

## Anti-Shadowing Exploration Opportunities with $F_2^A$

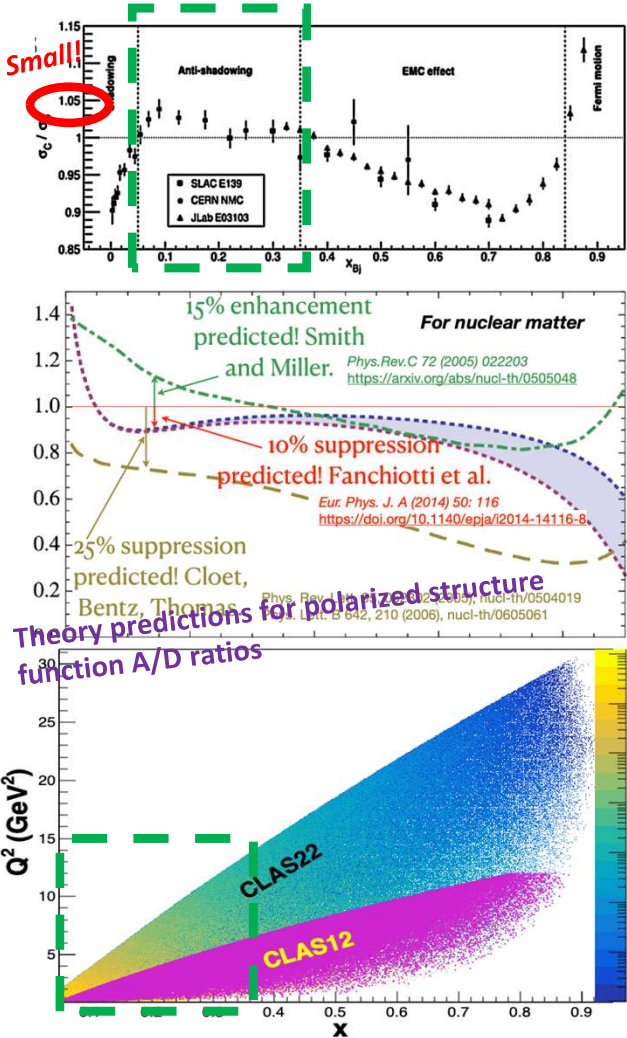
*N. Kalantarians (Virginia Union Univ.)*

QCD Evolution 11 May 2026

\*Work supported by NSF Award 2310076



# Anti-shadowing: solving a multi-decade puzzle



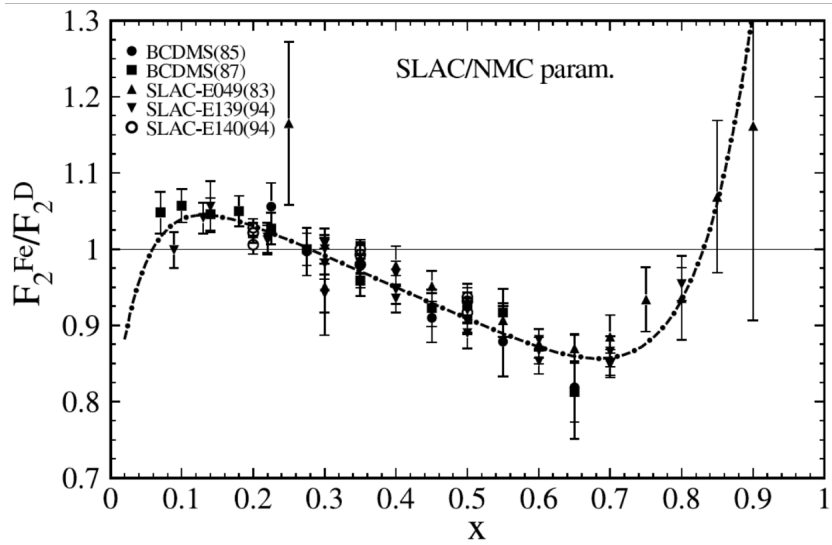
With  $\sim 20$  GeV e- can access the anti-shadowing region ( $x \sim 0.1-0.3$ ) at moderate  $Q^2$

- Region extremely interesting, near-equally dominated by valence quarks, sea-quarks, and gluons  $\rightarrow$  many many models!!
- Anti-Shadowing is the *least studied* nuclear structure function effect experimentally – *small effect requiring precision and high luminosity*
  - flavor dependence essentially uncharted
  - spin dependence essentially uncharted ( $\sim 50\%$  differences in predictions)
  - no tagged measurements
  - no L/T separations

A rigorous testing ground between shadowing, EMC regimes – models and theory must describe ALL

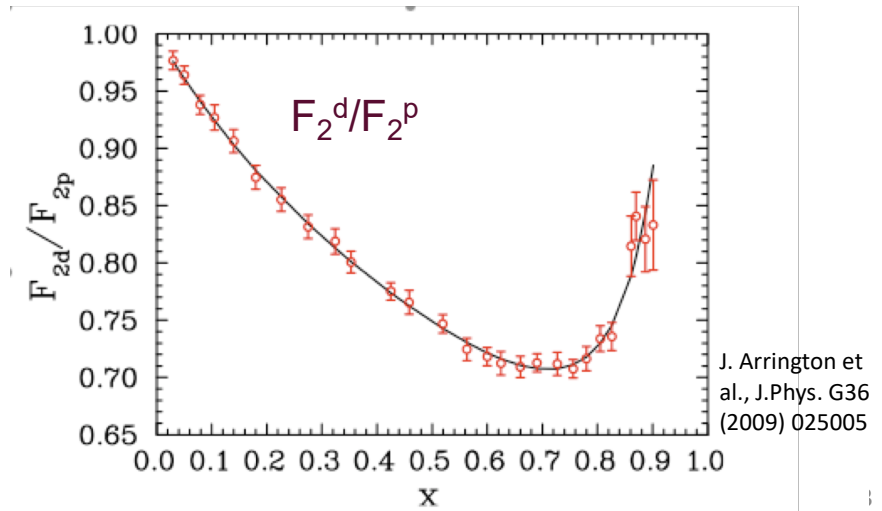
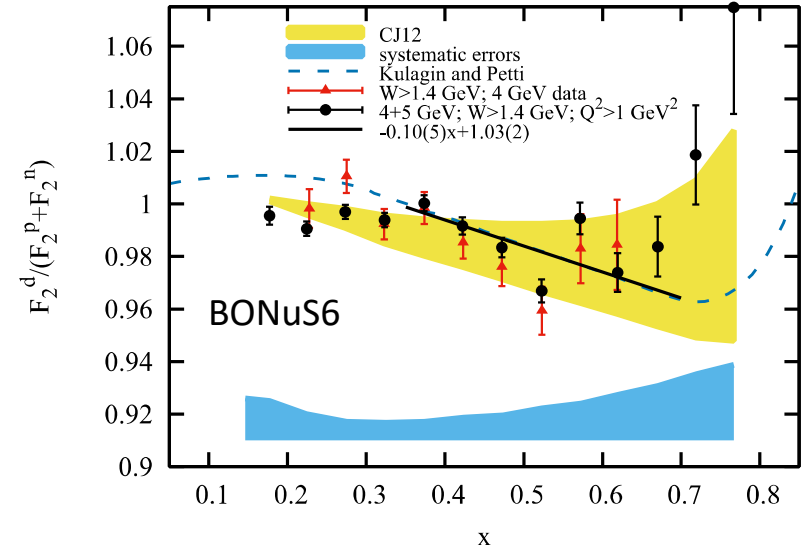
# EMC Effect and Nuclear Dependence

Representative EMC Ratio



- Seen numerous times.
- Deuteron also has a nuclear dependence

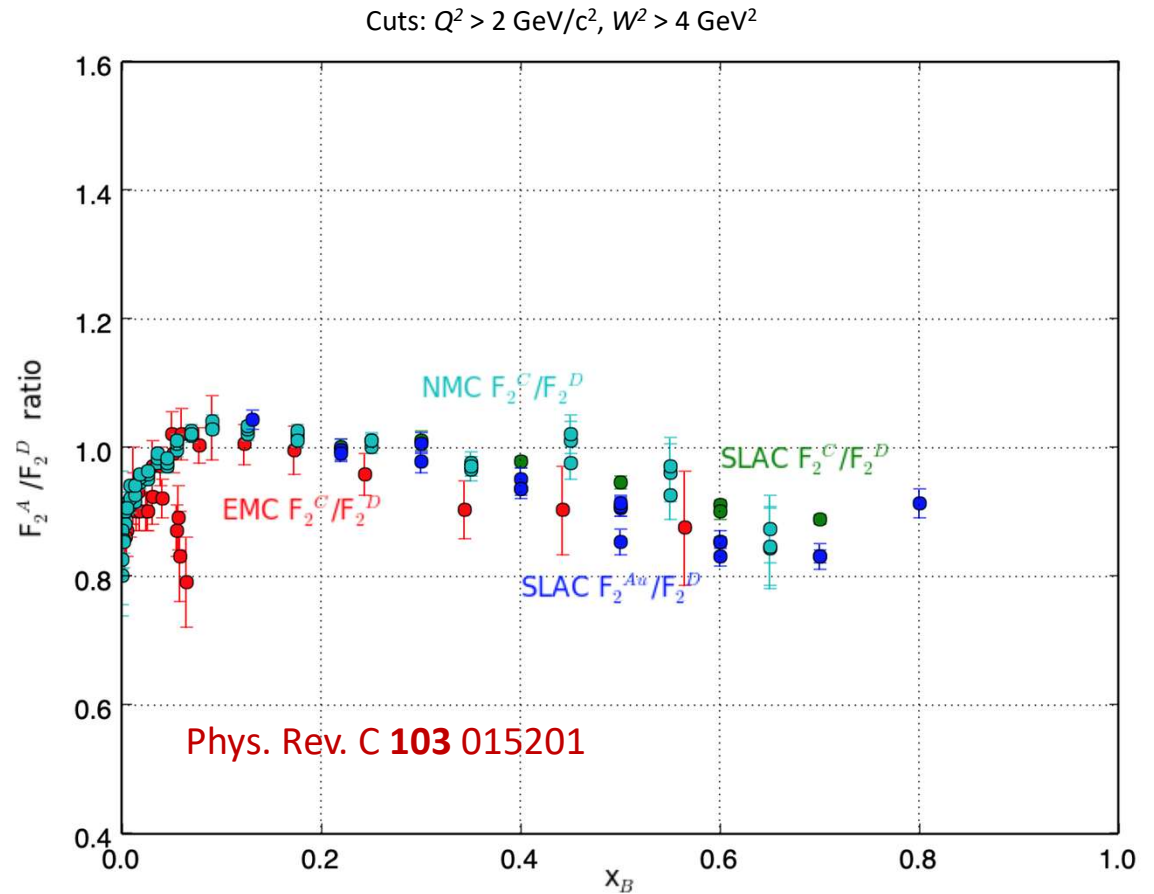
Phys. Rev. C 92 015211 (2015)



