New Measurements of the Deuteron to Proton F_2 Structure Function Ratio at Large x

New Measurements of the Deuteron to Proton F_2 Structure Function Ratio

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(for the Hall C Collaboration)

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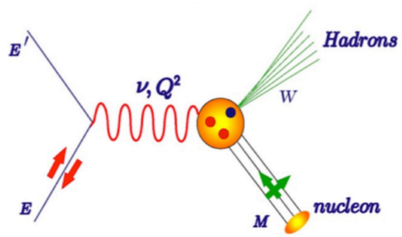
U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

The F2 experiment in Hall C

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2\sin^4\left(\frac{\theta}{2}\right)}\left(\frac{2}{M}F_1(x,Q^2)\sin^2\left(\frac{\theta}{2}\right) + \frac{1}{\nu}F_2(x,Q^2)\cos^2\frac{\theta}{2}\right)$$

$Q^2 = 4EE'\sin^2(\theta/2)$	4-momentum transfer
$\nu = E - E'$	Energy transfer
$W = M^2 + 2M\nu - Q^2$	Final state hadronic mass
θ	Scattering angle
$x = Q^2/2M\nu$	Quark fractional momentum

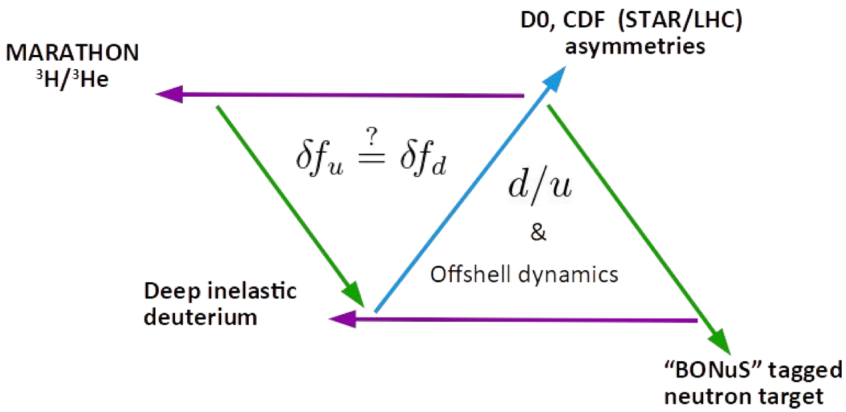


Physics motivation

- Constrain PDFs
- Quark hadron duality
- Non singlet moments
- Resonance /DIS modelling

The F2 experiment in Hall C

- Deuteron to proton F_2 ratio provides access to d/u at large x
- Three complimentary 12 GeV experiments, MARATHON in Hall A, BONuS12 in Hall B, and F2 in Hall C



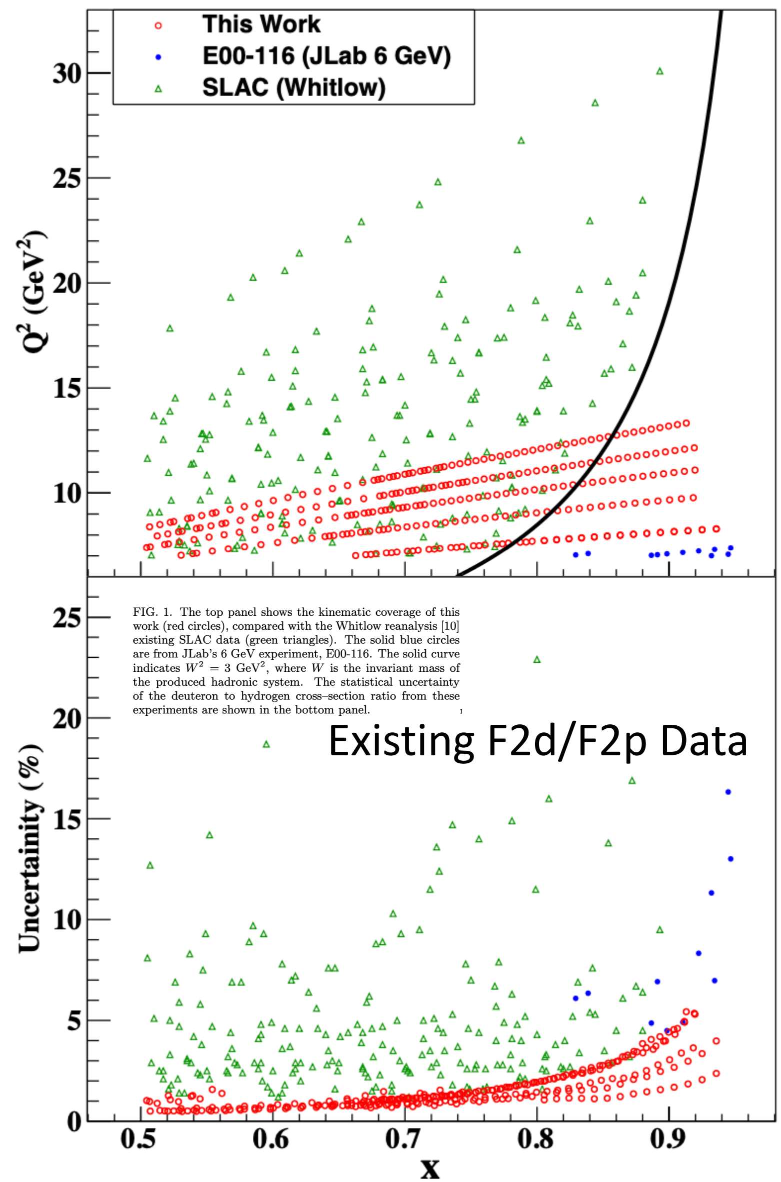


FIG. 1. The top panel shows the kinematic coverage of this work (red circles), compared with the Whitlow reanalysis [10] existing SLAC data (green triangles). The solid blue circles are from JLab's 6 GeV experiment, E00-116. The solid curve indicates $W^2 = 3$ GeV^2, where W is the invariant mass of the produced hadronic system. The statistical uncertainty of the deuteron to hydrogen cross–section ratio from these experiments are shown in the bottom panel.

The F2 experiment in Hall C

- JLab12 GeV Commissioning Experiment in Hall C
- Data taken in Spring 2018
- Single Arm (Inclusive) measurement
- Scattered e- detected in spectrometers
- Hydrogen and Deuterium Liquid Targets

Hall C Spectrometers

71% of total data were taken by SHMS

Push to high Q^2

LH_2, LD_2, Al

SHMS

Angle	Momentum(GeV/c)
21	2.7, 3.3, 4.0, 5.1
25	2.5, 3.0, 3.5, 4.4
29	2.0, 2.4, 3.0, 3.7
33	1.7, 2.1, 2.6, 3.2
39	1.3, 1.6, 2.0, 2.5

We will extract H,D(e,e') cross sections.

positron data

Angle	Momentum(GeV/c)
21	2.7
29	2.0, 2.7
39	1.3, 1.8

Cross Section Extraction: Data Yields

Number of scattered particles form the tracks in drift chambers and pass through all the PID (cerenkov and calorimeter) cuts

Acceptance Cuts for SHMS
$-10.0 < y_{tar} < 10.0$
$-0.1 < y'_{tar} < 0.1$
$-0.1 < x'_{tar} < 0.1$
$-10.0 < \delta < 22.0$
PID Cuts for SHMS
$N_{cer} > 2.0$
$E_{calo}/E' > 0.7$
Current Cut for SHMS
$I_{BCM\ 4C} > 5.0$

