PDFs and nuclear structure in the CJ global analysis

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with many thanks to my CTEQ-JLab collaborators:
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C.E. Keppel, W. Melnitchouk, P. Monaghan

Short-Distance Nuclear Structure and PDFs
Jefferson Lab, 20 June 2023

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The CTEQ-JLab collaboration

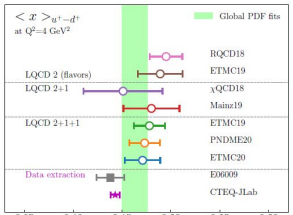
- **Coordinated Theory-Experiment Effort with Jefferson Lab:**
  - A. Accardi, **Xiaoxian Jing**, **Ishara Fernando**, W.Melnitchouk, J.F.Owens
  - C.E. Keppel, **Shujie Li**, P. Monaghan, **Sanghwa Park**

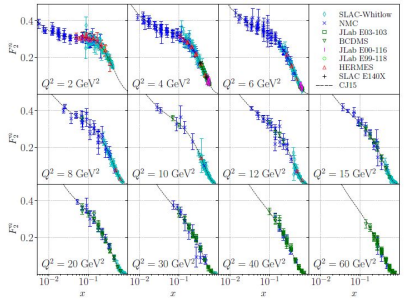
- **Focus and recent work:**
  - Large-x, low-Q^2 $\longrightarrow$ TMC, HT
  - Nuclear dynamics $\longrightarrow$ p,n motions, off-shell PDFs

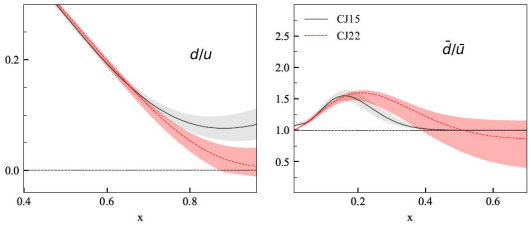
  } **CJ15** *Accardi et al.,PRD 93 (2016) 114017 `*

  - F2(n) extraction, **CJ15ht** and **CJ15sfn** (S. Li, I. Fernando)
  - Light antiquarks, **CJ22** (S. Park, X. Jing)
  - In the works (S. Park)
    $\longrightarrow$ [Strange sea with LHC data]

- **nCTEQ connection** $\longrightarrow$ nPDFs







Park et al., arXiv:2303.11509 (accepted in PRD)

Today's story:

- **Valence quarks and the deuteron**
  - Uncertainties and biases
- **Theoretical biases at large x**
  - Interplay of HT and off-shell corrections
  - Interplay of dbar/ubar (at medium x) with d/u and HT (at large x)
- **Perspectives**
  - Tagged protons and neutrons
  - PVDIS on p and D
  - … ← discussion
- **Extras**, if you are interested or not hungry:
  - F2(n) and F2(n/p) extraction
  - nCTEQ: nuclear PDF fits with JLab data and large x corrections

References

Large-x fits with nuclear corrections

- **CJ15**: Accardi et al., PRD 93 (2016) 114017
  - Accardi, DNP 2020 / Fernando, GHP 2021 / Accardi, APS 2022
- **CJ22:** Accardi et al. PRD 107 (2023) 113005
- **AKP**: Alekhin, Kulagin, Petti, PRD 96 (2017) 054005 & arXiv:2203.07333
- **JAM**: Cocuzza et al. (JAM), PRL 127 (2021) 24
- nCTEQ15HIX: Accardi et al., PRD 103 (2021) 114015

PDF uncertainties

- Hunt-Smith, Accardi, Melnitchouk, Sato, Thomas, White, arXiv:2206.10782

PVDIS study

- Brady, Accardi, Hobbs, Melnitchouk, PRD 84 (2011) 074008

Light quark asymmetry, QCD analysis

- Park, Accardi, Jing, and Owens, arXiv:2108.05786
- Guzzi et al. (CT), arXiv:2108.06596
- Cocuzza et al. (JAM), PRD 104 (2021) 074031
- Alekhin, Garzelli, Kulagin, Moch, arXiv:2306.01918

General References

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*

- **Valence quarks and the deuteron**
  - Uncertainties and biases

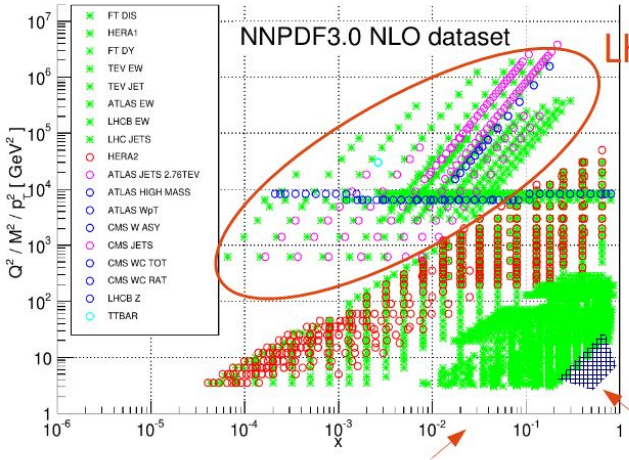
Global QCD fits

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

pQCD calc.

PDFs (from DIS fits)

- pQCD factorization & universality:
  can fit PDFs to a variety of hard scattering data
  - Hadron-hadron collisions
    - ⟶ Jets
    - ⟶ Electro-weak boson production
  - Electron-proton DIS
  - Electron-Deuteron DIS
- >1000‘s data points
- 40+ years of experience,
  - “High-energy” fitters:
    - ⟶ CTEQ-TEA, MMHT, NNPDF, HERAPDF
  - Lower-energy / nuclear focus:
    - ⟶ **CTEQ-JLab, AKP**, ABMP, **JAM**



LHC data

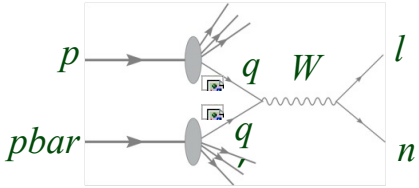
W and Z

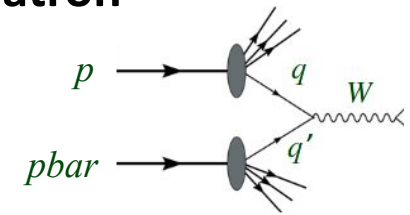
SLAC, JLab

DY and DIS (on p, d)

Large-x PDFs: the valence quark triangle

W bosons @ Tevatron

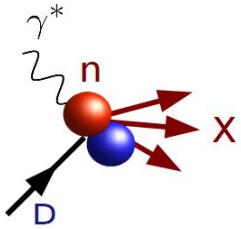




$$A_W(y) \xrightarrow{y \to y_{max}} \frac{1 - d/u}{1 + d/u}$$

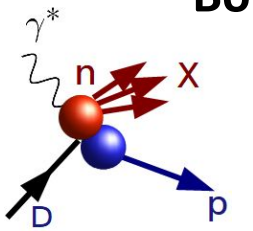
d/u
+
nuclear dynamics

DIS on Deuterium



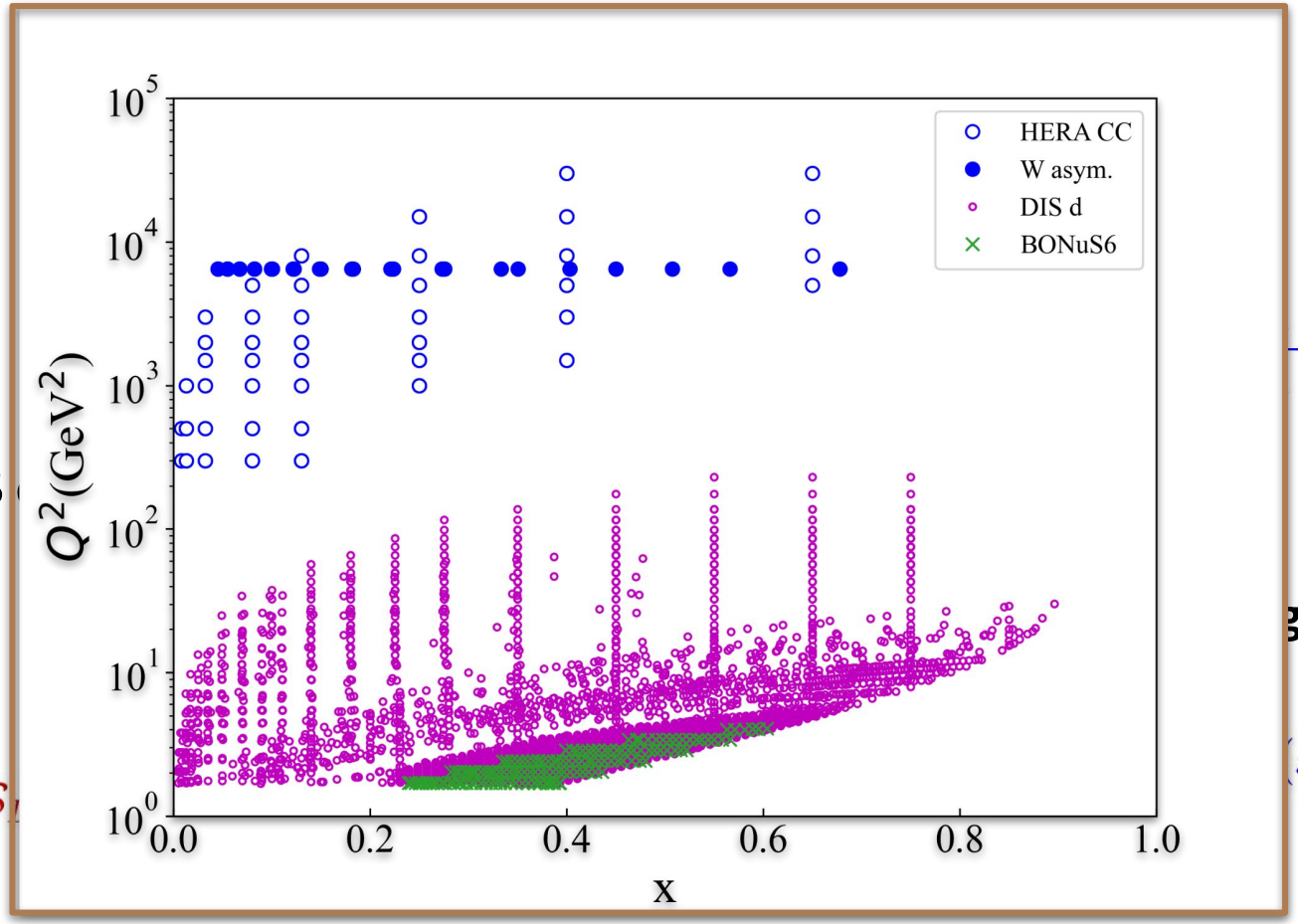
$$F_2^d \propto \mathcal{S}_D \otimes \left[x u_{\text{off}}(x) + x d_{\text{off}}(x) \right]$$

"BoNuS" tagged DIS



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

Large-x PDFs: the valence quark triangle



DIS

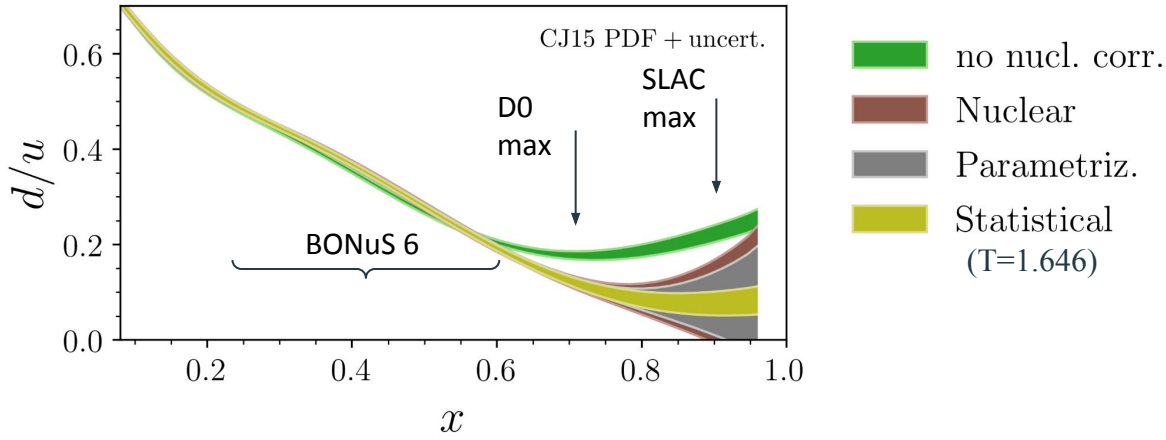
$\frac{-d/u}{+d/u}$

ged DIS

$F_2^d \propto \mathcal{S}$

$(x) + 4xd(x)$

The CJ15 d/u ratio

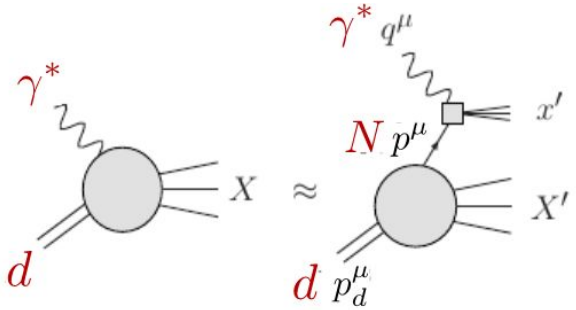


- **Statistical uncertainties**
  - Propagated from exp. stat. errors into the PDF parameters
- **Theoretical uncertainties**: difficult to quantify, e.g.:
  - Nuclear: wave function choice (here: WJC2, AV18, CD-Bonn)
  - Off-shell uncertainties are parametrized → partly included in statistical band
  - Parametrization: *d*-quark flexibility in extrapolation region
- **Theoretical biases**: even less obvious!
  - Interplay of HT and offshell implementation choices / parametrization flexibility

- **Theoretical biases at large x**
  - **Interplay of HT and off-shell corrections**
  - Interplay of d/u (at large x) and dbar/ubar (at medium x)

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**

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

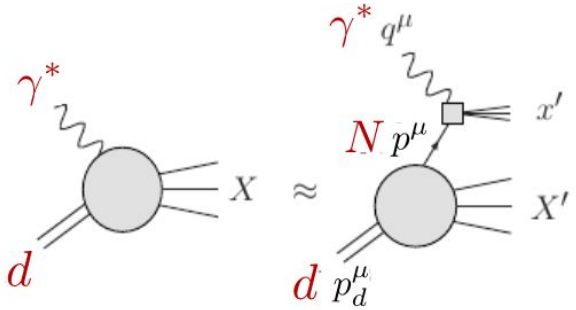
momentum fraction of d carried by N

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

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

Deuteron 2: Off-shell corrections

- **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:**
  - Expand PDFs in nucleon's virtuality $q_N(x, Q^2, p^2) = q_N^{\text{free}}(x, Q^2)\left[1 + \frac{p^2 - M^2}{M^2}\delta f_q^N(x)\right]$
  - With flavor-independent δf

