

# 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**.

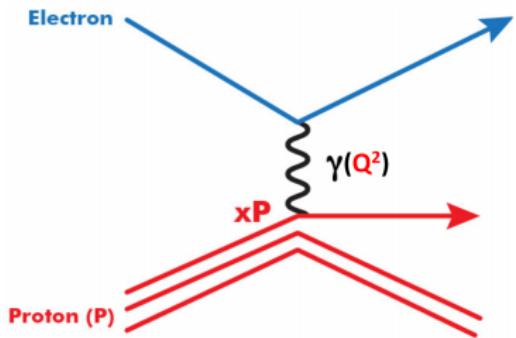


More than 1,500 nuclear physicists worldwide come to Jefferson Lab to conduct and collaborate on research.

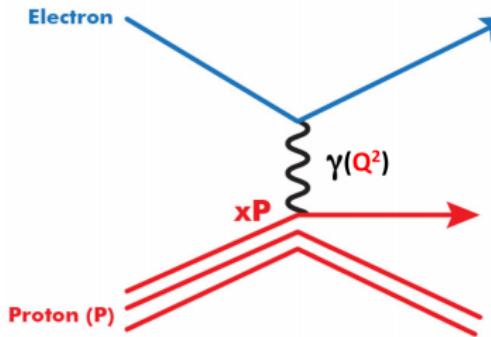
# Outline

- 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)

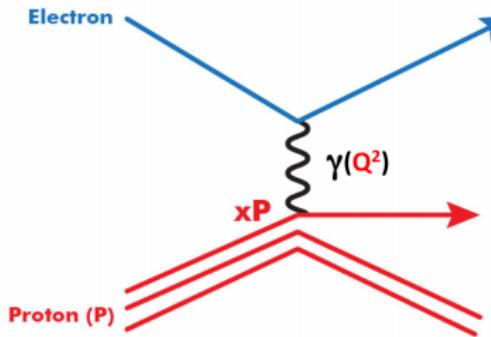


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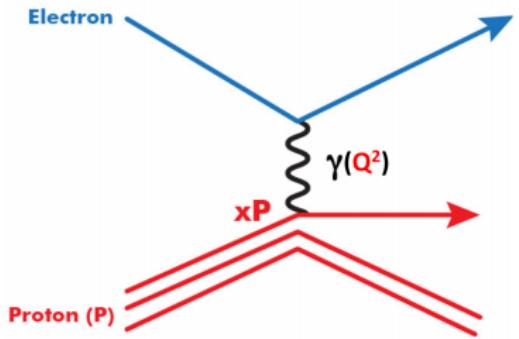
- $Q^2 \equiv 4EE' \sin^2 \frac{\theta}{2}$

# Deep Inelastic Scattering (DIS)



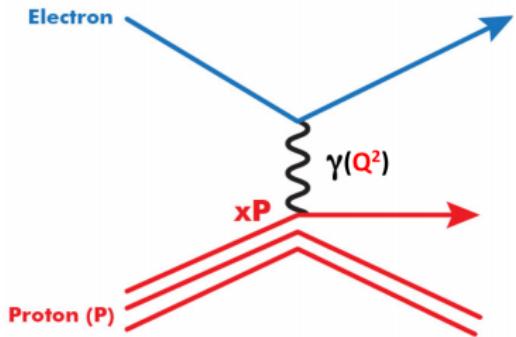
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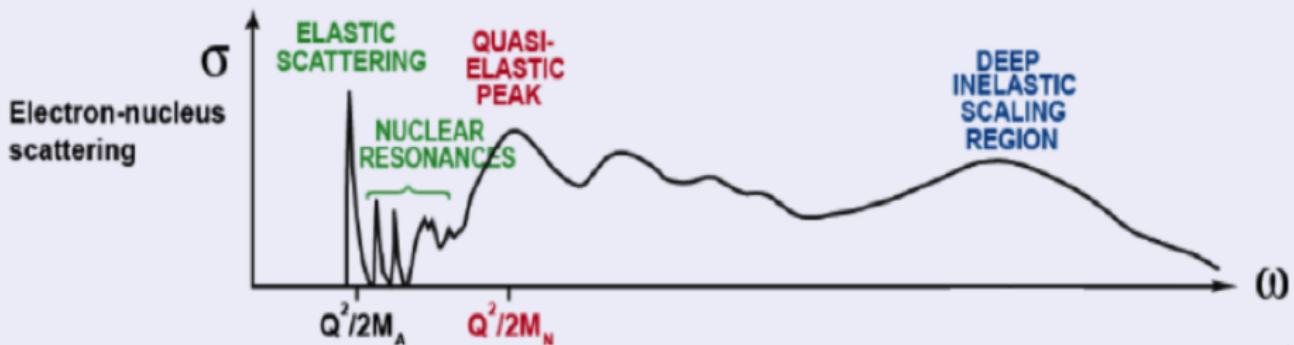
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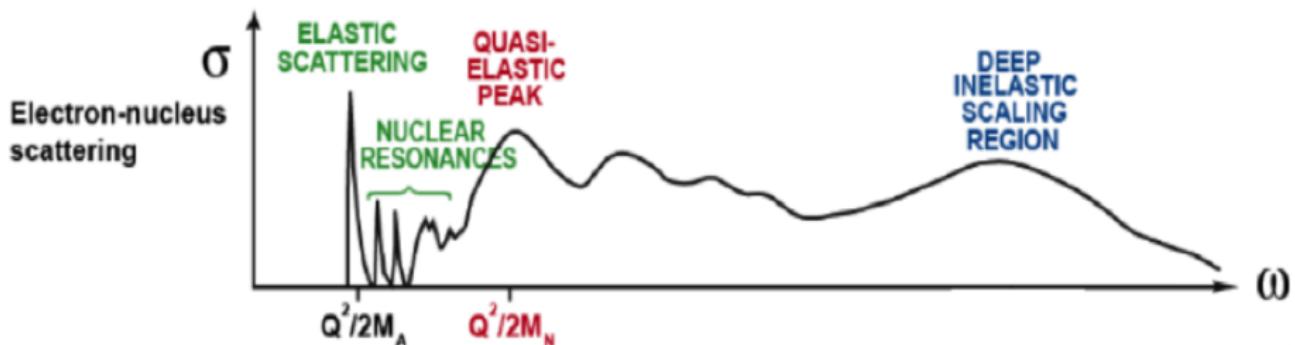


- $Q^2 \equiv 4EE' \sin^2 \frac{\theta}{2}$
- $\nu \equiv E - E'$
- $X_{Bj} = \frac{Q^2}{2\nu M}$
- $W^2 = 2M\nu + M^2 - Q^2$

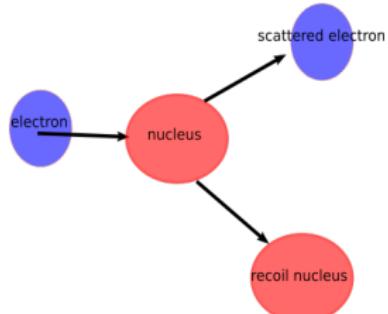
DIS ??????

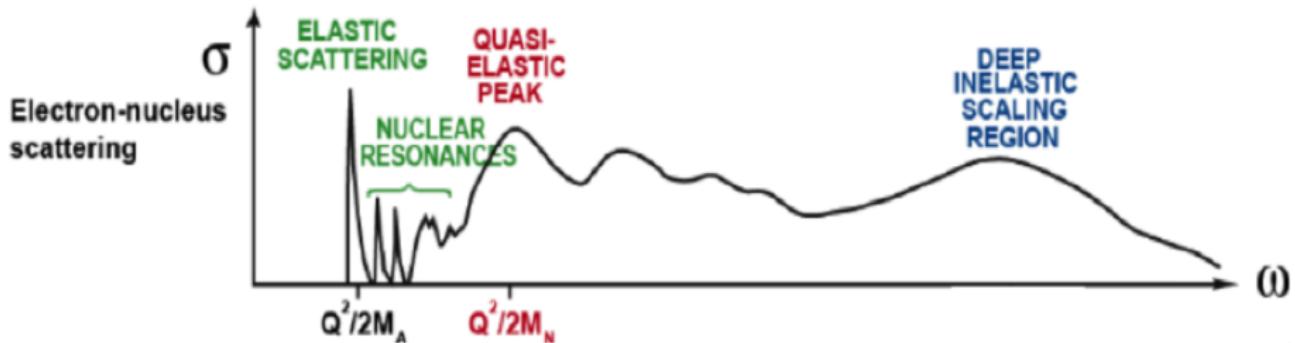


Idealized spectra of high-energy electron scattering as a function of energy transfer [G. T. Garvey, et al., 2015].

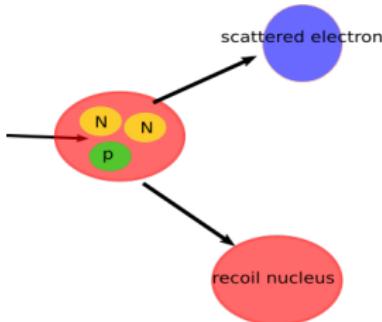


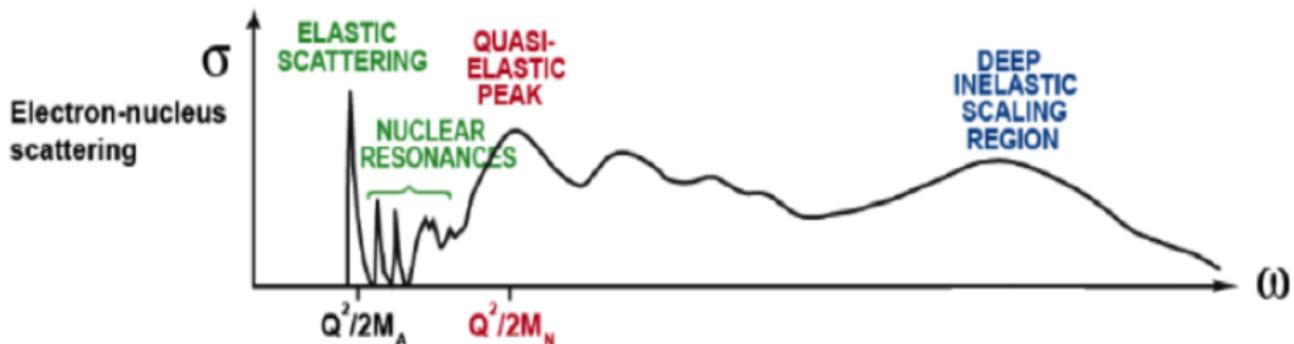
- Elastic scattering



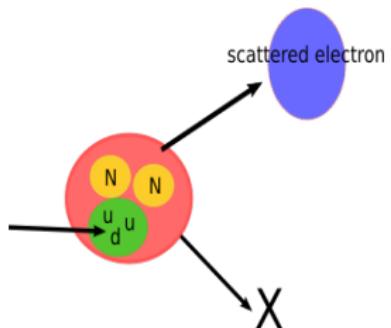


- Quaiselastic





- DIS

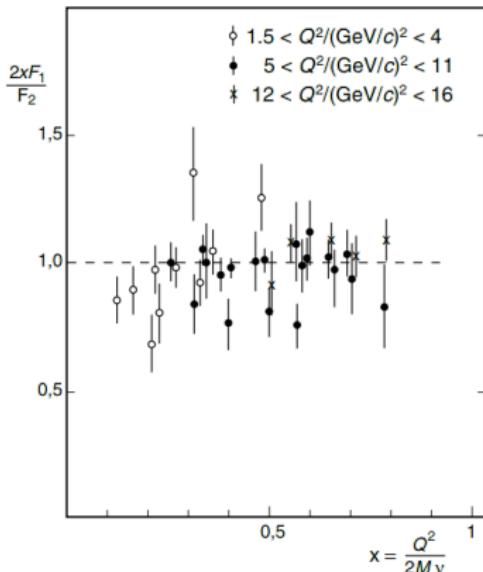


# Why DIS?

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

## 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**  
 $F_2(x) = F_1(x) \cdot 2x$

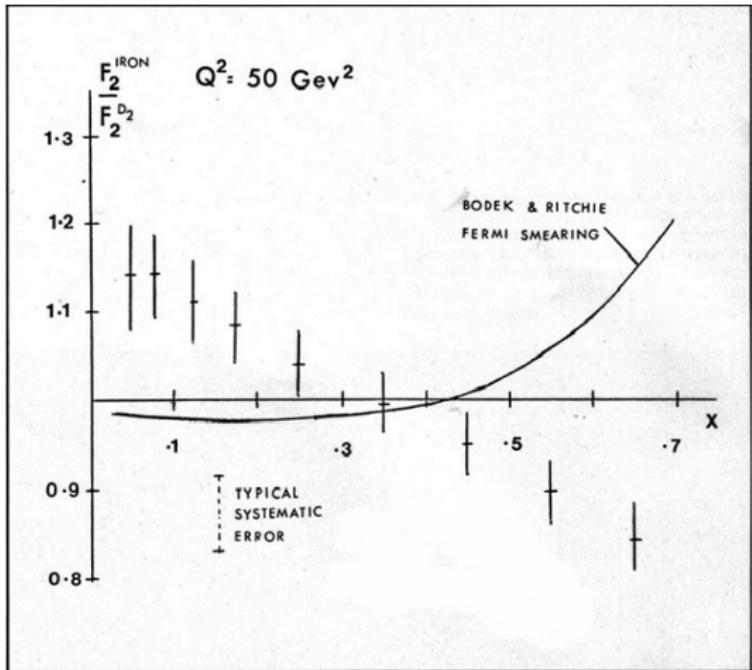


Ratio of  $2x \cdot F_1(x)$  and  $F_2(x)$  vs.  $x$ .  
[Povh, 1995]

