F2 Update in Hall C

Precision measurements of the F2 structure function at large x in the resonance region and beyond

E12-10-002

https://www.jlab.org/physics/hall-c

See past talks for more details on physics motivation and analysis

- Joint Hall A & C Summer Collaboration Meeting, June16-17, 2022
- Hall C Users Meeting, February 17-18, 2022
- Joint Hall A & C Summer Collaboration Meeting, July 8-9, 2021
- Hall C Users Meeting, January 28-29, 2021
- Joint Hall A & C Summer Collaboration Meeting, July 16-17, 2020
- Hall C Users Meeting, January 28-29, 2020
- Joint Hall A & C Summer Collaboration Meeting, June 27-28, 2019
- Hall C Users Meeting, January 28-29, 2019

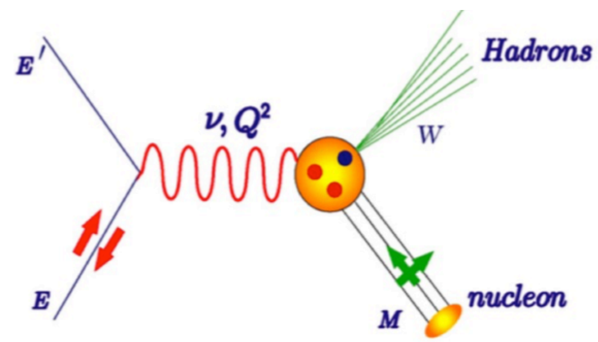
William Henry

June 16th, 2022

F2 Experiment in Hall C

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

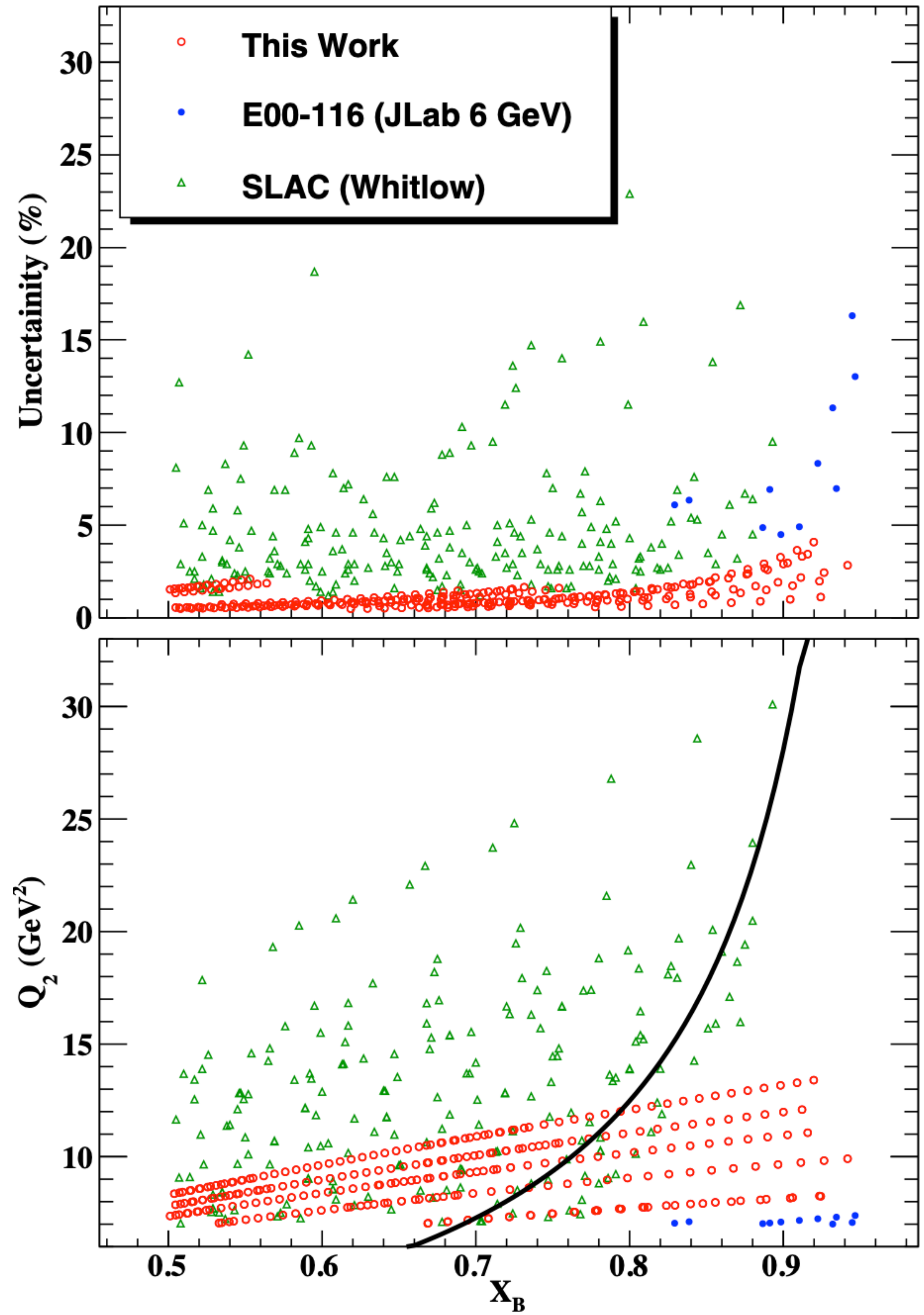
$Q^2 = 4EE'\sin^2(\theta/2)$	4-momentum transfer
$\nu = E - E'$	Energy transfer
$W = M^2 + 2M\nu - Q^2$	Final state hadronic mass
θ	Scattering angle
$x = Q^2/2M\nu$	Quark fractional momentum



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

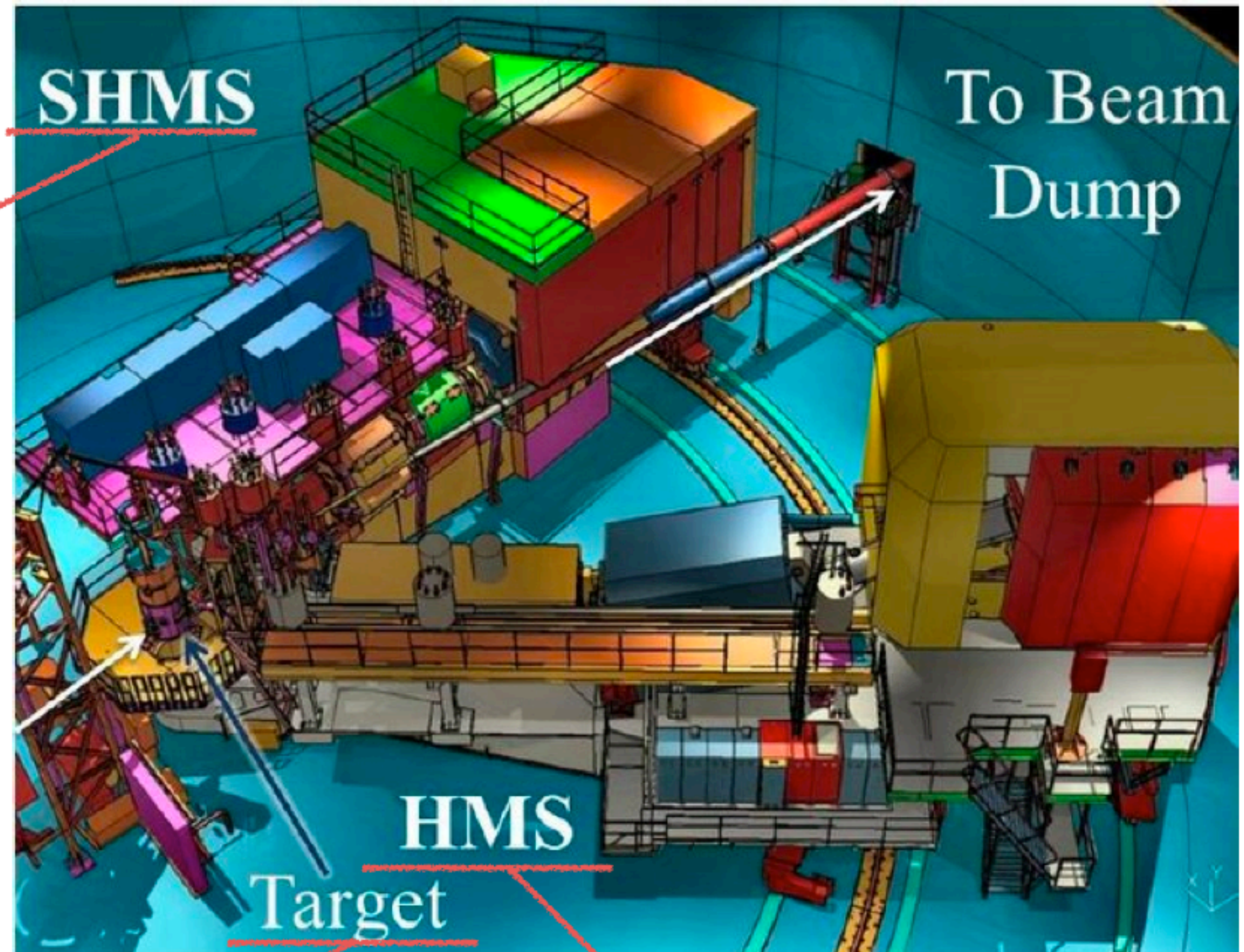
Physics motivation

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



F2 Experiment in Hall C

Hall C Spectrometers



71% of total data were taken by SHMS

LH_2, LD_2, Al

Push to high Q^2

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

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

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

Prescale

Total efficiency :

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

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

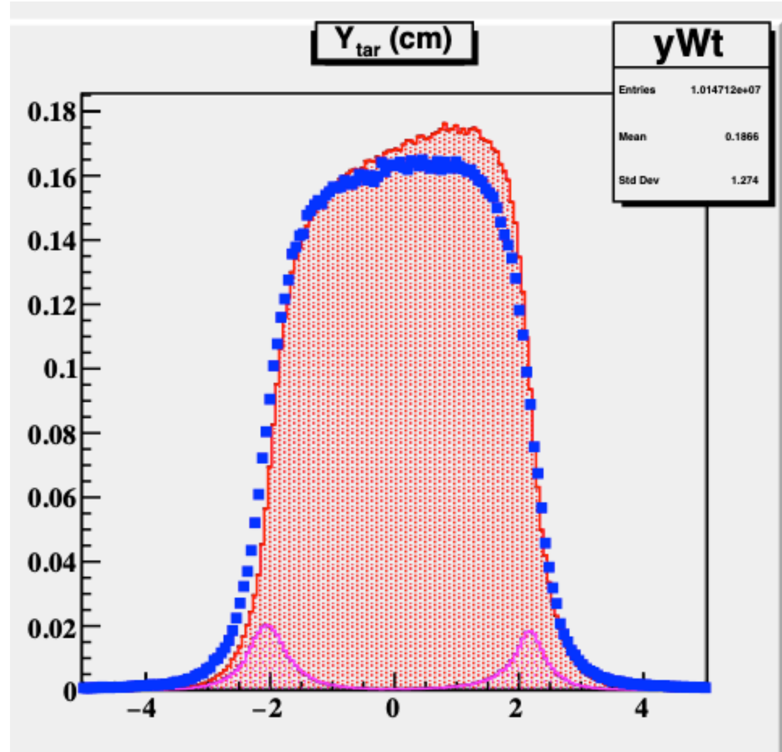
Monte Carlo (MC) Ratio Method

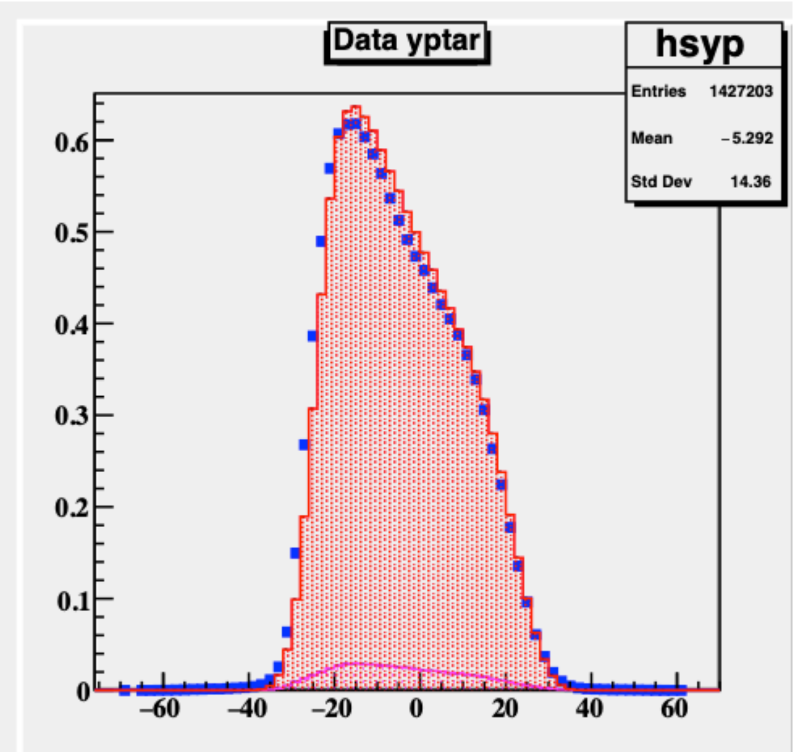
$$\left(\frac{d\sigma}{d\Omega dE'}\right)_{exp} = \left(\frac{d\sigma}{d\Omega dE'}\right)_{model} \frac{Y_{data}}{Y_{MC}}$$

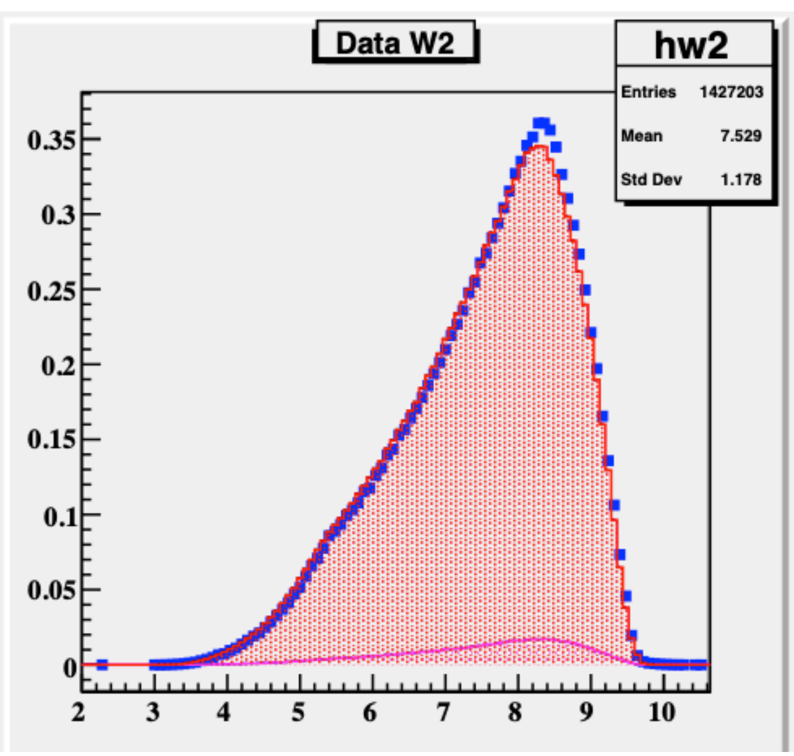
- MC ran for 50M events mc-single-arm
- Events are weighted after using radiated using rc_externals and f1f221 model
- Charge Symmetric Background added to MC

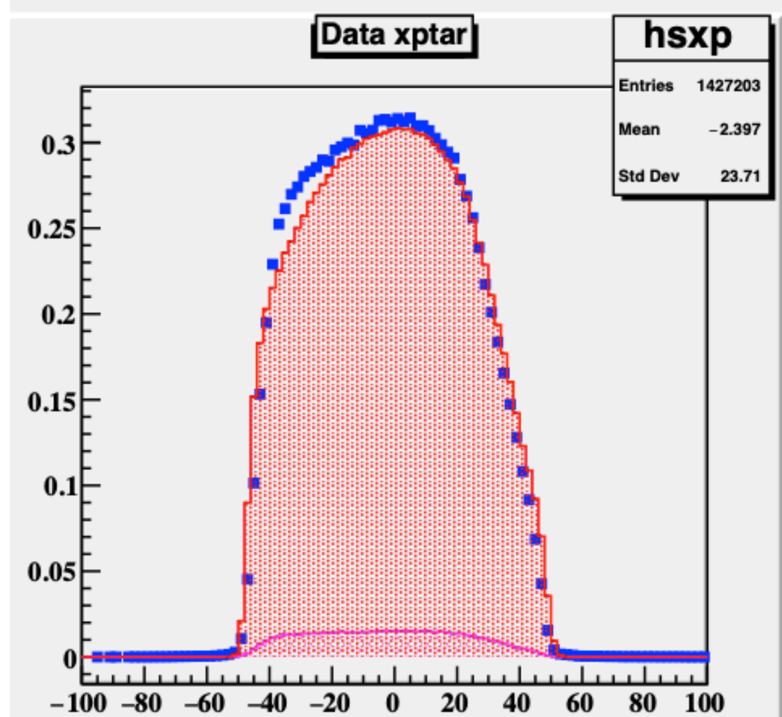
F2 Cross Section Extraction

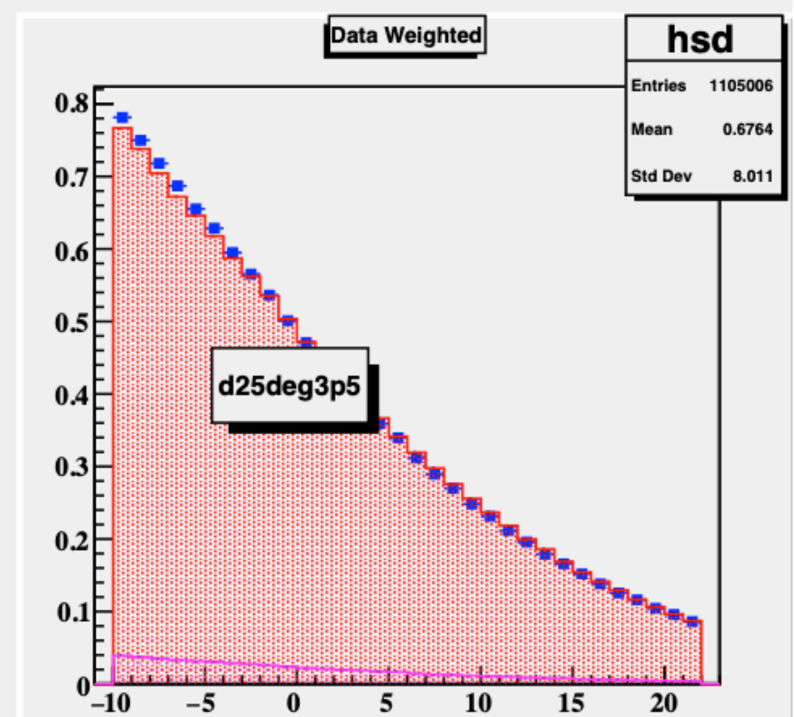
Data vs MC





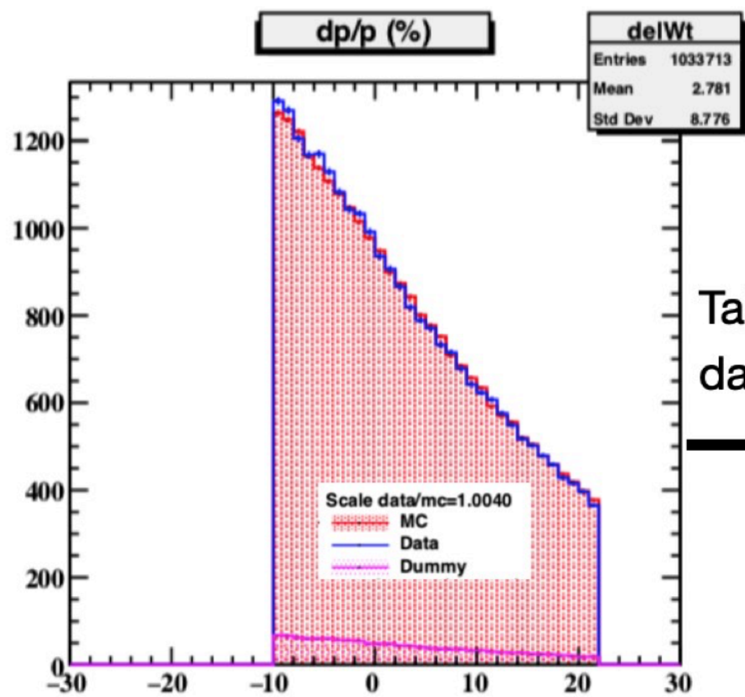






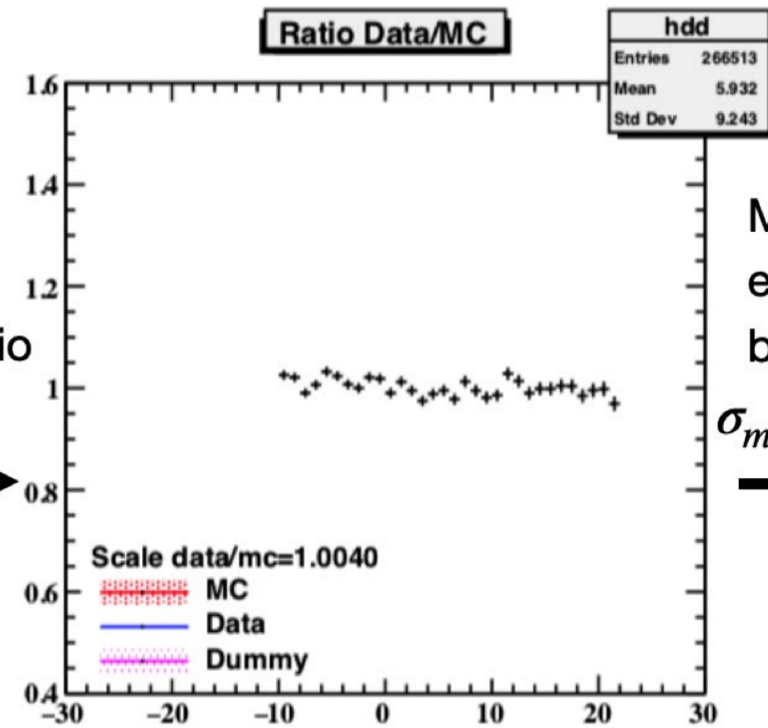
F2 Cross Section Extraction

Cross Section Extraction (MC Ratio Method)

