New Measurements of the Deuteron to Proton F_2 Structure Function Ratio and beyond…

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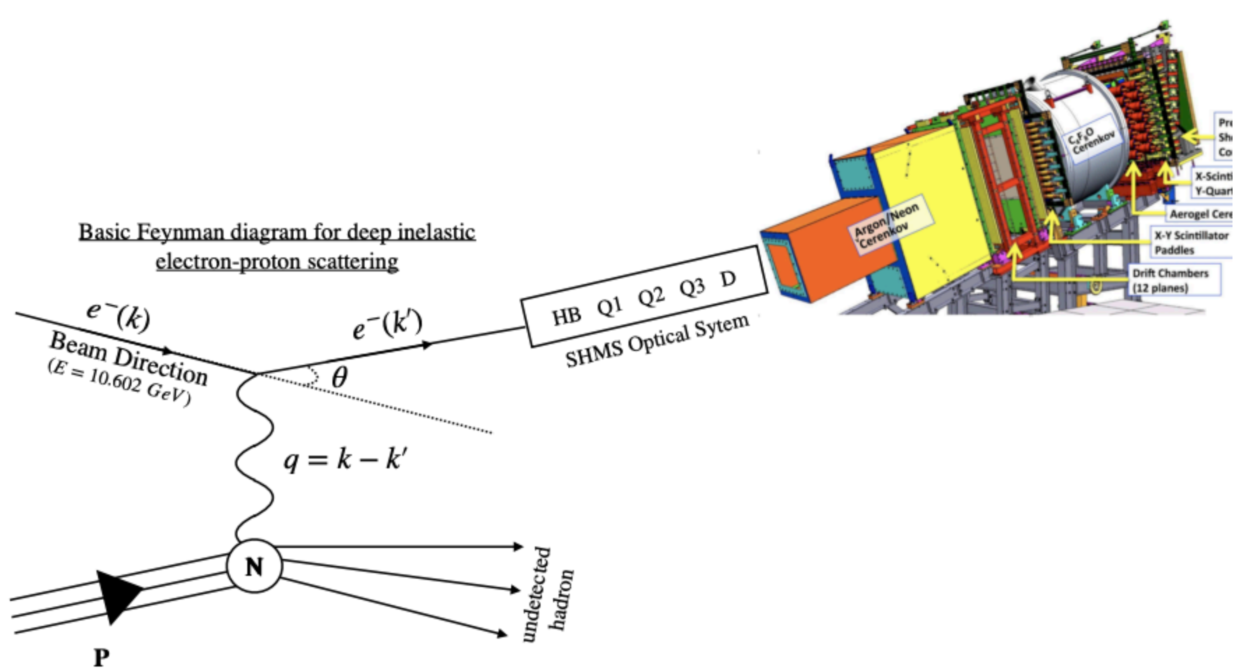
Hall C Winter collaboration Meeting

Jefferson Lab - Jan 27, 2026

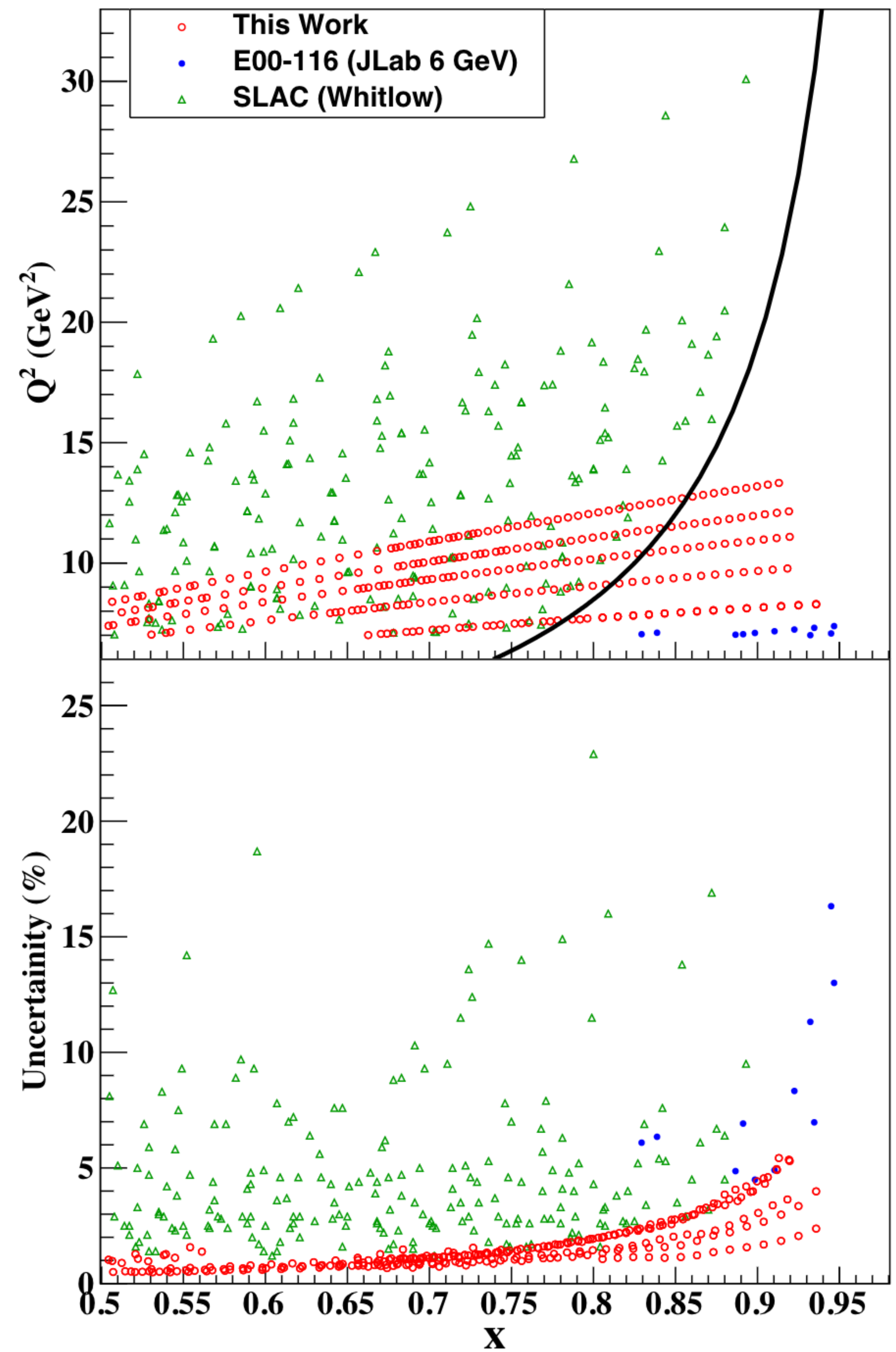
E12-10-002 Data

1. Top Panel
    1. Data are shown for the range $x > 0.5$ & $Q^2 > 6\ GeV^2$
    2. Green triangle : Whitlow reanalysis of the SLAC data
    3. Red circle : Kinematic coverage of E12-10-002 data
    4. Blue dots : JLab 6 GeV data , Experiment E00-116
    5. Solid curve corresponds to $W^2 = 3\ GeV^2$
2. Bottom Panel
    1. Statistical uncertainty of σ_D/σ_H
3. Take away
    1. Data was poorly populated prior to this experiment for $W^2 < 3\ GeV^2$ and $Q^2 > 6\ GeV^2$
    2. This work extends the data into the resonance region

- Ran in the spring of 2018 in parallel with EMC experiment
- Targets used : liquid hydrogen and liquid deuterium
- Large Bjorken x coverage
- Large Q^2 coverage using both the HMS and SHMS spectrometers



$$Q^2 = 4EE'sin^2(\frac{\theta}{2}) \qquad X = \frac{Q^2}{2M\nu} \qquad W^2 = M^2 + 2M\nu - Q^2$$



Cross Section Extraction Method

- The method used to extract the cross-section : **Monte-Carlo Ratio Method**

- For each bin in $(\Delta E', \Delta\Omega)$, number of total electrons detected by the spectrometer

$$N^{e-} = L \times (\frac{d\sigma}{d\Omega dE'}) \times (\Delta E' \Delta\Omega) \times \epsilon_{tot} \times A(E', \theta) + BG \qquad \ldots (1)$$

where, L = Integrated Luminosity = $N^{e-}_{beam} \times \frac{N_{target}}{Area}$

ϵ_{tot} = Total Efficiency

$A(E', \theta)$ **=** Acceptance for the bin

BG = Background

- Hence the efficiency corrected yield is defines as -

$$Y = \frac{N^{e-} - BG}{\epsilon_{tot}} = L \times \sigma \times (\Delta E' \Delta\Omega) \times A(E', \theta) \qquad \ldots (2)$$

Cross Section Extraction Method

- Yield can be measured from the experiment (Y_{data}) and also the Monte-Carlo (Y_{MC})

$$Y_{data} = L \times \sigma^{data} \times (\Delta E' \Delta\Omega) \times A(E', \theta) \qquad \ldots(3)$$

$$Y_{MC} = L \times \sigma^{MC} \times (\Delta E' \Delta\Omega) \times A_{MC}(E', \theta) \qquad \ldots(4)$$

- Taking ratio of equation (3) and (4)

$$\frac{Y_{data}}{Y_{MC}} = \frac{L \times \sigma^{data} \times (\Delta E' \Delta\Omega) \times A(E', \theta)}{L \times \sigma^{MC} \times (\Delta E' \Delta\Omega) \times A_{MC}(E', \theta)} \qquad \ldots(5)$$

- Considering $A(E', \theta) = A_{MC}(E', \theta)$ and Monte-Carlo generated with *same luminosity* with data-

$$\boxed{\sigma^{data} = \sigma^{MC} \times \frac{Y_{data}}{Y_{MC}} \qquad \ldots(6)}$$

- **Now the question is how to get the σ^{MC}, Y_{MC} and Y_{data} ?**

$\sigma^{data} = \sigma^{MC} \times \frac{Y_{data}}{Y_{MC}}$: Extraction of σ^{MC}

- F1F221 (by M. Eric Christy) model is used to get the σ^{MC}
- F1F221 is a fit to the global data which produces F_1 and F_2
- The structure functions are related to the reduced cross-sections as follows

Total differential scattering cross-section

Transverse virtual photon cross-section

$$\frac{d^2\sigma}{d\Omega dE'} = \Gamma[\sigma_T(x, Q^2) + \epsilon\sigma_L(x, Q^2)]$$

Longitudinal virtual photon cross-section

$$\Gamma = \frac{\alpha K}{2\pi Q^2}\frac{E'}{E}\frac{1}{1-\epsilon} \qquad K = \frac{2M\nu - Q^2}{2M} \qquad \epsilon = [1 + 2(1 + \frac{Q^2}{4M^2x^2}tan^2\frac{\theta}{2})]^{-1}$$

$$\sigma_T = \frac{4\pi\alpha}{KM}F_1 \qquad \sigma_L = \frac{4\pi^2\alpha}{KM\nu}[(1 + \frac{\nu^2}{Q^2})MF_2 - \nu F_1]$$

$\sigma^{data} = \sigma^{MC} \times \frac{Y_{data}}{Y_{MC}}$: Extraction of Y_{MC}

- For the Monte-Carlo first 50 million events of scattered electrons are generated uniformly in $(E', X' \equiv \frac{dY}{dZ}, Y' \equiv \frac{dY}{dZ})$ space using mc-single-arm

- Physics weighting is applied to the uniformly generated events

- The Monte-Carlo yield need to be calculated with the same luminosity as data. Physics weighted, (uniformly) generated Monte-Carlo events are multiplied with a factor to get the Y_{MC} :
  $Y_{MC}(E', \theta) = N^{e^-} \times scale\ factor$
  scale factor is defined as the ratio of data and MC luminosity:
  $$scale\ factor = \frac{L_{data}}{L_{MC}} \times \epsilon_{tot} \times \frac{E_{LT} \times C_{LT}}{PS}$$
  where,

  $$L_{data} = target\ density \times target\ length \times Avogadro's\ number \times \frac{1}{atomic\ mass} \times \frac{beam\ charge}{elementary\ charge}$$
  $L_{MC} = \frac{generated\ events}{\Delta E'\ \Delta\Omega}$ (because we generate the events uniformly)
  $\epsilon_{tot} = \epsilon_{tracking} \times \epsilon_{cerenkov} \times \epsilon_{calorimeter}$: total efficiency
  C_{LT} : computer live time
  E_{LT} : electronic live time
  PS : prescale factor

$\sigma^{data} = \sigma^{MC} \times \frac{Y_{data}}{Y_{MC}}$: Extraction of Y_{data}

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 :

