Partonic and Nuclear Dynamics through the CJ Global Analysis Lens

Alberto Accardi

M.Cerutti, et al – Phys.Rev.D 111 (2025) 9

QCD evolution 2025

23 May 2025

Christopher Newport University
School of Engineering and Computing

Jefferson Lab

CTEQ-Jefferson Lab Collaboration

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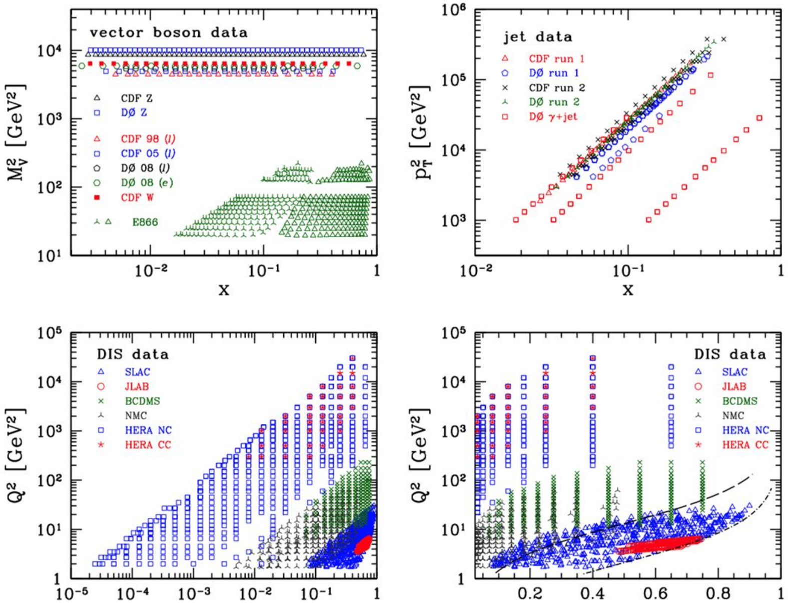
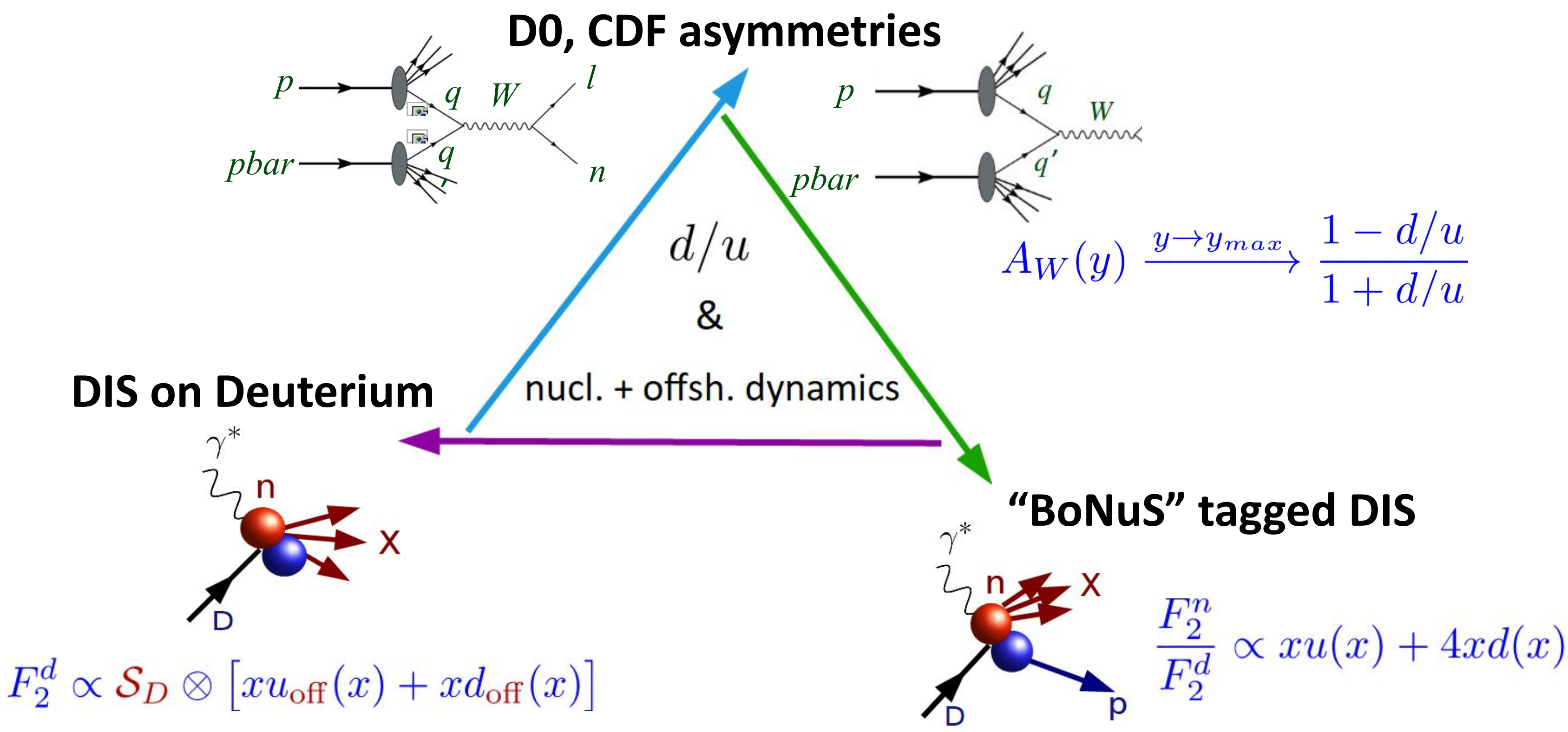
The CTEQ-JLab collaboration

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

- **Focus on large *x***
  - In this talk, d/u ratio
- **Maximize use of low-nrg DIS data**
  - SLAC, JLab 6, JLab 12
- **Global fits as a tool**
  - PDFs, nuclear dynamics



Large-x PDFs: interplay of observables



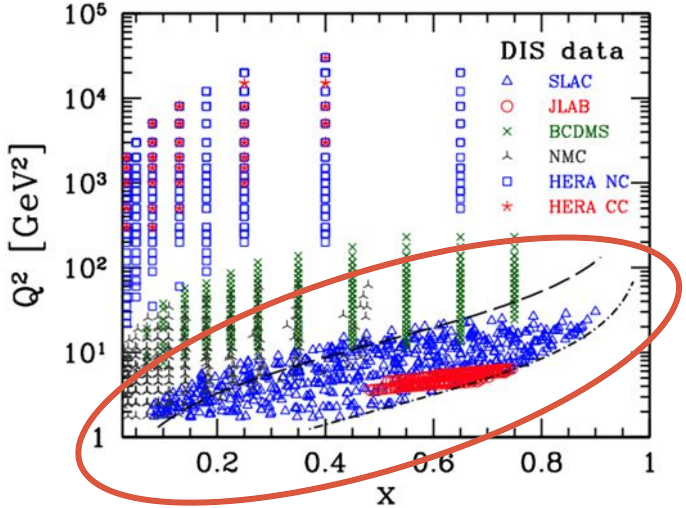
More high-low E connections: *M. Ubiali, Tue*

DIS at low energy

- **At large *x and small* Q^2, need:**
  - Target mass corrections
  - Other 1/Q2 corrections ("HT")
    - ⟶ Leftover TMCs
    - ⟶ Multiparton correlations
    - ⟶ Missing higher orders
    - ⟶ threshold resummation

A.SImonelli (Mon)

  - Deuteron target structure
    - ⟶ Binding and Fermi motion
    - ⟶ Offshell deformation of bound nucleons



DIS at low energy

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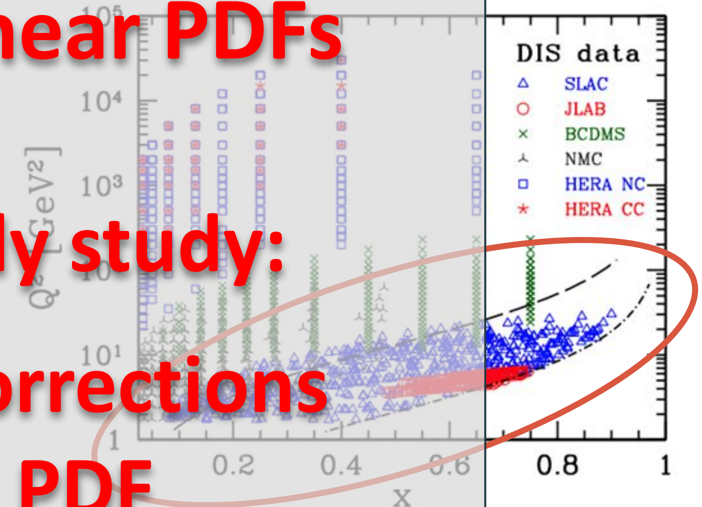
Highly non-trivial fits already for collinear PDFs



Need to carefully study:

⟶ interplay of corrections

⟶ effect on PDF

⟶ induced systematics

Recent history

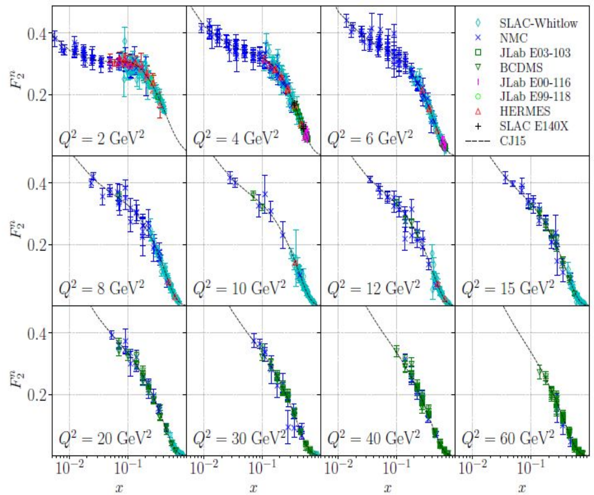
github.com/JeffersonLab/CJ-JAM-database

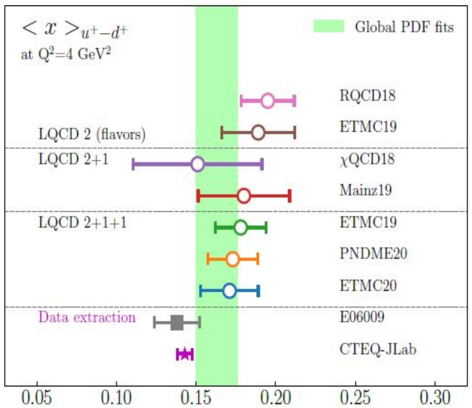
CJ15 ⟶ **CJ15ht** and **CJ15sfn** ⟷ **CJ-JAM DIS database**

PRD 93 (2016) 114017

PRD 109 (2024) 074036

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





JLab 6 data too!

