PDFs and Nuclear Structure in the CJ Global Analysis

Shujie Li

with many thanks to my CTEQ-JLab collaborators:
A. Alberto, I. Fernando, X. Jing, J. Owens, S. Park,
C.E. Keppel, W. Melnitchouk, P. Monaghan

JLUO Annual Meeting
June, 2023

BERKELEY LAB

CTEQ-Jefferson Lab Collaboration

Jefferson Lab

Global QCD fits

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

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

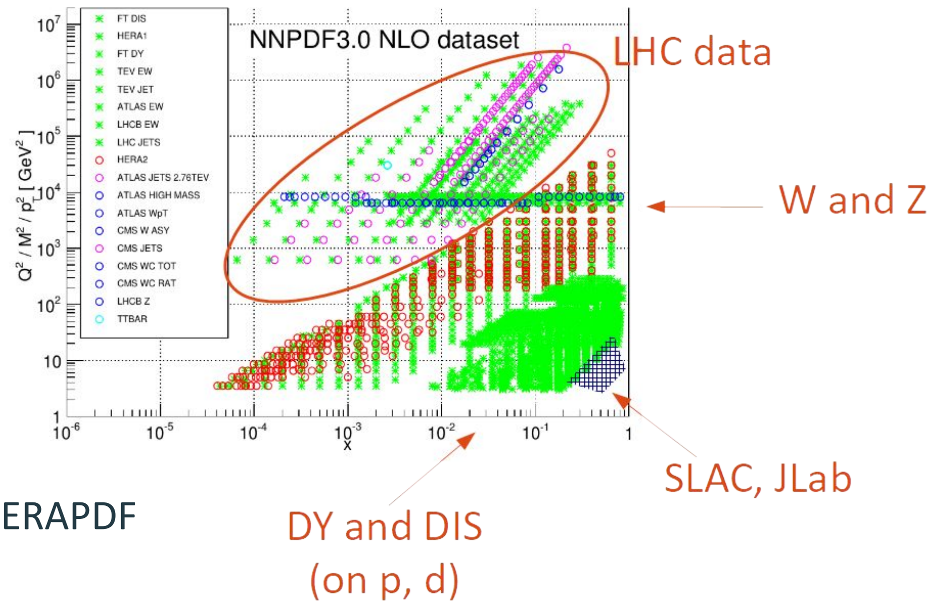
pQCD calc.

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**



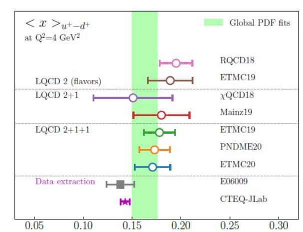
The CTEQ-JLab collaboration

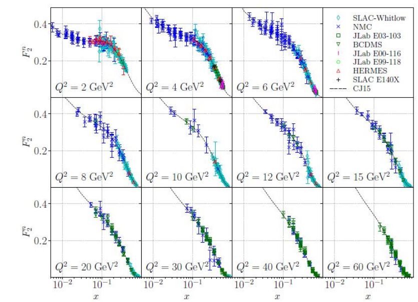
- **Coordinated Theory-Experiment Effort with Jefferson Lab:**
  - A. Accardi, **Xiaoxian Jing**, **Ishara Fernando**, W.Melnitchouk, J.F.Owens
  - C.E. Keppel, **Shujie Li**, P. Monaghan, **Sanghwa Park**

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

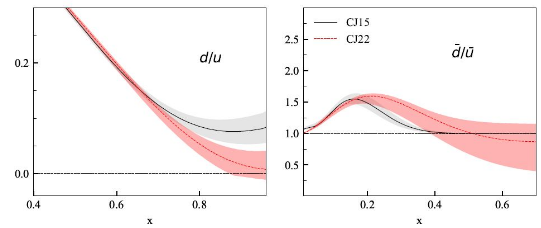
  } **CJ15** *Accardi et al.,PRD 93 (2016) 114017*

  - F2(n) extraction, **CJ15ht** and **CJ15sfn**
    (S. Li, I. Fernando)





  - Light antiquarks, **CJ22**
    (S. Park, X. Jing)



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

  - [In progress (S. Park)
    $\longrightarrow$ Strange sea with LHC data]

Light sea and valence quarks in the **CJ22** global PDF analysis

A.Accardi, X. Jing, J. Owens, S. Park, arXiv:2303.11509

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
  - 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

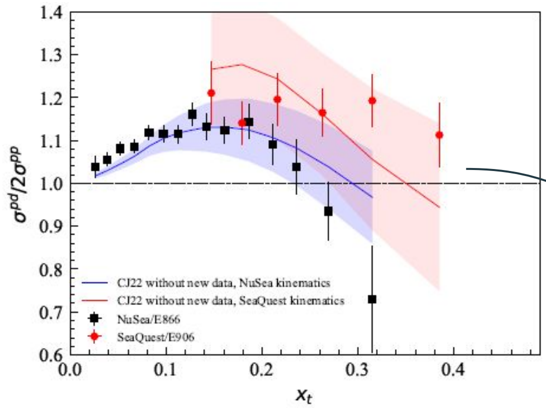
New: electroweak data

Obs.	Experiment	Ref.	# Points	χ^2
DIS	JLab (p)	[31]	136	161.0
	JLab (d)	[31]	136	119.1
	JLab (n/d)	[32]	191	213.2
	HERMES (p)	[33]	37	29.1
	HERMES (d)	[33]	37	29.5
	SLAC (p)	[34]	564	469.8
	SLAC (d)	[34]	582	412.1
	BCDMS (p)	[35]	351	472.2
	BCDNS (d)	[36]	254	321.8
	NMC (p)	[37]	275	416.5
	NMC (d/p)	[38]	189	199.6
	HERA (NC e^-p)	[39]	159	249.7
	HERA (NC e^+p 1)	[39]	402	598.9
	HERA (NC e^+p 2)	[39]	75	98.8
	HERA (NC e^+p 3)	[39]	259	250.0
	HERA (NC e^+p 4)	[39]	209	229.1
	HERA (CC e^-p)	[39]	42	45.6
	HERA (CC e^+p)	[39]	39	52.5

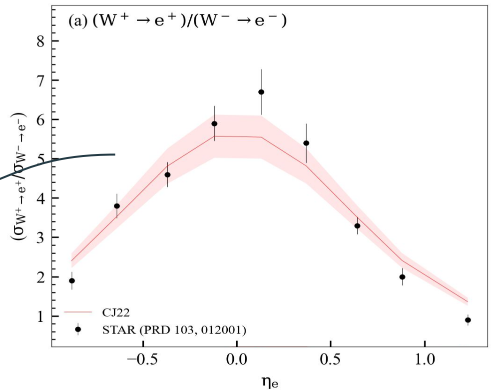
Obs.	Experiment	Ref.	# Points	χ^2
LPP	E866 (pp)	[4]	121	144.1
	E866 (pd)	[4]	129	157.4
	SeaQuest (d/p)	[5]	6	7.5
W	CDF (e)	[40]	11	12.6
	D0 (e)	[41]	13	28.8
	D0 (μ)	[42]	10	17.5
	CDF (W)	[43]	13	18.0
	D0 (W)	[44]	14	14.5
	STAR (e^+/e^-)	[6]	9	25.3
	(less $\eta_{\max}$ point)		(8)	(15.4)
Z	CDF	[45]	28	29.2
	D0	[46]	28	16.1
jet	CDF	[47]	72	14.0
	D0	[48, 49]	110	14.0
γ+jet	D0 1	[50]	16	8.7
	D0 2	[50]	16	19.3
	D0 3	[50]	12	25.0
	D0 4	[50]	12	12.2
	total		4557	4936.6
	total + norm		4573	4948.6

