Systematic uncertainty of off-shell corrections and higher-twist contribution in DIS at large x

Matteo Cerutti

CTEQ-JLab Collaboration

A. Accardi, I. Fernando, X. Jing, S. Li, J. Owens, S. Park, C.E. Keppel, W. Melnitchouk, P. Monaghan

Motivations

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Main focus: $\frac{d}{u}$

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DIS on proton target

Drell—Yan data

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DIS on Deuterium targets at JLab and SLAC
Proton-Tagged DIS (BONuS)
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We have to deal with Deuterium target at large-x

Deuterium: nuclear smearing

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Nuclear impulse approximation

Melnitchouk, Schreiber, Thomas, PRD 49 (1994)
Kulagin, Piller, Weise, PRC 50 (1994)
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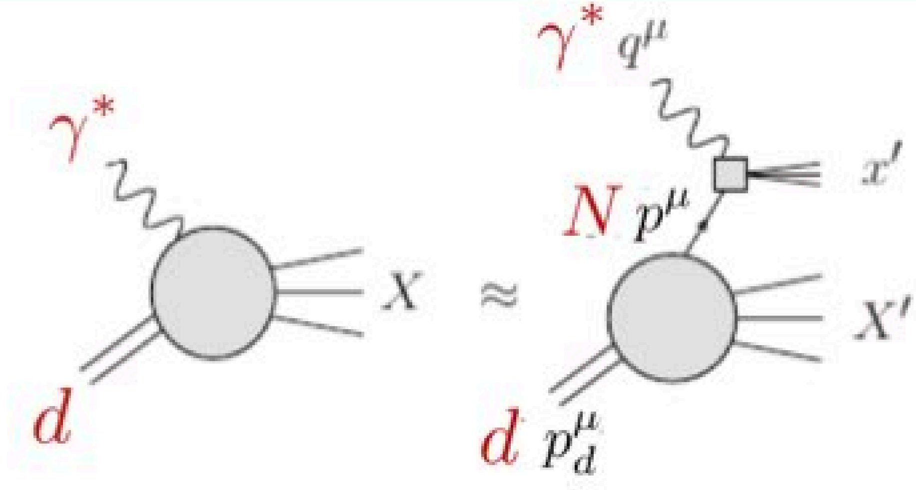

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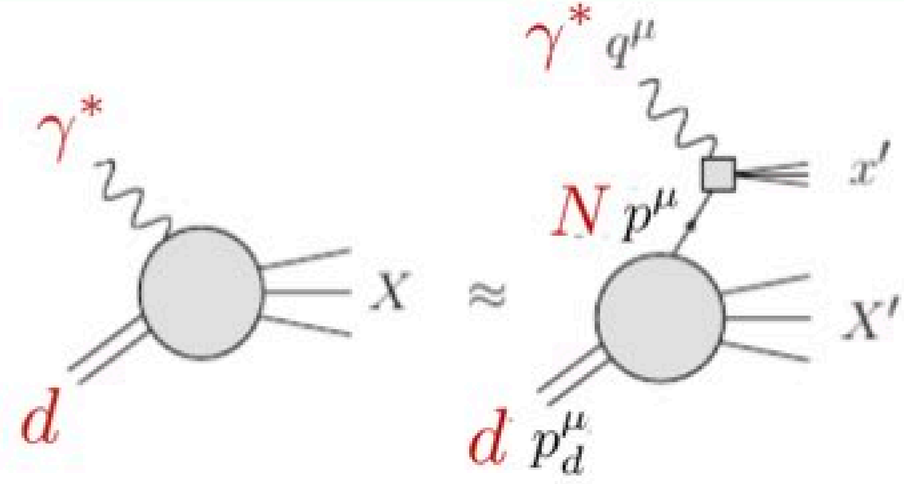

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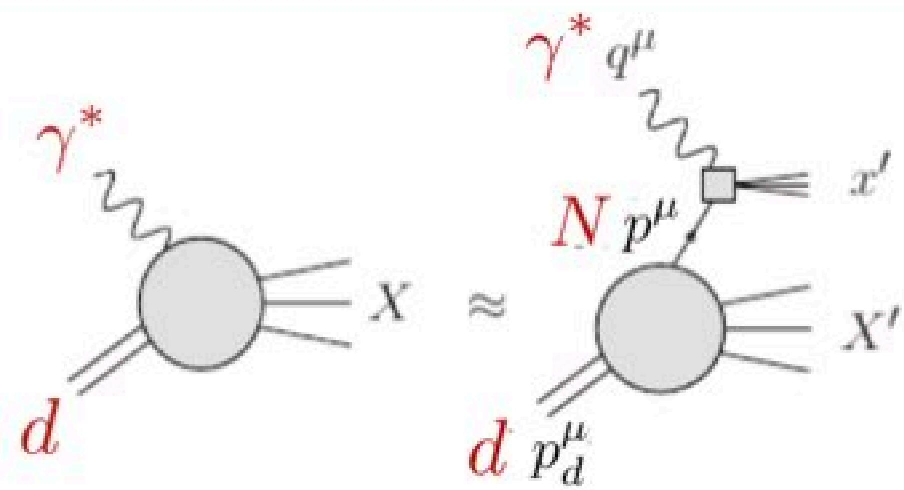

