

# The EMC Effect for Tritium and Helium-3 from MARATHON

Jason Bane

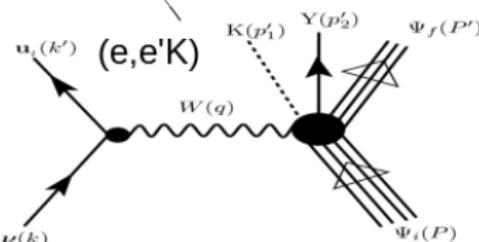
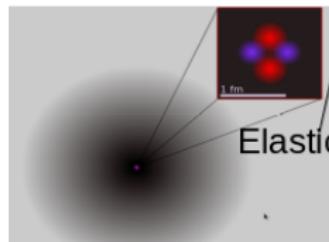
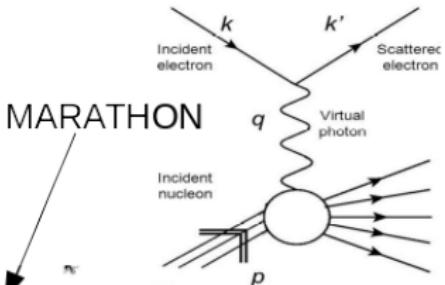
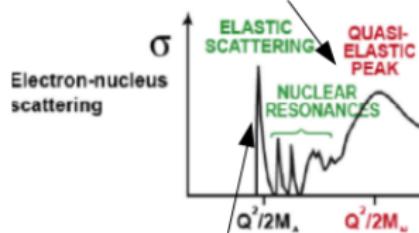
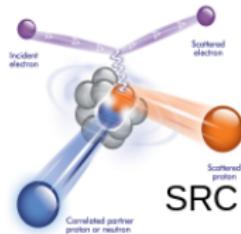
University of Tennessee

*jbane1@vols.utk.edu*

# Outline

- Introduction
  - ▶ MARATHON
  - ▶ EMC
  - ▶ Deep Inelastic Scattering
- The MARATHON Experiment
- Data Analysis
- EMC Effect of  $A=3$

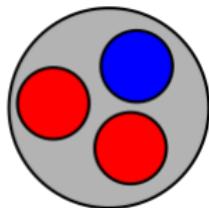
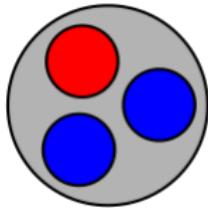
# Tritium Experiments





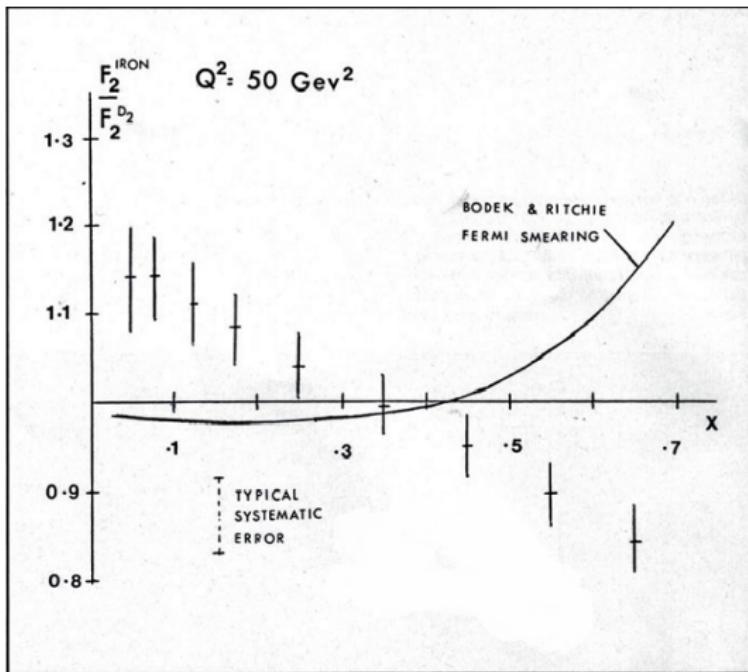
# MARATHON

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 EMC Effect



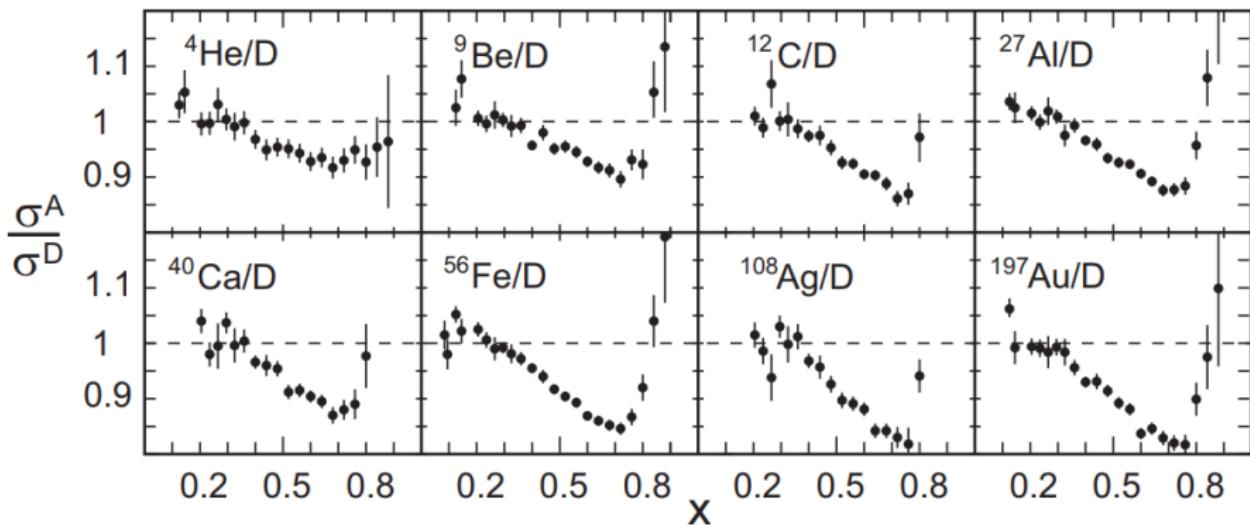
[D. Higinbotham, 2013]

## European Muon Collaboration

- $X$  = fraction of momentum carried by quark
- Expected Unity  $\rightarrow$  Binding  $<$  interaction
- $F^A = Z \cdot F^p + (A - Z) \cdot F^n$
- Unexpected Relative Decrease
- Missing high-momentum quarks in  $A > 2$
- EMC Effect  $\equiv$  structure of the A/D Ratio

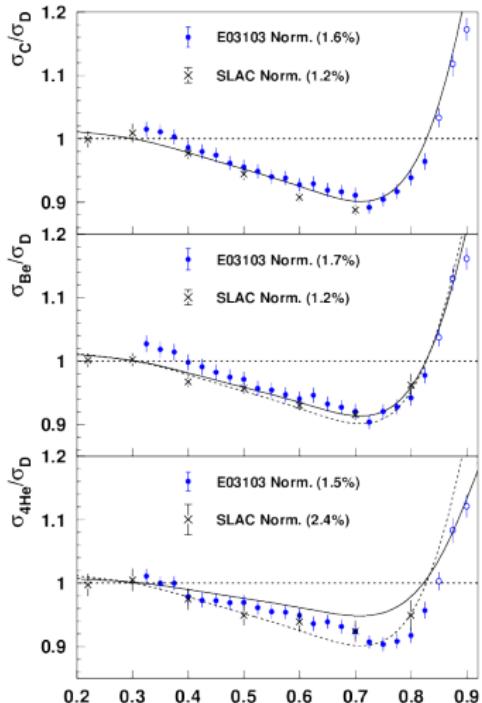
# EMC Effect

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



# EMC Effect

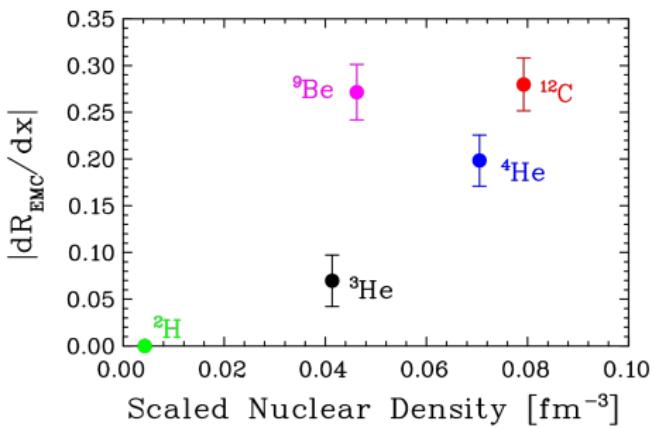
JLab experiment E03103  
[J.Seely, A. Daniel et al, 2009]



