Neutron F2 Extraction and Applications with CJ Global Analysis

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with many thanks to my CTEQ-JLab collaborators:
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arXiv:2309.16851

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Extraction of the neutron F2 structure function from inclusive proton and deuteron deep-inelastic scattering data

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The available world deep-inelastic scattering data on proton and deuteron structure functions F2p, F2d, and their ratios, are leveraged to extract the free neutron F2n structure function, the F2n/F2p ratio, and associated uncertainties using the latest nuclear effect calculations in the deuteron.Special attention is devoted to the normalization of the proton and deuteron experimental datasets and to the treatment of correlated systematic errors, as well as the quantification of procedural and theoretical uncertainties. The extracted F2n dataset is utilized to evaluate the Q2 dependence of the Gottfried sum rule and the nonsinglet F2p - F2n moments. To facilitate replication of our study, as well as for general applications, a comprehensive DIS database including all recent JLab 6 GeV measurements, the extracted F2n, a modified CTEQ-JLab global PDF fit named CJ15nlo_mod, and grids with calculated proton, neutron and deuteron DIS structure functions at next-to-leading order, are discussed and made publicly available.

CJ Global QCD fits

See A. Accardi's DIS2023 talk
https://indico.cern.ch/event/1199314/contributions/5193086/

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

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

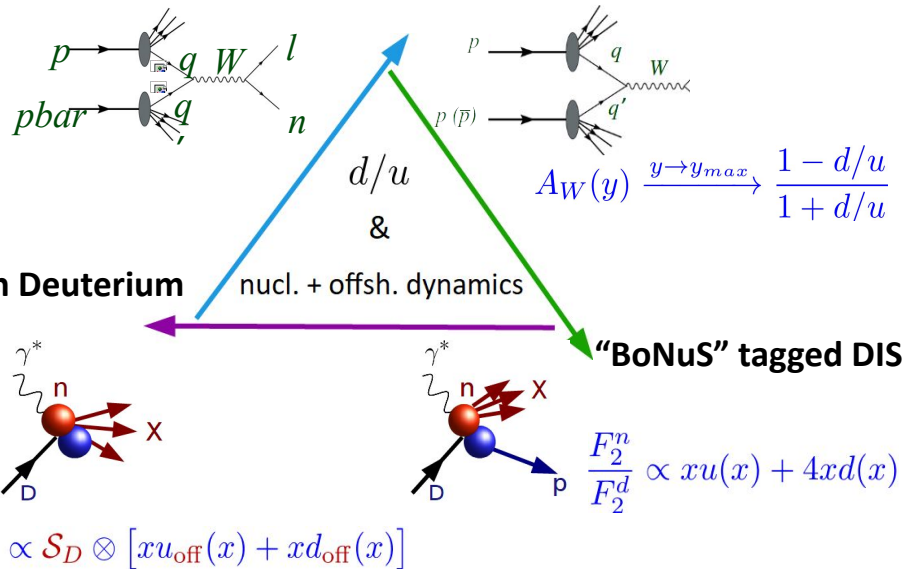
pQCD calc.

