



Constraining proton structure and deuteron effects at large x : the CJ26 global analysis

Matteo Cerutti

arXiv:2605.31424

lhpdf grids: <https://www.jlab.org/theory/cj/pdfs>

CTEQ-JLab collaboration

Coordinate **theory**+**experiment** effort within Jefferson Lab

- A. Accardi, MC, X. Jing, I. Fernando, P. Risse, J. F. Owens
- C. E. Keppel, S. Li, P. Monhagan, S. Park

Our focus

- Extraction of large- x behaviour of PDFs and light-nuclear dynamics
- Maximise the use of low- Q DIS data
HERA, SLAC, full JLab 6 GeV, first JLab 12 GeV
- Power corrections
Target-Mass corrections, “higher twists”
Deuteron corrections: binding, Fermi motion, off-shell nucleon dynamics

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Recent works:

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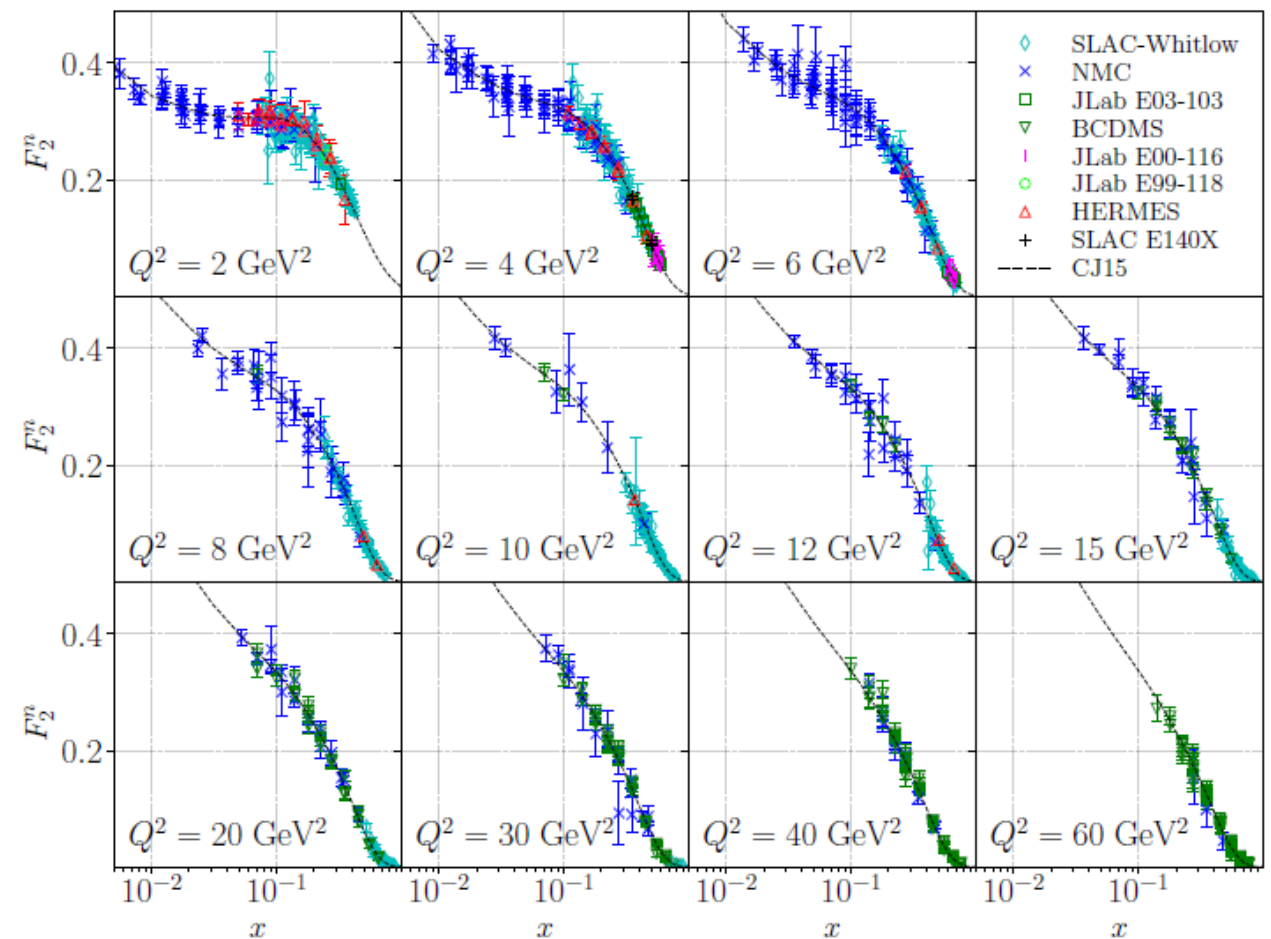
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Recent works:

○ Extraction of neutron $F_2(x, Q^2)$

F2(n) Li, Accardi, MC, Fernando et al., PRD 109 (2024)



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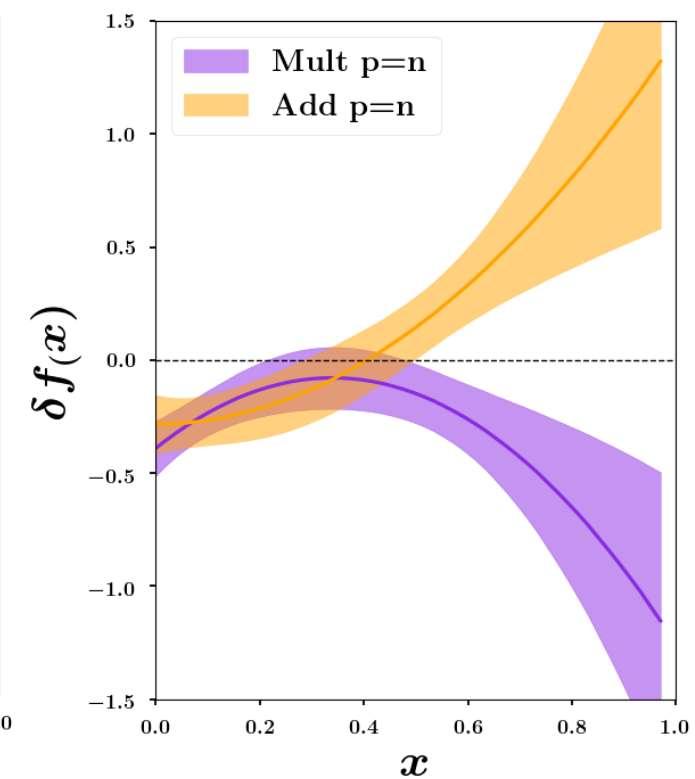
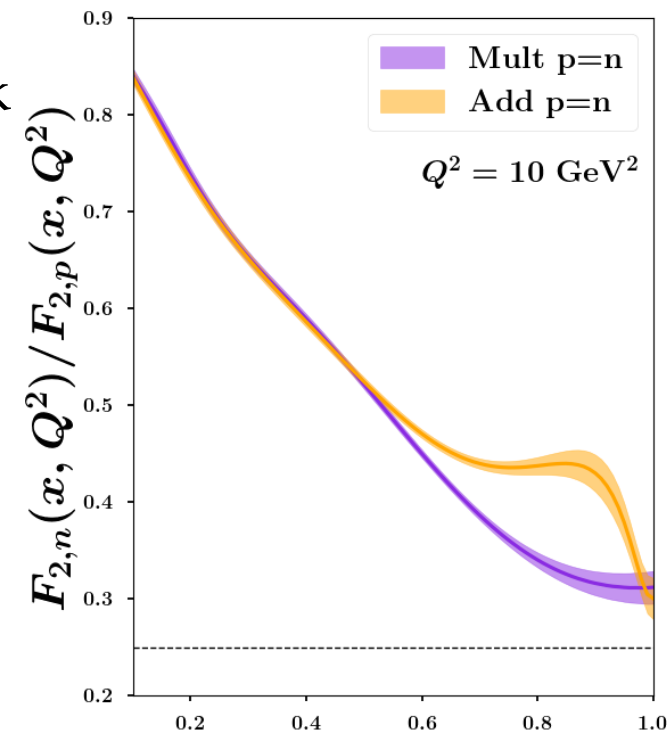
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- Systematic uncertainties from HT and off-shell corrections

CJ22ht MC, Accardi et al., PRD 111 (2025)



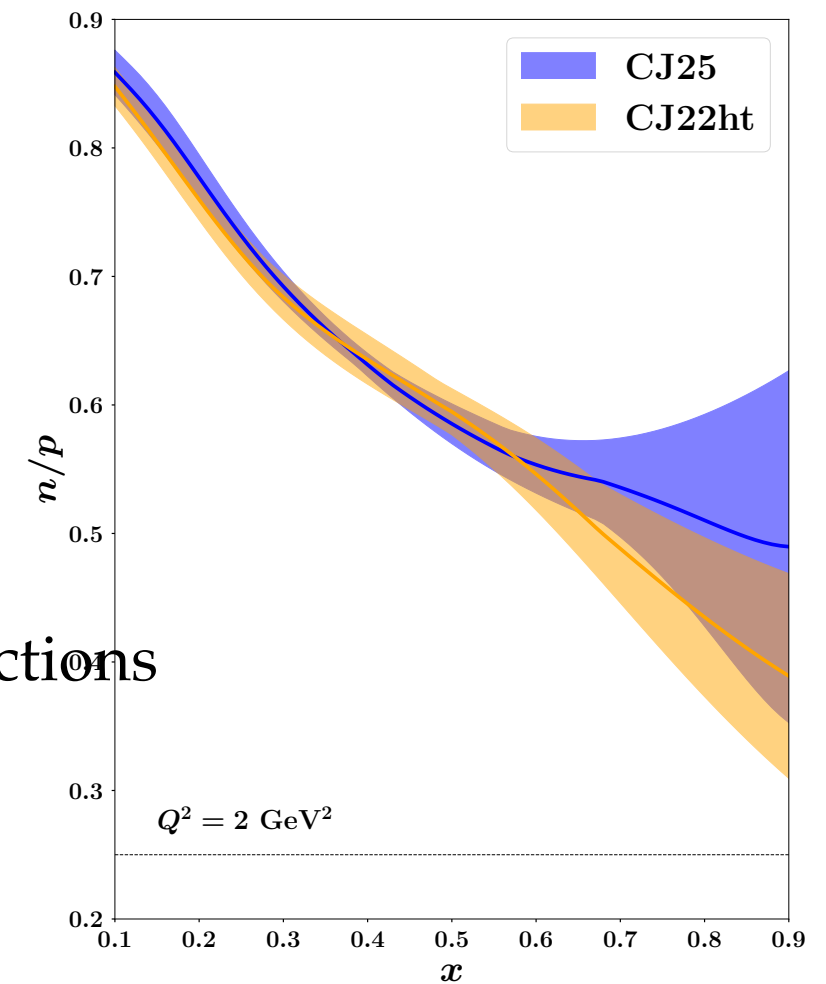
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- New global analysis including full JLab dataset
CJ26 Accardi, MC, Keppel, et al., arXiv:2605.31424



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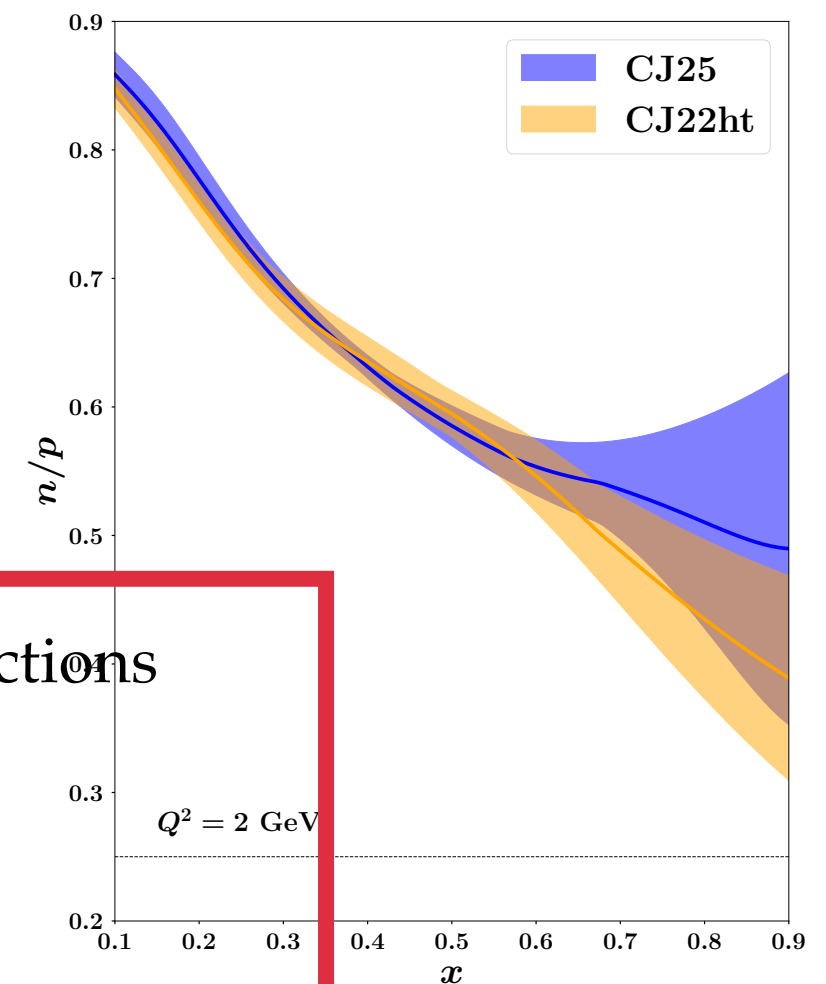
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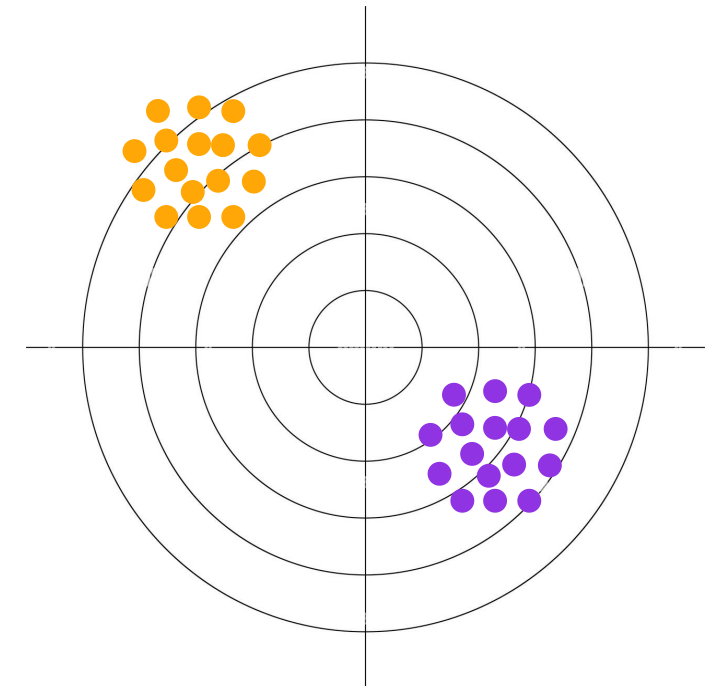
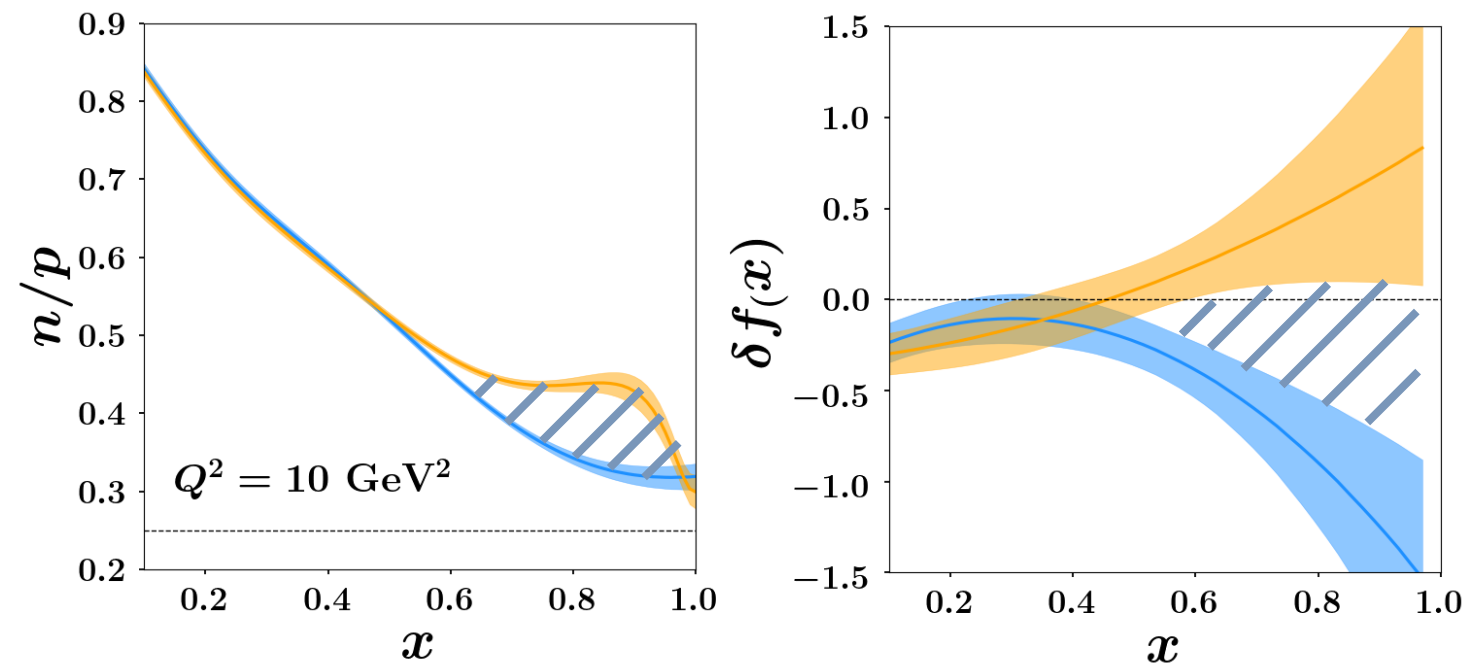
+ ...



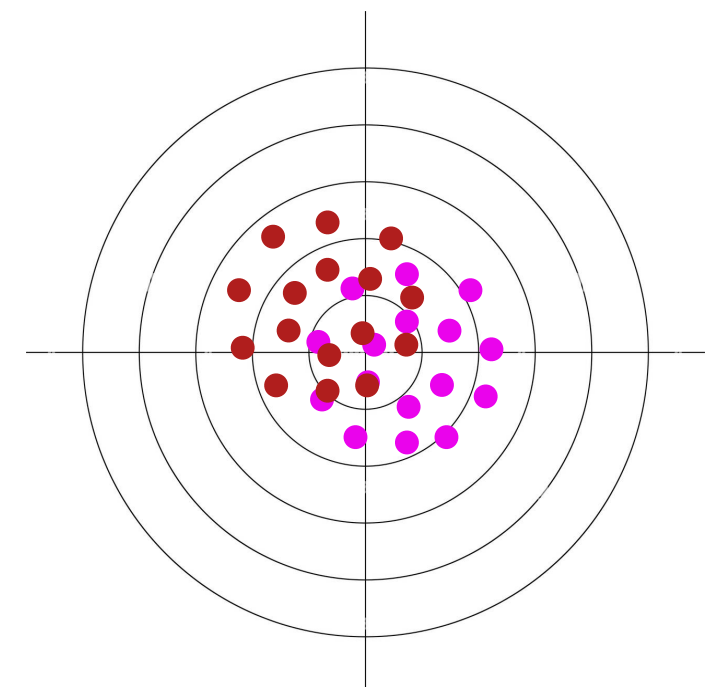
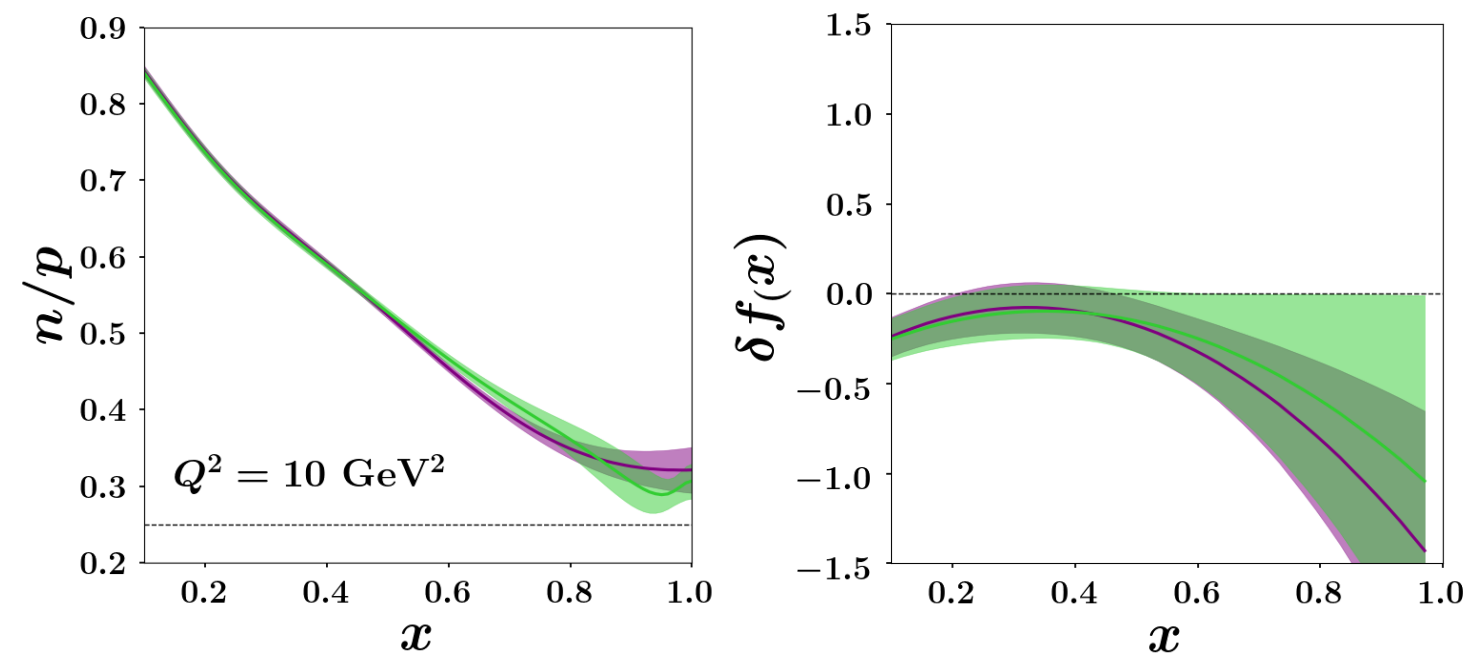
CJ22ht: Accuracy challenge met!

