New Neutron Structure Function Extraction from Global Inclusive Proton and Deuteron Data

Shujie Li

with many thanks to my **CTEQ-JLab** collaborators:
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Extraction of the neutron F_2 structure function from inclusive proton and deuteron deep-inelastic scattering data

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- Global fit with a focus on fixed-target data from Jefferson Lab
  - Large-x, low-Q^2 $\longrightarrow$ TMC, HT
  - Nuclear dynamics $\longrightarrow$ p,n motions, off-shell PDFs
- F2(n) extracted from global data, and also available as LHAPDF grids for
  - experiment result projection
  - “free” neutron data as input to other PDF fitter
  - nuclear PDF and neutrino scattering

CJ Global QCD fits

For the latest status, see Matteo Cerutti's talk, Wed noon, WG1

- pQCD factorization & universality: can fit PDFs to a variety of hard scattering data

$$d\sigma_{\text{hadron}} = \sum_{f_1,f_2,i,j} \phi_{f_1} \otimes \hat{\sigma}^{f_1 f_2 \to ij}_{\text{parton}} \otimes \phi_{f_2}$$

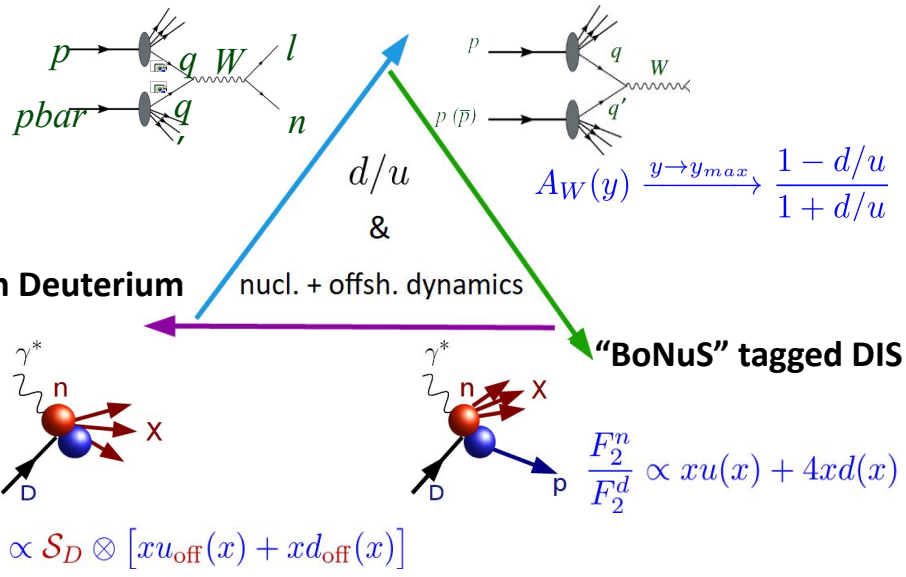
pQCD calc.

PDFs (from DIS fits)

  - Hadron-hadron collisions
    - ⟶ Jets
    - ⟶ Electro-weak boson production
  - Electron-proton DIS
  - Electron-Deuteron DIS

- Large-x PDFs: interplay of observables

D0, CDF asymmetries



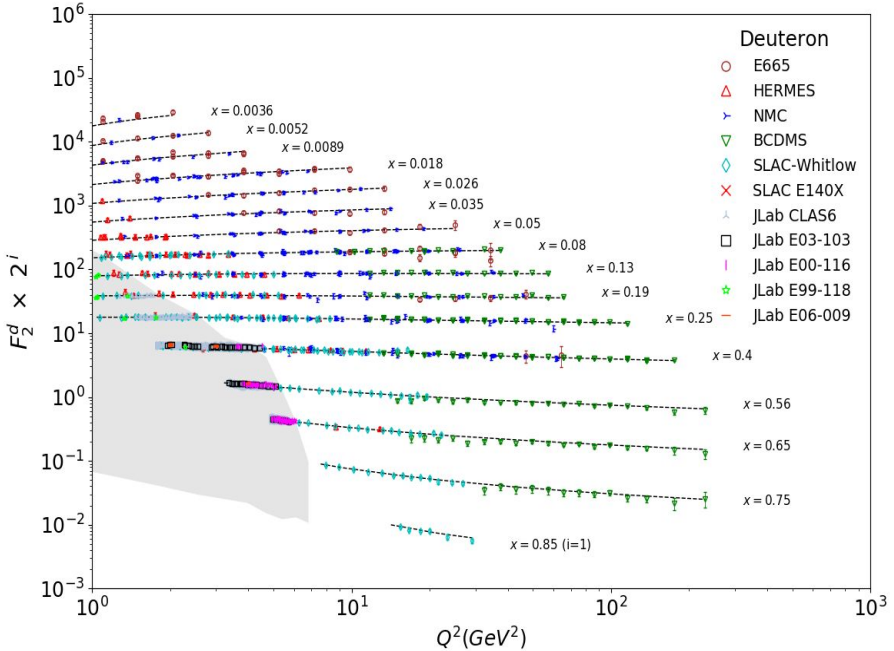
CJ Global QCD fits

CJ15: *Phys.Rev.D* 93, 114017 (2016)
CJ22: *Phys.Rev.D* 107, 113005 (2023)

- **1000+ data points**
  - including high x, low Q^2 data from JLab
  - W^2>3.0 GeV^2, Q^2>1.69 (GeV/c)^2

- **Lower-energy / nuclear focus:**
  - **Full treatment for HT, TMC, nuclear smearing, and offshellness**

    ⟶ Deuteron Fermi motion and binding with **W**eak **B**inding **A**pproximation



$$F_{2d}(x,Q^2) = \int \frac{dz}{z} dp_T^2 \, \mathcal{K}(z,p^2,\gamma) \left|\psi_{N/d}(|\vec{p}|)\right|^2 F_{2N}(x/z,Q^2,p^2)$$

kinematic and "flux" factors

Nucleon wave function

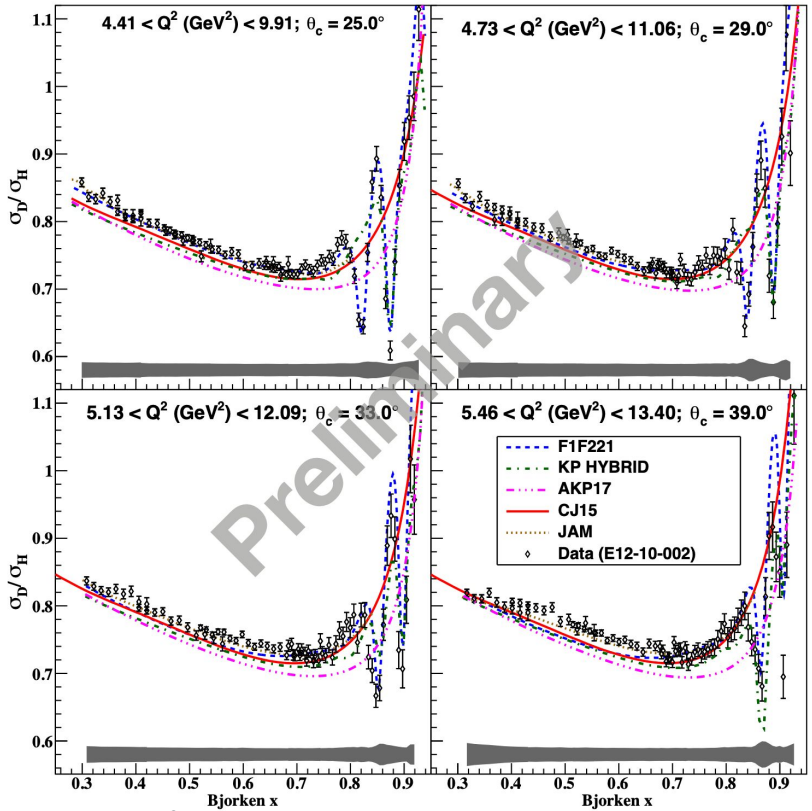
structure function of **bound, off-shell nucleon**