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

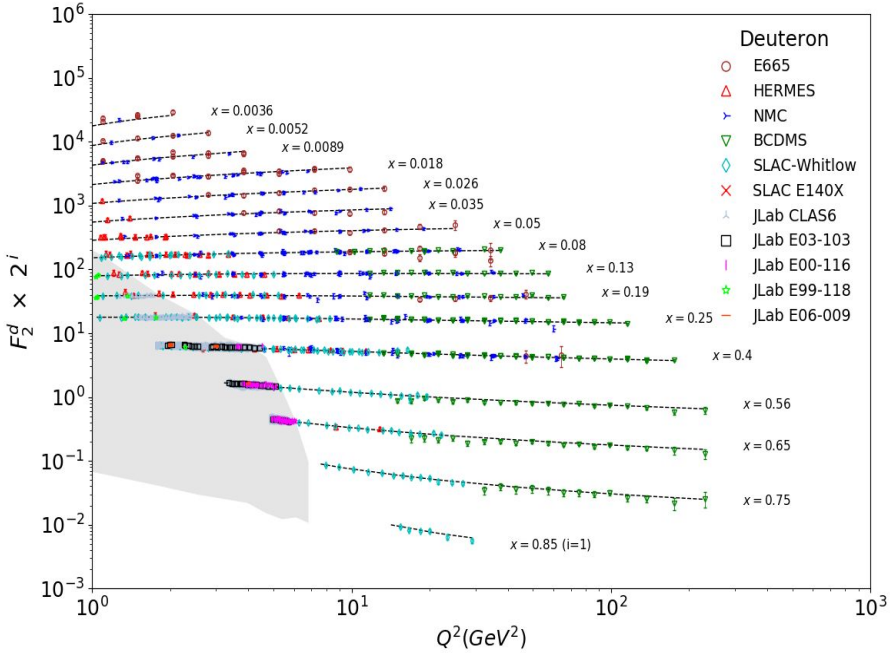


CJ Global QCD fits

CJ15: *Phys.Rev.D* 93 (2016) 11, 114017

- 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

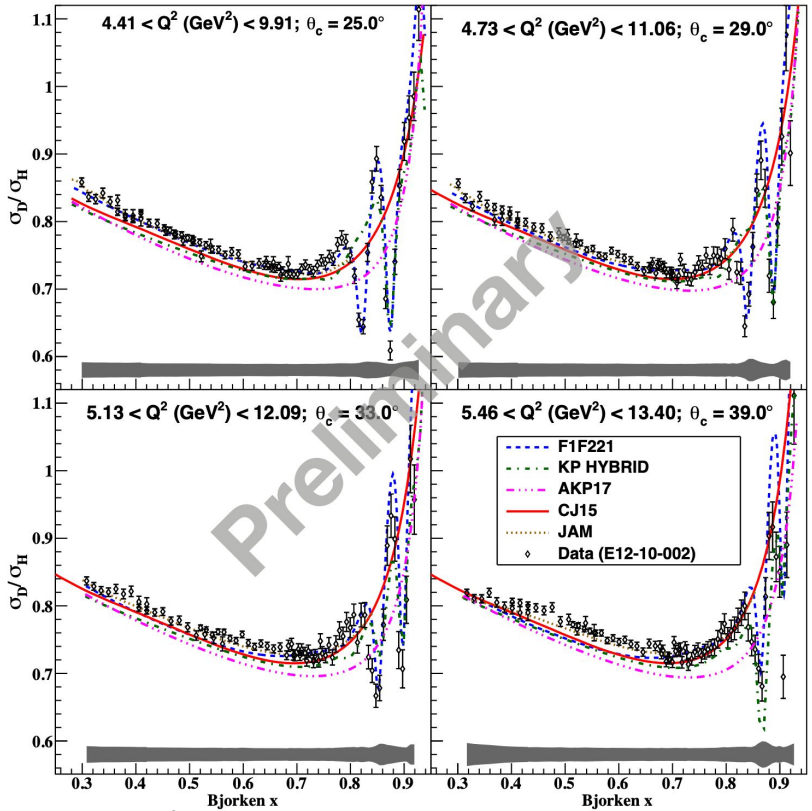
Nucleon wave function

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

Impact of Large-x Deuteron Data

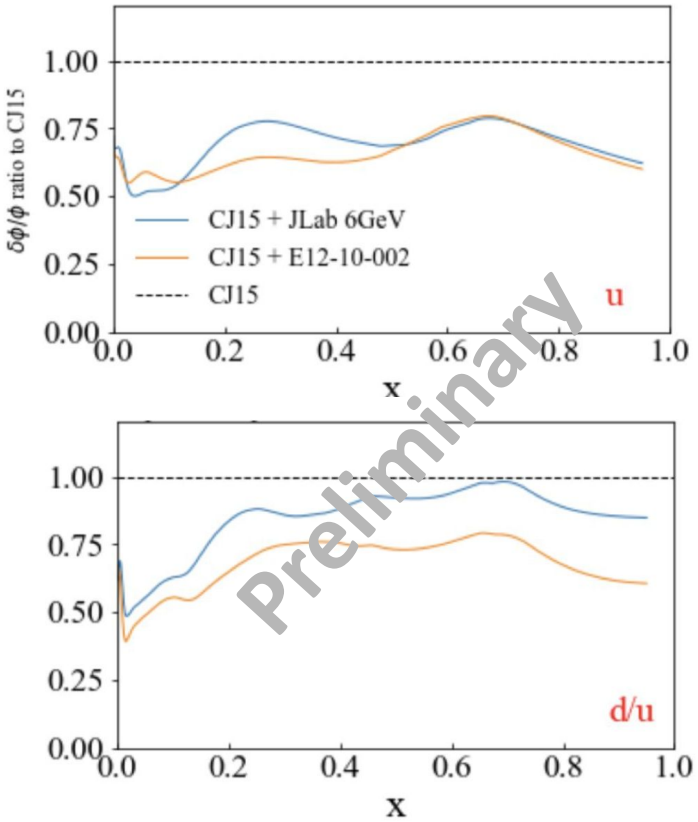
"Power of precision"

