New Measurements of the Deuteron to Hydrogen F2 Structure Function Ratio

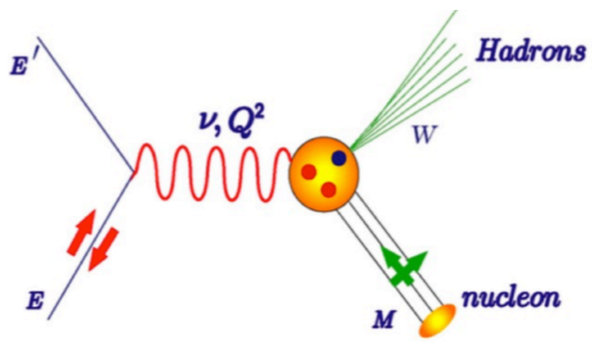
William Henry

June 20th, 2023

F2 Experiment in Hall C

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

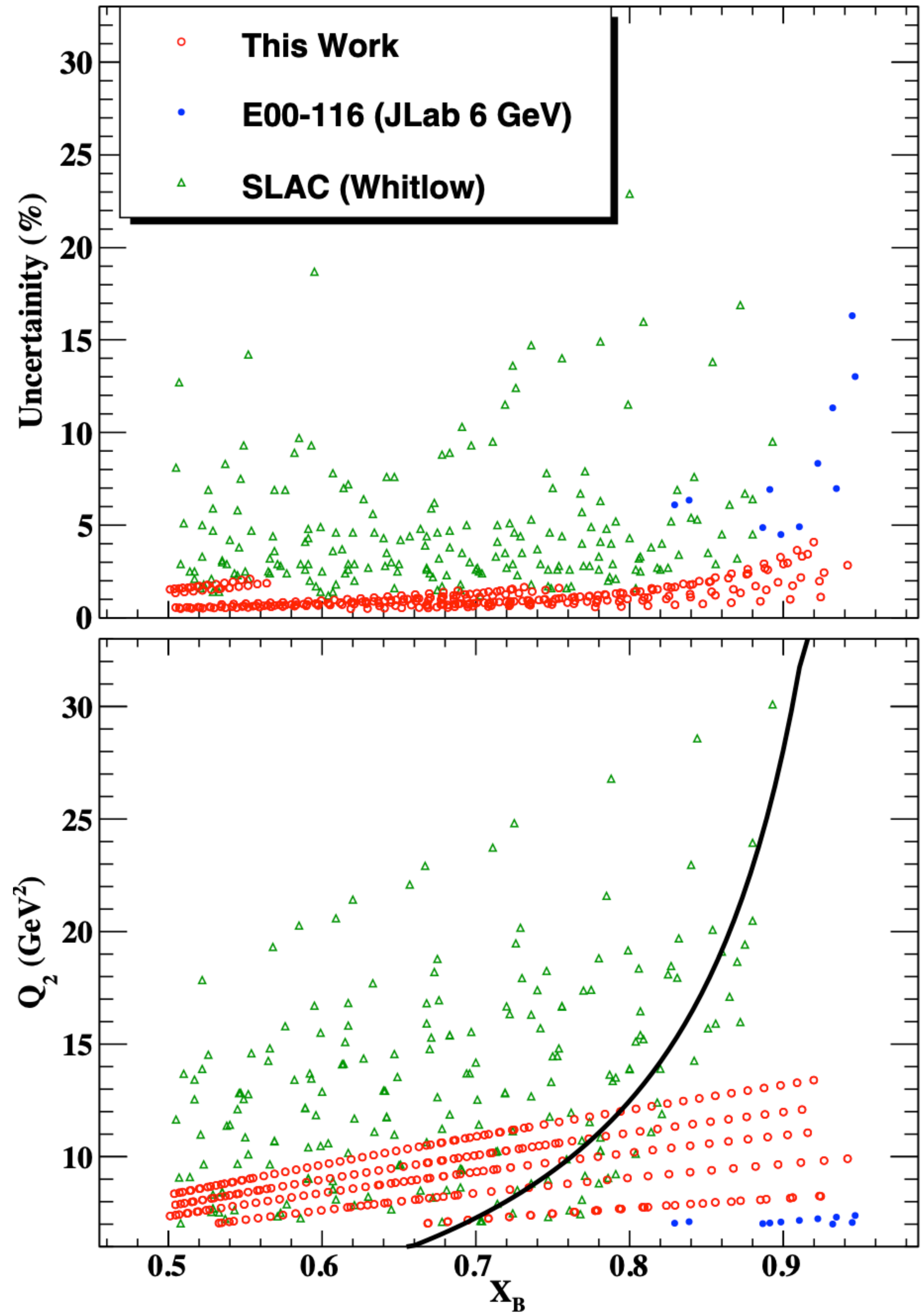
$Q^2 = 4EE'\sin^2(\theta/2)$	4-momentum transfer
$\nu = E - E'$	Energy transfer
$W = M^2 + 2M\nu - Q^2$	Final state hadronic mass
θ	Scattering angle
$x = Q^2/2M\nu$	Quark fractional momentum



- 12 GeV Commissioning Experiment
- Ran in Spring 2018
- Single Arm (Inclusive) measurement
- Scattered e- detected in spectrometers
- Hydrogen and Deuterium Liquid Targets

Physics motivation

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



F2 Experiment in Hall C

71% of total data were taken by SHMS

SHMS

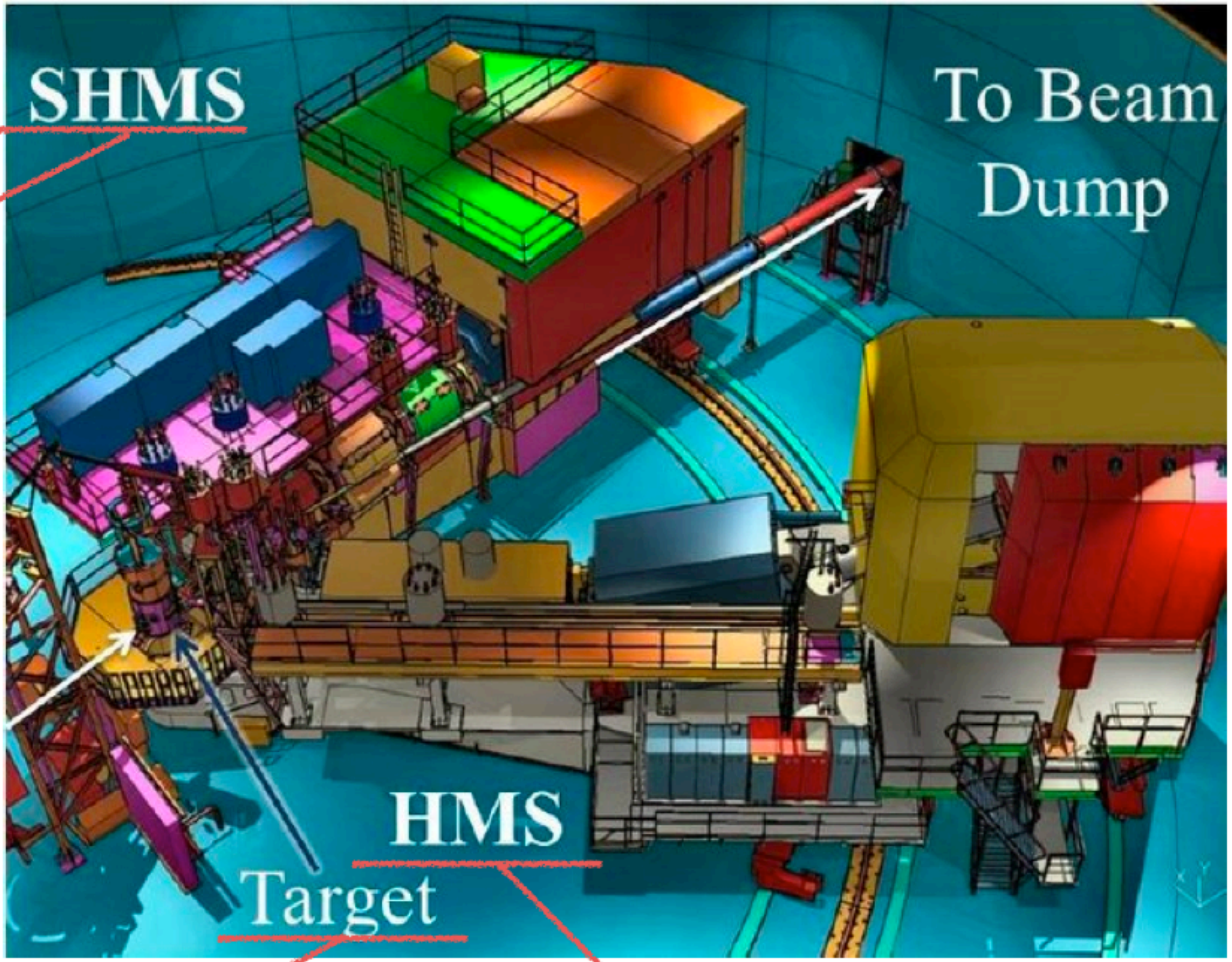
Angle	Momentum(GeV/c)
21	2.7, 3.3, 4.0, 5.1
25	2.5, 3.0, 3.5, 4.4
29	2.0, 2.4, 3.0, 3.7
33	1.7, 2.1, 2.6, 3.2
39	1.3, 1.6, 2.0, 2.5

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

Hall C Spectrometers



LH_2, LD_2, Al

Push to high Q^2

F2 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

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

PS → Prescale

Total efficiency :

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

Electronic live time

Computer live time

See talk at Winter Collaboration meeting for more analysis details (Pion contamination, Charge Symmetric Background, Livetime, PID, radiative corrections, etc)

F2 Cross Section Extraction

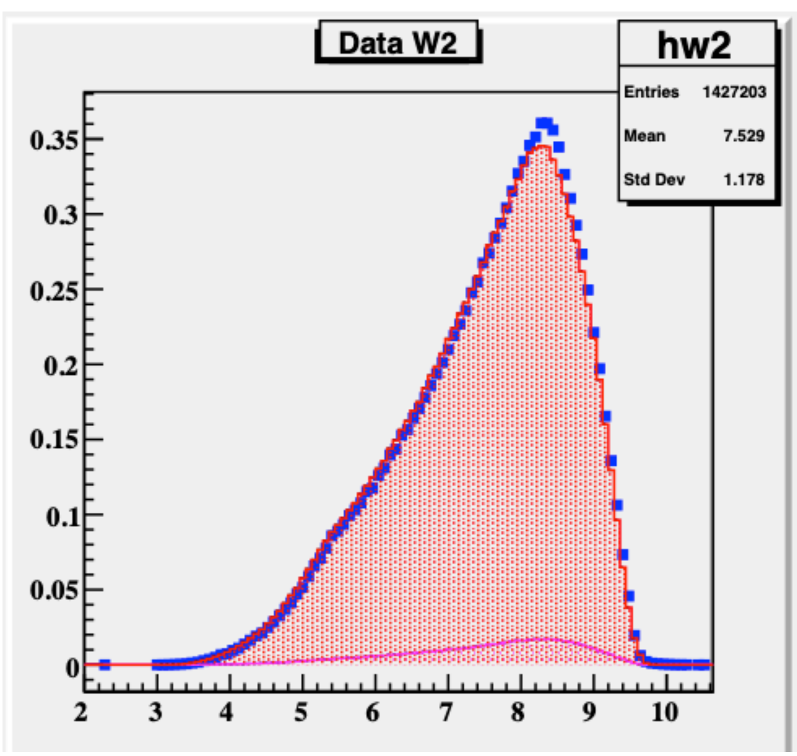
Monte Carlo (MC) Ratio Method

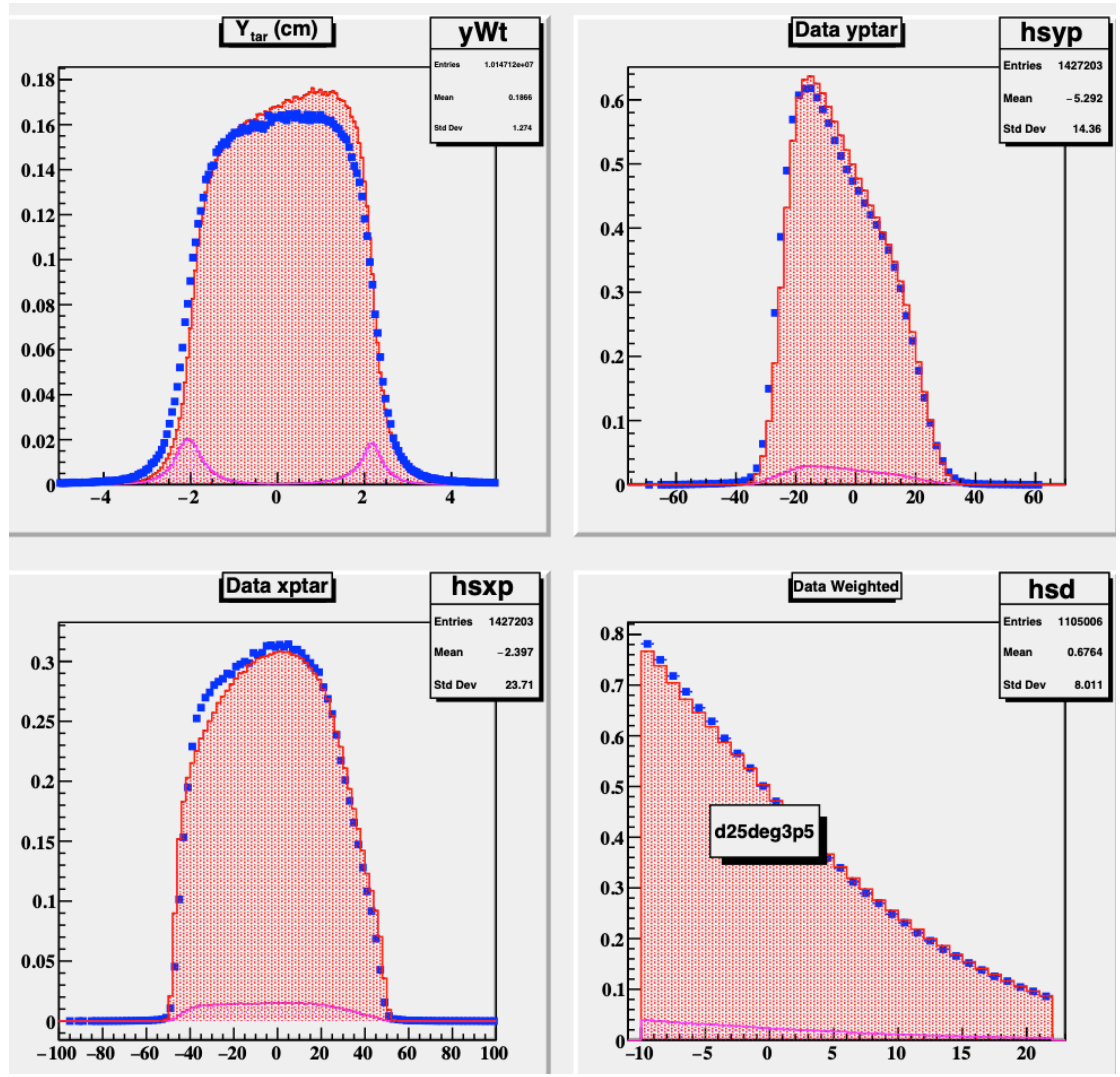
$$\left(\frac{d\sigma}{d\Omega dE'}\right)_{exp} = \left(\frac{d\sigma}{d\Omega dE'}\right)_{model} \frac{Y_{data}}{Y_{MC}}$$

- MC ran for 50M events mc-single-arm
- Events are weighted after using radiated using rc_externals and f1f221 model
- Charge Symmetric Background added to MC