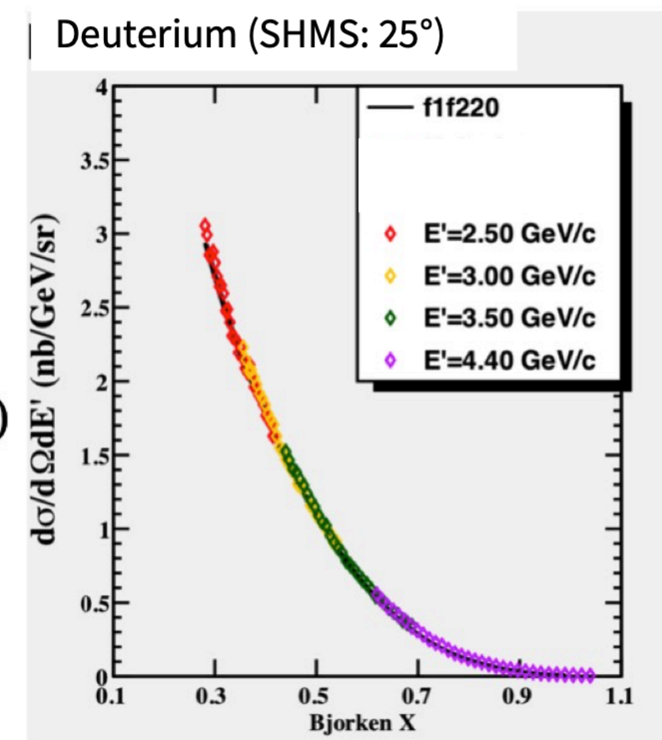


(Data is dummy subtracted)

Take Ratio data/MC



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



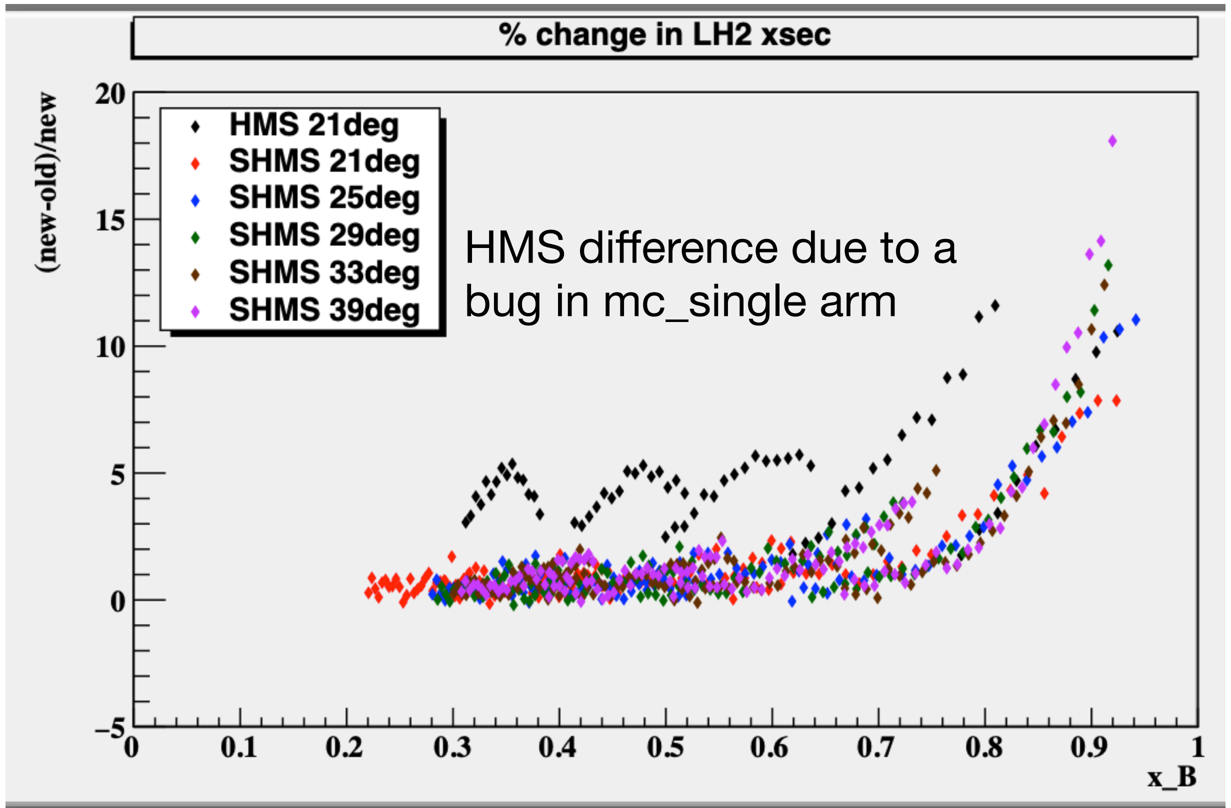
1) MC (weighted with radiative cxsec) and corrected data yields are binned in delta

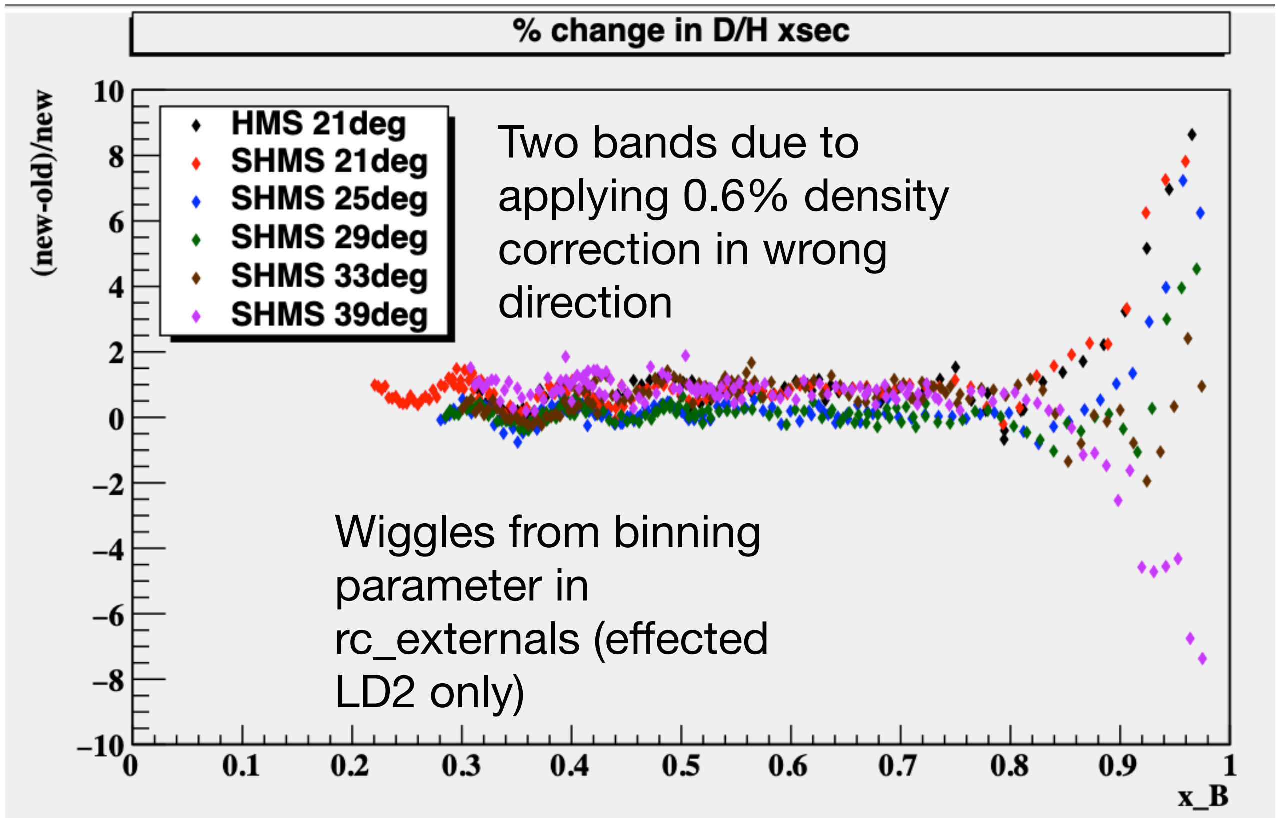
2) Take ratio of data and MC

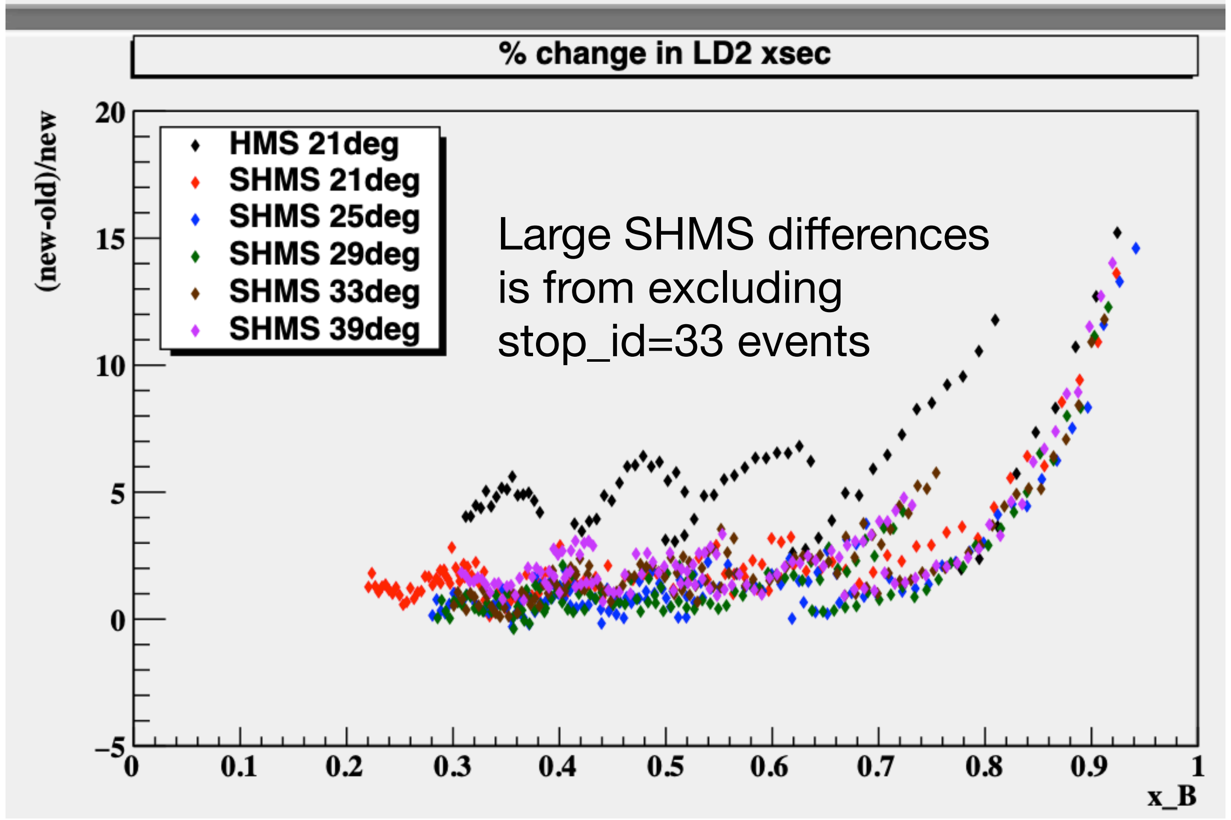
3) Multiply each bin by model (not radiated) to get cross section

Recent Changes to Analysis

- New Boiling Slopes (not reflected in these plots)
- HMS mc_single_arm fix
- SHMS Monte Carlo weighting fix
- Transitioned from delta binning to W2 binning
- Improvements on F1F221 model
- Included an addional error to account for model dependence
- Introduced and fixed new bugs in data analysis
- Corrections to dummy subtraction
- Corrections to reconstruction matrixes for two settings







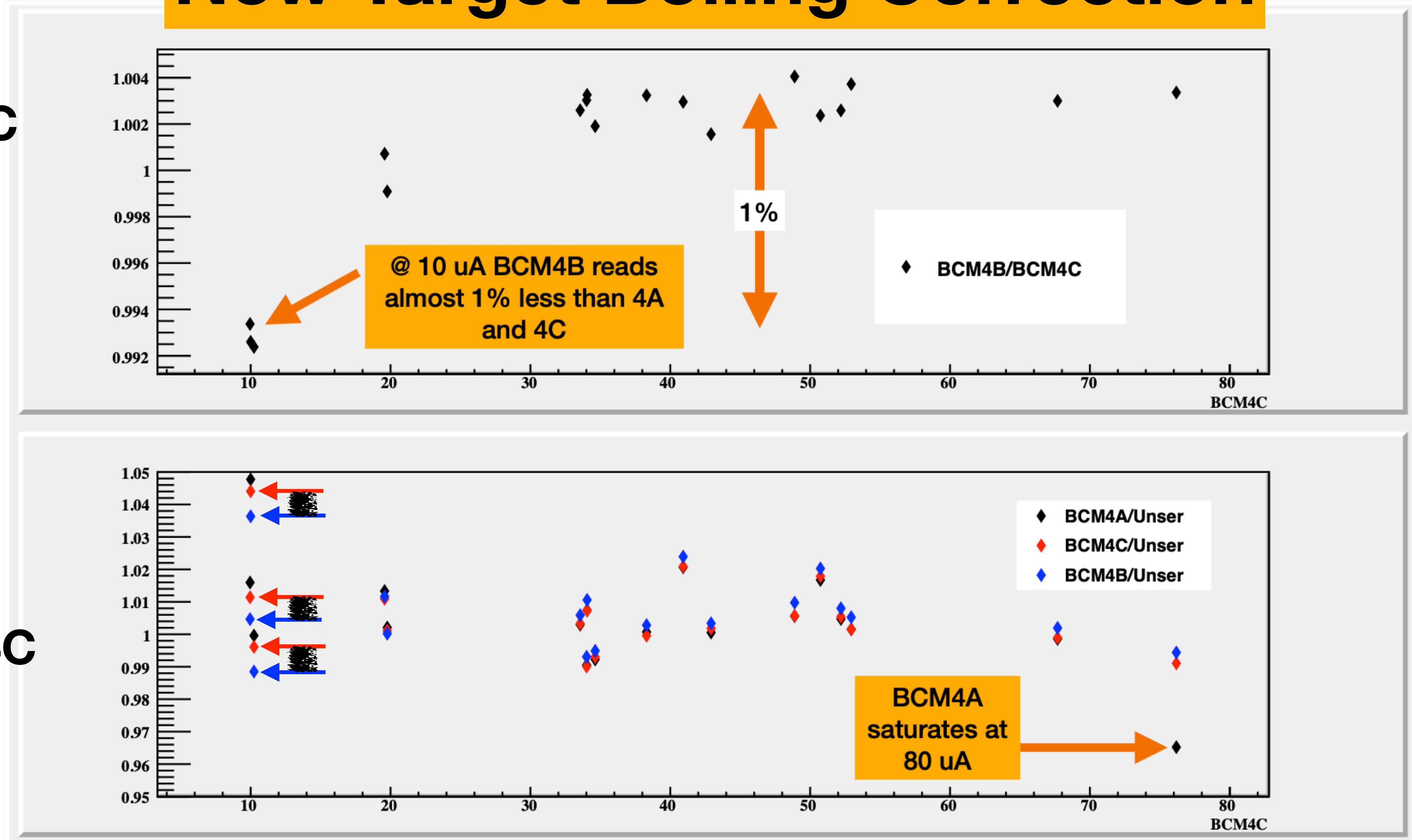
Recent Changes to Analysis

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



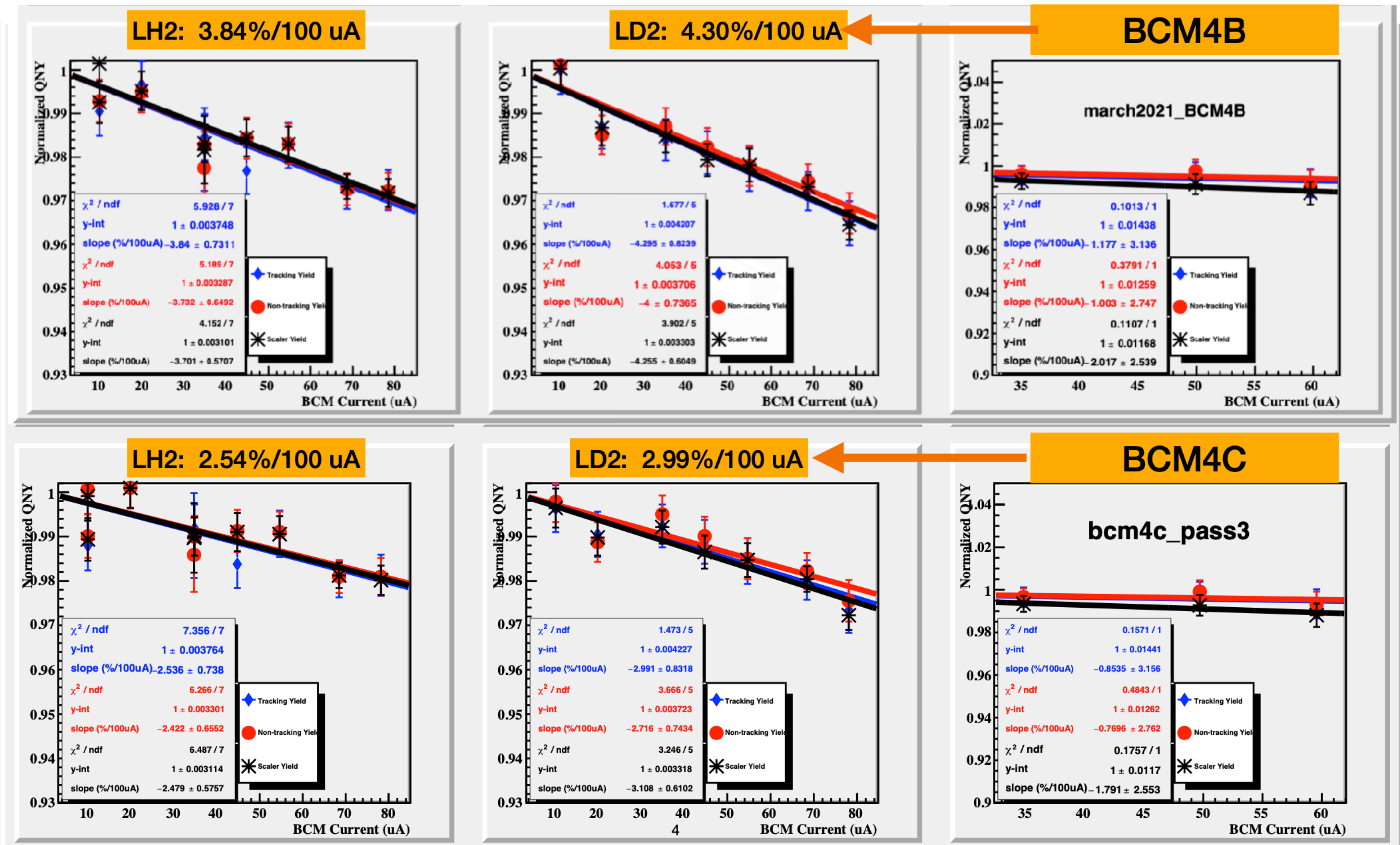
- Old boiling analysis used BCM4B
- BCM4B was not stable during luminocity scans
- BCM4A Saturated at the highest current settings
- BCM4C is the best BCM to use

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.

