Interplay of Higher-Twist And Nuclear Dynamics in PDF fits at large x

Alberto Accardi

and many thanks to my CTEQ-JLab collaborators:
Shujie Li, Ishara Fernando, X. Jing, S. Park
C.E. Keppel, W. Melnitchouk, P. Monaghan, J. Owens

Hall A Collaboration Meeting
10 Feb 2022

This work is in part supported by the DOE Office of Science

Outline

- **Basics of QCD global analysis and PDF extraction**
- **“Impact” studies**
    - JLab 12 p/D (E10-...) ⟶ valence quarks
    - STAR W & SeaQuest ⟶ light antiquarks
    - EIC ⟶ all partons (almost…)
- **Deuteron dynamics from Global QCD fits**
    - Simultaneous fit of PDFs and nuclear corrections
    - CJ15 vs. AKP17 fits
- **Interplay of Higher-Twists and Offshell Corrections**
    - Hidden theoretical biases uncovered
- **Tagged measurements to the rescue**
- **Conclusions**

References

Large-x fits with nuclear corrections:

- **CJ15**: Accardi et al., PRD 93 (2016) 114017
- **AKP**: Alekhin, Kulagin, Petti, PRD 96 (2017) 054005
- Accardi, talk at DNP 2020 / Fernando, talk at GHP 2021

QCD global analysis from protons to nuclei:

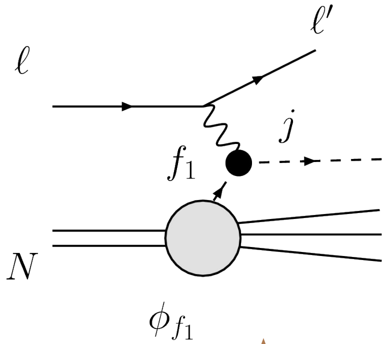
- Accardi, PoS DIS2015 (2015) 001
- Jimenez-Delgado, Melnitchouk, Owens, *J.Phys.G40 (2013) 093102*
- Ethier, Nocera, *Ann.Rev.Nucl.Part.Sci. (2020) 70, 1-34*

QCD global analysis and statistical methods:

- Kovarik, Nadolsky, Soper, *Rev.Mod.Phys. 92 (2020) 4, 045003*

Basics of QCD global analysis and PDF extraction

Factorization of Hard Scattering Processes



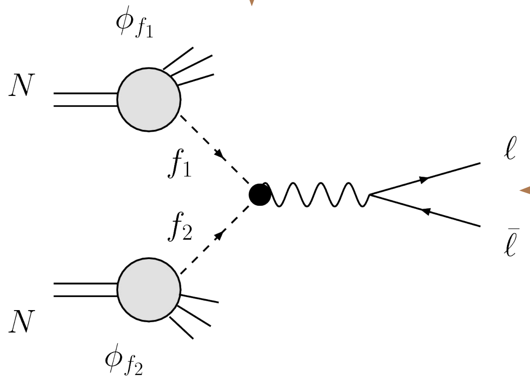
- **Perturbative QCD factorization**
  of short and long distance interactions

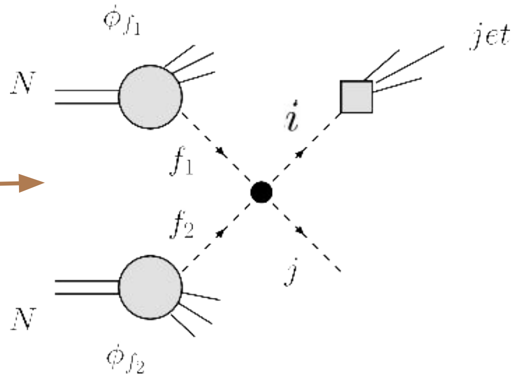
pQCD calc.

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

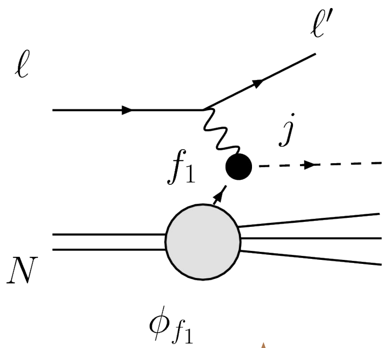
PDFs (from DIS fits)

- **Universality:** same PDFs for many processes





Factorization of Hard Scattering Processes



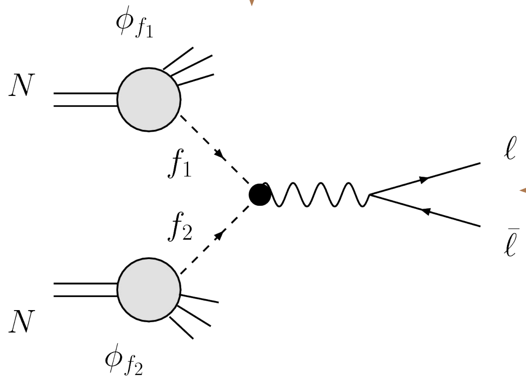
- **Perturbative QCD factorization**
  of short and long distance interactions

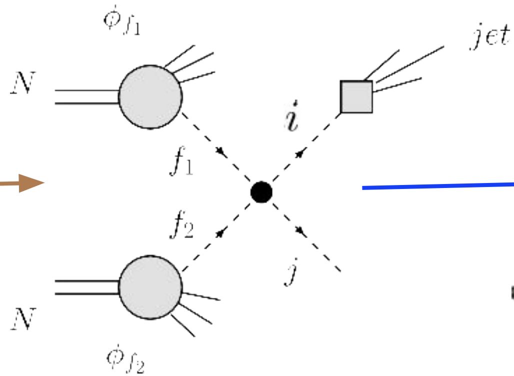
pQCD calc.

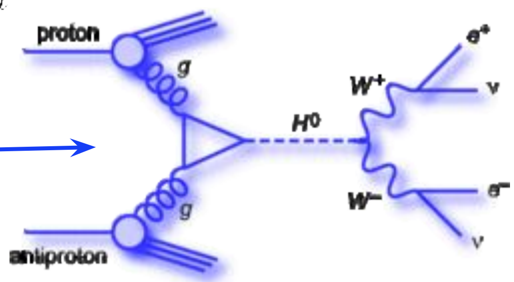
$$d\sigma_{\text{hadron}} = \sum_{f_1,f_2,i,j} \phi_{f_1} \otimes \hat{\sigma}^{f_1 f_2 \to ij}_{\text{parton}} \otimes \phi_{f_2}$$

PDFs (from DIS fits)

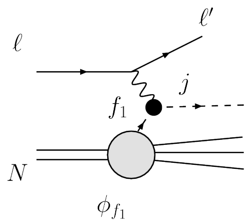
- **Universality:** calc. new ones (Higgs, SUSY, F2n, …)







Factorization of Hard Scattering Processes



$$\approx \sum_q e_q^2 q(x, Q^2)$$

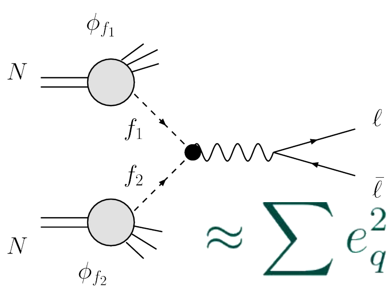
- **Perturbative QCD factorization**
  of short and long distance interactions

pQCD calc.

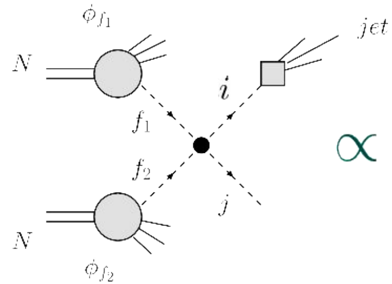
$$d\sigma_{\text{hadron}} = \sum_{f_1, f_2, i, j} \phi_{f_1} \otimes \hat{\sigma}^{f_1 f_2 \to ij}_{\text{parton}} \otimes \phi_{f_2}$$

PDFs (from DIS fits)

- **Universality:** flavor separation



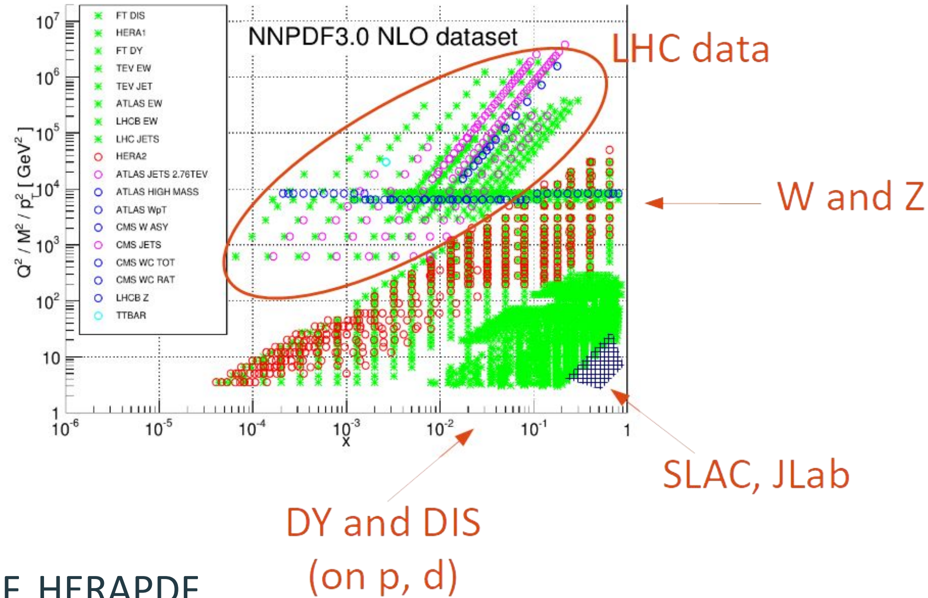
$$\approx \sum_q e_q^2 q(x_1) \bar{q}(x_2)$$



$$\propto q(x_1) g(x_2)$$

Global QCD fits

- Fit PDF to a variety of hard scattering data
  - Hadron-hadron collisions
    - ⟶ Jets
    - ⟶ Electro-weak boson production
  - Electron-proton DIS
  - Electron-Deuteron DIS