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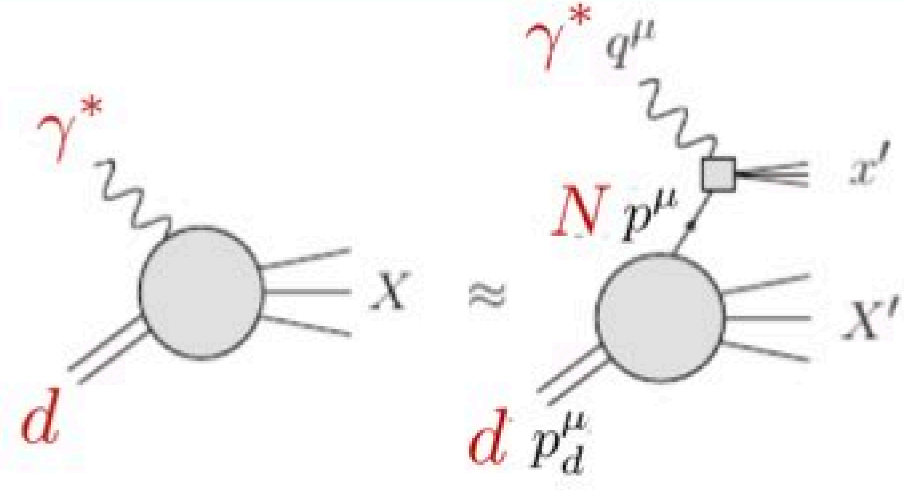

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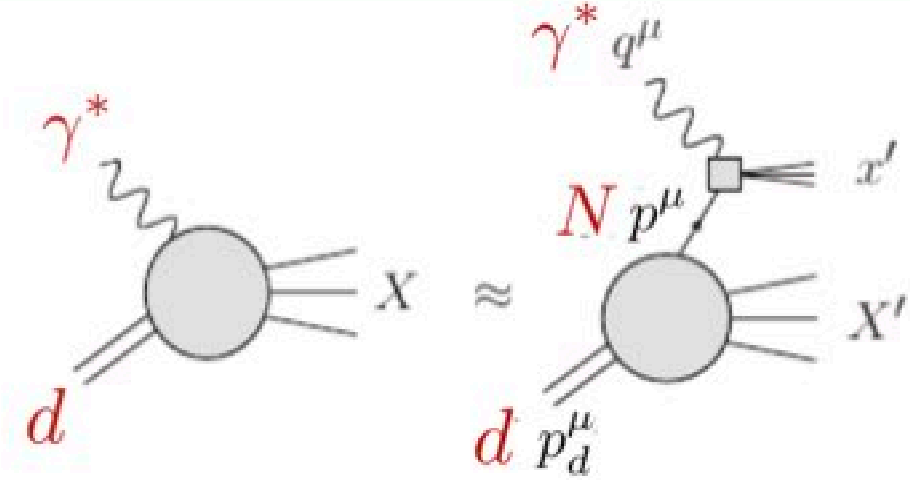

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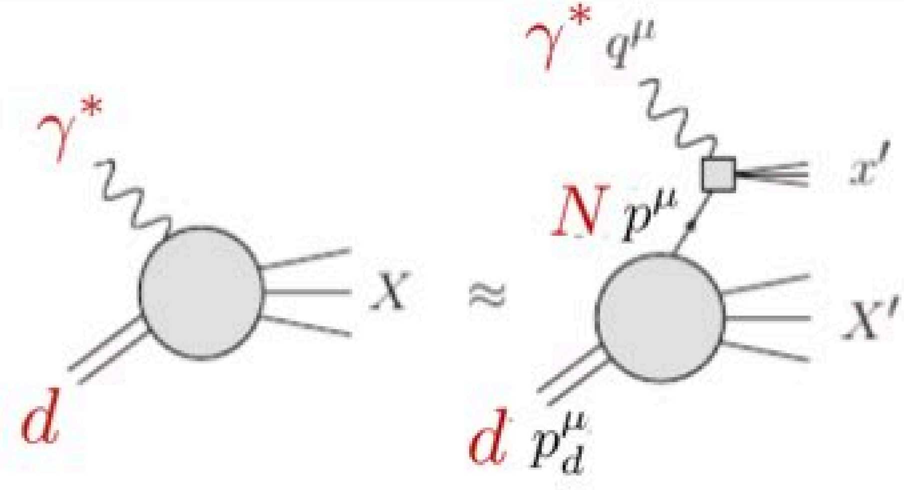

