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

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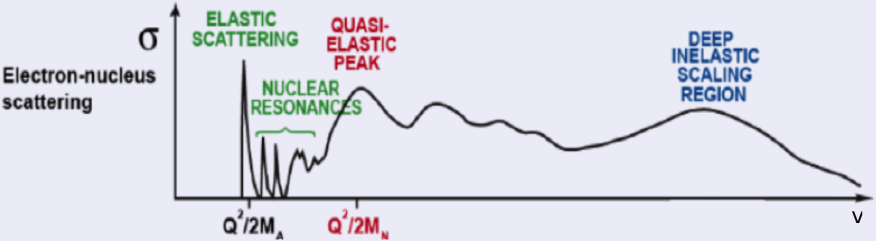
Thomas Jefferson National Accelerator Facility is a U.S. Department of Energy Office of Science national laboratory.

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**.

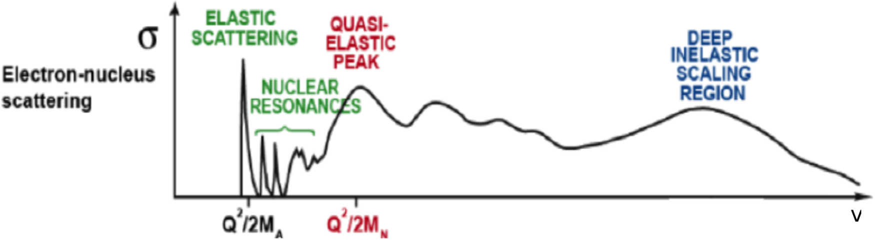
Outline

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

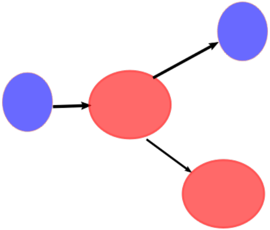
Deep Inelastic Scattering(DIS) ??????

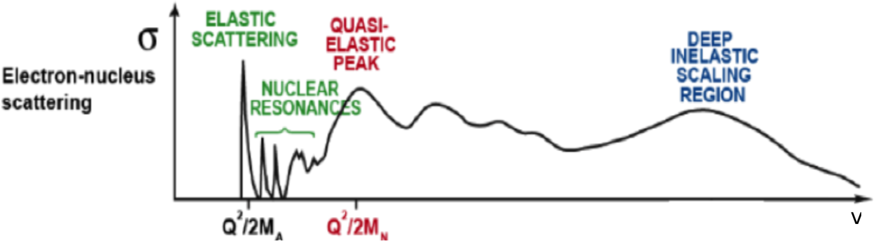


Idealized spectra of high-energy electron scattering as a function of energy transfer [G. T. Garvey, et al., 2015].

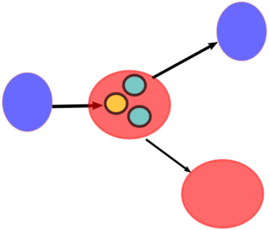


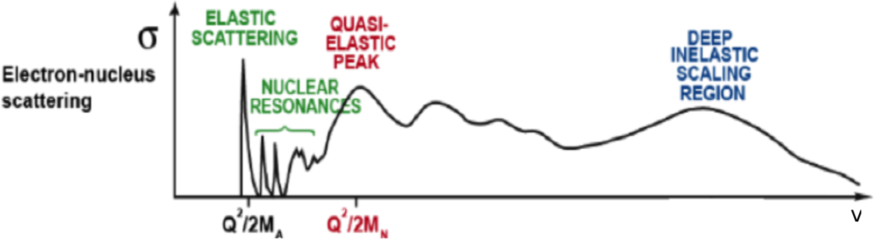
- **Elastic scattering**



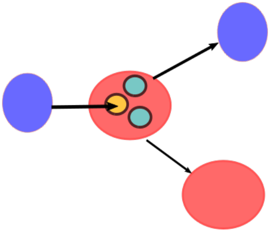


- **Quaiselastic**

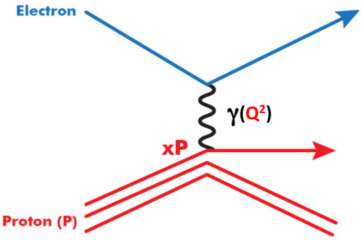



σ
Electron-nucleus scattering
ELASTIC SCATTERING
QUASI-ELASTIC PEAK
NUCLEAR RESONANCES
DEEP INELASTIC SCALING REGION
Q²/2M_A
Q²/2M_N
ν

- **DIS**



Deep Inelastic Scattering (DIS)



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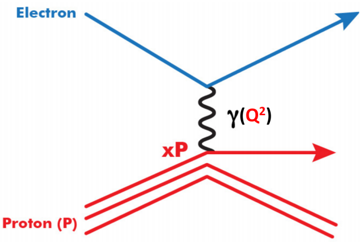
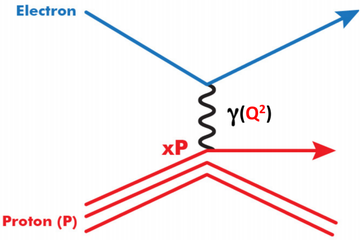


- $Q^2 \equiv 4EE' sin^2 \frac{\theta}{2}$

Deep Inelastic Scattering (DIS)



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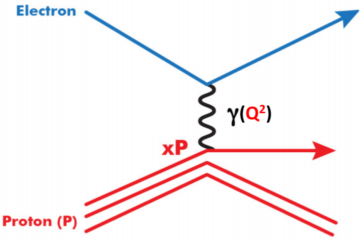

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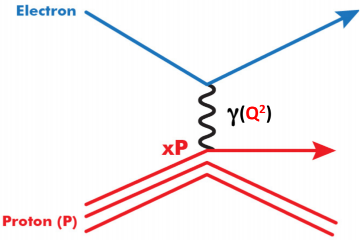


- $Q^2 \equiv 4EE'sin^2\frac{\theta}{2}$
- $\nu \equiv$ E-E$'$
- $X_{Bj} = \frac{Q^2}{2\nu M}$
- $W^2 = 2M\nu + M^2 - Q^2$

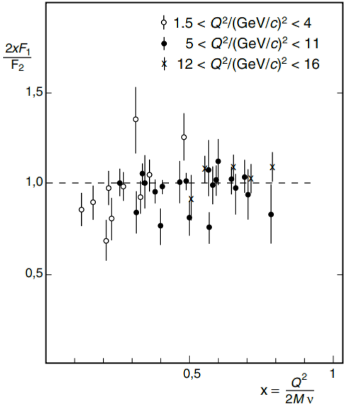
Why DIS?