MC, Accardi et al., PRD 111 (2025)

Case 1: isospin-independent HT



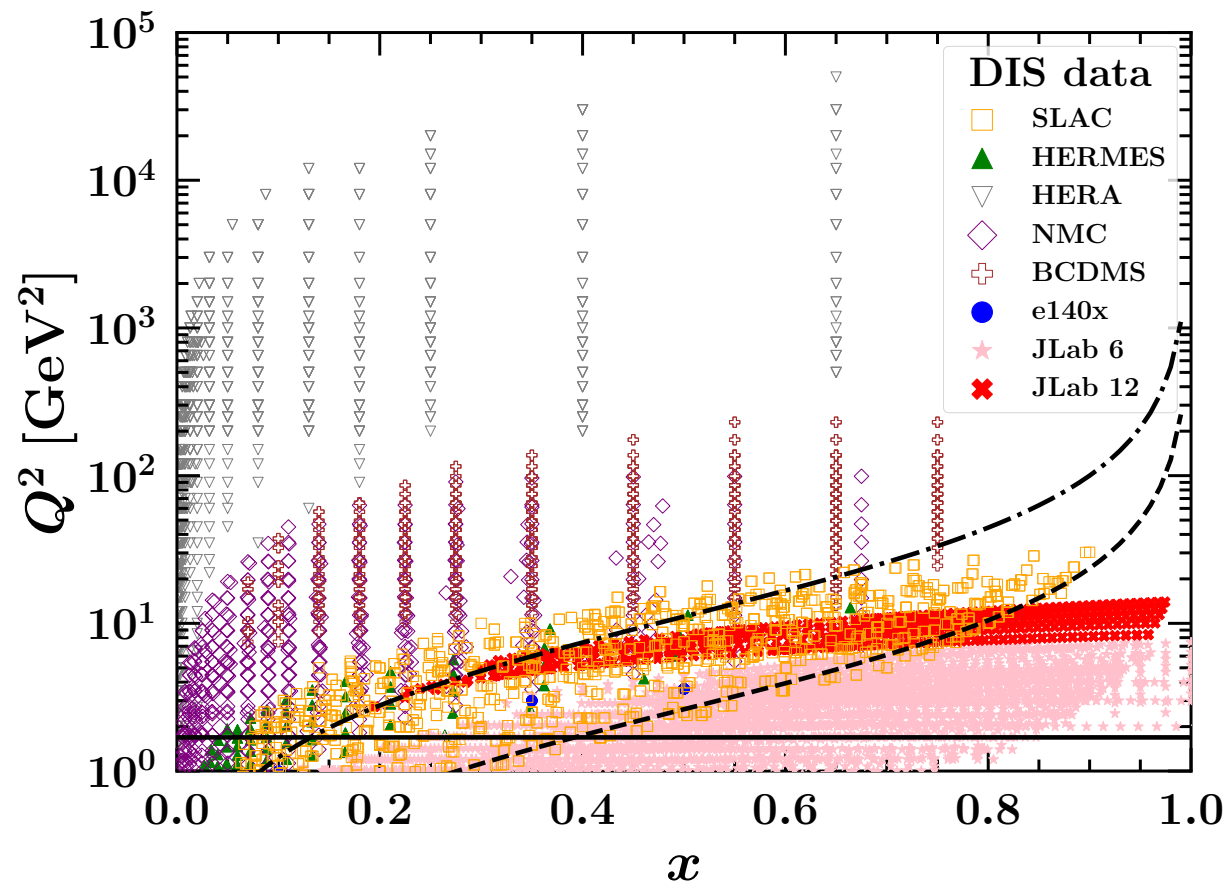
Case 2: isospin-dependent HT



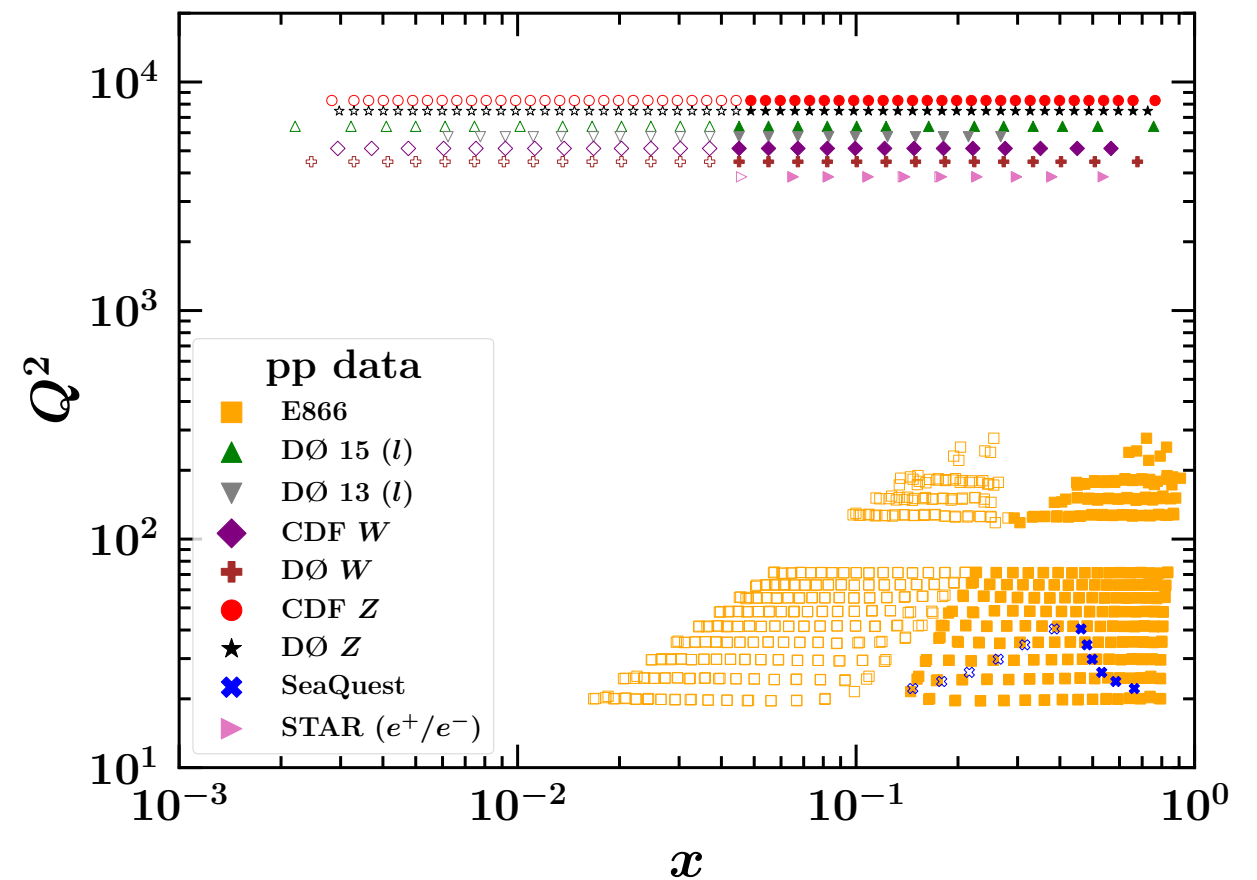
CJ26 global fit: included dataset

Goal: maximize use of DIS data

Main focus: $\frac{d}{u}$ at large x



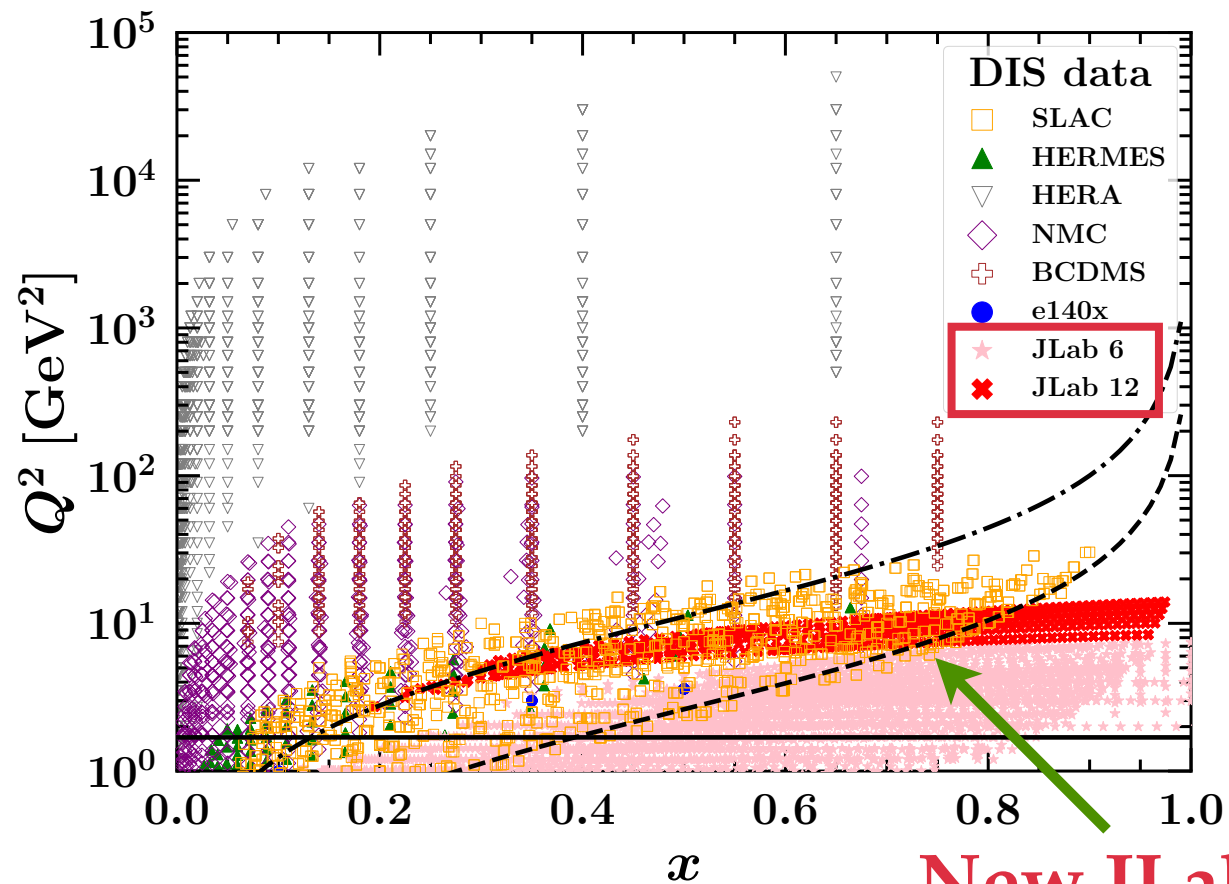
+ CDF / D0 *jet* and γ + *jet* data



CJ26 global fit: included dataset

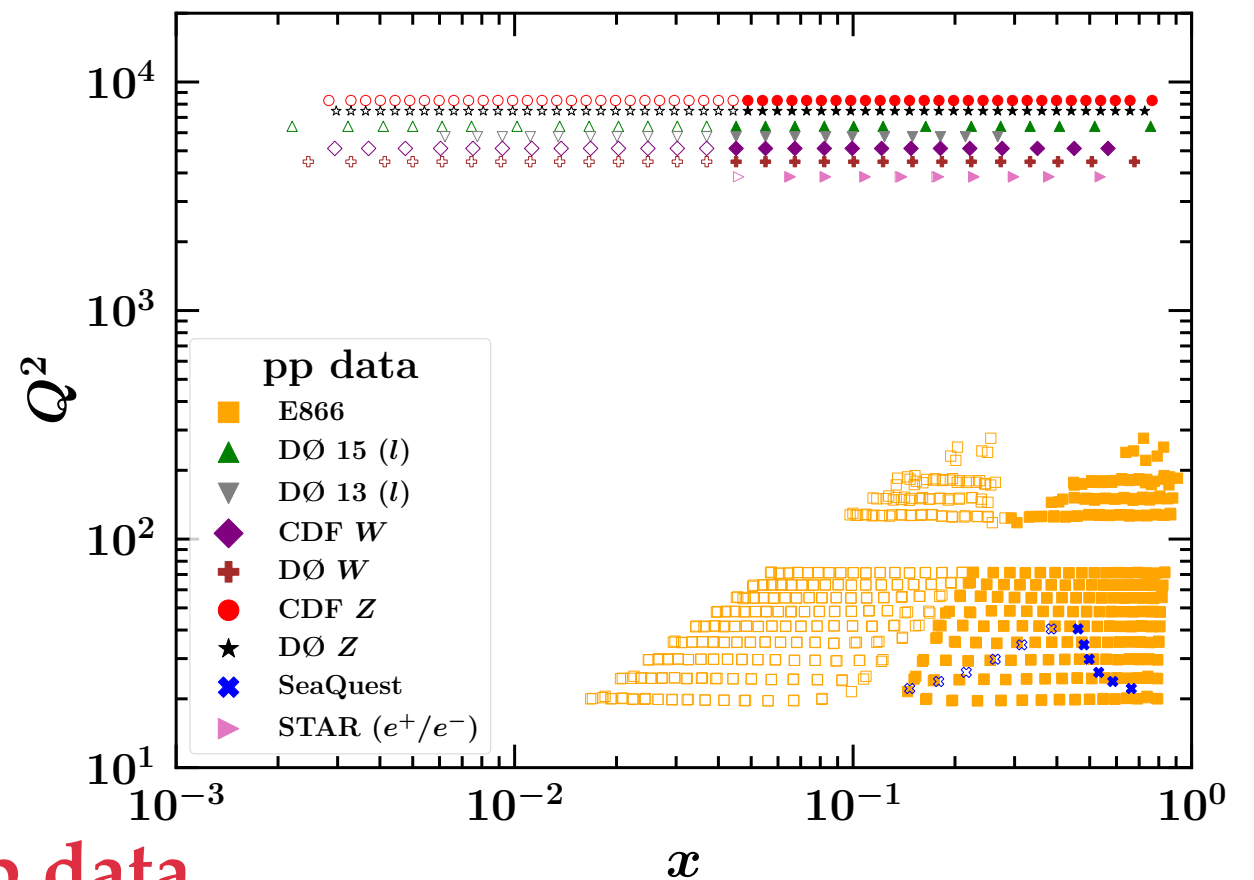
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New JLab data

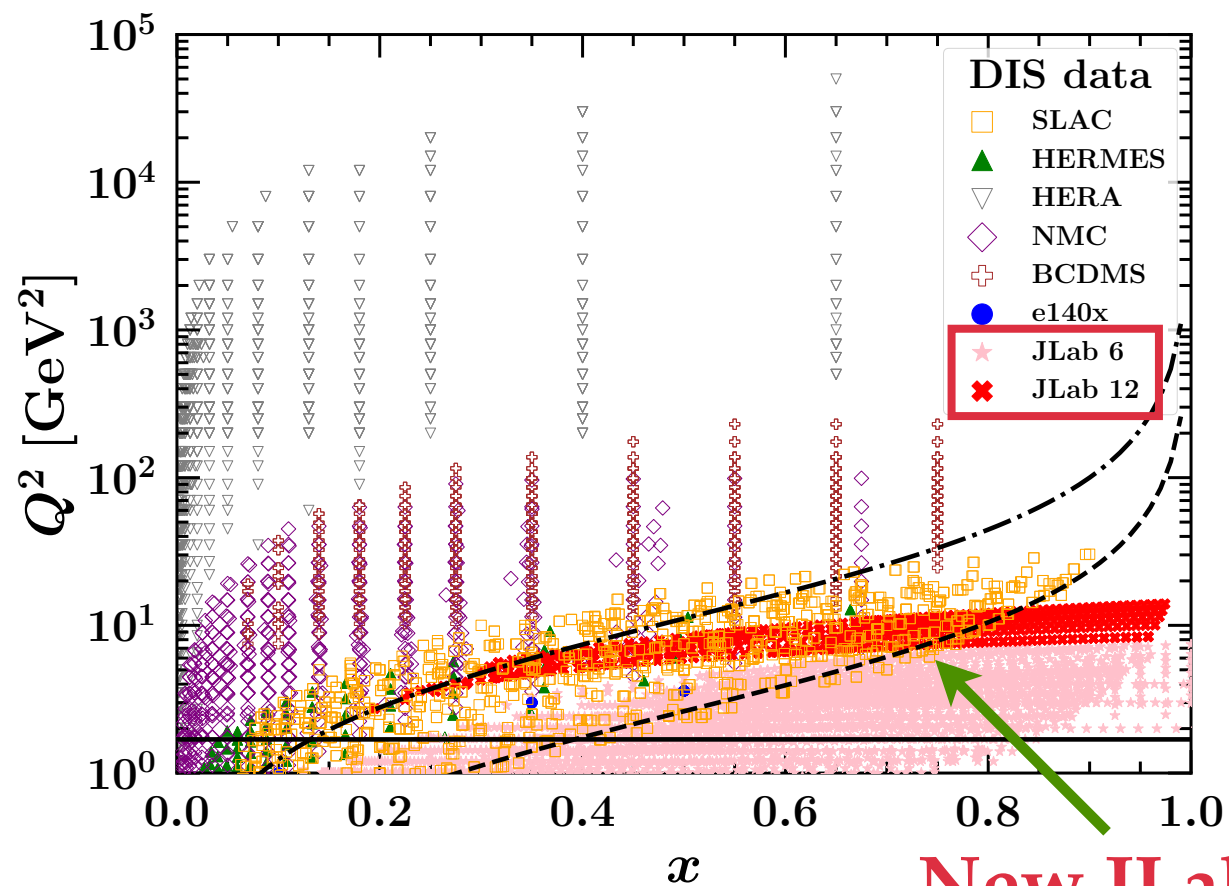
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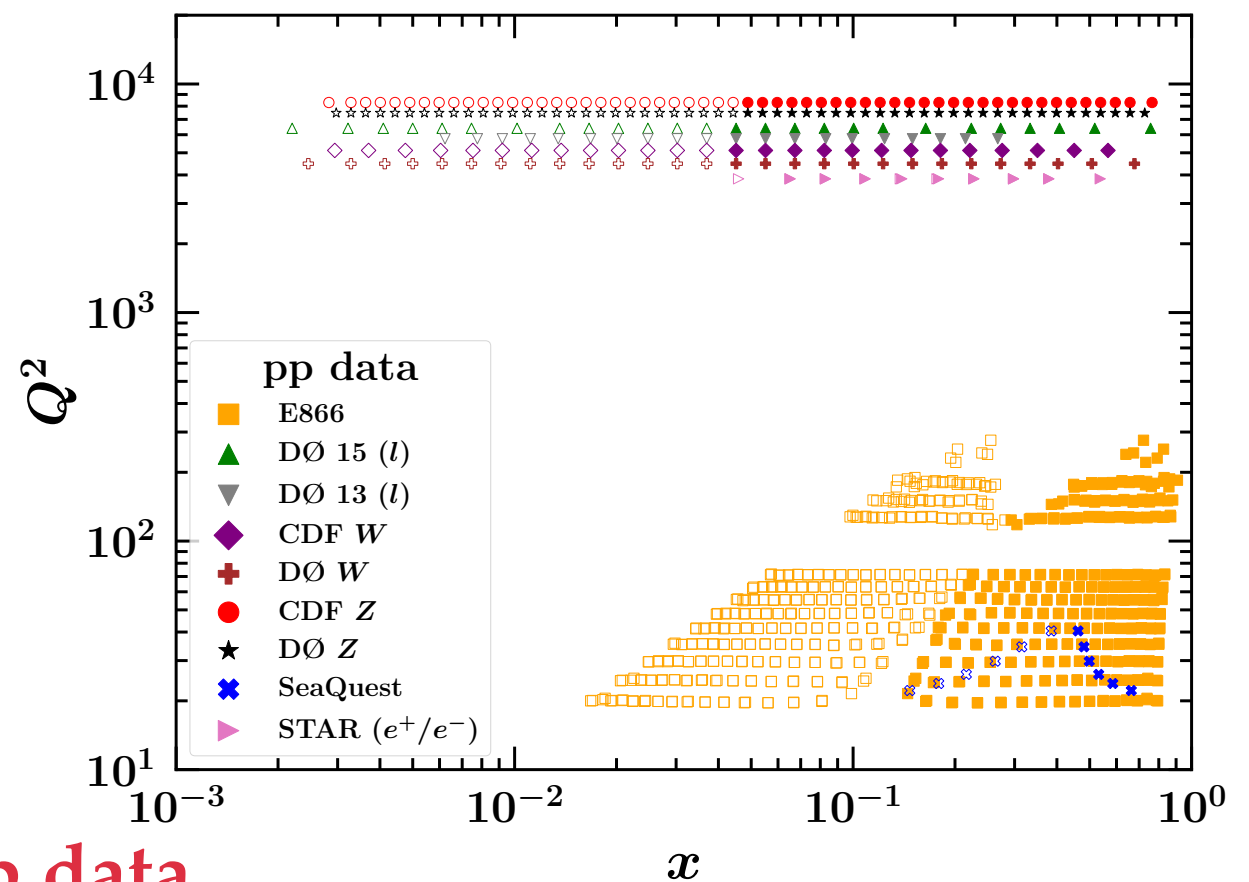
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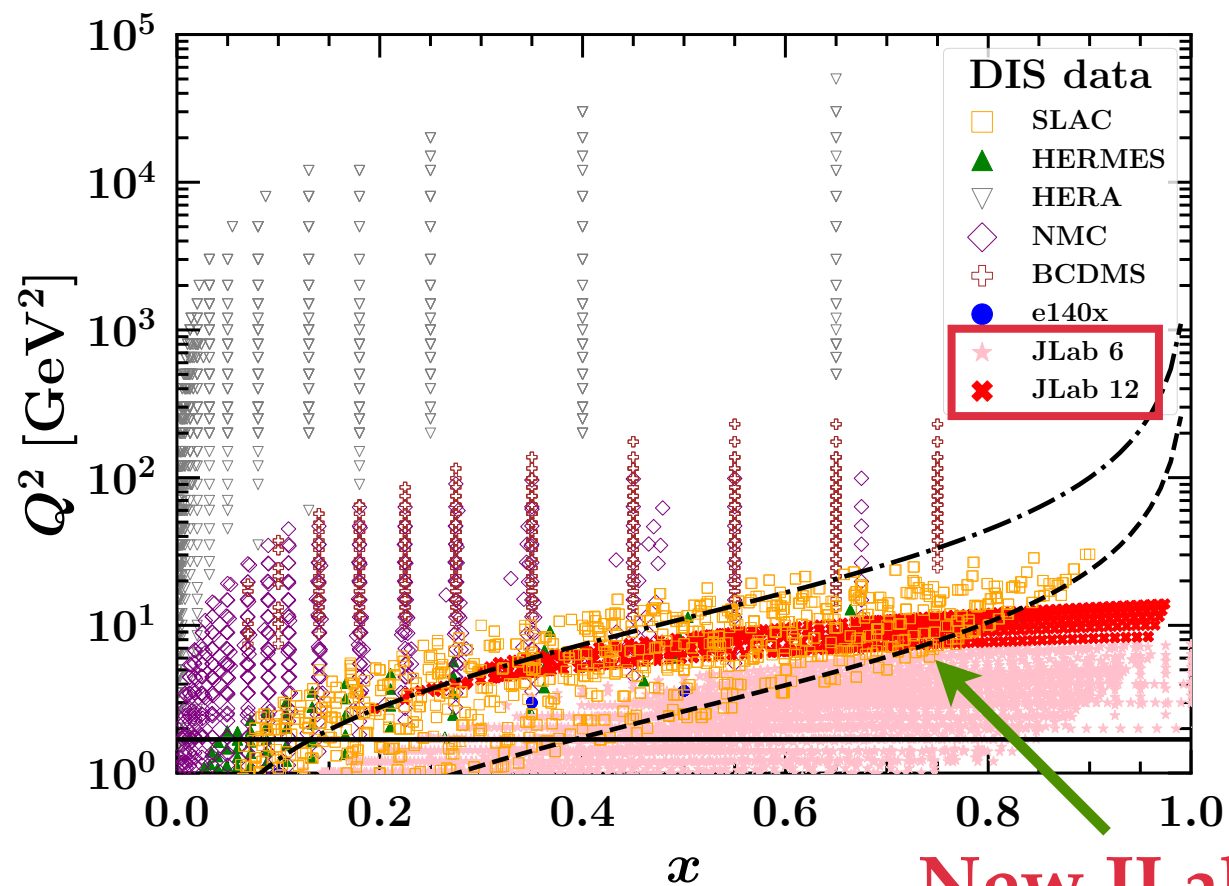


More than 5000 data points!