Pion contamination + Charge Symmetric background + Cryo Cell Contribution

$$Y_{data} = \frac{N^{e-} - BG}{\epsilon_{tot} E_{LT} C_{LT}} \times PS$$

→ Prescale

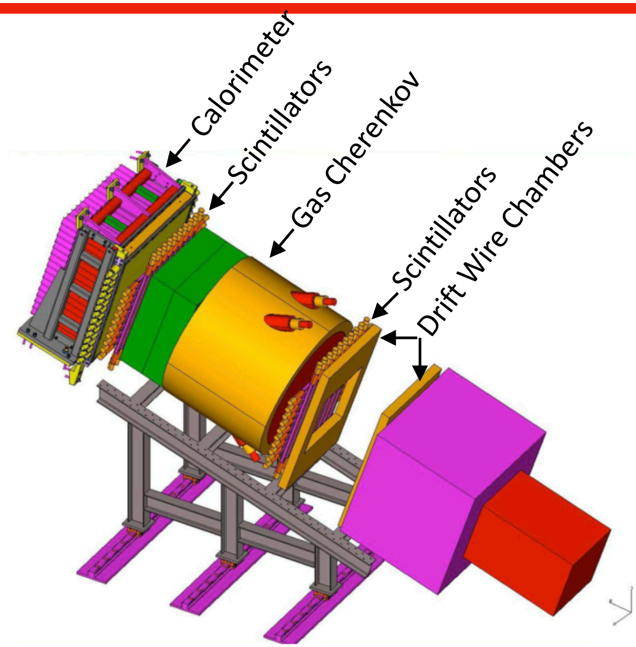
Total efficiency :

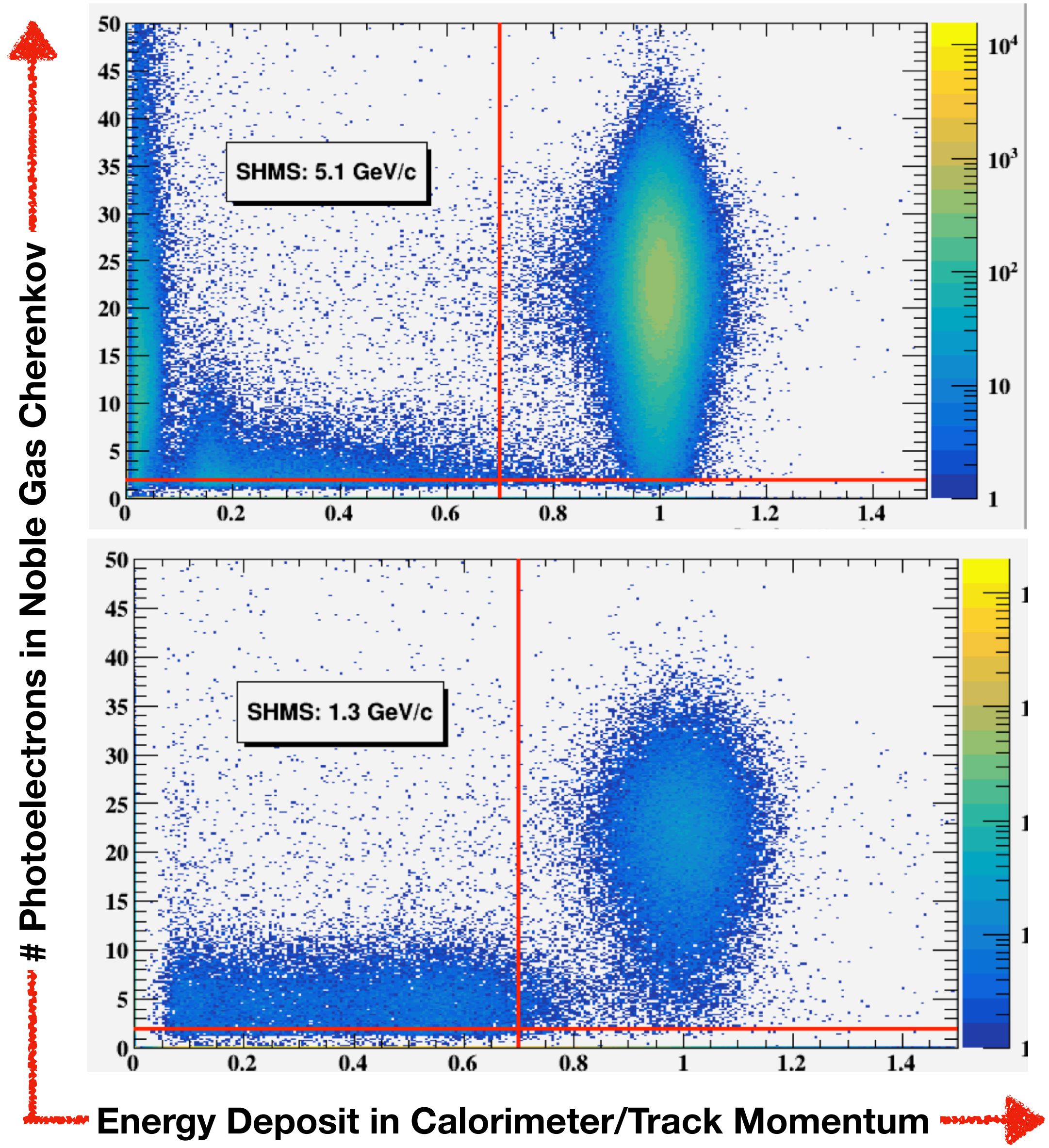
$$\epsilon_{tot} = \epsilon_{track} \times \epsilon_{cerenkov} \times \epsilon_{calorimeter}$$

