

Light sea and valence quarks in the CJ22 global PDF analysis

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arXiv:2303.11509

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The CTEQ-JLab collaboration

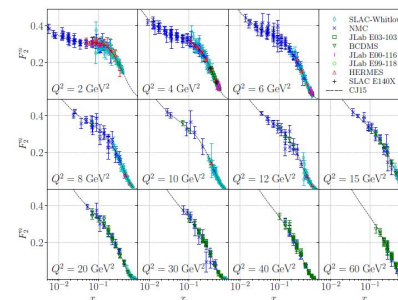
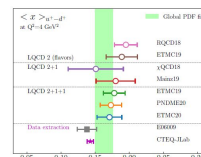
- Coordinated Theory-Experiment Effort with Jefferson Lab:

- A. Accardi, **Xiaoxian Jing**, **Ishara Fernando**, W.Melnitchouk, J.F.Owens
- C.E. Keppel, **Shujie Li**, P. Monaghan, **Sanghwa Park**

- Focus

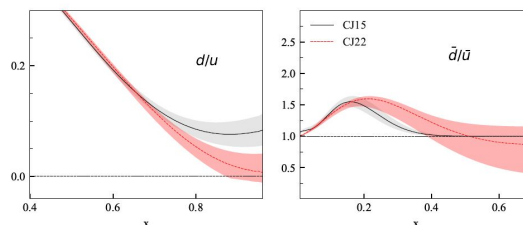
- Large- x , low- $Q^2 \rightarrow$ TMC, HT
- Nuclear dynamics \rightarrow p,n motions, off-shell PDFs
- F2(n) extraction, **CJ15ht** (S. Li, I. Fernando)
- Light antiquarks (S. Park, X. Jing)

CJ15



\rightarrow CJ22 \leftarrow this talk!!

- Strange sea

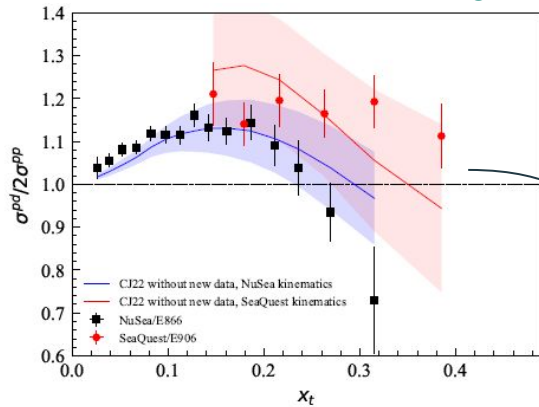


*Prelim. analysis:
Park et al., 2108.05786*

New: electroweak data

SeaQuest

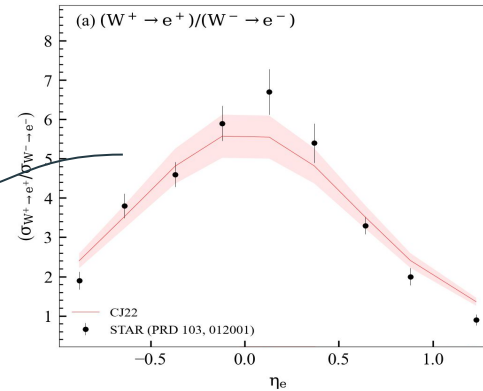
→ C.H. Leung, Tue



Fits w/o
new data

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

→ J.D. Nam, Tue



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

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

Anticorrelation: $db/ub \longleftrightarrow d/u$
 $\text{med. } x_t \longleftrightarrow \text{large } x_b$
 $(0.05 - 0.4) \quad (0.3 - 0.7)$

Correlation: $db/ub \longleftrightarrow d/u$
 $x \sim 0.16$

Need flexible enough
parametrization

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 $x \rightarrow 1$ limit
- Free \bar{a}_2 instead of fixing $\bar{a}_2 = a_2 + 2.5$
- **More flexibility**
 - more data, fix extra parameters
 - sensitivity to $d\bar{b}/u\bar{b} \longleftrightarrow d/u$ anticorrelation

New: 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:
 - $p_e > 15 \text{ GeV}, \quad 25 < E_e < 50 \text{ GeV}$
 - Jet suppression (as in STAR paper):
 - Vetoed jet production → 20% cross section suppression
- **STAR Z,**
 - see paper

New: PDF error analysis

- **“Adjusted” Hessian approximation** *Accardi et al., EPJC 81 (2021) 7*

- Diagonalize H
- Error PDFs defined in each eigendirection by

$$\Delta\chi_i^2, \pm = 1.645 \quad \longleftrightarrow \quad \text{” 90\% c.l.”}$$

- Local asymmetric tolerance criterion
→ Accounts for deviation from Gaussian likelihood

- Important for:

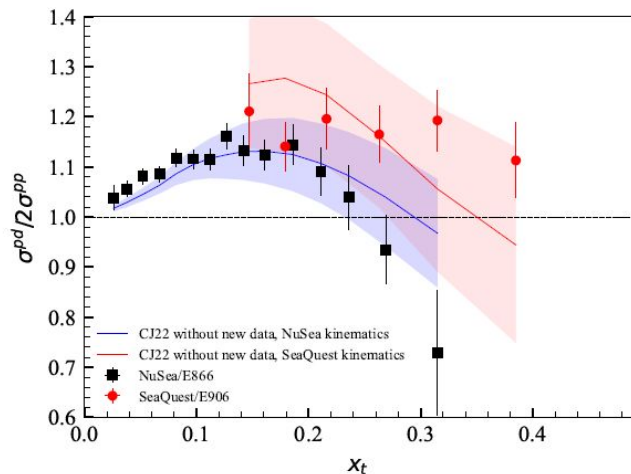
- Constrained observables (*e.g.*, $n/p \longleftrightarrow d/u$ at large x)
- Regions with poor data constraints (*e.g.*, db/ub at $x > 0.3$, extrapolation)