CJ26 global fit: included dataset

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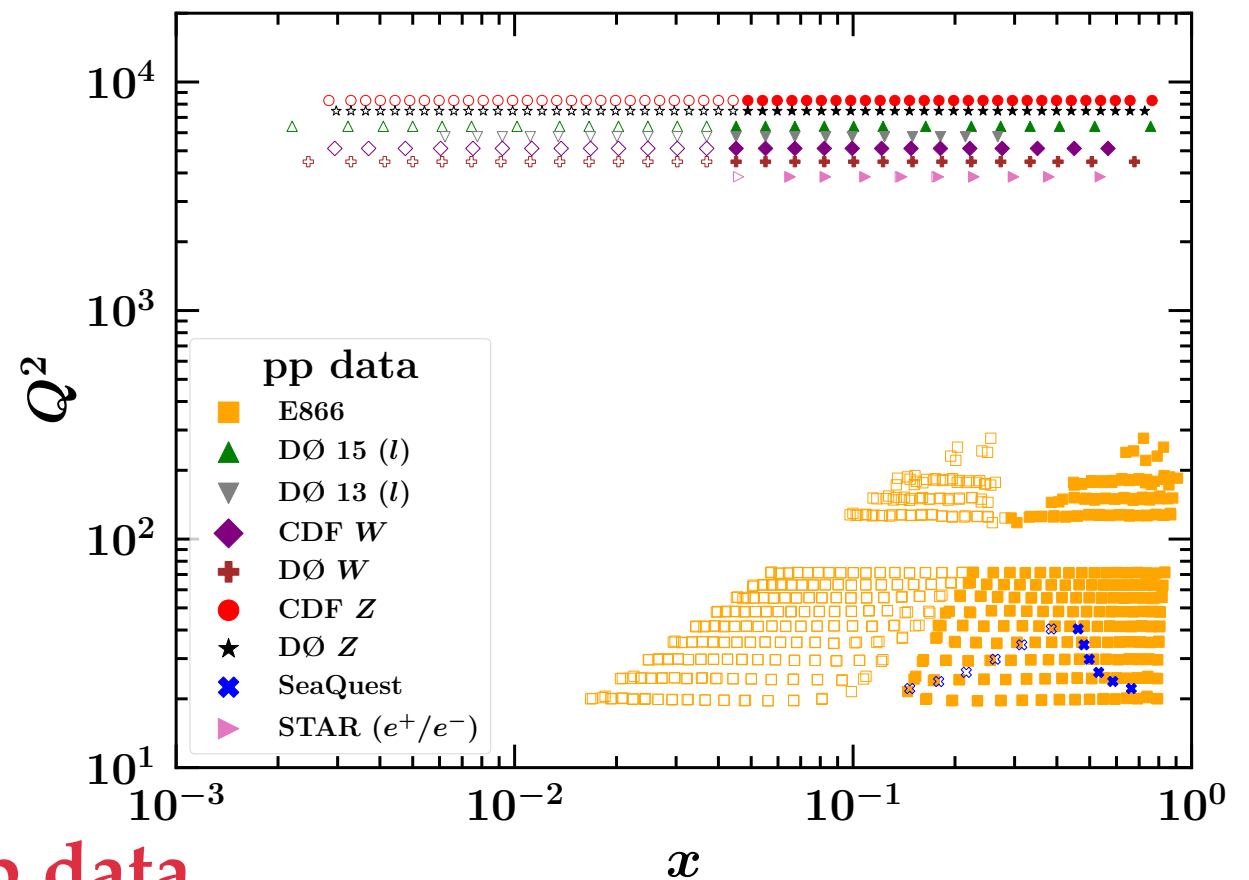
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New JLab data

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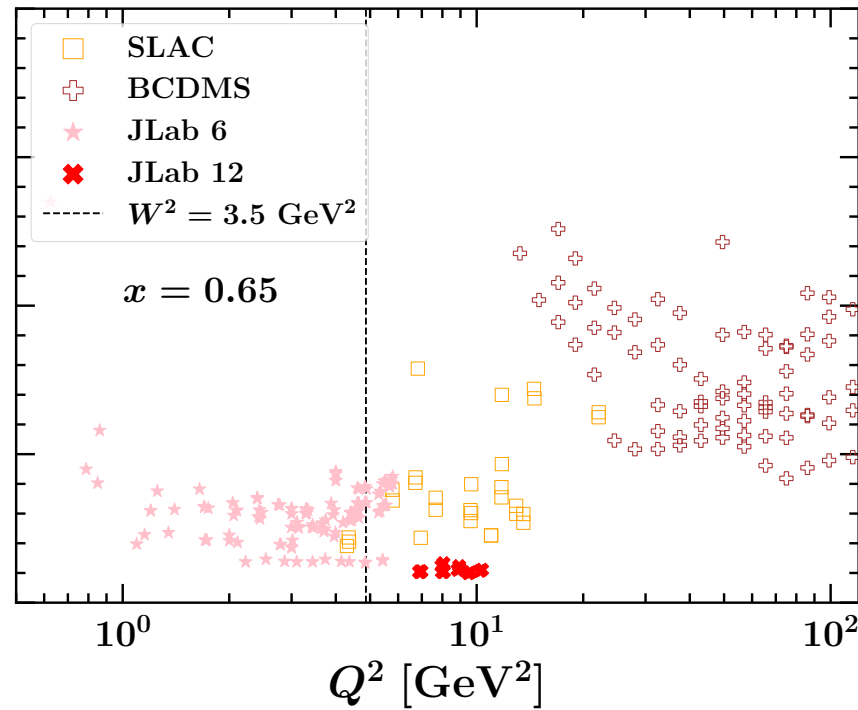
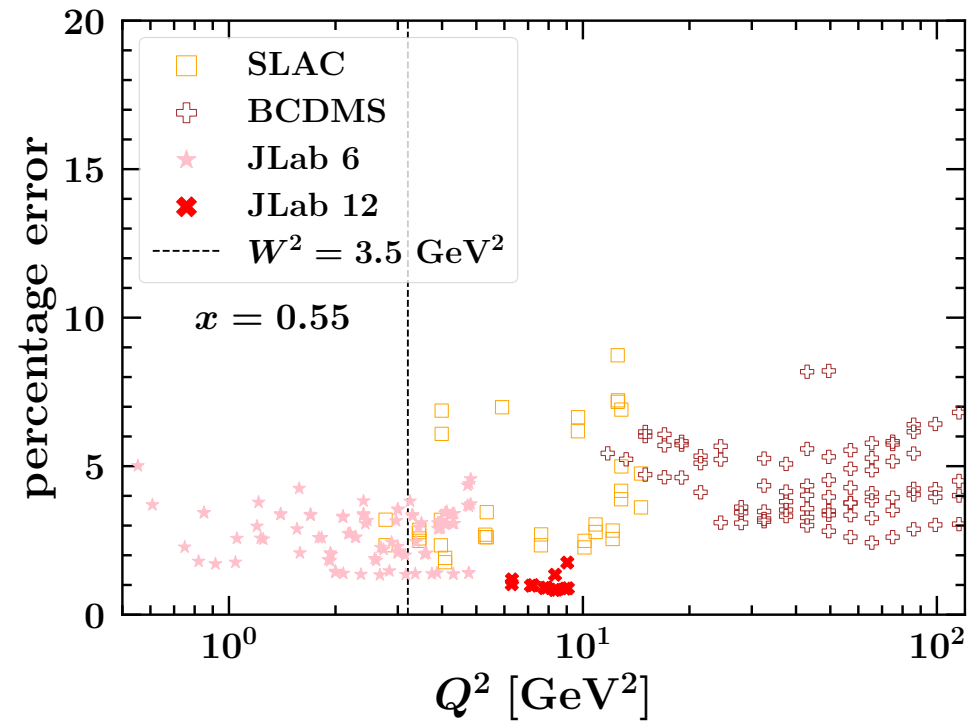
Information on large- x region



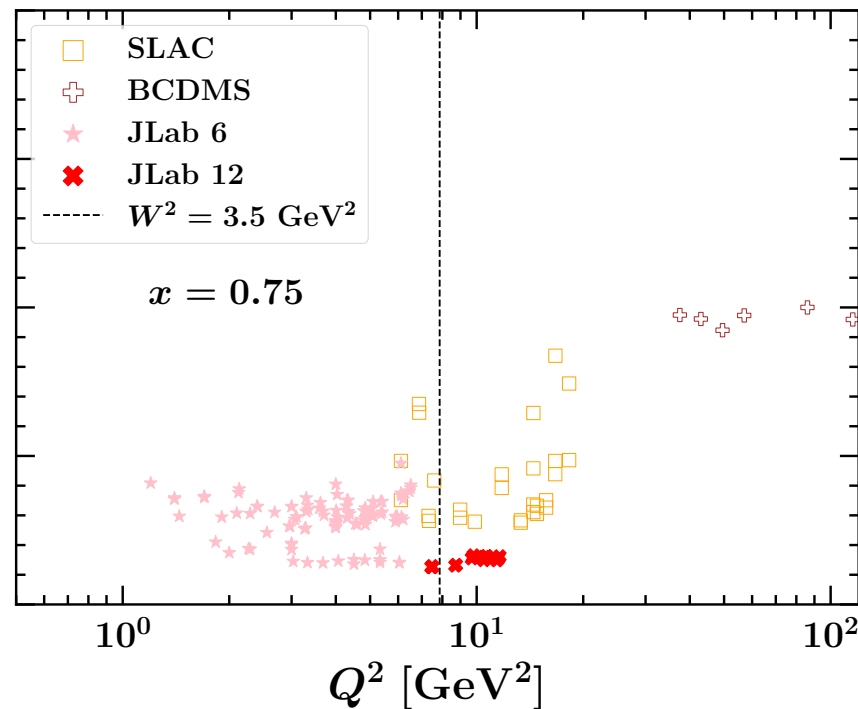
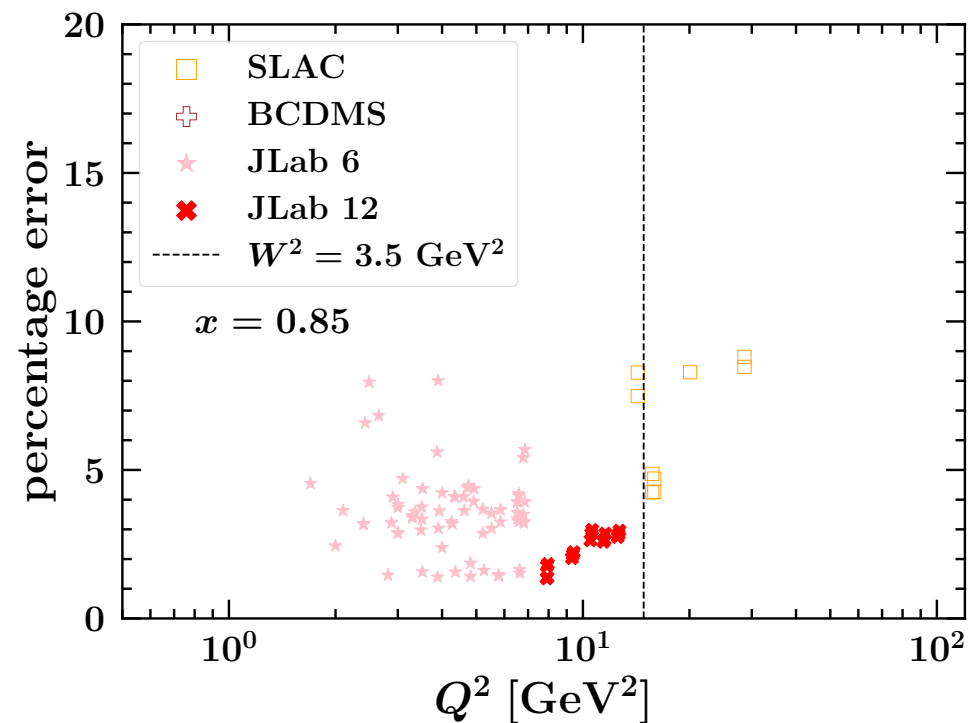
More than 5000 data points!

⇒ Small Q^2
Deuteron target (d quark)

CJ26 global fit: included dataset



1024 JLab
data points



Most precise
DIS data at
large x

CJ26 global fit: theory

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PDF parameterization $Q_0^2 = 1.69 \text{ GeV}^2$

$$\phi(x) = a_0 x^{a_1} (1-x)^{a_2} (1 + a_3 \sqrt{x} + a_4 x)$$

$$\phi = u_V, d_V, \bar{d} + \bar{u}, \bar{d} - \bar{u}, g$$

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+ additional flexibility on d/u as $x \rightarrow 1$

+ more stability on $\bar{d} - \bar{u}$

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Perturbative accuracy NLO

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Perturbative accuracy NLO

Heavy-quark scheme ACOT- χ

+ use of applgrids form xfitter for W/Z boson production

+ use of FastNLO for jet cross sections

Deuteron F_2 structure function

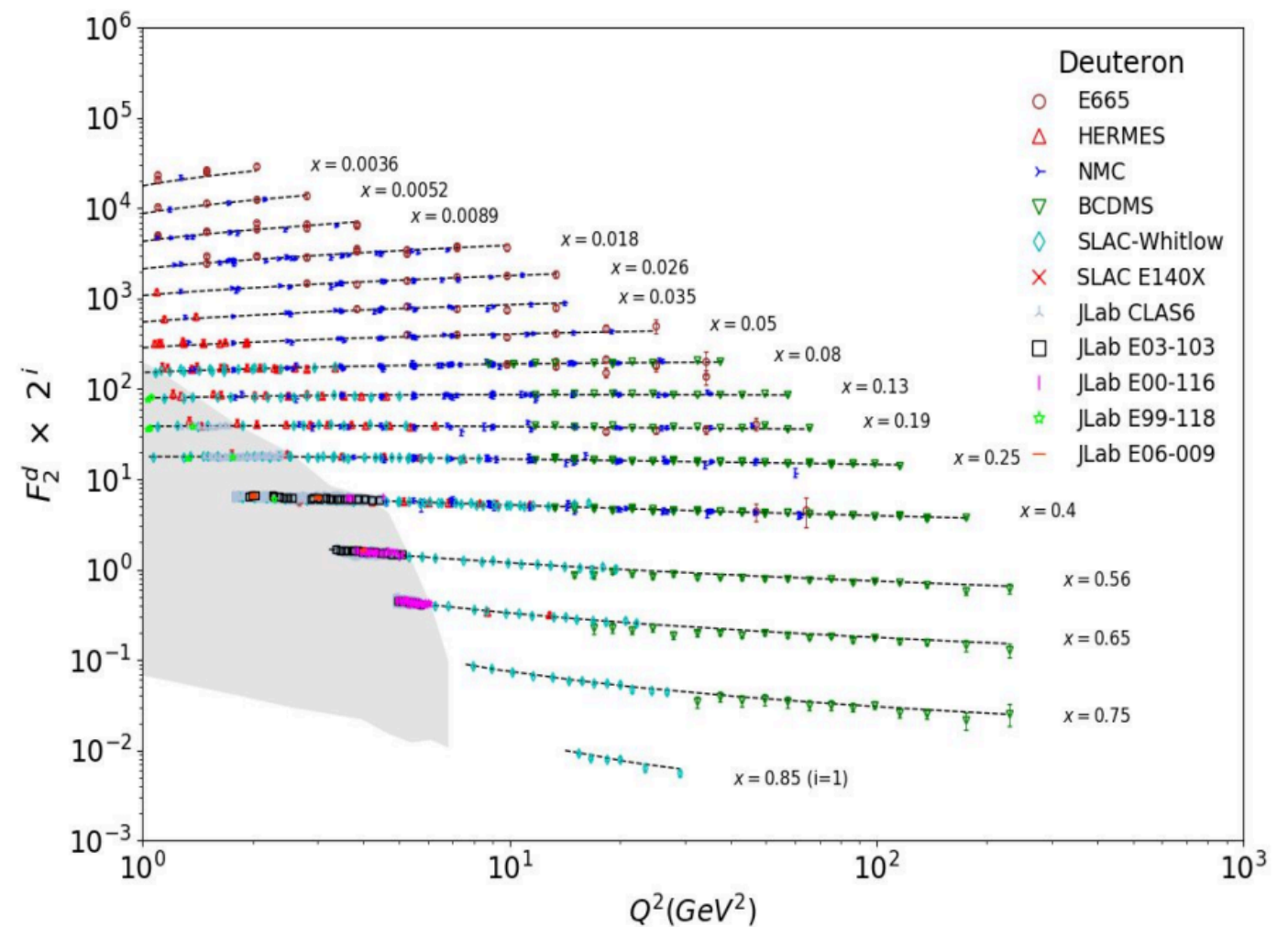
DIS on deuteron target

CJ global data set:

- 1000+ data points
- high- x and low- Q^2
- $W^2 > 3.5 \text{ GeV}^2$, $Q^2 > 1.69 \text{ GeV}^2$

Full treatment of nuclear corrections

Binding effects, Fermi motion, off-shell corrections, Higher Twist (HT), Target Mass Corrections (TMC)



$$F_{2,D}(x, Q^2) = \sum_{N=p,n} \int dy dp_T^2 f_{N/D}(y, p_T^2; \gamma) F_{2,N}^*\left(\frac{x}{y}, Q^2, p^2; \gamma^*\right)$$

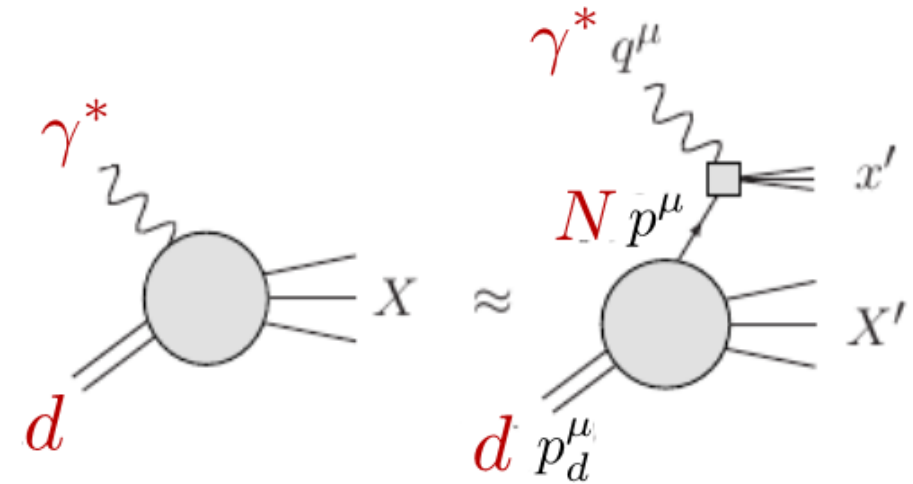
Smearing function

Structure function of a bound,
off-shell nucleon

Deuterium: off-shell corrections

Bound, off-shell nucleon inside the deuteron

$$p^2 \lesssim m_N^2$$

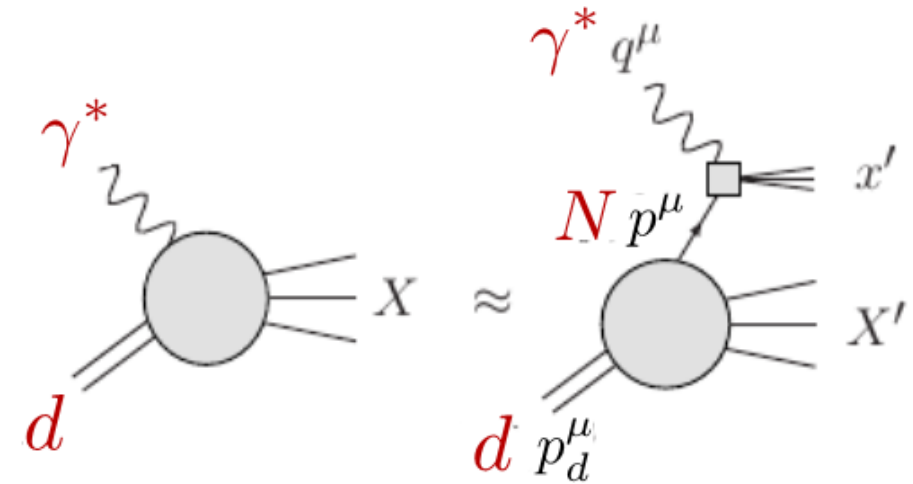


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Structure functions are deformed at large x

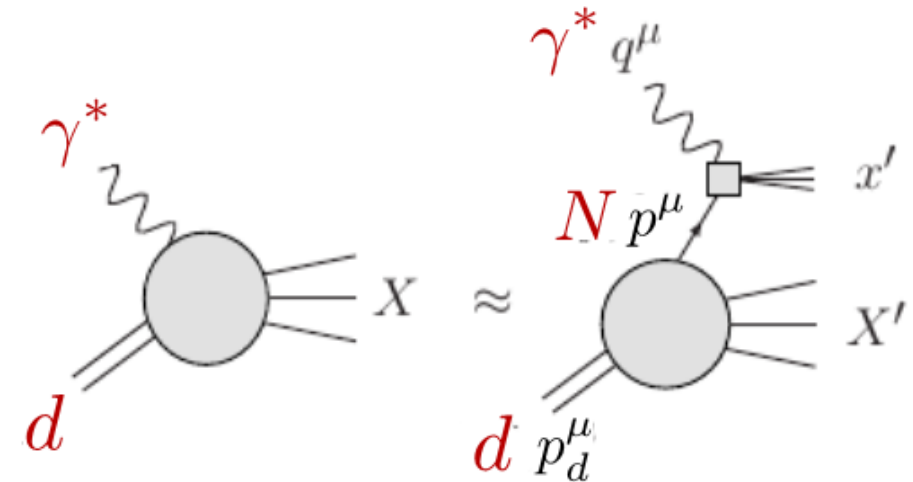


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Off-shell expansion (in nucleon virtuality p^2)

$$\phi^*(x, Q^2, p^2) = \phi(x, Q^2) \left(1 + \frac{p^2 - M^2}{M^2} \delta f(x) \right)$$

$$F_{2,N}^*(x, Q^2, p^2) = F_{2,N}(x, Q^2) \left(1 + \frac{p^2 - M^2}{M^2} \delta F(x) \right)$$

parton level

Kulagin, Piller, Weise, PRC 50 (1994)

Kulagin, Melnitchouk, et al., PRC 52 (1995)

Kulagin and Petti, NPA 765 (2006)

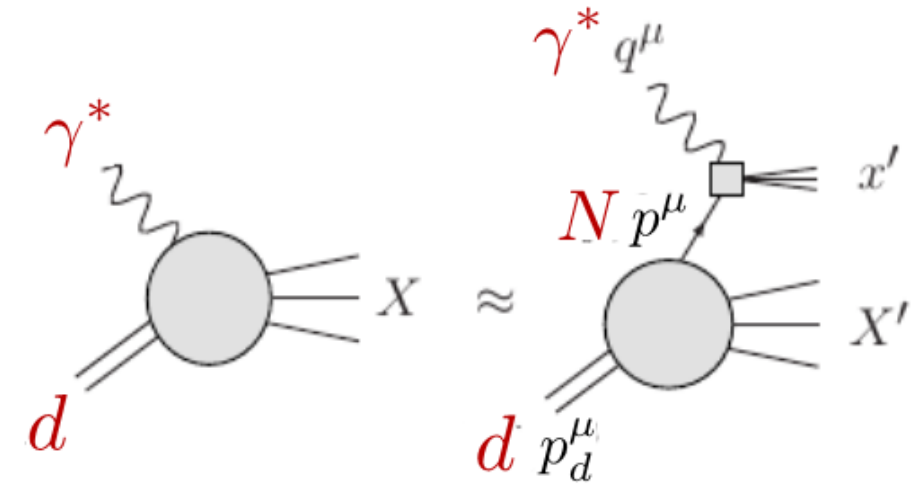
struct. func level

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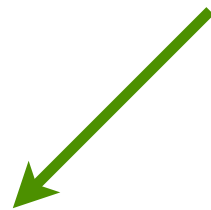
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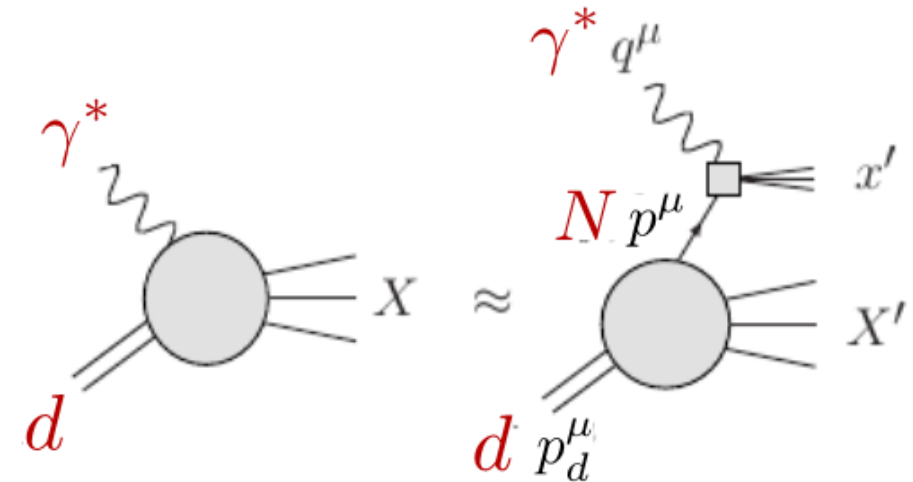
Free nucleon pdfs/SFs

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Free nucleon pdfs/SFs

Off-shell function
(To be fitted)

CJ26 global fit: power corrections

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Target-mass corrections Georgi-Politzer (approximated)

Schienbein et al., J. Phys. G 35 (2008)

CJ26 global fit: power corrections

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Off-shell corrections

Polynomial model

$$\delta f(x) = \sum_{n=0}^k a_{\text{off}}^{(n)} x^n$$

$k = 3$

Alekhin, Kulagin, Petti, PRD 96 (2017)
Alekhin, Kulagin, Petti, PRD 105 (2022)
Alekhin, Kulagin, Petti, PRD 107 (2023)
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Residual power corrections (“higher-twist”)

Multiplicative $F_{2,N}(x, Q^2) = F_{2,N}^{LT}(x, Q^2) \left(1 + \frac{C_N(x)}{Q^2} \right)$

$$C(x) = a_{ht}^{(1)} x^{a_{ht}^{(2)}} (1 + a_{ht}^{(3)} x + a_{ht}^{(4)} \sqrt{x})$$

