# The EMC Effect in A=3 Nuclei.

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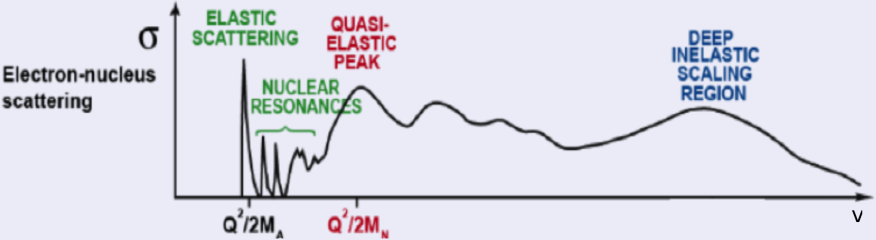
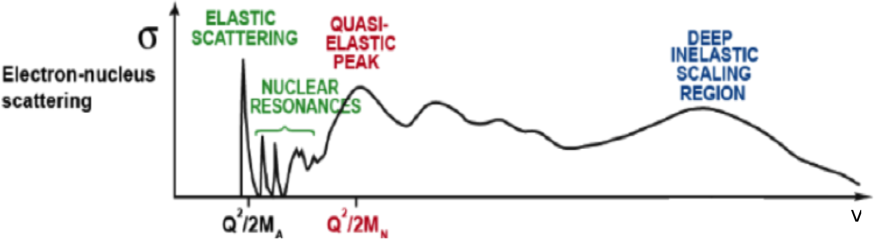
# Outline

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

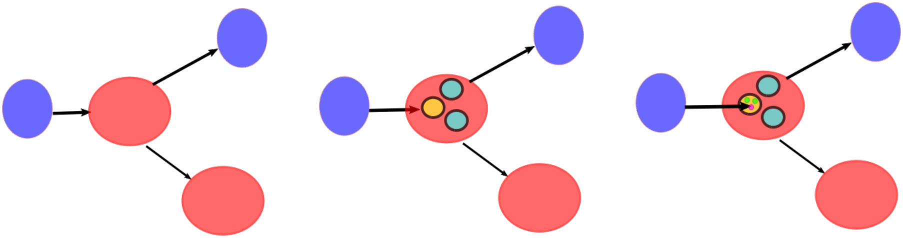
## Deep Inelastic Scattering(DIS) ??????



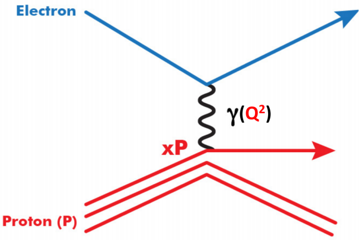

Idealized spectra of high-energy electron scattering as a function of energy transfer [G. T. Garvey, et al., 2015].




- **Elastic scattering**
- **Quaiselastic**
- **DIS**

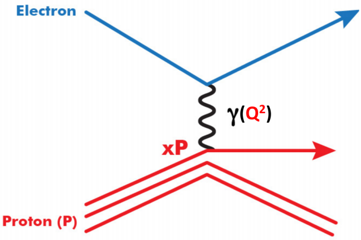


# Deep Inelastic Scattering (DIS)




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

# Deep Inelastic Scattering (DIS)




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

# Why DIS?

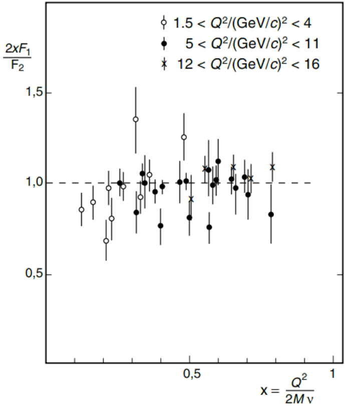
$$\sigma_{eN} = \frac{\alpha^2}{4E^2 sin^4(\frac{\theta}{2})}\left[\frac{F_2(x)}{\nu} cos^2\left(\frac{\theta}{2}\right) + \frac{2F_1(x)}{M} sin^2\left(\frac{\theta}{2}\right)\right]$$