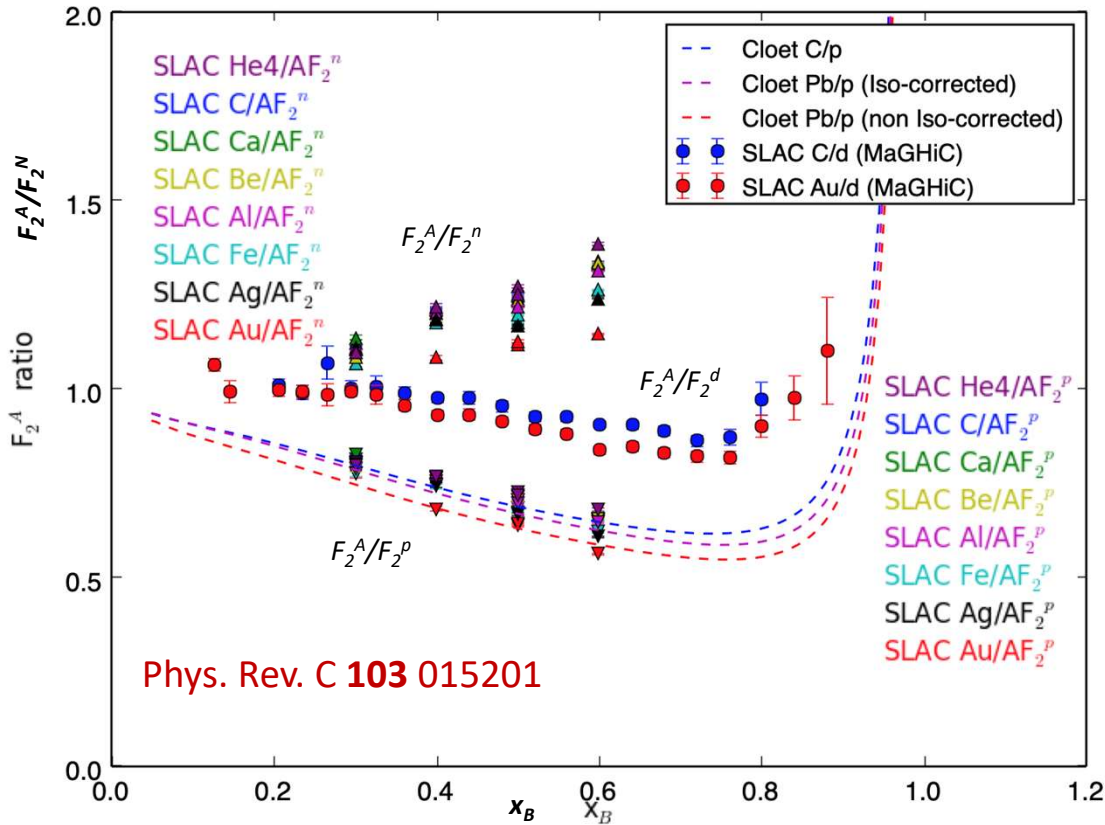
# EMC data-mining effort

- SLAC (E139) published cross-sections – Phys. Rev. D **49** 4348 (1994).
- Used R1990\* parameterization (assumes no nuclear dependence of R) to obtain  $F_2^A$ .

\* *L. Whitlow, et al., Phys.Lett.B 282 (1992)*

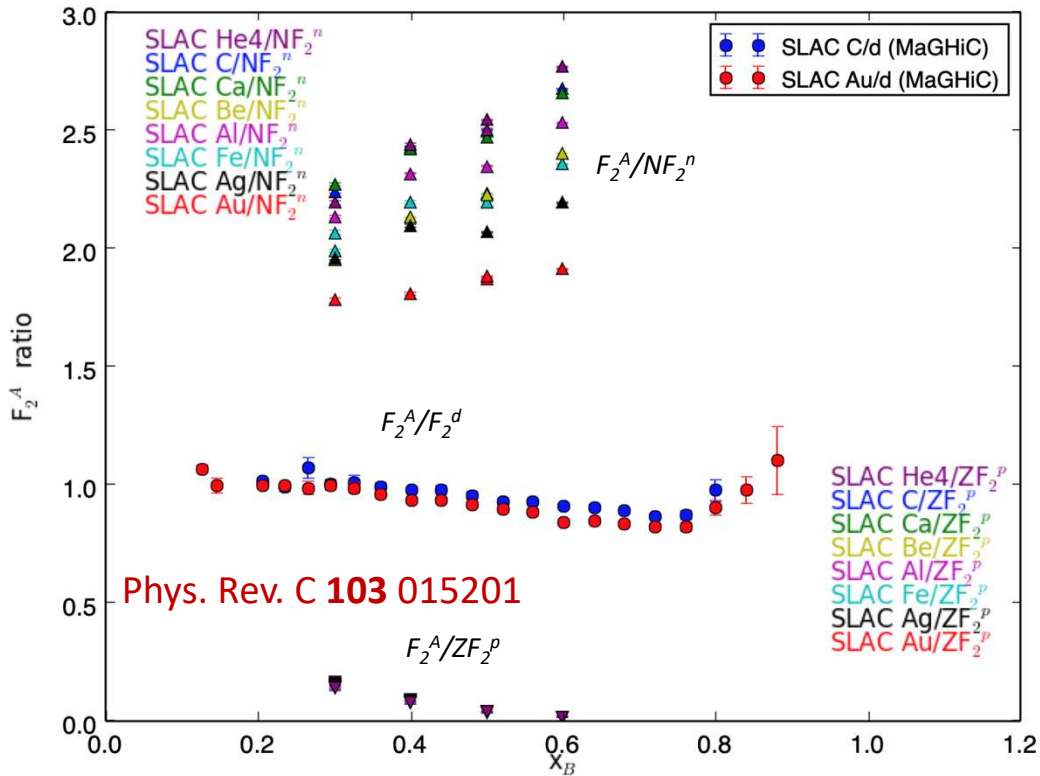


# $F_2^A/F_2^N$ ratios per nucleon



- We don't apply iso-scalar corrections for this analysis.
- Theory curves from I. Cloet.
- $F_2^p$  from NMC parameterization. Checked with CJ15 fit.
- $F_2^A/F_2^p$  seem to agree with theory.
- $F_2^A/F_2^n$  seem to have broader spread between nuclei.
- Expect some spread with nuclear asymmetry.
- "MaGHiC" Intl. Journ. Mod. Phys. E **23** 8 (2014).