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

Free proton, neutron structure function

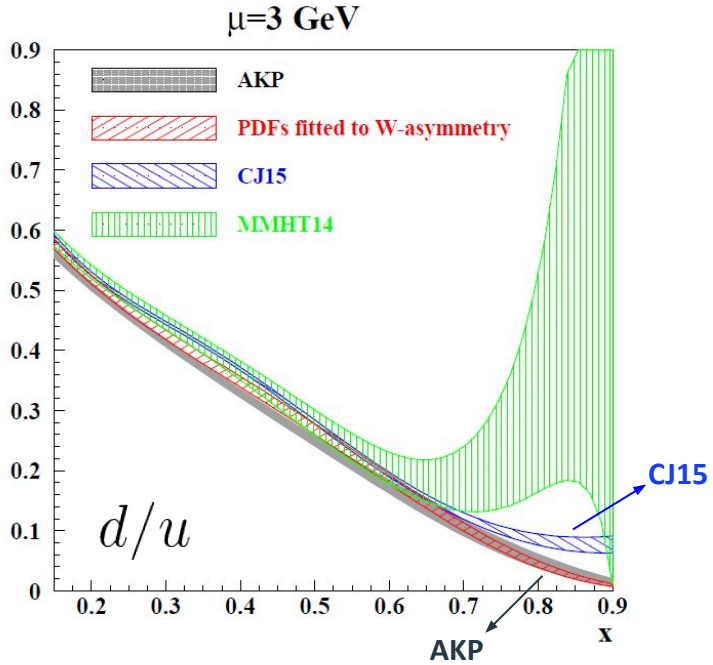
"offshell function"

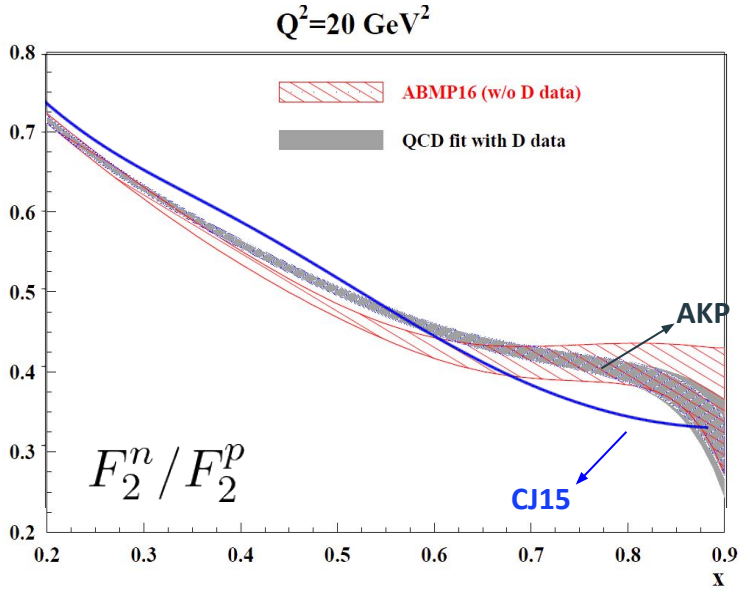
When fitted, this effectively becomes a phenomenological "catch-all" term (see later)

  - Parametrized and fitted (see the earlier triangle)

→ **CJ15, AKP, JAM**

CJ15 and AKP: free nucleons

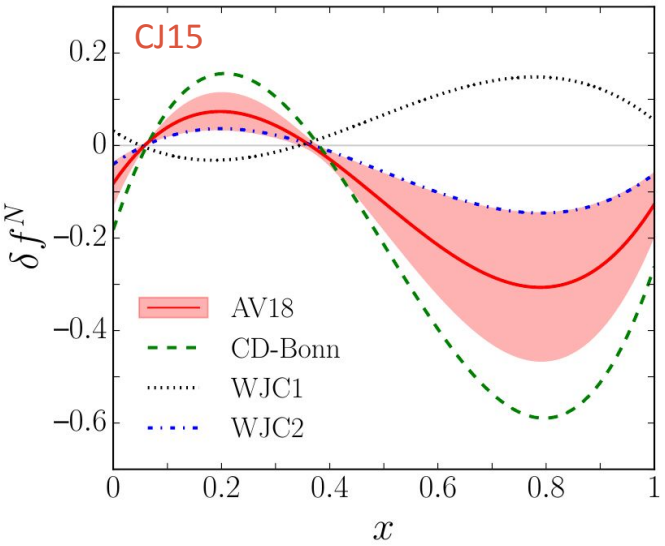


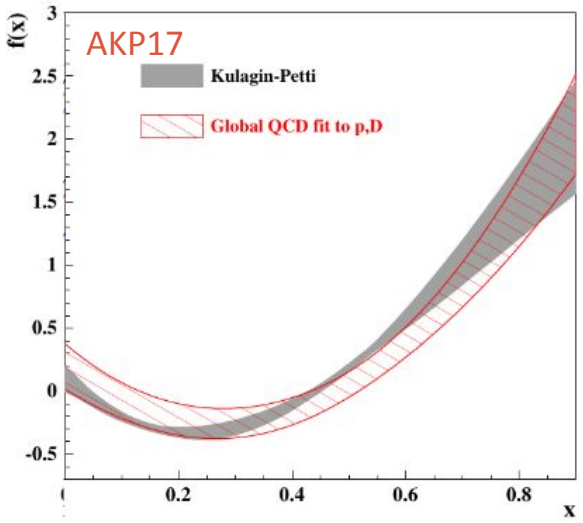


CJ15: *PRD 93 (2016) 114017*
AKP: *PRD 96 (2017) 054005*
(see also 2203.07333)

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

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 (MANY) 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
  - …

CJ + AKP benchmarking effort

The most important, in our opinion!

HT systematics

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

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

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

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

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

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

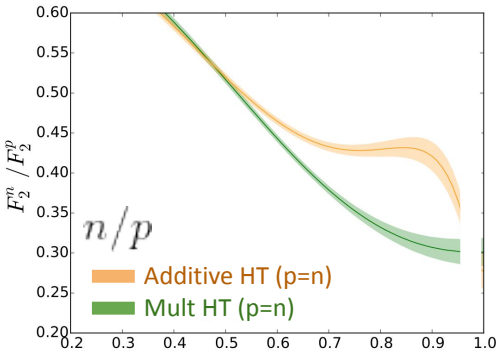
- **Non-negligible large-*x* bias**
  - **if using isospin-independent coefficients**
    → Multiplicative (CJ15) underestimates
    → Additive (AKP17) overestimates ($H > 0$)

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

CJ fits - isospin symmetric HT

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

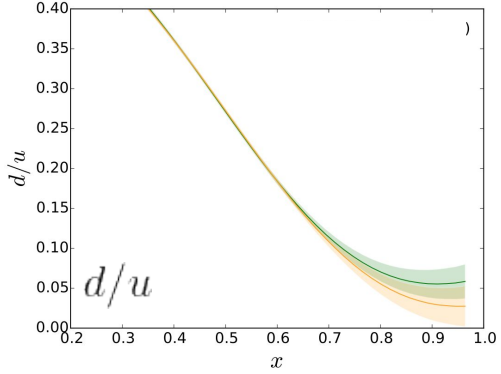
- Additive n/p
  - Larger than Mult n/p
  - Even if d/u is smaller
- Fitted offshell function compensates n/p bias
  - D/p well fitted, indeed
- **CJ15/AKP17 differences are reproduced!**
  - And explained

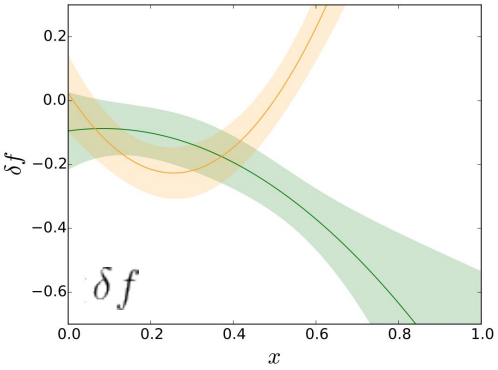


Isospin symmetric case

Additive HT (p=n)

Mult HT (p=n)
→ essentially* CJ15



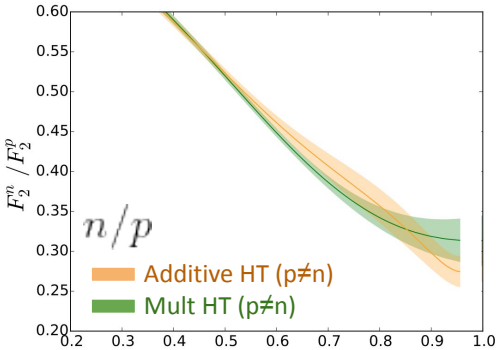


* uses generic 2nd order polynomial δf

CJ fits - isospin breaking HT

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

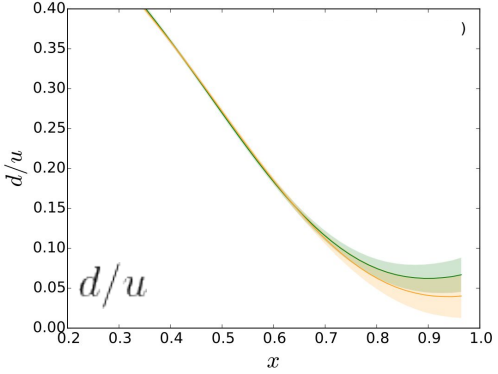
- **Bias removed !!!**
  - Small systematics remains
- ***n/p & d/u***
  - **Much closer to CJ15**
  - Attention when using AKP!
- Small *δf* offshell correction
  - When averaged over *p* and *n*
  - Large cancellation is possible, but need A=3 data to confirm
    (Tropiano et al., PRC 2019)
    (Cocuzza et al., PRD 2021)

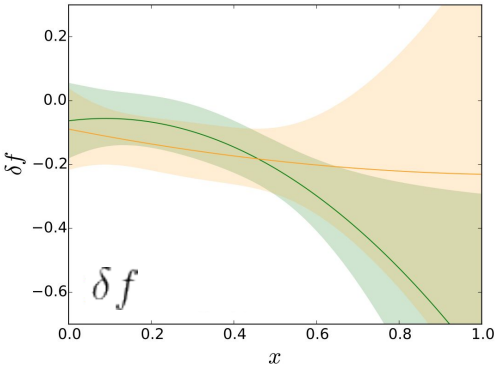


Isospin breaking case

Additive HT (p≠n)

Mult HT (p≠n)

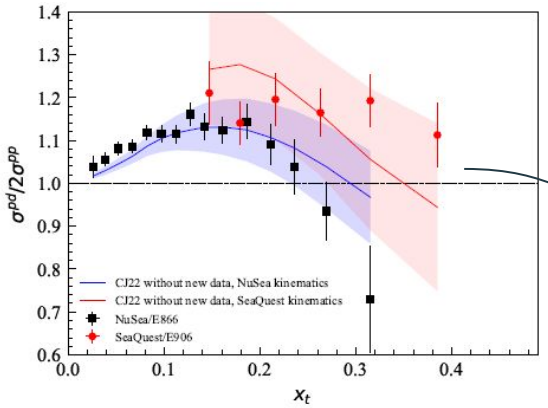




- **Theoretical biases at large x**
  - Interplay of HT and off-shell corrections
  - **Interplay of d/u (large x) and dbar/ubar (med. x)**

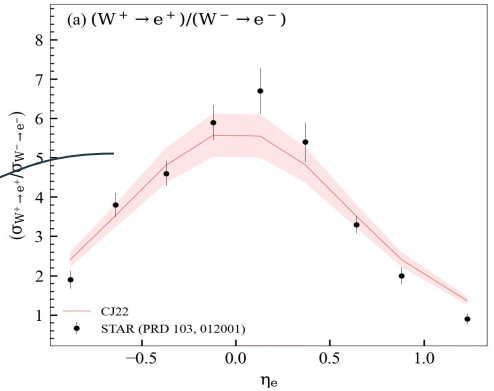
New electroweak data

SeaQuest



Fits w/o new data

STAR $W^+ \to e^+ / W^- \to e^-$



$$\frac{\sigma_{pd}}{\sigma_{pp}} \approx \frac{4 + \frac{d(x_b)}{u(x_b)}}{4 + \frac{d(x_b)}{u(x_b)}\frac{\bar{d}(x_t)}{\bar{u}(x_t))}} \left(1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right)$$

$$\frac{\sigma_{W^+}}{\sigma_{W^-}} \approx \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)} \underset{y_W \approx 0}{\approx} \frac{\bar{d}/\bar{u}}{d/u}$$

Anticorrelation: db/ub ⟷ d/u
med. xt ⟷ large xb
(0.05 – 0.4) (0.3–0.7)

Correlation: db/ub ⟷ d/u
x ~ 0.16

Need flexible enough parametrization

CJ22: new light antiquark parametrization

- **CJ15:** *Accardi et al., PRD 93 (2016) 11*

$$\bar{d}/\bar{u} = a_0\, x^{a_1}(1-x)^{a_2} + 1 + a_3 x(1-x)^{a_4}$$

  - Large *x*: tends to 1 from above
  - a_0 and a_3 fixed: shape "hugs" E866 data

- **CJ22:** follows `CJ15-a`, reverts back to `CJ12` param: *Accardi et al., PLB* 801 (2020) 135143

$$x(\bar{d}-\bar{u}) = \bar{a}_0\, x^{\bar{a}_1}(1-x)^{\bar{a}_2}(1+\bar{a}_4 x)$$

  - Unconstrained x⟶1 limit
  - Free $\bar{a}_2$ instead of fixing $\bar{a}_2 = a_2 + 2.5$
  - **More flexibility** → more data, fix extra parameters
    → sensitivity to db/ub ⟷ d/u anticorrelation

