OLD DOMINION UNIVERSITY

IDEA FUSION

The BONuS Experiment: New Results and Future Plans

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Old Dominion University

NuFact15, Rio de Janeiro, August 10 - 15, 2015

Outline

- Neutron Structure – inadequate data
- Spectator Tagging
- BONuS Experiment at Jefferson Lab
- F_2^n/F_2^p …
- Nuclear Effects
- Duality
- The EMC Effect in Deuterium
- Plans for BONuS with 11 GeV

Nucleon F_2 Structure Function at High x

$$F_2^p(x) = x\sum_q e_q^2 (q(x)+\bar{q}(x)) \underset{x\to 1}{\approx} x\left(\frac{4}{9}u(x)+\frac{1}{9}d(x)\right)$$

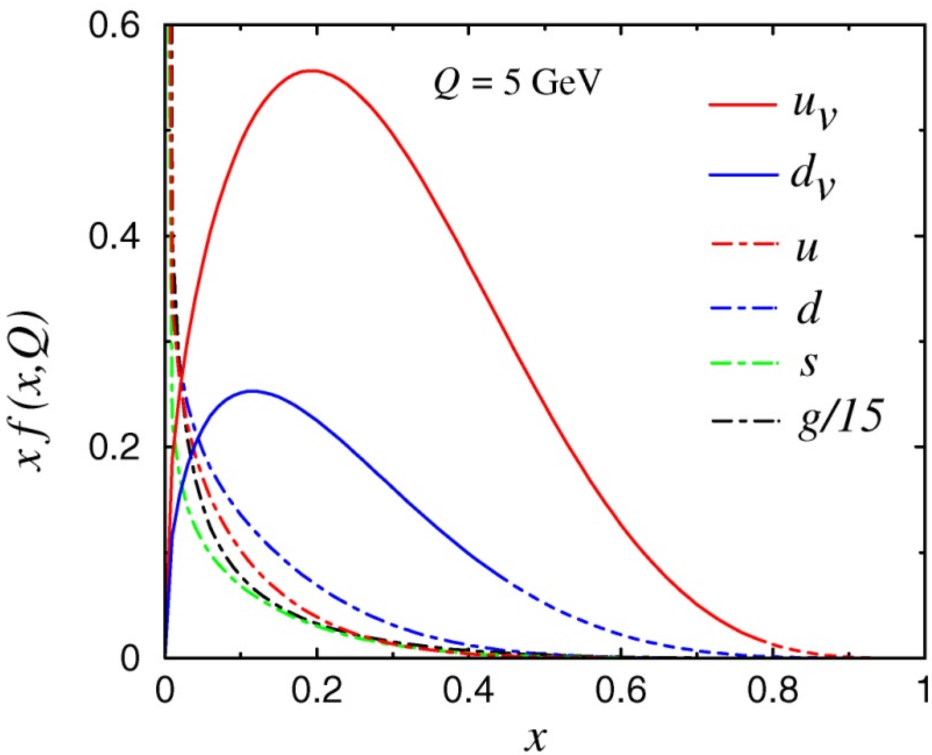
x is fraction of nucleon momentum carried by quark

$$F_2^n(x) \underset{x\to 1}{\approx} x\left(\frac{4}{9}d(x)+\frac{1}{9}u(x)\right)$$

for x > 0.5

$$\boxed{\frac{F_2^n}{F_2^p} \approx \frac{1+4d/u}{4+d/u}}$$

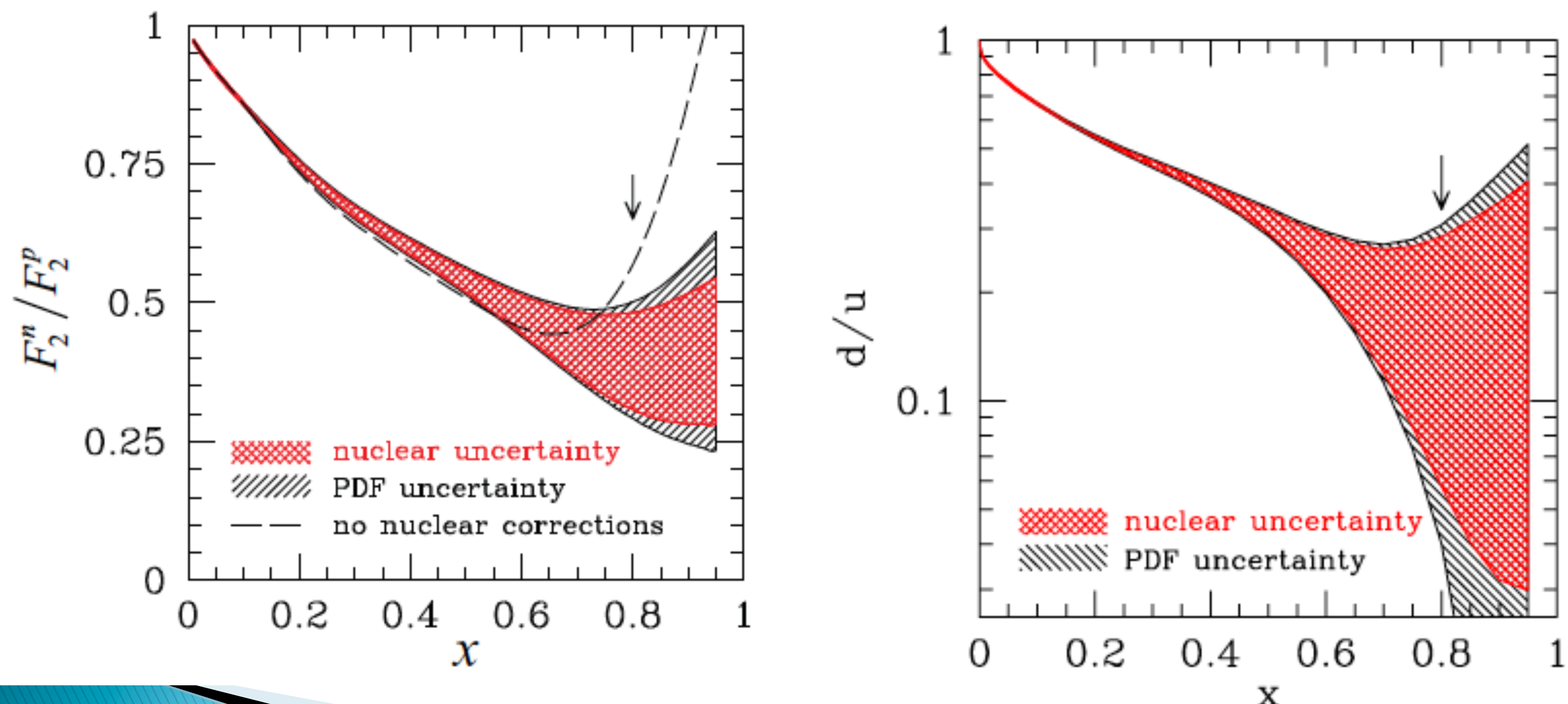
u at large x is relatively well known from proton data alone; *d* has large uncertainties



Valence quarks dominate above x ~ 0.4

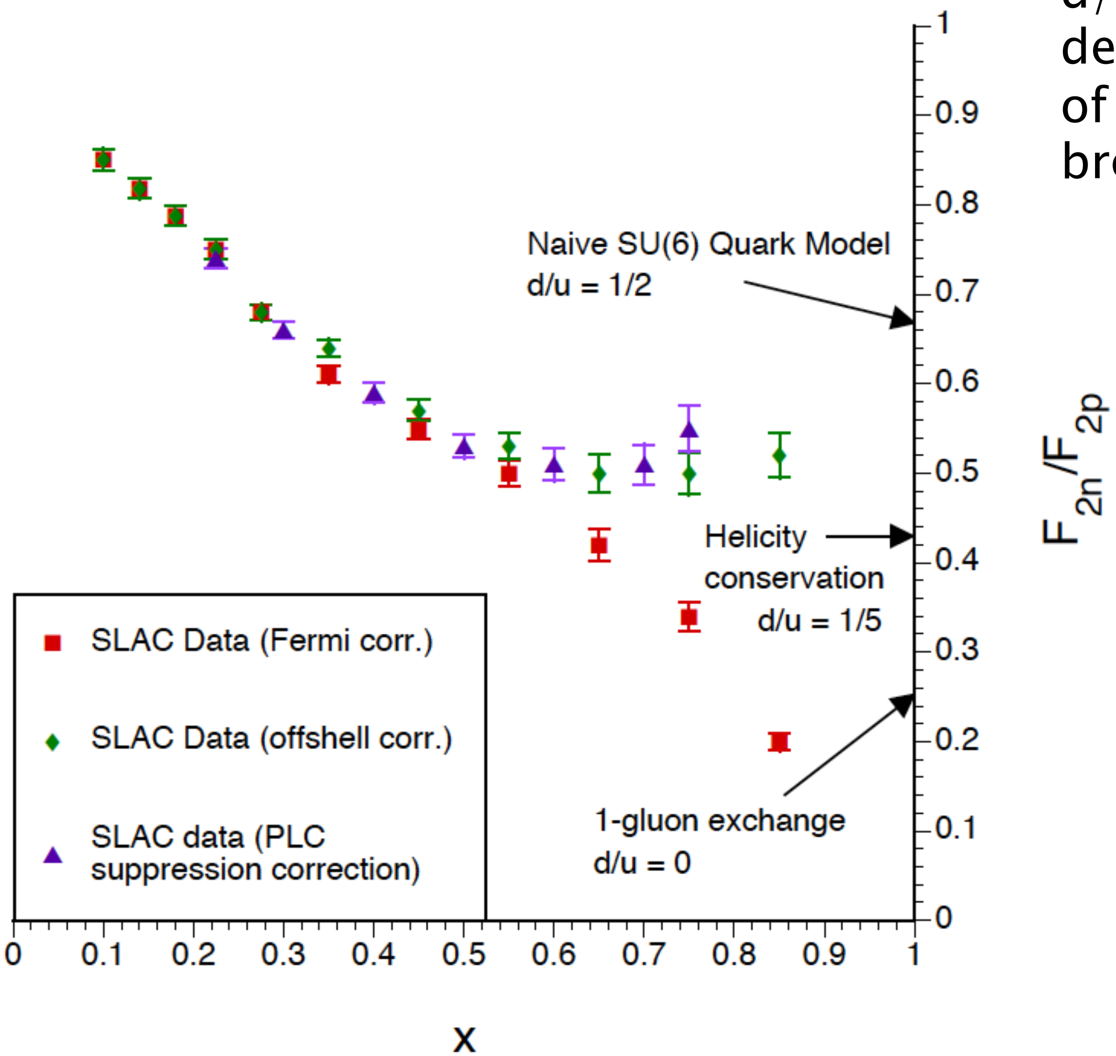
Using a Deuteron Target

Uncertainty in deuteron wave function and models of off-shell effects lead to large uncertainties in F_2^n at large x.



Accardi *et al.* PRD84 014008 (2011)

SLAC Data on Deuterium



d/u varies widely depending on mechanism of spin-flavor symmetry breaking.

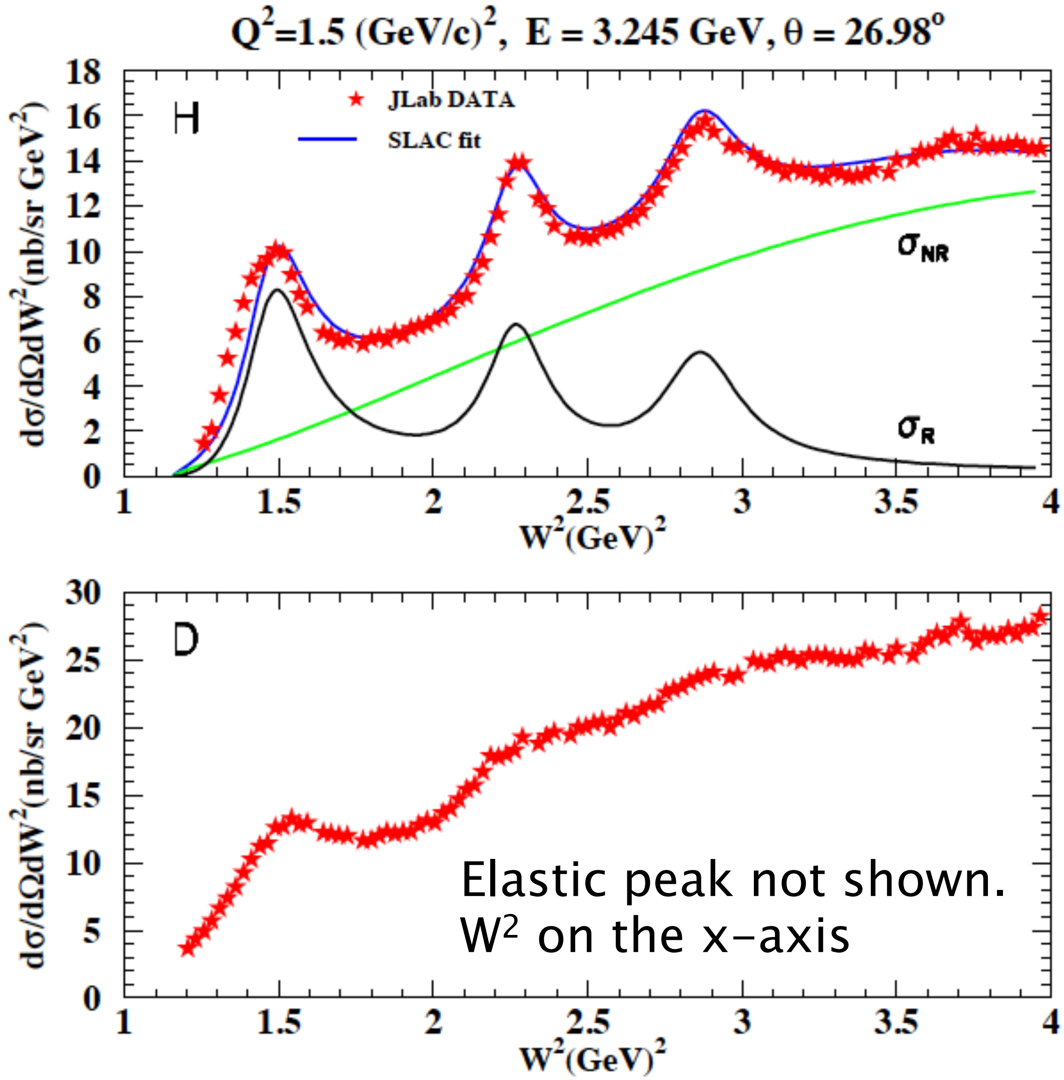
Whitlow *et al.* Phys Lett B **282** 475 (1992)

Resonance Region

In order to understand the full isospin decomposition of the nucleon resonances, both proton and neutron targets are needed.

Data on the deuteron are kinematically smeared due to binding, off-shell, final state interactions (FSI), etc.