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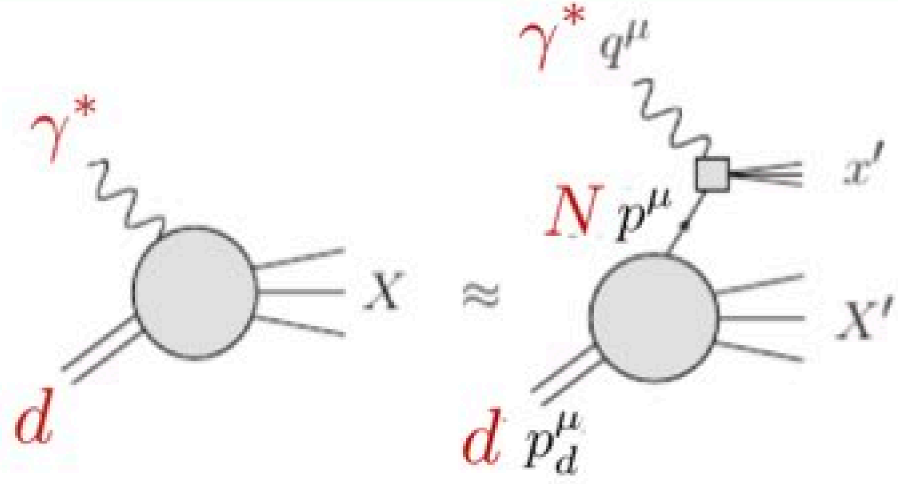

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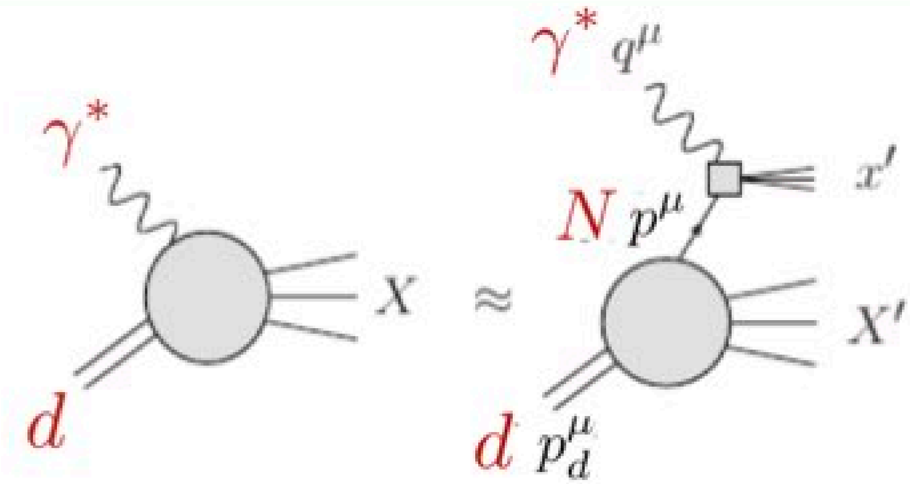

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Structure function

of a bound, off-shell nucleon

Deuterium: off-shell corrections

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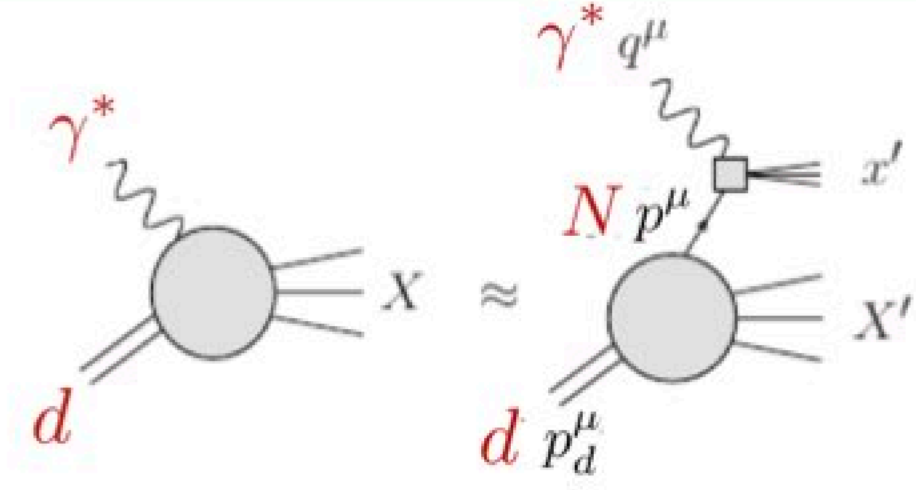
Bound, off-shell nucleon inside the deuteron



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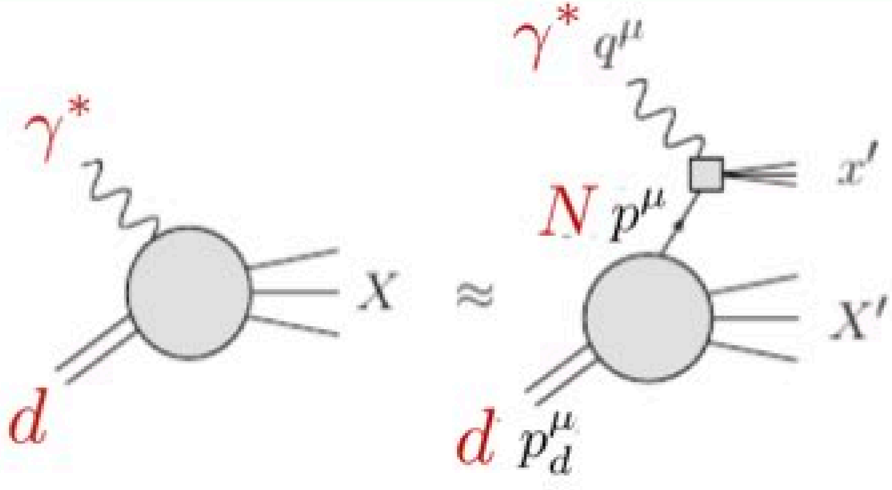

