Parton and nuclear dynamics at large x: the CJ26 global QCD analysis

Alberto Accardi

Paper → coming soon, arXiv:2605.xxxx
LHAPDF grids → https://www.jlab.org/theory/cj/pdfs
Structure Function grids → soon, same link

DIS 2026 - Bologna, Italy

Jefferson Lab

Christopher Newport University
School of Engineering and Computing

CTEQ-Jefferson Lab Collaboration

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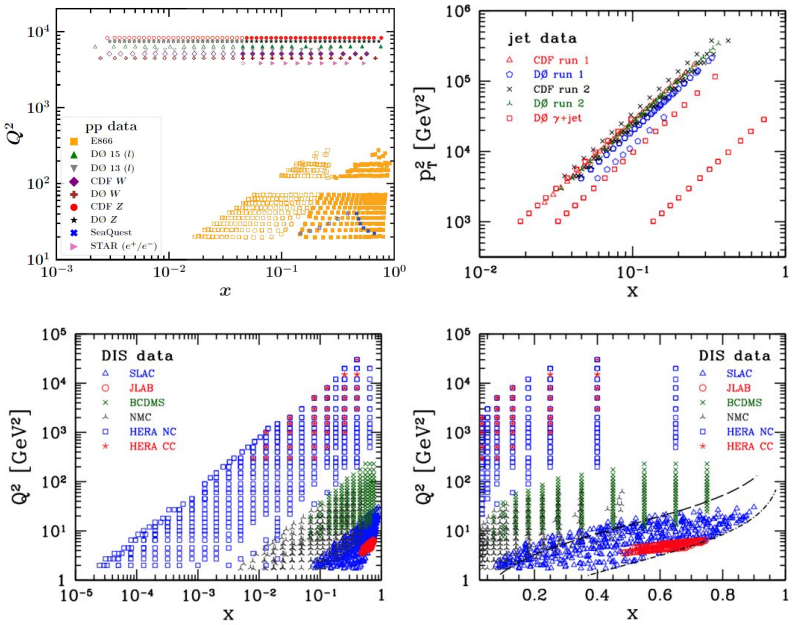
The CTEQ-JLab collaboration

- **Coordinated Theory-Experiment Effort with Jefferson Lab:**
  - A. Accardi, **Matteo Cerutti**, X. Jing, I. Fernando, W. Melnitchouk, J.F.Owens, **Peter Risse**
  - C.E. Keppel, **Shujie Li**, P. Monaghan, **Sanghwa Park**

- All-x PDFS
  - Focus: **large *x*, nuclear dynamics**
  - State-of-the-art **baseline w/o LHC data**

- **Maximize use of low-Q^2 DIS data**
  - SLAC, **full JLab 6, JLab 12** **(this talk)**

- **Power corrections:** Target mass, HT
  Deuteron: binding and Fermi motion, offshell nucleon dynamics



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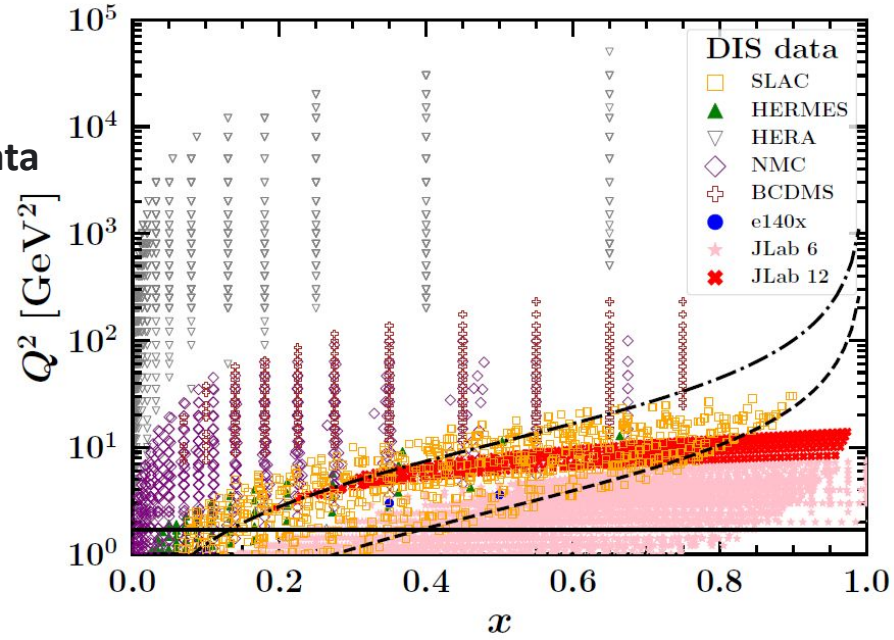
1024 JLab DIS points!



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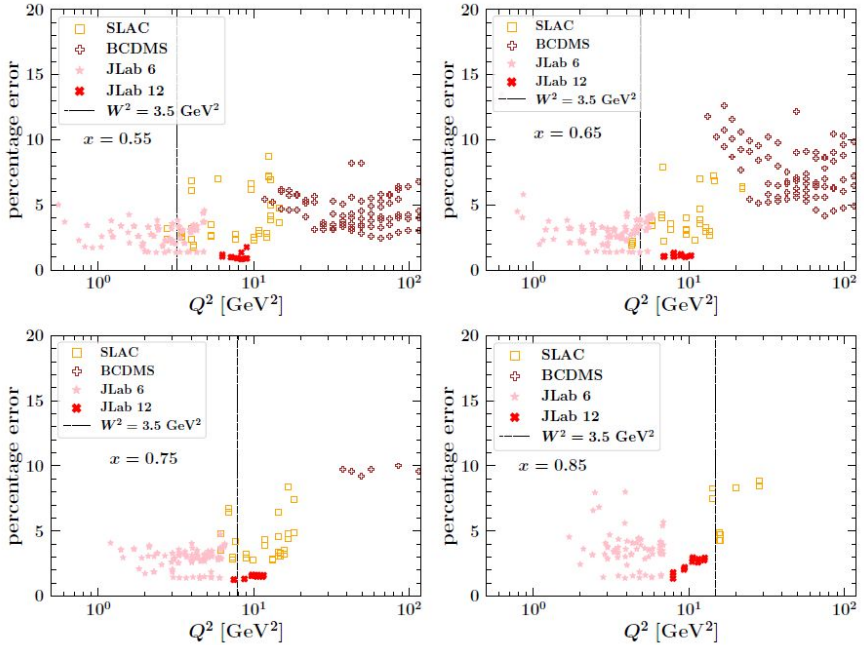
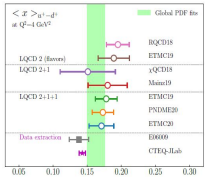


Recent history

Data-driven extraction of $F_2(n)$ and $\langle x \rangle_{u^+ - d^+}$



CJ15 → **CJ15ht** and **CJ15sfn** ↔ **CJ-JAM DIS database**

PRD 93 (2016) 114017

PRD 109 (2024) 074036

github.com/JeffersonLab/CJ-JAM-database

CJ22 → **CJ22ht** →

PRD 107 (2023) 113005

PRD 111 (2025) 094013

This talk:

CJ26 and **CJ26sfn**

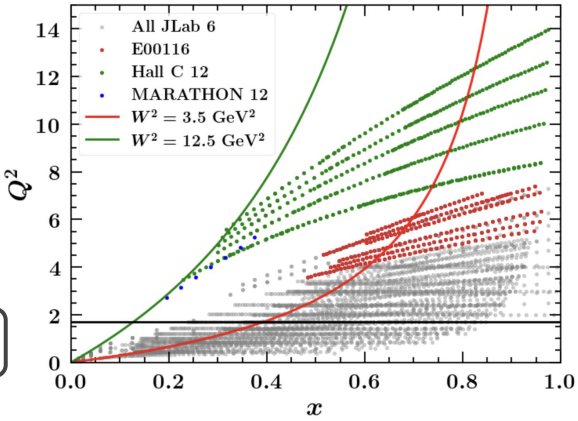
Theoretical + parametrization systematics

JLab 6 & 12 data:

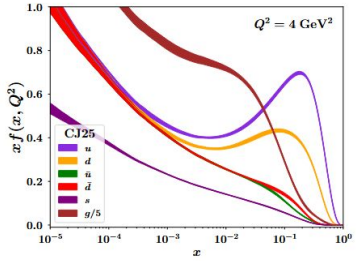
LT / HT separation up to x=0.8

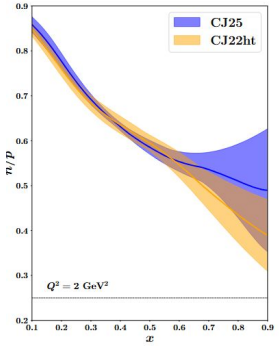
offshell dynamics up to x=0.7

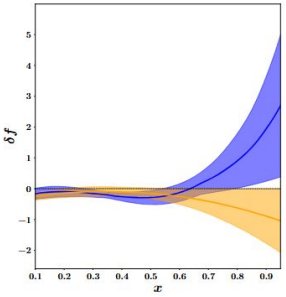
→ precise and accurate d/u , n/p, HT(p,n)