- >1000 data points

- 40+ years of experience,
  - “High-energy” fitters:
    - ⟶ CTEQ-TEA, MMHT, NNPDF, HERAPDF
  - Lower-energy / nuclear focus:
    - ⟶ **CTEQ-JLab, AKP**, ABMP, JAM

Global QCD fits

data

- DIS: p, d
- p+p(pbar) $\rightarrow$ l^+l^-, $W^\pm$, Z
- p+p(pbar) $\rightarrow$ jets, γ+jet

theory

- pQCD at NLO
- Factorization & universality
- **Large-*x*, low-Q^2, nuclear corr.**

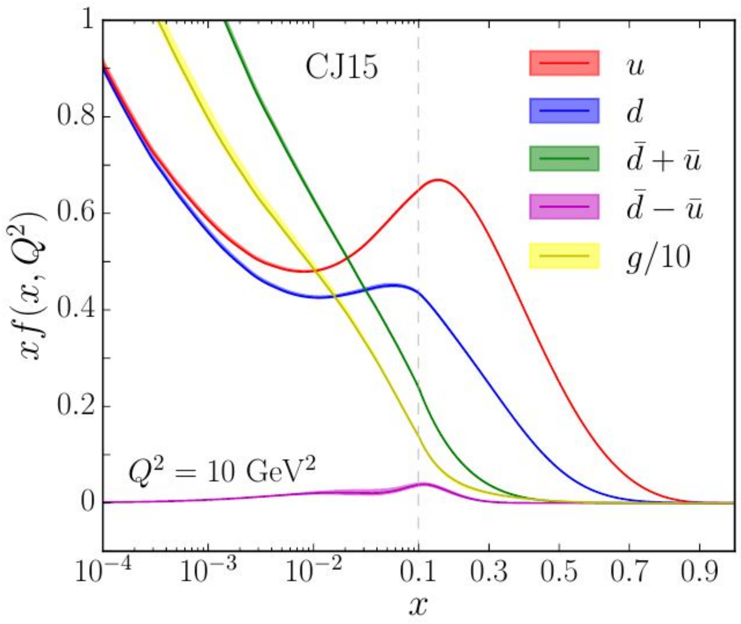
fits

- Parametrize PDF at Q_0, evolve to Q
- Minimize χ^2

PDFs

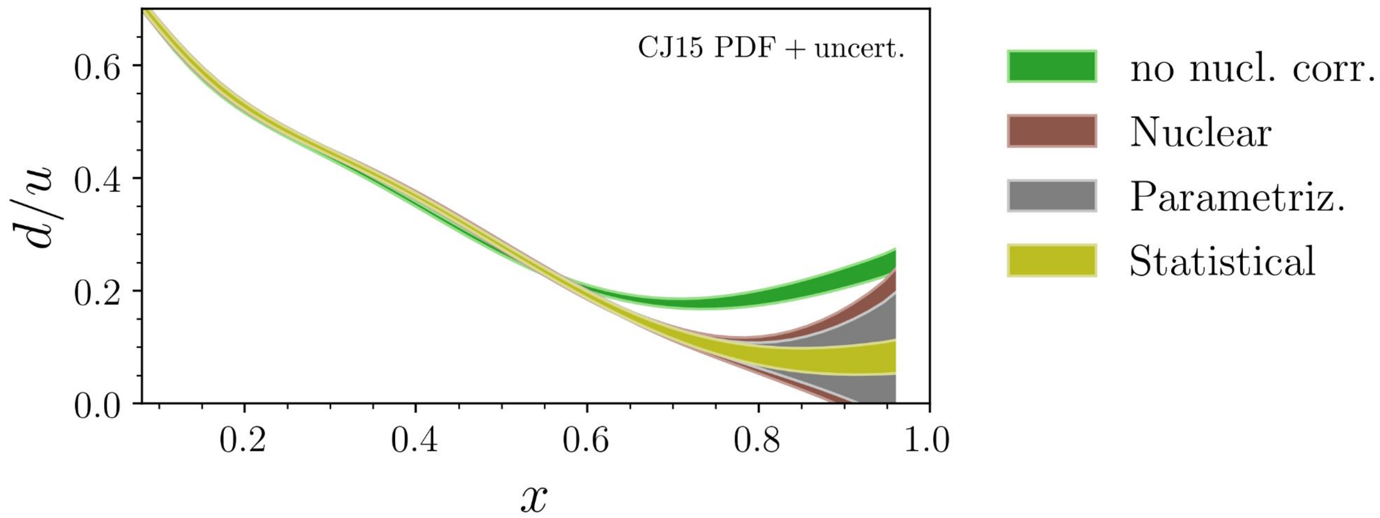
F_2(n)
W, Z / W',Z', Higgs
(or any other “hard” observable)

The CJ15 PDFs



- Fitted with χ^2 = 1.04 / datum
- Propagation of exp. errors
  - Hessian analysis
  - Correlated errors used if available
- “PDF error band” for $\Delta\chi^2$ = 2.71
  - $\rightarrow$ 90% c.l. in a perfect world
  - Many alternative methods
- Theoretical systematics more difficult

The CJ15 d/u ratio

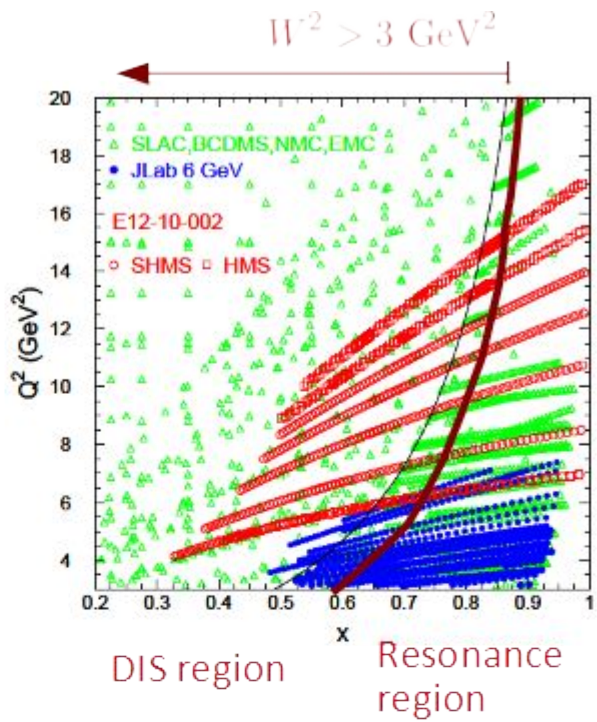


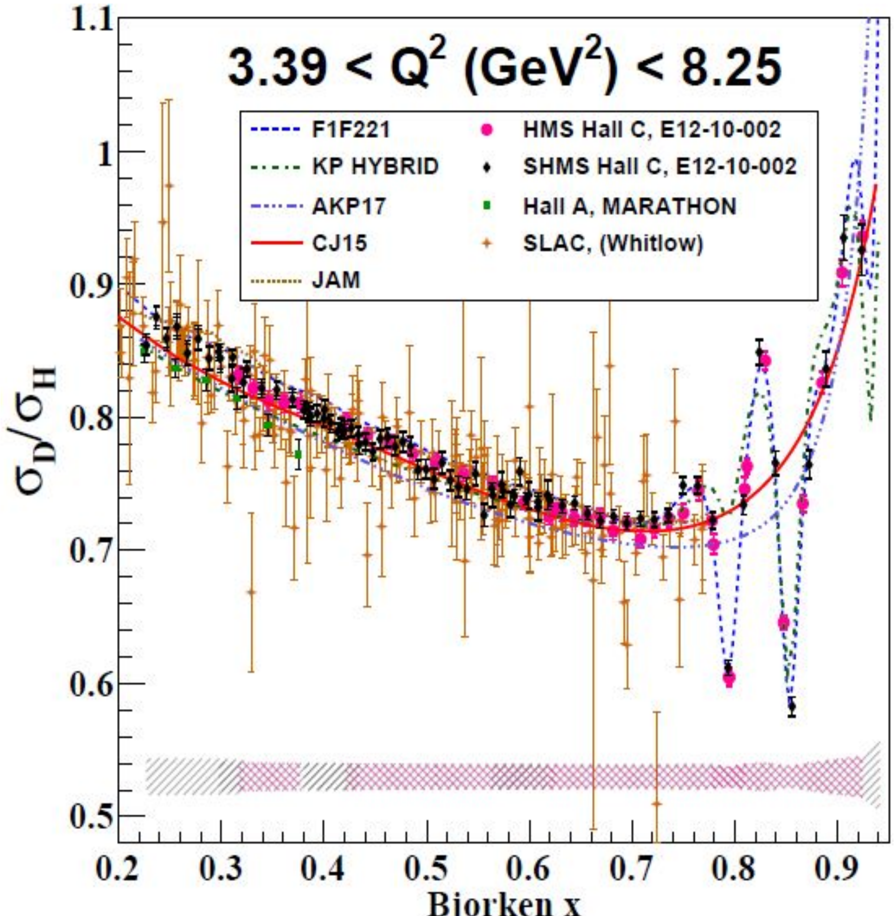
- **Theoretical uncertainties**: difficult to quantify, e.g.:
  - Nuclear: wave function choice
  - Off-shell uncertainties are parametrized → partly included in Statistical band
  - Parametrization: *d*-quark flexibility in extrapolation region
- **Theoretical biases**: even less obvious!
  - We shall discuss those from HT and offshell implementation choices