# The EMC Effect

European Muon Collaboration

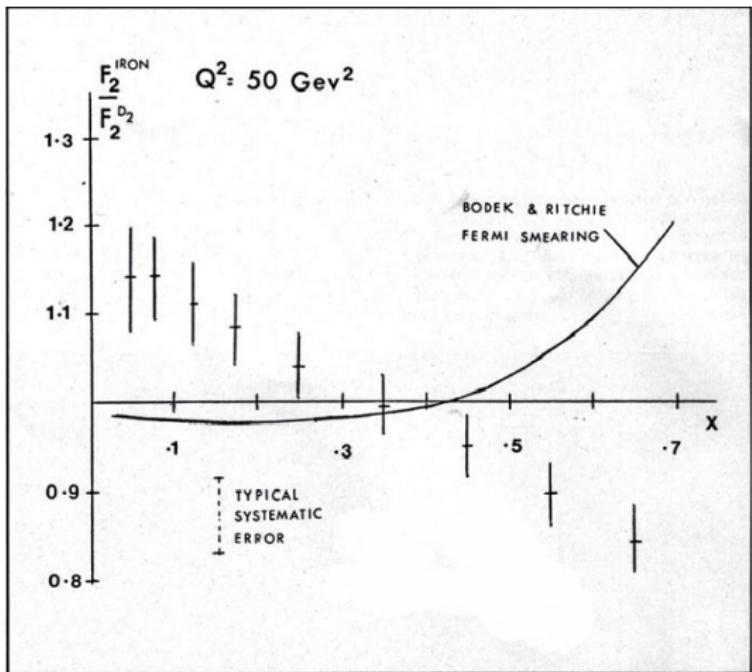
- $X$  = fraction of momentum carried by quark



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

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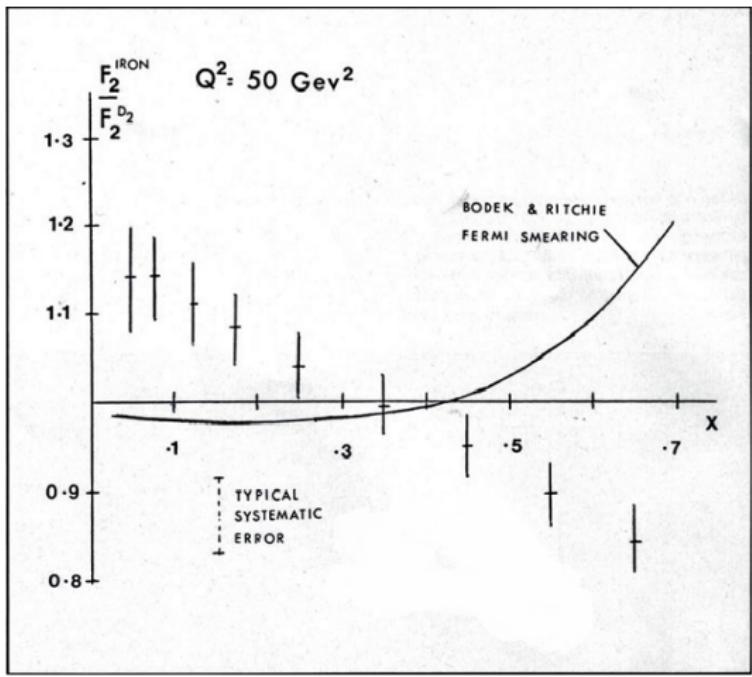
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[J.J. Aubert, et al. 1981]

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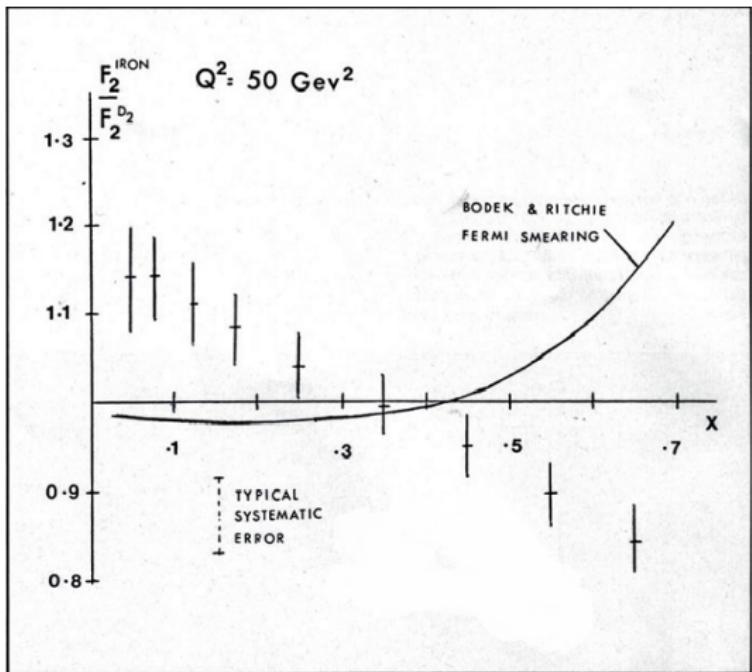


[J.J. Aubert, et al. 1981]

- $X$  = 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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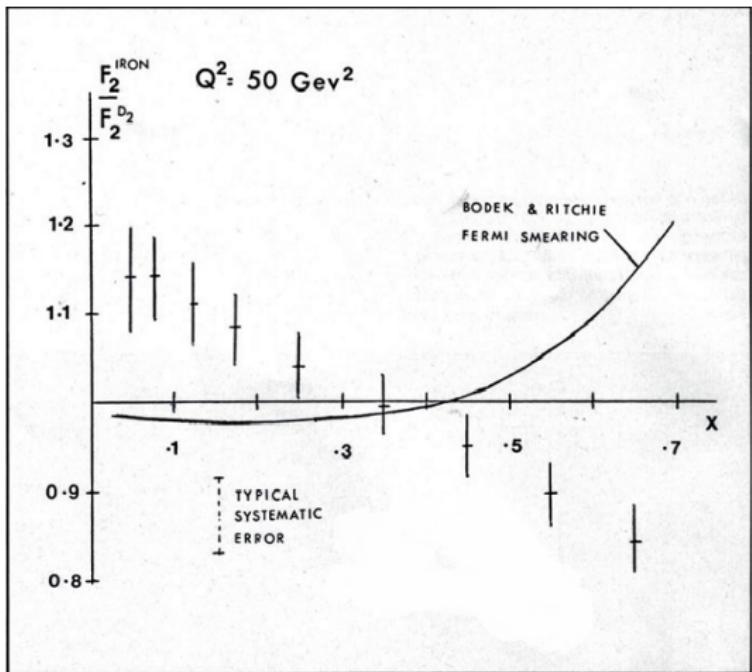


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- Missing high-momentum quarks in  $A > 2$

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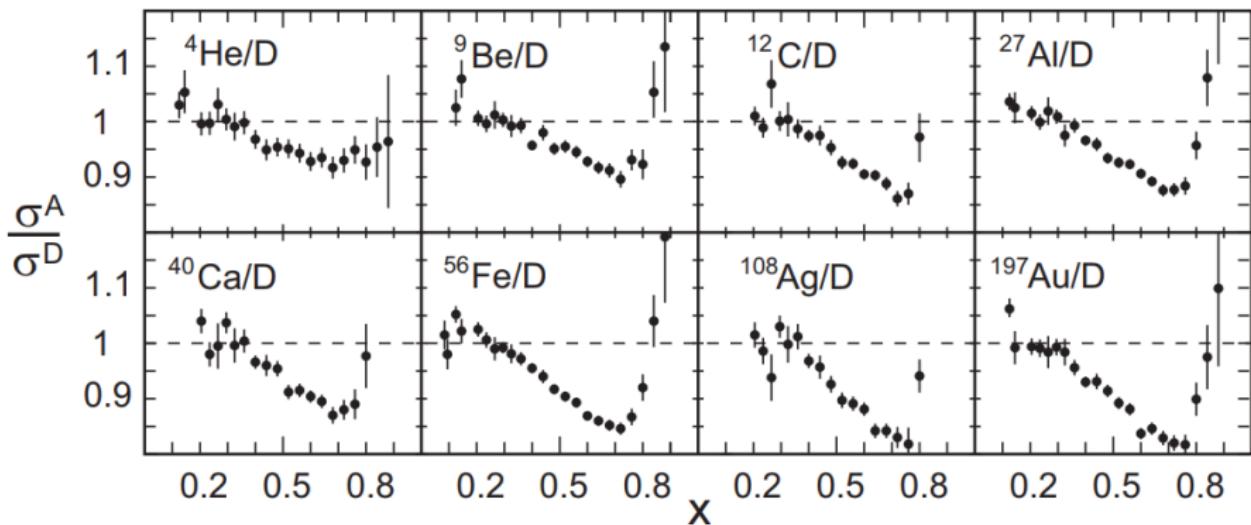


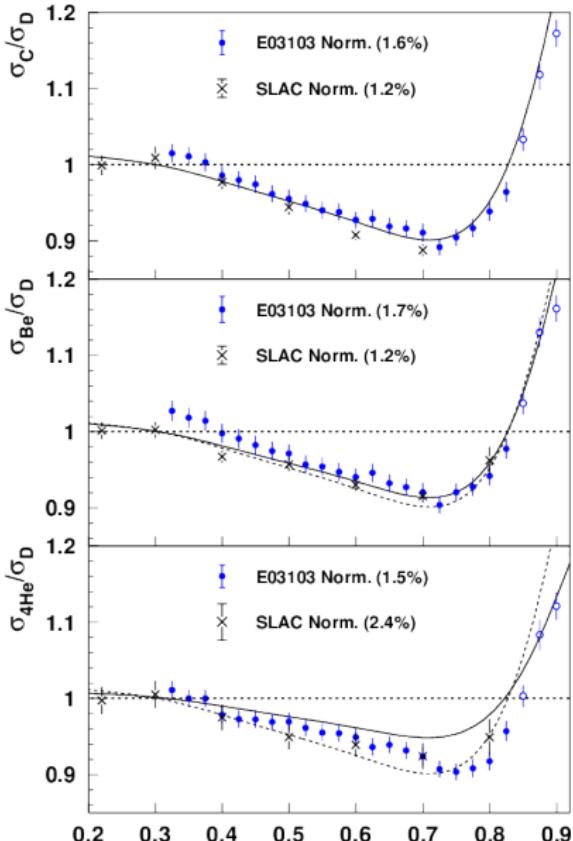
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- EMC Effect  $\equiv$  structure of the  $A/D$  Ratio