The CJ26 fit

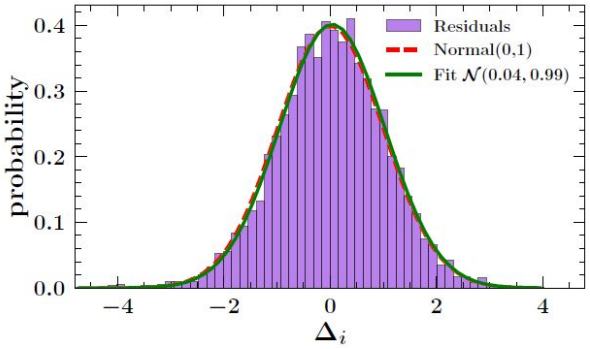

$Q^2 = 4$ GeV^2
CJ25
u
d
$\bar{u}$
$\bar{d}$
s
$g/5$
$xf(x, Q^2)$
x

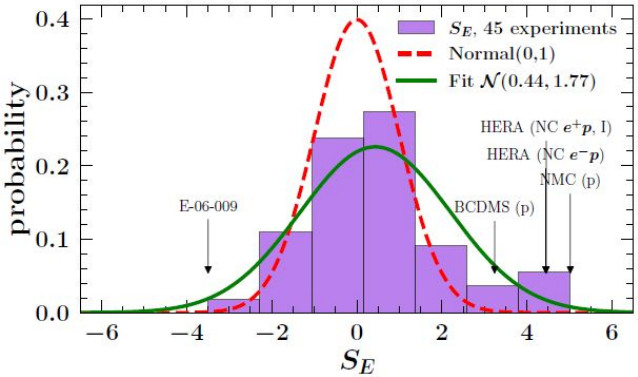

CJ25
CJ22ht
$Q^2 = 2$ GeV^2
n/p
x


δf
x

CJ26 fit quality

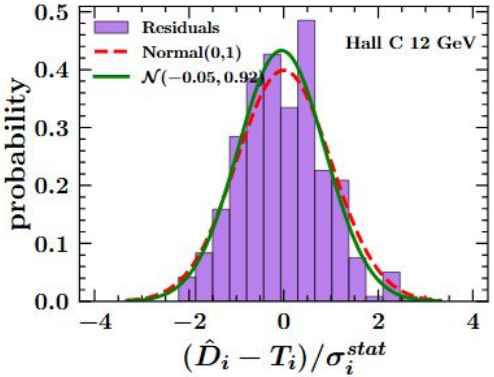
- **Good fit quality overall,** $\chi^2 = 1.10$ with known tensions

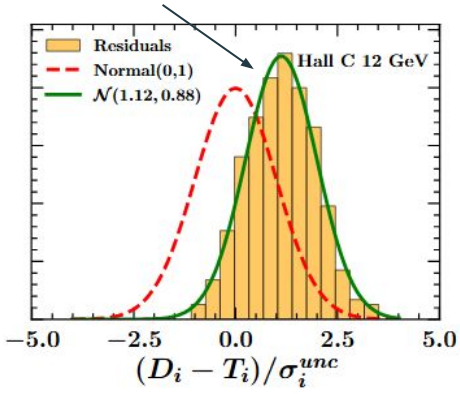




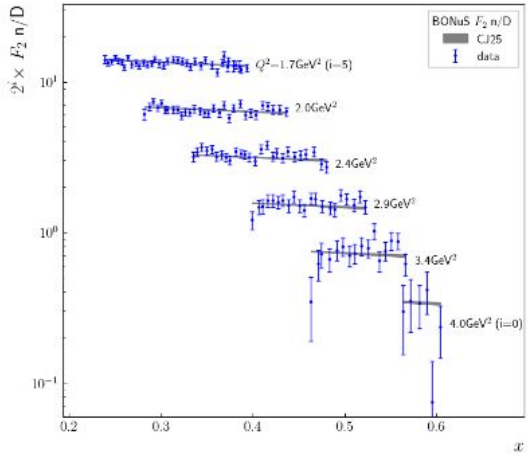
- **Point-to-point correlated systematics:**
  Include when available!

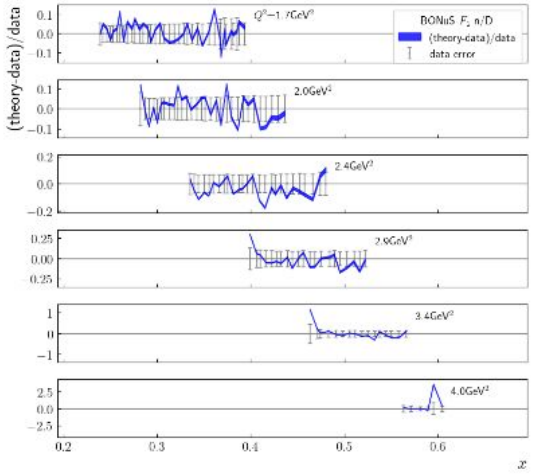
fit <u>without</u> correlated uncert.



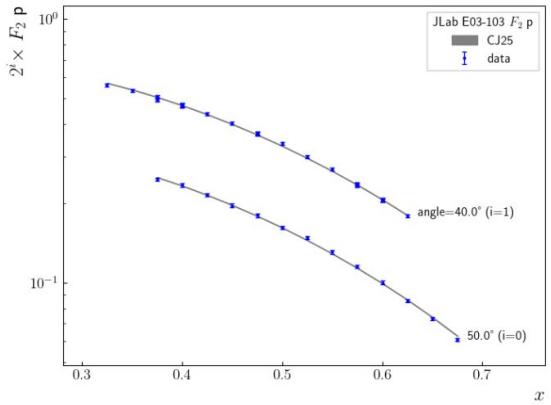


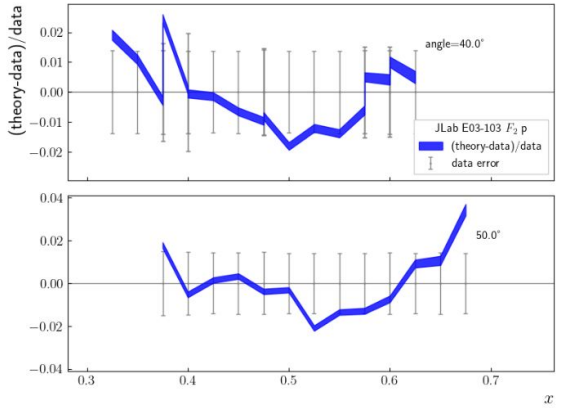
JLab 6 - selected data





BONuS: tagged $F_2(n)/F_2(d)$

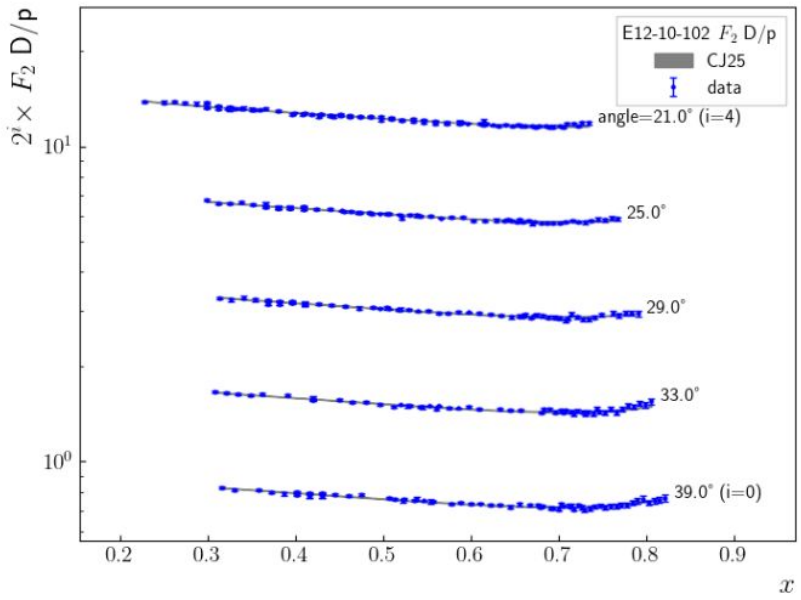


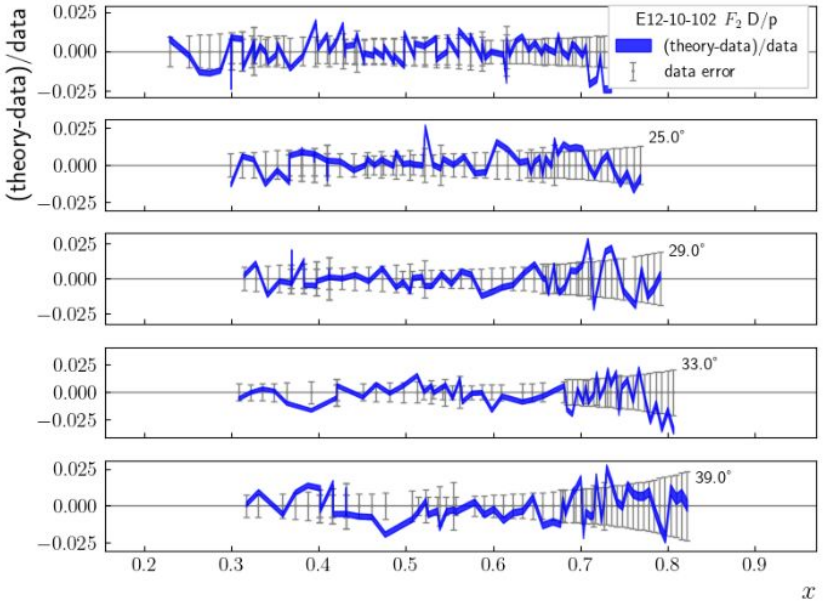


E03-103: inclusive $F_2(p)$

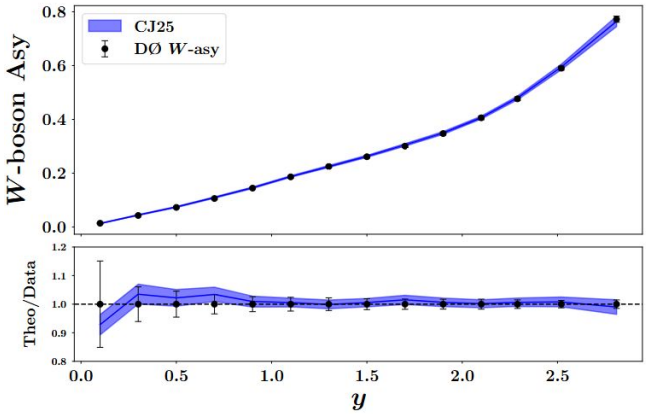
JLab 12: selected data

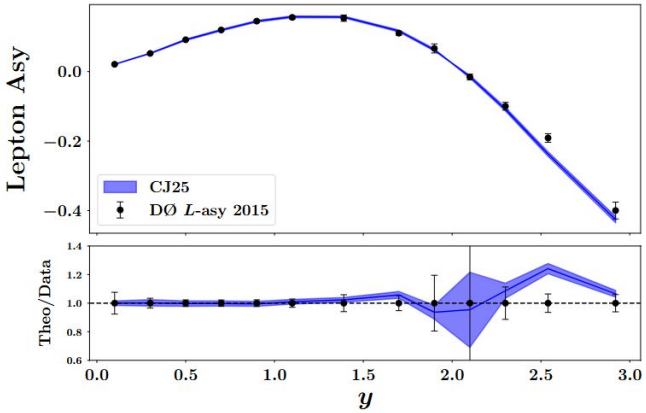
E12-10-102: inclusive $F_2(p)/F_2(d)$ ratio