# Comparing $F_2^A$ per free neutron, proton.

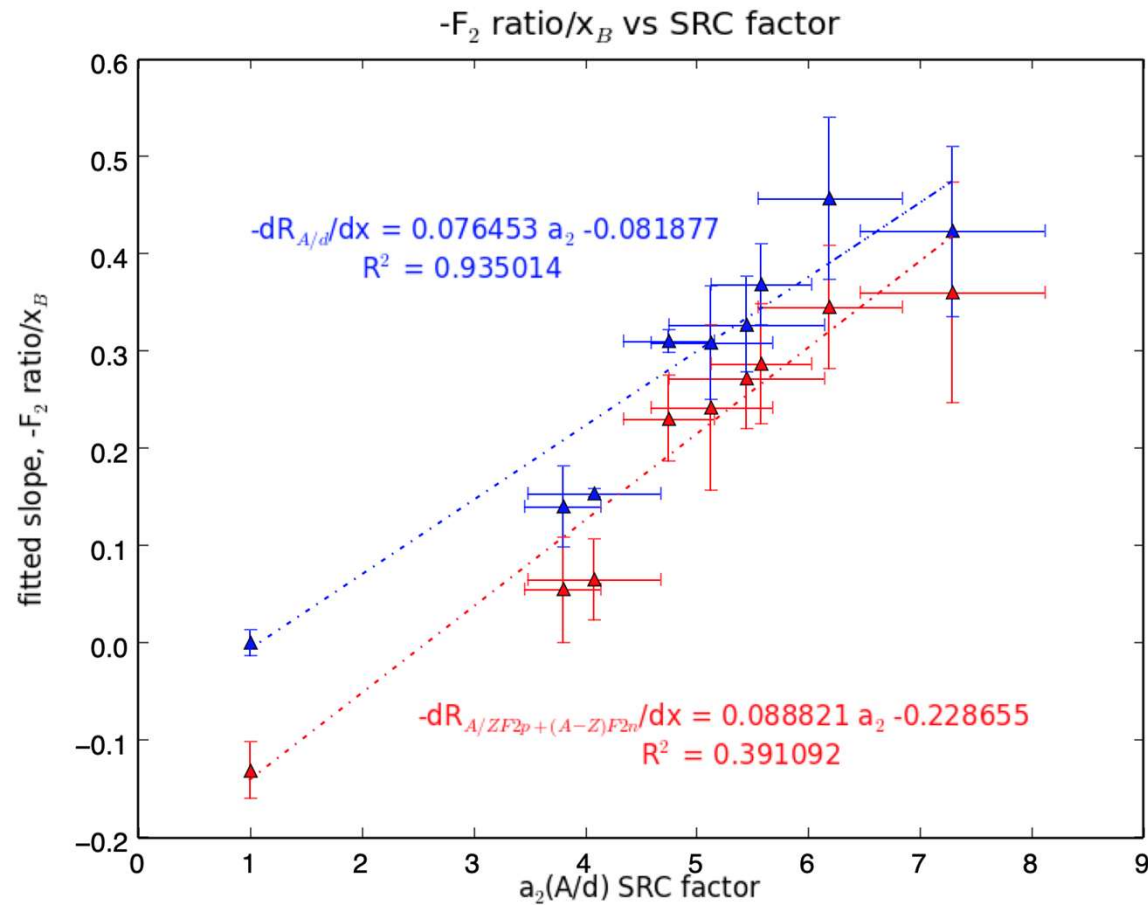


- Typically observed nucleon spread.
- Starts below 1; approximately 10%.
- Large spread in  $A/n$  compared to  $A/p$
- Expect some spread with nuclear asymmetry.
- “MaGHIC” Intl. Journ. Mod. Phys. E **23** 8 (2014).

# Comparison of $F_2^A/F_2^{n,p}$ to SRC factor $a_2$ (A/d)

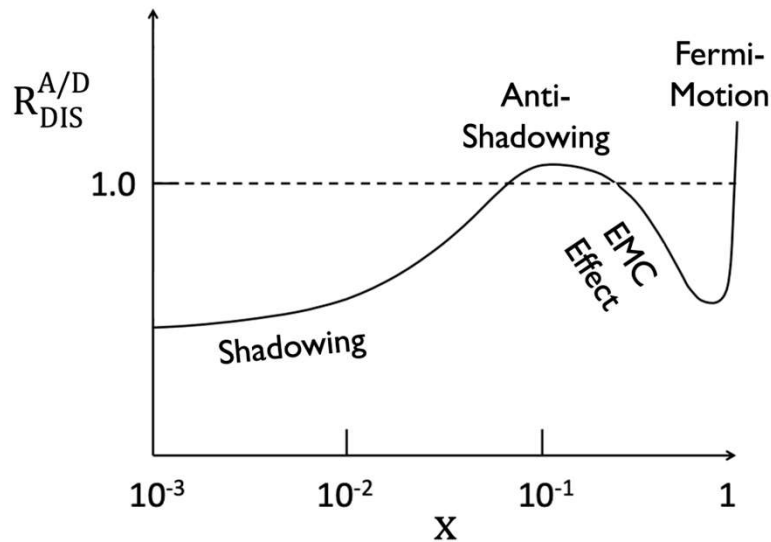
- $a_2$ (A/d) scaling factor: PRL **106** 052301 (2011). Blue points are for A/d; Red points are for A/n+p.
- Slope of near -0.08 (with deuteron point set to 0) consistent with previous studies.
- Difference in these 2 sets seems to come from nuclear effects from deuteron.
- $R^2$  orth. distance regression (goodness of fit).

$a_2$  probability nucleon belongs to a pair (represented as ratio for A/d)

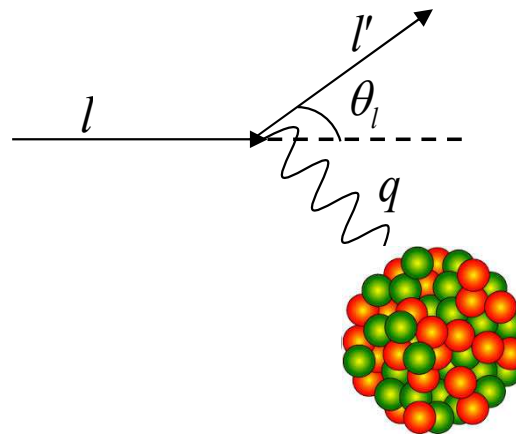


## Summary: *~20 GeV could access anti-shadowing regime*

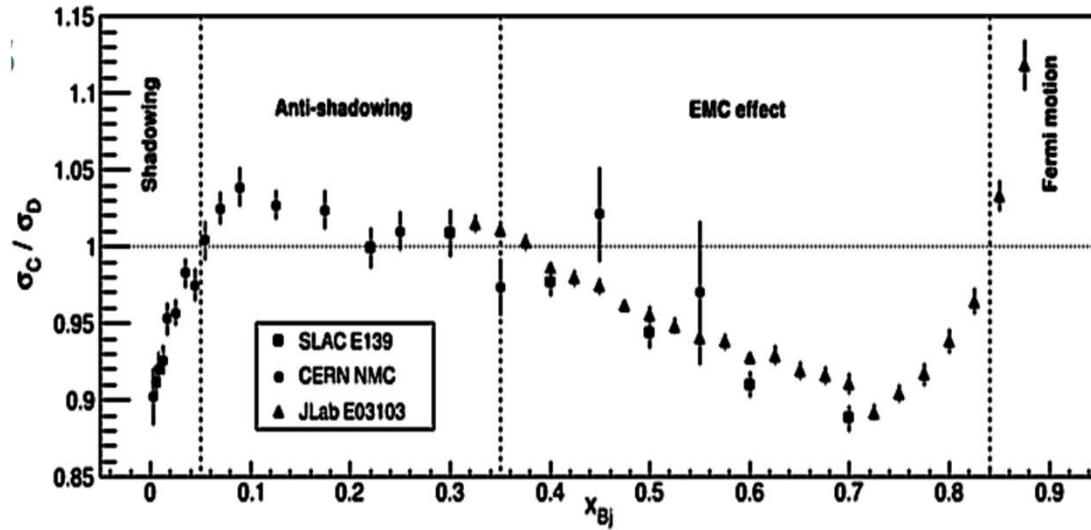
- e-A ( $x, Q^2$ ) “transition” range accessible for the first time in decades
- High precision required: perfect for JLab beam, spectrometers, ability to change targets quickly,...
- Polarized beam and target mapping across A, N, Z
- Nuclear tagging, mirror nuclei,.. – ALL POSSIBLE at Jlab-EIC



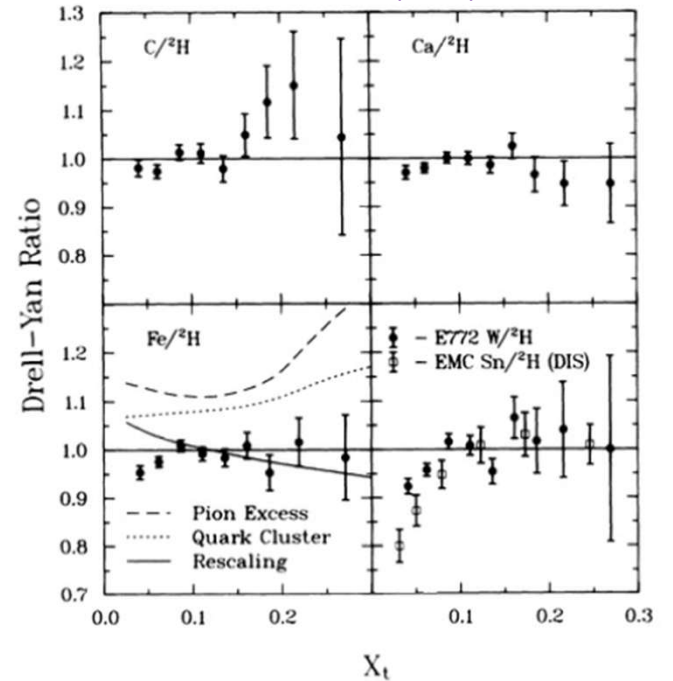
## Backup Slides



# EMC and Anti-shadowing



PRL 64, 2479 (1990)



- Hard probe with  $x$  in the anti-shadowing region is sensitive to the inter-nucleon distance in a nucleus. *J. Qiu, 2023 Workshop*
- A hard probe at small- $x$  can interact with multiple nucleons (partons from multiple nucleons) at the same impact parameter coherently
- No anti-shadowing seen in sea quarks (DY, E772): strong flavor dependence? Calculations needed!

# Effect Reproduced many times

PLB **123** (1983) 275.

Simple Parton Counting Expects One

**MANY Explanations**

## SLAC E139

Phys. Rev. D **49** (1994) 4348.