Electronic live time

Computer live time

Cross Section Extraction: Particle identification



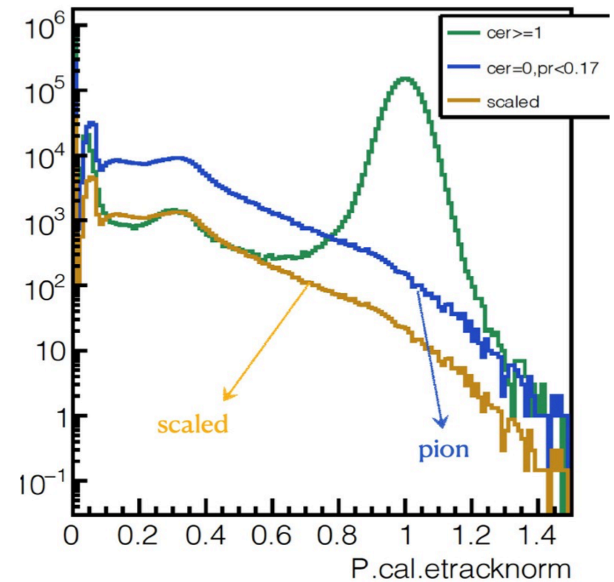


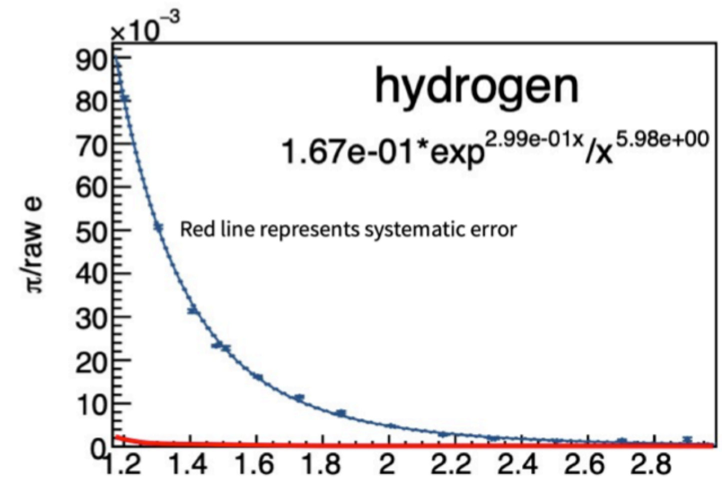
PID Cuts

- E/p > 0.7
- NPE > 2.0

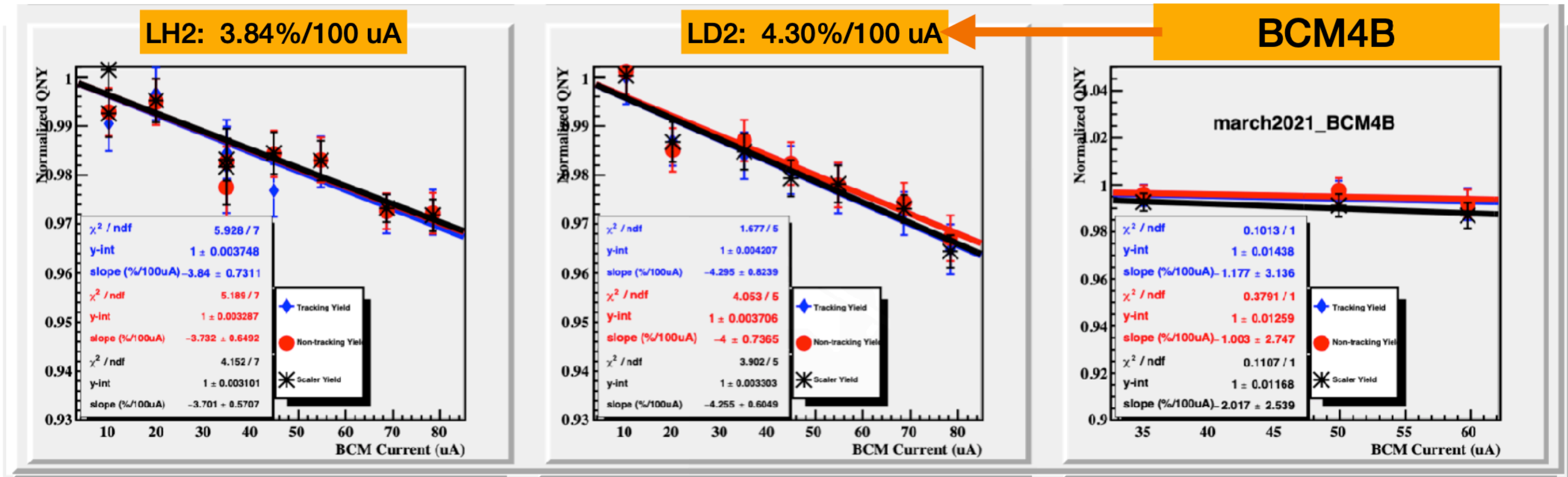
Cross Section Extraction: Pion Contamination

- Pions that pass the electron cuts need to be removed from yields
- The π/e ratio was calculated for each spectrometer angle and parameterized as a function of E’
- Analysis was done for each target (LH2, LD2, C12, AL)
- For large angle/ small E’ this can be very large (~10 % effect)

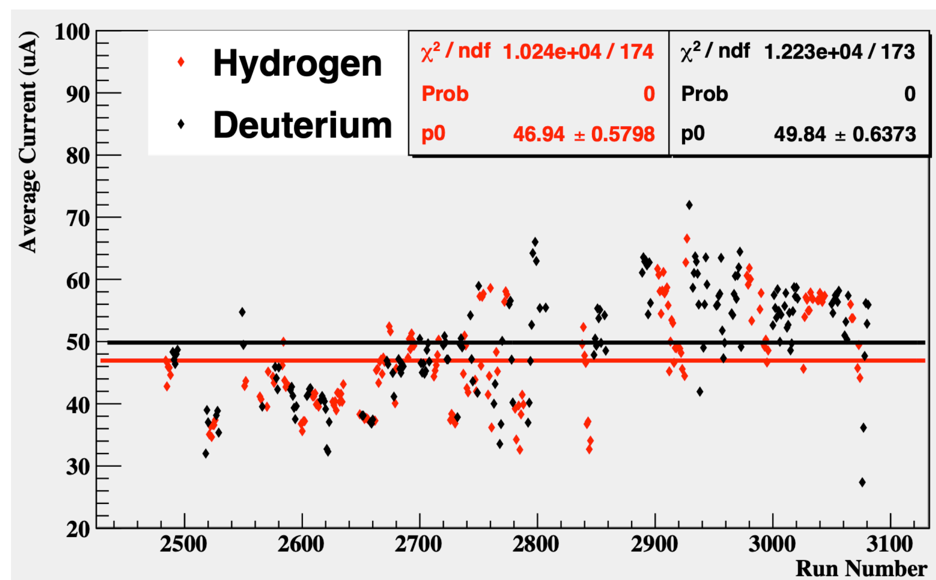




Target Density Correction

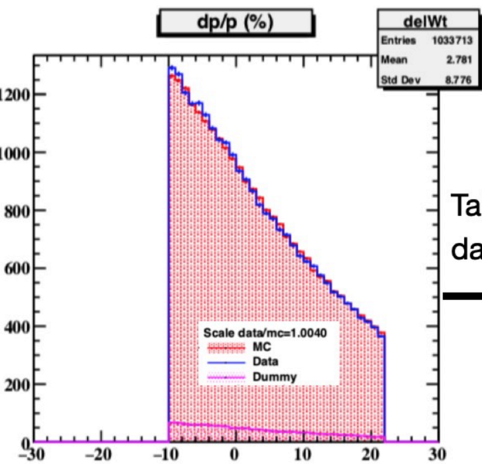


- Luminosity Runs were used to determine the density correction
- Experiment ran at an average beam current of 50 uA
- Target density uncertainty in D/H ratio ~1.1%



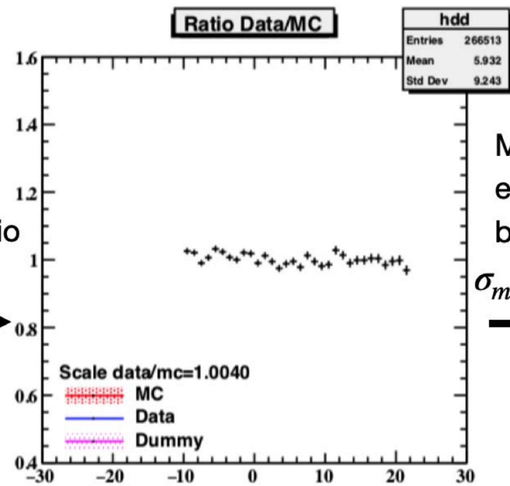
Cross Section Extraction: Monte Carlo Ratio Method

$$\left(\frac{d\sigma}{d\Omega dE'}\right)_{exp} = \frac{Y_{Data}}{Y_{MC}}\left(\frac{d\sigma}{d\Omega dE'}\right)_{model}$$