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

Computer live time

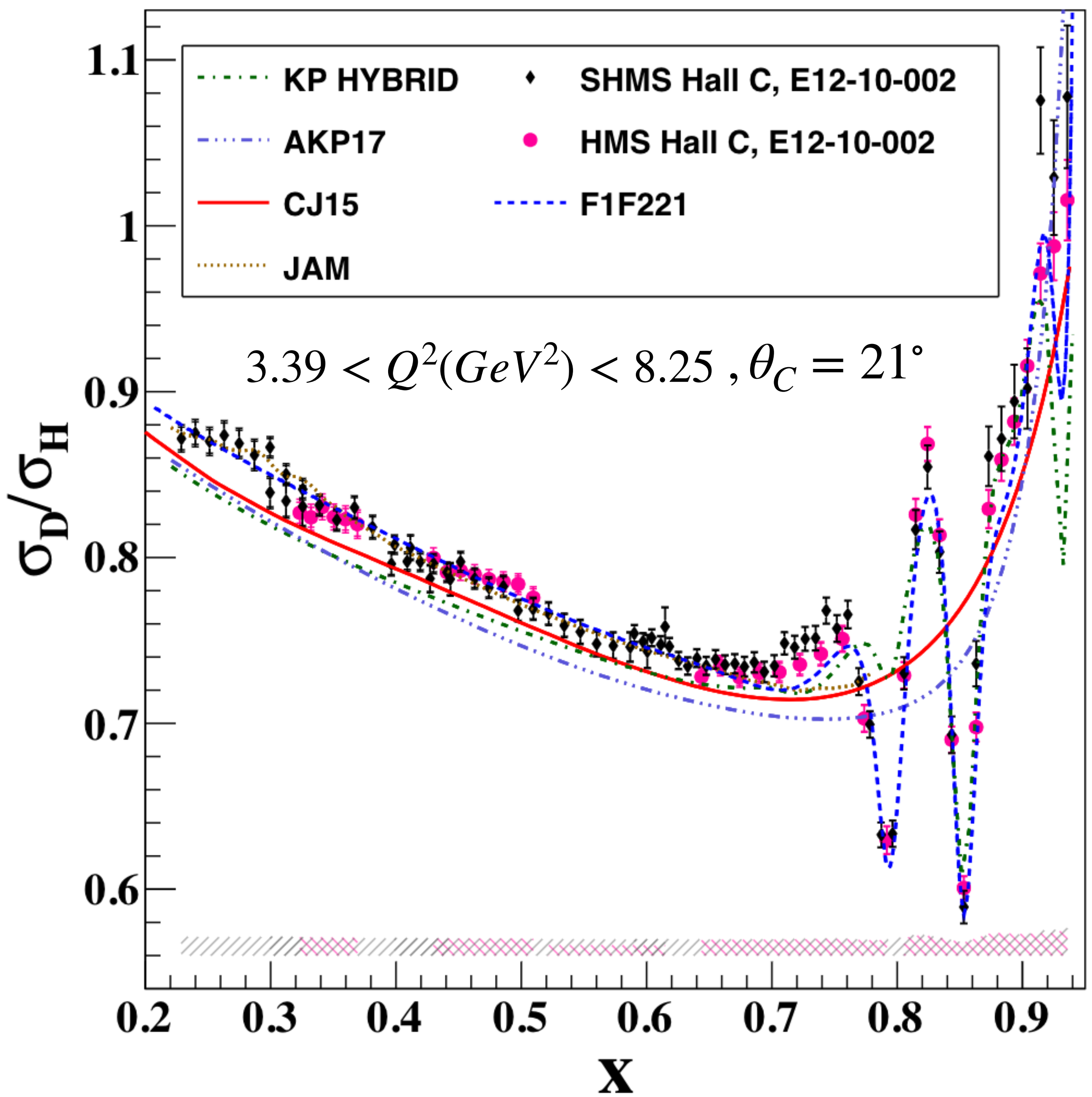
Electronic live time

$$\sigma^{data} = \sigma^{MC} \times \frac{Y_{data}}{Y_{MC}}$$

σ_D/σ_H : SHMS & HMS

1. σ_D/σ_H ratio were compared for :
    1. SHMS data
    2. HMS data
    3. F1F221 model (used to extract the cross sections in this work)
    4. KP HYBRID
    5. AKP17
    6. CJ15
    7. JAM
2. Excellent agreement between SHMS and HMS for $\theta_C = 21^\circ$
3. The error bars include uncorrelated statistical and systematic errors
4. The error band include correlated systematic error and an overall normalization uncertainty of 1.1% (due to the uncertainty in the target density)
5. F1F221 or any other model does not include this data
6. Total point to point error 0.6 - 5.4 (with $W^2 > 3\ GeV^2$ 2.9) %
7. Total correlated error 1.2 - 2.9 (with $W^2 > 3\ GeV^2$ 2.1) %

published in PRL



From :Bill Henry

σ_D/σ_H : SHMS

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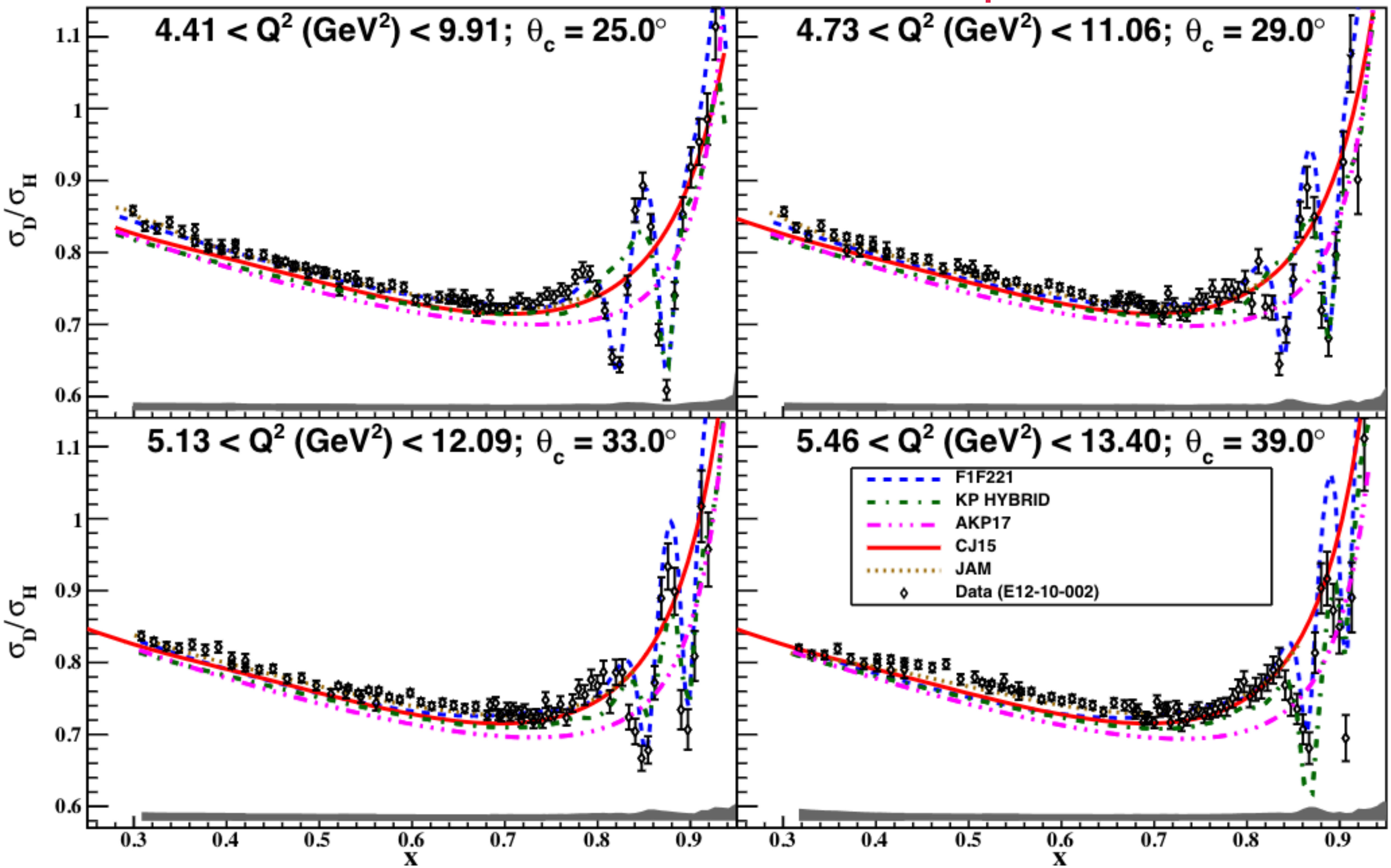

From :Bill Henry

Impact Study : PDF Fitting

1. Impact of the new data were studied with CJ15 framework
2. d/u ratio for proton were plotted for $Q = 3\ GeV$ and for wide range of x
3. $W^2 > 3.5\ GeV^2$ cut on data to eliminate the resonance region
4. Magenta : CJ15 fit ONLY
5. Pink : CJ15 fit + data from this work
6. The central value of the d/u changes as much as 10% for x>0.7
    1. Previous absence of the deuterium data at high x is responsible for this change
7. The relative error in d/u ratio decreases by approximately 20% across the entire range range of x
8. To fit the data with the model, a normalization factor of -2.1% was applied to the data
    1. The x dependent correlated error for the data is 1.3-2.1%
    2. Another experiment (E12-10-007, EMC effect) ran along with this experiment observe the 2% normalization shift in result compared to the previous data , and the direction of the shift is consistent with this work