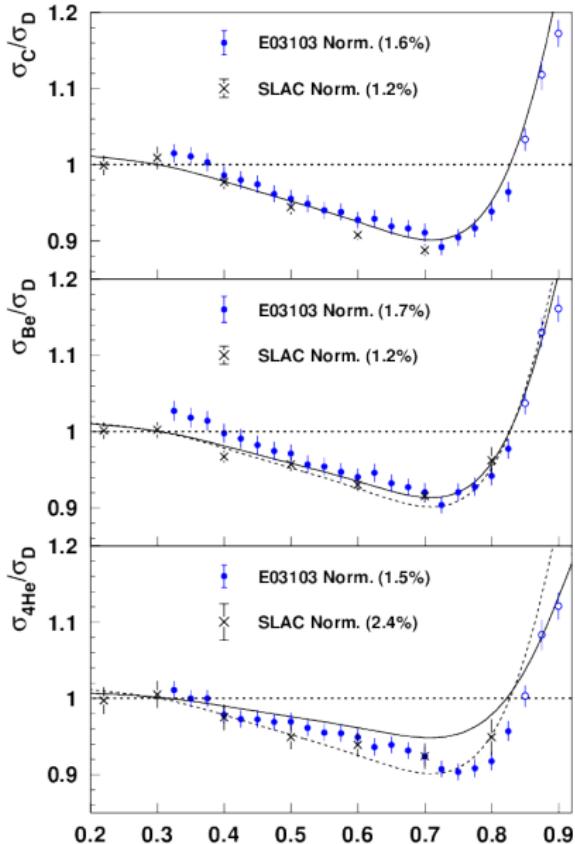
# The EMC Effect

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

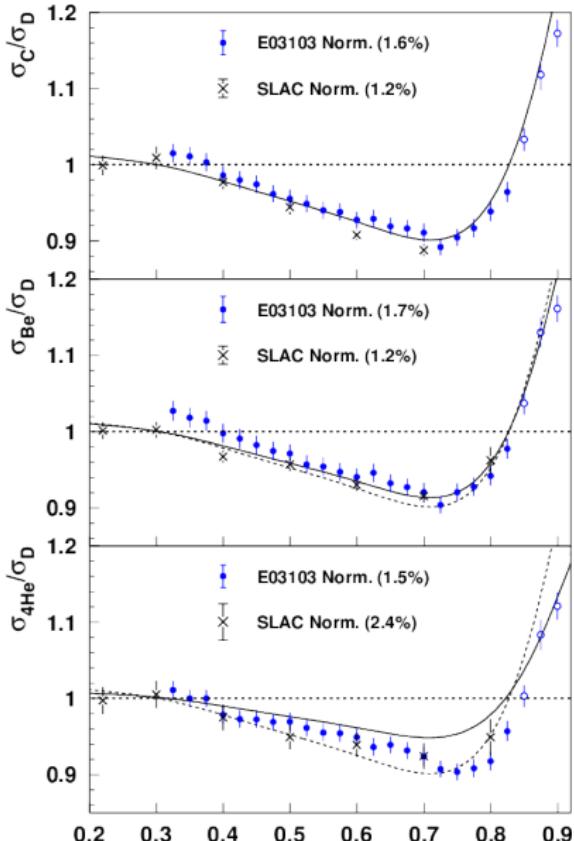




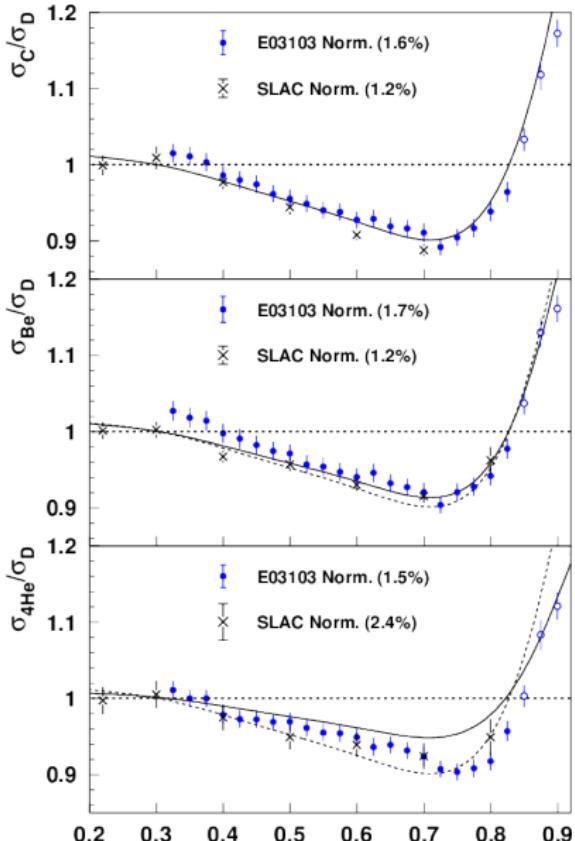
- JLab experiment E03103 [J.Seely, A. Daniel et al, 2009]



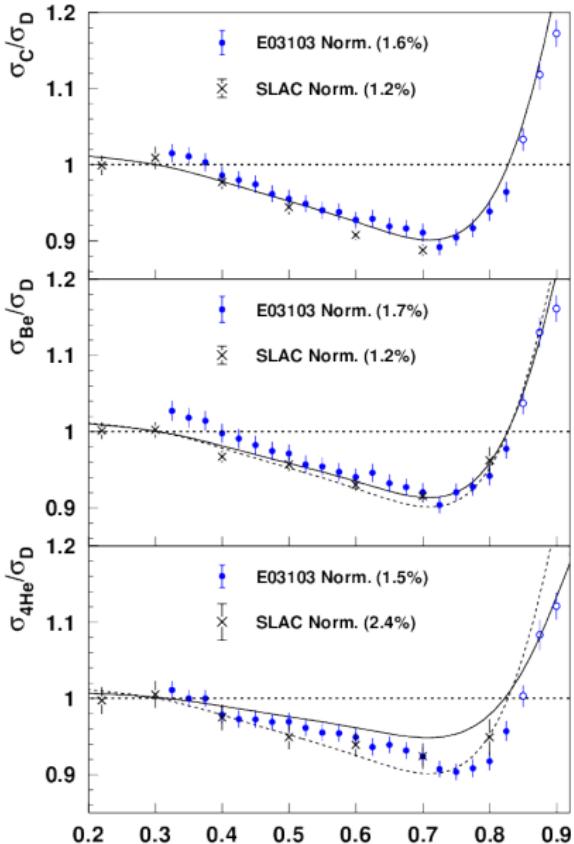
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- Quantized by slope of A/D ratios from 0.3 - 0.7 in  $x$



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- Models have difficulty matching data for all criteria

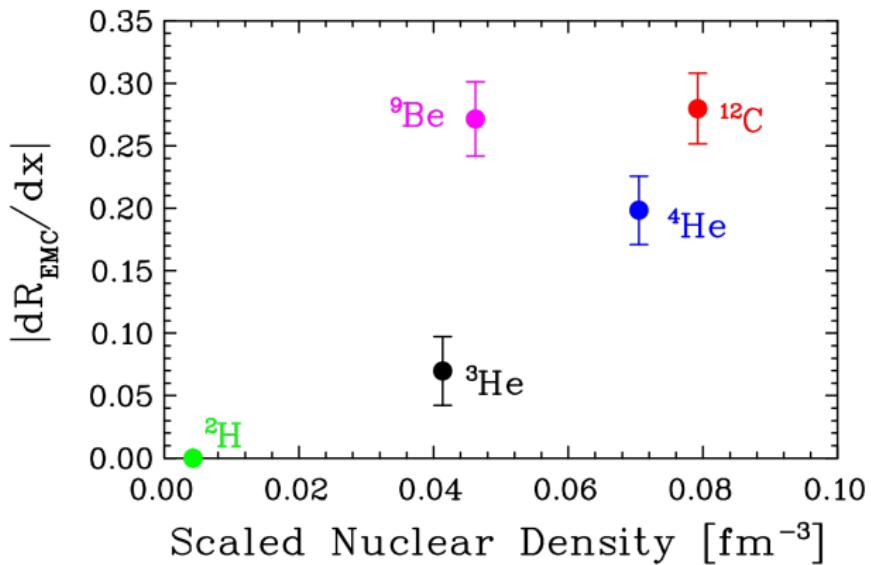


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- Quantized by slope of A/D ratios from 0.3 - 0.7 in x
- Models have difficulty matching data for all criteria
- $\approx \log$  dependence in A

# The EMC Effect

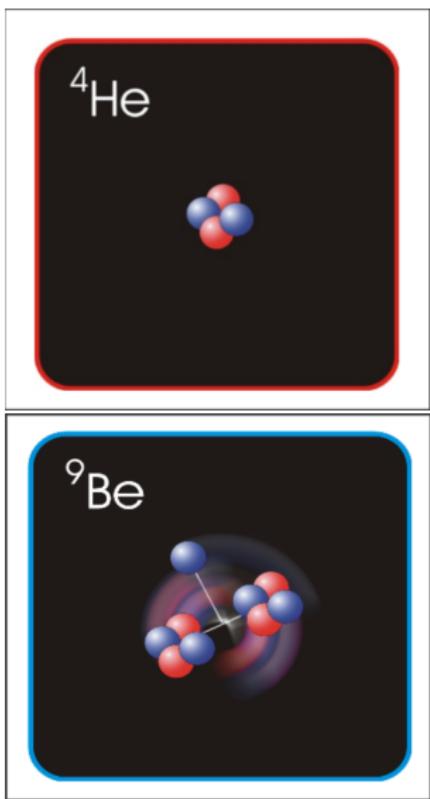
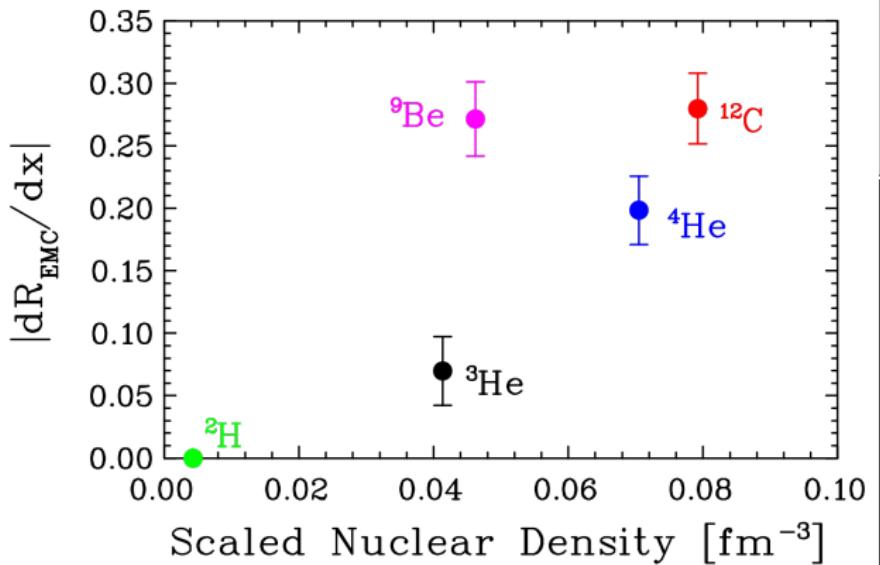
JLab experiment E03103

[J.Seely, A. Daniel et al, 2009]



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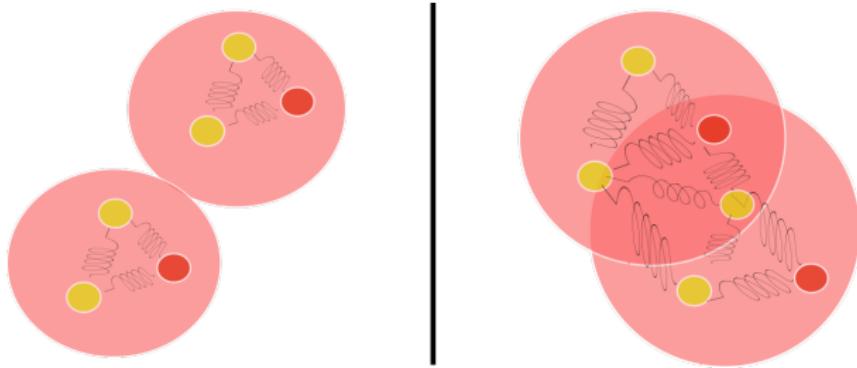
JLab experiment E03103  
[J.Seely, A. Daniel et al, 2009]



# 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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  - ▶ Could explain rapid rise in EMC ratio

## 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



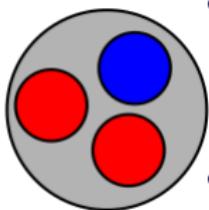
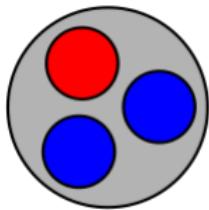
## The EMC puzzle

- 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?