Recent history

CJ15 → **CJ15ht** and **CJ15sfn**

PRD 93 (2016) 114017

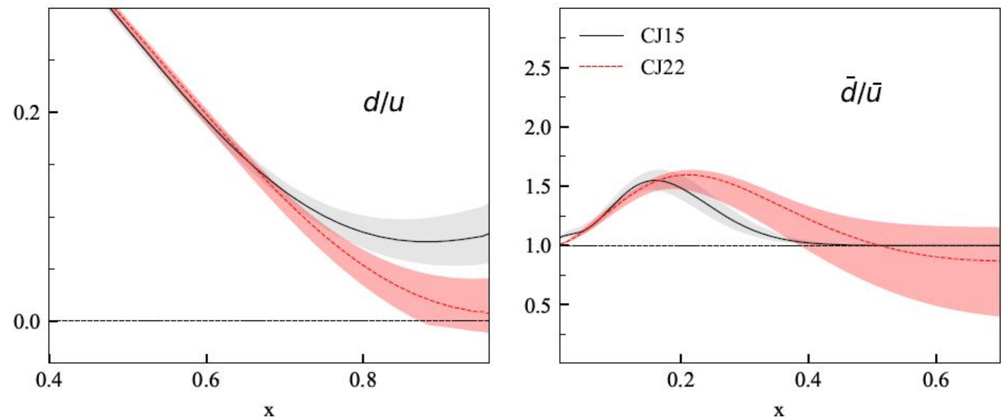
PRD 109 (2024) 074036

↓

CJ22

PRD 107 (2023) 113005

More flexible $\bar{d}/\bar{u}$
SeaQuest + STAR W/Z



New work

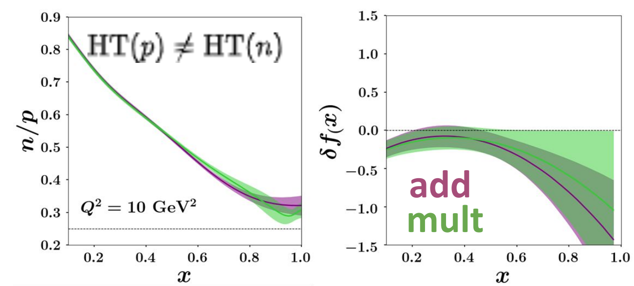
CJ15 → **CJ15ht** and **CJ15sfn**

PRD 93 (2016) 114017 — *PRD 109 (2024) 074036*

↓

CJ22 → **CJ22ht**

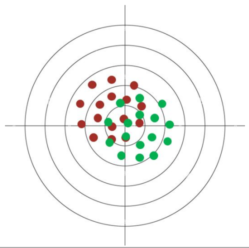
PRD 107 (2023) 113005 — *arXiv:2501.06849*



Flexible off-shell param,

Offshell vs. HT corrections:
Add vs. mult / isospin dependence

→ d/u, n/p, offshell stability (& accuracy?)
If HT(p) =/= HT(n)



New work

CJ15 → **CJ15ht** and **CJ15sfn**

PRD 93 (2016) 114017

PRD 109 (2024) 074036

CJ22 → **CJ22ht** → **high-statistics JLab 6/12 GeV data** (preliminary impact)

PRD 107 (2023) 113005

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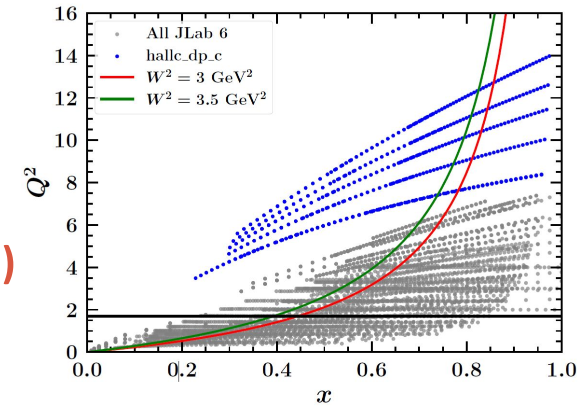

New work

CJ15 → CJ15ht and CJ15sfn

PRD 93 (2016) 114017

PRD 109 (2024) 074036

CJ22 → CJ22ht → high-statistics JLab 6/12 GeV data (preliminary impact)

PRD 107 (2023) 113005

This talk

CJ22ht

arXiv:2501.06849

high-statistics
JLab 6/12 GeV data
(preliminary impact)

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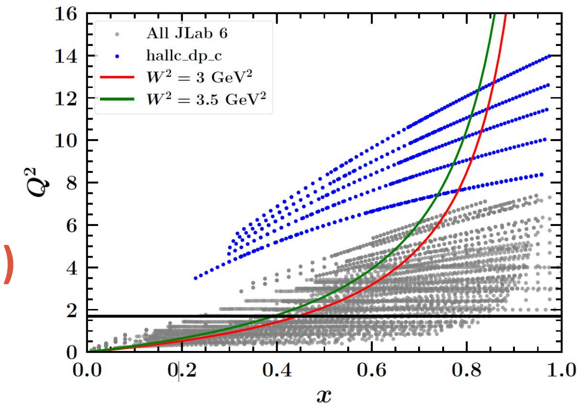
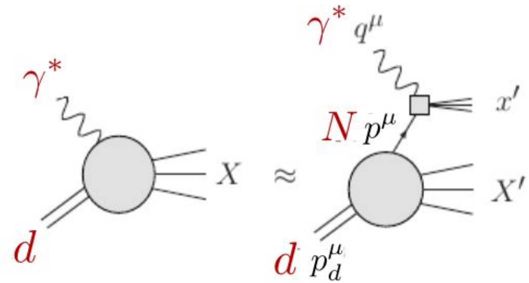


Deuteron target

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



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

kinematic and “flux” factors

Nucleon wave function

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

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

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

Free proton, neutron structure function

“offshell function”

Deuteron target

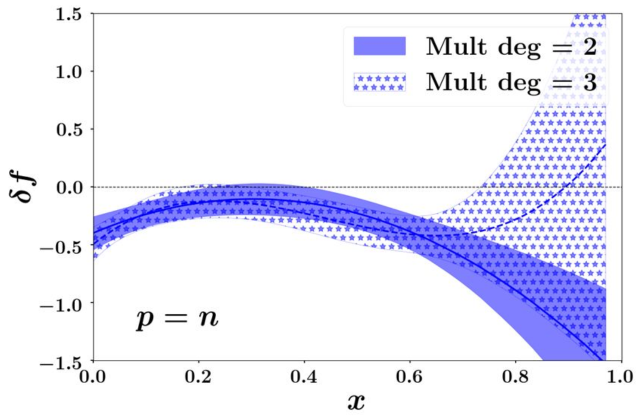
- **Offshell corrections**

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

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

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

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



CJ fitted data set constrains δf up to x<0.6

HT systematics

- **HT modeling**
  - Additive $F_2(x,Q^2) = F_2^{LT}(x,Q^2) + \frac{H(x)}{Q^2}$

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

  Isospin dependent or not

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

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

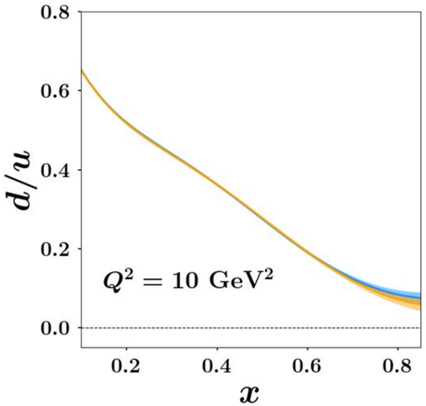
- **Non-negligible large-*x* bias**
  - **if using isospin-independent coefficients**

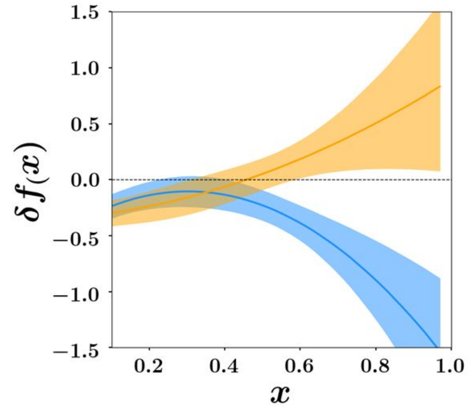
    ⟶ Multiplicative (CJ15) underestimates

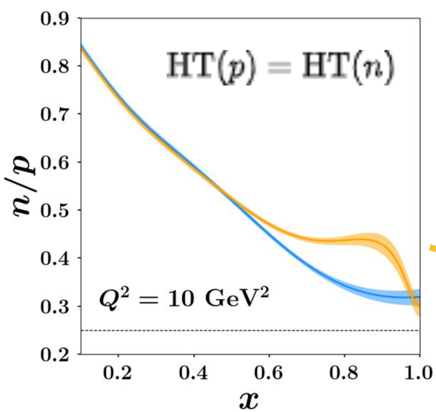
    ⟶ Additive (AKP17) overestimates ($H > 0$)

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

Fits 1 – isospin independent HT





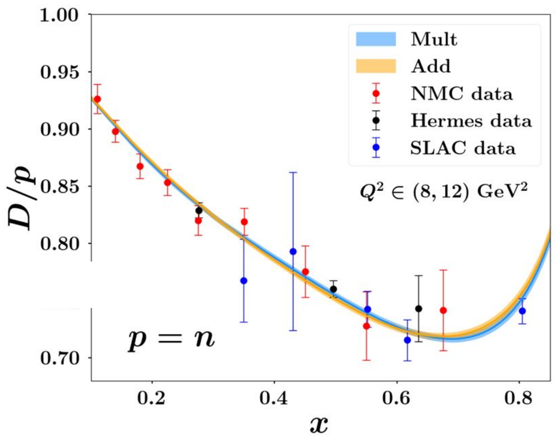


Additive (p = n)