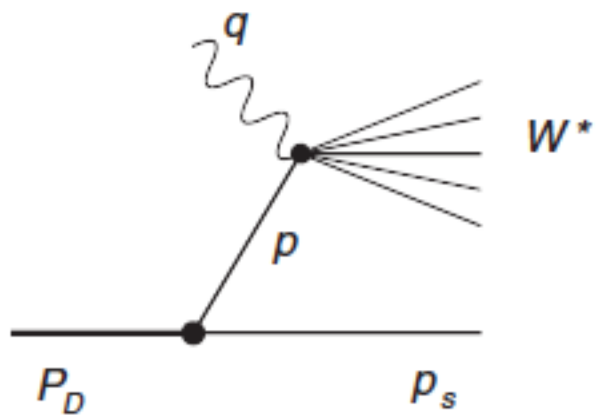
Q is the 4-momentum transfer to the target
θ is the electron scattering angle



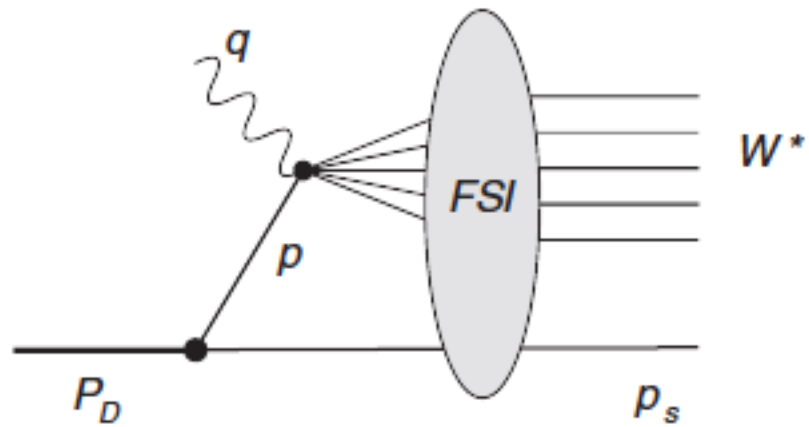
Whitlow *et al.* Phys Lett B **282** 475 (1992)
Niculescu *et al.*, PRL **85**, 1182 and 1186 (2000)

Spectator Tagging

$$e + d \rightarrow e' + p_s + X$$



Impulse approximation



Final state interactions between the spectator proton and neutron debris

$$p_s^{\mu} + p^{\mu} = d^{\mu} = (M_d, 0)$$

W* is the invariant mass of the γ + n, corrected for p_s
x* is the momentum fraction of the quark in the neutron
θ_{pq} is the angle between q and the spectator proton

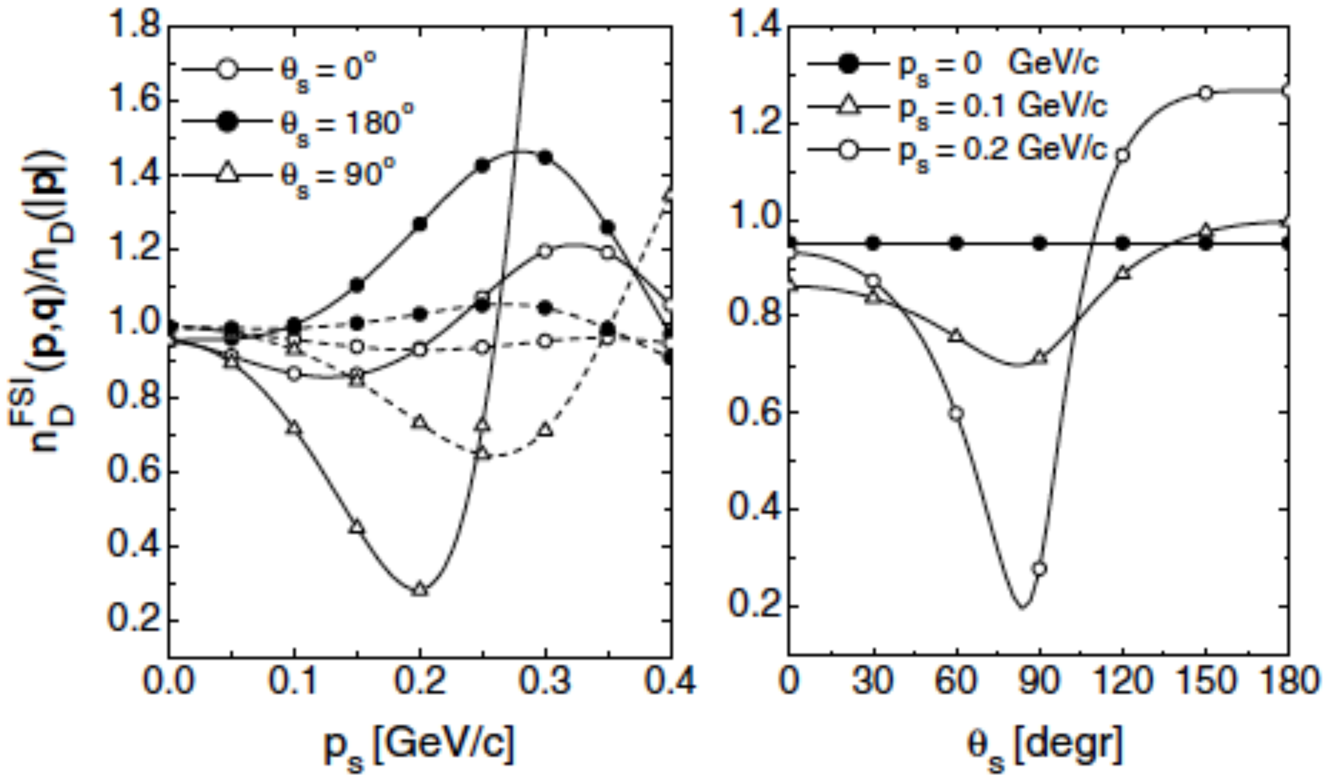
S. Tkachenko *et al.* PRC 89 045206 (2014)

When is the impulse approximation valid?

Final State Interactions (FSI) are minimized for low spectator momentum and backward angles.

FSI corrections are <~ 5% for $p_s < 100$ MeV/c and $\theta_{pq} > 100°$

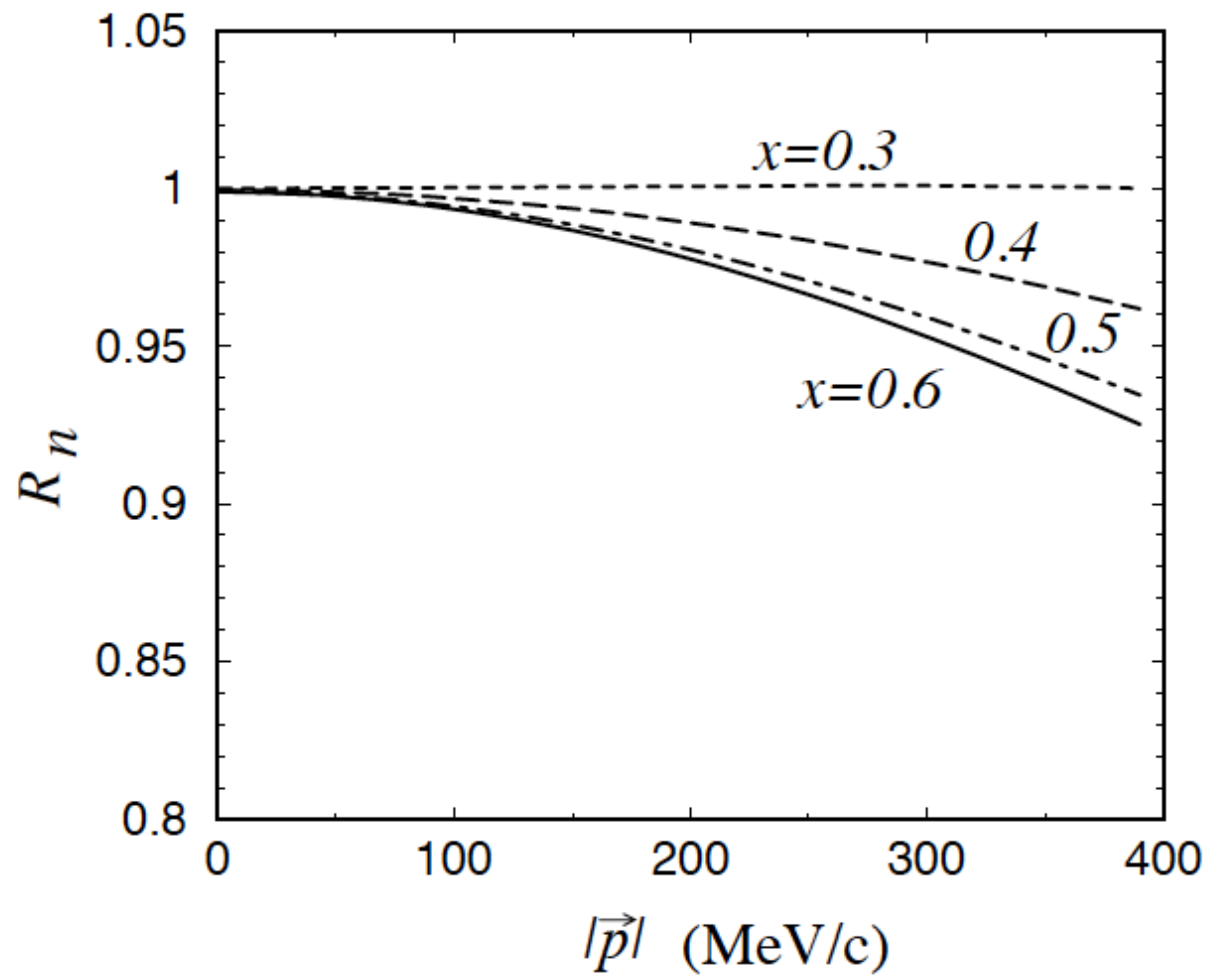
FSI effects are maximum around $\theta_{pq} \sim 90°$



C. degli Atti *et al*, Eur. Phys. J. A 19,145 (2004).

Off-Shell Effects

$$R_n \equiv F_2^{n(eff)}(W^2, Q^2, p^2)/F_2^n(W^2, Q^2)$$



Off-shell effects are negligible for p_s<100 MeV/c

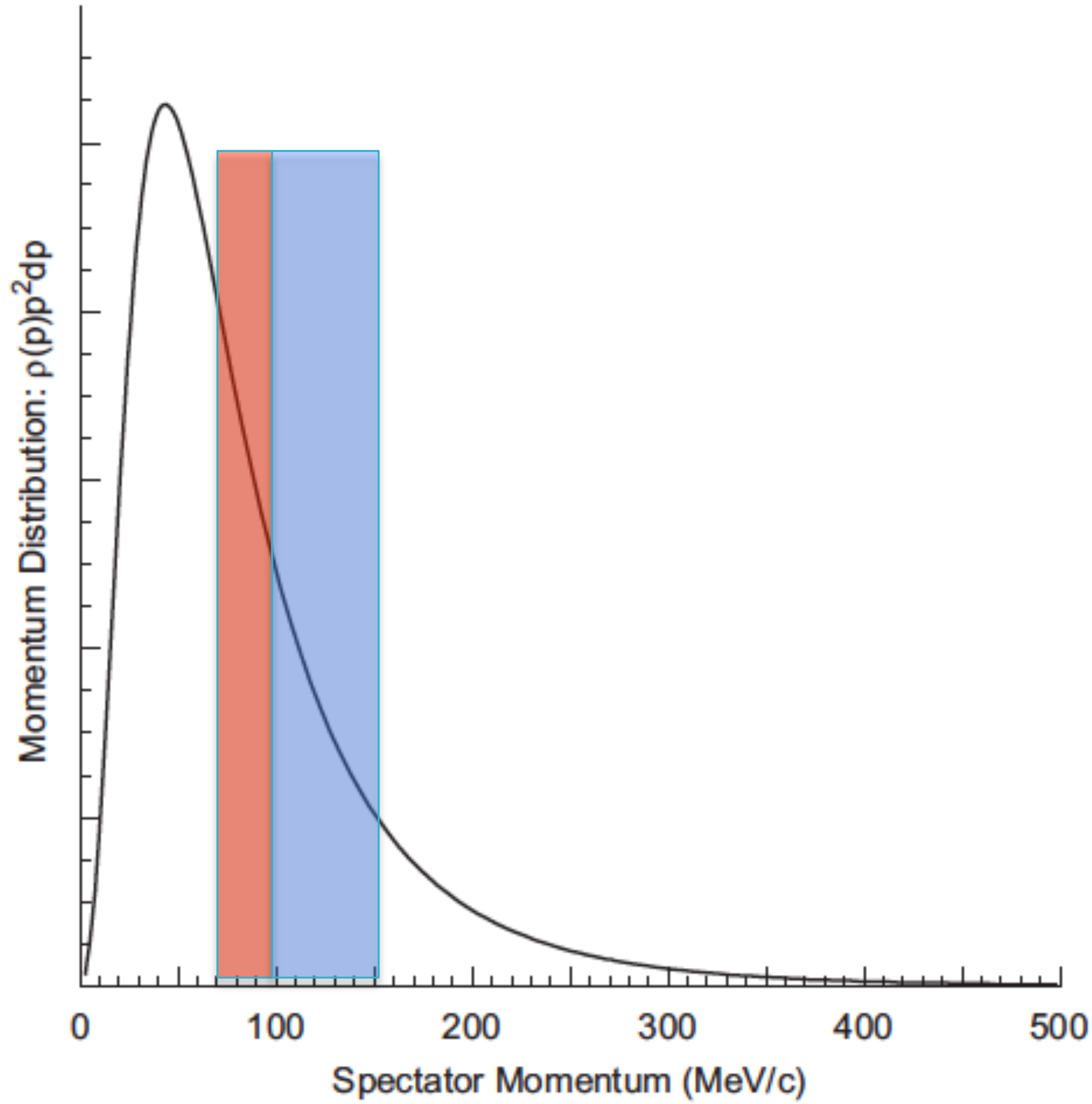
Target fragmentation is negligible for $\theta_{pq} > 90°$ (Simula 1996)

W. Melnitchouk *et al*, Phys. Lett. B**335**, 11 (1994); PRD **49**, 1183 (1994)

Spectator Momentum Distribution

It is critical to detect spectator protons with as low momentum as possible.

BONuS experiment can detect protons from 70 to 150 MeV/c



Jefferson Lab Experiment E03-12
Barely Off-shell Nucleon Structure (BONuS)

- Electron beam energies: 2.1, 4.2, 5.3 GeV
- Spectator protons were detected by the newly built Radial Time Projection Chamber (RTPC)
- Scattered electrons and other final state particles were detected by CEBAF Large Acceptance Spectrometer (CLAS)
- Target: 7 atm D_2 gas, 20 cm long
- Data were taken from Sep. to Dec. in 2005

Primary Goals:

1. to understand the momentum distribution of u and d quarks in the neutron
2. Study nuclear effects and deviations from the spectator model

Radial Time Projection Chamber (RTPC)

Sensitive to protons with momenta of 67-150 MeV/c

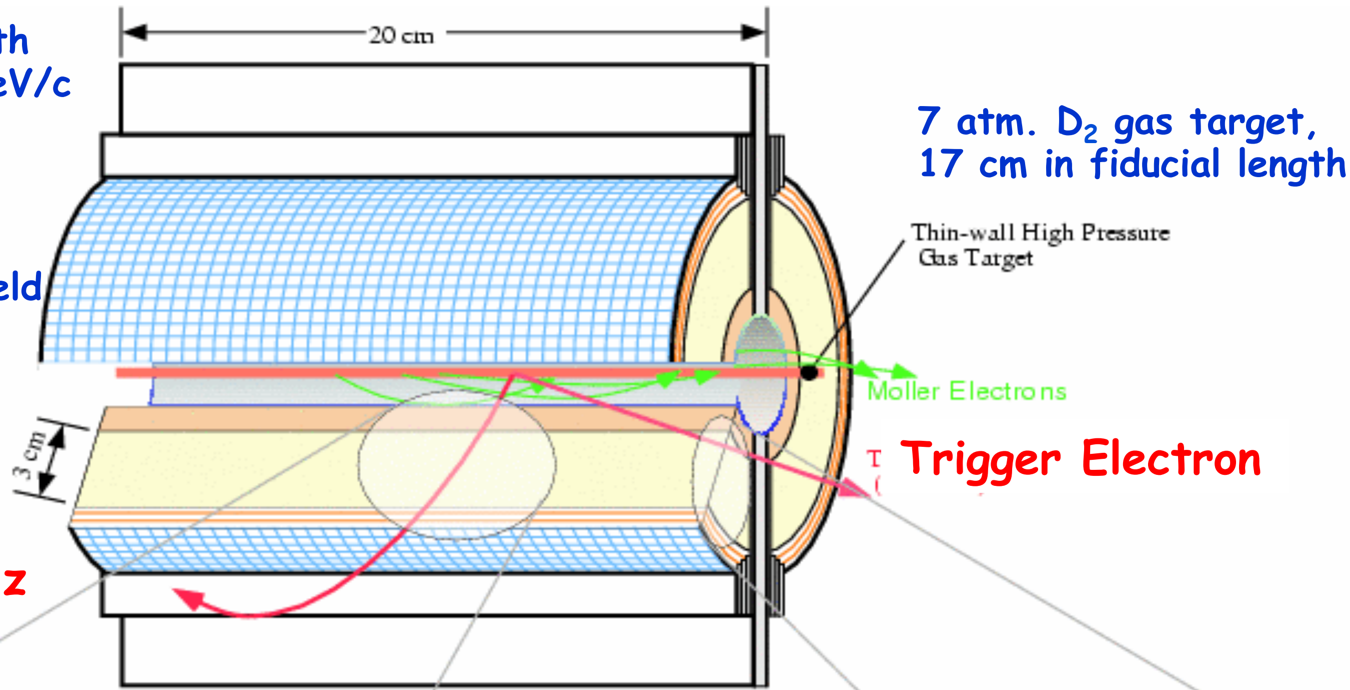
3 layers of GEM

3200 pads (channels)

