Extracting the Neutron Structure Function from Global DIS Data

Cynthia Keppel
Thomas Jefferson National Accelerator Facility

Deep Inelastic Scattering 2019
Torino, Italy

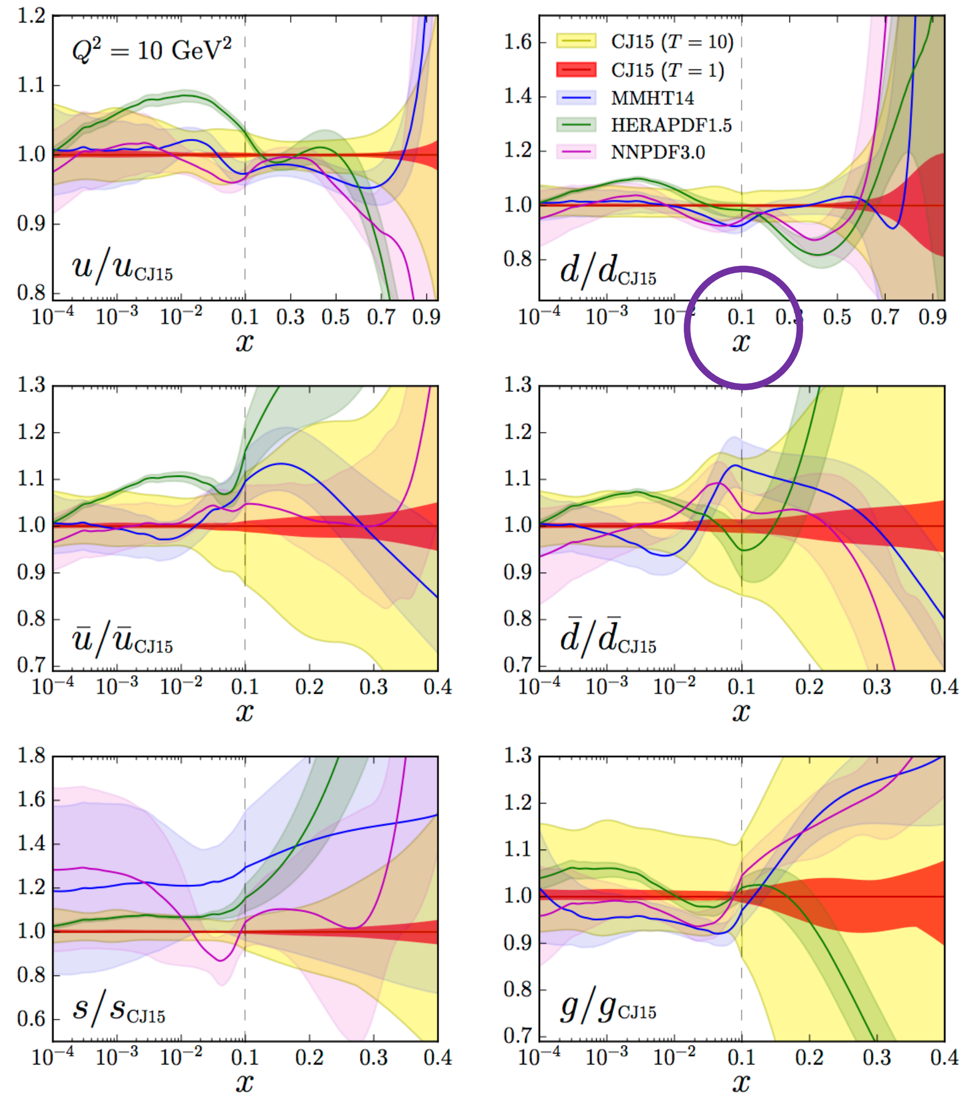
CTEQ-Jefferson Lab Collaboration

Shujie Li, Alberto Accardi, CK, Wally Melnitchouk, Peter Monaghan, Gabriel Niculescu, Ioana Niculescu, Jeff Owens

CTEQ-Jefferson Lab “CJ” PDF Fits

- CTEQ-based PDF fit **optimized for larger x, lower Q^2**
  - Necessary for experiments at Jefferson Lab, neutrino experiments, spin structure,…
  - Valence regime increasingly important for lattice comparisons
- Uses data previously subject to kinematic cuts (SLAC and JLab largely)
- Incorporates higher twist, target mass corrections
- Allow d/u to go to a constant
- *Need accurate deuteron nuclear corrections for DIS data*

http://www.jlab.org/CJ

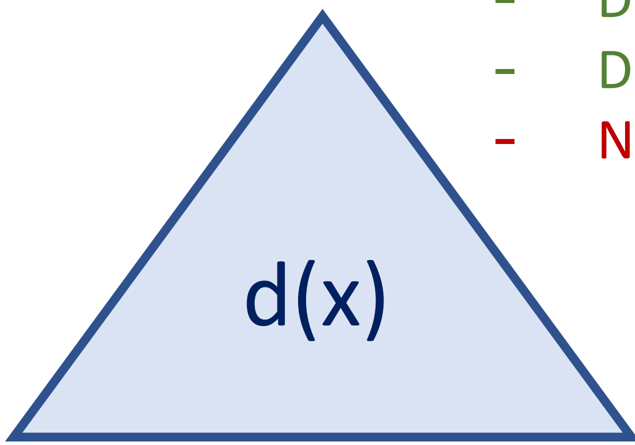


http://lhapdf.hepforge.org/lhapdf5/pdfsets

Current Data Constraints on d(x) at Large x

D0, CDF asymmetries

- Dominant constraint on d(x)
- Data up to x ~ 0.7
- Not much data (~a dozen points)



Deep inelastic deuterium

- Large body of data from multiple experiments
- Data up to x ~0.9
- Q^2 range for evolution
- Requires deuteron nuclear corrections

"BONuS" tagged neutron target

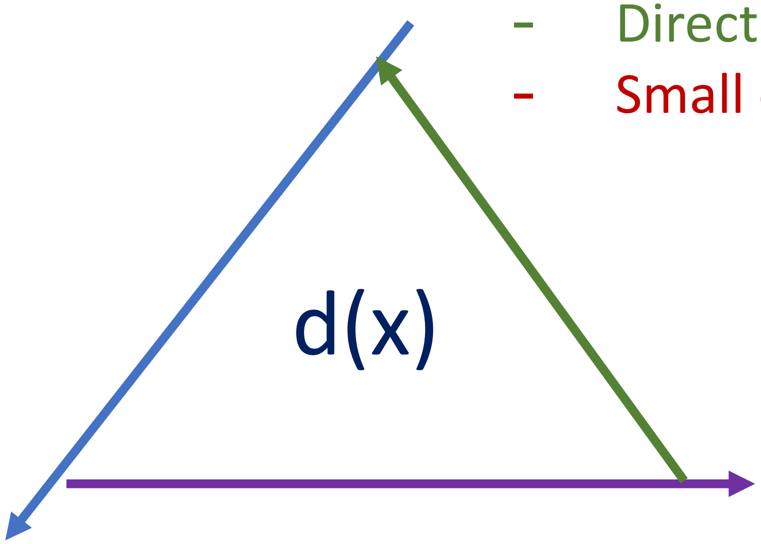
- Nearly model-independent *neutron* data
- Data obtained in 6 GeV JLab era at low W, Q

Current Data Constraints on d(x) at Large x:

The whole is greater than the sum of the parts.

D0, CDF W asymmetries

- Direct sensitivity to d(x)
- Small data set

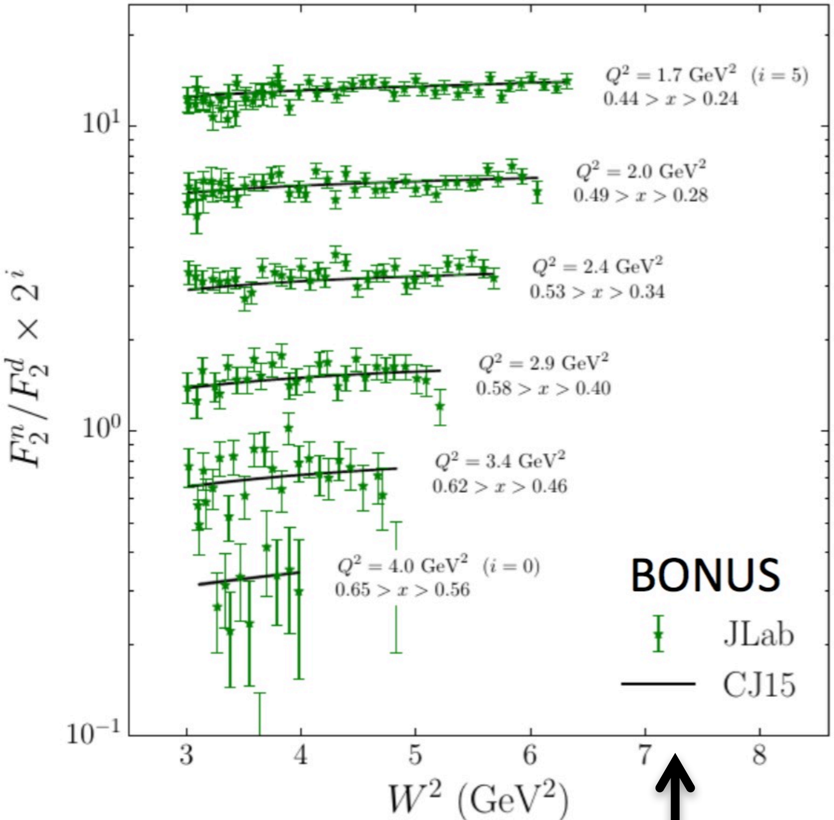


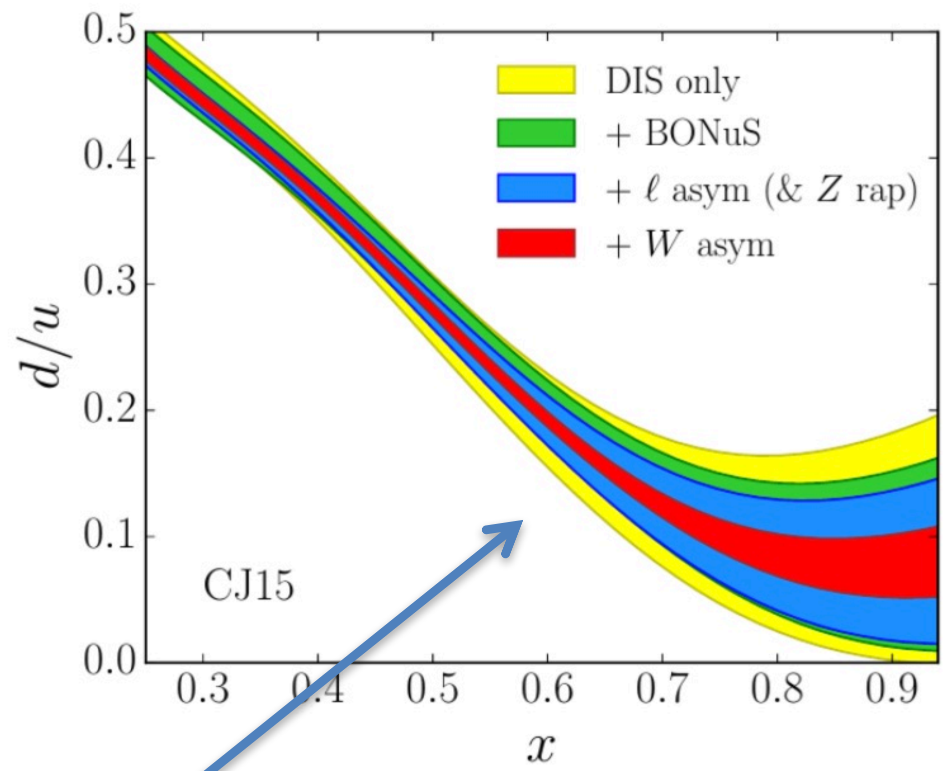
"BONuS" tagged neutron target

- Nearly model-independent *neutron* data
- Data obtained in 6 GeV JLab era at low W, Q