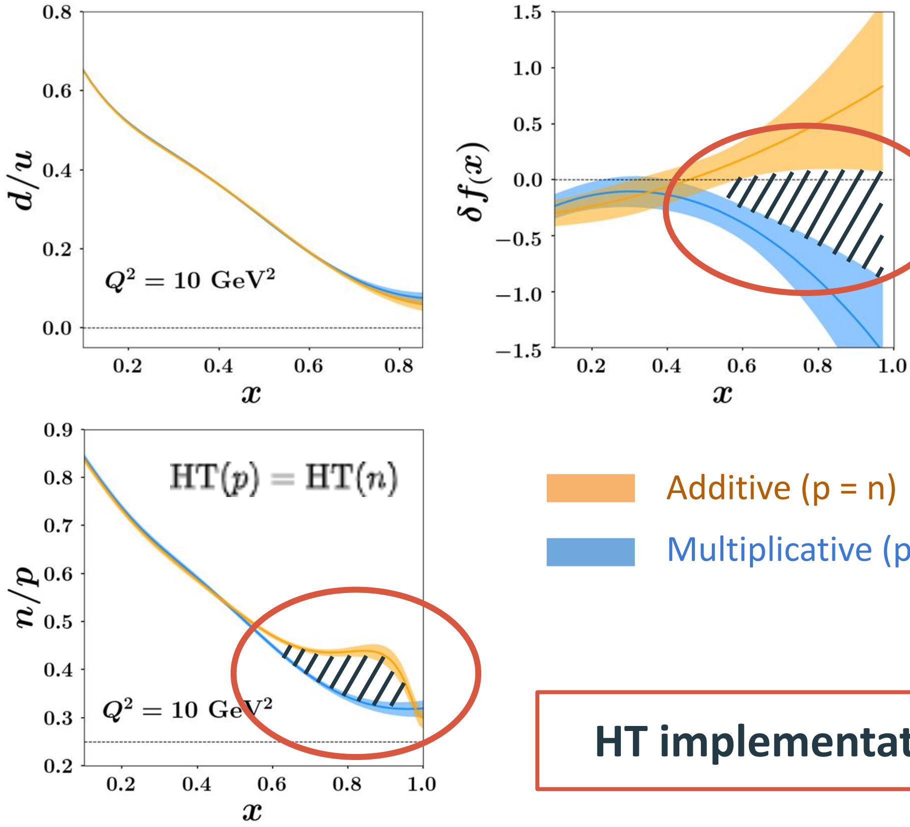
Multiplicative (p = n)

Artificially large n/p
(but smaller d/u…)

Bias identified!
Offshell compensates n/p



Fits 1 – isospin independent HT

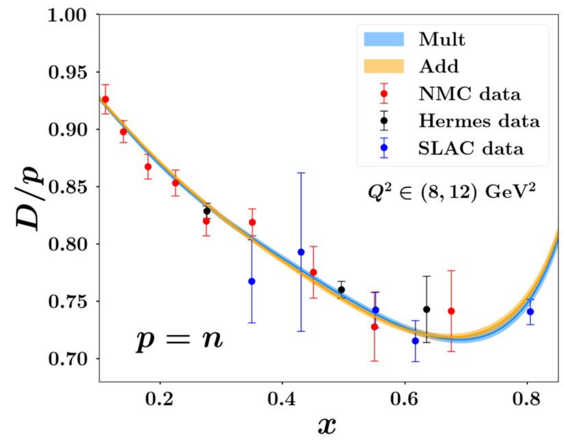


Additive (p = n)

Multiplicative (p = n)

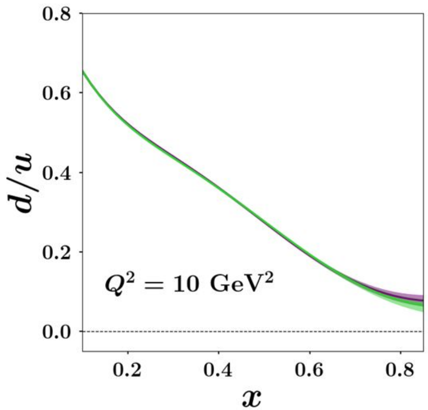
Bias identified!

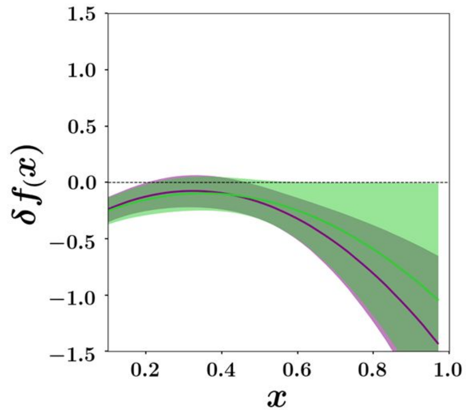
Offshell compensates n/p

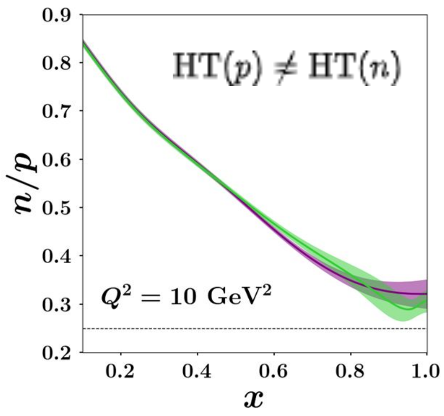


HT implementation bias

Fits 2 – isospin dependent case





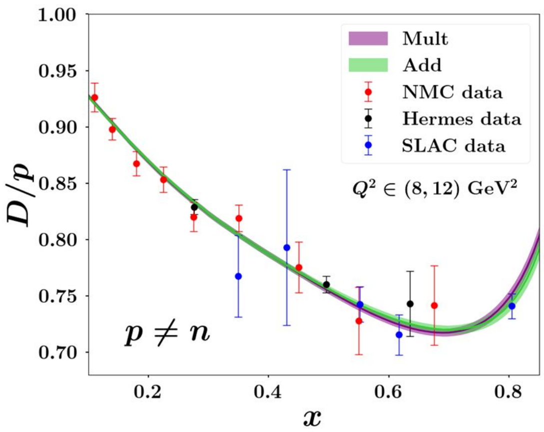


Additive (p ≠ n)

Multiplicative (p ≠ n)

Bias removed!

No need of compensation
(as expected theoretically)

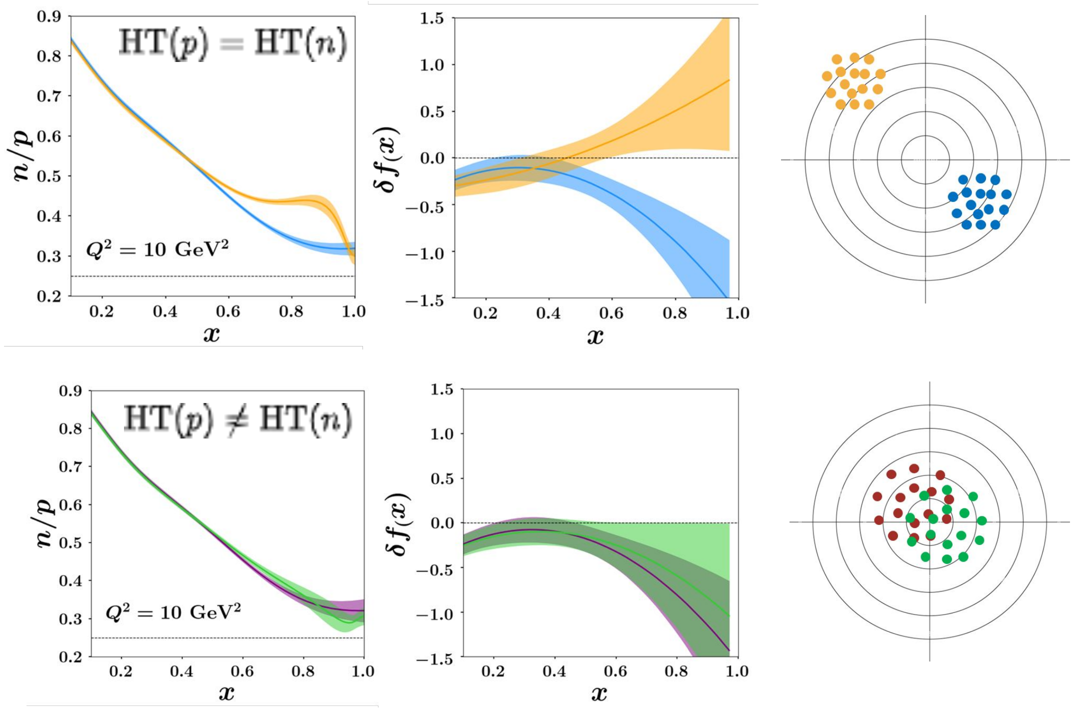


compatible n/p
& offshell
& d/u

Remaining differences are
theoretical uncertainties
(HT modeling)

Summary – Unbiasing the fit

Add. vs. mult. HT



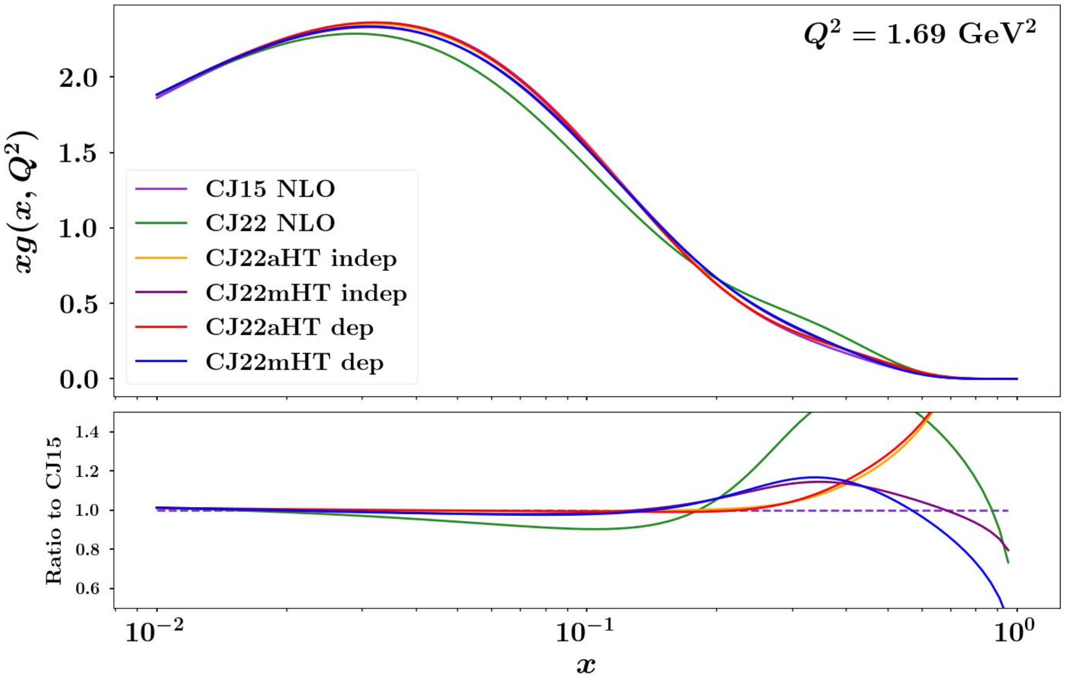
Accuracy challenge met! *

Systematic uncertainty from HT implementation

* a few more checks needed, but a big one done!

Gluon systematics

- **Assumptions matter → interplay of many sectors**



CJ15:

– db/ub constrained →1 as x→1

– factorized offshell parametzion

CJ22:

– flexible db/ub

→ gluons compensate for offshell assumptions (!!)