F2 Cross Section Extraction

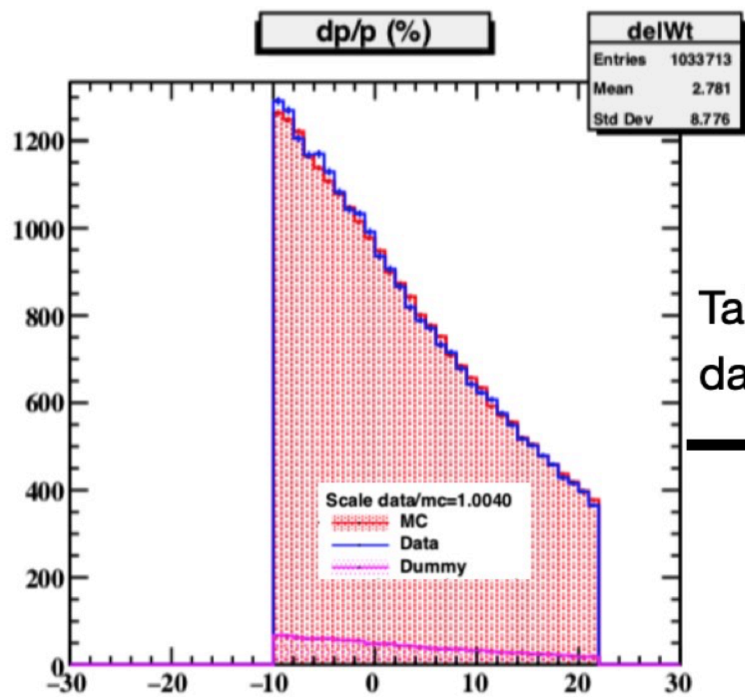
Data vs MC





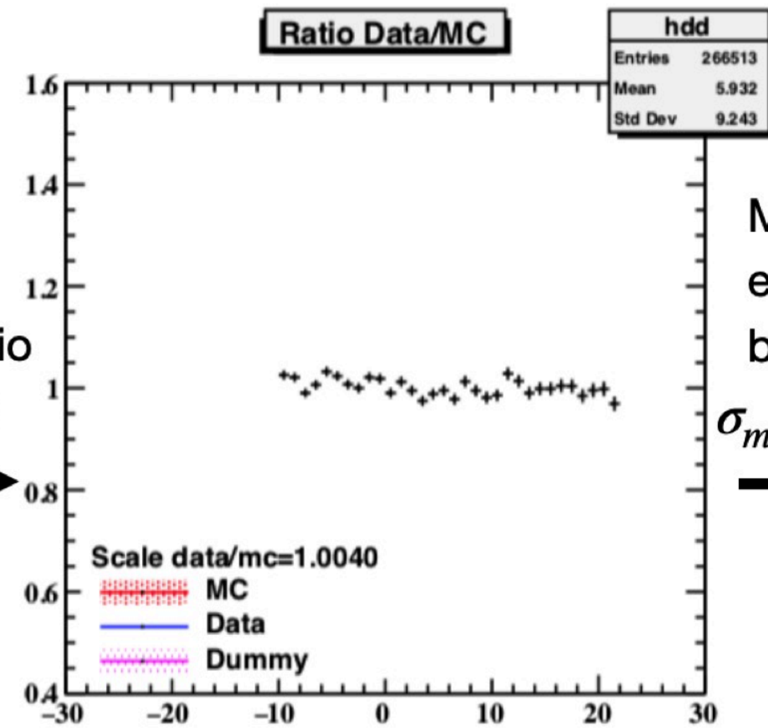
F2 Cross Section Extraction

Cross Section Extraction (MC Ratio Method)

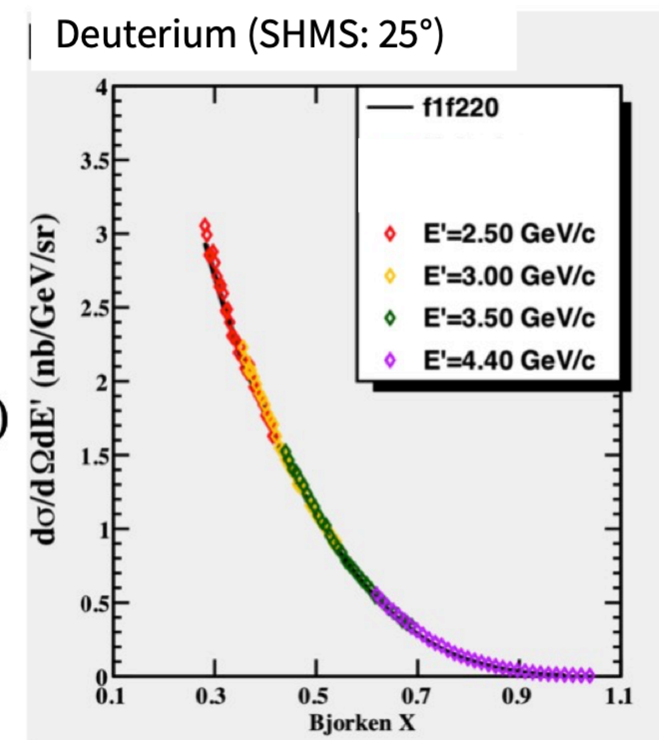


(Data is dummy subtracted)

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

F2 Cross Section Extraction: Acceptance Method

1) $$\frac{d\sigma}{dE'd\Omega} = \frac{Y(E',\theta)}{\Delta E' * \Delta\Omega * A(E',\theta) * \mathscr{L}}$$

2) $$A(E',\theta) = \frac{N_{accepted}(E',\theta)}{N_{Thrown}(E',\theta)}$$

3) $$\Delta\Omega_{Eff} = A(E',\theta) * \Delta\Omega$$

4) $$\frac{d\sigma}{dE'd\Omega} = \frac{Y(E',\theta)}{\Delta E' * \Delta\Omega_{Eff} * \mathscr{L}}$$

$A(E',\theta) = Acceptance$

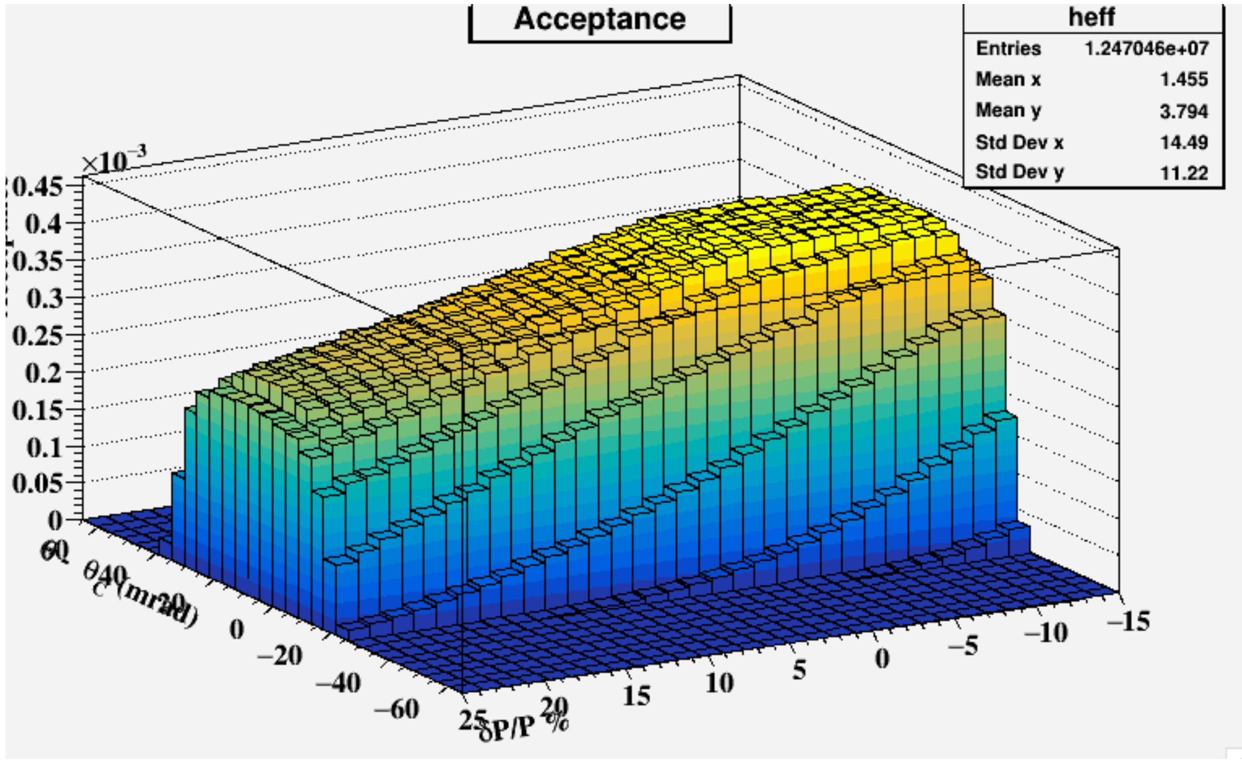
$\Delta\Omega = Solid\ Angle\ generated\ in$

$\Delta\Omega_{Eff} = Effective\ Solid\ Angle$

$Y(E',\theta) = data\ yield$

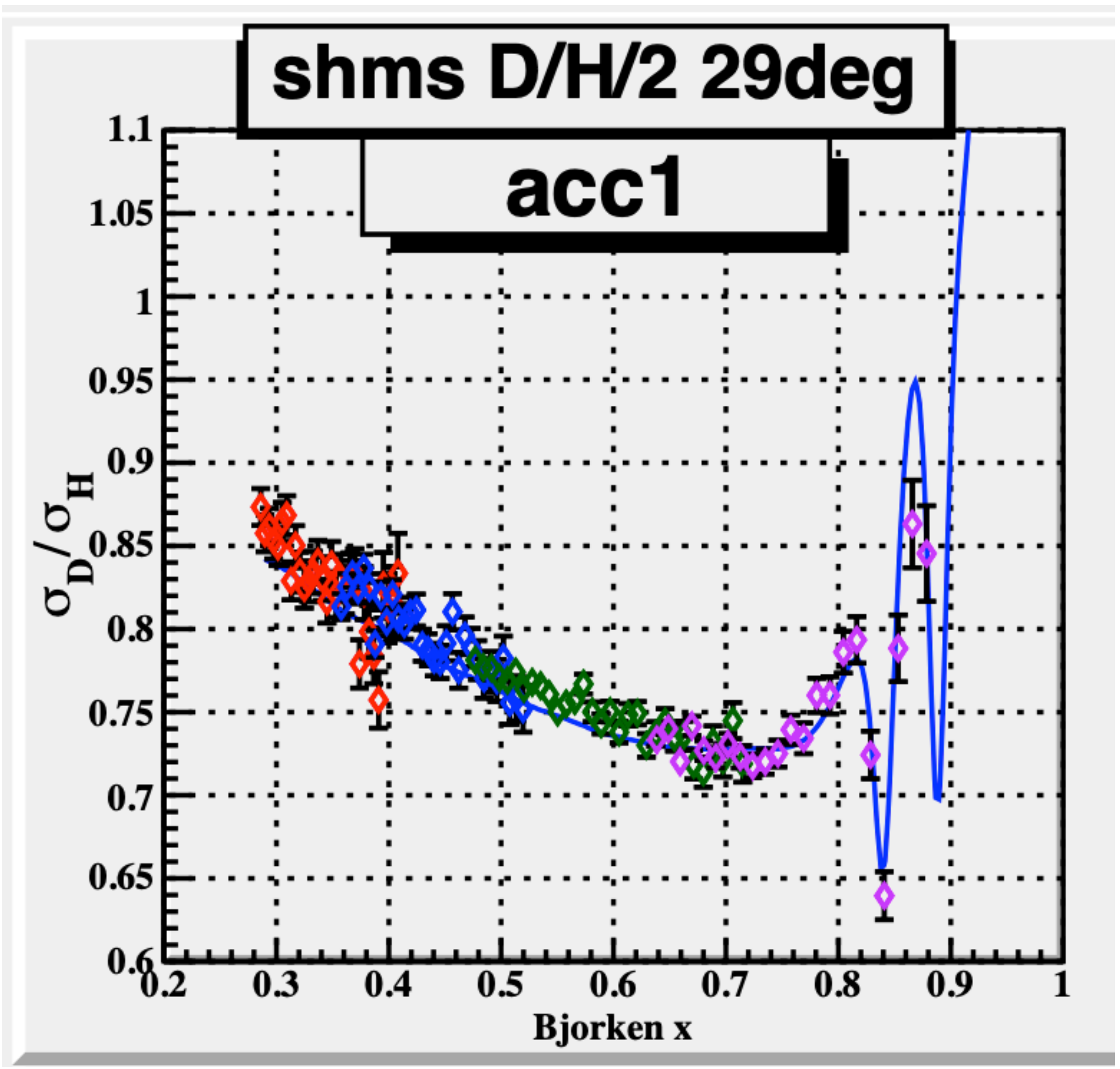
$\Delta E = width\ of\ delta\ bin\ (GeV)$

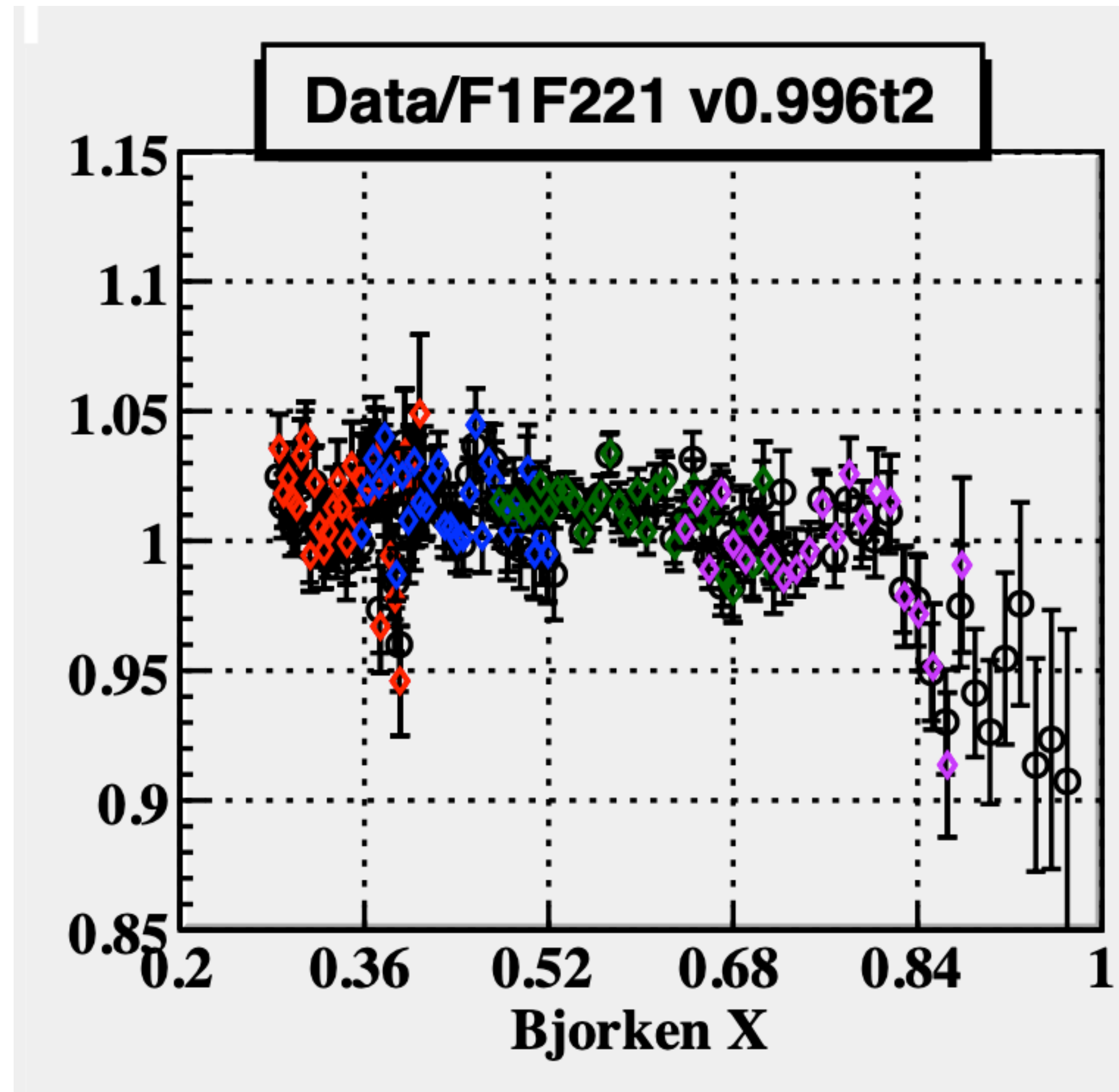
$\mathscr{L} = Luminosity(targets/nb)$



F2 Cross Section Extraction: Acceptance Method

Monte Carlos Ratio Vs Acceptance Methods





F2 Results

HMS and SHMS @ 21 degrees

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

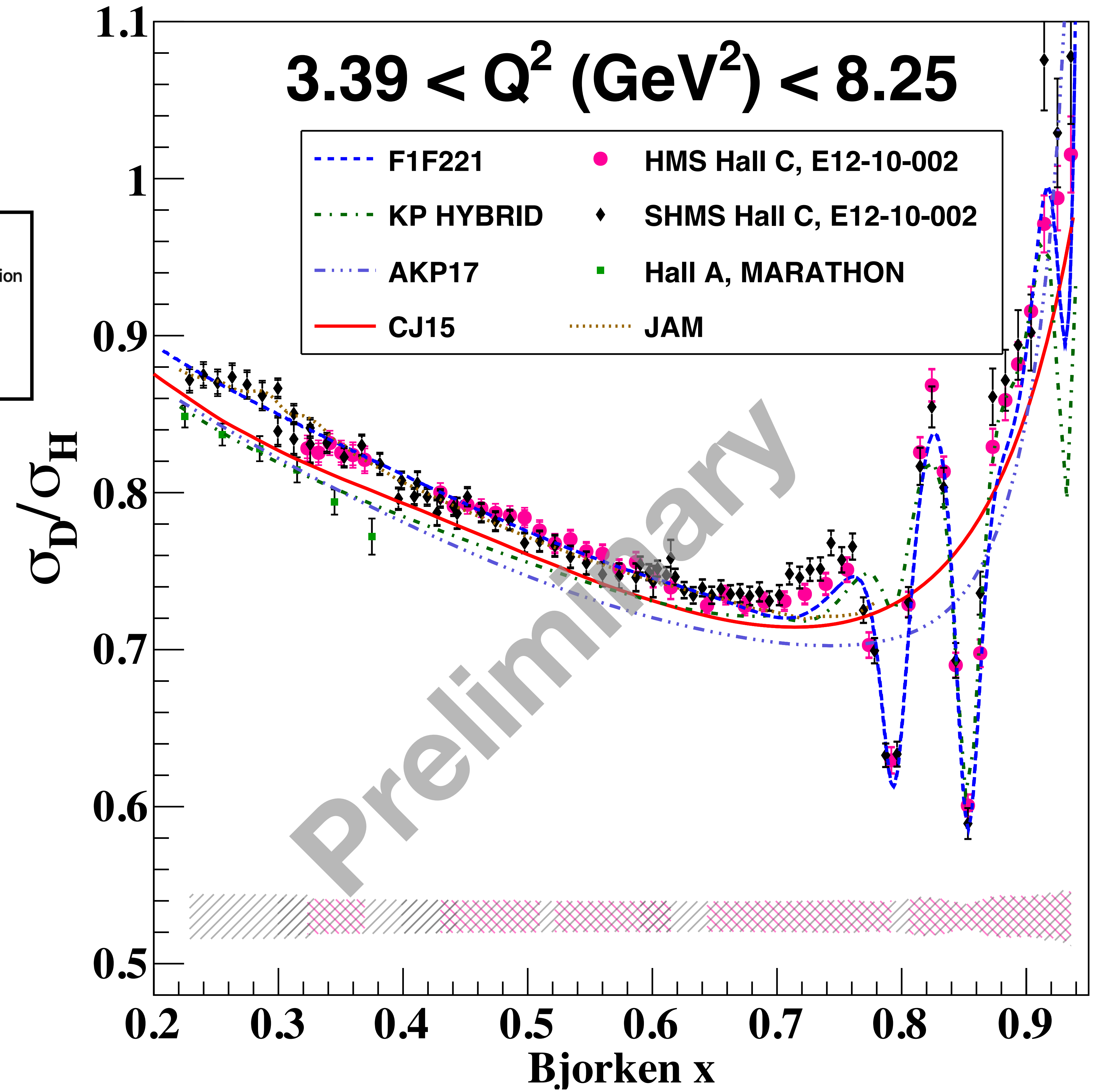
AKP17

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

S.I. Alekhin (Serpukhov, IHEP), S.A. Kulagin (Moscow, INR), R. Petti (South Carolina U.)