**Quark parton model**

In the Bjorken limit where $(Q^2/\nu)$ is fixed

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

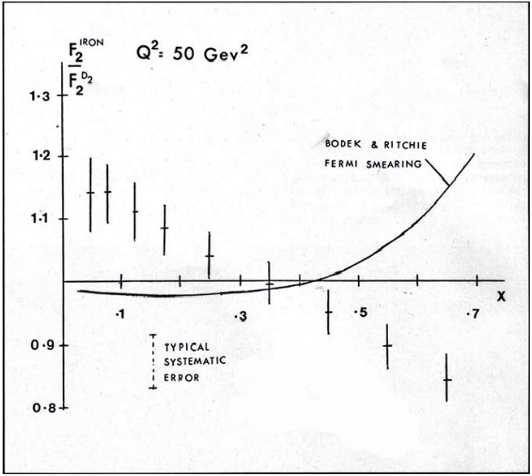
  $F_2(x) = F_1(x) \cdot 2x$




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

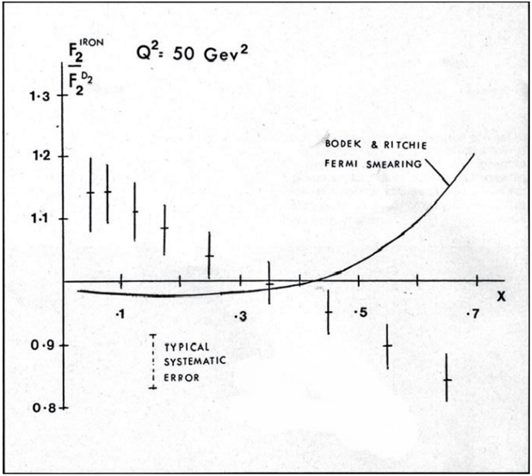
# The EMC Effect

**European Muon Collaboration**




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

# The EMC Effect



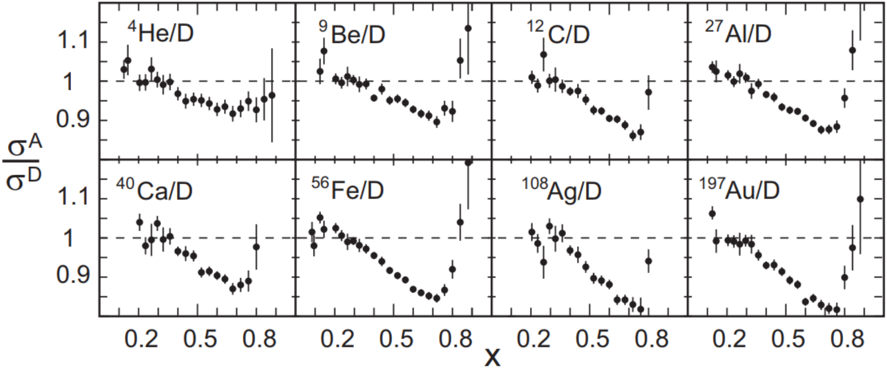

[J.J. Aubert, et al. 1981]

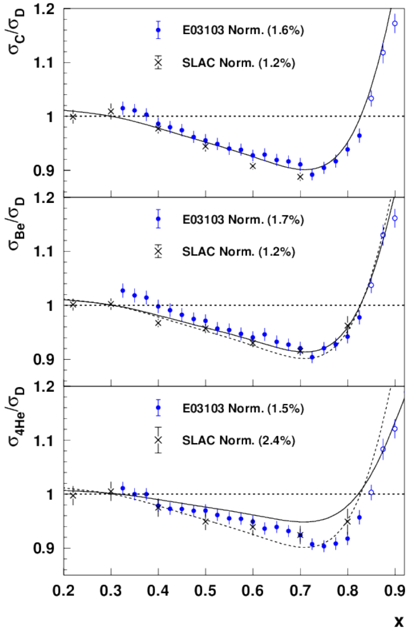
## European Muon Collaboration

- Expected Unity at low $x$
    - Binding $<$ momentum transfer
    - Free Nucleons
- $F^A = Z \cdot F^p + (A - Z) \cdot F^n$
- Isoscalar corrections
- Unexpected Relative Decrease
- Missing high-momentum quarks in A>2
- EMC Effect $\equiv$ structure of the A/D Ratio

# The EMC Effect

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

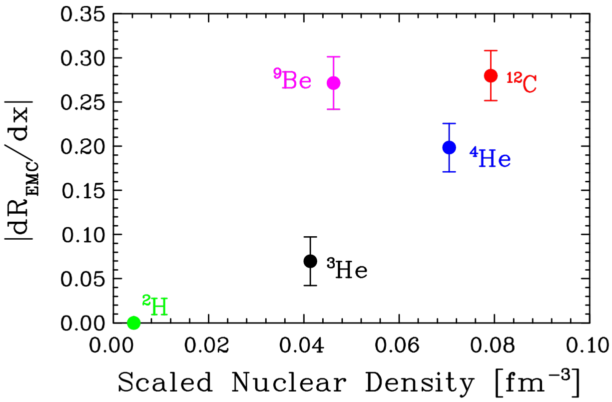





- JLab experiment E03103 [J.Seely, A. Daniel et al, 2009]
- CERN, SLAC, HERMES, BCDMS, and JLab
- Quantized by slope of A/D ratios from 0.3 - 0.7 in x
- Corrections for non-isoscalar nuclei
- Models have difficulty matching data for all criteria
- $\approx$ log dependence in A

# The EMC Effect

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



# The EMC Effect

JLab experiment E03103
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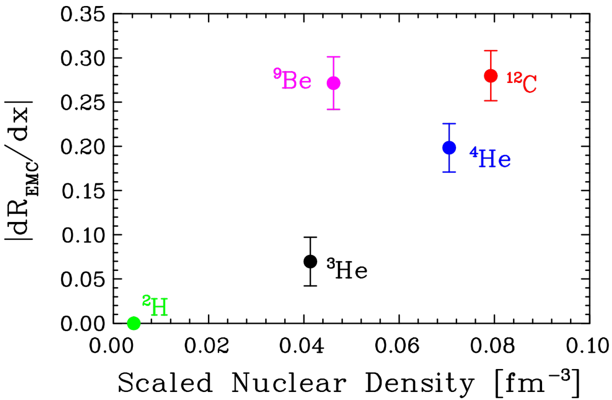
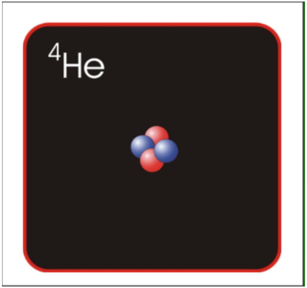
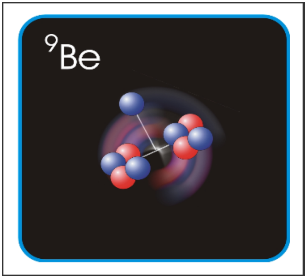
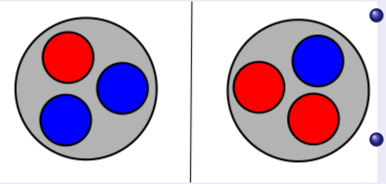


# MARATHON

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
- Can help determine the validity of the isoscalar correction procedure.
- Are we using the correct method of correcting the non-isoscalar nuclei?