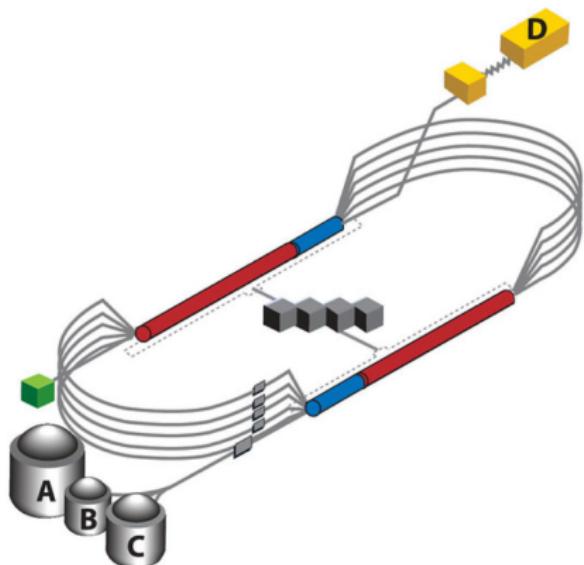
# MARATHON

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 MirOr 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

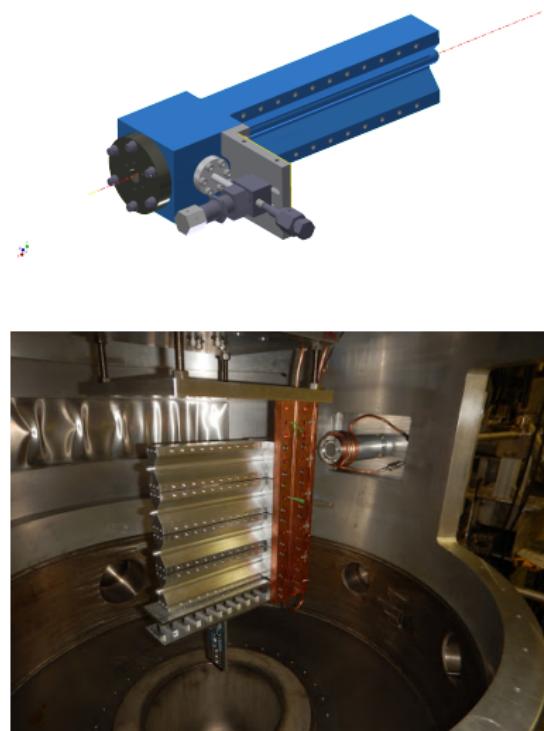
# Uses of Tritium



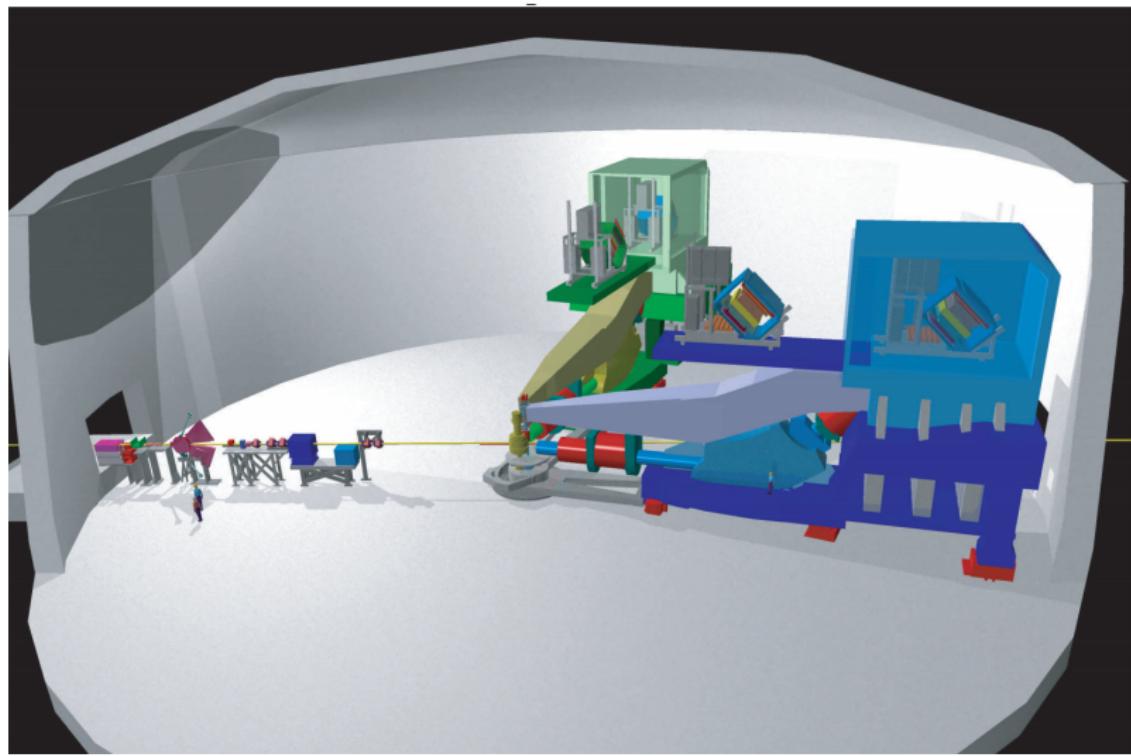
# Tritium Target Cell

First tritium target at JLab

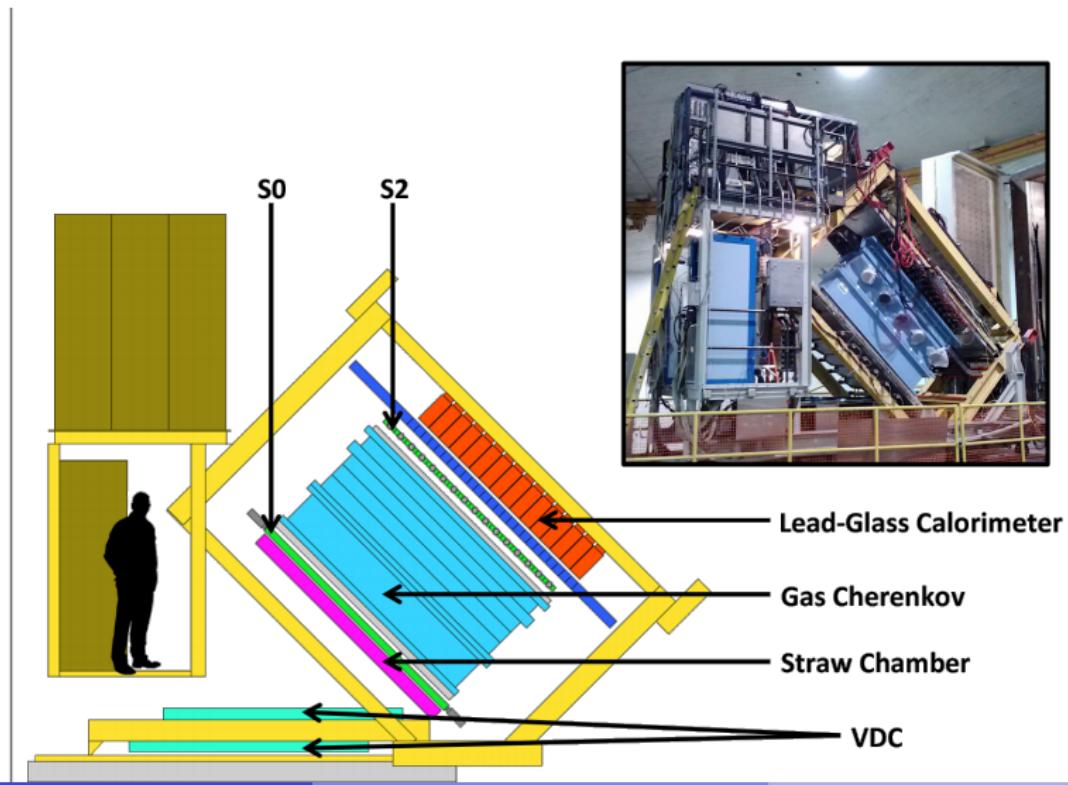
- Thin Al entrance and exit windows 0.01 inches
- 1090Ci of Tritium (0.1 g)
- 25 cm long
- Tritium Cell was filled in Savannah River
- 40 kelvin Helium is used to cool an attached heat sink