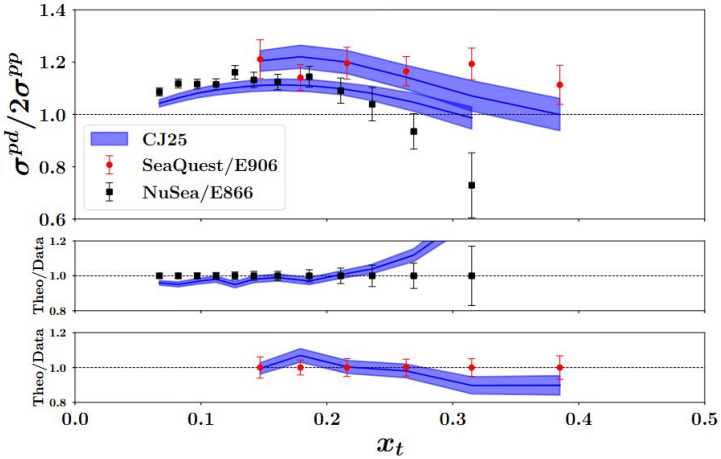


Electroweak processes





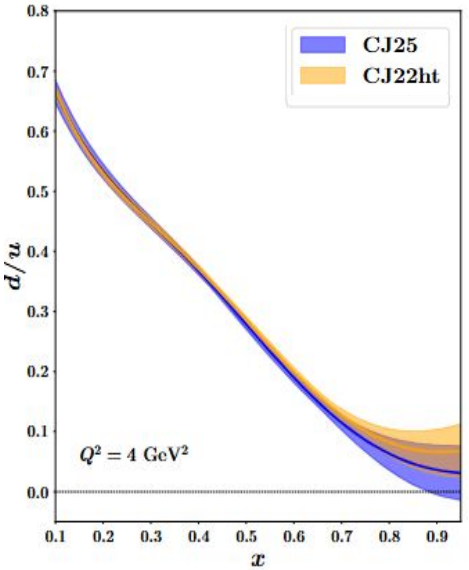
DØ: W asymmetry (left)
and decayed lepton asymmetry (right)



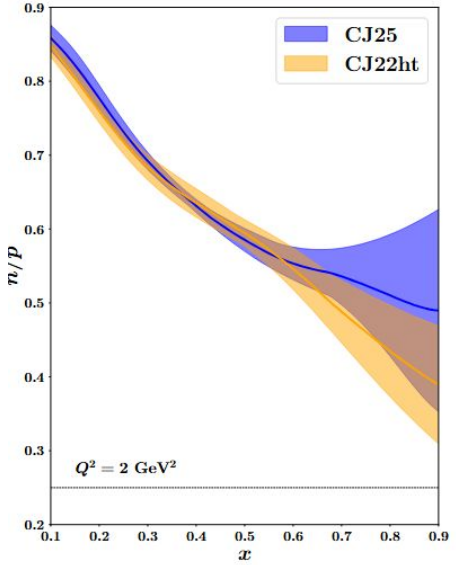
SeaQuest and **E866**:
Drell-Yan d/p cross section ratios
(ask us for CJ26 cross sections!)

CJ26 vs. CJ22ht

- "Statistical" uncertainty bands: adjusted Hessian T=1.646
  - Includes nodel HT and off-shell parameter uncertainty
- HT systematics: envelope of multiplicative and additive HT implementation

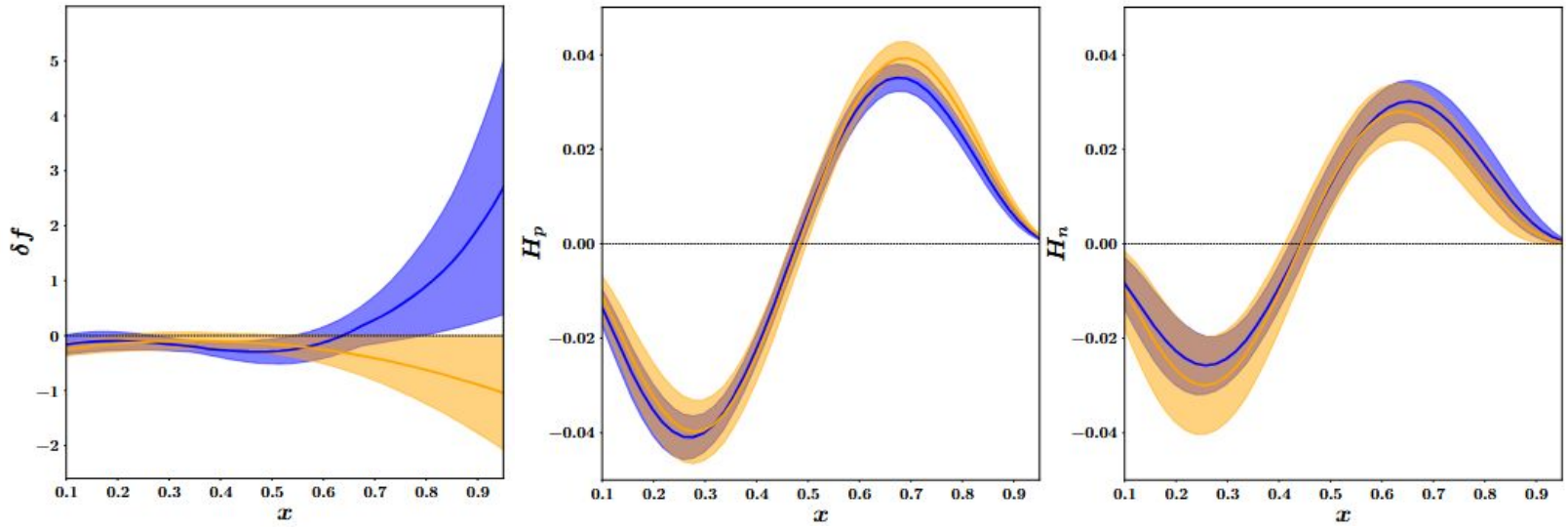


large power corrections!



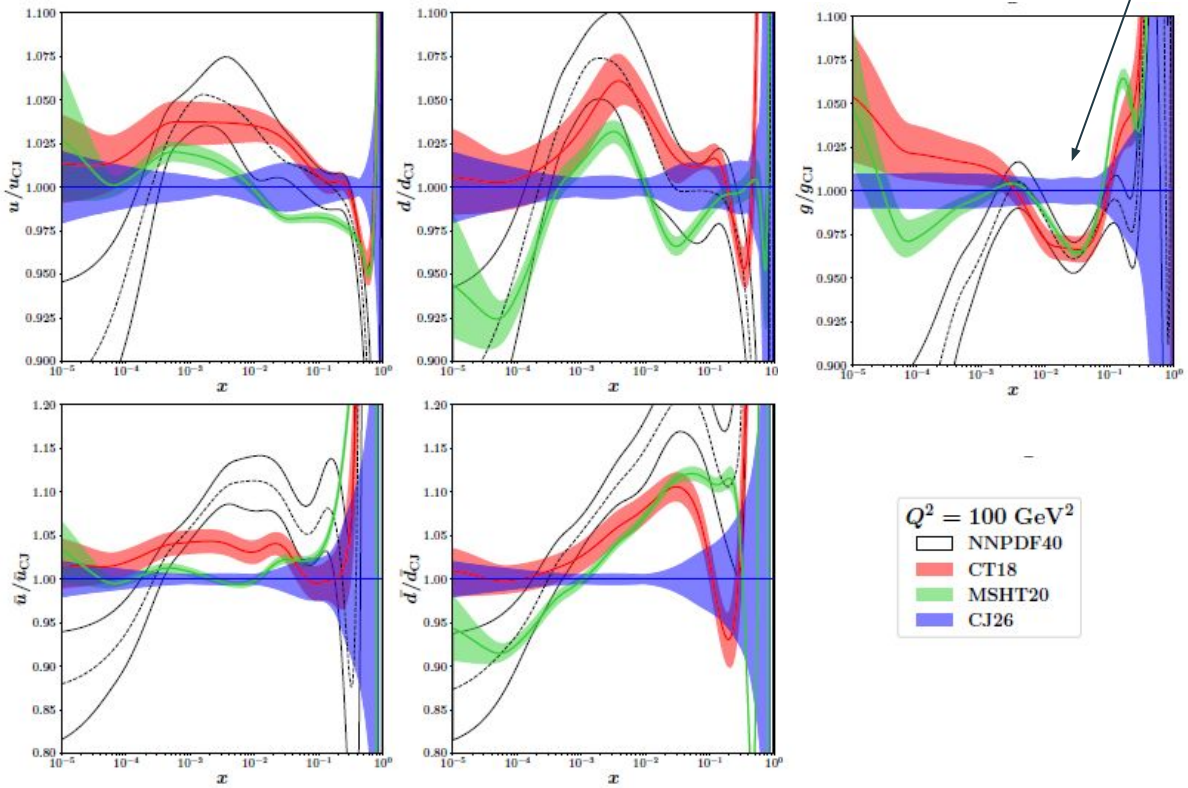
CJ26 vs. CJ22ht

- Offshell now convex (3rd order vs. 2nd polynomial parametrization) – as in AKP 17
- Proton HT smaller, neutron larger at high x ⟶ higher n/p



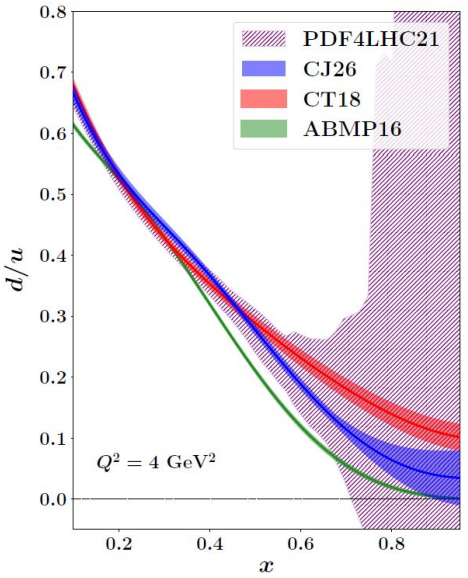
CJ26 vs. rest of the world

- Significant tensions between different analyses



indirect effect of nuclear corrections!