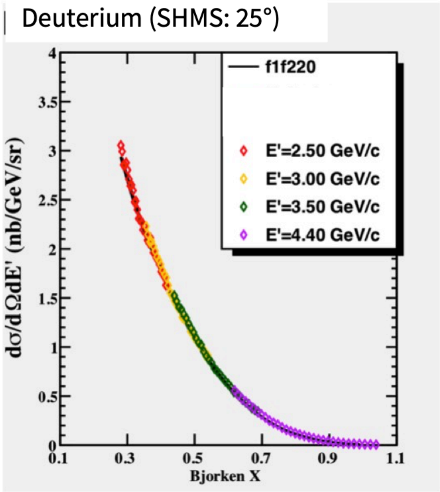


(Data is dummy subtracted)

Take Ratio data/MC



Multiply each bin by $\sigma_{model}(E',\theta)$



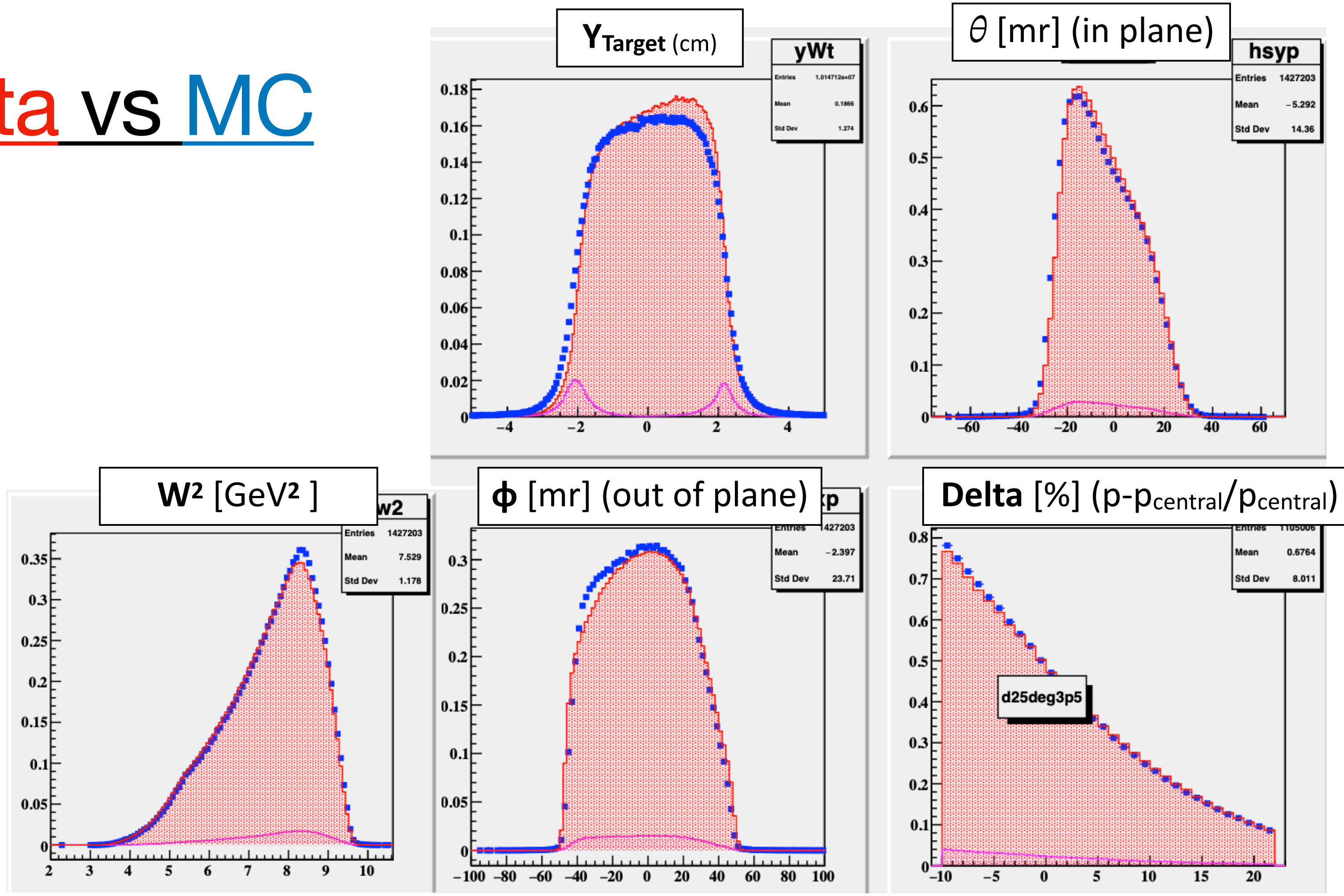
1) MC (weighted with radiative cxsec) and corrected data yields are binned in delta

2) Take ratio of data and MC

3) Multiply each bin by model (not radiated) to get cross section

Cross Section Extraction: Monte Carlo Ratio Method

Data vs MC



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Cross Section Extraction: Error Budget

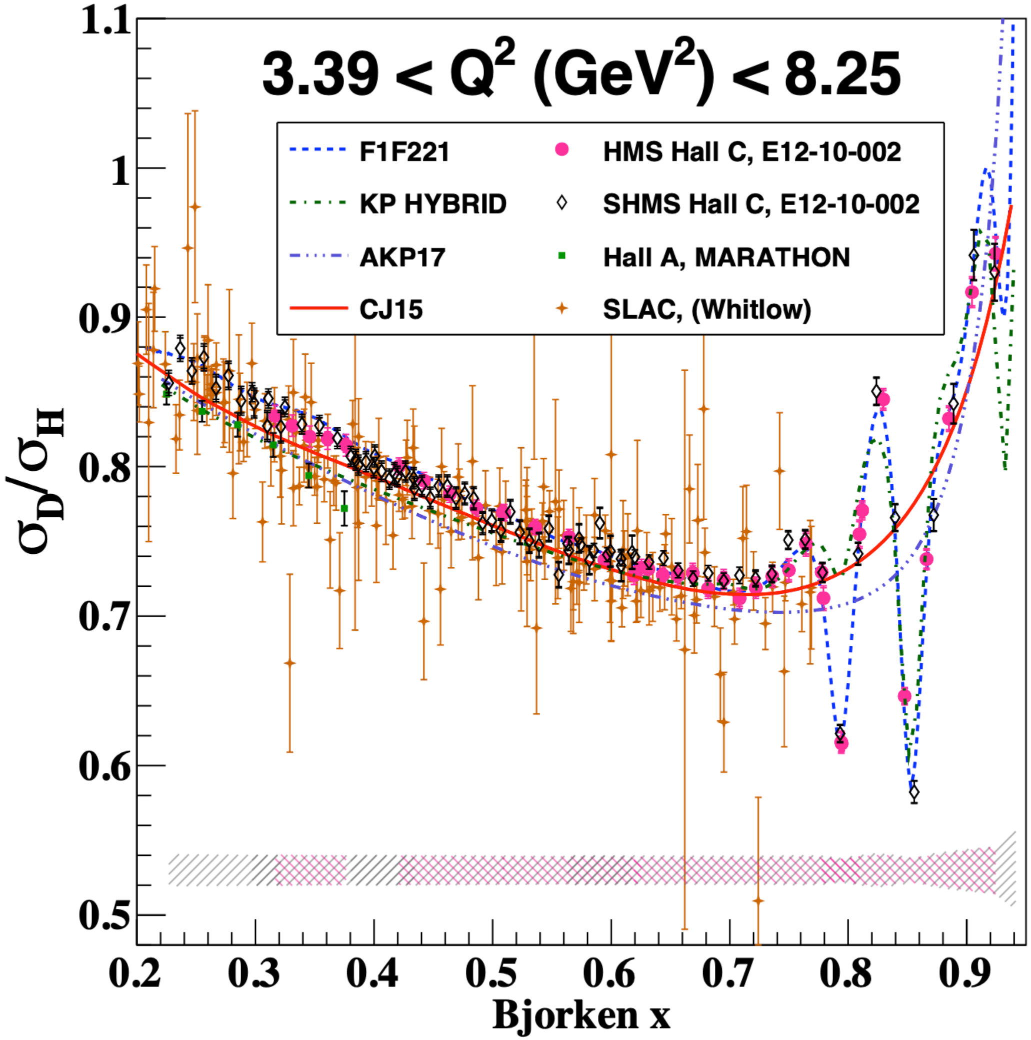
- In the ratio, F_2^D/F_2^p, many of the systematic errors are reduced
- Target density error: 1.1%
- Livetime errors approach 1% at the highest rate kinematics
- “Kinematic” error includes contributions from the $\delta E_{scat.}$’, δE_{beam}, and $\delta\theta_{central}$