## Hall A

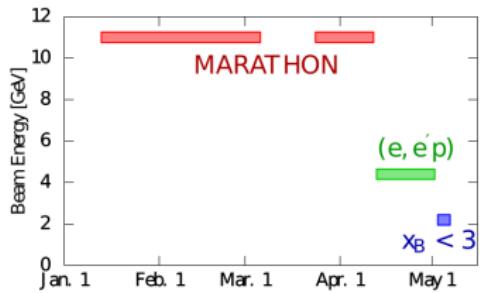


# High Resolution Spectrometers (HRSs)



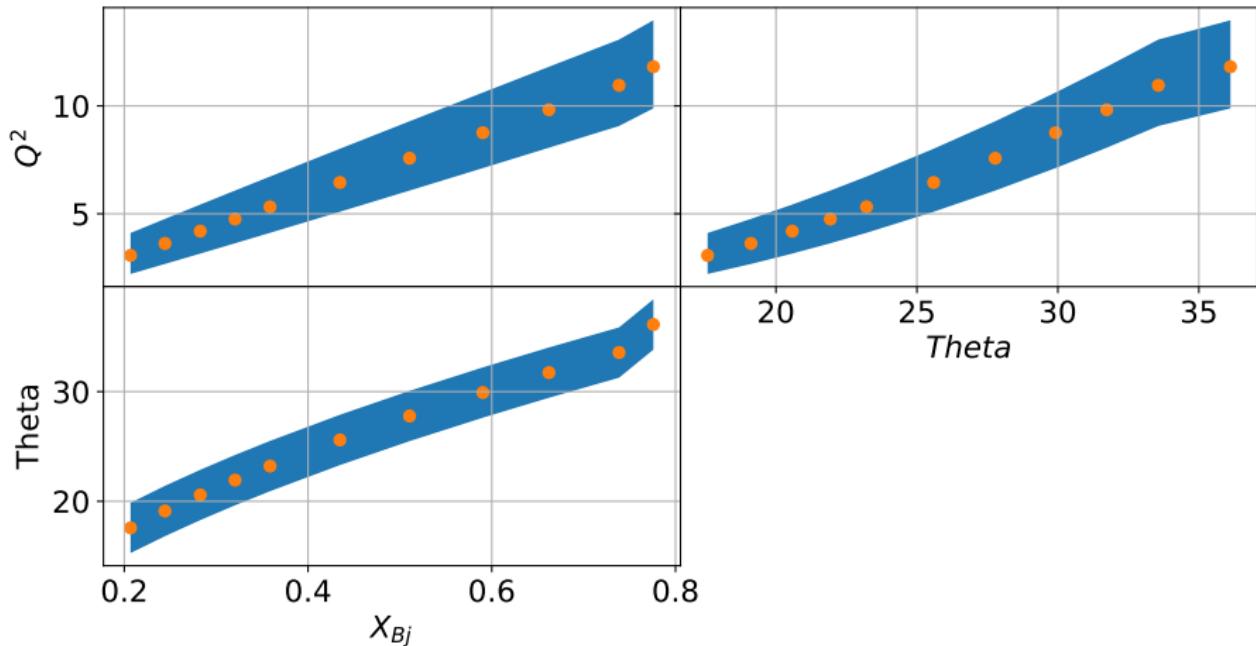


## The Run Period



Rey Torres

# 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

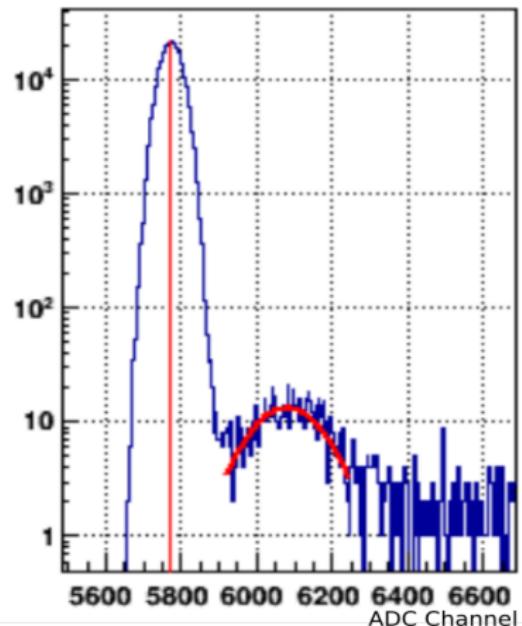
### TDC calibration

- Scintillators and VDC

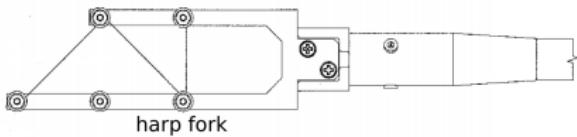
### Detector calibrations

- Beam Current Monitors
- Beam Position Monitors

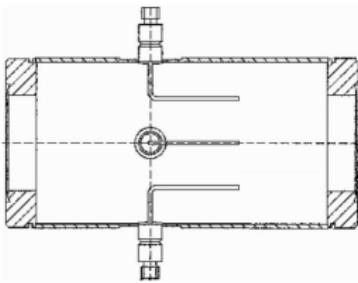
Cherenkov Calibration



# Beam Position Monitor(BPM) Calibration



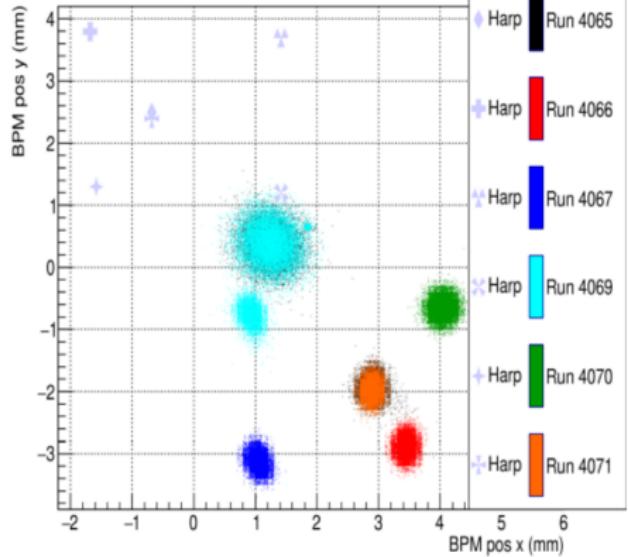
Intrusive absolute position measurement



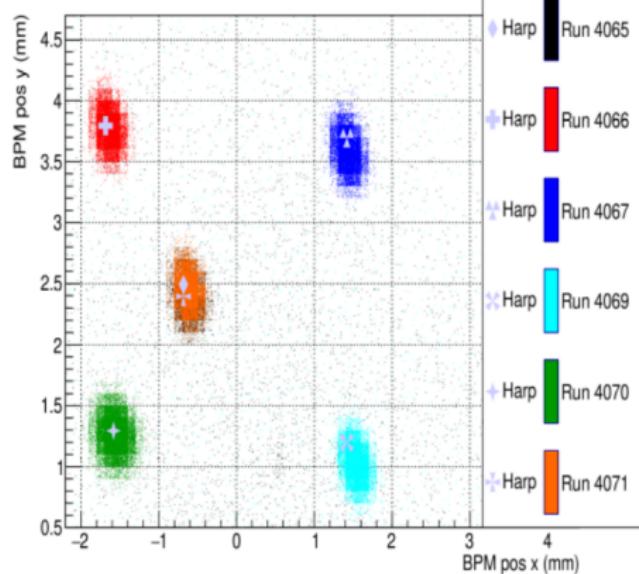
Relative position measurement

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

# 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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- $\epsilon$  = 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
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- Trigger
  - ▶ Scintillators & cherenkov
  - ▶  $\approx 99\%$

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## Calculating efficiencies

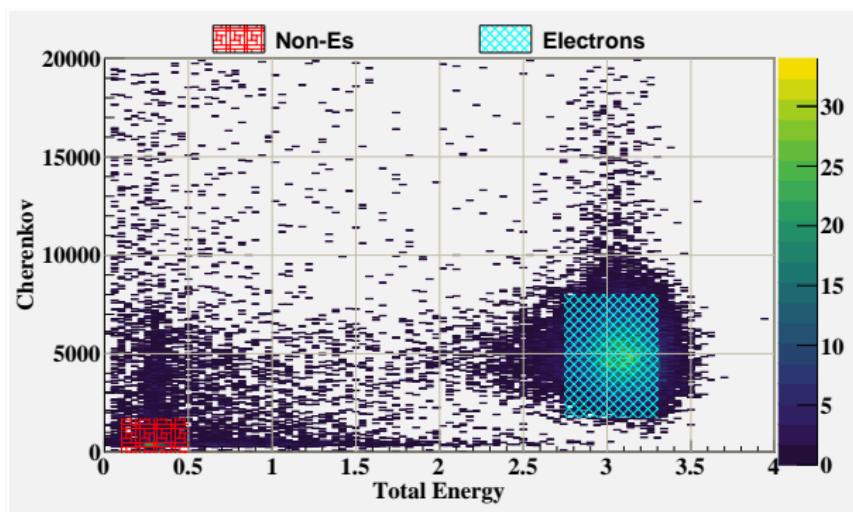
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  - ▶  $\approx 99\%$
- Tracking
  - ▶ Vertical Drift Chambers(VDCs)
  - ▶  $\approx 98\%$
- Electronic Deadtime
  - ▶  $\approx 96\%-99\%$

# Particle ID Efficiency



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

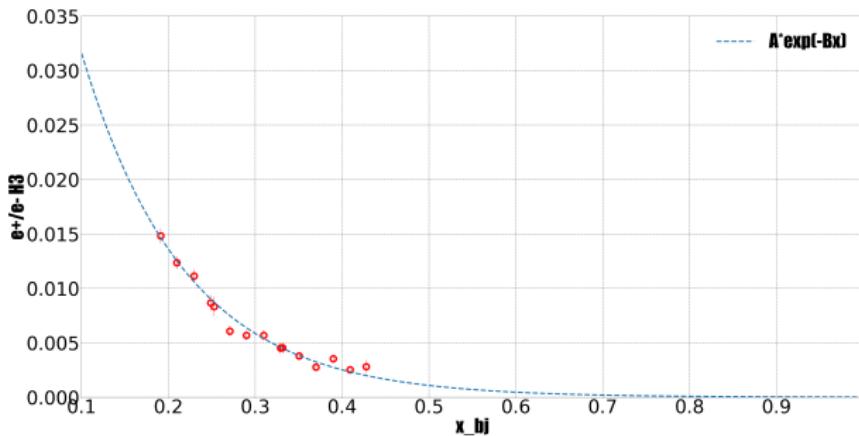
# Charge Symmetric Background

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

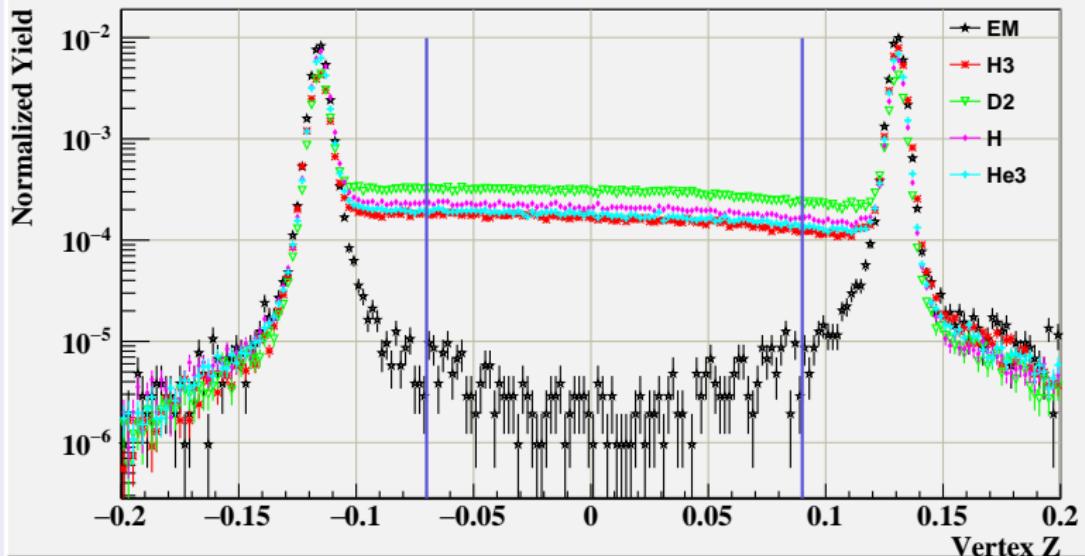
## Pair Production



Tritium positron contamination. Credit: Tong Su

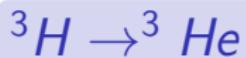


# Aluminum Endcap Background



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

# $^3H$ Decay

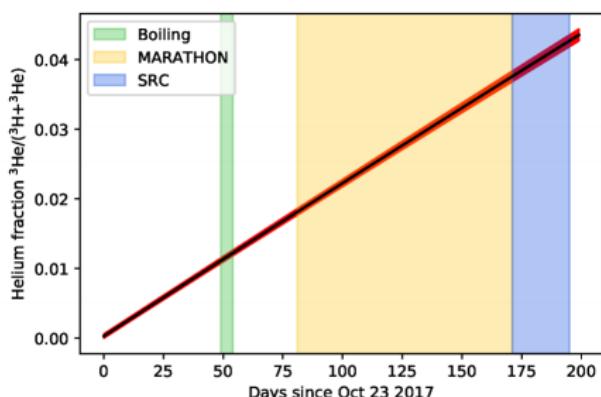


$$\tau(^3H) = 4500 \pm 8\text{ days}$$

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

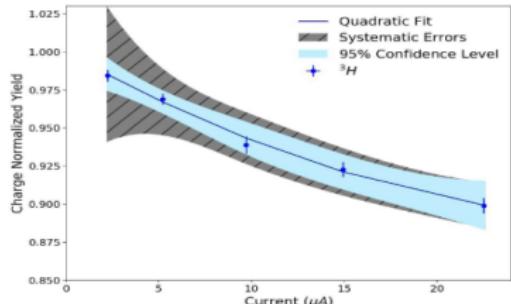
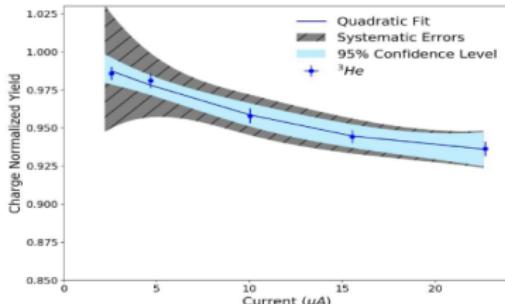
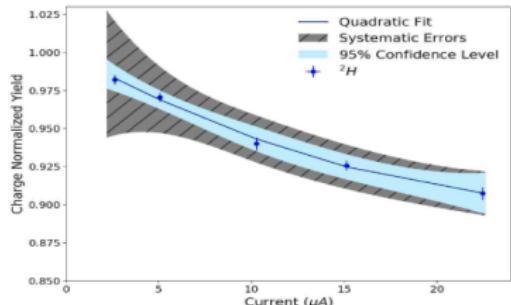
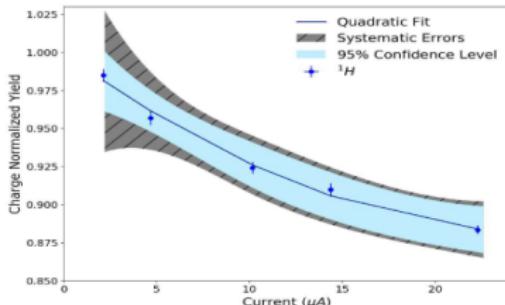
$$\sigma_{^3H} = \left( \frac{\sigma_{tot}}{\sigma_{^3He}} \right) \left( \frac{1}{1 - c} \right) - \left( \frac{1}{1 - c} \right)$$

Beta Decay Helium Fraction



Tyler Kutz

# Density Fluctuations

(a)  ${}^3\text{H}$  Density Analysis.(b)  ${}^3\text{He}$  Density Analysis.(c)  ${}^2\text{H}$  Density Analysis.(d)  ${}^1\text{H}$  Density Analysis.