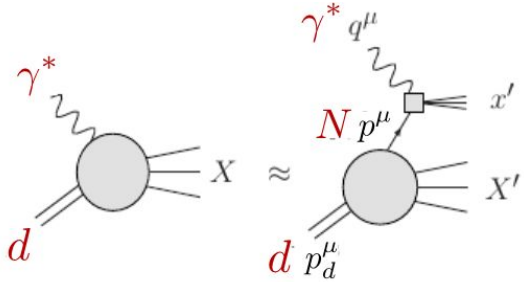
EPJC 81 (2021) 603



Theoretical systematics

Deuteron target

- **Weak binding approximation:**
  - Incoherent scattering from not too fast nucleons, neglect FSI



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

kinematic and "flux" factors

Nucleon wave function

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

- **Offshell expansion** (in bound nucleon's p^2)

$$F_{2N}(x,Q^2,p^2) = F_{2N}^{\text{free}}(x,Q^2)\left[1 + \frac{p^2 - M^2}{M^2}\delta f(x)\right]$$

Free proton, neutron structure function

"offshell function"

Deuteron target

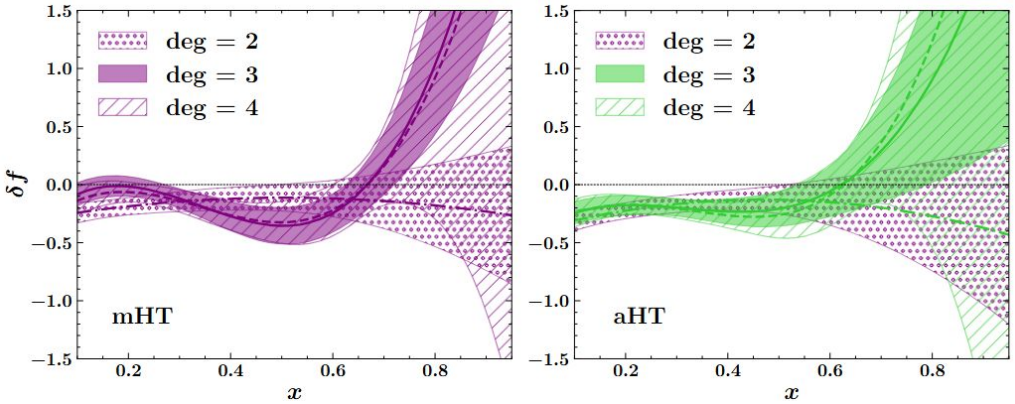
- **Offshell corrections**

$$q_N(x,Q^2,p^2) = q_N^{\text{free}}(x,Q^2)\left[1+\frac{p^2-M^2}{M^2}\delta f(x)\right]$$

  - CJ15 & 22: $\delta f^N = C(x-x_0)(x-x_1)(1+x_0-x)$

    + valence quark sum rule $\int_0^1 dx\,\delta f^N(x)\,[q(x)-\bar{q}(x)] = 0$

  - CJ22ht & CJ26: $\delta f(x) = \sum_n a_{off}^{(n)} x^n$ flexible polynomial



1. **Need at least n=3**
2. **JLab data constrain δf up to x < 0.7**
3. **Convexity required by data (n=2 concavity is artificial)**

HT systematics

- **HT modeling**
  - Additive $F_2(x,Q^2) = F_2^{LT}(x,Q^2) + \frac{H(x)}{Q^2}$
  - vs.
  - Multiplicative $F_2(x,Q^2) = F_2^{LT}(x,Q^2)\left(1 + \frac{C(x)}{Q^2}\right)$

  → **CJ26**: Isospin dependent

- **Isospin and Q^2 assumptions are not independent**

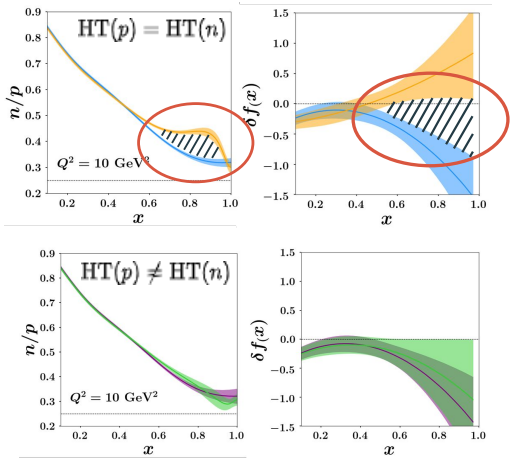
$$\widetilde{H}_{p,n}(x,Q^2) = C(x)\, F_{2p,n}^{LT}(x,Q^2)$$