See W. Henry's talk

Impact of Large-x Deuteron Data

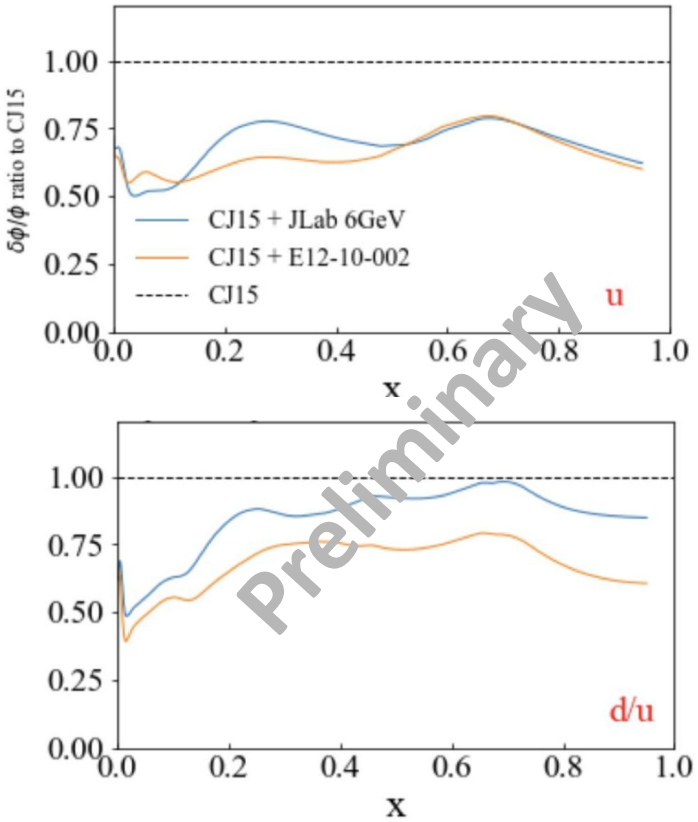
"Power of precision"

JLab E12-10-002 data



Courtesy of Bill Henry

Impact on PDF uncertainties



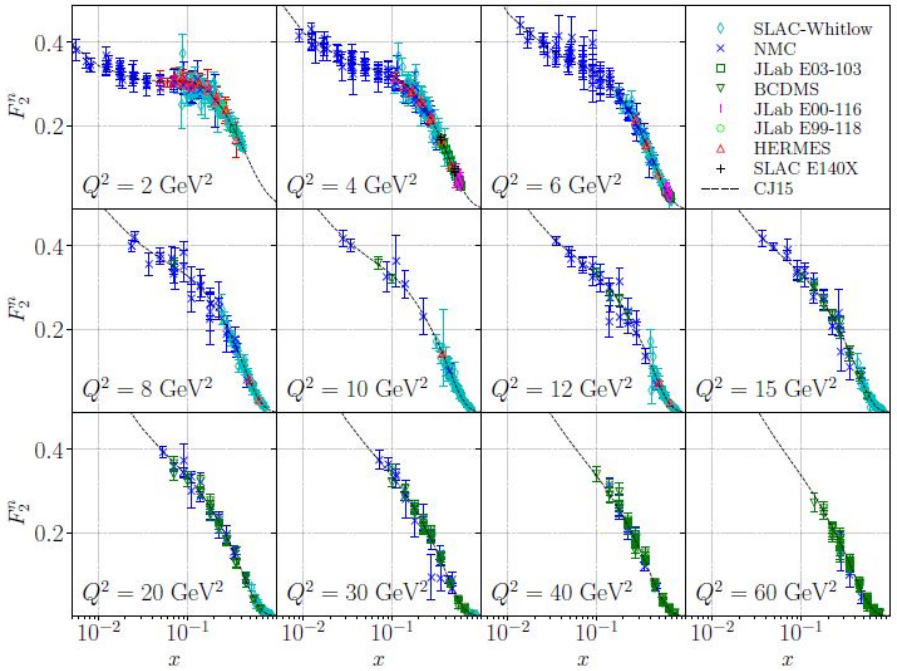
Neutron F_2 Extraction

Reference: S. Li et. al. arXiv:2309.16851, accepted by PRD

- **Basic idea:**

$$\widehat{F}_2^{n(0)}(x,Q^2) = \frac{2\,\widehat{F}_2^{d(0)}(x,Q^2)_{\rm exp}}{R_{d/N}^{\rm CJ}(x,Q^2)} - \widehat{F}_2^{p(0)}(x,Q^2)_{\rm exp}$$

- **But also:**
  - P, d data matching
  - Data cross normalization
    - ⟶ Based on CJ15 PDFs
    - ⟶ Refit of norm, Correlated errors
  - Bin-centered for applications such as Isosinglet moment
  - …



F2 neutron datasets and grids available at https://github.com/JeffersonLab/CJ-database/

F_2 n/p Extraction

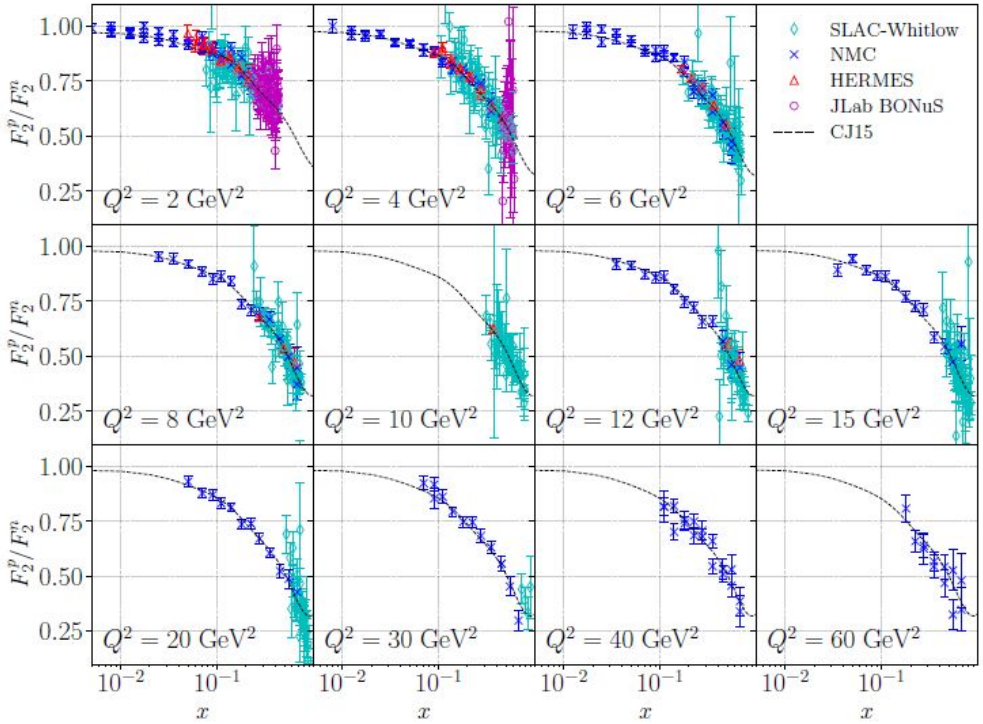
Reference: S. Li et. al.
arXiv:2309.16851, accepted by PRD

- Similar idea, but using
  - **d/p data**

$$\widehat{R}^{(0)}_{n/p} \equiv \frac{2\,\widehat{R}^{\exp,(0)}_{d/p}}{R^{\rm CJ}_{d/N} - 1}$$

  - **n/d BONuS data**

$$\widehat{R}^{(0)}_{n/p} \equiv \frac{\widehat{R}^{\exp,(0)}_{n/d}\; R^{\rm CJ}_{d/N}}{1 - \widehat{R}^{\exp,(0)}_{n/d}\; R^{\rm CJ}_{d/N}}$$