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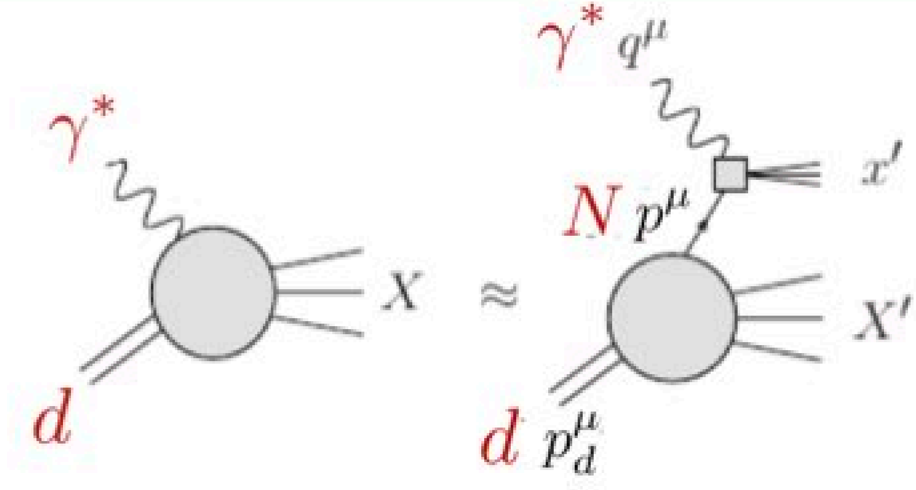

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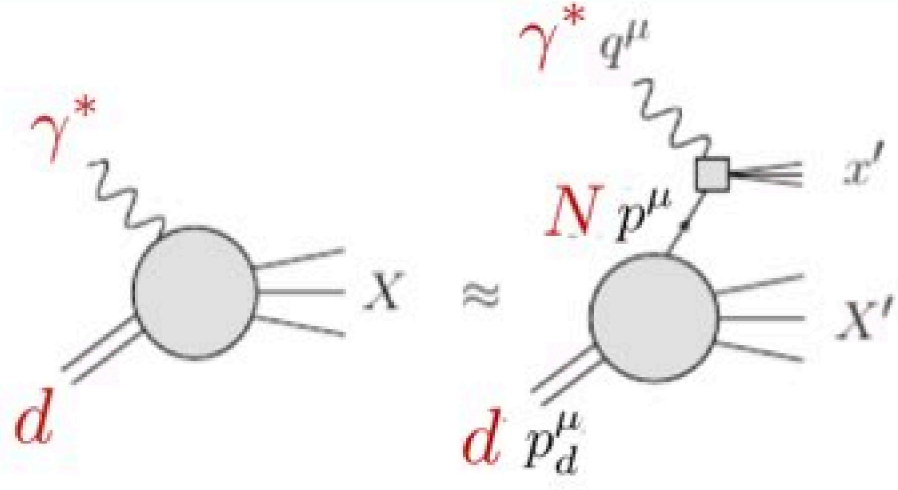

Off-shell expansion (in nucleon virtuality p^2)

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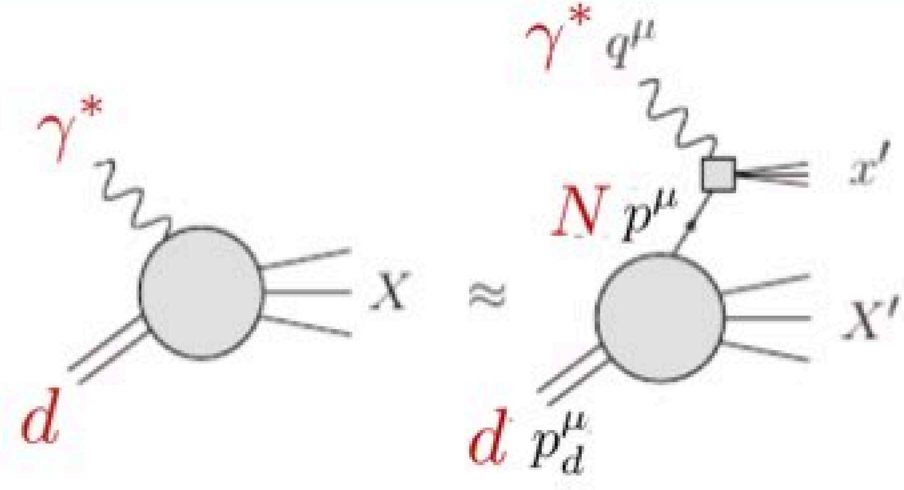

