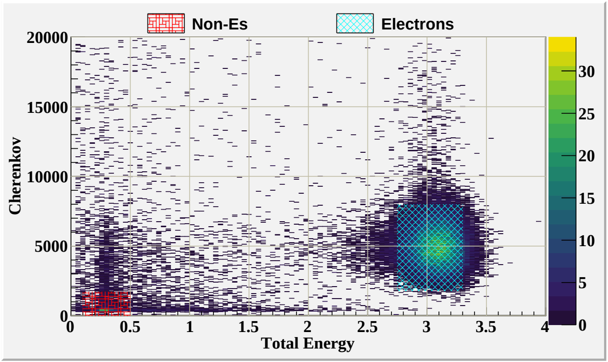
  - $\approx$ 98%
- Electronic Deadtime
  - $\approx$ 96%-99%

Particle ID Efficiency

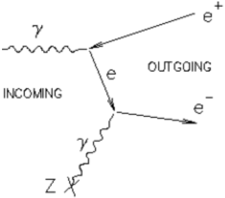


- Total energy absorber for electrons
- Cherenkov's pion threshold is > momentum setting
- PID efficiency ≈ 98% for all kinematics

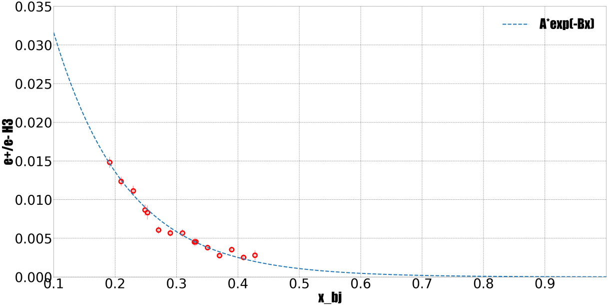
Charge Symmetric Background

- γ decay into an e^+e^- pairs
- Pair produced e^- by detecting e^+
- Extraction based on fit to Exponential function

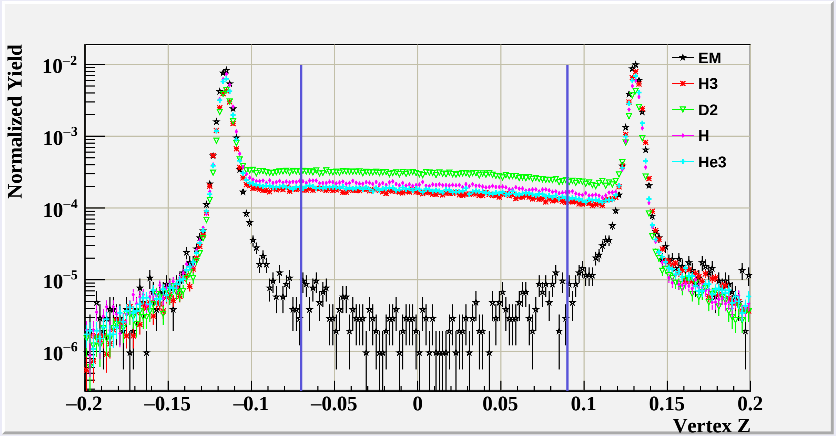
Pair Production



Tritium positron contamination. Credit: Tong Su



Aluminum Endcap Background



- Extract ratio of the normalized yield from the gas cell to that of the empty cell

^3H Decay

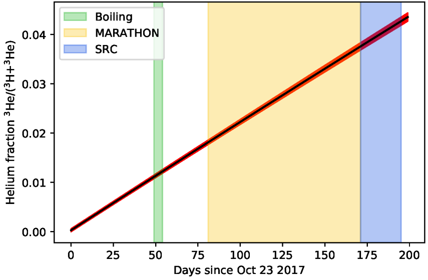
$^3H \rightarrow ^3He$

$$\tau(^3H) = 4500 \pm 8 days$$

$$c = \frac{\eta_{^3He}}{\eta_{tot}}$$

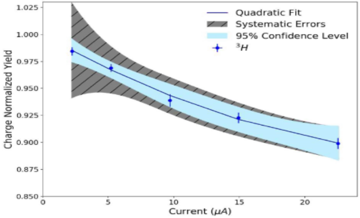
$$\sigma_{^3H} = \left(\frac{\sigma_{tot}}{\sigma_{^3He}}\right)\left(\frac{1}{1-c}\right) - \left(\frac{1}{1-c}\right)$$