# The JLab 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

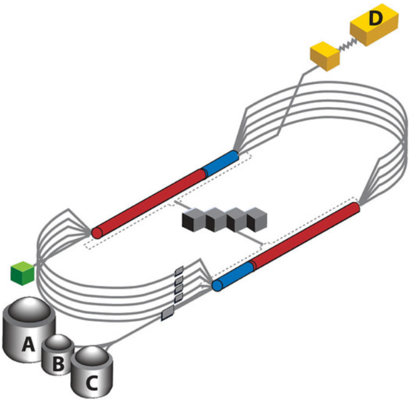
**Blue-Boldfaced Names**: Tritium Program postdoctoral associates

# The JLab 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.

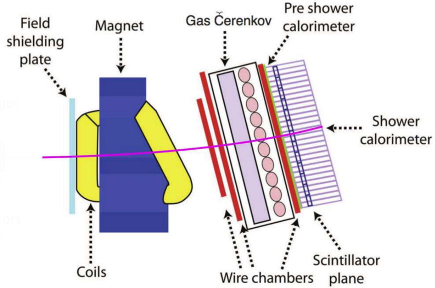



- $\approx$ 2.2 GeV per revolution
- 12 GeV for Hall D
- Superconducting RF cavities
- RF separators split the beam to each Hall

**MARATHON's proposal**

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

# 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

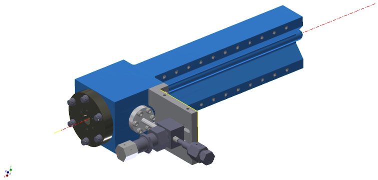
Removed from the run plan for safety and logistical concerns