F2 neutron datasets and grids available at
https://github.com/JeffersonLab/CJ-database/

Uncertainties

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

correlated error

normalization

$$\chi^2 = \sum_{\text{exp}} \left[\sum_{i=1}^{N_{\text{data}}} \left(\frac{D_i + \Delta_i - T_i/n}{\delta D_i} \right)^2 + \left(\lambda^{\text{norm}}\right)^2 + \sum_{k=1}^{K} \lambda_k^2 \right]_{\text{exp}}$$

uncorrelated error

```
# fit parameters
LAMBDA        0.22680         0.0000
a0uv           2.4067         0.0000
a1uv          0.61537        0.19856E-01
a2uv           3.5433        0.12414E-01
a3uv           0.0000         0.0000
a4uv           3.4609        0.42903
a5uv           0.0000         0.0000
a0dv           24.684         0.0000
a1dv           1.1595        0.33533E-01
a2dv           6.5514        0.15936
a3dv          -3.5030        0.86332E-01
a4dv           4.6787        0.14209
a5dv           0.0000         0.0000
a0ud          0.14658        0.50348E-02
a1ud         -0.20775        0.37551E-02
a2ud           8.3286        0.19114
a3ud           0.0000         0.0000
a4ud           14.606         1.2151
a5ud           0.0000         0.0000
a0du           35712.         0.0000
a1du           4.0249        0.74070E-01
a2du           20.154        0.87862
a3du           17.000         0.0000
a4du           51.156         10.239
a0g            45.542         0.0000
a1g           0.60307        0.31164E-01
a2g            6.4812        0.96748
a3g           -3.3064        0.13418
a4g            3.1721        0.31376
a5g            0.0000         0.0000
kappa         0.40000         0.0000
a6dv        -0.36005E-02    0.66324E-03
a7dv           2.0000         0.0000
off1          -3.6735         1.5278
off2         0.57717E-01    0.14842E-01
ht1           -3.2874        0.26061
ht2            1.9274        0.10524
ht3           -2.0701        0.19888E-01
ht4            0.0000         0.0000
```

Data - Fit Residual After Cross-normalization

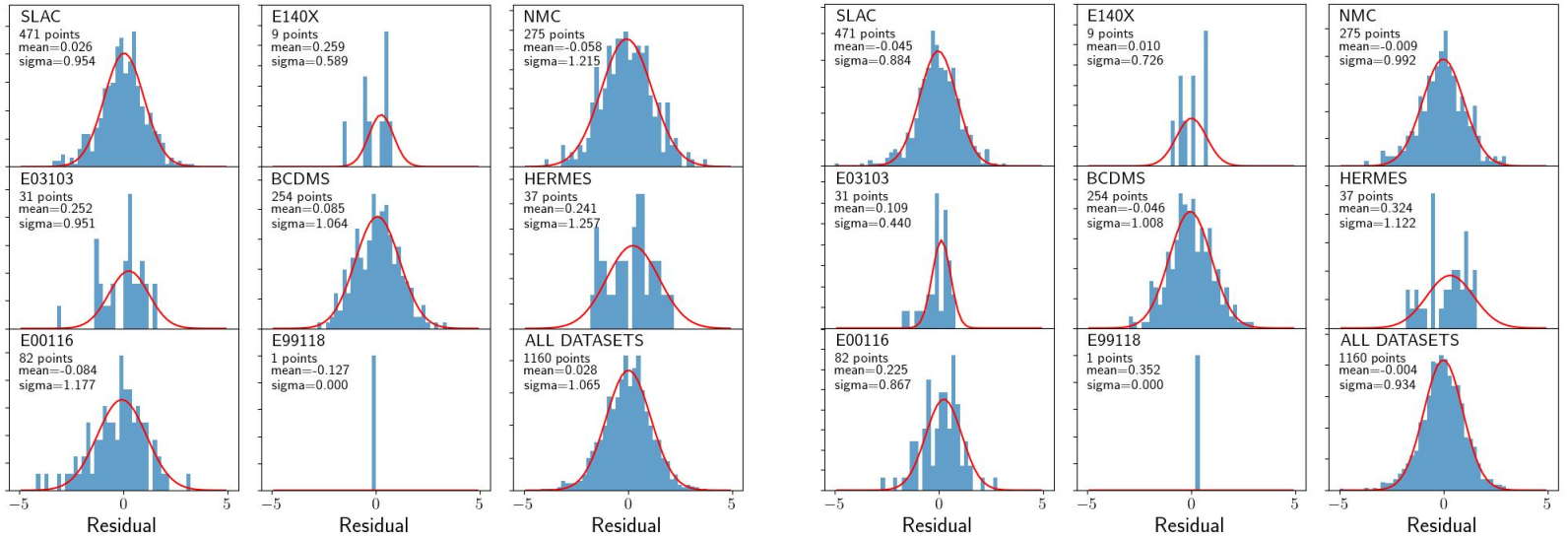
10.1103/RevModPhys.92.045003

$$r_k(a_{\rm fit}, \lambda_{\rm fit}) = \frac{D_k - T_k(a_{\rm fit})}{\sigma_k} - \sum_I \beta_{kI} \lambda_I^{\rm fit}$$

uncorrelated

Correlated uncertainty

Proton



Application: non-singlet moments

F2 from data

Nachtmann moment M^{NS}

$$M_2^{p-n}(Q^2) = \int_0^1 \mathrm{d}x \, \frac{\xi^3}{x^3}\left[\frac{3+9r+8r^2}{20}\right] F_2^{p-n}(x,Q^2)$$

$$\xi = 2x/(1+r) \qquad r = \sqrt{1+4M^2x^2/Q^2}.$$

accounts for kinematic TMC.

It connects to **non-singlet moments** by

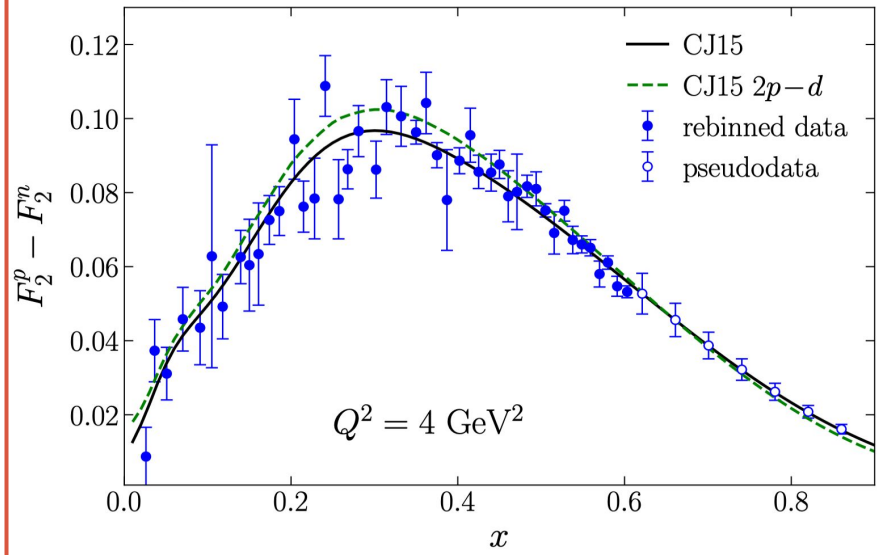
$$\frac{3}{C_2} M_2^{\mathrm{NS}} = \langle x \rangle_{u^+-d^+} + \mathrm{HT}$$

Application: non-singlet moments

F2 from data

$$M_2^{p-n}(Q^2) = \int_0^1 \mathrm{d}x \, \frac{\xi^3}{x^3}\left[\frac{3+9r+8r^2}{20}\right] F_2^{p-n}(x,Q^2)$$

$$\frac{3}{C_2} M_2^{\mathrm{NS}} = \langle x \rangle_{u^+-d^+} + \mathrm{HT}$$



At given Q^2:

- **x<0.1**: fit according to Reggie theory

$$F_2^p - F_2^n = Ax^\alpha$$

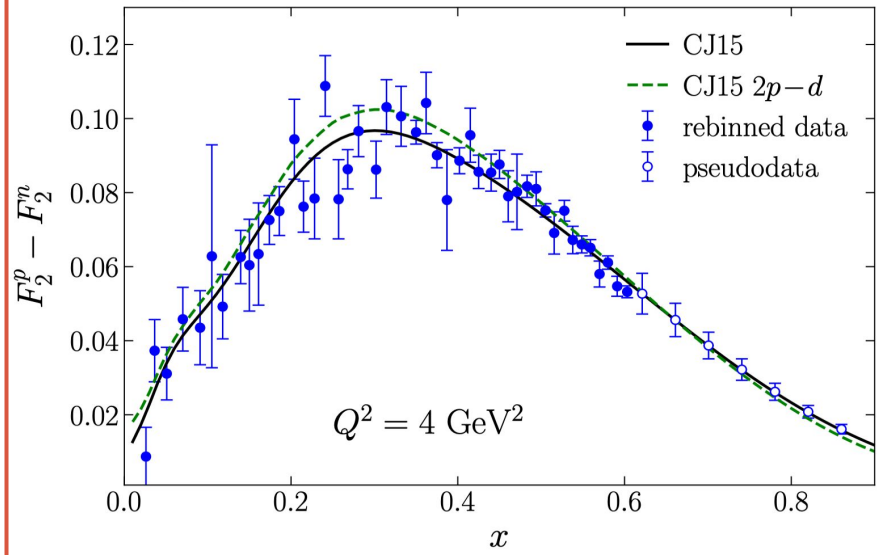
- **x in measured range:** binned and interpolated
- **High x:** two theory models, CJ15 and F1F209, cutoff at pion threshold

Application: non-singlet moments

F2 from data

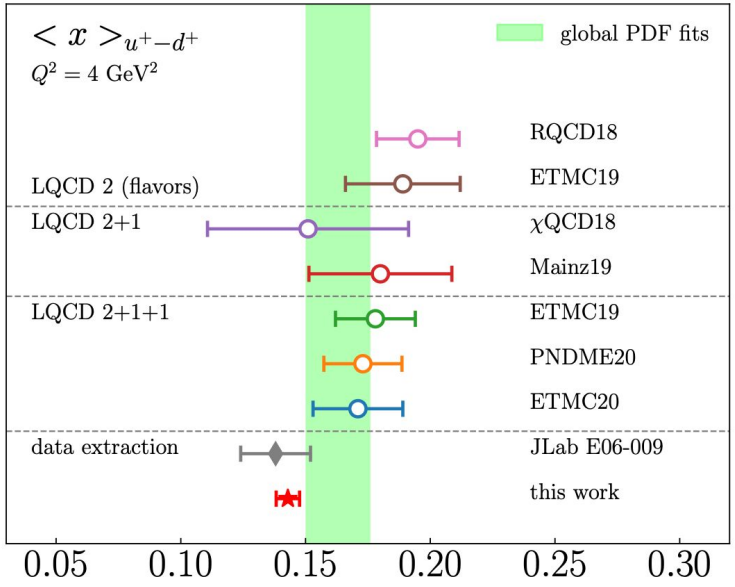
$$M_2^{p-n}(Q^2) = \int_0^1 \mathrm{d}x \, \frac{\xi^3}{x^3}\left[\frac{3+9r+8r^2}{20}\right] F_2^{p-n}(x,Q^2)$$

$$\frac{3}{C_2} M_2^{\mathrm{NS}} = \langle x \rangle_{u^+-d^+} + \mathrm{HT}$$



Moments from LQCD

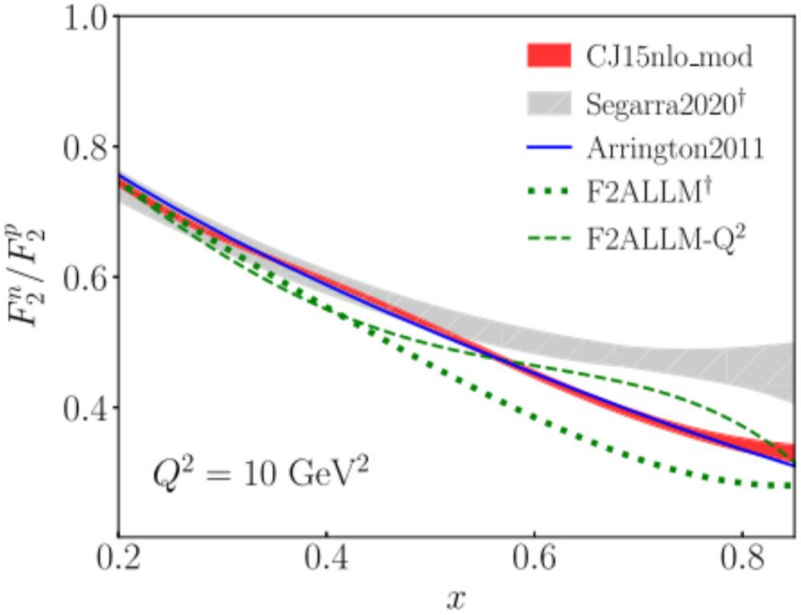
$$\langle x \rangle_{u^+-d^+} = \int \mathrm{d}x \, x \left[u(x) + \bar{u}(x) - d(x) - \bar{d}(x)\right]$$

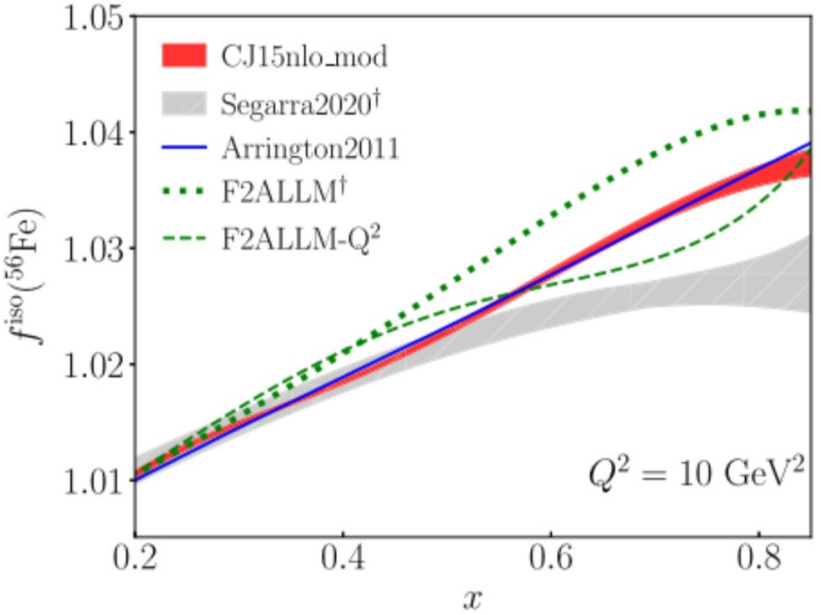


Application: isoscalar corrections

$$f_A^{\text{iso}} \approx \left(\frac{A}{2}\right) \frac{1 + F_2^n/F_2^p}{Z + N F_2^n/F_2^p}$$

Correction depends on x and Q^2, important for EMC effect and neutrino scattering





Open Database on Github

https://github.com/JeffersonLab/CJ-database

CJ Unpolarized DIS Database Homepage

Reference: arXiv:2309.16851.

See also

- CTEQ-JLab collaboration website.
- note for reduced cross section and F2 calculation.

World DIS data tables

World **proton** and **deuteron** data of unpolarized DIS cross sections, F2 structure functions, and the longitudinal to transverse cross section ratio R are collected or extracted from various experiments. Data were collected for the CJ global fit and related analysis. Now open for general use. See details under the data directory.