Deep inelastic deuterium

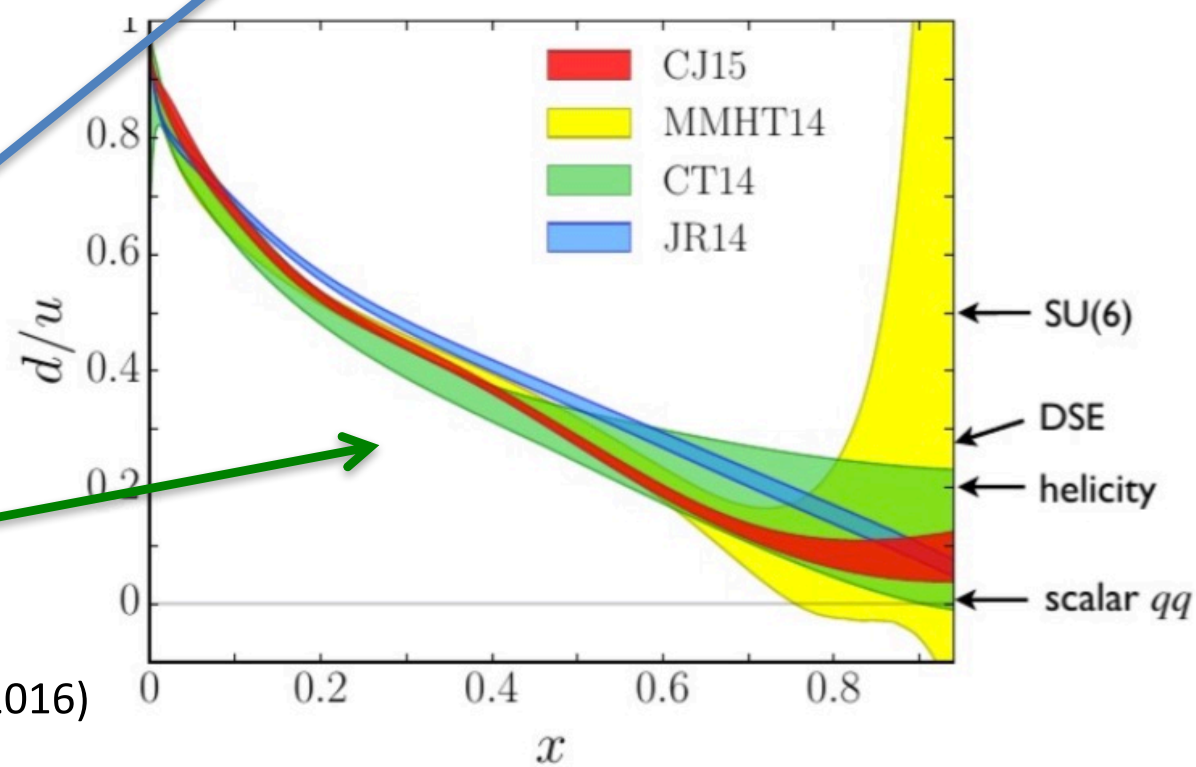
- Large body of data from multiple experiments
- Range in x and Q^2
- Requires deuteron nuclear corrections





CJ15

- BONuS data well fit by CJ
- Effect of adding BONUS (also W, l asymmetries from D0)
- **Substantial reduction in d/u uncertainty at large x!**



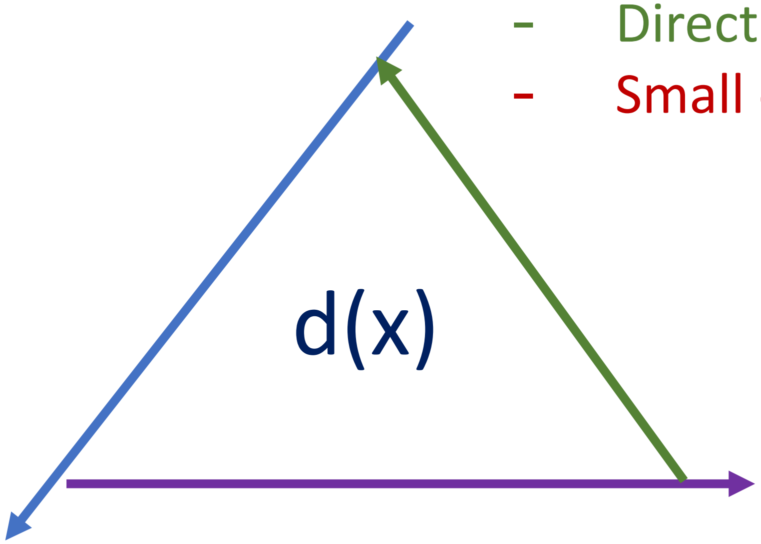
A. Accardi, et al., Phys. Rev. D **93** 114017 (2016)

Current Data Constraints on d(x) at Large x:

The whole is greater than the sum of the parts.

D0, CDF W asymmetries

- Direct sensitivity to d(x)
- Small data set



"BONuS" tagged neutron target

- Nearly model-independent *neutron* data from deuterium
- Data obtained in 6 GeV JLab era at low W, Q

Deep inelastic deuterium

- Large body of data from multiple experiments
- Range in x and Q^2
- Requires deuteron nuclear corrections

Combined agreement ($0.9 < \chi^2/\mathrm{dof} < 1.1$) suggests OK to use CJ deuteron nuclear corrections to **create F_2^n data set**

WHY CREATE F_2^n DATA SET?

- Improve neutron excess “isoscalar corrections
  - EMC effect
  - Neutrino experiments

- Flavor separation
  - d/u
  - Nucleon structure / confinement at large x

- Experimental values for sum rules and moments involving $\int F_2^p - F_2^n \, dx$
  - Gottfried Sum Rule (dbar - ubar)
  - Compare to lattice ($u^+ - d^+$)

- Input for PDF efforts that do not currently incorporate deuteron nuclear corrections
  - Can input F_2^n data set into ***<u>any</u>*** global fit

- Can compare free and bound nucleons (*both* proton and neutron) in nuclei
  - New window on the EMC effect

CJ Database

- DIS data example
- Currently adding 2000+ new data points from (SLAC and) JLab 6 GeV era!

See N. Sato talk, Tuesday

SLAC (Whitlow, E140, E140x)

JLab (JLCEE96, E06-009, E94-110, E03-103, E99-118, E00-116, CLAS6, BONuS)

Revisited correlated systematics for NMC, SLAC,…

Cross sections and d/p as well

A = data is available but not collected 10001-10070 = data ID in JAM databsae

Experiment	σ_r	F2	R
SLAC-Whitlow	p: 10014	p: 10010	p: 10064
	d: 10015	d: 10011	d: 10065
	d/p: 10034	d/p (*): 10034	
SLAC-E140			d: 10066
SLAC-E140x	p: 10037	p: 10035	p: 10067
	d: 10038	d: 10036	d: 10068
NMC	p: 10022	p: 10020	
	d: 10040	d: 10039	
	d/p:10021	d/p (*):10021	
BCDMS	p: 10018	p: 10016	p: 10069
	d: 10019	d: 10017	d: 10070
JLab E06-009	d: 10042	d: 10041	

The full database will become available to the public soon – stay tuned!

Data Selection for Neutron Structure Function Analysis

Require both p and d data from SAME experiment

Match the proton and deuteron data points requiring:

$|x_{proton} - x_{deuteron}| < 0.01$

$|Q^2_{proton} - Q^2_{deuteron}| < 1\%$

same beam energy

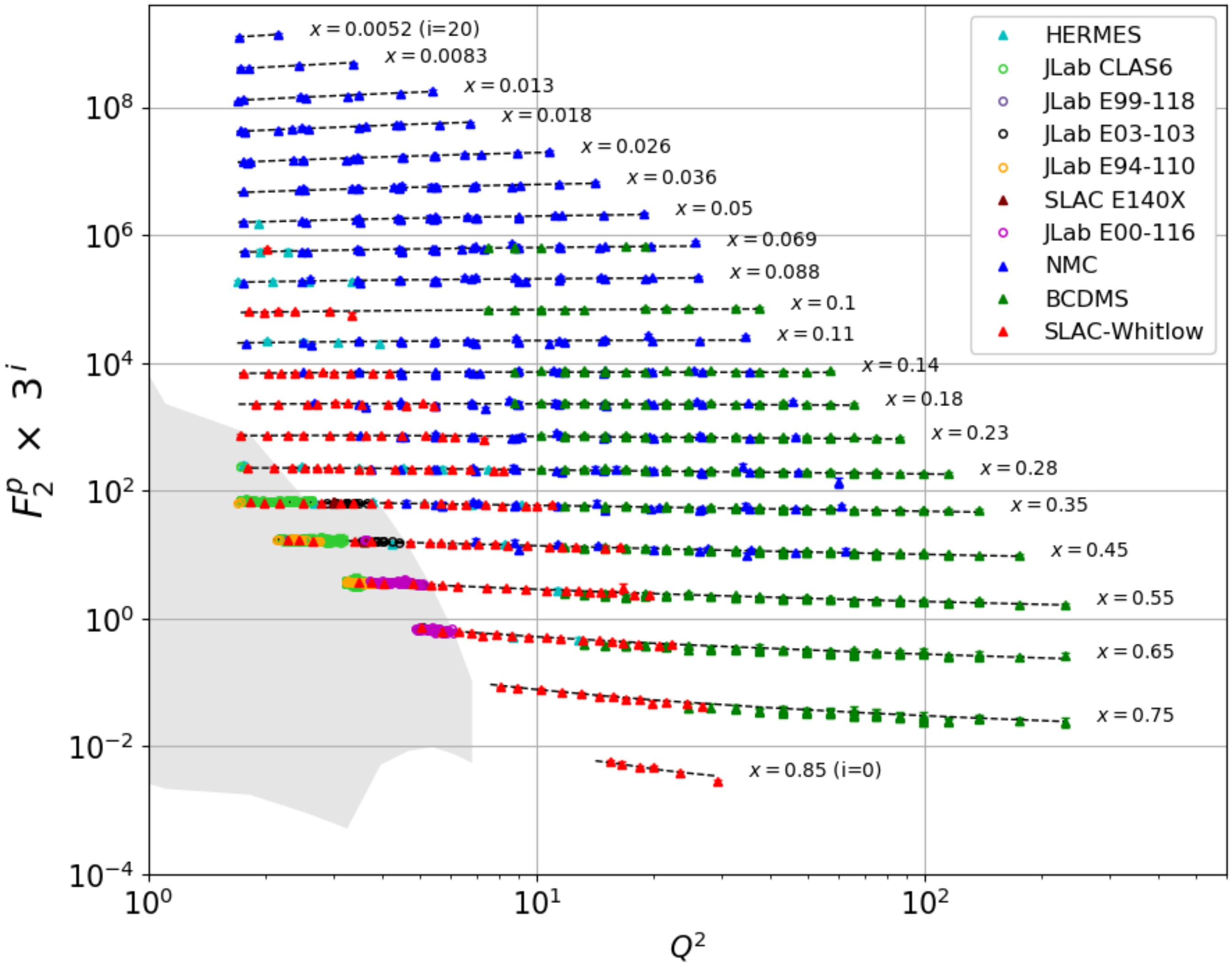
DIS kinematic cuts:

$Q^2 > 1.691$ GeV^2/c^2

$W^2 > 3.5$ GeV^2

Experiments	# of Proton F2 Data Points	# of Deuteron F2 Data Points	# of Constructed Neutron Points
SLAC-Whitlow[2]	564	582	470
BCDMS	351 [3]	254 [4]	254
HERMES [5]	45	45	45
JLab E-00-116 [6]	136	136	120
NMC [7]	275	275	258
SLAC-E140x [8]	9	13	9
JLab E-03-103 [9]	37	69	37
JLab CLAS6	609 [10]	1723 [11]	0
JLab E-94-110 [12]	112	0	0
JLab E-06-009 [13]	0	79	0
JLab E-99-118 [14]	2	2	2

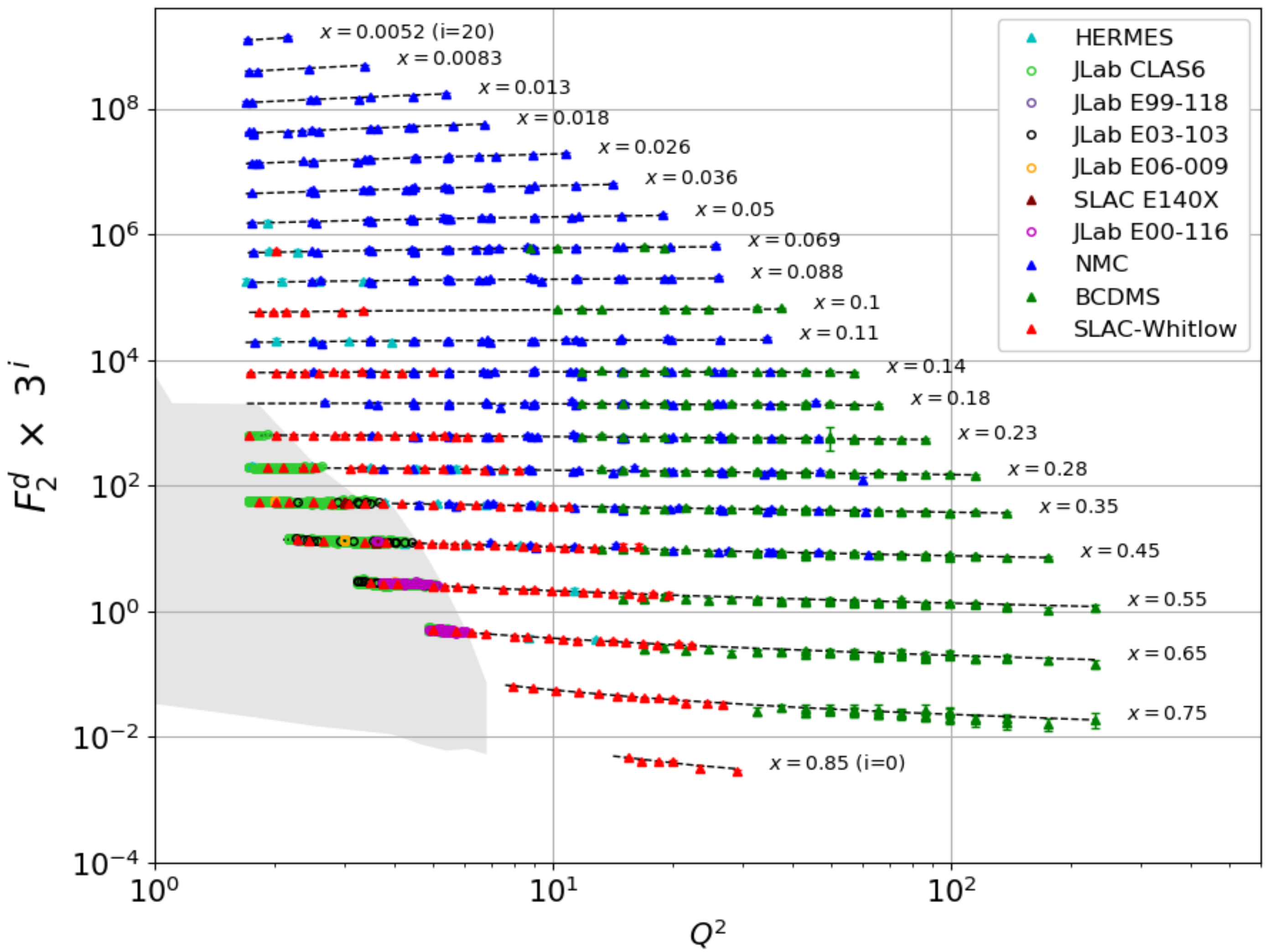
F_2^p data, kinematics



Shaded area: JLab data

Dashed line: CJ15

F_2^d data, kinematics



Shaded area: JLab data

Dashed line: CJ15

Kinematics same by construction

F_2 Neutron Extraction

Used CJ15 to remove nuclear effects in F_2 deuteron data:

The free nucleon (proton + neutron) F_2 in the CJ15 framework:

$$(p+n)_{data} = d_{data} * (p+n)_{cj} / d_{cj}$$

The F_2 neutron data are constructed as:

$$n_{data} = (p+n)^{*}_{data} - p^{*}_{data} = d^{*}_{data} * (p+n)_{cj}/d_{cj} - p^{*}_{data}$$

Where d^{*}_{data} is the original F_2 data shifted *within the correlated and normalization uncertainties* (shifts determined within CJ15 fit) so that it's consistently cross-normalized and ready for use.

F_2 Neutron Extraction

Used CJ15 to remove nuclear effects in F_2 deuteron data:

The free nucleon (proton + neutron) F_2 in the CJ15 framework:

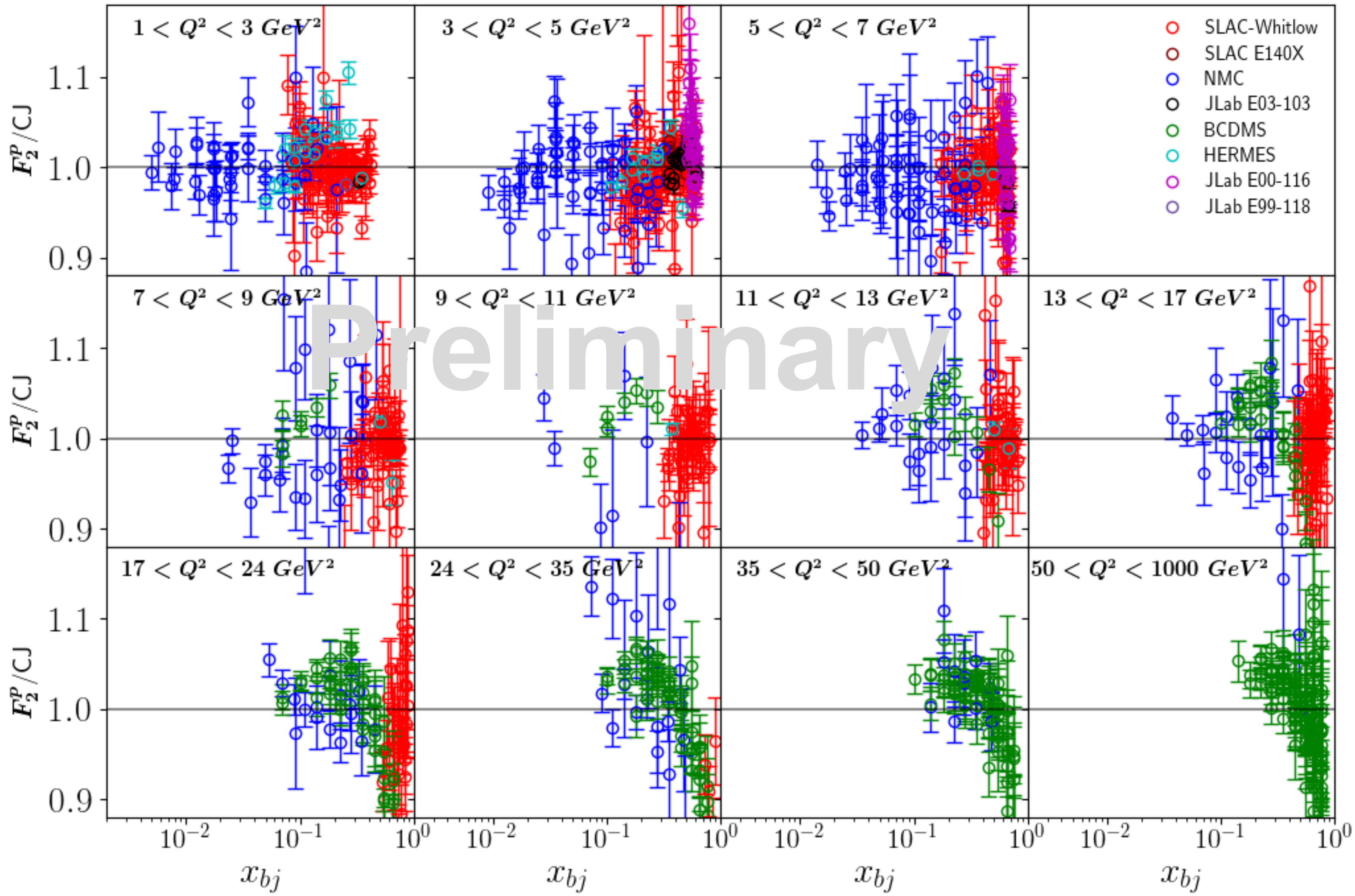
$$(p+n)_{data} = d_{data} * (p+n)_{cj} / d_{cj}$$

The F_2 neutron data are constructed as:

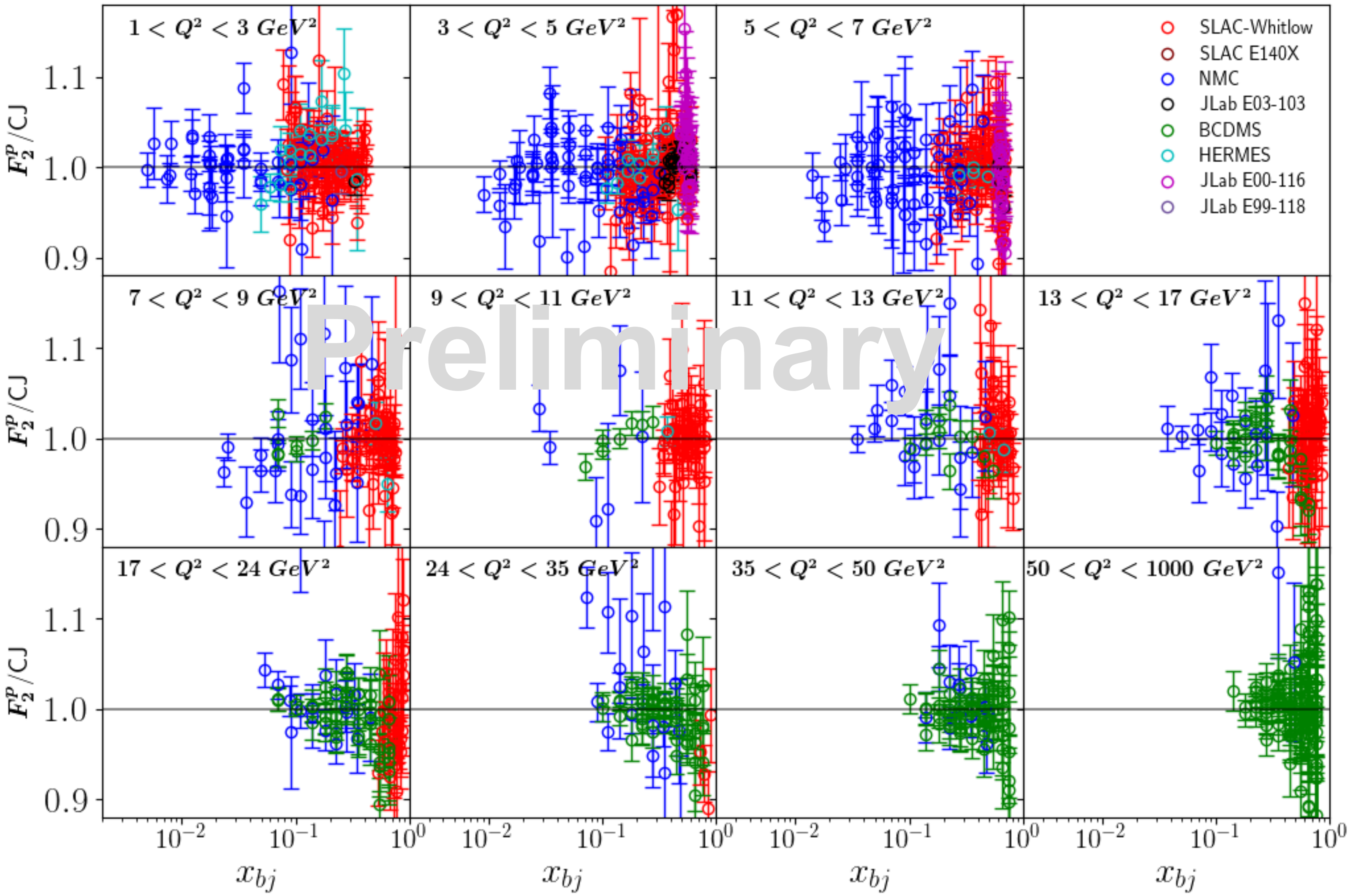
$$n_{data} = (p+n)^{*}_{data} - p^{*}_{data} = d^{*}_{data} * (p+n)_{cj}/d_{cj} - p^{*}_{data}$$

Where d^{*}_{data} is the original F_2 data shifted *within the correlated and normalization uncertainties* (shifts determined within CJ15 fit) so that it's consistently cross-normalized and ready for use.

raw F_2^p Data/CJ



modified+normed F_2^p Data/CJ



F_2 Neutron Extraction

Used CJ15 to remove nuclear effects in F_2 deuteron data:

The free nucleon (proton + neutron) F_2 in the CJ15 framework:

$$(p+n)_{data} = d_{data} * (p+n)_{cj} / d_{cj}$$

The F_2 neutron data are constructed as:

$$n_{data} = (p+n)^{*}_{data} - p^{*}_{data} = d^{*}_{data} * (p+n)_{cj}/d_{cj} - p^{*}_{data}$$

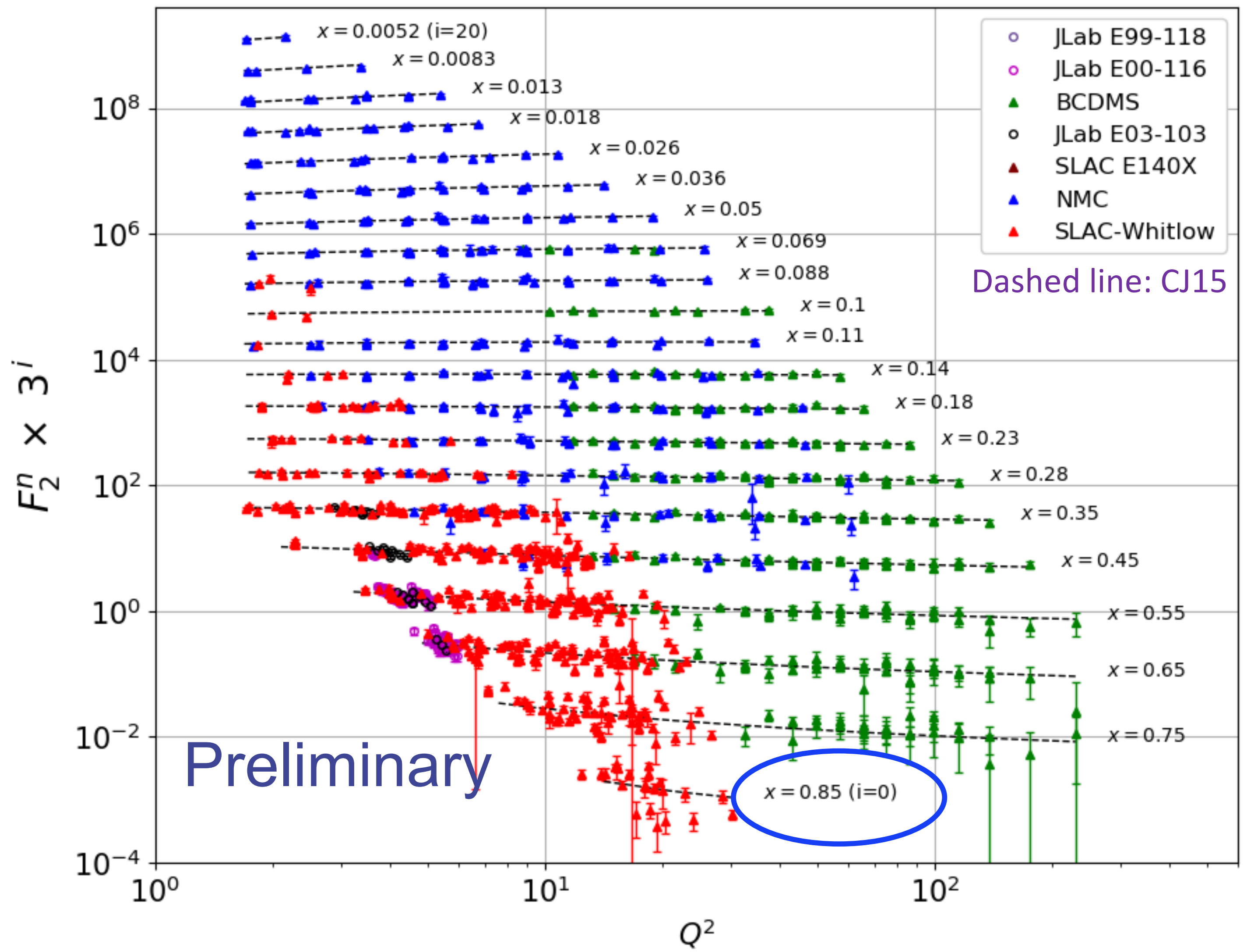
Where d^{*}_{data} is the original F_2 data shifted *within the correlated and normalization uncertainties* (shifts determined within CJ15 fit) so that it's consistently cross-normalized and ready for use.

Similar approach also for d/p experiments (HERMES, NMC...) and BONuS n/d!

Neutron Uncertainty Evaluation

- Experimental uncertainties
  - Statistical
  - Uncorrelated systematics
- Theoretical systematics (PDF uncertainties) using 2* 24 (= 19 PDF + 2 off-shell + 3 higher-twist parameters) eigen-PDF sets:
  - Normalization + correlated shift uncertainties
  - Nuclear correction (d/(p+n)) uncertainties

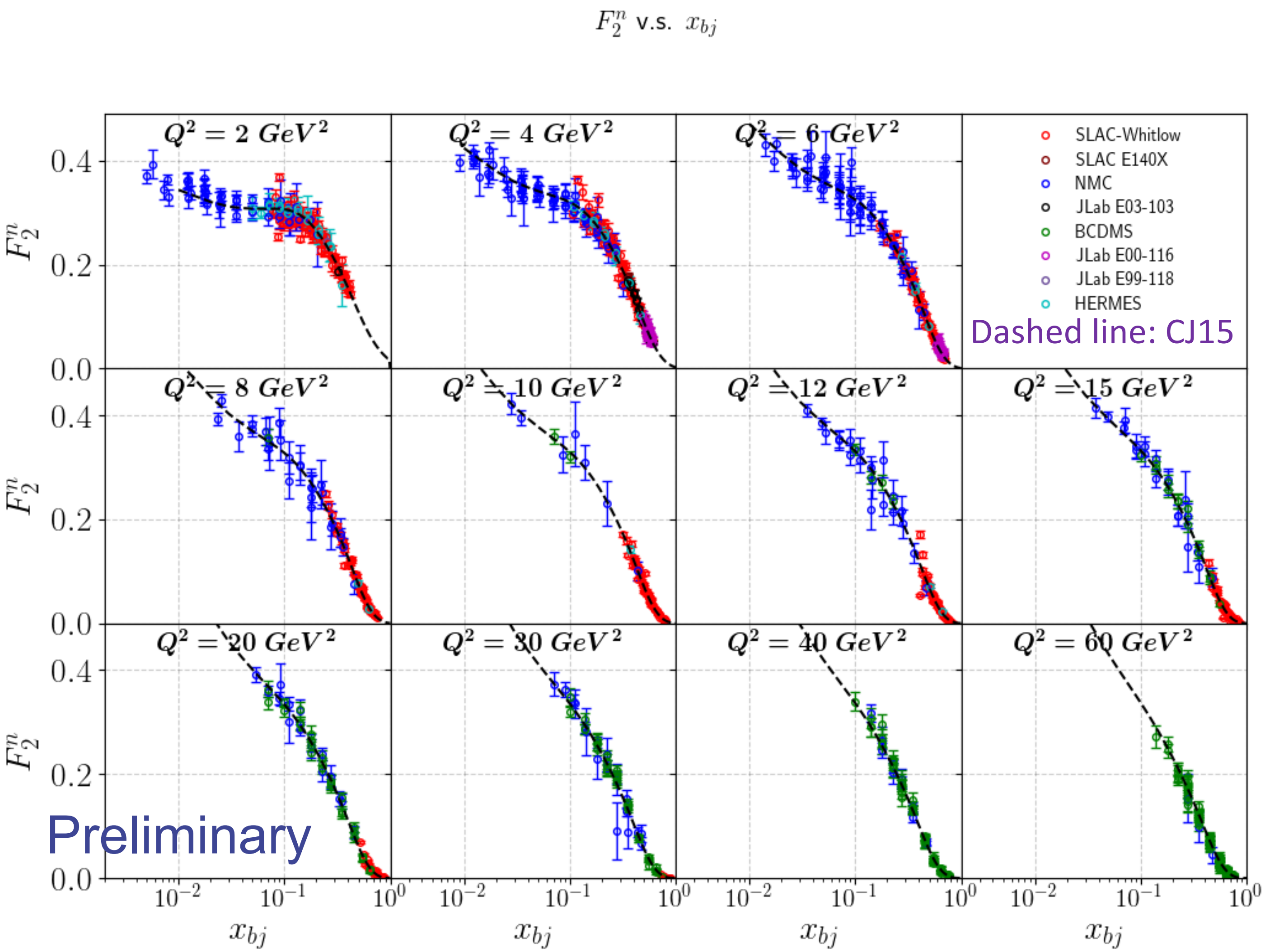
F_2 *Neutron* Results!