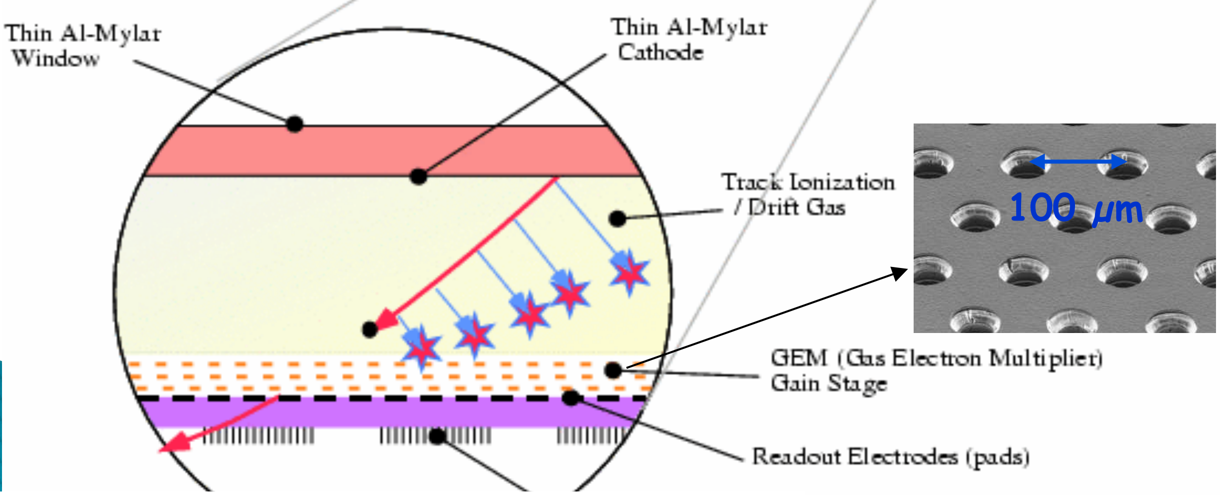
3.5 and 4.7 Tesla B field

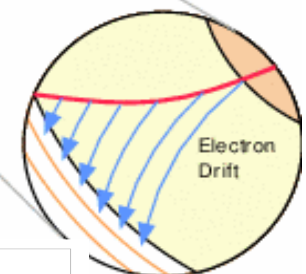
Particles ID by dE/dx

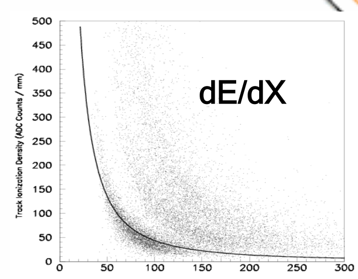
7 atm. D_2 gas target, 17 cm in fiducial length



3-D tracking:
time of drift -> r
pad position -> φ, z

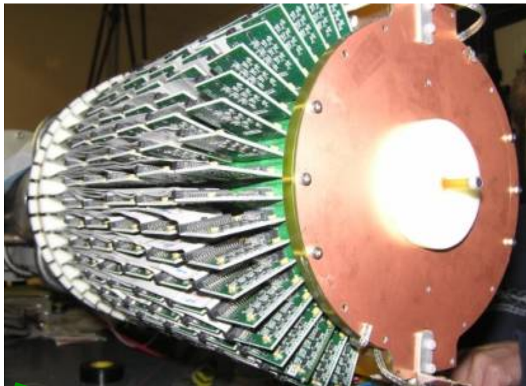




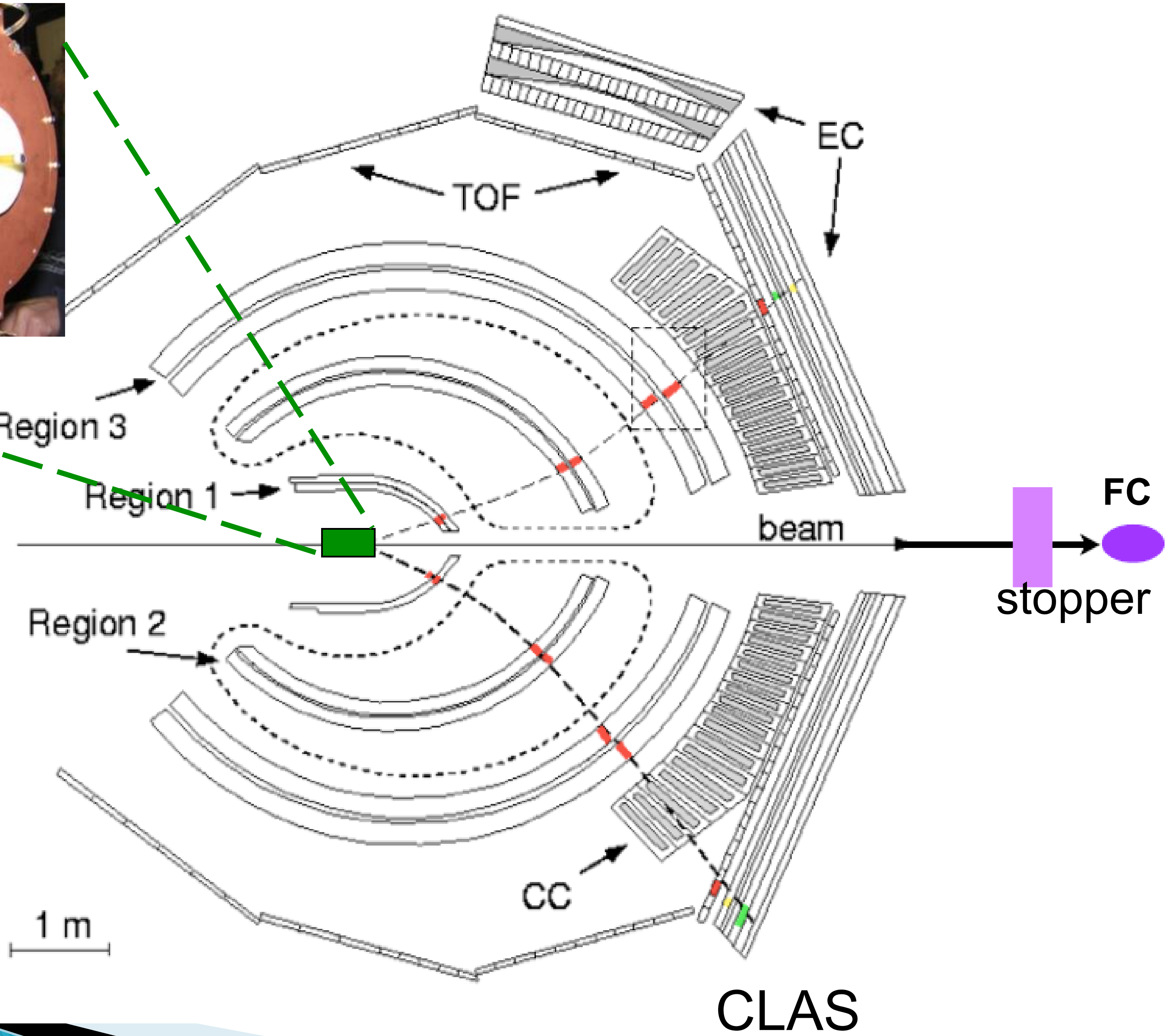


H. Fenker *et al.* NIM A592 273 (2008)

RTPC Sits at the Center of CLAS

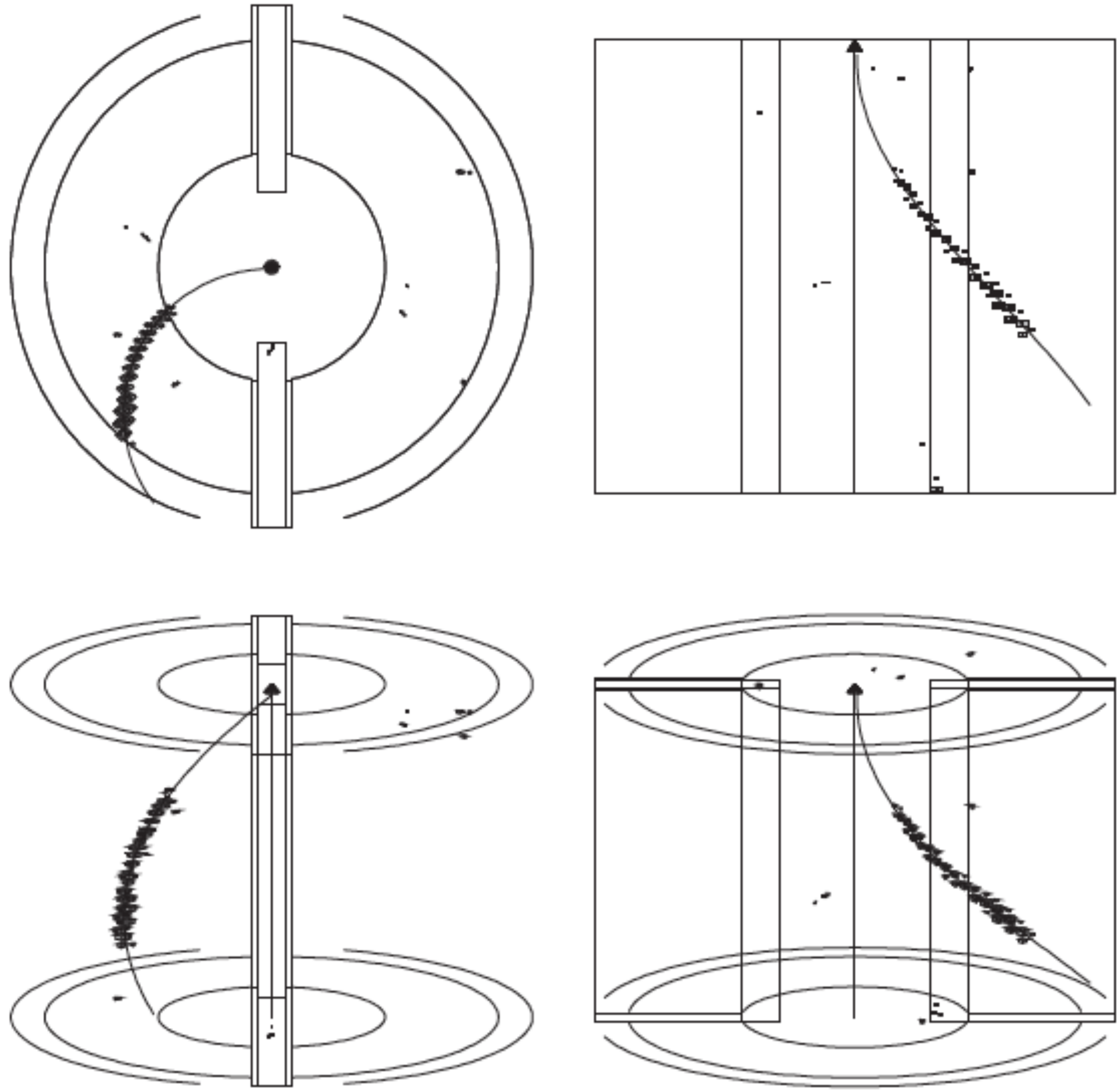


BoNuS RTPC



RTPC Track

We convert the time of arrival of ionization electrons at the GEM foils to the radial position where the ionization occurred. Then we fit a helix to the ionization events and extract radius of curvature.

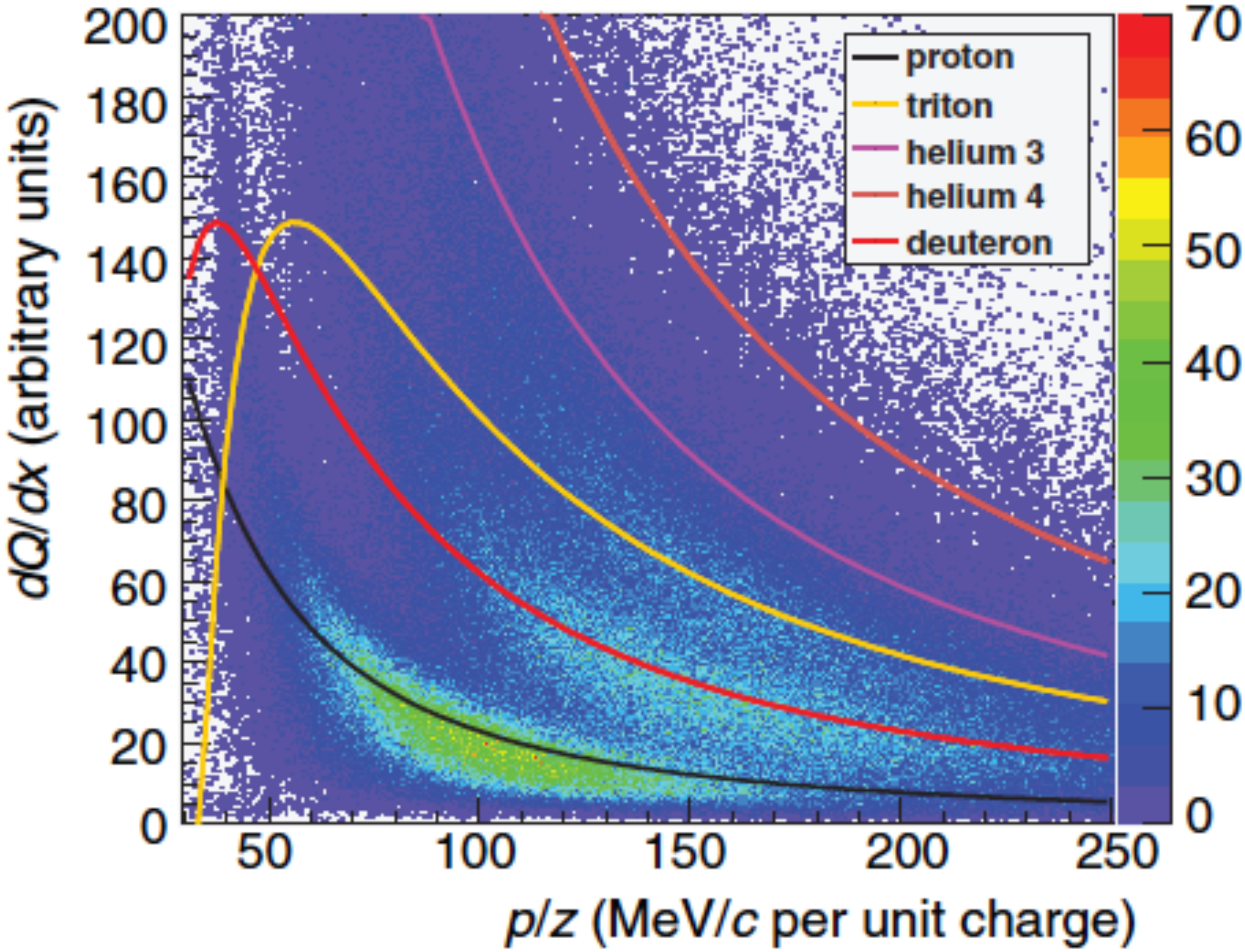


H. Fenker *et al.* NIM A592 273 (2008)

Particle ID

Helium target in this case.

Protons clearly separated from deuterons

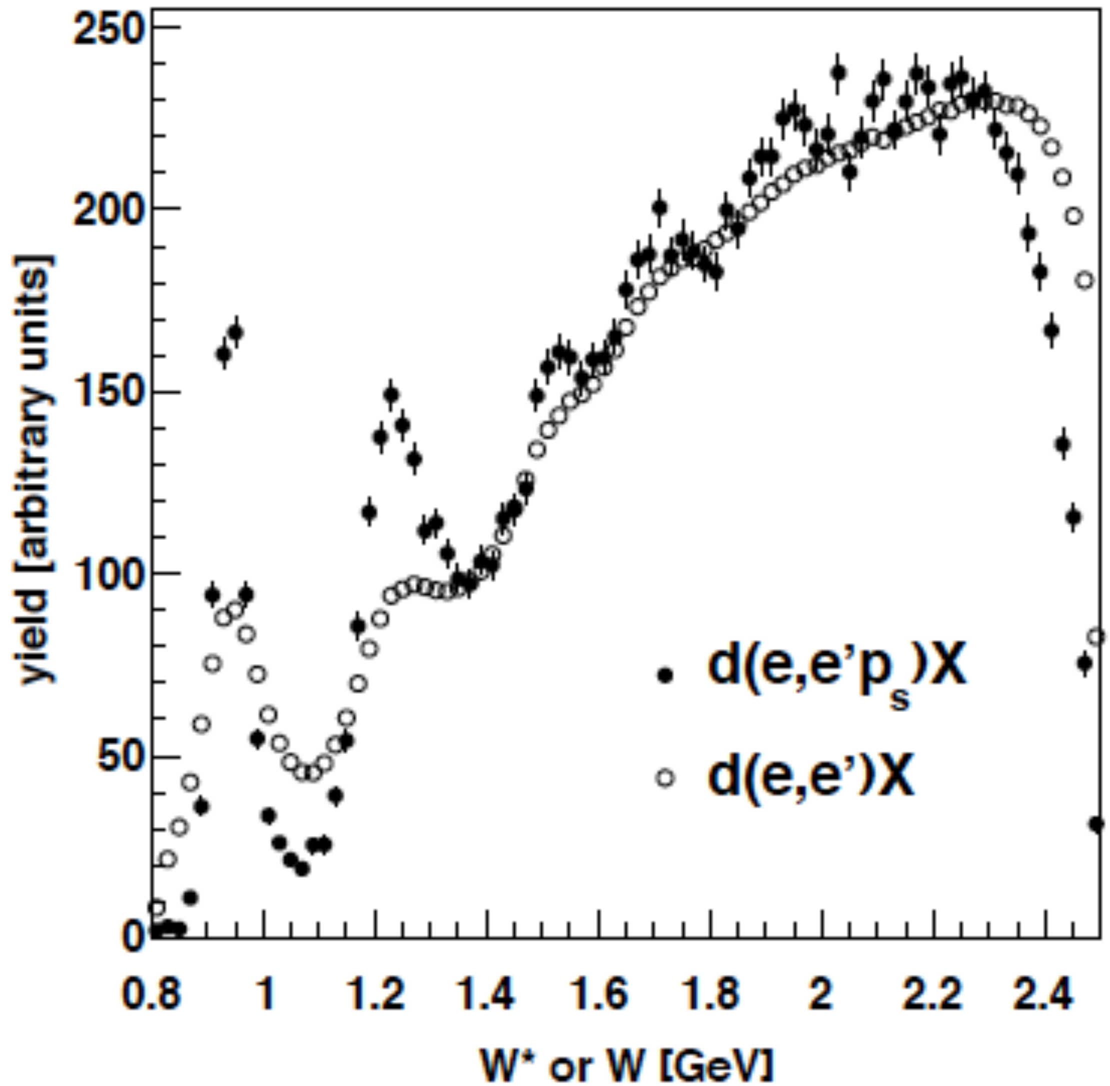


S. Tkachenko *et al.* PRC 89 045206 (2014)

BoNuS Data

W* is the invariant mass of the photon plus neutron.