Our analysis on Spring 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

New F2 Boiling Slopes

LH2: 2.55 +/- 0.74

LD2: 3.09 +/- 0.84

Good agreement when comparing Fall and Spring Boiling Slopes

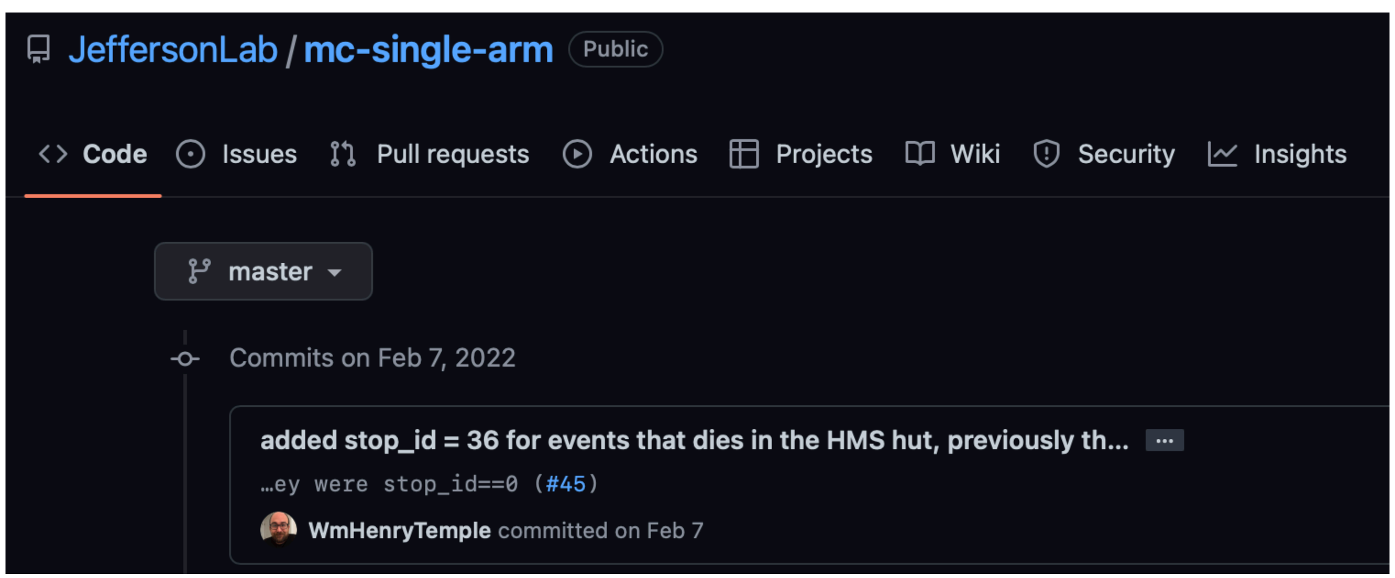
***The LH2 fan speed was different between Fall and Spring Runs so we can't compare those results**

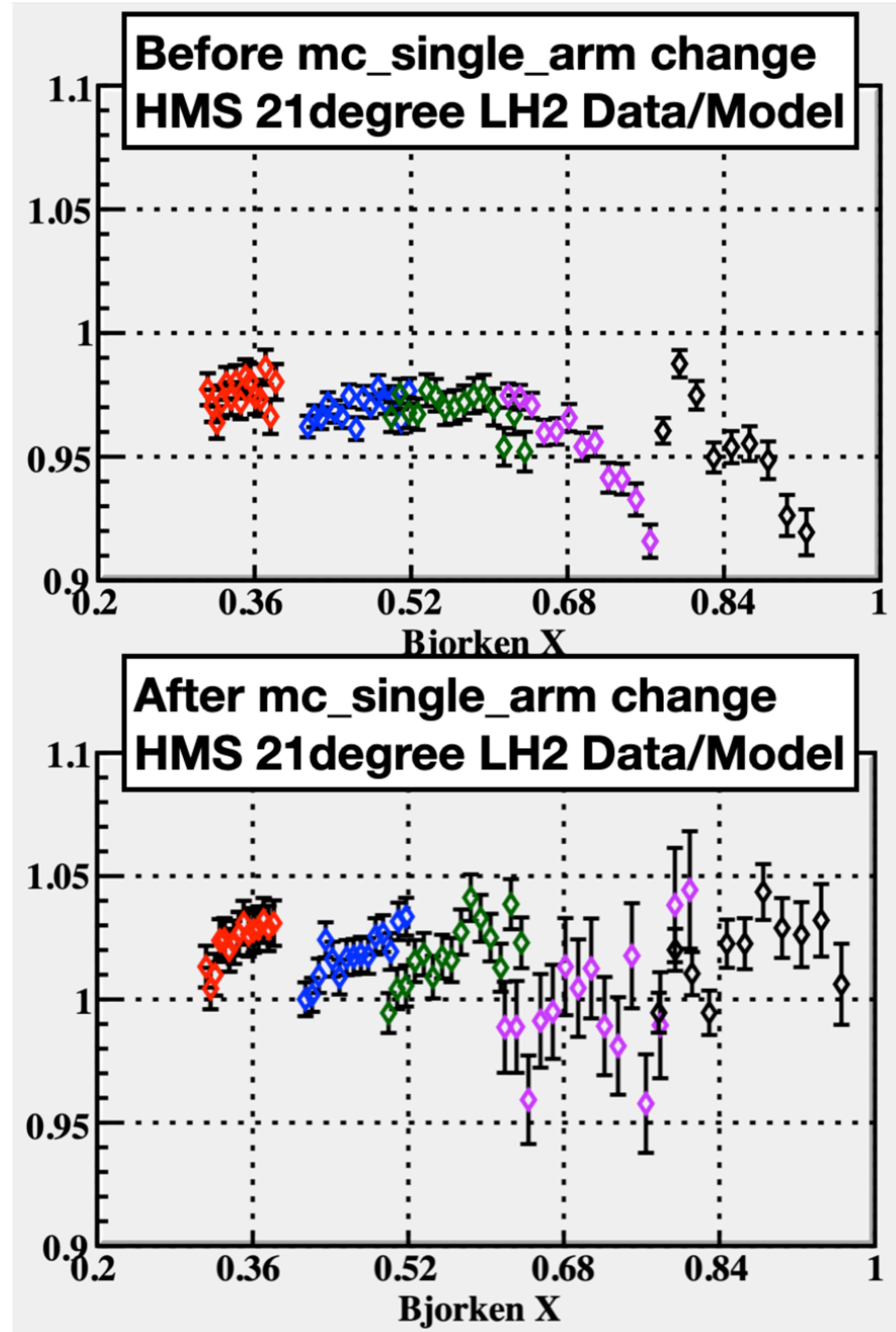
***Slightly different slopes than shown in previous slide because the PID cuts were changed to match the the cuts used in the main analysis**

Recent Changes to Analysis

Monte Carlo Update

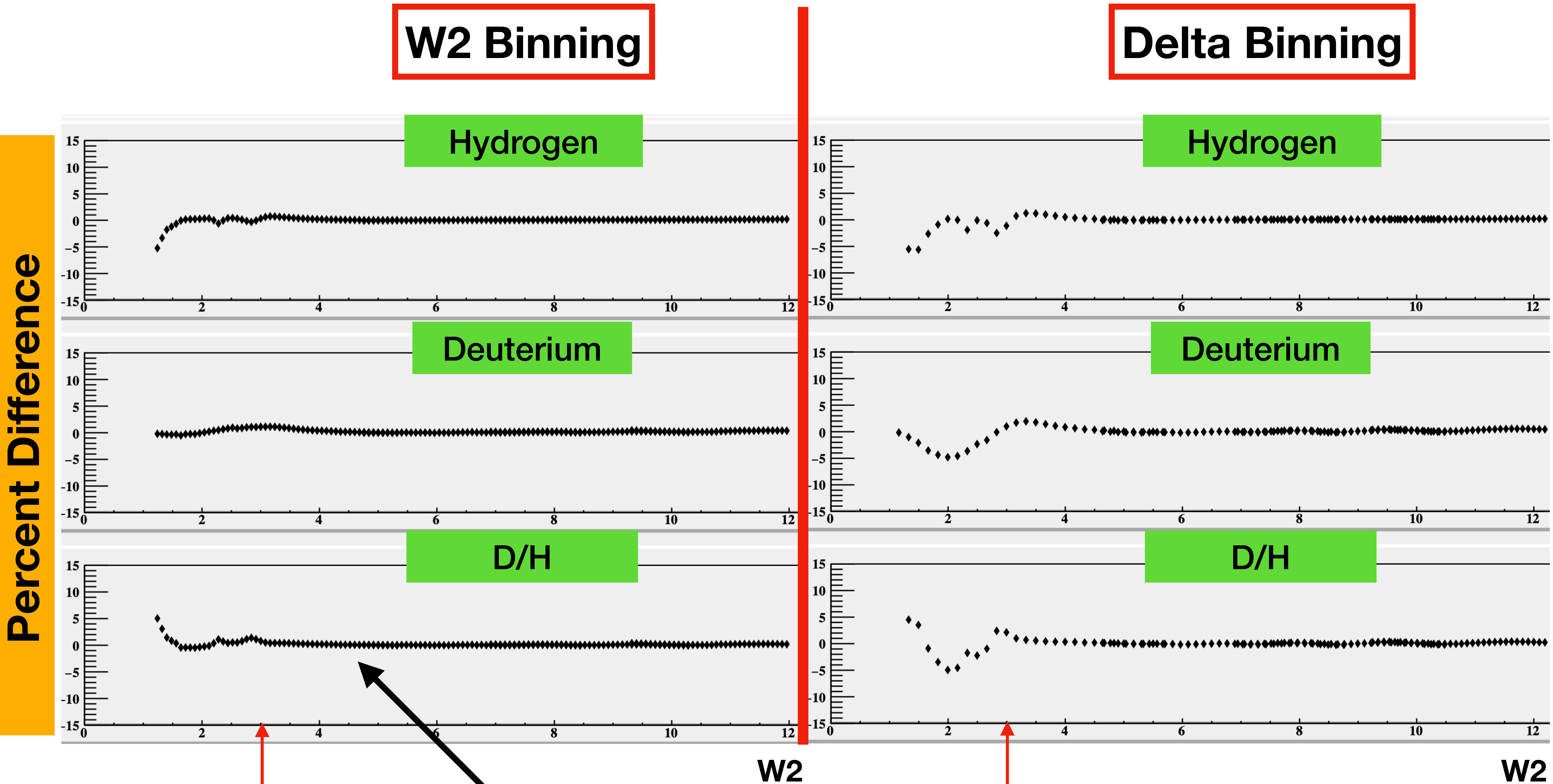
- A bug was found in mc-single-arm. Events that would make it into the detector hut but miss the detector stack were being included as successful events
- It was corrected and pushed to the JeffersonLab github in February of 2022
- After the fix, raw cross sections change by ~ 5%?
- Little impact of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





Recent Changes to Analysis

Change in extracted cross section when using different input models



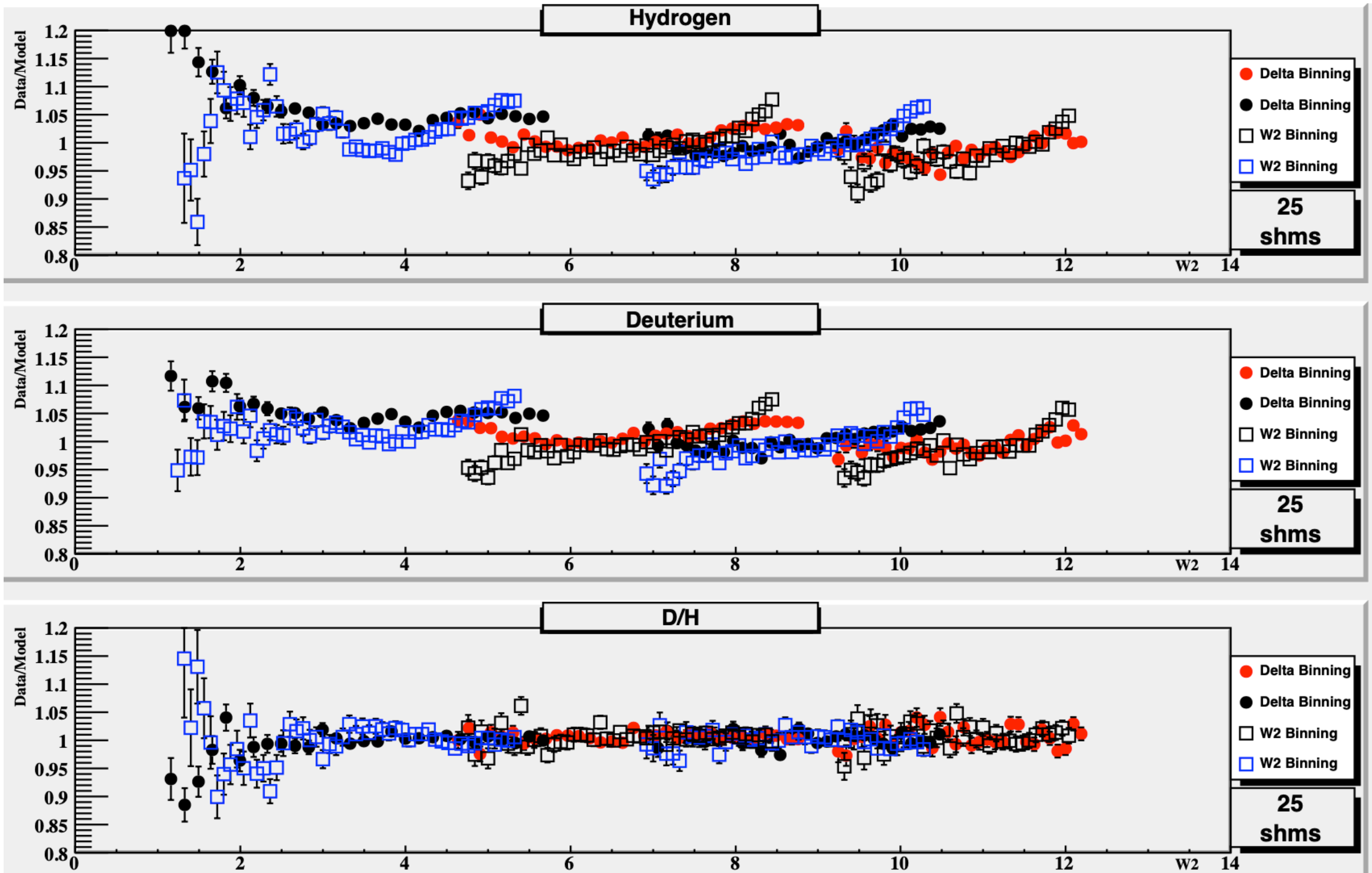
- Apply as additional systematic error

- **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

D/H Ratio Error Budget

Error	Global (correlated) or point to point (uncorrelated)	Size (%)
Statistical	Point to Point	0.6 - 5.6 (2.9**)
Charge	Point to Point	0.1 - 0.6
Target Density	Point to Point	0.0 - 0.2
Target Density	Global	1.1
Livetime	Global	0.0 - 1.0
Model Dependence	Global	0.0 - 2.6 (2.1**)
Charge Symmetric Background	Global	0.0 - 1.4
Acceptance	Global	0.0 - 0.6 (0.3**)
Kinematic*	Global	0.0 - 0.4
Radiative Correction	Global	0.5 - 0.7 (0.6**)
Pion Contamination	Global	0.1 - 0.3
Cerenkov Efficiency	Global	0.1
Total Global	Global	1.3 - 1.9 (2.1**)
Total Point to Point	Point to Point	0.6 - 5.7 (2.9**)

$$\star\, Kinematic\ Error : \frac{\delta E'}{E} = \frac{\delta E_{Beam}}{E_{Beam}} = 0.1\,\%\,, \frac{\delta\theta}{\theta} = 0.25mr$$

** **With DIS cut ($W^2 > 3$ GeV^2)**

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

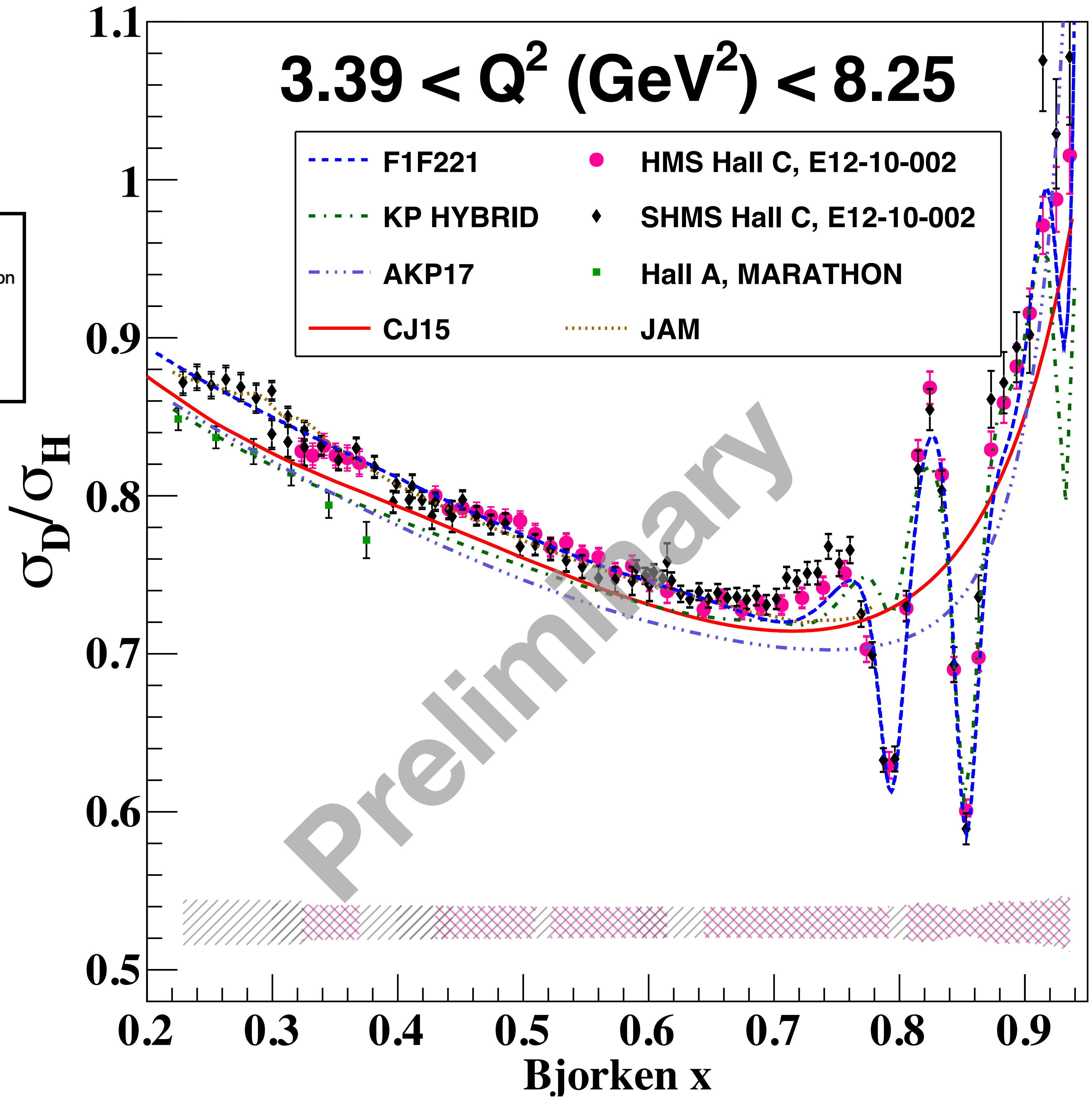
AKP17

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!