- **With 1000 JLab DIS data can <u>fit HT(p) & HT(n)</u>**

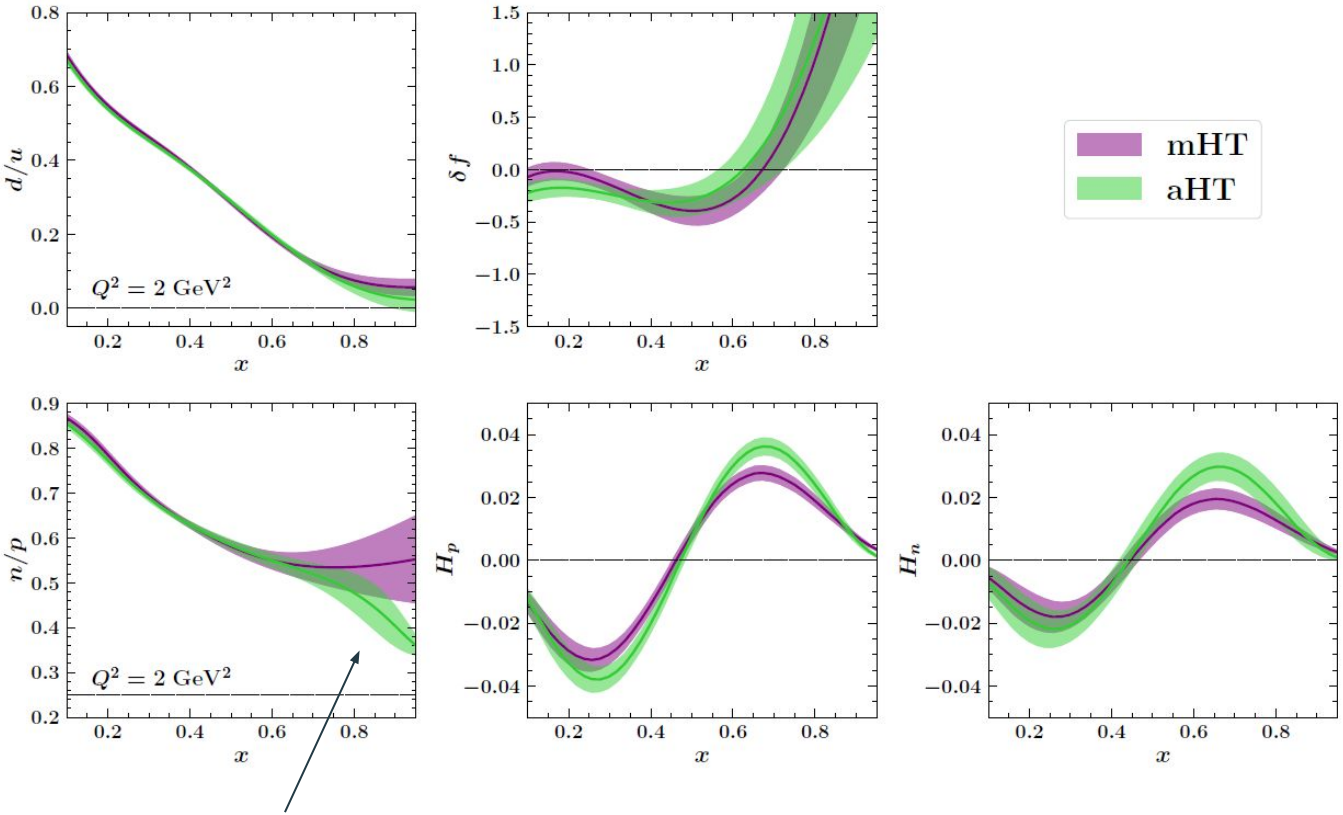
  …and avoid parametrization bias

  ⟶ Multiplicative p=n (CJ15) underestimates

  ⟶ Additive p=n (AKP17) overestimates



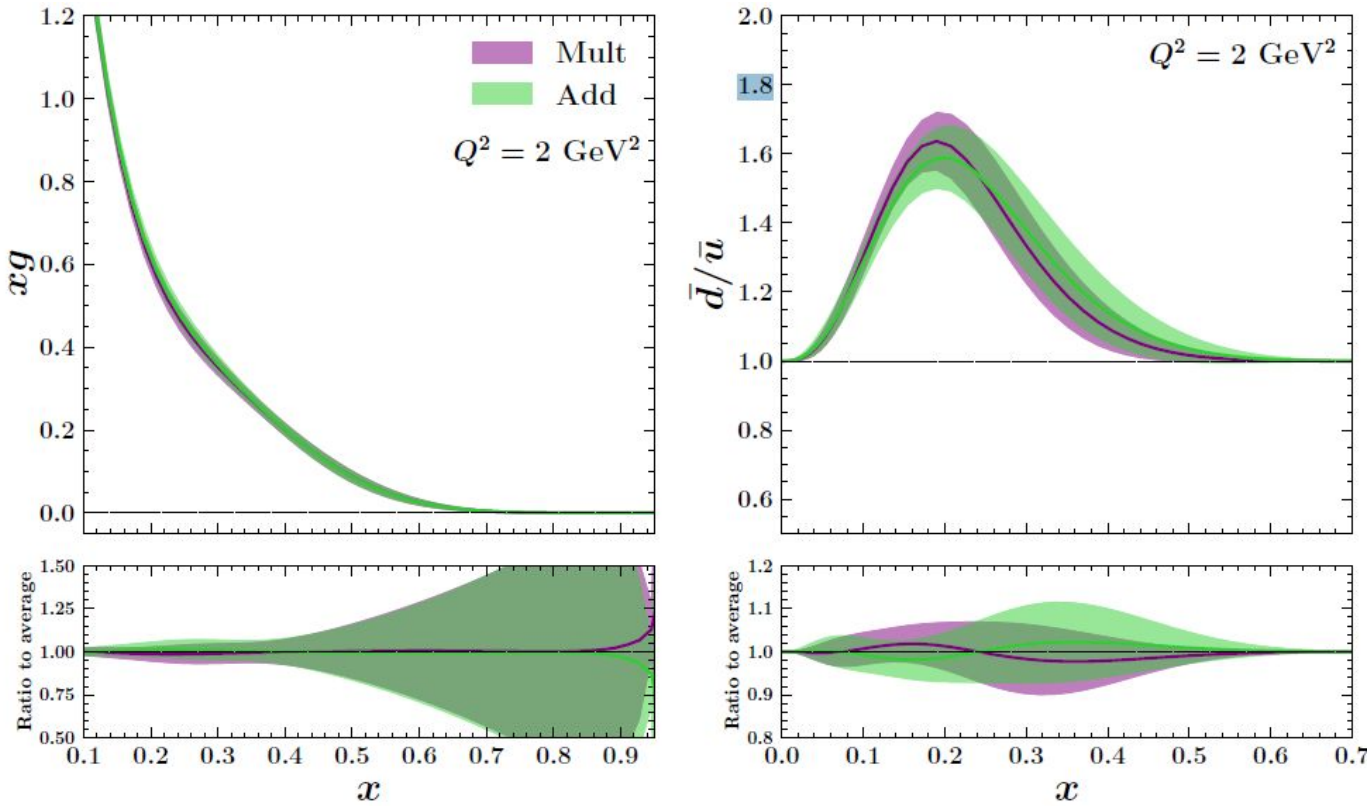
HT systematics



Remaining implementation bias: detects x>0.8 extrapolation region

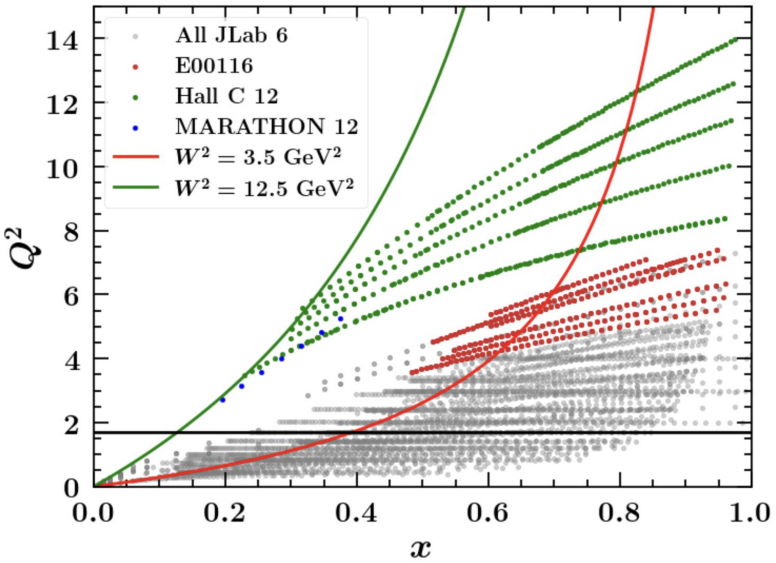
$$H(x) \to 0 \text{ as } x \to 1$$

Gluons and sea quarks



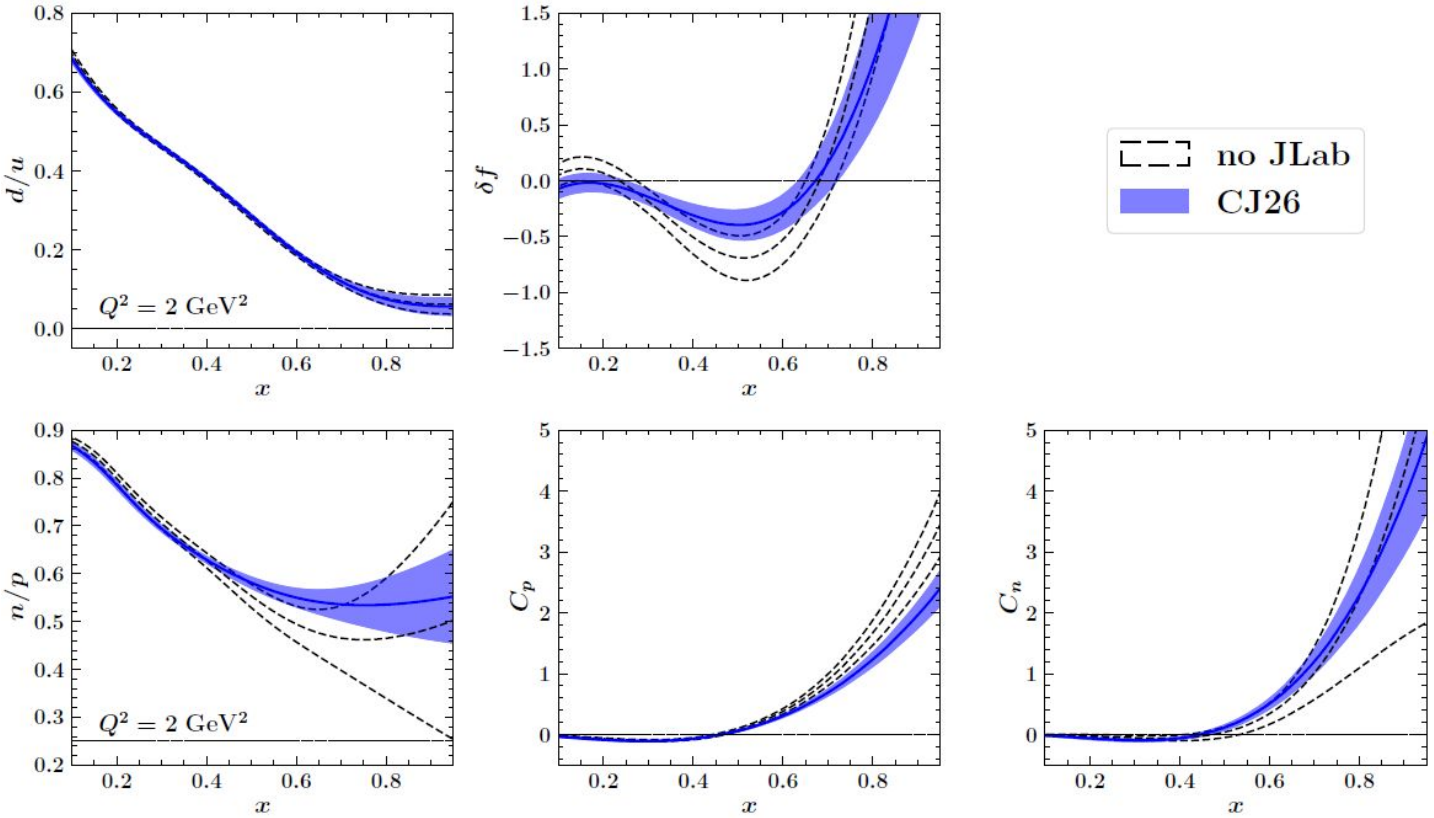
Impact of full JLab DIS data

for the first time in a global fit!

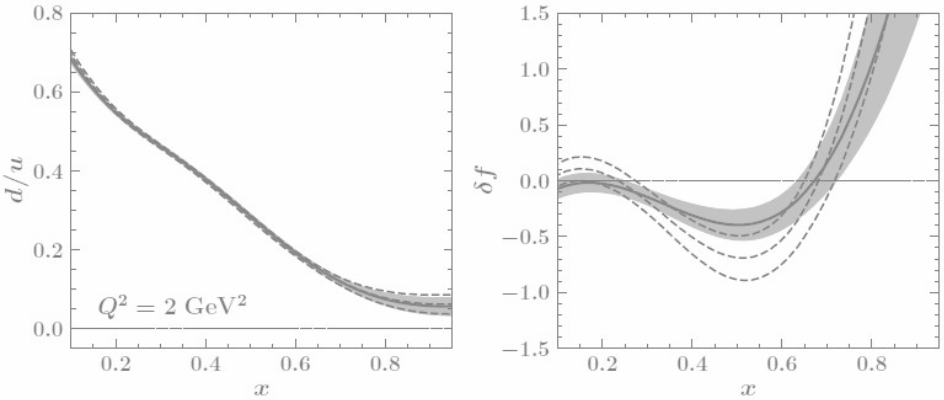


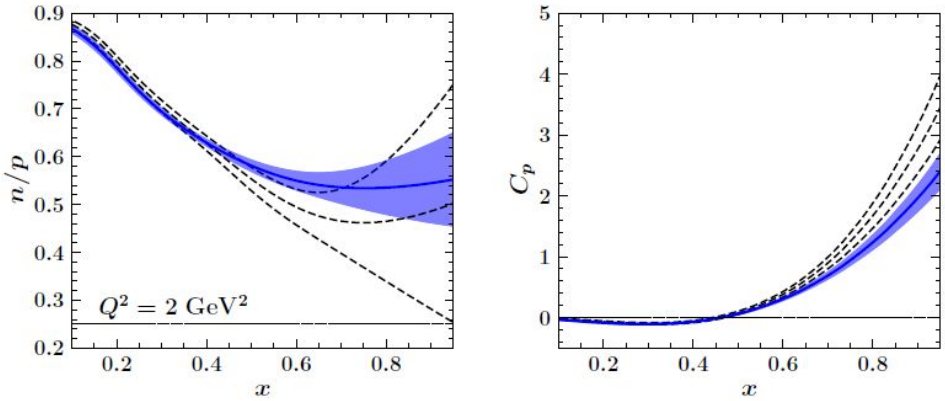
Leading vs. higher twist physics

Note: using only multiplicative HT for clarity



Take away (simplifying a little bit)