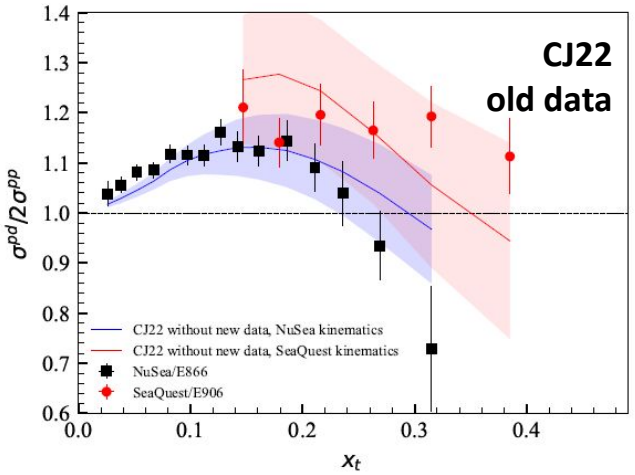
CJ22: new fit framework

- **Electroweak pair production** *(Xiaoxian Jing)*
  - γ, **W, Z**
  - DYnamical NLO calculations with APPLgrid + MCFM
  - Tested against E866, D0 W asymmetry in CJ15
  - New MCFM grids for STAR W and Z production

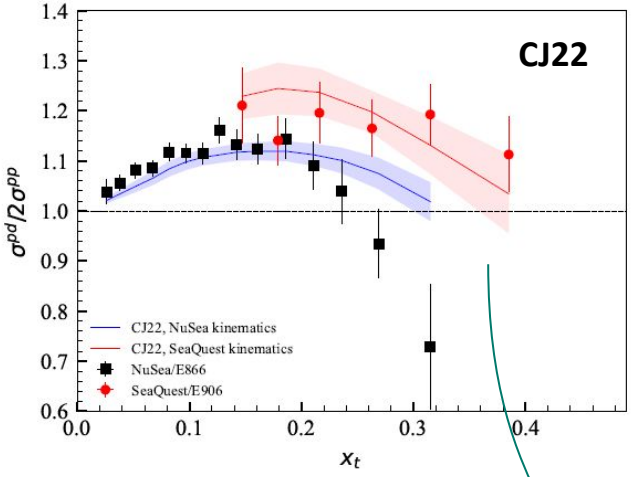
    $\longrightarrow$ Preliminary grids also for W and Z at the LHC

- **"Adjusted" Hessian approximation** *Accardi et al., EPJC 81 (2021) 7*
  - Constrained observables (e.g., n/p $\longleftrightarrow$ d/u at large x)
  - Regions with poor data constraints (e.g., db/ub at x > 0.3, extrapolation)

Lepton Pair Production



Fit new data
(SeaQuest & STAR)



SeaQuest: χ^2/datum = 3.19 → 1.25

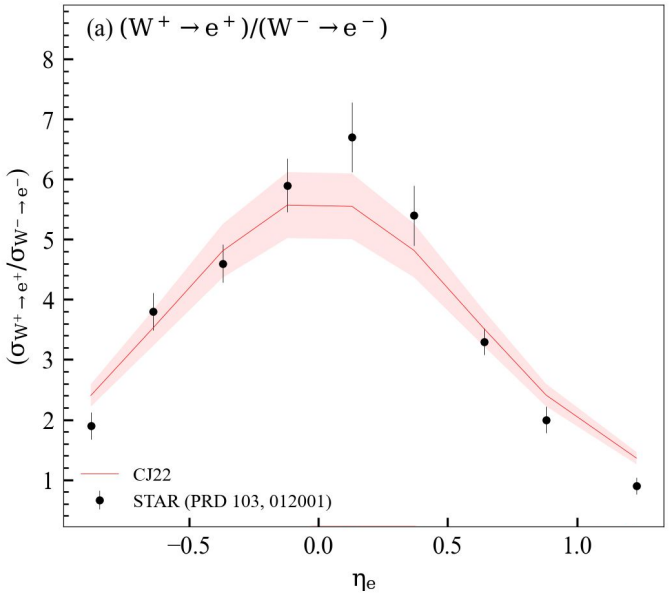
E866 : χ^2/datum = 1.63 → 1.93

- Comparable results to JAM, CT

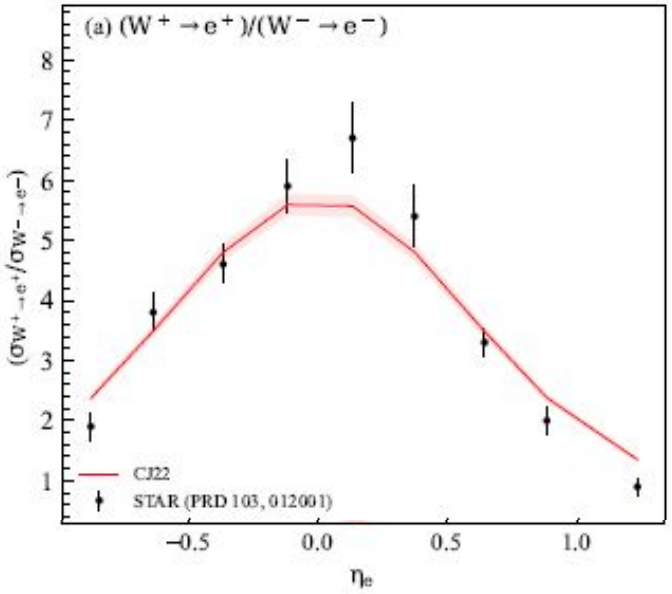
E866, SeaQuest disagree:
How to include in error bands?

→ new idea, K. Mohan @ DIS 2023

Weak boson production

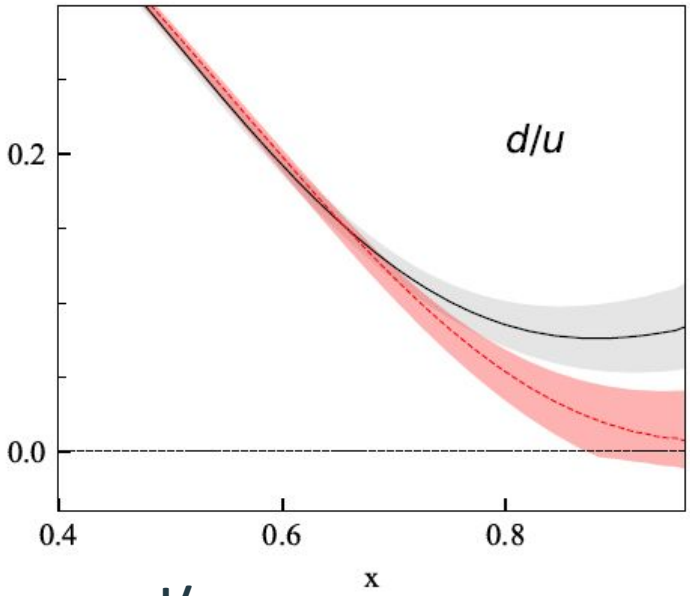


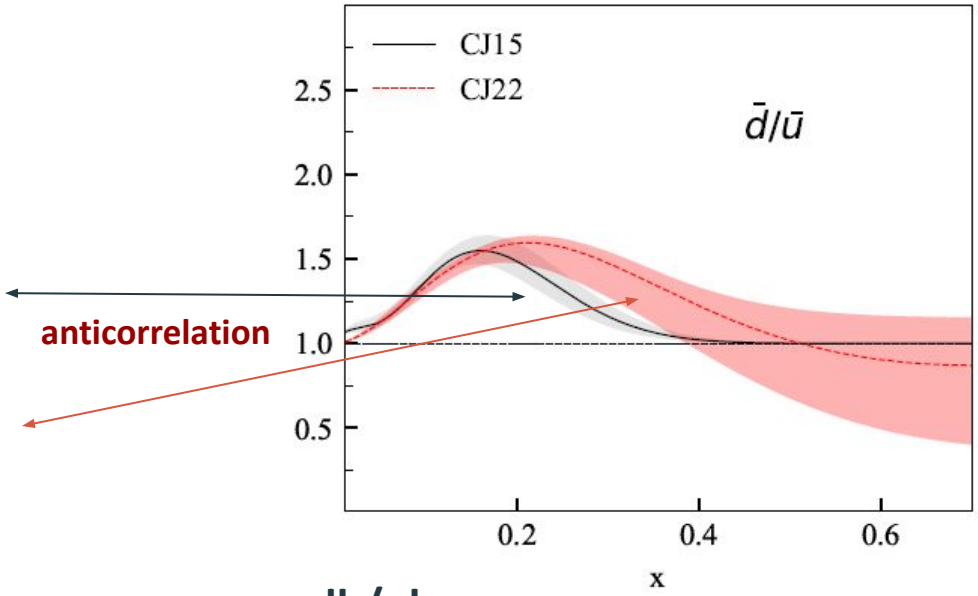
Fit new data
(SeaQuest & STAR)



- Large reduction in uncertainty driven by SeaQuest data
- STAR contributes ~ 15% reduction around x~0.16
  - distributed between d/u (5%) and db/ub (10%) PDF ratios

Light quarks and anti quarks

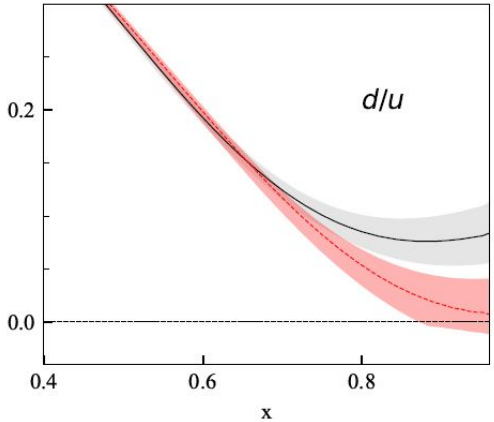


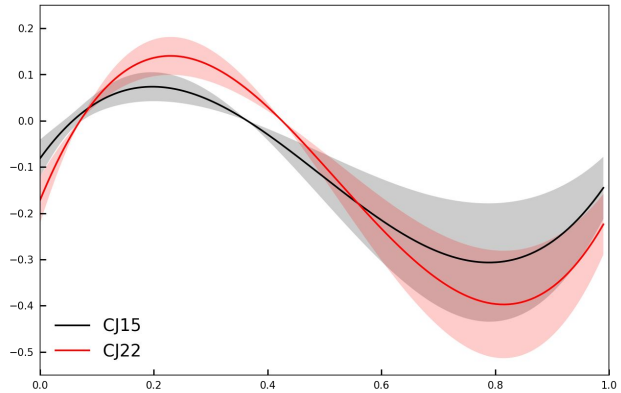


- **d/u**
  - CJ15 was biased upwards
  - CJ22 agrees with AKP
- **db/ub**
  - pulled up by SeaQuest
  - Naturally relaxes to 1 at large *x*

What about the offshell function?

- **No big change!**
  - **Difference in d/u largely absorbed by HT term**
  - But, HT still multiplicative, p=n, old parametrization



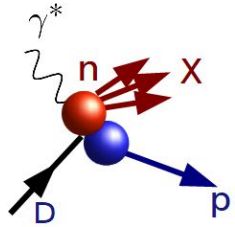


- **Need to revisit the HT/offshell unbiasing analysis** with CJ22
  - Allow p=n, polynomial offshell parametrization, mult vs. add HT
  - Expect small, approx 0 offshell function

    ⟶ Similar to JAM result

- **Open Questions & Perspectives**
  - Tagged protons and neutrons
  - PVDIS on p and D
  - … ← discussion

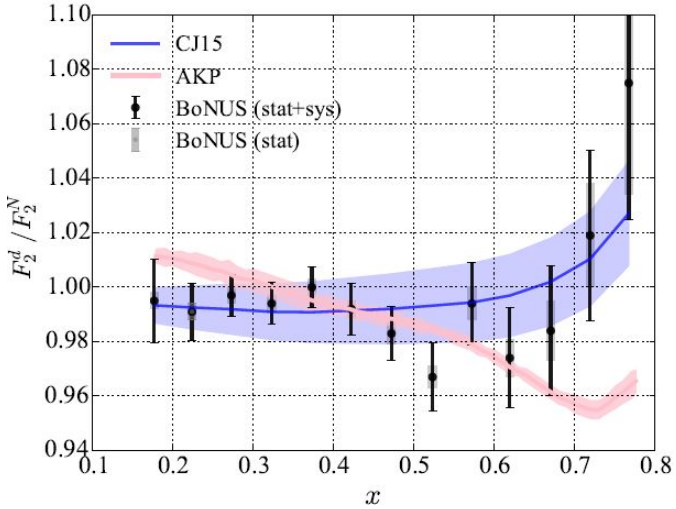
Open questions 1

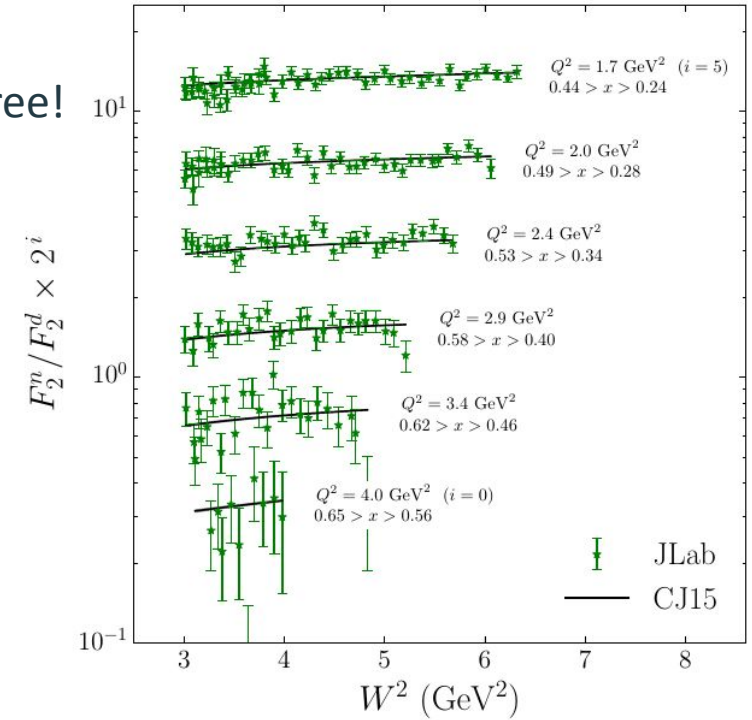


- Can we confirm the nuclear model used? Is δf zero or negative?
  - **Need direct experimental sensitivity to δf** (through p^2 dependence)
  - **Tagged DIS** experiments at **JLab 6, 12 and EIC**