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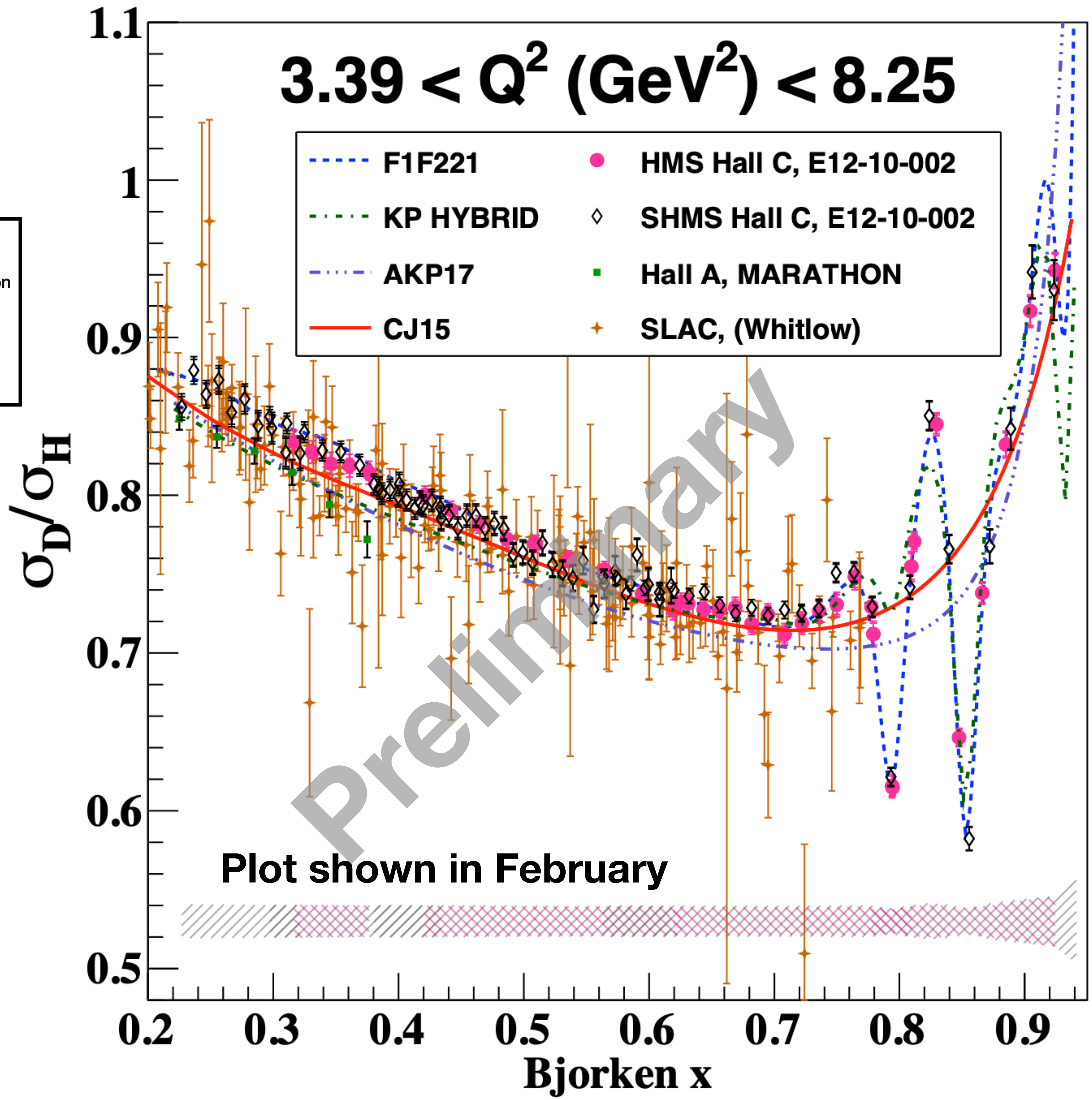
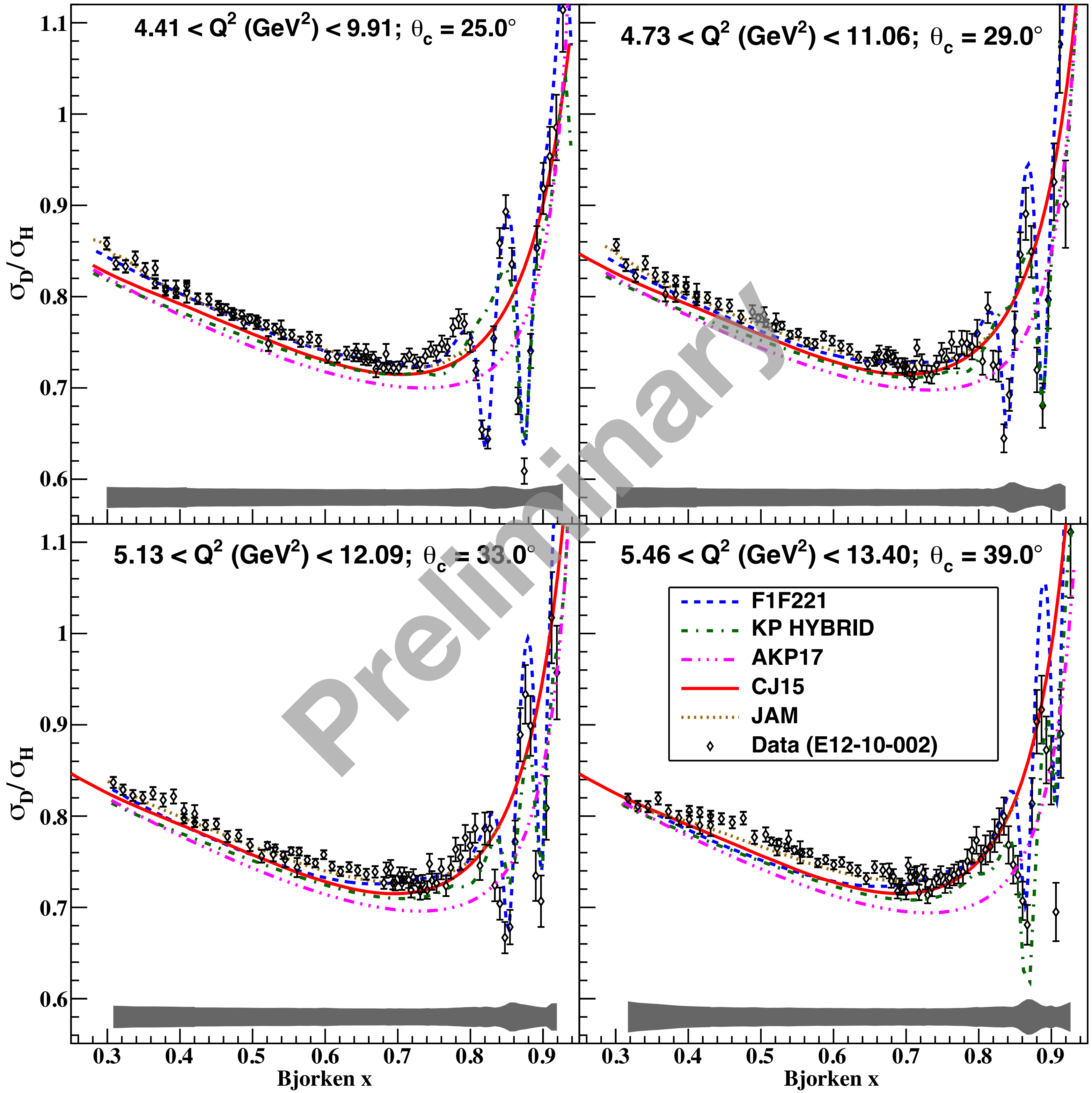
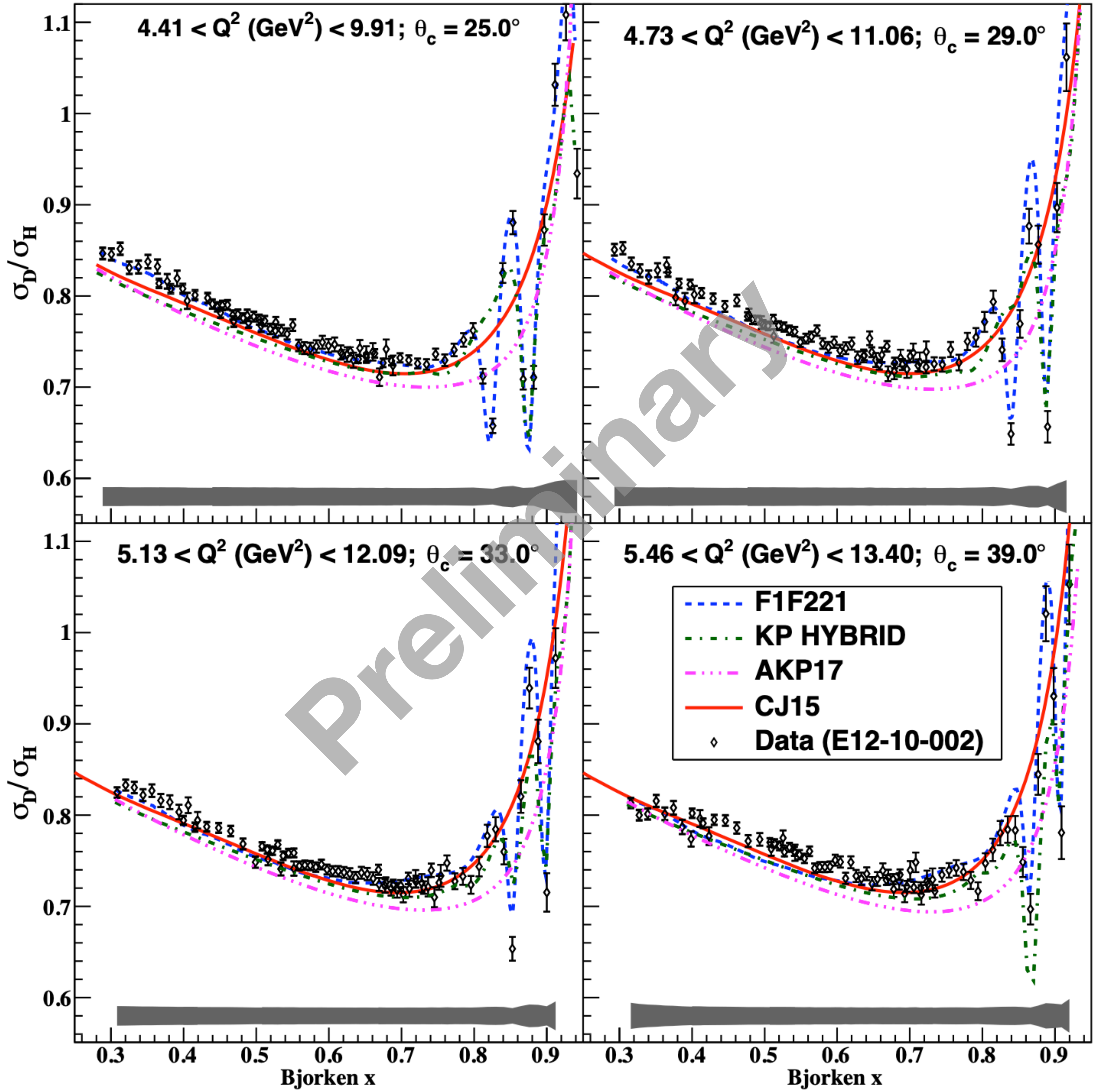


F2 Results

New Results!



F2 Results

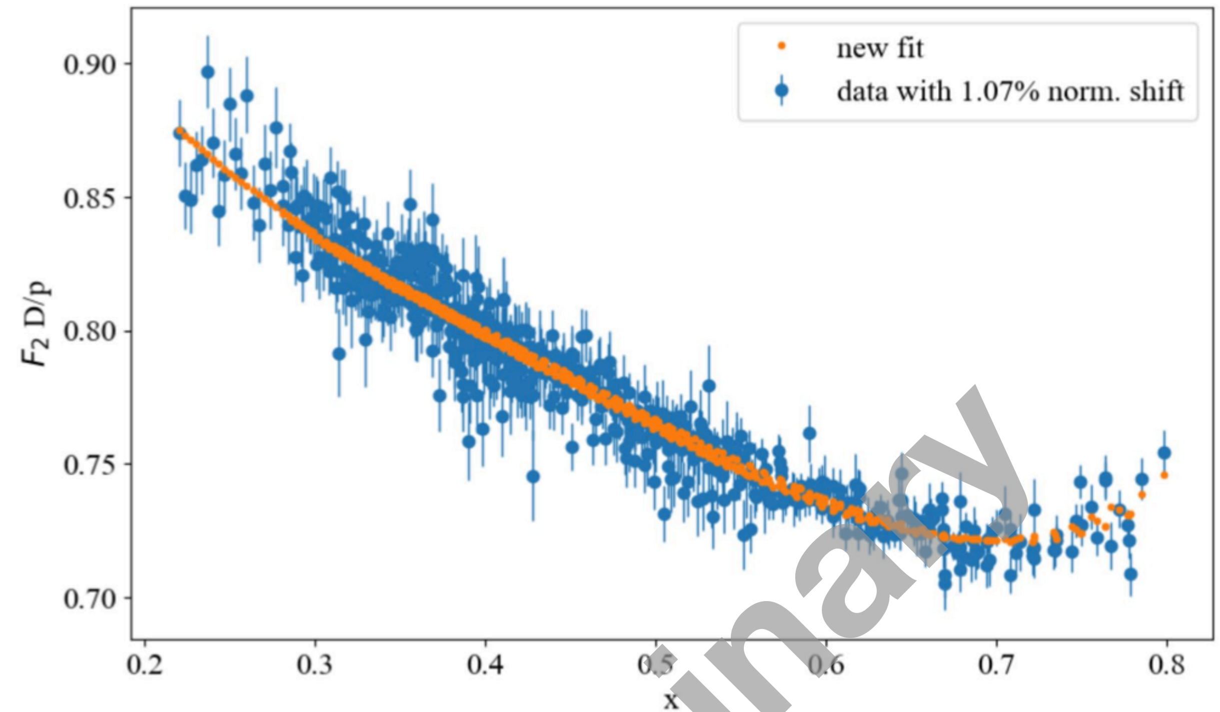


Plot shown in February

F2 Results

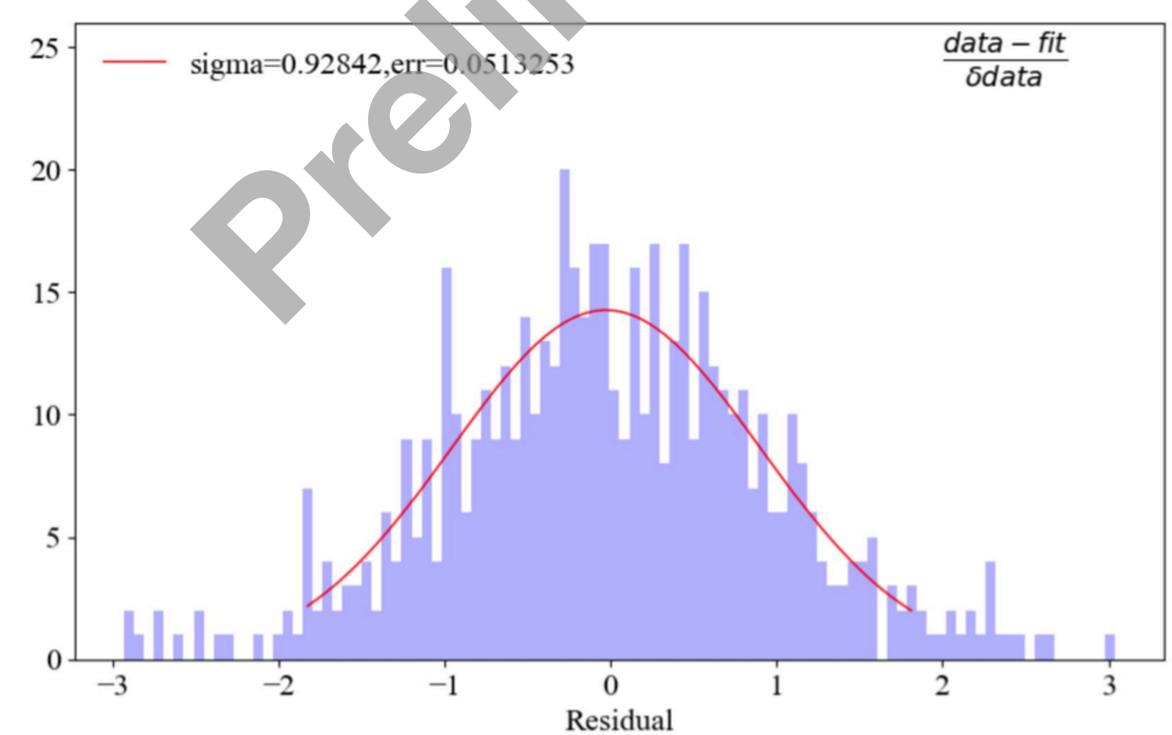
CJ Impact Study

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)