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

Quark parton model

In the Broken limit

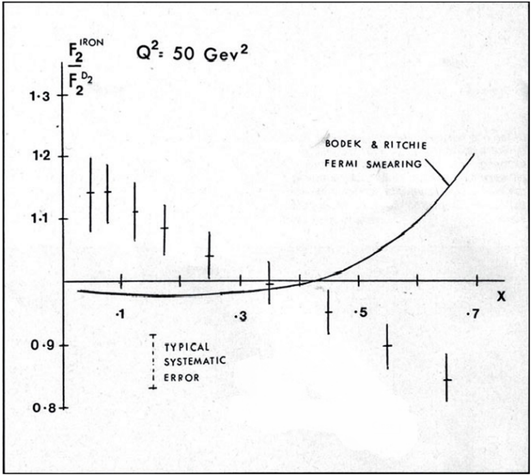
- $F_2(x) = x \cdot \sum_i z_i^2 f_i(x)$
- $F_1(x) = 1/2 \cdot \sum_i z_i^2 f_i(x)$
- **Spin 1/2 quarks**
  $F_2(x) = F_1(x) \cdot 2x$



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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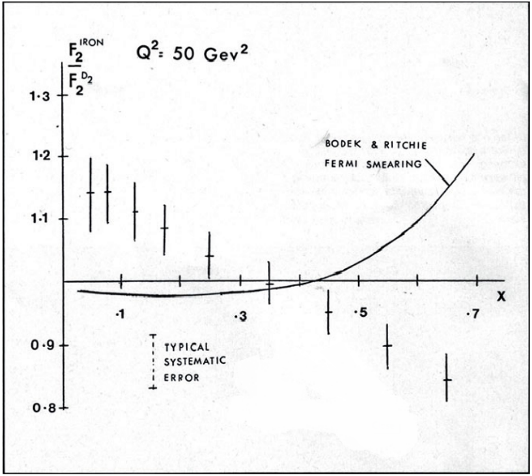

[J.J. Aubert, et al. 1981]

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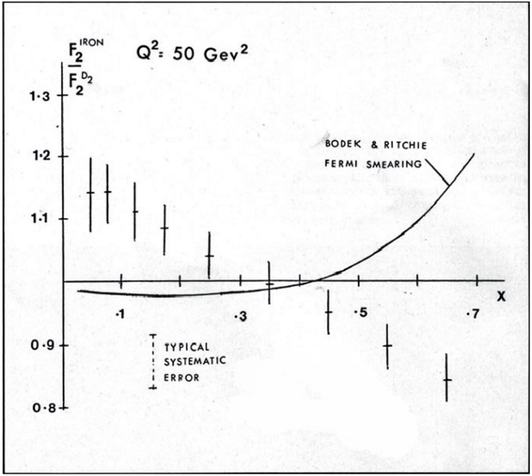

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European Muon Collaboration

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

The EMC Effect

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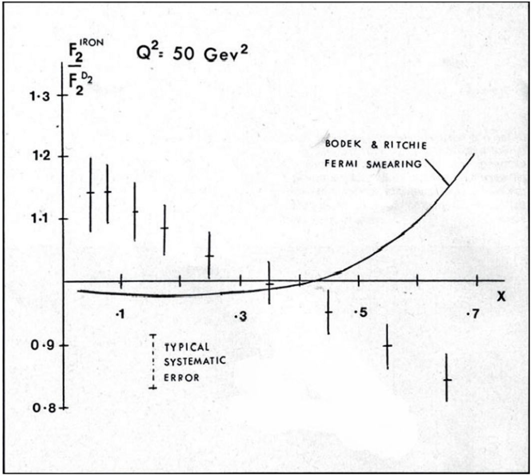

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- Missing high-momentum quarks in A>2

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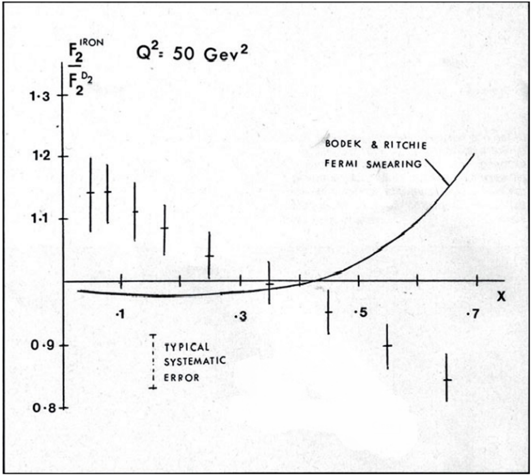

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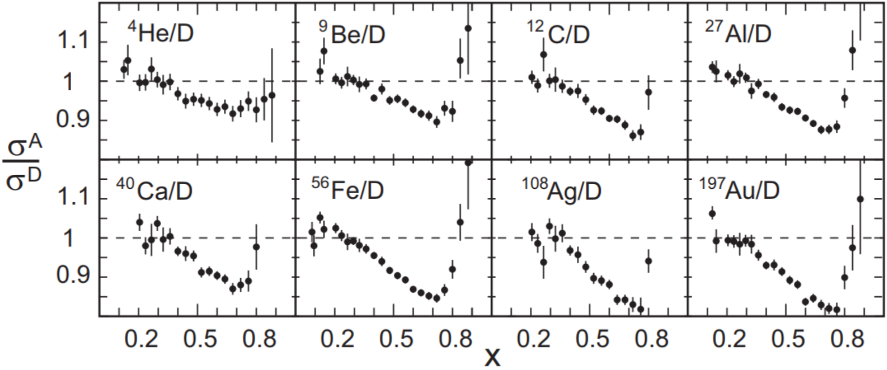
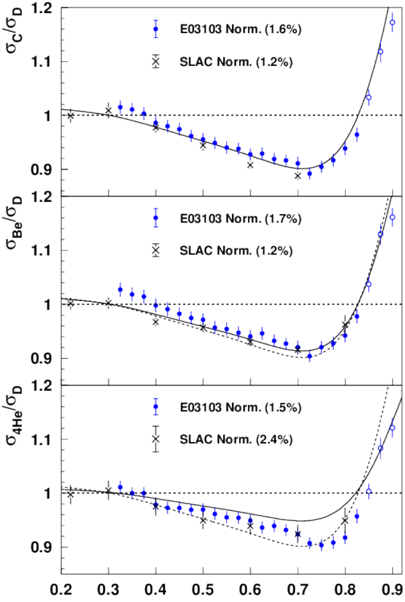
- EMC Effect ≡ structure of the A/D Ratio

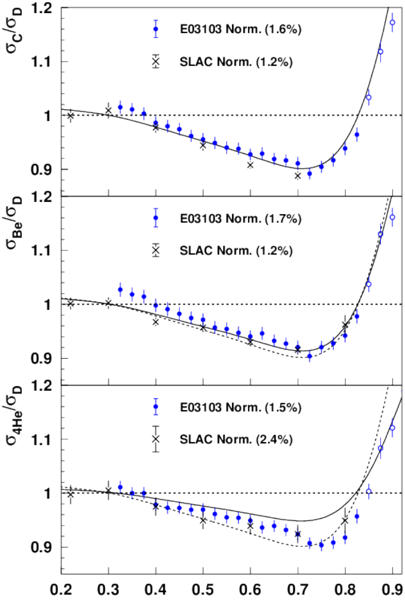
The EMC Effect

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





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



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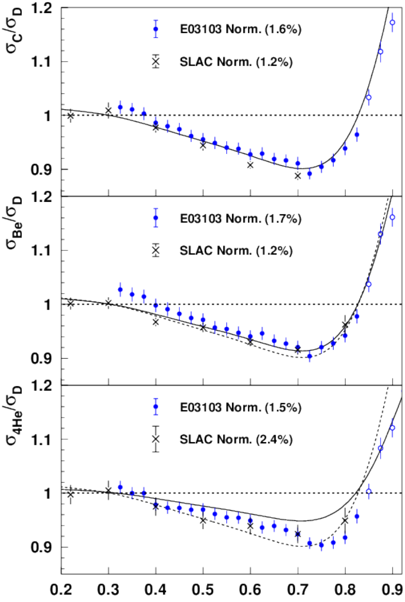