Off-shell expansion (in nucleon virtuality p^2)

parton level

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

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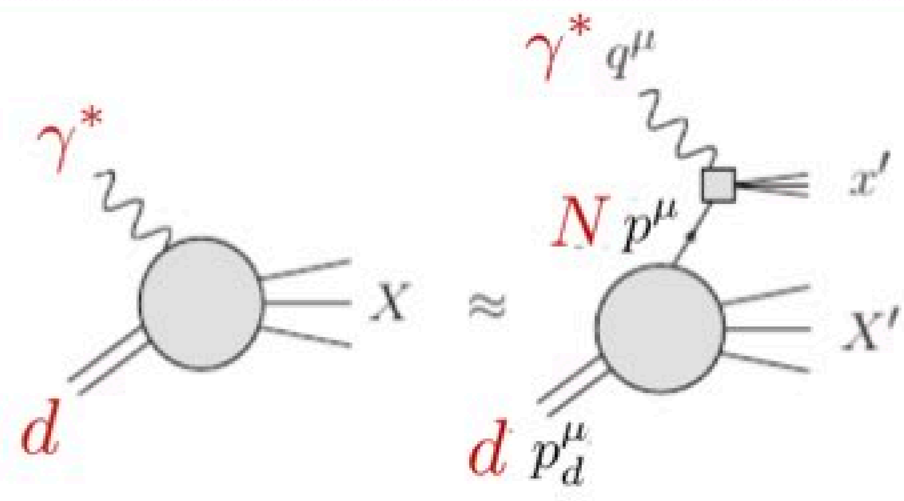

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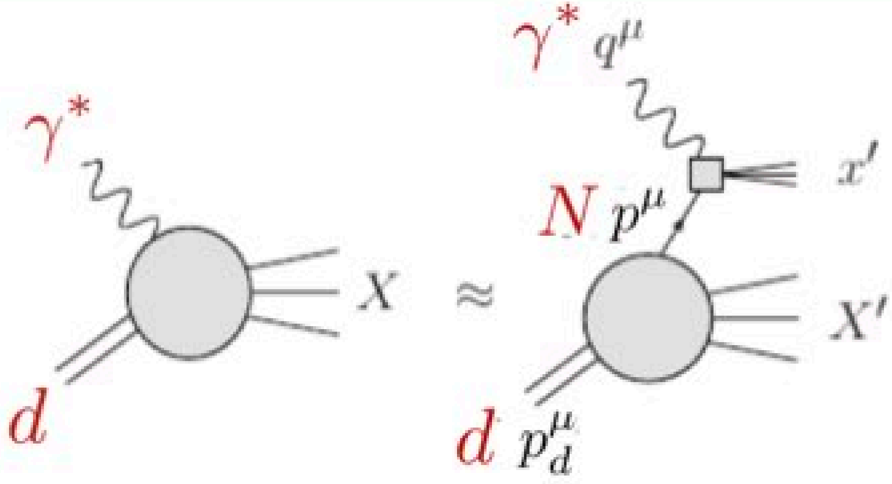

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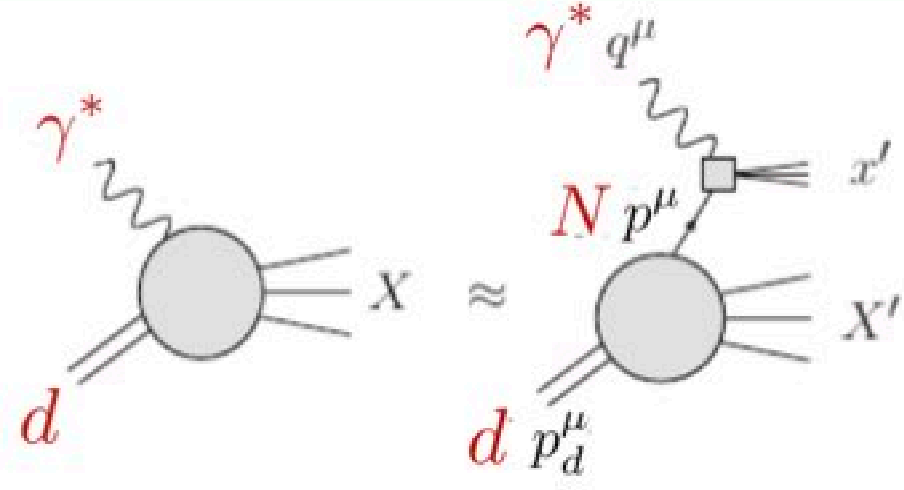

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Off-shell function

(To be fitted)

Latest results from QCD fits in CJ framework

CJ15 fit

Accardi, Brady, et al., PRD 93 (2016)

Latest results from QCD fits in CJ framework

CJ15 fit $\delta f^N = C(x - x_0)(x - x_1)(1 + x_0 - x)$ $\int_0^1 dx\, \delta f^N(x)\, [q(x) - \bar{q}(x)] = 0$