- Studied for last 30+ years
- CERN, SLAC, HERMES, BCDMS, and JLab
- 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

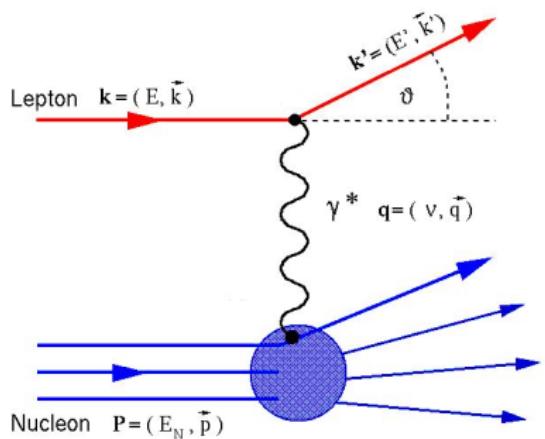
# EMC Effect

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



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- CERN, SLAC, HERMES, BCDMS, and JLab
- 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
- sensitivity to "local" effects

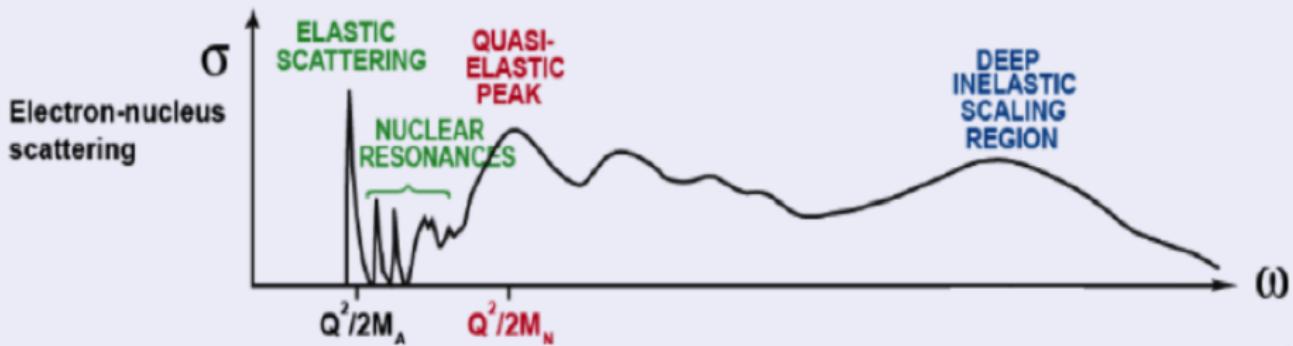
# Deep Inelastic Scattering (DIS)



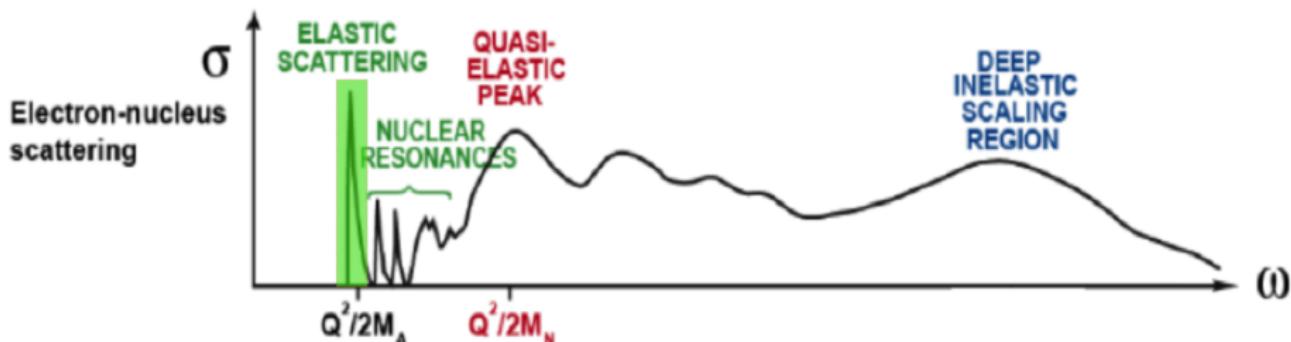
- $Q^2 \equiv 4EE' \sin^2 \frac{\theta}{2}$
- $X_{Bj} = \frac{Q^2}{2\nu M}$
- $\nu$  or  $\omega \equiv E - E'$
- $W^2 = 2M\nu + M^2 - Q^2$
- $W^2 > M^2 \rightarrow$  Inelastic Scattering

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

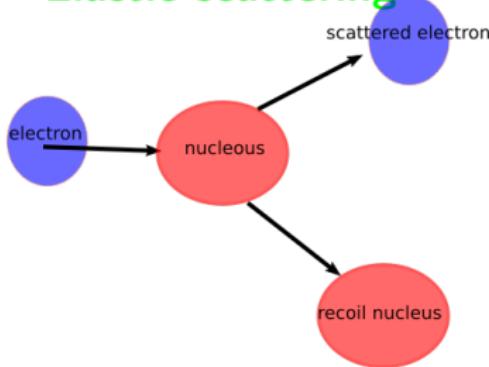
DIS ??????

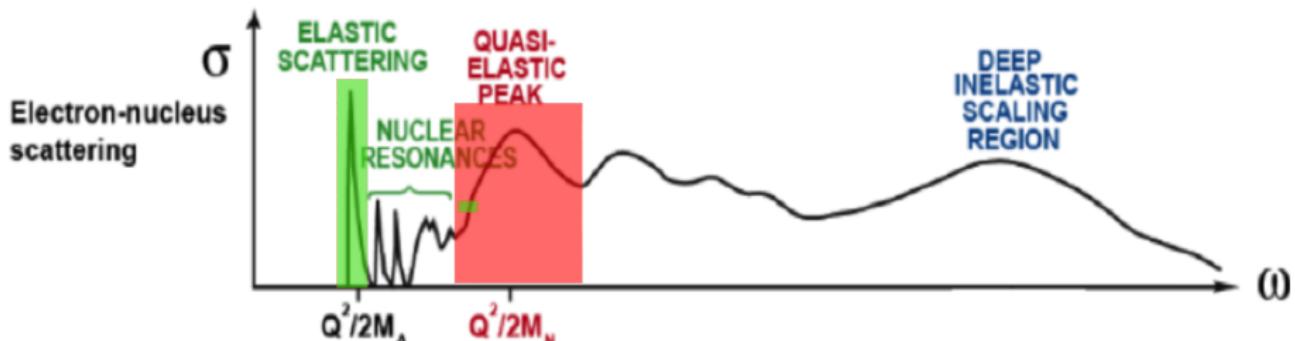


[G. T. Garvey, et al., 2015].