“Impact studies”

Valence quarks at JLab 12 *(courtesy of W. Henry)*

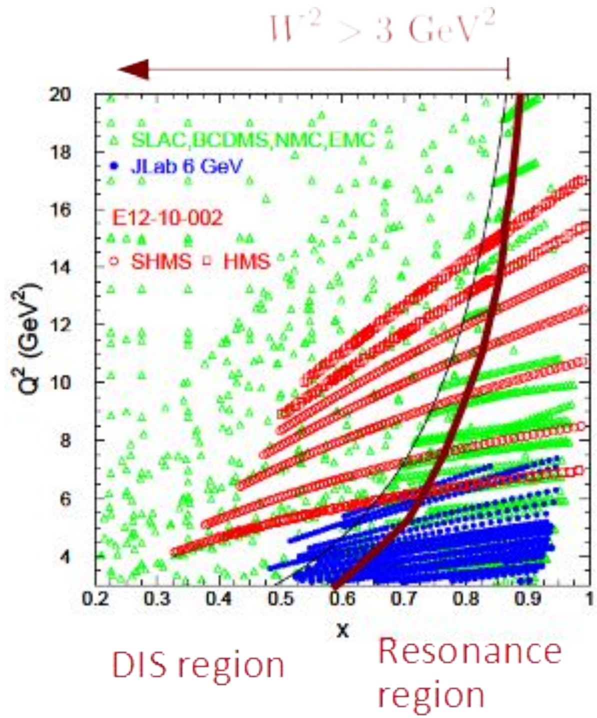
- **p/D ratio from E12-10-002**
  - Larger x, Q2 range than at JLab 6
  - More precise than SLAC

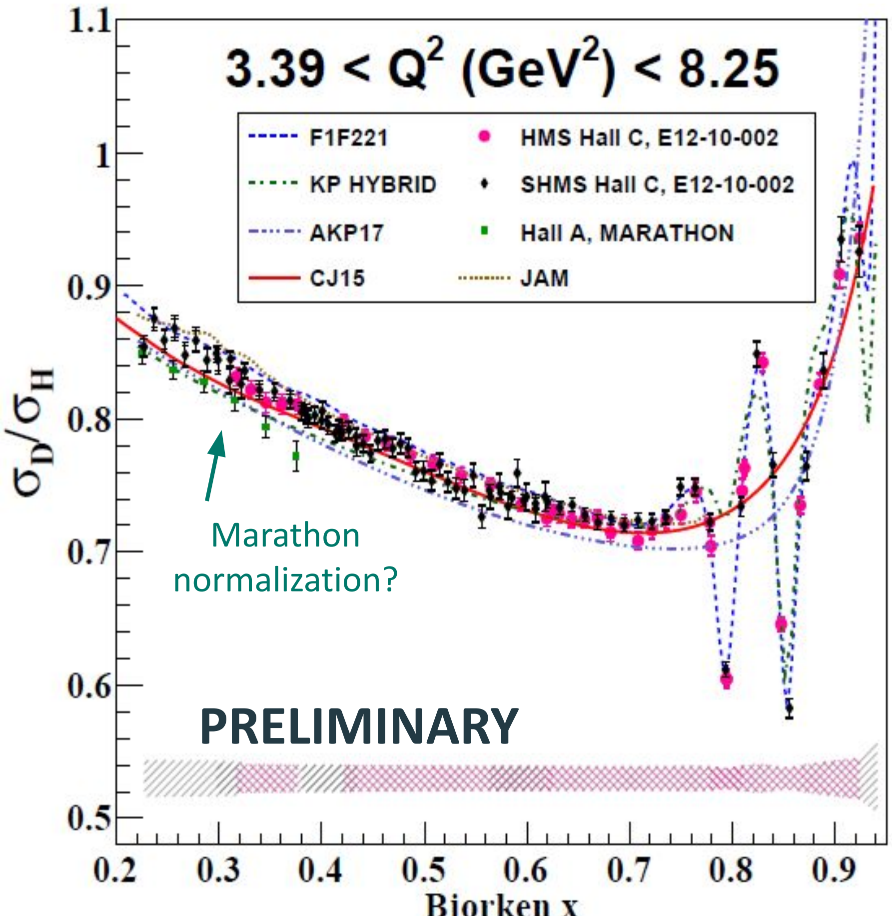




Valence quarks at JLab 12 *(courtesy of W. Henry)*

- **p/D ratio from E12-10-002**
  - Larger x, Q2 range than at JLab 6
  - More precise than SLAC

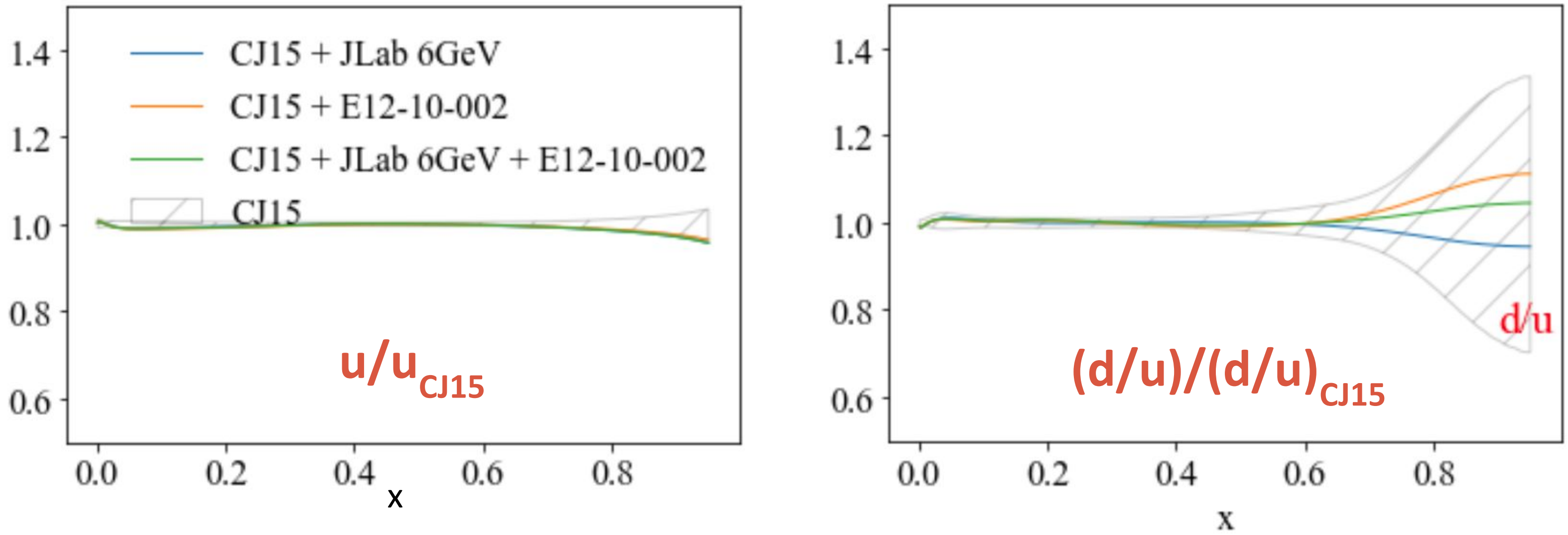




Valence quarks at JLab 12

Shujie.Li, A.A

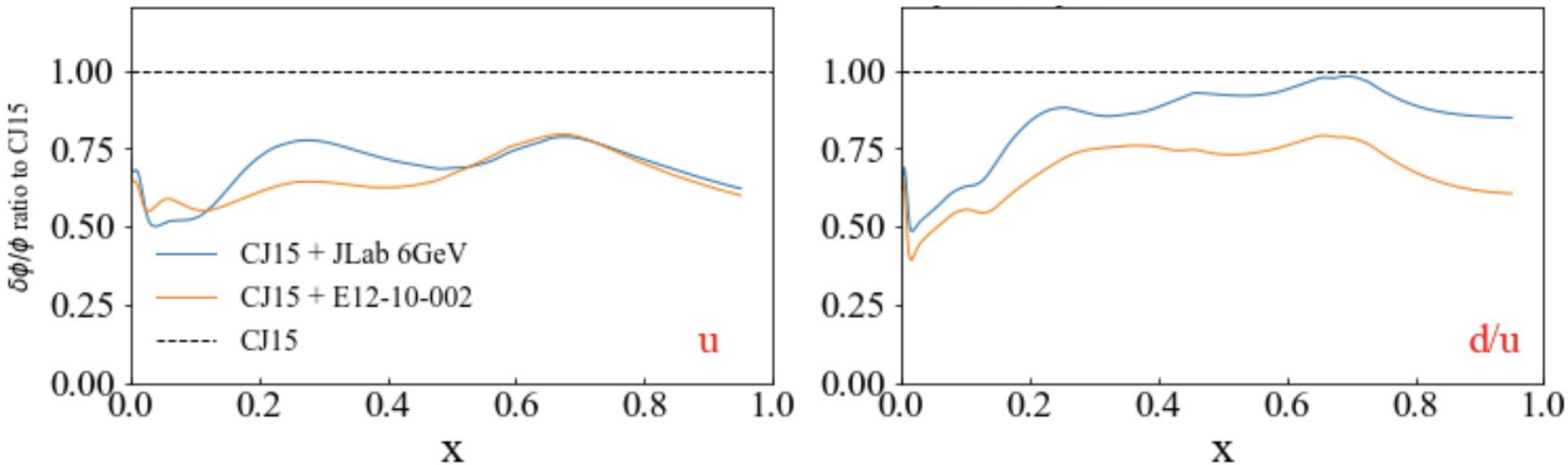
- **No tension with original CJ15 data set**
  - ⟶ Data compatible with global data set (not always the case…)
  - ⟶ Otherwise, one can bring to light neglected systematic uncertainties