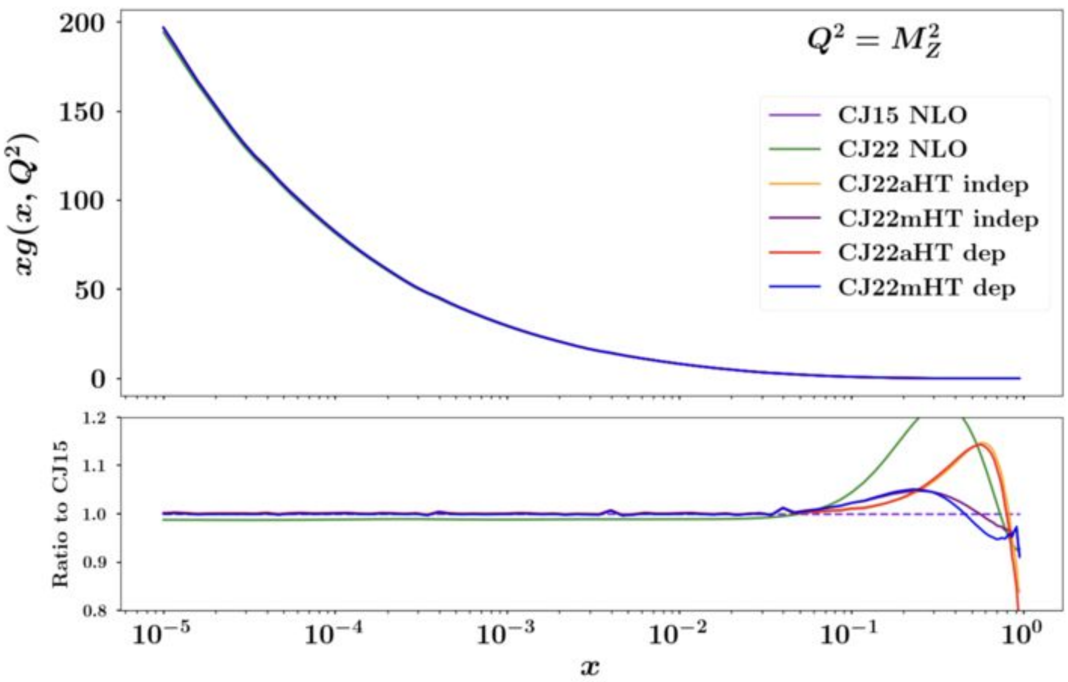
CJ22ht:

– flexible db/ub & flexible offshell

→ gluons only need to take care of HT modeling

Gluon systematics

- **Assumptions matter → interplay of many sectors**



At large Q^2, differences at large x

→ **need larger Q^2 data:**

- Suppress HT
- Constrain offshell
- Gluons through DGLAP evolution

- Cross sections (but HT for FL!)

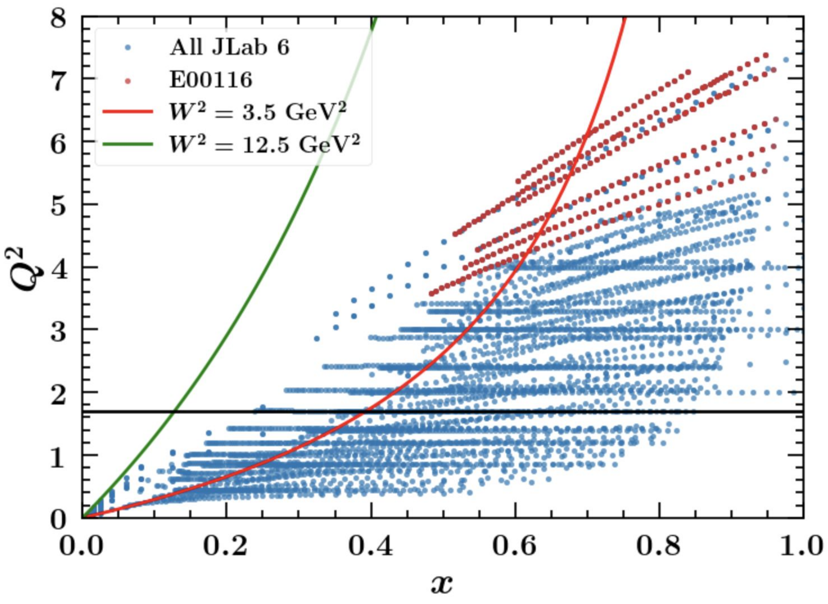
- Jet data at forward rapidity, large mass

Impact of JLab DIS data

(very preliminary, but tantalizing!)

Impact of JLab 6 GeV

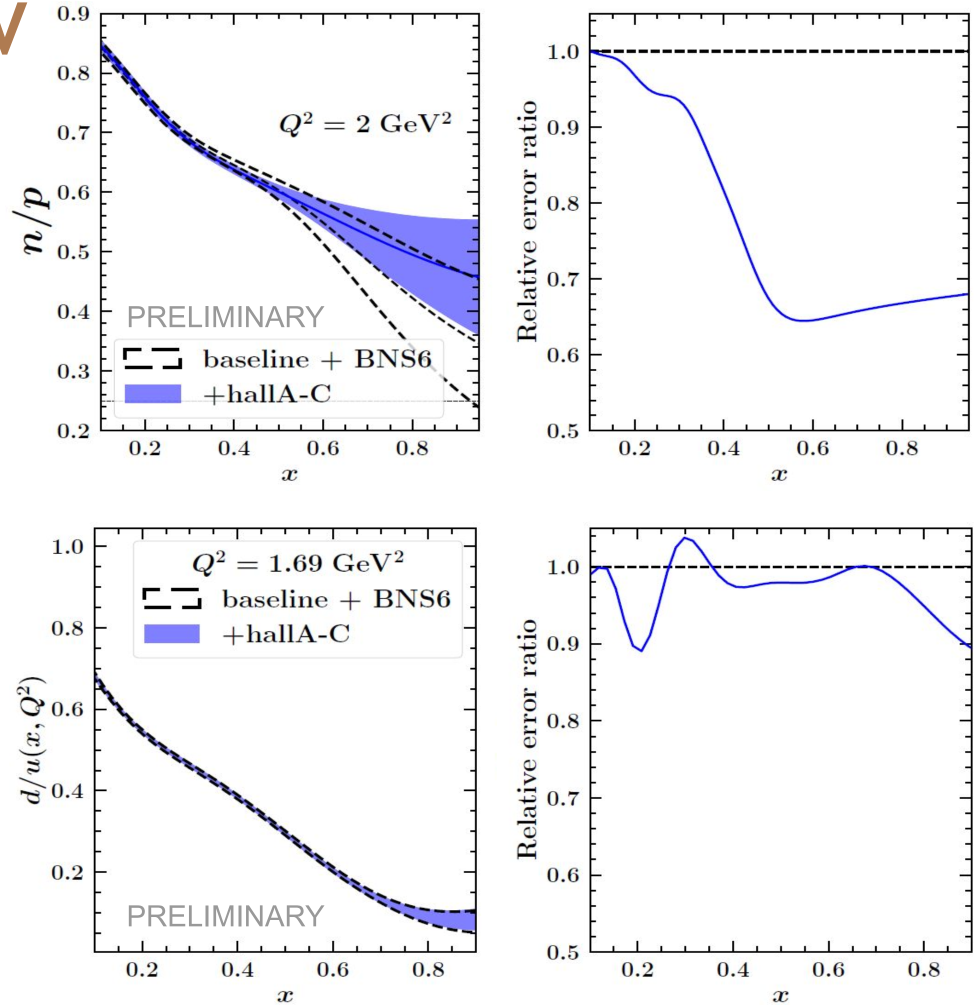
- **New no-JLab baseline:**
  - CJ22ht data, except BONuS, E00-116
- **Good fit**
  - With W2 > 3.5 GeV
  - Cuts resonances, largest kinematics



	W2cut 3.5 (3.0)	
Dataset	Npts	Chi2
e00116p	**91** (136)	**93.9** (163.8)
e00116d	**91** (136)	**93.8** (124.8)
e03103p	**32** (37)	**25.0** (86.8)
e03103d	**45** (69)	**18.0** (52.7)
e06009_d_c	**44** (79)	**39.4** (57.2)
e94110p	**46** (112)	**47.4** (119.8)
e99118p	**2** (2)	**0.0** (0.1)
e99118d	**2** (2)	**0.7** (0.3)
jlcee96p	**100** (158)	**93.4** (282.1)
Jlcee96d	**97** (157)	**68.7** (146.2)
BONuS6	**137** (191)	**147.3** (212.2)

Impact of JLab 6 GeV

- **Large impact large at x > 0.3,**
  - Mostly absorbed by HT(p,n)