Apr 1, 2017

New Results!



F2 Results

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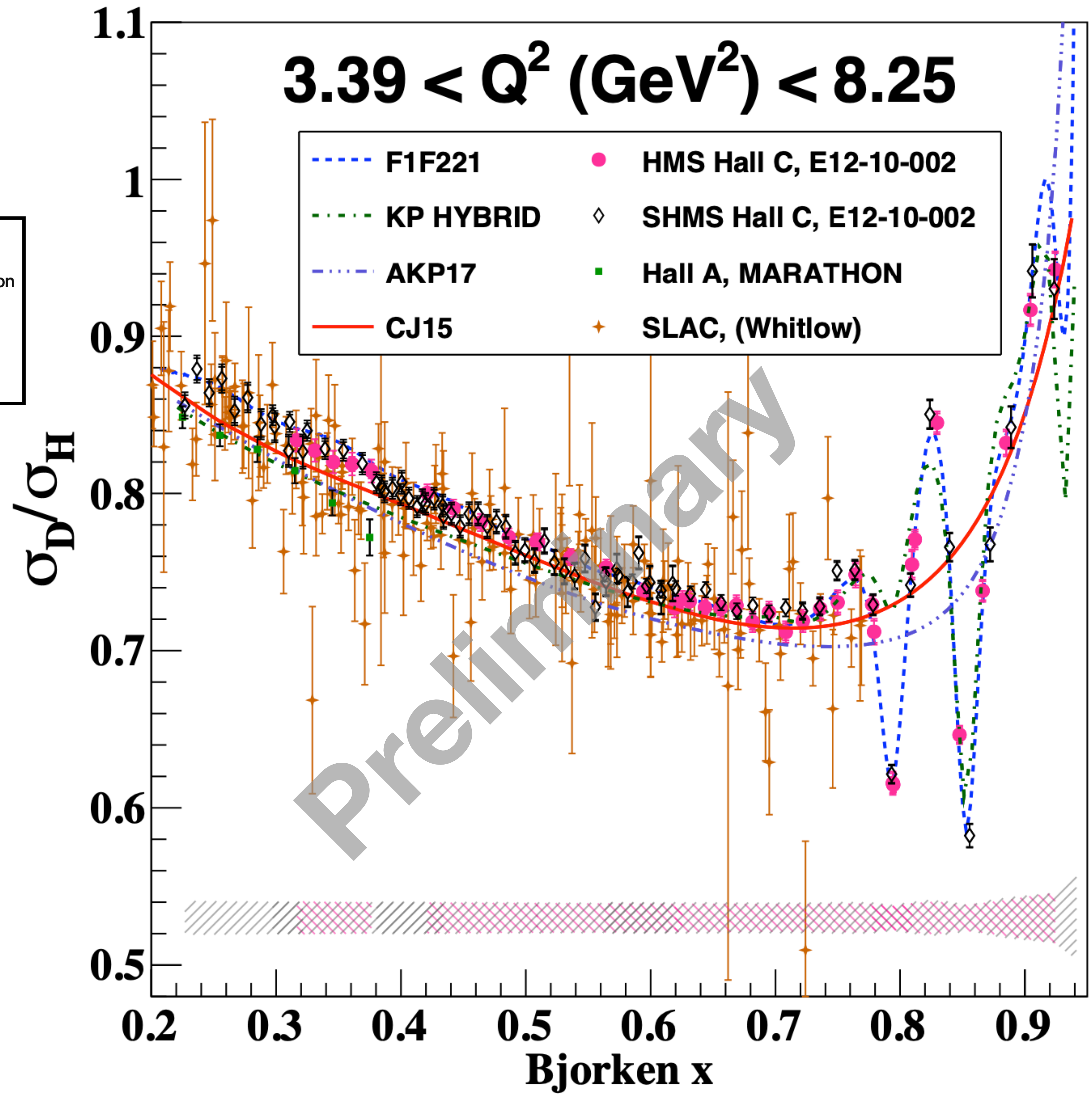
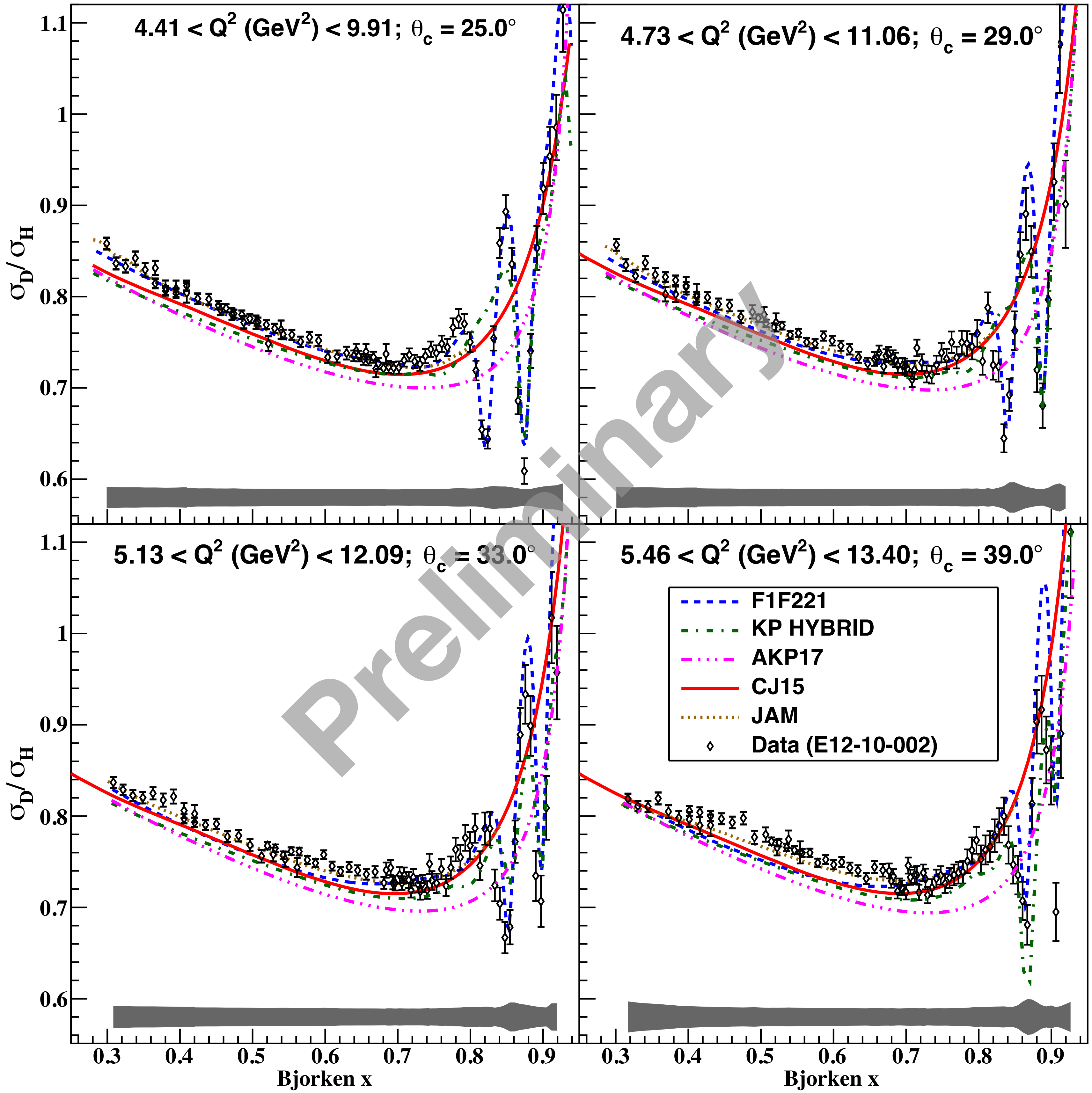


F2 Results

New Results!



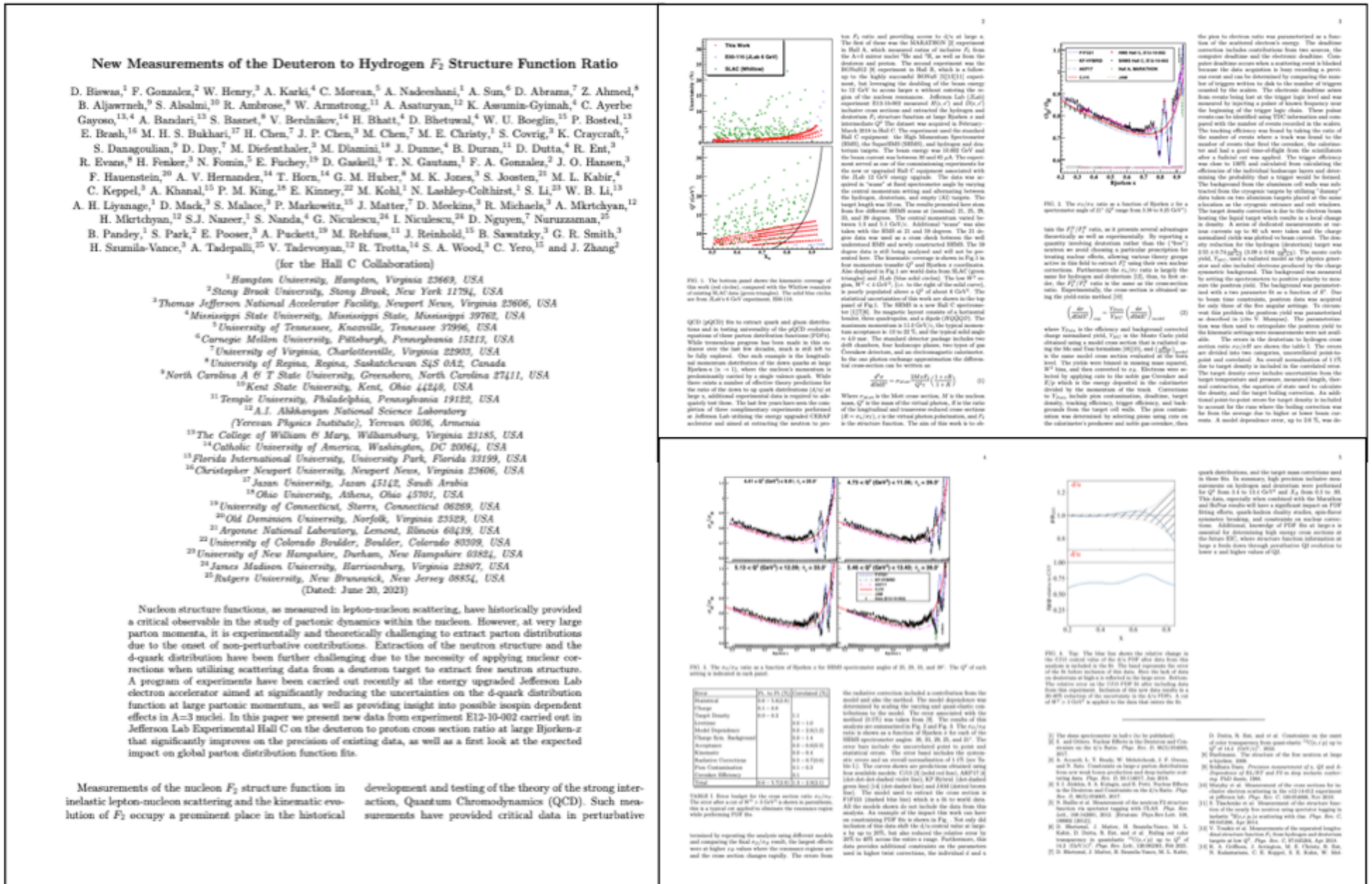
D/H Ratio Error Budget

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.

Publication Status

PRL paper to be submitted this summer



New Measurements of the Deuteron to Hydrogen F_2 Structure Function Ratio

(for the Hall C Collaboration)

(Dated: June 20, 2023)

Nucleon structure functions, as measured in lepton-nucleon scattering, have historically provided a critical observable in the study of partonic dynamics within the nucleon. However, at very large parton momenta, it is experimentally and theoretically challenging to extract parton distributions due to the onset of non-perturbative contributions. Extraction of the neutron structure and the d-quark distribution have been further challenging due to the necessity of applying nuclear corrections when utilizing scattering data from a deuteron target to extract free neutron structure. A program of experiments have been carried out recently at the energy upgraded Jefferson Lab electron accelerator aimed at significantly reducing the uncertainties on the d-quark distribution function at large partonic momentum, as well as providing insight into possible isospin dependent effects in A=3 nuclei. In this paper we present new data from experiment E12-10-002 carried out in Jefferson Lab Experimental Hall C on the deuteron to proton cross section ratio at large Bjorken-x that significantly improves on the precision of existing data, as well as a first look at the expected impact on global parton distribution function fits.