Correcting for the spectator proton makes the neutron resonance spectrum look similar to a proton spectrum.



N. Baillie *et al.*, PRL **108** 199902 (2012)

Two Methods of Analysis

Very Important Protons (VIP):
$70 < p_s < 100$ MeV/c
$\theta_{pq} > 100°$

The Ratio Method (for VIP events only)

- measure tagged counts divided by inclusive counts
- correct this ratio for backgrounds
- one scale factor (close to 1) gives F_2^n/F_2^d
- Normalize to parametrization of world data by Christy *et al.* (which has a 5-10% statistical uncertainty)

The Monte Carlo Method (produce $R_{D/S}$ and $F_2^{n,eff}$)

- Measured tagged counts
- Divide by spectator model Monte Carlo results -> $R_{D/S}$
- Multiply by F_2^n used in the model to get $F_2^{n,eff}$
- Results used to study range of validity of spectator model

The two methods have different systematic errors, but give very similar results.

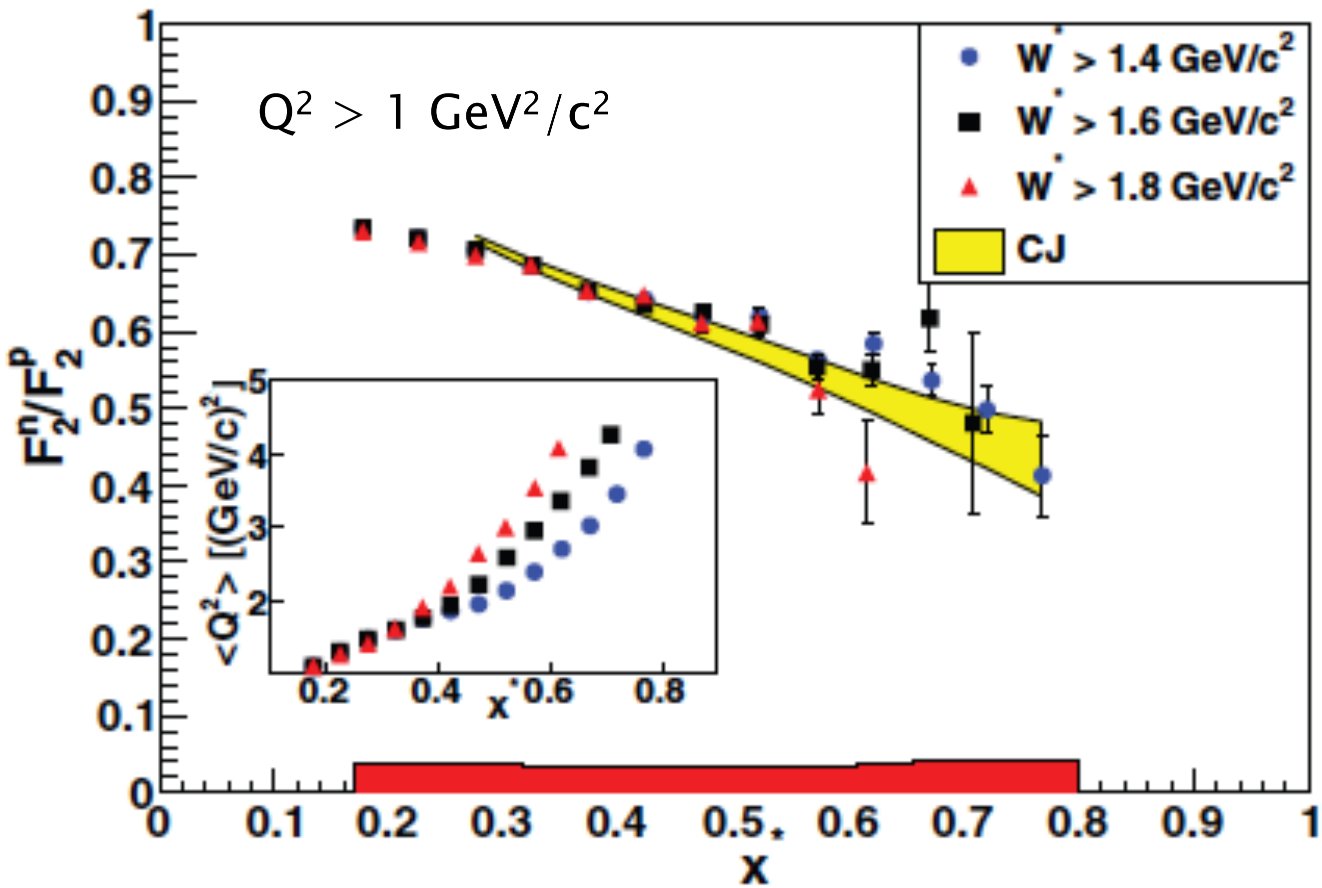
P.E. Bosted and M.E. Christy, PRC **77**, 065206 (2008).
M.E. Christy and P.E. Bosted, PRC **81**, 055213 (2010).

F_2^n/F_2^p – Ratio Method

Updated with most recent fits to world data for F_2^d and F_2^p.

Data only go to x ~ 0.6 for the best W* cut.

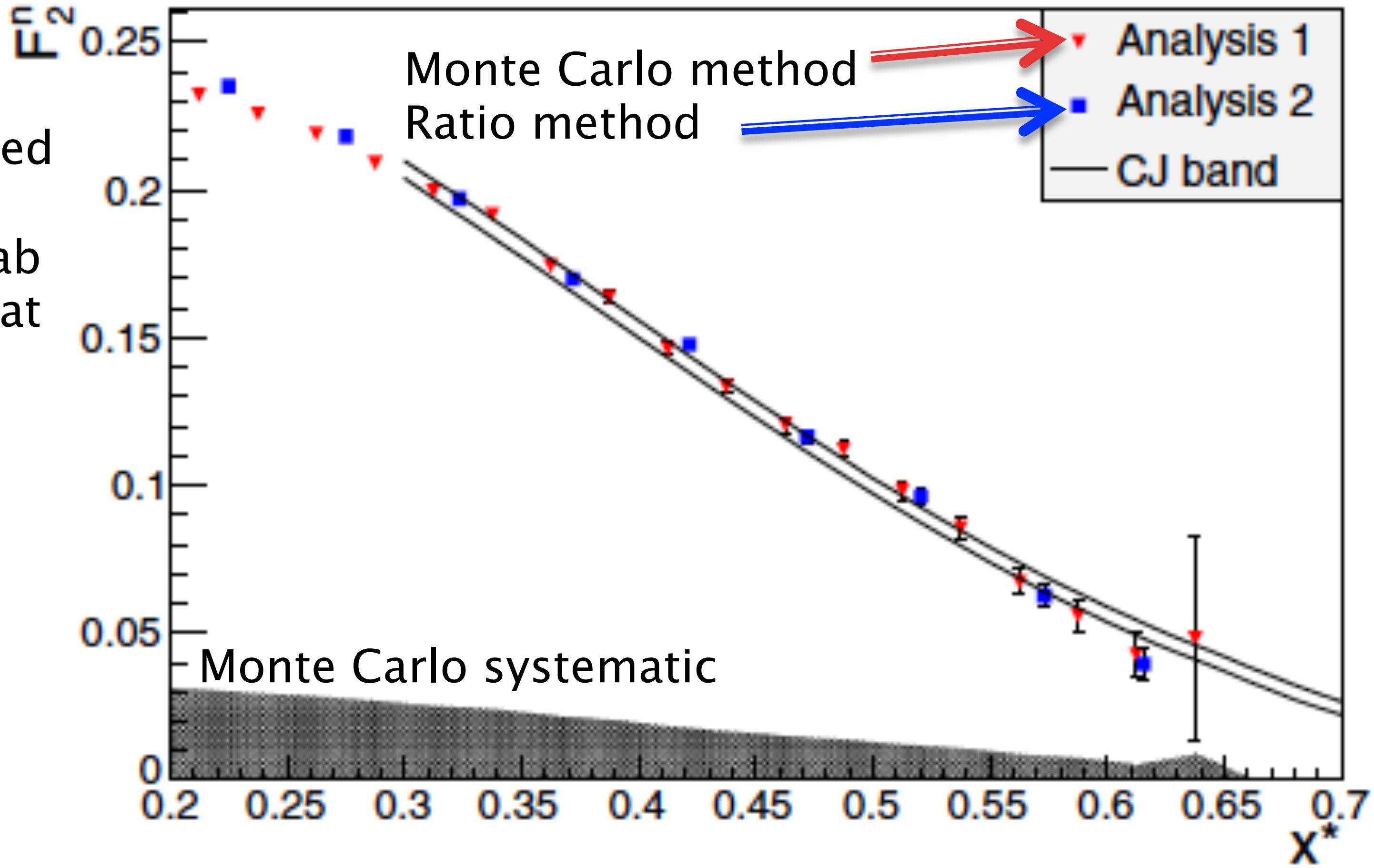
Impossible to make conclusion from these data about d/u as x -> 1. We need higher beam energy!



S. Tkachenko *et al.* PRC 89 045206 (2014)

Comparison of Two Analysis Methods

Data are normalized to global fit by CTEQ-Jefferson Lab (CJ) collaboration at x = 0.32



Good agreement; Different systematic uncertainties

CJ: Accardi *et al.* PRD84 014008 (2011)

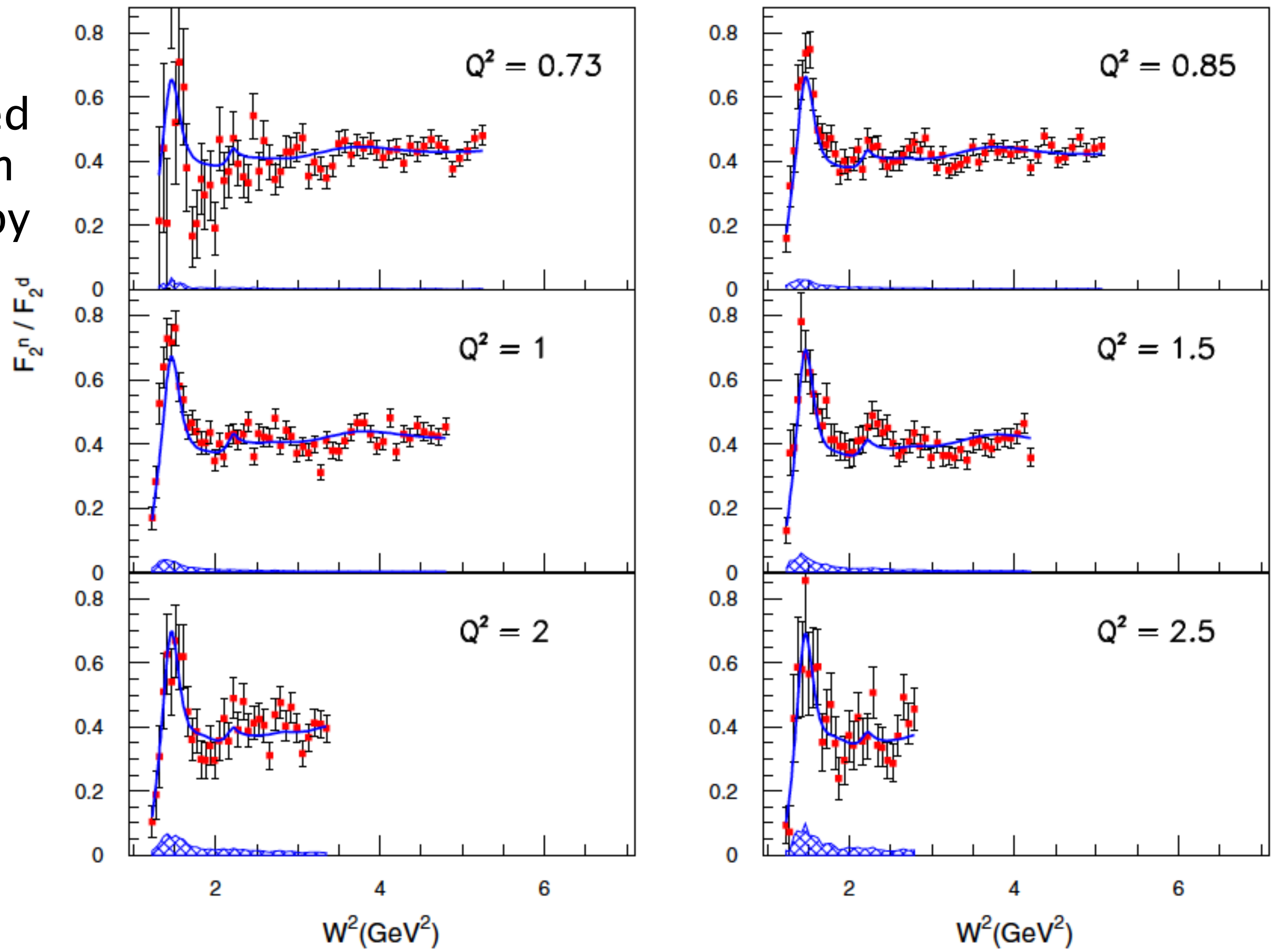
F_2^n/F_2^d – 4.2 GeV

BONuS main result

Data are normalized to new fit of proton and neutron data by Christy et al. (blue line), which does not include BONuS data.