CJ22 data set

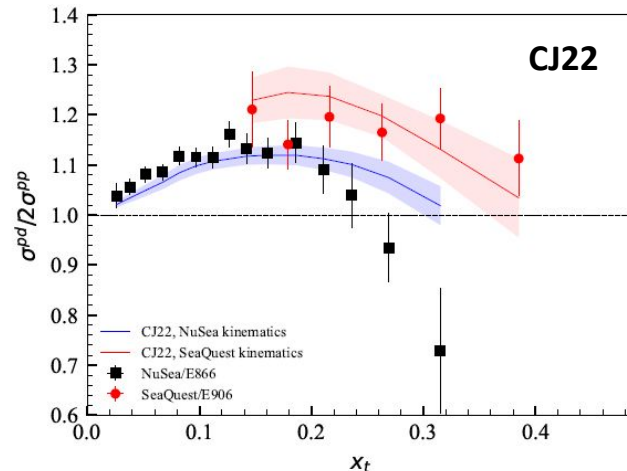
Obs.	Experiment	Ref.	# Points	χ^2
DIS	JLab (p)	[31]	136	161.0
	JLab (d)	[31]	136	119.1
	JLab (n/d)	[32]	191	213.2
	HERMES (p)	[33]	37	29.1
	HERMES (d)	[33]	37	29.5
	SLAC (p)	[34]	564	469.8
	SLAC (d)	[34]	582	412.1
	BCDMS (p)	[35]	351	472.2
	BCDNS (d)	[36]	254	321.8
	NMC (p)	[37]	275	416.5
	NMC (d/p)	[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
W	SeaQuest (d/p)	[5]	6	7.5
	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^-) (less η_{\max} point)	[6]	9 (8)	25.3 (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

Lepton Pair Production



Fit new data
(SeaQuest & STAR)



SeaQuest: $\chi^2/\text{datum} = 3.19$



1.25

E866 : $\chi^2/\text{datum} = 1.63$

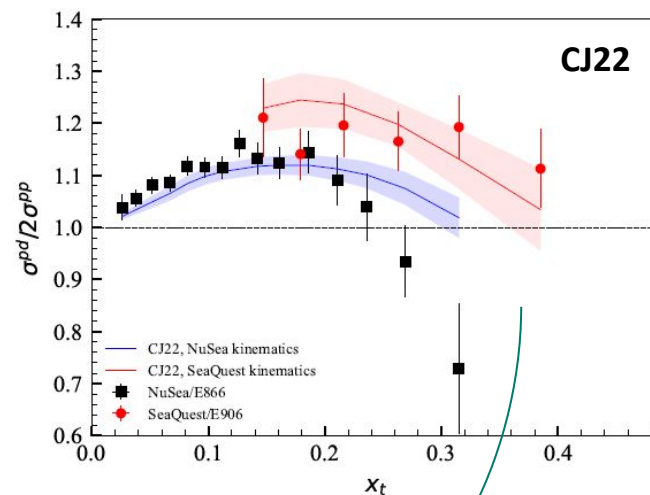
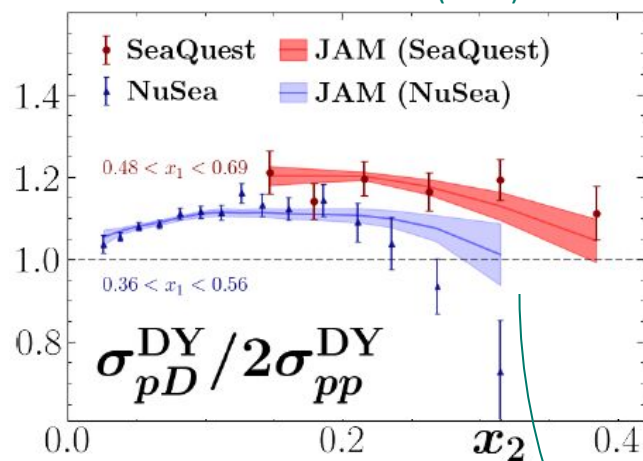


1.93

Lepton Pair Production

- Comparable results to JAM, CT:

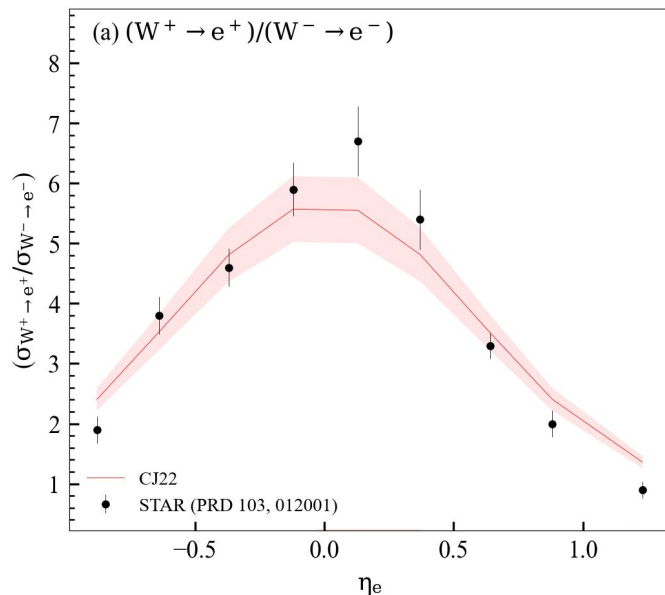
Cocuzza et al. PRD 104 (2021) 074031



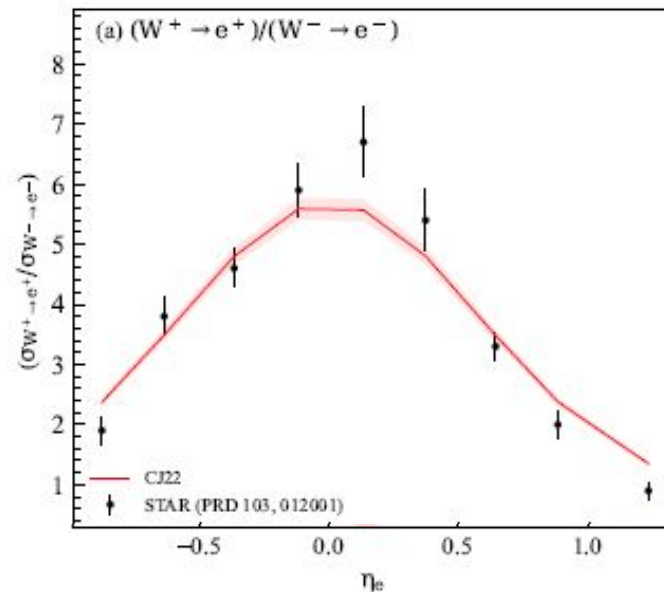
E866, SeaQuest disagree:
How to include in error bands?

→ K. Mohan, WG1 Wed

Weak boson production



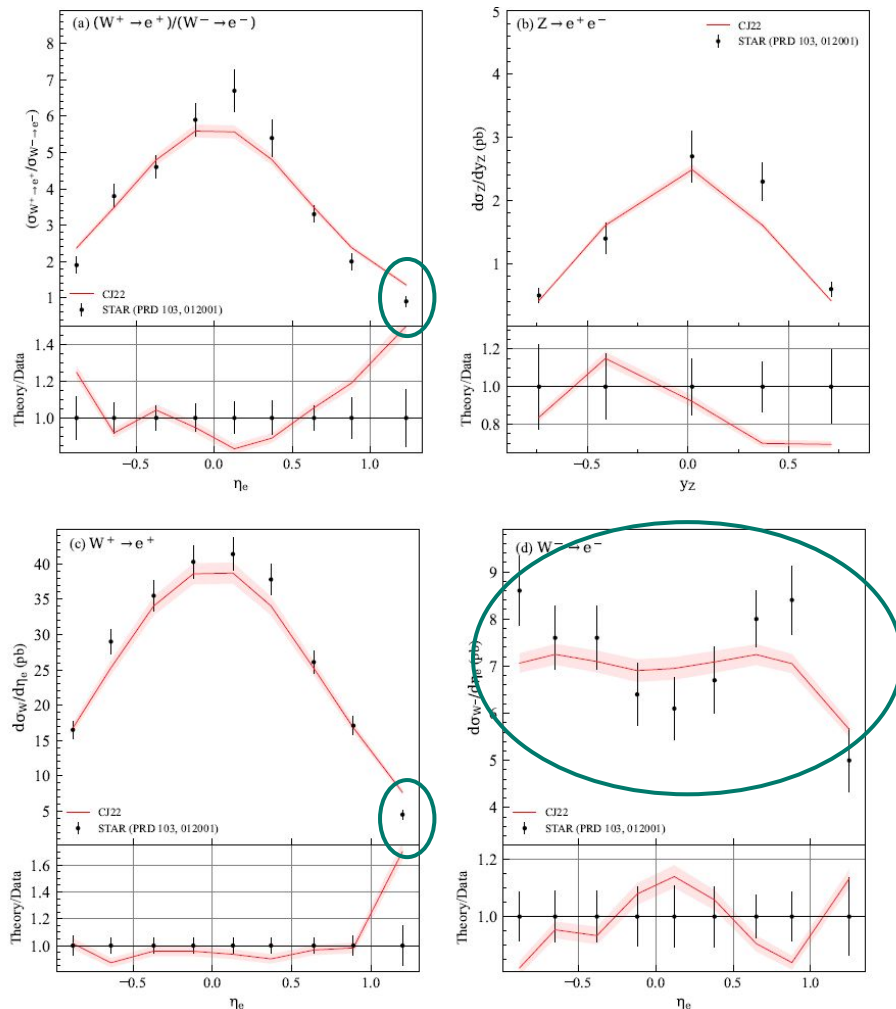
→
Fit new data
(SeaQuest & STAR)