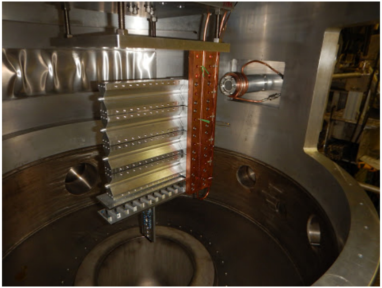
# Uses of Tritium

# Tritium Target Cell

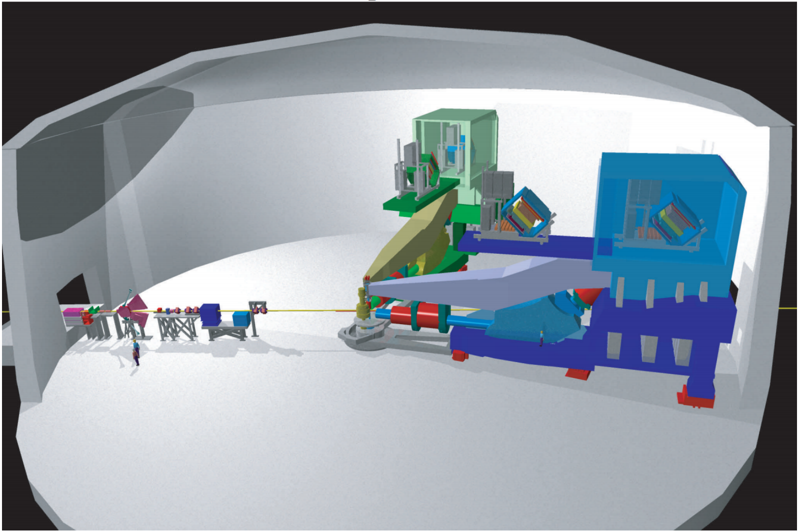
First tritium target at JLab

- 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

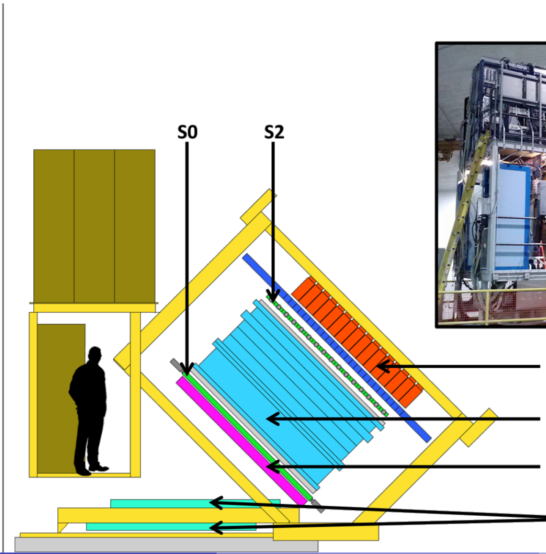




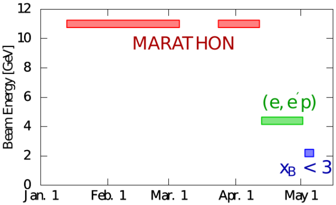
# Hall A



# High Resolution Spectrometers (HRSs)

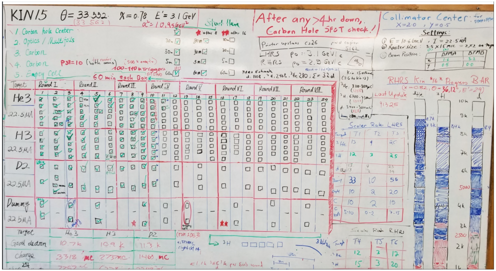



# The Run Period

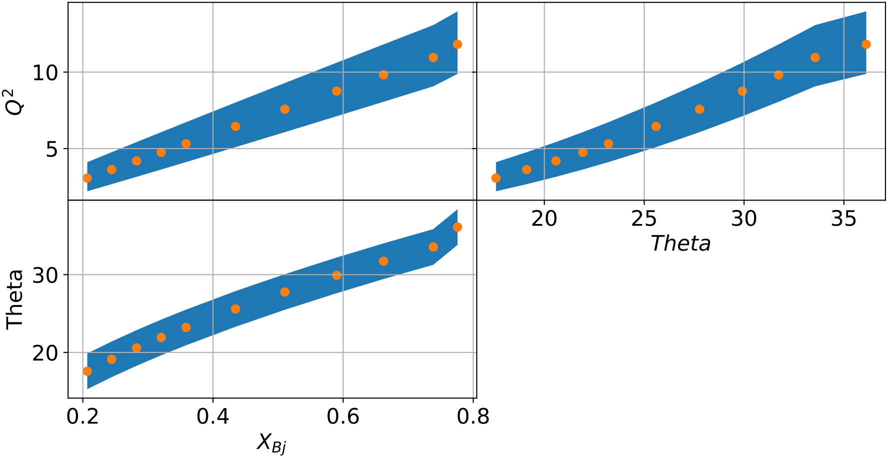



*Rey Torres*

- 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**

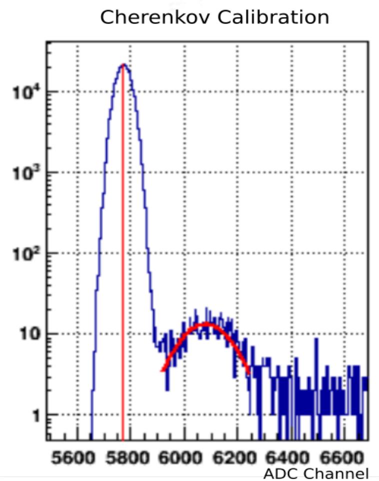
- Calorimeters, Scintillators, and **Cherenkov**

**TDC calibration**

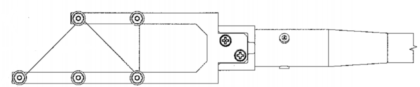
- Scintillators and VDC

**Detector calibrations**

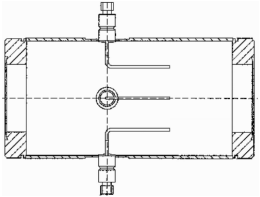
- Beam Current Monitors
- **Beam Position Monitors**



# Beam Position Monitor(BPM) Calibration



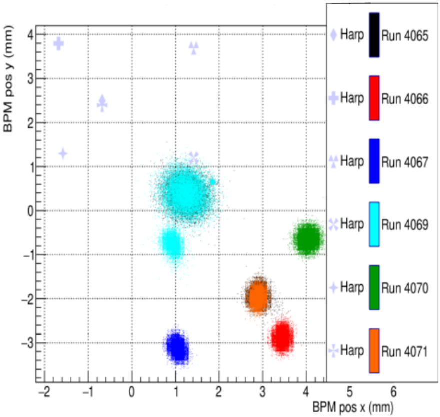

Intrusive absolute position measurement



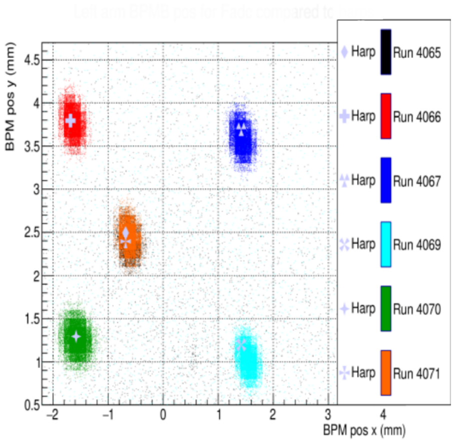
Relative position measurement

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

# Beam position from BPM and harp for a collection of runs




**Before Calibration**




**After Calibration**

# Experimentally Measured Cross Section

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

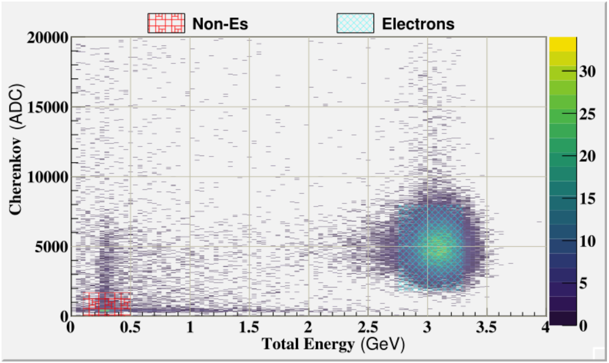
# Efficiencies ($\epsilon$)

Calculating efficiencies

- Use well defined samples from separate system(s)
  - Testing cherenkov use calorimeters
  - Testing VDC use scintillators.
- 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 Lifetime
  - $\approx$ 96%-99%

# Particle ID Efficiency

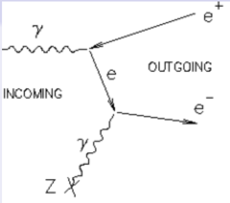



- Total energy absorber for electrons
- Cherenkov's pion threshold is > momentum setting
- PID efficiency ≈ 98% for all kinematics