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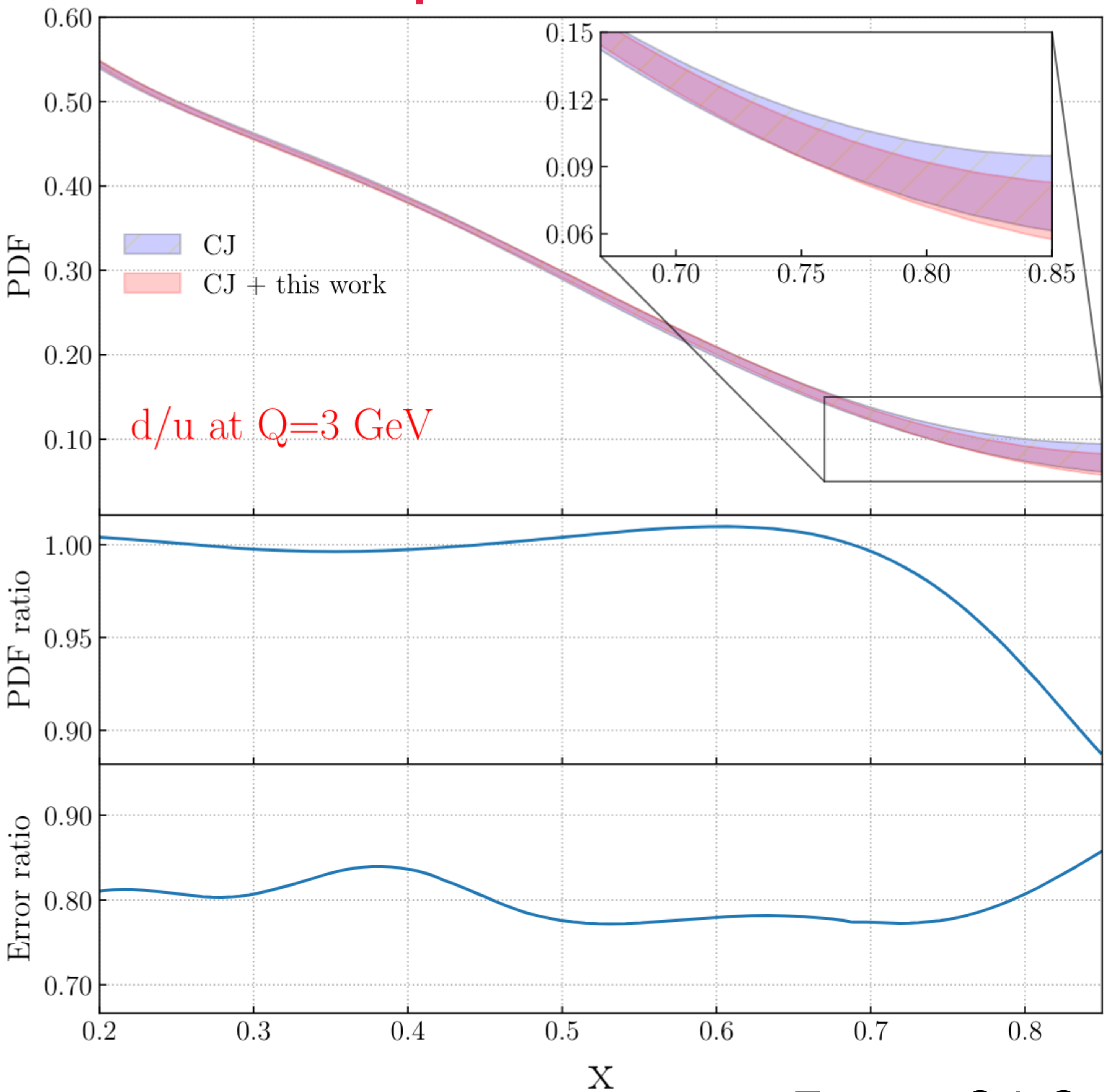
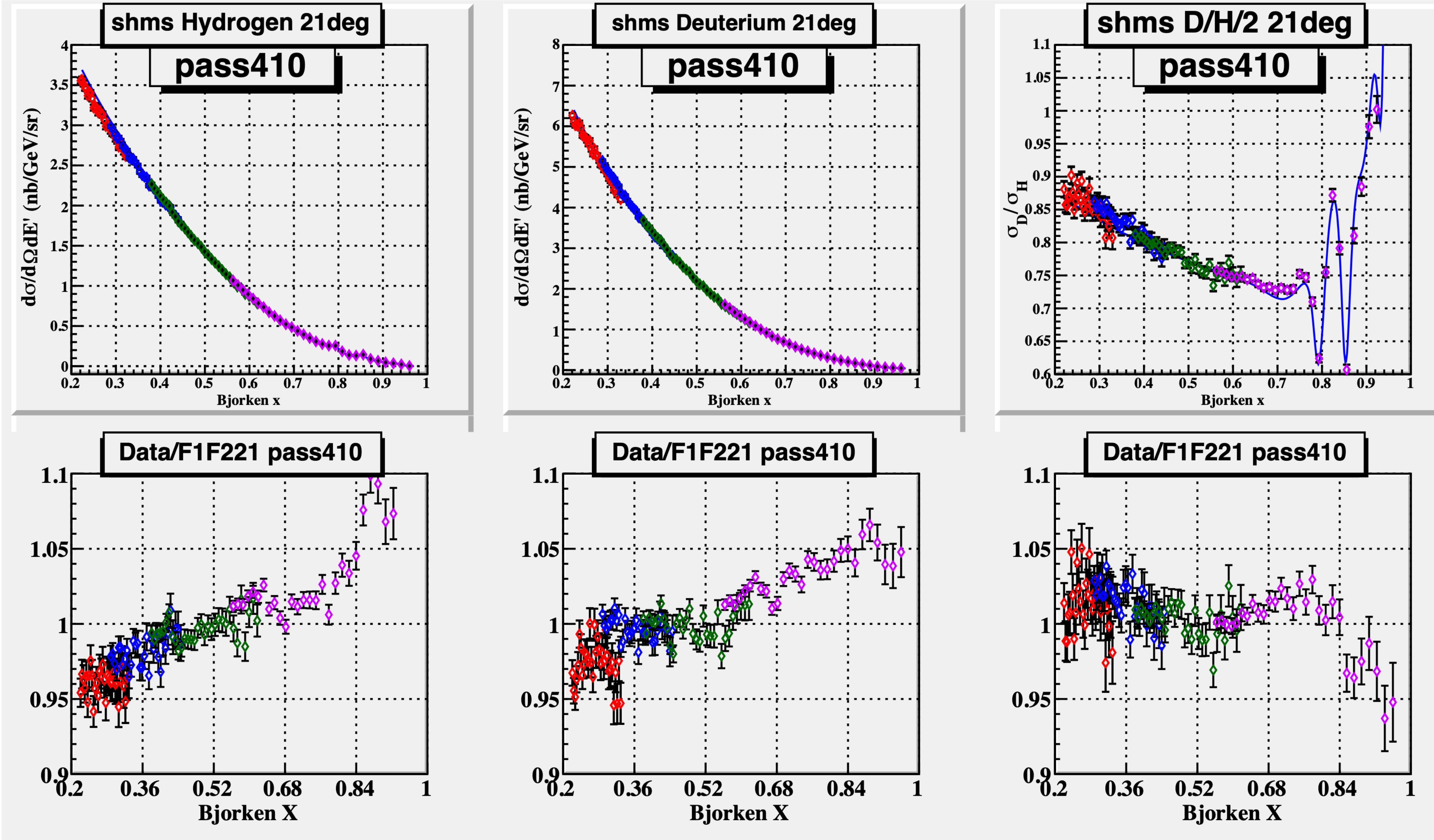


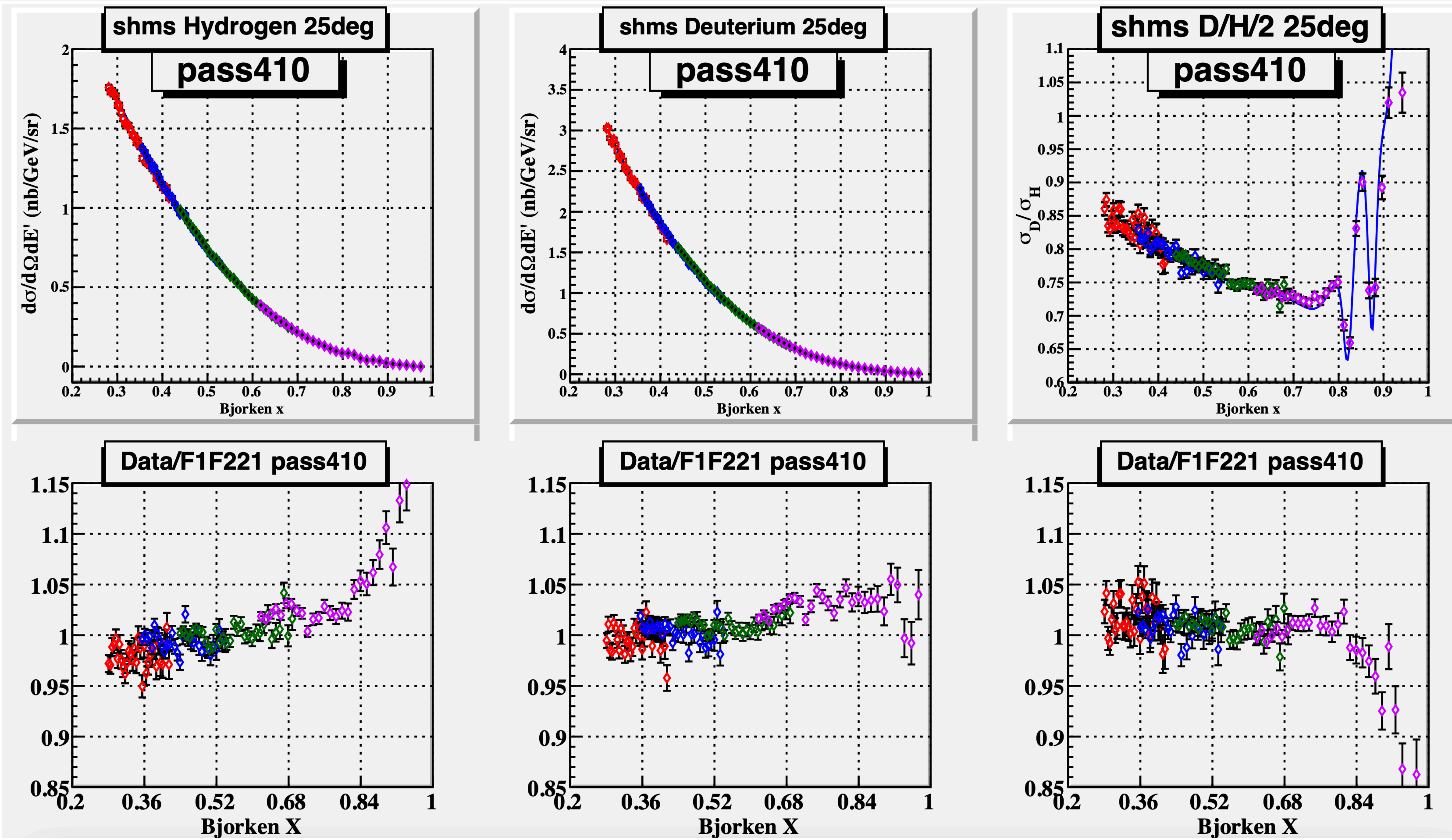
From :CJ Collab.