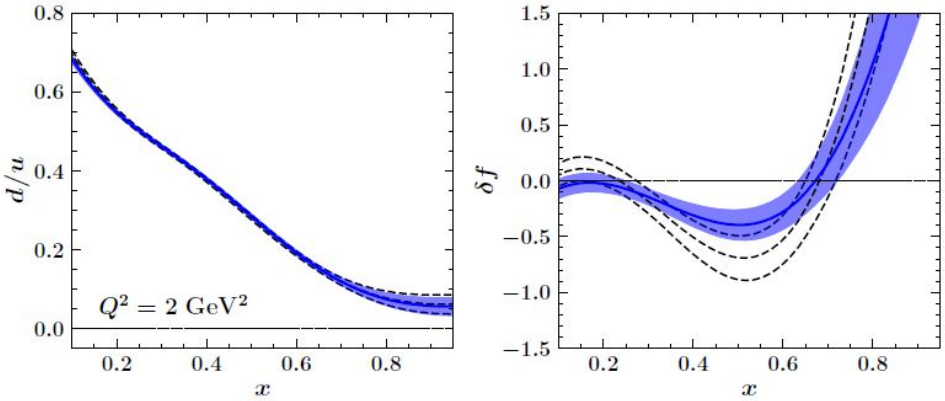




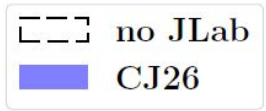
(1) JLab 6 data

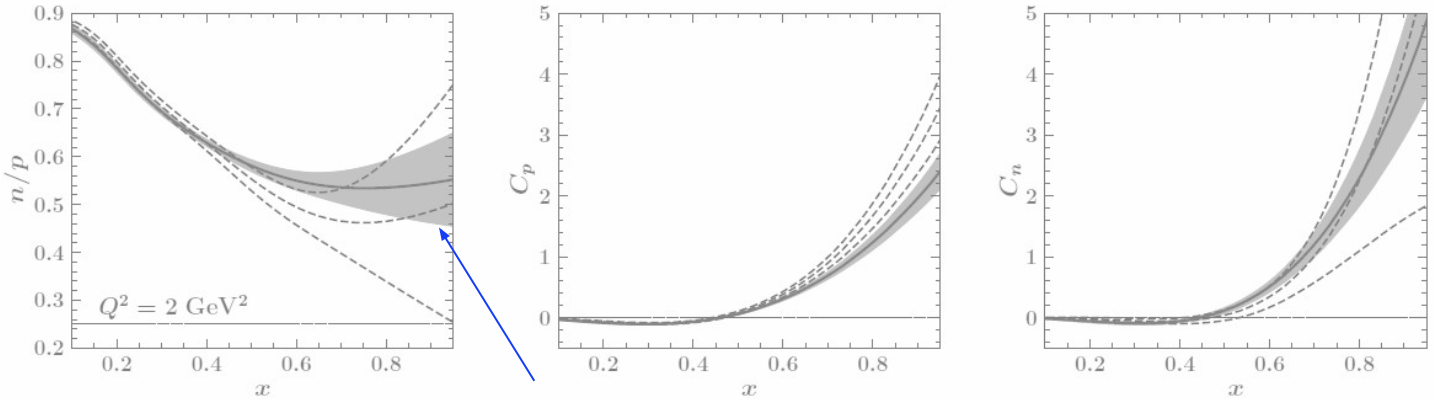
constrain the HT effects

Take away (simplifying a little bit)



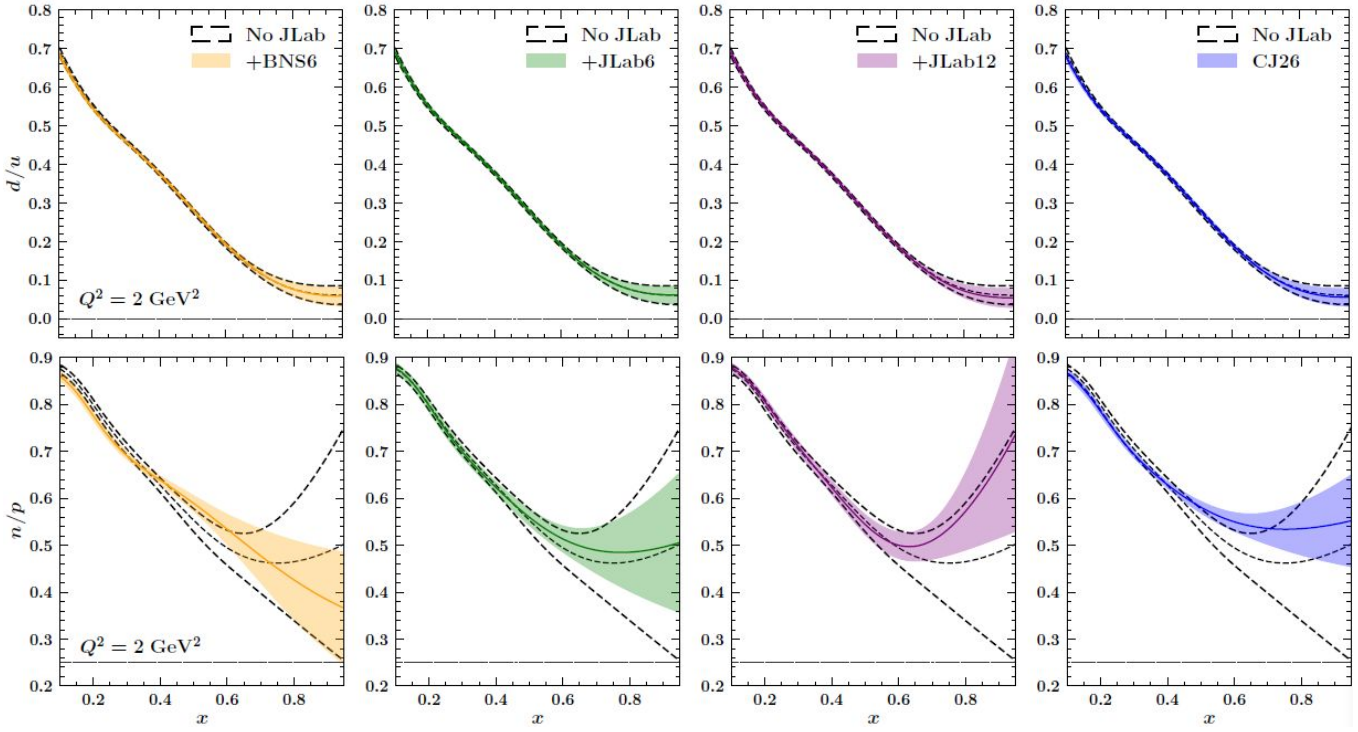
(2) JLab 12 data: expand Q2 range, & **constrain LT partonic physics**



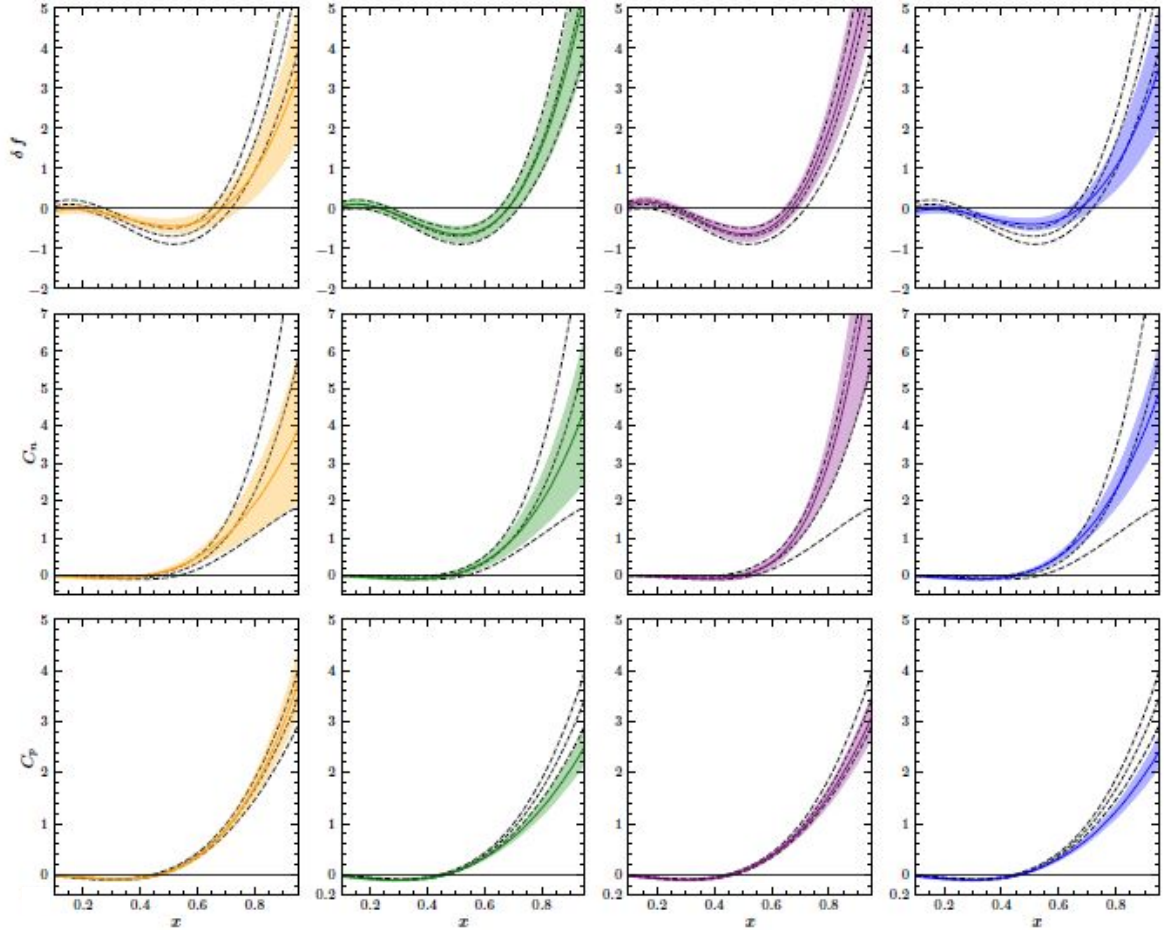


(3) …and confirm large HT effects!