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

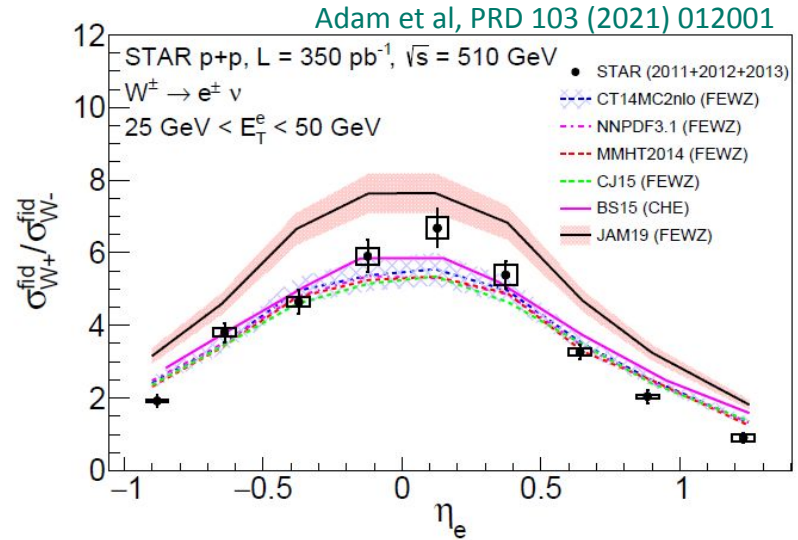
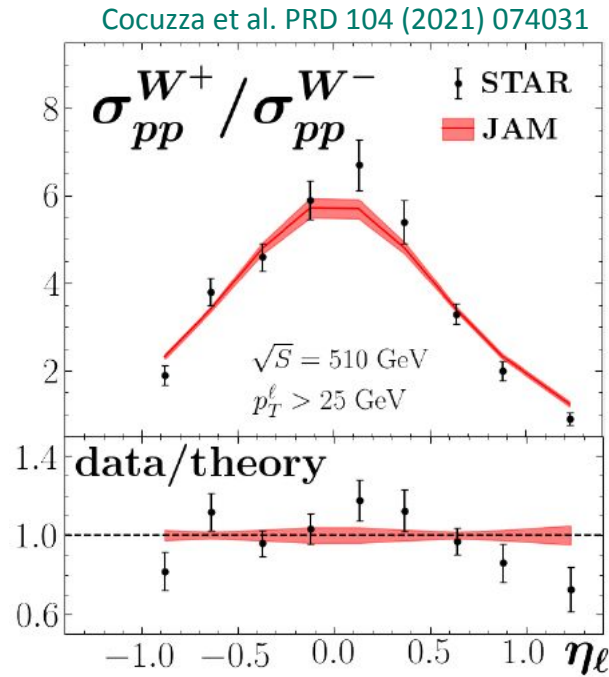
Weak boson production