Beta Decay Helium Fraction

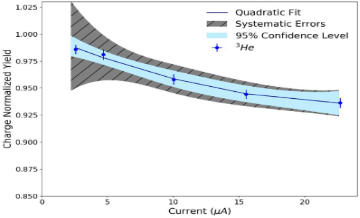


Tyler Kutz

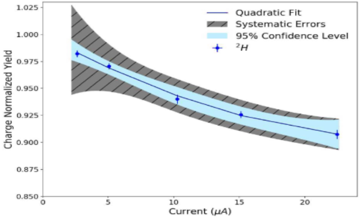
Density Fluctuations



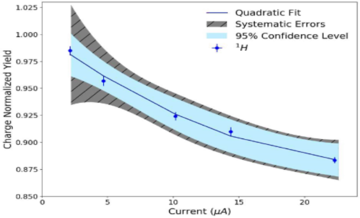
(a) ^{3}H Density Analysis.



(b) ^{3}He Density Analysis.



(c) ^{2}H Density Analysis.



(d) ^{1}H Density Analysis.

[S.N.Santiesteban et. al (2019)]

Monte Carlo Ratio Method

$$Y_{MC}(E', \theta) = L \cdot \sigma^{model} \cdot (\Delta E' \Delta\Omega) \cdot A(E', \theta)$$

$$\sigma_{data} = \frac{Y_{data}(E', \theta)}{L \cdot (\Delta E' \Delta\Omega) \cdot A(E', \theta)}$$

Use a Monte Carlo simulation

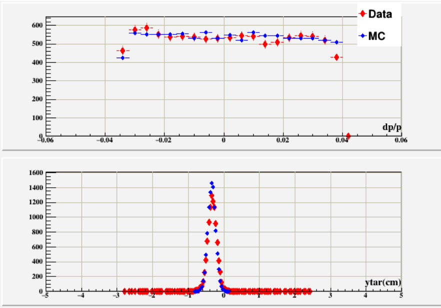
- $(\Delta E' \Delta\Omega)_{Data} = (\Delta E' \Delta\Omega)_{MC}$
- $A(E', \theta)_{Data} = A(E', \theta)_{MC}$

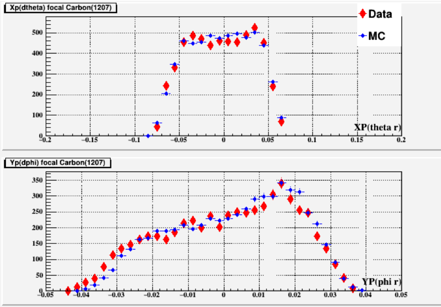
$$\sigma_{Data} = \sigma_{model} \cdot \frac{Y_{Data}}{Y_{MC}}$$

Monte Carlo

- Generate events → Pass through Magnetic apertures
- Tune Simulation offsets to match detector response
- Use model to weight events
    - Deep Inelastic and resonance region from Ari Bodek Fit from E139
    - Full Mo and Tsai radiative correction

[A. Bodek and U.K. Yang, 2002]
[L.W. Mo and Y.S. Tsai, 1969]





Result

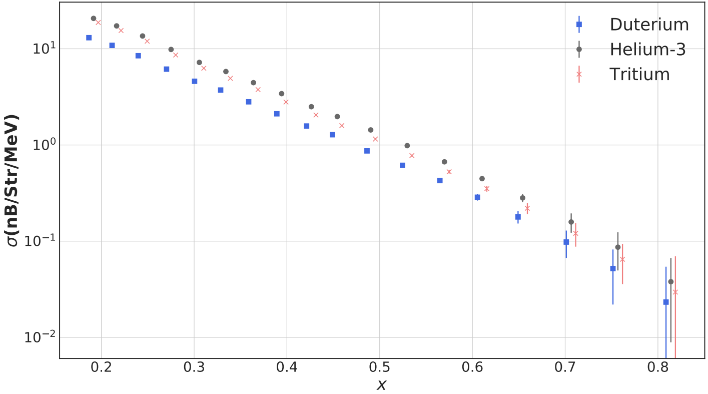
Deep Inelastic Cross Section

10.6 GeV Beam, $W^2 > 3.5$

Cross Section Ratios

EMC Effect

DIS Cross Section



Normalization uncertainty due to target thickness uncertainty
^{3}He - 1.12% • ^{3}H - 0.97% • D - 0.56%