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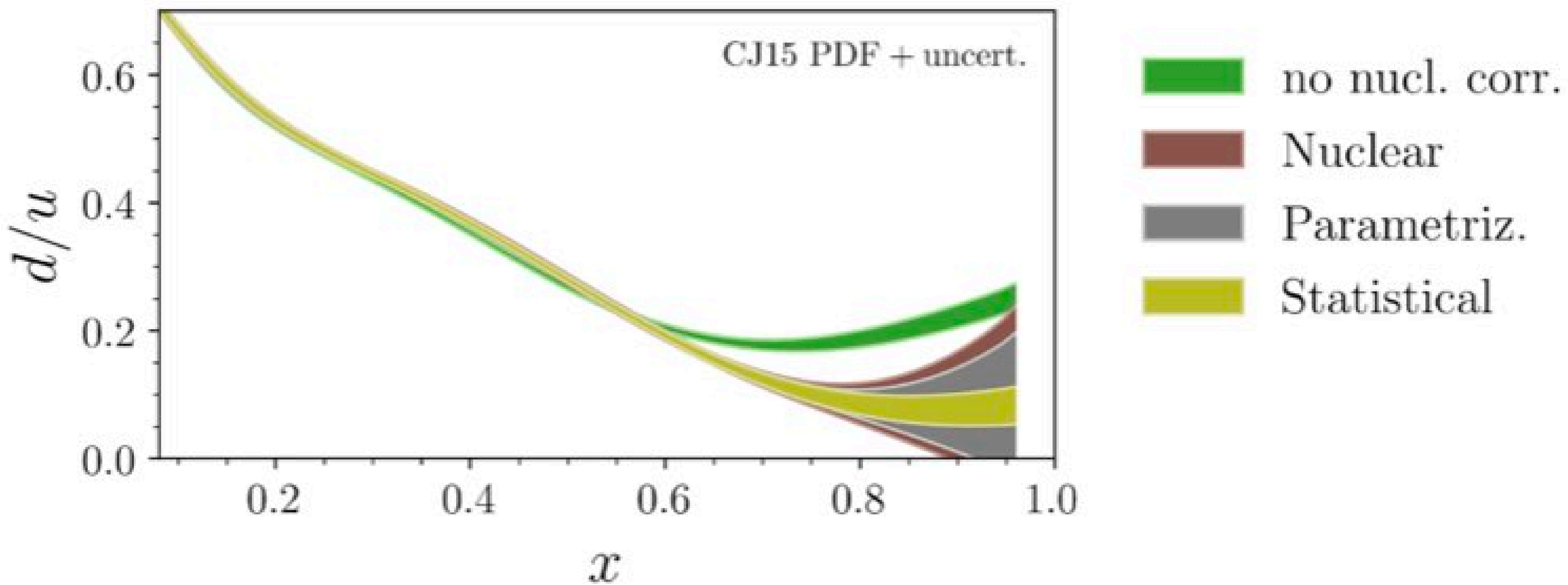

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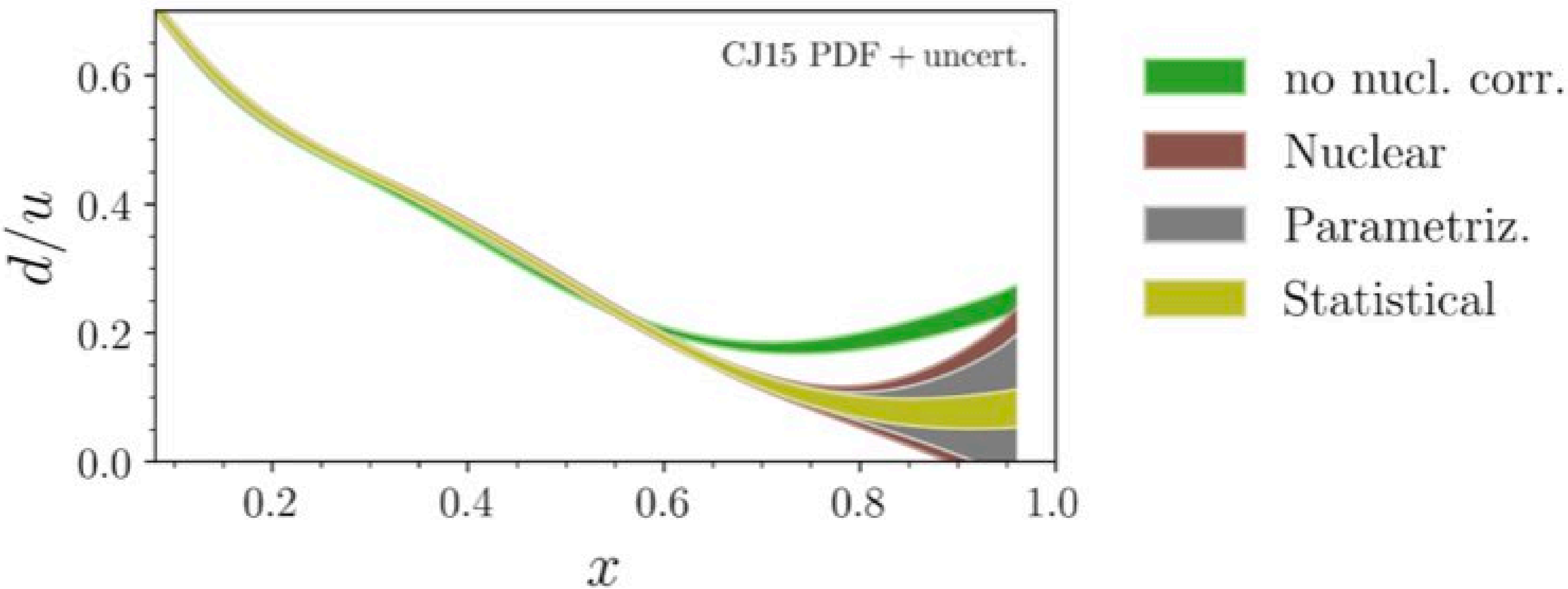