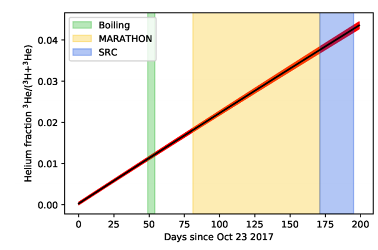
# Background Subtraction

## Pair Production

- $\gamma$ decay into an $e^+e^-$ pairs
- Fit use to extrapolate correction



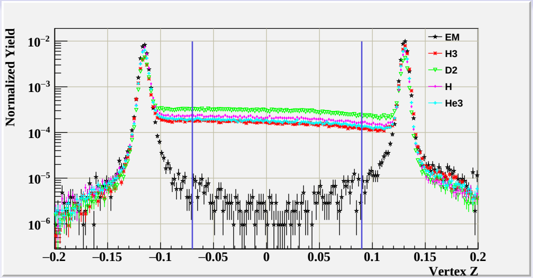

## Beta Decay




*Tyler Kutz*

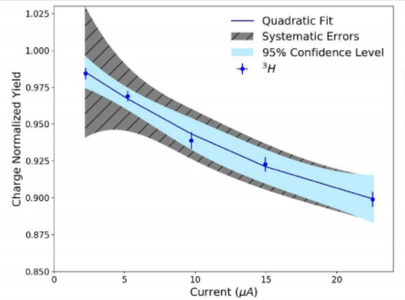
- $^3H$ beta decays into $^3He$
- Time depended correction

# EndCap Subtraction




# Density Correction

- Local density fluctuations due to beam heating
- S.N. Santiesteban, J. Bane, et. al *Nucl. Instrum. Meth. A* 940 (2019) 351-358



## Monte Carlo Ratio Method

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

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

Monte Carlo simulation :

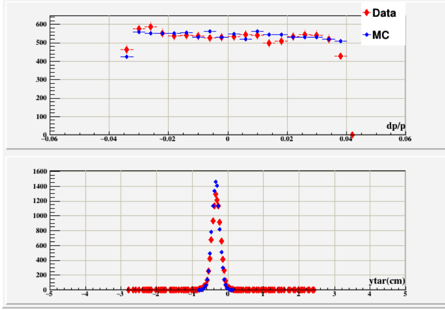
- $(\Delta E' \Delta \Omega)_{Data} = (\Delta E' \Delta \Omega)_{MC}$
- $A(E', \theta)_{Data} = A(E', \theta)_{MC}$

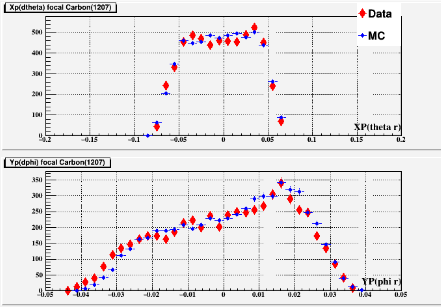
$$\sigma_{Data} = \sigma_{model} \cdot \frac{Y_{Data}}{Y_{MC}}$$

# Monte Carlo

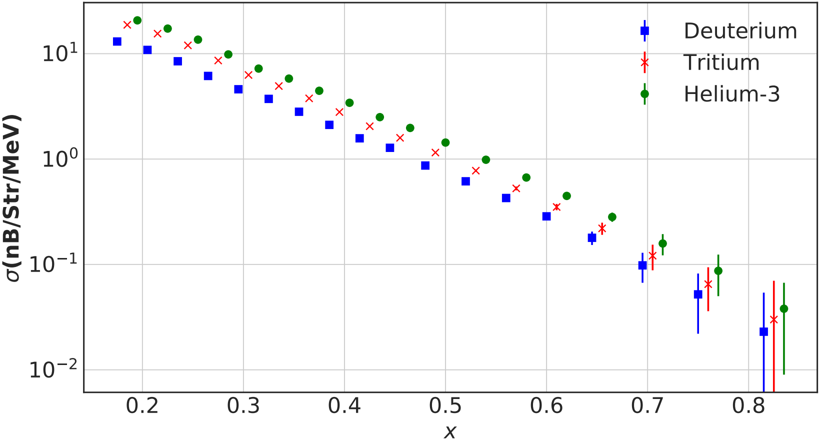
- Generate events → Pass through magnetic apertures
- Tune Simulation offsets to match detector response
- Use model to weight events
  - Deep Inelastic and resonance region from Ari Bodek Fit from E139
  - Full Mo and Tsai radiative correction

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



# DIS Cross Section




Normalization uncertainty due to target thickness uncertainty

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

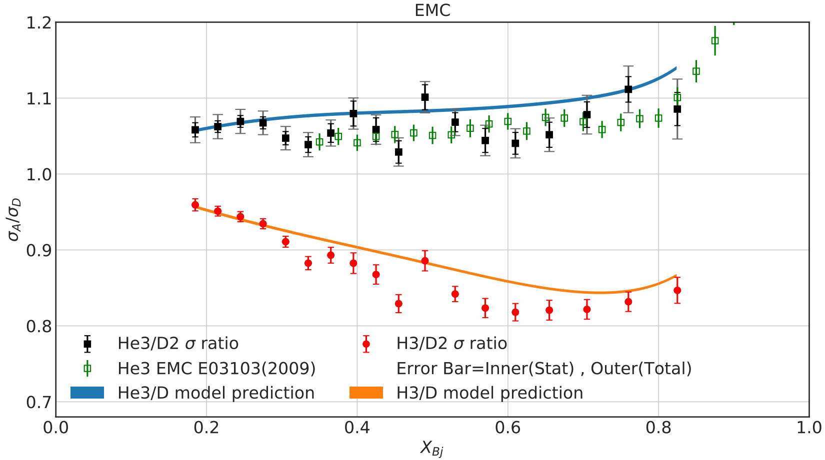
Relative uncertatiny contributions for the cross section $^3$H.

| **Xbjc** | **0.185** | **0.305** | **0.49** | **0.57** | **0.705** | **0.825** |
|---|---|---|---|---|---|---|
| **Yield** | 0.01 | 0.0107 | 0.0149 | 0.0151 | 0.0141 | 0.0163 |
| Stat * | 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 |
| Efficiency * | 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** | 0.019 | 0.018 | 0.02 | 0.022 | 0.033 | 0.04 |

* Largest contributers to the uncertainty in the yield calculation

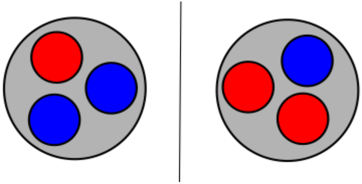
** Largest contributers to the uncertainty in Monte Carlo and Cross section model calculation.