Additive $F_{2,N}(x, Q^2) = F_{2,N}^{LT}(x, Q^2) + \frac{H_N(x)}{Q^2}$

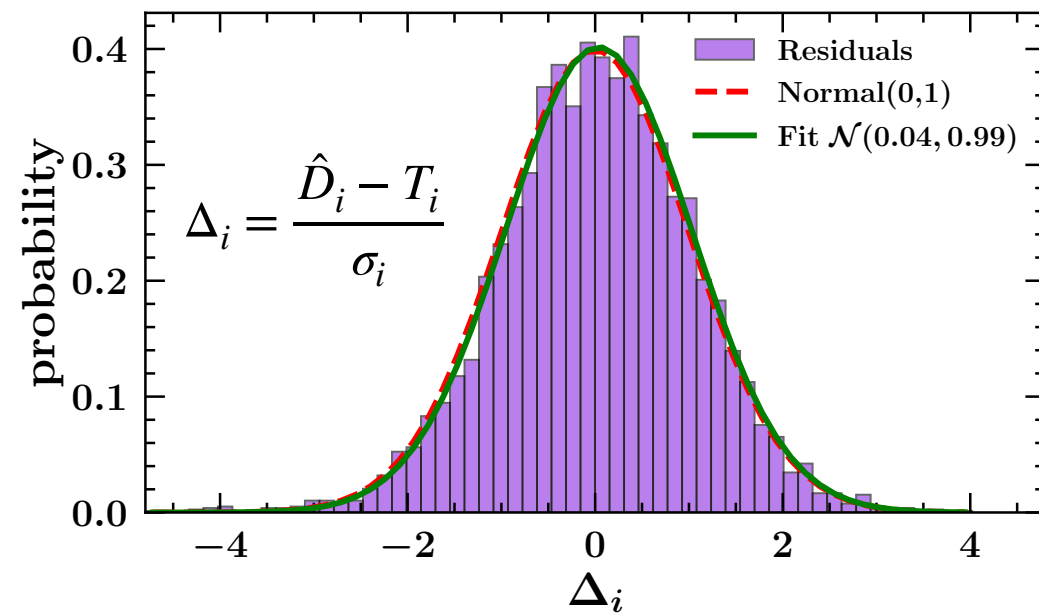
$$H(x) = a_{ht}^{(0)} x^{a_{ht}^{(1)}} (1 - x)^{a_{ht}^{(2)}} (1 + a_{ht}^{(3)} x)$$

ISOSPIN DEPENDENT $p \neq n$ (no biases)

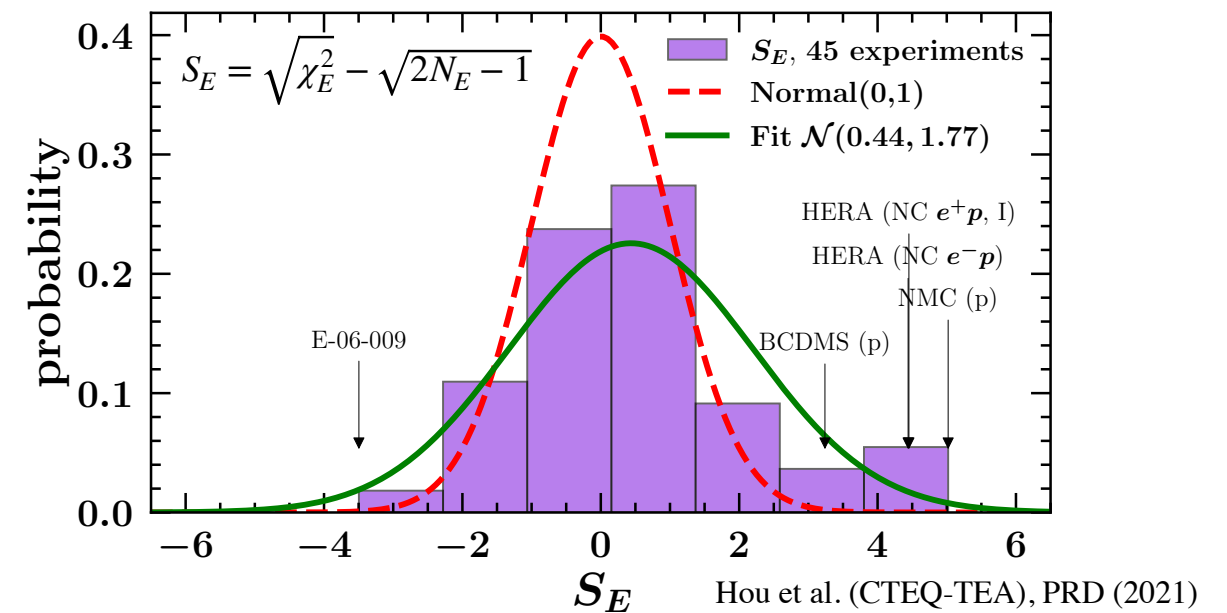
MC, Accardi et al., PRD 111 (2025)

CJ26 global fit: results

Good fit quality overall $\chi^2/N_{\text{data}} = 1.10$

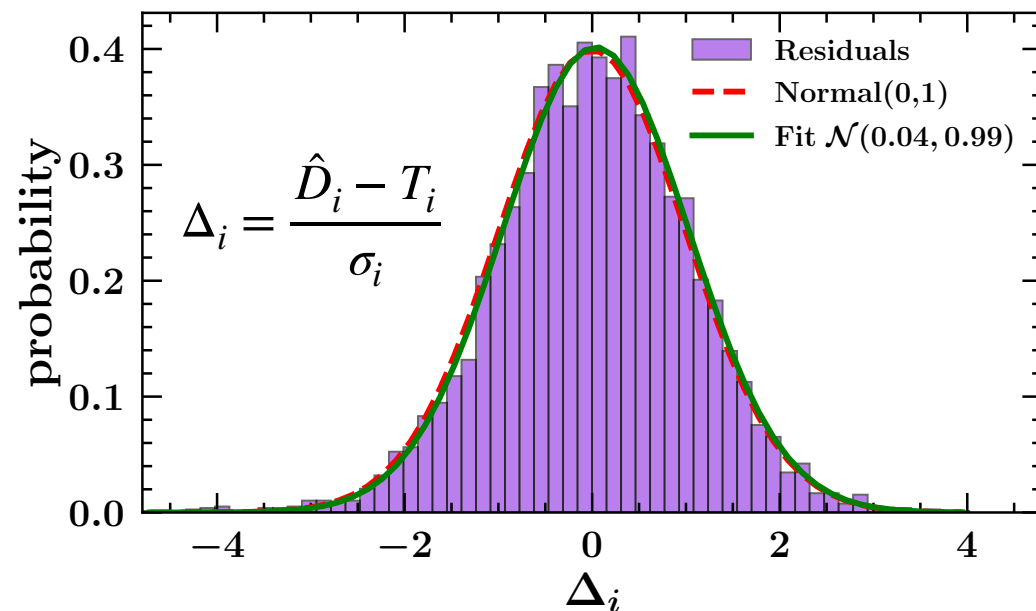


known tensions

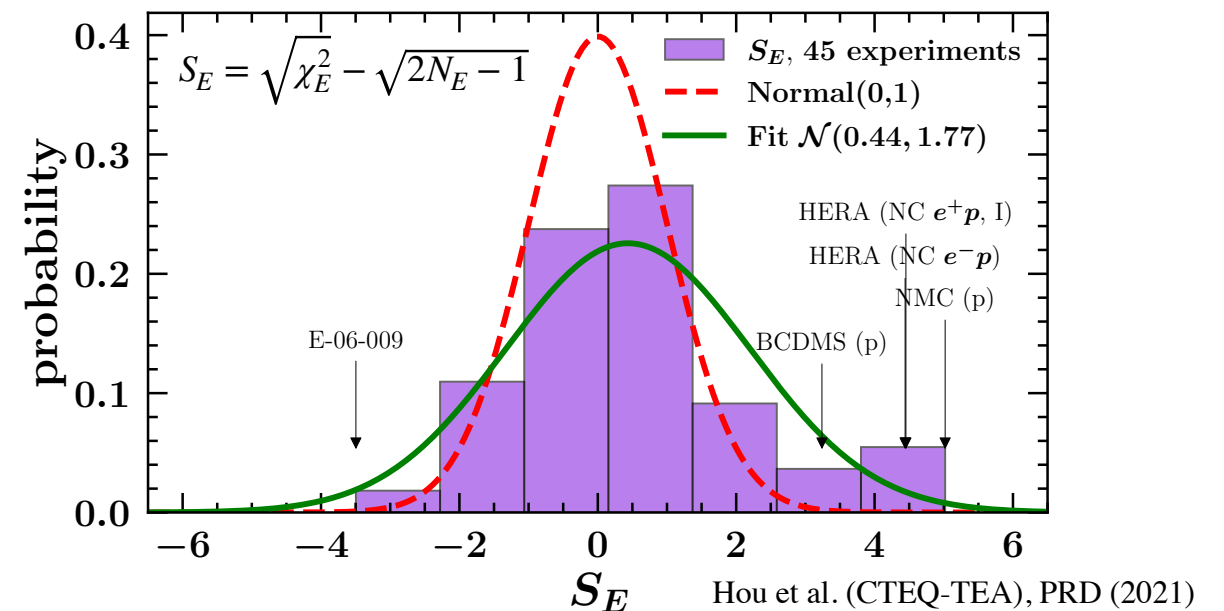


CJ26 global fit: results

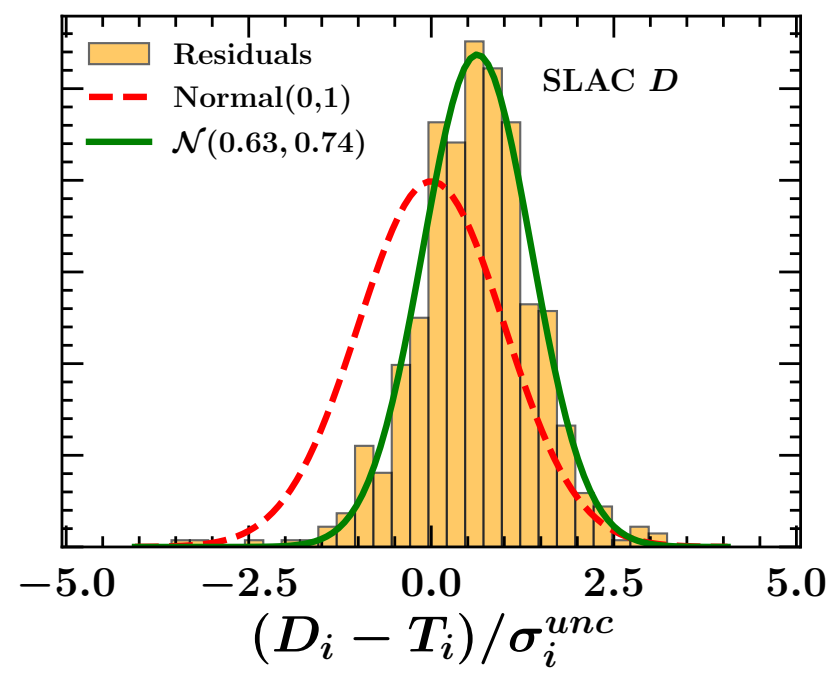
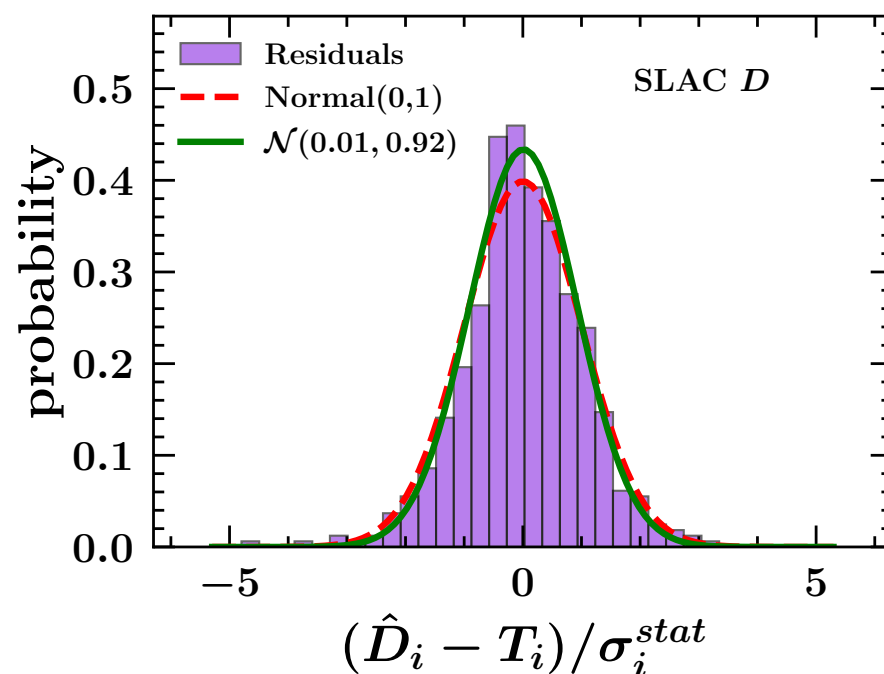
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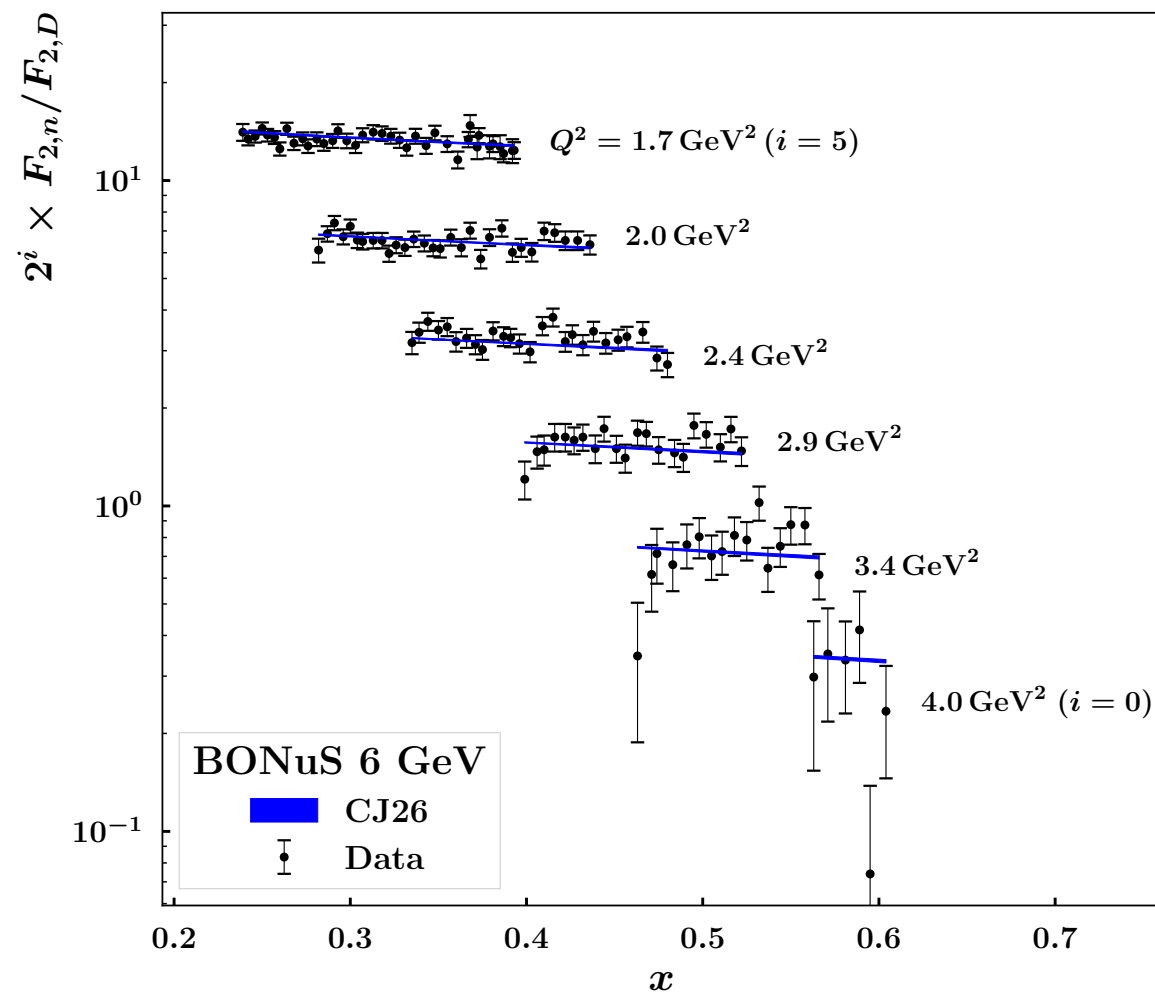
known tensions



Correlated errors when available



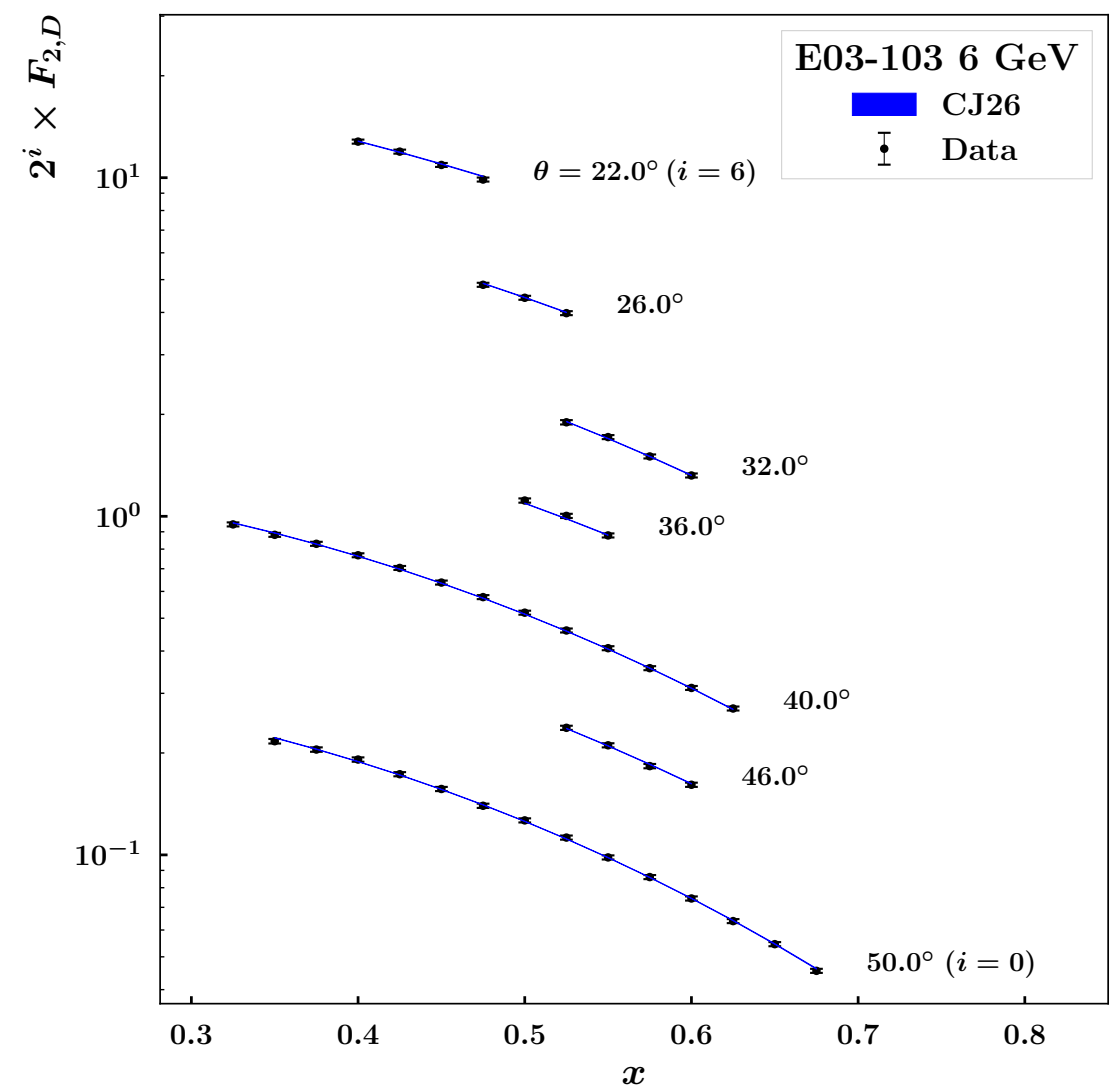
CJ26 global fit: results



BONUS: tagged DIS

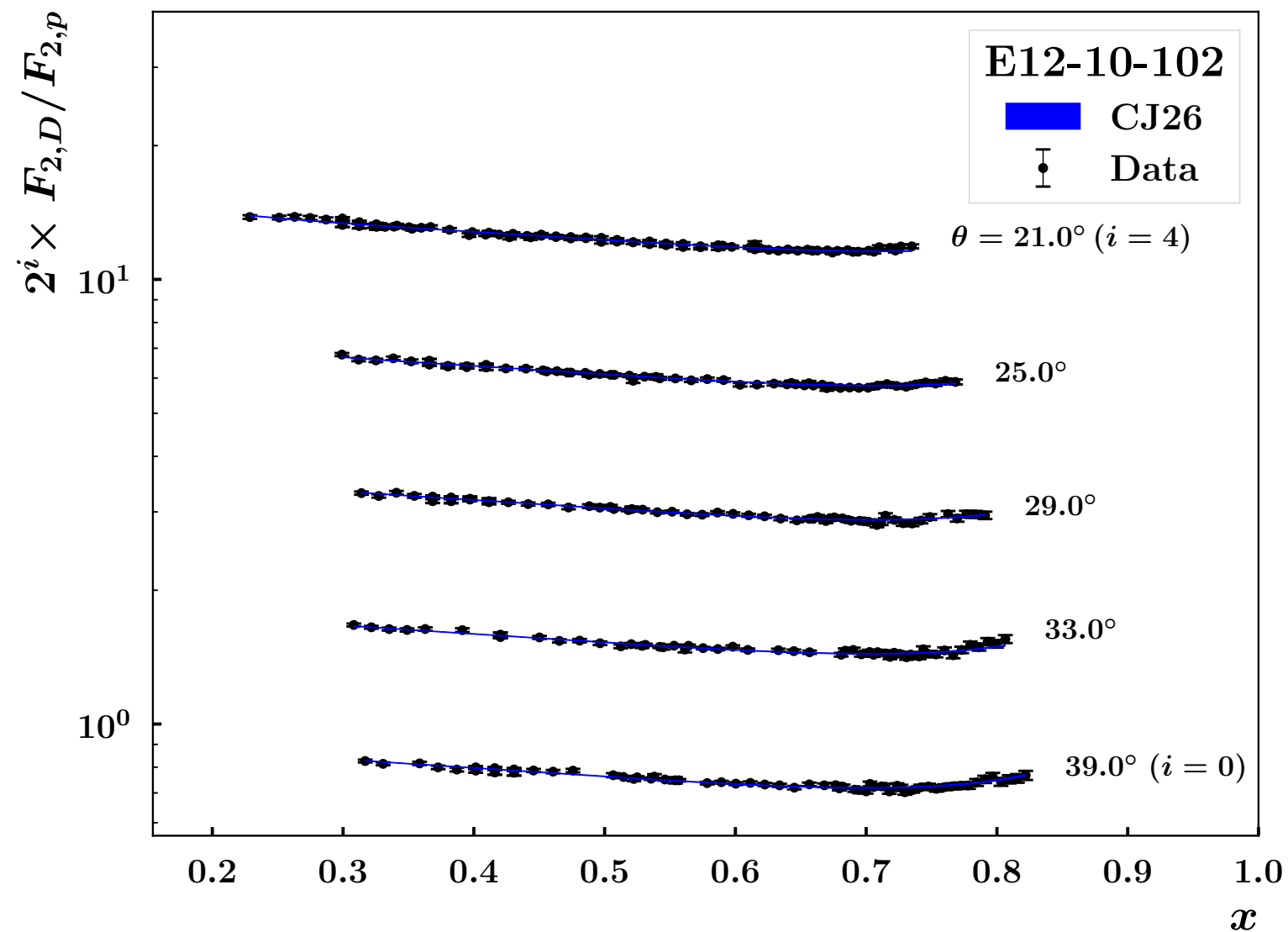
E03-103: inclusive DIS

JLab 6 GeV measurements



CJ26 global fit: results

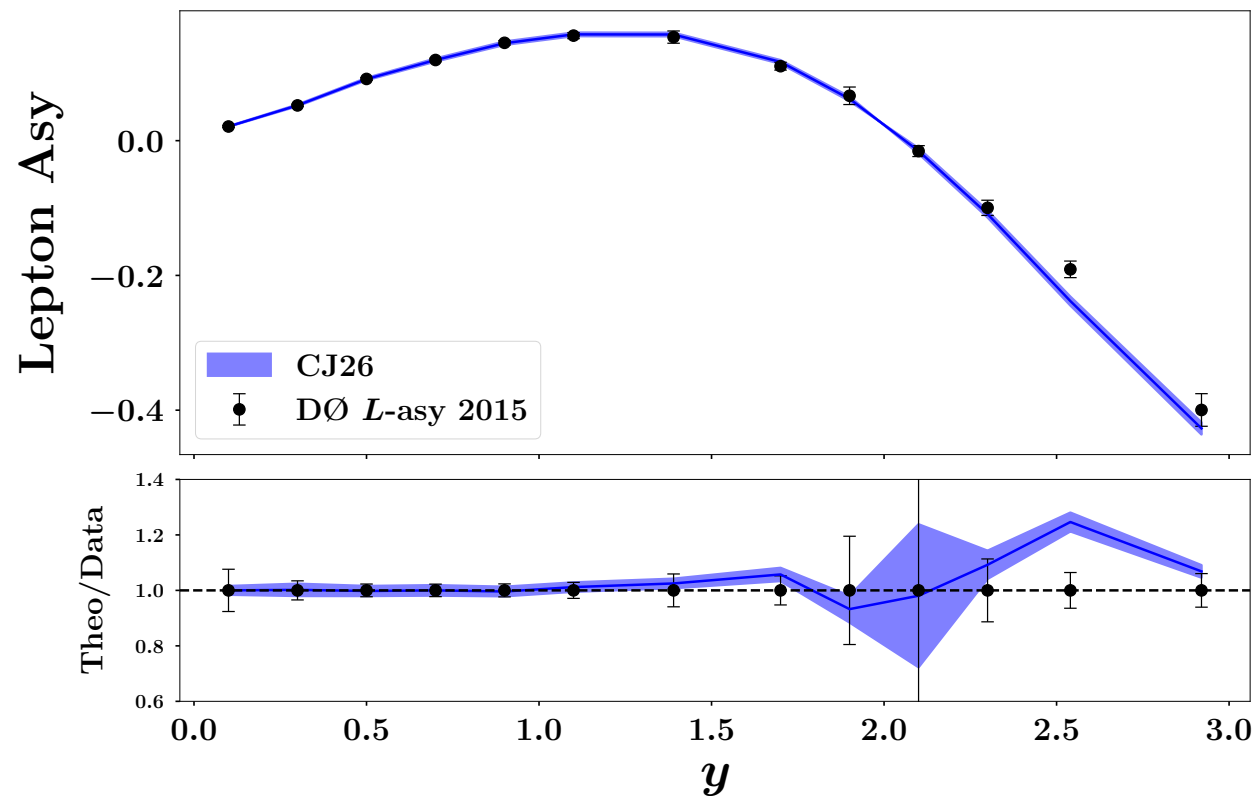
JLab 12 GeV measurements



E12-10-102: inclusive D/p ratio

waiting for BONus12, ...