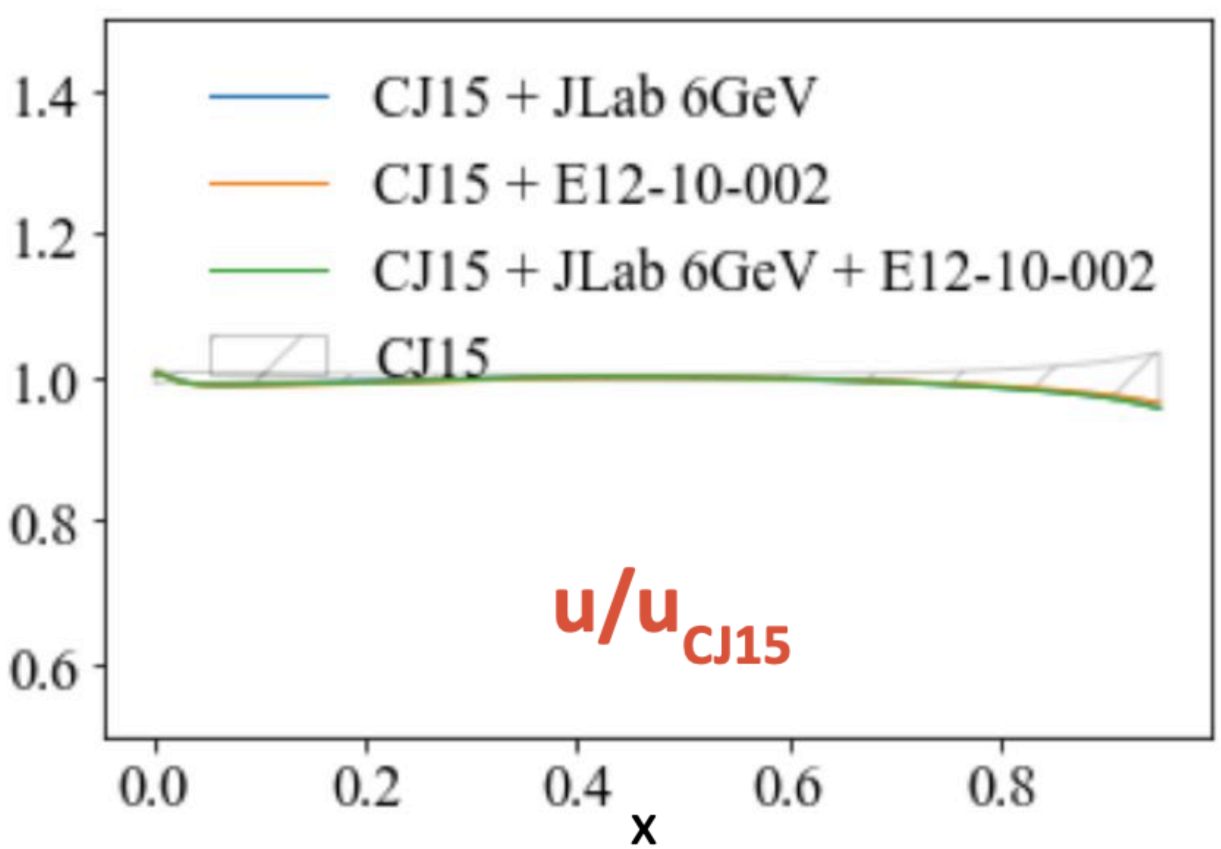


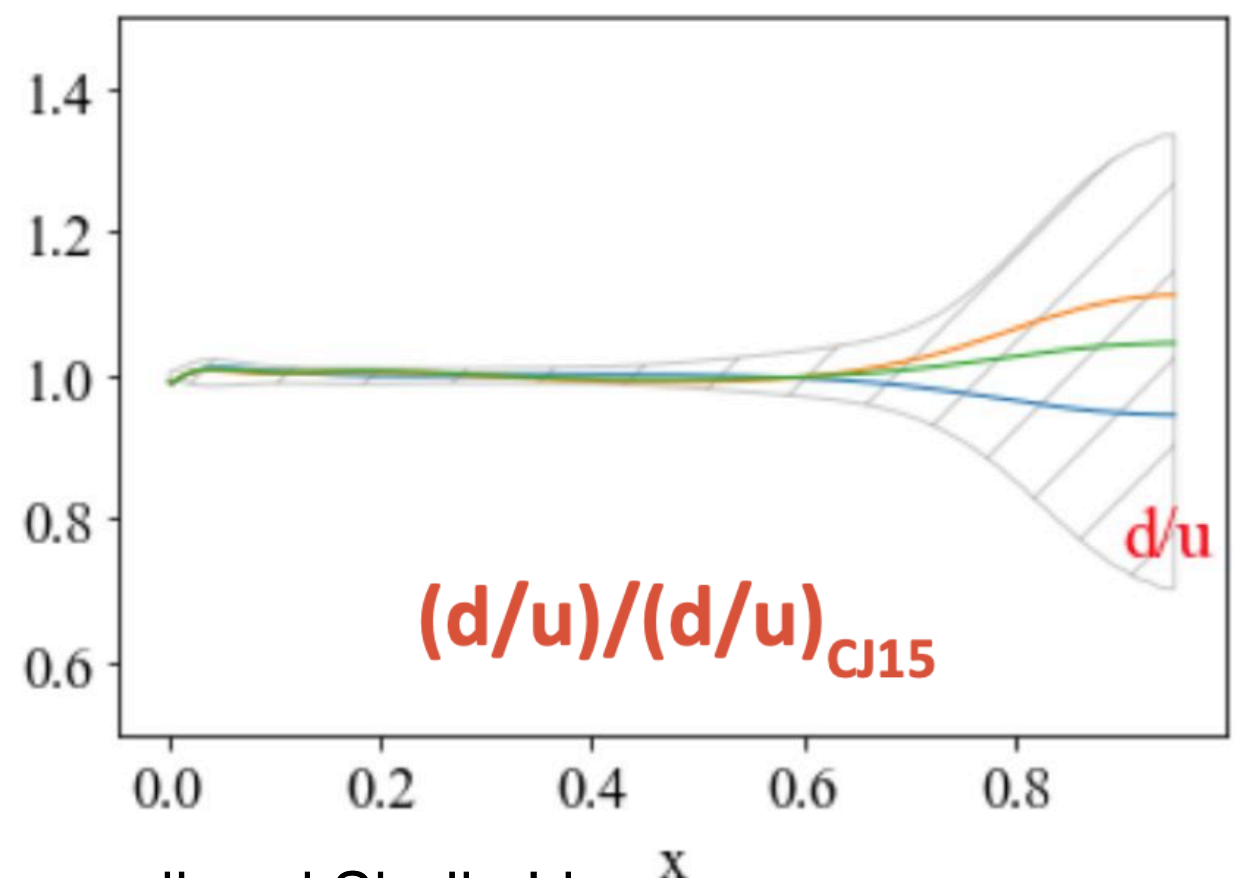
Preliminary

F2 Results

CJ15 Impact Study

- **No tension with original CJ15 data set**
  - ⟶ Data compatible with global data set (not always the case…)
  - ⟶ Otherwise, one can bring to light neglected systematic uncertainties





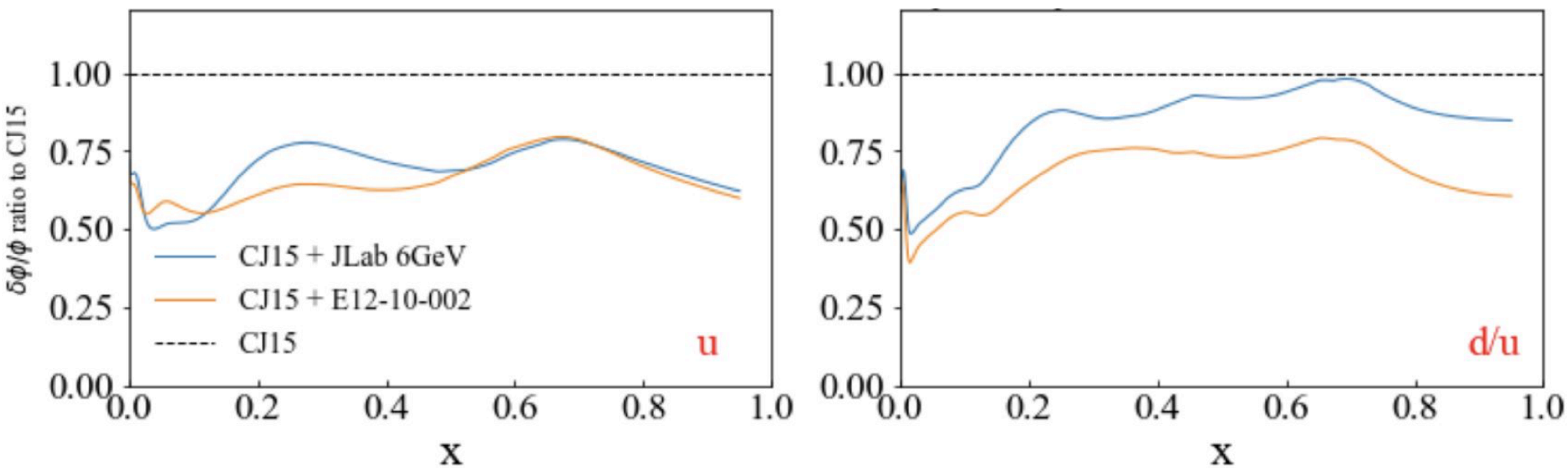
Courtesy of Alberto Accardi and Shujie Li

(Analysis needs to be revisted with new data)

F2 Results

CJ15 Impact Study

- **No tension with original CJ15 data set**
  - ⟶ Data compatible with global data set (not always the case…)
  - ⟶ Otherwise, one can bring to light neglected systematic uncertainties
- **Uncertainty reduction comparable to full JLab 6 data set**



Courtesy of Alberto Accardi and Shujie Li

(Analysis needs to be revisted with new data)

F2 Results

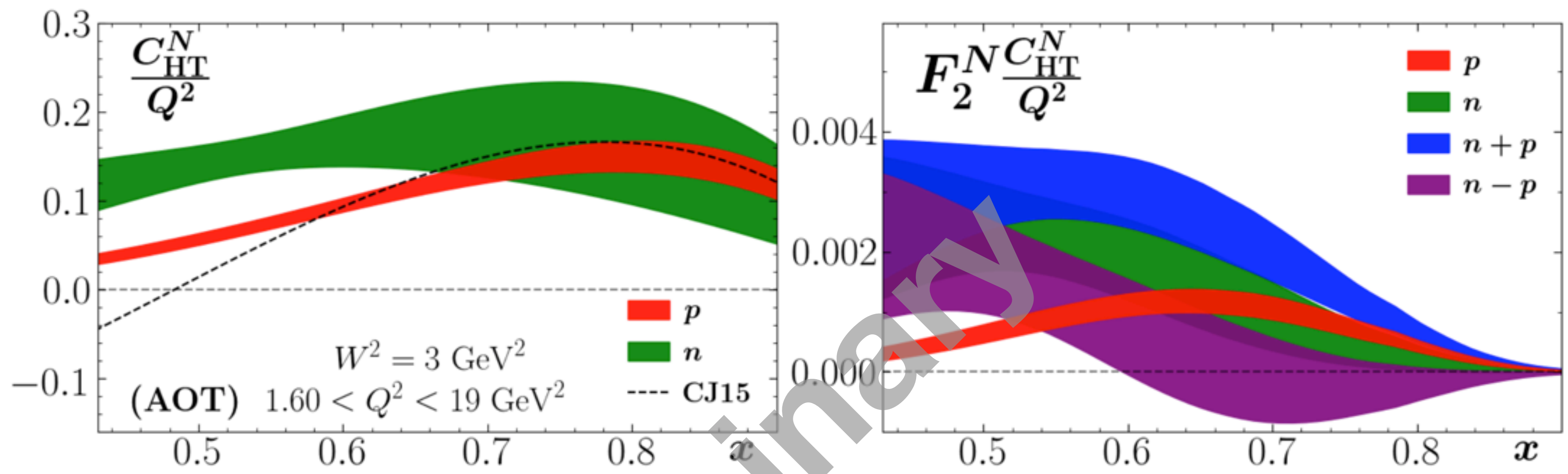
JAM Impact Study

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

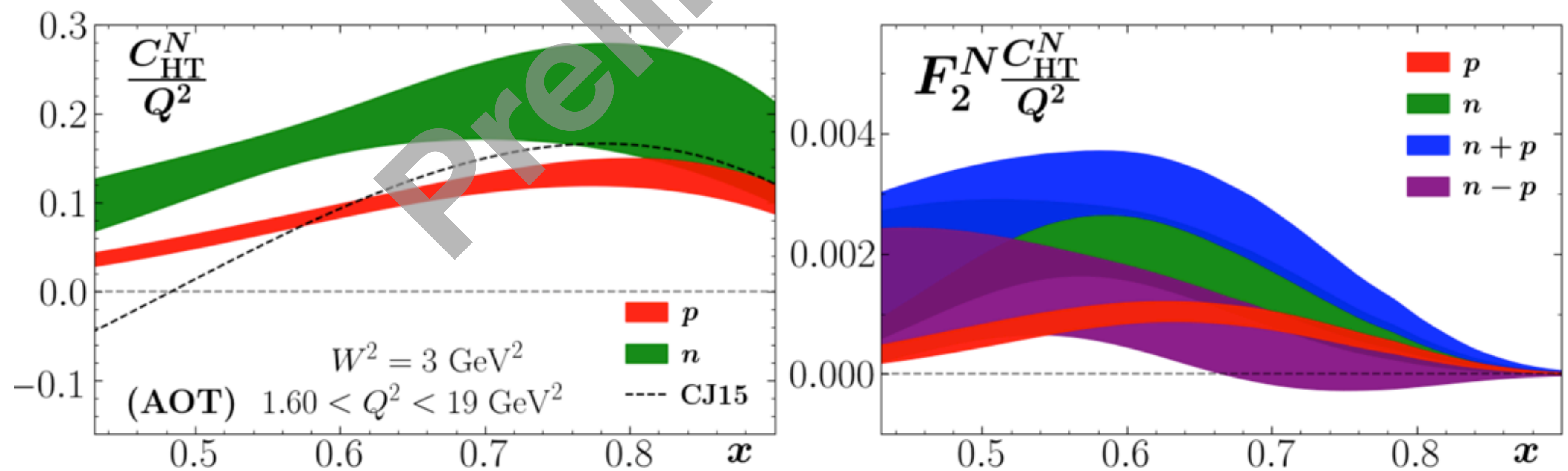
- D/H ratio was provided to Jefferson Lab Angular Momentum Collaboration (JAM) to incorporate into their global QCD analysis of PDFs
- E12-10-002 data reduces the uncertainty to higher twist corrections on F2