New: electroweak data

SeaQuest



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



Fits w/o new data

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

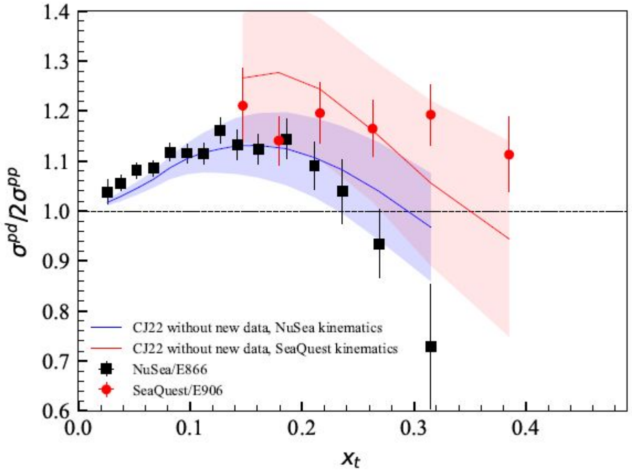
$$\frac{\sigma_{W^+}}{\sigma_{W^-}} \approx \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)} \underset{y_W \approx 0}{\approx} \frac{\bar{d}/\bar{u}}{d/u}$$

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

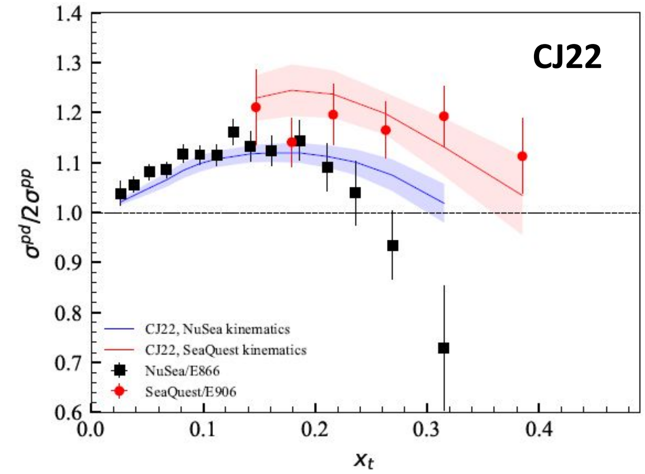
Need flexible enough parametrization

Lepton Pair Production



Fit new data

(SeaQuest & STAR)