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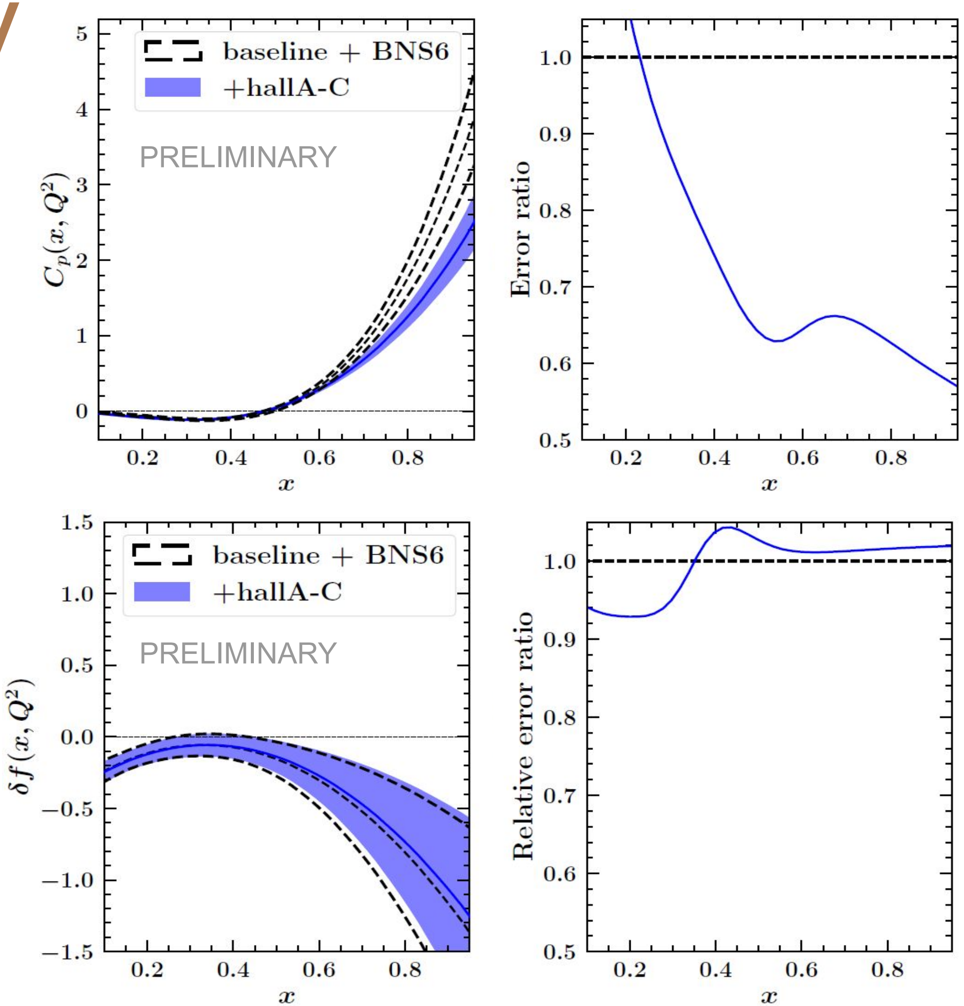
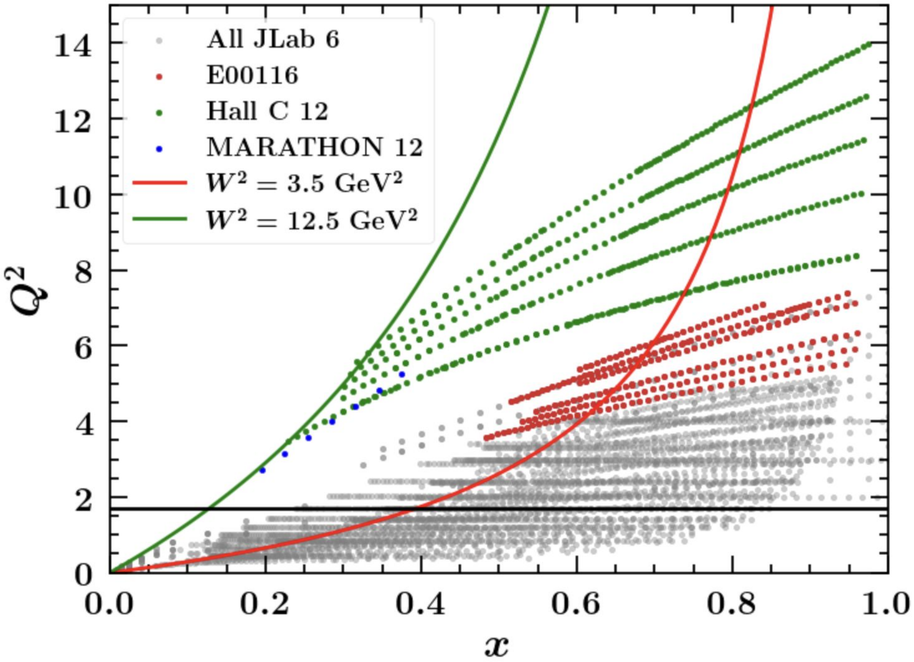


Impact of JLab 12 GeV

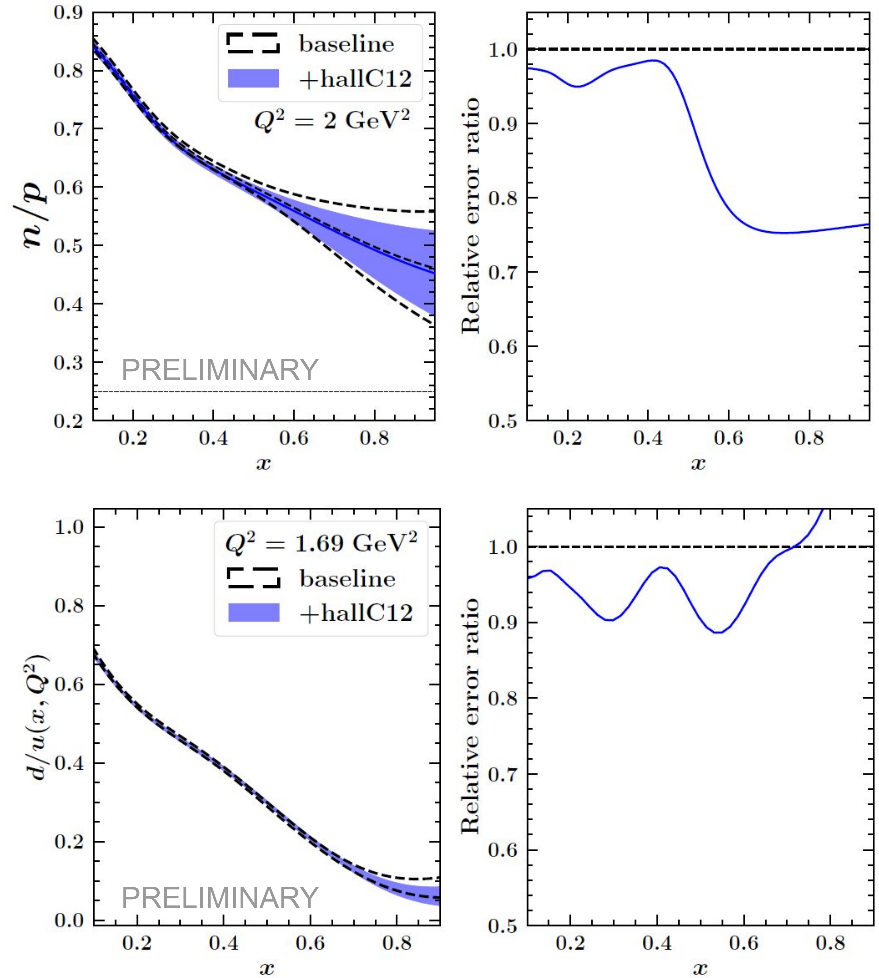
- **Larger leverage in Q^2**
- Increased large-x & small-x range



	$W^2 > 3.5$ (3.0)GeV^2		
D/p	Npts	Chi2	Chi2/npts
Hall C (corr errs)	**332** (360)	**286** (500)	**0.86** 1.39
Marathon	**7**	**5.25**	**0.75**

Impact of JLab 12 GeV

- Baseline = CJ22ht + all JLab 6 GeV
- **Statistical impact also on LT**
  - **d/u**
  - **offshell corrections**
    (not shown)

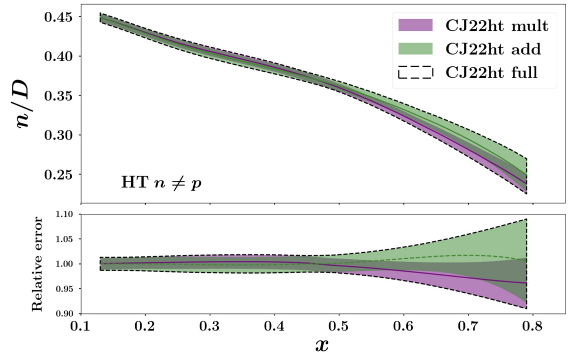


Into the future!

Into the future (12 GeV)

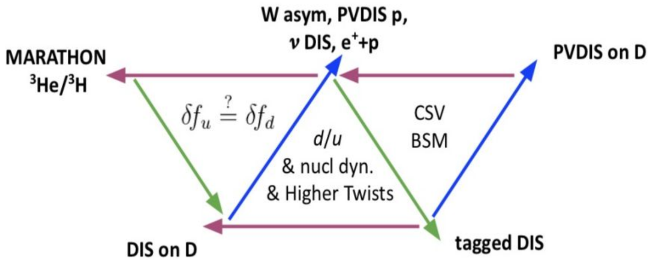
JLab E12-6-113 proposal

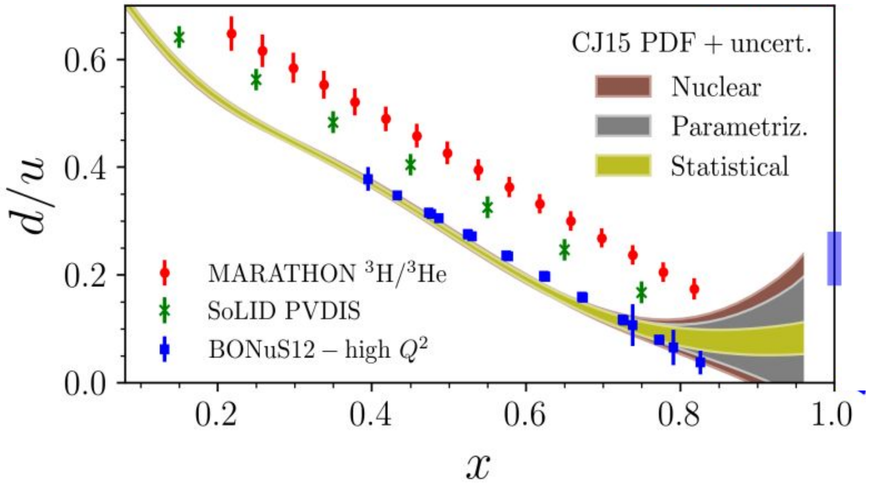
- **BONus12 – Tagged spectator proton $\longrightarrow$ n/D ratio**
  - Ongoing analysis
  - Very high statistics (many more bins than shown here)
  - Will impact off-shell extraction,
    check theory framework (would need also bins in p_{spec} !)



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

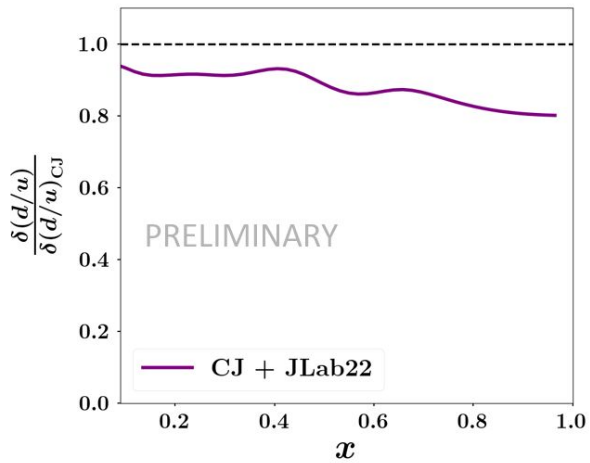
- **PVDIS @ SOLID**
  - **d/u without nuclear target** & more!
  - Parity Violating electron
    helicity asymmetry



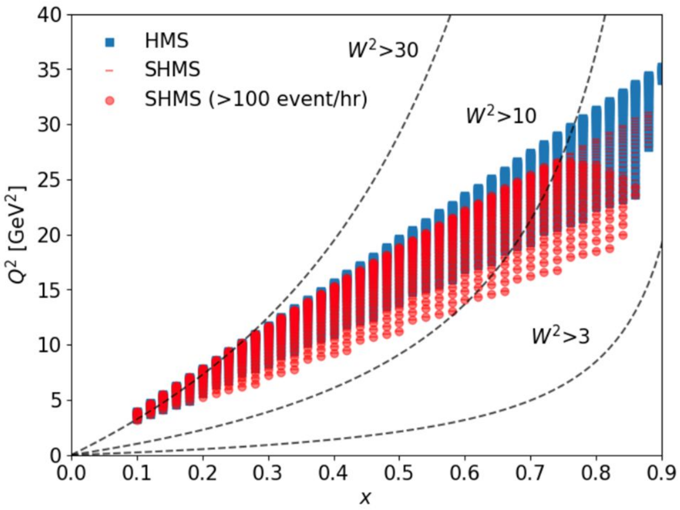


Into the future: JLab 22

- **Even larger Q^2**
  - HT suppressed
- **Impact on "LT" quantities**
  - d/u & nuclear modifications (offshell)
  - (baseline here = CJ22ht)