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

Without E12-10-002

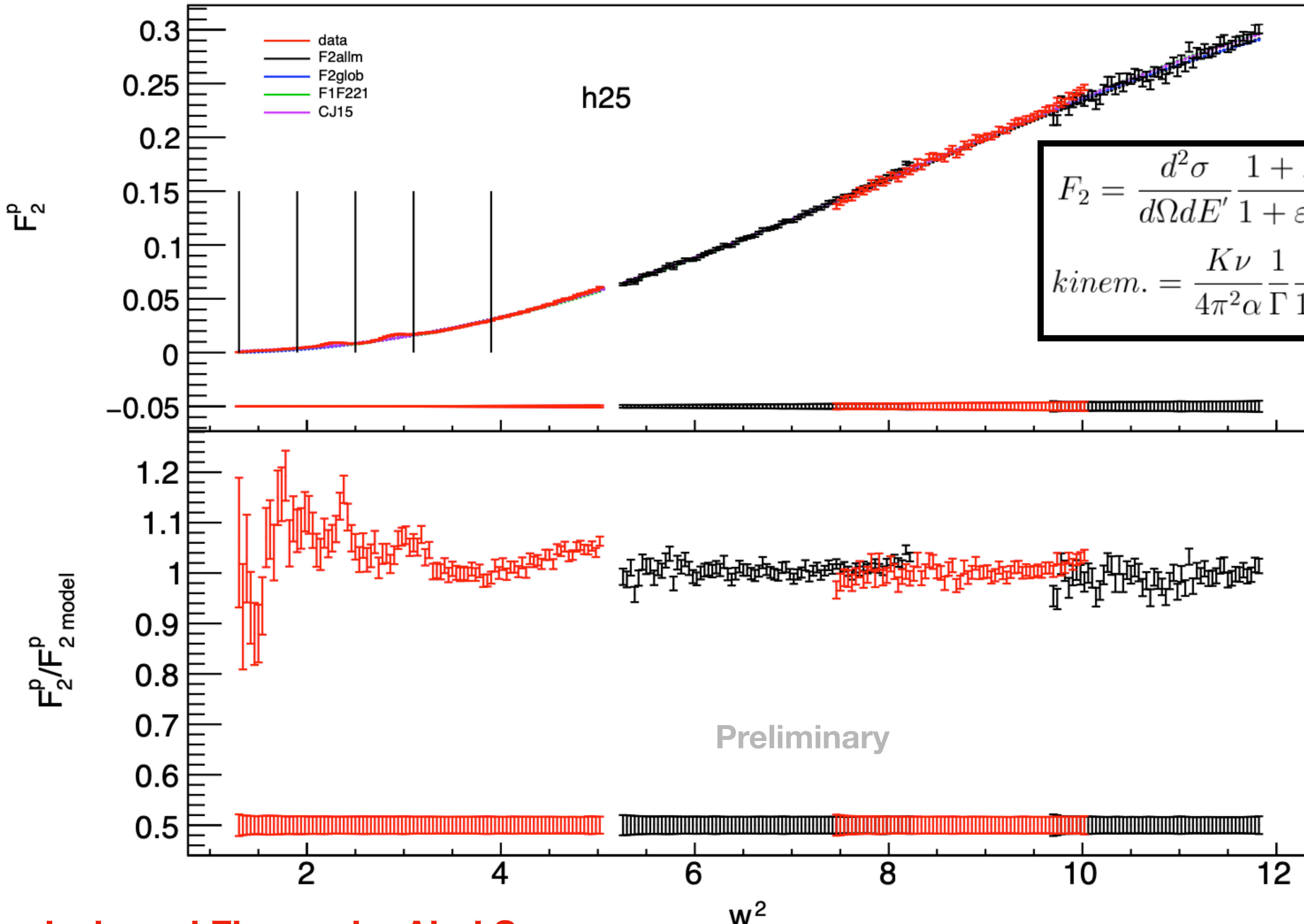


With E12-10-002



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

Quark Hadron Duality Studies

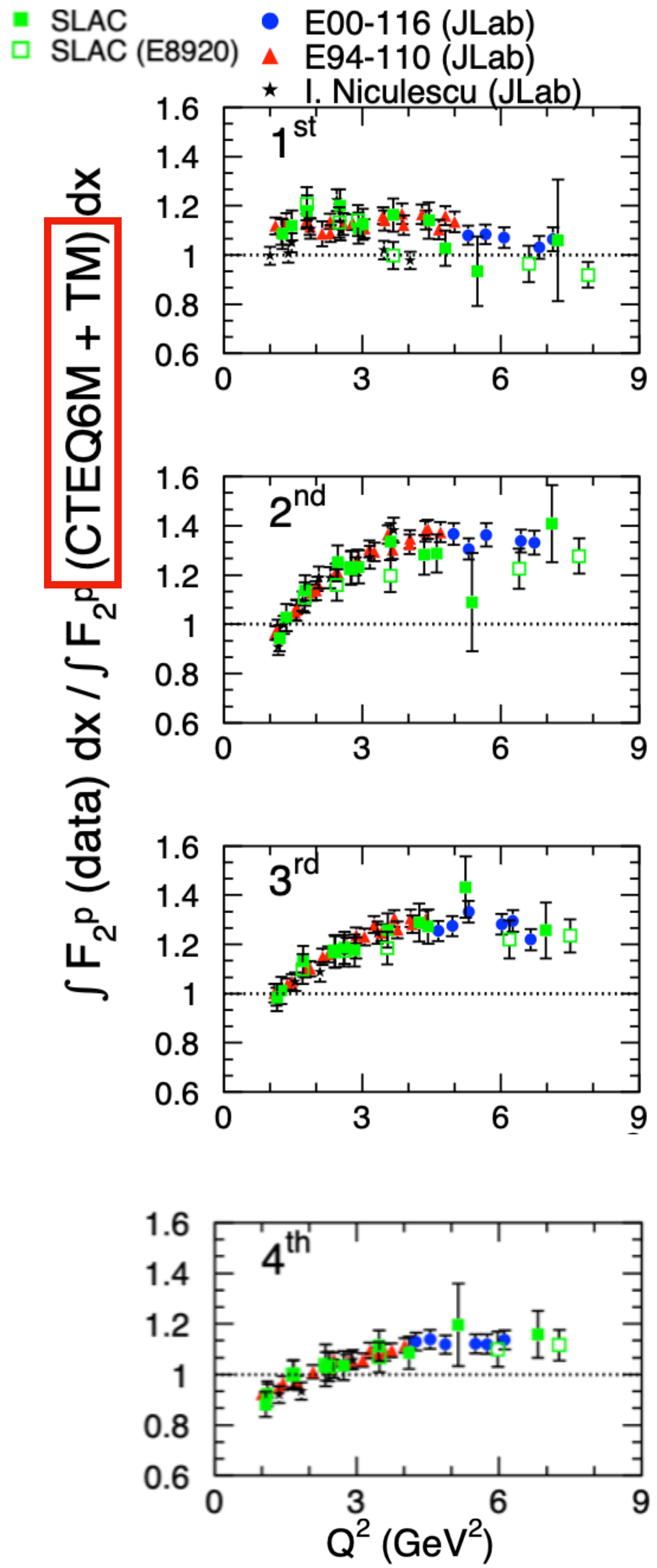


$$F_2 = \frac{d^2\sigma}{d\Omega dE'}\frac{1+R}{1+\varepsilon R} \times kinem$$

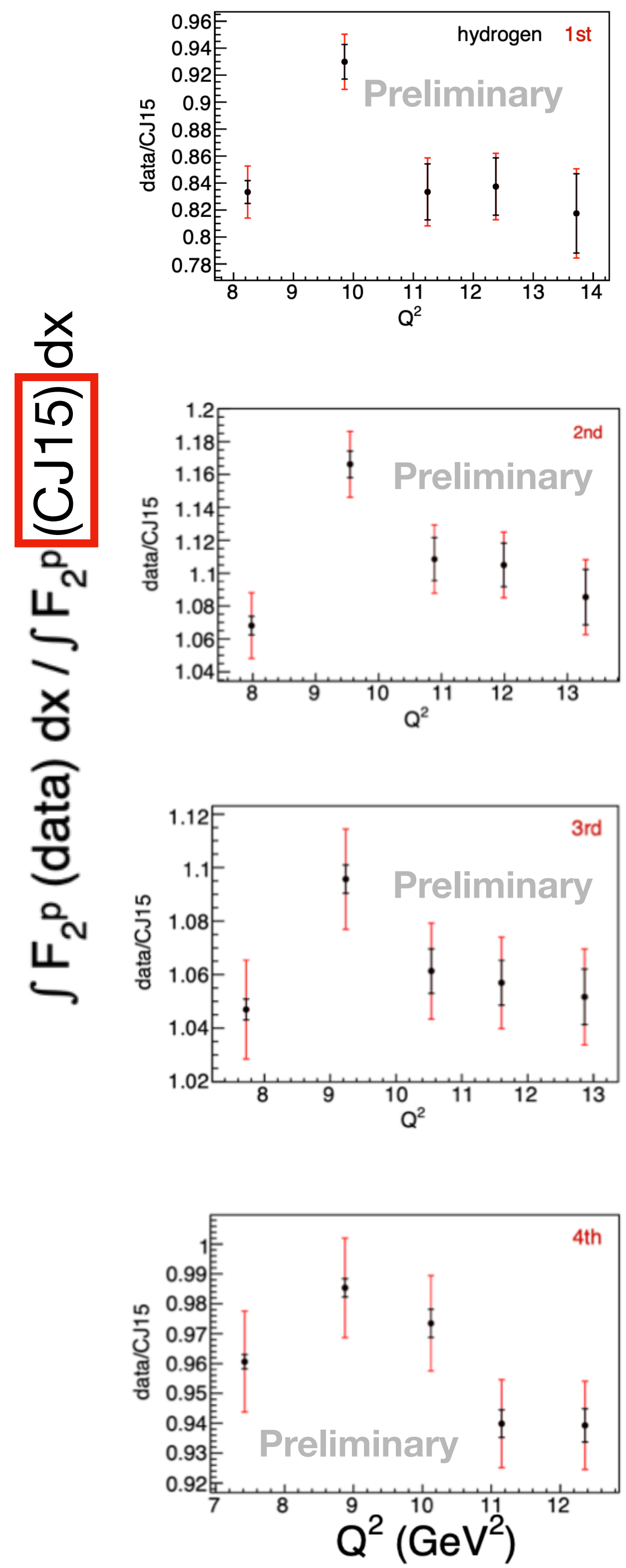
$$kinem. = \frac{K\nu}{4\pi^2\alpha}\frac{1}{\Gamma}\frac{1}{1+\nu^2/Q^2}.$$

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

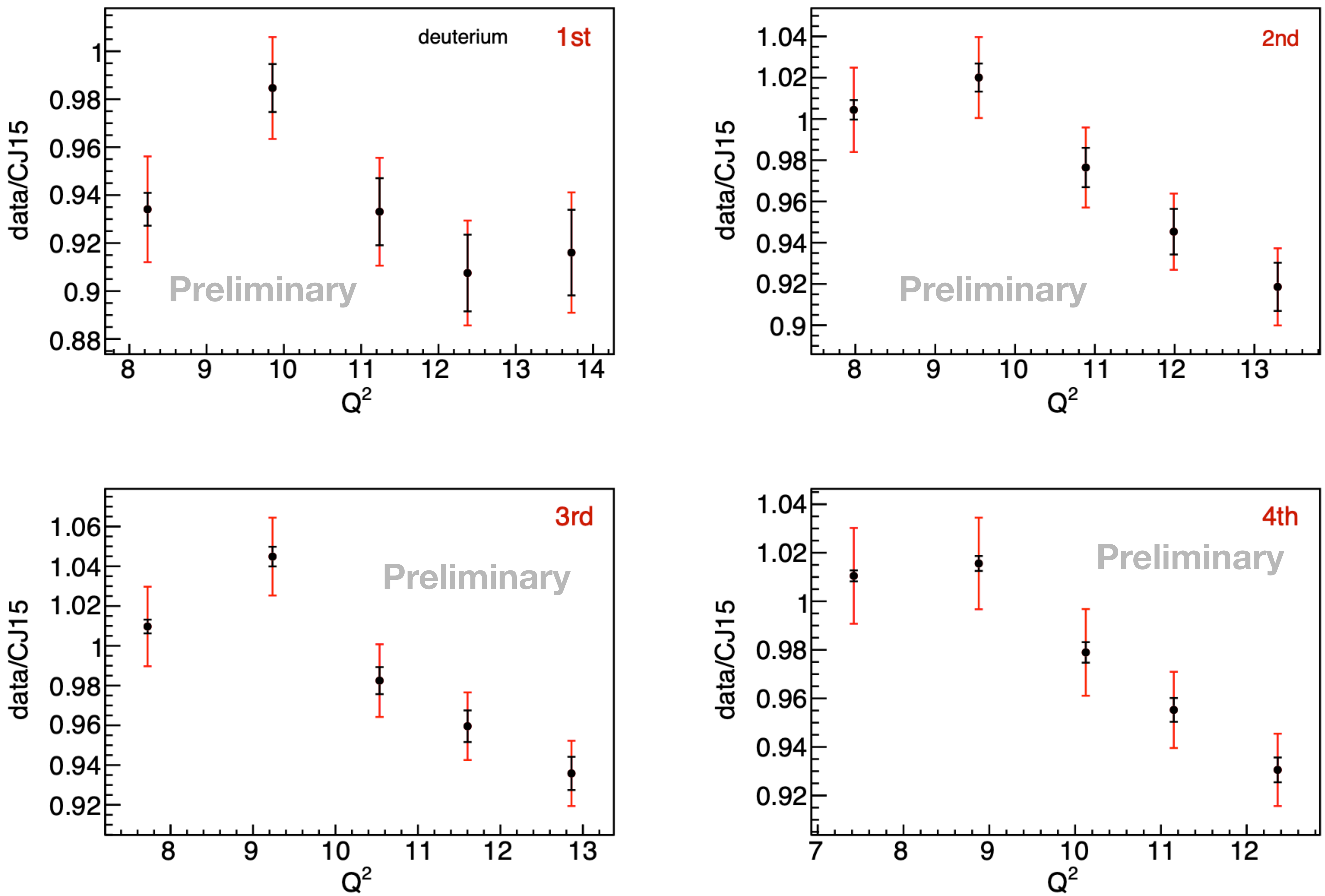
- Calculate ratio:

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

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

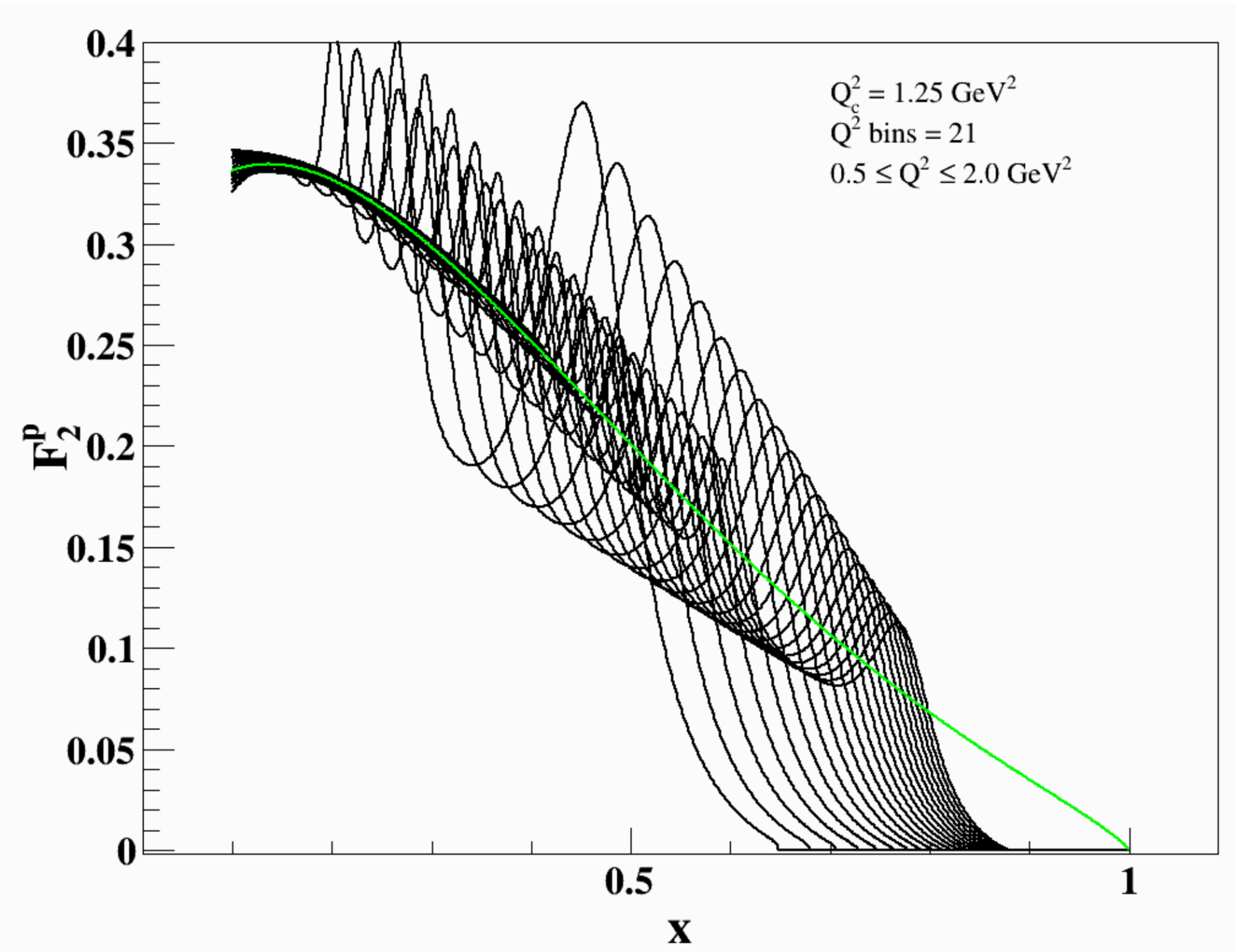
Analysis and Figures by Abel Sun

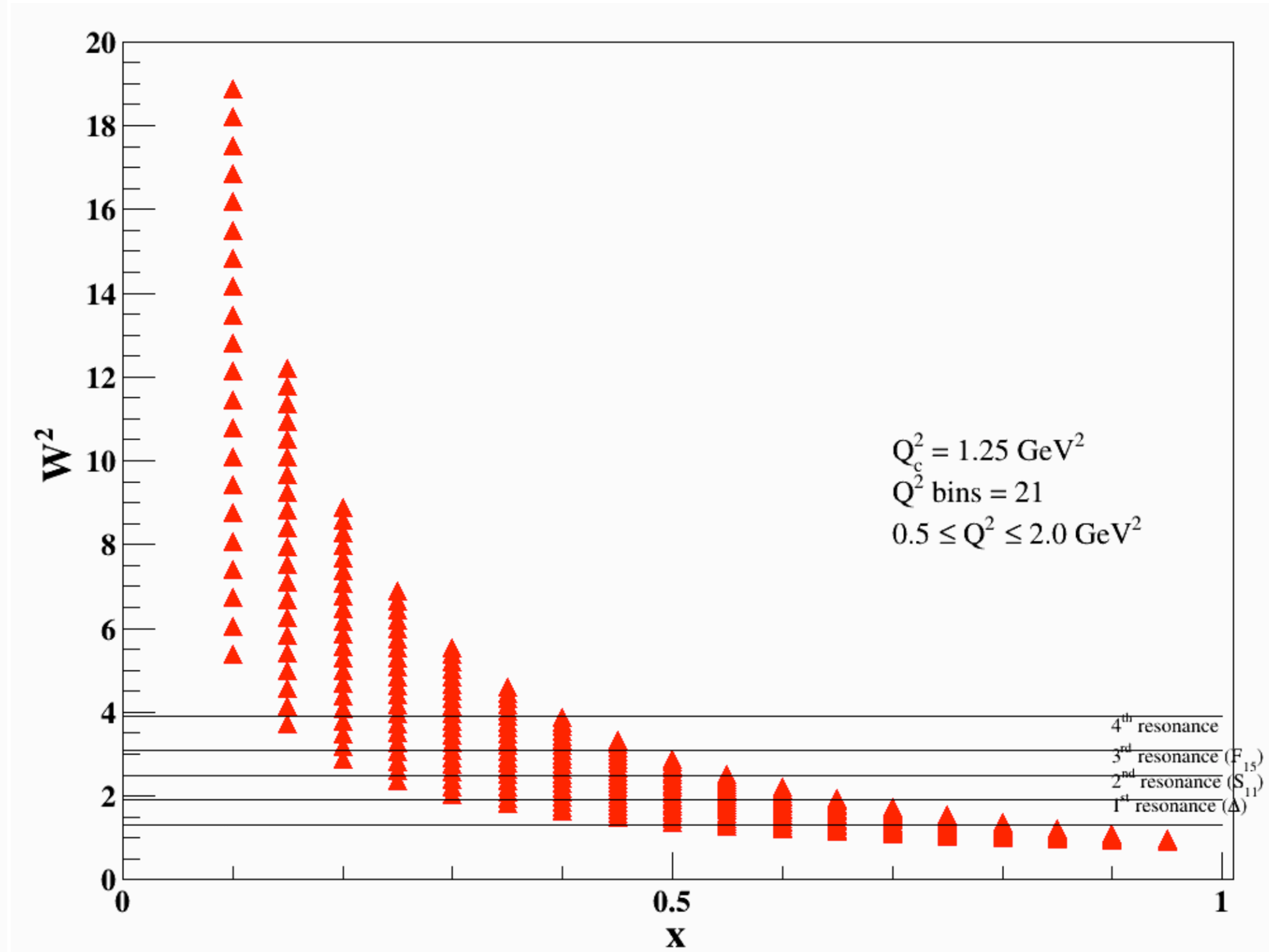
Quark Hadron Duality Studies



Analysis and Figures by Abel Sun

Quark Hadron Duality Studies

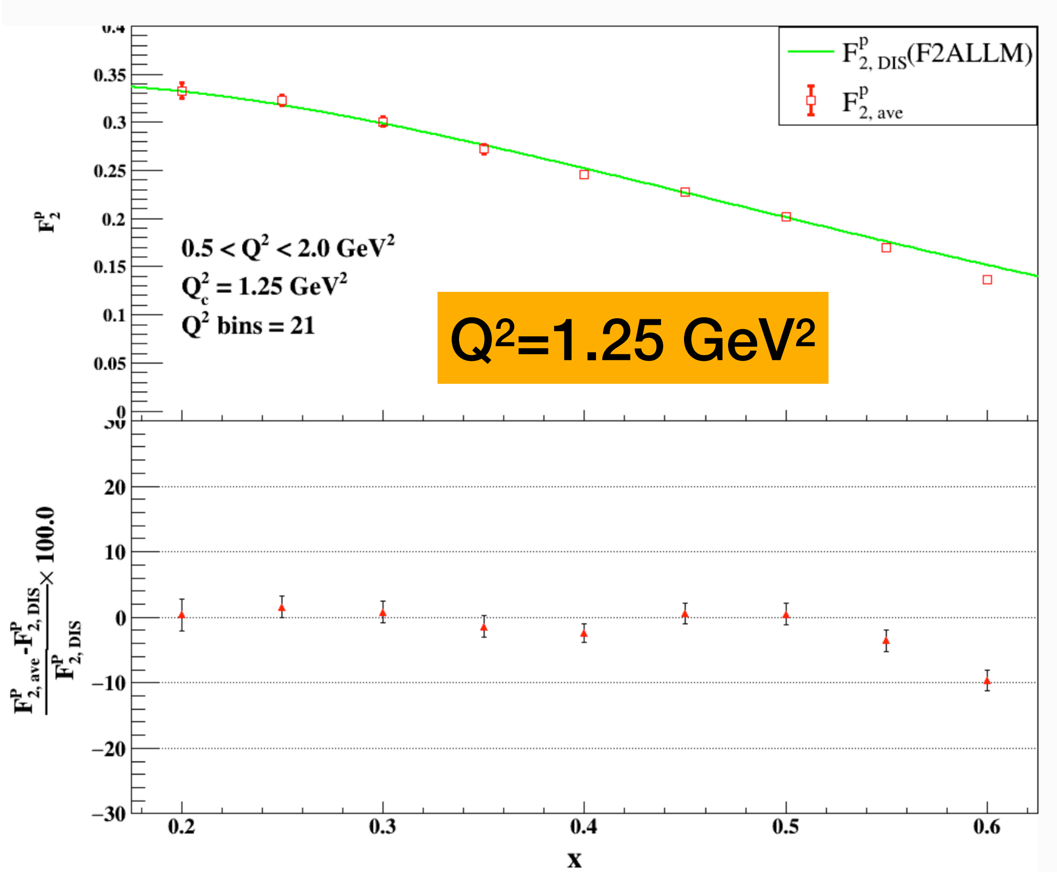


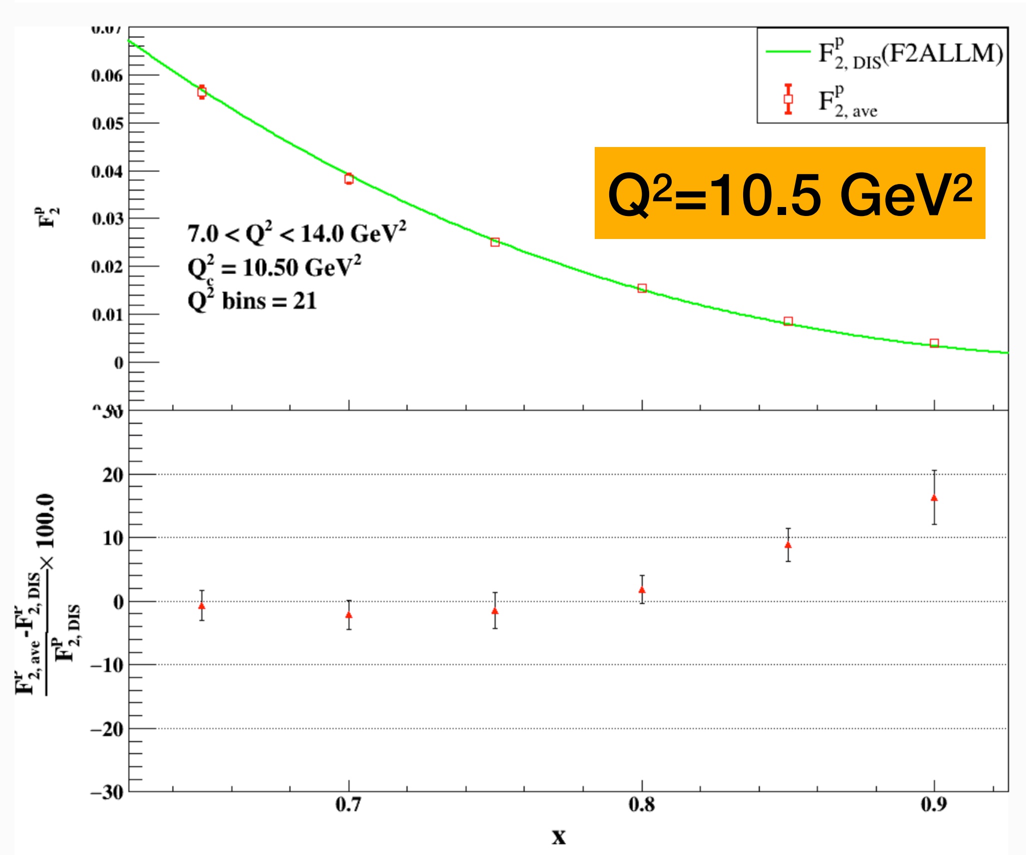


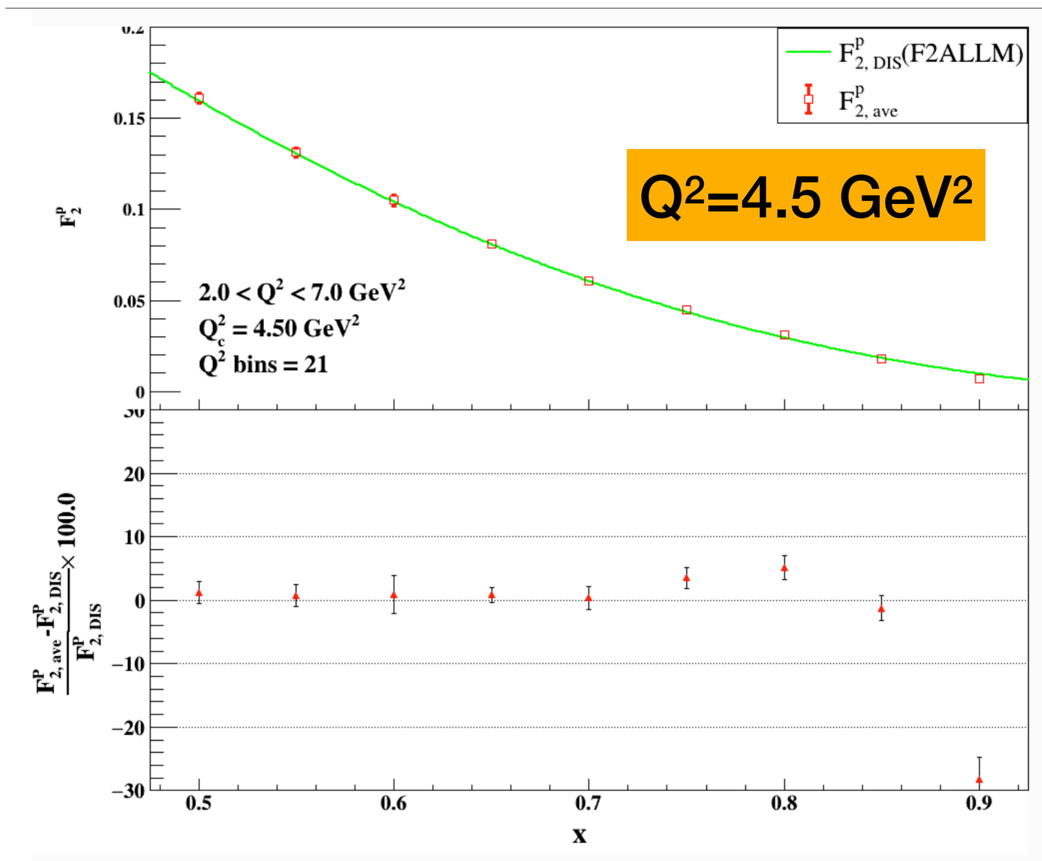
- **Duality studies at fixed x over a range of Q^2**
- **Peaks and valleys in resonance region shift along x as Q^2 changes**
- **Allows us to average x bins as an alternative method to study duality**
- **Analysis includes world data + E12-10-002**

Analysis and Figures by Debaditya Biswas

Quark Hadron Duality Studies







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

D. Biswas,[1] F. Gonzalez,[2] W. Henry,[3] A. Karki,[4] C. Morean,[5] A. Nadeeshani,[1] A. Sun,[6] D. Abrams,[7] Z. Ahmed,[8] B. Aljawrneh,[9] S. Alsalmi,[10] R. Ambrose,[8] W. Armstrong,[11] A. Asaturyan,[12] K. Assumin-Gyimah,[4] C. Ayerbe Gayoso,[13,4] A. Bandari,[13] S. Basnet,[8] V. Berdnikov,[14] H. Bhatt,[4] D. Bhetuwal,[4] W. U. Boeglin,[15] P. Bosted,[13] E. Brash,[16] M. H. S. Bukhari,[17] H. Chen,[7] J. P. Chen,[3] M. Chen,[7] M. E. Christy,[1] S. Covrig,[3] K. Craycraft,[5] S. Danagoulian,[9] D. Day,[7] M. Diefenthaler,[3] M. Dlamini,[18] J. Dunne,[4] B. Duran,[11] D. Dutta,[4] R. Ent,[3] R. Evans,[8] H. Fenker,[3] N. Fomin,[5] E. Fuchey,[19] D. Gaskell,[3] T. N. Gautam,[1] F. A. Gonzalez,[2] J. O. Hansen,[3] F. Hauenstein,[20] A. V. Hernandez,[14] T. Horn,[14] G. M. Huber,[8] M. K. Jones,[3] S. Joosten,[21] M. L. Kabir,[4] C. Keppel,[3] A. Khanal,[15] P. M. King,[18] E. Kinney,[22] M. Kohl,[1] N. Lashley-Colthirst,[1] S. Li,[23] W. B. Li,[13] A. H. Liyanage,[1] D. Mack,[3] S. Malace,[3] P. Markowitz,[15] J. Matter,[7] D. Meekins,[3] R. Michaels,[3] A. Mkrtchyan,[12] H. Mkrtchyan,[12] S.J. Nazeer,[1] S. Nanda,[4] G. Niculescu,[24] I. Niculescu,[24] D. Nguyen,[7] Nuruzzaman,[25] B. Pandey,[1] S. Park,[2] E. Pooser,[3] A. Puckett,[19] M. Rehfuss,[11] J. Reinhold,[15] B. Sawatzky,[3] G. R. Smith,[3] H. Szumila-Vance,[3] A. Tadepalli,[25] V. Tadevosyan,[12] R. Trotta,[14] S. A. Wood,[3] C. Yero,[15] and J. Zhang[2]
(for the Hall C Collaboration)

Experiment Spokespeople
Eric Christy
Thia Keppel
Simona Malace
Ioana Niculescu
Gabriel Niculescu
Dave Gaskell (EMC)

Graduate Students
Deb Biswas
Aruni Nadeeshani
Abel Sun
Abishek Karki (EMC)
Casey Morean (EMC)

Post Doc
Bill Henry (Contact)

Special Thanks to
Mark Jones
Carlos Yero
Greg Smith

Back-Ups

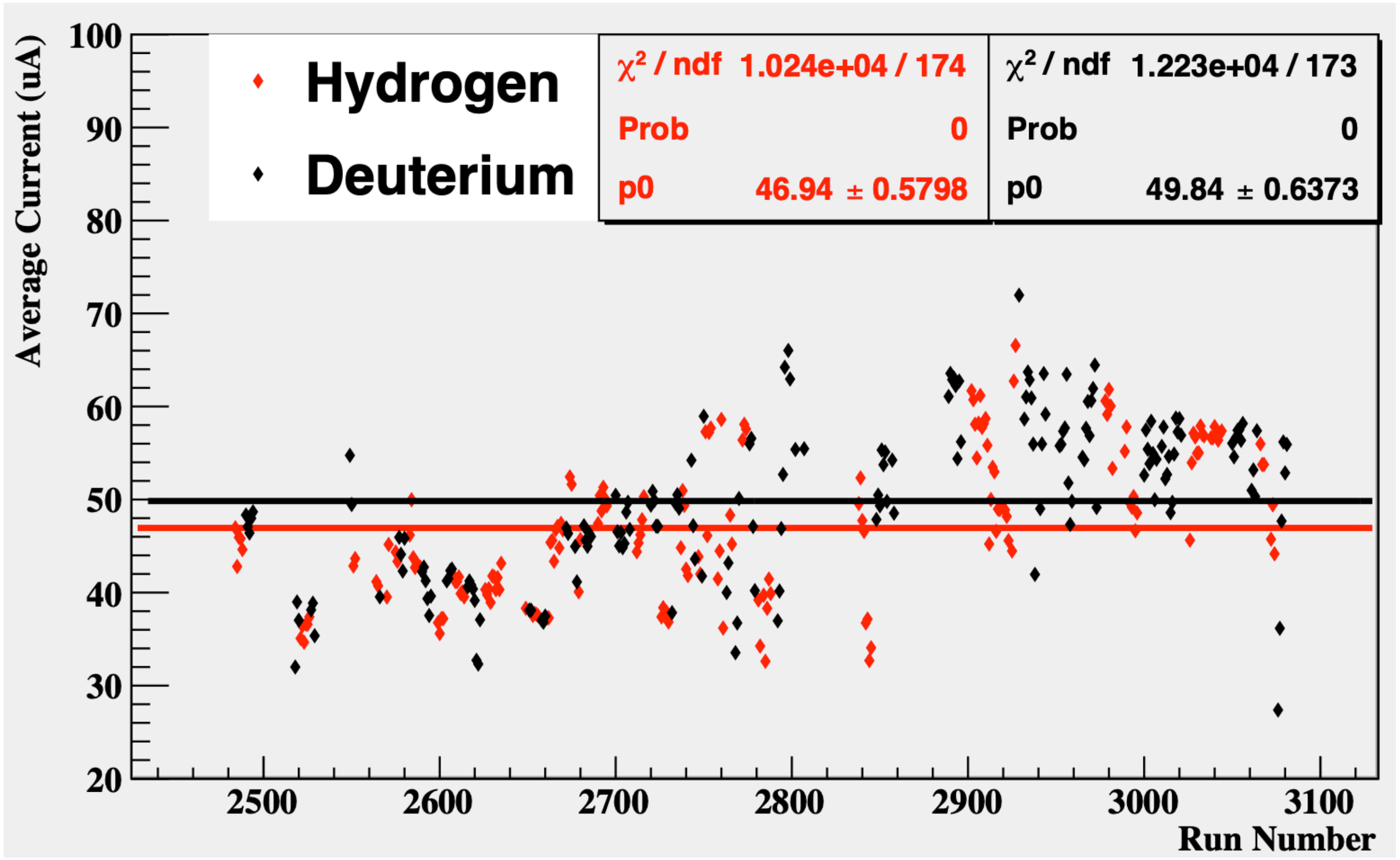
Target Density Uncertainty

- 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.

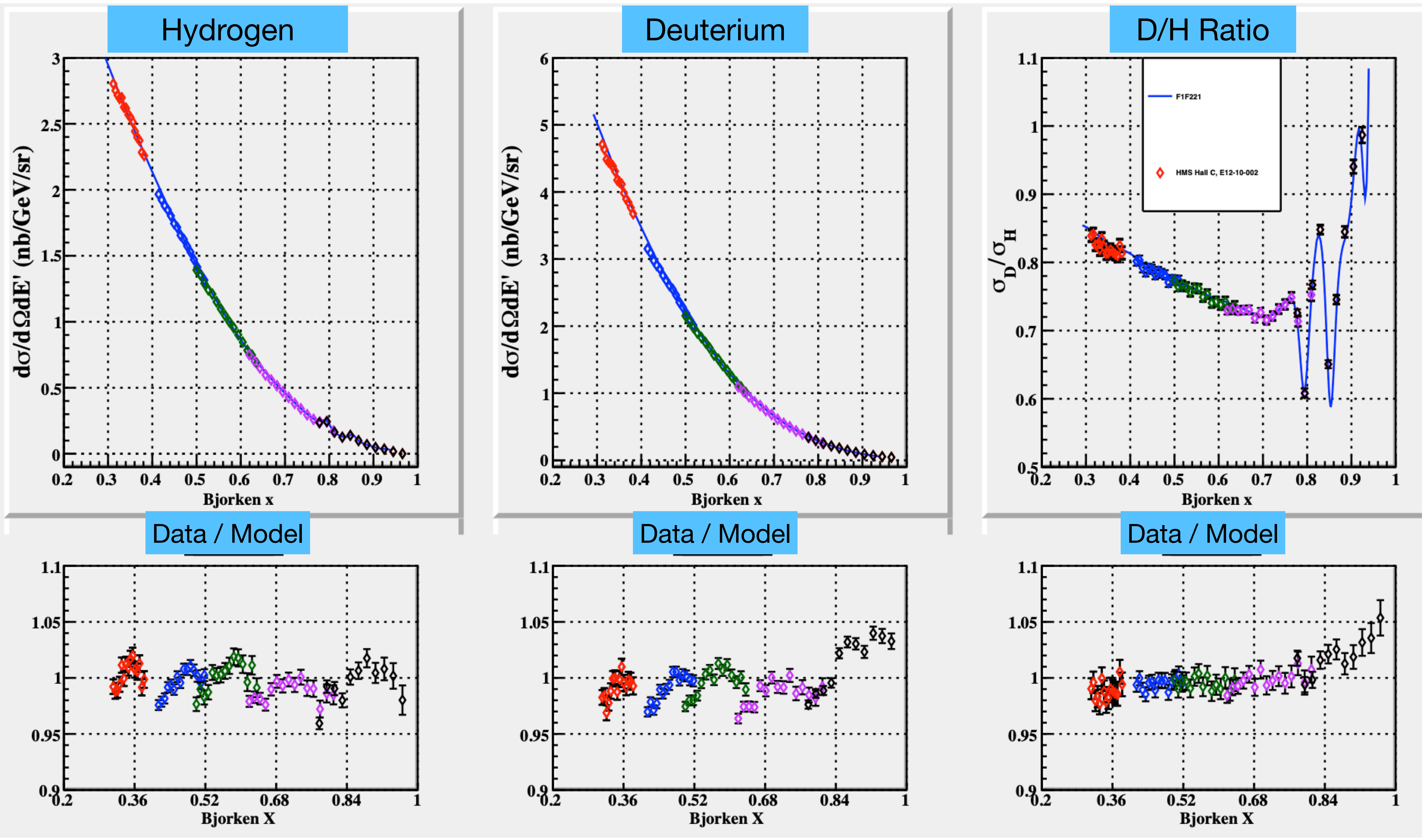
- An additional point to point uncertainty is calculated by taking the difference with the average current

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%	$\pm 0.1\%$	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%)