Measurements of the nucleon F_2 structure function in inelastic lepton-nucleon scattering and the kinematic evolution of F_2 occupy a prominent place in the historical development and testing of the theory of the strong interaction, Quantum Chromodynamics (QCD). Such measurements have provided critical data in perturbative

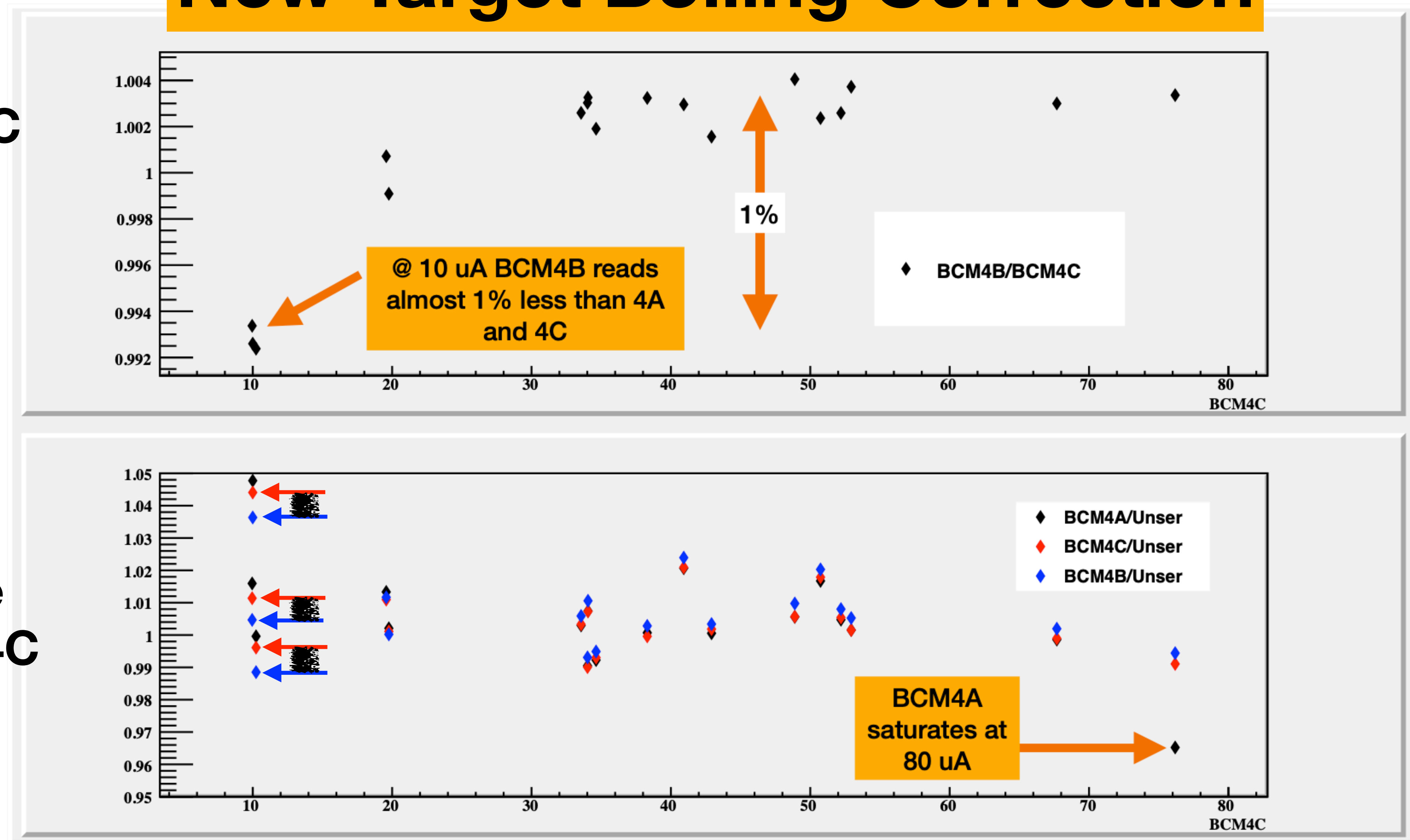
Recent Changes to Analysis

BCM= Beam Current Monitor

New Target Boiling Correction

BCM4B and BCM4C are in diagreement at the % level

Comparing with the Unser shows BCM4C is the most stable



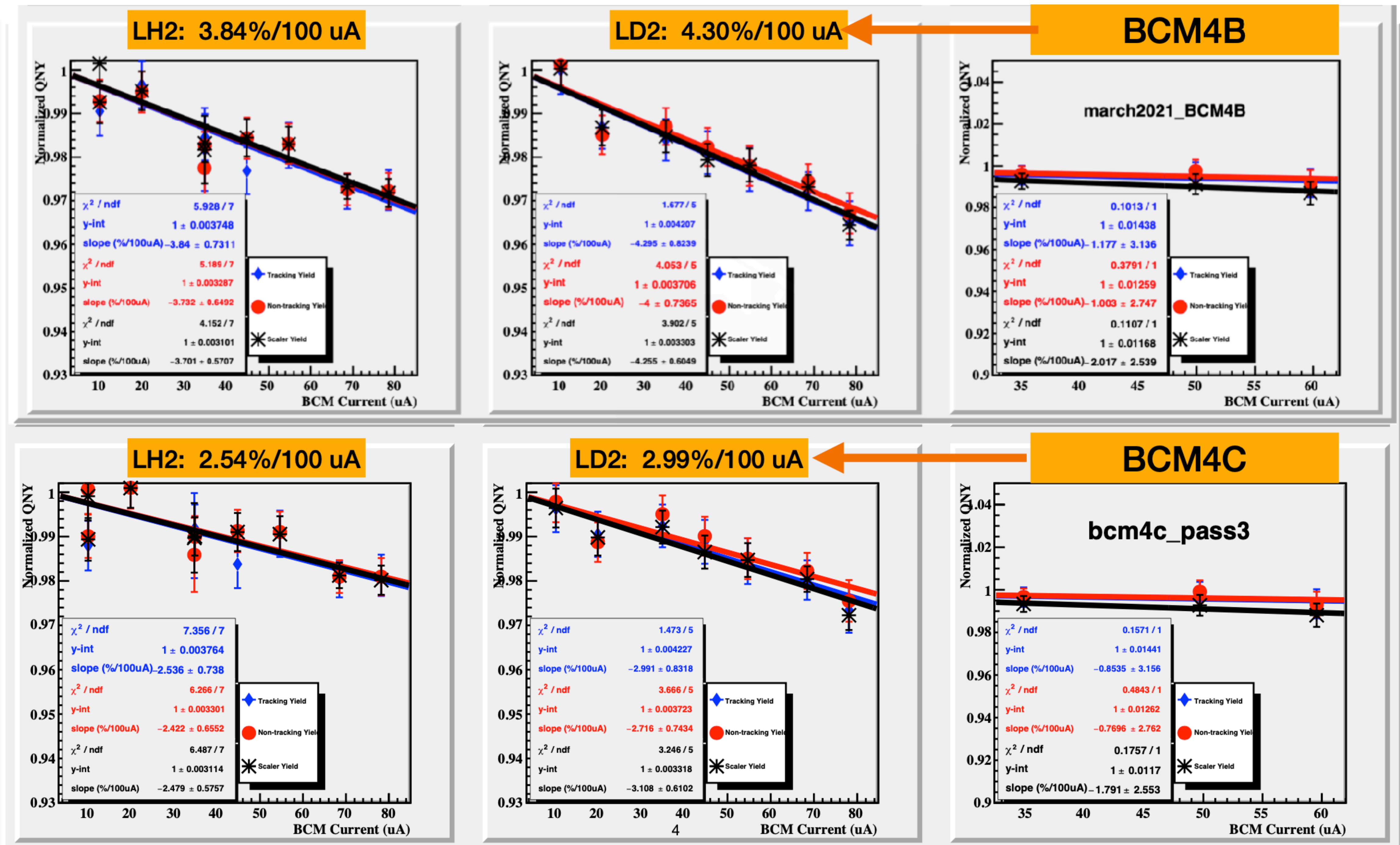
- Old boiling analysis used BCM4B
- BCM4B was not stable during luminocity scans
- BCM4A Saturated at the highest current settings
- BCM4C is the best BCM to use

Recent Changes to Analysis

New Target Boiling Correction

OLD

NEW



Recent Changes to Analysis

New Target Boiling Correction

Dave Mack's Scaler Analysis on Fall 2018 data.

Target	Measured El Real Slope (%/100muA)	El Real Slope with Window Correction (%/100muA)	Total Error
C	-0.10	n/a	+-0.2
LH2	-2.26	-2.50	+-0.30
LD2	-2.71	-2.84	+-0.32

Our analysis on Spring 2018 Data

New F2 Boiling Slopes

LH2: 2.55 +/- 0.74

LD2: 3.09 +/- 0.84

Good agreement when comparing Fall and Spring Boiling Slopes

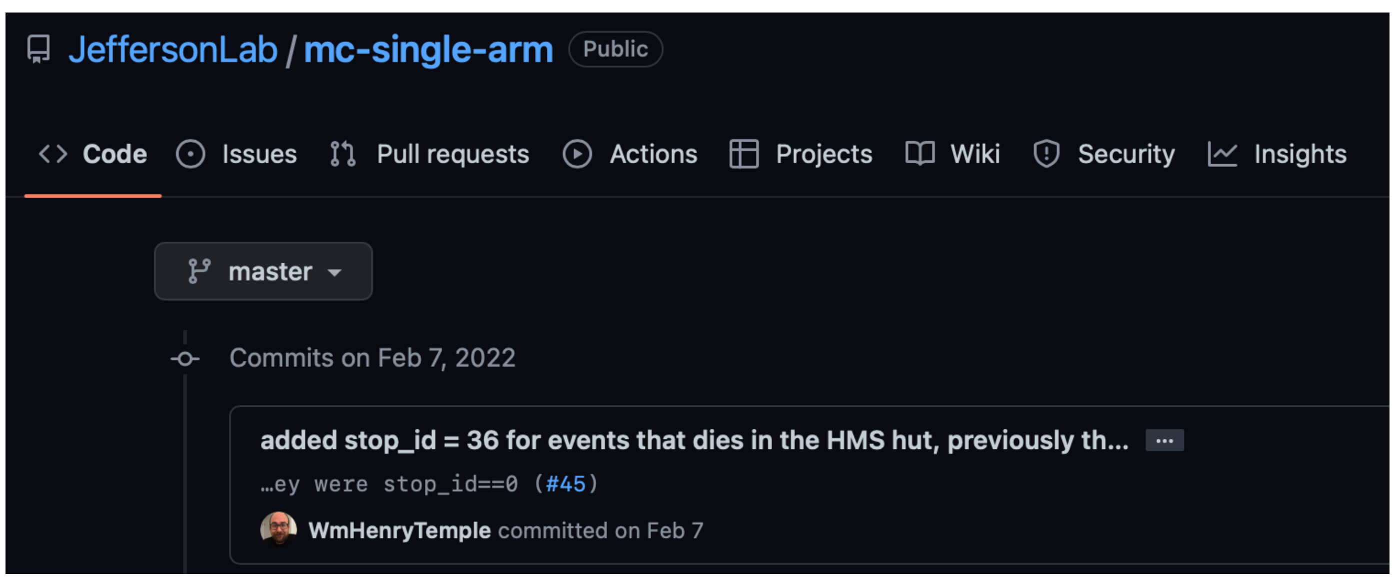
***The LH2 fan speed was different between Fall and Spring Runs so we can't compare those results**

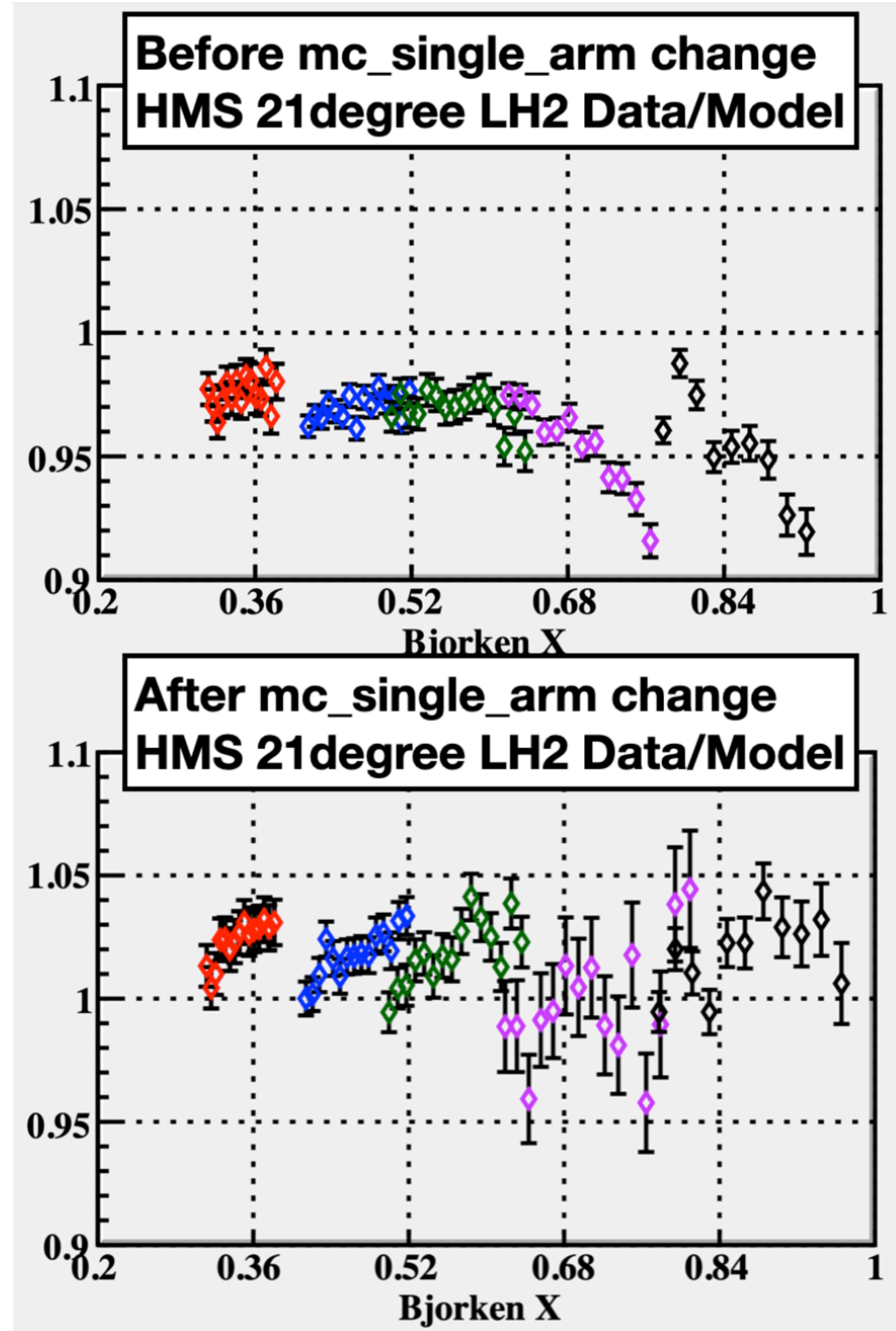
***Slightly different slopes than shown in previous slide because the PID cuts were changed to match the the cuts used in the main analysis**

Recent Changes to Analysis

Monte Carlo Update

- A bug was found in mc-single-arm. Events that would make it into the detector hut but miss the detector stack were being included as successful events
- It was corrected and pushed to the JeffersonLab github in February of 2022
- After the fix, raw cross sections change by ~ 5%?
- Little impact of D/H ratio