Extraction of Cross-section : SHMS 21 deg



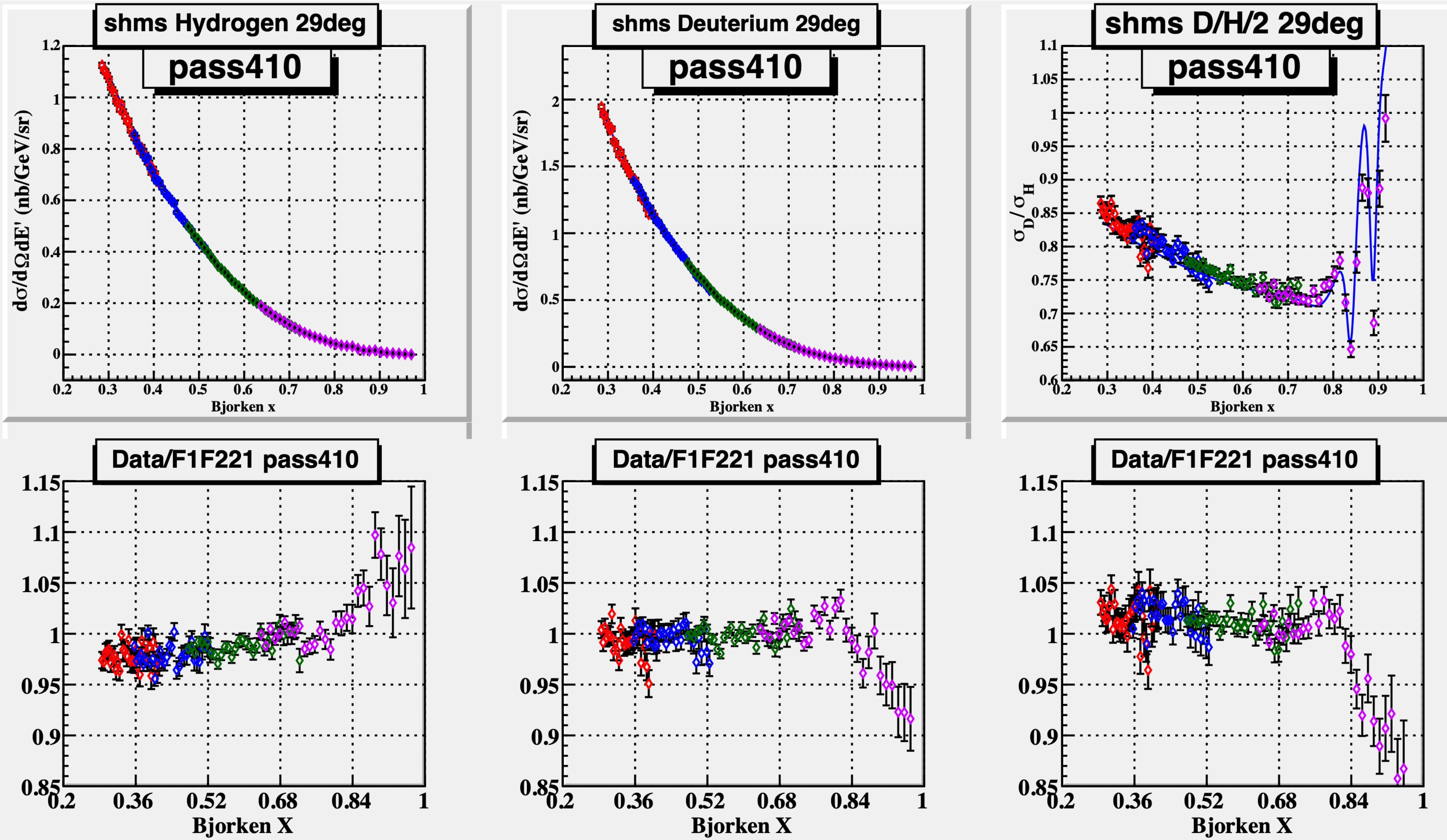
From :Bill Henry

Extraction of Cross-section : SHMS 25 deg



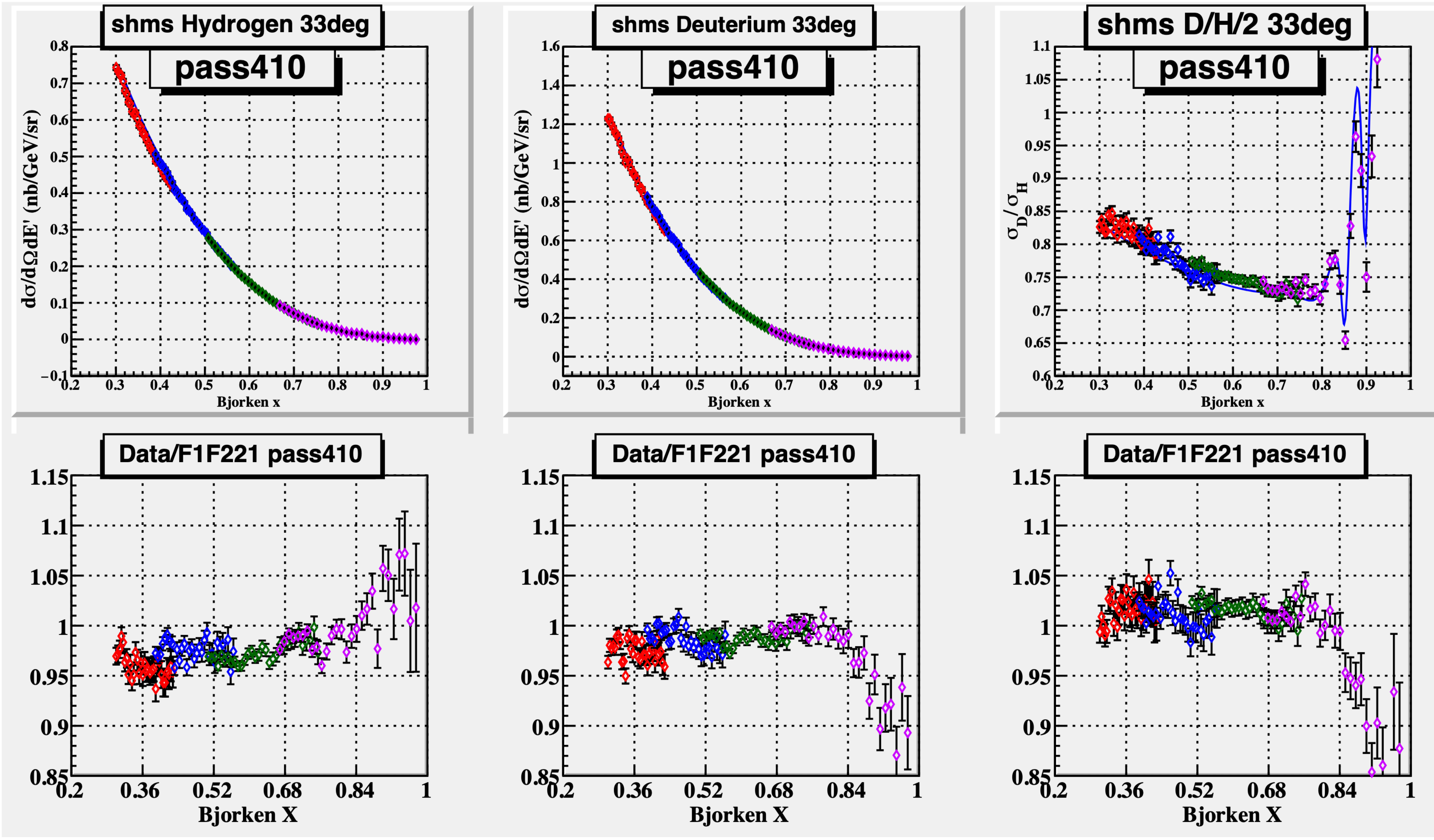
From :Bill Henry

Extraction of Cross-section : SHMS 29 deg



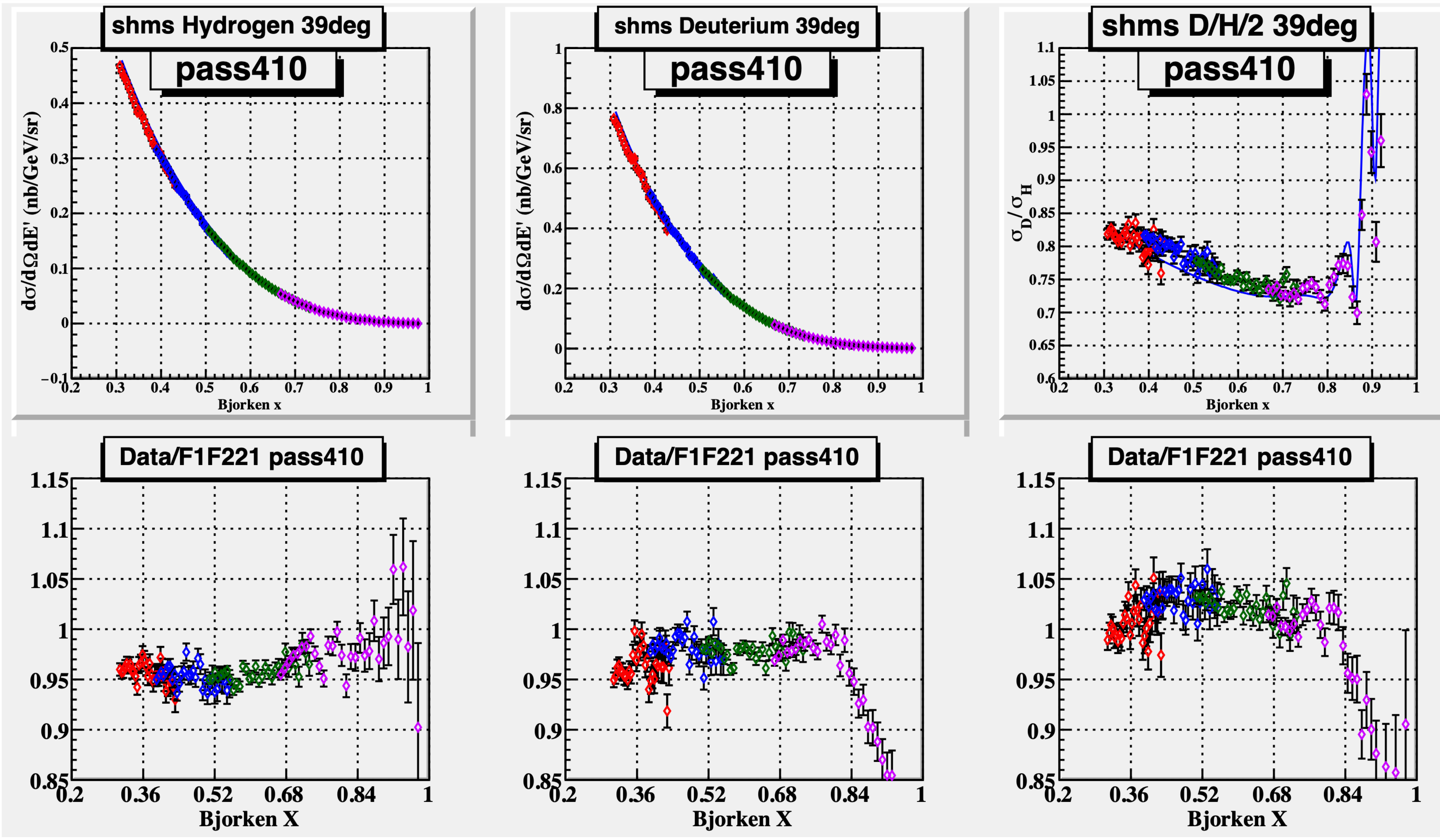
From :Bill Henry

Extraction of Cross-section : SHMS 33 deg



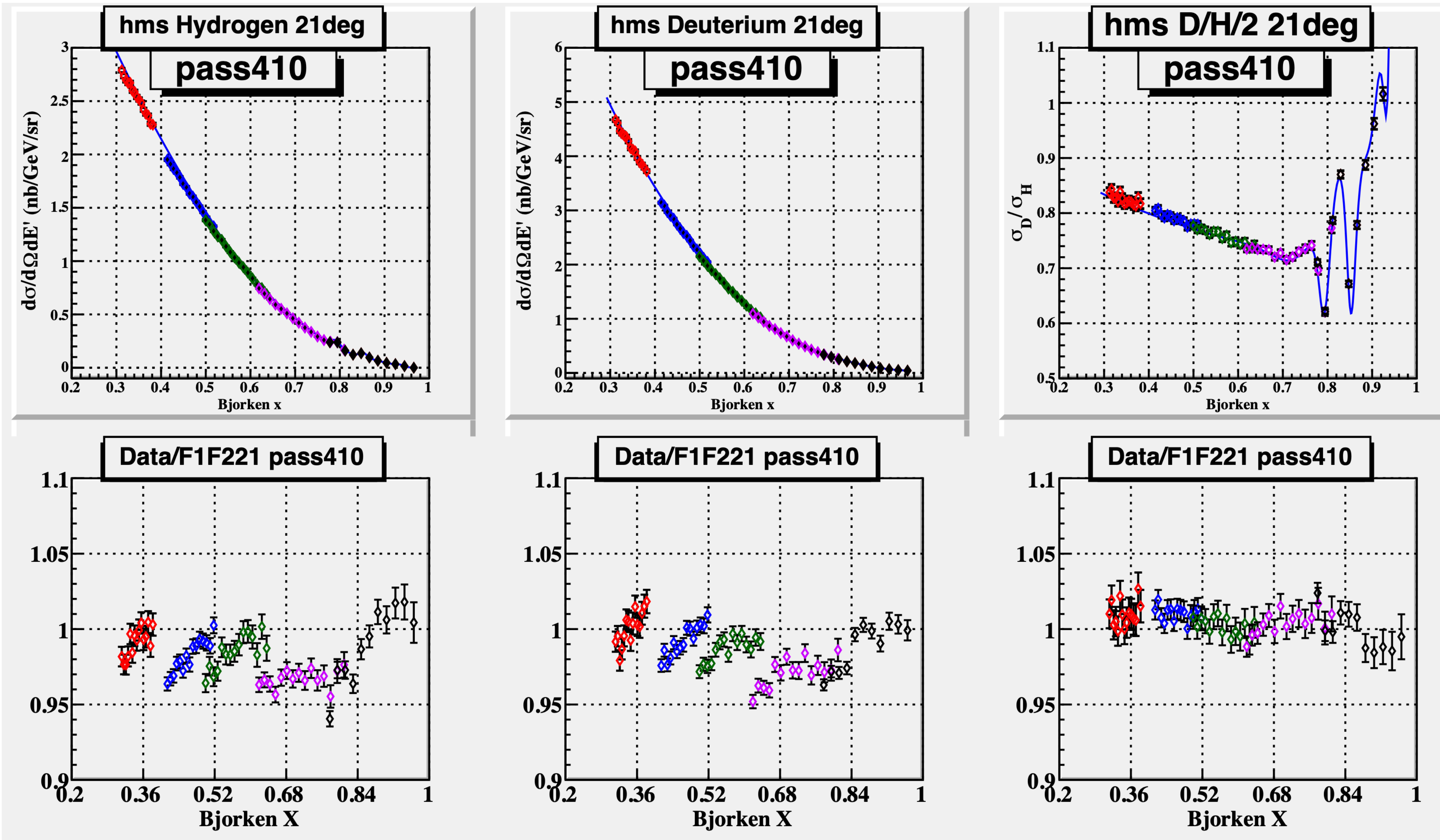
From :Bill Henry

Extraction of Cross-section : SHMS 39 deg



From :Bill Henry

Extraction of Cross-section : HMS 21 deg



From :Bill Henry

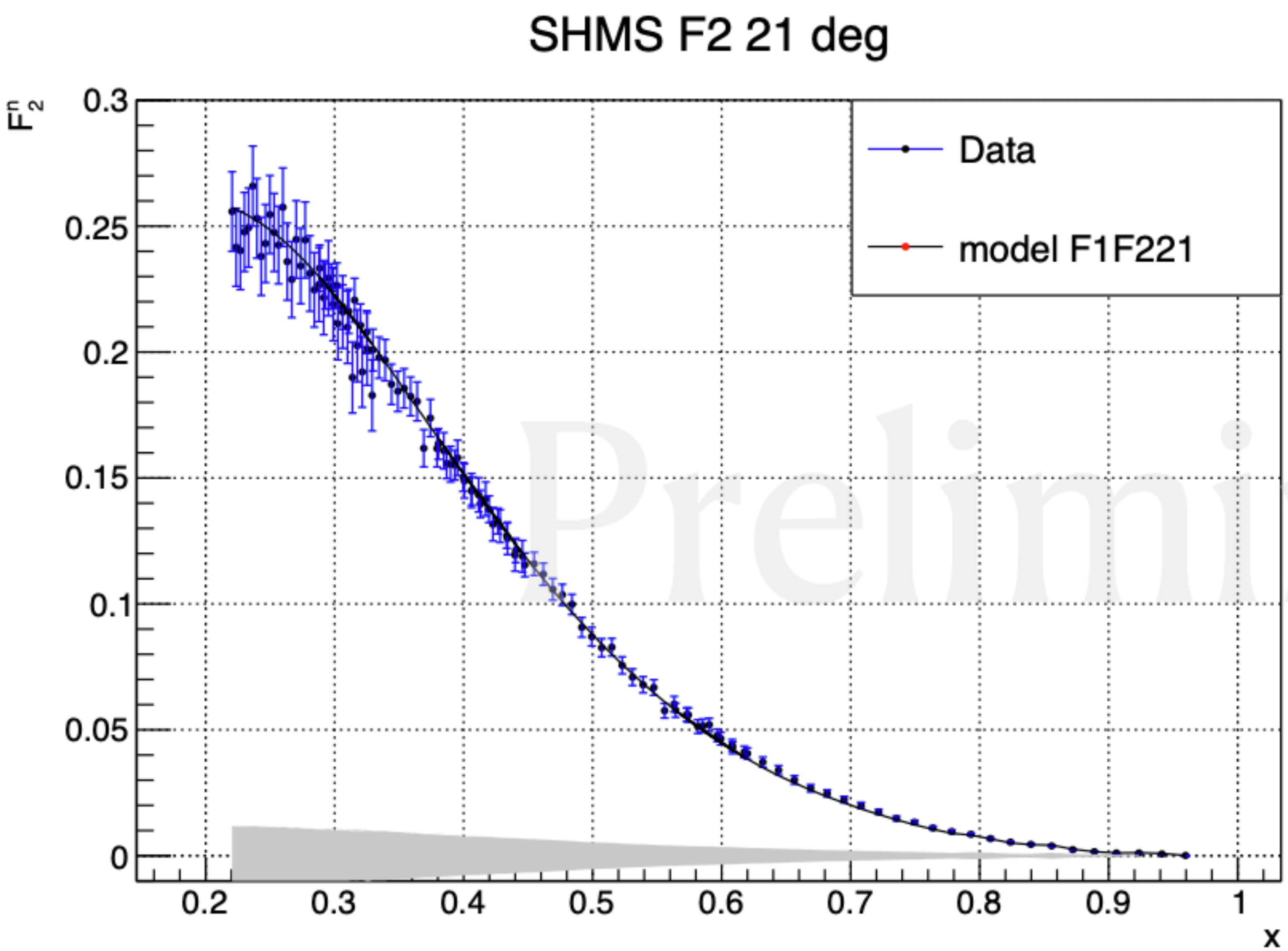
Extraction of Cross-section : work in progress

1. HMS 59 deg data analysis :
   1. Pion Contamination is done
   2. CSB Correction is done
   3. Re-run the rc-external is done
   4. Analysis 59 deg HMS data is in progress

2. Ytar dependence on Delta
3. MC shows Excess events at Ytar = 0
4. Dip in data at Yptar = 0