# Per Nucleon Cross Section Ratio



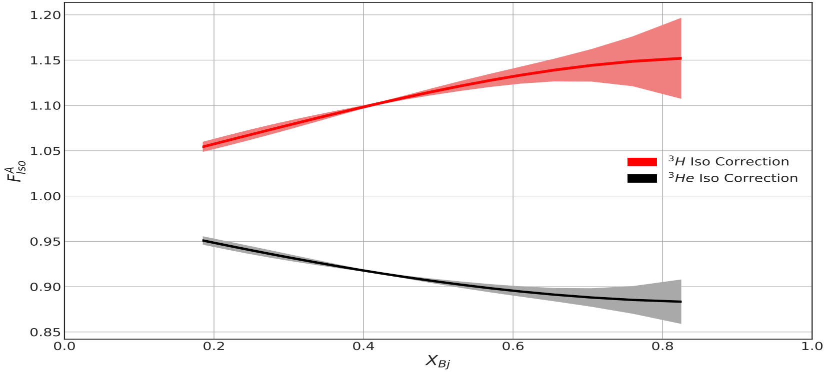

MARATHON results compared with E03103 [J.Seely, A. Daniel et al, 2009] and the A/D ratios from a DIS scattering model from Arie Bodek model [A. Bodek and U.K. Yang, 2002].

# Isoscalar Corrections

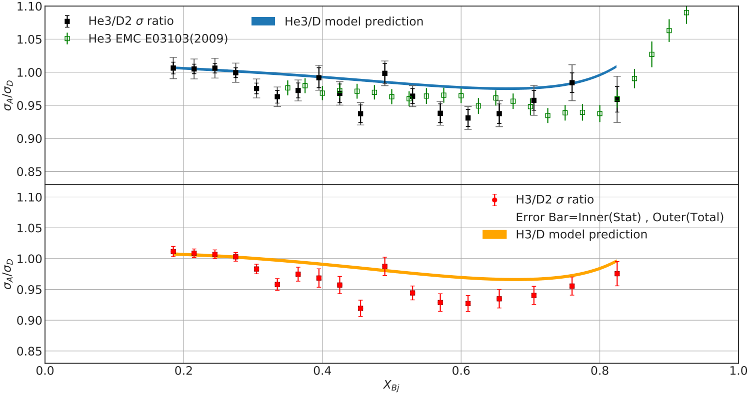


- Correct for the unpaired nucleon in the A/D ratio.

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

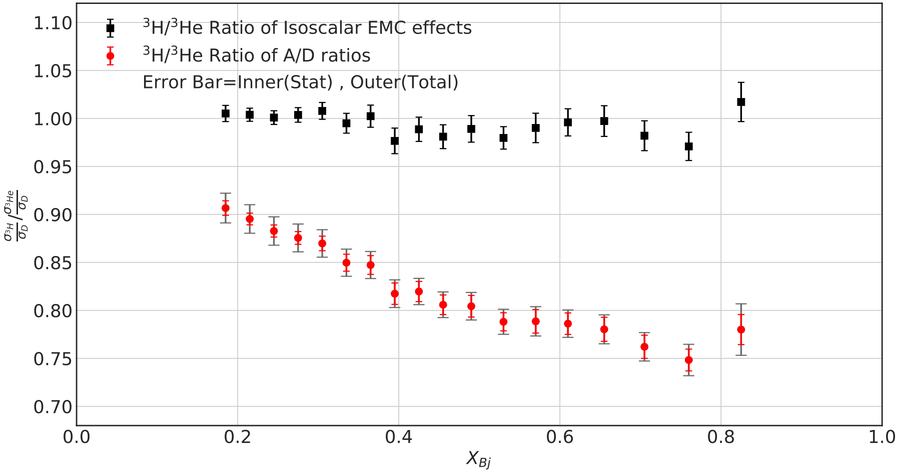


- My EMC results for He3 in black • H3 in red
- Previous Jlab He3 in green




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




Ratio of EMC effects.

## Summary

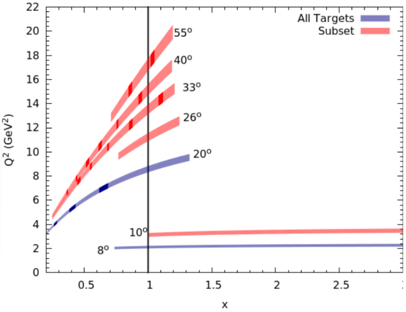
- Used DIS to extract inclusive cross section for $^3$H, $^3$He, and D
- Looked at the A/D ratio for both $^3$H and $^3$He
- Compared the EMC effects of the two, A=3 nuclei.
  - See no difference for Isoscalar EMC effects within analysis accuracy

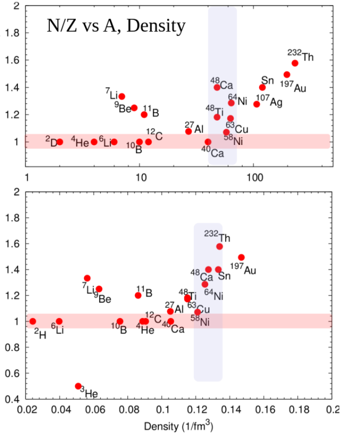
## Special Thanks


- The Tritium Students
- JLab staff and technicians
- Nadia Fomin and Douglas Higinbotham
- DOE and JSA(Jefferson Science Associates)
- CMRU for allowing me the opportunity to present.