Precise large-x data

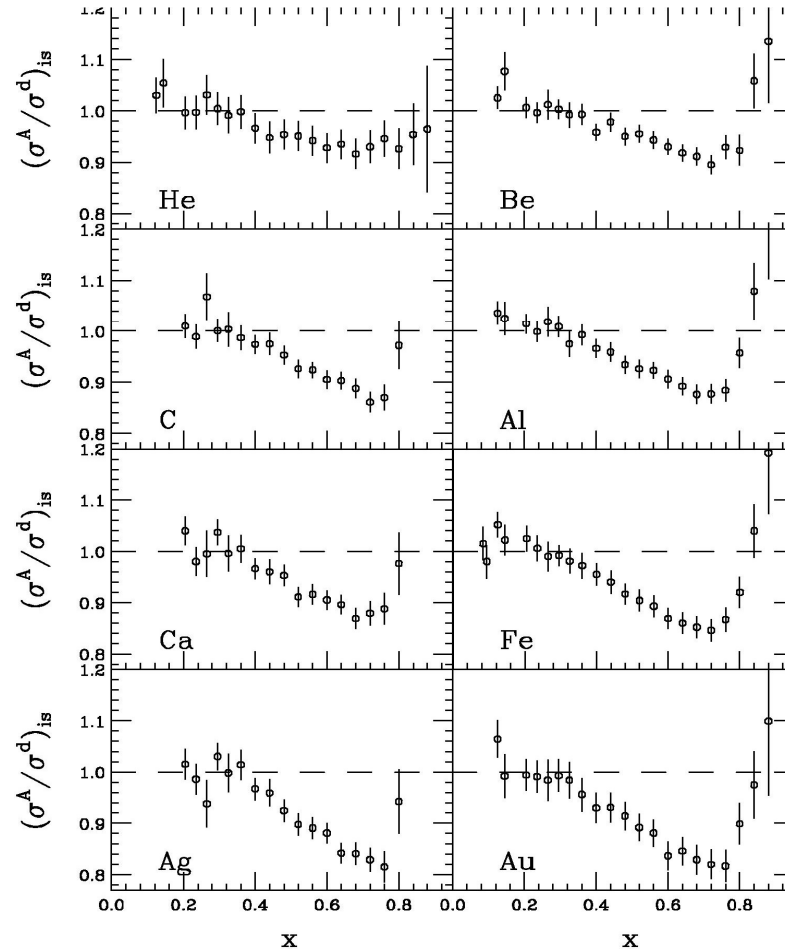
Nuclei from A=4 to 197

## Conclusions from SLAC data

Nearly  $Q^2$ -independent

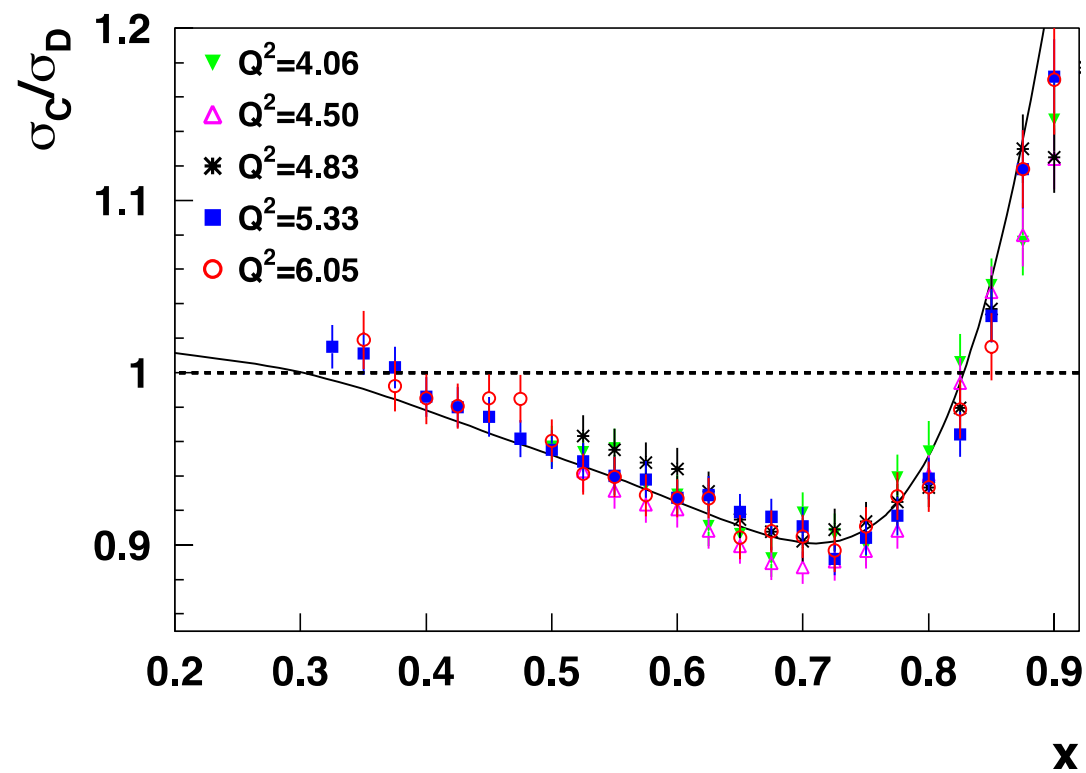
Universal x-dependence (shape)

Some A dependence

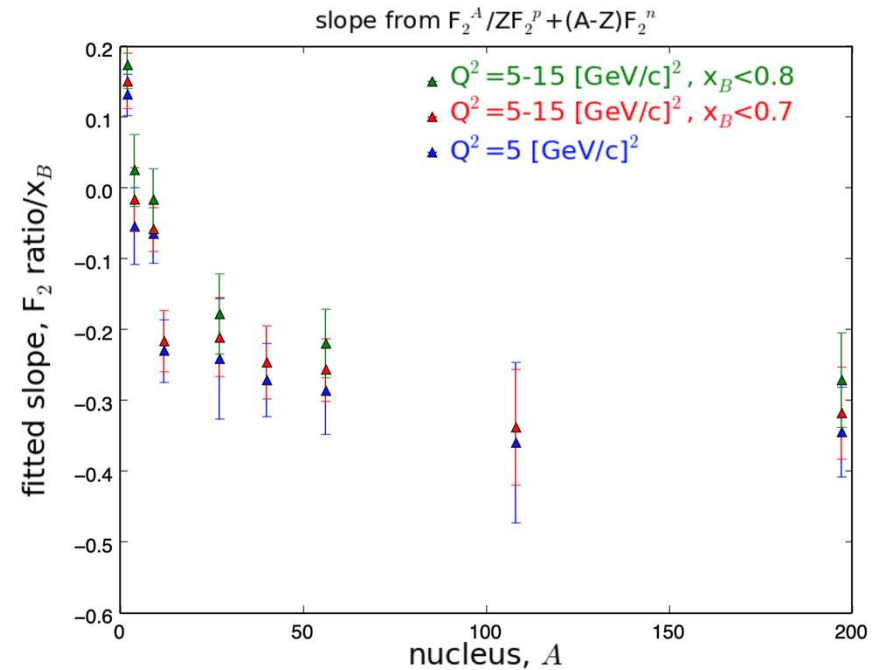
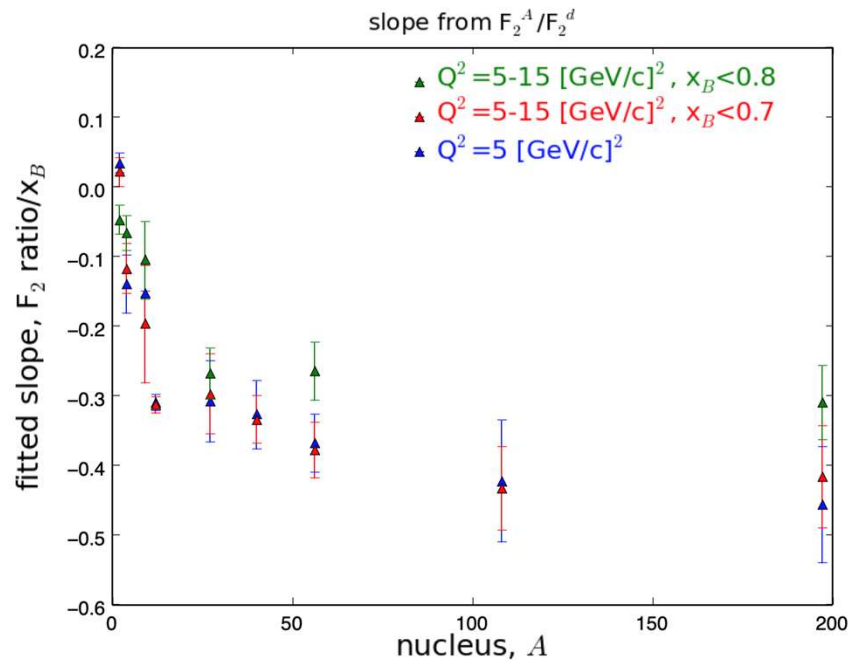


# JLab EMC Data

Phys, Rev. Lett. **103** (2009) 202301.