CJ26 global fit: results

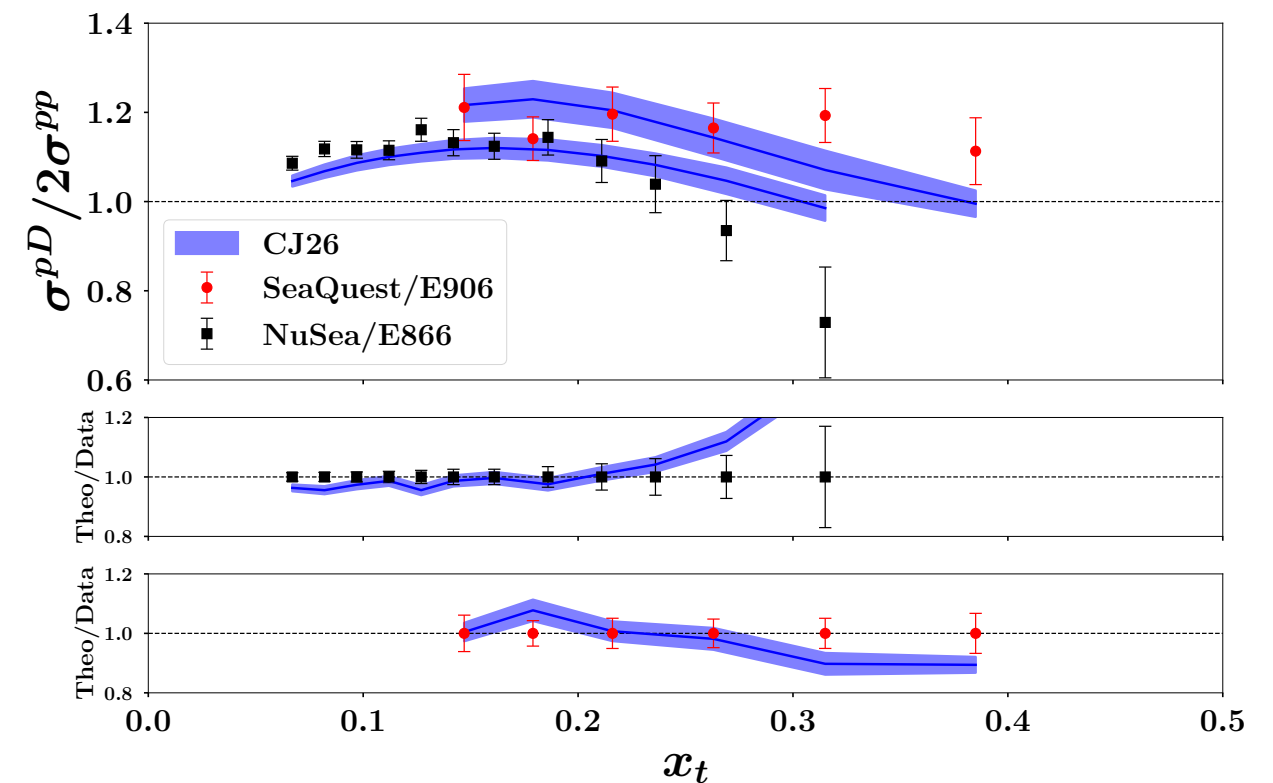
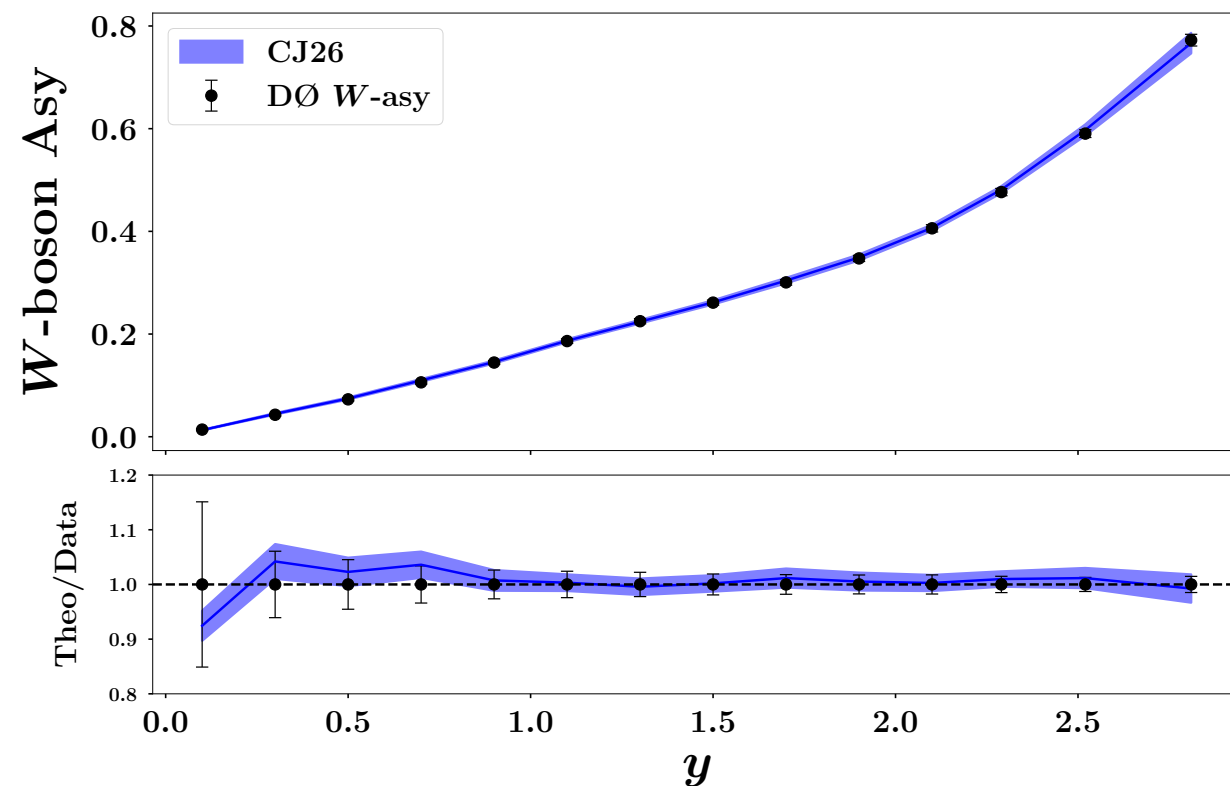


Drell-Yan/ Vector boson

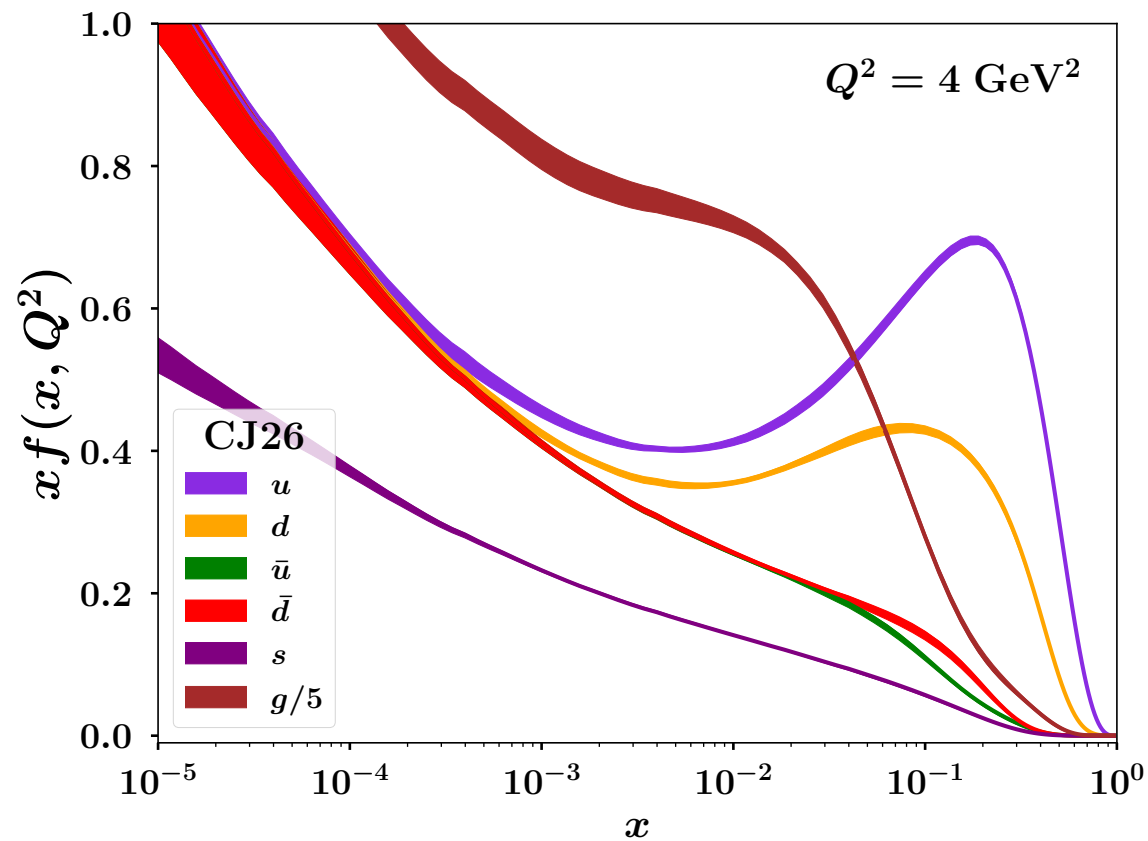
DØ lepton asymmetry

DØ W-boson asymmetry

SeaQuest/NuSea d/p ratio



CJ26 global fit: extracted PDFs

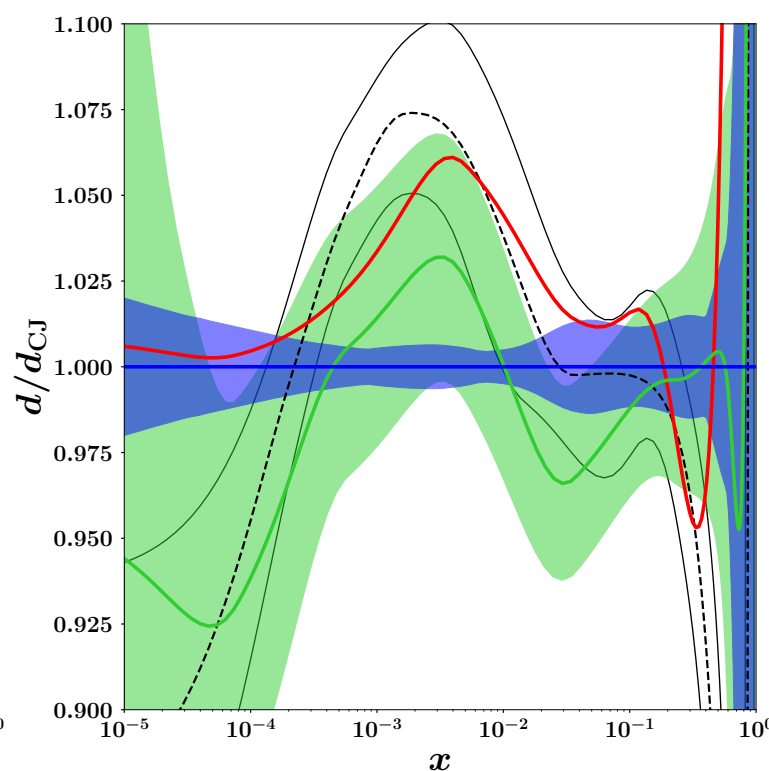
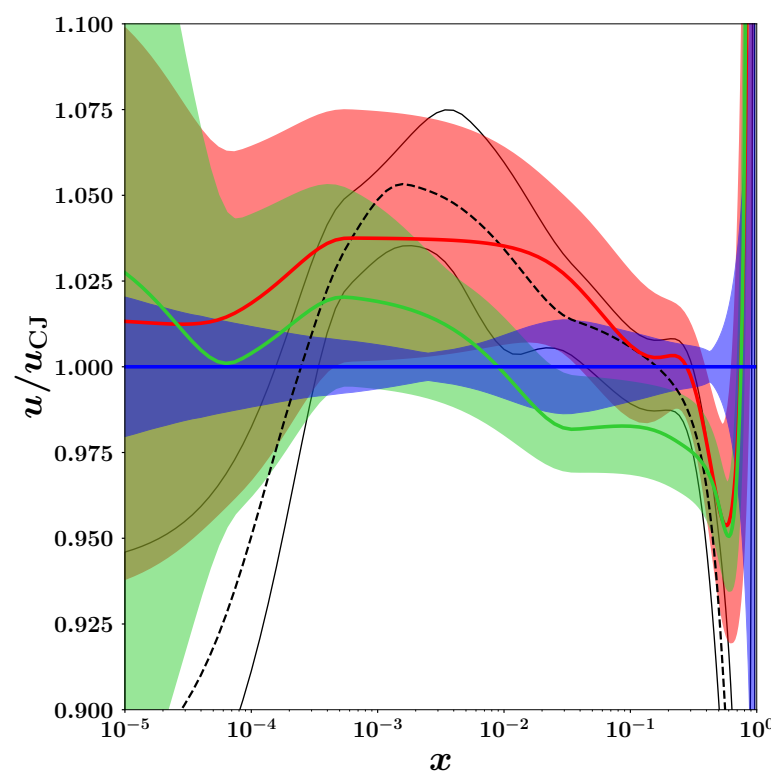


Error propagation:

● Experimental errors: Hessian $T^2 = 2.71$

● Epistemic errors (Add/Mult HTs):
envelope of the two results

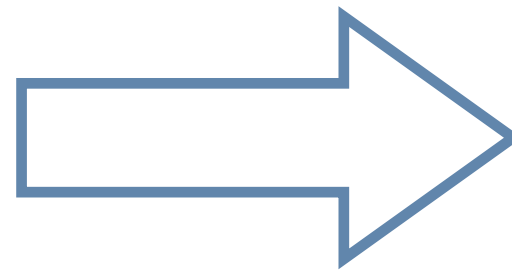
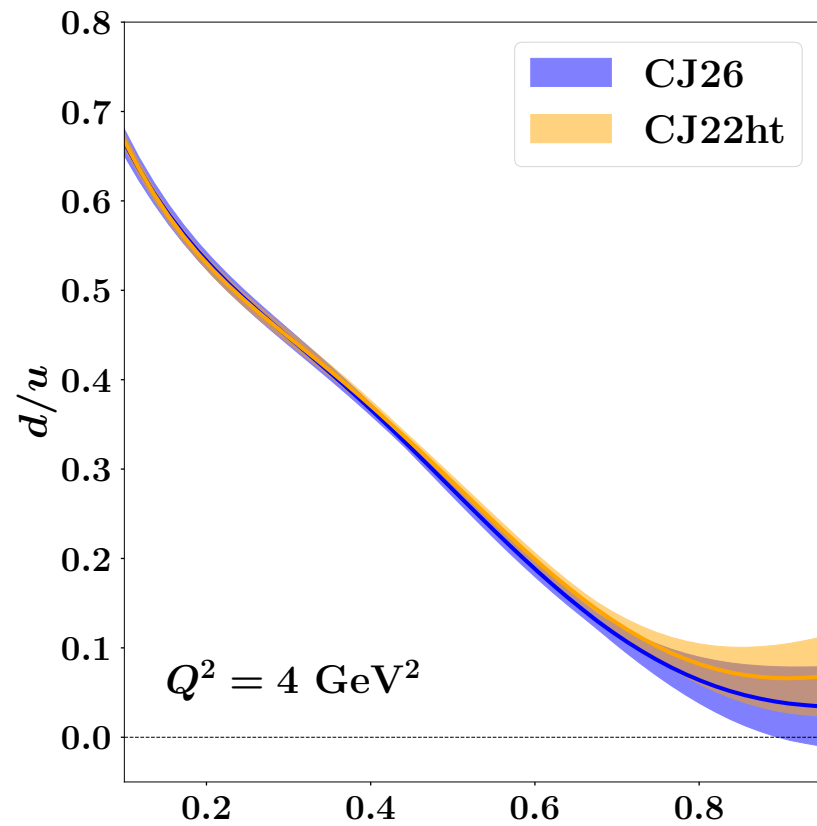
(work in progress on more sophisticated propagation...)



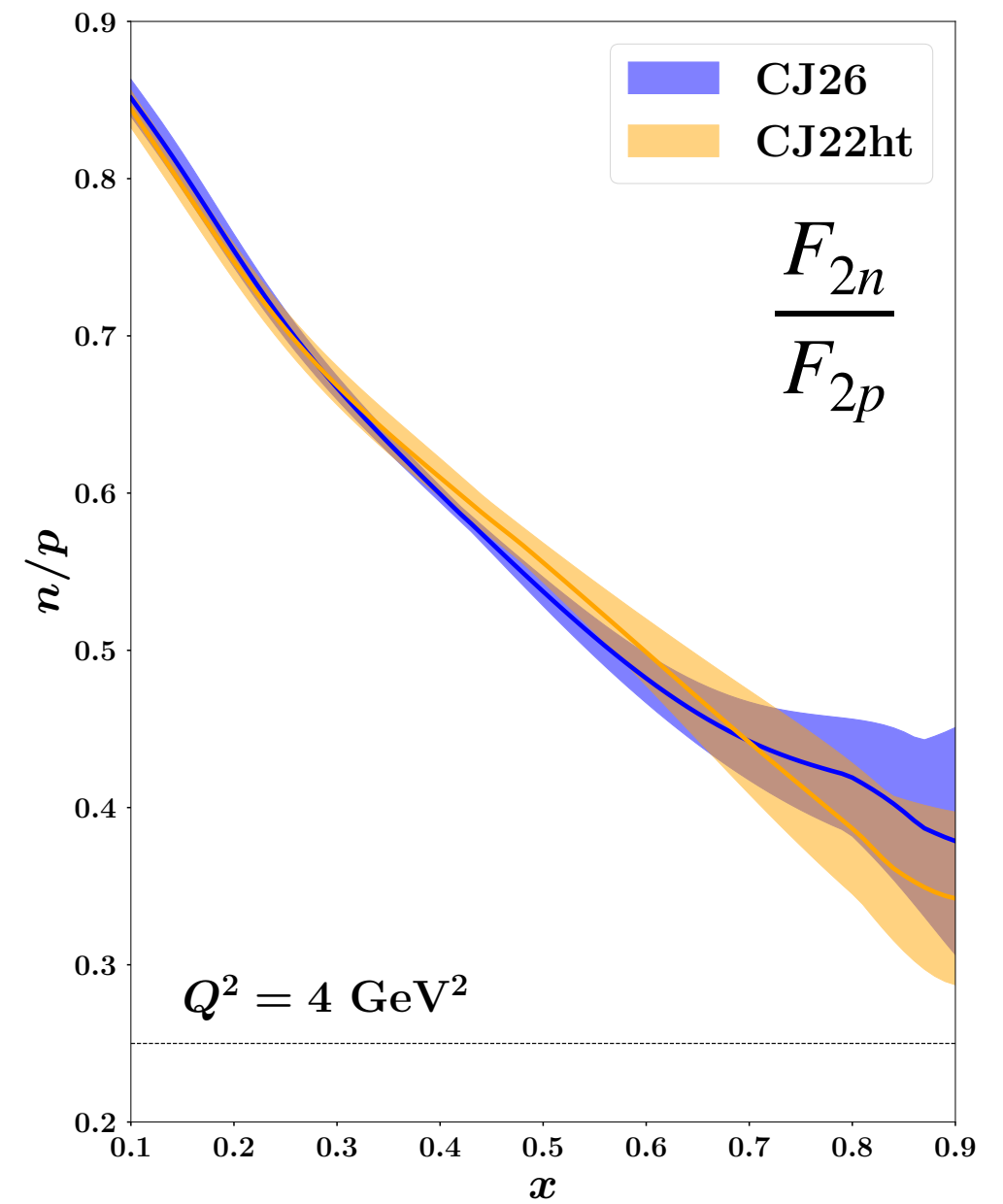
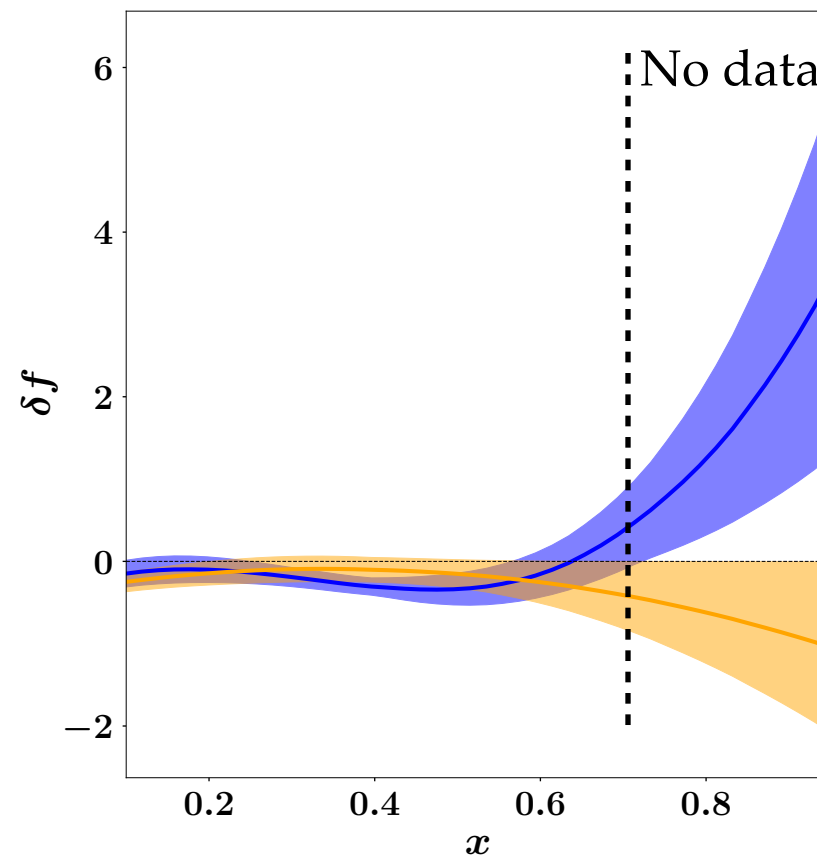
$Q^2 = 100 \text{ GeV}^2$