# 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**



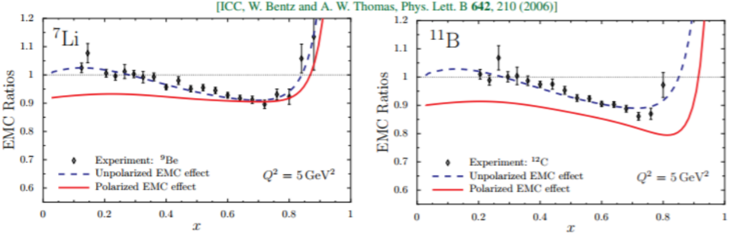

**Coming soon* in Hall C**

*What **is** soon?*

Slide credit Nadia Fomin

# The EMC effect in spin structure functions

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




- 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

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## Refereed Papers

- R. Cruz Torres. et. al. Comparing proton momentum distributions in A=2 and 3 nuclei via $^2$H $^3$H and $^3$He (e,e′p) measurements. *Phys. Let. B 797*, (2019)
- S. N. Santiesteban, et. al. Density Changes in Low Pressure Gas Targets for Electron Scattering Experiments. *Nucl. Instrum. Meth. A 940* (2019)
- H. Dai, et. al. First Measurement of the Ar(e,e′) Cross Section at Jefferson Lab. *Phys. Rev. C 99*, (2019)
- H. Dai, et. al. First Measurement of the Ti(e,e′) Cross Section at Jefferson Lab. *Phys. Rev. C 98*, (2019)

# 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.

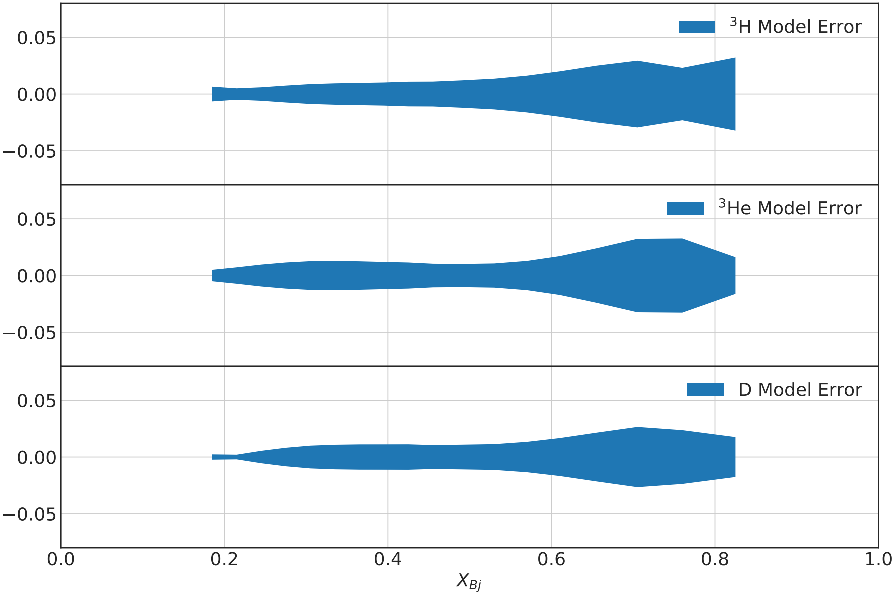
Relative Error Contributions for the Cross Section D.

| **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 |

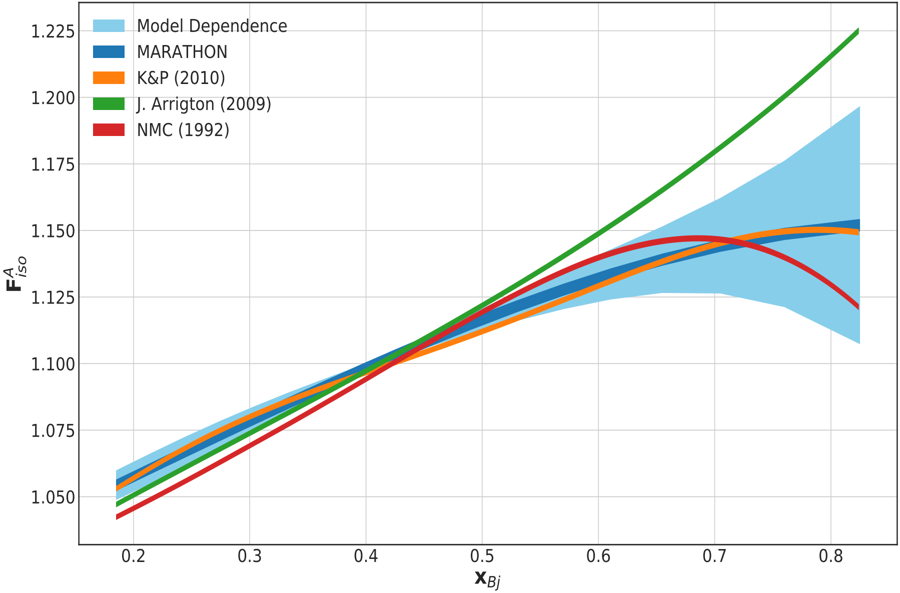
* Largest contributers to the error in the yield calculation