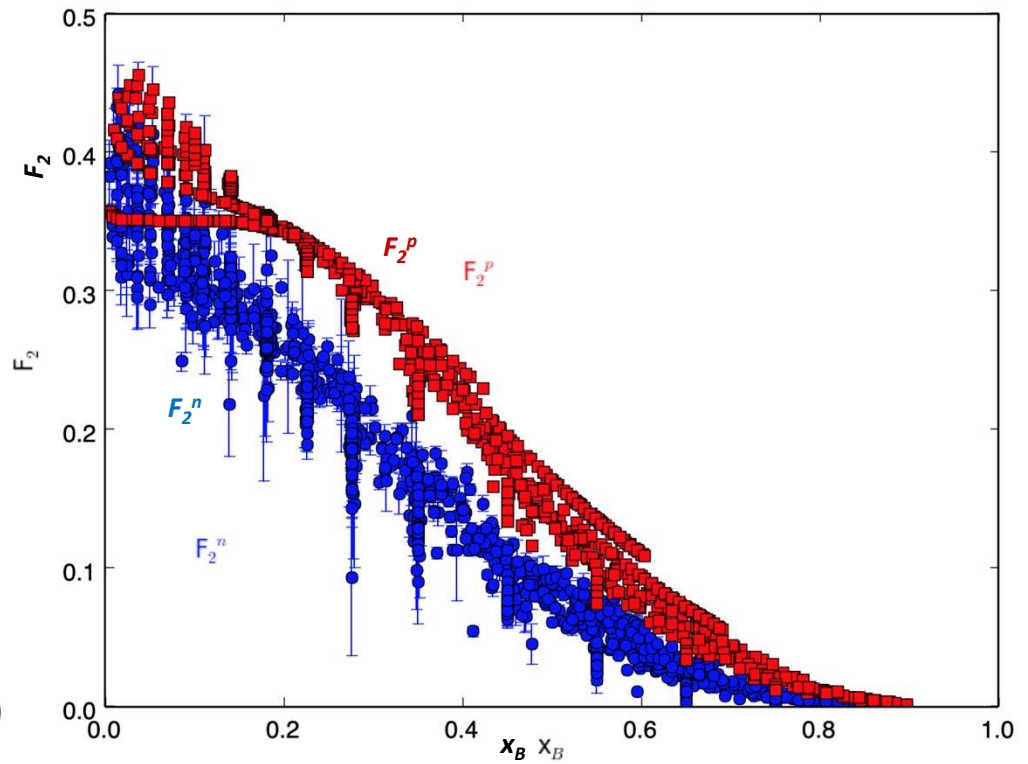
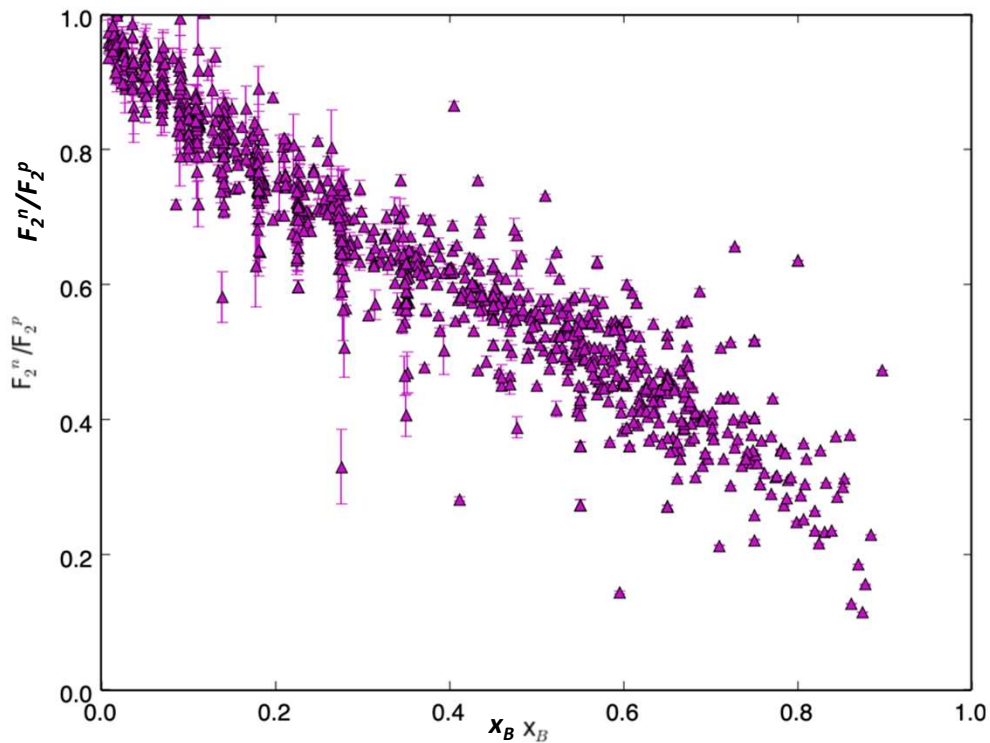


# Fitting Slopes of Ratios.



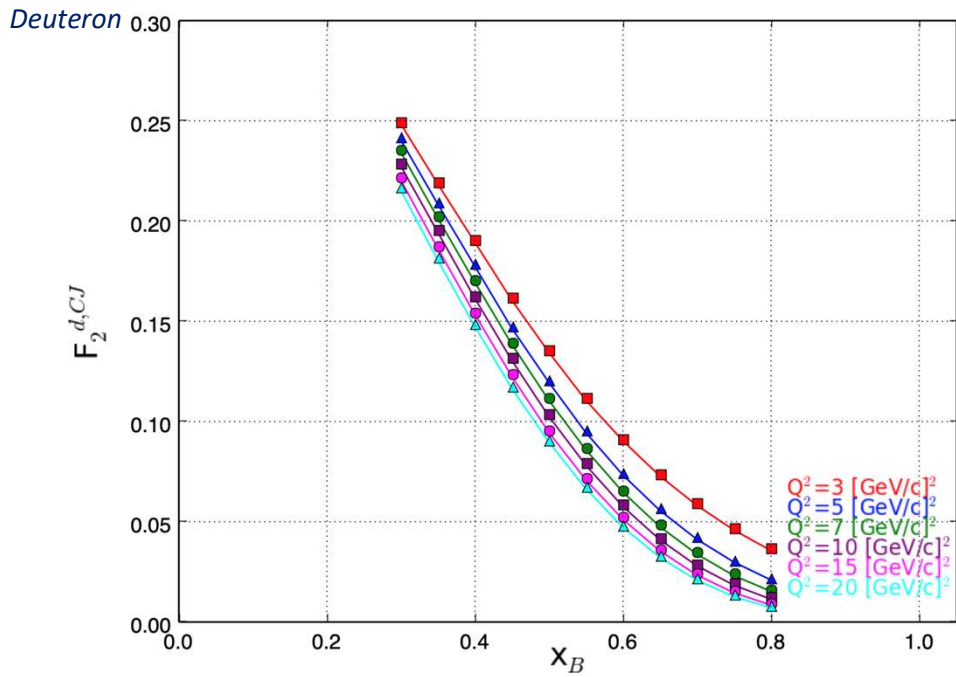
- Fits done in region  $0.3 < x < 0.6$ , with 0.7 included
- Non-negligible nuclear effects in  $x$  0.6-0.7 for extracting EMC Effect in meaningful way.
- Not trivial to disentangle between  $x$  and  $Q^2$ .
- Inclusion of higher  $x$  and  $Q^2$  generates somewhat shallower slopes from rise in nuclear effects.

## Looking at $F_2^n/F_2^p$ via data



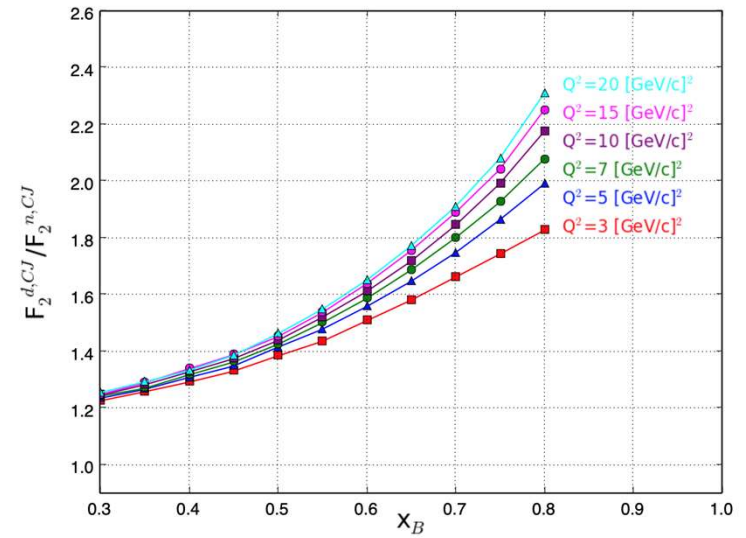
- $F_2^n$  from world data: S. Li's analysis using CJ15 nuclear corrections for deuteron Phys. Rev. D **93** 114017 (2016). Data publication being drafted.
- $F_2^p$  (at same  $x$  and  $Q^2$ ) using SFTM - J. Phys. G **35** 053101 (2008).