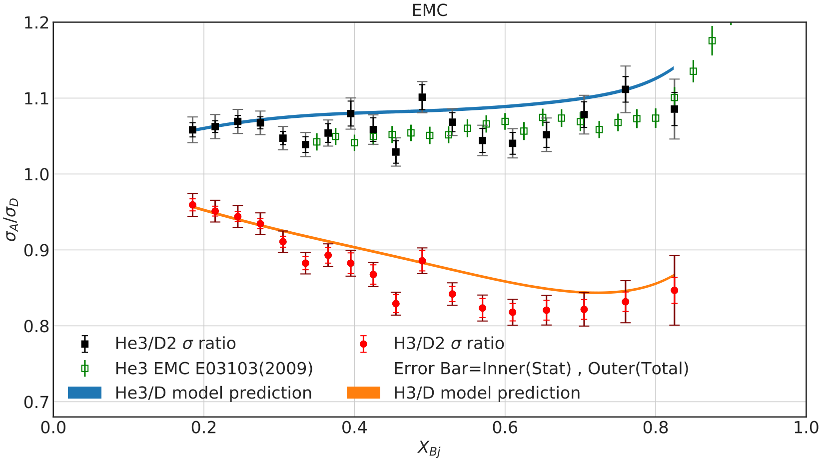
Relative Error Contributions for the Cross Section ^{3}H.

Xbjc	**0.185**	**0.305**	**0.49**	**0.57**	**0.705**	**0.825**
Yield Error	0.01	0.0107	0.0149	0.0151	0.0141	0.0163
Stat Error*	0.0055	0.0059	0.01	0.0111	0.0113	0.0143
End Cap*	0.007	0.007	0.007	0.007	0.007	0.007
Eff Error*	0.004	0.0051	0.0083	0.0071	0.0041	0.0032
MC&Model	0.016	0.014	0.013	0.016	0.03	0.037
Resolution**	0.015	0.011	0.005	0.001	0.007	0.018
Model**	0.006	0.009	0.012	0.016	0.029	0.032
Total Error	0.019	0.018	0.02	0.022	0.033	0.04

* Largest contributers to the error in the yield calculation

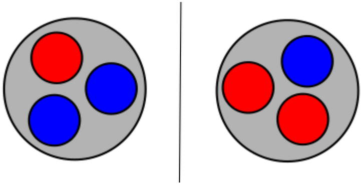
** Largest contributers to the error in Monte Carlo and Cross section model calculation.

Per Nucleon Cross Section Ratio



MARATHON results compared with E03103 [J.Seely, A. Daniel et al, 2009] and the A/D ratios from a DIS scattering model from Arie Bodek model [A. Bodek and U.K. Yang, 2002].

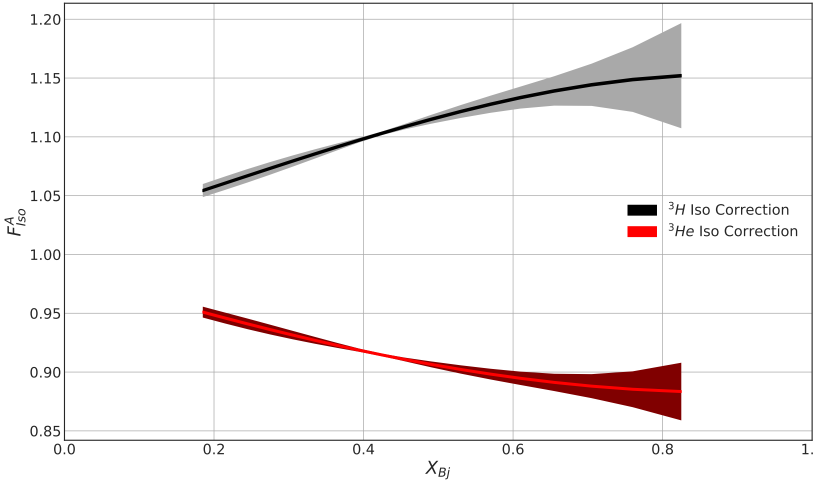
Isoscalar Corrections



- Correct for the unpaired nucleon in the A/D ratio.