- NNPDF40
- CT18
- MSHT20
- CJ26

CJ26 global fit: comparison with CJ22ht



Effect of power corrections



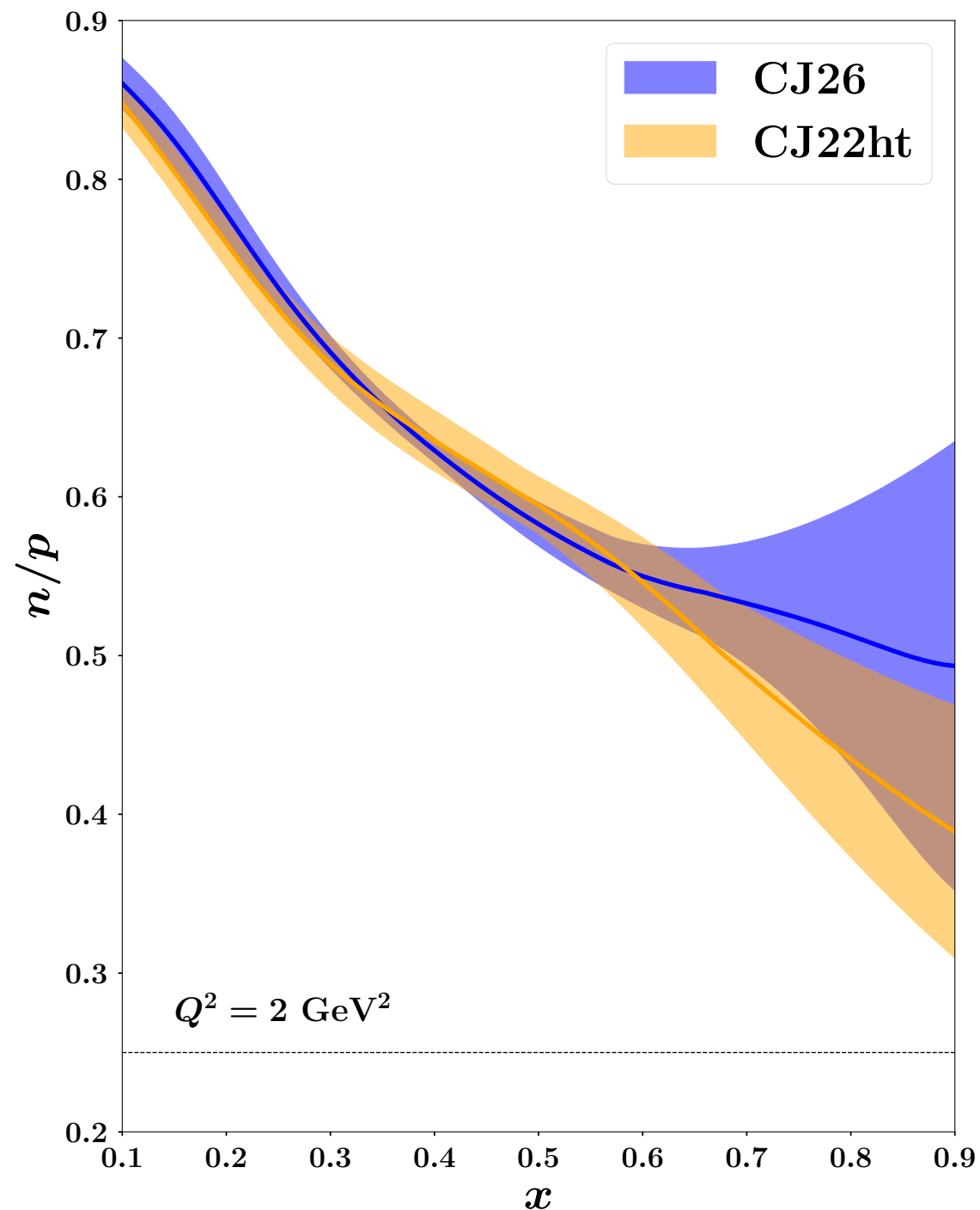
More compatible with AKP

Alekhin, Kulagin, Petti, PRD 105 (2022)

Alekhin, Kulagin, Petti, PRD 107 (2023)

CJ26 global fit: extracted quantities

The neutron-to-proton ratio

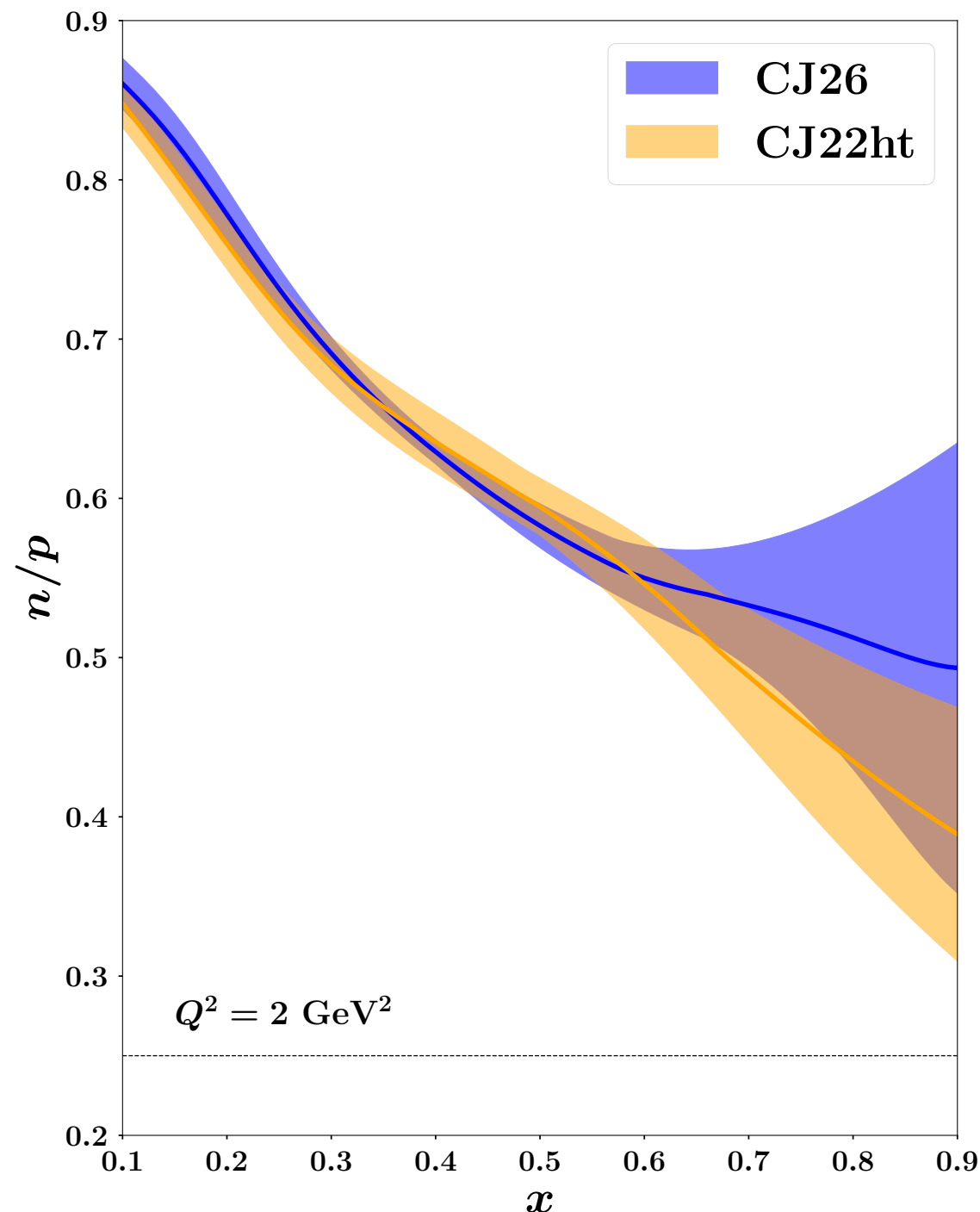


n/p ratio has LARGER tail

The difference from CJ22ht is data driven!

CJ26 global fit: extracted quantities

The neutron-to-proton ratio



n/p ratio has LARGER tail

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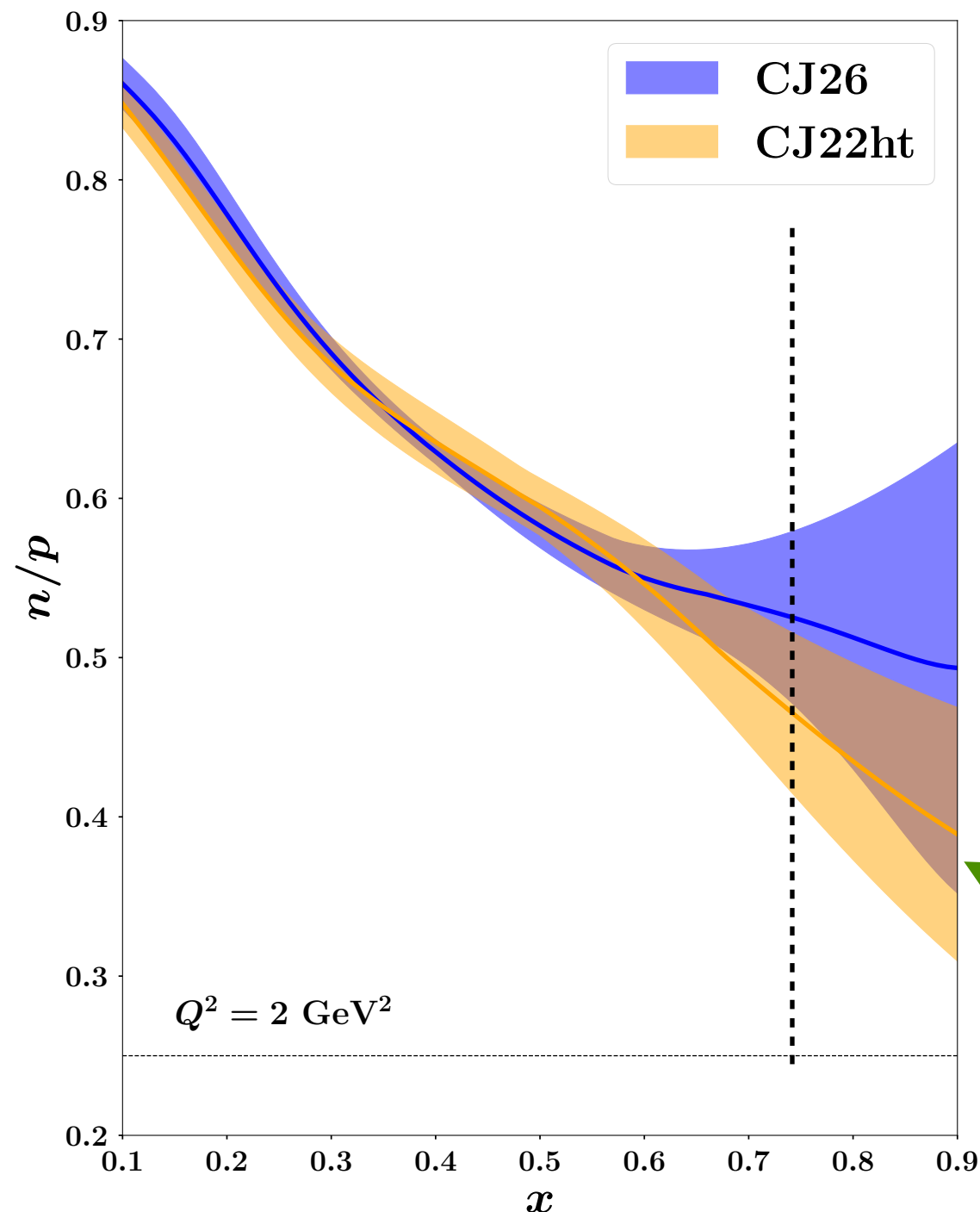
New extraction is more consistent with

MARATHON $\frac{{}^3\text{He}}{{}^3\text{H}}$ data AND

preliminary BONuS12 data

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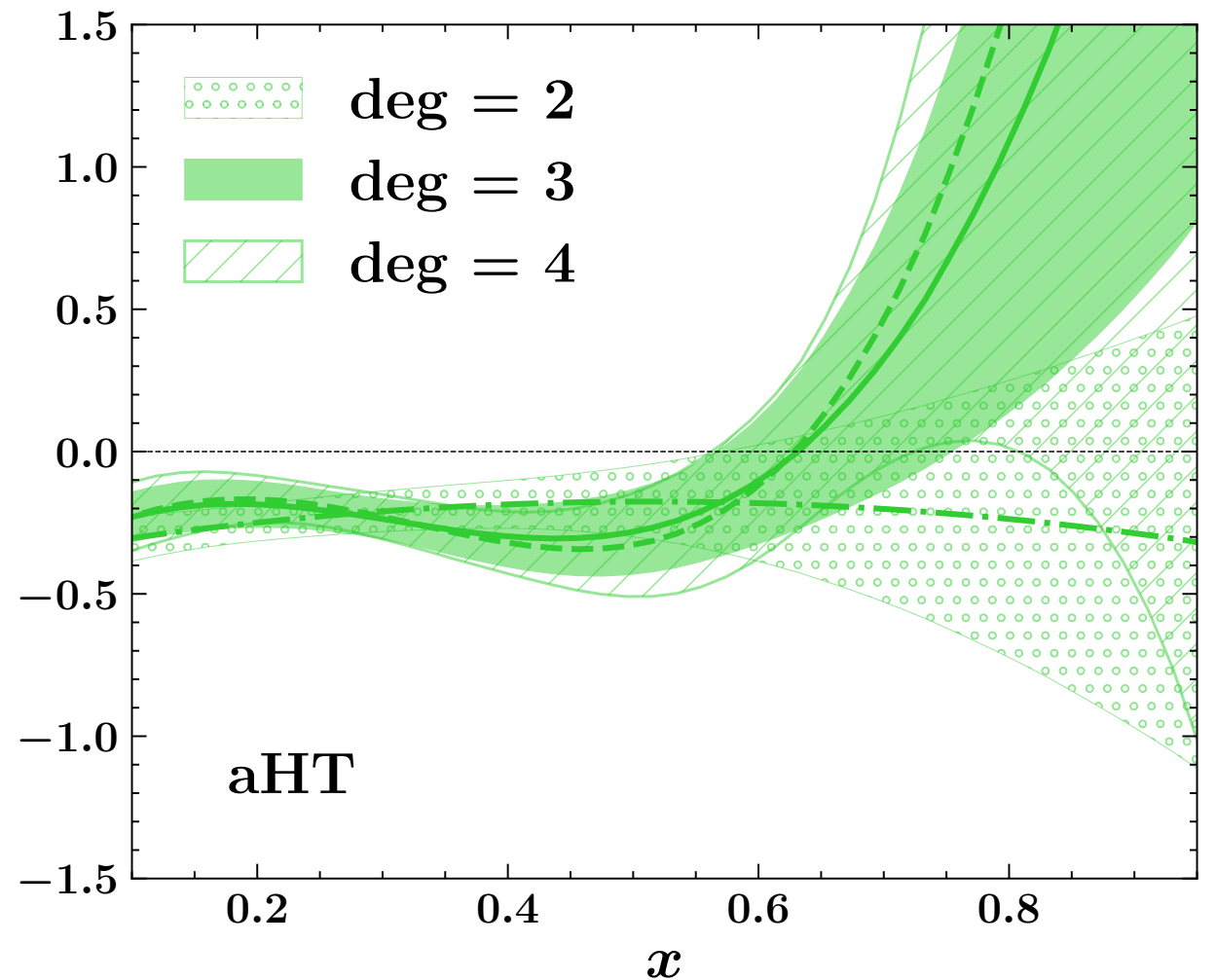
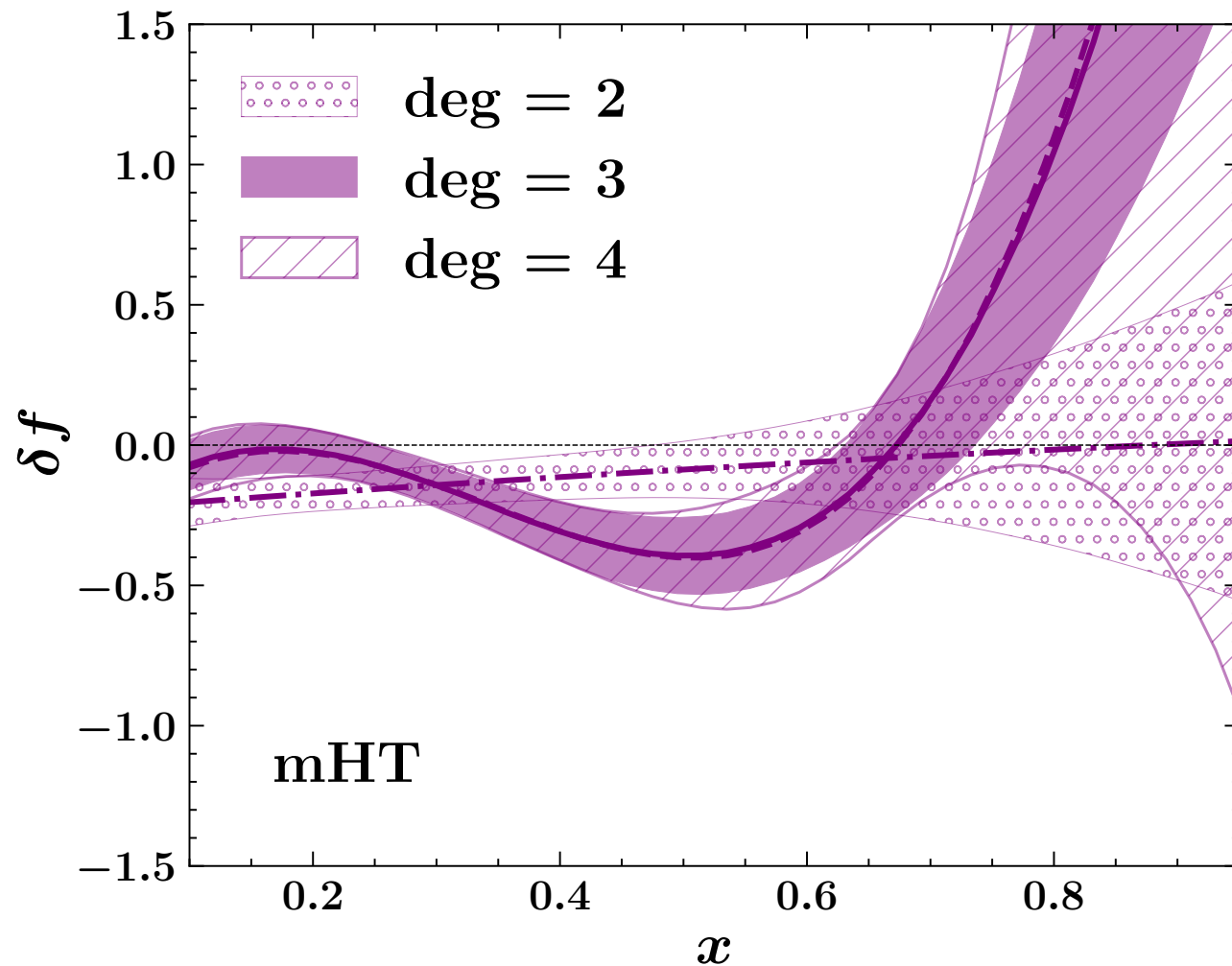
preliminary BONuS12 data

**Necessity of new data
(EIC/JLab12)**

CJ26 global fit: theoretical systematics

Off-shell parametrisation

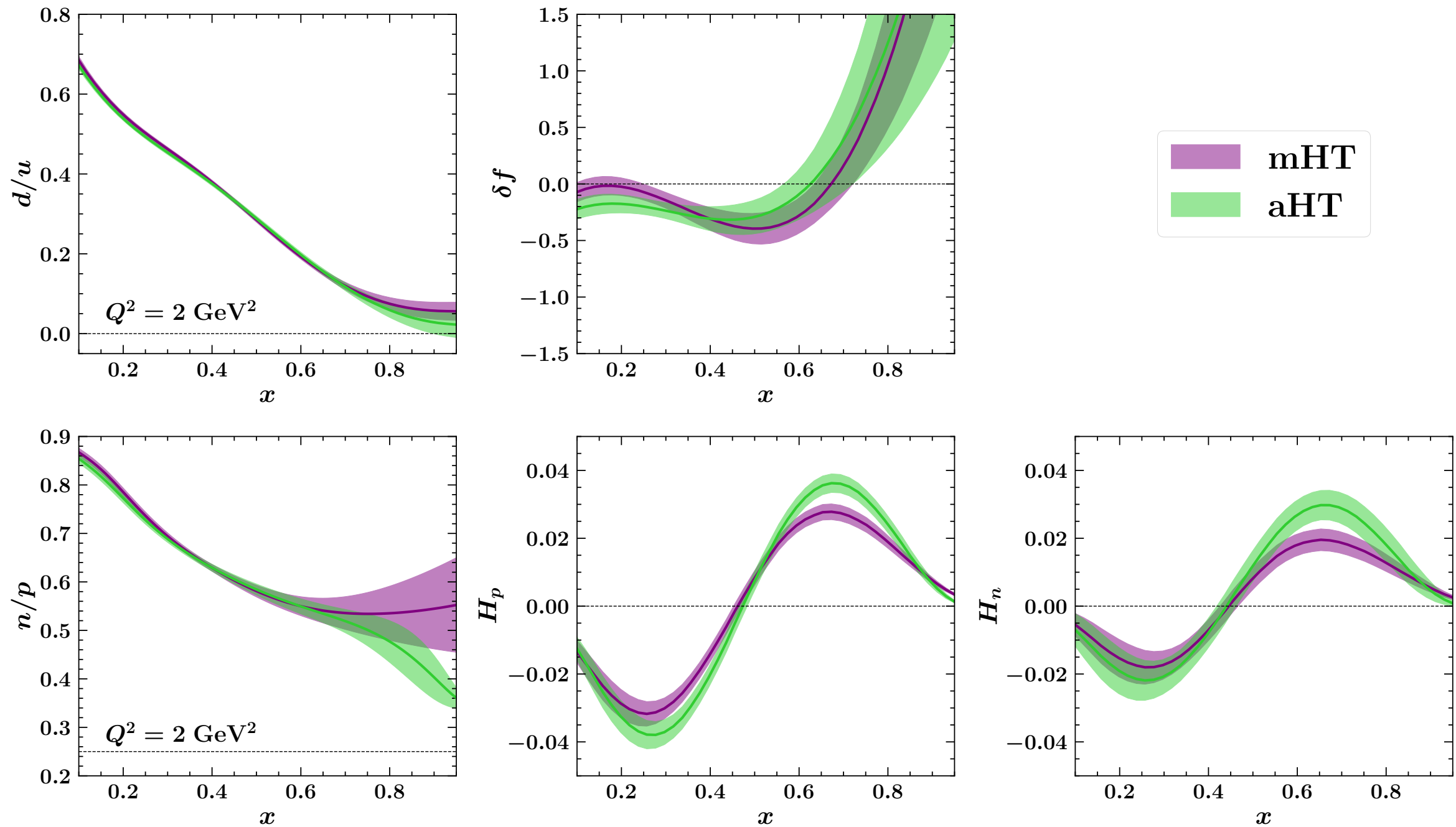
$$\delta f(x) = \sum_{n=0}^k a_{\text{off}}^{(n)} x^n$$



- Need at least $k=3$ to reach stability
- Data constrain up to $x \simeq 0.75$
- Compatible with other extractions in the literature