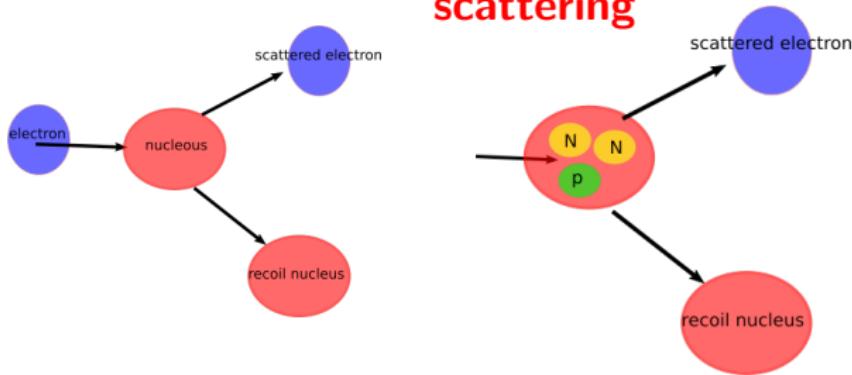


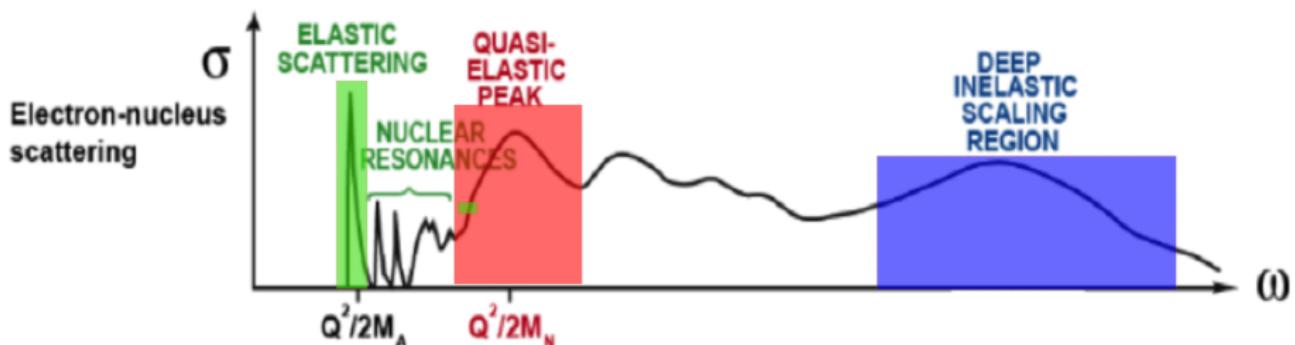
- Elastic scattering





- Elastic scattering
- Quasielastic scattering

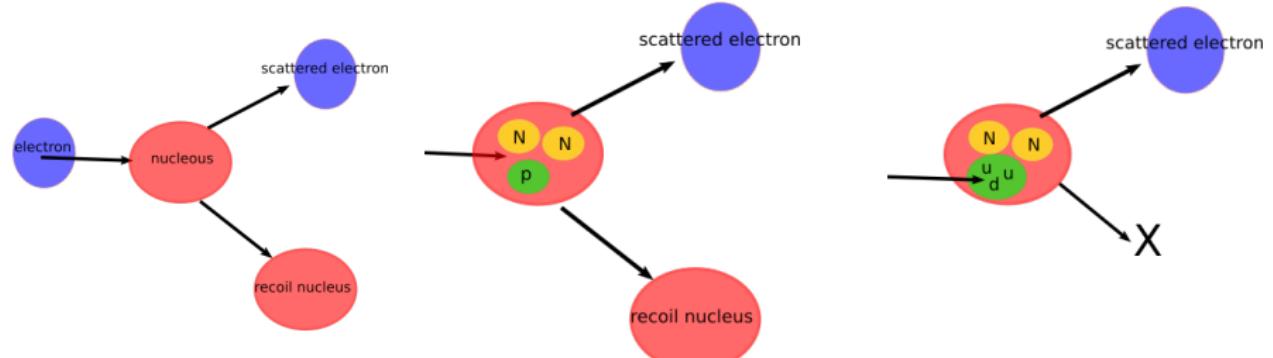




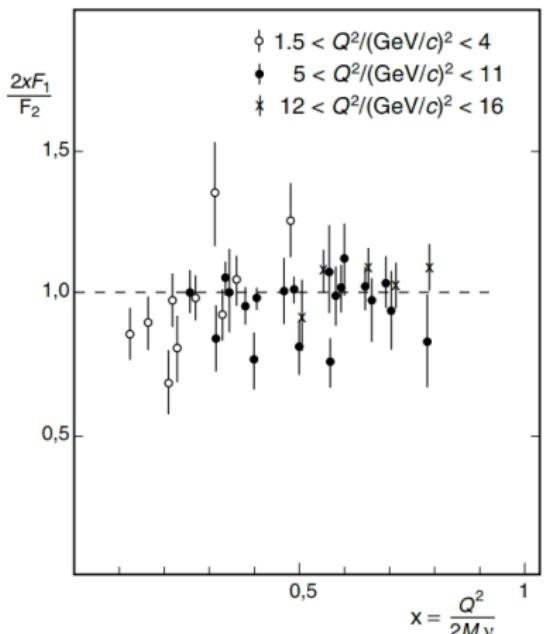
- Elastic scattering

- Quasieastic scattering

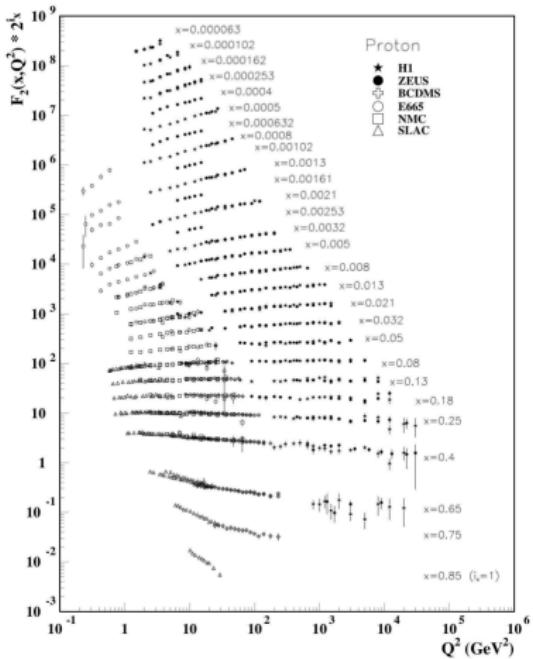
- DIS



# Why DIS?

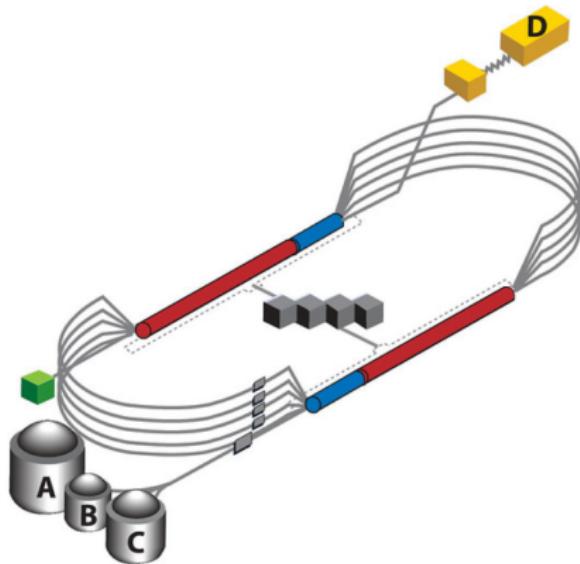


Ratio of  $2x \cdot F_1(x)$  and  $F_2(x)$  vs.  $x$ .  
[Povh, 1995]



Proton structure function  $F_2(x, Q^2)$  for different  $x$  settings.  
[K. Nakamura et. al. 2010]

# 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

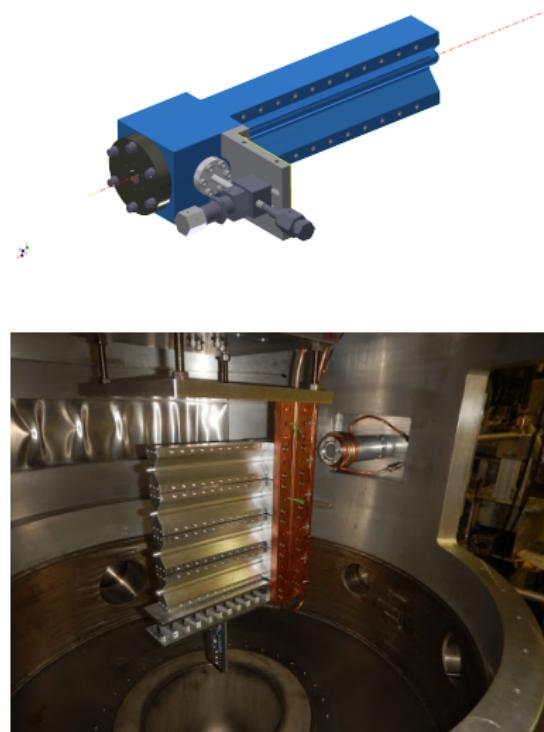
## MARATHON

- 11 GeV Beam
- $22.5 \mu\text{A}$  current
- Hall A's high resolution spectrometers