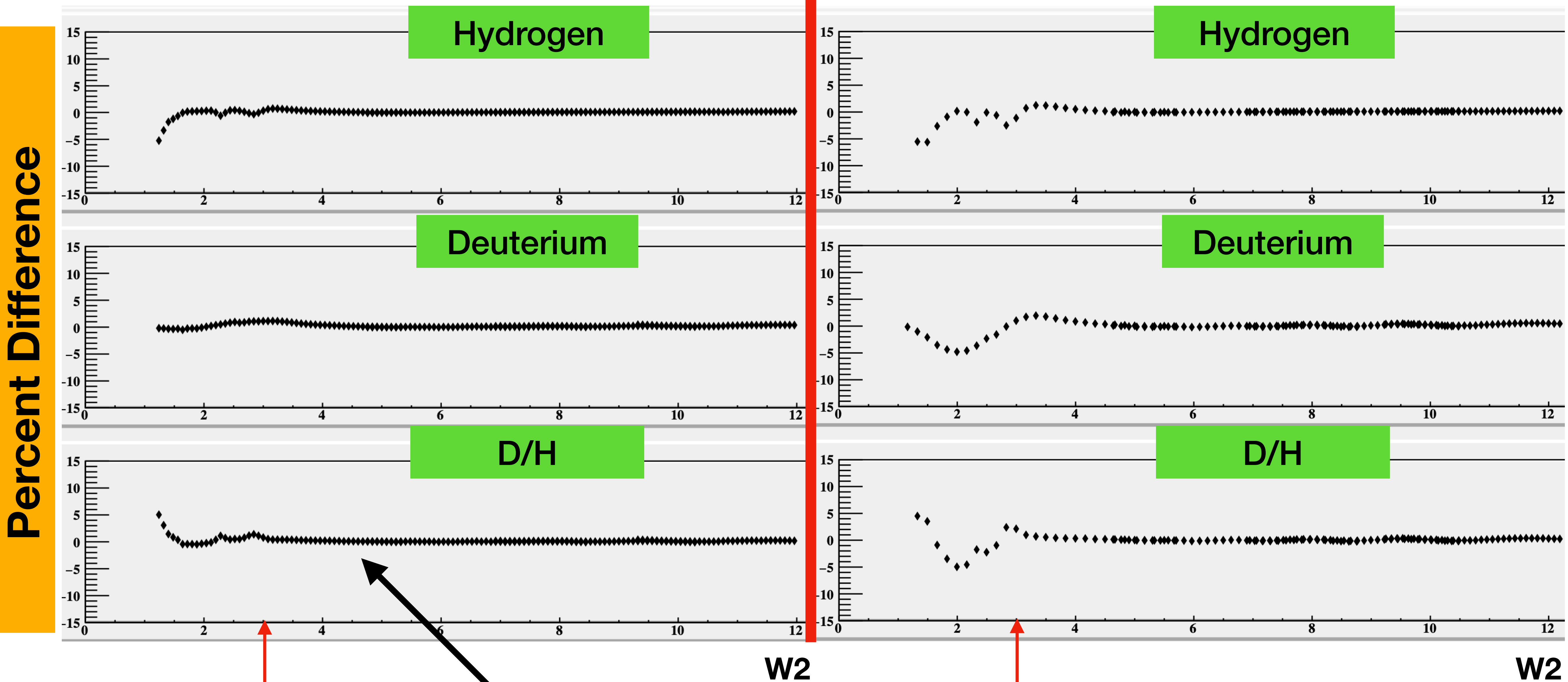




Recent Changes to Analysis

Change in extracted cross section when using different input models

W2 Binning | **Delta Binning**



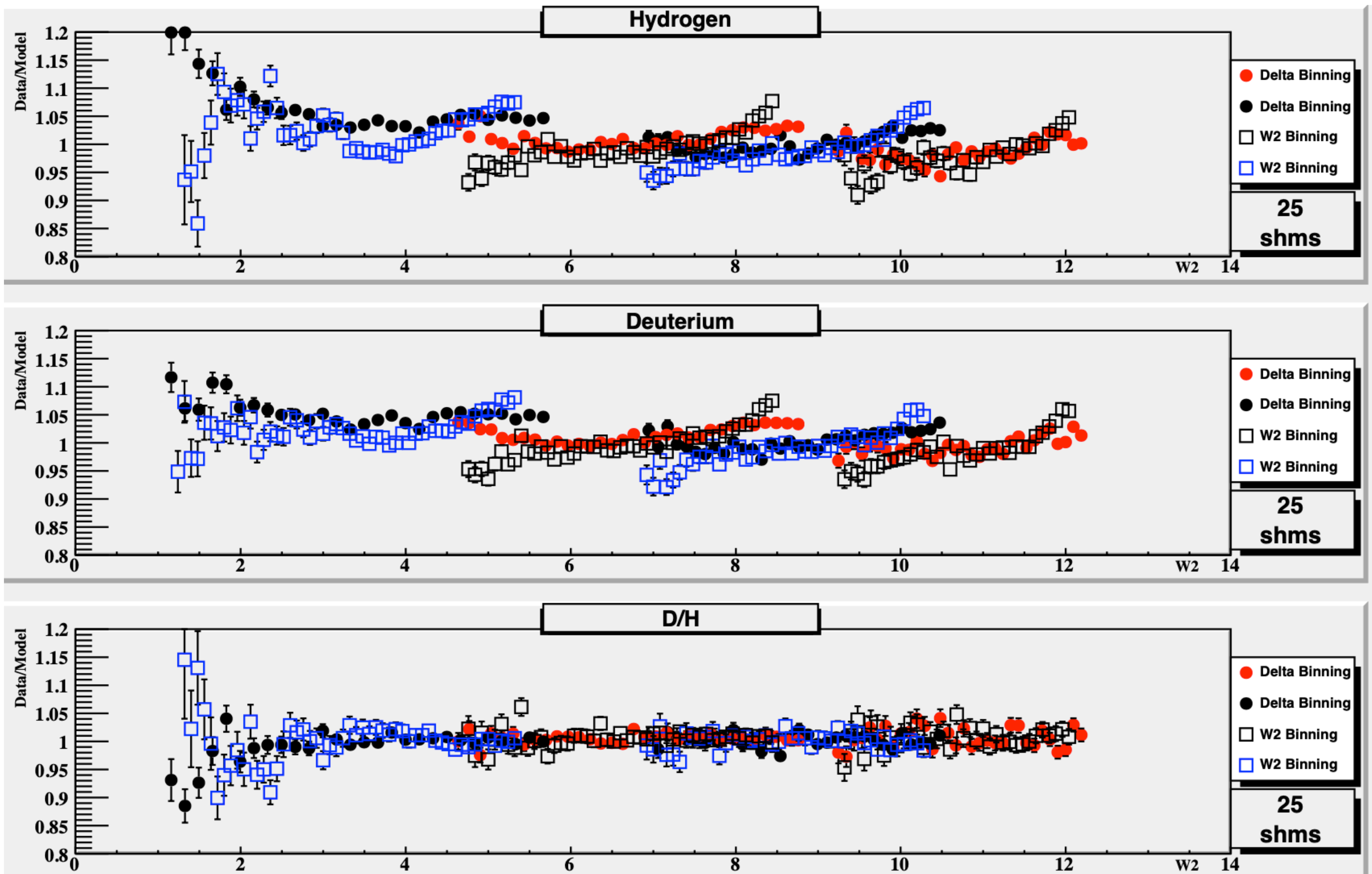
- **Apply as additional systematic error**

- **W2 Binning is less sensitive to model dependence, especially in the resonance region!**

Recent Changes to Analysis

Cross section extraction: W2 vs Delta binning

Cross Section / Model



- Overlap region in cross section is worst with W2 binning but vanishes in D/H ratio
- Needs to be addressed for absolute cross sections

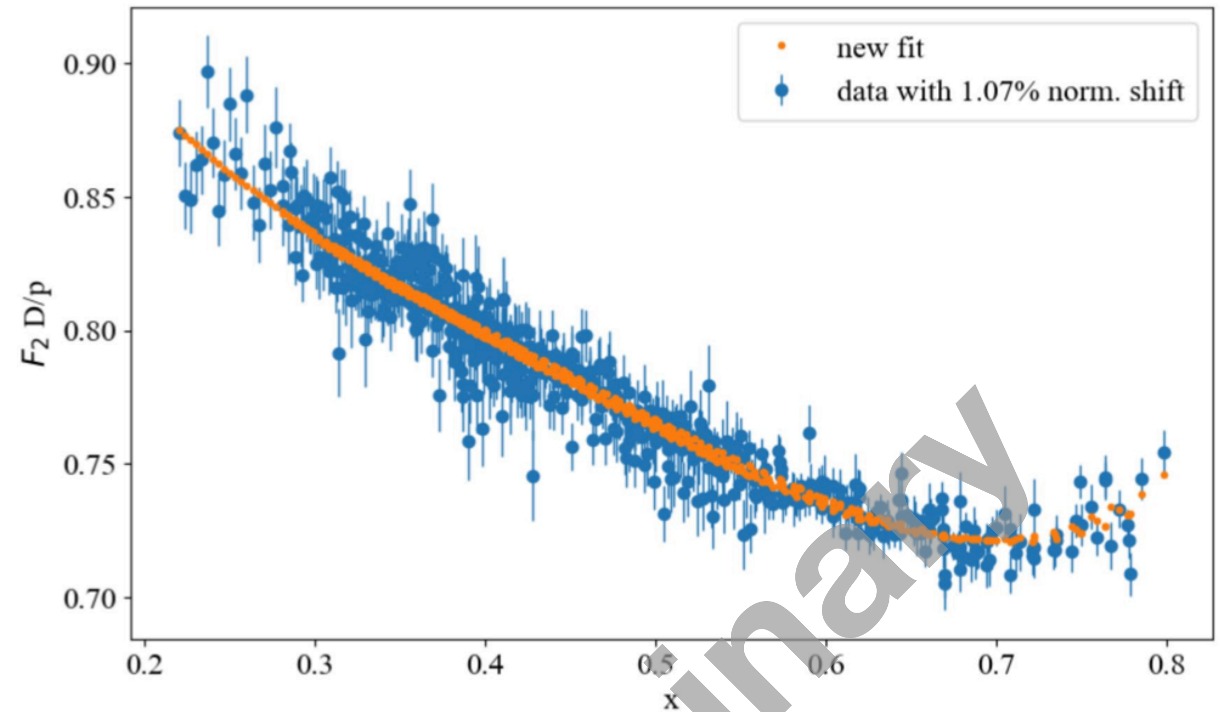
F2 Results

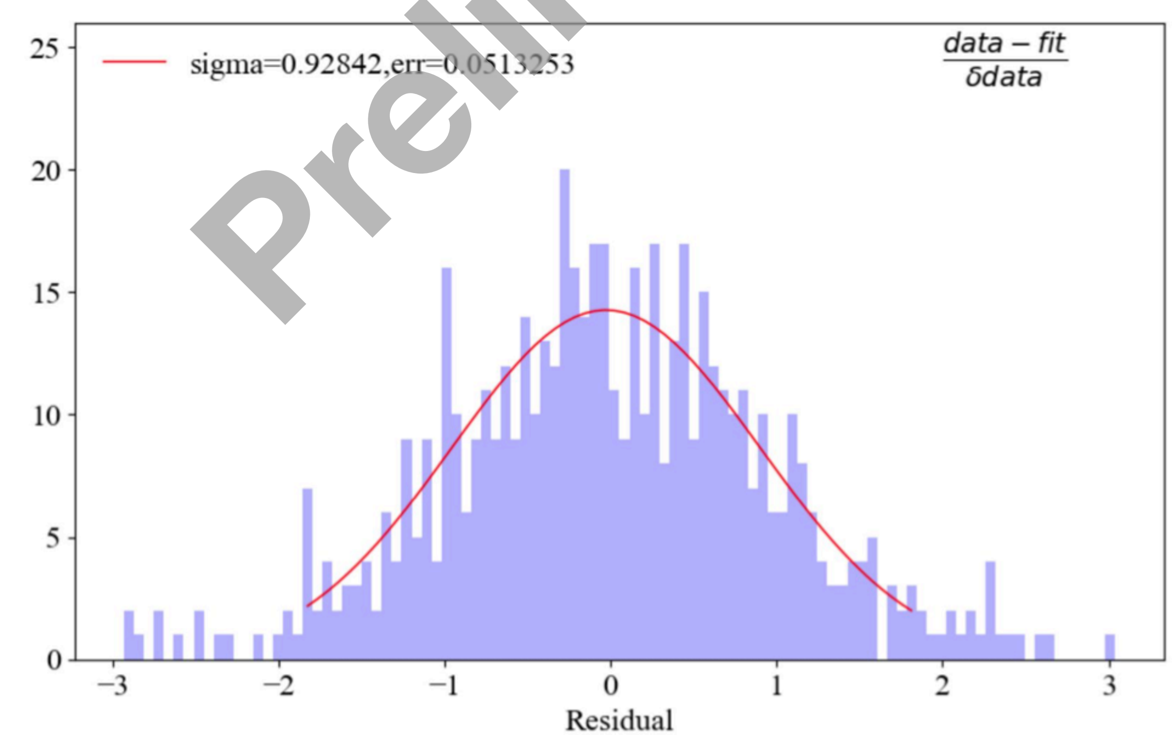
CJ Impact Study

1. Data set from Bill: Normalization=1.1%, correlated/uncorrelated ptp errors are provided.
2. Perform a new fit with this new dataset together with the CJ15 original datasets. The fit will shift data points within given normalization and correlated errors.
3. Compare the modified data with calculation from new fit. The residual = (data - fit) / data_err should be a gaussian with width close to 1

Courtesy of Alberto Accardi and Shujie Li

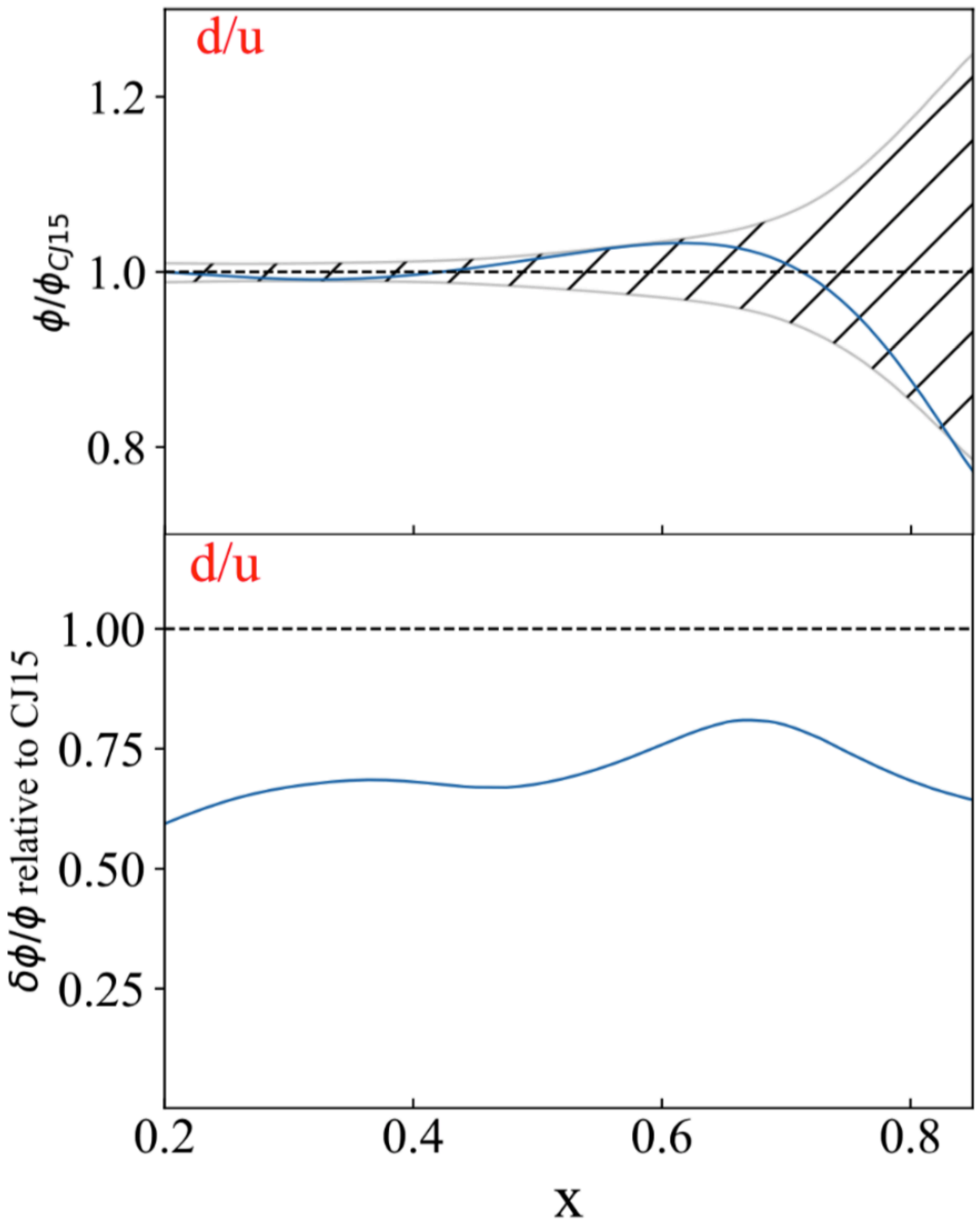
(Analysis needs to be revisted with new data)





Preliminary

F2 Results



CJ15 Impact Study

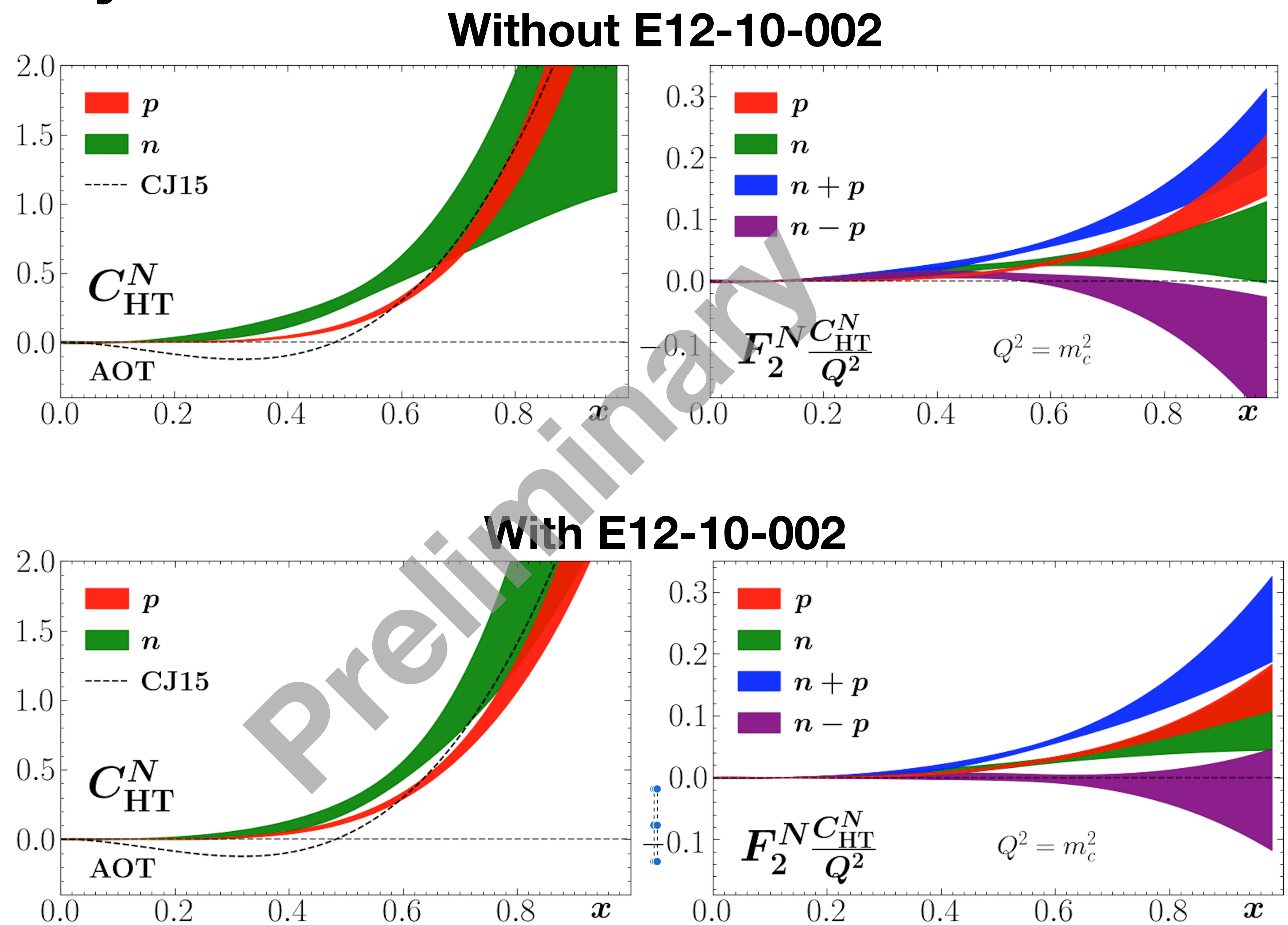
FIG. 4. Top: The blue line shows the relative change in the CJ15 central value of the d/u PDF after data from this analysis is included in the fit. The band represents the error of the fit before inclusion of this data. Here the lack of data on deuterium at high-x is reflected in the large error. Bottom: The relative error on the CJ15 PDF fit after including data from this experiment. 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.