- **Detector: Standard SHMS@Hall C**
  - Momentum: up to 11 GeV/c
  - scattering angle: up to 40 degrees
  - Acceptance: 50mrad x 18mrad x ±10%
- **Luminosity:** 50uA on liquid hydrogen target ⇒ 10^{38}/s/cm^2
- **Cross Section model:** F1F2in21 (DIS only) + radiative corrections
- **Systematics**:
  - Point-to-point: 4% on absolute xsection, 2% on ratio
  - Normalization: 1%
- HMS TBD

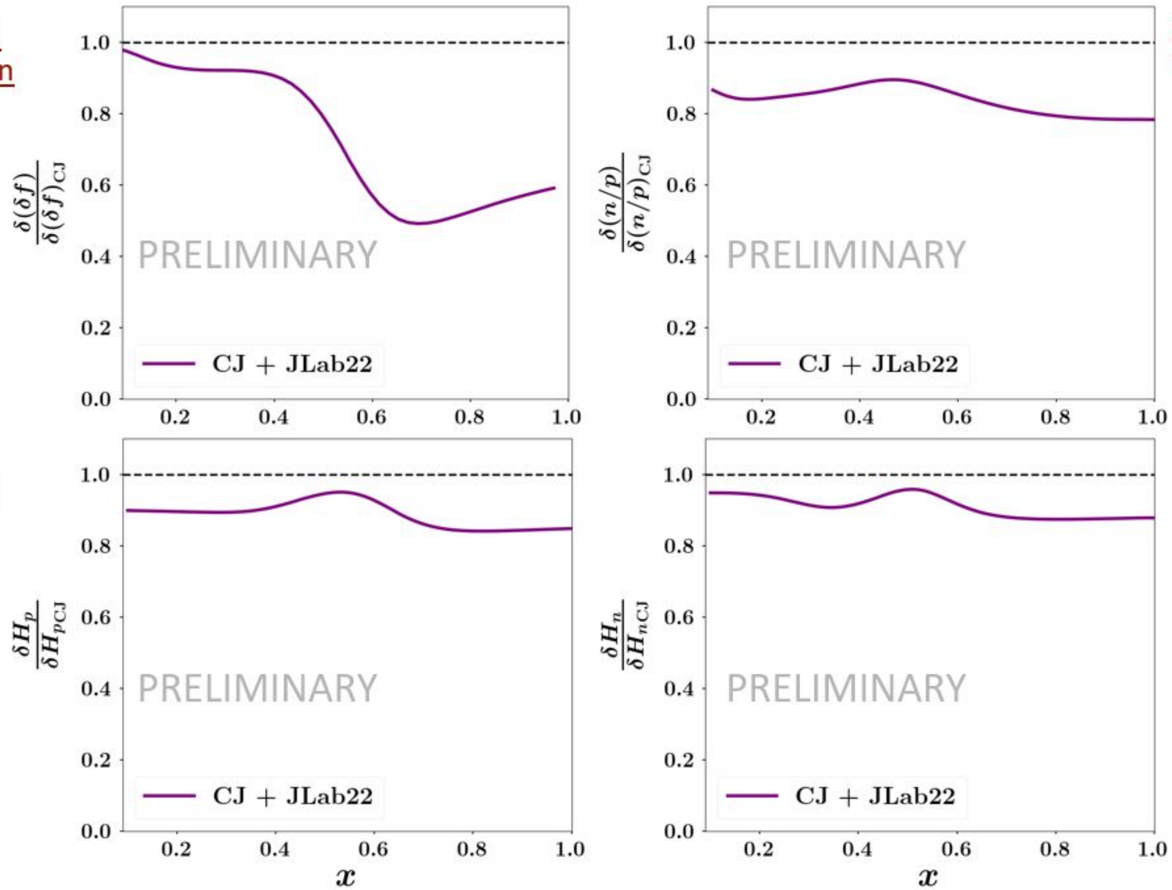


Into the future: JLab 22

offshell function

$\frac{n}{p}$ ratio

higher twists



Summary and perspective

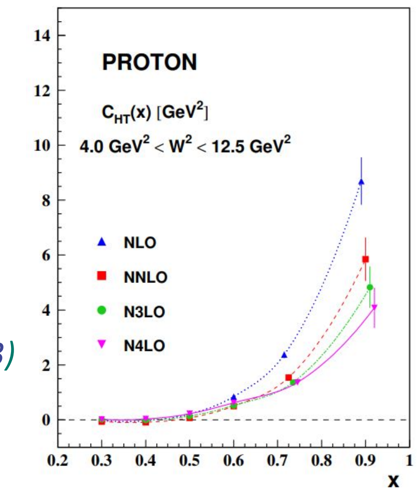
- **JLab provides large-x reach for quarks** (and gluons, another time)
  - But low-Q^2

- **TMC, HT, nuclear corrections**
  - Need to be addressed carefully
  - Assess implementation biases and uncertainties
    - ⟶ Many internal and external feedback loops
    - ⟶ Needed and possible!!
  - **TMD, GPD** analysis more delicate
    - ⟶ Even more insidious to fit? **Be extra careful!**

- **Rich datascape for precisions and accuracy**
  - Now: Jlab 6 GeV, and early JLab 12
  - Soon : Bonus 12, ALERT, …
  - Later: SOLID & JLab 22 GeV

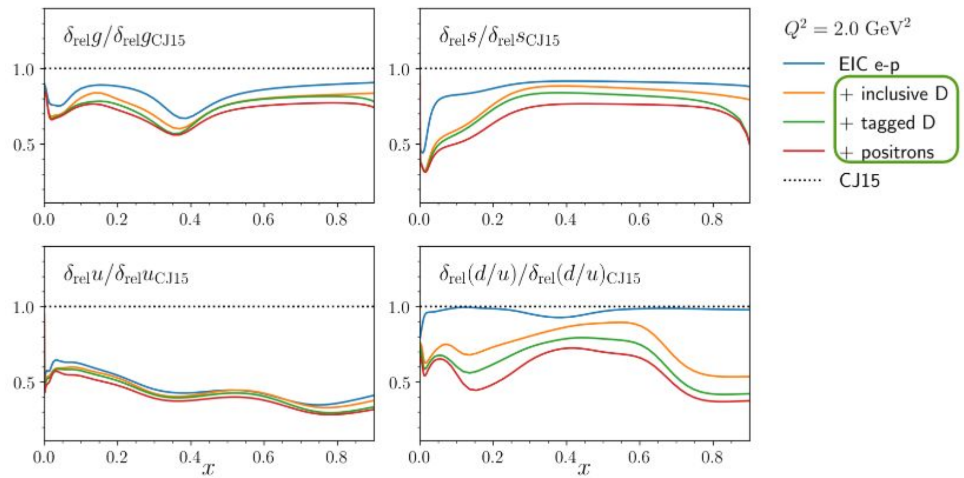
Are we done?

- **More theoretical systematics studies needed**
  - MHOT
    - ⟶ Largely absorbed in HT terms, for now
  - Large-x resummation *(⟶ Simonelli at al., 2502.15033)*
    - ⟶ Partially absorbed, too (likely)
  - …



Blumlein, Bottcher PLB 662 (2008)

- **Even higher energy:**
  - **EIC**



Prepared for: EIC yellow report – NPA 1026 (2022) 122447

Backup - 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
  - 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: 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

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)

CJ22 data set

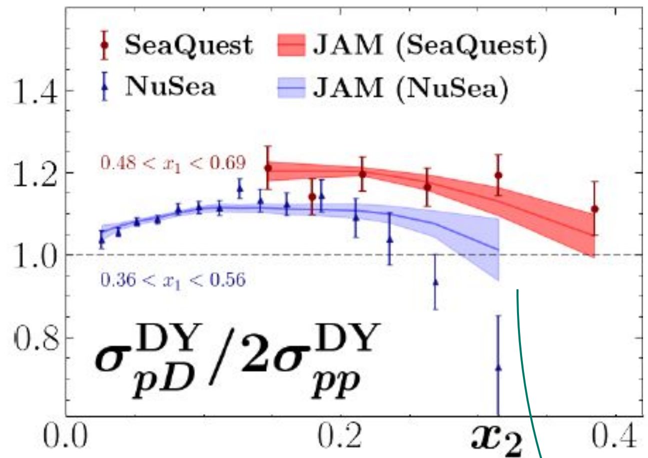
Obs.	Experiment	Ref.	# Points	χ^2
DIS	JLab (p)	[31]	136	161.0
	JLab (d)	[31]	136	119.1
	JLab (n/d)	[32]	191	213.2
	HERMES (p)	[33]	37	29.1
	HERMES (d)	[33]	37	29.5
	SLAC (p)	[34]	564	469.8
	SLAC (d)	[34]	582	412.1
	BCDMS (p)	[35]	351	472.2
	BCDNS (d)	[36]	254	321.8
	NMC (p)	[37]	275	416.5
	NMC (d/p)	[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

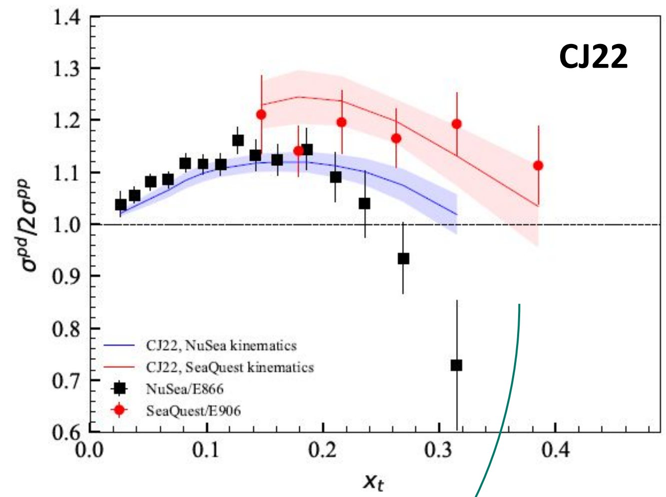
Obs.	Experiment	Ref.	# Points	χ^2
LPP	E866 (pp)	[4]	121	144.1
	E866 (pd)	[4]	129	157.4
	SeaQuest (d/p)	[5]	6	7.5
W	CDF (e)	[40]	11	12.6
	D0 (e)	[41]	13	28.8
	D0 (μ)	[42]	10	17.5
	CDF (W)	[43]	13	18.0
	D0 (W)	[44]	14	14.5
	STAR (e^+/e^-)	[6]	9	25.3
	(less $\eta_{\max}$ point)		(8)	(15.4)
Z	CDF	[45]	28	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