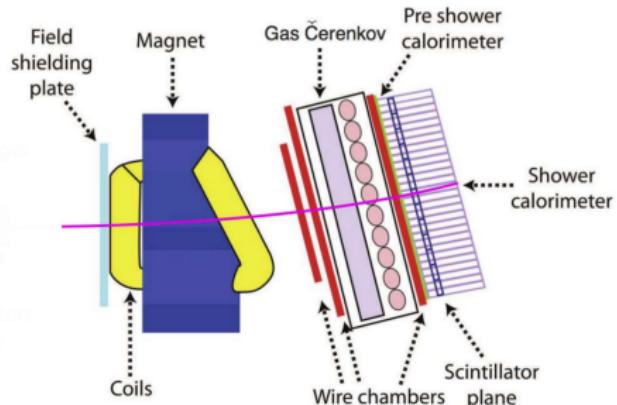
# Tritium Target Cell

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



# Hardware Experience



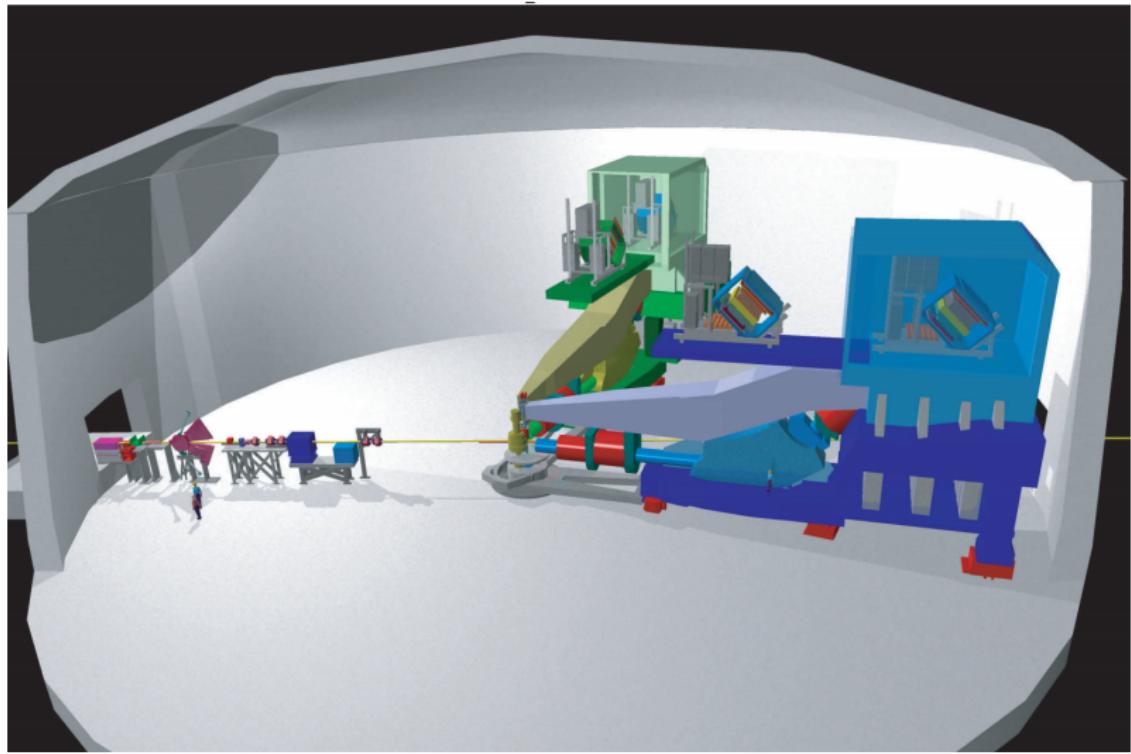
## Large Acceptance Spectrometer

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

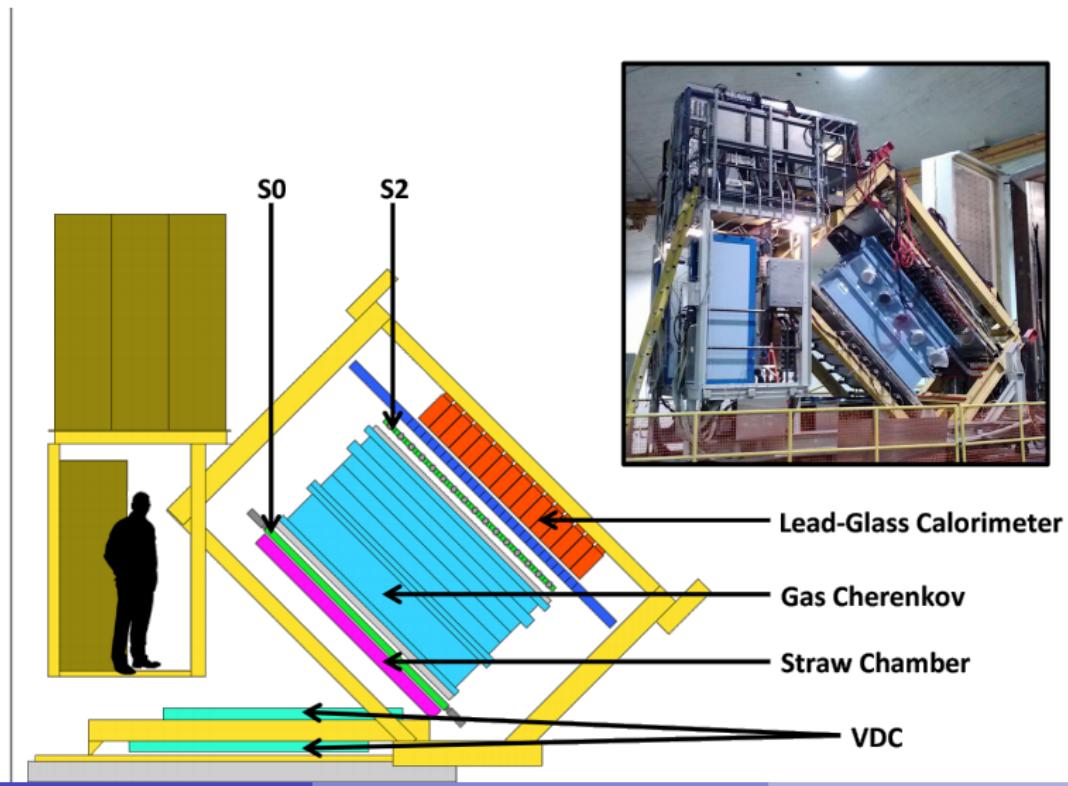
## Preparing Bigbite

- Refurbishing signal electronics and cables
- Testing then repairing or replacing PMTs
- Building front end electronics and coincidence trigger logic
- Testing High voltage power sources and providing power to the detectors

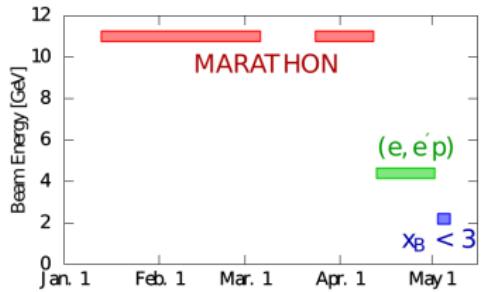
## Hall A



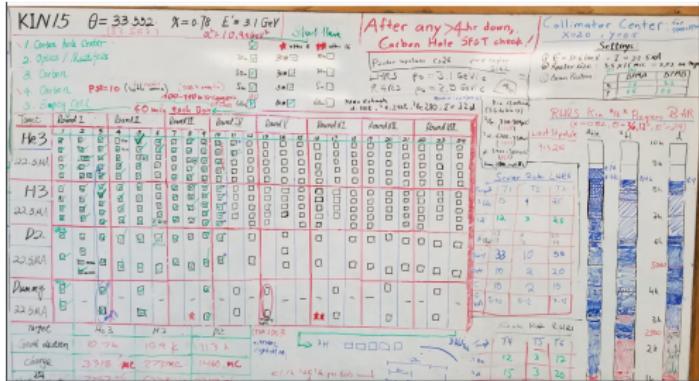
# High Resolution Spectrometers (HRSs)