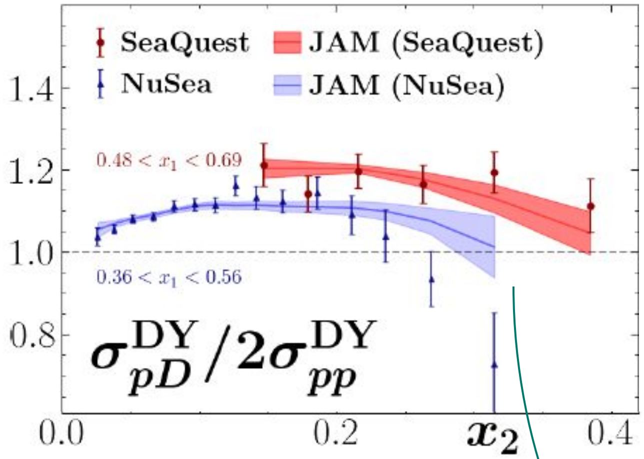
SeaQuest: χ^2/datum = 3.19 → 1.25

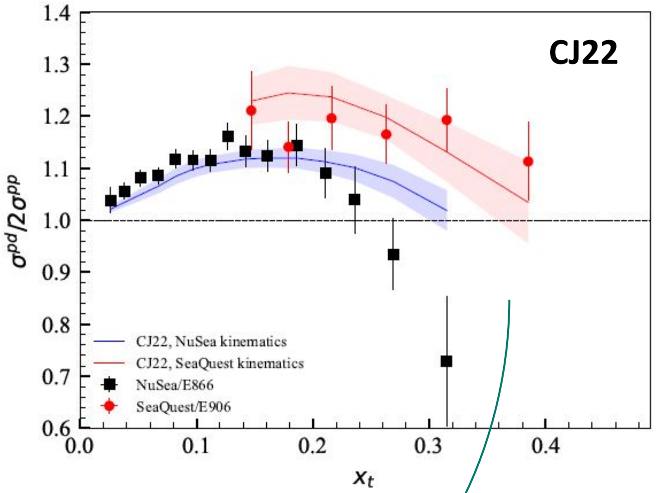
E866 : χ^2/datum = 1.63 → 1.93

Lepton Pair Production

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

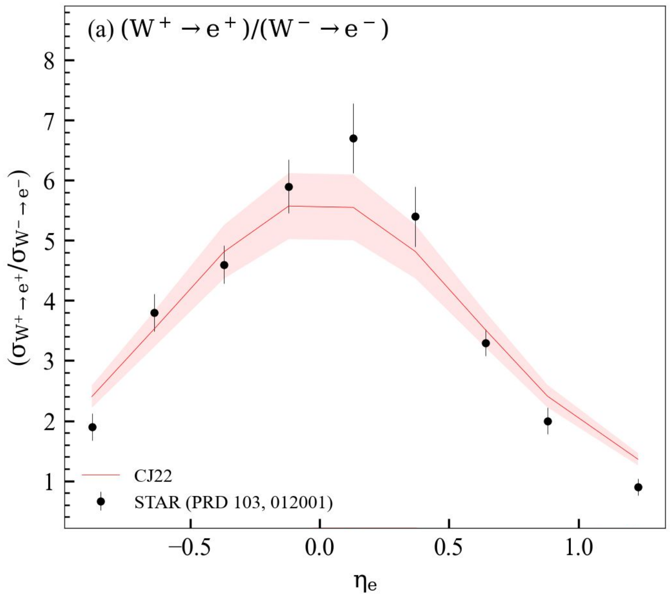
Cocuzza et al. PRD 104 (2021) 074031



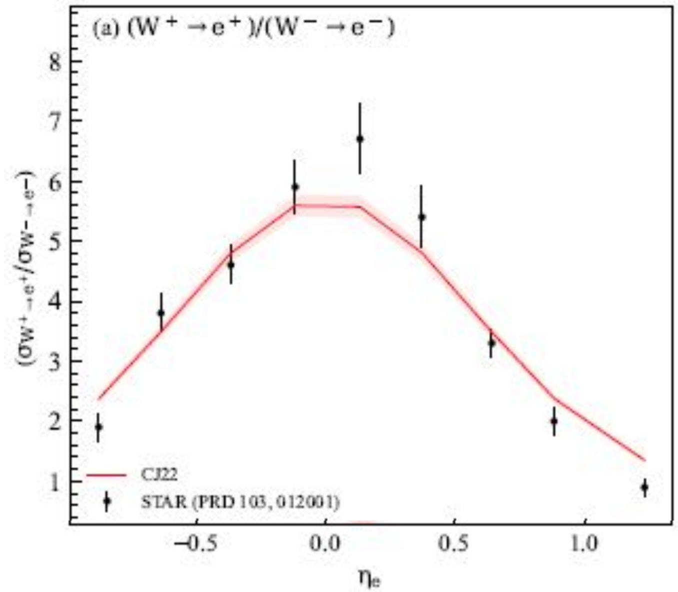


E866, SeaQuest disagree:
How to include in error bands?

Weak boson production



Fit new data
(SeaQuest & STAR)

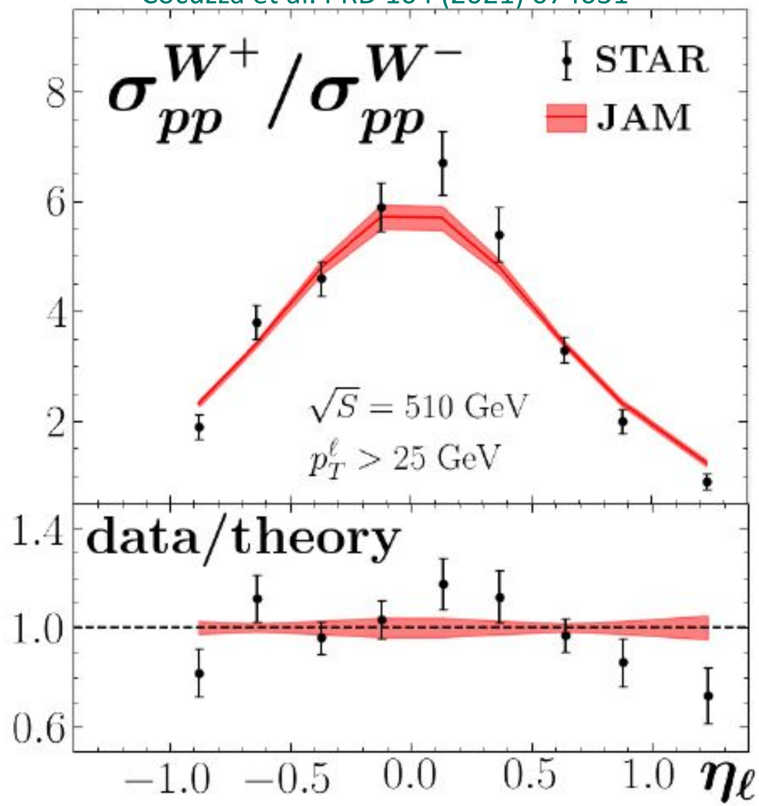


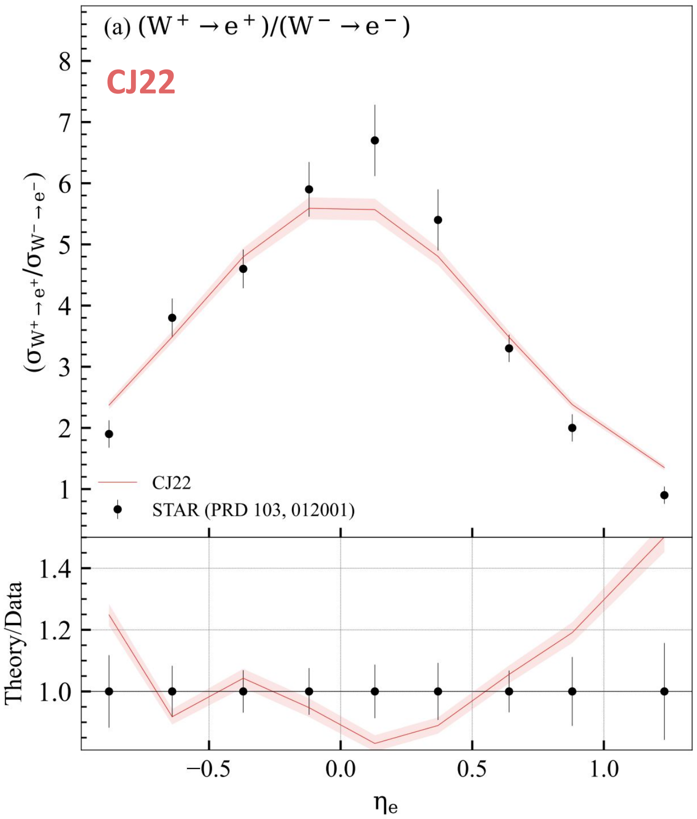
- Large reduction in uncertainty driven by SeaQuest data
- STAR contributes ~ 15% reduction around x~0.16
  - distributed between d/u (5%) and db/ub (10%) PDF ratios