The inclusion of nuclear corrections is impacting the output of the fit

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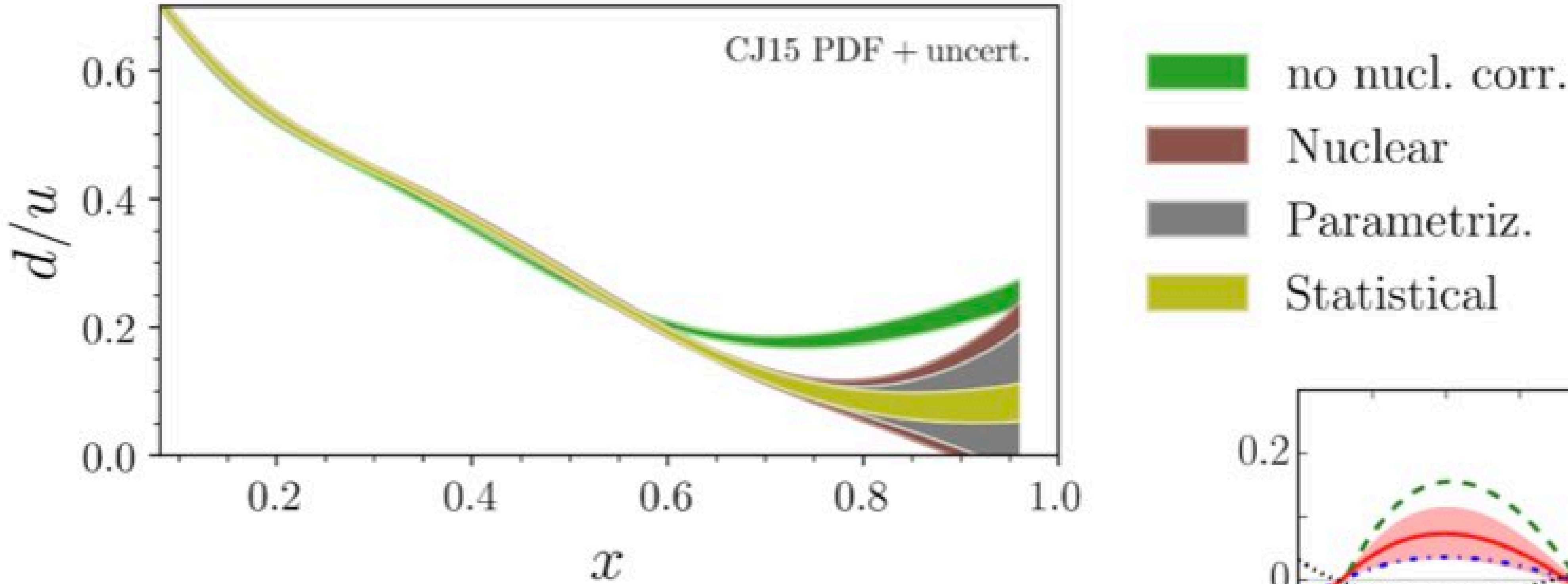