Neutron F2 extraction

Based on the collected F2 data, we performed a data-driven extraction of **neutron F2** and **neutron-to-proton F2n/F2p ratio** within the CJ15 framework (see eq. 7-9 in reference for details). Data from all experiemnts are cross-normalized and combined into a single Excel file, both in the original kineamtics, as well as rebinned in Q^2. Check the f2n directory.

Structure function grids

Within CJ framework, we calculated various structure functions (F2, F3, FL, etc) at given x, Q^2 grids. Results are provided under folder SFN_grids in the LHAPDF format. An example plotting script is available at `src/plot_sfn.py`

LHAPDF grids on F2,FL, F3 with gamma, gz, Z
F2 come with HT

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-Whitlow(rebinned)		rebinned p: 10012	
		rebinned d: 10013	
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	d: 10071
(includes E04-001, E02-109)			
JLab E94-110	p: 10044	p: 10043	p: 10074
JLab E03-103	p:10047	p:10045	
	d:10048	d:10046	
JLab E99-118	p:10052	p:10049	p: (A)
	d:10053	d:10050	p-d: (A)
	d/p:10054	d/p:10051	
JLab JLCEE96	p: 10055	p: 10072	
	d: 10056	d: 10073	
JLab E00-116	p: 10003	p: 10001	
	d: 10004	p: 10002	
CLAS6	p: 10059	p: 10057	
	d: 10060	d: 10058	
BONUS		n: 10061	
		n/d: 10033	
HERA I+II	p: 10026 - 10032		
HERMES	p: 10007	p: 10005	
	d: 10008	d: 10006	
	d/p: 10009		
E665		p: 10062	
		d: 10063	

Outlook

https://github.com/JeffersonLab/CJ-database/

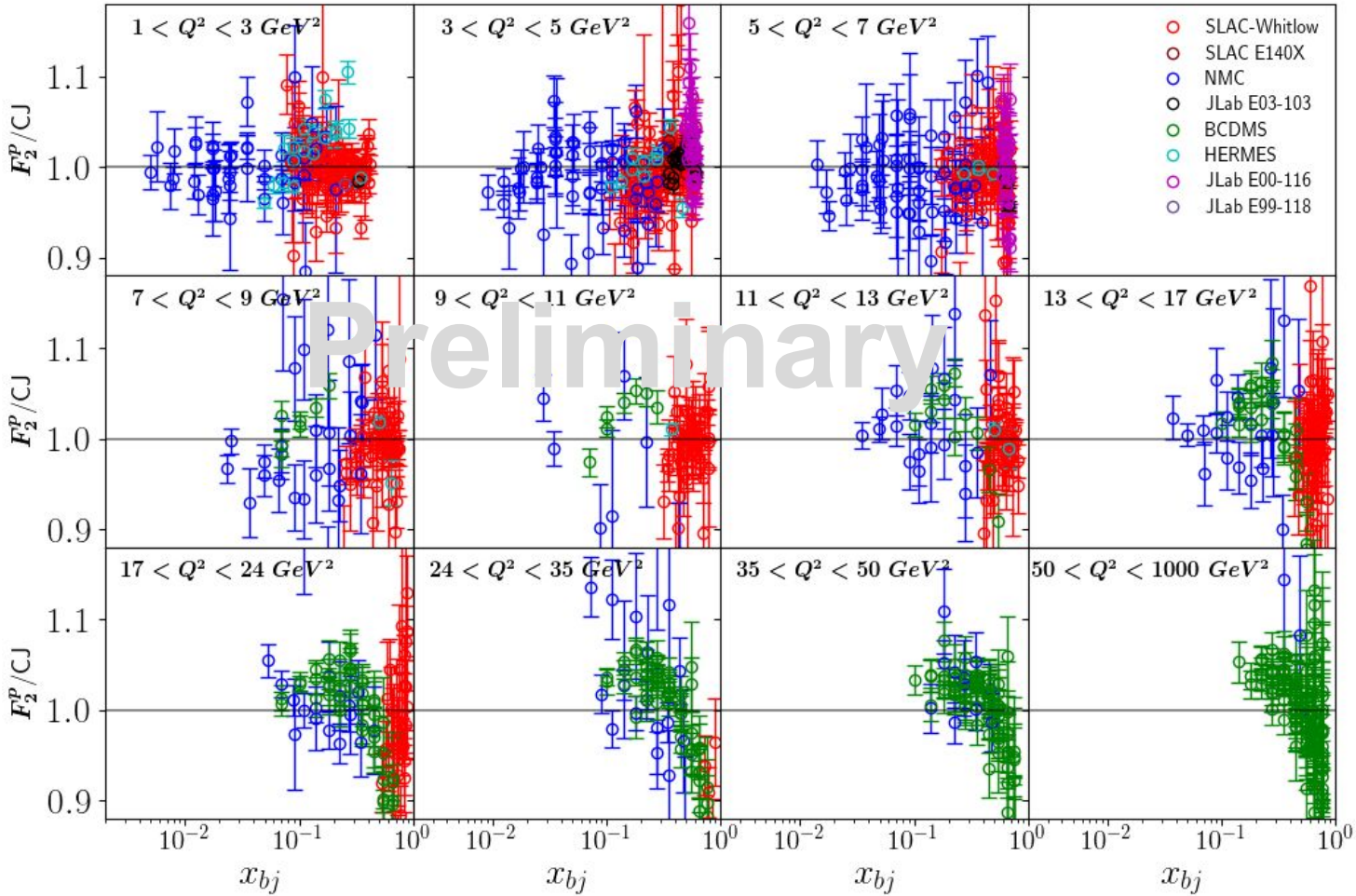
- We provided a **data-driven extraction of F2n** from Deuteron data, with our best knowledge of HT and nuclear effects
- **World data on F2p and d** are sorted into a database with clear documentation on **uncertainties**
- F2n data sets are available, can be used e.g. as input to other global analysis
- F2 grids in LHAPDF format, can provide **isoscalar corrections** with uncertainties

- **Next step:** continue the coordinated Theory-Experiment Effort:
  - Interplay of HT and off-shell
  - Strange sea with LHC data
  - NNLO
  - Structure function with CJ22 and updated uncertainties