## The Run Period



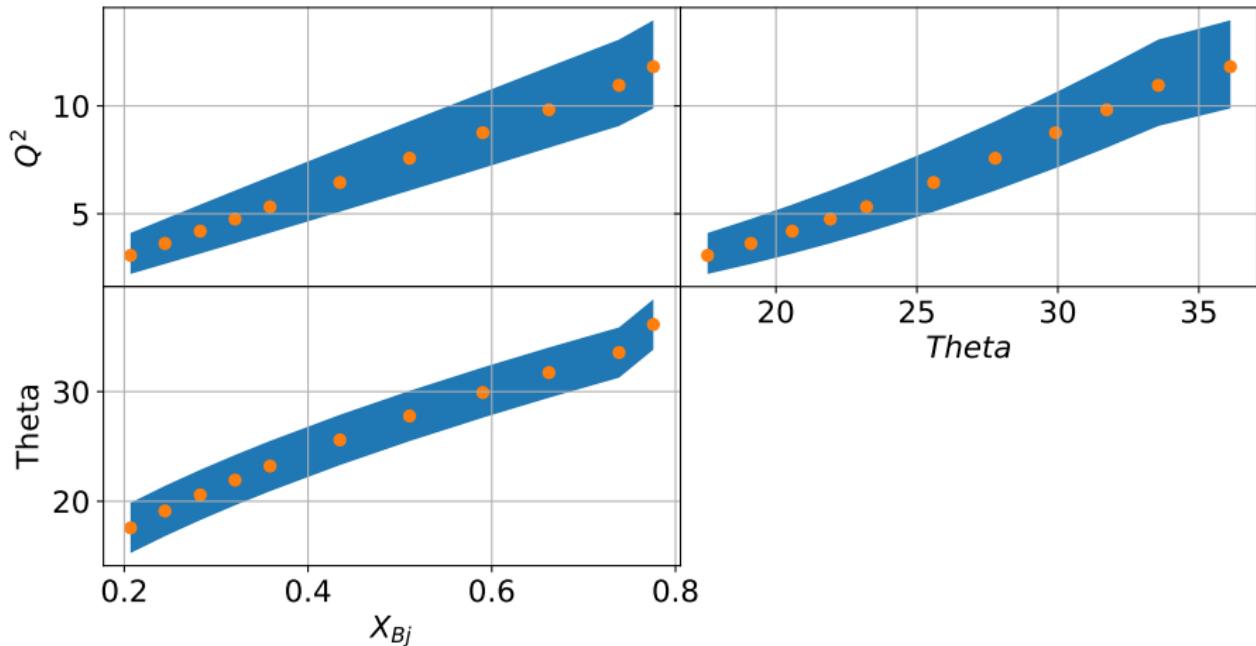
Rey Torres



Jason Bane (UTK)

EMC A=3

# Kinematic Coverage



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

# Preparing Data for Analysis

## Calibration

### ADC calibration

- Calorimeters, Scintillators, and Cherenkov

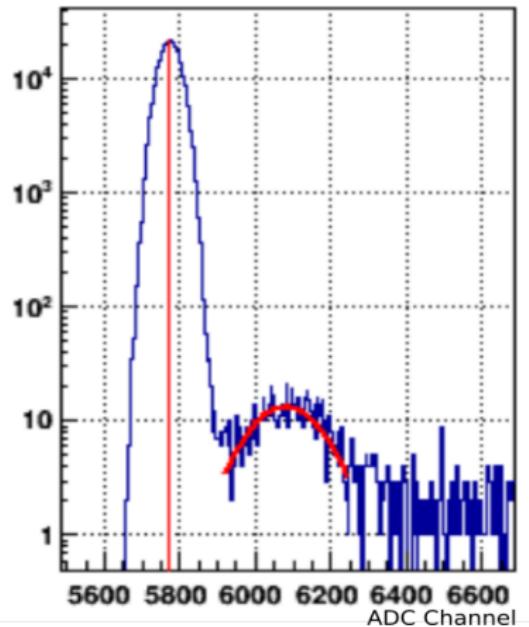
### TDC calibration

- Scintillators and VDC

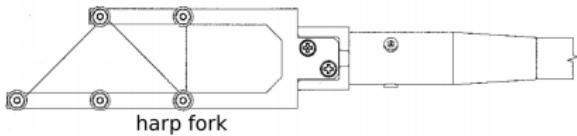
### Detector calibrations

- BPMs, BCMS, Optics

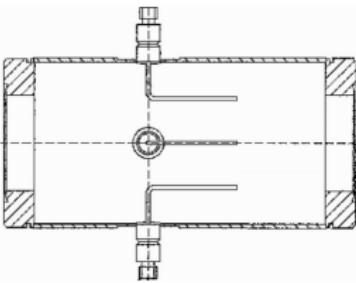
Cherenkov Calibration



# Beam Position Monitor(BPM) Calibration



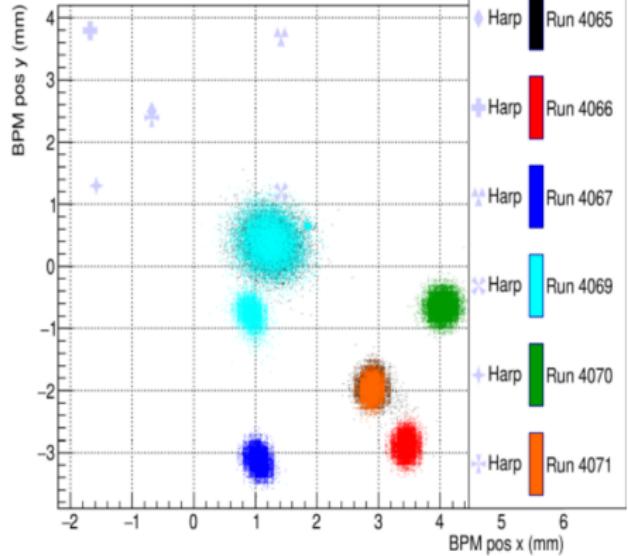
Intrusive absolute position measurement



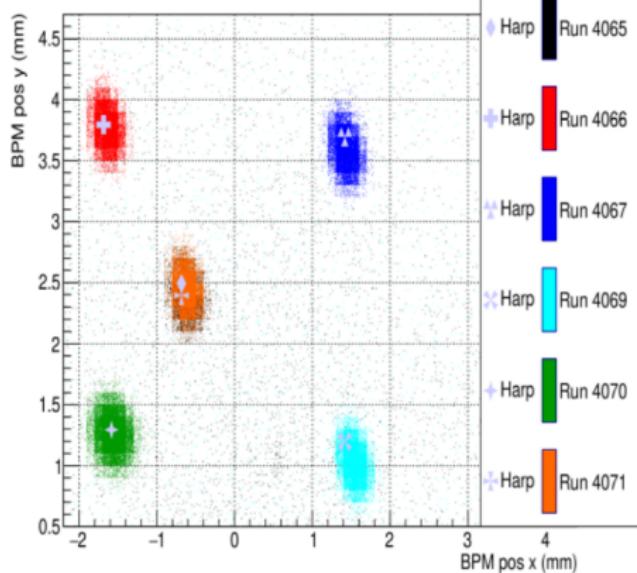
Relative position measurement

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

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



Before Calibration



After Calibration

## Experimentally Measured Cross Section

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

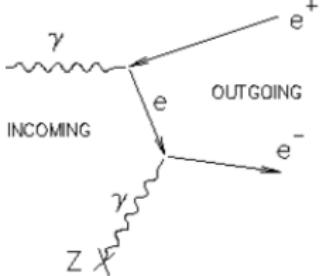


- $N$  = Number of electrons
- $BG$  = Background
- $L$  = Luminosity
- $\epsilon$  = Efficiency
- $\Delta E' \Delta \Omega$  = Bin Size
- $A(E', \theta)$  = Acceptance probability