Weak boson production

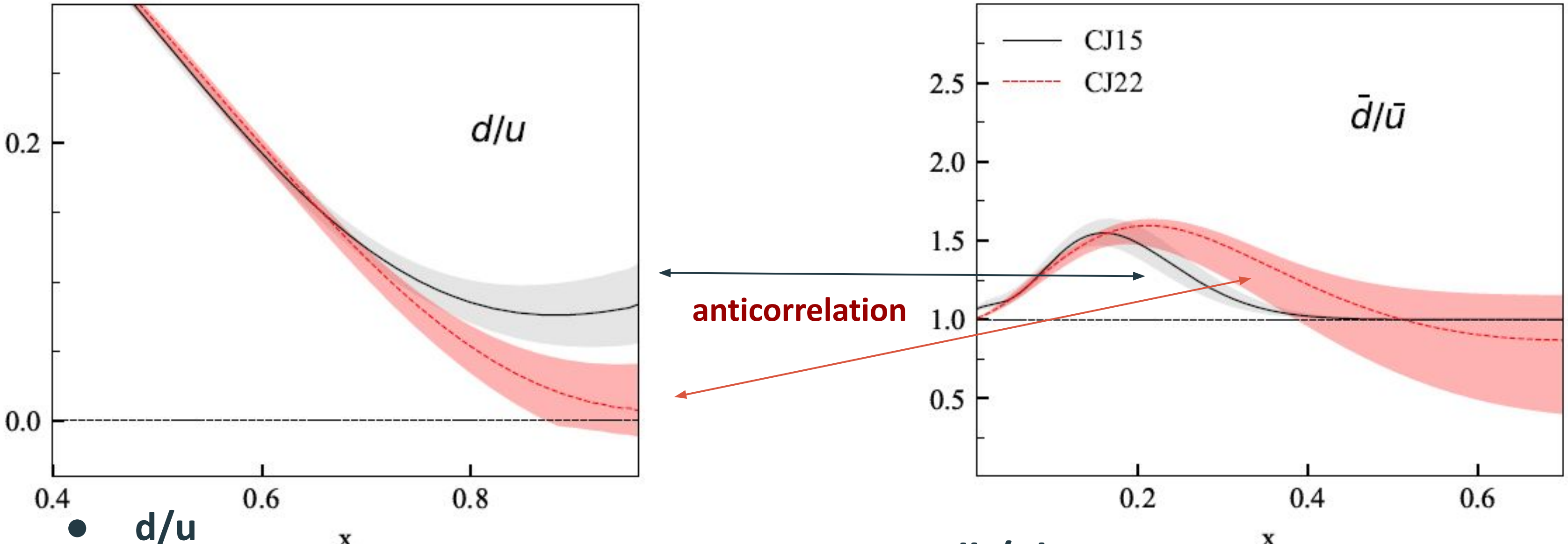
- Only W+/W- ratio was fitted

Cocuzza et al. PRD 104 (2021) 074031





Light quarks and anti quarks



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

New: PDF error analysis

- **"Adjusted" Hessian approximation** *Accardi et al., EPJC 81 (2021) 7*
  - Diagonalize H
  - Error PDFs defined in each eigendirection by

$$\Delta\chi^2_{i,\pm} = 1.645 \quad \longleftrightarrow \quad \text{" } 90\% \ c.l. \text{"}$$

  - Local asymmetric tolerance criterion

    $\longrightarrow$ Accounts for deviation from Gaussian likelihood

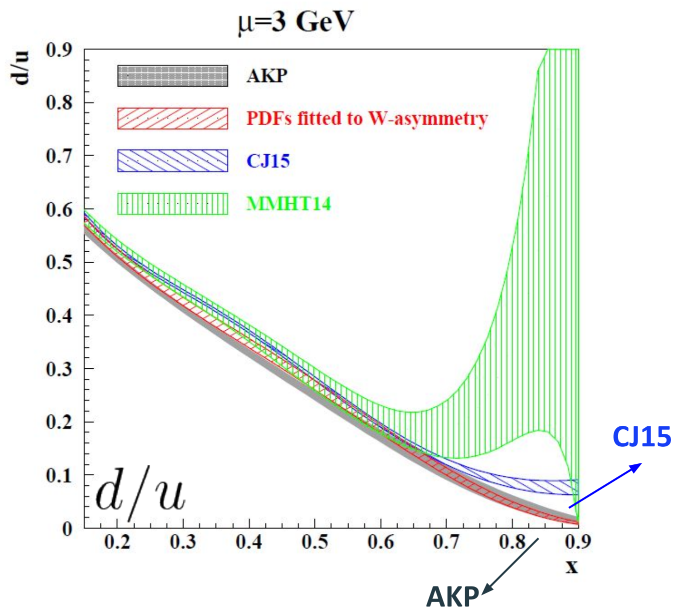
- Important for:
  - Constrained observables (*e.g.*, n/p $\longleftrightarrow$ d/u at large *x*)
  - Regions with poor data constraints (*e.g.*, db/ub at *x* > 0.3, extrapolation)

Structure functions at large x: offshell effect and higher twist

A.Accardi, I. Fernando, C.E. Keppel, SL,
W. Melnitchouk, P. Monaghan, J. Owens

CJ15 and AKP: d/u to free nucleons

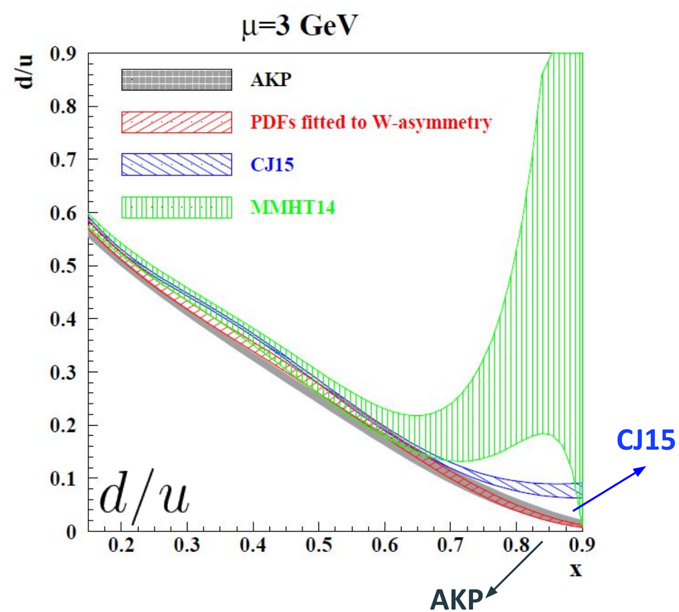
CJ15: *PRD 93 (2016) 114017*
AKP: *PRD 96 (2017) 054005*
(see also 2203.07333)