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

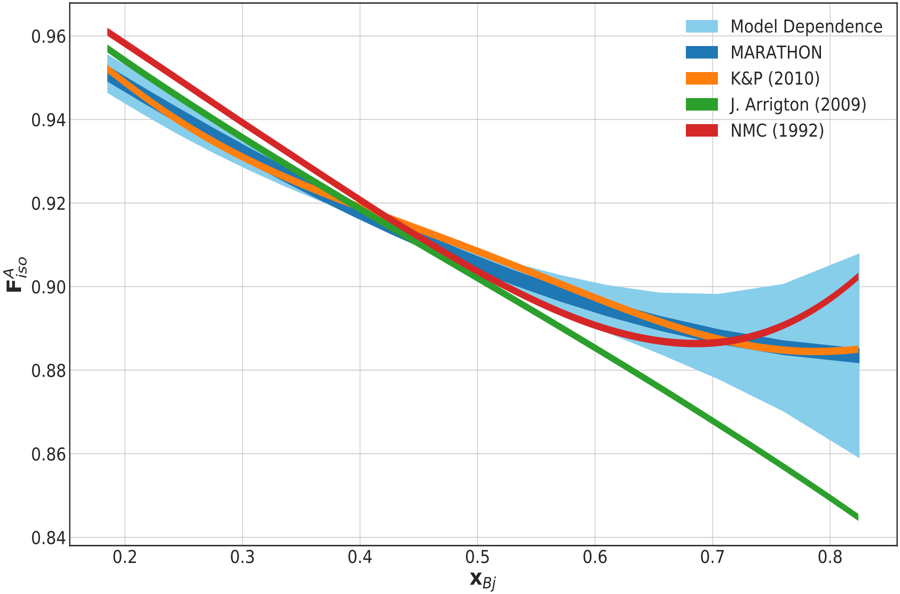
# Model Cross Section Error



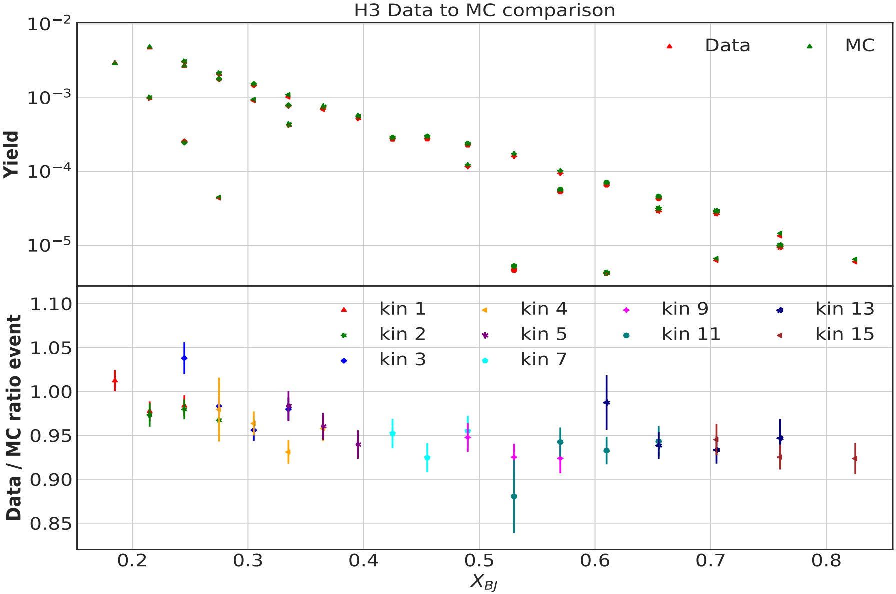
# Isoscalar Correction Error for $^3$H



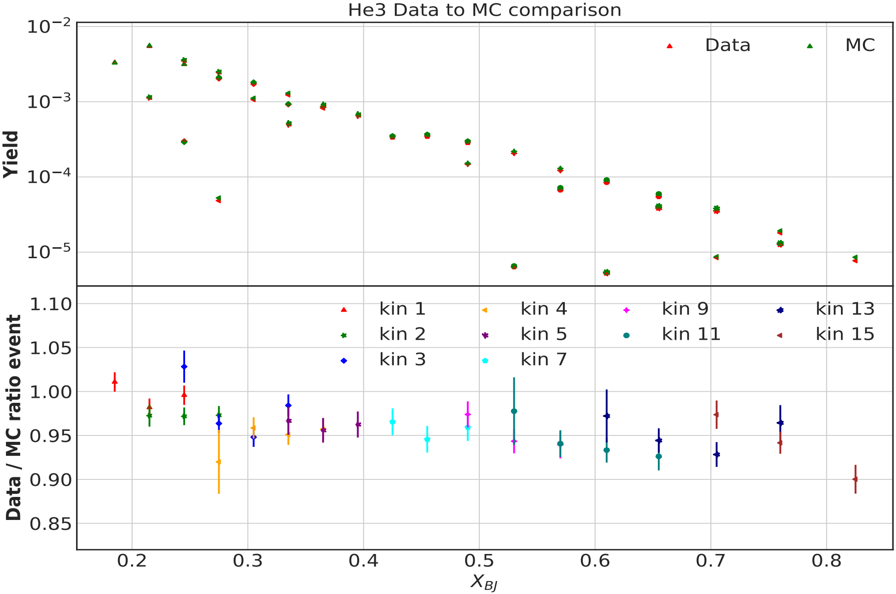
# Isoscalar Correction Error for $^3$He



# Yield & MC ratio $^3$H



# Yield & MC ratio $^3$He



# Yield & MC ratio D