Publication in progress

Please USE THESE DATUMS and let us know what you observe!

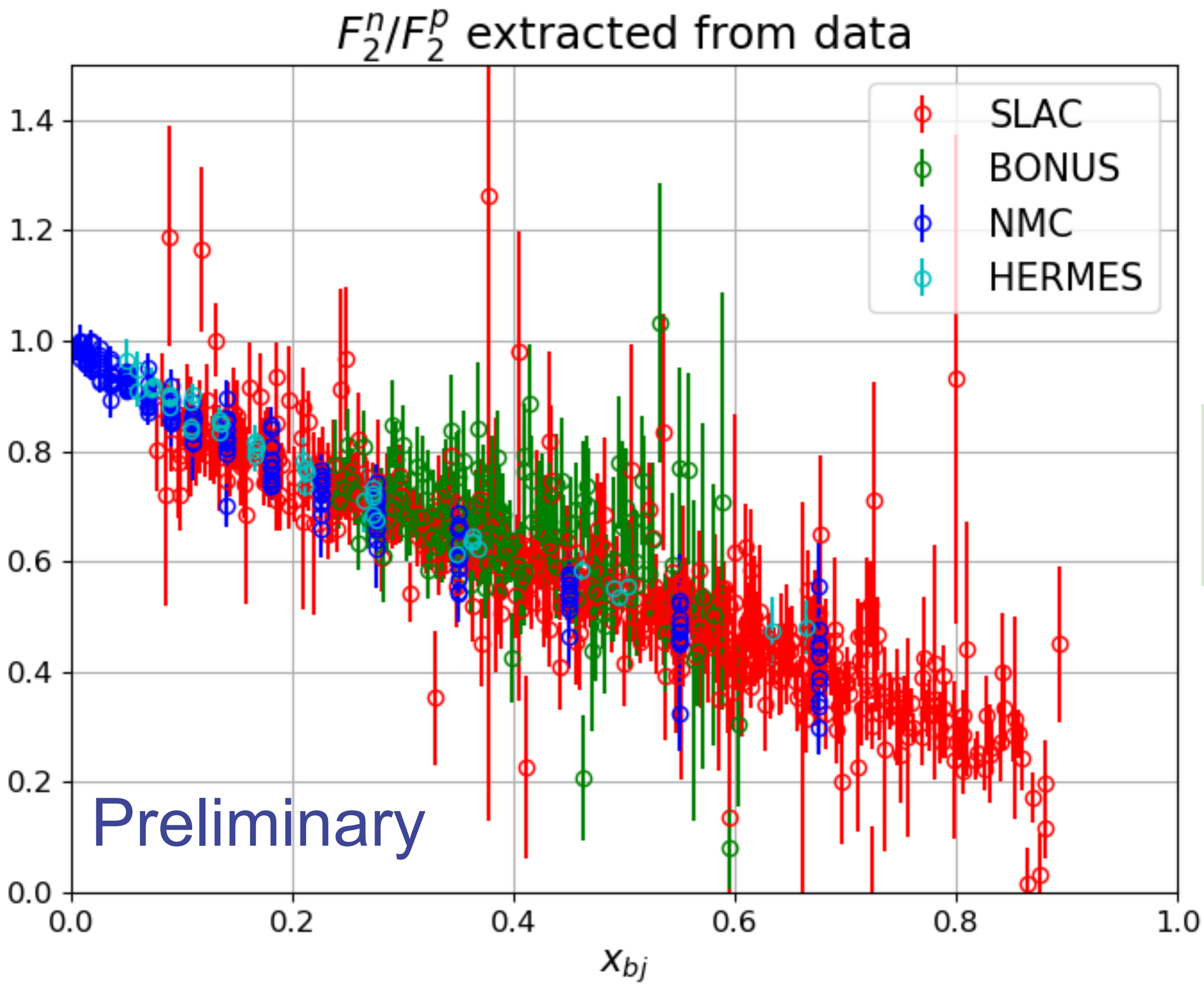
F_2 *Neutron* Results!



Publication in progress

Please USE THESE DATUMS and let us know what you observe!

F_2^n/F_2^p from Data



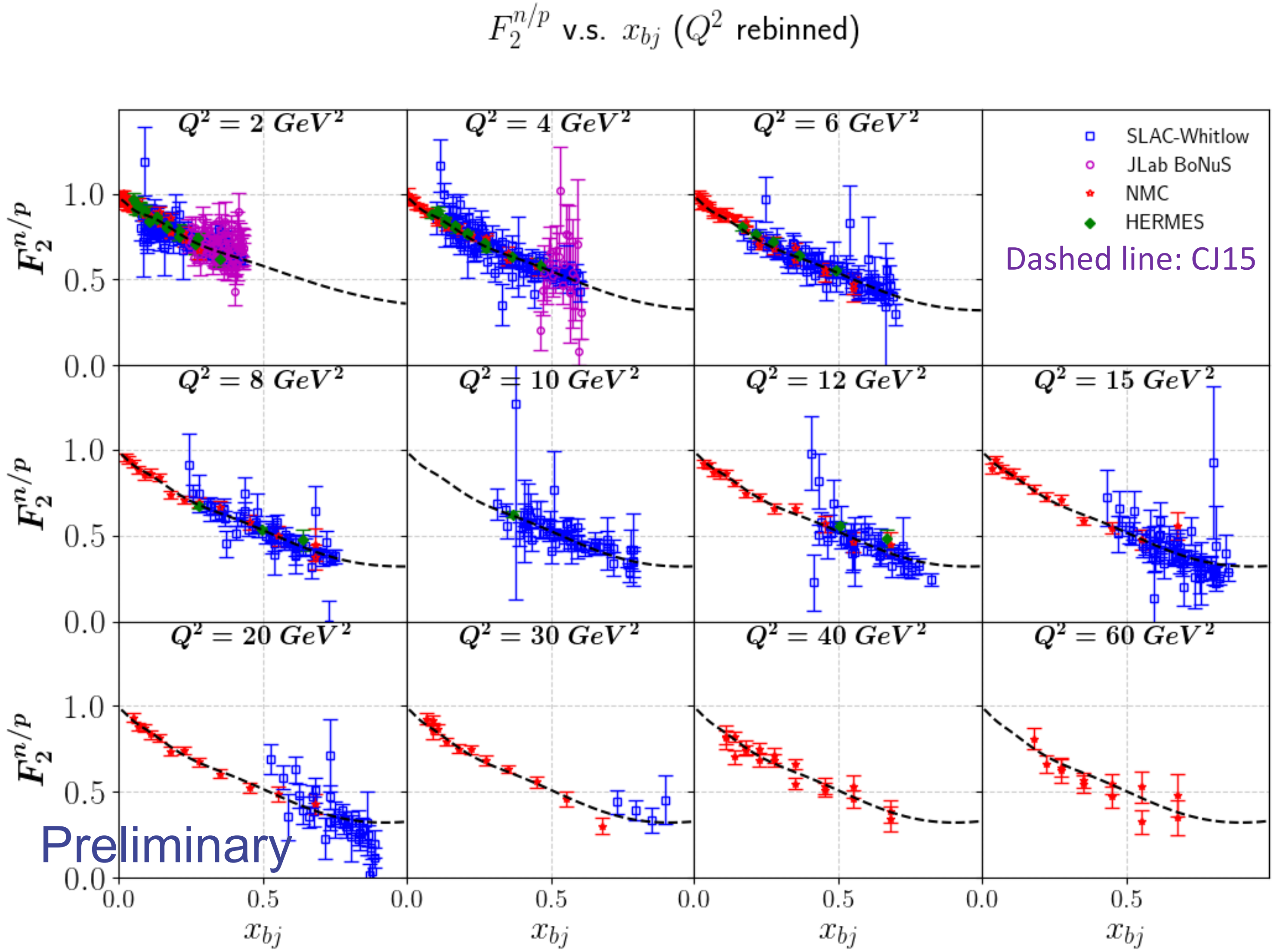
Leverages also precision d/p data (NMC, HERMES, SLAC) and spectator tagged n/d (BONuS)

$n/p = (d/p)_{data} - (d/(n+p))_{CJ}$

$n/p = 1/\{1/[(n/d)_{data}\ (d/(n+p))_{CJ}] - 1\}$

Look closer to understand spread in data….

$F_2^n/F_2^p(x,Q^2)$



Spread in data in part from few large uncertainty data points

Also BONuS

Small Q^2 dependence

WHY CREATE F_2^n DATA SET?

- Improve neutron excess “isoscalar corrections
  - EMC effect
  - Neutrino experiments

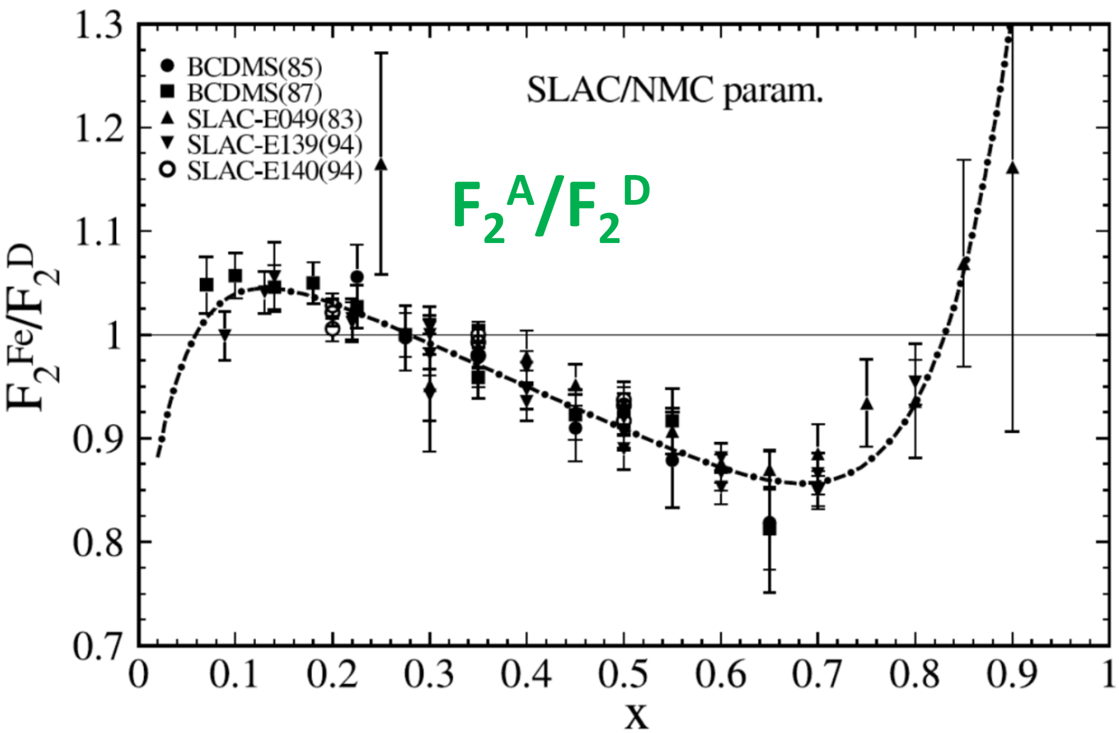
- Flavor separation
  - d/u
  - Nucleon structure / confinement at large x