Valence quarks at JLab 12

Shujie.Li, A.A

- **No tension with original CJ15 data set**
  - ⟶ Data compatible with global data set (not always the case…)
  - ⟶ Otherwise, one can bring to light neglected systematic uncertainties
- **Uncertainty reduction comparable to full JLab 6 data set**

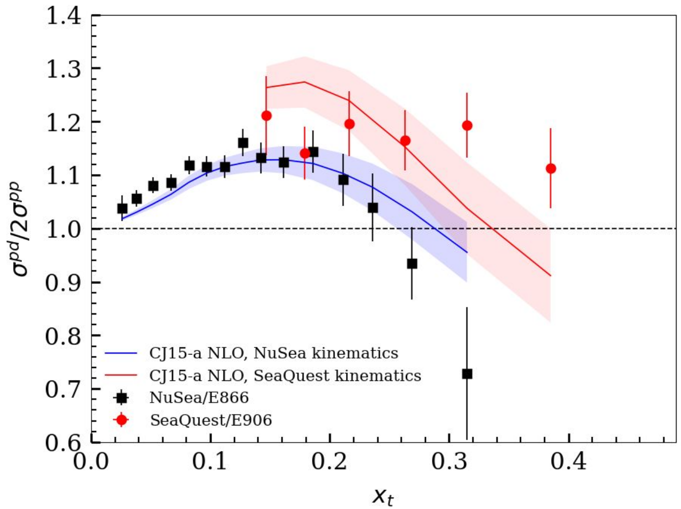


Light antiquarks: SeaQuest

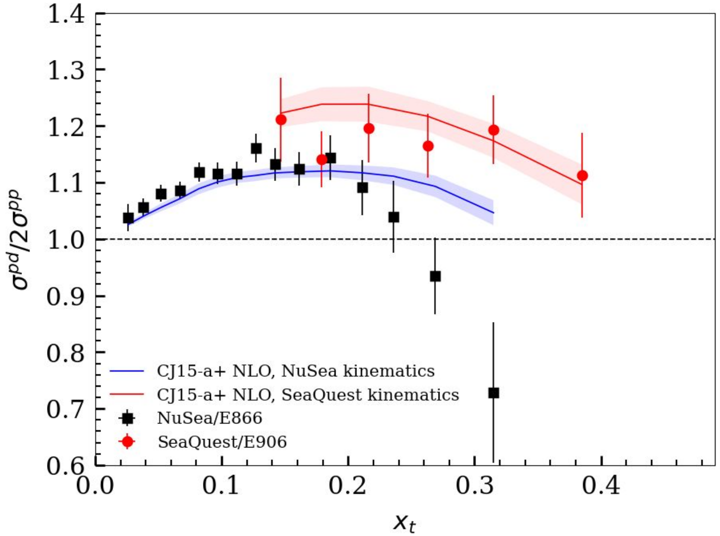
S.Park, A.A, J.Owens

- **Low-energy DY from SeaQuest** ($x \sim 0.15$-0.4)
  - p+d / p+p ratio
  - Explores kinematics beyond E866 reach

CJ15 PDFs
(only E866 is fitted)



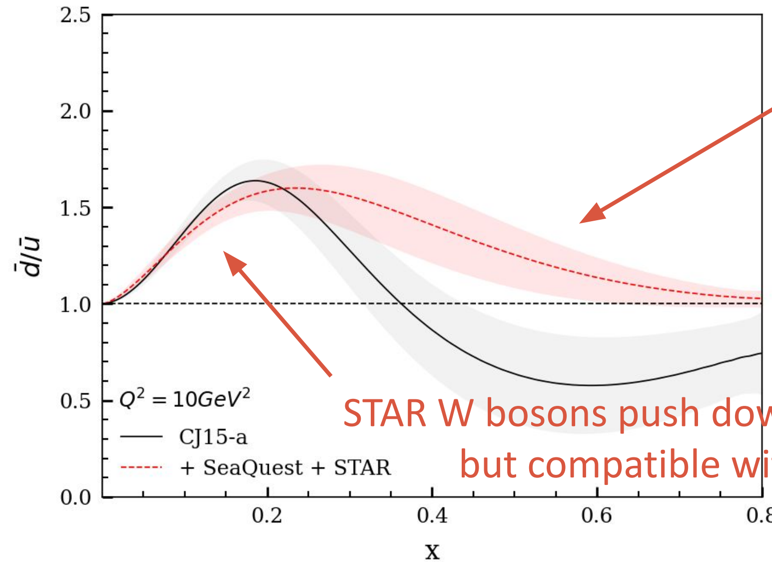
CJ15 + SeaQuest PDFs
(both are fitted)



Light antiquarks: SeaQuest and STAR

S.Park, A.A, J.Owens

- **low-energy DY from SeaQuest** ($x \sim 0.15$-0.4)
  - p+d / p+p ratio, explores kinematics beyond E866 reach ($x \sim 0.02$-0.3)
- **Light antiquark ratio remains positive at all x values**
  - Improved precision all over the x>0.1 range
  - Thanks also to STAR W-bosons ($x \sim 0.05$-0.25)



SeaQuest pulls ratio up
→ **Tension with E866**
→ **How to quote PDF errors?**

STAR W bosons push down a bit,
but compatible with E866

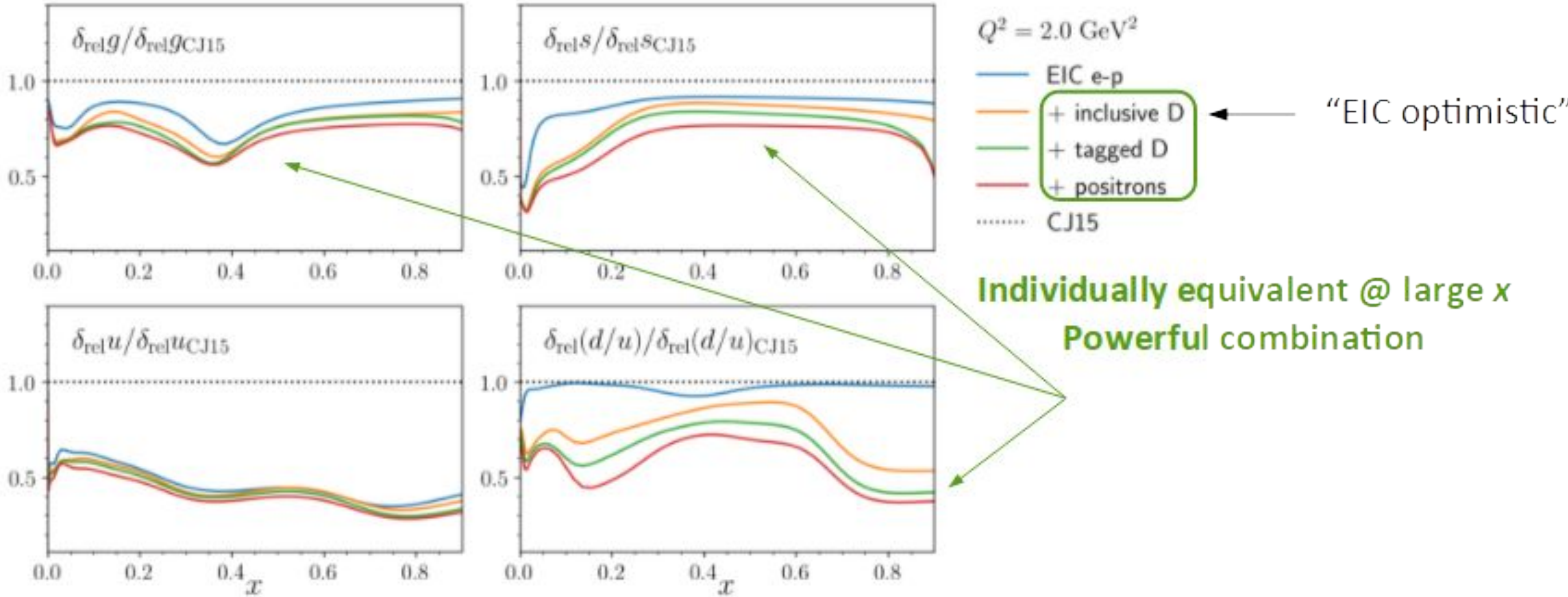
EIC impact → *EIC yellow report*

- **DIS at the EIC:**
  - Large x, Q2 coverage
  - Weak and Neutral currents
  - Positron and electron beams
- **Flavor separation without deuterons** (in principle)
- **“Easy” proton and neutron tagging**