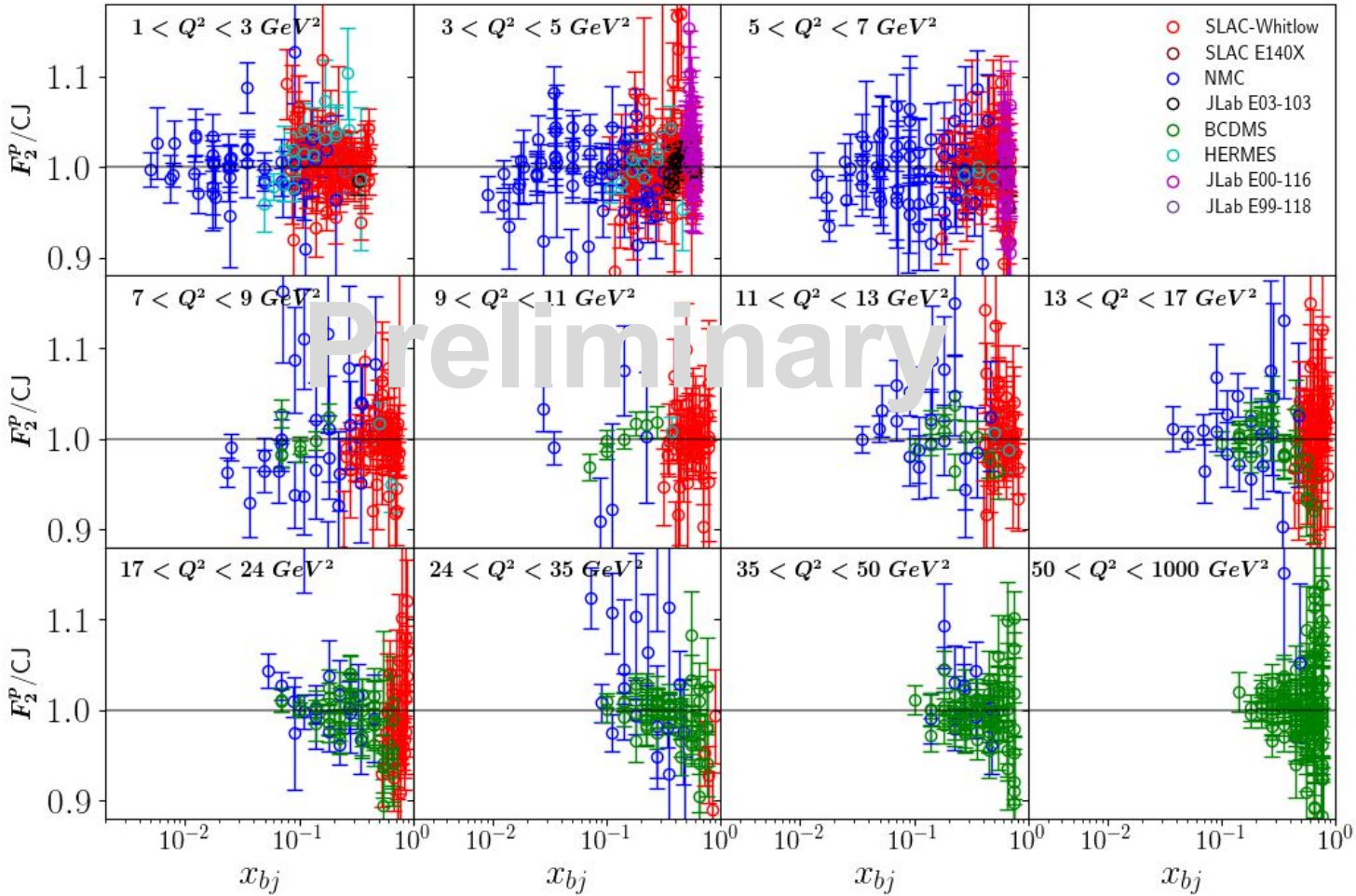
Thank you!

Backups

raw F_2^p Data/CJ



modified+normed F_2^p Data/CJ



Data Selection

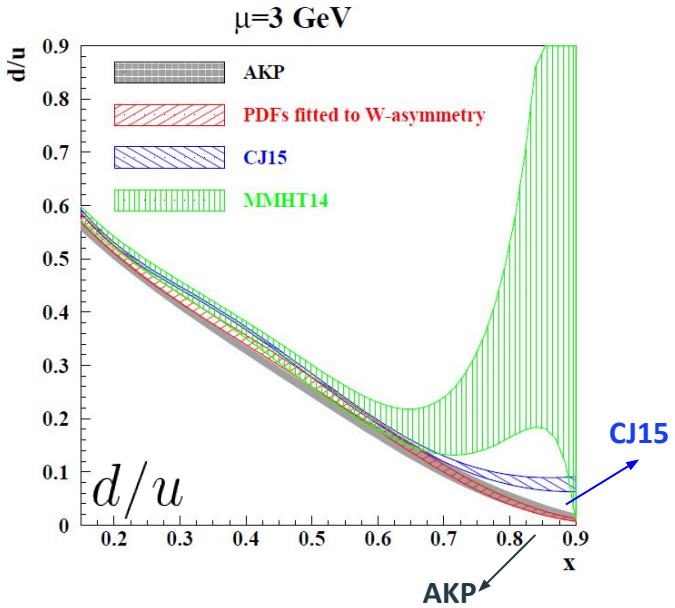
1. **DIS cuts:**
   a. $Q^2 > 1.691\ GeV^2/c^2$
   b. $W^2 > 3.5\ GeV^2$

2. **Within each experiment**, we match the proton and deuteron data points by requiring:
   a. same beam energy,
   b. $|x_{proton} - x_{deuteron}| < 0.01$,
   c. $|Q^2_{proton} - Q^2_{deuteron}| < 1\%$.

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

CJ15 and AKP: d/u to free nucleons

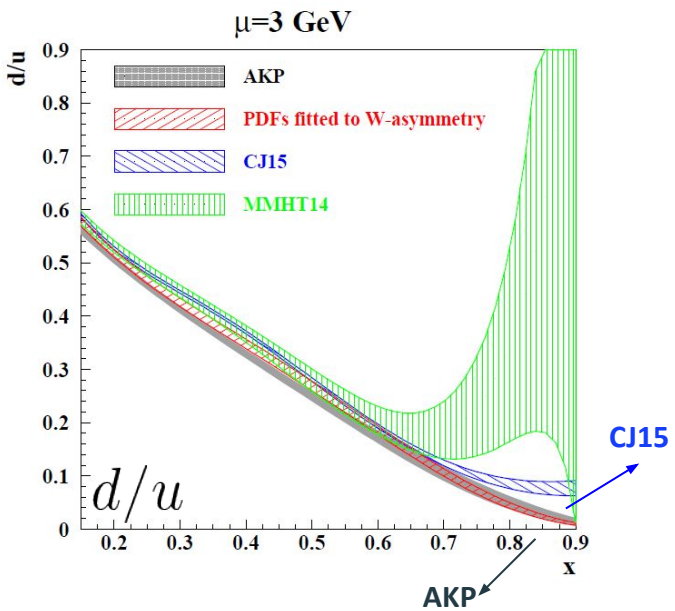
CJ15: *PRD 93 (2016) 114017*
AKP: *PRD 96 (2017) 054005*
(see also 2203.07333)

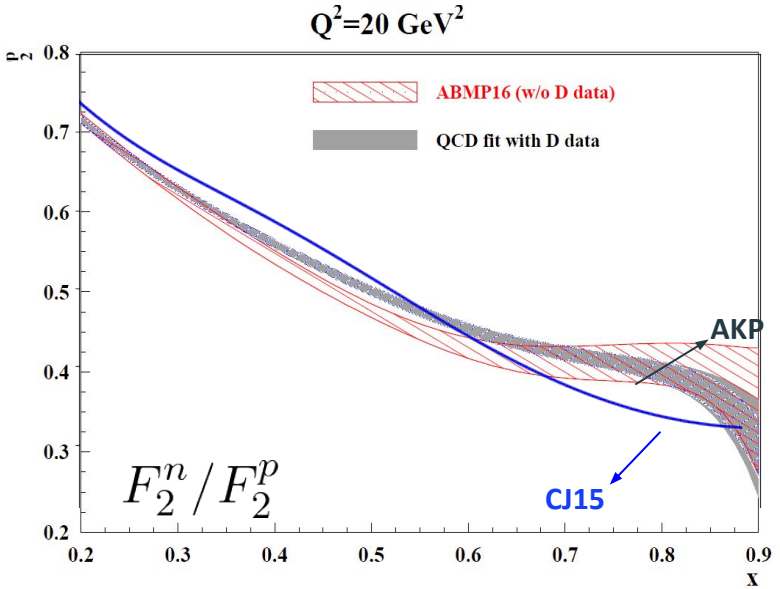


$$\frac{F_{2n}}{F_{2p}} \approx \frac{1+4d/u}{4+d/u}$$

CJ15 and AKP: d/u to free nucleons

CJ15: *PRD 93 (2016) 114017*
AKP: *PRD 96 (2017) 054005*
(see also 2203.07333)