F2 Results

Slide from Winter

JAM Impact Study

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



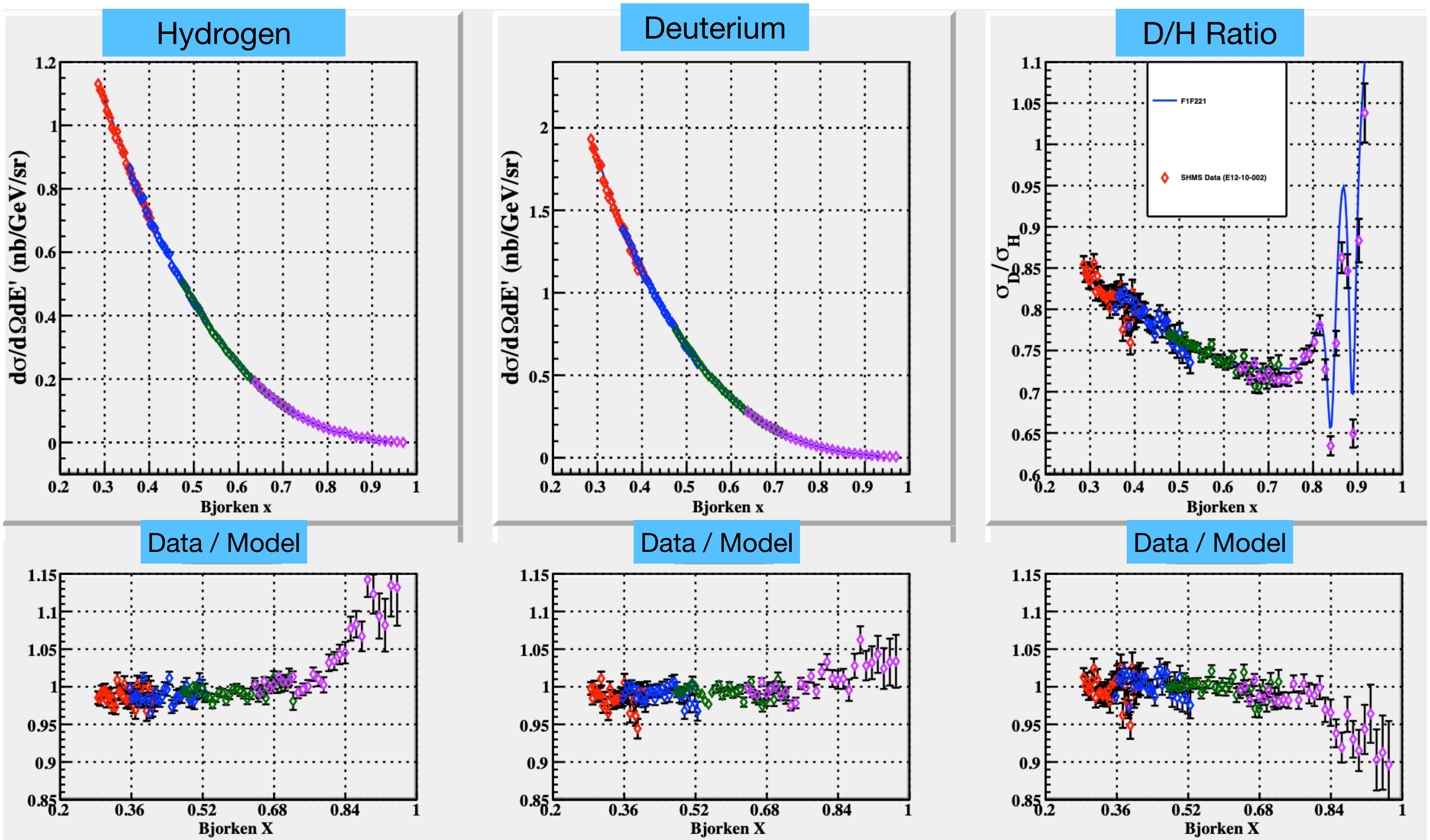
- D/H ratio was provided to Jefferson Lab Angular Momentum Collaboration (JAM) to incorporate into their global QCD analysis of PDFs
- New F2 data significantly improves the uncertainty of higher twist corrections to F2

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

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

Absolute Cross Sections Tasks

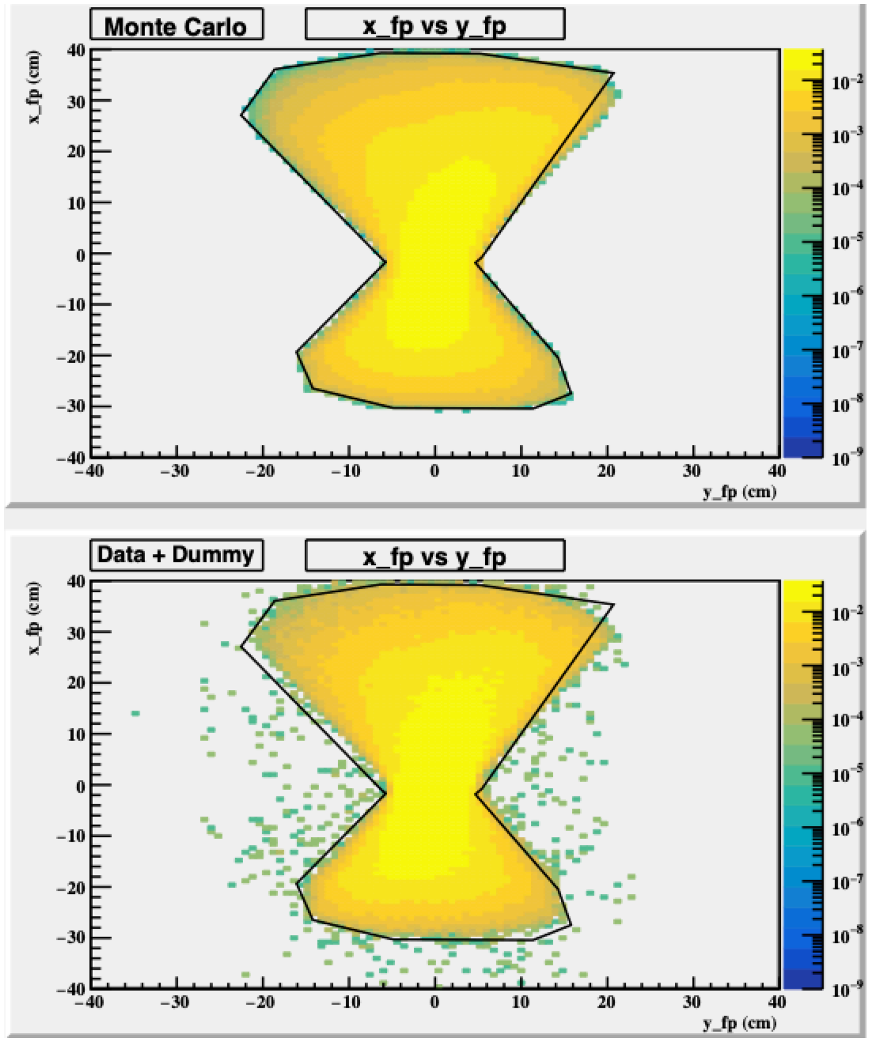
SHMS @ 29 degrees

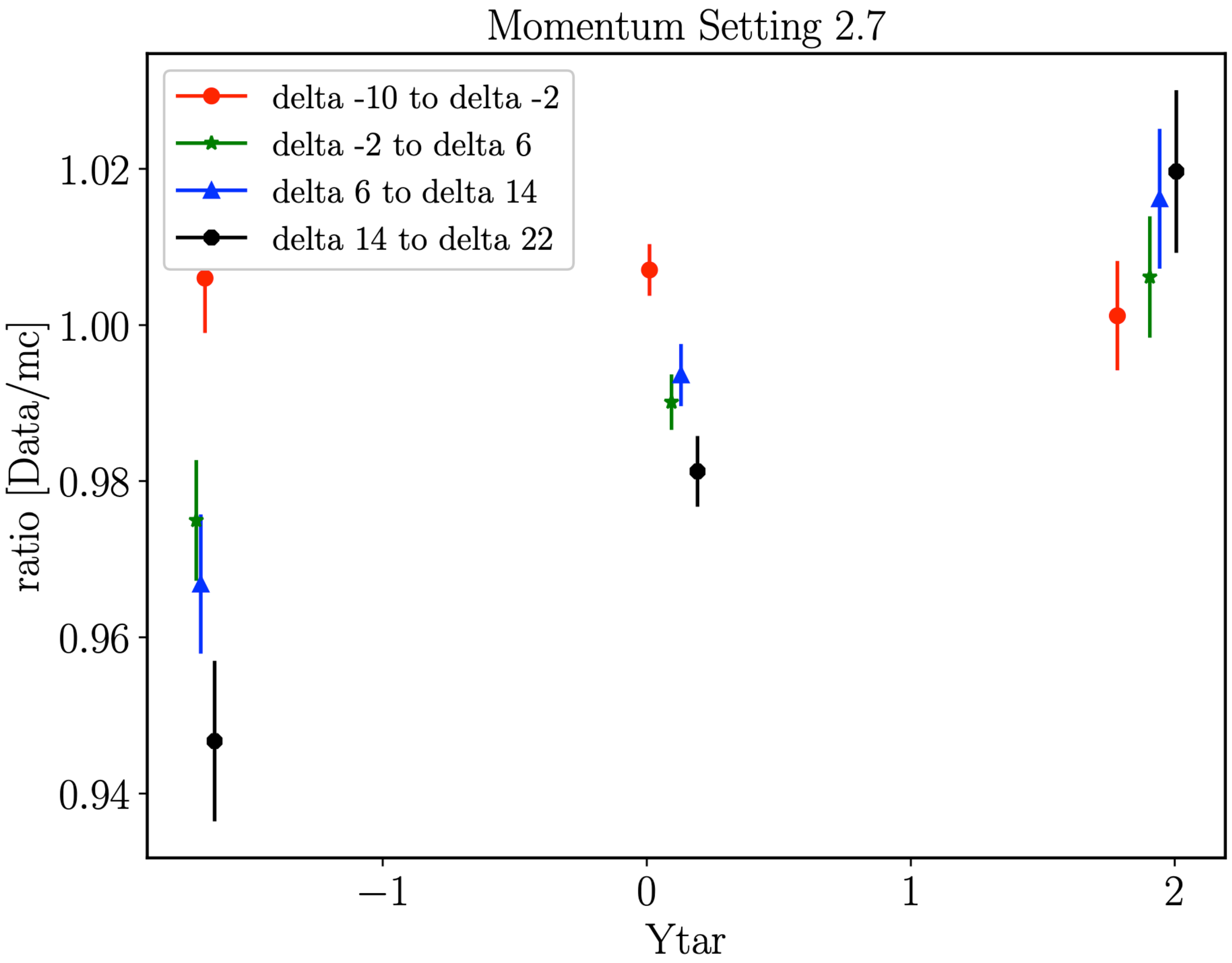


Future Work

Absolute Cross Sections Tasks

- **Revisit Calorimeter Efficiency**
- **Understand Y_target acceptance dependence**
- **Monte Carlo studies (Matrices, aperature check, ….)**