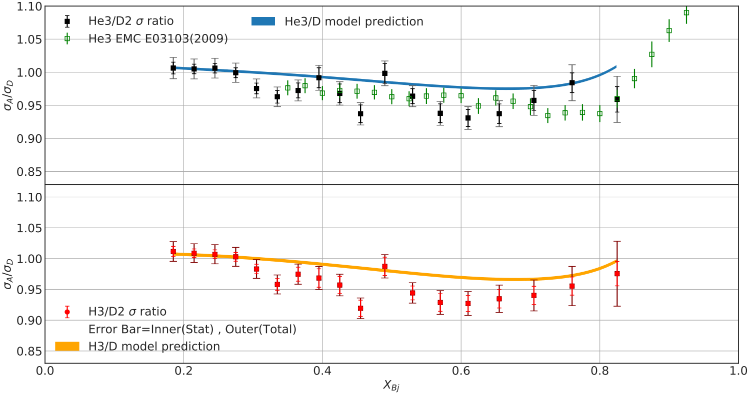
$$F^{A}_{Iso} = \frac{\left(0.5 * (1.0 + \frac{F_2^n}{F_2^p})\right)}{\left(\frac{1}{A} \cdot (Z + (A - Z) \cdot \frac{F_2^n}{F_2^p})\right)}$$

Isoscalar Corrections



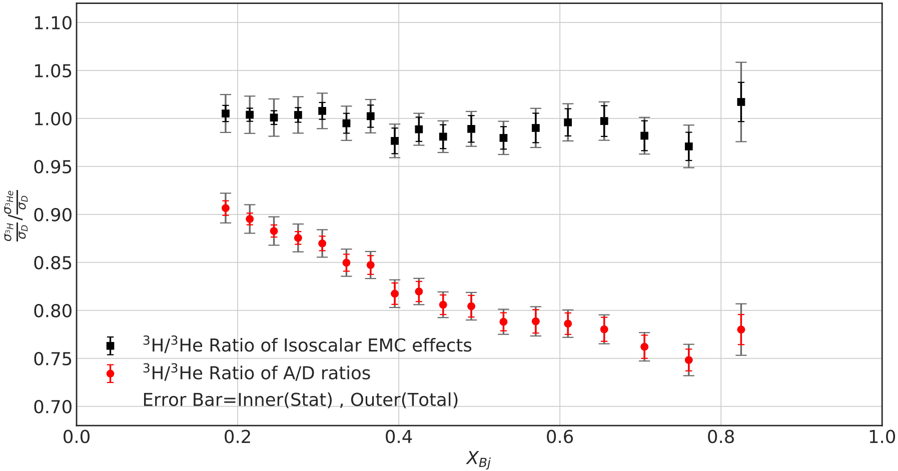
Isoscalar correction factor for both ^{3}He and ^{3}H. Model dependent calucation, error is calcualted via comparing different models for $\frac{F_2^n}{F_2^p}$.

- My EMC results for He3 in black • H3 in red
- Previous Jlab He3 in green



MARATHON results compared with E03103 [J.Seely, A. Daniel et al, 2009] and the EMC ratios from a DIS scattering model from Arie Bodek model [A. Bodek and U.K. Yang, 2002].

Ratio of $^3H/^3He$ EMC effects



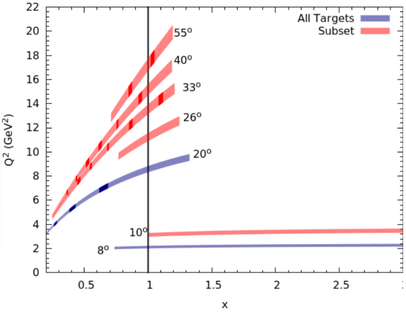
Ratio of EMC effects. Black is Isoscalar correct, red is not.

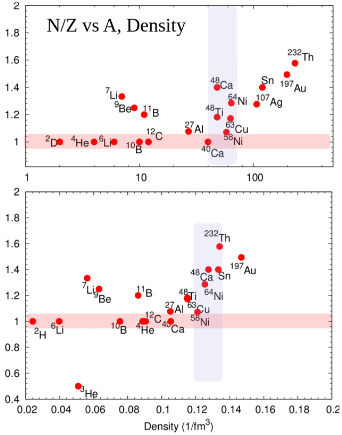
Summary

- Used DIS to extract inclusive cross section for ^{3}H, ^{3}H3, and D
- Looked at the A/D ratio for both ^{3}H and ^{3}H3
- Applied model dependent correction for excess protons and neutrons.
- Compared the EMC effects of the two, A=3 nuclei.
  - See no difference for Isoscalar EMC effects within analysis accuracy

Detailed Studies of the nuclear dependence of F2 in light nuclei [E12-100-008: J. Arrington, A Daniel, NF, D. Gaskell]

Target Choice motivated by physics impact





Coming soon* in Hall C

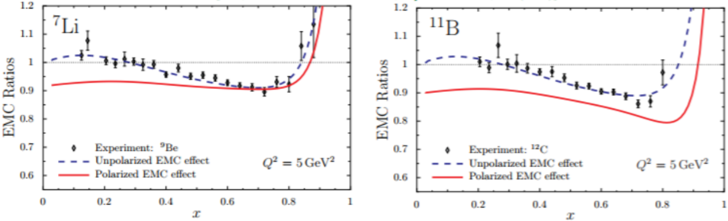
What is soon?