Error	Pt. to Pt (%)	Correlated (%)
Statistical	0.6 – 5.6(2.9)	
Charge	0.1 – 0.6	
Target Density	0.0 – 0.2	1.1
Livetime		0.0 – 1.0
Model Dependence		0.0 – 2.6(1.2)
Charge Sym. Background		0.0 – 1.4
Acceptance		0.0 – 0.6(0.3)
Kinematic		0.0 – 0.4
Radiative Corrections		0.5 – 0.7(0.6)
Pion Contamination		0.1 – 0.3
Cerenkov Efficiency		0.1
Total	0.6 – 5.7(2.9)	1.3 – 2.9(2.1)

TABLE I. Error budget for the cross section ratio σ_D/σ_H. The error after a cut of $W^2 > 3$ GeV^2 is shown in parenthesis, this is a typical cut applied to eliminate the resonance region while performing PDF fits.

Results

- Excellent agreement between SHMS and HMS
- Vast improvement in statisical precision from SLAC data
- "F1F221" model does not include this work



Results

$\theta_C = 21^\circ$

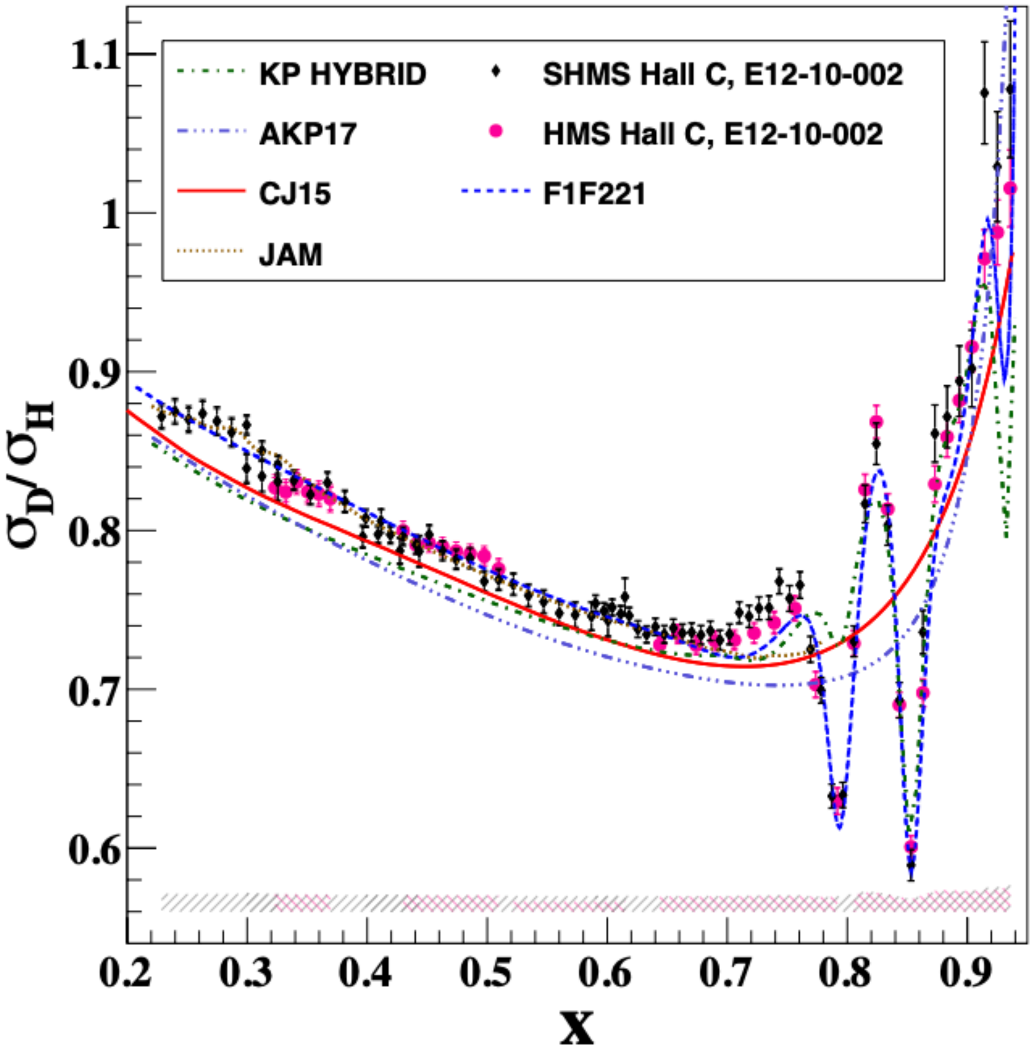


FIG. 2. The σ_D/σ_H ratio as a function of x for a spectrometer angle of 21 deg (Q^2 range from 3.39 to 8.25 GeV^2). The error bars include uncorrelated systematic and statistical errors. The error bands include correlated systematic errors and an overall normalization of 1.1%(see Table I.). F1F221 (blue dashed line) is the model used in this analysis, the other curves are from different PDF fits (see text). Good agreement is observed between the well-understood HMS and newly constructed SHMS spectrometers.