Lepton Pair Production

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

Cocuzza et al. PRD 104 (2021) 074031



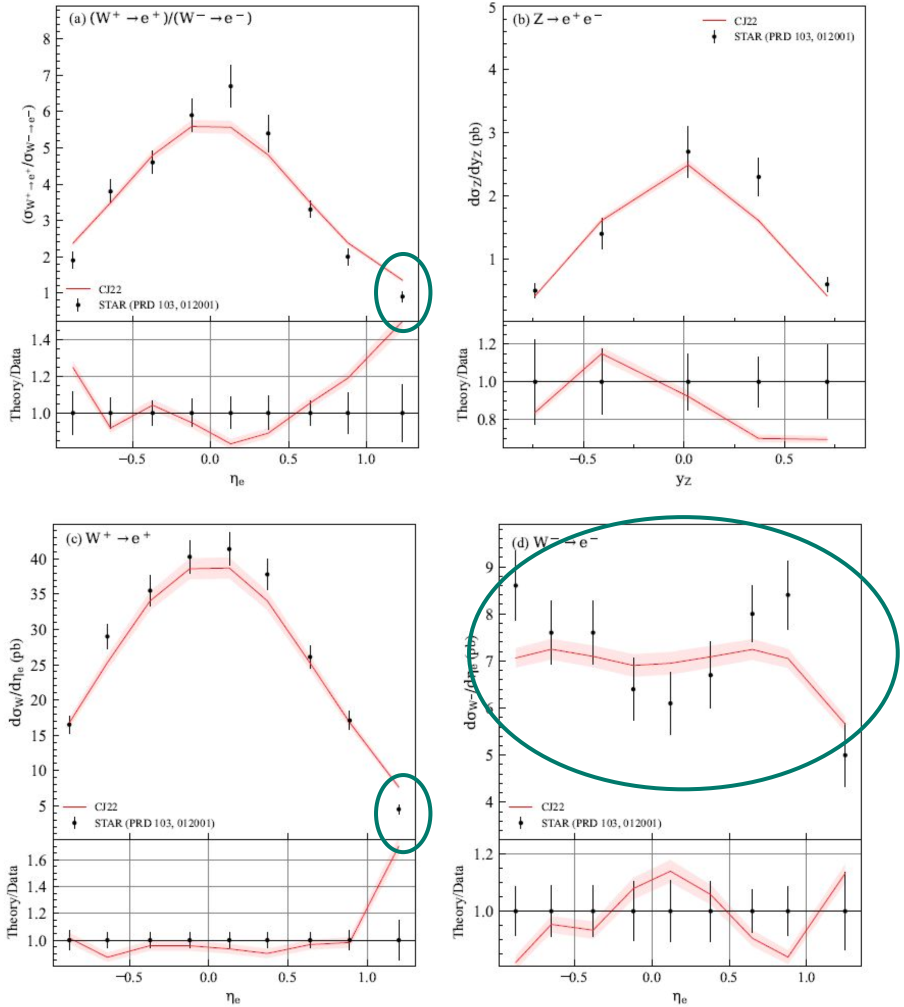


E866, SeaQuest disagree:
How to include in error bands?

→ K. Mohan, WG1 Wed

Weak boson production

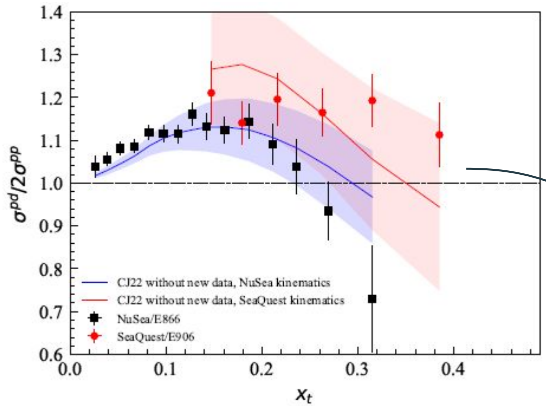
- Only W+/W- ratio was fitted
  - Other plots compare data to theory
- **Largest rapidity W^+ not reproduced**
  - Would require too small db/ub
  - Or too large d/u
- **More structure in W^- data** than in the theory calculation



New: electroweak data

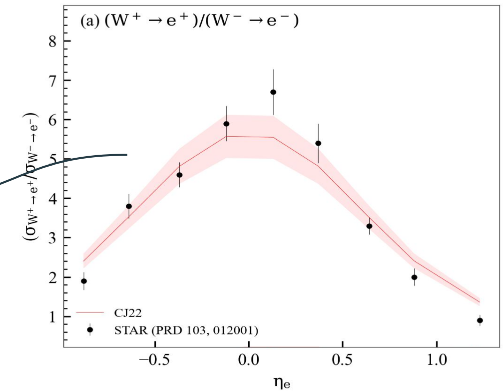
SeaQuest

→ C.H. Leung, WG1 Tue



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

→ J.D. Nam, WG1 Tue



Fits w/o new data

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

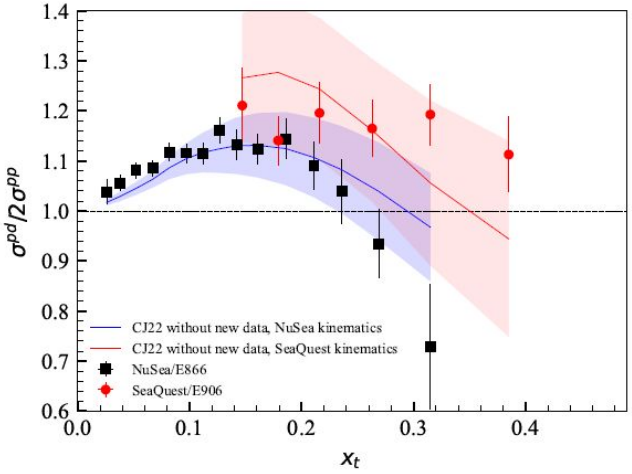
$$\frac{\sigma_{W^+}}{\sigma_{W^-}} \approx \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)} \underset{y_W \approx 0}{\approx} \frac{\bar{d}/\bar{u}}{d/u}$$

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

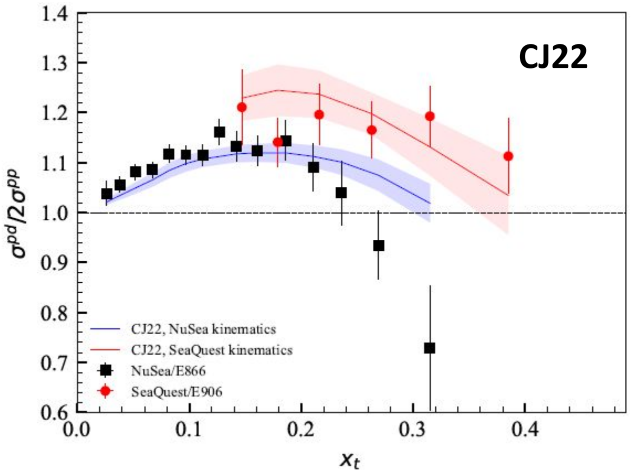
Correlation: db/ub ⟷ d/u
x ~ 0.16

Need flexible enough parametrization

Lepton Pair Production



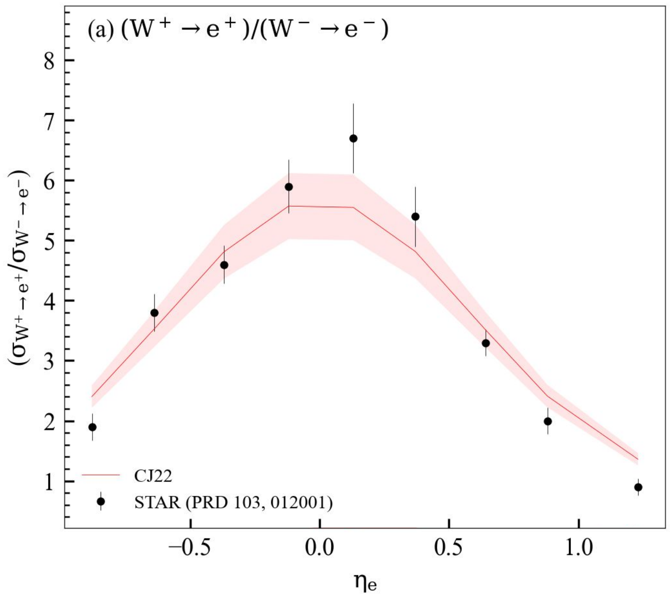
Fit new data
(SeaQuest & STAR)