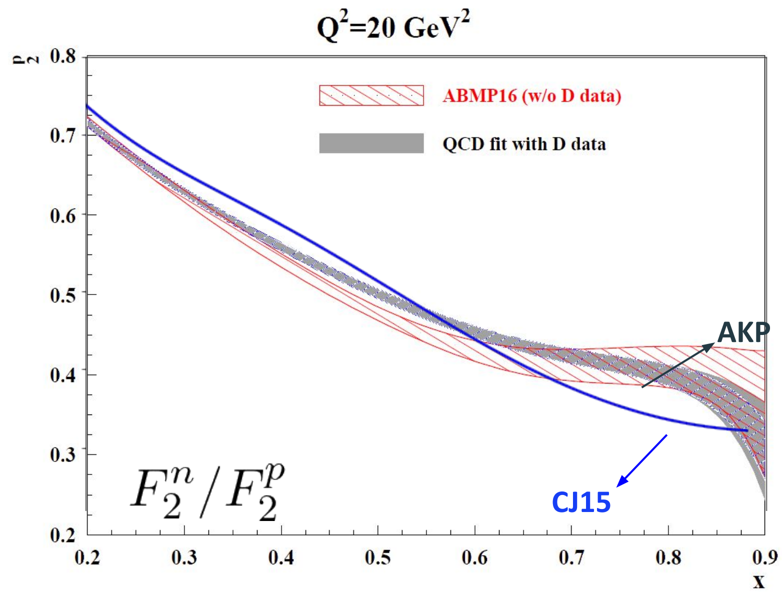


$$\frac{F_{2n}}{F_{2p}} \approx \frac{1+4d/u}{4+d/u}$$

CJ15 and AKP: d/u to free nucleons

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





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

HT systematics & offshell corrections

Paper in progress

- **Additive vs. Multiplicative**

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

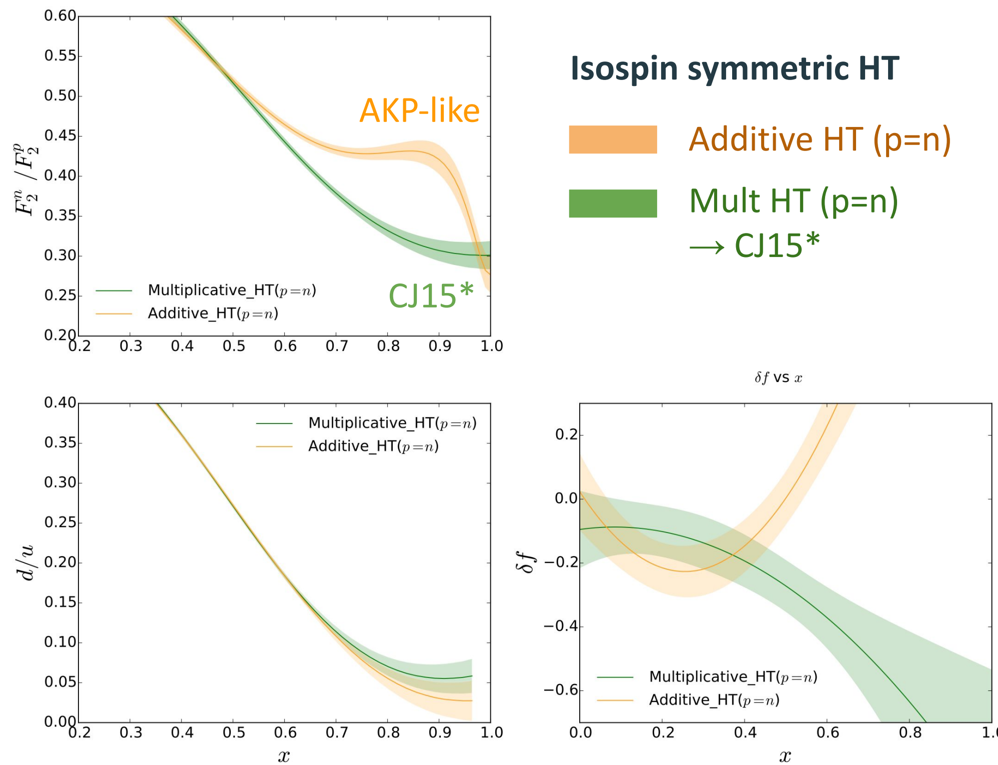
$$F_2(x,Q^2) = F_2^{LT}(x,Q^2)\left(1 + \frac{C(x)}{Q^2}\right)$$

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

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

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

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



I. Fernando

HT systematics & offshell corrections

- **Additive vs. Multiplicative**

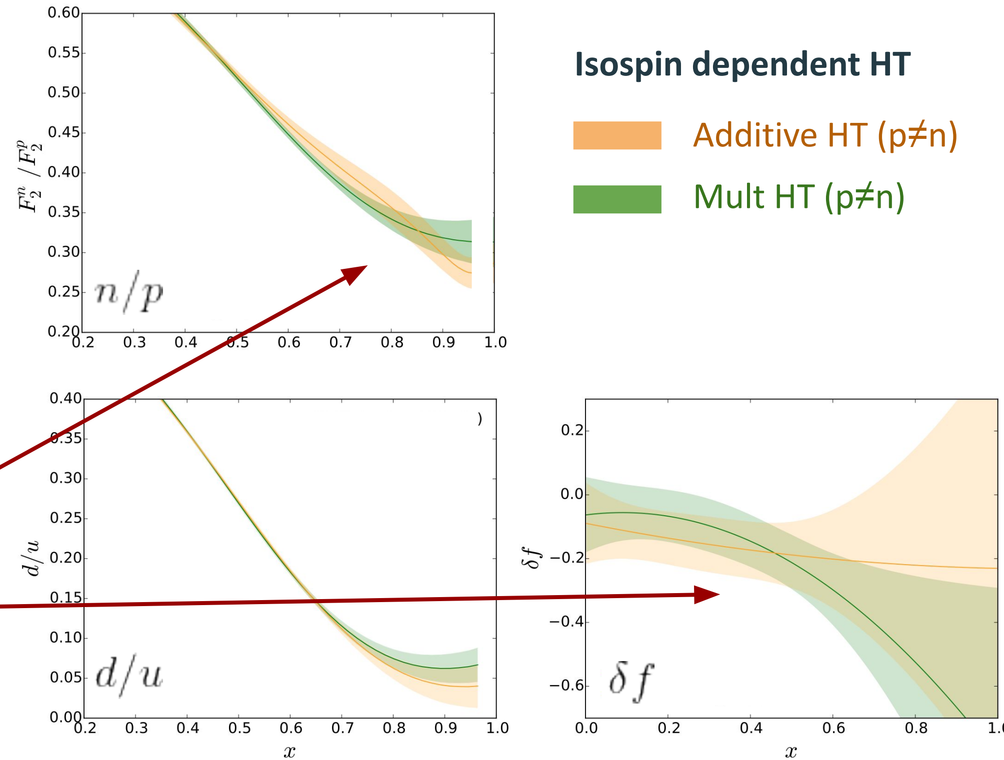
$$F_2(x,Q^2) = F_2^{LT}(x,Q^2) + \frac{H(x)}{Q^2}$$