CJ15

Constraints on large-x parton distributions from new weak boson production and deep-inelastic scattering data

A. Accardi (Hampton U. and Jefferson Lab), L.T. Brady (Jefferson Lab and UC, Santa Barbara), W. Melnitchouk (Jefferson Lab), J.F. Owens (Florida State U.), N. Sato (Jefferson Lab)

Feb 9, 2016

KP Hybrid

Nuclear effects in the deuteron in the resonance and deep-inelastic scattering region

S.A. Kulagin (Moscow, INR)

Dec 31, 2018

AKP17

Nuclear Effects in the Deuteron and Constraints on the d/u Ratio

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Apr 1, 2017

Results

In the one-photon exchange approximation the differential cross–section for inclusive electron scattering can be written as:

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott} \frac{2MxF_2}{Q^2\varepsilon}\left(\frac{1+\varepsilon R}{1+R}\right) \quad (1)$$

Where σ_{Mott} is the Mott cross–section, M is the nucleon mass, Q^2 is the negative of the four-momentum transfer squared, R is the ratio of the longitudinal and transverse reduced cross–sections ($R = \sigma_L/\sigma_T$), ε is the virtual photon polarization, F_2 is the structure function and x is the Bjorken scaling variable. The aim of this work is to obtain the F_2^D/F_2^H ratio, as it presents several advantages theoretically as well as experimentally. By reporting a quantity involving deuterium rather than the ("free") neutron we avoid choosing a particular prescrip-

tion for treating nuclear effects, allowing theory groups active in this field to extract F_2^n using their own nuclear corrections. Furthermore, the σ_L/σ_T ratio is largely the same for hydrogen and deuterium [19], thus, to first order, the F_2^D/F_2^H ratio is the same as the cross–section ratio.

Approved future experiment

E12-14-002: Precision Measurements and Studies of a Possible Nuclear Dependence of R

Results

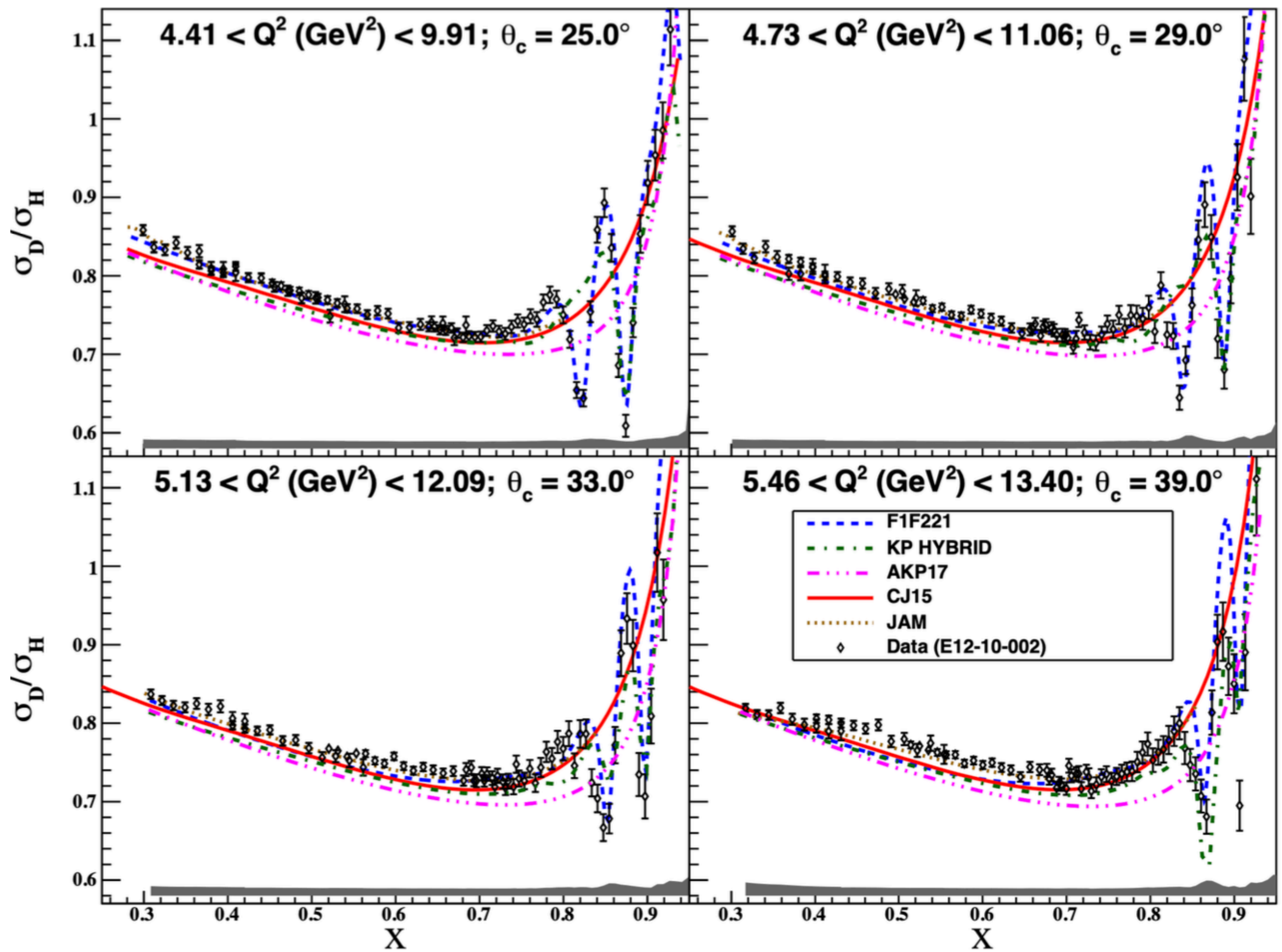
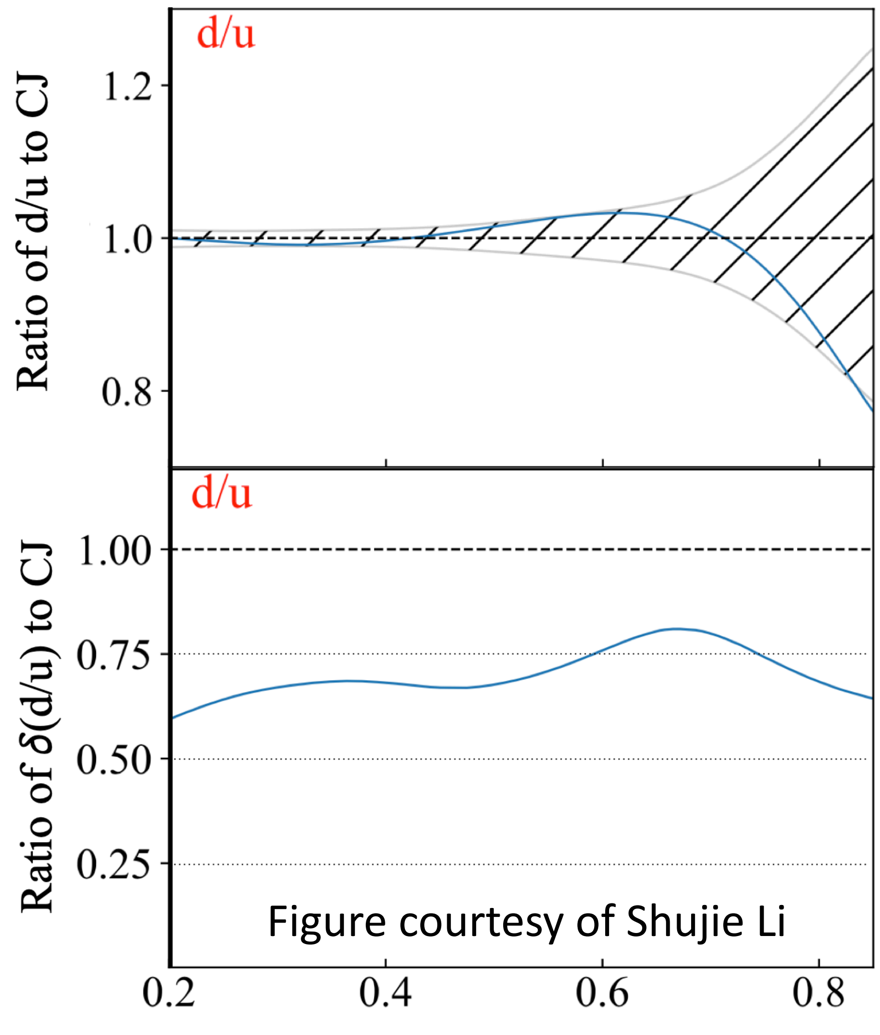


FIG. 3. The σ_D/σ_H ratio as a function of x for SHMS spectrometer angles of 25, 29, 33, and 39 deg. The Q^2 range of each setting is indicated in each panel.