JLab E12-10-002 data



Courtesy of Bill Henry

Impact on PDF uncertainties



Neutron F_2 Extraction

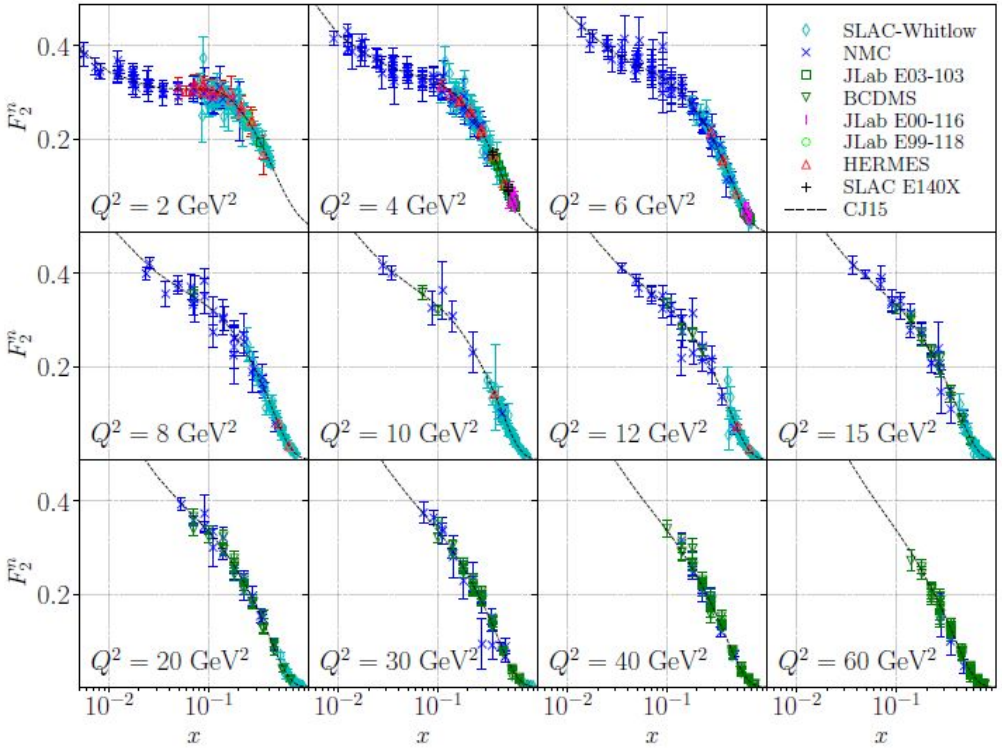
Reference: S. Li et. al. arXiv:2309.16851

Combined F2 datasets available at https://github.com/JeffersonLab/CJ-database/

- **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
    - ⟶ using CJ15 PDFs
    - ⟶ refitting norm, Correlated shifts
  - Bin-centering for Isosinglet moment
  - …