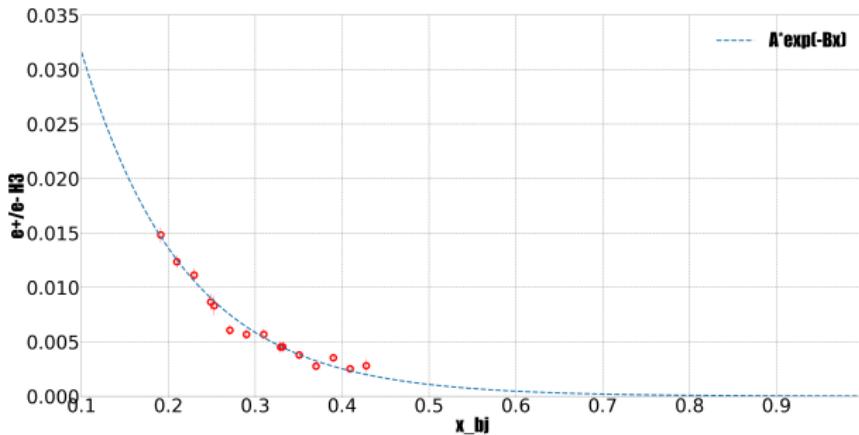
# Charge Symmetric Background

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

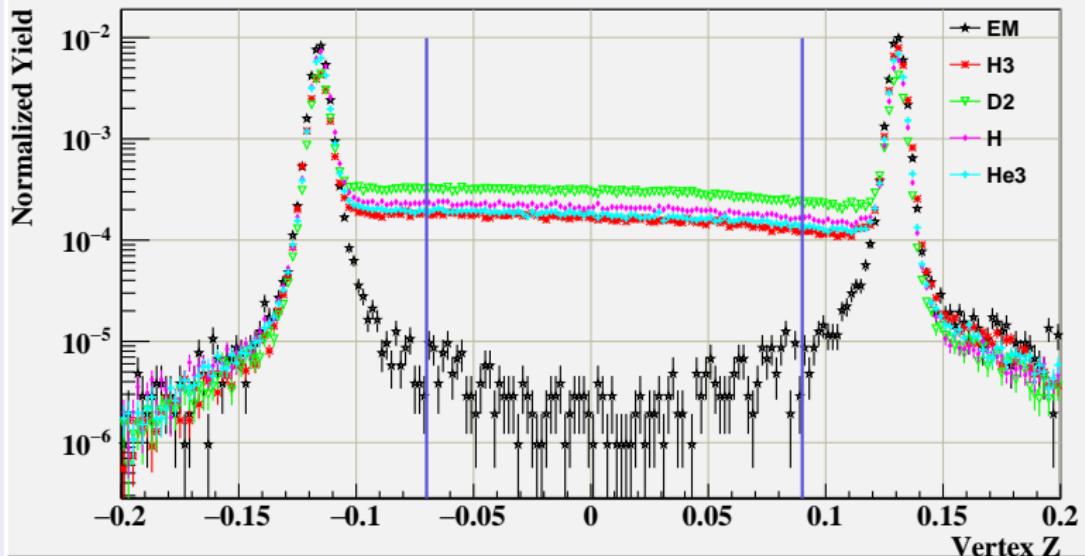
## Pair Production



Tritium positron contamination. Credit: Tong Su

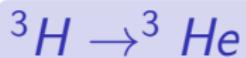


# Aluminum Endcap Background



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

# $^3H$ Decay

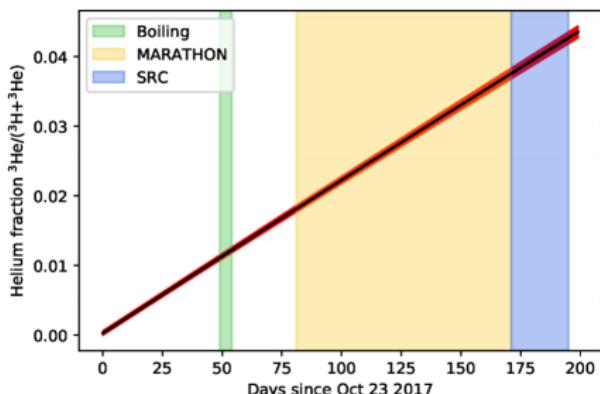


$$\tau(^3H) = 4500 \pm 8\text{ days}$$

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

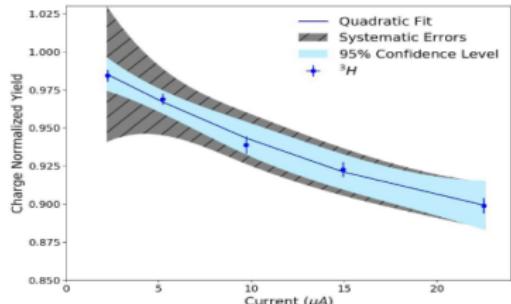
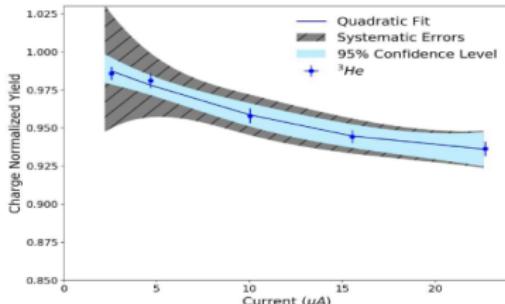
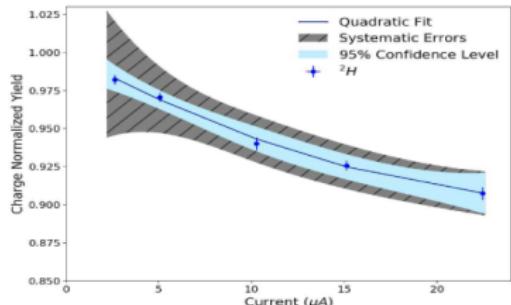
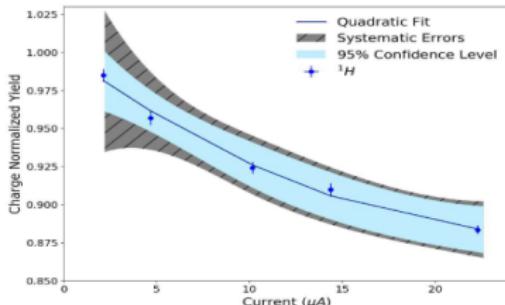
$$\sigma_{^3H} = \left( \frac{\sigma_{tot}}{\sigma_{^3He}} \right) \left( \frac{1}{1 - c} \right) - \left( \frac{1}{1 - c} \right)$$

Beta Decay Helium Fraction



Tyler Kutz

# Density Fluctuations

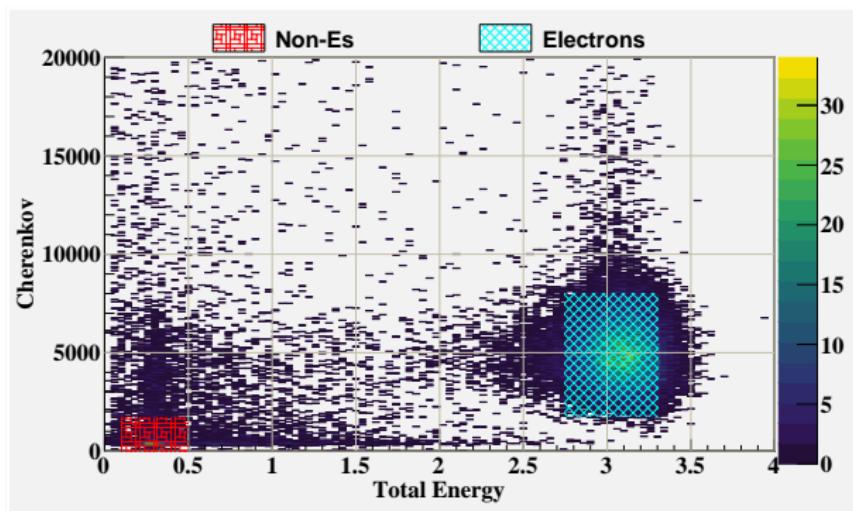
(a)  ${}^3\text{H}$  Density Analysis.(b)  ${}^3\text{He}$  Density Analysis.(c)  ${}^2\text{H}$  Density Analysis.(d)  ${}^1\text{H}$  Density Analysis.