Slide credit Nadia Fomin

The EMC effect in spin structure functions

[E12-14-001: Will Brooks and Sebastian Kuhn]

[ICC, W. Bentz and A. W. Thomas, Phys. Lett. B **642**, 210 (2006)]



- A polarized EMC effect arises because in-medium quarks are more relativistic
  - Lower components of quark wave functions are enhanced
  - Quark Spin is converted to orbital angular momentum
- Spin Dependent cross-section is suppressed by 1/A
- Experiment to measure spin structure functions of 7Li

Slide credit Nadia Fomin

Special Thanks

- The Tritium Students
- JLab staff and technicians
- Nadia Fomin and Douglas Higinbotham
- DOE and JSA(Jefferson Science Associates)

The JLab MARATHON Tritium Collaboration

D. Abrams, H. Albataineh, **S. Alsalmi**, D. Androic, K. Aniol, W. Armstrong, J. Arrington, H. Atac, T. Averett, C. Ayerbe Gayoso, X. Bai, **J. Bane***, **S. Barcus**, A. Beck, V. Bellini, H. Bhatt, D. Bhetuwal, D. Biswas, D. Blyth, W. Boeglin, D. Bulumulla, A. Camsonne, **M. Carmignotto**, **J. Castellanos**, J-P. Chen, C. Ciofi degli Atti, E. O. Cohen, S. Covrig, K. Craycraft, **R. Cruz-Torres**, B. Dongwi, M. Duer, B. Duran, D. Dutta, N. Fomin, E. Fuchey, C. Gal, T. N. Gautam, S. Gilad, K. Gnanvo, T. Gogami, J. Gomez, C. Gu, A. Habarakada, **T. Hague***, O. Hansen, M. Hattawy, **F. Hauenstein**, O. Hen, D. W. Higinbotham, R. Holt, E. Hughes, C. Hyde, H. Ibrahim, S. Jian, S. Joosten, A. Karki, B. Karki, A. T. Katramatou, C. Keppel, M. Khachatryan, V. Khachatryan, A. Khanal, D. King, P. King, I. Korover, S. A. Kulagin, **T. Kutz***, N. Lashley-Colthirst, G. Laskaris, **S. Li**, W. Li, **H. Liu***, S. Liuti, N. Liyanage, D. Lonardoni, R. Machleidt, L.E. Marcucci, P. Markowitz, **E. McClellan**, D. Meekins, W. Melnitchouk, S. Mey-Tal Beck, Z-E. Meziani, R. Michaels, M. Mihovilovič, V. Nelyubin, **D. Nguyen**, N. Nuruzzaman, **M. Nycz***, R. Obrecht, M. Olson, L. Ou, V. Owen, E. Pace, **B. Pandey**, V. Pandey, A. Papadopoulou, M. Paolone, S. Park, M. Patsyuk, S. Paul, G. G. Petratos, R. Petti, E. Piasetzky, R. Pomatsalyuk, S. Premathilake, A. J. R. Puckett, V. Punjabi, R. Ransome, M. N. H. Rashad, P. E. Reimer, S. Riordan, J. Roche, F. Sammarruca, G. Salmè, **N. Santiesteban**, B. Sawatzky, J. Segal, E. P. Segarra, B. Schmookler, A. Schmidt, S. Scopetta, A. Shahinyan, S. Širca, N. Sparveris, **T. Su***, R. Suleiman, H. Szumila-Vance, A. S. Tadepalli, L. Tang, W. Tireman, F. Tortorici, G. Urciuoli, M. Viviani, L. B. Weinstein, B. Wojtsekhowski, S. Wood, **Z. H. Ye**, Z. Y. Ye, and J. Zhang.