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

## Monte Carlo Ratio Method

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

## Monte Carlo Ratio Method

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

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

## 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

## 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

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

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

Use a Monte Carlo simulation

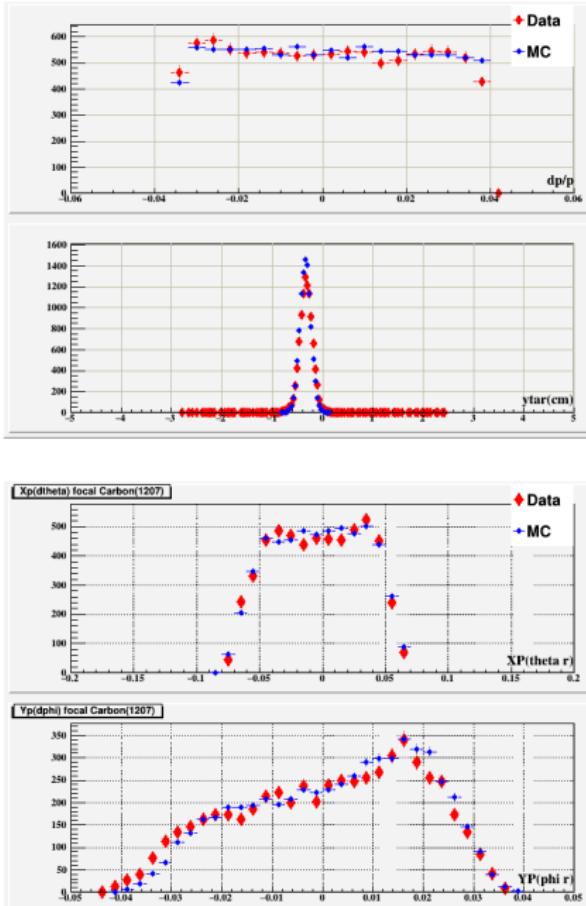
- $(\Delta E' \Delta \Omega)_{Data} = (\Delta E' \Delta \Omega)_{MC}$
- $A(E', \theta)_{Data} = A(E', \theta)_{MC}$

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

## 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

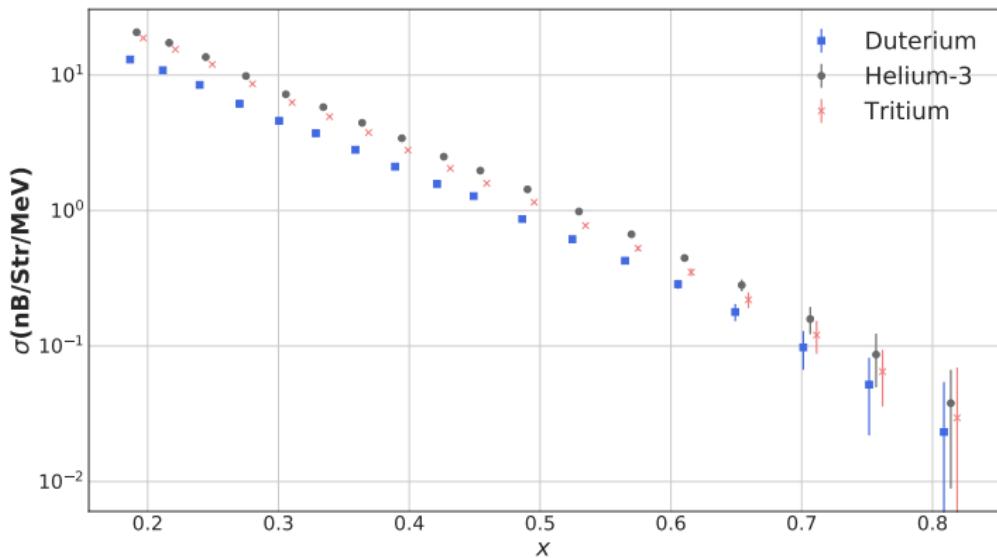
10.6 GeV Beam,  $W^2 > 3.5 \text{ Gev}^2$

Scatted angles  $17.5^\circ$  to  $31^\circ$

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  
 ${}^3\text{He} - 1.12\% \bullet {}^3\text{H} - 0.97\% \bullet \text{D} - 0.56\%$

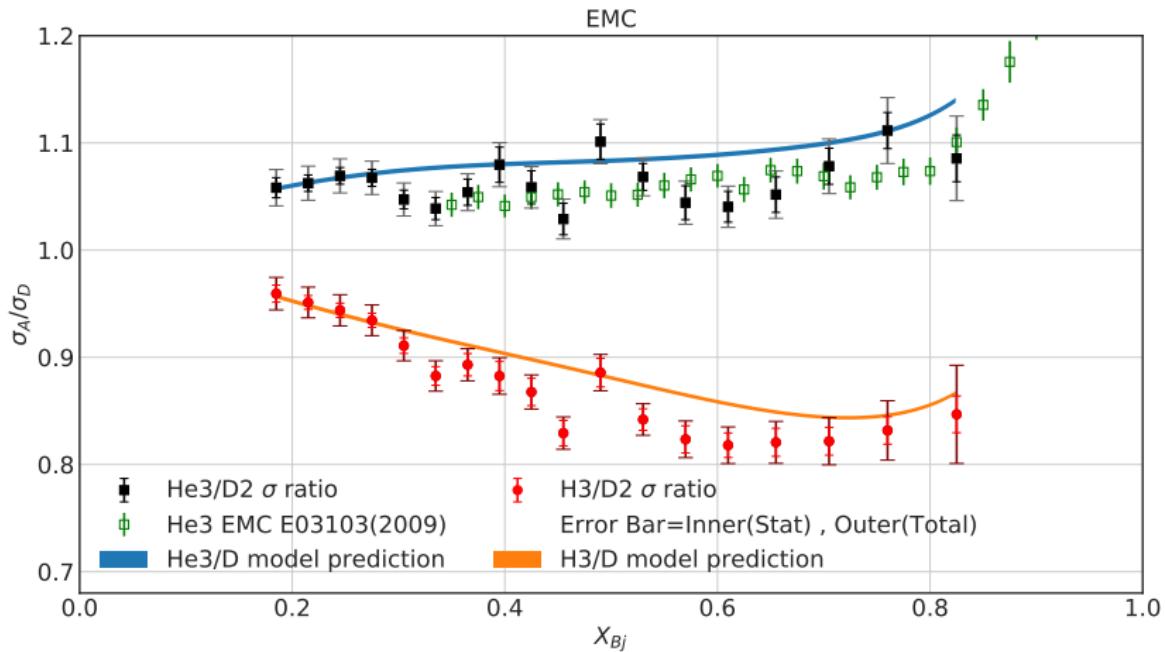
## Relative Error Contributions for the Cross Section ${}^3\text{H}$ .

<b>Xbjc</b>	<b>0.185</b>	<b>0.305</b>	<b>0.49</b>	<b>0.57</b>	<b>0.705</b>	<b>0.825</b>
<b>Yield Error</b>	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
<b>MC&amp;Model</b>	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
<b>Total Error</b>	0.019	0.018	0.02	0.022	0.033	0.04

\* Largest contributors to the error in the yield calculation

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

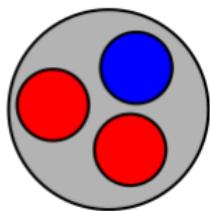
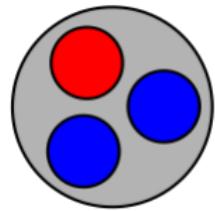
# Per Nucleon Cross Section Ratio



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].

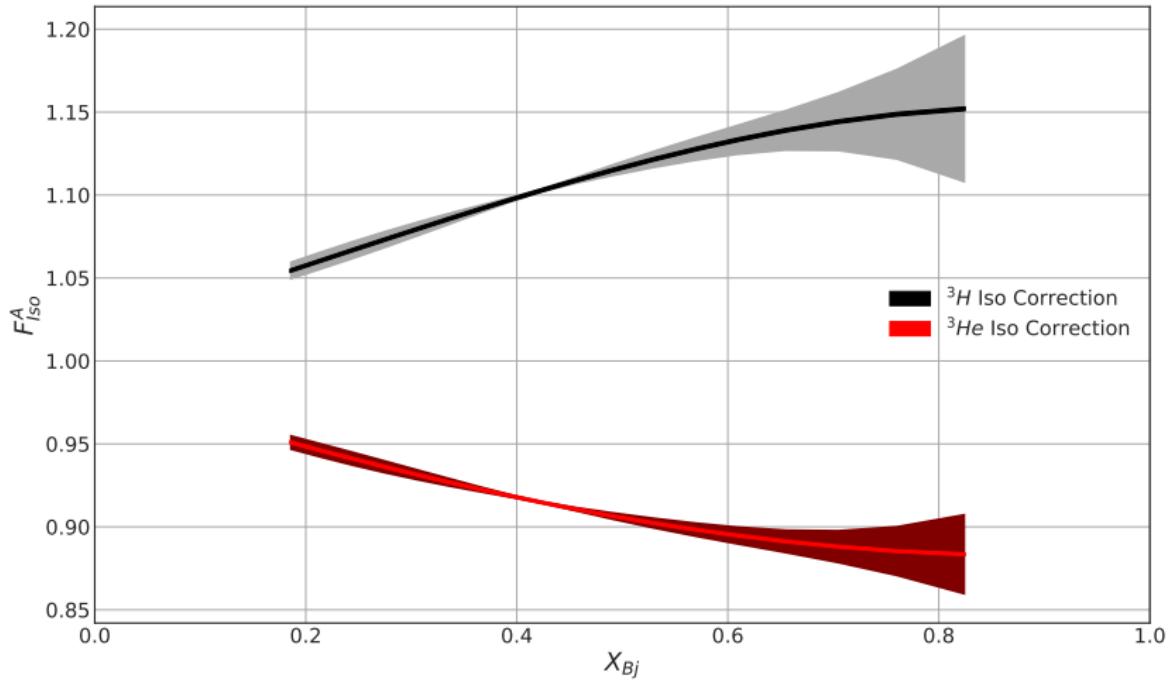
# Isoscalar Corrections



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

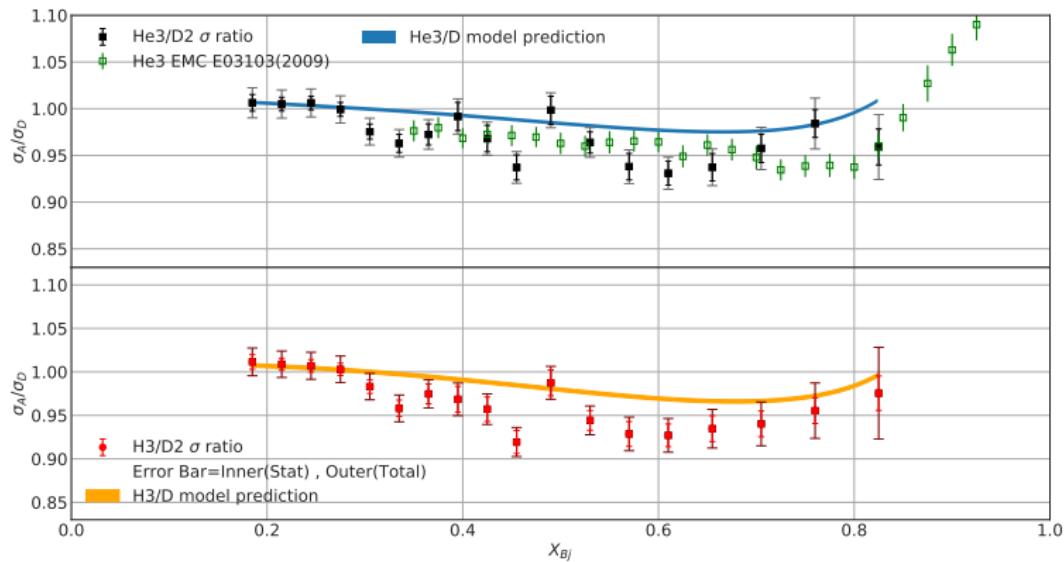
$$F_{Iso}^A = \frac{\left(0.5 * (1.0 + \frac{F_2^n}{F_2^p})\right)}{\left(\frac{1}{A} \cdot (Z + (A - Z) \cdot \frac{F_2^n}{F_2^p})\right)}$$