5. Calorimeter Cut Efficiency :
   1. Previously Calorimeter cut efficiency was studied by a previous F2 student
   2. We could not reproduce the result so revisiting the Calorimeter Cut Efficiency
   3. We are trying to take advantage of the Kaon-LT elastic runs to redo the study
6. Extraction of neutron structure function
7. Extraction of physics results (quark-hadron duality, non-singlet moments …)

Extraction of Neutron Cross-section

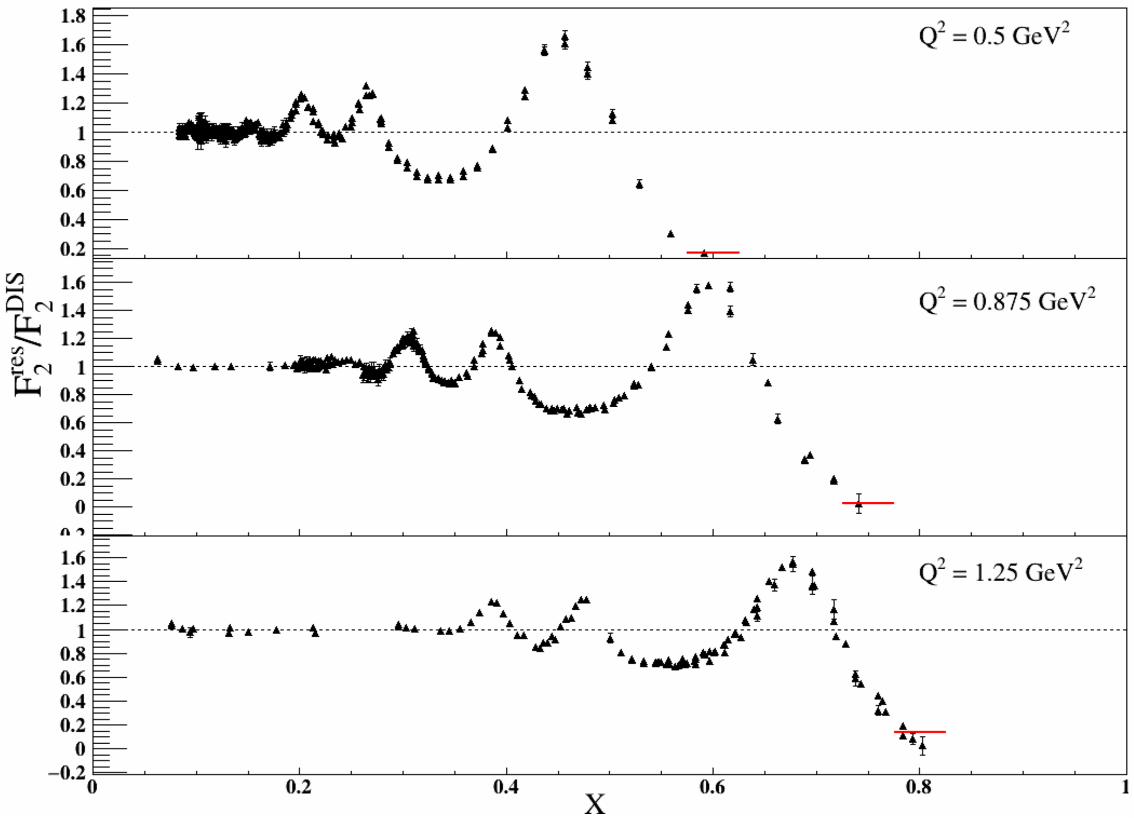


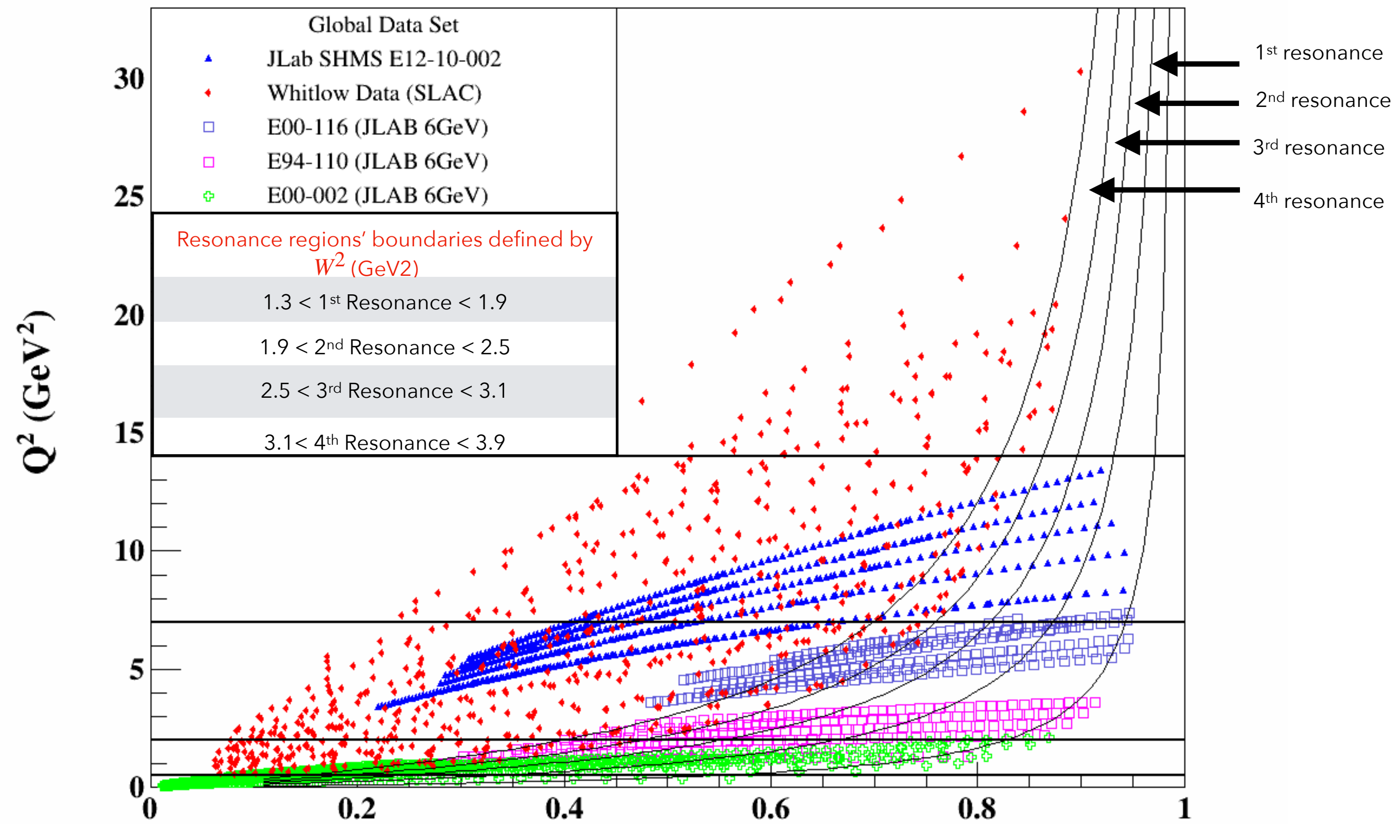
- In deuterium proton and neutron are in bound state
- Neutron cross-section can be calculated by subtracting the proton cross-section from the deuteron and nuclear effects removed
- To get the unbound p+n cross-section from the bound p+n state inside deuterium-

$$\sigma^{p+n} = \frac{\sigma_{p+n}^{model}}{\sigma_d^{model}} \times \sigma_d^{data}$$