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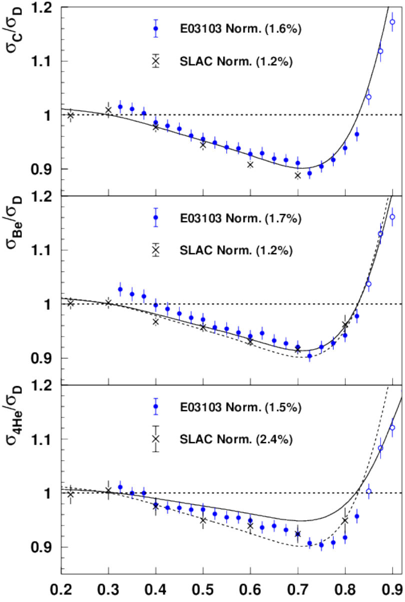

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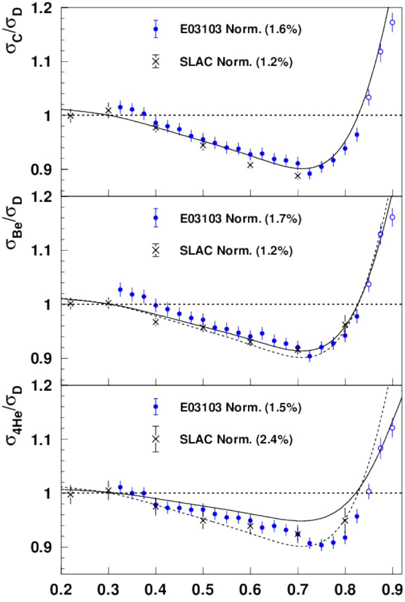

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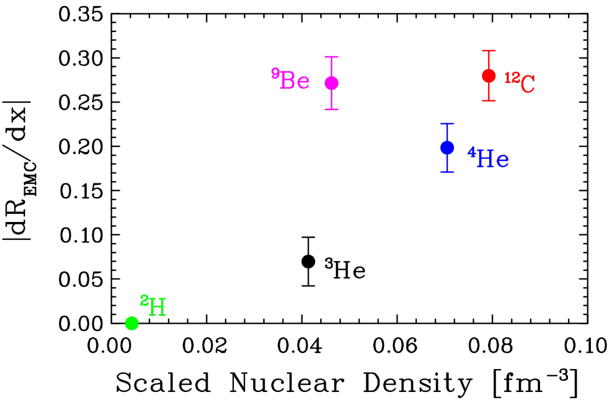
- Models have difficulty matching data for all criteria
- $\approx$ log dependence in A

The EMC Effect

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



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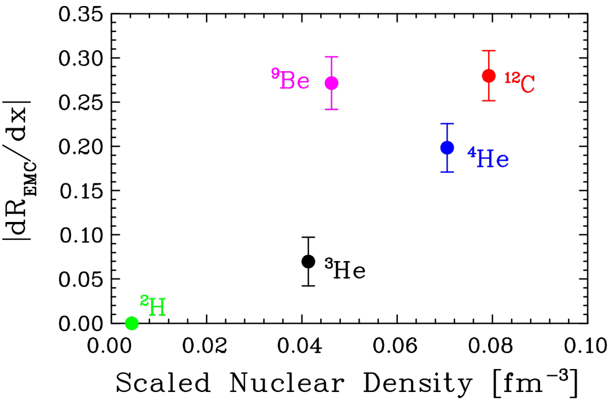
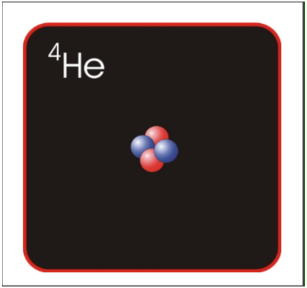
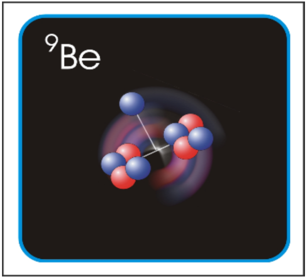


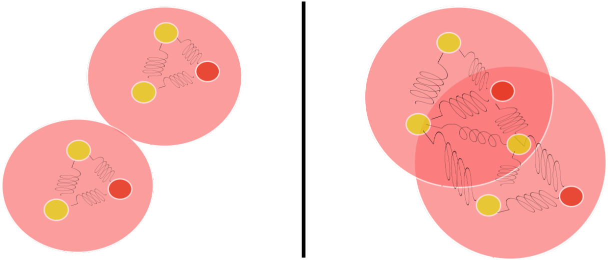




EMC Models

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

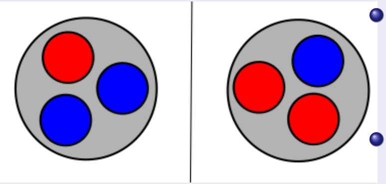
The EMC puzzle

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

The EMC results show a modification to nuclear structure.
Are we treating it correctly?

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 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

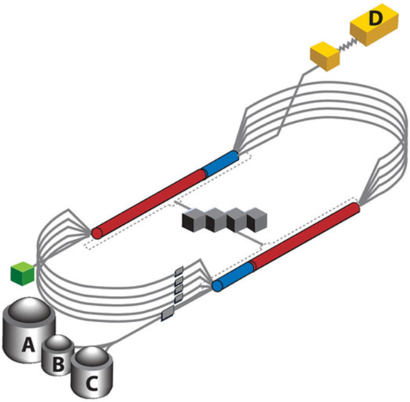
Blue-Boldfaced Names: Tritium Program postdoctoral associates

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.