# Isoscalar Corrections



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

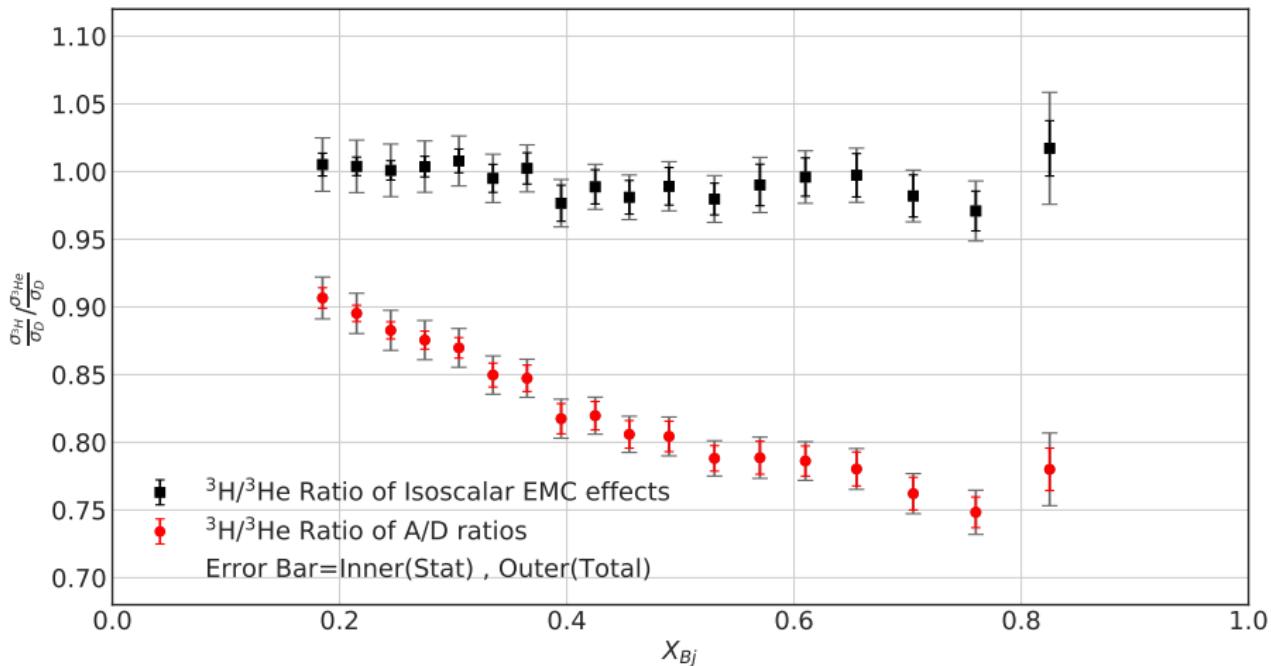
- My EMC results for He3 in black • H3 in red
- Previous Jlab He3 in green



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 $^3\text{H}/^3\text{He}$ EMC effects



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

## Summary

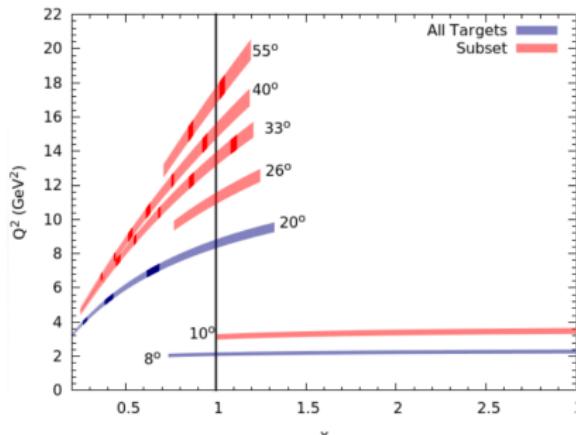
- Used DIS to extract inclusive cross section for  ${}^3\text{H}$ ,  ${}^3\text{He}$ , and D
- Looked at the A/D ratio for both  ${}^3\text{H}$  and  ${}^3\text{He}$
- Applied model dependent correction for excess protons and neutrons.
- Compared the EMC effects of the two, A=3 nuclei.
  - ▶ See no difference 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]

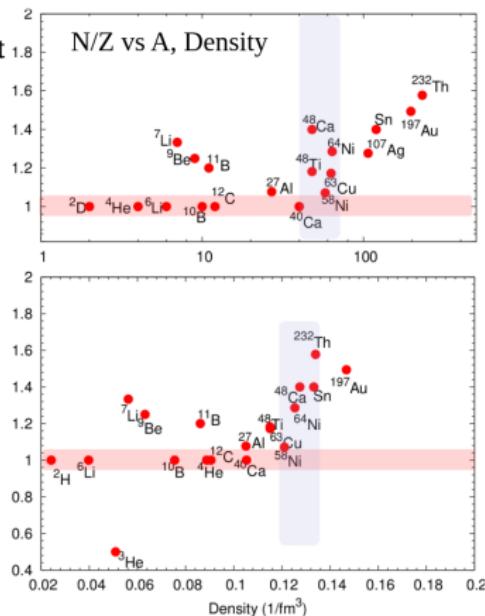
Target Choice motivated by physics impact



Coming soon\* in Hall C

What is soon?

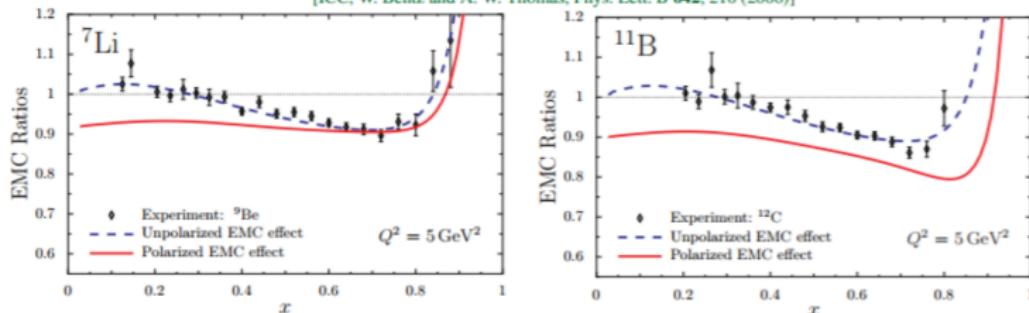
Slide credit Nadia Fomin



# 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  ${}^7\text{Li}$

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. Mihovilović, 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. Pettit, 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. Sirca, 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. Wojtsekowski, 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 ${}^3\text{He}$ .

<b>Xbjc</b>	<b>0.185</b>	<b>0.305</b>	<b>0.49</b>	<b>0.57</b>	<b>0.705</b>	<b>0.825</b>
<b>Yield Error</b>	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
<b>MC&amp;Model</b>	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
<b>Total Error</b>	0.019	0.02	0.019	0.02	0.036	0.029

\* Largest contributors to the error in the yield calculation

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

## Relative Error Contributions for the Cross Section D.

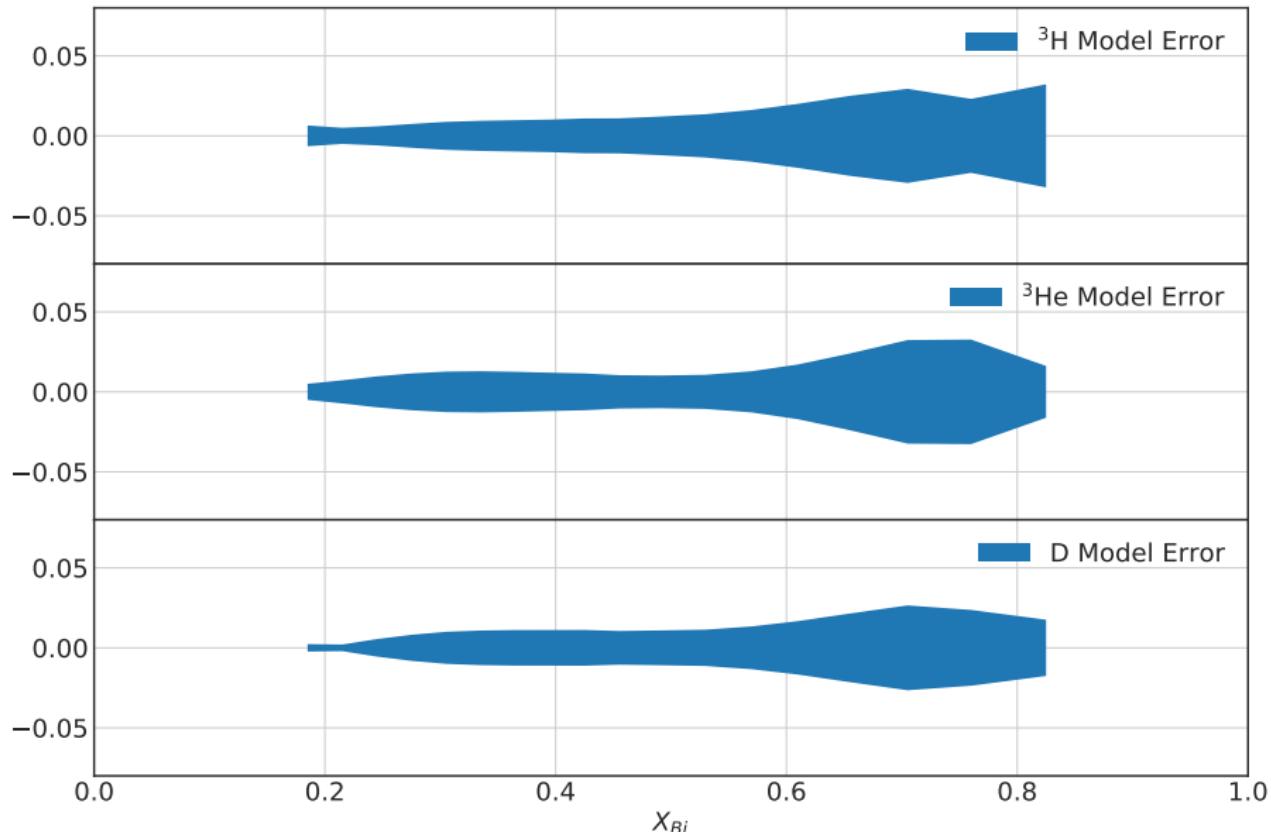
<b>Xbjc</b>	<b>0.185</b>	<b>0.305</b>	<b>0.49</b>	<b>0.57</b>	<b>0.705</b>	<b>0.825</b>
<b>Yield Error</b>	0.0104	0.0104	0.0159	0.0148	0.0139	0.0164
Stat Error*	0.0062	0.0053	0.0113	0.0106	0.011	0.0143
End Cap*	0.007	0.007	0.007	0.007	0.007	0.007
Eff Error*	0.004	0.0051	0.0081	0.0071	0.0041	0.0032
<b>MC&amp;Model</b>	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
<b>Total Error</b>	0.018	0.018	0.021	0.02	0.031	0.031

\* Largest contributors to the error in the yield calculation

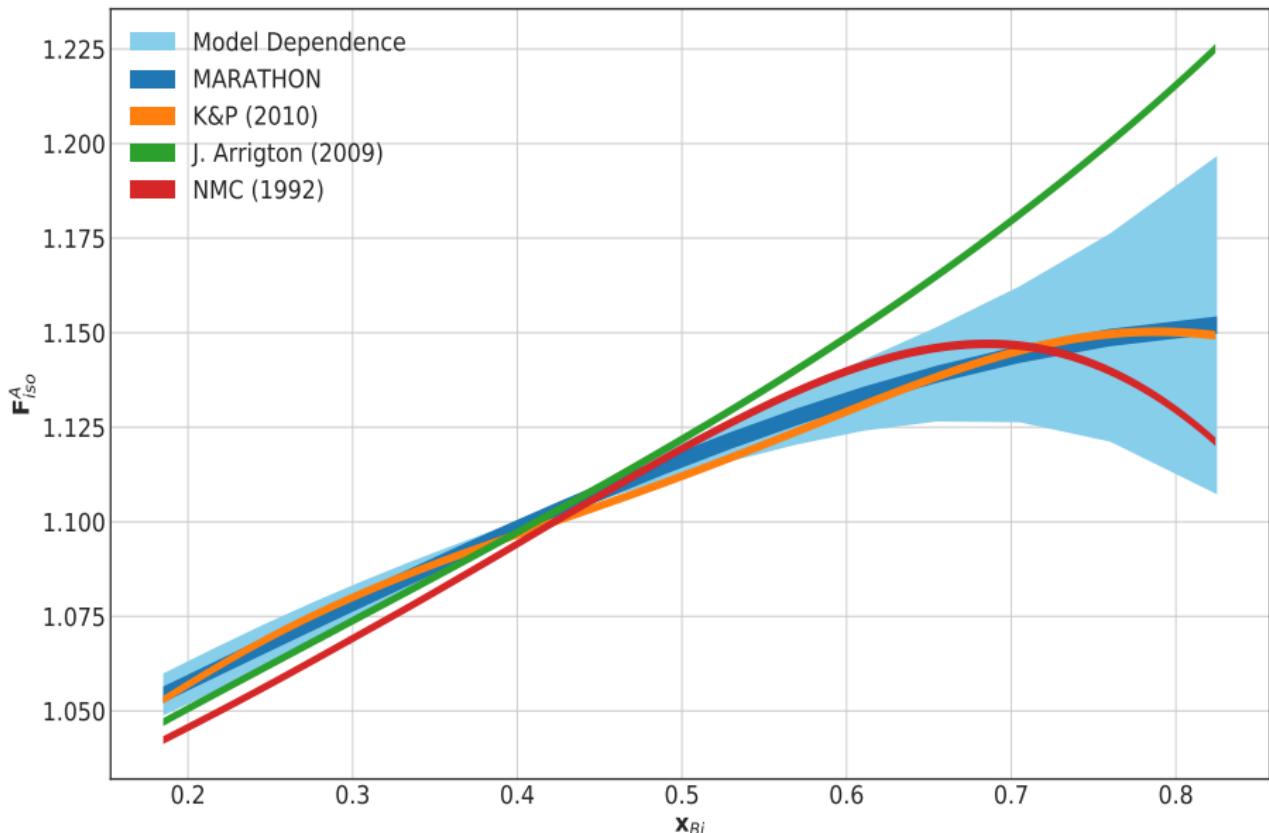
\*\* Largest contributors to the error in Monte Carlo and Cross section model calculation.