# Looking at $F_2^D/F_2^{n,p}$ via CJ15

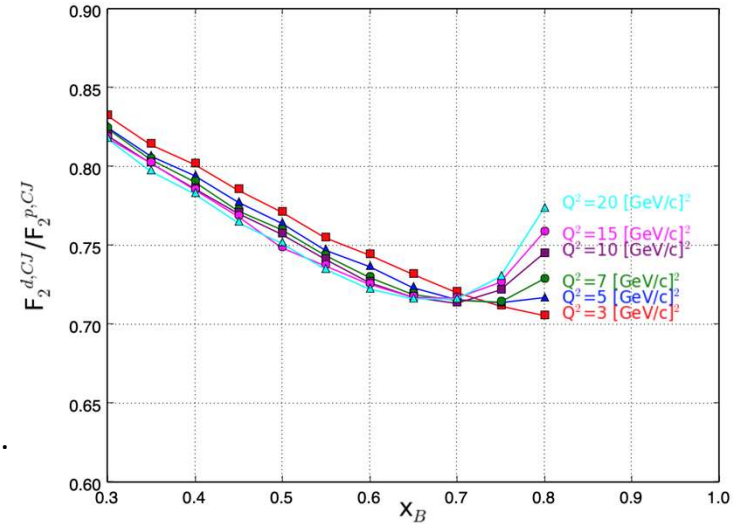


- Neglecting uncertainties on purpose to highlight behavior in the plot.
- There is  $Q^2$  dependence, in particular at large  $x$ .
- Phys. Rev. D **93** 114017 (2016)

$D/n$

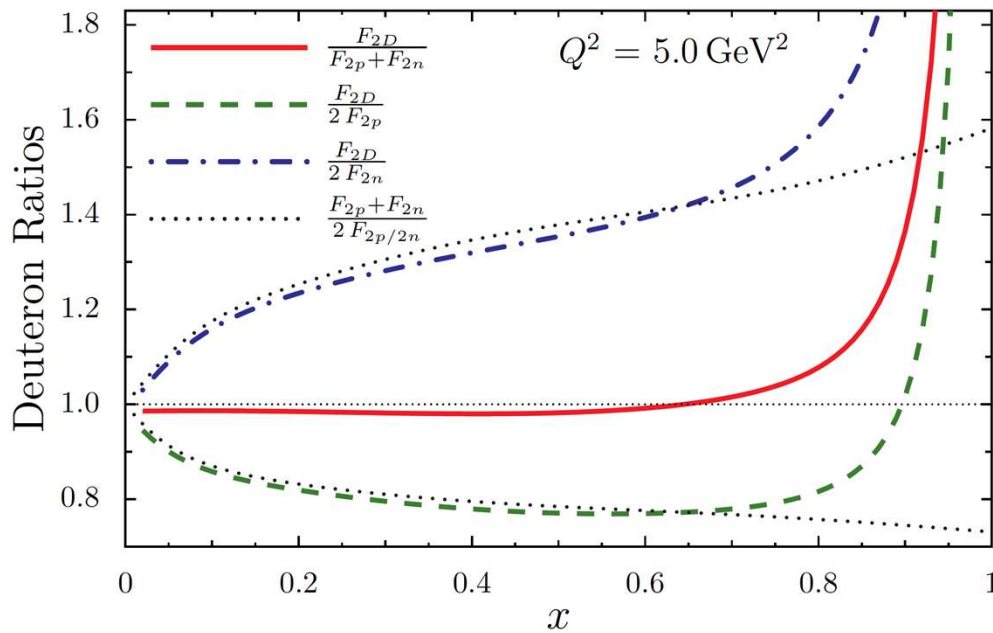


$D/p$

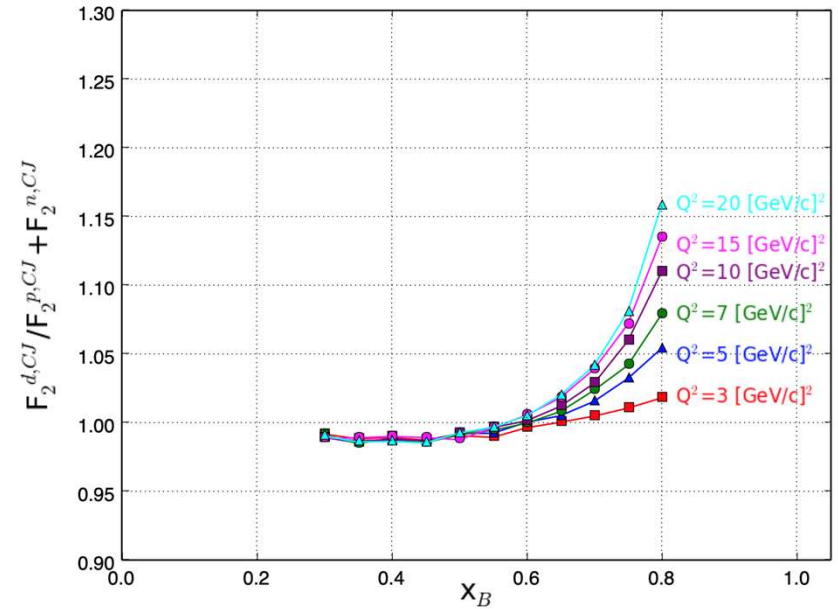


# Looking at $F_2^D/F_2^{n+p}$

Theory-driven

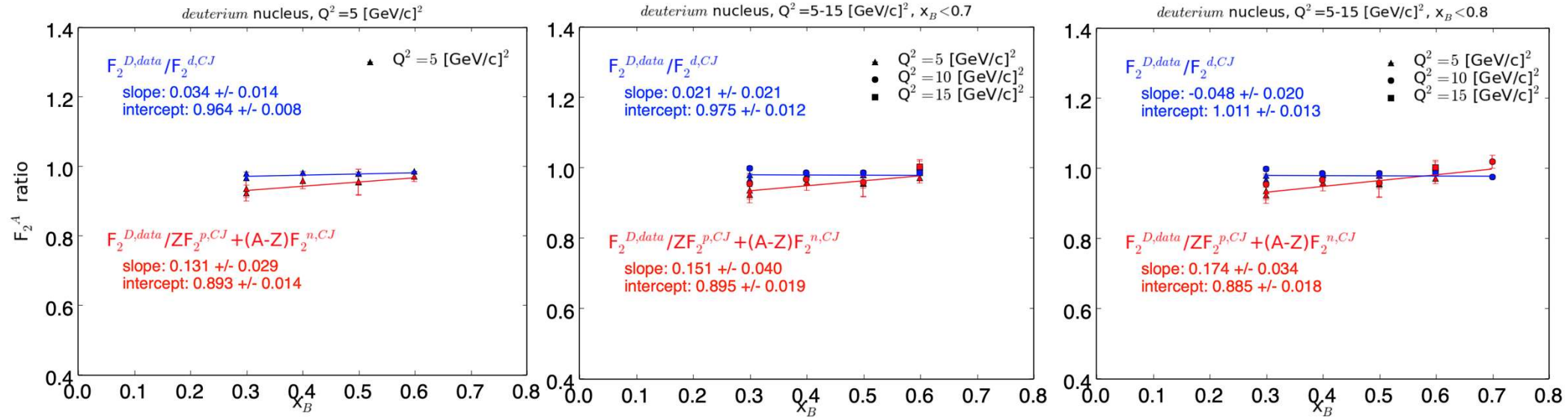


CJ15



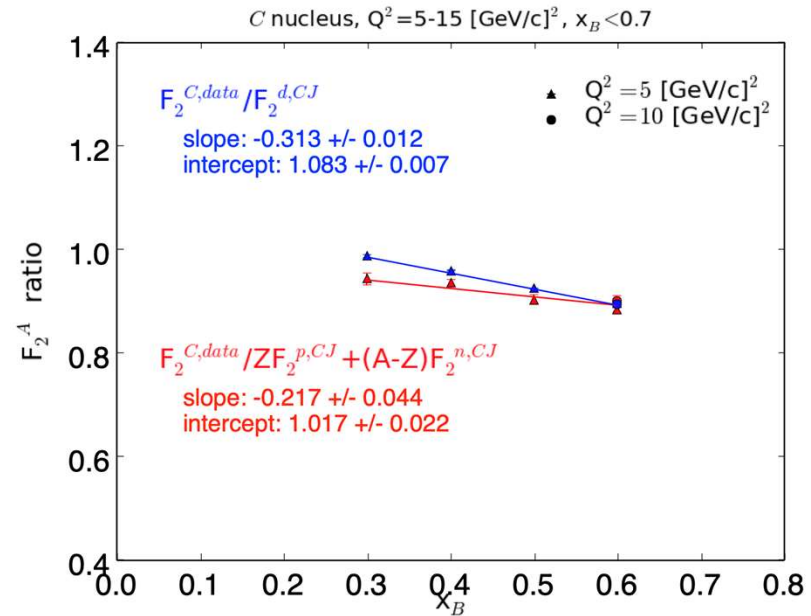
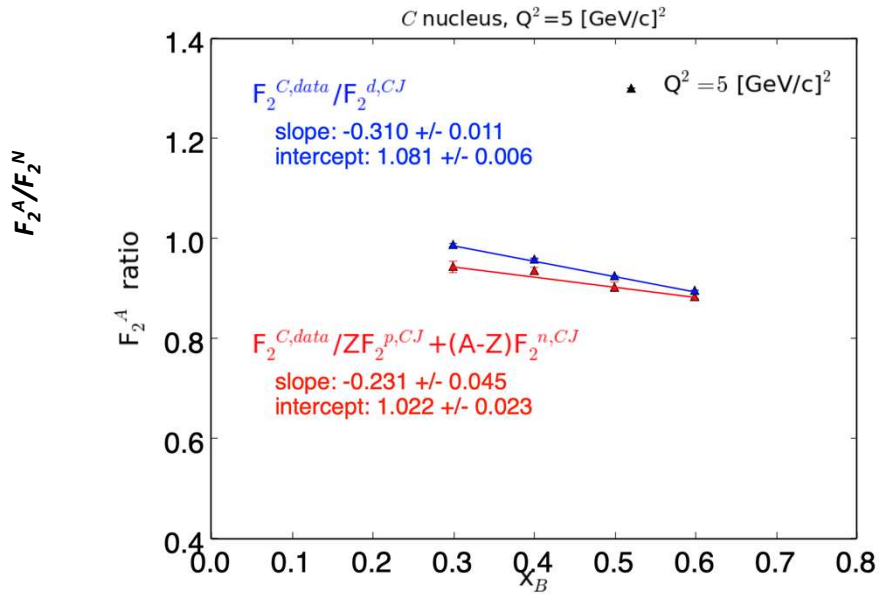
- Theory-driven deuteron to sum of free neutron and proton ratio (in red) dips just below unity in EMC region.
- $F_2^D/2F_2^p$  well below unity with similar shape.  $F_2^D/2F_2^n$  well above unity with positive slope.
- Phys. Rev. D **93** 114017 (2016)