In more detail - d/u and n/p ratios



In more detail - offshell and higher twists



Conclusions and perspective

Summary and perspective

- **JLab provides large-x reach for quarks**
  - But low-Q^2

- **TMC, HT, nuclear corrections**
  - Need to be addressed carefully
  - Assess interplay, implementation biases and uncertainties
  - Extract rich (nuclear) physics

- **Rich data scape for precisions and accuracy**
  - Now: Jlab 6 GeV, and early JLab 12
  - Soon: BONuS 12 & more inclusive data (next slide)
  - Later: PVDIS at SOLID (next slide) & JLab 22 GeV
  - Not soon enough: EIC

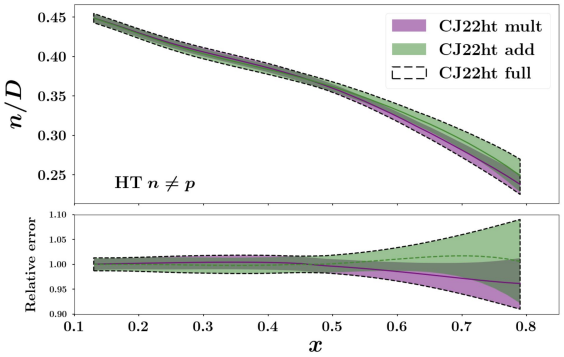
    ⟶ large Q^2 leverage

    ⟶ let's try and **maximize the EIC large-x reach and precision, it's worthwhile!**

Into the future (12 GeV)

JLab E12-6-113 proposal

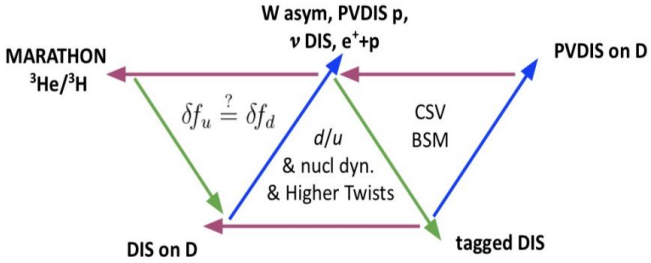
- **BONus12 – Tagged spectator proton → n/D ratio**
  - Ongoing analysis
  - Very high statistics (<u>many more bins</u> than shown here)
  - Will impact off-shell extraction, check theory framework

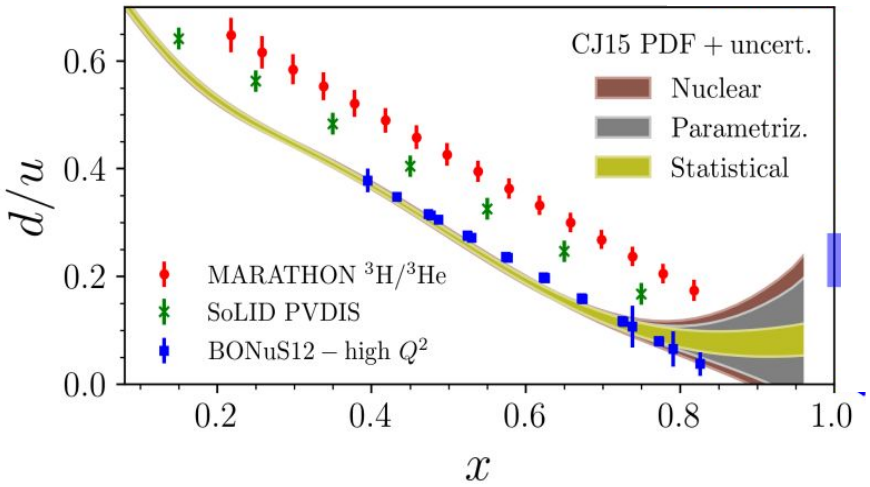


- **PVDIS @ SOLID**

JPG 50 (2023) 110501
also Ye Tian, Hall A mtg, Jan 2024

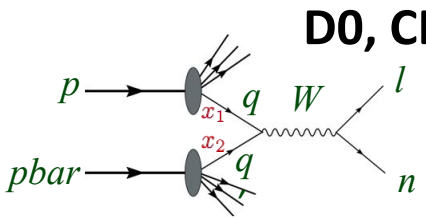
  - **d/u without nuclear target** & more!
  - Parity Violating electron helicity asymmetry



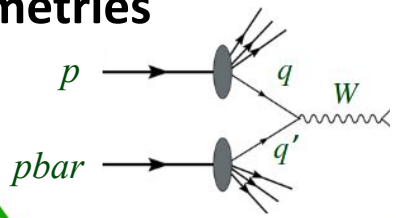


Backup

Not only PDFs: global fits as a tool



D0, CDF asymmetries



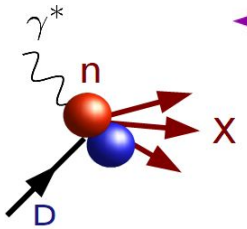
$$A_W(y) \xrightarrow{y \to y_{max}} \frac{1 - d/u}{1 + d/u}$$

d/u

&

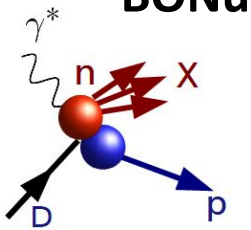
nucl. + offsh. dynamics

DIS on Deuterium



$$F_2^d \propto \mathcal{S}_D \otimes \left[x u_{\text{off}}(x) + x d_{\text{off}}(x) \right]$$

"BONuS" tagged DIS



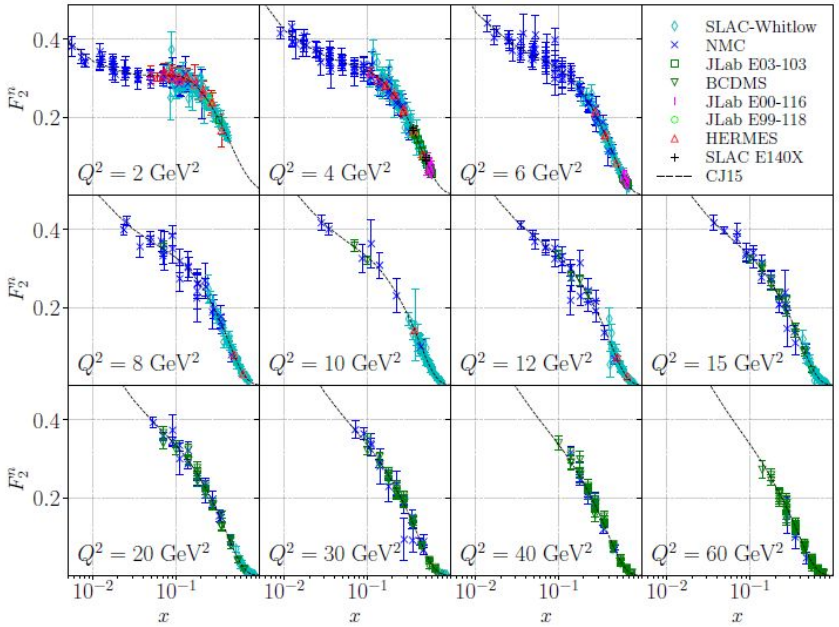
$$\frac{F_2^n}{F_2^d} \propto xu(x) + 4xd(x)$$

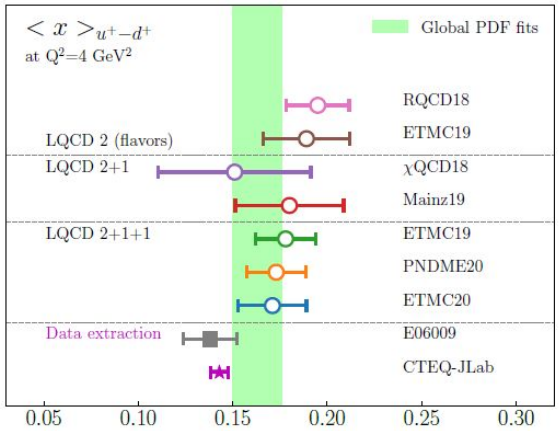
$F_2(n)$ extraction and apps

- **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
  - …





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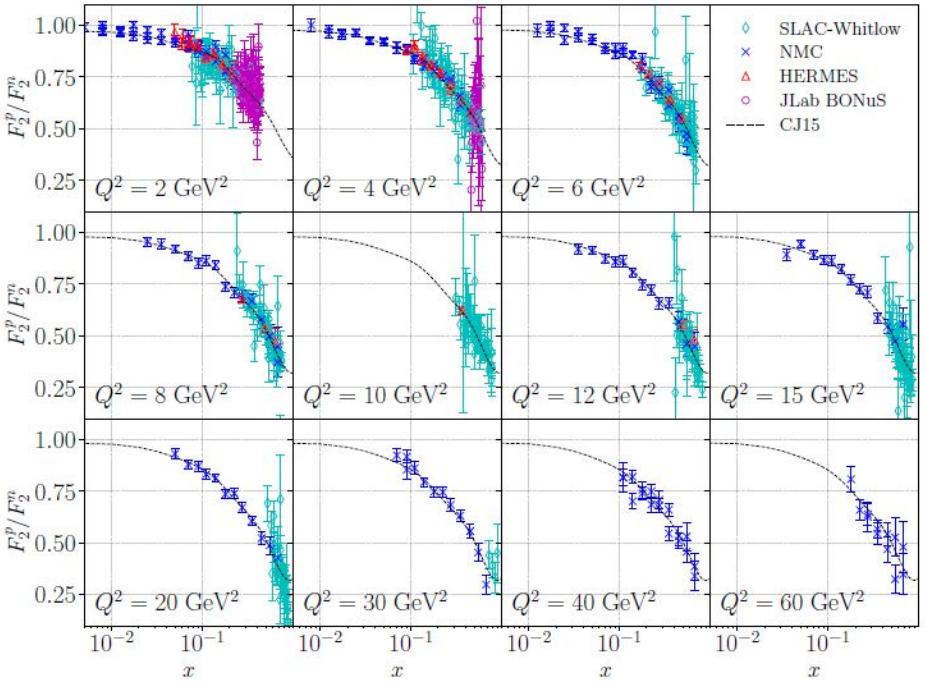
F_2(n/p) extraction