    ⟶ **With p^2 binning!**

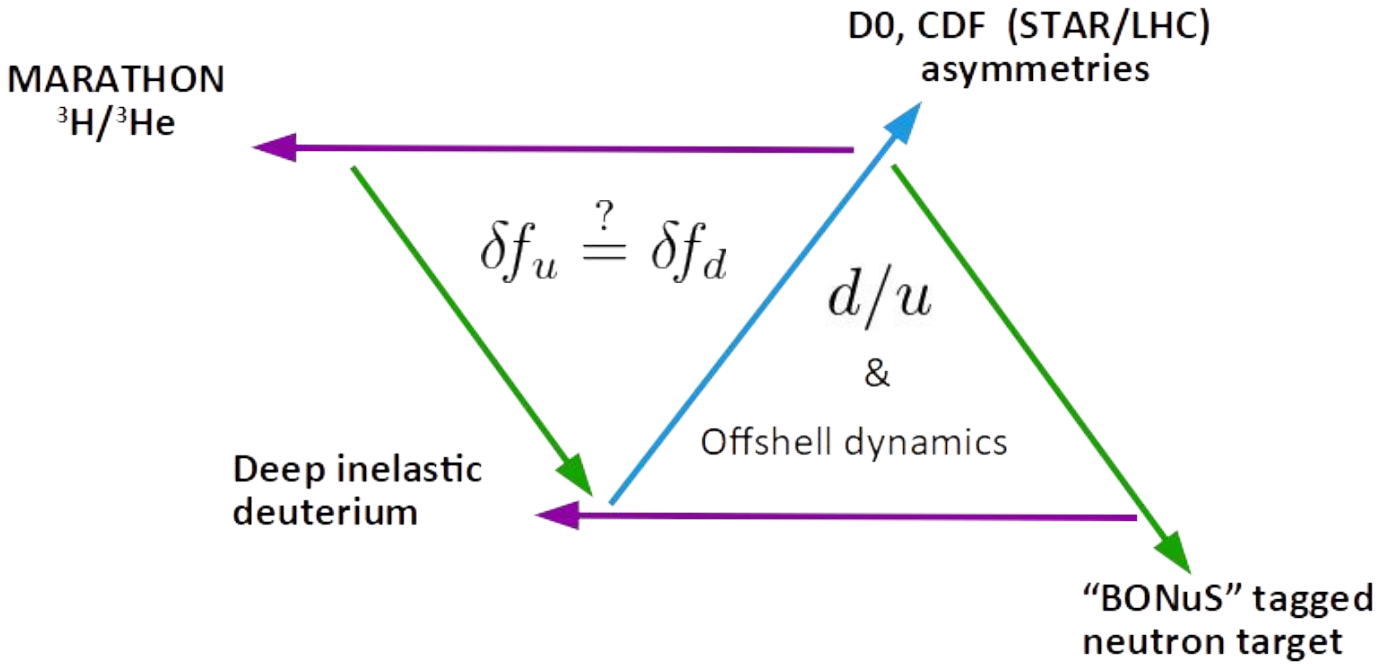
- To start with, BONuS 6 don't seem to disagree!
  - But may not be precise enough at large x





Open questions 2

- We can extend the large-*x* triangle to a parallelogram
  - ⟶ **and verify if off-shell is flavor independent or not !!**
  - ⟶ …hence if off-shell protons ~ off-shell neutrons



Open questions 2

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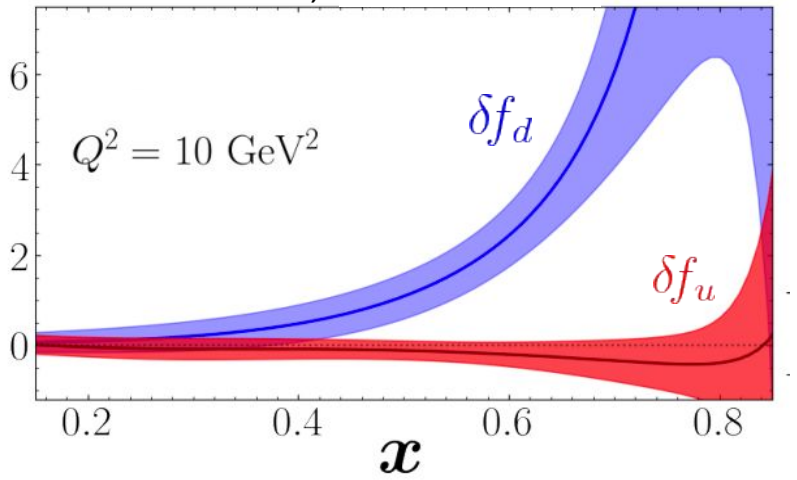
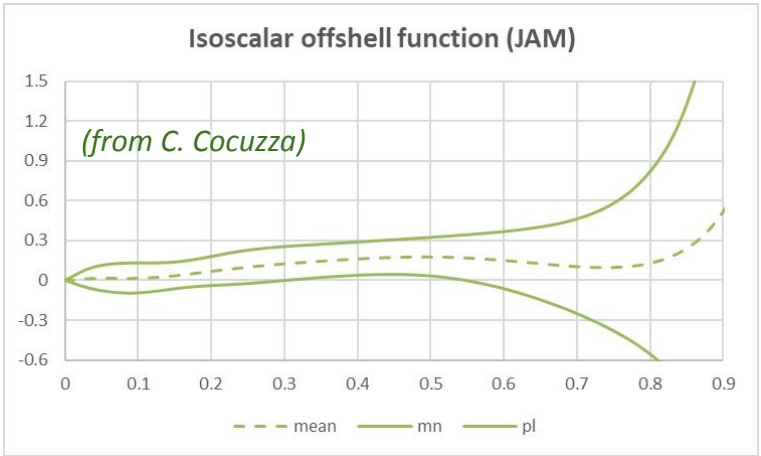
JAM

C. Cocuzza et. al., arXiv:2104.06946



$$\delta f|_{\rm CJ} \approx \frac{u\,\delta f_u + d\,\delta f_d}{u+d}$$



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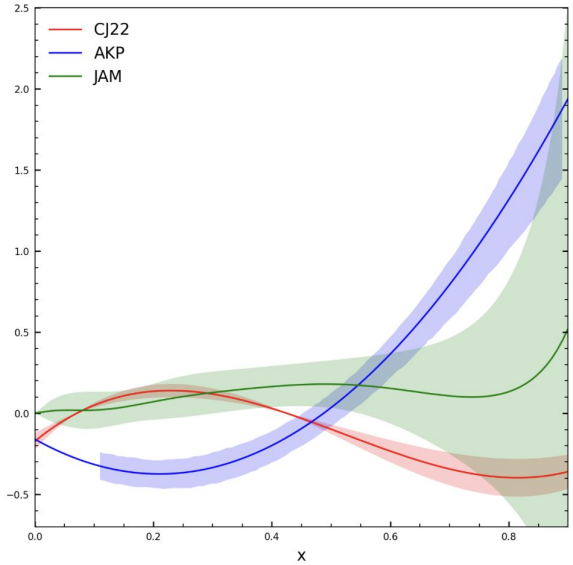


AKP: add, p=n

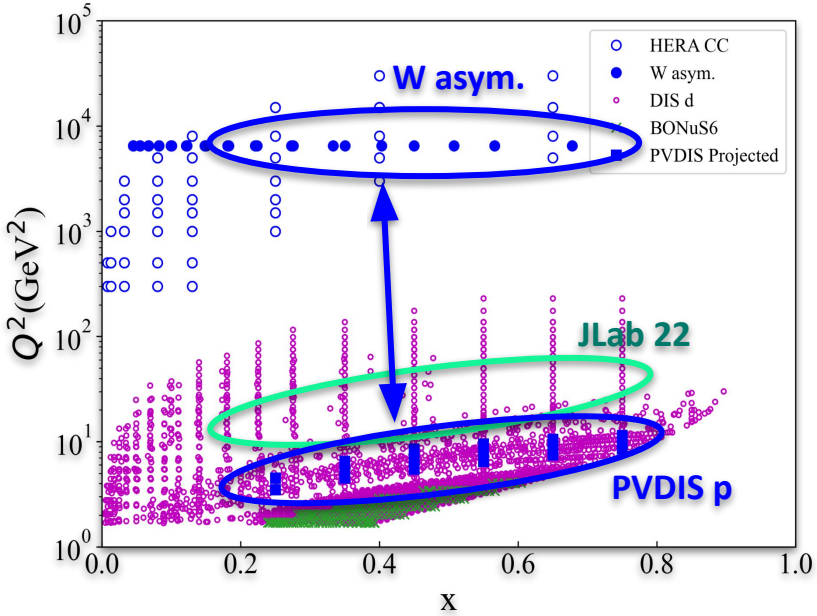
JAM: mult, p≠n
(actually, u ≠ d)

CJ22: mult, p=n

Open questions 3

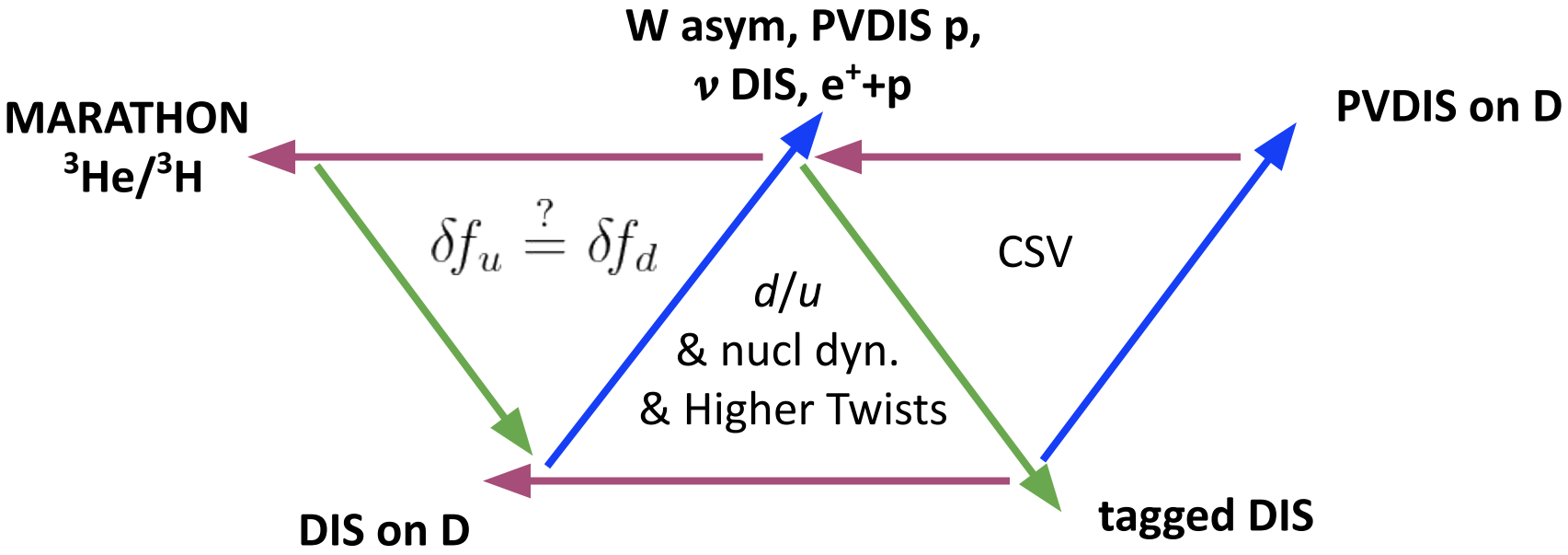
- But is also $\delta f_u^p \stackrel{?}{=} \delta f_d^n$ as assumed in the JAM analysis?
  - **Are there nuclear-level CSV effects?**

- How to tell?
  - **PVDIS on protons and deuterons?**



Need half a honeycomb, at least!

- **Global QCD analysis is a powerful tool:**
  - ⟶ d/u, nuclear dynamics, parton correlations, CSV
  - ⟶ PVDIS still relevant in BONuS 12 / Marathon era !!



Finally...

Final thoughts

- **Large-*x* data analysis in global QCD fits: PDFs and nuclear structure!**
  - Needs careful attention to systematic bias
    - ⟶ HT assumptions can deform the extracted offshell function
    - ⟶ Isospin-asymmetric parameterization is needed
      - How to best formulate this
      - Is charge symmetry a suitable assumption?
    - ⟶ Is the off-shell expansion framework too naive?

- **Need**
  - **Spectator tagging data – binned in $v = p^2/M^2 - 1$!!**
    - ⟶ Direct test of off-shell expansion,
      - and test of FSI models *e.g., talk by C.Weiss*
    - ⟶ Cross check with on-shell extrapolated data *(Sargsian & Strikman, Weiss et al.)*
  - **PVDIS in a global QCD analysis**
    - ⟶ Proton: will contribute to *d/u* fit precision and accuracy
    - ⟶ Deuteron: with HT under control, can focus on CSV / BSM / EMC

talk by Reimer

Final thoughts

- **High-quality data is expected**
  - **Need high-quality phenomenology and theory**
    - ⟶ We are in time to develop this! *see talks by Rinaldi, Fornetti, Weiss*
- For example,
  - Nuclear/off-shell and CSV corrections currently assume

$$D = \mathcal{S} \otimes \left[p + n\right] = \mathcal{S} \otimes \left[(u^* u^* d^* + \ldots) + (u^* d^* d^* + \ldots)\right]$$

    - ⟶ Neglects higher Fock hadronic states
    - ⟶ Off-shell function may just be a phenomenological, cover-all blanket
  - Maybe better to describe the Deuteron at parton level?

$$D = \left[u\,u\,d\,u\,d\,d\ + \ldots\right]$$

    - ⟶ Lattice QCD powerful enough these days, can guide pheno assumptions
  - Novel ideas – e.g., hard gluon exchange at large x talk by Sargsian

Thank you!