- Experimental values for sum rules and moments involving $\int F_2^p - F_2^n \, dx$
  - Gottfried Sum Rule (dbar - ubar)
  - Compare to lattice ($u^+ - d^+$)

- Input for PDF efforts that do not currently incorporate deuteron nuclear corrections
  - Can input F_2^n data set into ***any*** global fit

- Can compare free and bound nucleons (*both* proton and neutron) in nuclei
  - New window on the EMC effect

$F_2^n/F_2^p(x,Q^2)$ and Nuclei



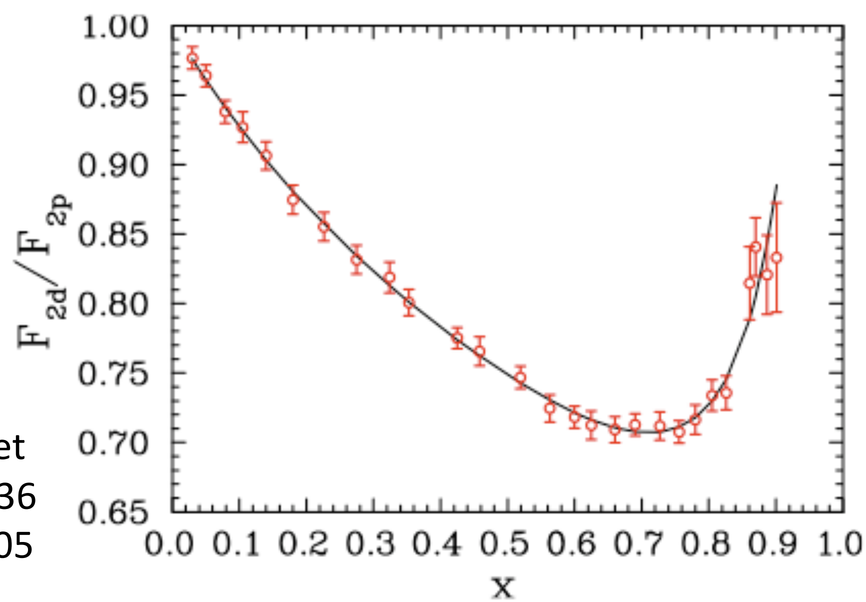
Will make user-friendly parameterization available for neutron excess corrections *(soon - publication in progress)*

$$f_{iso}^{A} = \frac{\frac{1}{2}\left(1 + F_2^n/F_2^p\right)}{\frac{1}{A}\left(Z + (A-Z)F_2^n/F_2^p\right)}.$$

May be important to precision studies of the EMC effect

- Can be a large data correction
- Possible flavor dependence

F_2^d/F_2^p

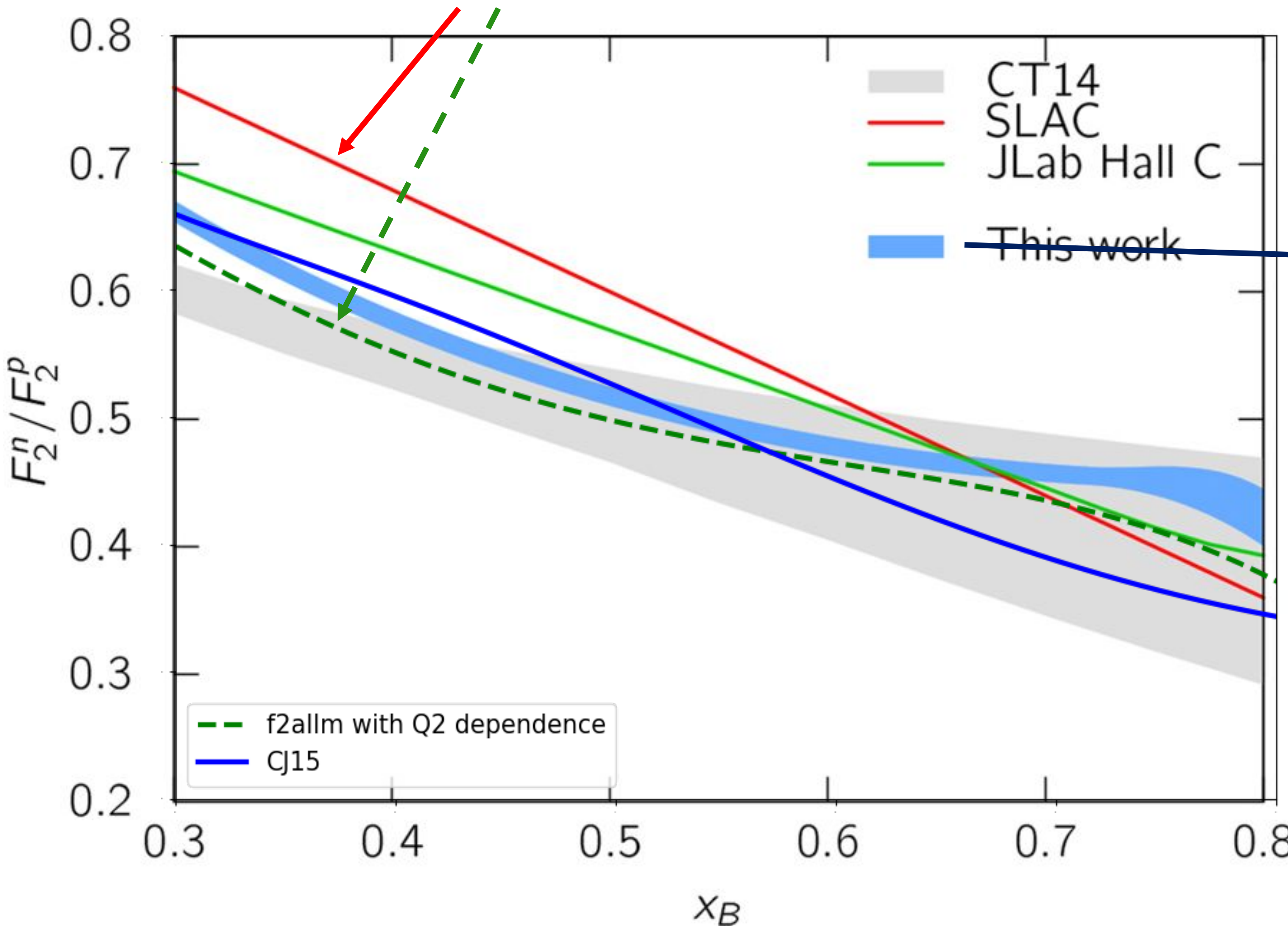


J. Arrington et al., J.Phys. G36 (2009) 025005

A range of F_2^n/F_2^p models are currently deployed…

Q^2=10 GeV^2

Canonical (SLAC, NMC) data use one of these

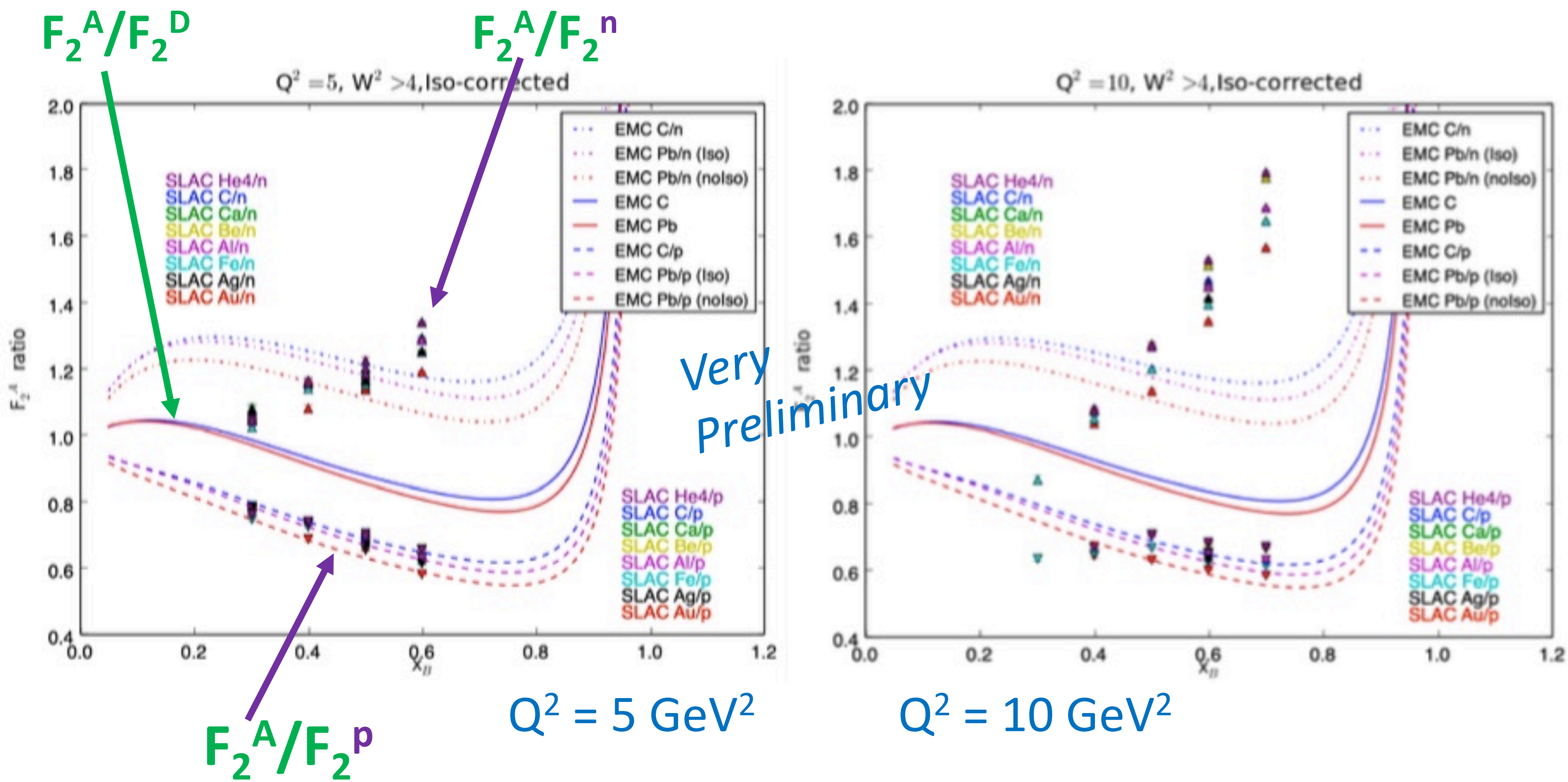


Plot from *Nature* **Volume 56 6** (2019)

...with additions

Study medium modifications of p,n separately

- Q^2 dependence
- Larger spread in A for n?



Plots from Holly Szumilla-Vance

WHY CREATE F_2^n DATA SET?

- Improve neutron excess “isoscalar corrections
  - EMC effect
  - Neutrino experiments

- Flavor separation
  - d/u
  - Nucleon structure / confinement at large x

- Experimental values for sum rules and moments involving $\int F_2^p - F_2^n \, dx$
  - Gottfried Sum Rule (dbar - ubar)
  - Compare to lattice ($u^+ - d^+$)

- Input for PDF efforts that do not currently incorporate deuteron nuclear corrections
  - Can input F_2^n data set into ***any*** global fit

- Can compare free and bound nucleons (*both* proton and neutron) in nuclei
  - New window on the EMC effect

NON-SINGLET MOMENT COMPARISON TO LATTICE

Non-singlet moments of difference between u and d PDFs

$$\langle x^{N-1} \rangle_{u-d} = \int dx x^{N-1} [u(x) - d(x) + \bar{u}(x) - \bar{d}(x)]$$

Precise lattice calculations of this quantity are now available

Can compare to data!