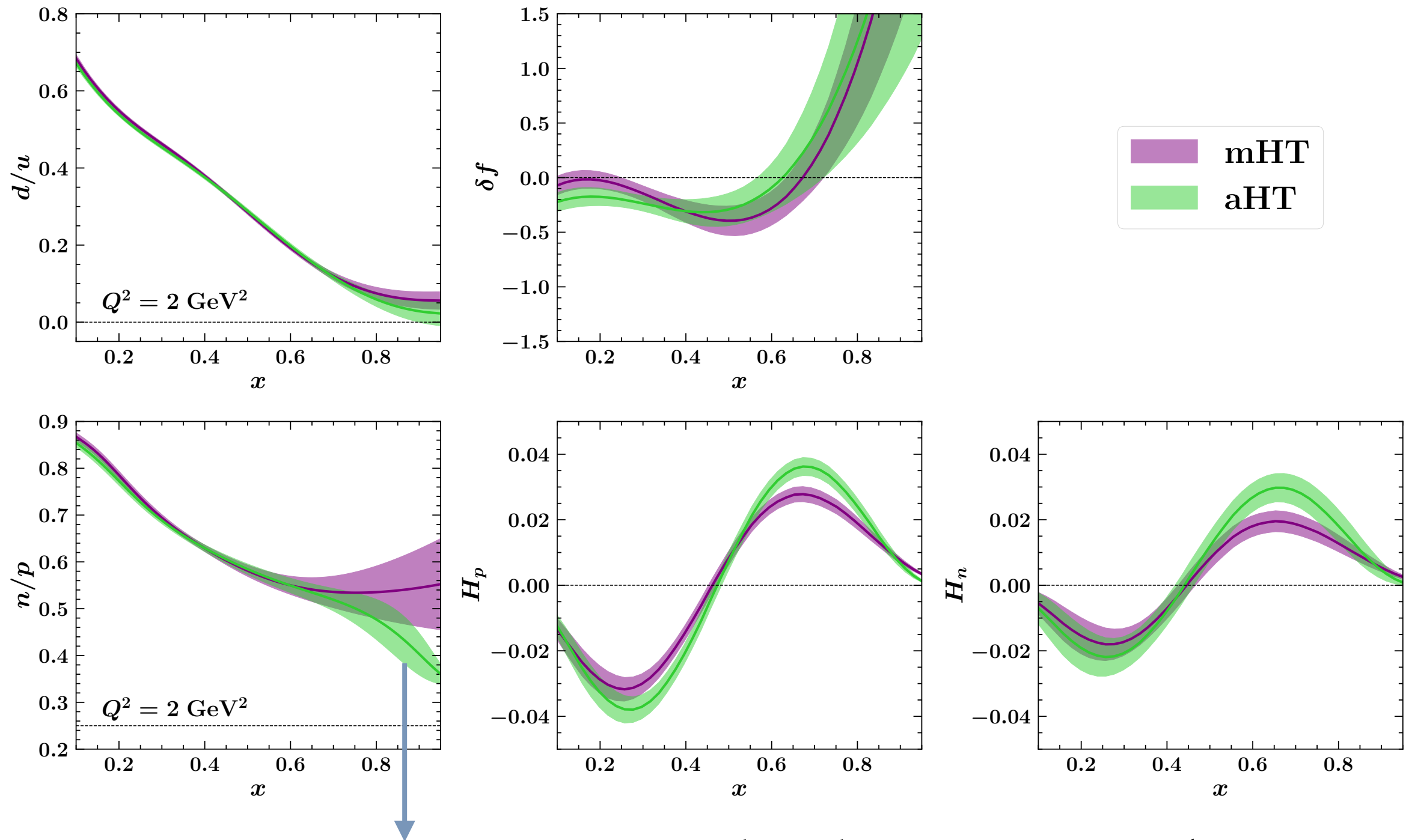
CJ26 global fit: theoretical systematics

Additive/Multiplicative HTs



CJ26 global fit: theoretical systematics

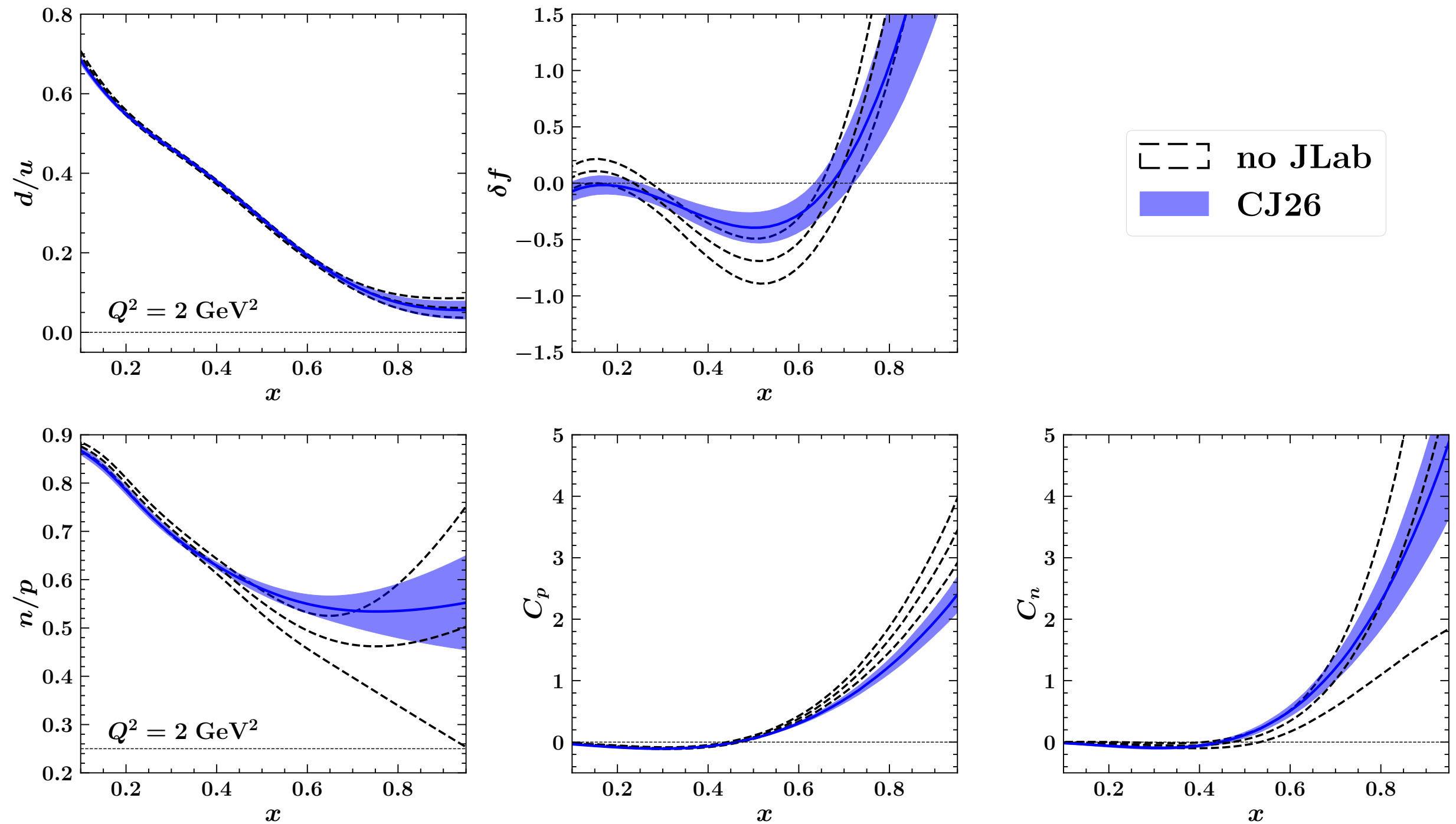
Additive/Multiplicative HTs



Remaining extrapolation bias: aHT $\rightarrow 0$ as $x \rightarrow 1$

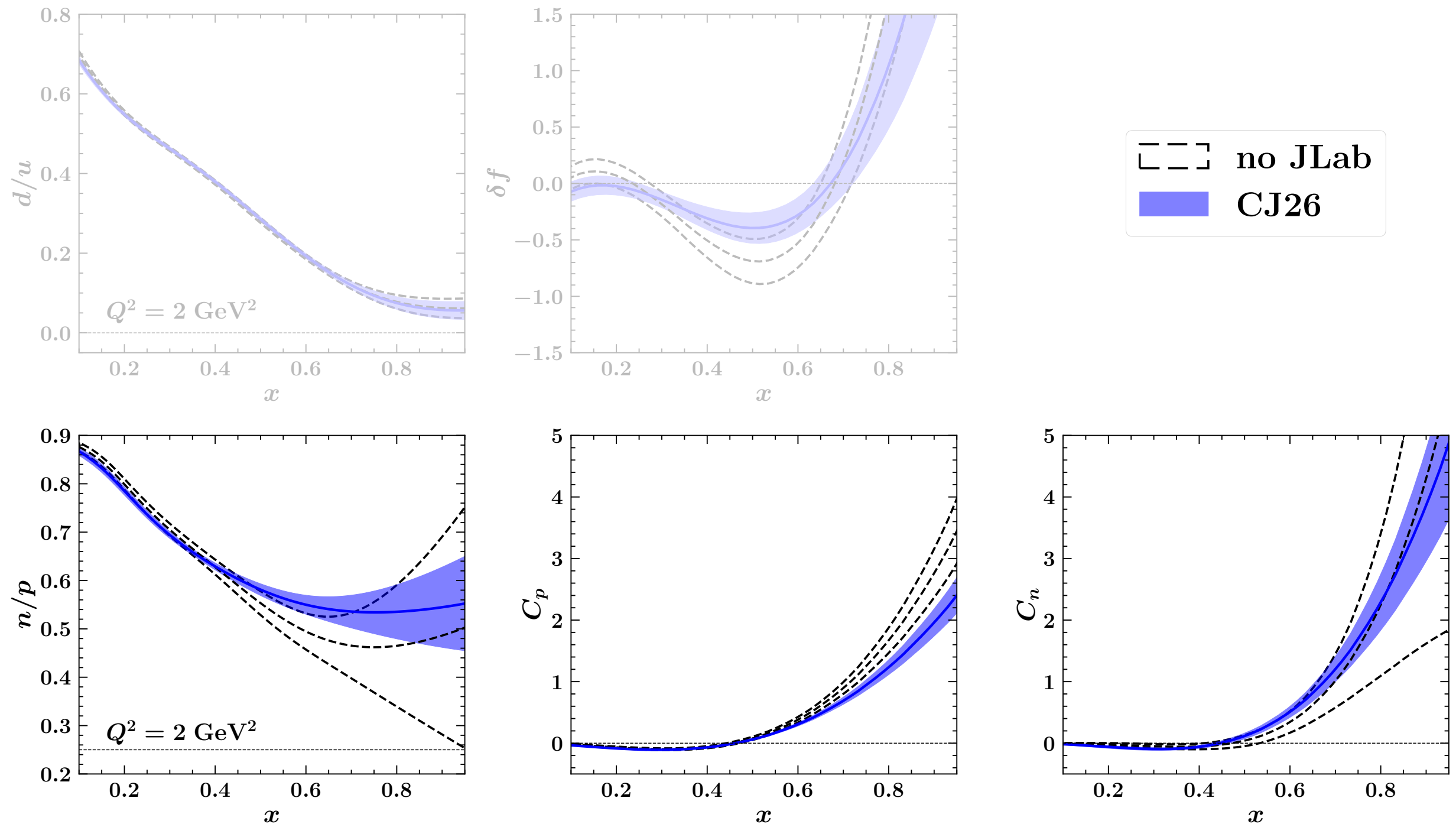
CJ26 global fit: impact of JLab data

Note: using only mHT for clarity



CJ26 global fit: impact of JLab data

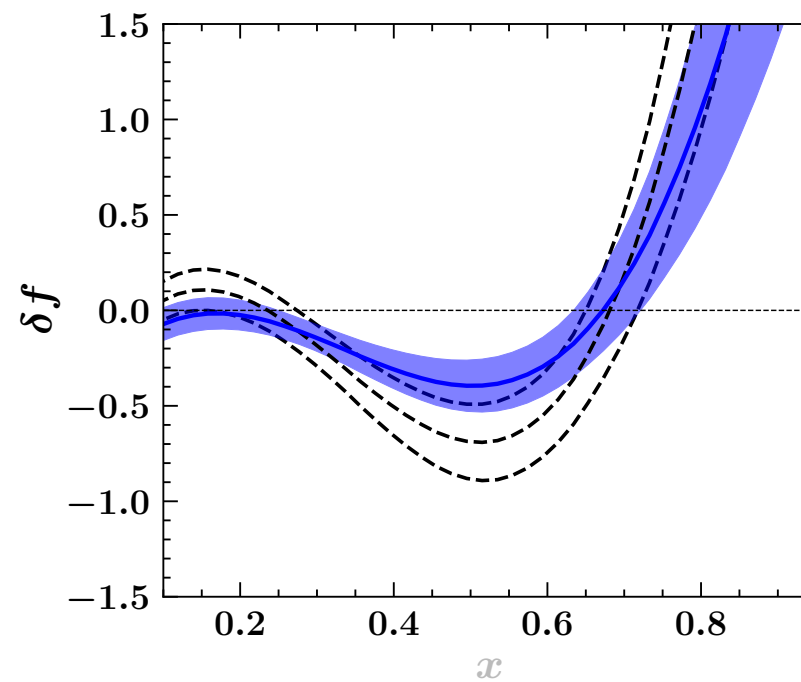
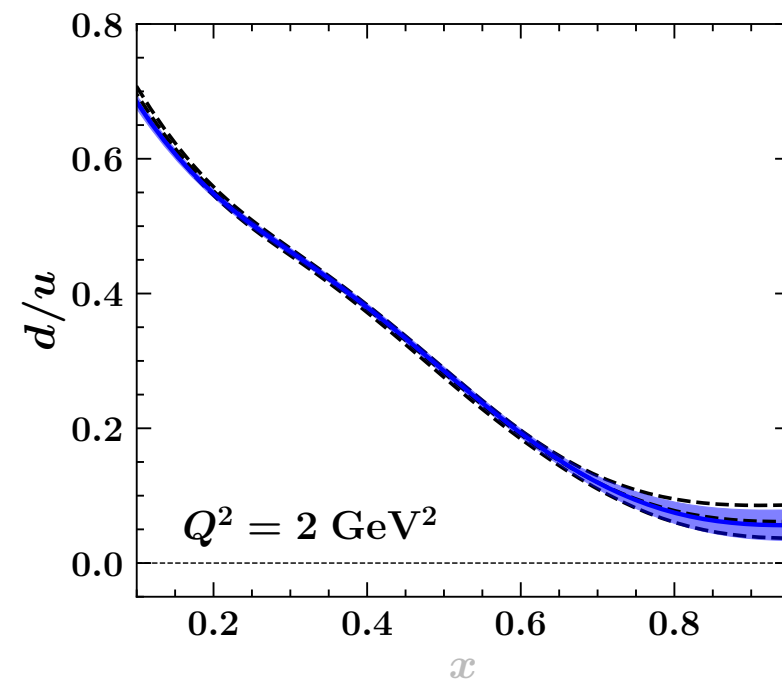
Note: using only mHT for clarity



JLab 6 GeV data provide constraints on higher-twist effects

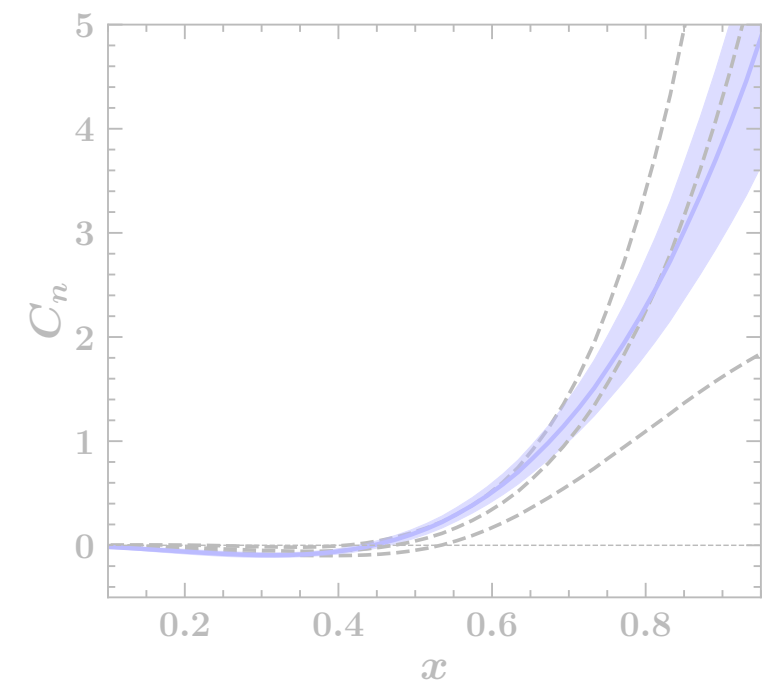
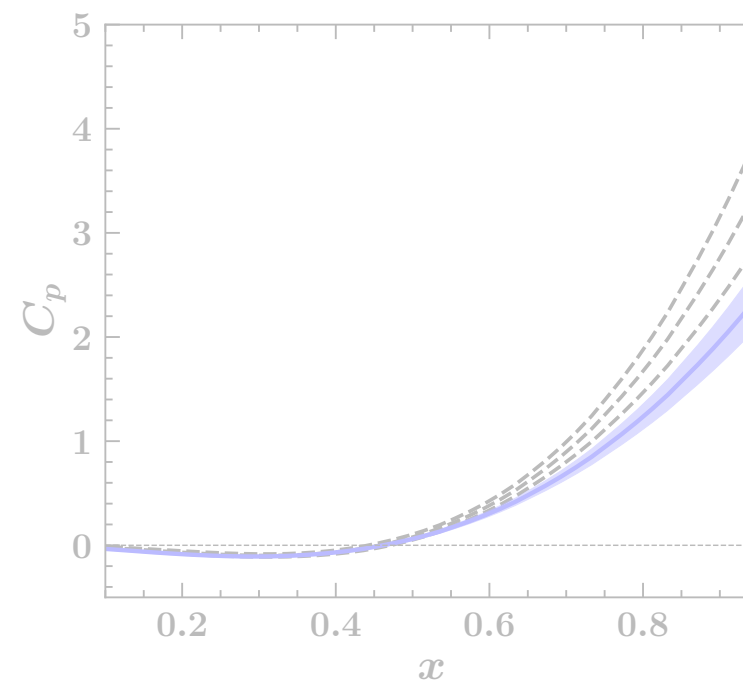
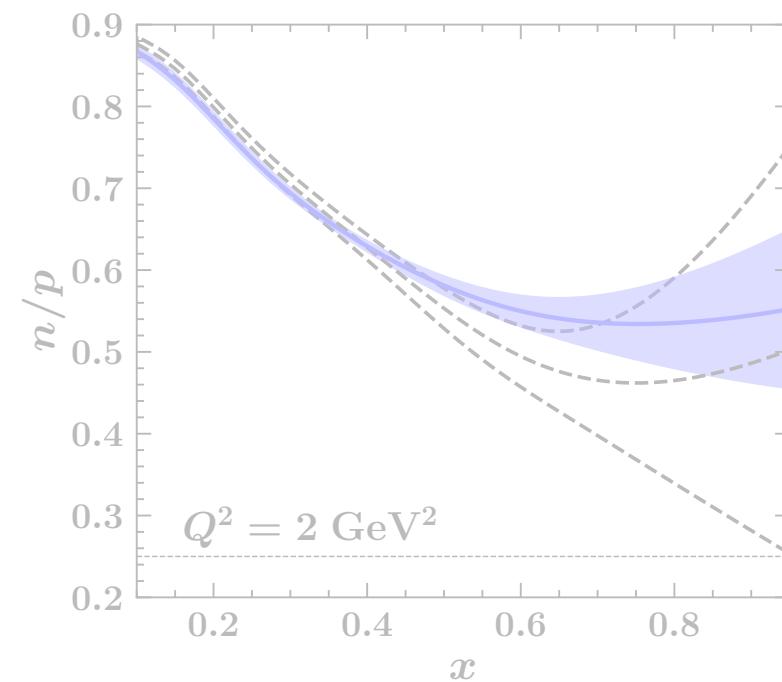
CJ26 global fit: impact of JLab data

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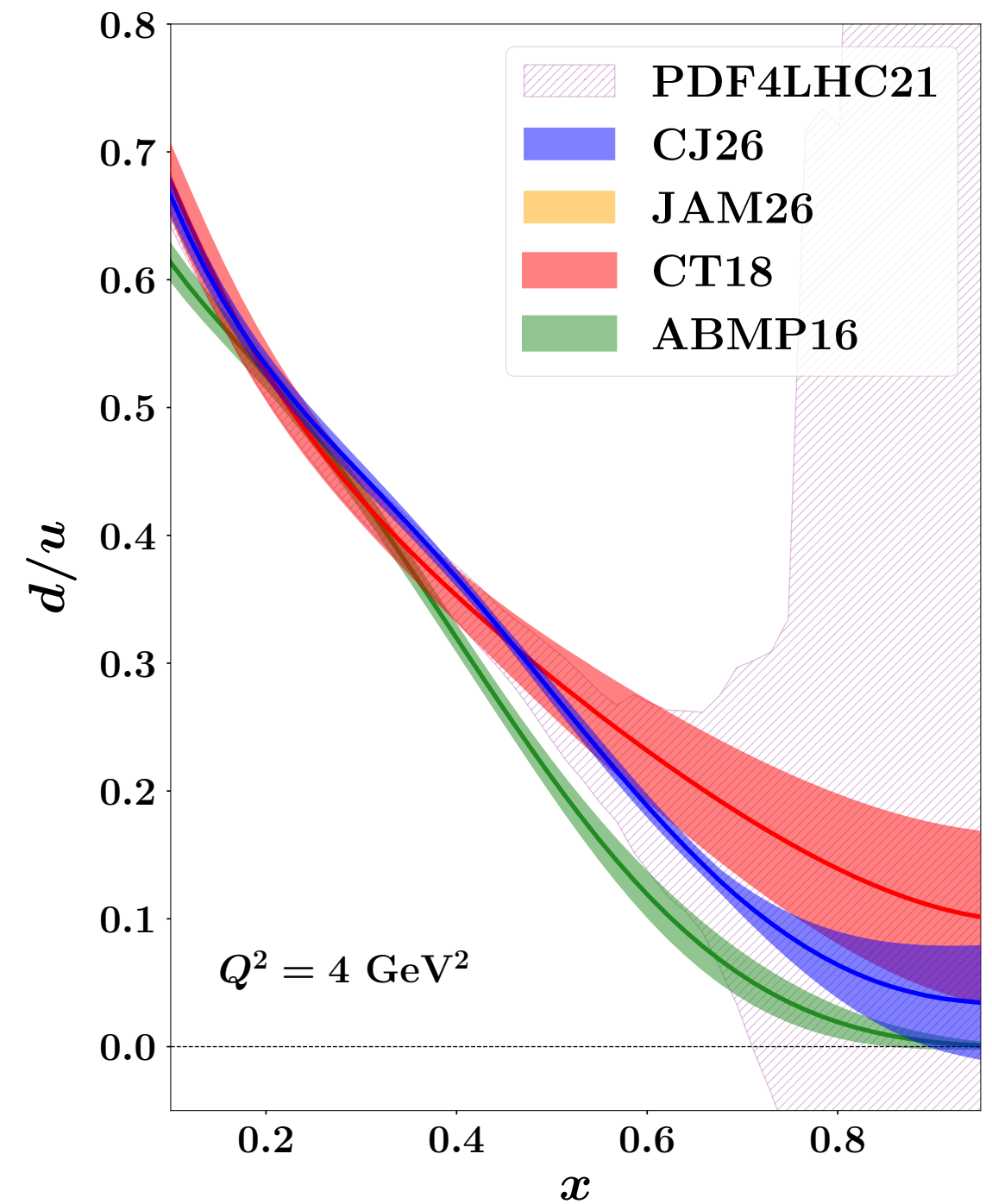


no JLab
CJ26

JLab 12 GeV data
constrain LT dynamics



Conclusions and Outlook

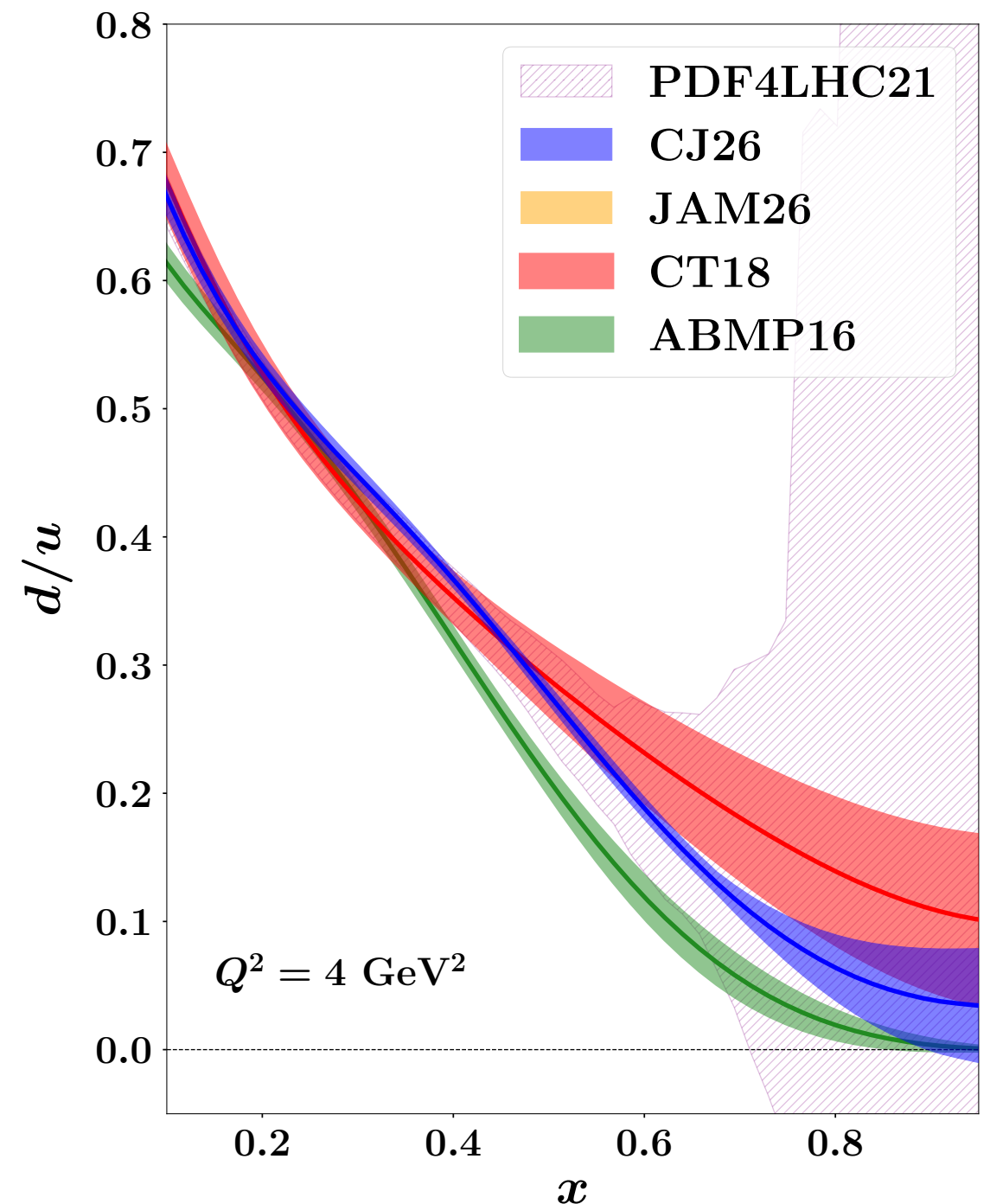


Conclusions and Outlook

- ★ **CJ26**: new global fit of unpolarized PDFs at NLO with focus on large- x region