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

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

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

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



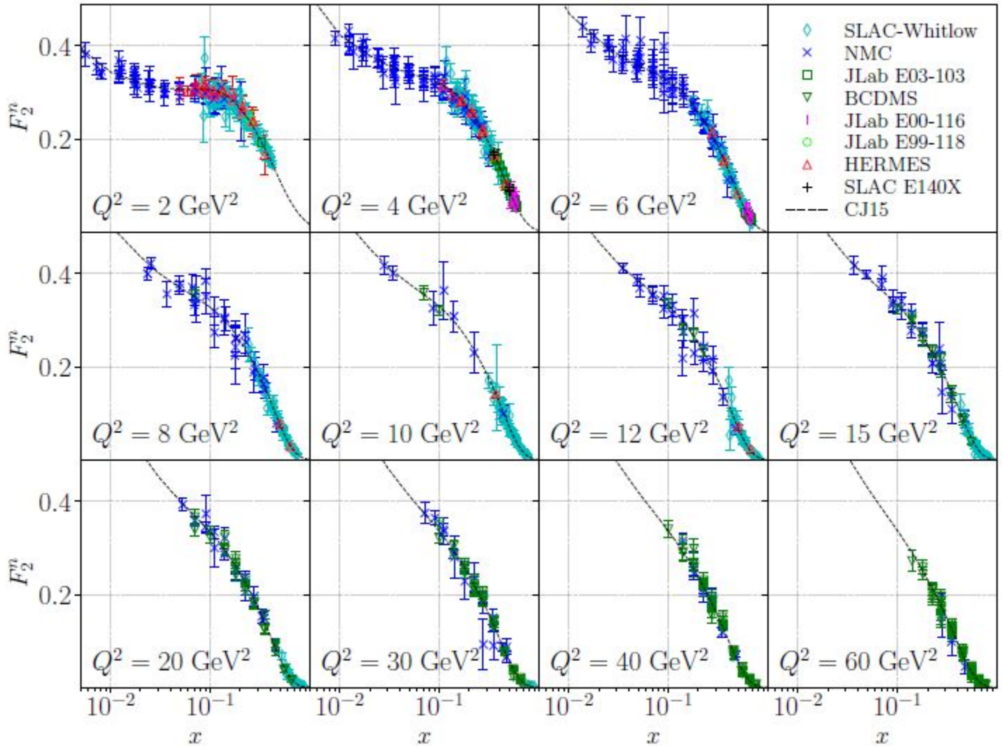
I. Fernando

F_2(n) extraction and applications

S. Li & CJ – nearly finished

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

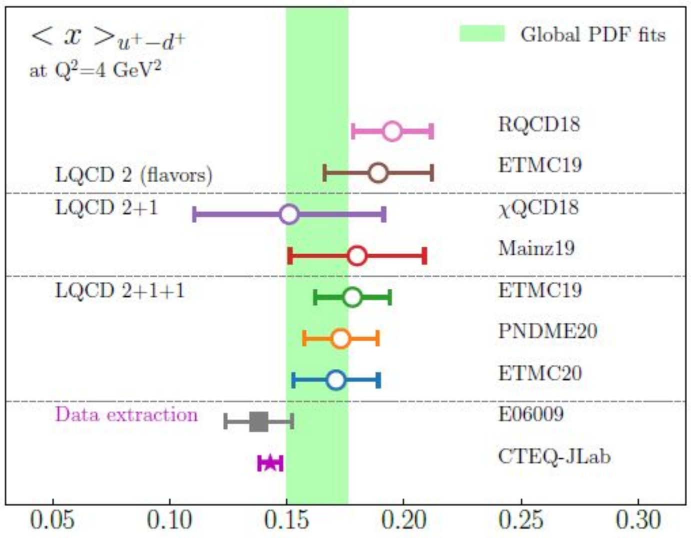
- **But also:**
  - P, d data matching
  - Data cross normalization
    - ⟶ using CJ15 PDFs
    - ⟶ refitting norm, Correlated shifts
  - Bin-centering for Isosinglet moment
  - …