- 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**

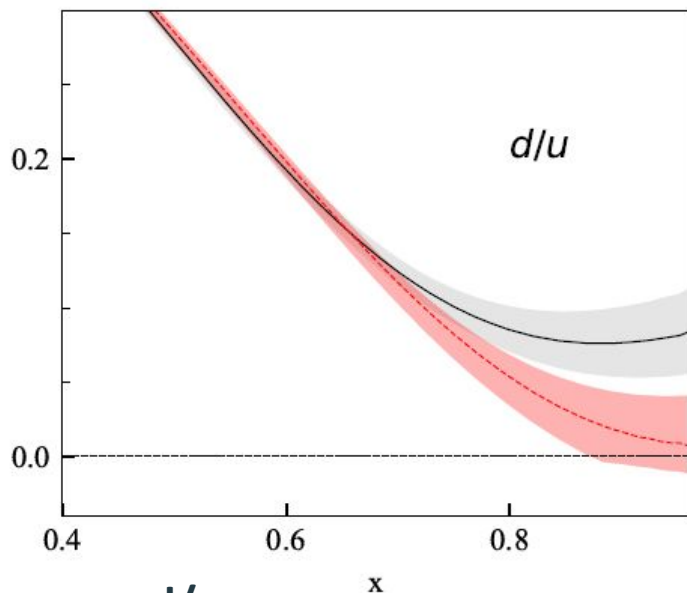


Weak boson production

- Similar results from JAM, other calcs

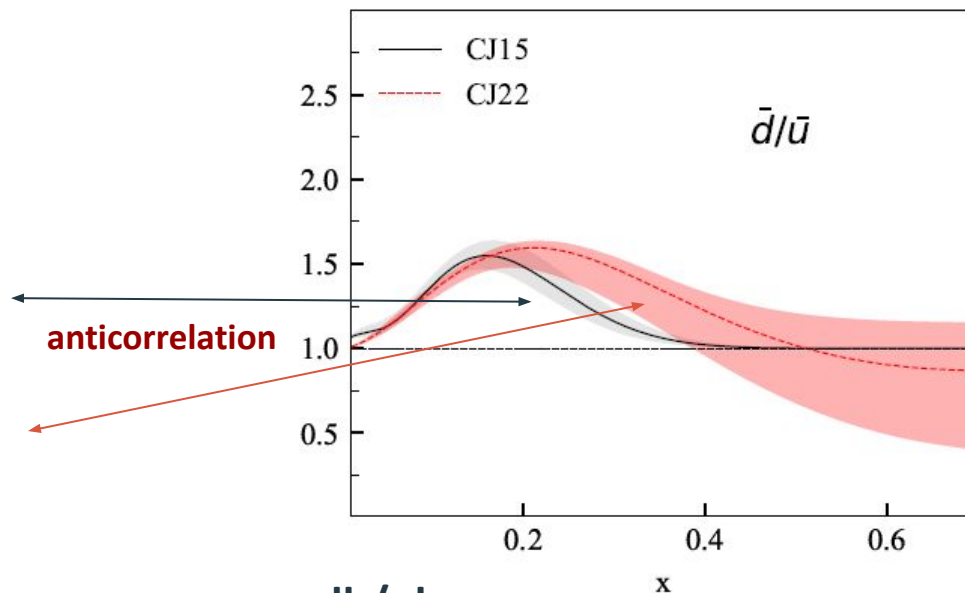


Light quarks and anti quarks



- **d/u**

- CJ15 was biased upwards
- CJ22 agrees with AKP



- **db/ub**

- pulled up by SeaQuest
- Naturally relaxes to 1 at large x

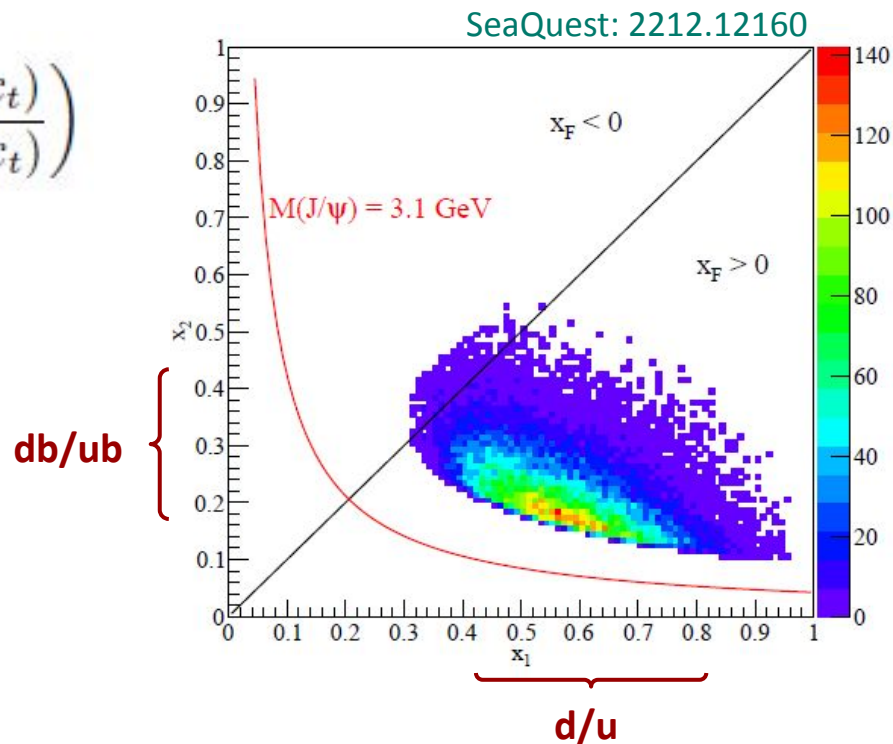
Summary

- **CJ22: new electroweak data, flexible antiquark parametrization**
 - SeaQuest data
 - Pulls up $d\bar{b}/u\bar{b}$, naturally relaxes to 1 from above at large x
 - $d\bar{b}/u\bar{b}$ anticorrelated with d/u
 - Pushes down d/u relative to CJ15, now closer to 0 as $x \rightarrow 1$
- **Upcoming from CJ (see backup):**
 - $F_2(n)$ “data” extraction – very soon!
 - HT, offshell systematics
 - (Strange sea with LHC electroweak data)

Backup

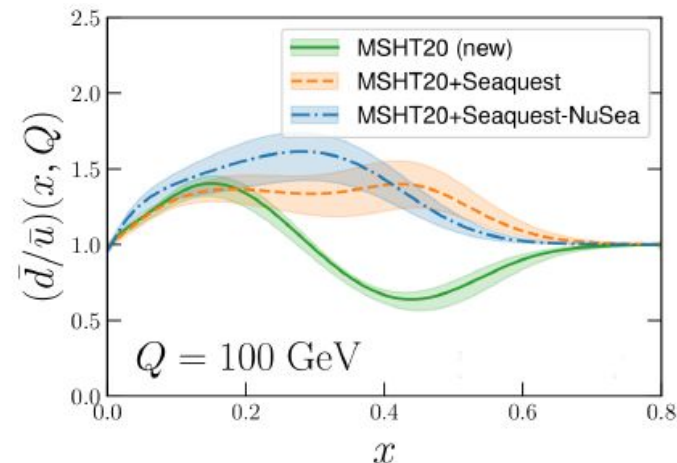
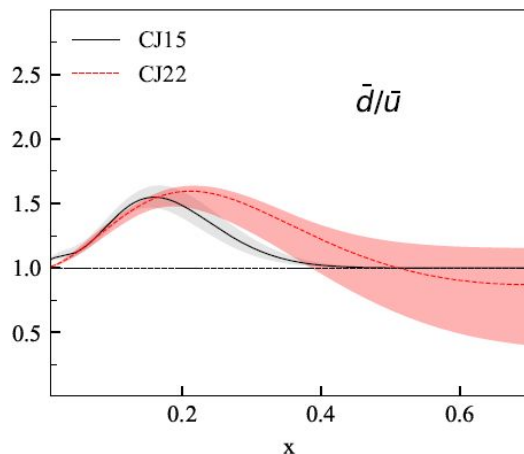
SeaQuest kinematics