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

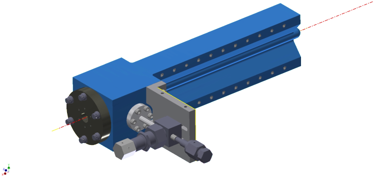
- 11 GeV Beam
- Hall A's high resolution spectrometers (HRS)
- Tritium

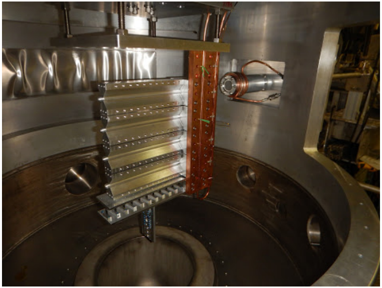
Uses of Tritium

Tritium Target Cell

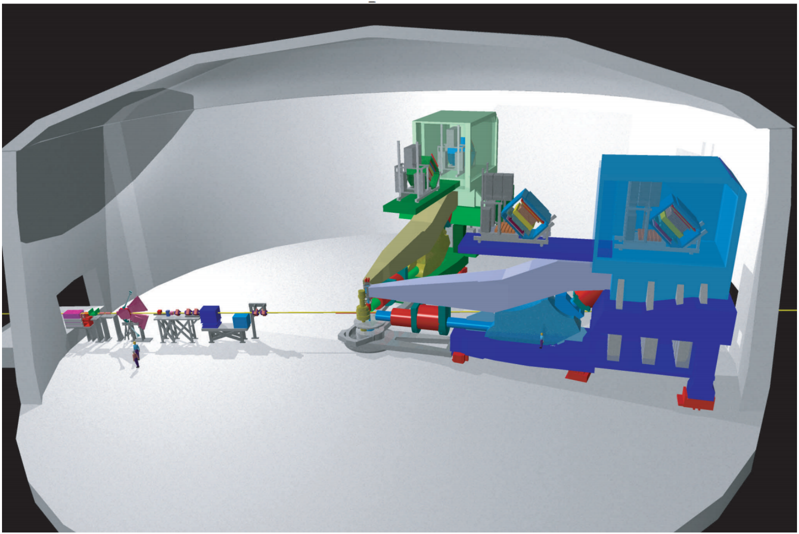
First tritium target at JLab

- 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

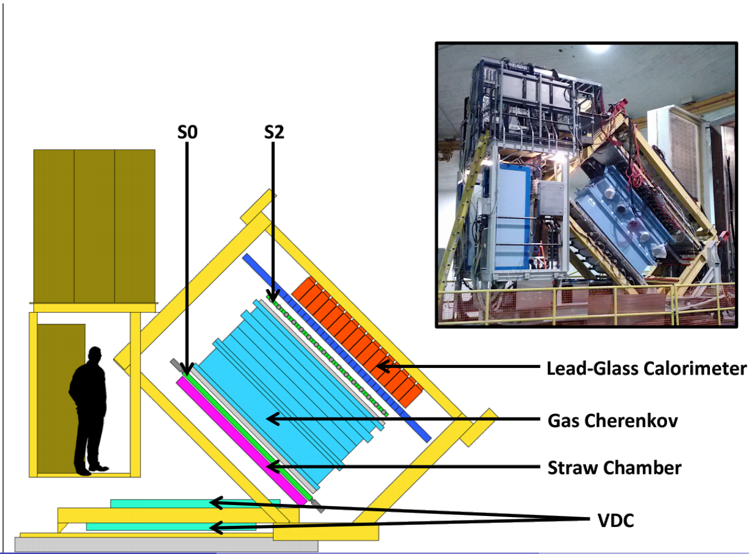




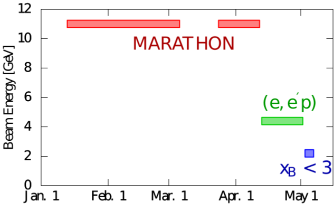
Hall A



High Resolution Spectrometers (HRSs)

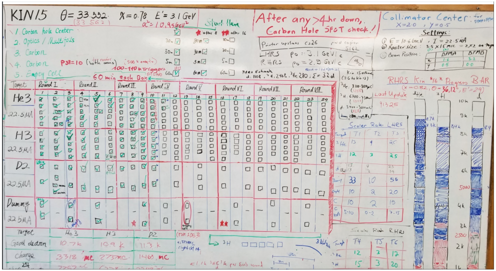


The Run Period

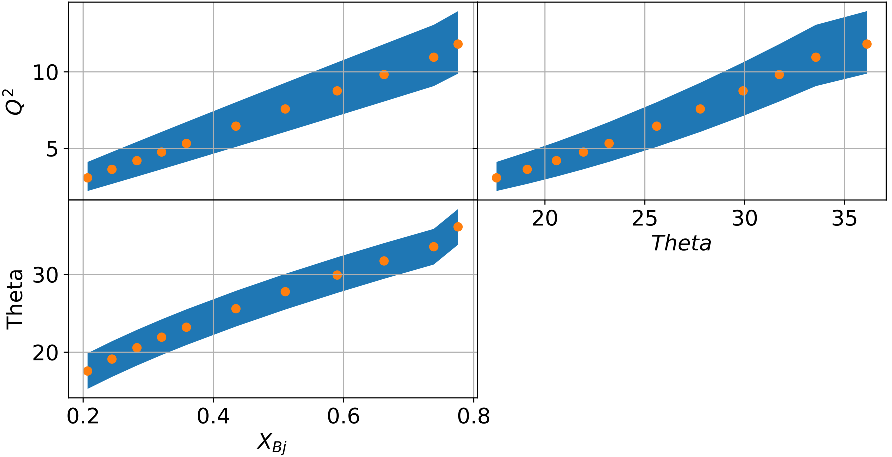


Rey Torres

- 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

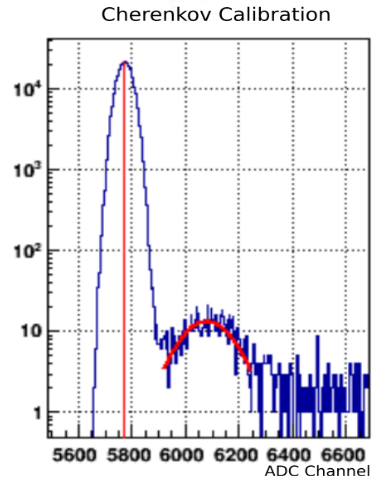
- Calorimeters, Scintillators, and **Cherenkov**

TDC calibration

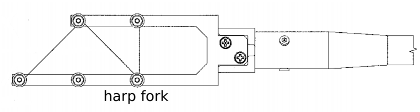
- Scintillators and VDC

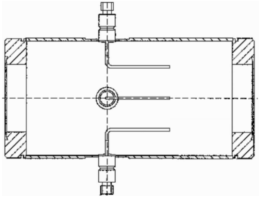
Detector calibrations

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



Beam Position Monitor(BPM) Calibration



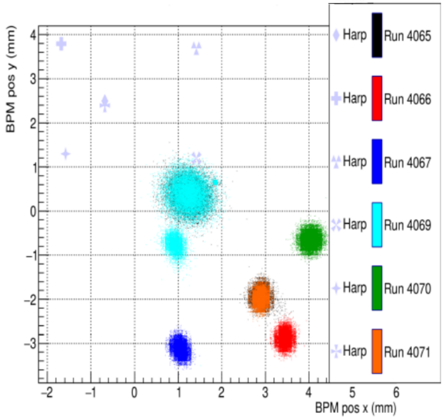


Intrusive absolute position measurement

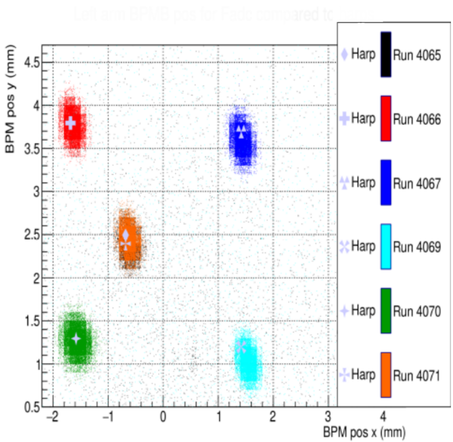
Relative position measurement

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

Beam position from BPM and harp for a collection of runs



Before Calibration



After Calibration

Experimentally Measured Cross Section

Experimentally Measured Cross Section

- N = Number of electrons
- L = Luminosity

Experimentally Measured Cross Section

- N = Number of electrons
- L = Luminosity
  - Density Correction

Experimentally Measured Cross Section

- N = Number of electrons
- ϵ = Efficiency
- L = Luminosity
  - Density Correction