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

## Efficiencies ( $\epsilon$ )

- Particle Identification(PID)
  - ▶ Cherenkov
  - ▶ Calorimeters
- Trigger
  - ▶ Scintillators
- Tracking
  - ▶ Vertical Drift Chambers(VDCs)
- Electronic Deadtime

# Particle ID Efficiency



- Use well defined samples
- Apply PID cuts and count
- PID efficiency  $\approx 98\%$  for all kinematics

## Monte Carlo Ratio Method

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

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

Use a Monte Carlo simulation

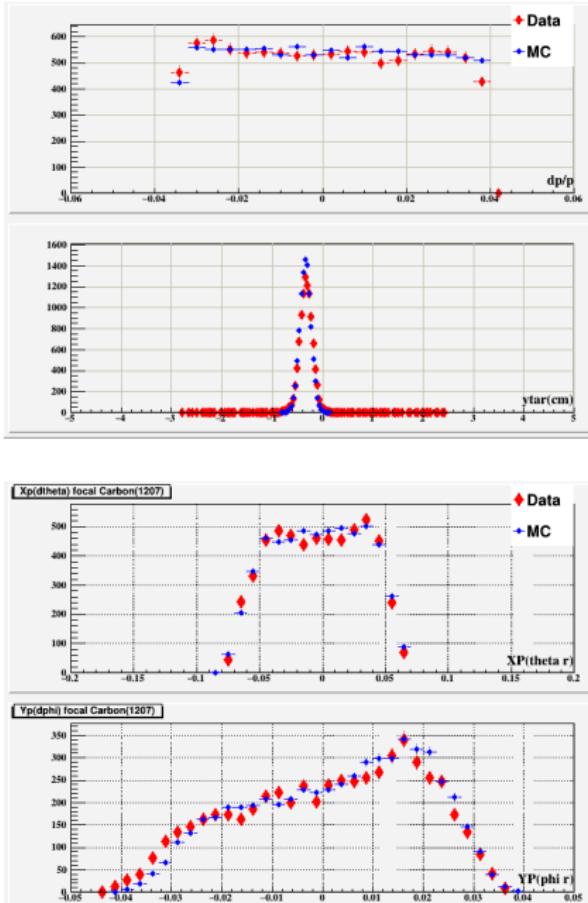
- $(\Delta E' \Delta \Omega)_{Data} = (\Delta E' \Delta \Omega)_{MC}$
- $A(E', \theta)_{Data} = A(E', \theta)_{MC}$

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

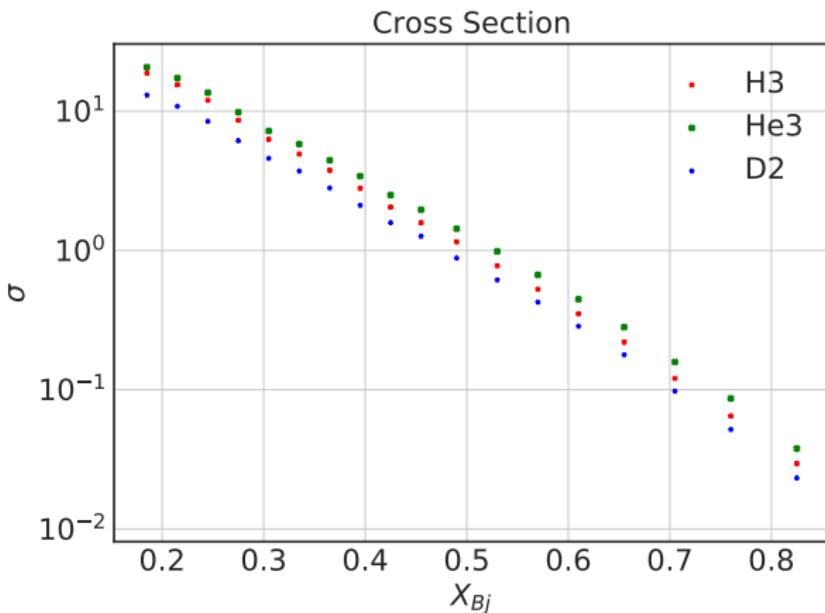
## Monte Carlo

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

[A. Bodek and U.K. Yang, 2002]



# DIS Cross Section



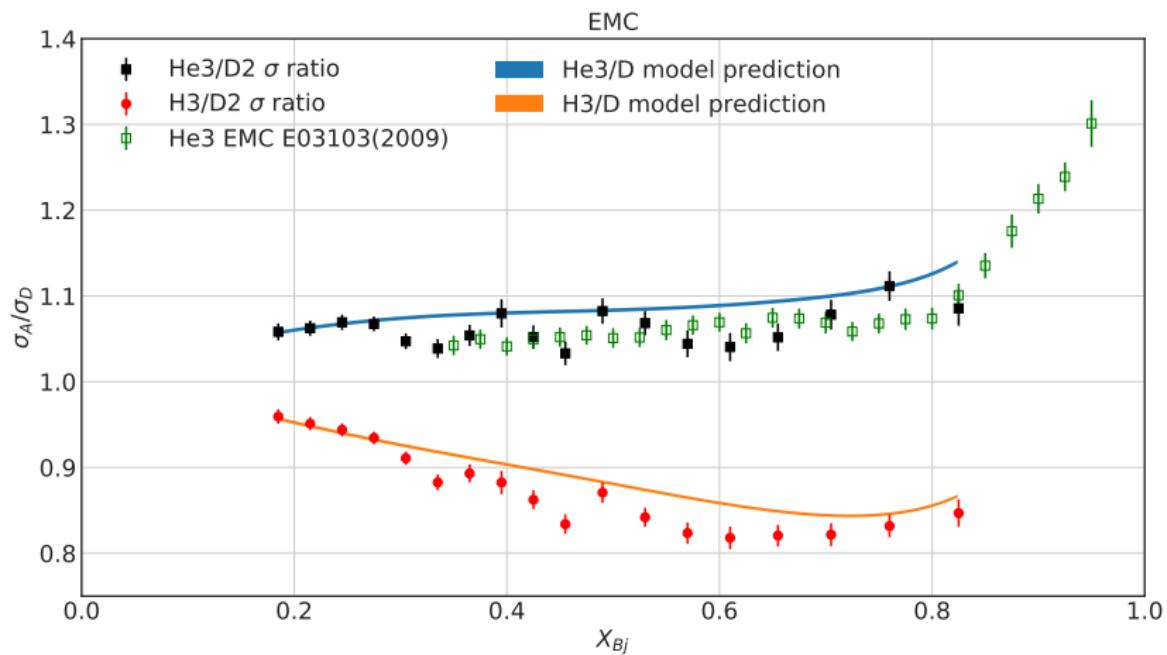
Normalization uncertainty due to target thickness uncertainty  
He3 - 1.12% • H3 - 0.97% • D - 0.56%

## Relative Error Contributions in % for Cross Section for a selection of bins

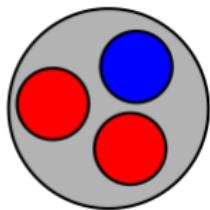
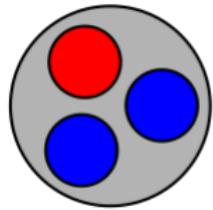
X bin	0.215	0.455	0.705
Statistical Error	0.512	0.889	1.106
Positron Correction Error	0.036	0.016	0.005
Efficiency Error*	0.665	1.477	2.951
Density Correction Error	0.002	0.002	0.002
Monte Carlo Error	0.193	0.217	0.209
Total Error	0.95	1.931	3.316

\* Contains contributions from PID, tracking, trigger, and livetime

# Per Nucleon Cross Section Ratio



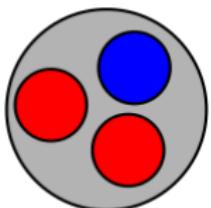
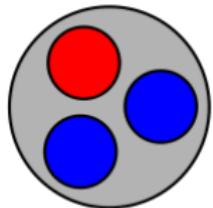
# Isoscalar Corrections