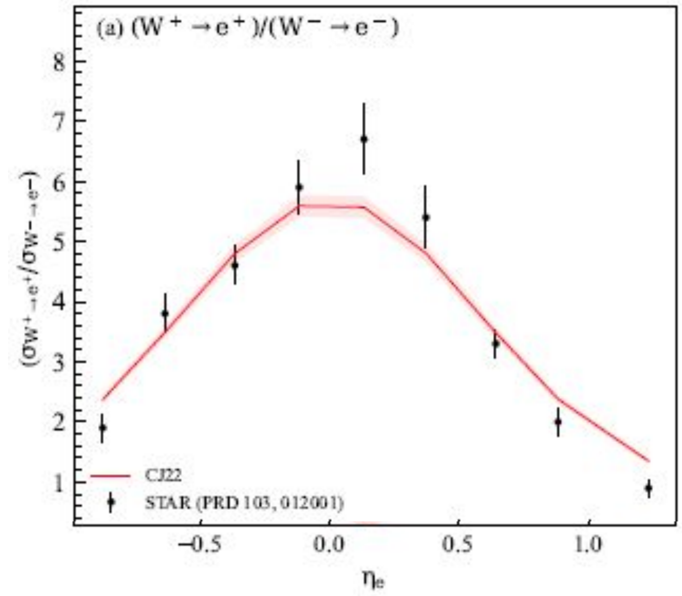
SeaQuest: χ^2/datum = 3.19 → 1.25

E866 : χ^2/datum = 1.63 → 1.93

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

HT systematics & offshell corrections

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

- **Additive vs. Multiplicative**

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

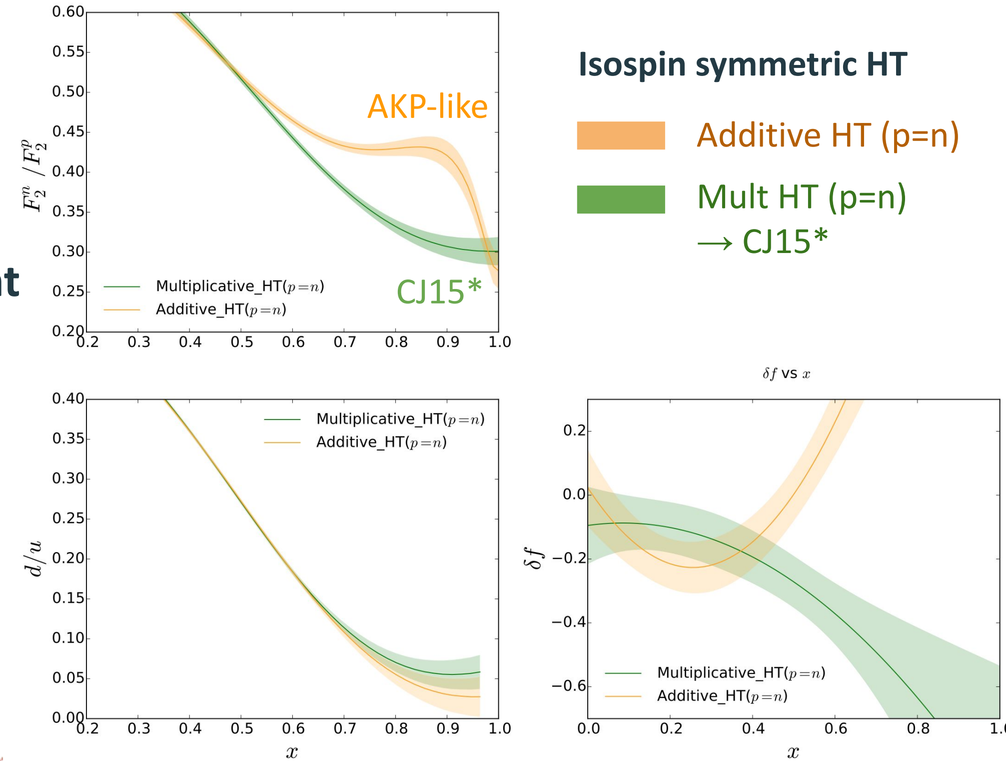
$$F_2(x,Q^2) = F_2^{LT}(x,Q^2)\left(1 + \frac{C(x)}{Q^2}\right)$$

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

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

- **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

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See also Accardi, talk at DNP 2020

- **Additive vs. Multiplicative**

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

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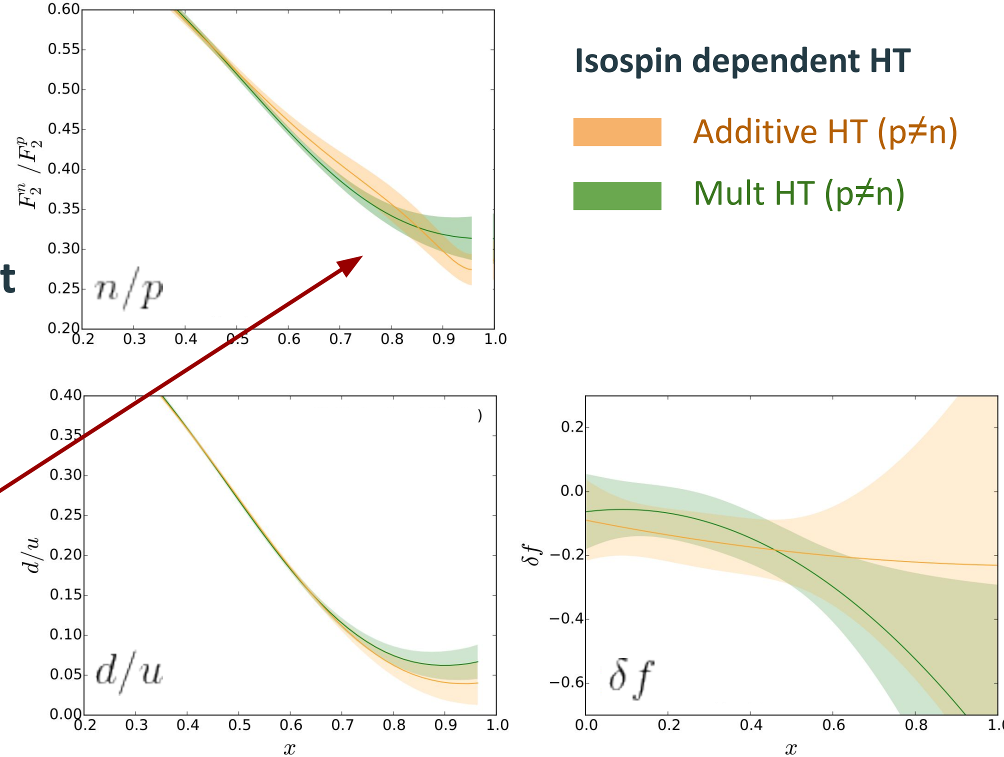
- **Isospin, Q^2 evol. not independnt**

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

- **Isospin dependent HT:**

BIAS REMOVED!



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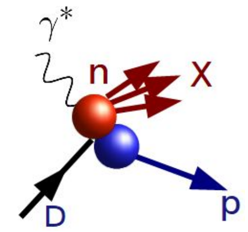
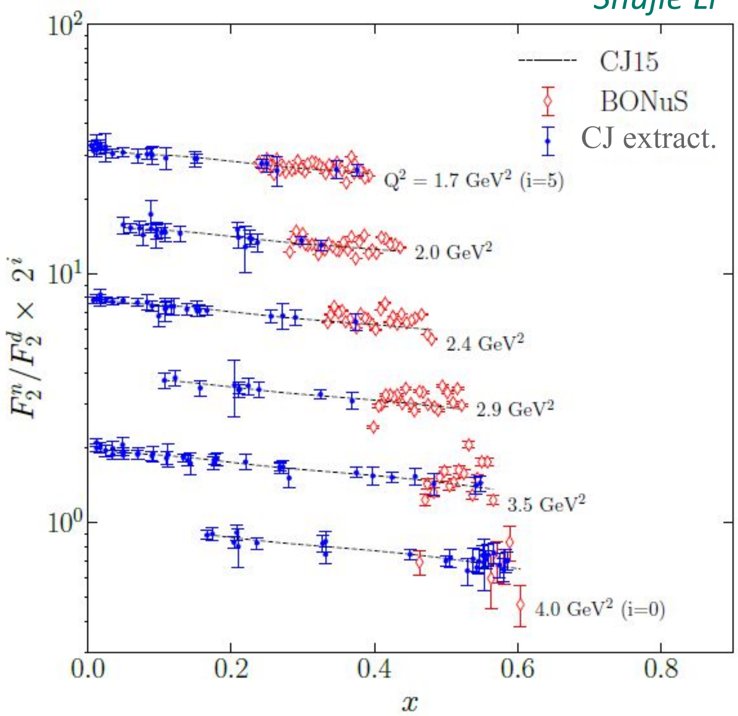
Backup - F2(n) extraction

Bonus cross-checks

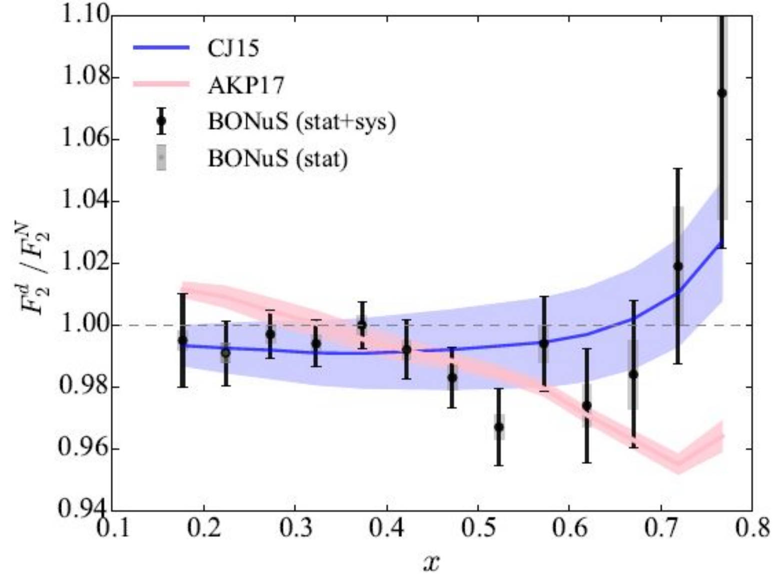
- **BONuS: Tagged proton DIS** measurements



Shujie Li



I. Fernando

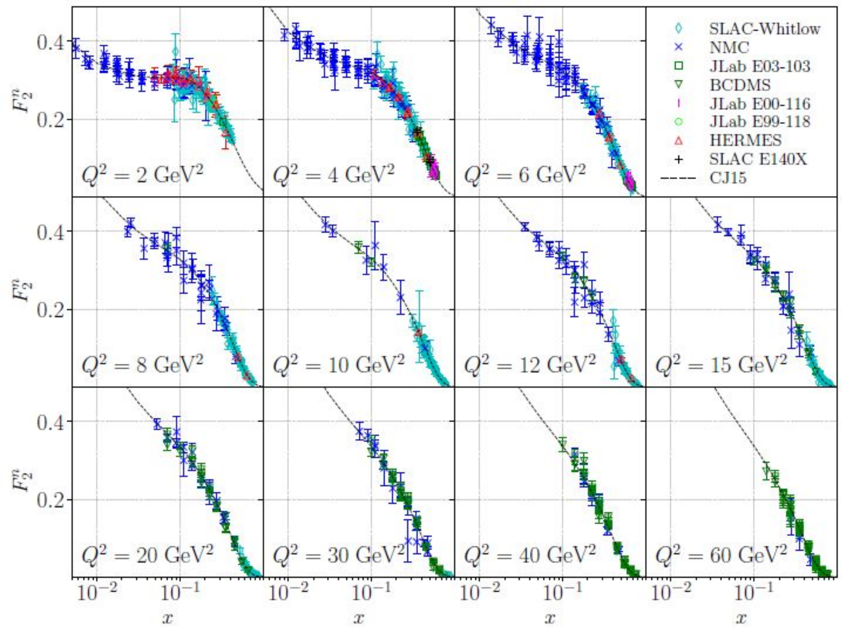


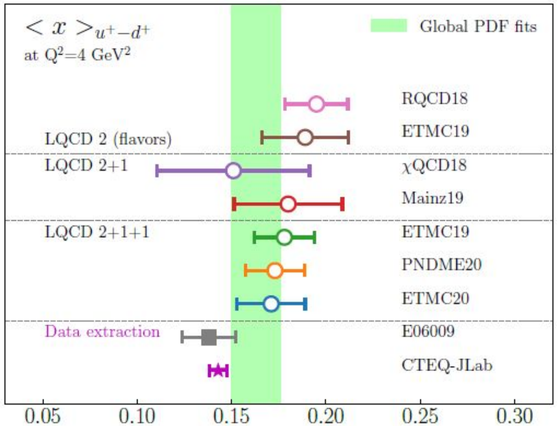
F_2(n) extraction and apps

- **Basic idea:**

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

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





Shujie Li

$F_2(n/p)$ 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

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