CJ Impact Studies

- Impact studies from the CJ collaboration demonstrate the constraining power of this data on PDF fits
- Shifted central value of PDF at large x
- Reduction in uncertainty

Data from this work was included into the PDF fitting framework of the CJ collaboration, which deploys state-of-the-art deuteron nuclear corrections and leverages recent results[cite neutron paper], the The impact of this work can been seen in Fig. 4 where the significant reduction in uncertainity demonstrates the importance of high precision data in PDF extractions. Not only did the inclusion of this data shift the d/u central value at large-x by as much as 20%, but it also reduced the relative error by 20%–40% across the entire x range. Furthermore, this data provides additional constraints on the parameters used in higher twist corrections, the individual d and u quark distributions, and the target mass corrections used in these fits. Fig. 4 depicts the d/u ratio, a fundamental quantity and testing ground for multiple (p)QCD predictions regarding nucleon structure It should be noted that,



CJ Impact Studies:

Current Figure in paper

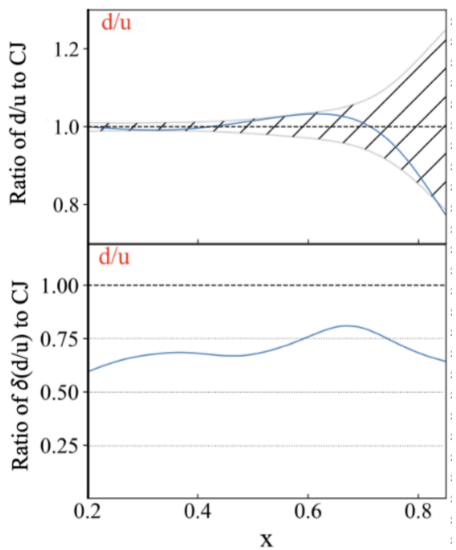
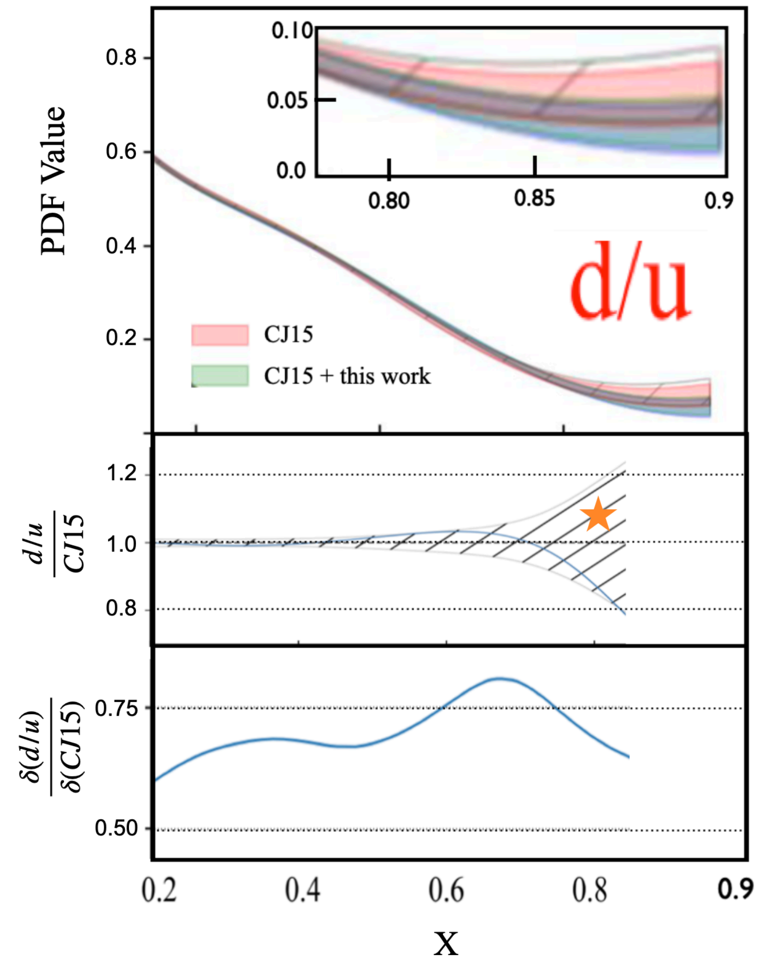


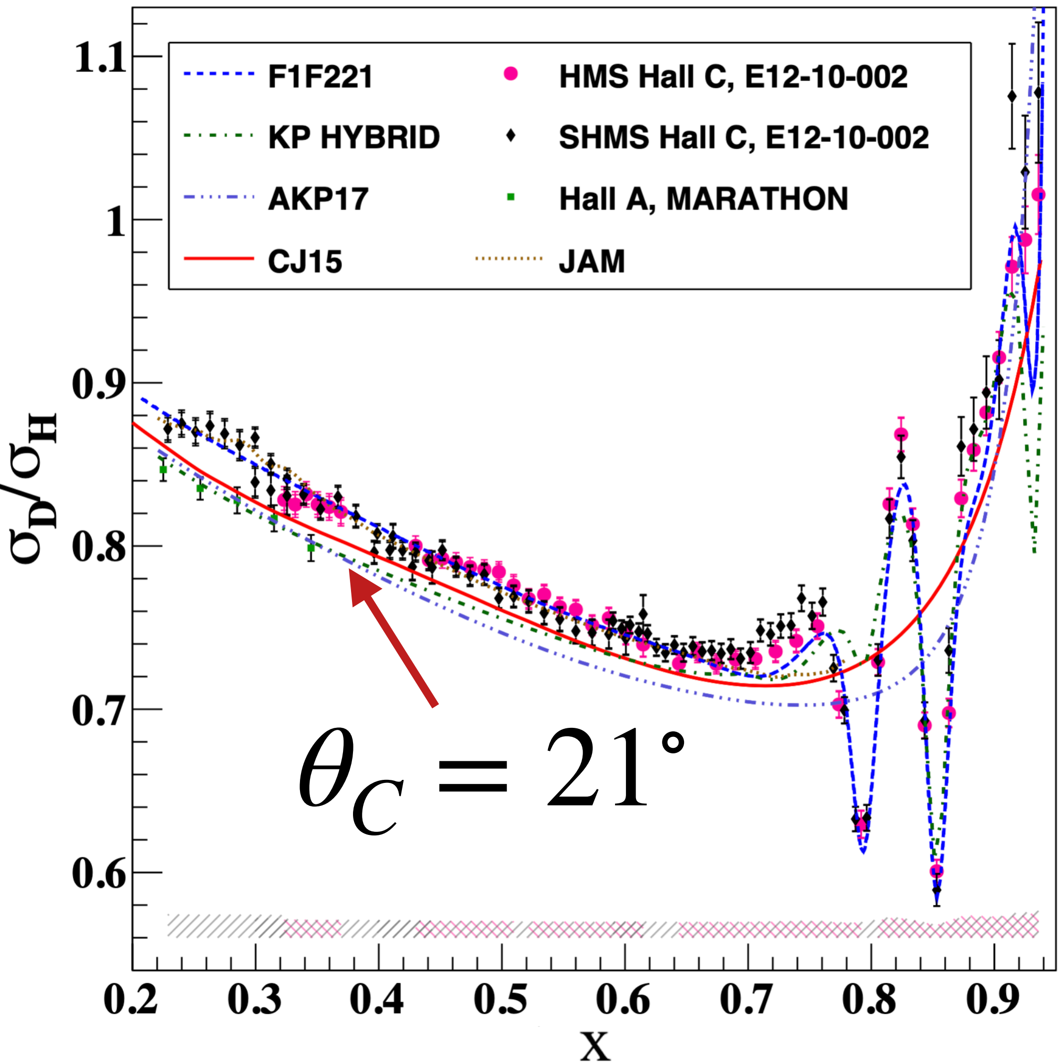
FIG. 4. Top: The blue line shows the relative change in the CJ15 central value of the d/u PDF after data from this analysis are included in the fit. The band represents the error of the fit before the inclusion of this data. Here the lack of data on deuterium at high-x is reflected in the large error. Bottom: The relative error on the CJ15 PDF fit after including data from this experiment. The inclusion of this new data results in a 20-40% reduction of the uncertainty in the d/u PDFs. A cut of $W^2 > 3$ GeV^2 is applied to the data that enters the fit.