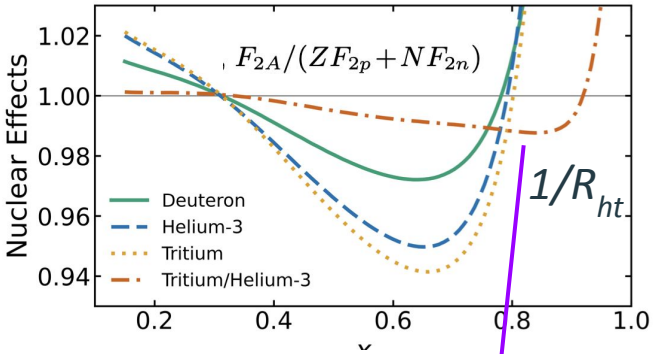


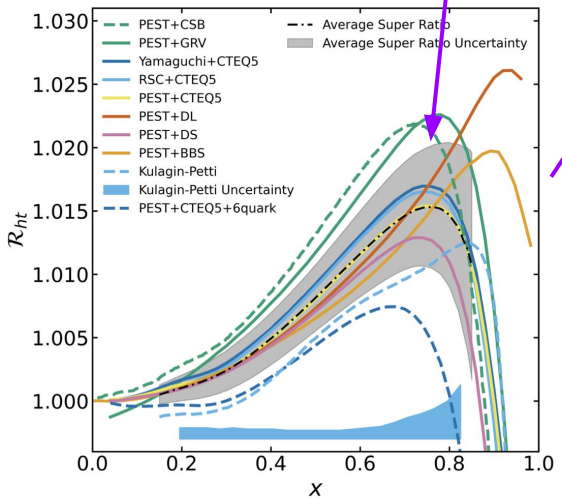


- **AKP has smaller *d/u* but bigger *n/p* ???**
  - Not possible at Leading Twist!
  - → **Large HT contributions to high-*x* *n/p* ratio**

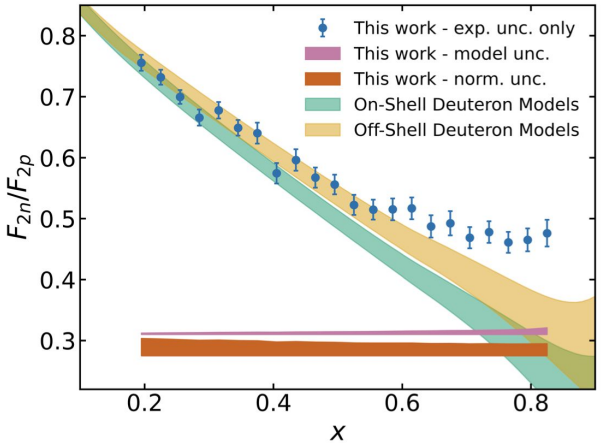
F2 n/p from MARATHON data impact study

T. Hague, et. al., arxiv 2312.13499, NOT a CJ work





Norm. shift: original 2.5%, here 1.3%



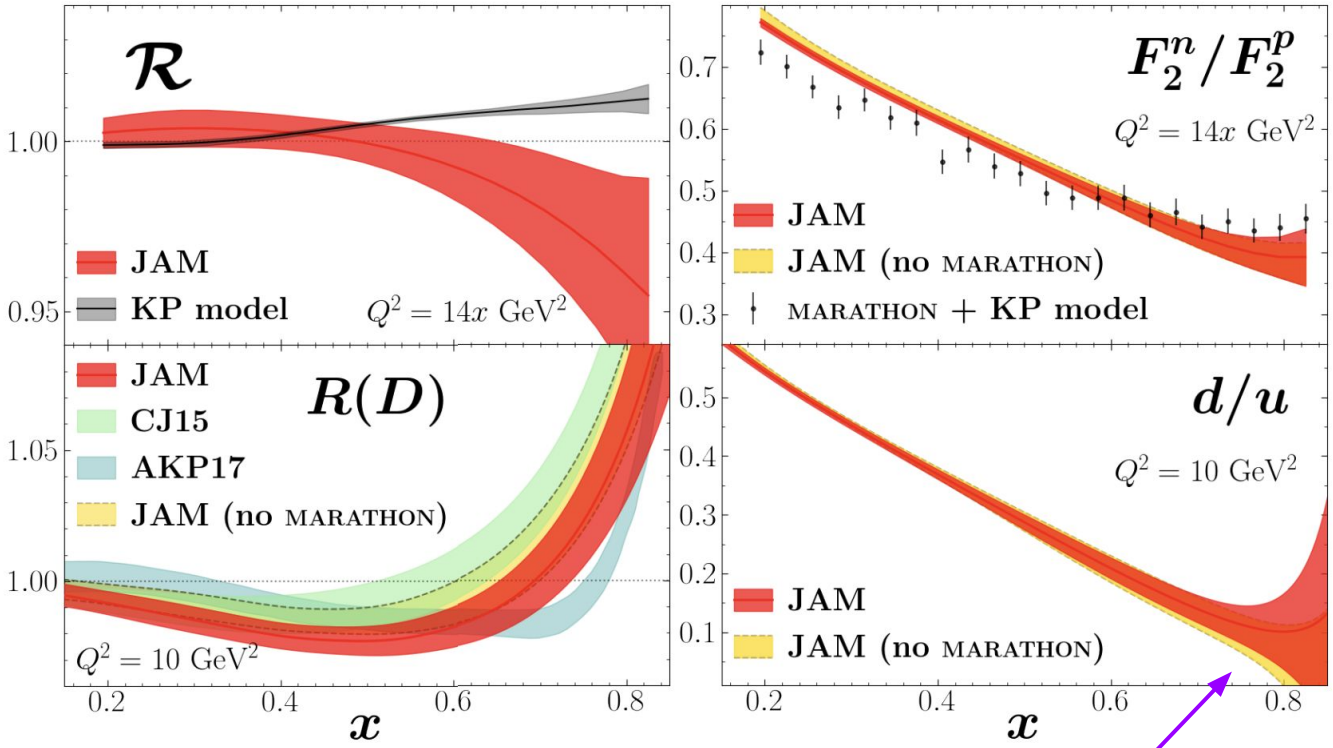
Varying R_{ht} didn't change the n/p shape at high x noticeably:

⇒ n/p is different in deuteron and A=3 nuclei?

⇒ More likely: larger than expected isospin dependence in nuclear effects

Iso-vector nuclear effect?

C. Cocuzza et. al. (JAM), arxiv: 2104.06946



The fit miserably hanging in/between deuteron and A=3 data, still not the full answer

CJ's answer: (very likely) the interplay b/w HT and offshell

HT systematics & offshell corrections

Paper in progress

- **Additive vs. Multiplicative**

$$F_2(x,Q^2) = F_2^{LT}(x,Q^2) + \frac{H(x)}{Q^2}$$

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

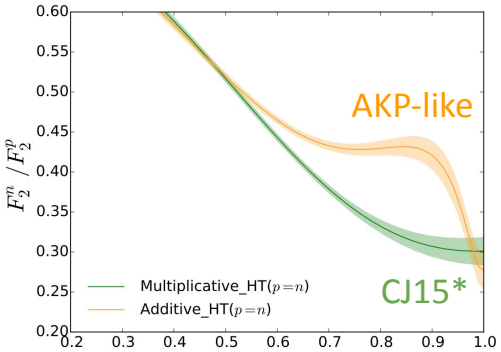
- **Isospin, Q^2 evol. not independent**

$$\widetilde{H}_{p,n}(x,Q^2) = C(x)\, F_{2p,n}^{LT}(x,Q^2)$$

- **Non-negligible large-x bias**

$$\frac{n}{p} \xrightarrow[x\to 1]{} \begin{cases} \frac{1}{4} + 3\,\frac{H}{u} & \text{add. } p = n \\ \frac{1}{4} + \frac{H}{u} & p \neq n \\ \frac{1}{4} & \text{mult. } p = n \end{cases}$$

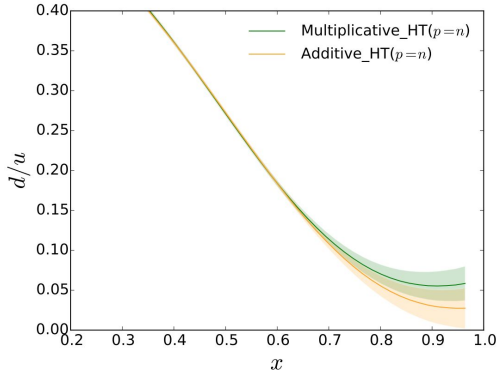
- With the same CJ15 data sets, no A=3 data