F_2(n) extraction and applications

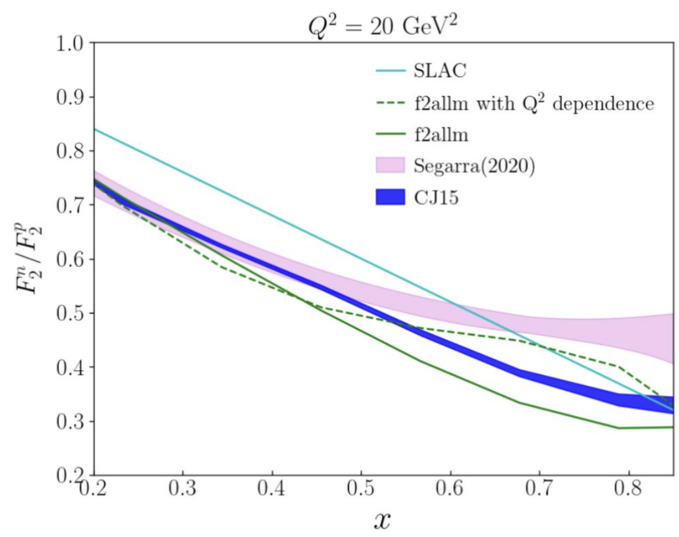
Check https://www.jlab.org/theory/cj

- **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)
```

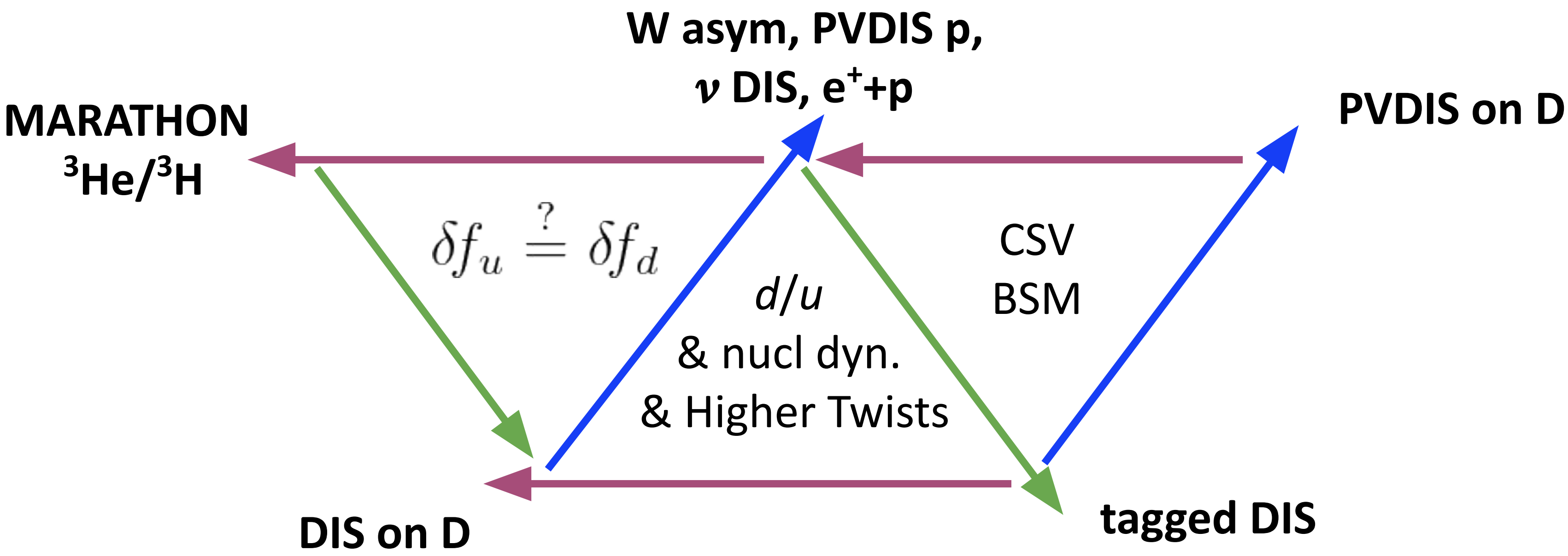


OUTLOOK

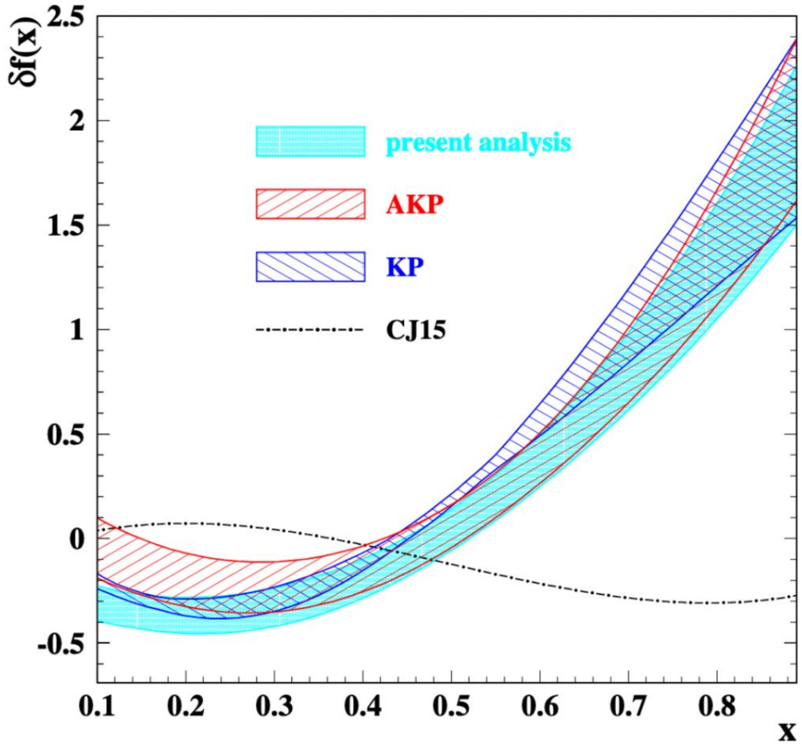
- CJ22 (accepted in PRD)
- F2n (almost done)
- HT and offshell effect (in progress)

} CJ22 + isospin dependent HT/offshell

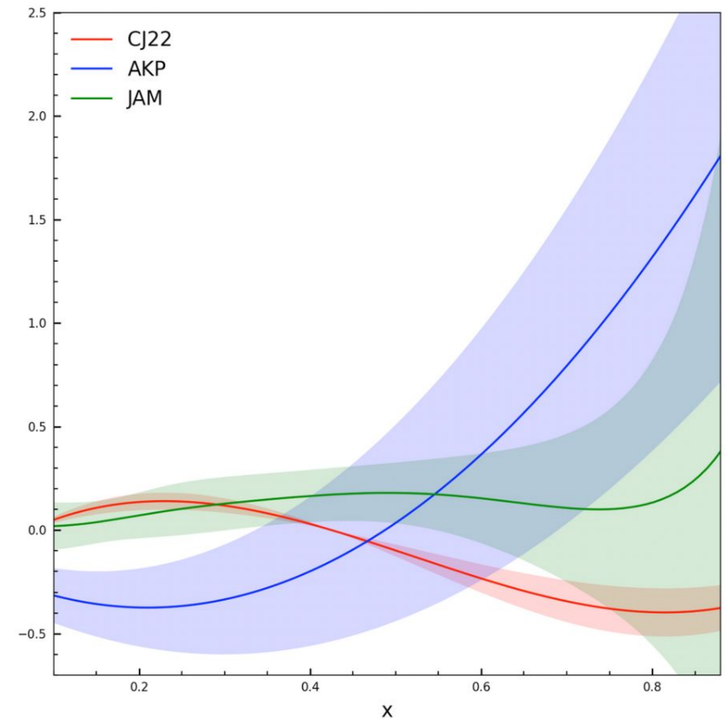
- Strange sea with LHC data
- Tagged DIS, and nuclear effect with A=3
- PVDIS



Backups



AKP: https://arxiv.org/pdf/2203.07333.pdf
Polynomial paramterization,
$c_0 = -0.16\pm0.11$, $c_1 = -2.04\pm0.73$, and $c_2 = 4.86\pm1.13$

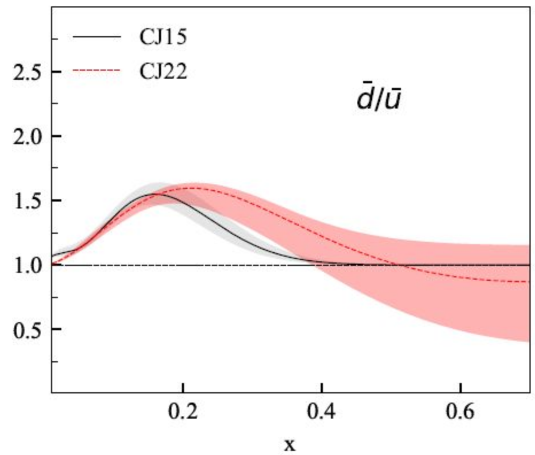


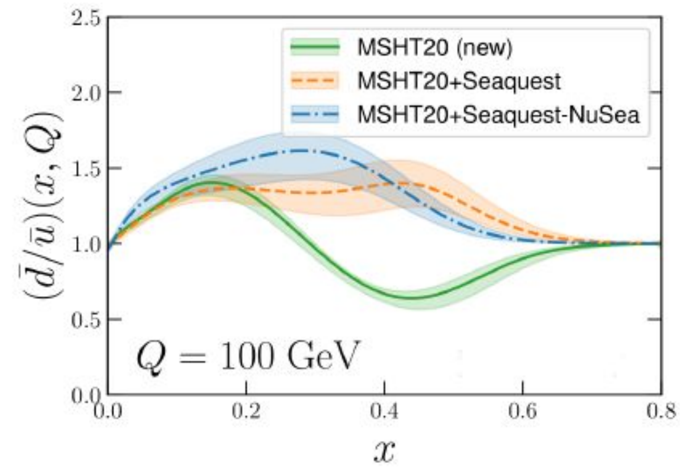
KP-like off-shell function parameters:
$N(x - x_0)(x - x_1)(1 + x_0 - x)$

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

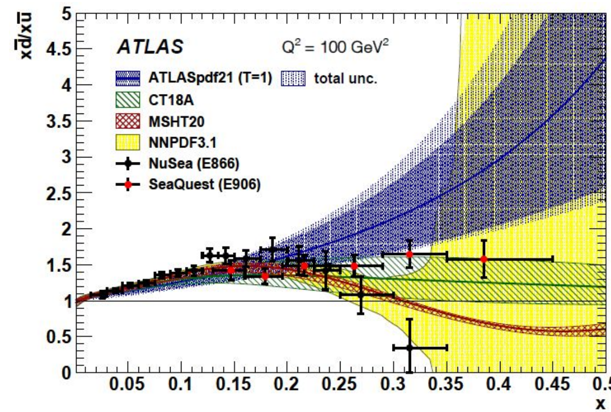
Comparison to other recent PDFs