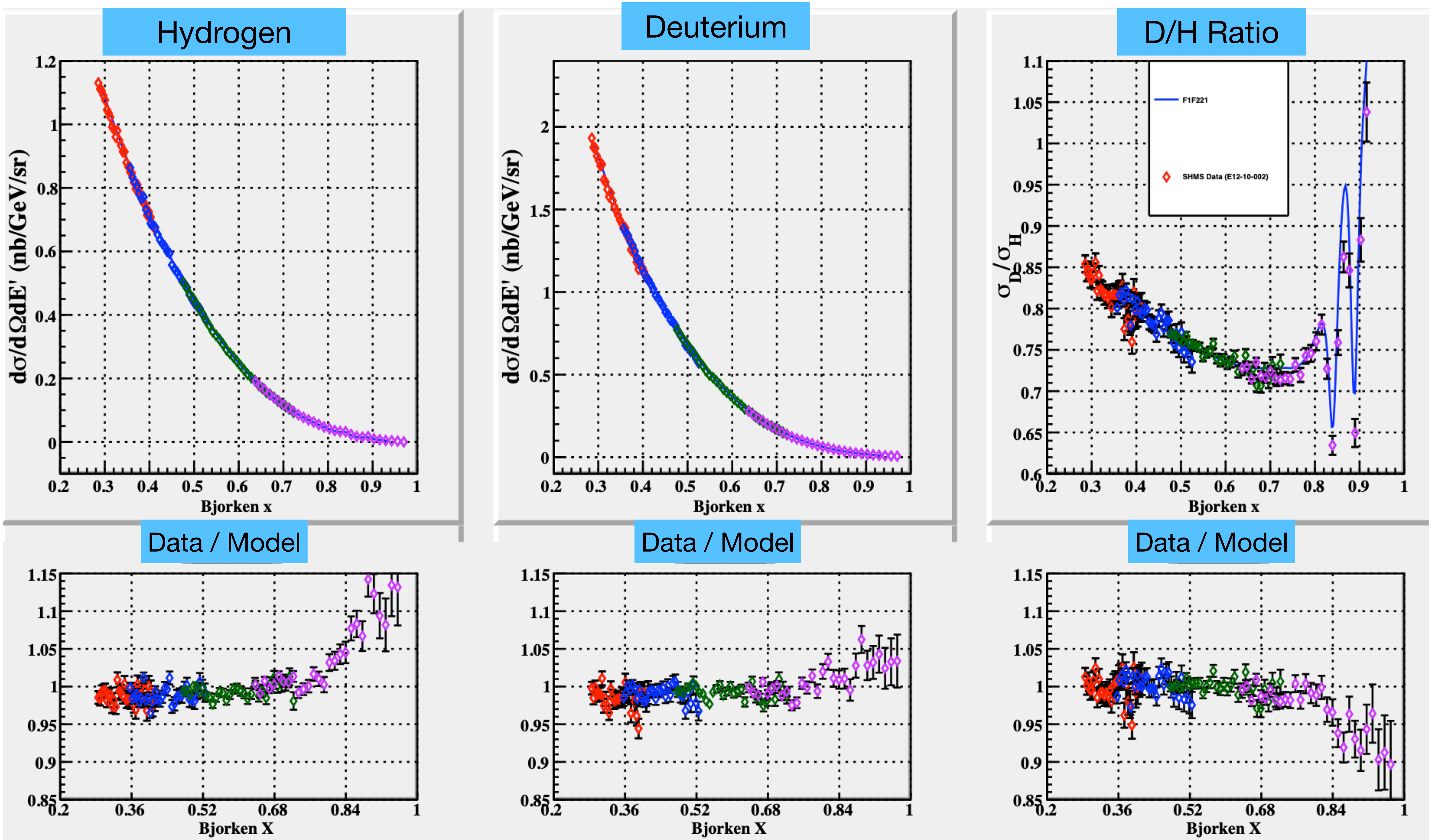
F2 Results

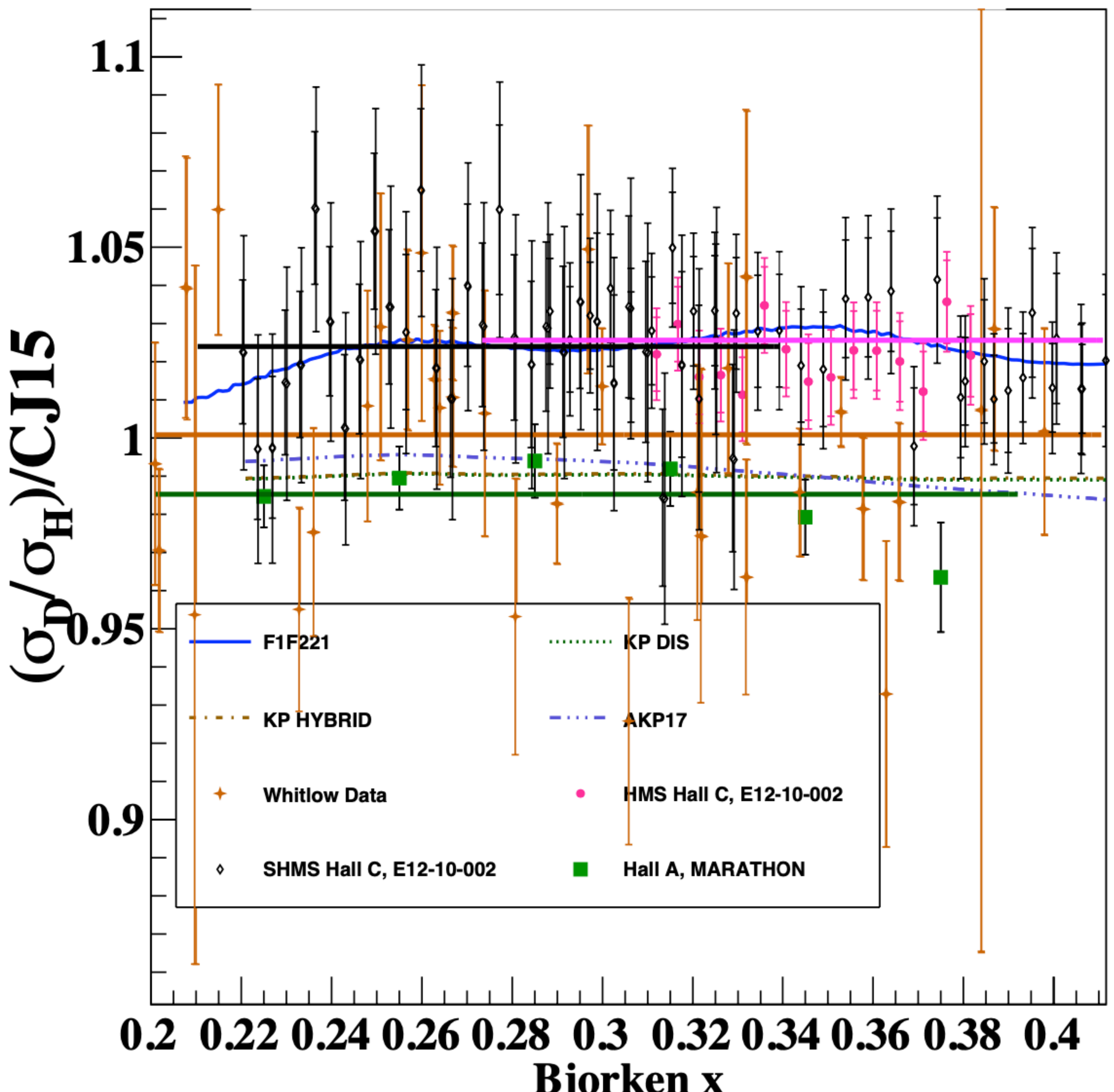
HMS @ 21 degrees



F2 Results

SHMS @ 29 degrees



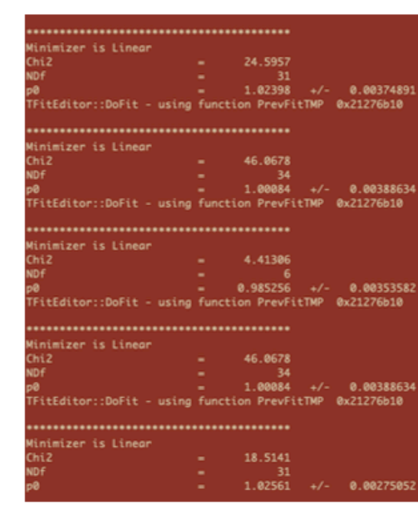


1.023 +/- 0.004

1.026 +/- 0.003

1.001 +/- 0.004

0.985 +/- 0.004



```
****************************************
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

C. Cocuzza,[1] C. E. Keppel,[2] H. Liu,[3] W. Melnitchouk,[2] A. Metz,[1] N. Sato,[2] and A. W. Thomas[4]

[1] *Department of Physics, SERC, Temple University, Philadelphia, Pennsylvania 19122, USA*
[2] *Jefferson Lab, Newport News, Virginia 23606, USA*
[3] *Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003, USA*
[4] *CSSM and CoEPP, Department of Physics, University of Adelaide SA 5005, Australia*

Jefferson Lab Angular Momentum (JAM) Collaboration

(Dated: April 15, 2021)

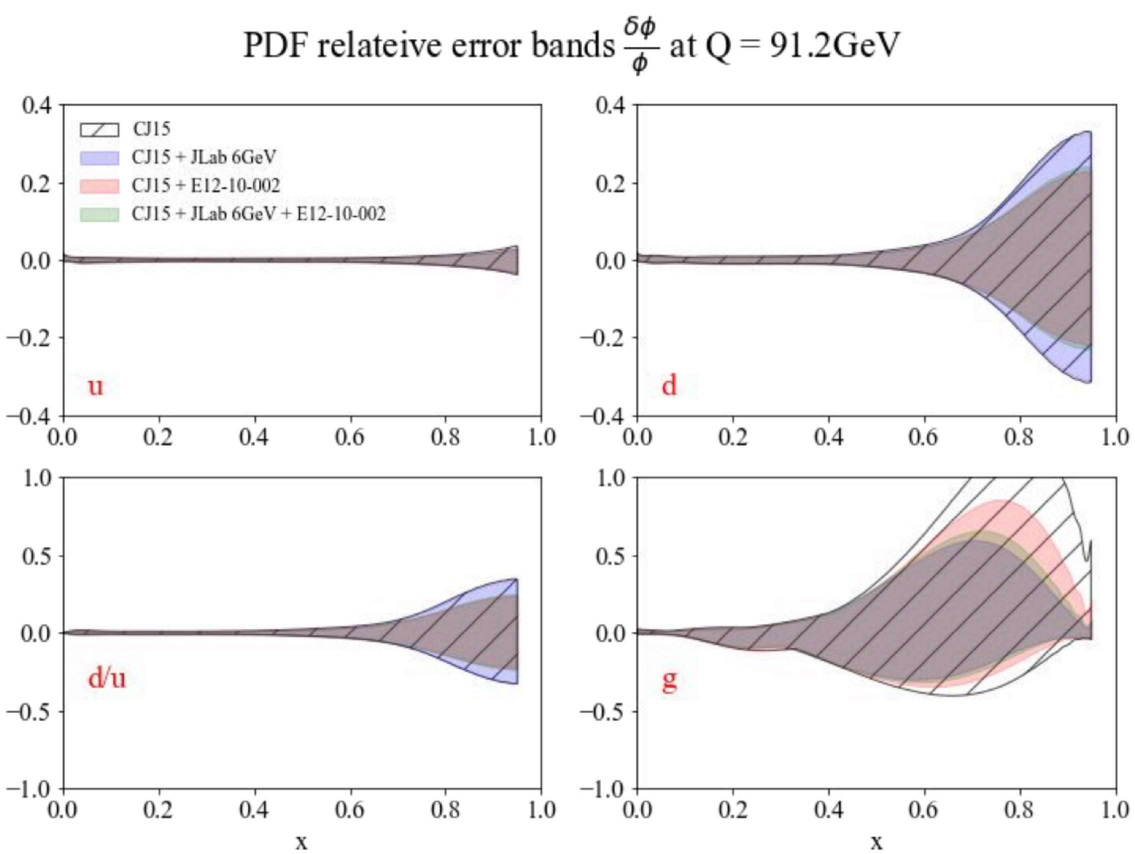
arXiv:2104.06946

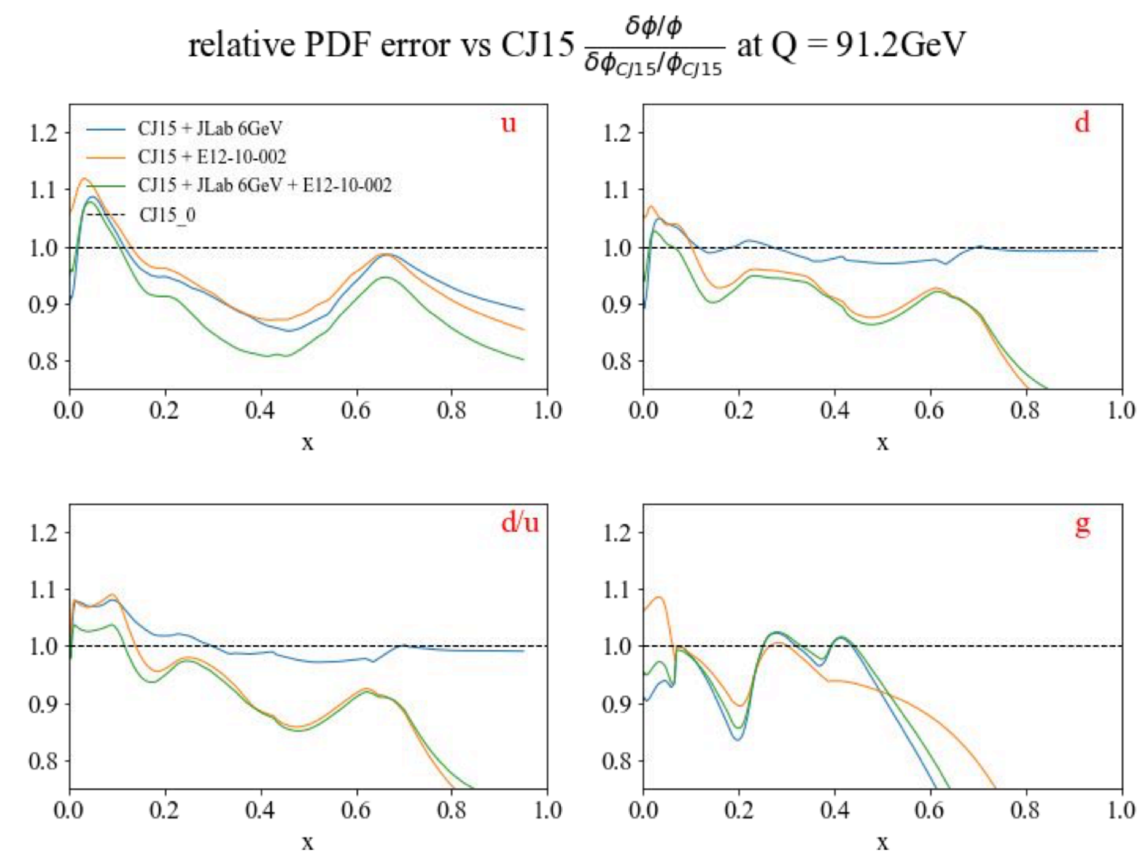
TABLE I. Summary of the χ^2 values per number of points $N_{\rm dat}$ for the data used in this analysis. The MARATHON and JLab E03-103 ^{3}He/D are separated from the rest of the fixed target data, and their fitted normalizations are shown.

process	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$	fitted norm.
DIS			
MARATHON ^{3}He/^{3}H	22	0.63	1.007(6)
MARATHON D/p	7	0.95	1.019(4)
JLab E03-103 ^{3}He/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**	

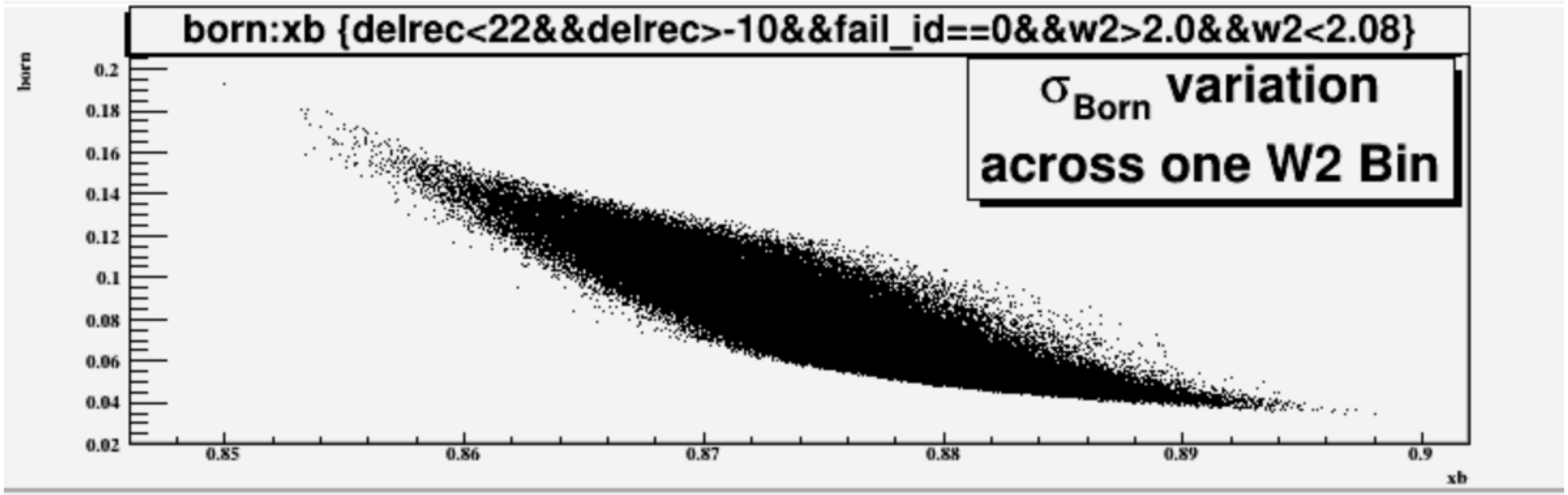
Impact on PDF uncertainties

Reference: CJ15_0 (the original CJ15 which already included BoNUS6 and E00116)
Set 1: CJ15 + this data
Set 2: CJ15 + more JLab 6GeV data (Ioana, E99118, E94110, E06009, E03103)
Set 3: CJ15 + this data + JLab 6GeV data

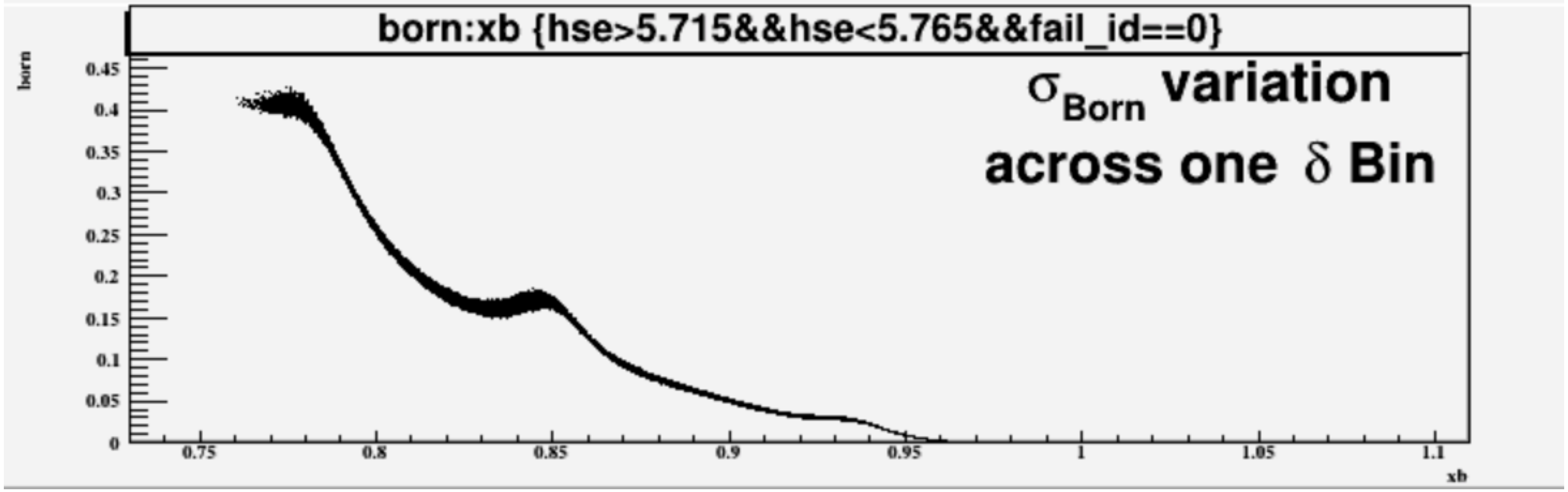




Back Up



born:xb {delrec<22&&delrec>-10&&fail_id==0&&w2>2.0&&w2<2.08}
σ_{Born} variation
across one W2 Bin
born
xb



born:xb {hse>5.715&&hse<5.765&&fail_id==0}
σ_{Born} variation
across one δ Bin
born
xb

F2 Results

Slide from Winter

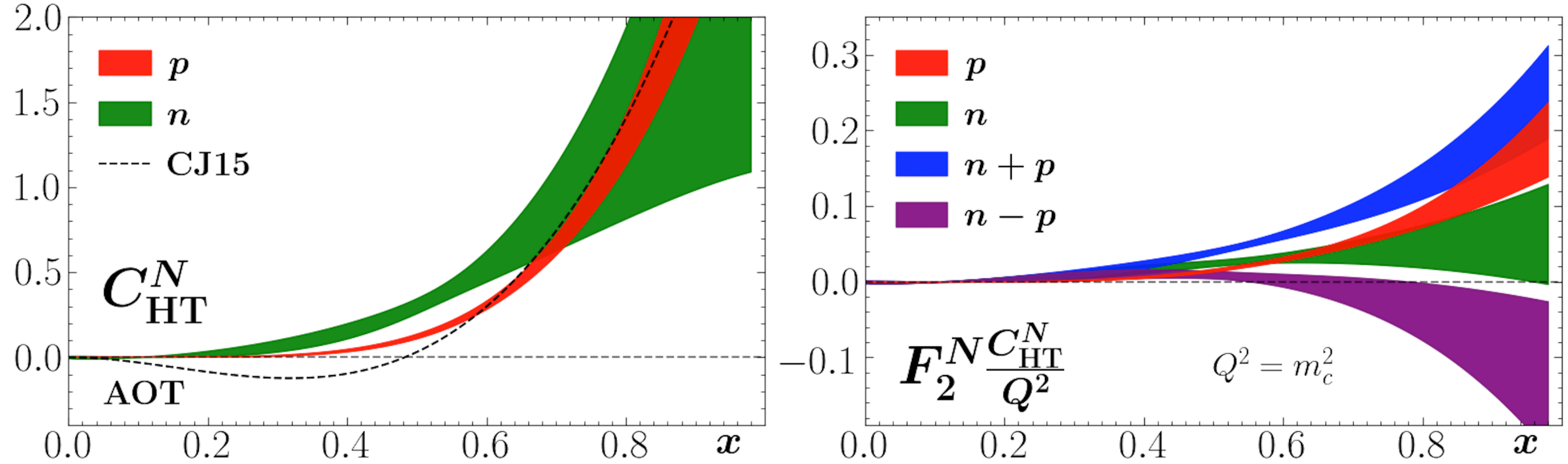
JAM Impact Study

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

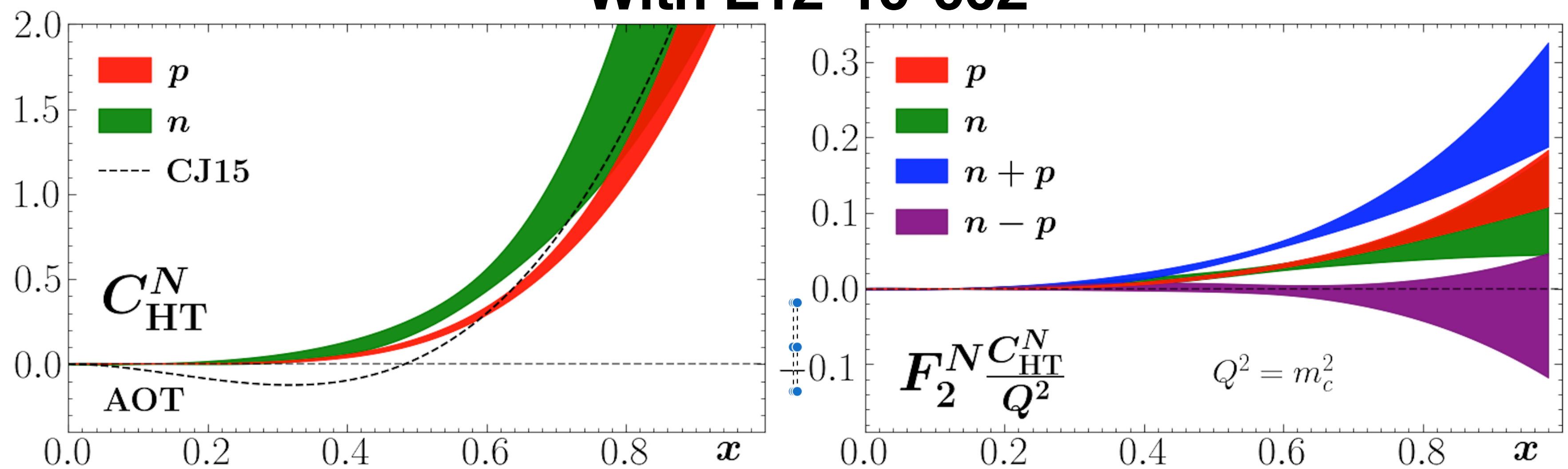
- D/H ratio was provided to Jefferson Lab Angular Momentum Collaboration (JAM) to incorporate into their global QCD analysis of PDFs
- New F2 data significantly improves the uncertainty of higher twist corrections to F2

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

Without E12-10-002



With E12-10-002



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