EIC impact → *EIC yellow report*

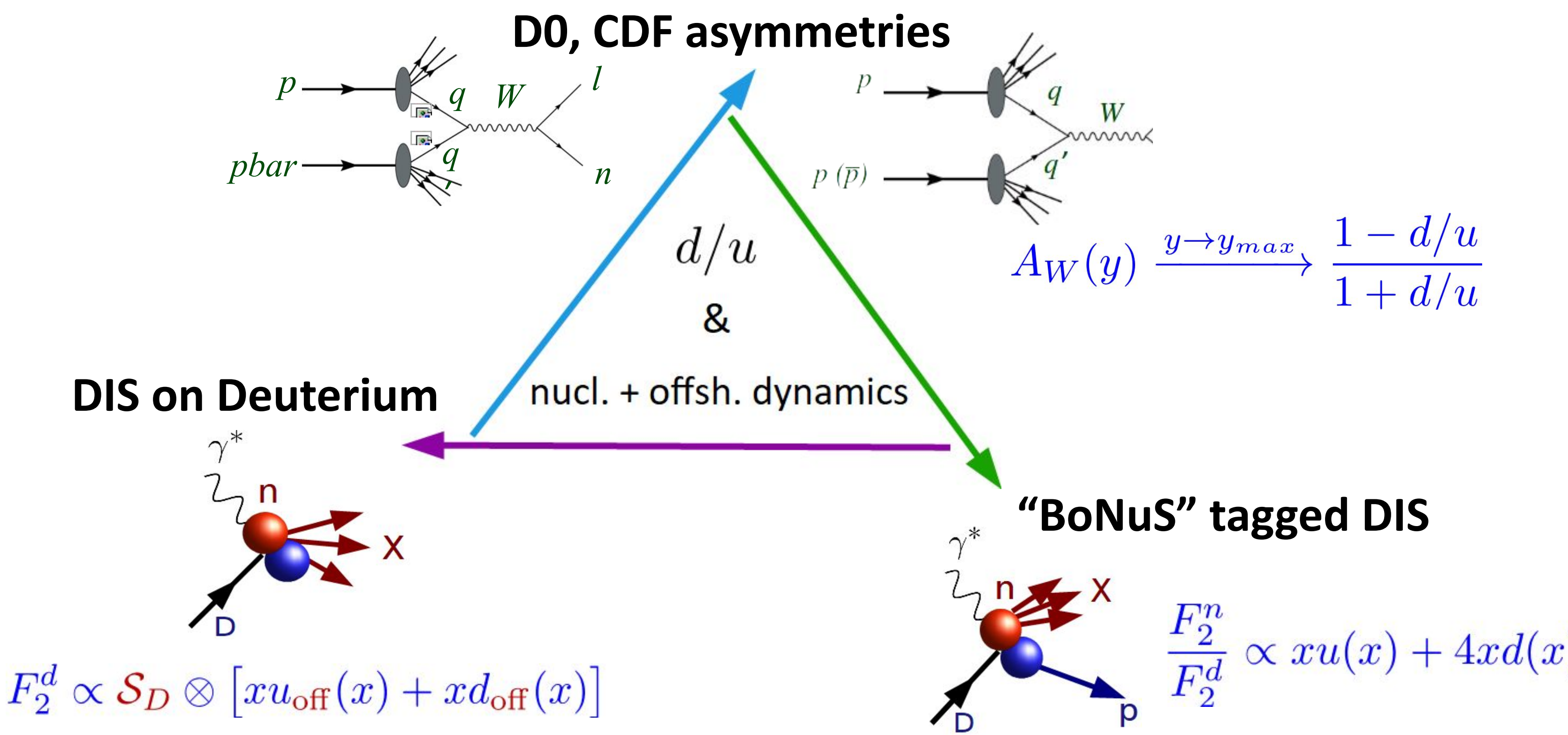
A.A, X. Jing, S. Li

- **Fitting strategy**
  - Kinematics, uncertainties from simulations
  - Central values from CJ15 + bootstrap



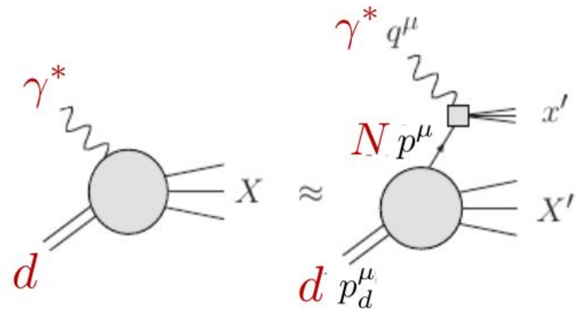
Deuteron dynamics from Global QCD fits

Large-x PDFs: interplay of observables



Deuteron 1: Fermi motion and binding

- **Weak binding approximation:**
  - Incoherent scattering from
  - not too fast individual nucleons
  - Neglects 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**

$\longrightarrow$ $z = \dfrac{p\cdot q}{p_d\cdot q} \approx 1 + \dfrac{p_0+\gamma p_z}{M}$ $\quad \left[p_0 = M+\varepsilon,\quad \varepsilon = \varepsilon_d - \dfrac{\vec{p}^{\,2}}{2M}\right]$

momentum fraction of d carried by N

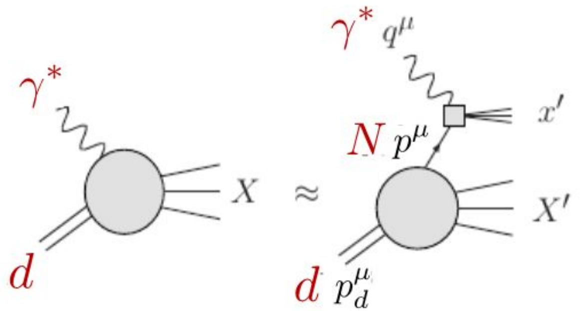
$\longrightarrow$ at finite Q^2, $\gamma = \sqrt{1+4x^2p^2/Q^2}$

quantifies how far the nucleon is from the light cone ($\gamma = 1$)

accardi@jlab.org

Off-shell corrections in Deuteron

- **Nucleons are bound in the deuteron:**
  - $p^2 < M^2$
  - Structure functions are deformed (but not too much if x not too large)



- **Offshell expansion:**
  - parametrize first order coefficient

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

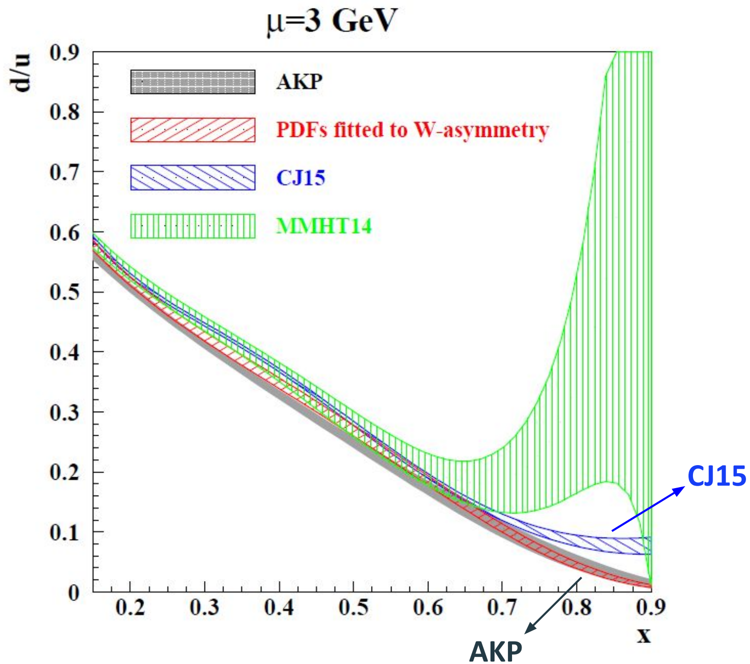
Free proton, neutron structure function

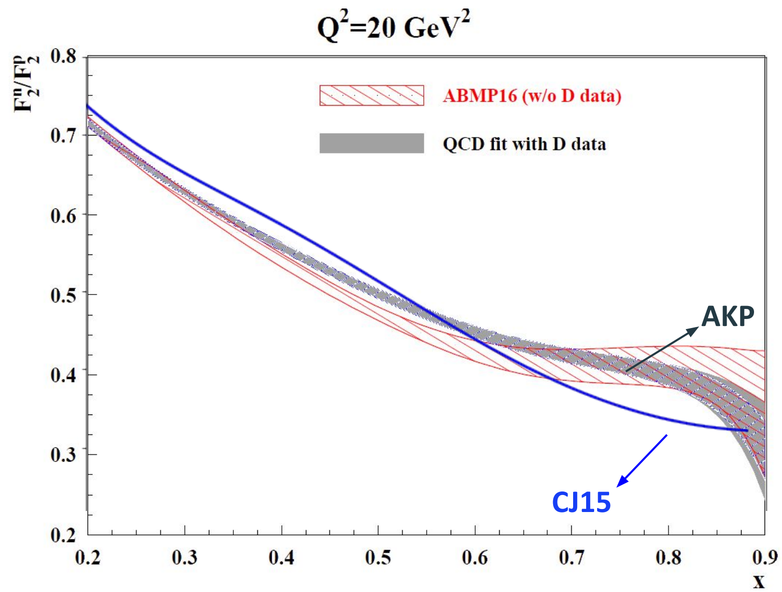
"offshell function"