EXTRAS

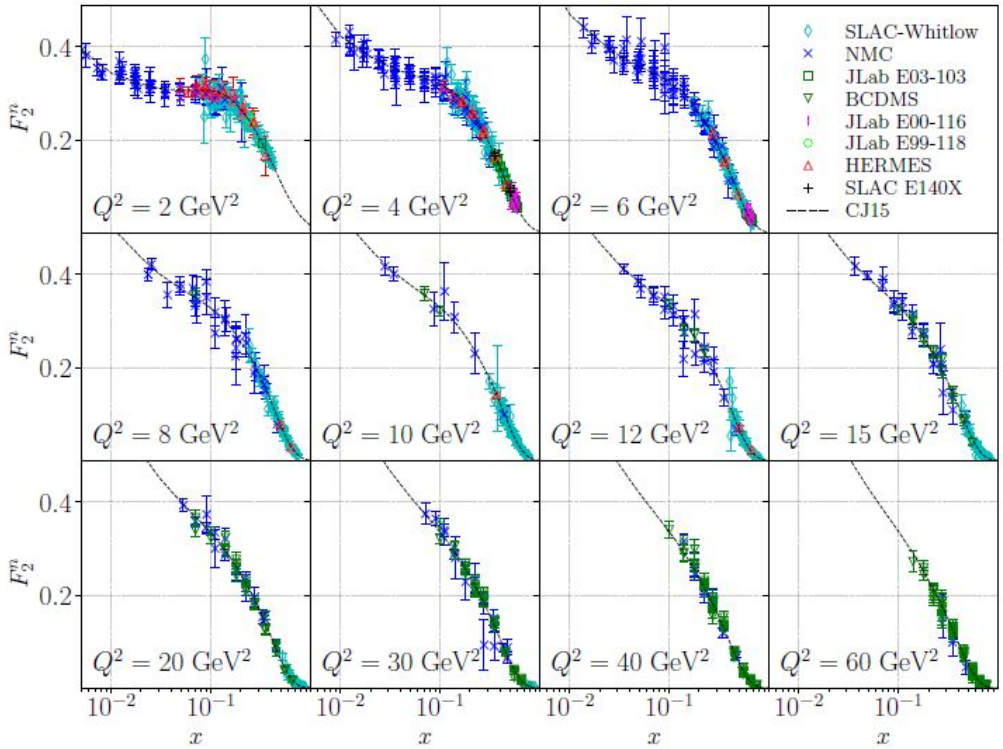
F_2(n) extraction and applications

S. Li & CJ – nearly finished

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

- **But also:**
  - P, d data matching
  - Data cross normalization
    - ⟶ using CJ15 PDFs
    - ⟶ refitting norm, Correlated shifts
  - Bin-centering for Isosinglet moment
  - …

- **SImilarly for n/d & d/p ⟶ n/p**



$F_2(n)$ extraction and applications

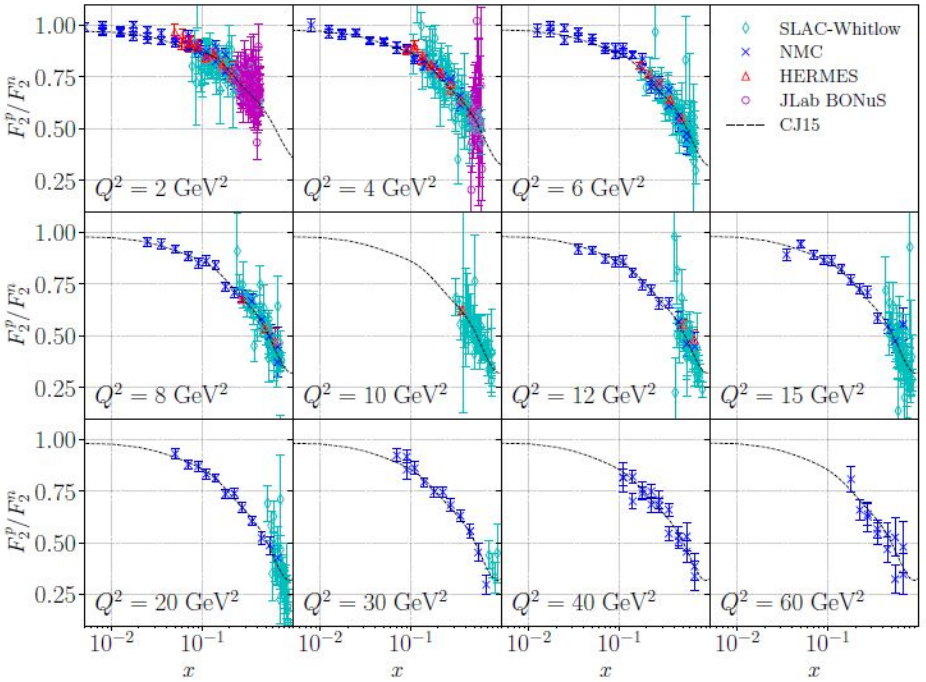
S. Li & CJ – nearly finished

- 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

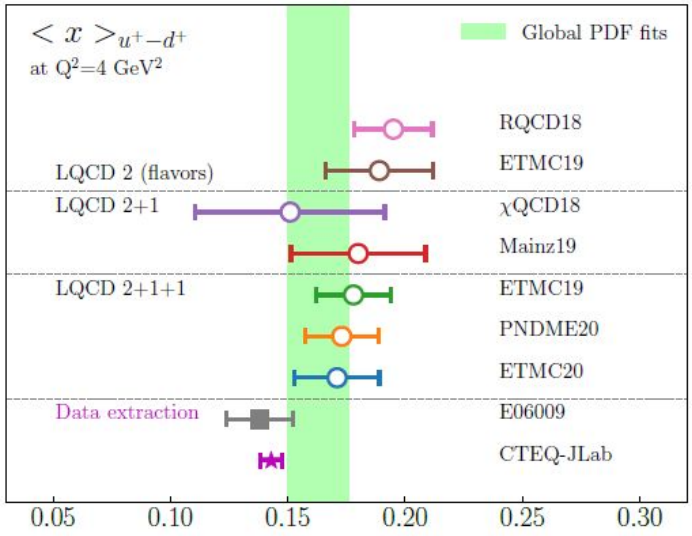
$$\widehat{R}^{(0)}_{n/p} \equiv \frac{\widehat{R}^{\mathrm{exp},(0)}_{n/d}\; R^{\mathrm{CJ}}_{d/N}}{1 - \widehat{R}^{\mathrm{exp},(0)}_{n/d}\; R^{\mathrm{CJ}}_{d/N}}$$



F_2(n) extraction and applications

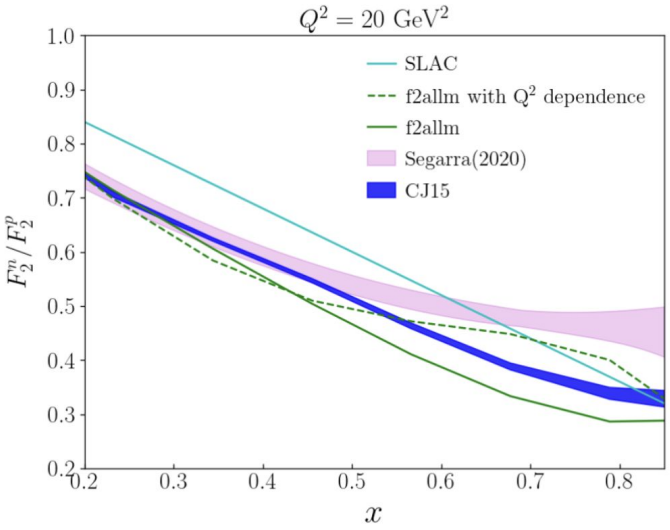
Soon on
https://www.jlab.org/theory/cj

- **World DIS database and extracted F2n, n/p ⇒** $\int F_2^p - F_2^n$



- **LHAPDF style structure function grids:**
  - NC and CC
  - w/ and w/o HT, TMC

```
sfn_p  = lhapdf.mkPDF("CJ15_FpNC",0)
f2p    = sfn_p.xfxQ2(iset=908,x,Q2)
```

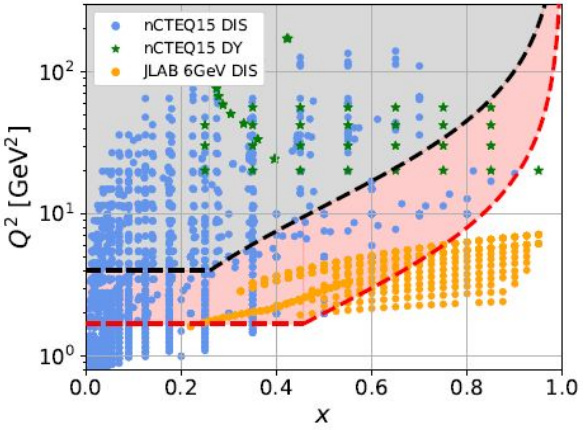


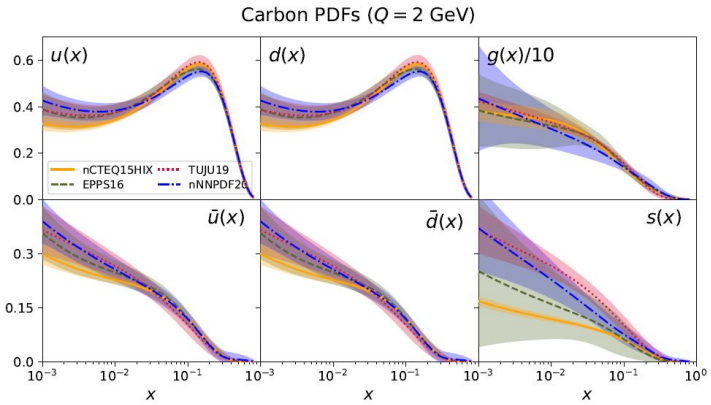
The nCTEQ connection

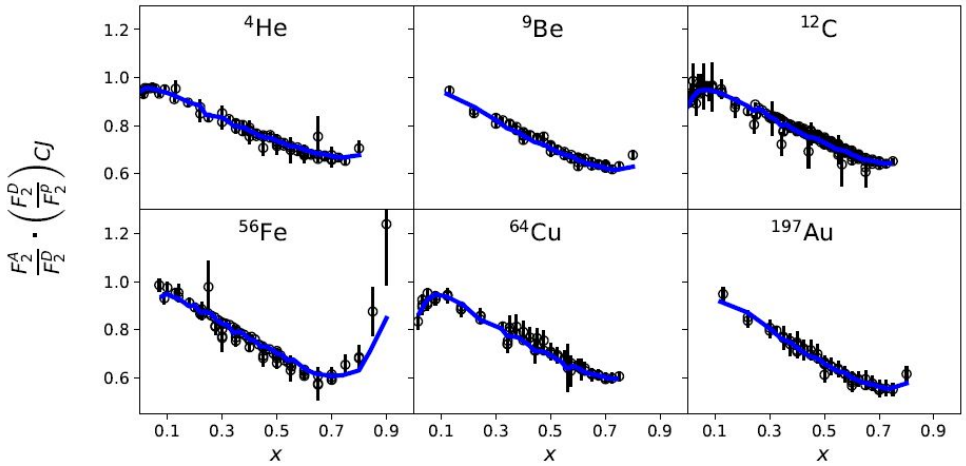
- Nuclear PDF fits: $\sigma_A = \sum_i f_{i/A} \otimes \hat{\sigma}_i$

Accardi et al., PRD 103 (2021), 114015

- First time including JLab data: **nCTEQ15HIX**
  - using CJ experience in HT, deuteron corrections at low-Q2 and large-x







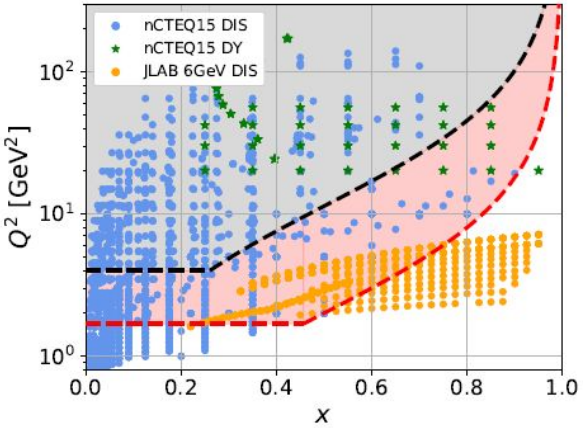
The nCTEQ connection

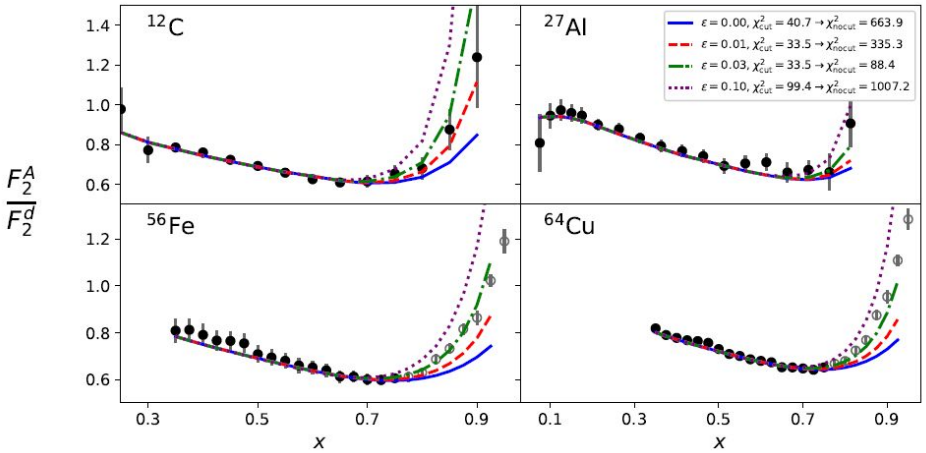
- Nuclear PDF fits: $\sigma_A = \sum_i f_{i/A} \otimes \hat{\sigma}_i$

- First time including JLab data: nCTEQ15HiX *Accardi et al., PRD 103 (2021), 114015*
  - using CJ experience in HT, deuteron corrections at low-Q2 and large-x
  - "Fermi motion" upturn (mostly in resonance region)

    Roughly parametrized by

$$x'_A = x - \varepsilon\, x^\kappa \log_{10} A$$

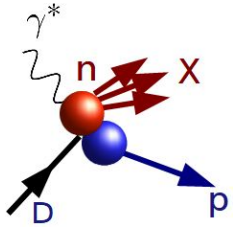




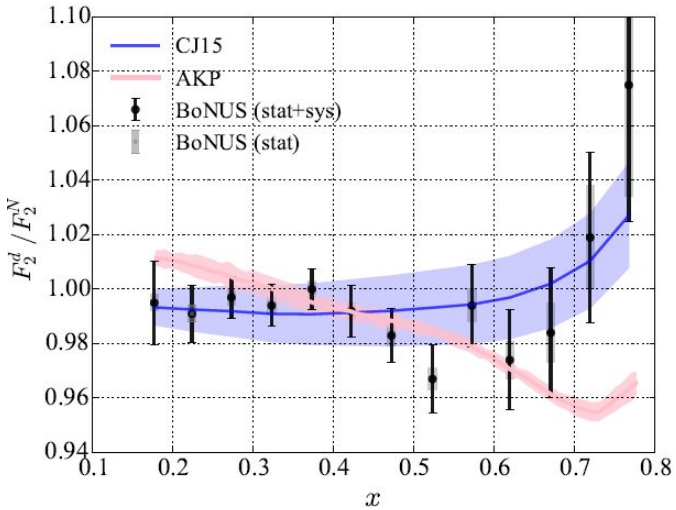
- New fit in preparation *Talk by P. DUwentaster & Risse et al @ DIS 2023, arXIv:2307.07814*
  - Explored also a SRC-inspired parametrization: *Denniston et al., inspirehep/2660149*