More than 140 Collaborators

Red-Boldfaced Names: Tritium Program grad students; **starred**: MARATHON Ph.D. students

Blue-Boldfaced Names: Tritium Program postdoctoral associates

The JLab MARATHON Tritium Collaboration

Forty Five Institutions (in no particular order): University of Virginia; Texas A & M University; Kent State University; University of Zagreb; California State University, Los Angeles; Argonne National Laboratory; Temple University; The College of William and Mary; University of Tennessee; Massachusetts Institute of Technology; INFN Sezione di Catania; INFN Sezione di Roma, INFN Sezione di Pisa; Mississippi State University; Hampton University; Florida International University; Old Dominion University; Jefferson Lab; University of Perugia; Tel Aviv University; University of Connecticut; Tohoku University; Columbia University; Cairo University; Ohio University; Stony Brook, State University of New York; Syracuse University; Nuclear Research Center-Negev, Beer-Sheva; Institute for Nuclear Research of the Russian Academy of Sciences; University of New Hampshire; University of Regina; Columbia University; Facility for Rare Isotope Beams, Michigan State University; Los Alamos National Laboratory; University of Idaho; University of Pisa; Jožef Stefan Institute, University of Ljubljana; Johannes Gutenberg-Universität Mainz; Saint Norbert College; Center for Neutrino Physics, Virginia Tech; University of South Carolina; Kharkov Institute of Physics and Technology; Norfolk State University; Rutgers University; Artem Alikhanian National Laboratory; Tel Aviv University; Northern Michigan University; University of Illinois, Chicago.

Twelve Countries: Armenia, Canada, Croatia, Egypt, Germany, Israel, Italy, Japan, Russia, Slovenia, Ukraine, United States.

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Backup Slides

Relative Error Contributions for the Cross Section ^{3}He.

Xbjc	**0.185**	**0.305**	**0.49**	**0.57**	**0.705**	**0.825**
Yield Error	0.0104	0.011	0.0147	0.0149	0.0139	0.0161
Stat Error*	0.0063	0.0064	0.0098	0.0108	0.0111	0.0141
End Cap*	0.007	0.007	0.007	0.007	0.007	0.007
Eff Error*	0.004	0.0051	0.0083	0.0071	0.0041	0.0031
MC&Model	0.016	0.017	0.012	0.013	0.033	0.024
Resolution**	0.015	0.012	0.006	0.002	0.007	0.018
Model**	0.005	0.013	0.01	0.013	0.032	0.016
Total Error	0.019	0.02	0.019	0.02	0.036	0.029

* Largest contributers to the error in the yield calculation

** Largest contributers to the error in Monte Carlo and Cross section model calculation.

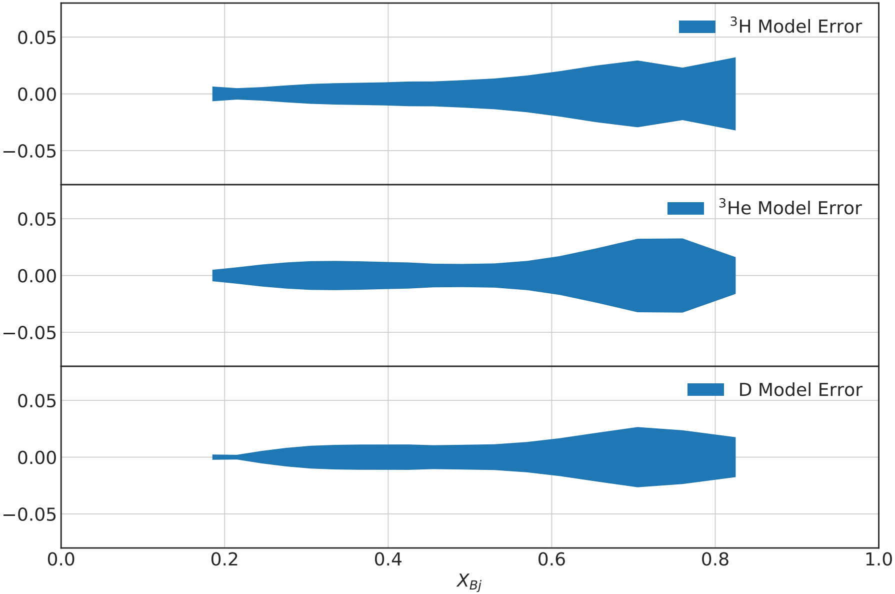
Relative Error Contributions for the Cross Section D.