# Fitting Slopes of Ratios: Deuteron



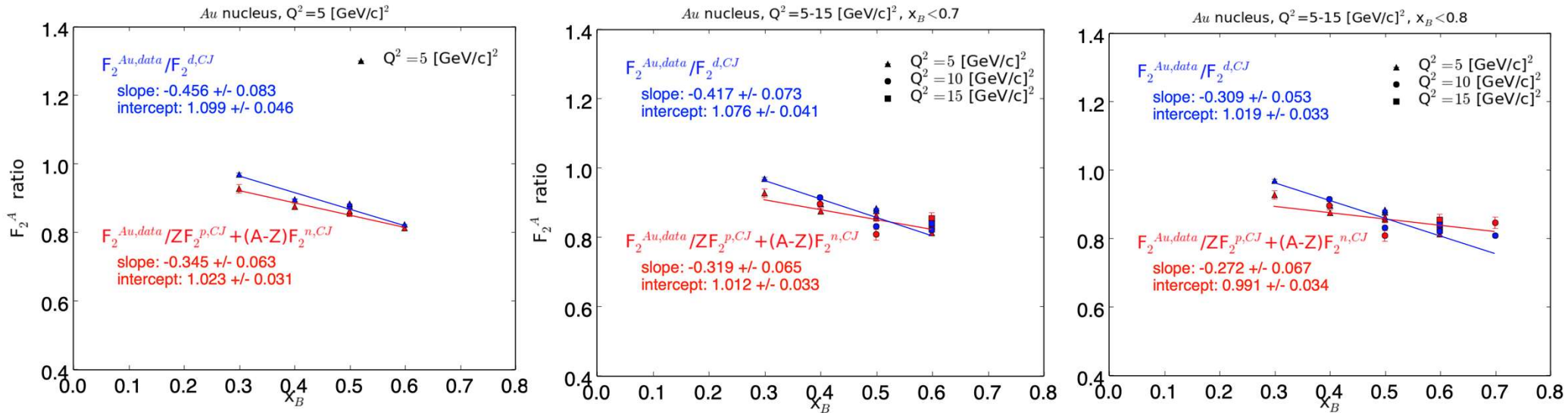
- Linear fits to deuteron data, with cuts on  $Q^2$  and  $x_B$ .
- Blue points are ratio of E139 data to deuteron from CJ15.
- Red points are ratio of E139 data to sum of free (CJ15) neutron and proton, without nuclear effects.

# Fitting Slopes of Ratios: Carbon



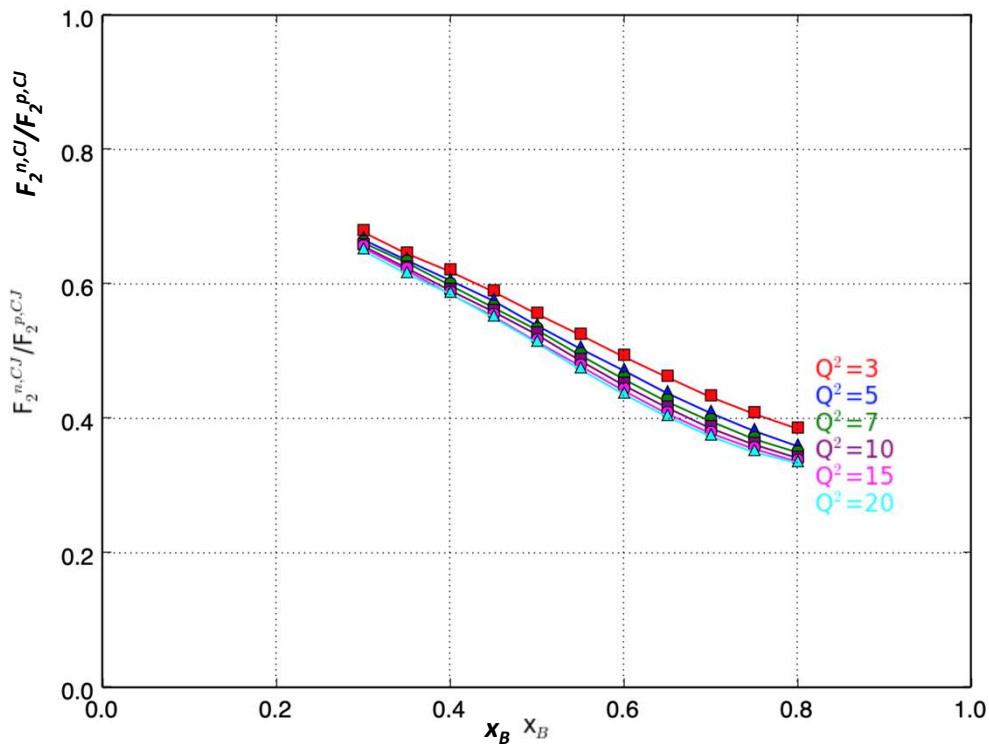
- Linear fits to deuterium data, with cuts on  $Q^2$  and  $x_B$ .
- Blue points are ratio of E139 data to deuterium from CJ15.
- Red points are ratio of E139 data to sum of free (CJ15) neutron and proton, without nuclear effects.
- E139 Carbon data didn't go to  $x_B > 0.6$ .

# Fitting Slopes of Ratios: Gold

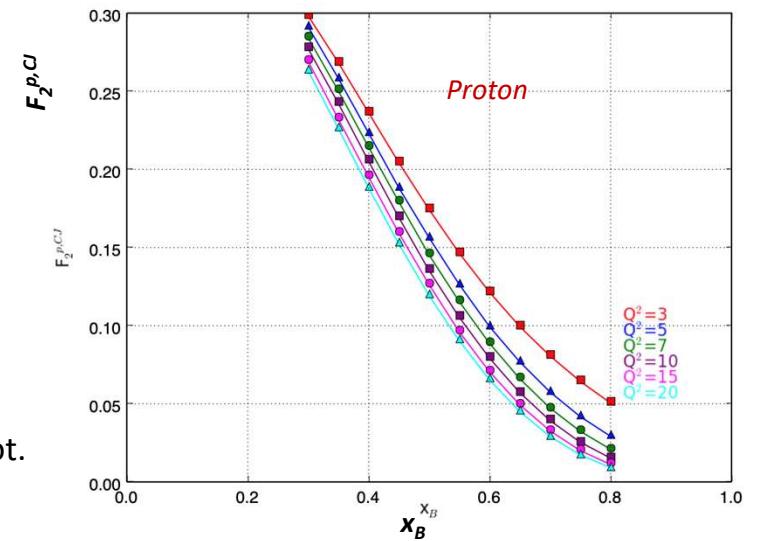
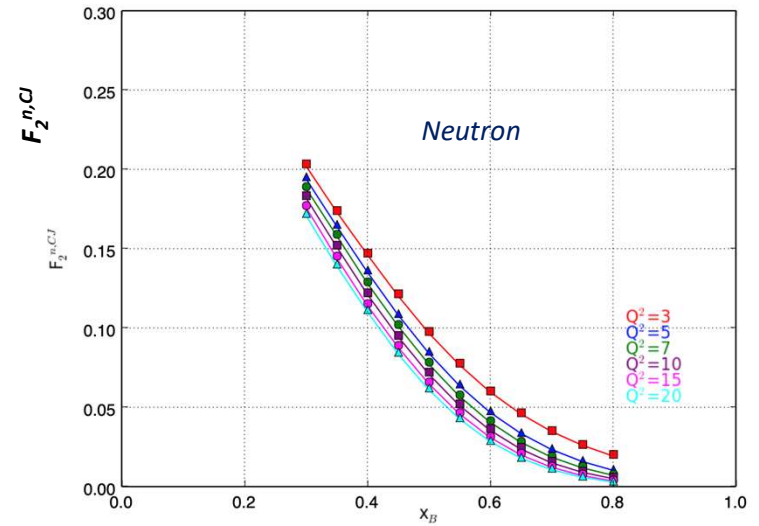


- Linear fits to deuterium data, with cuts on  $Q^2$  and  $x_B$ .
- Blue points are ratio of E139 data to deuterium from CJ15.
- Red points are ratio of E139 data to sum of free (CJ15) neutron and proton, without nuclear effects.