Point to point systematic shown

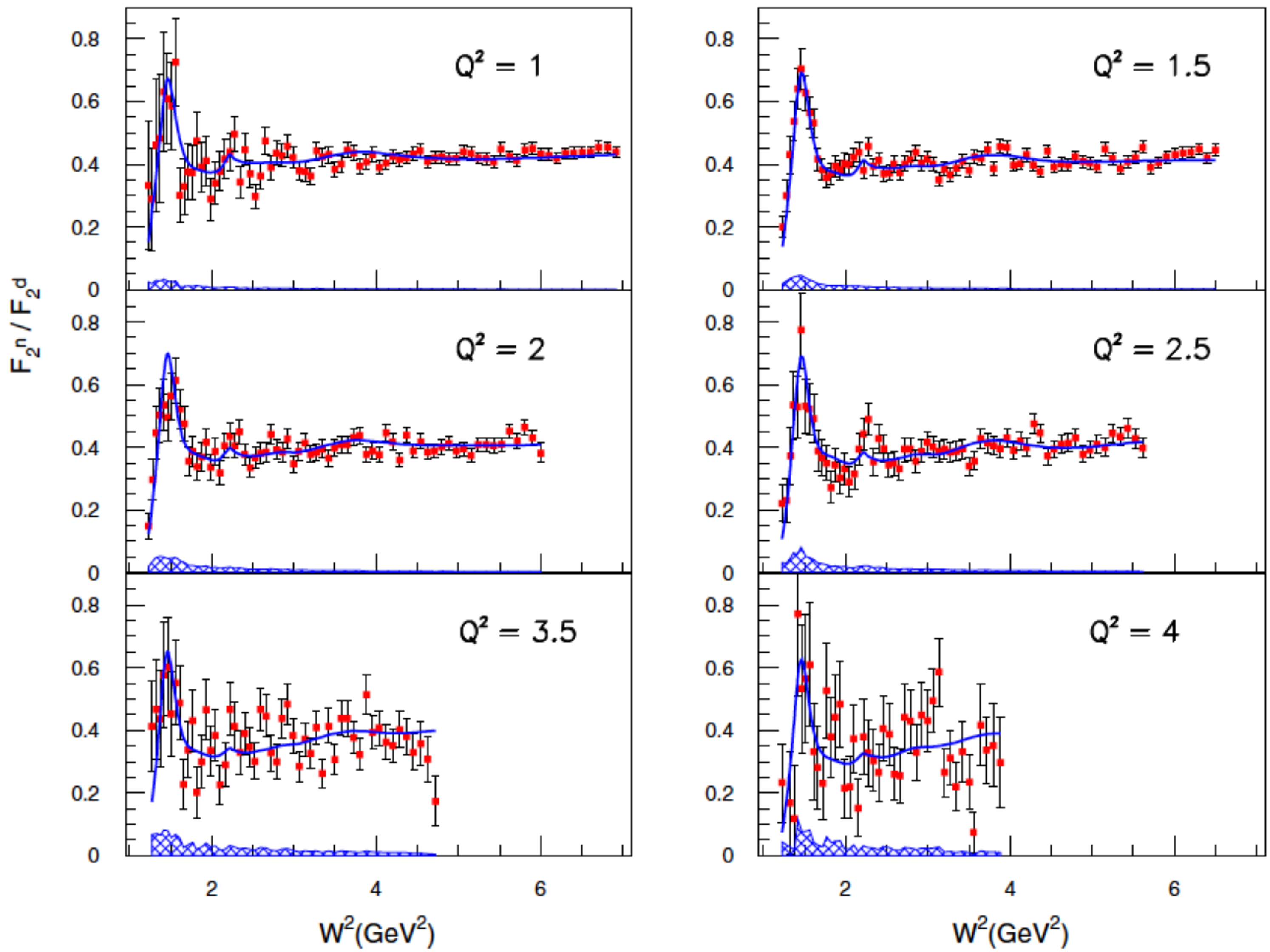
Overall 10% normalization uncertainty estimated



S. Tkachenko *et al.* PRC 89 045206 (2014)

F_2^n/F_2^d – 5.3 GeV

BONuS main result

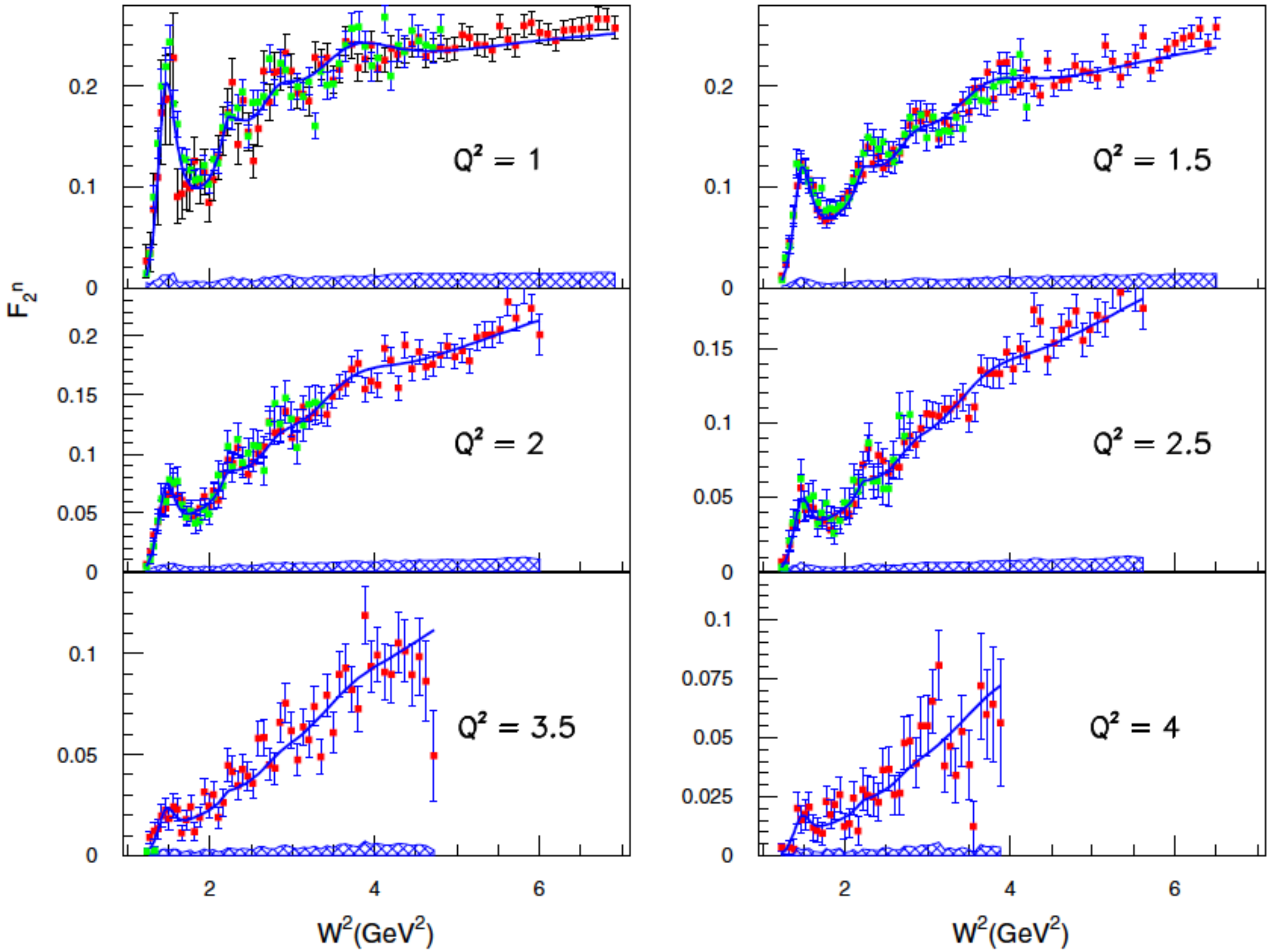


S. Tkachenko *et al.* PRC 89 045206 (2014)

F_2^n

F_2^n/F_2^d multiplied by Christy fit for F_2^d

Systematic shown for 5.3 GeV data

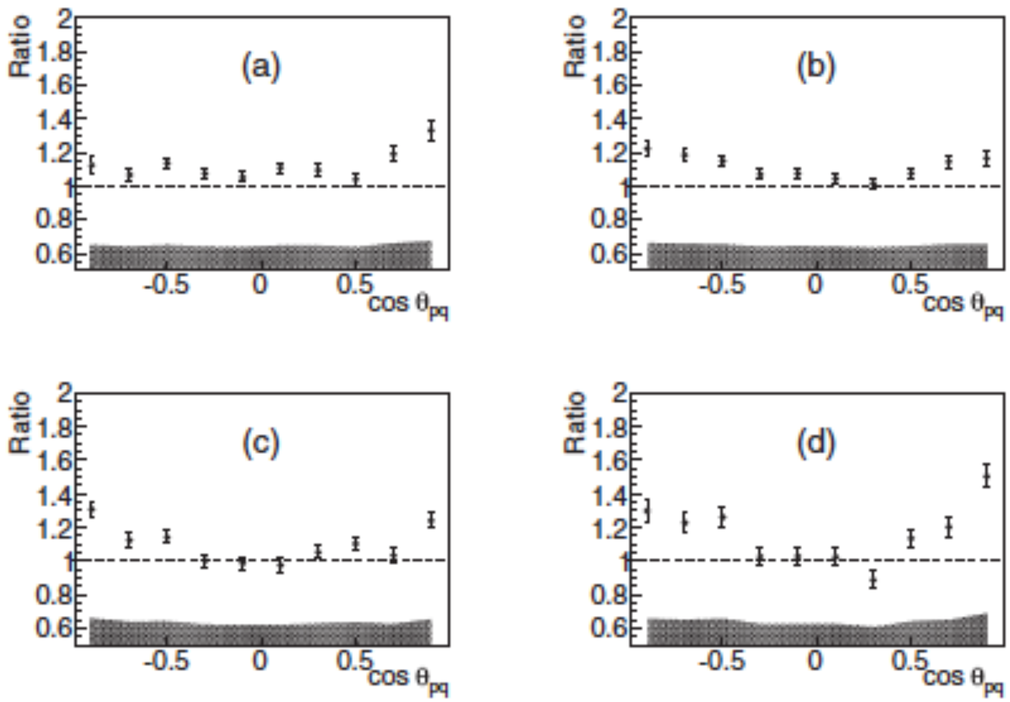


4.2 GeV
5.3 GeV

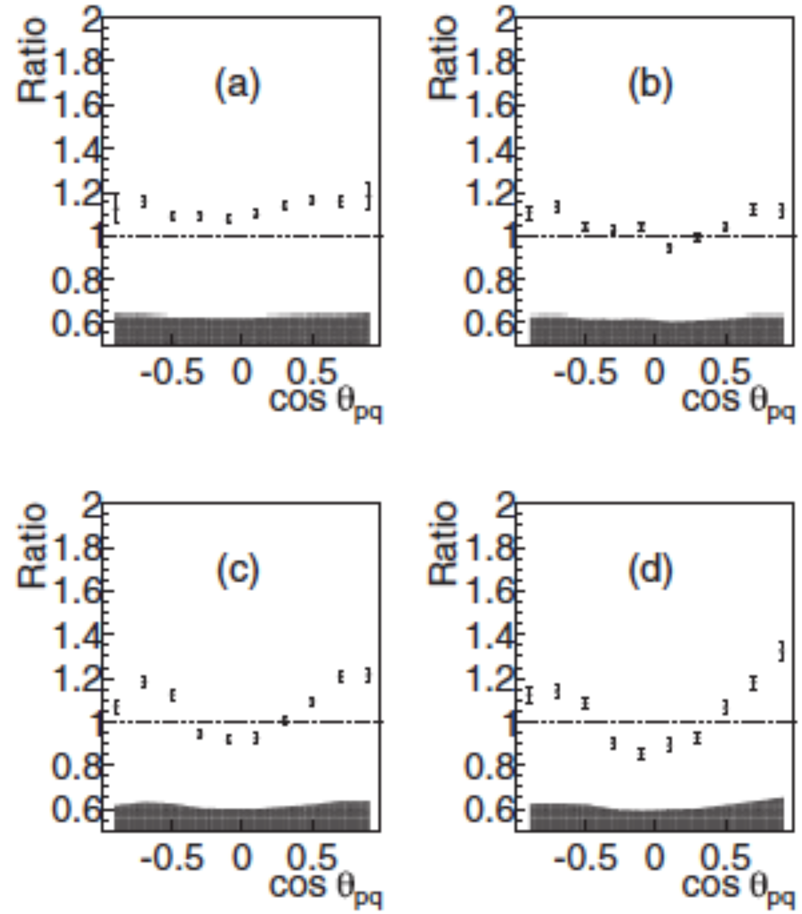
S. Tkachenko *et al.* PRC 89 045206 (2014)

$R_{D/S}$ as a function of θ_{pq}

5.25 GeV



4.23 GeV



p_s bins:
(a) 70 – 85 MeV/c
(b) 85 – 100 MeV/c
(c) 120 – 120 MeV/c
(d) 120 – 150 MeV/c

Q^2: 1.10 – 2.23 MeV^2/c^2
W*: 1.35 – 1.6 GeV

S. Tkachenko *et al.* PRC 89 045206 (2014)

$R_{D/S}$ as a function of θ_{pq}

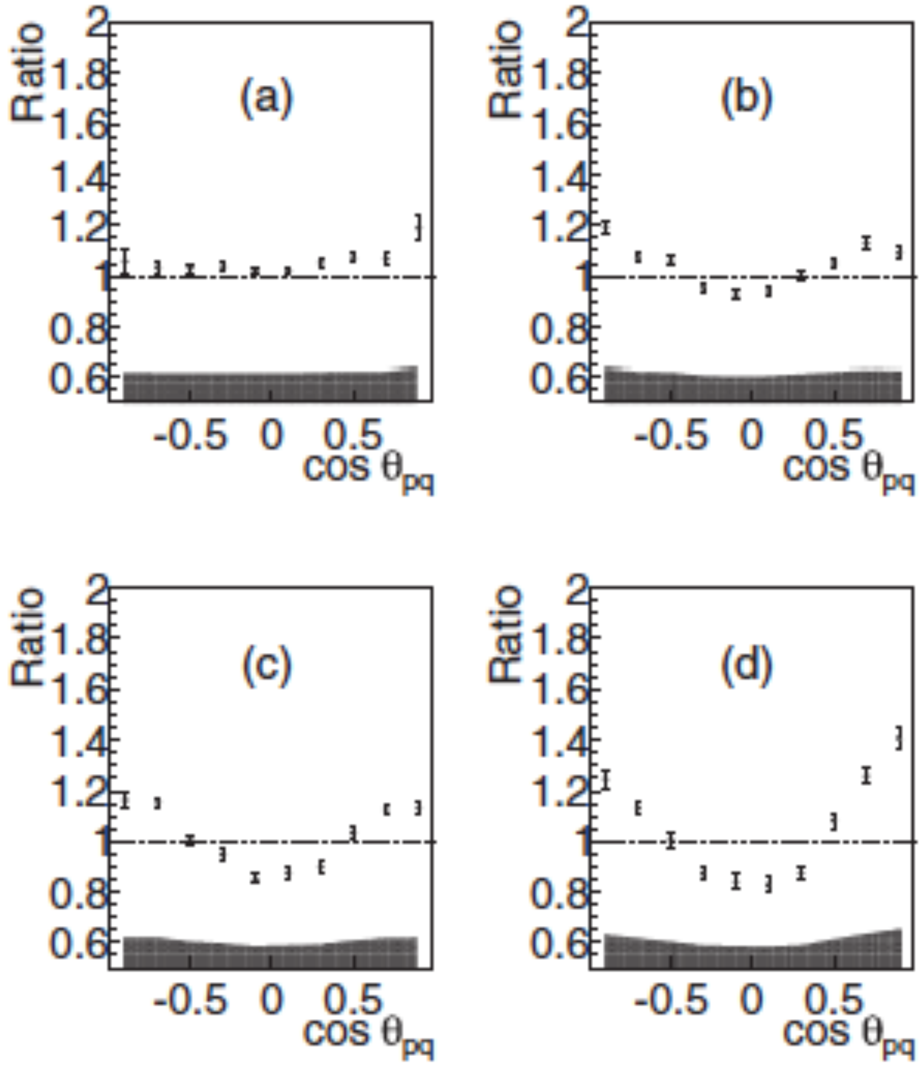
Deviation from spectator model is smallest at backward angles and lowest p_s.

Dip at 90° is consistent with predictions.

Perhaps some leakage from higher momentum in the 2nd bin.

No noticeable dependence on beam energy.

These data should enable improved models of FSI.



Beam Energy: 5.25 GeV

W*: 1.85 – 2.2 GeV

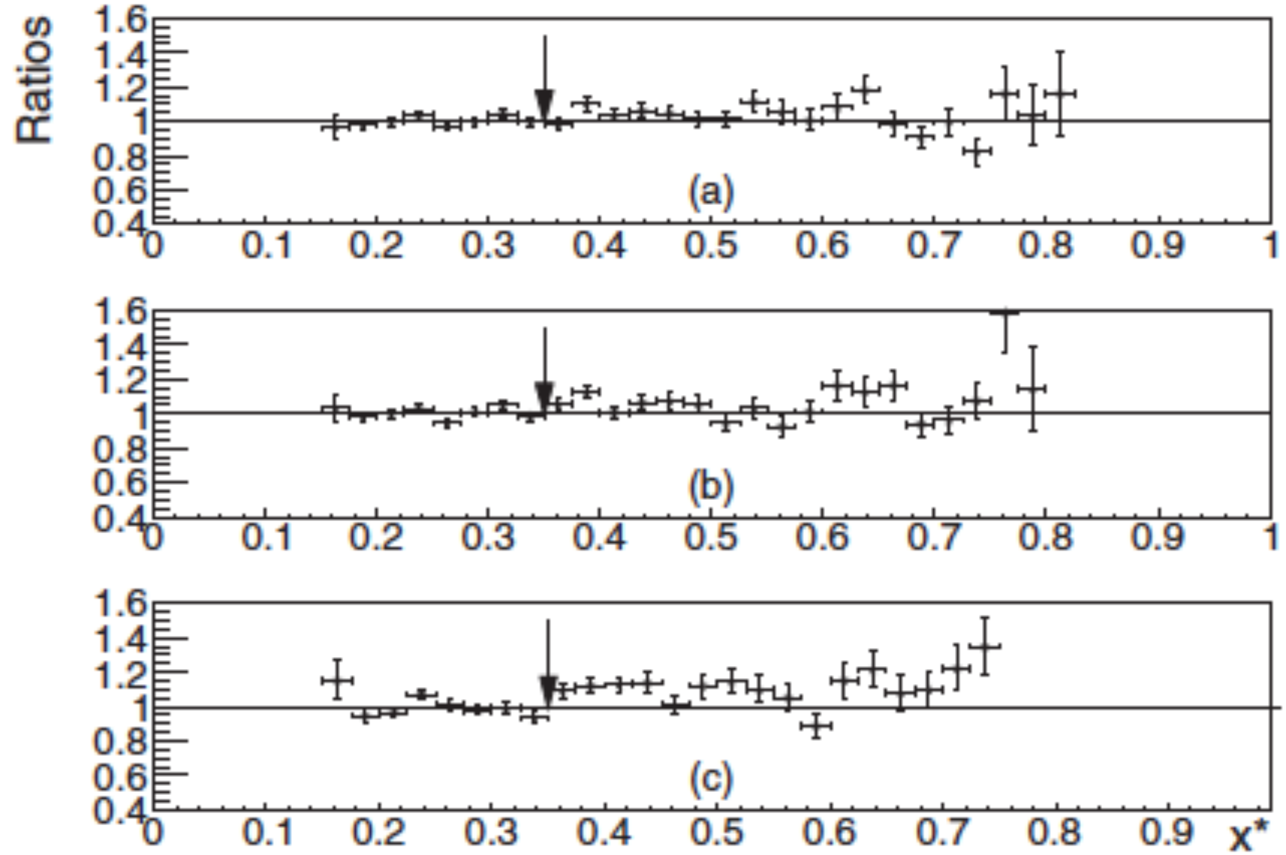
S. Tkachenko *et al.* PRC 89 045206 (2014)

Binding Effects

Is F_2^n modified for off-shell nucleons?