- **SeaQuest fitted:**



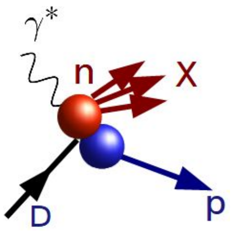


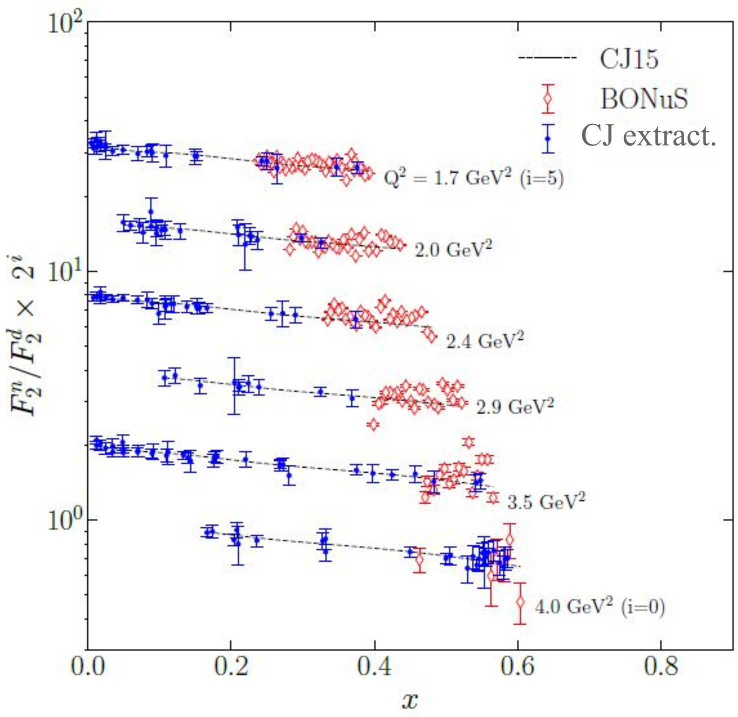
- **PDFs w/o SeaQuest:**

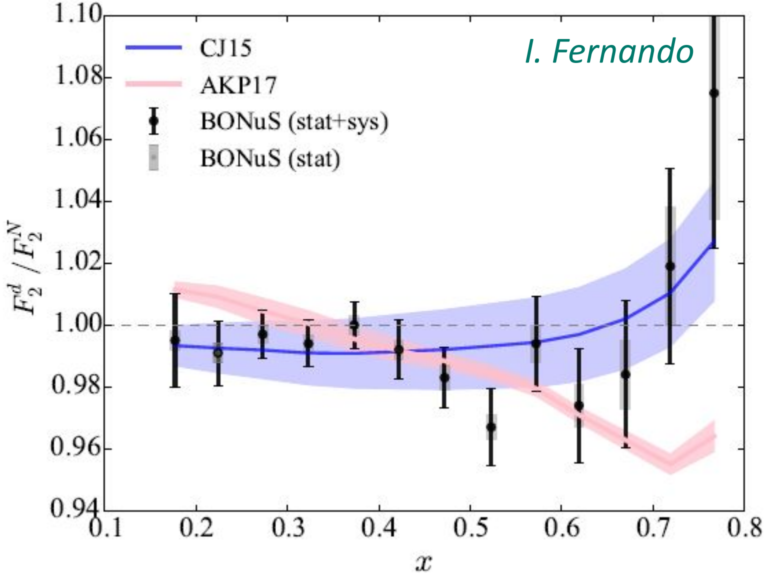


Bonus cross-checks

- **BONuS: Tagged proton DIS** measurements







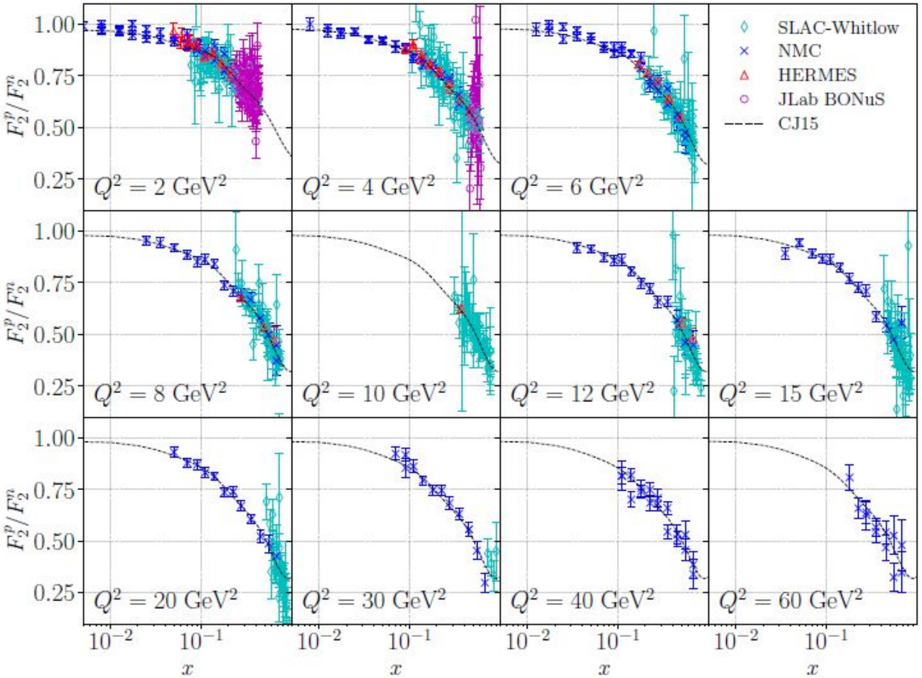
$F_2(n/p)$ extraction

- Similar idea, but using
  - d/p data

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

  - n/d BONuS data

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



CJ22: fit framework

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

- **STAR *W* grids** *(Sanghwa Park)*
  - Exp. cuts:
    $\longrightarrow \quad p_e > 15\ \mathrm{GeV}, \quad 25 < \mathrm{E_e} < 50\ \mathrm{GeV}$
  - Jet suppression (as in STAR paper):
    $\longrightarrow$ Vetoed jet production $\rightarrow$ 20% cross section suppression

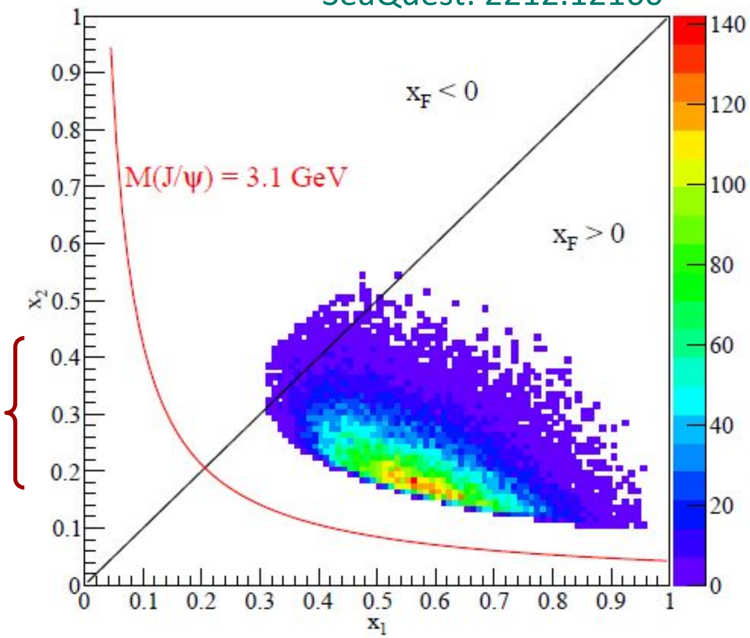
- STAR Z,
  - see paper

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

db/ub



d/u