Experimentally Measured Cross Section

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

Experimentally Measured Cross Section

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

Experimentally Measured Cross Section

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

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

Efficiencies (ϵ)

Calculating efficiencies

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- Use well defined samples from separate system(s)

Efficiencies (ϵ)

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

Efficiencies (ϵ)

Calculating efficiencies

- Use well defined samples from separate system(s)
  - Testing cherenkov use calorimeters
  - Testing VDC use scintillators.
- Determine good event samples with cuts

Efficiencies (ϵ)

Calculating efficiencies

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

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- Particle Identification(PID)
  - Cherenkov
  - Calorimeters

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Calculating efficiencies

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

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- Use well defined samples from separate system(s)
  - Testing cherenkov use calorimeters
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- $\#$ of events which fail the criteria $\rightarrow$ inefficiency

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- Tracking
  - Vertical Drift Chambers(VDCs)
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Calculating efficiencies

- Use well defined samples from separate system(s)
  - Testing cherenkov use calorimeters
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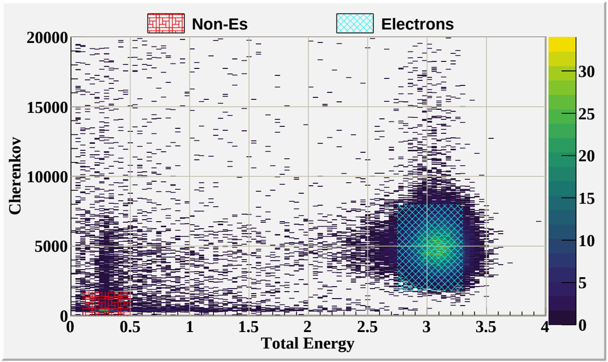
- Determine good event samples with cuts
- # of events which fail the criteria $\rightarrow$ inefficiency

- Particle Identification(PID)
  - Cherenkov
  - Calorimeters
- Trigger
  - Scintillators & cherenkov
  - $\approx$ 99%
- Tracking
  - Vertical Drift Chambers(VDCs)
  - $\approx$ 98%
- Electronic Deadtime
  - $\approx$ 96%-99%

Particle ID Efficiency

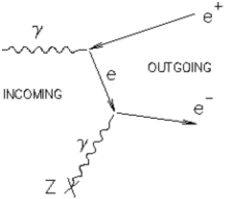


- Total energy absorber for electrons
- Cherenkov's pion threshold is $>$ momentum setting
- PID efficiency $\approx 98\%$ for all kinematics

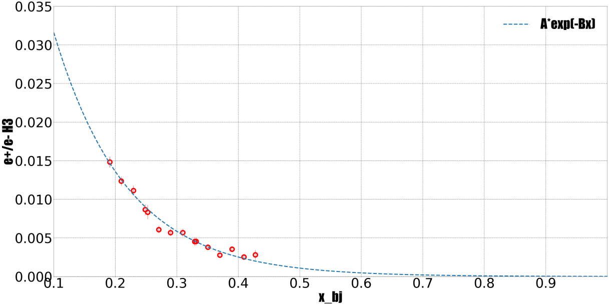
Charge Symmetric Background

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

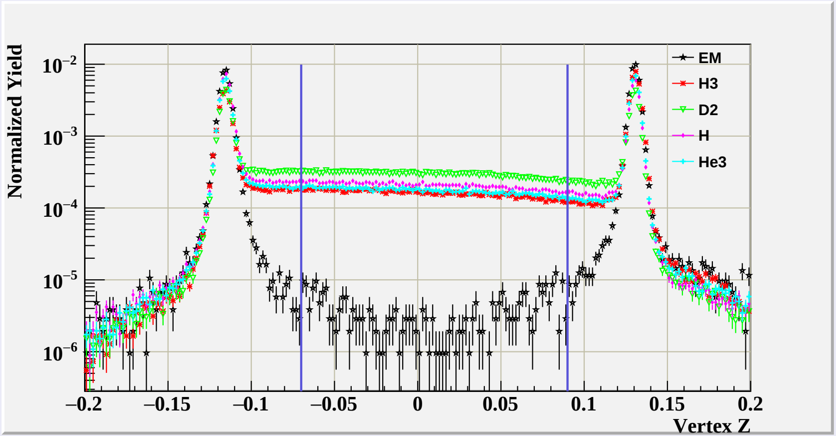
Pair Production



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

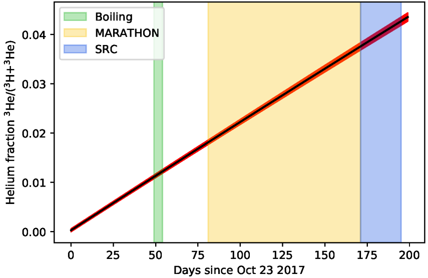
$^3H \rightarrow ^3He$

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

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

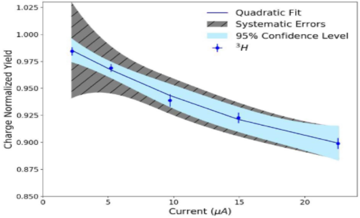
$$\sigma_{^3H} = \left(\frac{\sigma_{tot}}{\sigma_{^3He}}\right)\left(\frac{1}{1-c}\right) - \left(\frac{1}{1-c}\right)$$

Beta Decay Helium Fraction

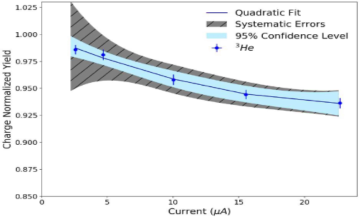


Tyler Kutz

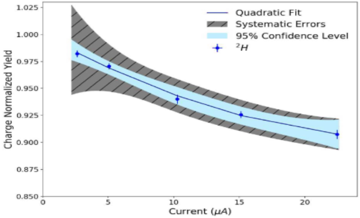
Density Fluctuations



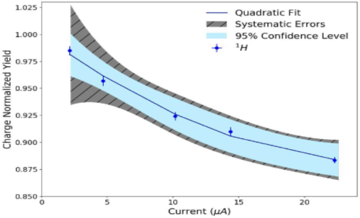
(a) ^{3}H Density Analysis.



(b) ^{3}He Density Analysis.



(c) ^{2}H Density Analysis.



(d) ^{1}H Density Analysis.