$F_2^{n,eff}$ for three highest p_s bins compared to lowest p_s bin as a function of x*. Look for EMC-like dependence on x*. None seen within uncertainties.

Binding effects are small up to p_s = 150 MeV/c



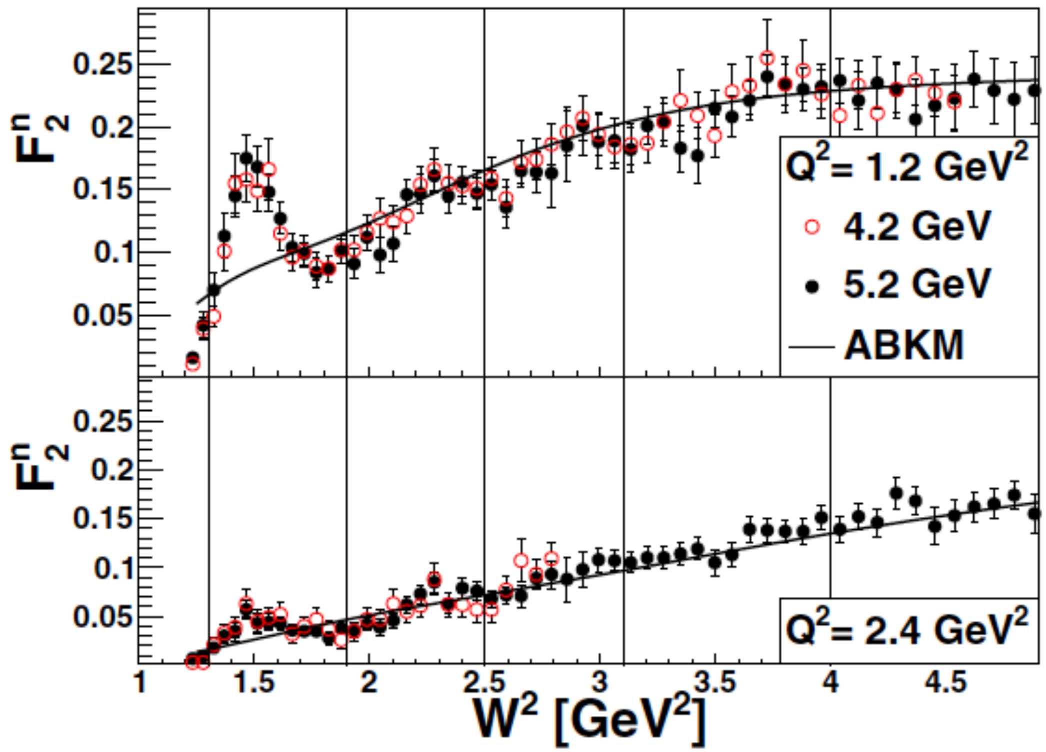
$1.1 < Q^2 < 2.2$ GeV^2/c^2
$\theta_{pq} > 100°$

We find a similar result for higher Q^2.

S. Tkachenko *et al.* PRC 89 045206 (2014)

Duality

- Duality is the observation, originally by Bloom and Gilman, that nucleon resonances at low Q^2 average to the scaling curve measured in DIS.
- Local duality is a similar effect for smaller ranges in W, for example for one resonance region.
- Global and local duality has been observed in the proton and in nuclei (D and ^{3}He) for polarized and unpolarized structure functions.



What about the neutron? A model dependent study of the neutron suggested that local duality does hold for the neutron. However, one explanation for duality (Brodsky) in the proton involves accidental cancellations that would cause cause strong duality violations for the neutron.

I. Niculescu *et al.* PRC 91 055206 (2015)

Duality for the neutron

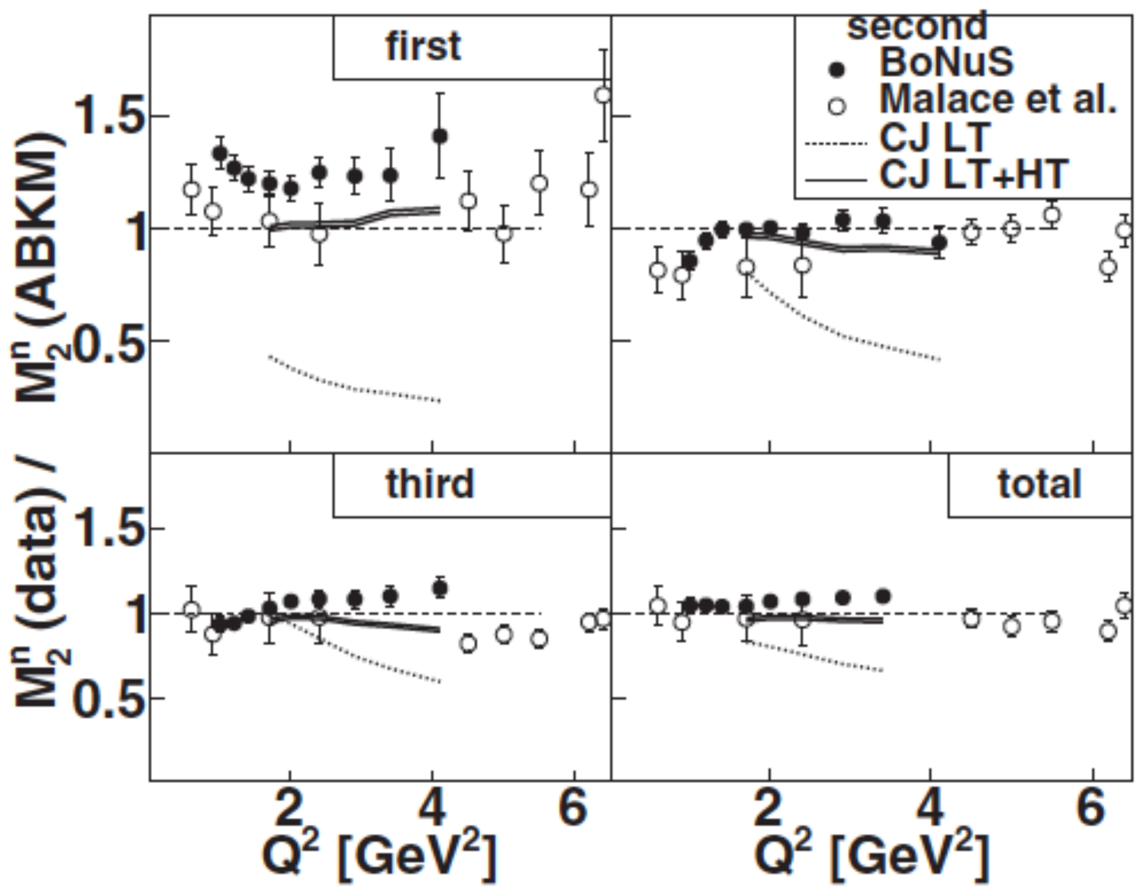
$$M_N^n(Q^2) = \int_{x_{\min}}^{x_{\max}} x^{N-2} F_2^n(x,Q^2)\,dx$$

Ratio of M_2^n to DIS PDF fit as a function of Q^2.

Duality holds for the neutron, except in the Δ resonance region, down to $Q^2 \sim 1$ GeV^2.

Discrepancy in the Δ region may be related to uncertainty in high-x PDF fits.

Higher twist corrections to PDF fit are important for testing duality.



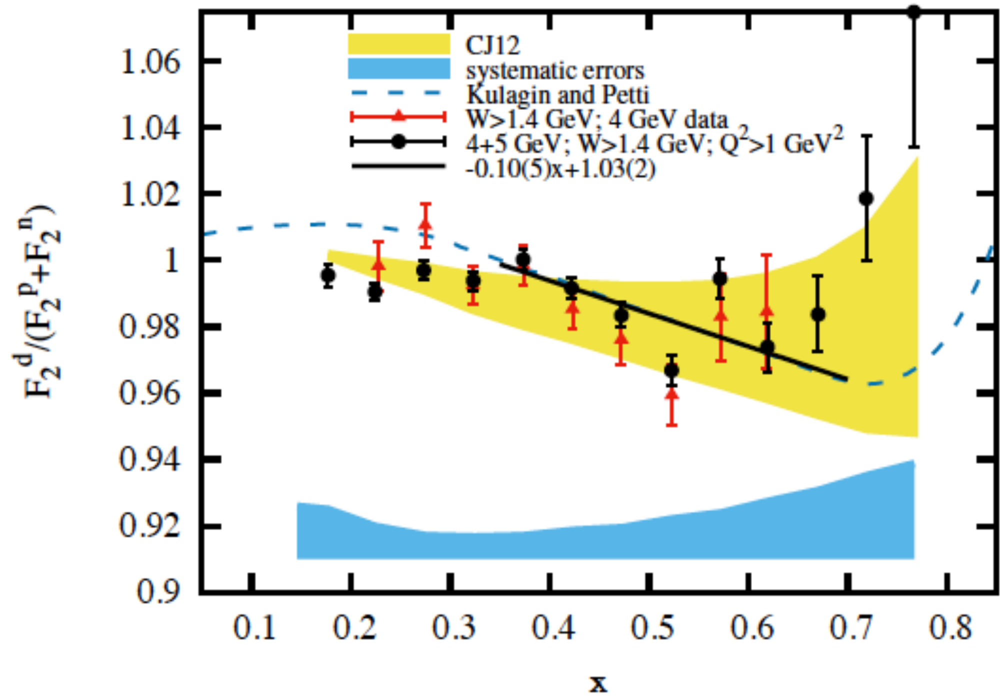
I. Niculescu *et al.* PRC **91** 055206 (2015)
S. Alekhin *et al.* PRC **81** 014032 (2010)
J.F. Owens *et al.* PRD **87** 094012 (2013)

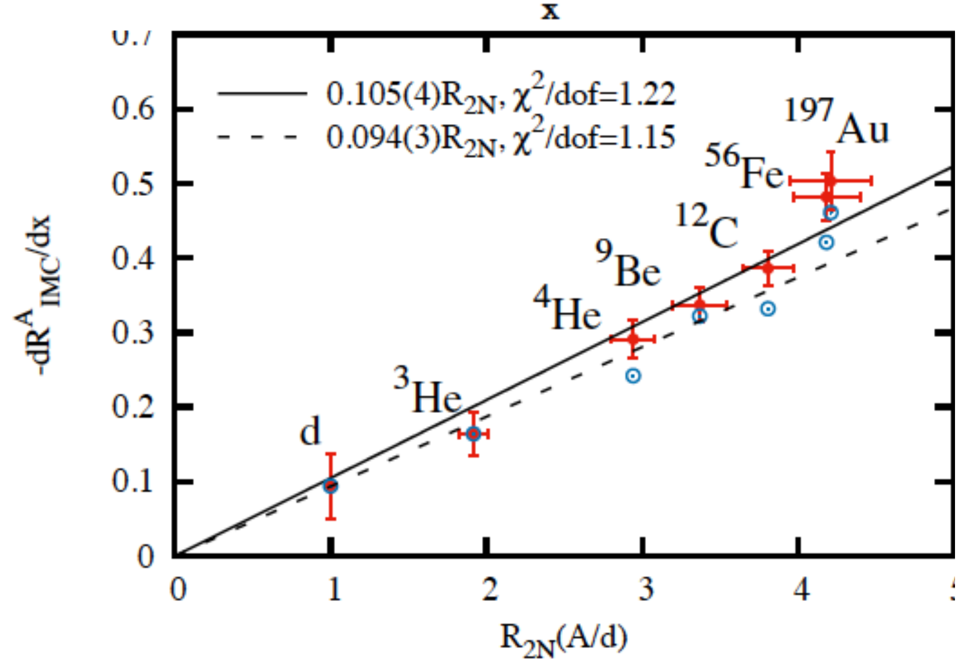
EMC Effect

- The EMC Effect refers to the observation that the $(F_2^A/A)/(F_2^d/2)$ has a negative slope in x from 0.35 to 0.7.
- Slope varies with probability of NN correlations compared to deuterium.
- Does the deuteron have an EMC effect?

$$F_2^d/(F_2^p + F_2^n)$$

- Yes, but it is small
- Consistent with NN correlations trend.



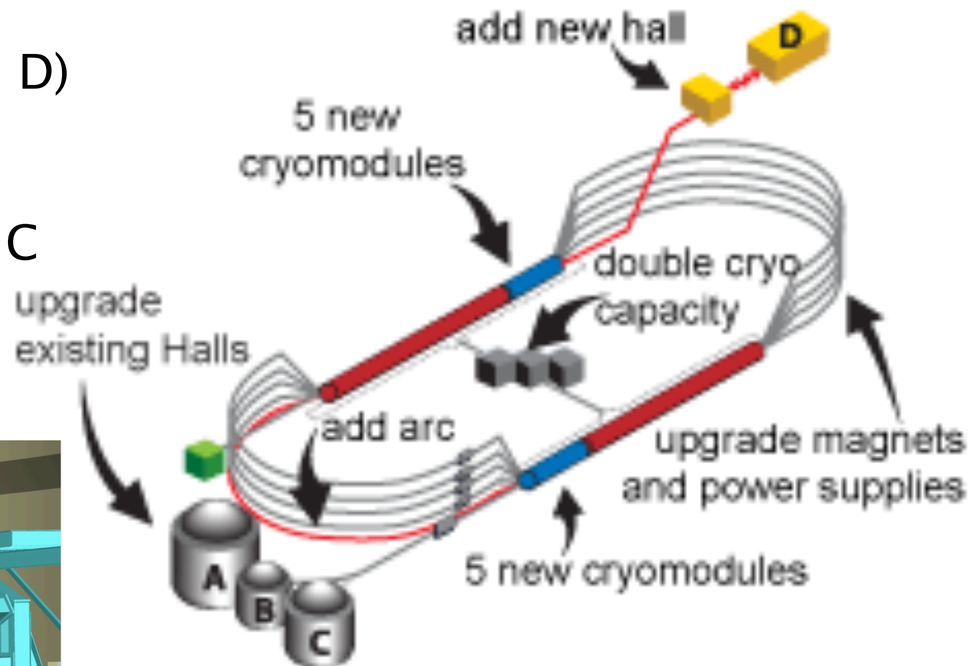


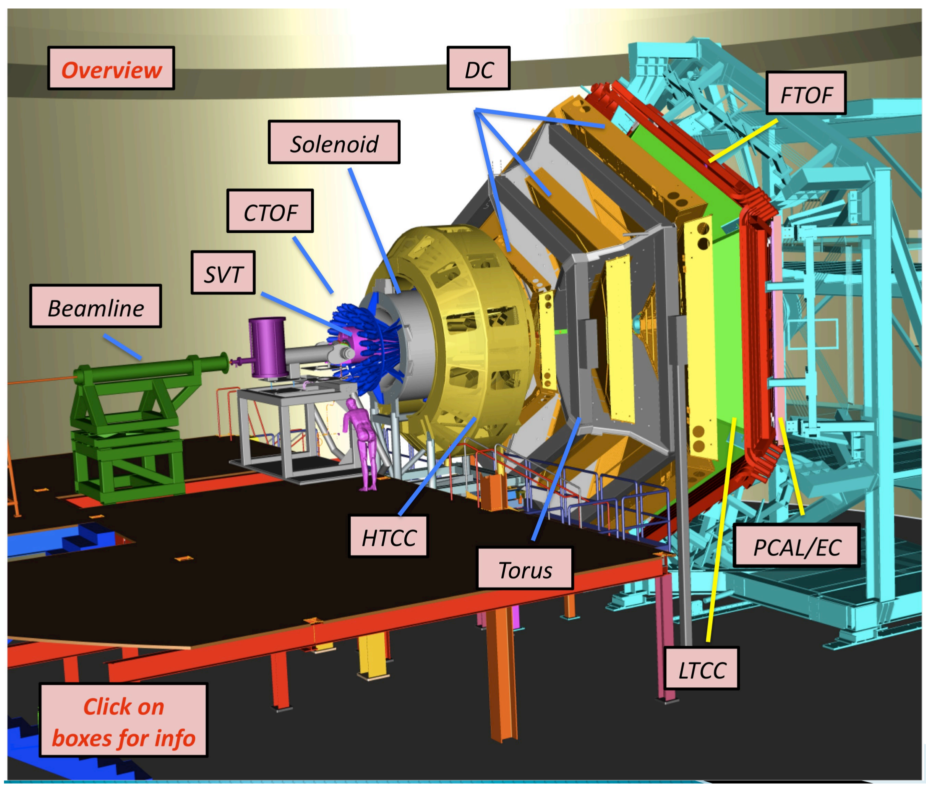
K.A. Griffioen *et al.*, PRC **92** 015211 (2015)