Xbjc	**0.185**	**0.305**	**0.49**	**0.57**	**0.705**	**0.825**
Yield Error	0.0104	0.0104	0.0159	0.0148	0.0139	0.0164
Stat Error*	0.0062	0.0053	0.0113	0.0106	0.011	0.0143
End Cap*	0.007	0.007	0.007	0.007	0.007	0.007
Eff Error*	0.004	0.0051	0.0081	0.0071	0.0041	0.0032
MC&Model	0.015	0.015	0.013	0.014	0.028	0.026
Resolution**	0.015	0.011	0.006	0.002	0.007	0.02
Model**	0.002	0.01	0.011	0.013	0.027	0.018
Total Error	0.018	0.018	0.021	0.02	0.031	0.031

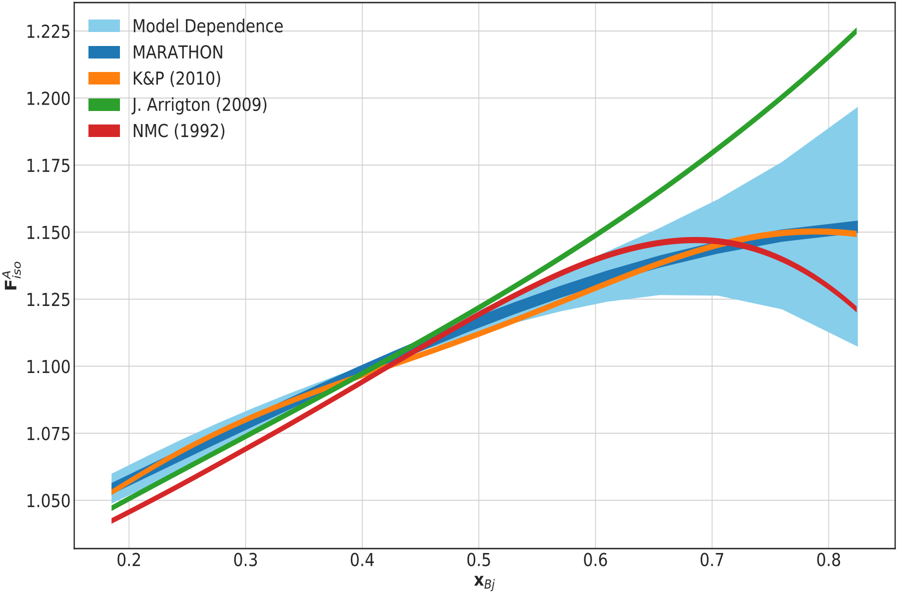
* Largest contributers to the error in the yield calculation