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

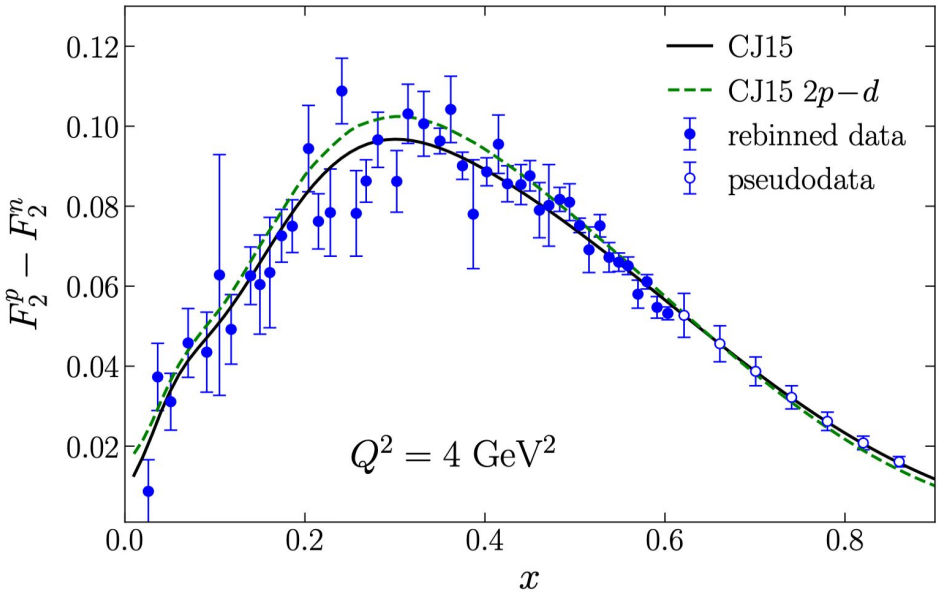
# fit parameters		
LAMBDA	0.22680	0.0000
a0uv	2.4067	0.0000
a1uv	0.61537	0.19856E-01
a2uv	3.5433	0.12414E-01
a3uv	0.0000	0.0000
a4uv	3.4609	0.42903
a5uv	0.0000	0.0000
a0dv	24.684	0.0000
a1dv	1.1595	0.33533E-01
a2dv	6.5514	0.15936
a3dv	-3.5030	0.86332E-01
a4dv	4.6787	0.14209
a5dv	0.0000	0.0000
a0ud	0.14658	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

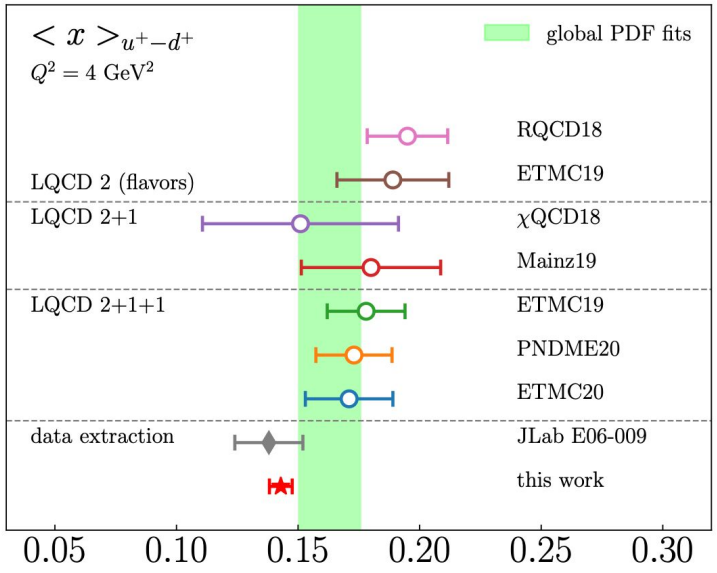
Application: non-singlet moments

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

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

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





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 unploarized 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`

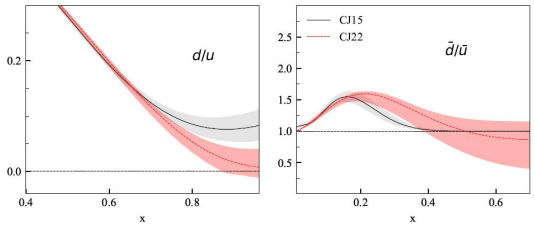
Outlook

- **Coordinated Theory-Experiment Effort with Jefferson Lab:**
  - A. Accardi, **Xiaoxian Jing**, **Ishara Fernando**, W.Melnitchouk, J.F.Owens
  - C.E. Keppel, **Shujie Li**, P. Monaghan, **Sanghwa Park**

- **Focus and recent work:**
  - Large-x, low-Q^2 $\longrightarrow$ TMC, HT
  - Nuclear dynamics $\longrightarrow$ p,n motions, off-shell PDFs

  } *Accardi et al.,PRD 93 (2016) 114017* **CJ15**

  - New light antiquark parameterization **CJ22** *Accardi et al., Phys. Rev. D 107, 113005*
    (S. Park, X. Jing)
  - F2(n) extraction, updated uncertainties and deuteron smearing *S. Li et. al. arXiv:2309.16851*
    (S. Li, I. Fernando)
  - [In progress: isospin-dependent HT and offshell effect]
  - [In progress (S. Park)
    $\longrightarrow$ Strange sea with LHC data]



Thank you!