S.N. Santiesteban, J. Bane, et. al *Nucl. Instrum. Meth. A* 940 (2019) 351-358

Monte Carlo Ratio Method

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

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Use a Monte Carlo simulation

Monte Carlo Ratio Method

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

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

Use a Monte Carlo simulation

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

Monte Carlo Ratio Method

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

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Use a Monte Carlo simulation

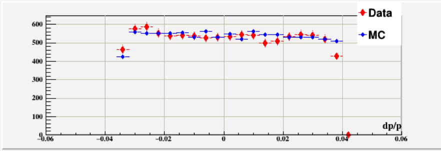
- $(\Delta E' \Delta\Omega)_{Data} = (\Delta E' \Delta\Omega)_{MC}$
- $A(E',\theta)_{Data} = A(E',\theta)_{MC}$

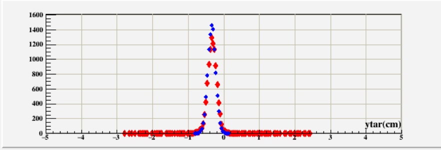
$$\sigma_{Data} = \sigma_{model} \cdot \frac{Y_{Data}}{Y_{MC}}$$

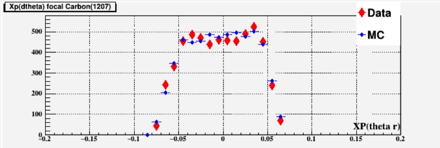
Monte Carlo

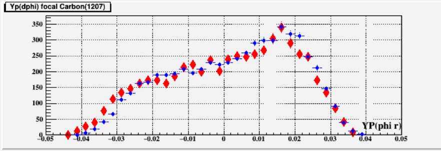
- Generate events → Pass through magnetic apertures
- Tune Simulation offsets to match detector response
- Use model to weight events
    - Deep Inelastic and resonance region from Ari Bodek Fit from E139
    - Full Mo and Tsai radiative correction

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









Result

Deep Inelastic Cross Section

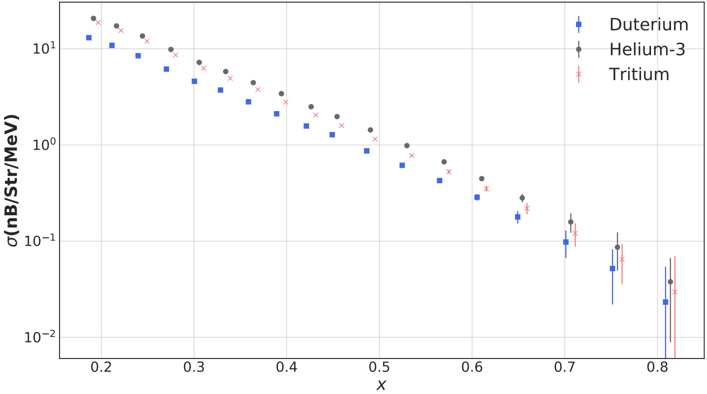
10.6 GeV Beam, $W^2 > 3.5$ Gev^2

Scatted angles 17.5° to 31°

Cross Section Ratios

EMC Effect First DIS cross section and EMC measurement of ^3H First direct comparison of two A=3 EMC effects.

DIS Cross Section



Normalization uncertainty due to target thickness uncertainty

^{3}He - 1.12% • ^{3}H - 0.97% • D - 0.56%

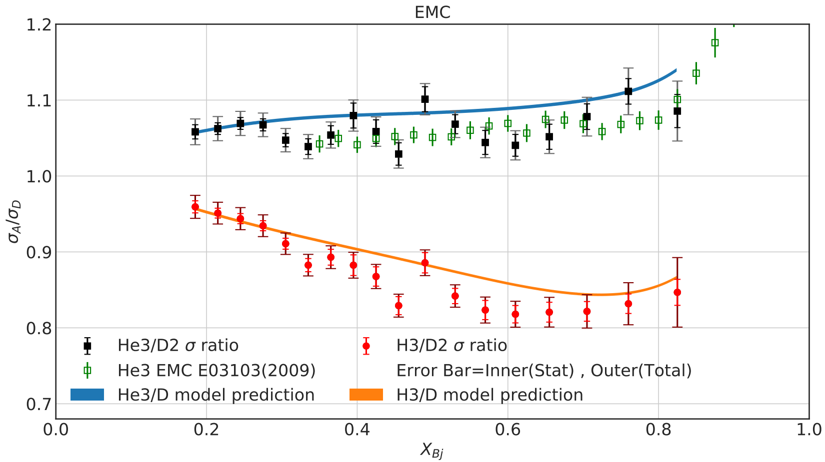
Relative Error Contributions for the Cross Section ^{3}H.

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

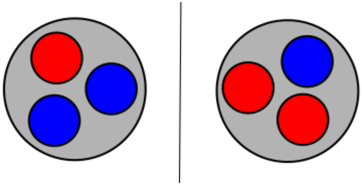
** Largest contributers to the error in Monte Carlo and Cross section model calculation.

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].

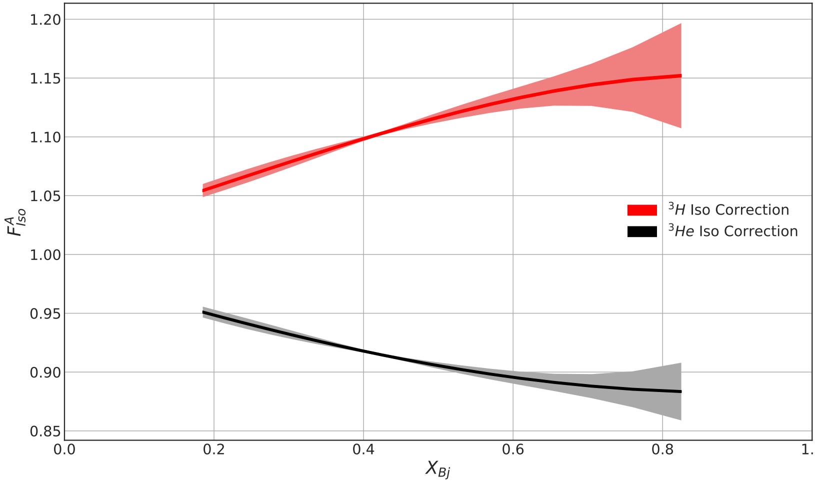
Isoscalar Corrections



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

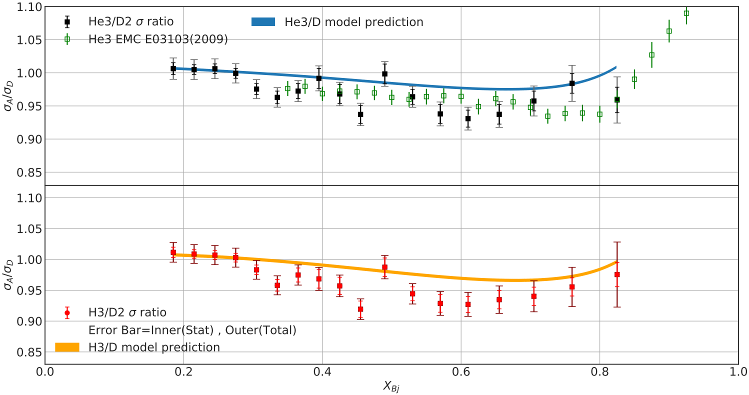
$$F^A_{Iso} = \frac{\left(0.5 * (1.0 + \frac{F_2^n}{F_2^p})\right)}{\left(\frac{1}{A} \cdot (Z + (A - Z) \cdot \frac{F_2^n}{F_2^p})\right)}$$