** Largest contributers to the error in Monte Carlo and Cross section model calculation.

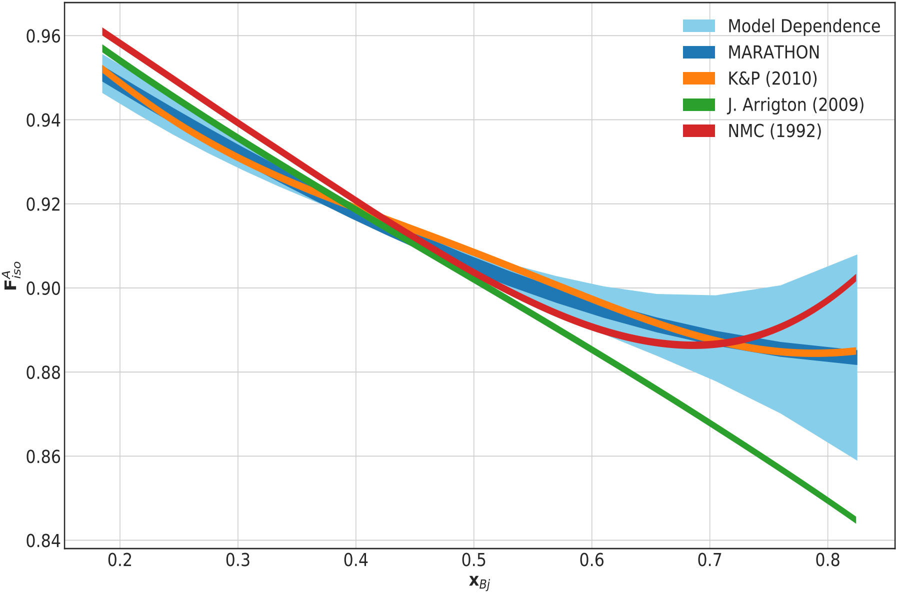
Model Cross Section Error



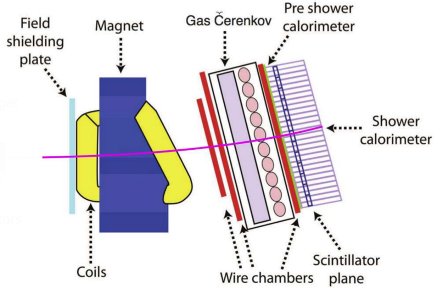
Isoscalar Correction Error for ^{3}H



Isoscalar Correction Error for ^{3}He



Bigbite Spectrometer



Large Acceptance Spectrometer

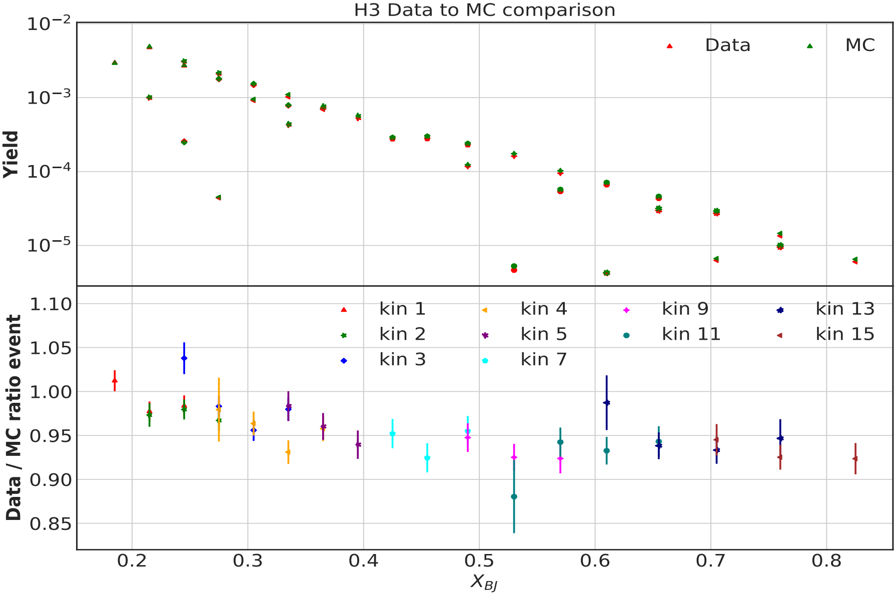
- Solid angle = 96 mrad
- Large Momentum Acceptance: > 500 MeV/c

My contributions in preparing Bigbite

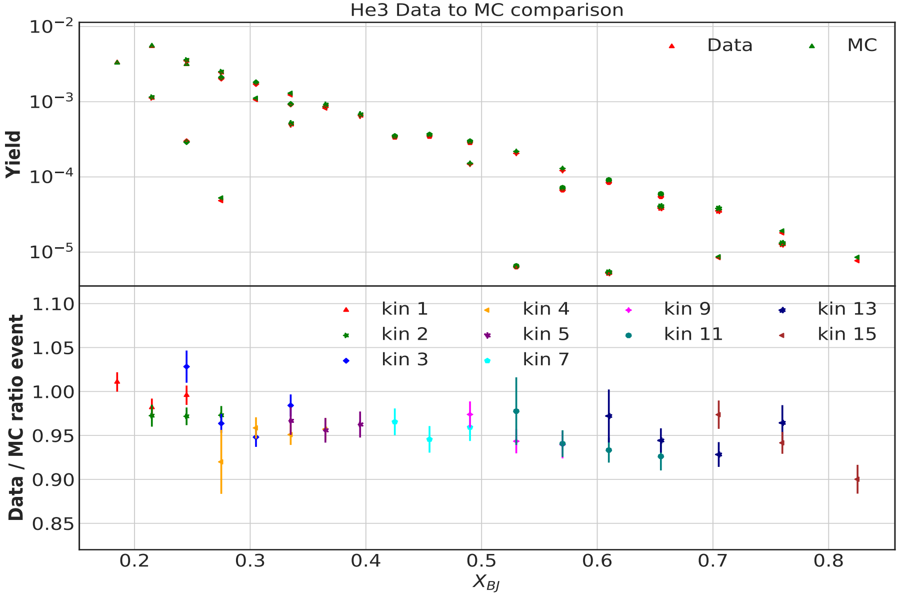
- Constructing the data acquisition system
- PMT performance studies
- Designing trigger logic
- Ensuring consistent and dependable HV power

Removed from the run plan for safety and logistical concerns

Yield & MC ratio ^{3}H



Yield & MC ratio ^{3}He



Yield & MC ratio D