When fitted, this effectively becomes a phenomenological "catch-all" term (see later)

  - Parametrized and fitted (see the earlier triangle)
    $\longrightarrow$ **CJ15, AKP**

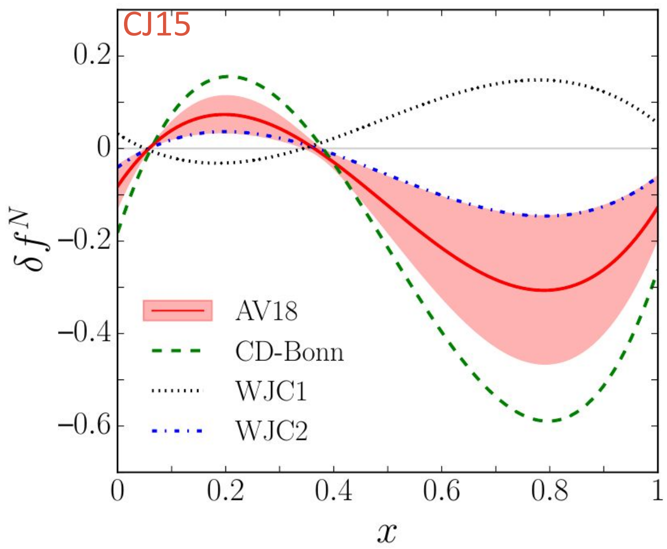
CJ15 and AKP: free nucleons

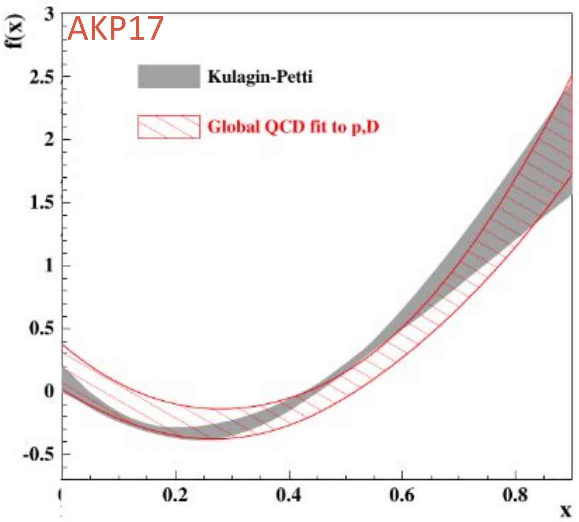




- **AKP has smaller *d/u* but bigger *n/p* ???**
  - Not possible at Leading Twist
  - **Large HT contributions to high-*x* *n/p* ratio**

CJ15 and AKP17: off-shell function





Kulagin, Petti (e+A fits), NPA 765 (2006) 126

Alekhin + KP (e+d global fits) PRD96 (2017) 054005

CJ15:
PRD 93 (2016) 114017

- **Different shape and size ??**
- **But many (<u>MANY</u>) differences**
  - Extended d-quark (CJ15) vs. conventional (AKP, d/u-->0)
  - Fit real W asymetry vs. only decay lepton W ⟶ l + (n) asymmetry
  - **Off-shell, HT choices**, and their interplay
  - . . .

The most important, in our opinion!

Ongoing CJ + AKP benchmarking effort

Interplay of HT and offshell corrections

HT systematics

CTEQ-JLab study, in progress
See also Accardi, talk at DNP 2020

- **HT assumptions**
  - Additive vs. Multiplicative
    - $\longrightarrow$ In both cases, Q^2-independent
  - Isospin symmetric or not

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

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

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

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

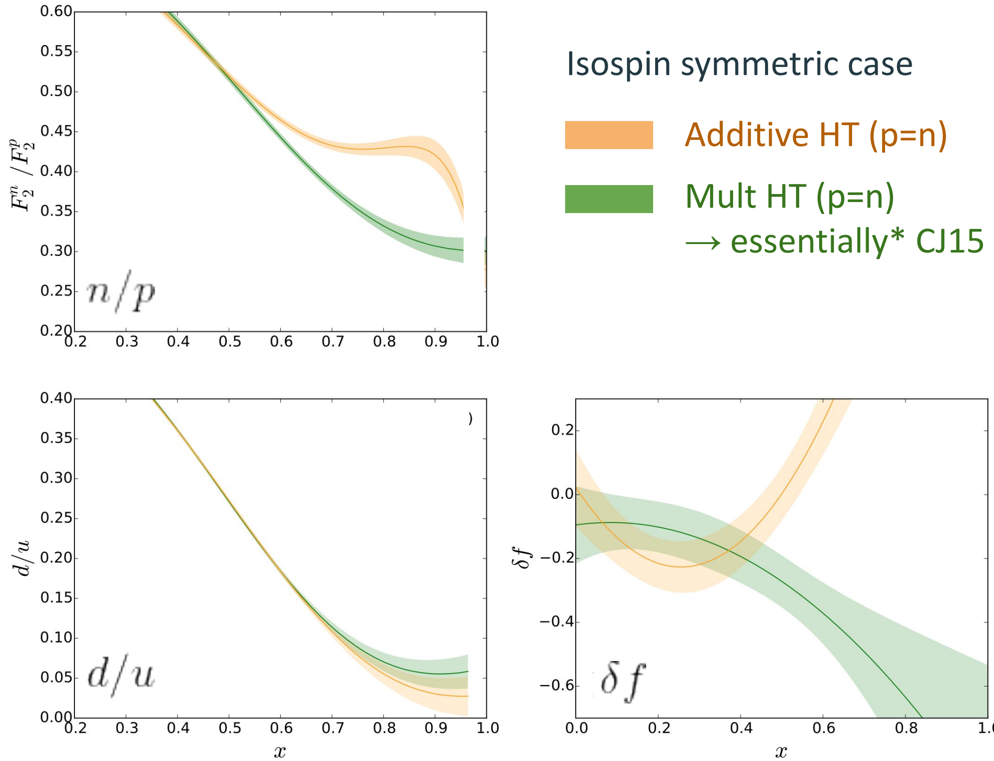
- **Non-negligible large-x bias**
  - if using isospin-independent coefficients
    - $\longrightarrow$ Mult (CJ15) underestimates
    - $\longrightarrow$ Additive (AKP17) overestimates ($H > 0$)

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

CJ fits - isospin symmetric HT

CTEQ-JLab study, in progress
See also Accardi, talk at DNP 2020

- Additive n/p
  - Larger than Mult n/p
  - Even if d/u is smaller
- Fitted offshell function compensates n/p bias
  - D/p well fitted, indeed
- **CJ15/AKP17 differences are reproduced!**
  - And explained

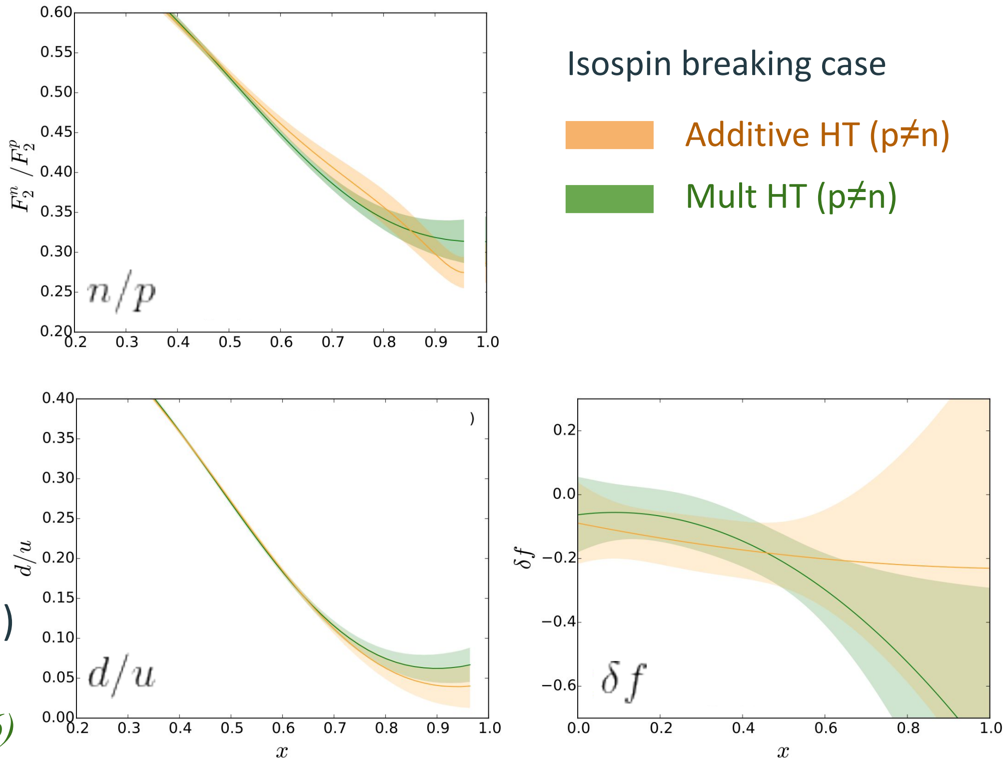


* also includes full JLab 6 data; uses generic 2nd order polynomial δf

CJ fits - isospin breaking HT

CTEQ-JLab study, in progress
See also Accardi, talk at DNP 2020

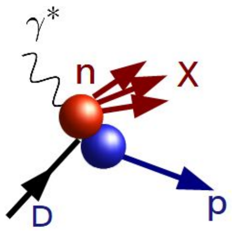
- **Bias removed !!!**
  - Small systematics remains
- *n/p & d/u*
  - Much closer to CJ15
- Small δf offshell correction
  - When averaged over *p* and *n*
  - Large cancellation is possible (but need A=3 data to confirm)
    (Tropiano et al., PRC 2019)
    (Cocuzza et al., arXiv:2104.06946)