Isoscalar Corrections



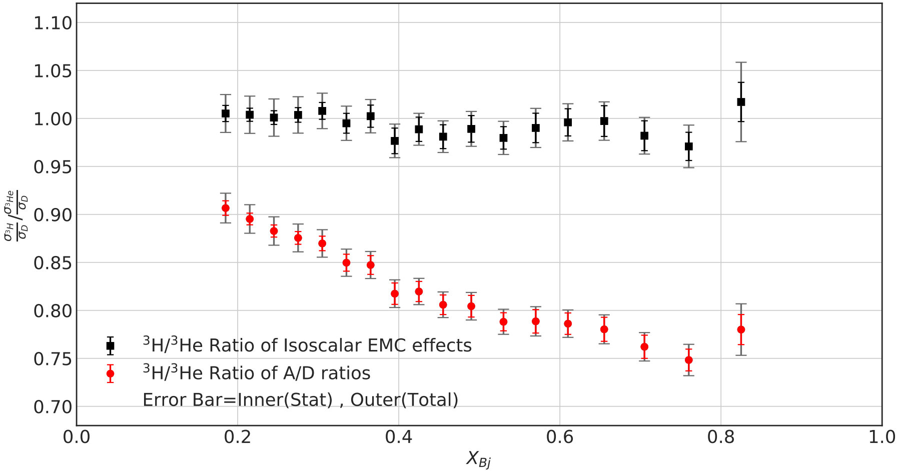
Isoscalar correction factor for both ^{3}He and ^{3}H. Model dependent calucation, error is calcualted via comparing different models for $\frac{F_2^n}{F_2^p}$.

- 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



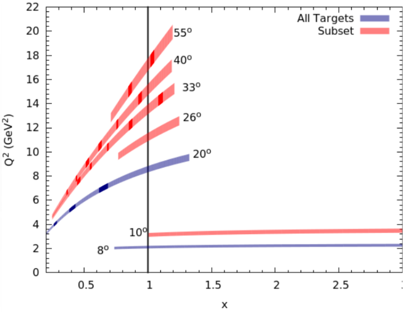
Ratio of EMC effects. Black is Isoscalar correct, red is not.

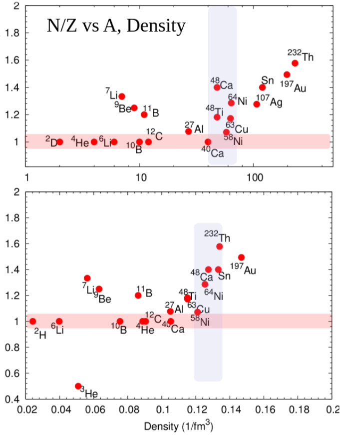
Summary

- Used DIS to extract inclusive cross section for ^{3}H, ^{3}He, and D
- Looked at the A/D ratio for both ^{3}H and ^{3}He
- 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

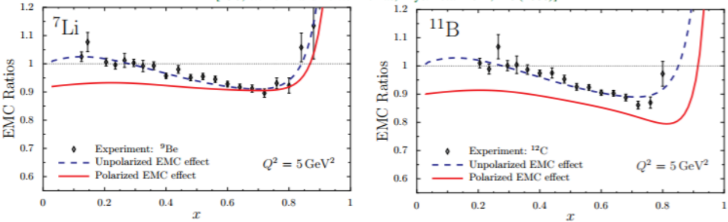
What is soon?

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)

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S.N.Santiestebana et. al

Nucl. Instrum. Meth. A 940 (2019) 351-358

J. Seely, A. Daniel et al

Phys. Rev. Lett. 103, 202301 (2009).

J. R. Smith and G. A. Miller

Chiral solitons in nuclei: Saturation, EMC effect and Drell-Yan experiments. *Phys. Rev. Lett.*, 91, 2003. Erratum: *Phys. Rev. Lett*, 98, 2007.

Bogdan Povh,

Particles and Nuclei: An Introduction to the Physical Concepts, (1995)

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.

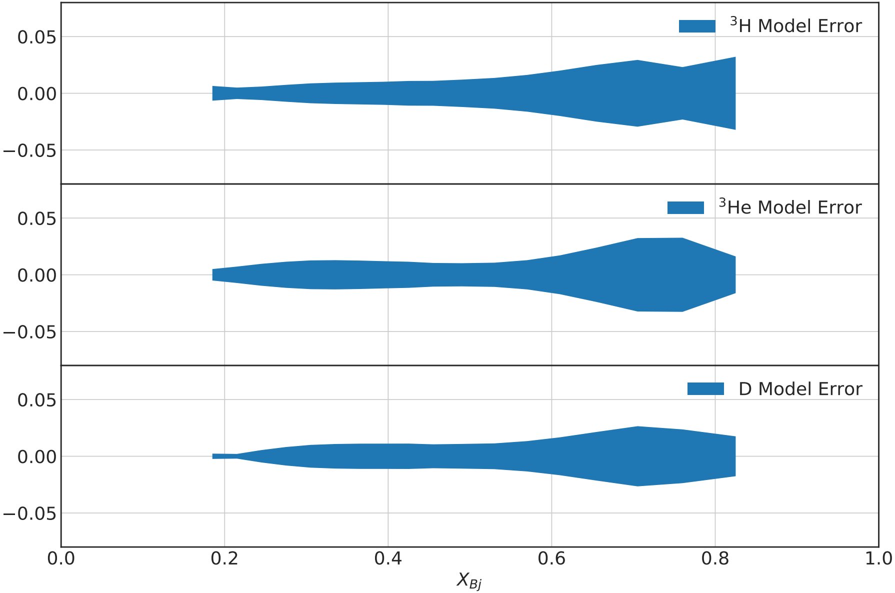
Relative Error Contributions for the Cross Section D.

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

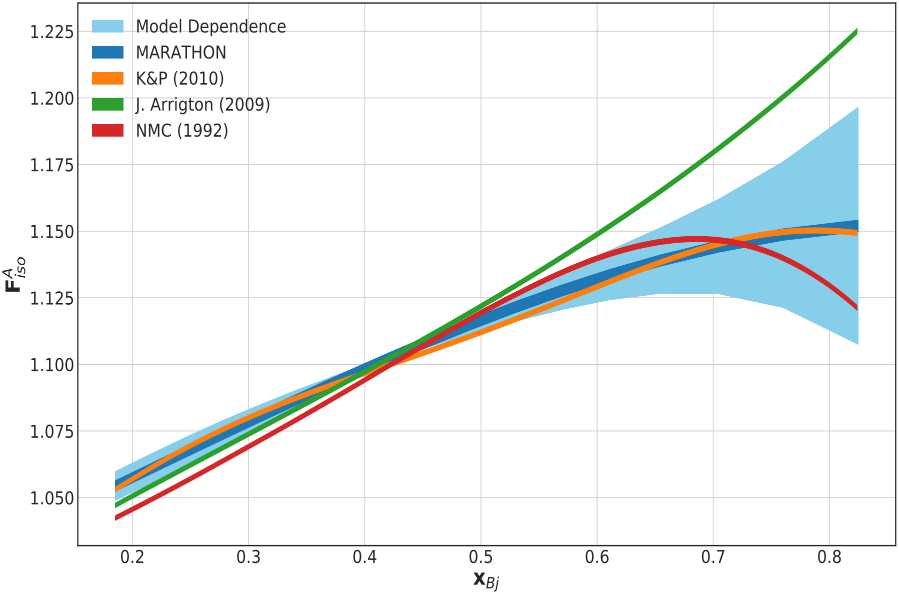
* Largest contributers to the error in the yield calculation