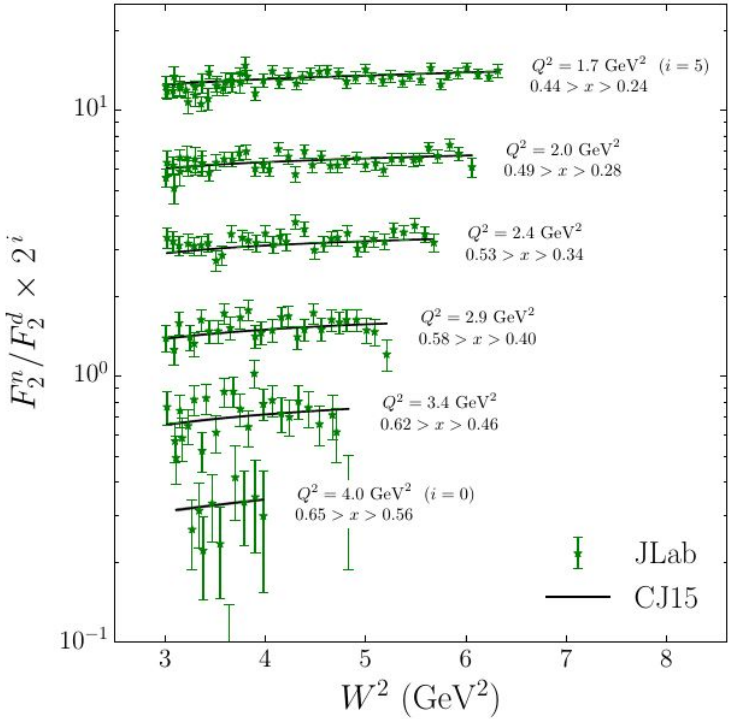
Tagged DIS to the rescue

Open questions

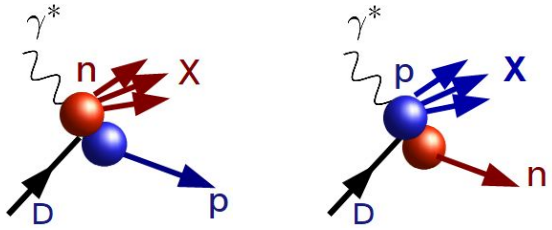


- Can we confirm the picture just painted? Is δf negative?
  - **Need direct experimental sensitivity to δf**
  - **Tagged DIS** experiments
- BONuS 6 data don't seem to disagree!
  - But may not be precise enough at large x





Open questions



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

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

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

- Cross check the extracted free F2N with on-shell extrapolation methods?
  - Different systematics, use of tagged data

- Are FSI negligible?
  - Inclusive DIS only probes small off-shellness
  - Can absorb FSI into df only up to some point

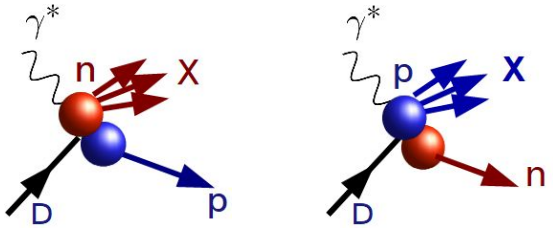
    ⟶ One can perhaps verify onset of FSI against above baseline model

More data, please!

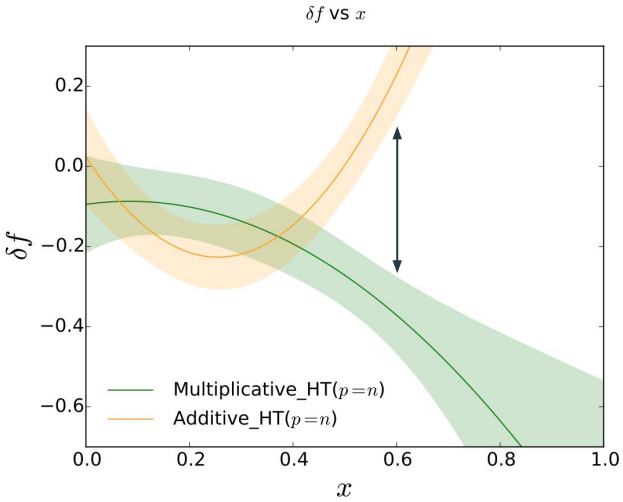
- **One can extract *δf***

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

  - Experiment by experiment
  - or in a global QCD fit

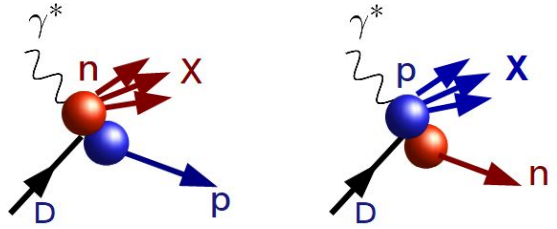


- **Need more tagged DIS data with**
  - FSI under control (small *v*, backward *φ*)
  - Large lever arm, good resolution on *v* (or p_S)
  - x>0.6 would clearly distinguish the two cases



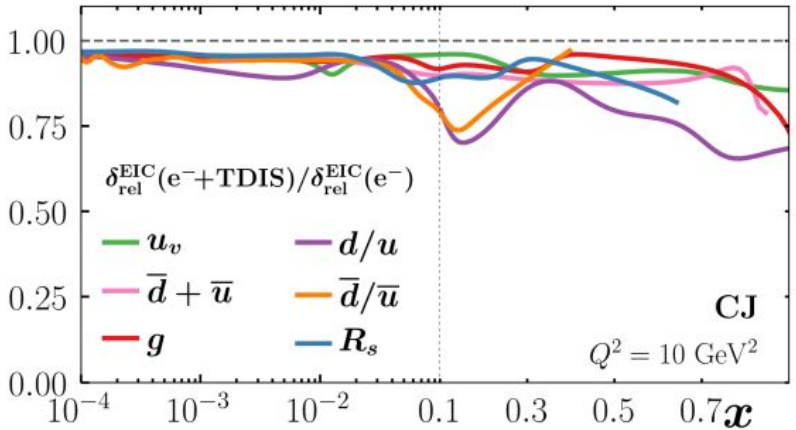
More data, please!

- **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*

EIC yellow report, arXiv:2103.05419



PVDIS in global fits

- **PVDIS in global fits**
  - **PVDIS on p**

    ⟶ “ Still needed in the BONuS 12 and Marathon era? ”
  - PVDIS on D

    ⟶ CSV from nuclear, HT dynamics ?

PVDIS on protons

W bosons

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

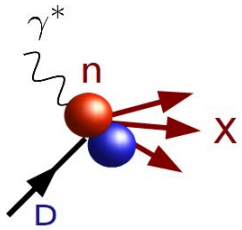
PVDIS on p

$$A_{PV} \approx \frac{1 + 0.91\, d/u}{1 + 0.25\, d/u} + HT + Y_3\, a_3$$

ν's can help

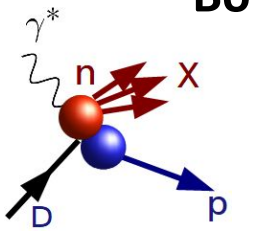
d/u
+
nuclear dynamics

DIS on Deuterium



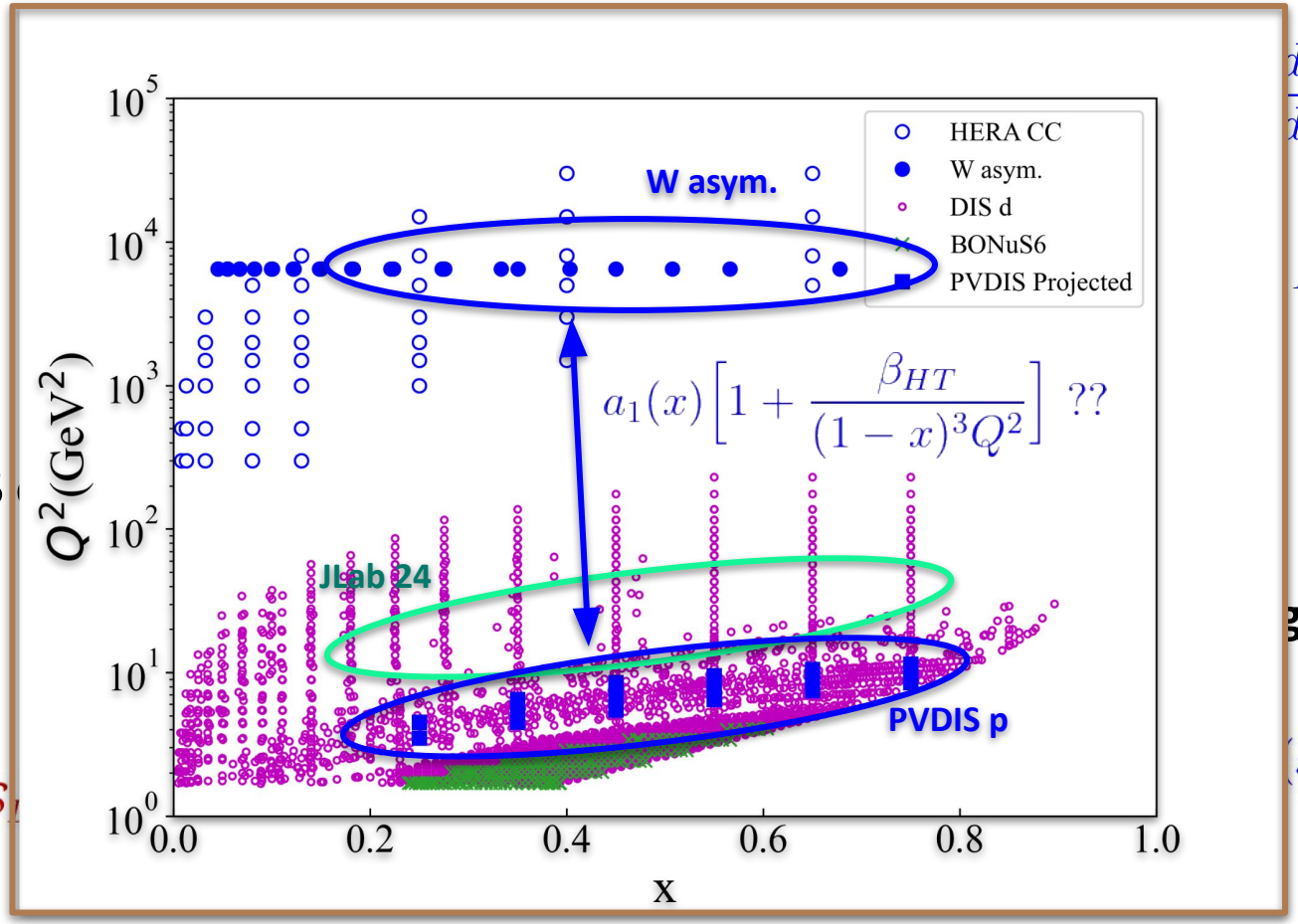
$$F_2^d \propto \mathcal{S}_D \otimes \left[x u_{\text{off}}(x) + x d_{\text{off}}(x)\right]$$

"BoNuS" tagged DIS



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

PVDIS on protons



$\frac{d/u}{d/u}$

$HT + Y_3\, a_3$

DIS

ged DIS

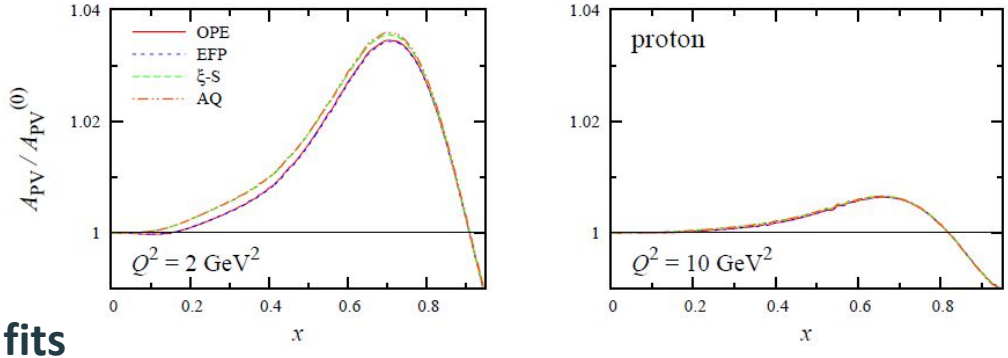
$F_2^d \propto \mathcal{S}$

$(x) + 4xd(x)$

PVIDS on protons - notes

Brady, AA, Hobbs, Melnitchouk, PRD 84 (2011)

- **Can focus on dynamical HT**
  - TMCs are under control
  - Kinematics far enough from x=1 end point



- **Clean access to d/u in global fits**
  - Large effective Q^2 leverage
    - ⟶ Power corrections efficiently removed
      Global fits can extract d/u

- **JLab 24: higher Q^2**
  - More precision for HT extraction
    - ⟶ hence more statistics for d/u fitting
  - Less kinematic shift x ⟶ ξ:
    - ⟶ higher *x* reach for d/u

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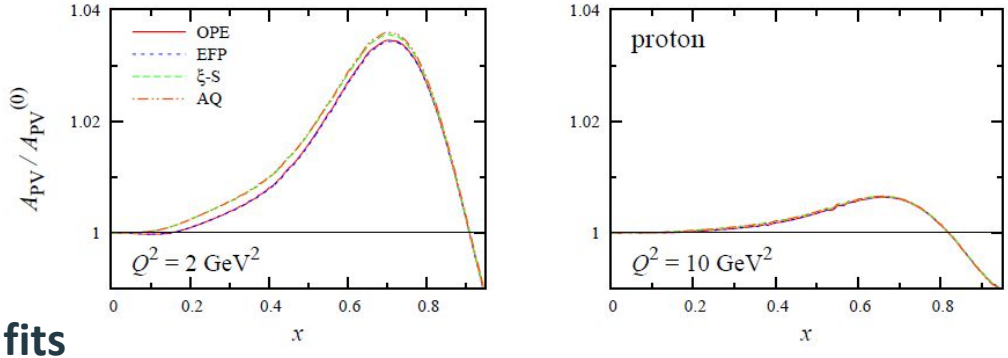

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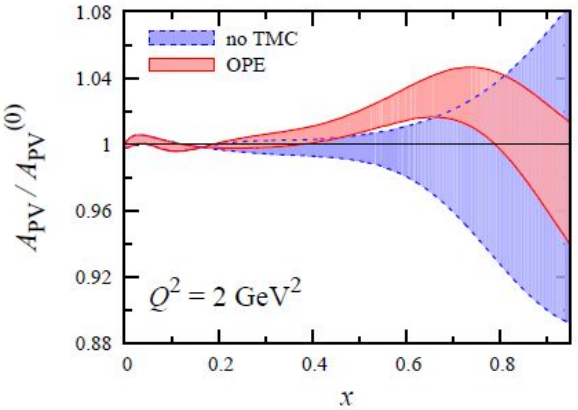