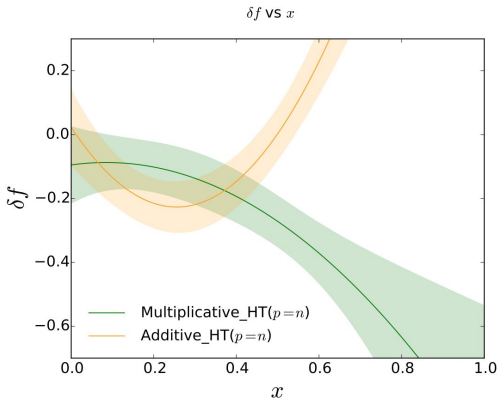


Isospin symmetric HT

Additive HT (p=n)

Mult HT (p=n)
→ CJ15*





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HT systematics & offshell corrections

- **Additive vs. Multiplicative**

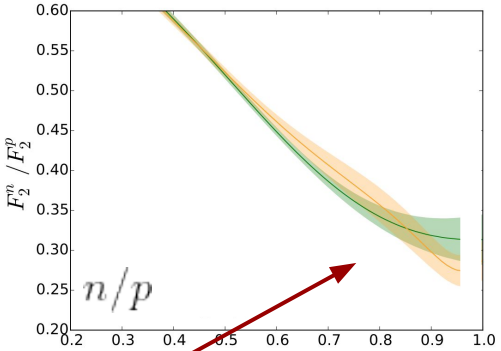
$$F_2(x,Q^2) = F_2^{LT}(x,Q^2) + \frac{H(x)}{Q^2}$$

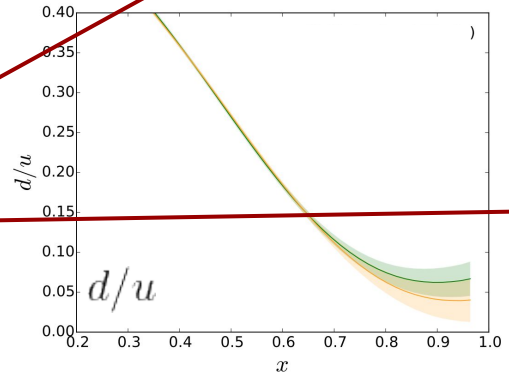
$$F_2(x,Q^2) = F_2^{LT}(x,Q^2)\left(1 + \frac{C(x)}{Q^2}\right)$$

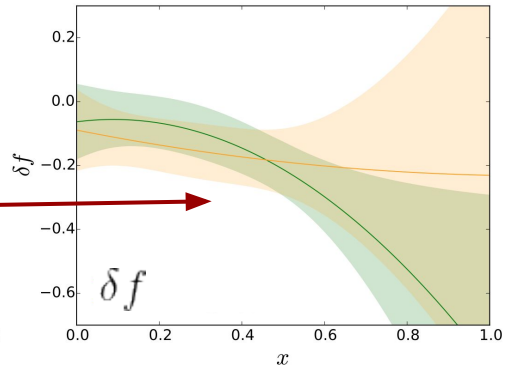
- **Isospin, Q^2 evol. not independent**

$$\widetilde{H}_{p,n}(x,Q^2) = C(x)\, F_{2p,n}^{LT}(x,Q^2)$$

- **Isospin dependent HT:**
  - **BIAS REMOVED!**
  - Very small change in d/u
  - Offshell remains ~ 0 up to x=0.6







Isospin dependent HT

Additive HT (p≠n)

Mult HT (p≠n)

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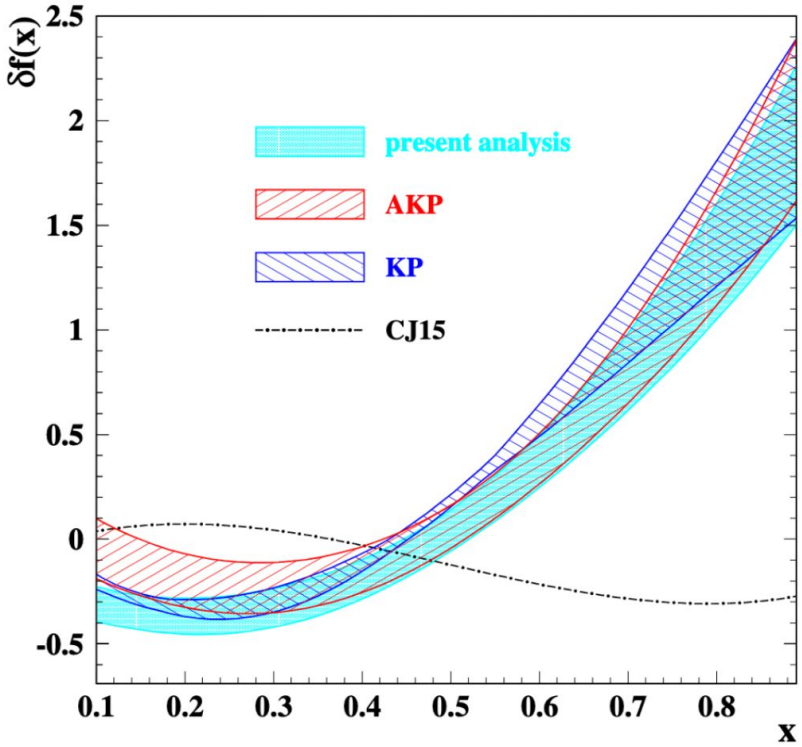

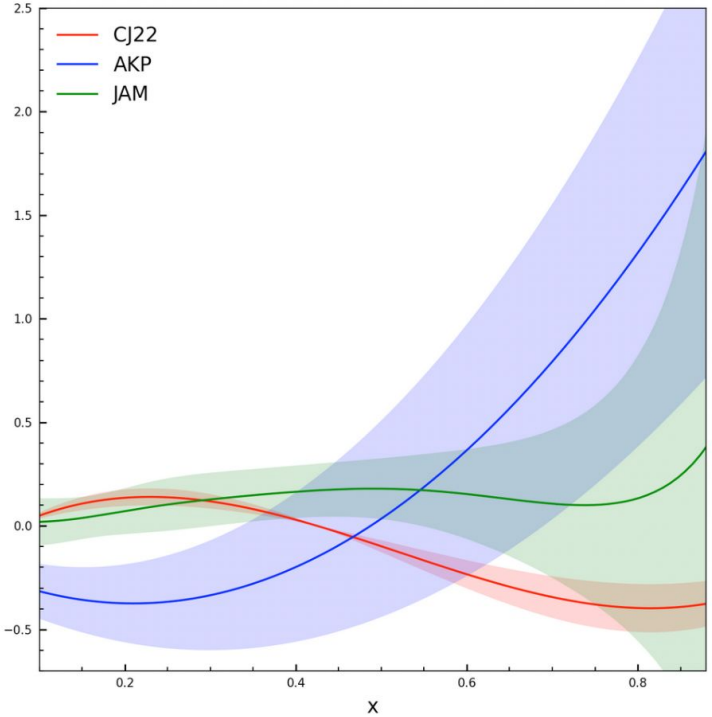

AKP: https://arxiv.org/pdf/2203.07333.pdf
Polynomial paramterization,
$c_0 = -0.16 \pm 0.11$, $c_1 = -2.04 \pm 0.73$, and $c_2 = 4.86 \pm 1.13$

KP-like off-shell function parameters:
$N(x - x_0)(x - x_1)(1 + x_0 - x)$

Parameter	CJ15	CJ22
N	-3.6735 ± 1.5278	-5.3600 ± 1.5674
x_0	0.57717E091 ± 0.14842E-01	0.70549E-01 ± 0.44990E-03
x_1	0.36419	0.42527

Bonus cross-checks

- **BONuS: Tagged proton DIS** measurements