See also P. Nadolsky talk, Wednesday

$$M_2^{NS} = M_2^p - M_2^n = \frac{1}{3} C_N^v \langle x \rangle_{u-d}$$

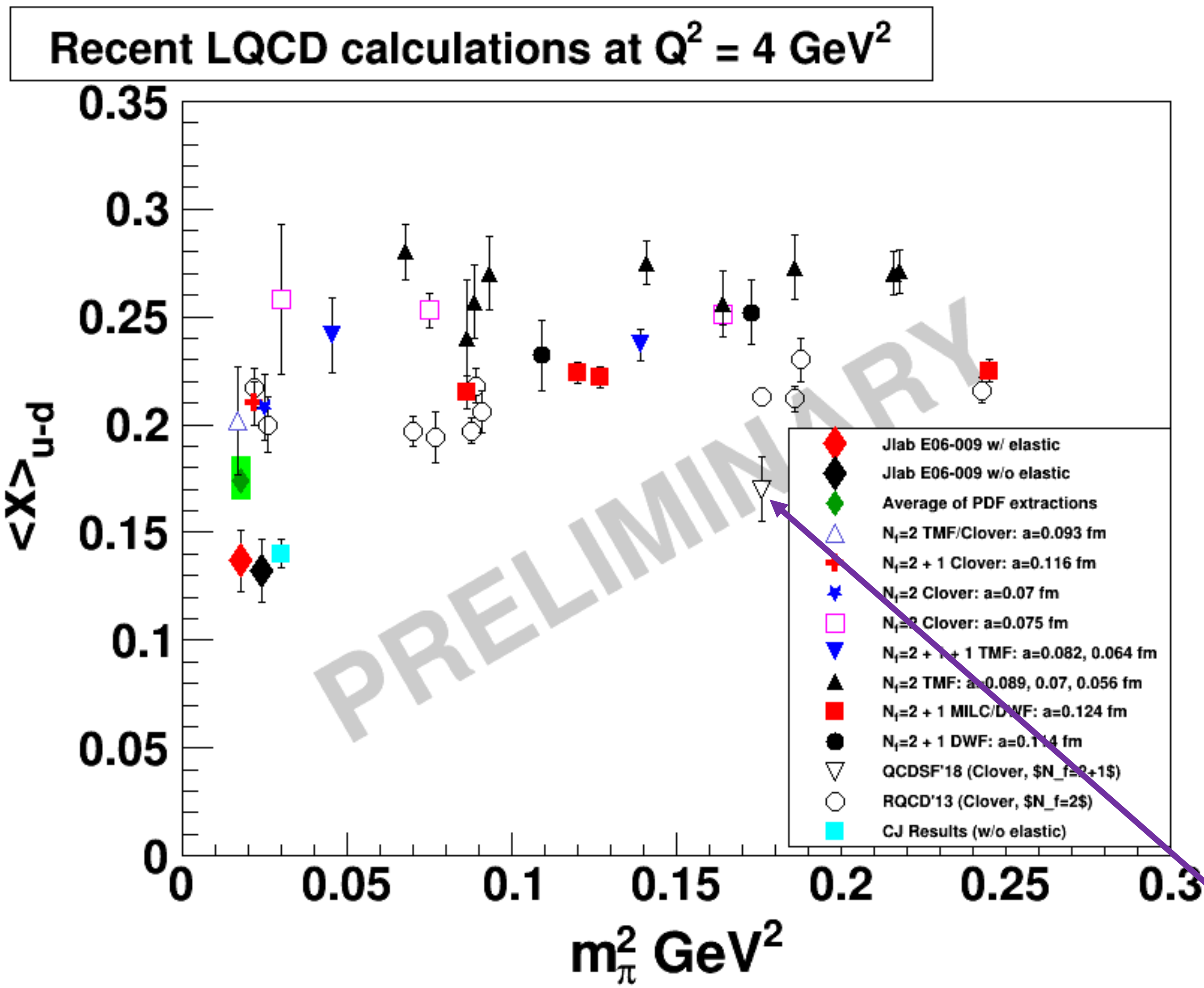
Right-hand side:

- C_N^v are Wilson coefficients (Weigl and Melnitchouk, Nucl. Physics B 465, 267 (1996))
- $\langle x \rangle_{u-d}$ are the lattice moments

Left-hand side:

- M_2 is moment of p or n F_2 structure function
- N=2,4,6 increasingly sensitive to large x
- *obtain from F_2^p and $\boldsymbol{F_2^n}$ data*

NON-SINGLET MOMENT COMPARISON TO LATTICE



CJ agrees with recent JLab analysis using resonance data at large x (I. Albayrak et al. arXiv:1807.06061v2 (2018))

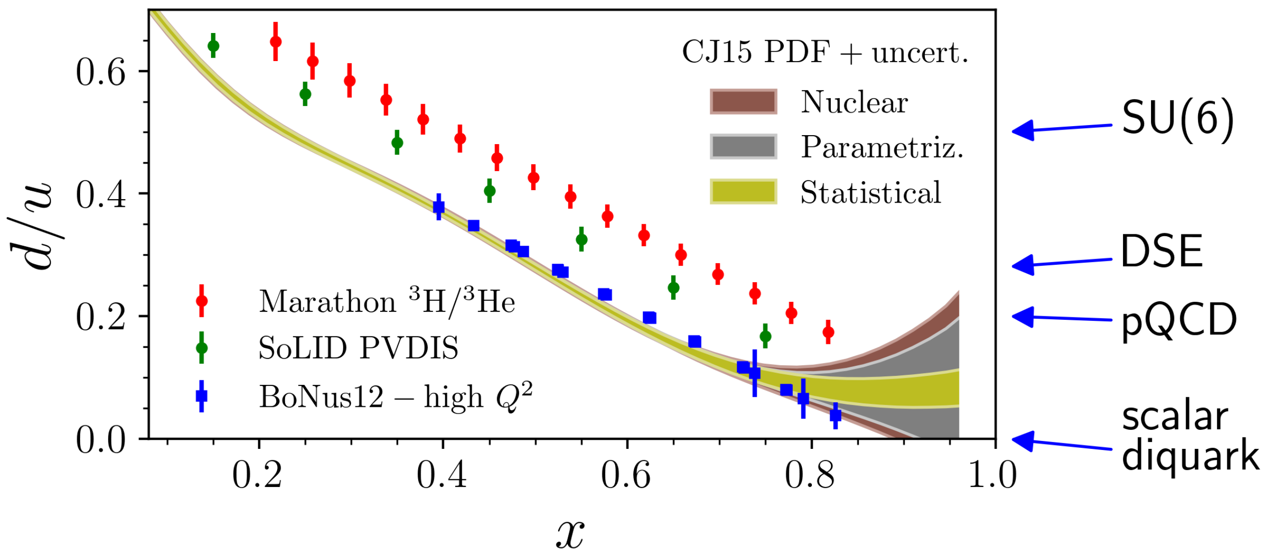
Both data extractions smaller than lattice calculations at real pion mass and previous PDF extractions

Residual finite volume effects, renormalization and mixing,…?

Better agreement with QCDSF novel lattice approach calculating distributions directly before determining moments

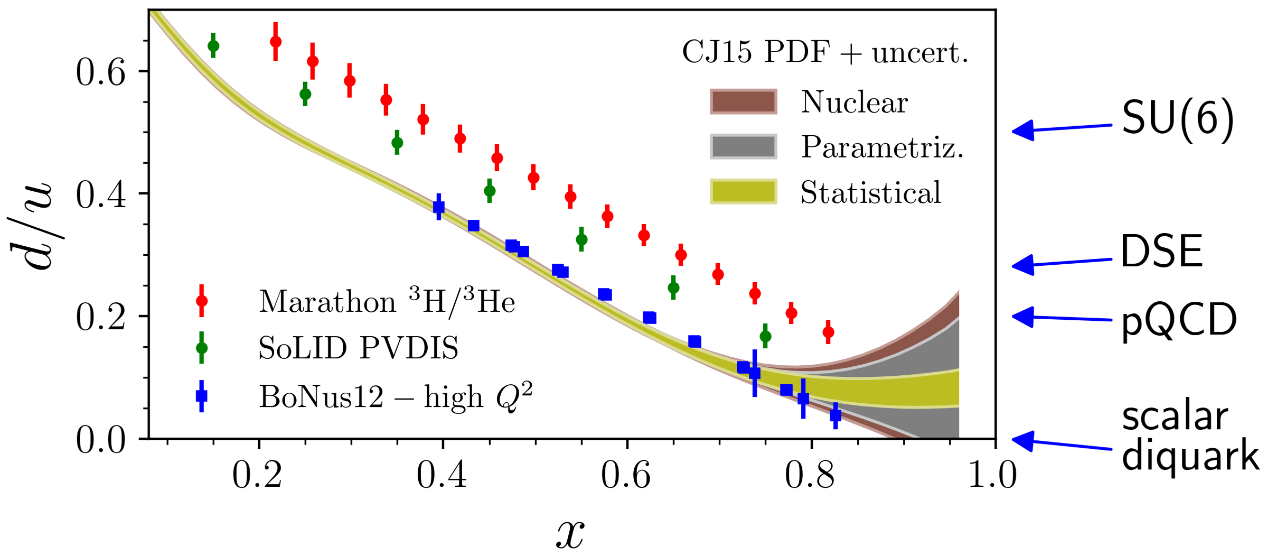
Plot from Peter Monaghan

Probing the Valence Regime at JLab12



- New generation of experiments at JLab at 12 GeV will access the regime where valence quarks dominate
- First experiments ***COMPLETED!***
  - ✓ Hall C $F_2^{p,d}$
  - ✓ Hall A $^3H/^3He$
- BONUS12 to run this Fall
- PVDIS (further future) on p target
- Dedicated effort to extract valence PDFs
  - "CJ", (CTEQ-Jefferson Lab) – and also "JAM" (polarized PDF, SIDIS) collaborations
- Also SeaQuest Drell-Yan experiment E906 at FNAL focused on high x sea