Proposed new figure



★ Remove band, adjust y-axis accordingly

MARATHON vs F2 results



- There exists a 4.3% discrepancy between MARATHON and F2 results
- The JAM collaboration found they needed to shift the MARATHON result up 1.9%
- The CJ collaboration found they need to shift the F2 result down 2.1%
- This shift in the F2 data is consistent with the normalization of 2% applied to the EMC data which ran in parallel with this work

on average, the results from this work and MARATHON differ by as much as 4.3%. The overall normalization uncertainty for the MARATHON result is 0.55% [34]. For this work the total correlated error is 1.6% in the x range where the data sets overlap. In a recent study[35] where the MARATHON data was included in a global QCD analysis, the data needed to be normalized by +1.9% to agree with existing data. In a CJ15 study [36] it was found the data from this work needed to be shifted down 2.1% to agree with the CJ model [9]. This experiment ran in parallel with E12-10-007 (a measurement of the EMC effect) which observed a 2.0% normalization difference with previous EMC measurements [37]. The direction of this normalization difference is consistent with that found in the CJ15 study. All the aforementioned data agree with the previously available SLAC data, which have large uncertainties [10].

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Summary/Outlook

- Deuteron to proton ratios complete
  - Dataset is available for inclusion in PDF fits, models, etc
  - 2nd draft of PRL publication to be submitted this month
- Future work
  - $\theta_C = 59^\circ$ ratios from HMS. Analysis ongoing
  - Absolute deuteron and proton cross section.
    - Quark-Hadron duality Averaging
    - Compute non single moments
    - Improve resonance/DIS modeling

Experiment Spokespeople	Graduate Students	JLab Staff
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Thia Keppel	Aruni Nadeeshani	
Simona Malace	Abel Sun	**Special Thanks to**
Ioana Niculescu	Abishek Karki (EMC)	Mark Jones
Gabriel Niculescu	Casey Morean (EMC)	Carlos Yero
Dave Gaskell (EMC)		Greg Smith

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(for the Hall C Collaboration)

Impact Studies

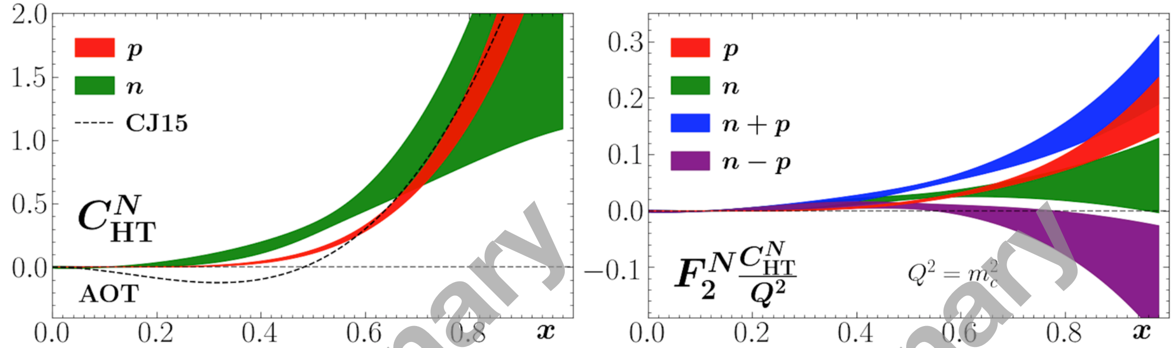
JAM Impact Study

https://www.jlab.org/theory/jam

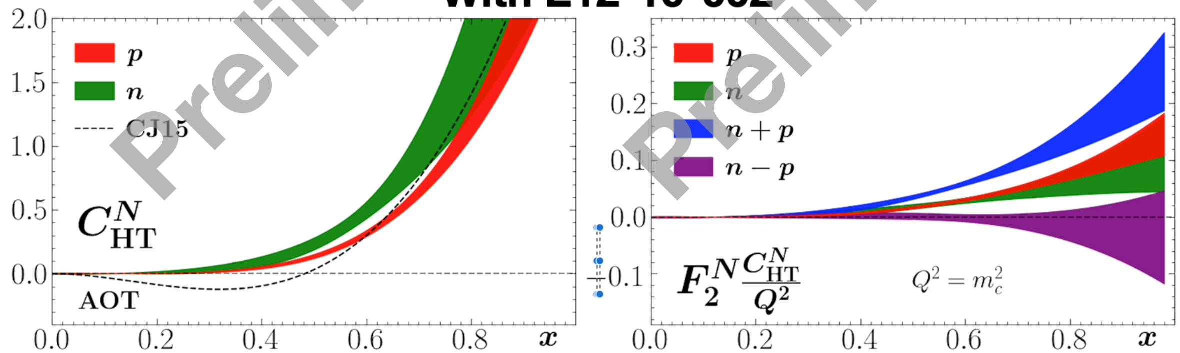
- D/H ratio was provided to Jefferson Lab Angular Momentum Collaboration (JAM) to incorporate into their global QCD analysis of PDFs
- New F2 data significantly improves the uncertainty of higher twist corrections to F2

$$F_2(x,Q^2) = F_2^{\mathrm{LT}}(x,Q^2)\left(1+\frac{C_{\mathrm{HT}}(x)}{Q^2}\right)$$

Without E12-10-002



With E12-10-002



Courtesy of Chris Cocuzza, W. Melnitchouk, and N. Gonzalez