$$\sigma_{data}^{n} = \sigma^{p+n} - \sigma_{data}^{p}$$

Impact Study : Duality Averaging Procedure



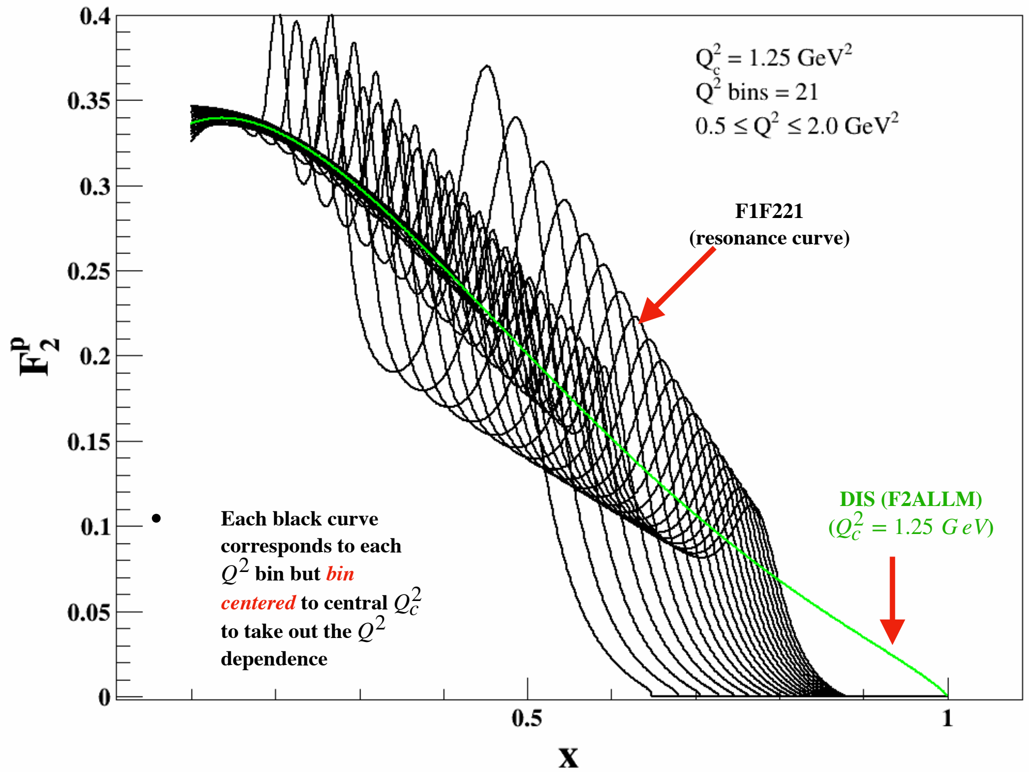


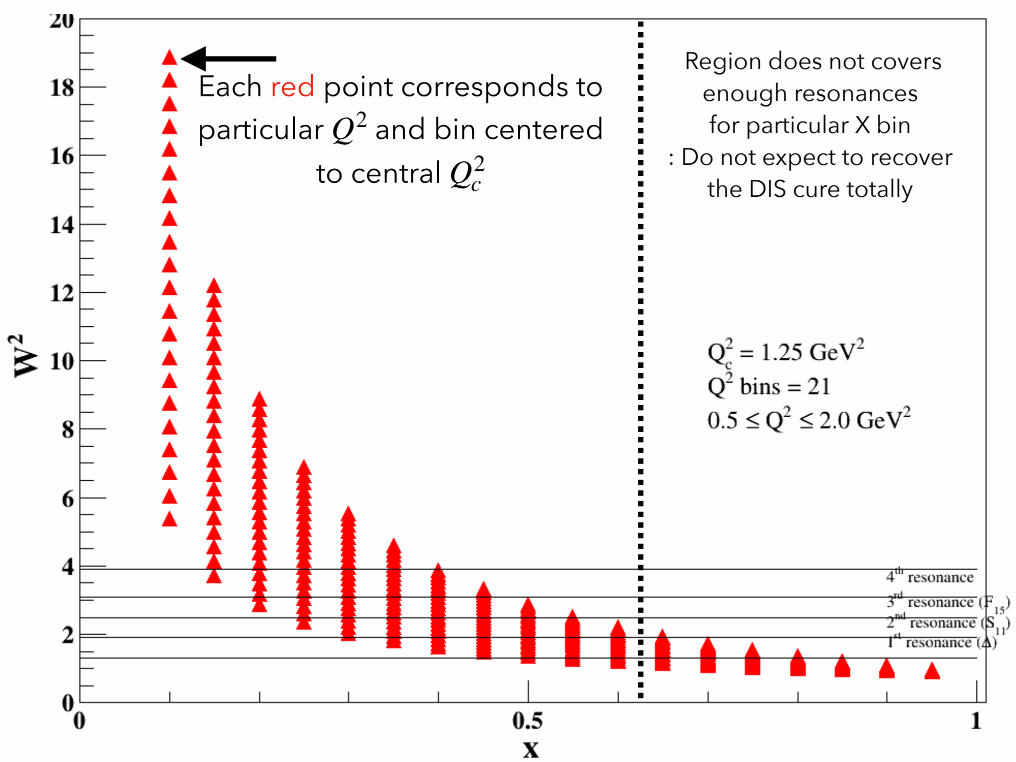
1. F_2^{res}/F_2^{DIS} vs $BjorkenX$ for 3 different Q^2
   1. F_2^{res} : world data (SLAC + JLAB)
   2. F_2^{DIS} : F2ALLM
2. Observation 1 : Resonance structure wiggles around F_2^{res}/F_2^{DIS} = 1 line
3. Indicates : Average Q^2 dependence of the resonance region is same as the Q^2 dependence of the DIS region
4. Observation 2: A particular $BjorkenX$ can see different resonance regions if we include enough Q^2
5. Can we recover the DIS curve in the resonance region if we average it over enough Q^2 values ?

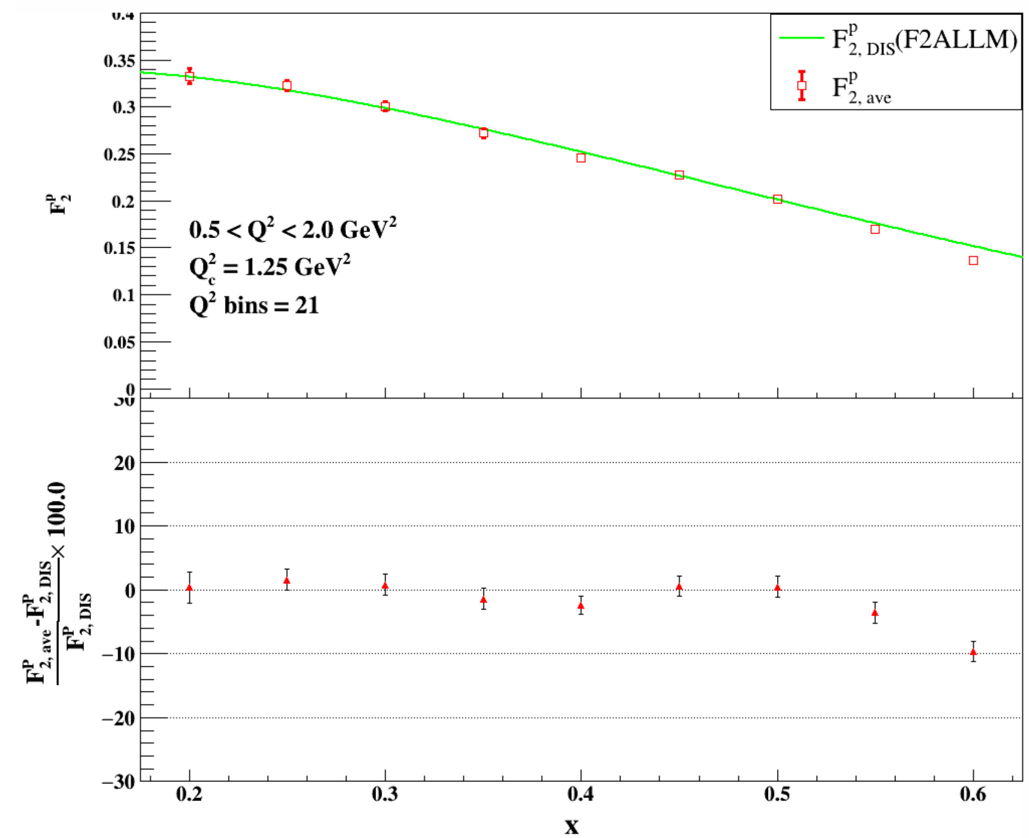
1. *E12-10-002 data enables us to explore the duality average procedure at higher Q^2 region*
2. The larger the Q^2 harder is to get enough resonance region for a fixed X bin
3. For very large Q^2 the resonance regions are almost parallel to each other
4. Divide the data in 3 Q^2 Region :
   1. $0.5 < Q^2 < 2.0$,$Q_c^2 = 1.25\ GeV^2$
   2. $2.0 < Q^2 < 7.0$,$Q_c^2 = 4.5\ GeV^2$
   3. $7.0 < Q^2 < 14.0$,$Q_c^2 = 10.5\ GeV^2$

With : Eric Christy

Impact Study : Duality Averaging Procedure







1. $0.5 < Q^2 < 2.0$, with $Q^2_c = 1.25\ GeV^2$ is divided into 21 Q^2 bins and model is plotted for Q^2 and bin centered as $F_2^{res}(x, Q_c^2) = \frac{F_2^{DIS}(x, Q_c^2)}{F_2^{DIS}(x, Q^2)} \cdot F_2^{res}(x, Q^2)$

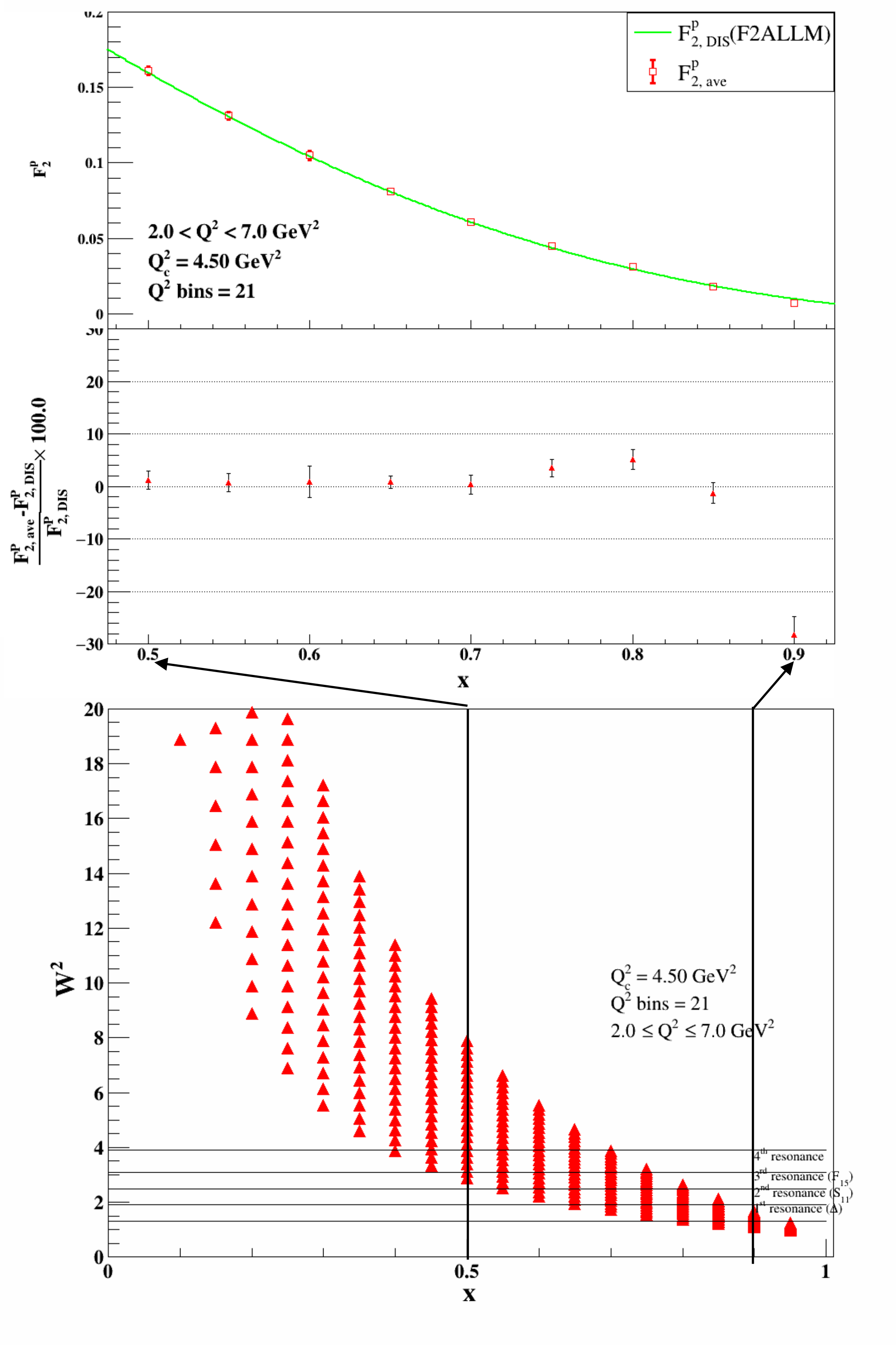
2. Then the F1F221 model is corrected by data in that bin as $F_2^{data}(Q_{bc}^2, x_{nom}) = F_2^{data}(Q_{data}^2, x_{data}) \times \frac{F_2^{res}(Q_{bc}^2, x_{nom})}{F_2^{res}(Q_{data}^2, x_{data})}$ where $x_{nom} = Q_{data}^2/(W_{data}^2 + Q_{data}^2 - M_P^2)$