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

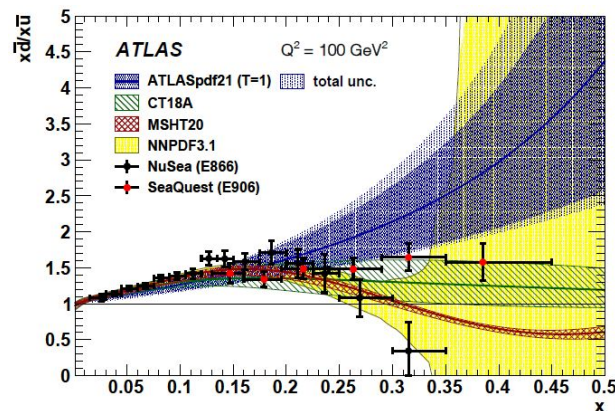


Comparison to other recent PDFs

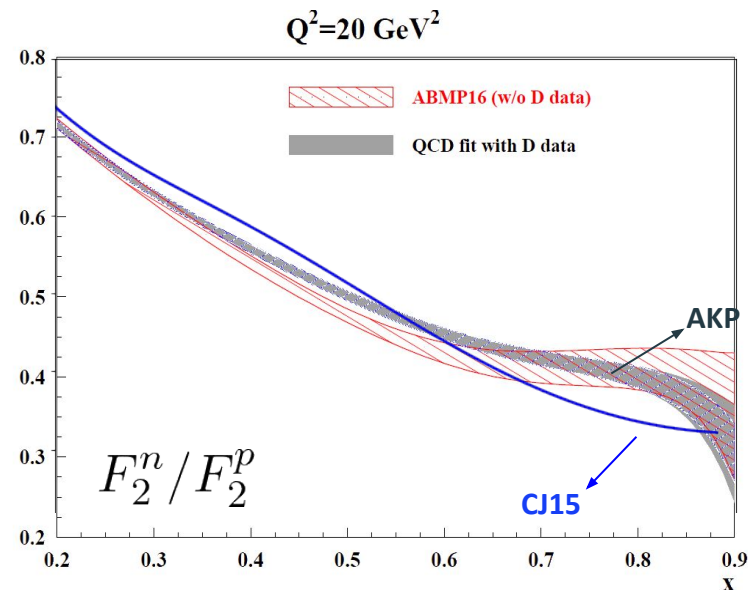
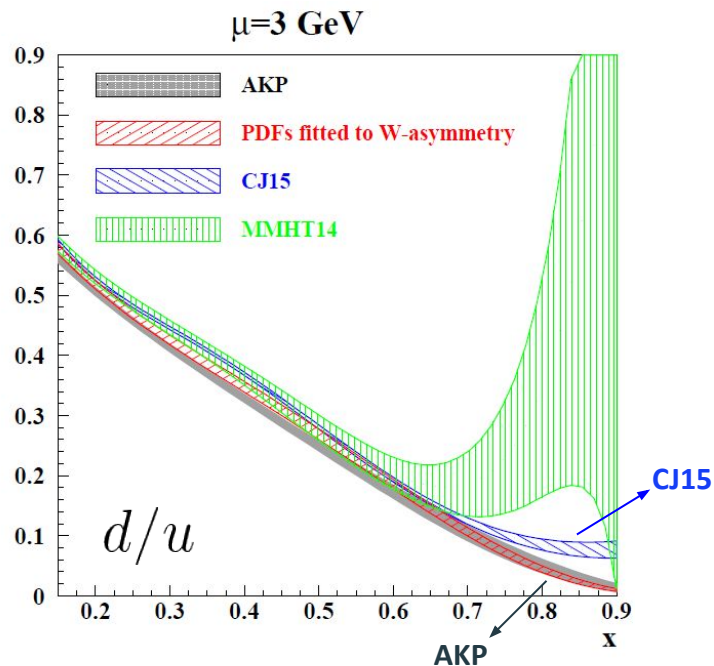
- SeaQuest fitted:



- PDFs w/o SeaQuest:



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**

HT systematics & offshell corrections

CTEQ-JLab study, in progress

See also Accardi, talk at DNP 2020

- Additive vs. Multiplicative**

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

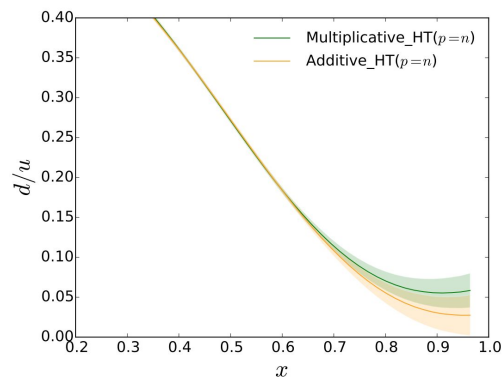
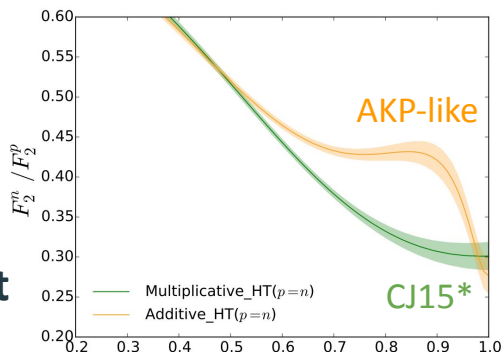
$$F_2(x, Q^2) = F_2^{LT}(x, Q^2) \left(1 + \frac{C(x)}{Q^2}\right)$$