- Similar idea, but using
  - d/p data

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

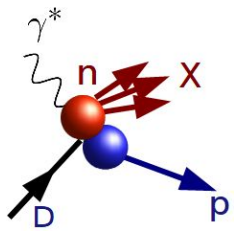
  - n/d BONuS data

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

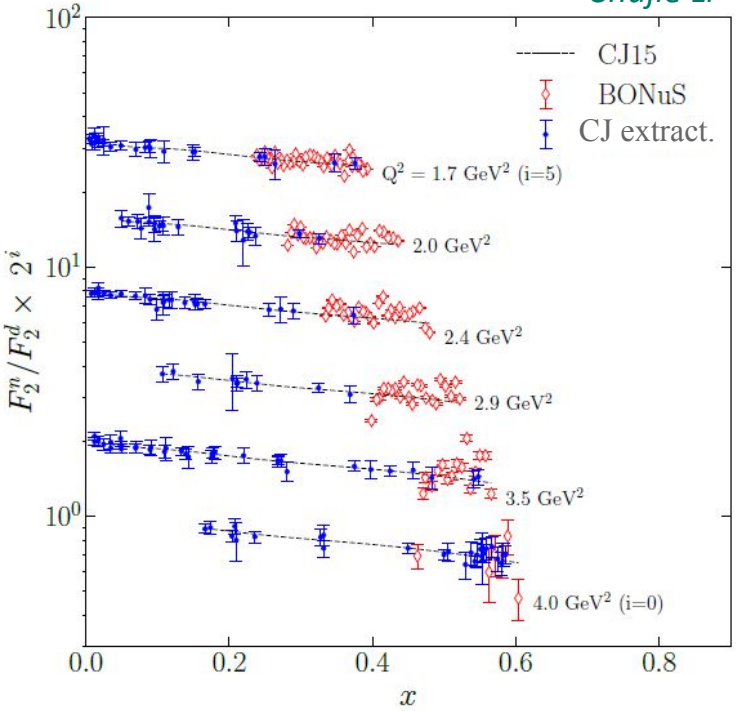


Bonus cross-checks

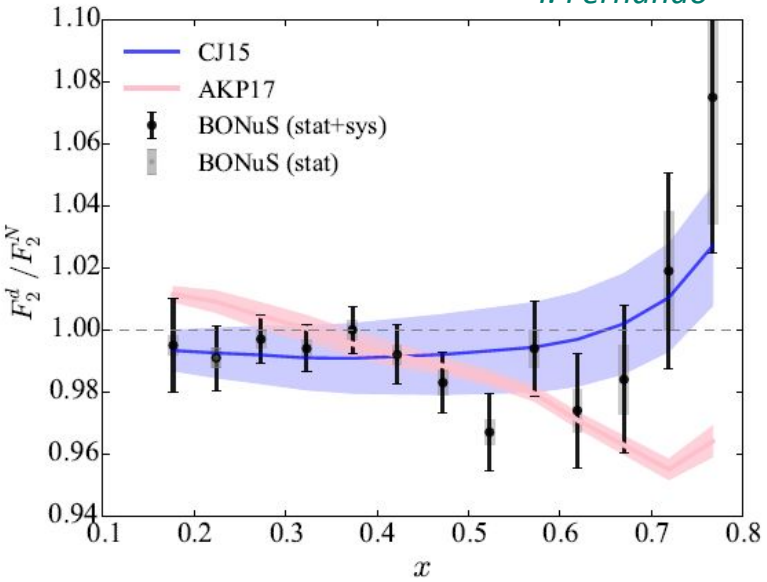
- **BONuS: Tagged proton DIS** measurements



Shujie Li



I. Fernando



HT systematics

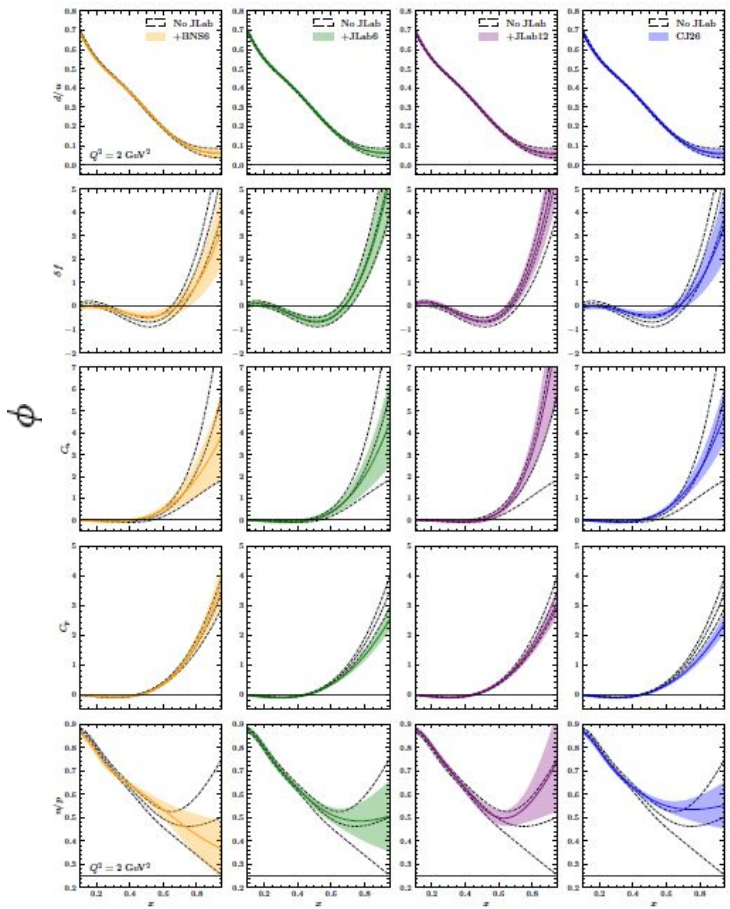
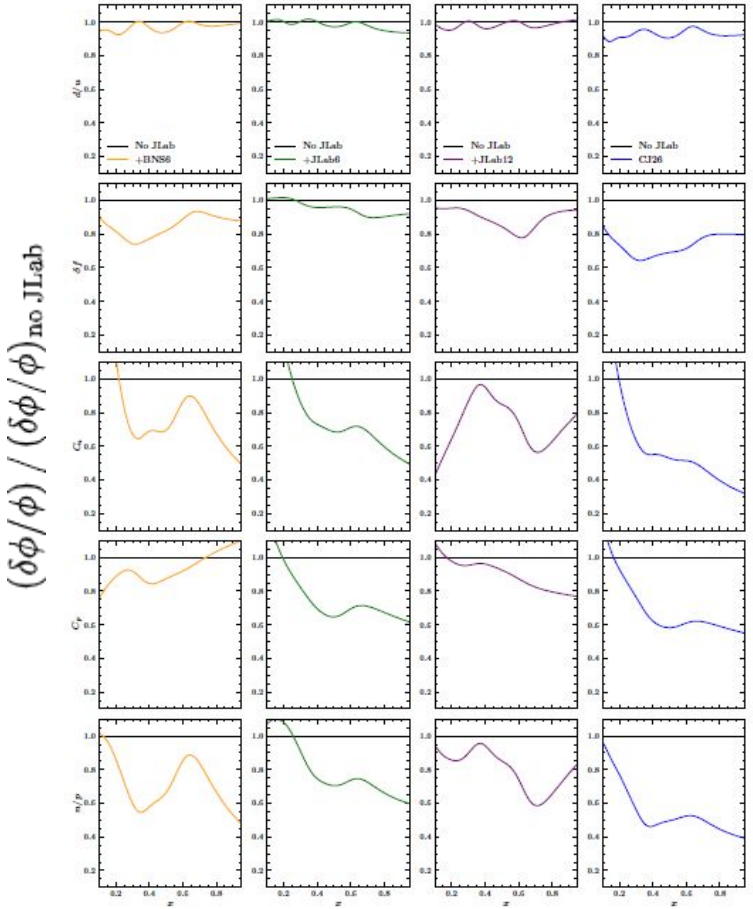
- **HT modeling**
  - Additive $F_2(x,Q^2) = F_2^{LT}(x,Q^2) + \dfrac{H(x)}{Q^2}$
  - vs.
  - Multiplicative $F_2(x,Q^2) = F_2^{LT}(x,Q^2)\left(1 + \dfrac{C(x)}{Q^2}\right)$

  isospin dependent or dependent

- **Isospin and Q^2 assumptions are not independent**
  - *e.g.*, a Q^2–independent, isospin-independent multiplicative HT generates an equivalent additive HT that depends on both

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

- **Non-negligible large-*x* bias**
  - **if using isospin-independent coefficients**
    - ⟶ Multiplicative (CJ15) underestimates
    - ⟶ Additive (AKP17) overestimates ($H > 0$)

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

Impact of JLab data