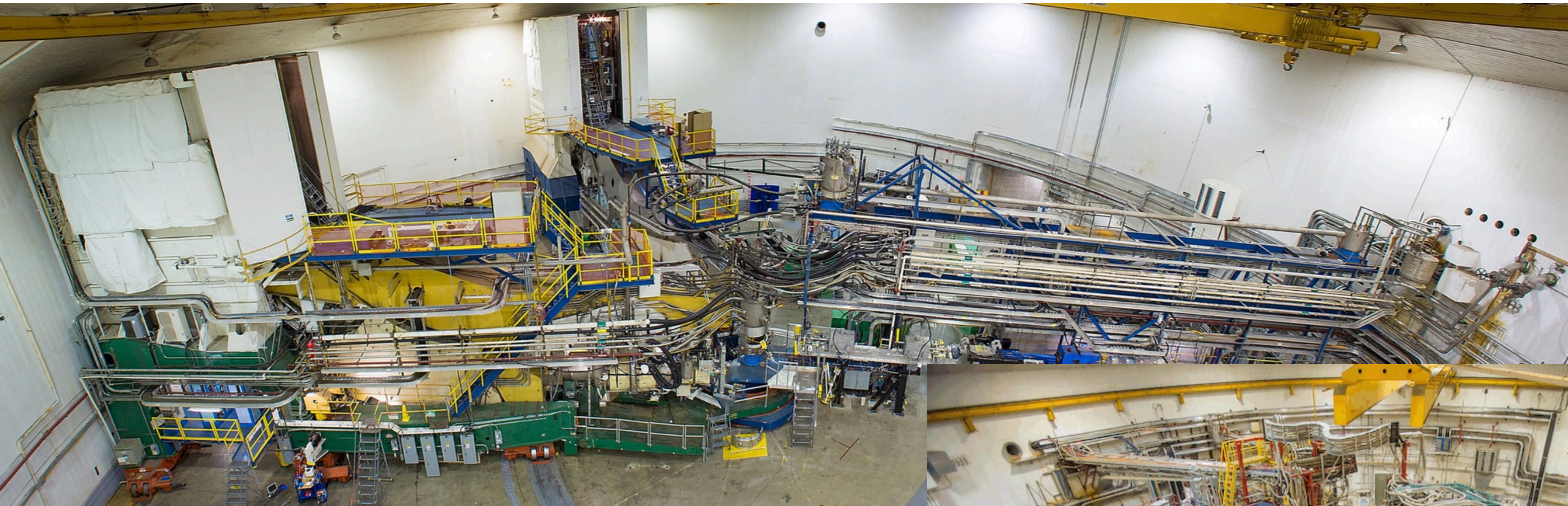
Probing the Valence Regime at JLab12



- New generation of experiments at JLab at 12 GeV will access the regime where valence quarks dominate
- First experiments *COMPLETED!*
  - ✓ Hall C $F_2^{p,d}$
  - ✓ Hall A $^3H/^3He$
- BONUS12 to run this Fall
- PVDIS (further future) on p target
- Dedicated effort to extract valence PDFs
  - "CJ", (CTEQ-Jefferson Lab) – and also "JAM" (polarized PDF, SIDIS) collaborations
- Also SeaQuest Drell-Yan experiment E906 at FNAL focused on high x sea

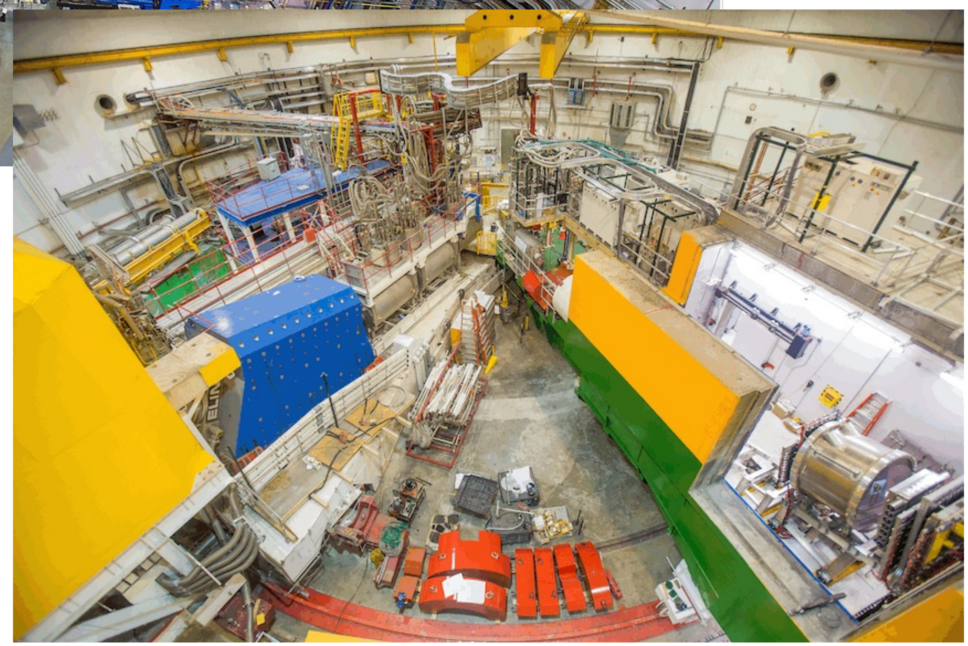
Expect significant improvement in large x PDFS in next 1-2 years!!

Thank You!

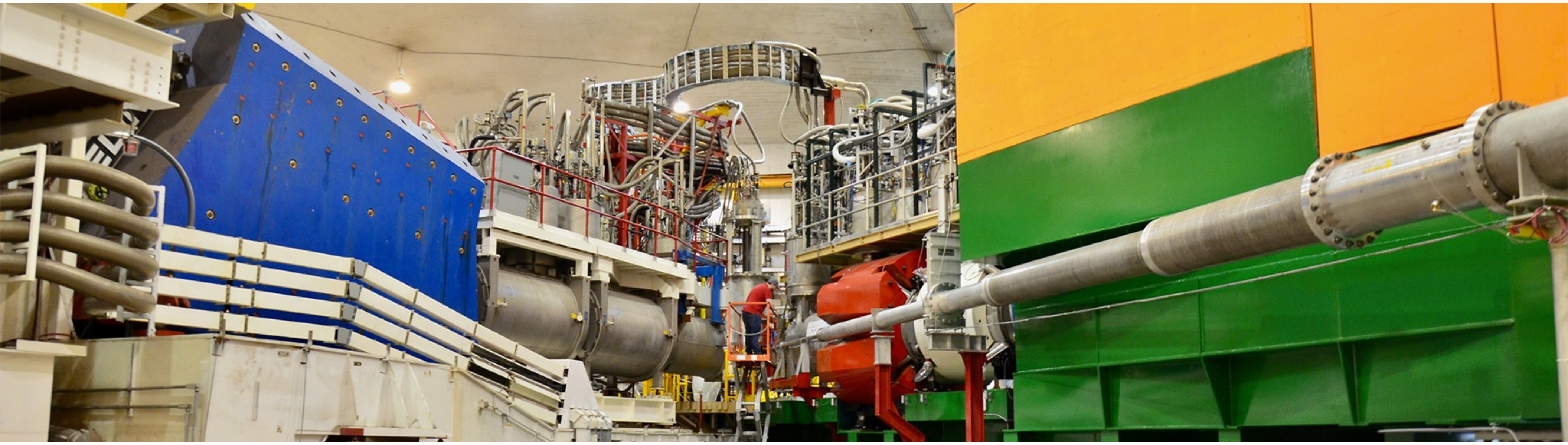


Jefferson Lab Hall A

Jefferson Lab Hall C



Jefferson Lab Hall C



Backups!

Improved Extraction of F_2^n from F_2^d and F_2^p

Method employs iterative procedure of solving integral convolution equations

Y. Kahn, W. Melnitchouk, S.A. Kulagin, Phys. Rev. C 79, 035205 (2009)

- Impulse Approximation – virtual photon scatters incoherently from individual nucleons

(Beyond IA: FSI not addressed in present analysis)

$$\tilde{\mathcal{F}}^n(x) = \mathcal{N}\,\mathcal{F}^n(x) + (\delta f \otimes \mathcal{F}^n)(x)$$

$$F_2^A(x,Q^2) = \sum_{N=p,n} \int_x^{M_A/M} dy\, f_0^{N/A}(y,\gamma)\, F_2^N\left(\frac{x}{y}, Q^2\right) \qquad \gamma = \sqrt{1+\frac{4M^2x^2}{Q^2}}$$

nuclear F_2

light-cone momentum distribution of nucleons in nucleus (smearing function)

nucleon F_2

$$\left(f_0^{N/A} \otimes F_2^N\right)(x,Q^2)$$

Convolution of light cone momentum distribution on nucleons in nucleus

Application to Deuterium…

F_2^n/F_2^p Models

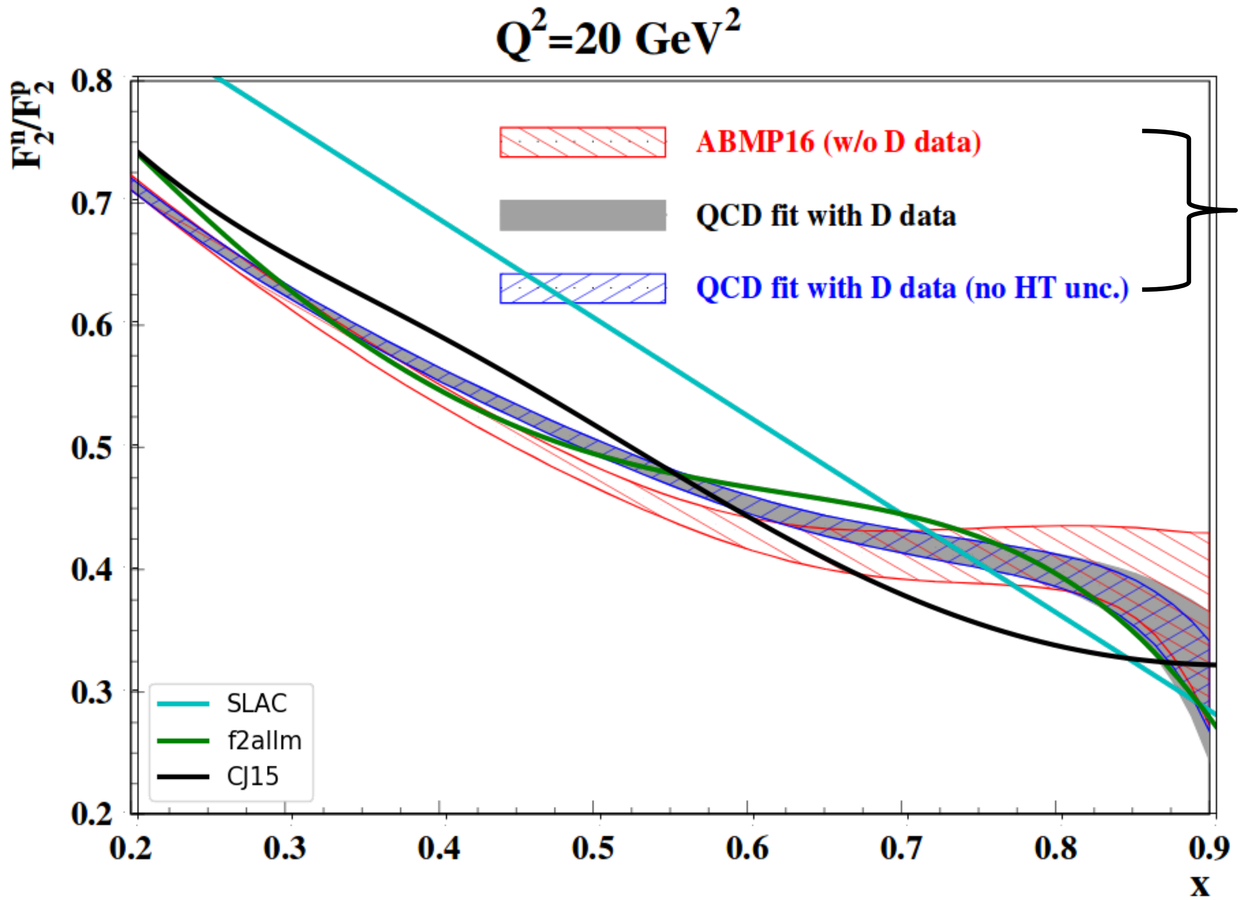


Fig 10 from S. I. Alekhin, S. A. Kulagin, and R. Petti

Phys. Rev. D 96, 054005(2017)