## Looking at $F_2^n/F_2^p$ via CJ15

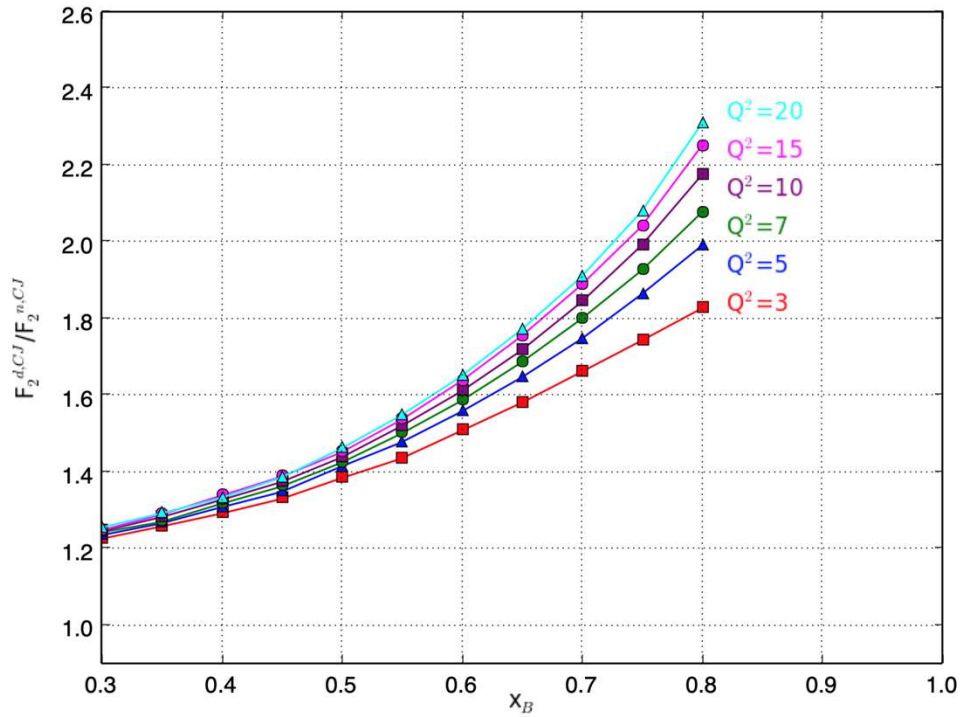


- Neglecting uncertainties on purpose to highlight behavior in the plot.
- There is  $Q^2$  dependence, in particular at large  $x$  and low  $Q$ .
- Phys. Rev. D **93** 114017 (2016)

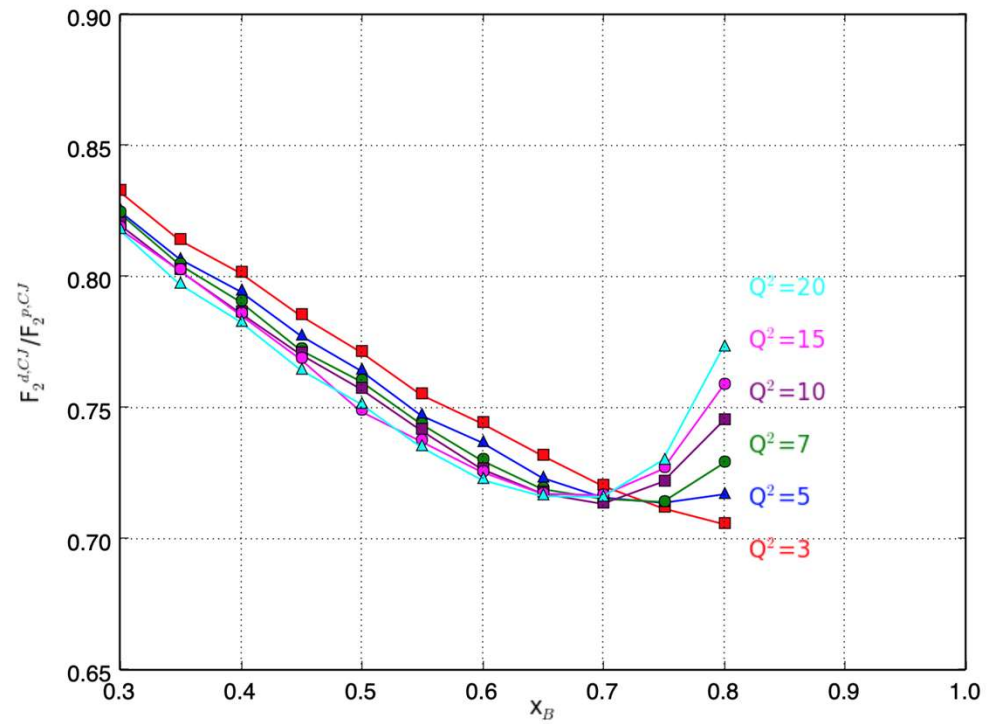


# Looking at $F_2^d/F_2^{n,p}$ via CJ15

$d/n$

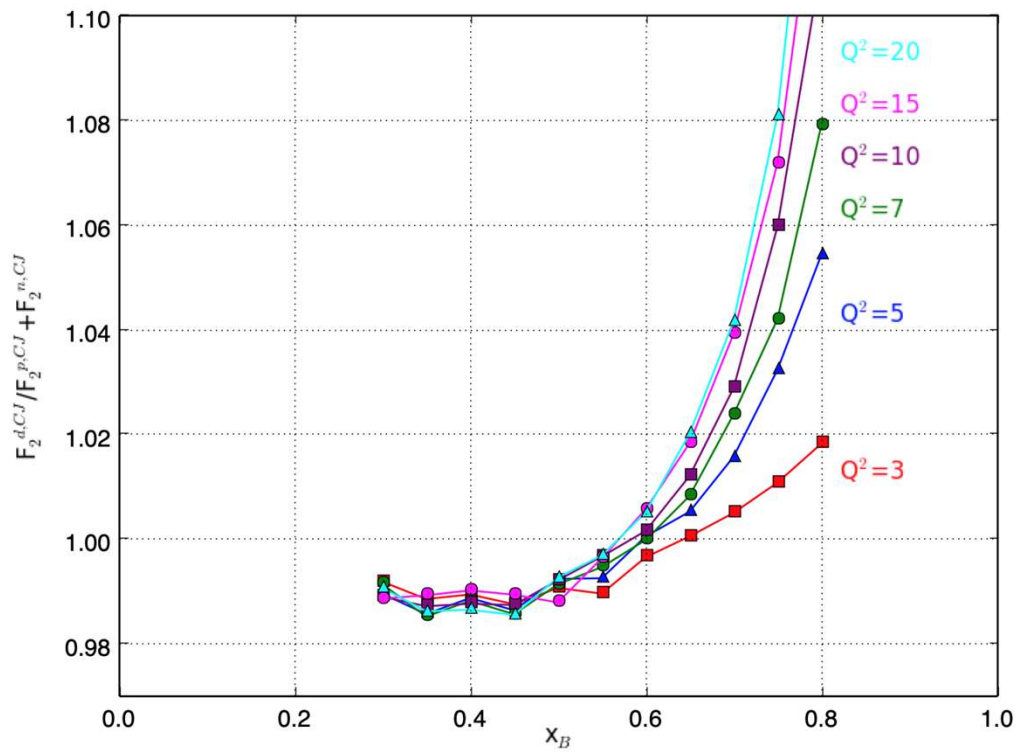


$d/p$



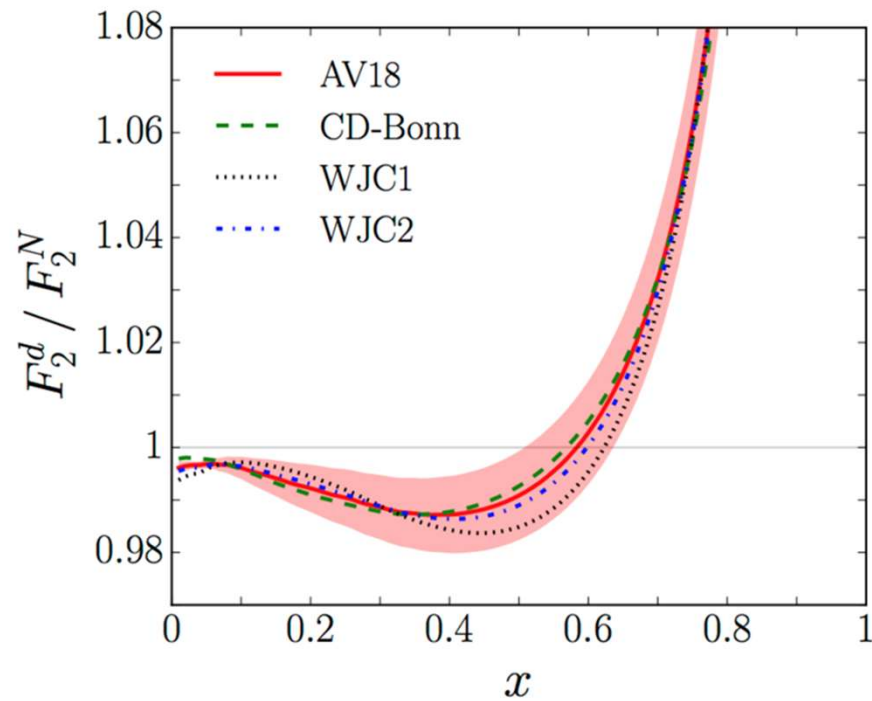
- Phys. Rev. D **93** 114017 (2016)

# Looking at $F_2^d/F_2^{n+p}$ via CJ15



- Phys. Rev. D **93** 114017 (2016)

## Looking at $F_2^d/F_2^N$ Theory



- Theoretical extraction of  $F_2^d/F_2^N$ .
- Some  $x$  dependence ->  $\sim 2\%$  effect in 0.3-0.7  $x$  region.
- Phys. Rev. D **93** 114017 (2016)