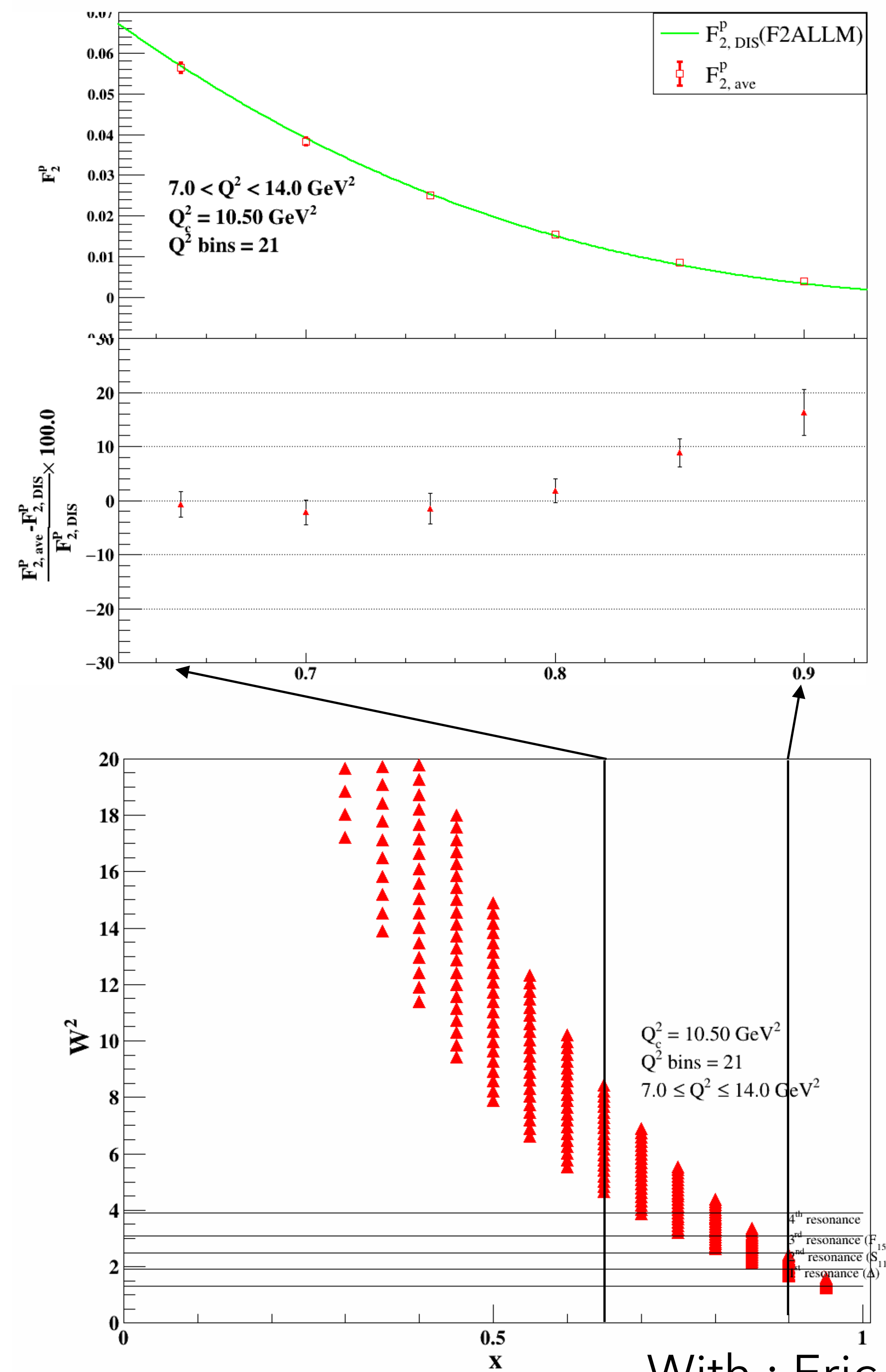
3. $0.2 \leq x \leq 0.5$ DIS curve is recovered better than 3% by averaging the resonance structure

4. For $x = 0.55$ and $x = 0.6$ enough resonances are not covered and W^2 crossed the pion production threshold limit - not it not expected to recover the DIS curve fully

With : Eric Christy

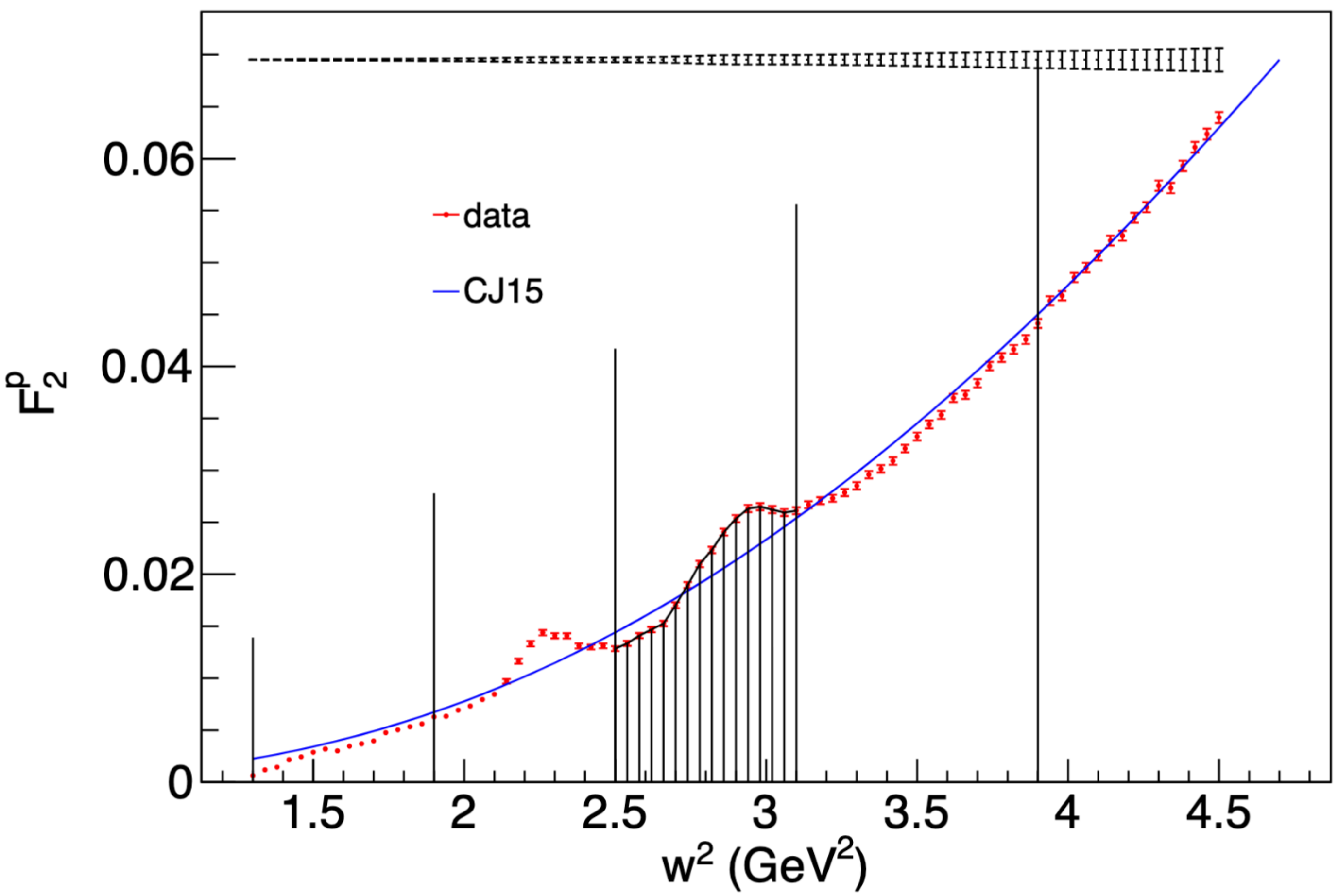
Impact Study : Duality Averaging Procedure





With : Eric Christy

Impact Study : Quark-Hadron Duality



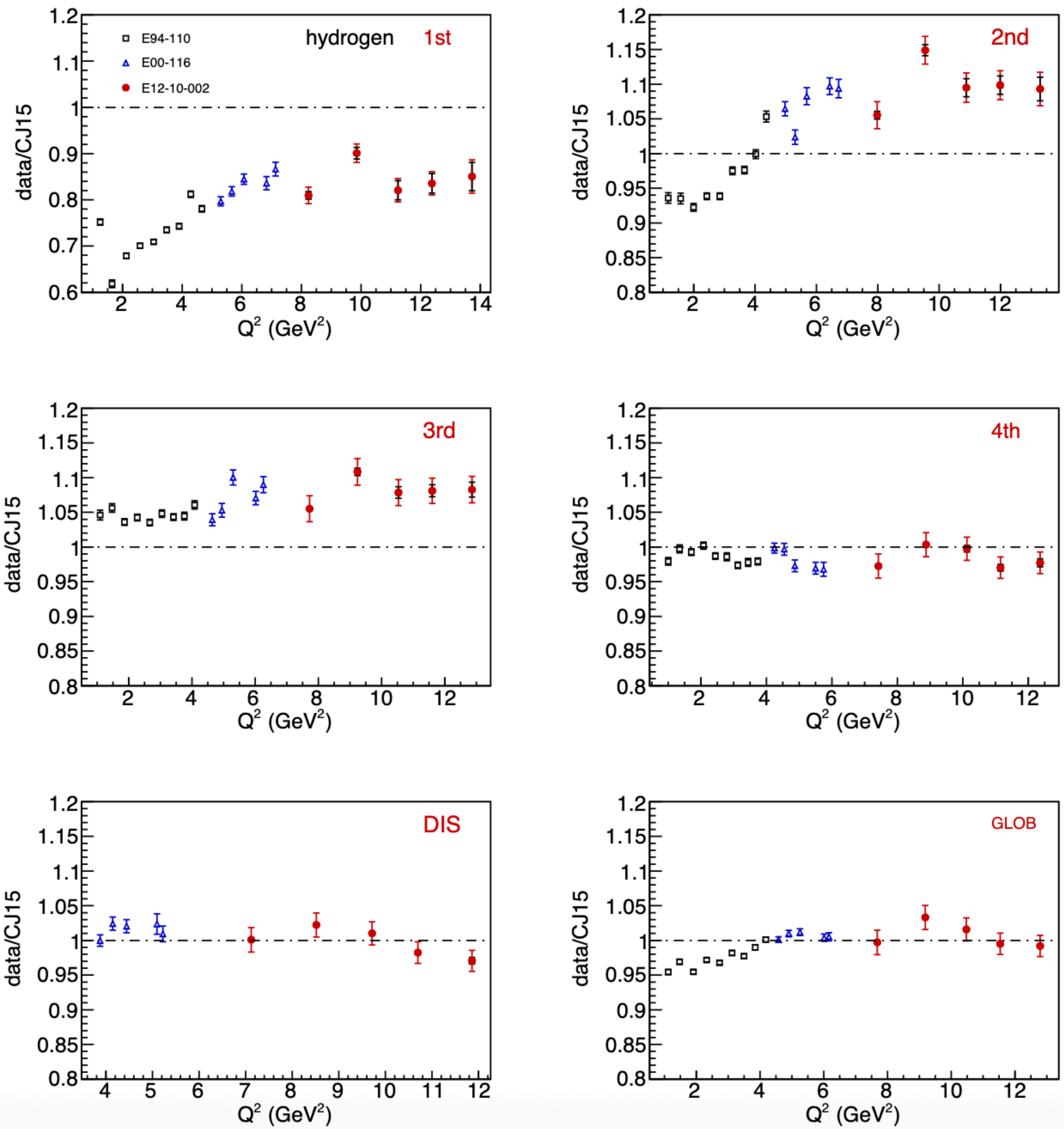
- Quark hadron duality is tested by plotting the quantity :

$$I(res/DIS) = \frac{\int F_2^{DATA} dW^2}{\int F_2^{scaling} dW^2}$$

- CJ15 curve is used for the DIS / scaling curve
- Vertical lines show the boundaries for the different resonance regions
- $$\int F_2^{data} = \sum_i \frac{(F_2(W_i^2) + F_2(W_{i+1}^2))\Delta W^2}{2}$$
- I is plotted vs the average Q^2 for different resonance regions, DIS region and for global (next slide)
- This experiment extends the previous study to larger Q^2