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

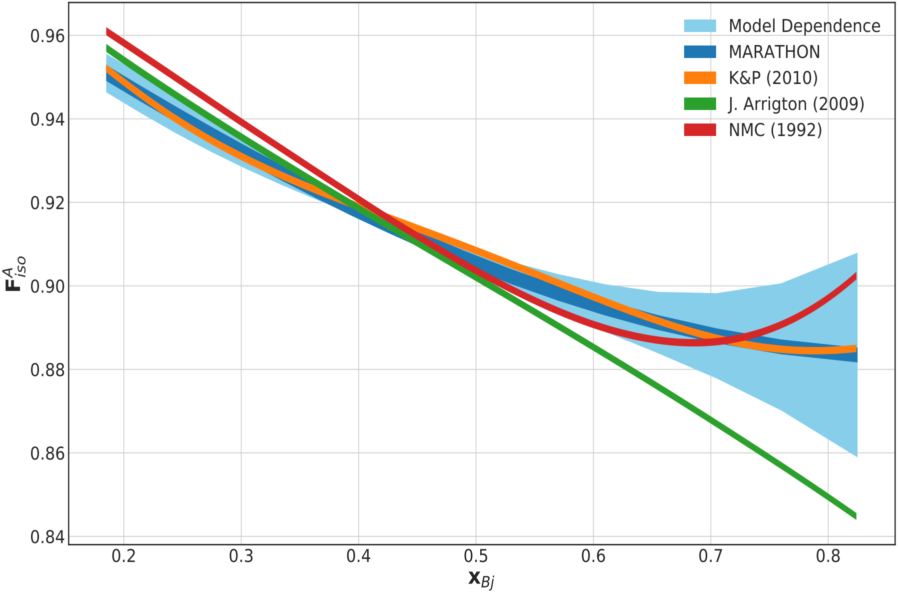
Model Cross Section Error



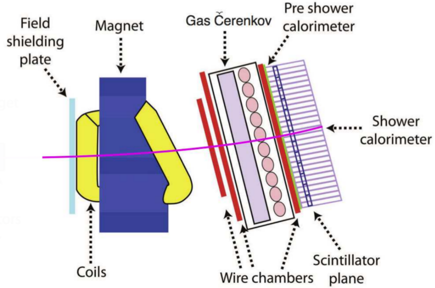
Isoscalar Correction Error for ^{3}H



Isoscalar Correction Error for ^{3}He



Bigbite Spectrometer



Large Acceptance Spectrometer

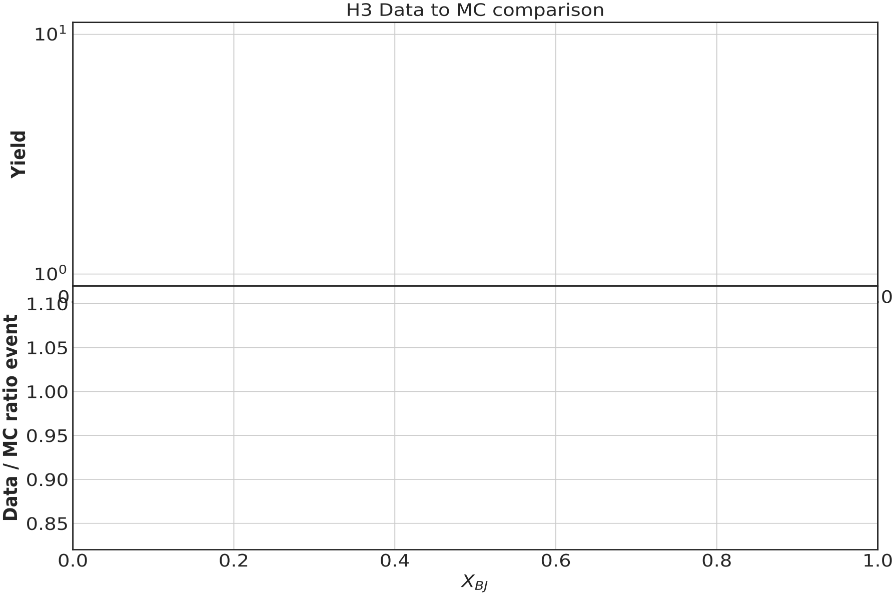
- Solid angle $= 96$ mrad
- Large Momentum Acceptance: > 500 MeV/c

My contributions in preparing Bigbite

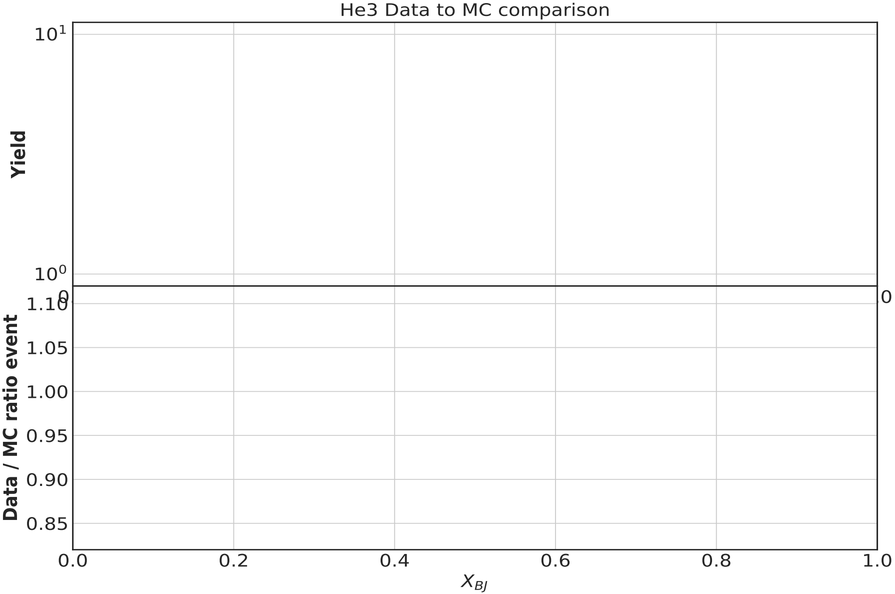
- Constructing the data acquisition system
- PMT performance studies
- Designing trigger logic
- Ensuring consistent and dependable HV power

Removed from the run plan for safety and logistical concerns

Yield & MC ratio ^{3}H



Yield & MC ratio ^{3}He



Yield & MC ratio D