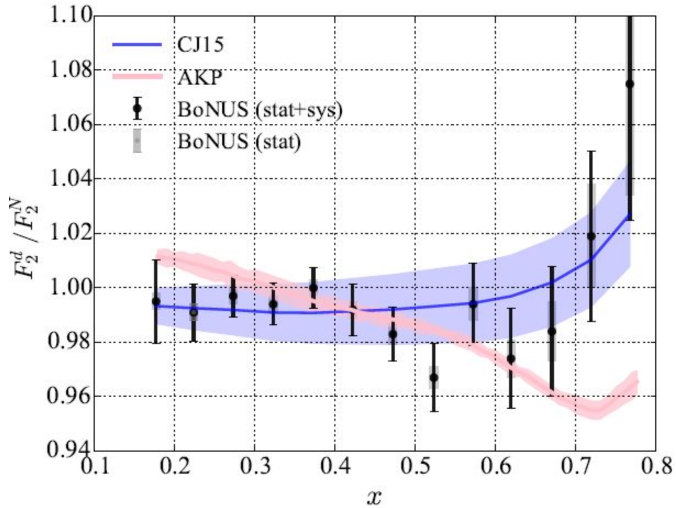
* also includes full JLab 6 data; uses generic 2nd order polynomial δf

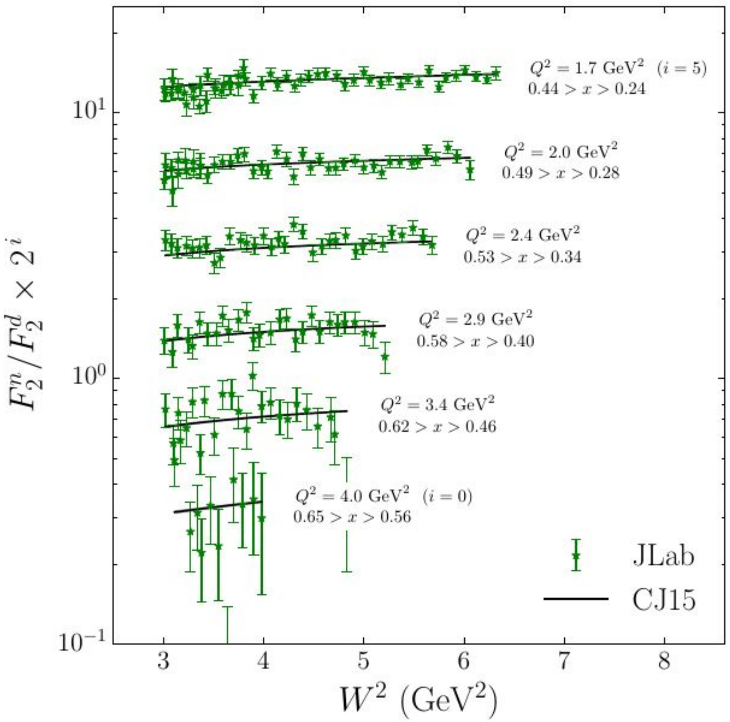
Tagged DIS to the rescue

Open questions



- Can we confirm the picture just painted? Is δf negative?
  - **Need direct experimental sensitivity to δf**
  - Tagged DIS experiments
- BONuS 6 data don't seem to disagree!
  - But may not be precise enough at large *x*





Open questions

- Is the simple proposed factorization correct?
  - Or at least phenomenologically acceptable ?

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

$$v = \frac{p^2 - M^2}{M^2}$$

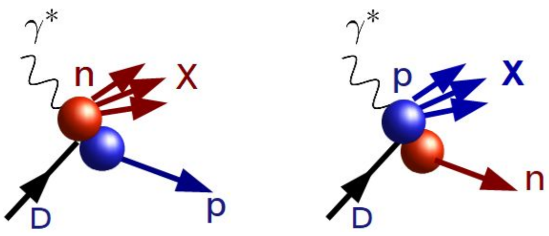
- Are FSI negligible?
  - Inclusive DIS only probes small off-shellness

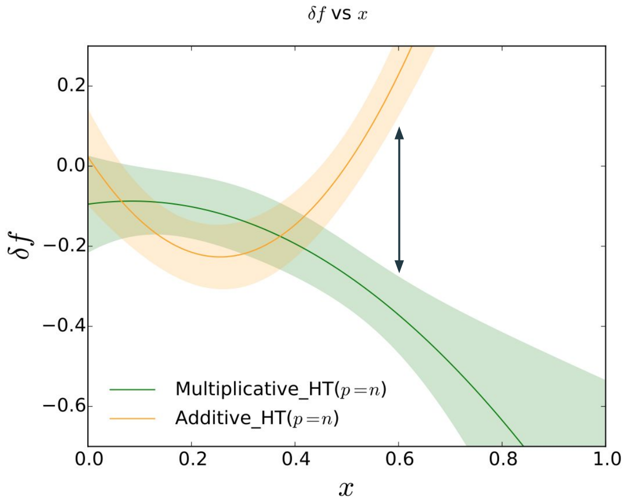
More data, please!

- **One can extract δf**
  - Experiment by experiment
  - or in a global QCD fit

$$\frac{F_{2N}}{F_{2N}^{free}} = 1 + v\,\delta f(x)$$

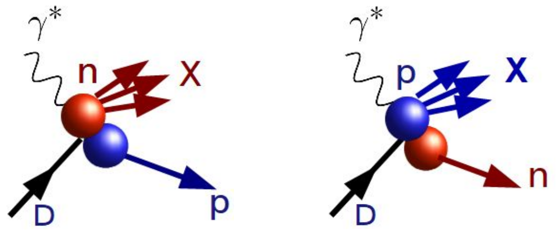
- **Need more tagged DIS data with**
  - FSI under control (small *v*, backward *φ*)
  - Large lever arm and good resolution on *v* (or p_s)
  - x>0.6 preferred to distinguish two cases





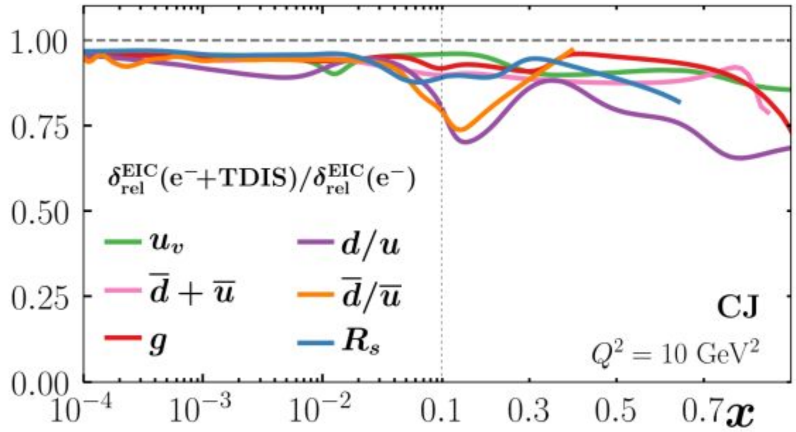
More data, please!

- **At JLab:**
  - BONuS 12, TDIS-n, BAND, LAD…
  - Proton and neutron tagging



- **At the EIC**
  - Simulated Data *(C.Weiss et al. - JLab LDRD 2014)*

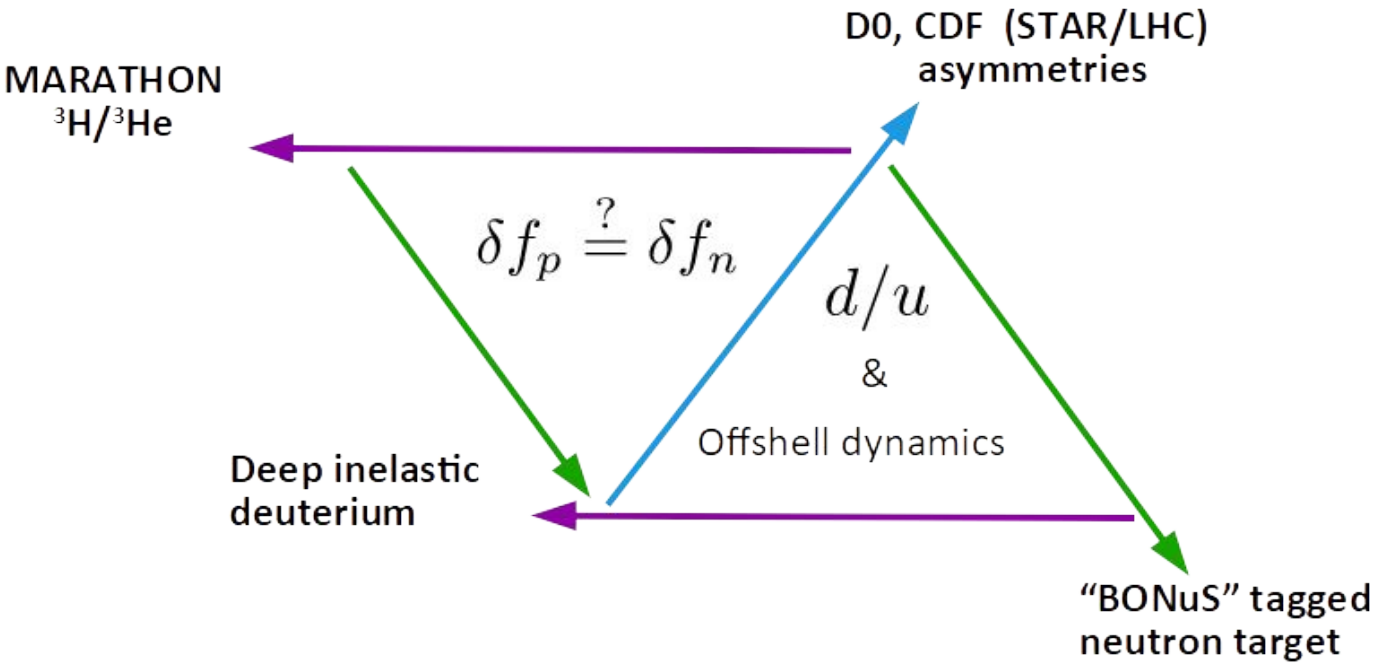
    ⟶ Proton tagging + on-shell extrapolation method
  - Fits by *X.Jing and S.Li*