From :Abel Sun

Impact Study : Quark-Hadron Duality



Duality also can be checked for each resonance

- E12-10-002 data extends the work previously done by S. Malace in 6 GeV era

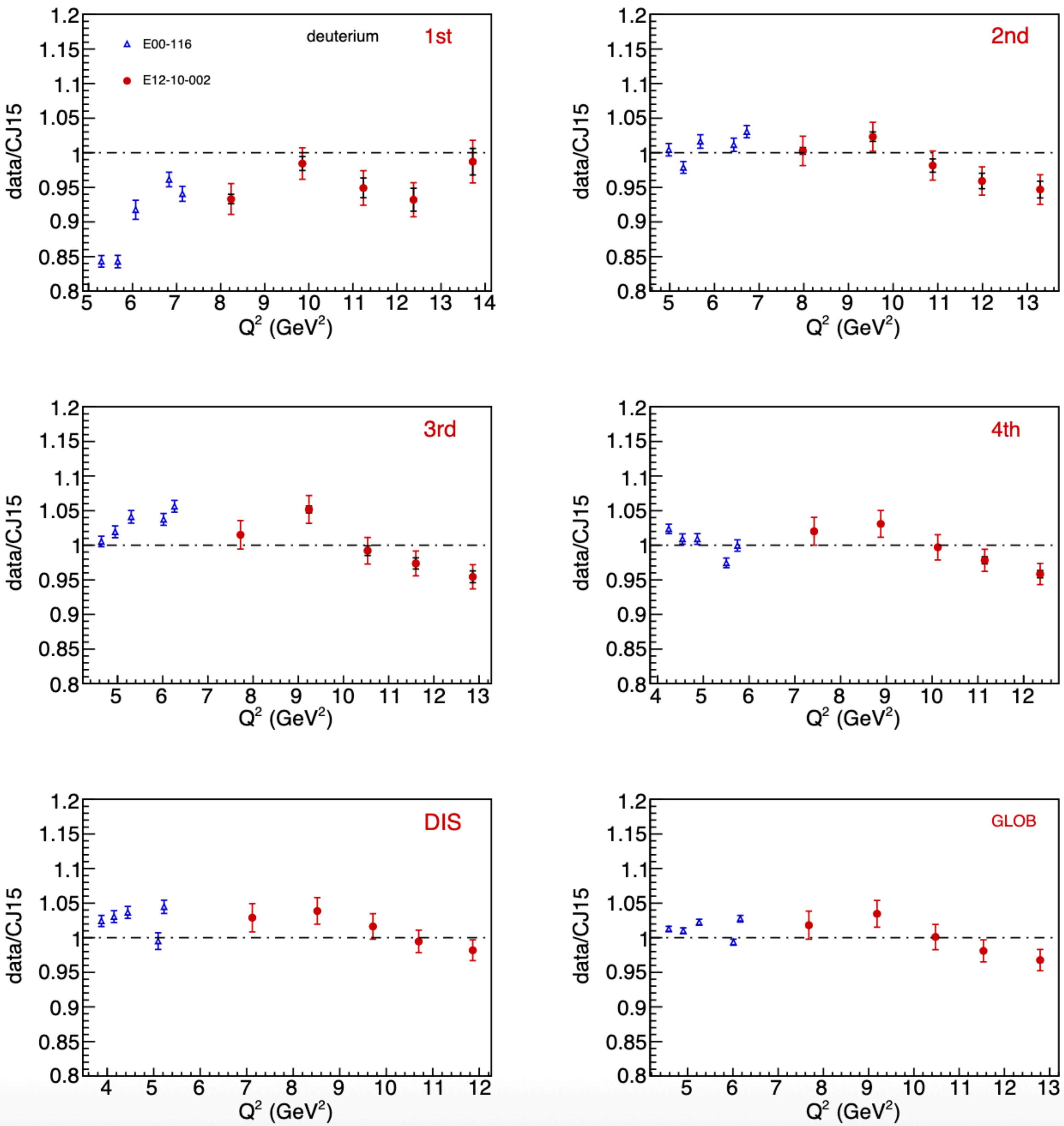
- Left plot for hydrogen

- Each point in every plot indicated an particular angle

- Six panels corresponds to 1st resonance, 2nd resonance, 3rd resonance, 4th resonance, 5th resonance, DIS, and Global

From :Abel Sun

Impact Study : Quark-Hadron Duality



Duality also can be checked for each resonance

- E12-10-002 data extends the work previously done by S. Malace in 6 GeV era
- Left plot for deuterium
- Each point in every plot indicated an particular angle
- Six panels corresponds to 1st resonance, 2nd resonance, 3rd resonance, 4th resonance, 5th resonance, DIS, and Global

From :Abel Sun

Summary

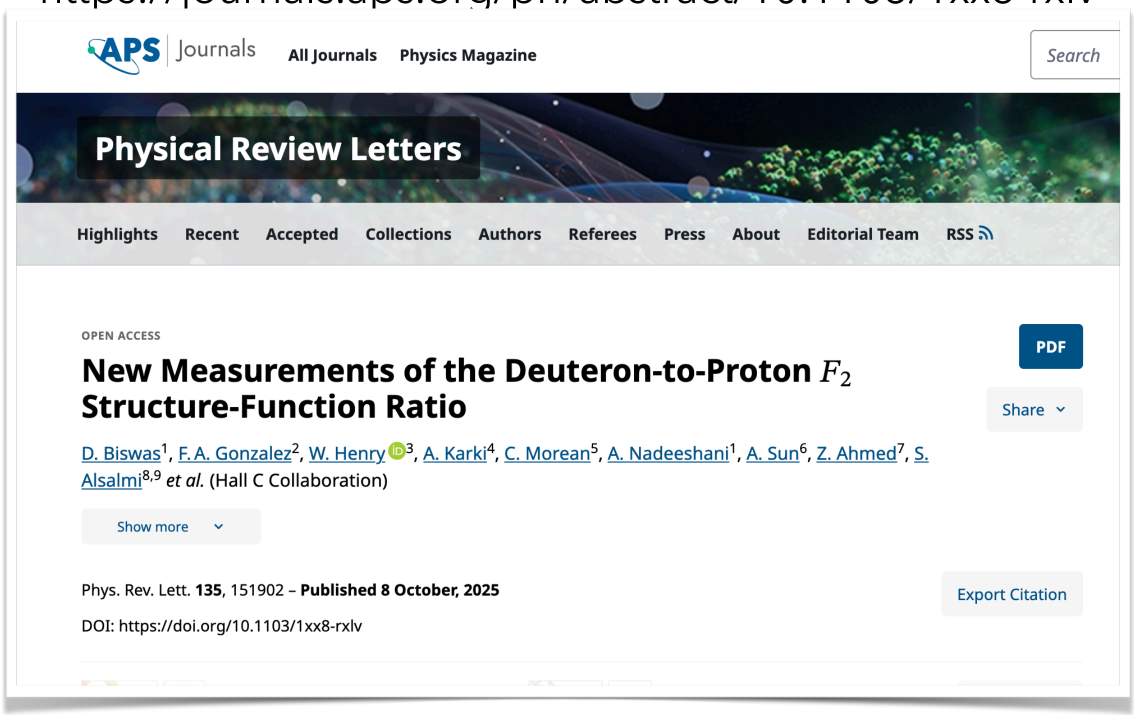
D. Biswas,[1] F. A. Gonzalez,[2] W. Henry,[3] A. Karki,[4] C. Morean,[5] A. Nadeeshani,[1] A. Sun,[6] Z. Ahmed,[7] S. Alsalmi,[8,9] W. Armstrong,[10] A. Asaturyan,[3] C. Ayerbe Gayoso,[11,4] V. Berdnikov,[12,3] H. Bhatt,[4] D. Bhetuwal,[4] P. Bosted,[11] E. Brash,[13] M. H. S. Bukhari,[14] J. P. Chen,[3] M. Chen,[15] M. E. Christy,[1,3] S. Covrig Dusa,[3] K. Craycraft,[5] S. Danagoulian,[16] D. Day,[15] M. Diefenthaler,[3] M. Dlamini,[17] J. Dunne,[4] B. Duran,[10] D. Dutta,[4] R. Ent,[3] H. Fenker,[3] N. Fomin,[5] E. Fuchey,[18] D. Gaskell,[3] T. N. Gautam,[1] J. O. Hansen,[3] F. Hauenstein,[19,3] A. V. Hernandez,[12] T. Horn,[12] G. M. Huber,[7] M. K. Jones,[3] S. Joosten,[20] M. L. Kabir,[4] C. Keppel,[3] A. Khanal,[21] P. M. King,[17] E. Kinney,[22] M. Kohl,[1] N. Lashley-Colthirst,[1] S. Li,[23] W. B. Li,[11] A. H. Liyanage,[1] D. Mack,[3] S. Malace,[3] P. Markowitz,[21] J. Matter,[15] D. Meekins,[3] R. Michaels,[3] A. Mkrtchyan,[24] H. Mkrtchyan,[24] Z. Moore,[25] S. J. Nazeer,[1] S. Nanda,[4] G. Niculescu,[25] I. Niculescu,[25] D. Nguyen,[15] Nuruzzaman,[26] B. Pandey,[1,27] S. Park,[2] E. Pooser,[3] A. J. R. Puckett,[18] M. Rehfuss,[10] J. Reinhold,[21] B. Sawatzky,[3] G. R. Smith,[3] H. Szumila-Vance,[3,21] A. S. Tadepalli,[26] V. Tadevosyan,[24] R. Trotta,[12] S. A. Wood,[3] C. Yero,[21,12] and J. Zhang[2]

(Hall C Collaboration)

1. **Ratio paper is published in PRL**
2. Ratio data set is available for inclusion in PDF fits, model …

3. Future Work
    1. Extraction of absolute Cross-section
    2. Extraction of Physics :
        1. Quark-Hadron Duality study
        2. Non-Singlet Moments
        3. Improve resonance / DIS modeling
4. Goal : Finish the analysis by the end of the 2026

https://journals.aps.org/prl/abstract/10.1103/1xx8-rxlv



σ_D/σ_H : SHMS & HMS

1. σ_D/σ_H ratio were compared for :
    1. SHMS data
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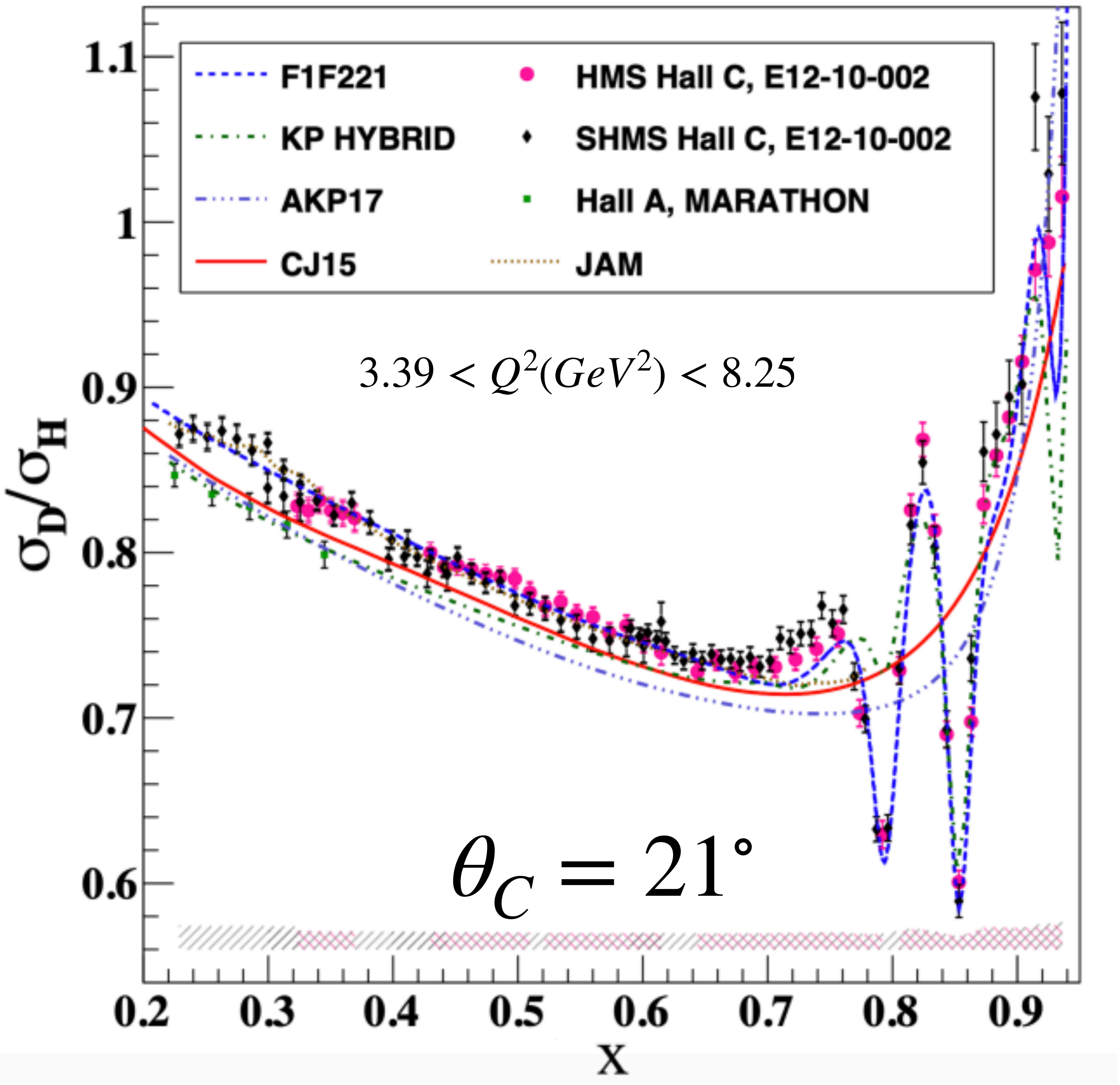
    8. JAM
2. Excellent agreement between SHMS and HMS for $\theta_C = 21^{\circ}$
3. The error bars include uncorrelated statistical and systematic errors
4. The error band include correlated systematic error and an overall normalization uncertainty of 1.1% (due to the uncertainty in the target density)
5. F1F221 or any other model does not include this data
6. As much as 4.3% discrepancy exists between MARATHON (Hall A) and E12-10-002 (Hall C) data
7. Total point to point error 0.6 - 5.4 (with $W^2 > 3\ GeV^2$ 2.9) %
8. Total correlated error 1.2 - 2.9 (with $W^2 > 3\ GeV^2$ 2.1) %



Error Budget : σ_D/σ_H Ratio

Error	Point to point (%)	Correlated (%)
Statistical	0.5 – 5.4(2.9)	
Charge	0.1 – 0.6	
Target density	0.0 – 0.2	1.1
Live time		0.0 – 1.0
Model dependence		0.0 – 2.6(1.2)
Charge symmetric 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
Cherenkov efficiency		0.1
Total	0.6 – 5.4(2.9)	1.2 – 2.9(2.1)