LHAPDF grids available:

<https://www.jlab.org/theory/cj/pdfs>



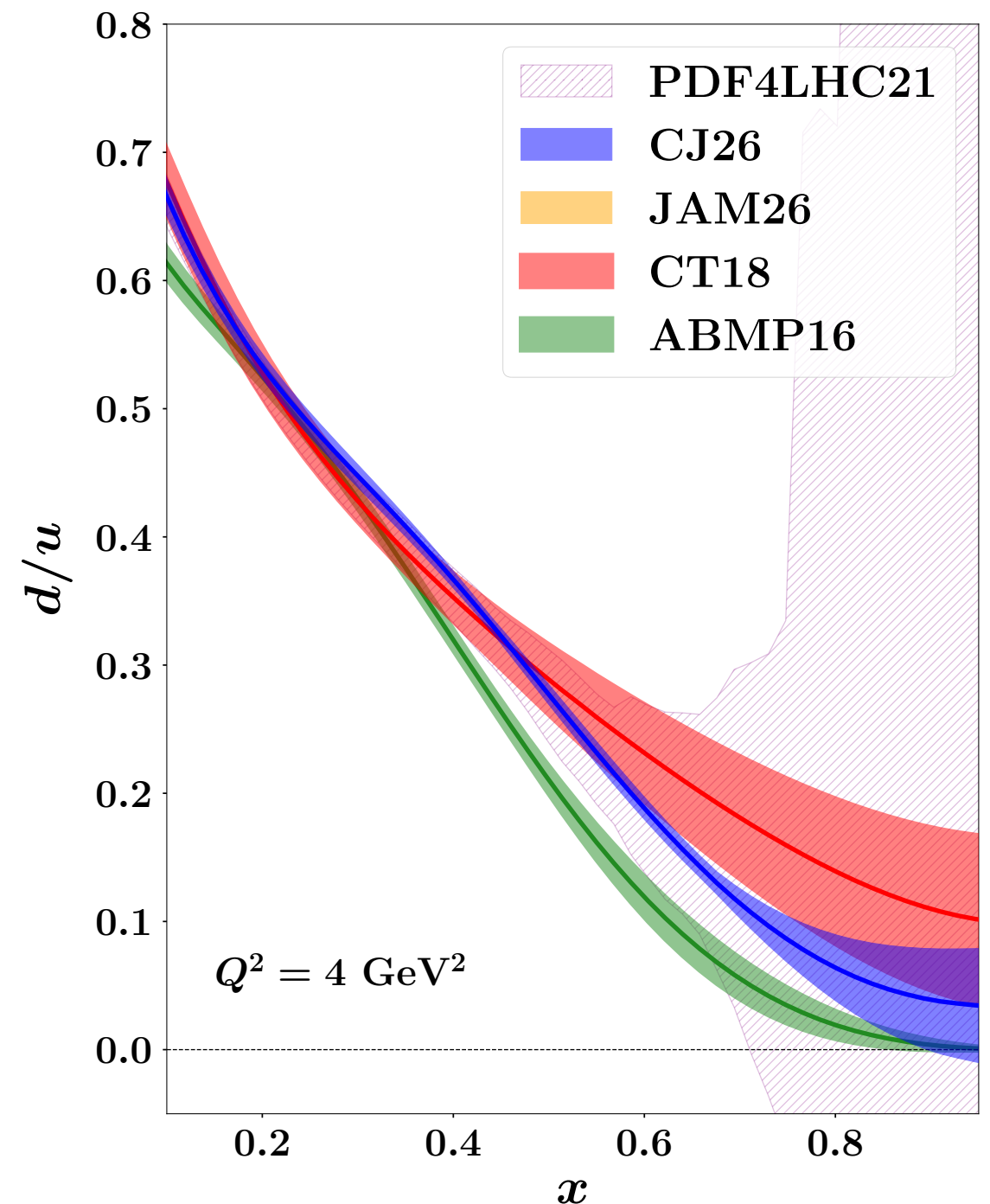
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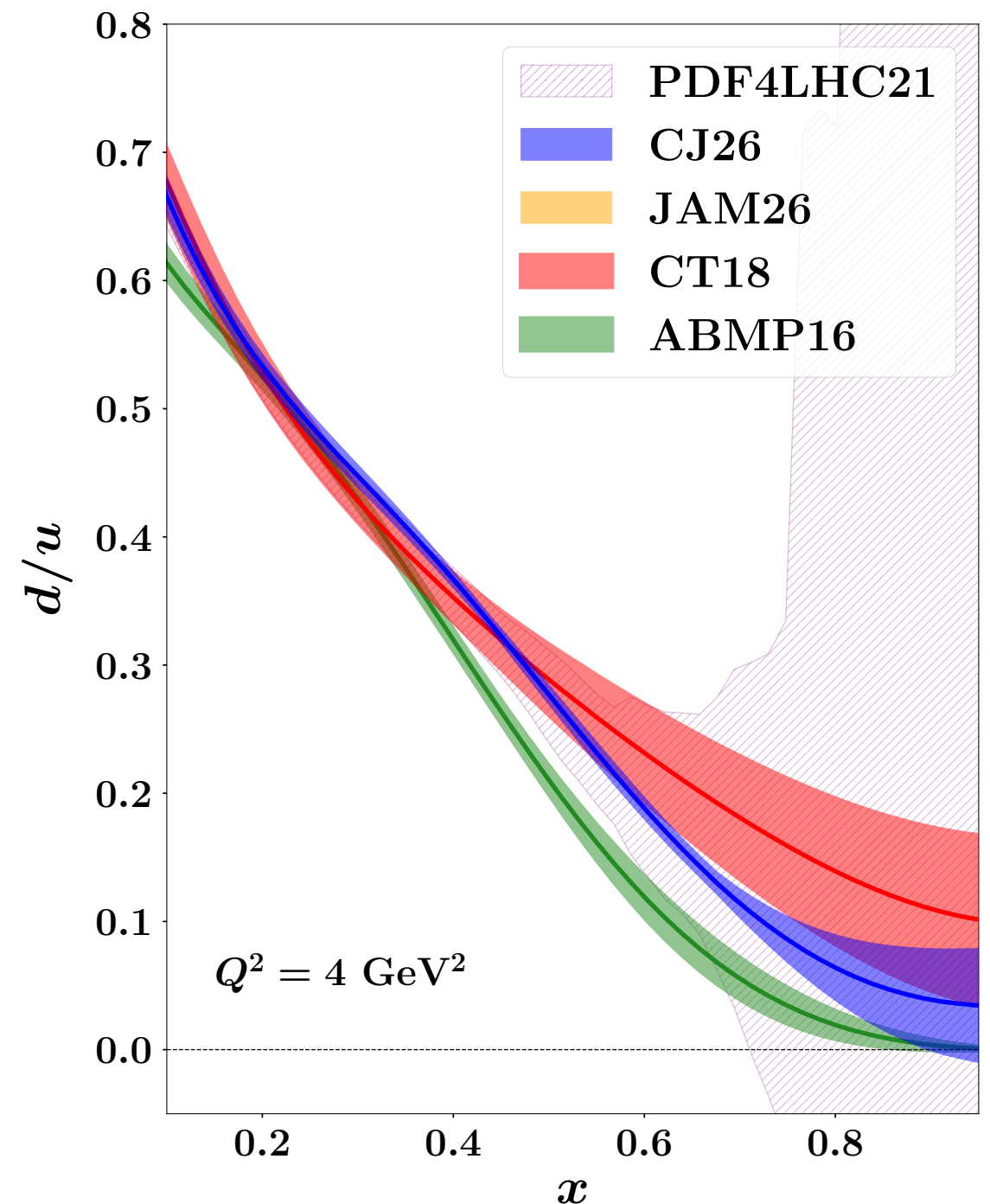
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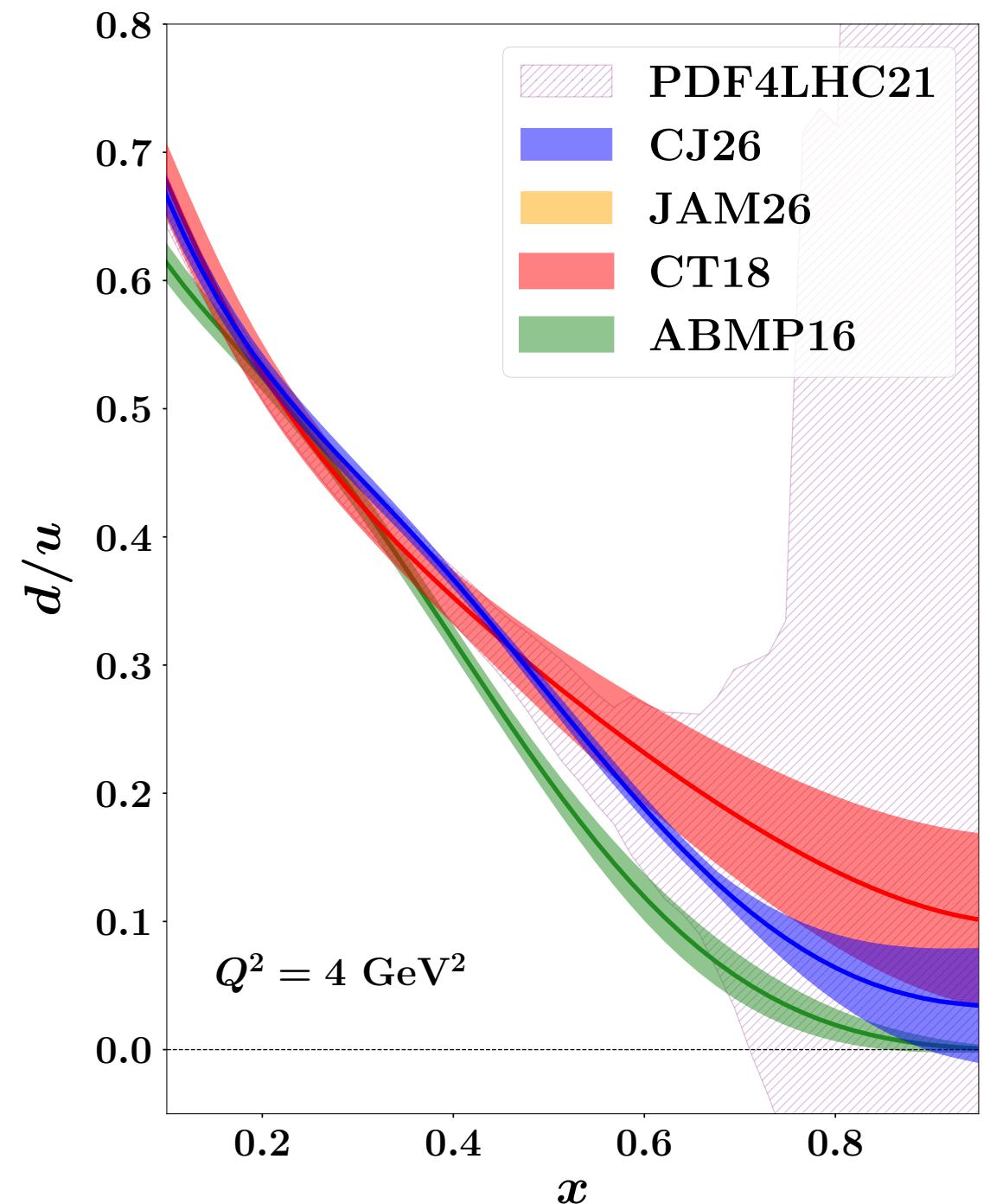
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- ★ **High precision in d/u up to $x \simeq 0.75$**
- ★ **Next steps**: improve error propagation, NNLO++, PVDIS, LHC data, ...



Backup

Impact of HT on n/p ratio

Are experimental observables independent of the choice of the HT?

$$\frac{F_{2,n}}{F_{2,p}} = \frac{n}{p} \xrightarrow{x \rightarrow 1} \frac{4d + u}{4u + d} \simeq \frac{1}{4}$$

Mult HT

$$C_p(x) = C_n(x) = C(x)$$

$$\frac{(4d + u)(1 + C/Q^2)}{(4u + d)(1 + C/Q^2)} \simeq \frac{1}{4}$$

Add HT

$$H_p(x) = H_n(x) = H(x)$$

$$\frac{4d + u + H/Q^2}{4u + d + H/Q^2} \simeq \frac{u + H/Q^2}{4u + H/Q^2}$$

$$\text{expansion in } \frac{H}{uQ^2} \simeq \frac{1}{4} + \boxed{3 \frac{H}{16uQ^2}} + p.s$$

Bias in n/p function

Impact of HT on n/p ratio

Are experimental observables independent of the choice of the HT?

$$\frac{n}{p} \xrightarrow{x \rightarrow 1} \frac{1}{4} \quad \text{LT} \quad \text{Mult HT} \quad C_p(x) = C_n(x) = C(x)$$

Add HT

$$H_p(x) \neq H_n(x)$$

$$\frac{u + H_n/Q^2}{4u + H_p/Q^2}$$

$$\simeq \frac{1}{4} + \frac{4H_n - H_p}{16uQ^2} + p.s$$

$$\begin{array}{c} \nearrow H_p(x) = H_n(x) \\ \xrightarrow{H_p(x) = 2H_n(x)} \end{array}$$

$$\frac{1}{4} + 3 \frac{H}{16uQ^2}$$

$$\frac{1}{4} + \frac{H}{16uQ^2}$$

structure function
is smaller

Mult HT

$$C_p(x) \neq C_n(x)$$

$$\frac{u + \tilde{H}_n/Q^2}{4u + \tilde{H}_p/Q^2}$$

same as Add

Bias not present!

Results in the CJ fitting framework

Case 1: isospin symmetry

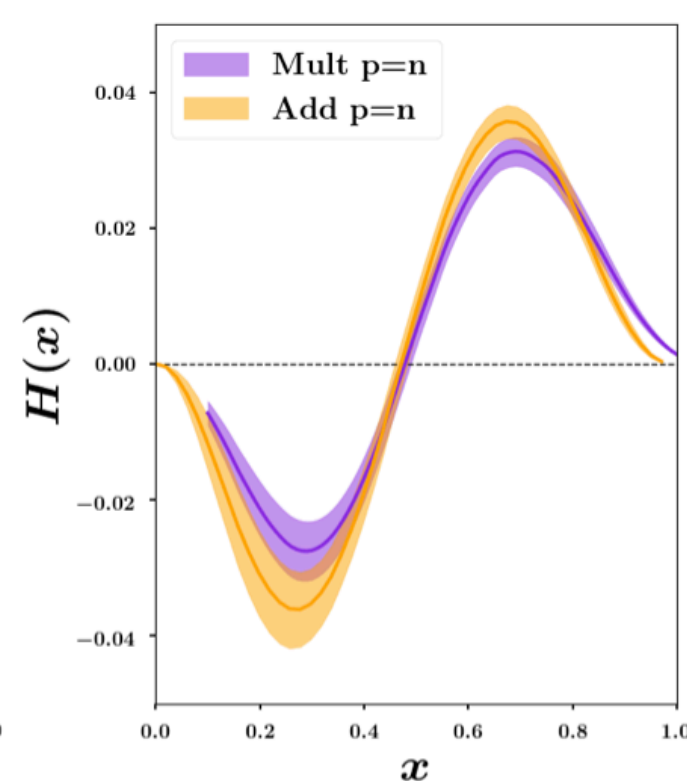
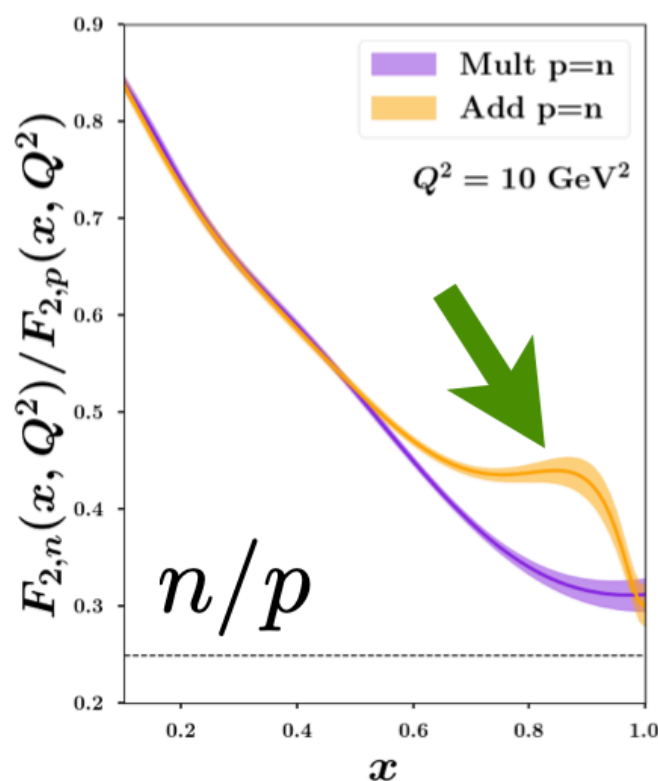
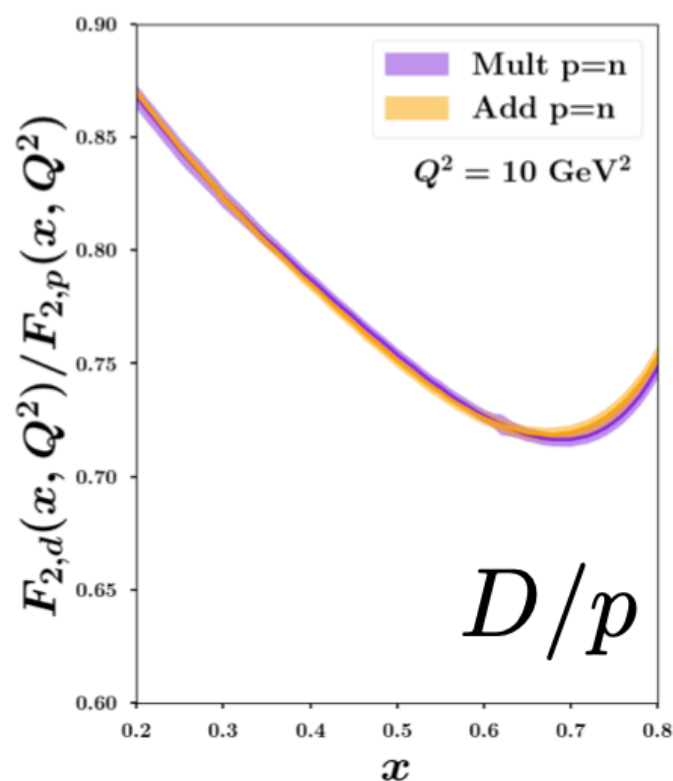
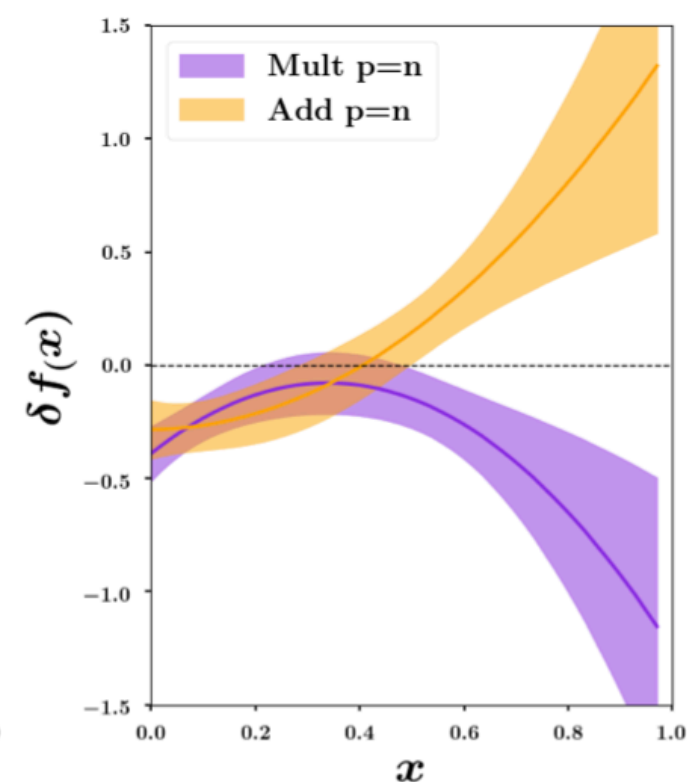
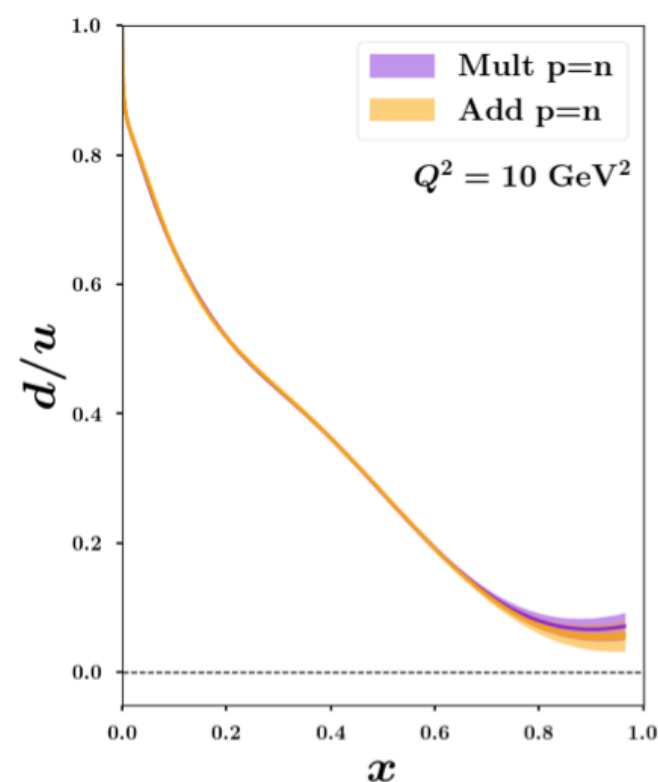
Add HT

Unnaturally large n/p

BUT smaller d/u than Mult

Bias identified

Off-shell compensates n/p bias



Results in the CJ fitting framework

Case 2: isospin breaking

Compatible n/p

$$H_n(x) \simeq \frac{1}{2}H_p(x)$$

Bias removed

No need of compensation by off-shell
Theory calculation confirmed!