The MARATHON parallelogram

- Can extend the CJ15 triangle to a parallelogram

  ⟶ **and verify if off-shell protons ~ off-shell neutrons !!**



Summary

- **Large-x $F_2(n)$ extraction in global fits:**
  - has (large) systematic bias due to the HT parameterization
  - This bias also deforms the extracted offshell function
  - Isospin-asymmetric HT parameterization is needed

- **Need good quality tagged DIS data to**
  - Measure bound nucleon structure function in nuclei
  - Confirm factorized formula for δf
  - BONuS 12, TDIS-n, BAND, LAD… at JLab / Electron-Ion Collider

- **Global QCD fit can incorporate tagged and inclusive data, and**
  - Combine the statistical power of proposed and future measurements
  - Identify pulls against, or confirm compatibility with, other DIS, DY, jet data
  - Measure δf, indeed, with highest precision and accuracy

    $\longrightarrow$ And provide robust free $F_2(n)$ extraction

Thank you!

What can we learn from TRITIUM

C. Cocuzza et. al., arXiv:2104.06946

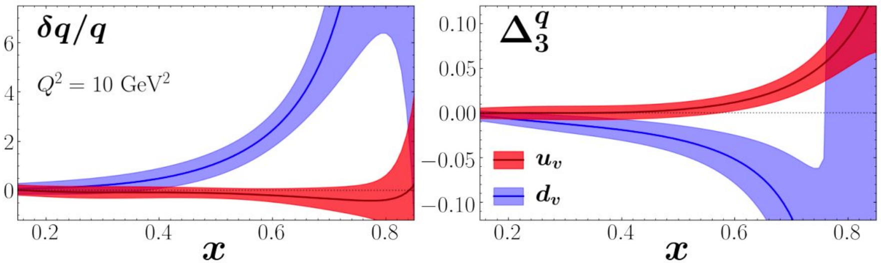


FIG. 3. Ratio of off-shell to on-shell PDFs $\delta q/q$ (left) and the difference between proton valence quarks in ^{3}He and ^{3}H normalized to the sum, Δ_3^q (right), for valence u (red bands) and d (blue bands) quarks, at $Q^2 = 10$ GeV^2.

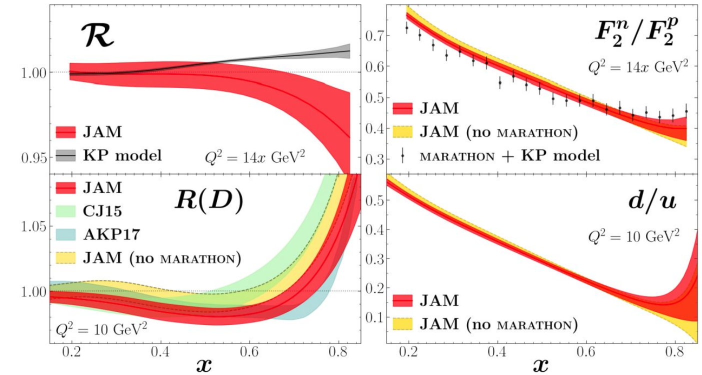


FIG. 2. Results from the present JAM analysis including MARATHON data (red bands) for the super-ratio $\mathcal{R}$ (top left), F_2^n/F_2^p ratio (top right), deuteron EMC ratio $R(D)$ (bottom left), and the d/u ratio (bottom right), compared with those without the MARATHON data (yellow bands). The super-ratio $\mathcal{R}$ is compared with the KP model input (gray band) used to extract the F_2^n/F_2^p ratio in [12]. The deuteron EMC ratio $R(D)$ is also compared with that from CJ15 [5] (green band) and AKP17 [6] (light blue band).

Backup for kinematics

$$x^* = \frac{Q^2}{2p_N^\mu q^\mu} \approx \frac{Q^2}{2M\nu(2-\alpha_s)} = \frac{x}{2-\alpha_s}$$

$$y^* = \frac{p_N^\mu q_\mu}{p_N^\mu k_\mu} \approx y,$$

$$M^{*2} = (M_d - E_s)^2 - \vec{p}_s^{\,2}.$$

$$M^{*2} = (M_d - E_s)^2 - \vec{p}_s^{\,2}.$$

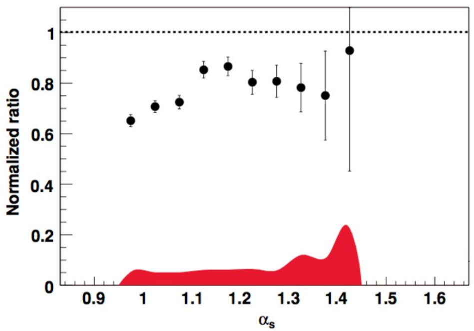


Figure 11: Ratio of the extracted off-shell structure function F_{2n} at $x' = 0.55$, $Q^2 = 2.8\,\mathrm{GeV}^2$ to that at $x' = 0.25$, $Q^2 = 1.8\,\mathrm{GeV}^2$, divided by the ratio of free structure functions at those kinematic points. The error bars show the statistical uncertainty; the shaded band indicates the systematic uncertainty. [31]

The ratio between the $d(e,en_s)$ cross section at two different x' values, keeping the recoil nucleon kinematics the same, is:

$$\frac{d^4\sigma}{dx_1 dQ_1^2 d\vec{p}_s} \Big/ \frac{d^4\sigma}{dx_2 dQ_2^2 d\vec{p}_s} = (K_1/K_2)[F_2^*(x_1', \alpha_s, p_T, Q_1^2)/F_2^*(x_2', \alpha_s, p_T, Q_2^2)]$$

Using $x_1' \approx 0.5-0.6$ and $x_2' \approx 0.3$ we will measure the ratio of effective structure functions:

$$[F_2^*(x_1', \alpha_s, p_T, Q_1^2)/F_2^*(x_2', \alpha_s, p_T, Q_2^2)] = \left(\frac{d^4\sigma}{dx_1 dQ_1^2 d\vec{p}_s}/K_1\right) \Big/ \left(\frac{d^4\sigma}{dx_2 dQ_2^2 d\vec{p}_s}/K_2\right)$$

Integrating over the recoil scattering angle in the range where the FSI is expected to be small, we will compare the measured ratio as a function of α_s to the measured free proton structure function.

Are we done with (nuclear) corrections?

Theoretical choices →

Corrections (increasing-x) ↓

	KP	AKP	CJ15	AKP-like
shadowing	yes	yes (which one?)	MST x<0.1	(same)
smearing	Paris	AV18	AV18 x>0.1	(same)
pi-cloud	yes	yes	----	----
TMC	GP O(Q4)?	GP O(Q4)??	GP approx.	(same)
HT	H (p=n ??)	H (p=n)	C (p=n)	H & C, p=n & p!=n
HT(x)	??	5 pt. spline	parametrized	parametrized
off-shell	O(p2-M2)	O(p2-M2)	O(p2-M2)	(same)
df(x)	factorized	polyn. 2nd/3rd	factorized + sum rule	polyn. 2nd/3rd
pi thresh.	yes	yes	----	----

Are we done with (nuclear) corrections?

Theoretical choices →

Corrections (increasing-x) ↓

	KP	AKP	CJ15	AKP-like
shadowing	yes	yes (which one?)	MST x<0.1	(same)
smearing	Paris	AV18	AV18 x>0.1	(same)
pi-cloud	yes	yes	[illegible]	----
TMC	GP O(Q4)?	GP O(Q4)??	GP approx.	(same)
HT	H (p=n ??)	[illegible]	[illegible]	H & C, p=n & [illegible]
HT(x)	??	5 pt. spline	parametrized	parametrized
off-shell	[illegible]	[illegible]	[illegible]	(same)
df(x)	factorized	polyn. 2nd/3rd	[illegible] rule	polyn. 2nd/3rd
pi thresh.	yes	yes	----	----

There is no "off-the-shelf" nuclear correction model:

One needs to know and pay attention to the detail

(yes: that means reading the theory papers without rush….)