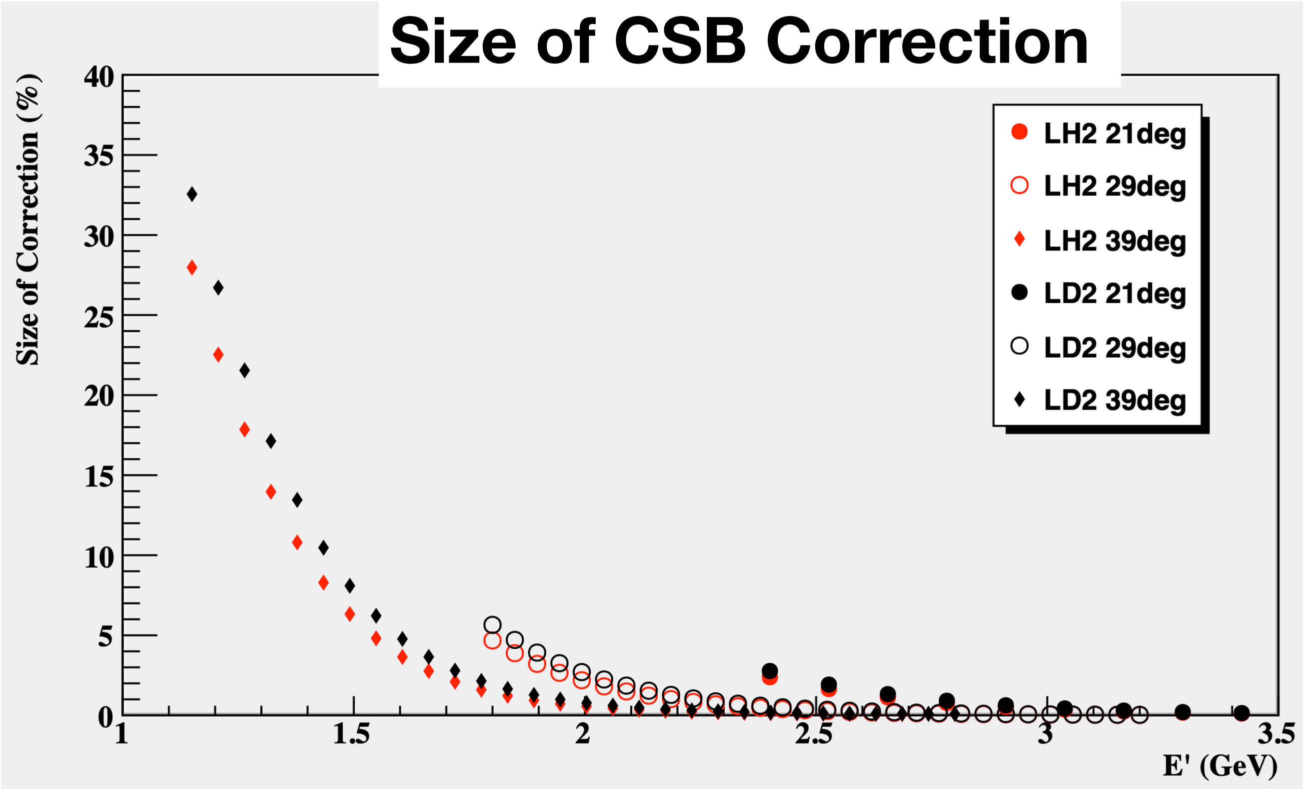


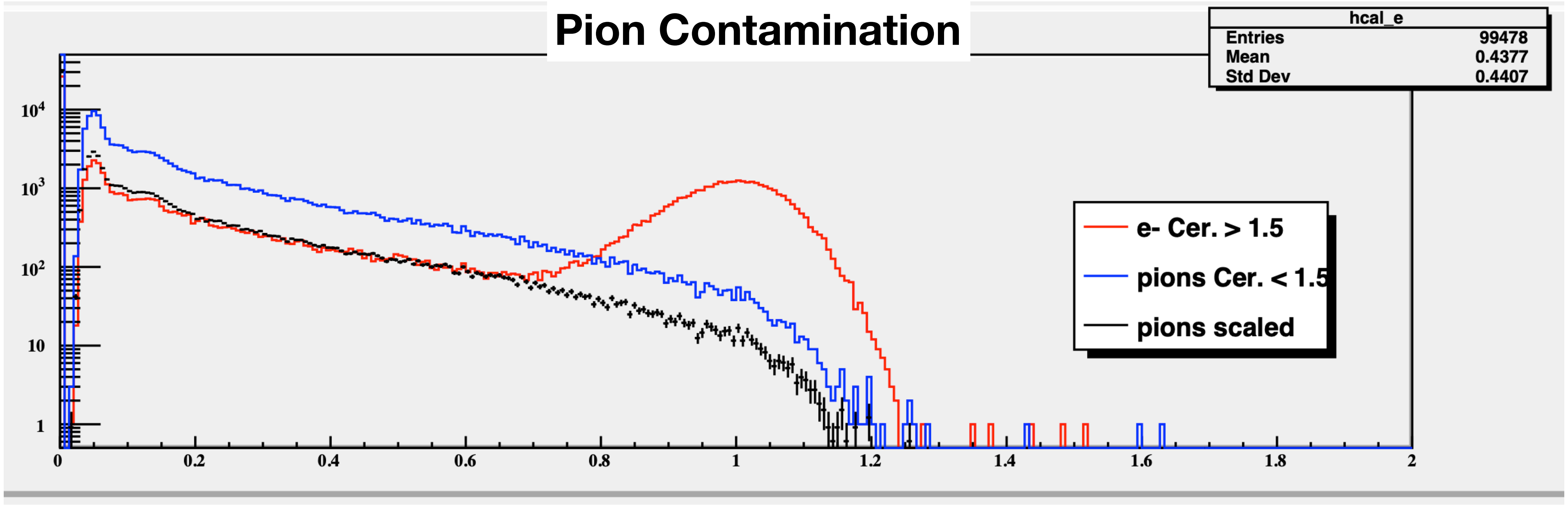


Future Work

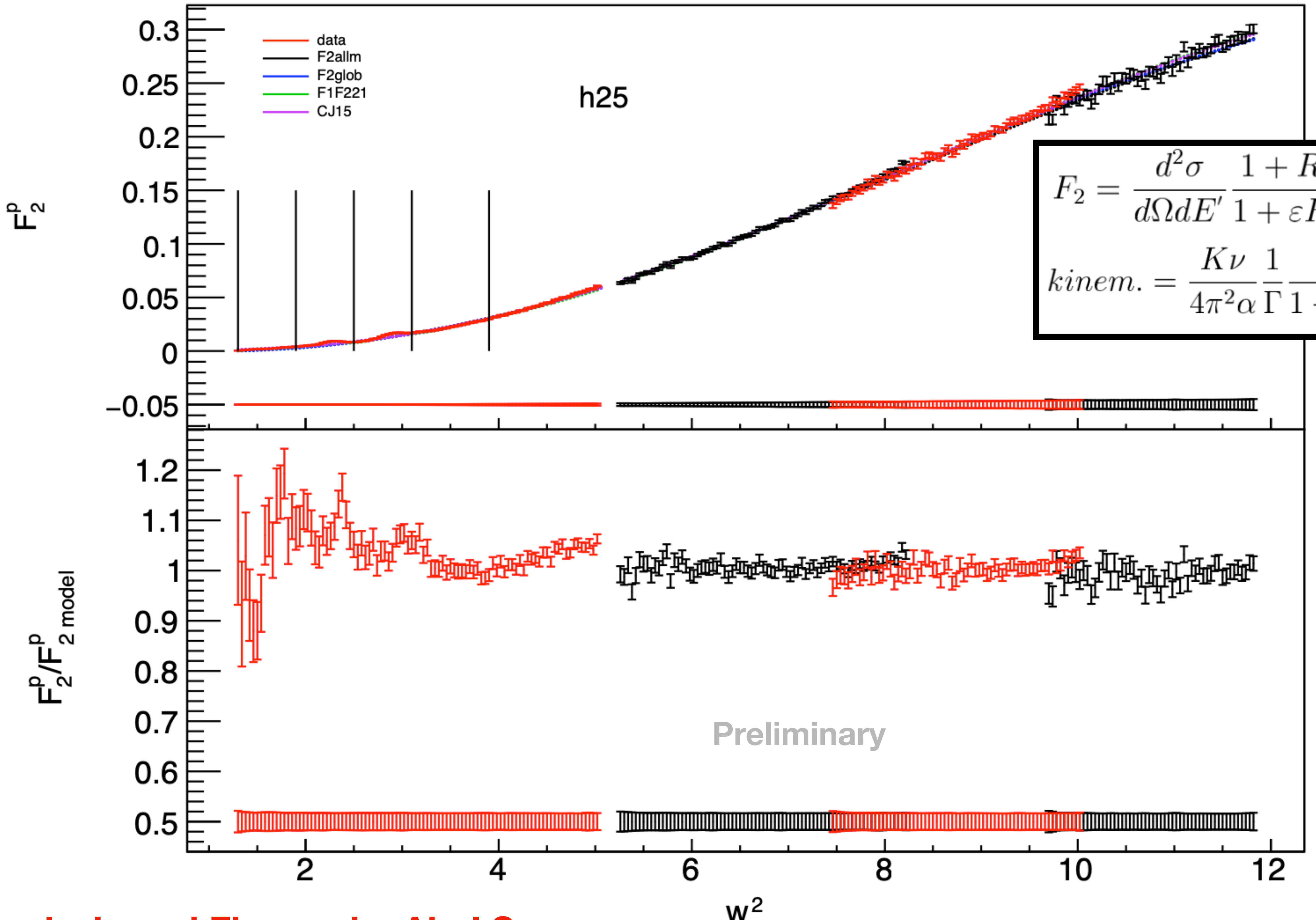
HMS Highest Q2 setting

- 59 Degree data taken with HMS still needs to be analyzed
- Work is ongoing to finalize Charge Symmetric Background and pion contamintion





Quark Hadron Duality Studies

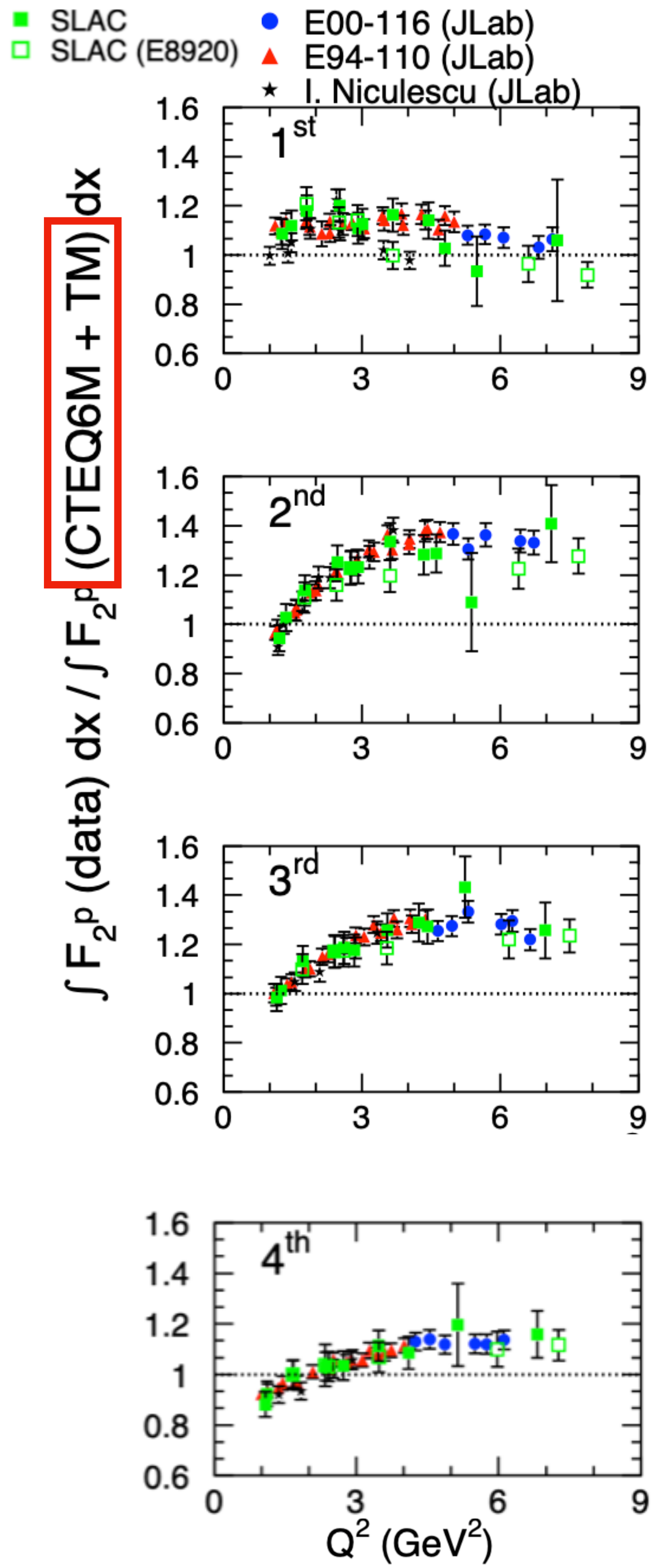


$$F_2 = \frac{d^2\sigma}{d\Omega dE'} \frac{1+R}{1+\varepsilon R} \times kinem$$

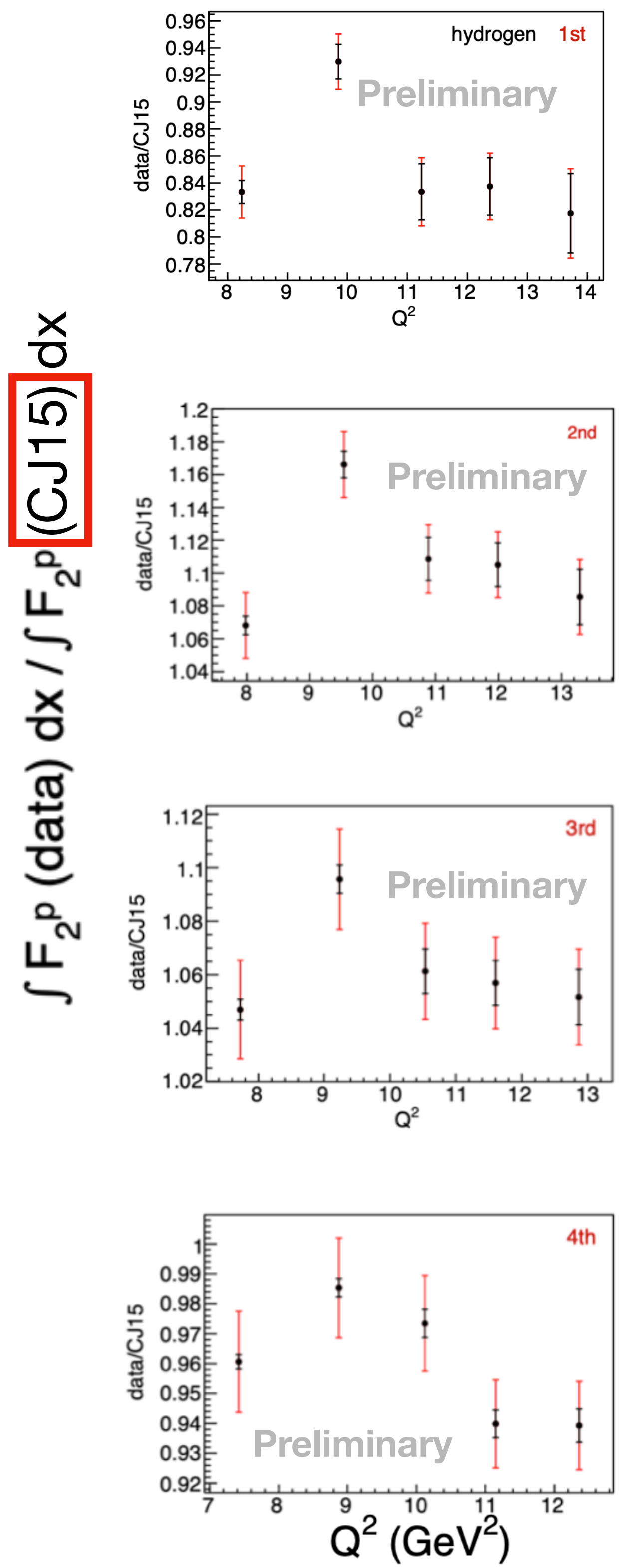
$$kinem. = \frac{K\nu}{4\pi^2\alpha} \frac{1}{\Gamma} \frac{1}{1+\nu^2/Q^2}.$$

Analysis and Figures by Abel Sun

Quark Hadron Duality Studies



E12-10-002 Proposal



E12-10-002 Data

- Define duality intervals

Region	1st	2nd	3rd	4th	DIS	global
W_{min}	1.3	1.9	2.5	3.1	3.9	1.9
W_{max}	1.9	2.5	3.1	3.9	4.5	4.5

→ There is arbitrariness in defining the local W intervals; typically try to catch peaks and valleys within one interval

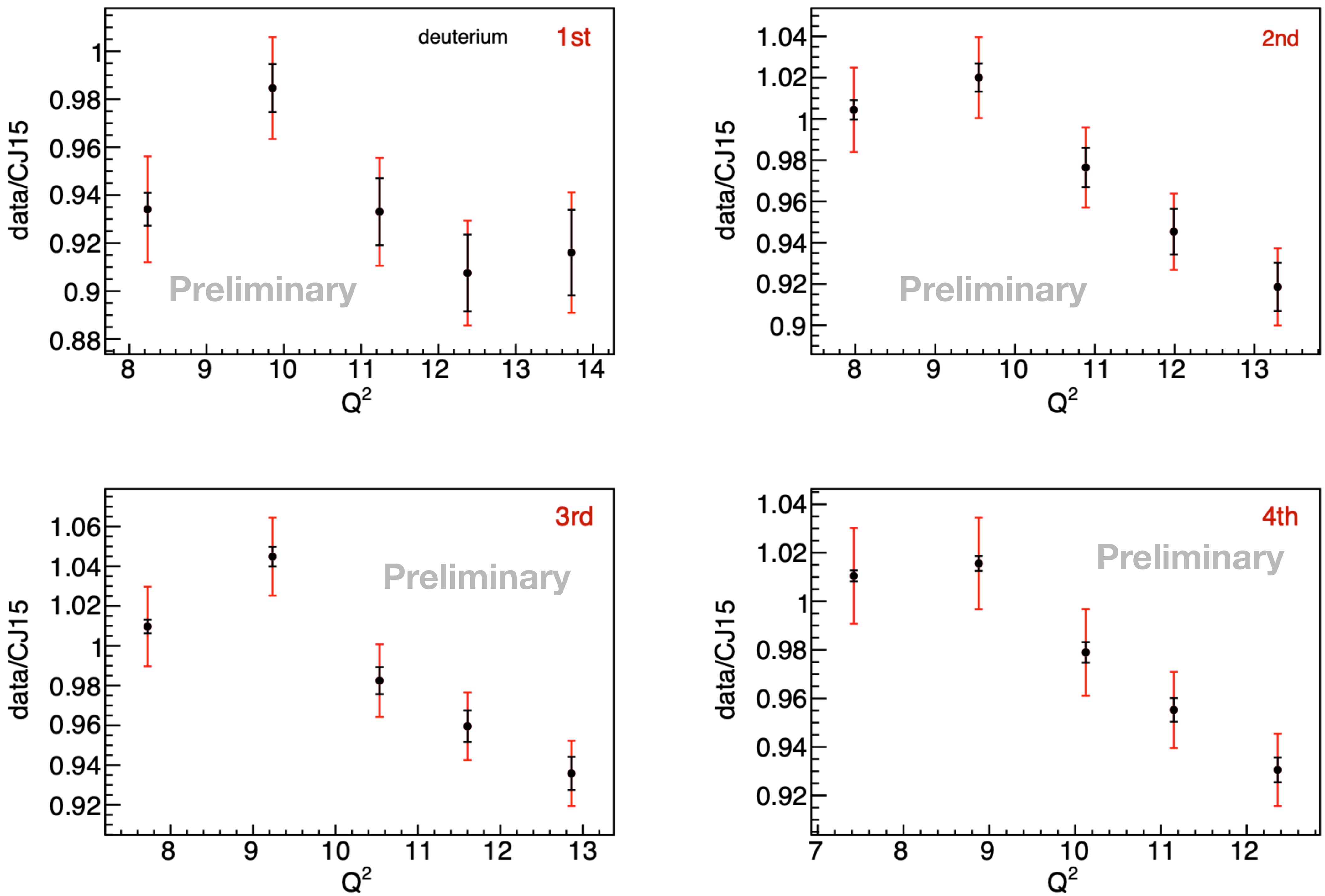
- Calculate ratio:

$$\int_{x_{min}}^{x_{max}} F^{data}(x,Q^2)\,dx \Big/ \int_{x_{min}}^{x_{max}} F^{param.}(x,Q^2)dx$$

- Very prelimary since analysis on absolute cross sections not nearly complete
- This data can push duality integrals to higher Q^2