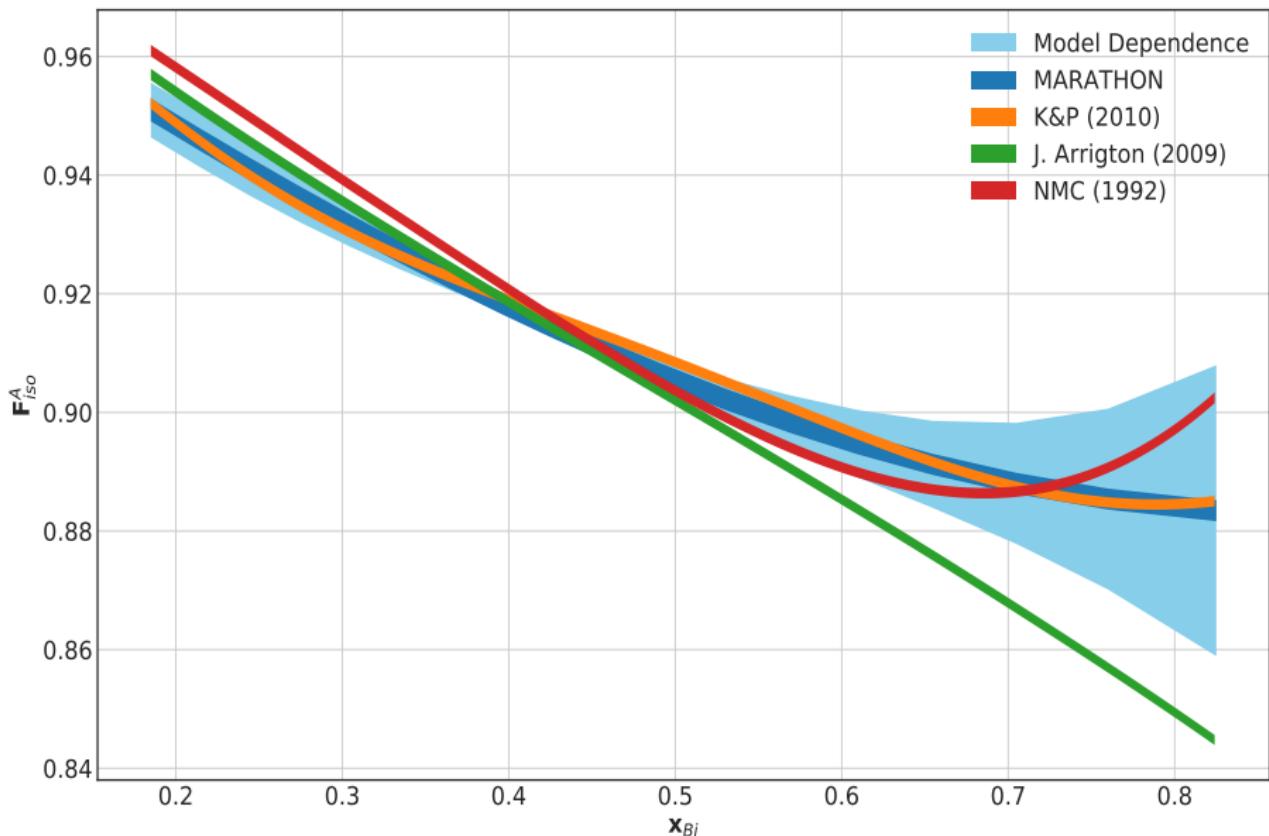
# Model Cross Section Error



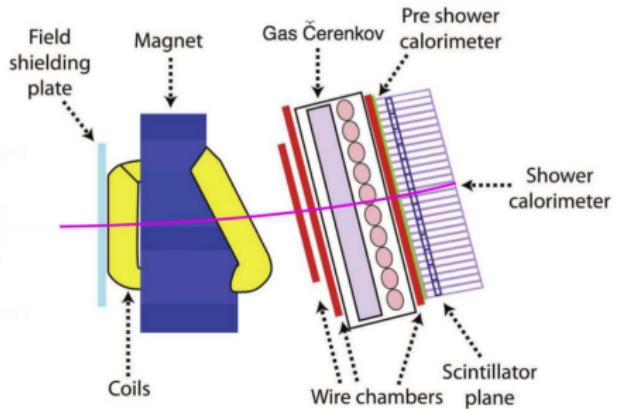
# Isoscalar Correction Error for ${}^3\text{H}$



# Isoscalar Correction Error for ${}^3\text{He}$



# Bigbite Spectrometer



Large Acceptance  
Spectrometer

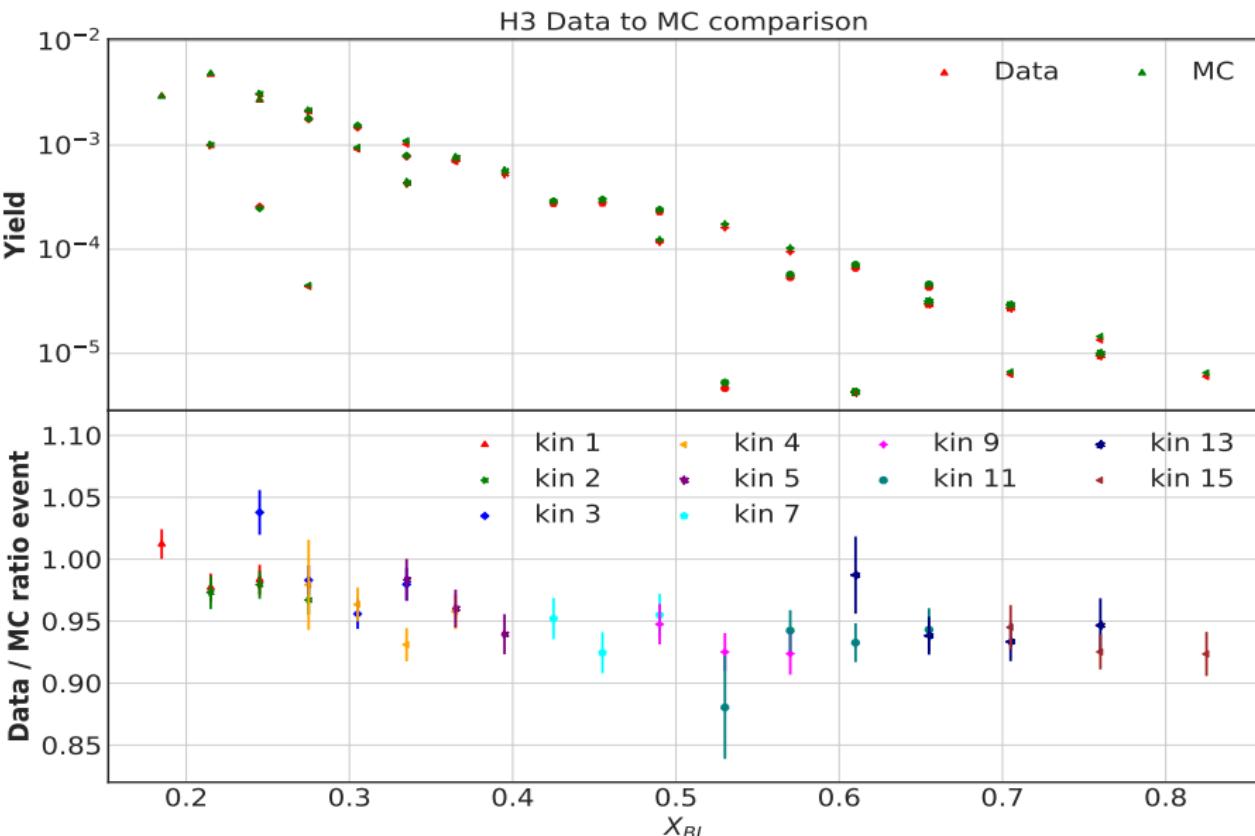
- Solid angle = 96 mrad
- Large Momentum Acceptance:  $> 500 \text{ MeV}/c$

## My contributions in preparing Bigbite

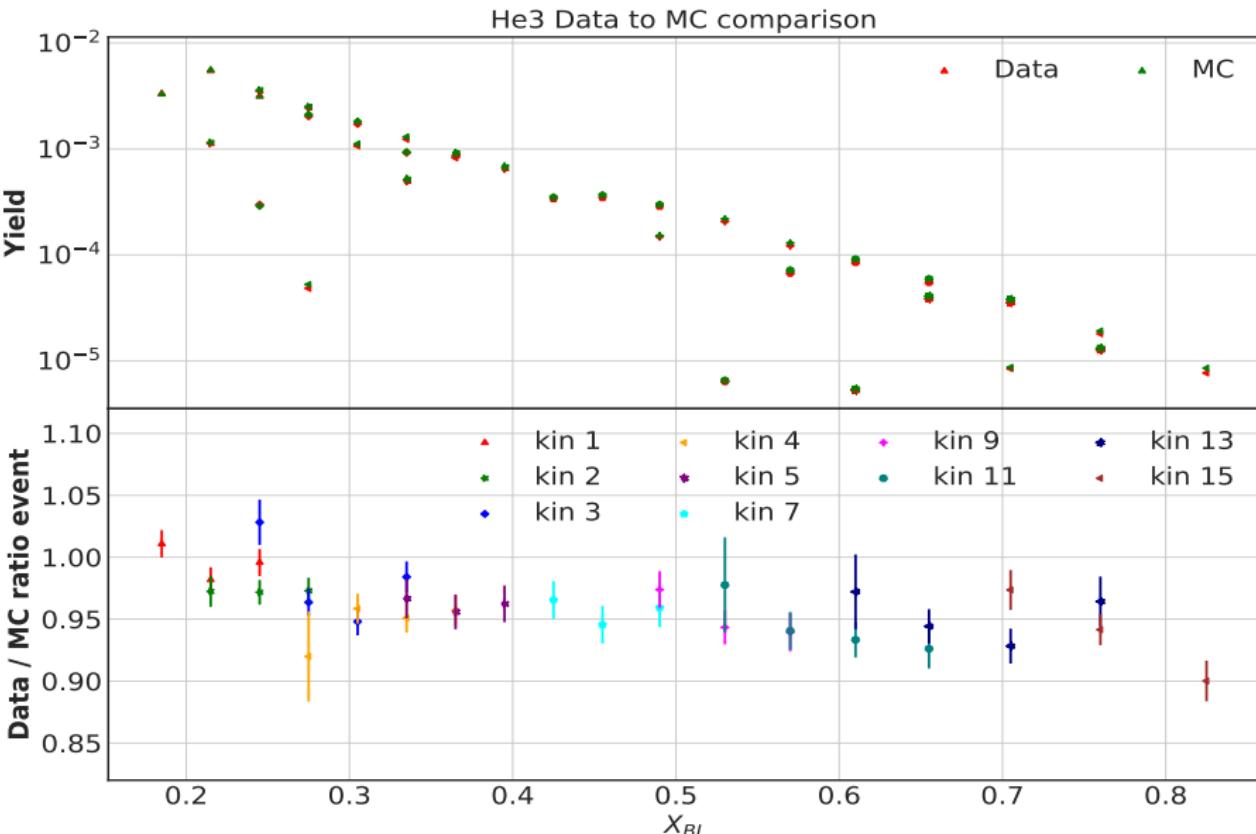
- Constructing the data acquisition system
- PMT performance studies
- Designing trigger logic
- Ensuring consistent and dependable HV power

Removed from the run plan for safety and logistical concerns

# Yield & MC ratio ${}^3\text{H}$



# Yield & MC ratio $^3\text{He}$



# Yield & MC ratio D

D2 Data to MC comparison