Jefferson Lab Upgrade Almost Complete

Added a 4th experimental hall (Hall D) for photon experiments – GlueX

11 GeV available in Halls A, B, and C





CLAS12 is under construction

BONuS12 may be the first experiment – January 2018

Expected Results F_2^n/F_2^p

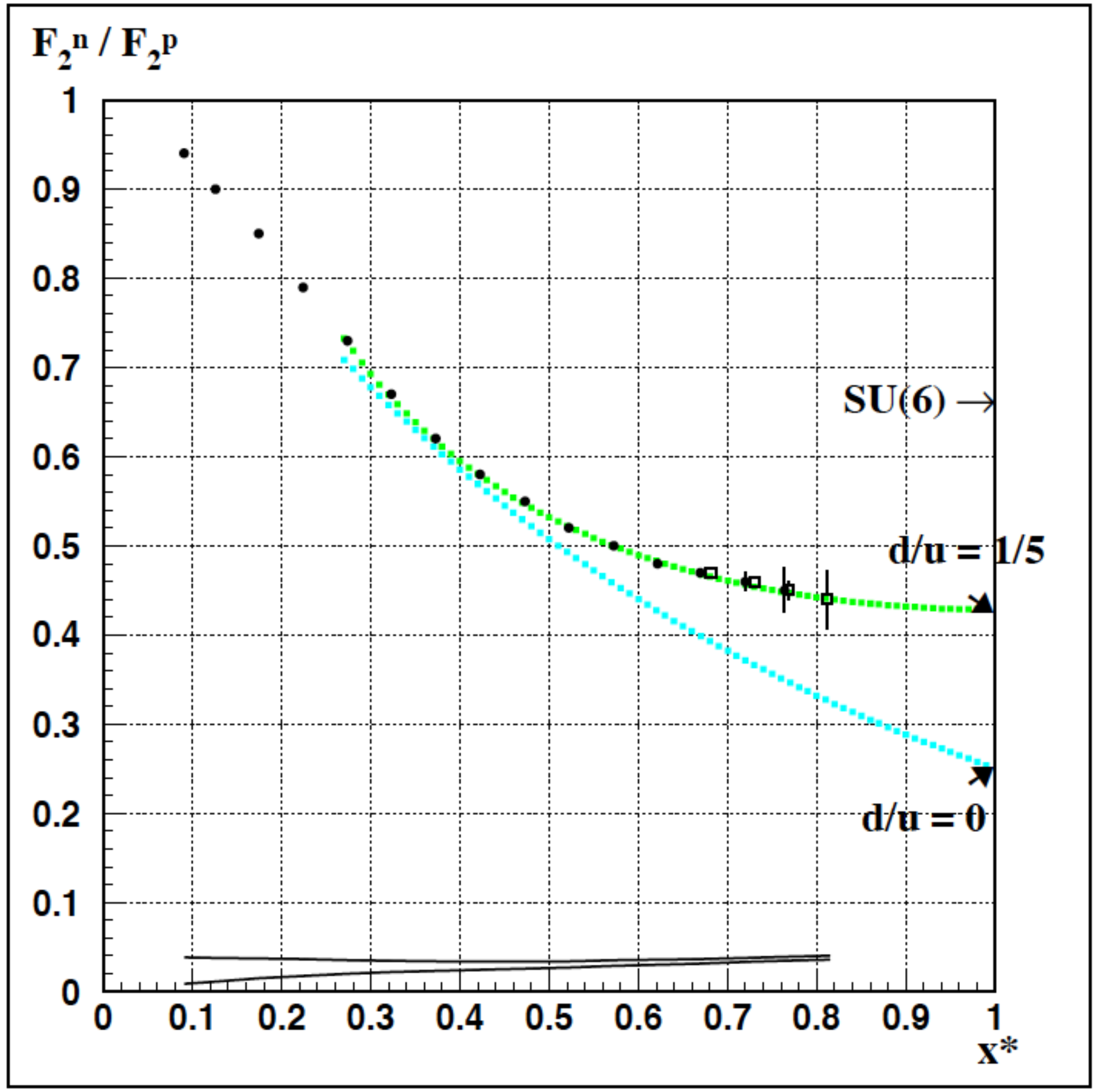
40 cm long target
7.5 atm D_2 gas
200 nA beam

42 days approved

Luminosity 2×10^{34} cm^{-2}s^{-1}

$Q^2 > 1$ GeV^2
$p_s < 100$ MeV/c
$\theta_{pq} > 110°$

$W^* > 2.0$ GeV -> $x^*_{max} = 0.76$
$W^* > 1.8$ GeV -> $x^*_{max} = 0.81$

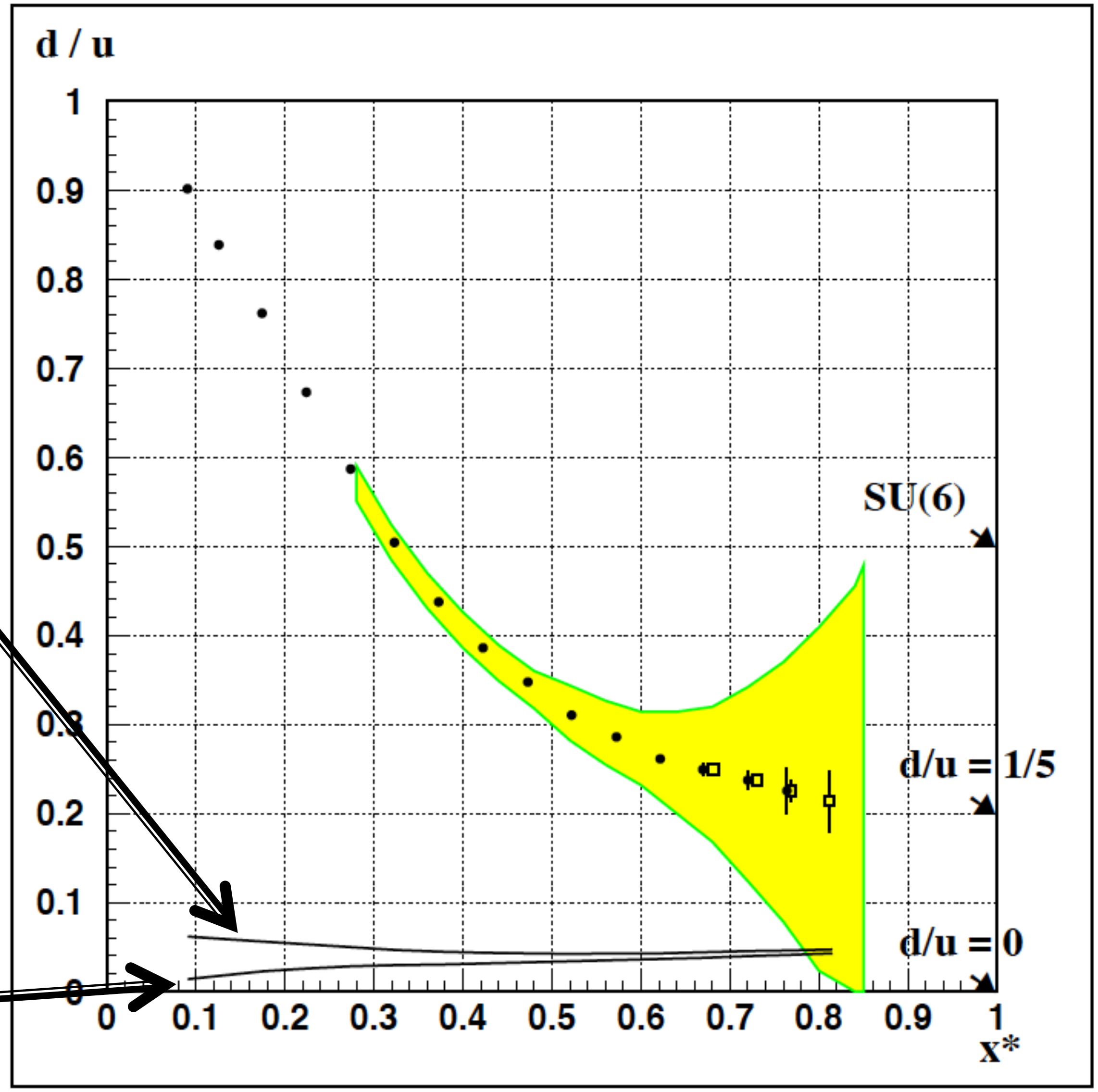


E12-06-13, S. Bueltmann *et al.*

Expected d/u

Combined experimental and theoretical systematic uncertainty

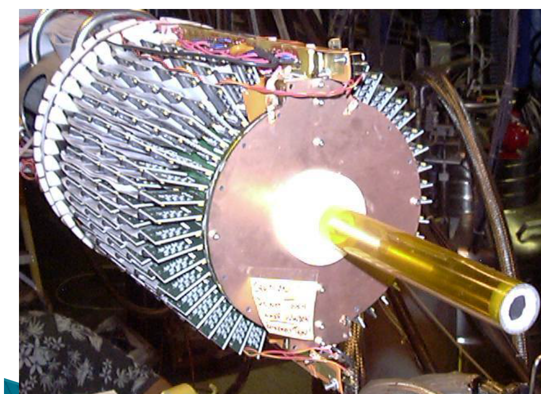
Estimate of point to point systematic uncertainty

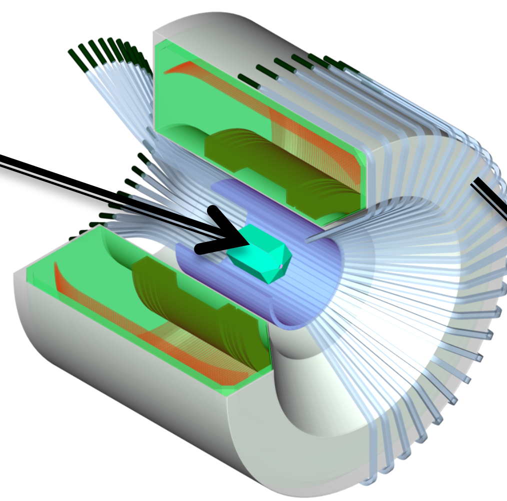


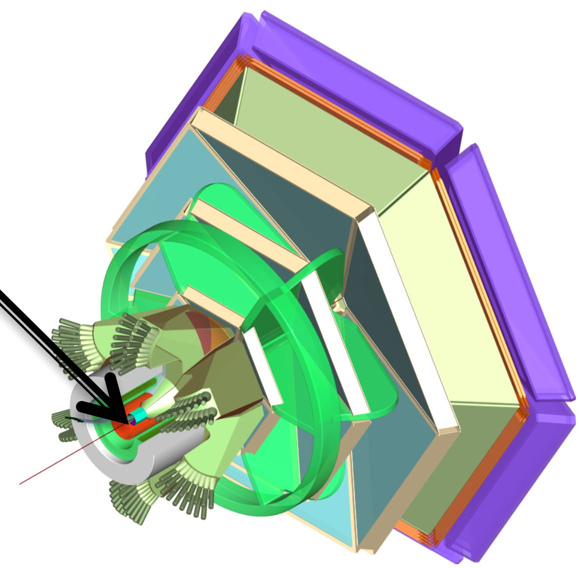
E12-06-13, S. Bueltmann *et al.*

Two Possibilities for the New Recoil Detector

- Upgraded RTPC
  - DREAM chip; Improved electronics
  - Larger drift region; better momentum
  - Better rate capabilities
- Drift Chamber
  - Faster
  - Potentially lower momenta accessible







Summary

- The BONuS experiment at Jefferson Lab used spectator tagging at low p_s and backward angles to select events in which the neutron target is essentially "free."
- F_2^n/F_2^d was measured over a wide kinematic range.
- F_2^n/F_2^p unable to reach high enough x* to determine d/u ratio as x -> 1.
- Nuclear effects studied: validity of VIP kinematics confirmed; FSI seems to be consistent with models
- Duality for the neutron is observed, except for Delta resonance region, down to $Q^2 \sim 1$ GeV^2/c^2
- Deuteron exhibits weak (as expected) EMC effect – consistent with trend in A
- In 2018 we will run again with 11 GeV beam and higher precision

Stay Tuned!

Thank You!

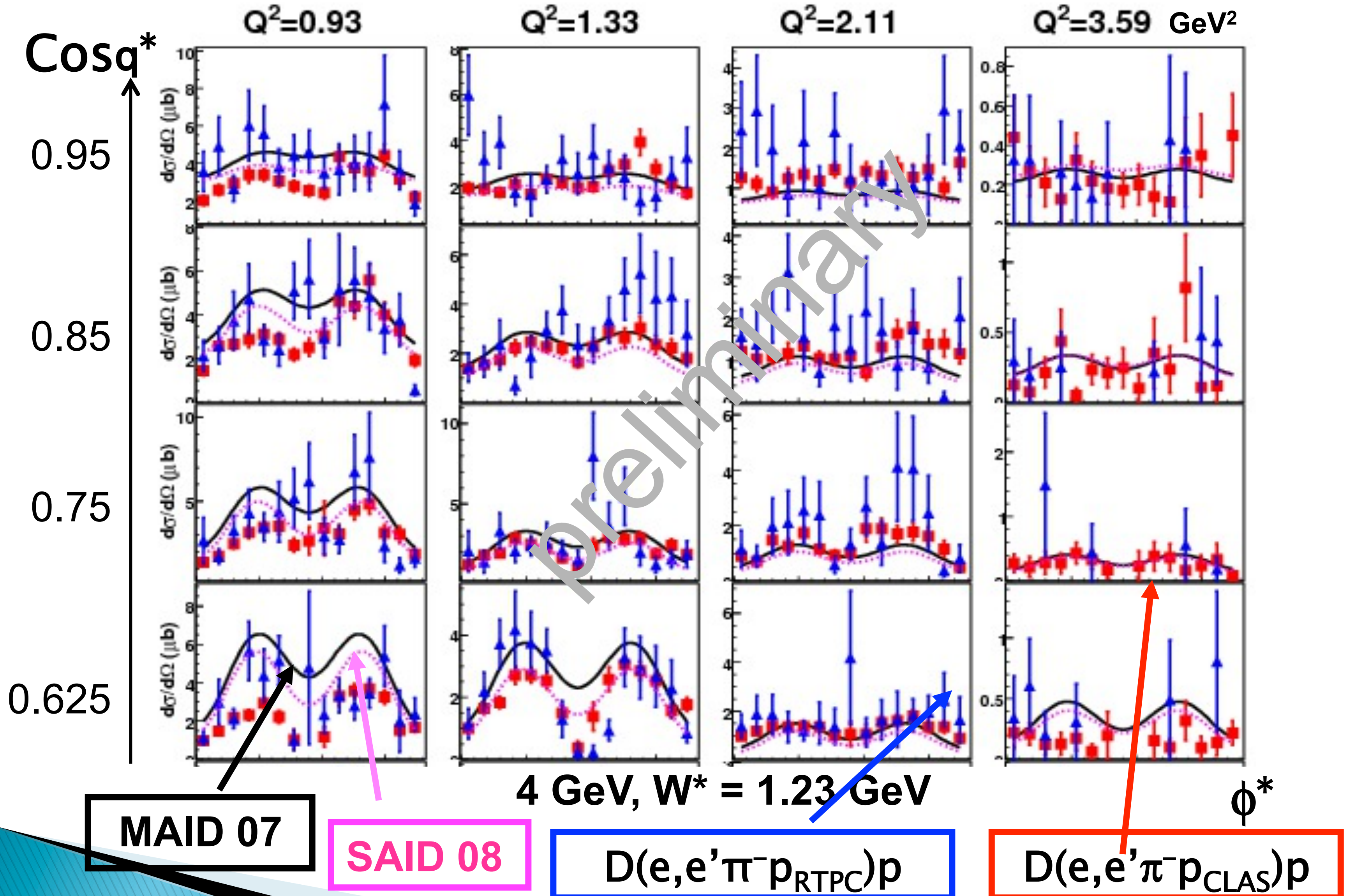
Graduate Students:

- Nate Baillie
- Jixie Zhang
- Slava Tkachenko
- Narbe Kalantarians

Papers:

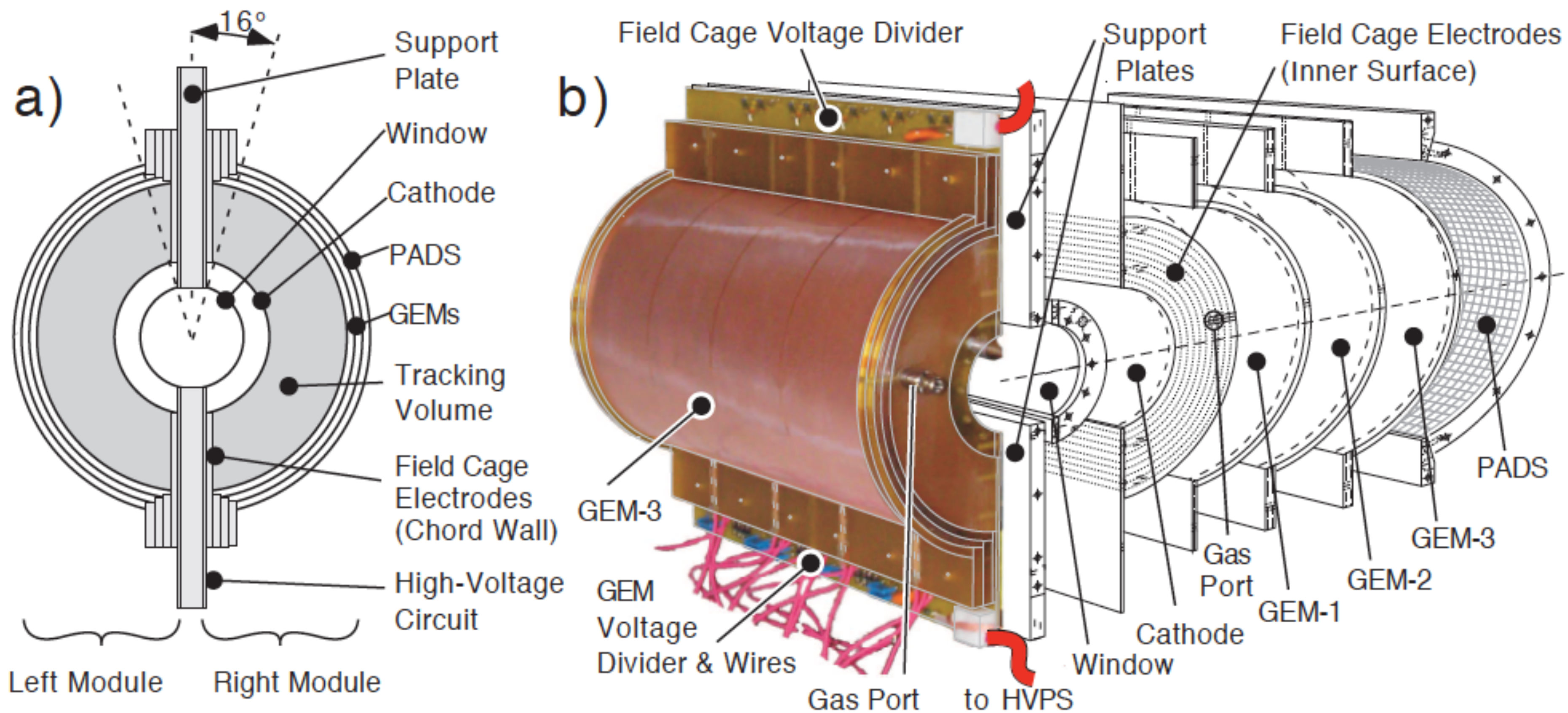
- H. Fenker *et al.* NIM A**592** 273 (2008)
- N. Baillie *et al*., PRL **108** 199902 (2012)
- S. Tkachenko *et al.* PRC **89** 045206 (2014)
- I. Niculescu *et al.* PRC **91** 055206 (2015)
- K.A. Griffioen *et al*., PRC **92** 015211 (2015)

D(e,e'π⁻p)p Cross Sections in the Resonance Region



J. Zhang et al., unpublished

RTPC



H. Fenker *et al.* NIM **A592,** 273 (2008)

Monte Carlo

- Elastic electron scattering off of deuterium
- Quasi-free scattering off one nucleon in deuterium in the spectator picture
  - Quasielastic scattering from one nucleon
  - Inelastic scattering from one nucleon
- Radiative corrections using Mo and Tsai
- Does not include FSI, NN correlations, etc

$$\frac{d\sigma}{dE'\,d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Point}} \frac{2MxF_2(x,Q^2)}{\epsilon Q^2} \frac{1+\epsilon R(x,Q^2)}{1+R(x,Q^2)},$$

where

$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_2}{2xF_1}\left(1+\frac{Q^2}{\nu^2}\right) - 1,$$

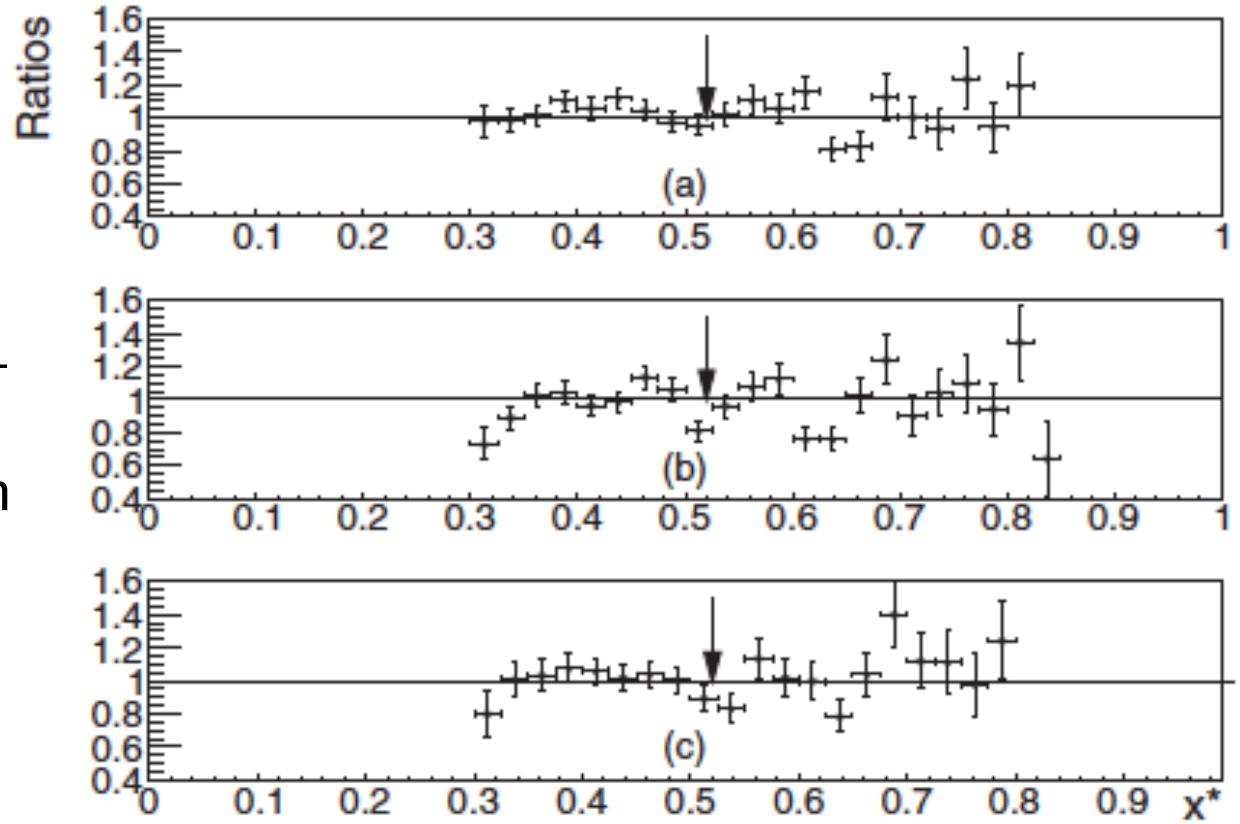
Why RTPC?

- Magnetic field is not parallel to z because solenoid length is less than diameter
- Need to minimize material in forward direction for detection of high momentum particles in CLAS
- RTPC geometry makes it easier to avoid effects of Moller electrons

Binding Effects – Higher Q^2 bin

$F_2^{n,eff}$ for three highest p_s bins compared to lowest p_s bin as a function of x^*. Look for EMC-like dependence on x^*. None seen within uncertainties.

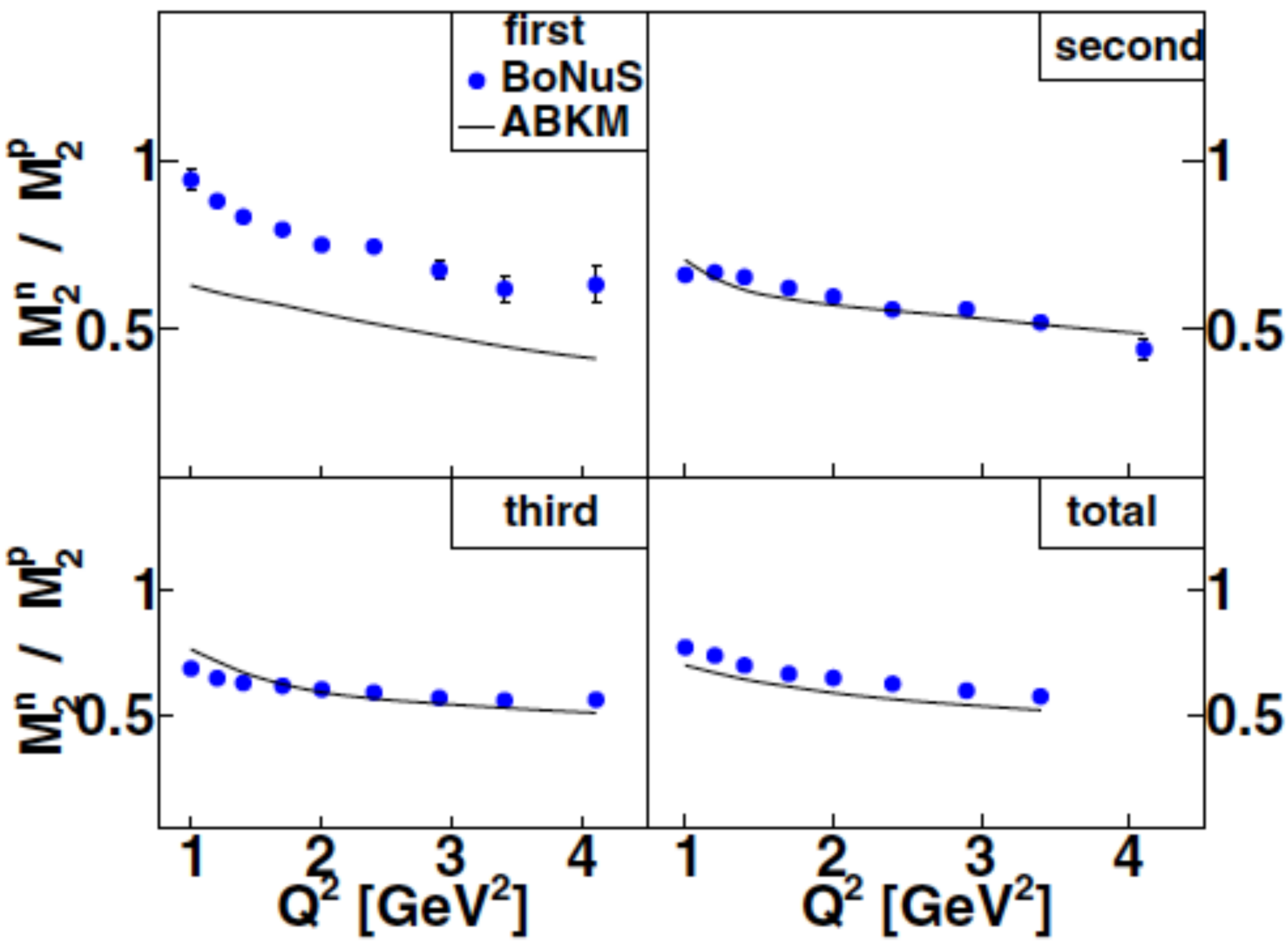
Binding effects are small up to $p_s = 150$ MeV/c



$2.2 < Q^2 < 4.5$ GeV^2/c^2

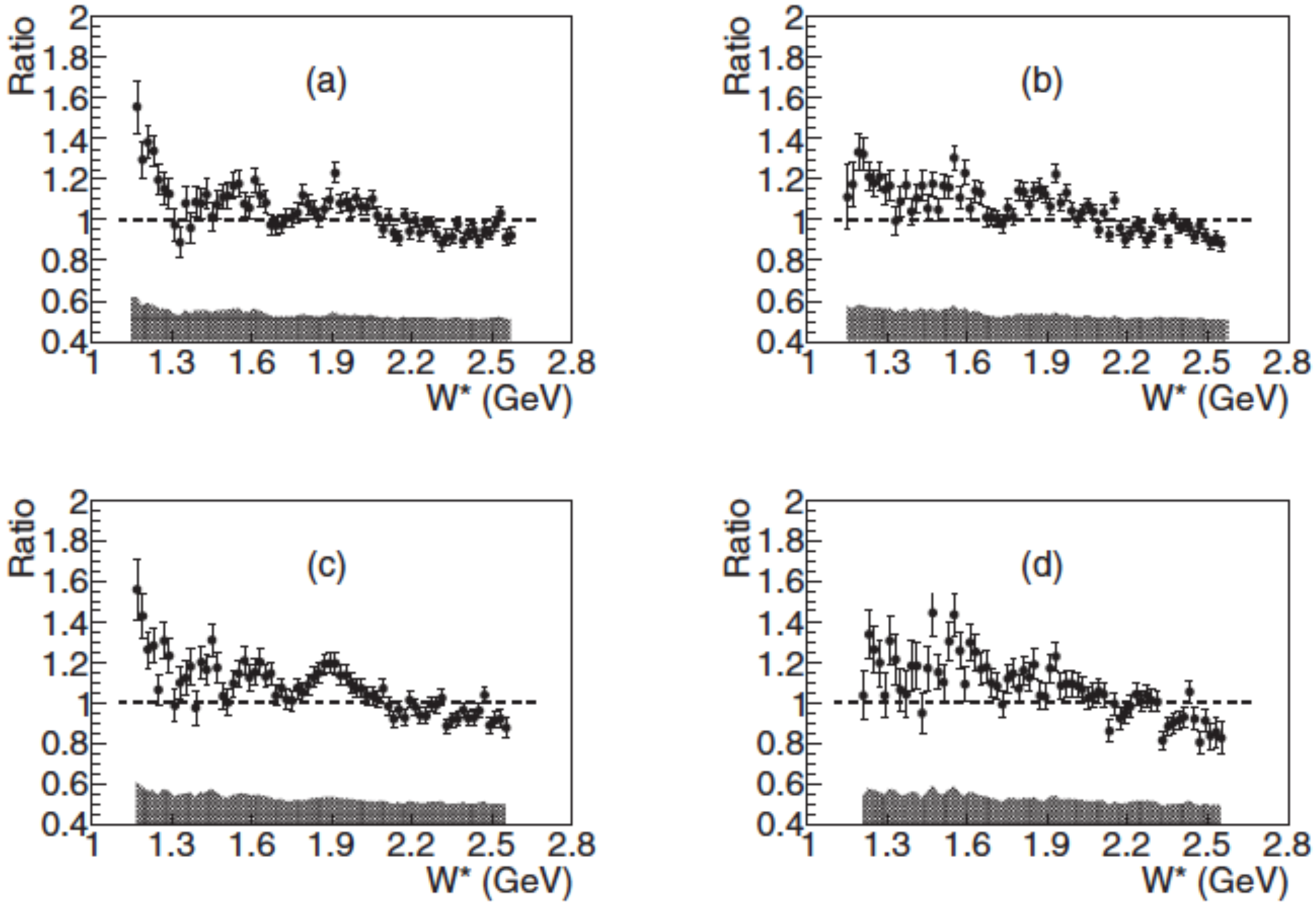
S. Tkachenko *et al.* PRC 89 045206 (2014)

F_2 moment: M_2^n/M_2^p



I. Niculescu *et al.* PRC 91 055206 (2015)

W* Dependence



W* dependence is similar in different p_s bins. Spectator picture OK, but fit to world data needs improvement in resonance region.

S. Tkachenko *et al.* PRC 89 045206 (2014)

CLAS12 Kinematic Range