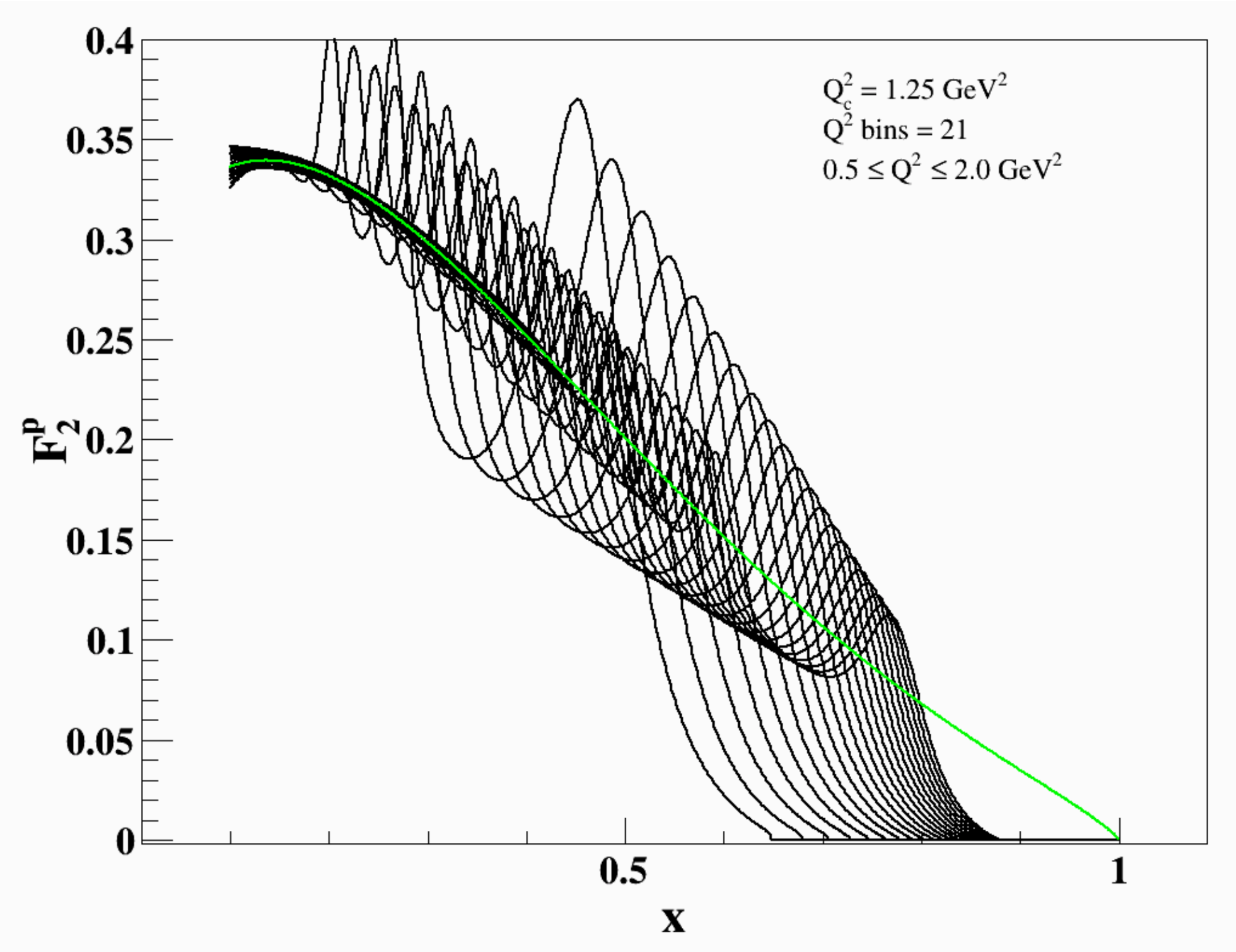
Analysis and Figures by Abel Sun

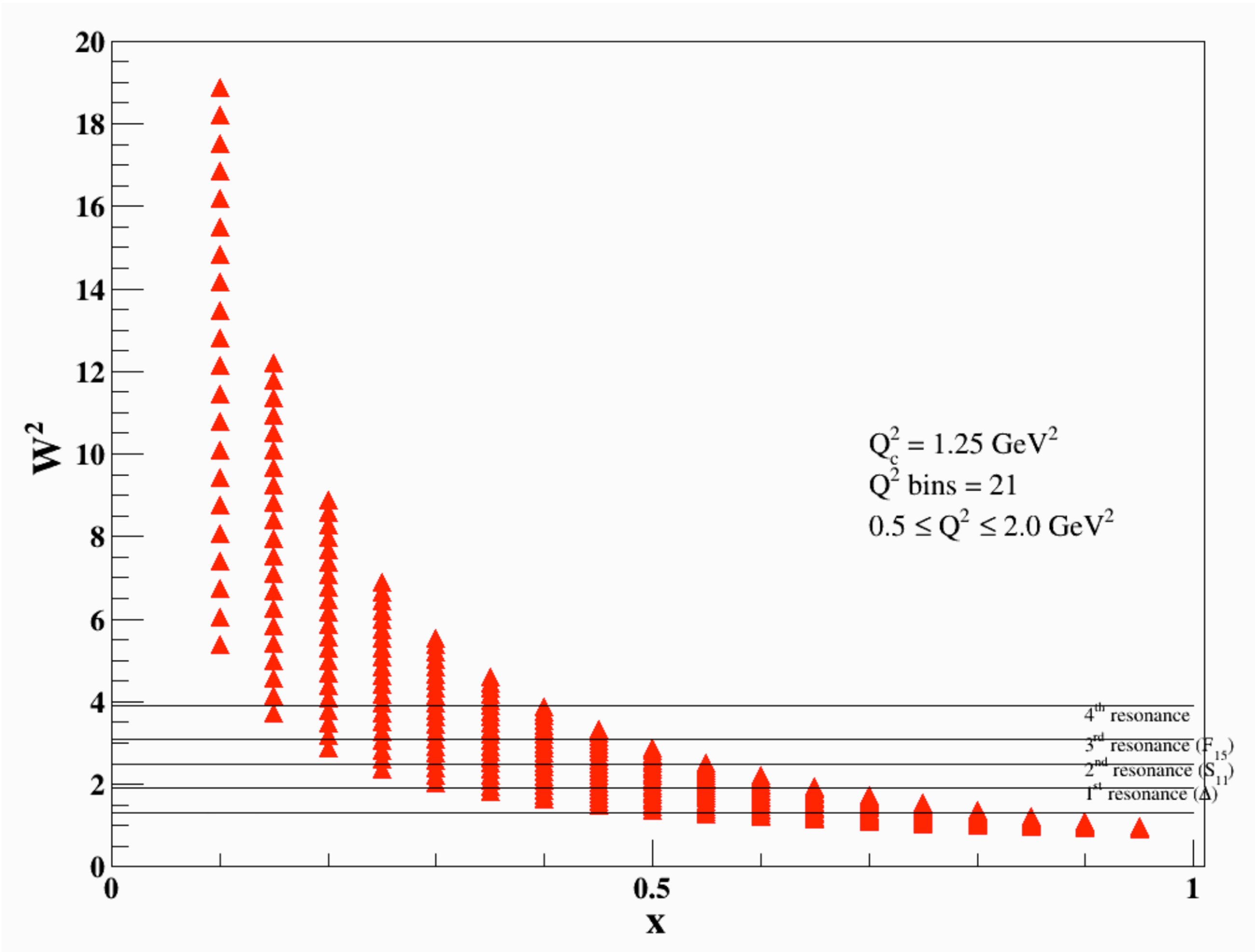
Quark Hadron Duality Studies



Analysis and Figures by Abel Sun

Quark Hadron Duality Studies





- Duality studies at fixed x over a range of Q^2
- Peaks and valleys in resonance region shift along x as Q^2 changes
- Allows us to average x bins as an alternative method to study duality
- Analysis includes world data + E12-10-002

Analysis and Figures by Debaditya Biswas

Summary and Acknowledgments

To Do List

- D/H ratios complete and impact studies are being finalized. Paper being drafted (PRL)
- High Q2 setting in the HMS (59°) needs to be analyzed
- Absolute Cross Section Tasks
    - Revisit Calorimeter Efficiency
    - Revisit forward and reconstruction matrices
    - F2d and F2n extraction
    - MC Ratio method vs Acceptance Method
- Quark-Hadron duality Averaging
- Compute non single moments
- Improve resonance/DIS modeling

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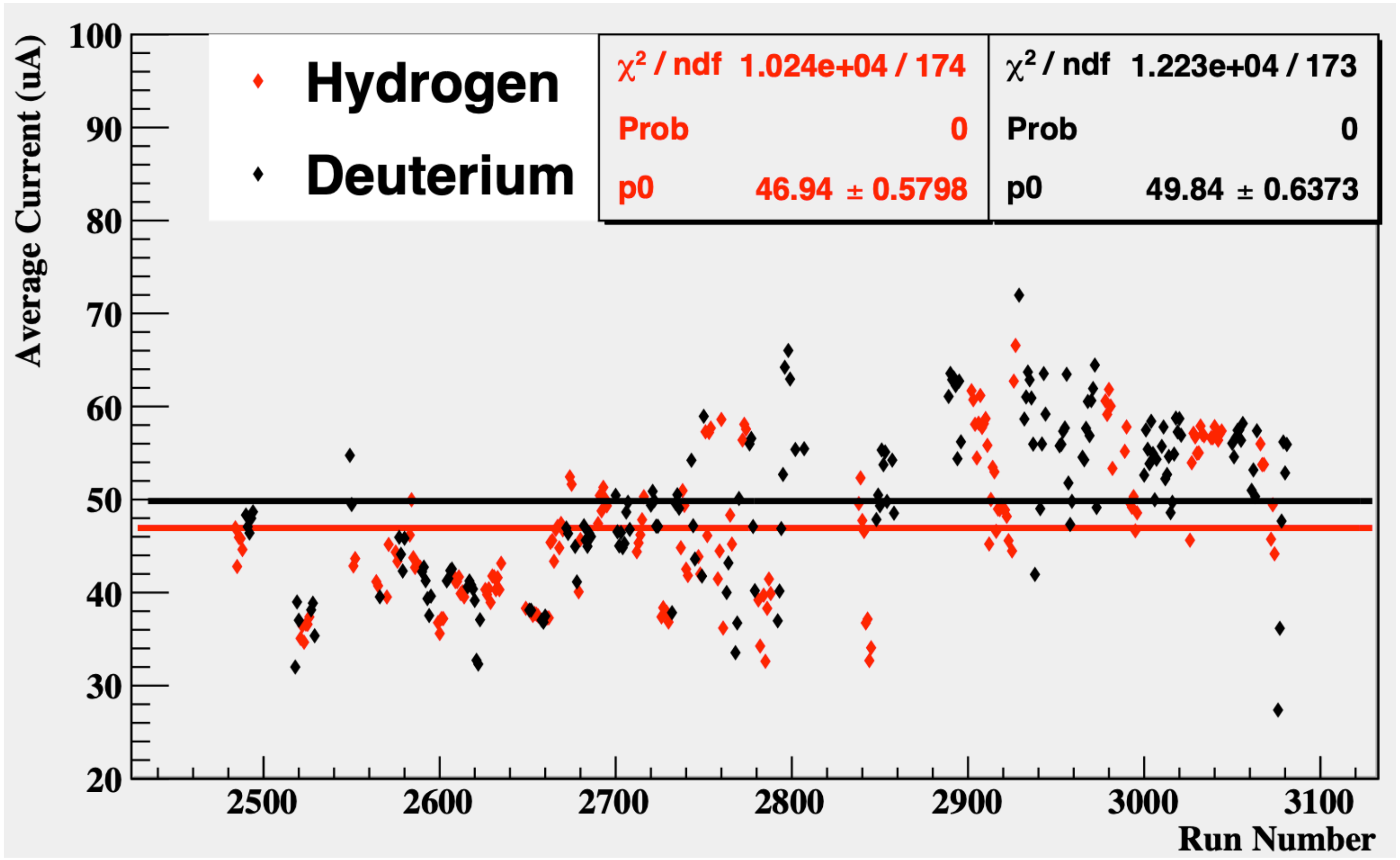
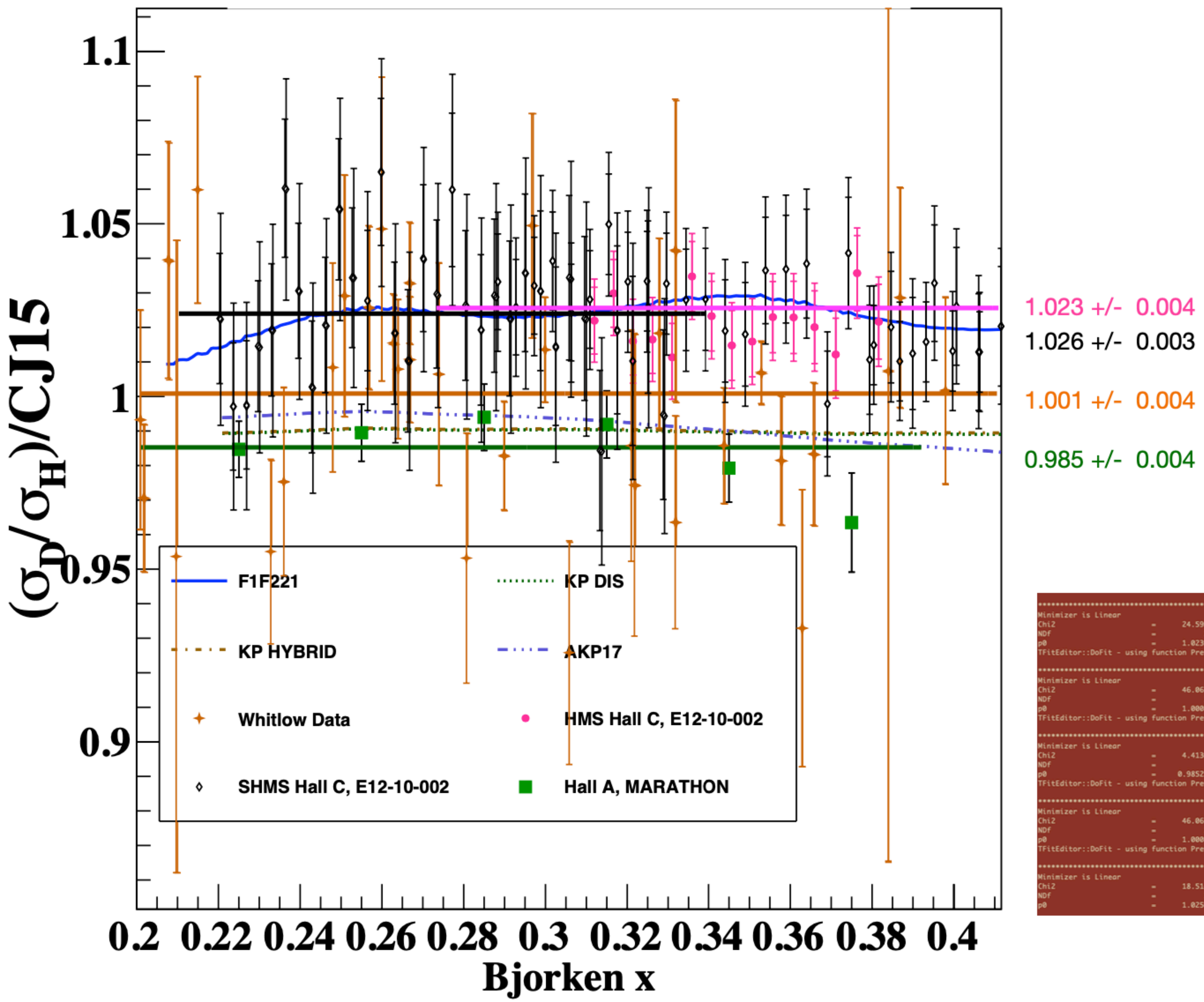
Back-Ups

Target Density Uncertainty

Error	Value	Uncertainty	$\frac{\delta\rho t}{\rho t}$
Temperature	19 K	$\pm 182 mK$	0.27%
Pressure	25 psia	$\pm 2 psia$	0.02%
Equation of State			0.1%
Length Measurement Precision	100 mm	$\pm 0.26 mm$	0.26%
Length (Inner or Outer?)	100 mm	$\pm 0.26 mm$	0.26%
Target Contraction	99.6%	±0.1%	0.1%
Beam Position	0	$\pm 3 mm$	0.2%
Avg Boiling Correction LH2(LD2)			0.30% (0.36%)
Total LH2 (LD2)			0.60% (0.63%)

- The overall normalization uncertainty used is slightly larger than the table; 0.75% in cross sections and 1.1% in D/H ratio.
- Global error reflects our lack of knowledge to the target boiling, temperature, density, length and beam position.
- An additional point to point uncertainty is calculated by taking the difference with the average current






```
****************************************
Minimizer is Linear
Chi2                      =     24.5957
NDf                       =          31
p0                        =     1.02398   +/-   0.00374891
TFitEditor::DoFit - using function PrevFitTMP  0x21276b10

****************************************
Minimizer is Linear
Chi2                      =     46.0678
NDf                       =          34
p0                        =     1.00084   +/-   0.00388634
TFitEditor::DoFit - using function PrevFitTMP  0x21276b10

****************************************
Minimizer is Linear
Chi2                      =     4.41306
NDf                       =           6
p0                        =    0.985256   +/-   0.00353582
TFitEditor::DoFit - using function PrevFitTMP  0x21276b10

****************************************
Minimizer is Linear
Chi2                      =     46.0678
NDf                       =          34
p0                        =     1.00084   +/-   0.00388634
TFitEditor::DoFit - using function PrevFitTMP  0x21276b10

****************************************
Minimizer is Linear
Chi2                      =     18.5141
NDf                       =          31
p0                        =     1.02561   +/-   0.00275052
```

Isovector EMC effect from global QCD analysis with MARATHON data

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TABLE I. Summary of the χ^2 values per number of points N_{dat} for the data used in this analysis. The MARATHON and JLab E03-103 $^3He/D$ are separated from the rest of the fixed target data, and their fitted normalizations are shown.

process	N_{dat}	χ^2/N_{dat}	fitted norm.
DIS			
MARATHON $^3He/^3H$	22	0.63	1.007(6)
MARATHON D/p	7	0.95	1.019(4)
JLab E03-103 $^3He/D$	16	0.25	1.006(10)
other fixed target	2678	1.05	
HERA	1185	1.27	
Drell-Yan	205	1.20	
W-lepton asym.	70	0.81	
W charge asym.	27	1.14	
Z rapidity	56	1.04	
jet	200	1.11	
total	**4466**	**1.11**	