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

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

- Non-negligible large- x bias**

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

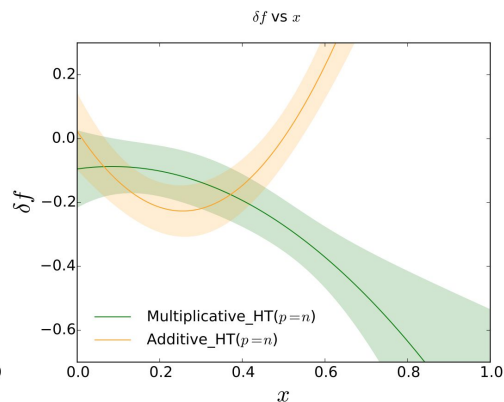


Isospin symmetric HT

■ Additive HT ($p=n$)

■ Mult HT ($p=n$)

→ CJ15*



I. Fernando

HT systematics & offshell corrections

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

- Additive vs. Multiplicative

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

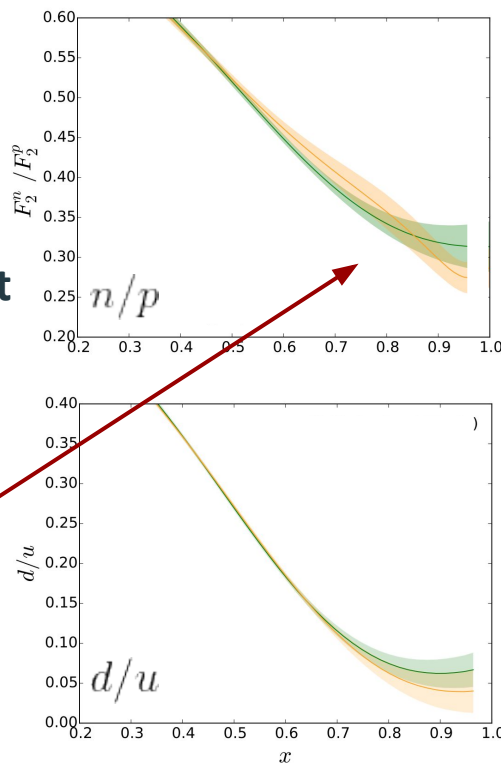
$$F_2(x, Q^2) = F_2^{LT}(x, Q^2) \left(1 + \frac{C(x)}{Q^2}\right)$$

- Isospin, Q^2 evol. not independent

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

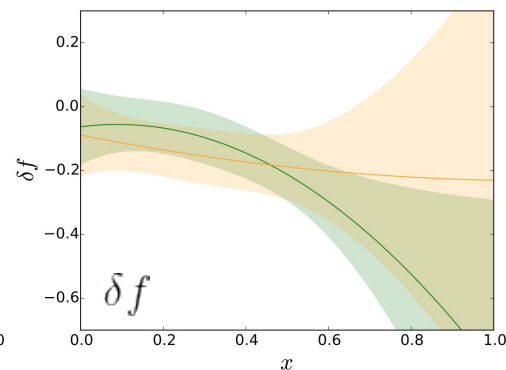
- Isospin dependent HT:

BIAS REMOVED!