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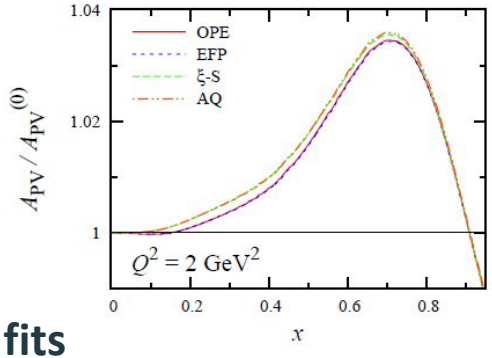

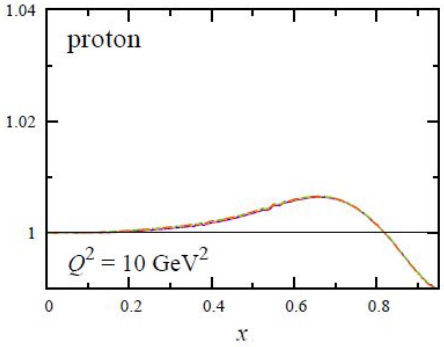

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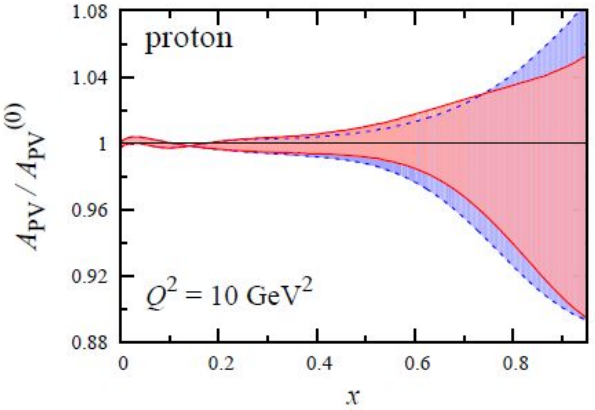
  - Less kinematic shift x ⟶ ξ:
    - ⟶ higher *x* reach for d/u

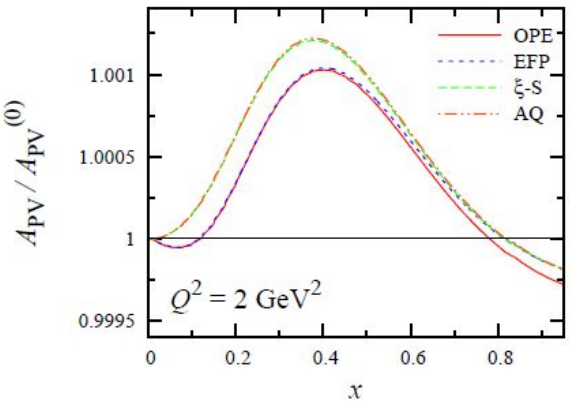


- **PVDIS in global fits**
  - PVDIS on p
    ⟶ Still needed in the BONuS 12 and Marathon era?
  - **PVDIS on D**
    ⟶ CSV from nuclear, HT dynamics ?

PVDIS on Deuterons

- **TMC**
  - Per mille level, very small model dependence
  - Don't forget the kinematic shift
- **Nuclear corrections**
  - Likely small, too
  - (But not quantified)

Brady, AA, TJH, WM, PRD 84 (2011)



- **Higher twists - analogous to proton discussion**
  - Large Q^2 lever arm when analyzed in a global fit
  - Need to fit HT(p) ≠ HT(n) to avoid biases
    - ⟶ Formulate this at quark level and impose/verify charge symmetry
    - ⟶ Attention to HT/offshell interplay

$$HT_u^p \stackrel{?}{=} HT_d^n \,;\, HT_d^p \stackrel{?}{=} HT_u^n$$

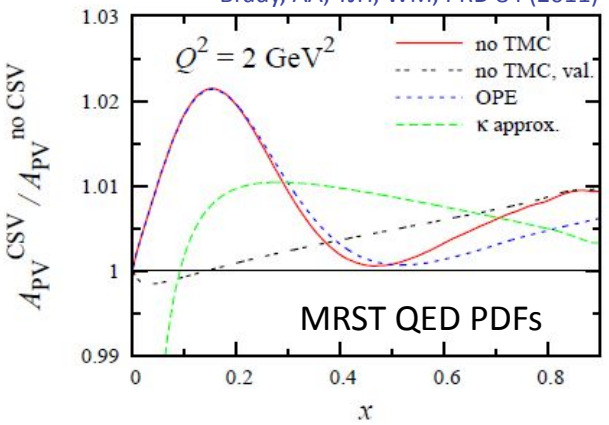
$$\delta f_u^p \stackrel{?}{=} \delta f_d^n \,;\, \delta f_d^p \stackrel{?}{=} \delta f_u^n$$

PVDIS on Deuterons

- **CSV from nuclear and HT dynamics, as well?**

$$R^{CSV} = \underbrace{R^{CSV}_{pdf} + R^{CSV}_{off}}_{\text{How to tell?}} + R^{CSV}_{HT}$$

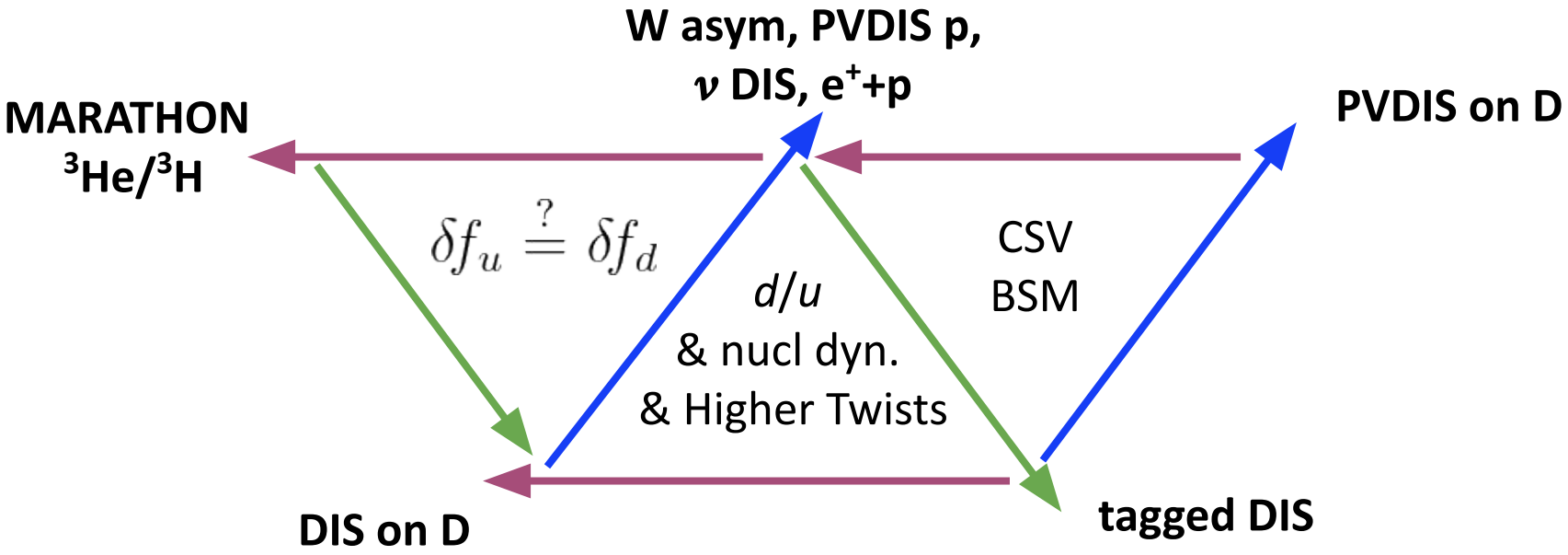
Brady, AA, TJH, WM, PRD 84 (2011)



- **If we find an "anomaly": is it BSM or nuclear physics?**
  - ⟶ Remember the NuTeV anomaly
  - ⟶ Here we have a deuteron, no p/n asymmetry to possibly trick us
  - ⟶ Still, let's keep our eyes and minds open

Need half a honeycomb, at least!

- **Global QCD analysis is a powerful tool:**
  - ⟶ d/u, nuclear dynamics, parton correlations, CSV
  - ⟶ PVDIS still relevant in BONuS 12 / Marathon era !!



Nuclear Corrections

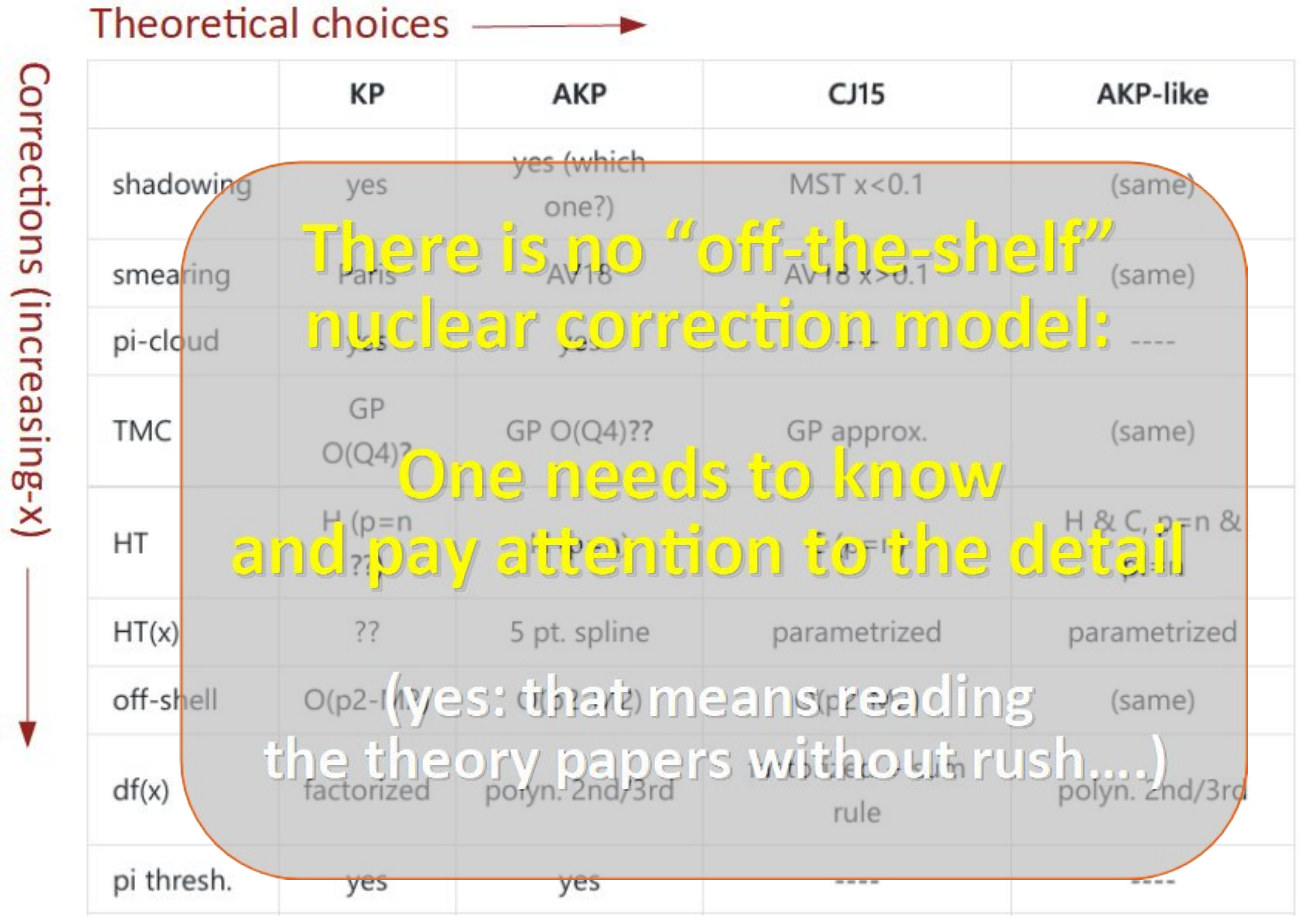
Are we done with (nuclear) corrections?

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?



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

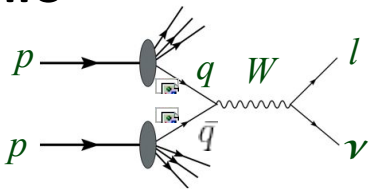
One needs to know and pay attention to the detail

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

Light quark sea

Medium-x PDFs: the light sea triangle

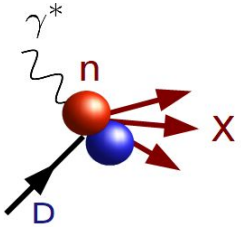
W bosons @ RHIC



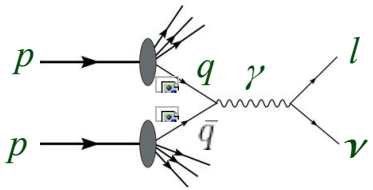
$$\frac{\sigma_{W^+}}{\sigma_{W^-}} \underset{y_W \approx 0}{\approx} \frac{\bar{d}/\bar{u}}{d/u}$$

$$\bar{d} - \bar{u}$$

DIS @ NMC (largely)



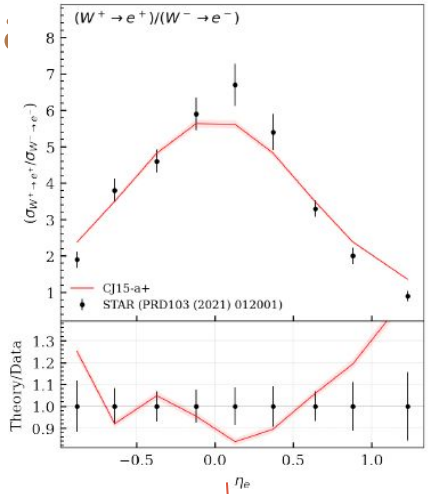
Drell-Yan @ Fermilab



$$\frac{\sigma^{pd}}{\sigma^{pp}} \approx 1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}$$