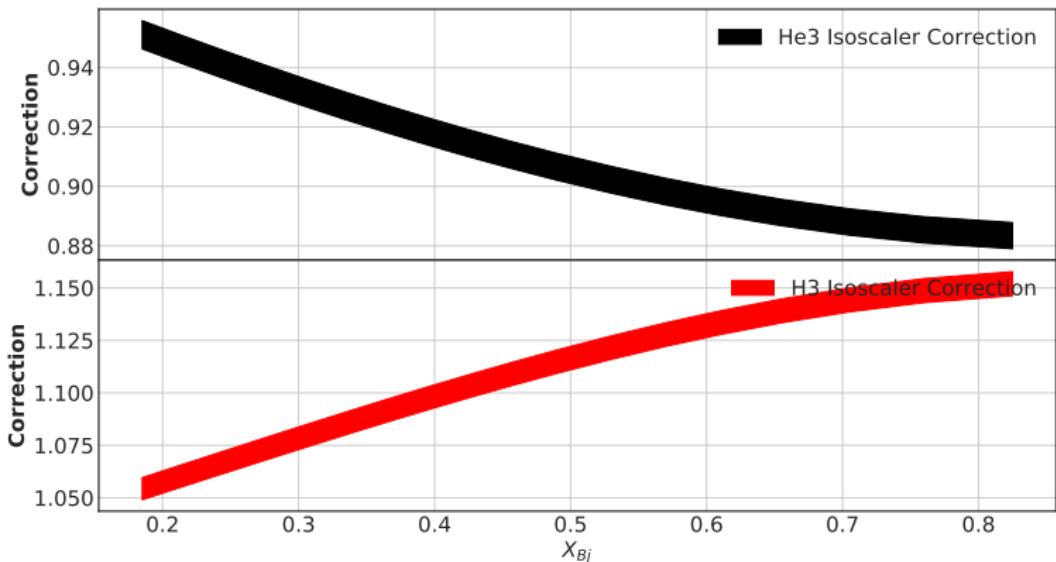
- Correct for the unpaired nucleon in the A/D ratio.

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

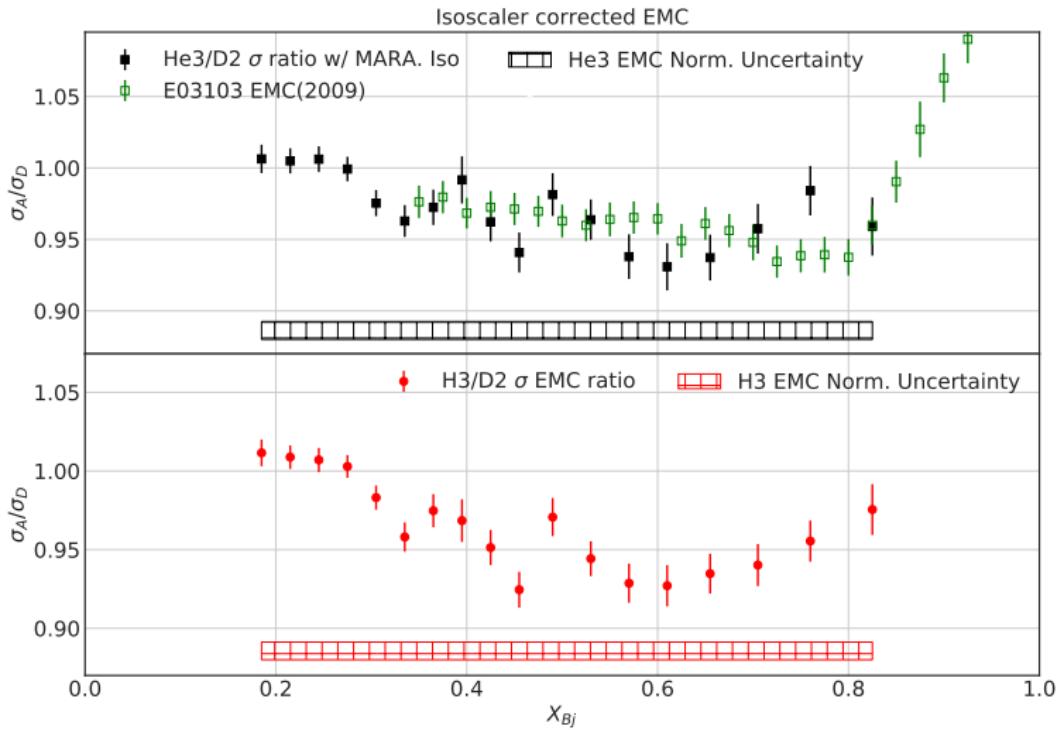
# Isoscalar Corrections



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



# EMC Effect



## Future Plans

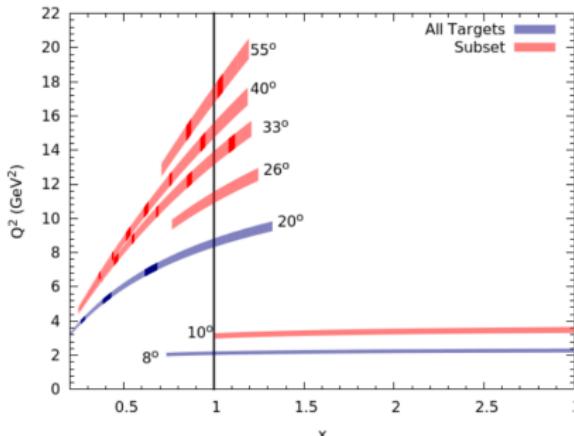
- Model dependence on cross section extraction
- Study the edge of the HRS acceptance for a long target
- Model Dependence on Isoscalar correction
- Determine the magnitude of the EMC effect for Tritium and Helium-3



# Detailed Studies of the nuclear dependence of F2 in light nuclei

[E12-100-008: J. Arrington, A Daniel, NF, D. Gaskell]

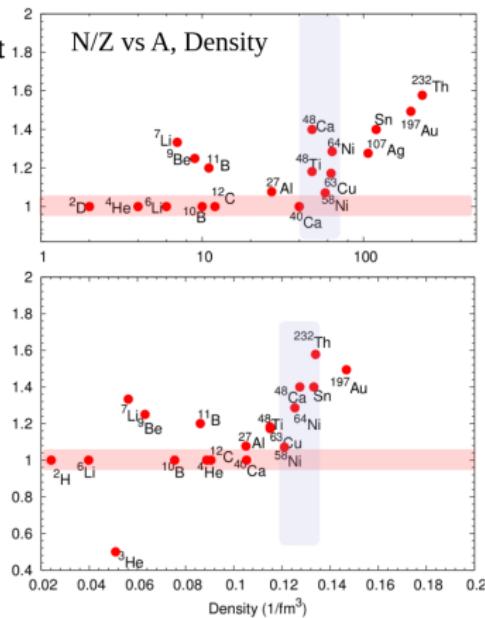
Target Choice motivated by physics impact



Coming soon\* in Hall C

What is soon?

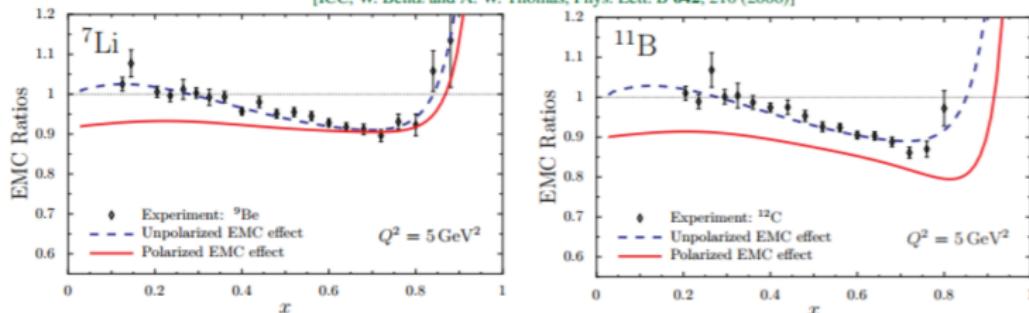
Slide credit Nadia Fomin



# 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



# The JLab MARATHON Tritium Collaboration

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## More than 140 Collaborators

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

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



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**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.

## Summary

- The puzzling EMC Effect - decrease in high momentum quarks
- DIS - probe the quarks
- DOE and JSA
- Rex Tayloe for the invite.

## Special Thanks

- Nadia Fomin and Douglas Higinbotham
- The Tritium Students
- DOE and JSA
- Rex Tayloe for the invite.



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