Isospin dependent HT

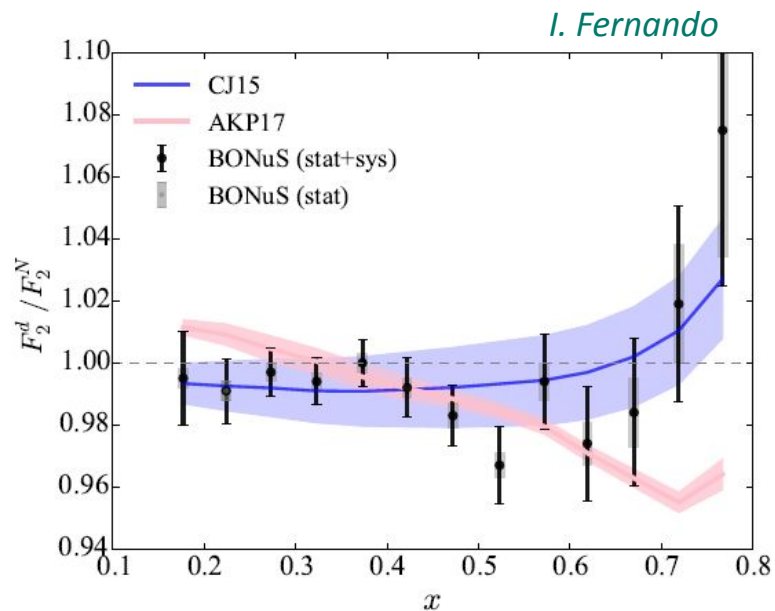
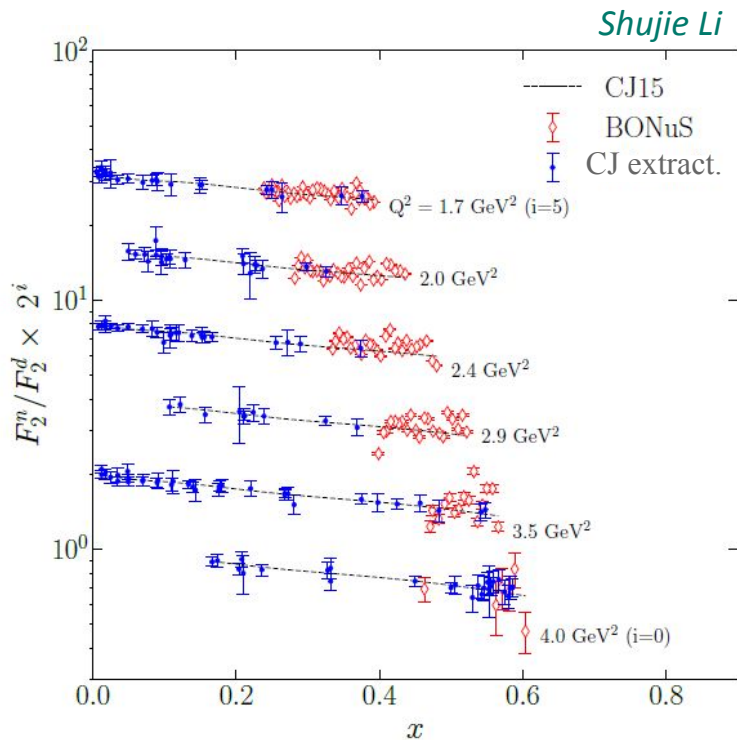
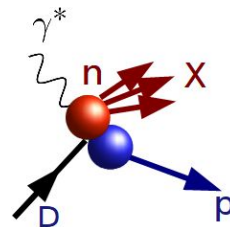
- Additive HT ($p \neq n$)
- Mult HT ($p \neq n$)



I. Fernando

Bonus cross-checks

- **BONuS: Tagged proton DIS measurements**



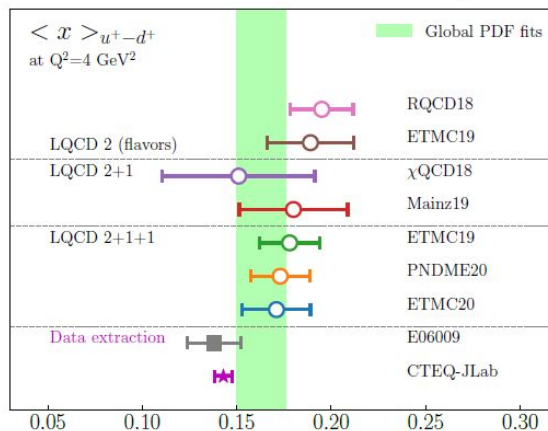
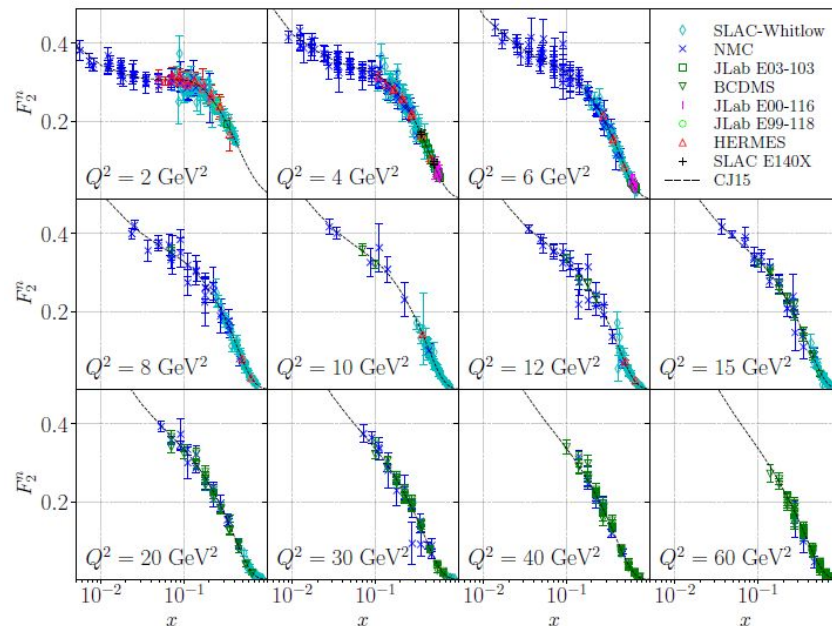
$F_2(n)$ extraction and apps

- **Basic idea:**

$$\hat{F}_2^{n(0)}(x, Q^2) = \frac{2 \hat{F}_2^{d(0)}(x, Q^2)_{\text{exp}}}{R_{d/N}^{\text{CJ}}(x, Q^2)} - \hat{F}_2^{p(0)}(x, Q^2)_{\text{exp}}$$

- **But also:**

- P, d data matching
- Data cross normalization
 - using CJ15 PDFs
 - refitting norm, Correlated shifts
- Bin-centering for Isosinglet moment
- ...



Shujie Li

$F_2(n/p)$ extraction

- Similar idea, but using

- d/p data

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

- n/d BONuS data

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