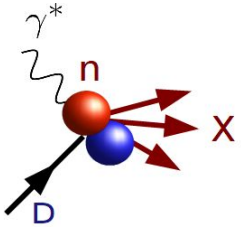
Medium-x PDFs: the light sea tri

W bosons @ RHIC

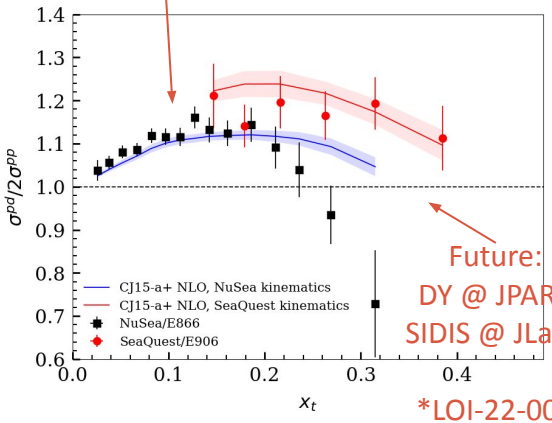


$\bar{d} - \bar{u}$

DIS @ NMC (largely)



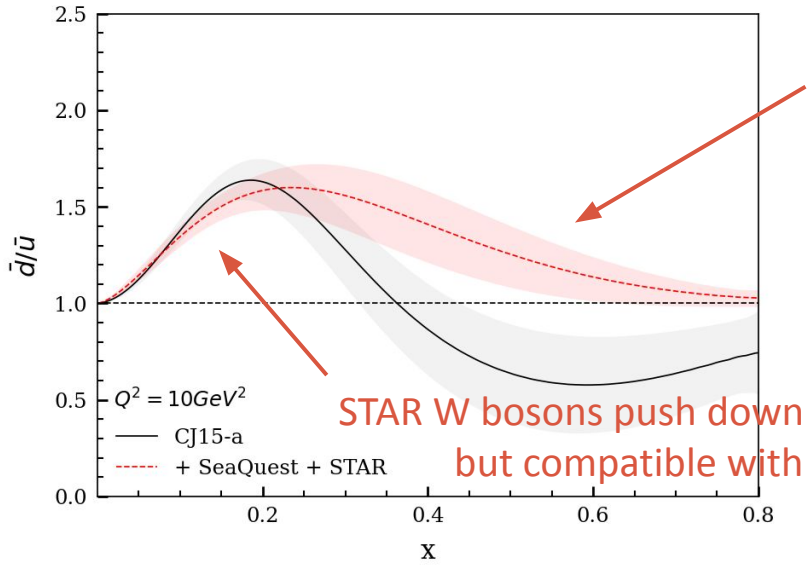
Drell-Yan @ Fermilab



Future:
DY @ JPARC
SIDIS @ JLab*

*LOI-22-002

Medium-x PDFs: the light sea triangle



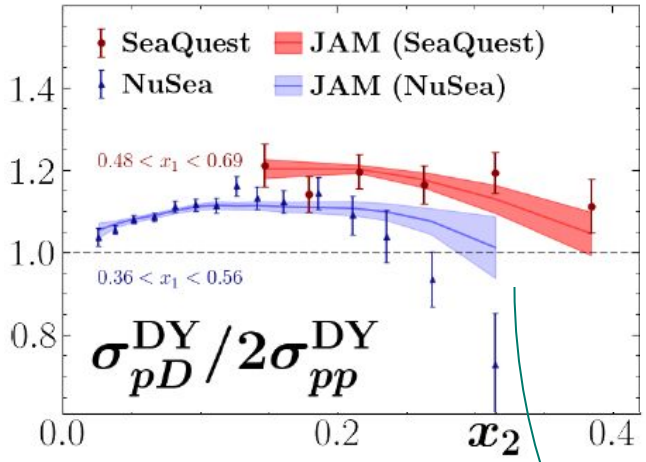
SeaQuest pulls ratio up
→ **Tension with E866**
→ **How to quote PDF errors?**

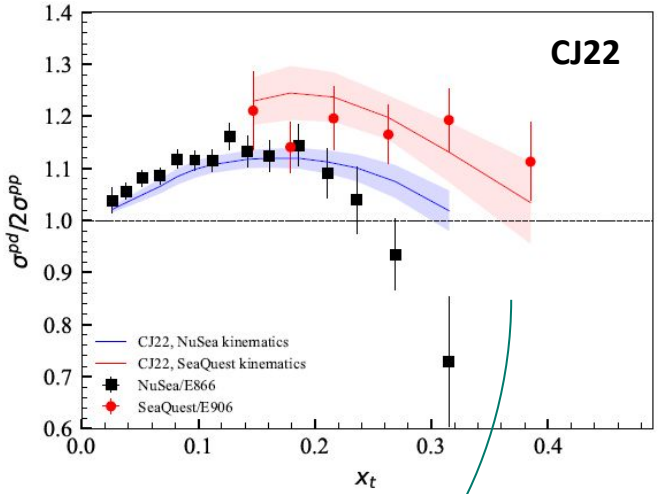
STAR W bosons push down a bit,
but compatible with E866

Lepton Pair Production

- **Comparable results to JAM, CT:**

Cocuzza et al. PRD 104 (2021) 074031





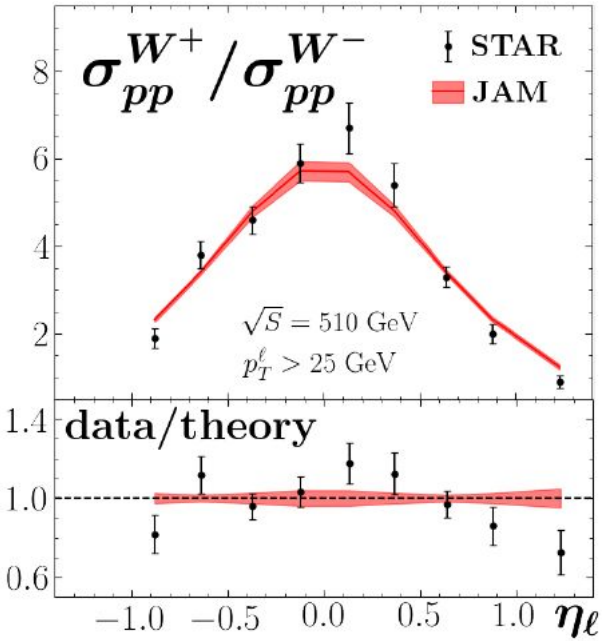
E866, SeaQuest disagree:
How to include in error bands?

→ new idea, K. Mohan @ DIS 2023

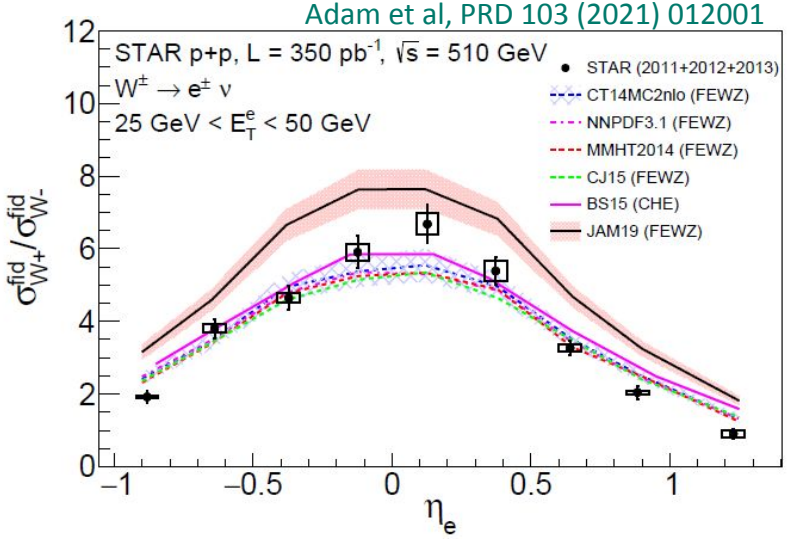
Weak boson production

- **Similar results from JAM, other calcs**

Cocuzza et al. PRD 104 (2021) 074031

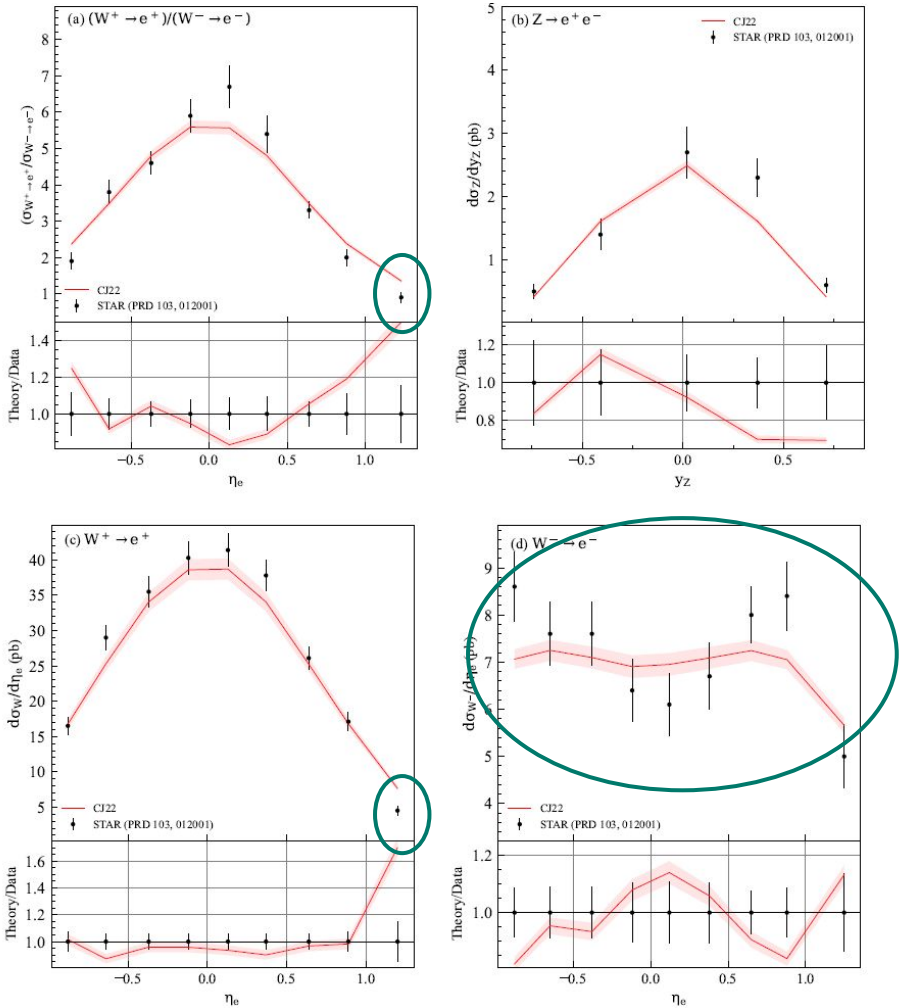


Adam et al, PRD 103 (2021) 012001



Weak boson production

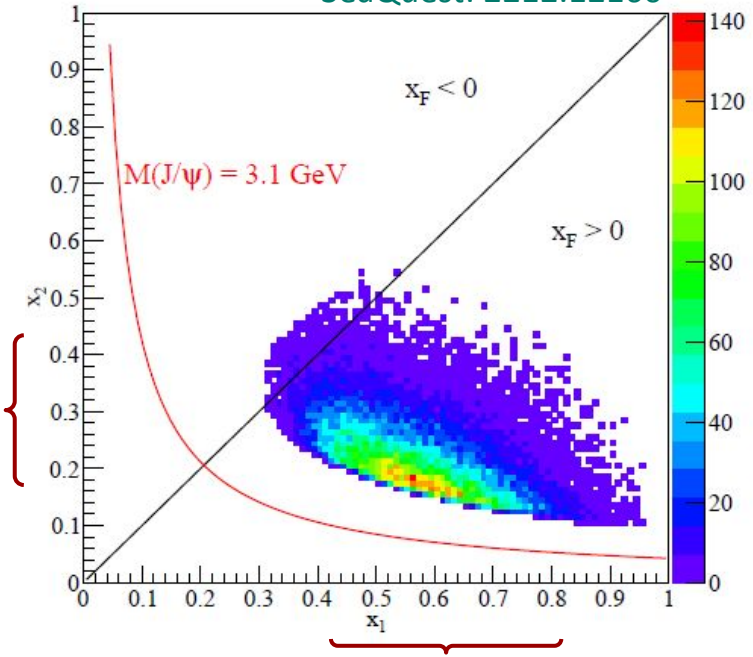
- Only W+/W- ratio was fitted
  - Other plots compare data to theory
- **Largest rapidity W^+ not reproduced**
  - Would require too small db/ub
  - Or too large d/u
- **More structure in W^- data** than in the theory calculation



SeaQuest kinematics

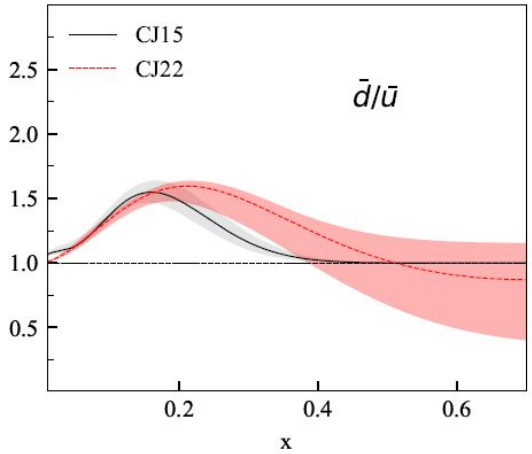
$$\frac{\sigma_{pd}}{\sigma_{pp}} \approx \frac{4 + \frac{d(x_b)}{u(x_b)}}{4 + \frac{d(x_b)}{u(x_b)} \frac{\bar{d}(x_t)}{\bar{u}(x_t))}} \left(1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right)$$

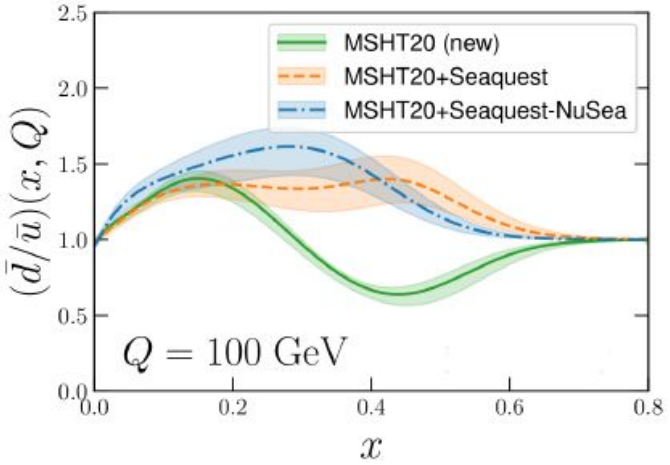
SeaQuest: 2212.12160



Comparison to other recent PDFs

- **SeaQuest fitted:**





- **PDFs w/o SeaQuest:**