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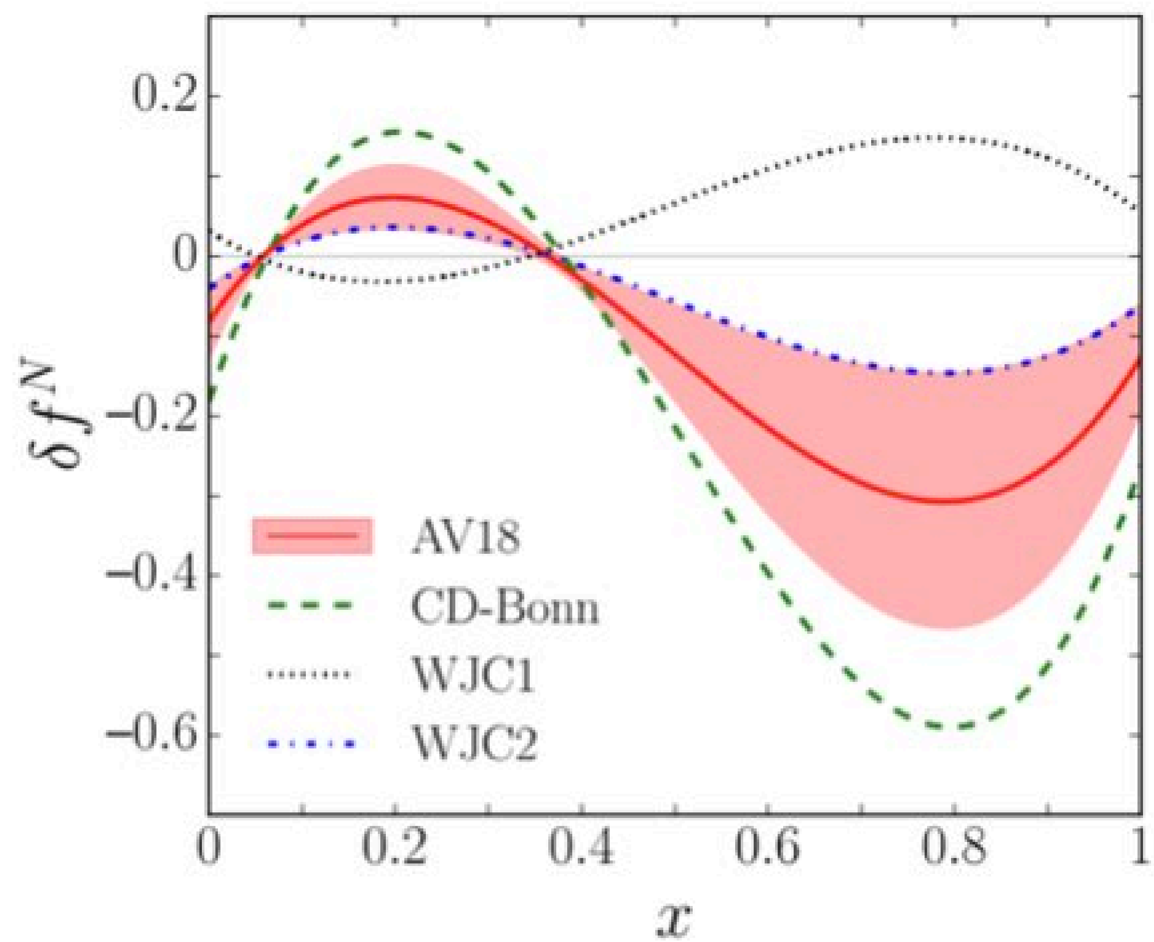

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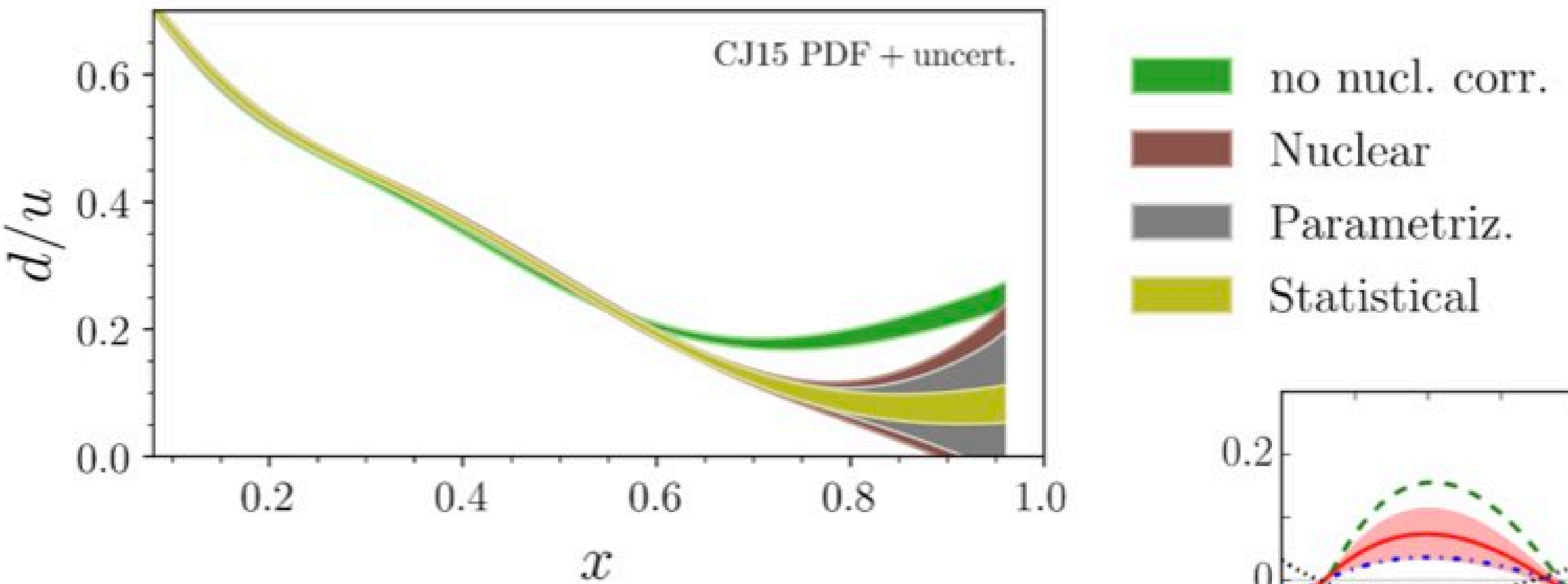

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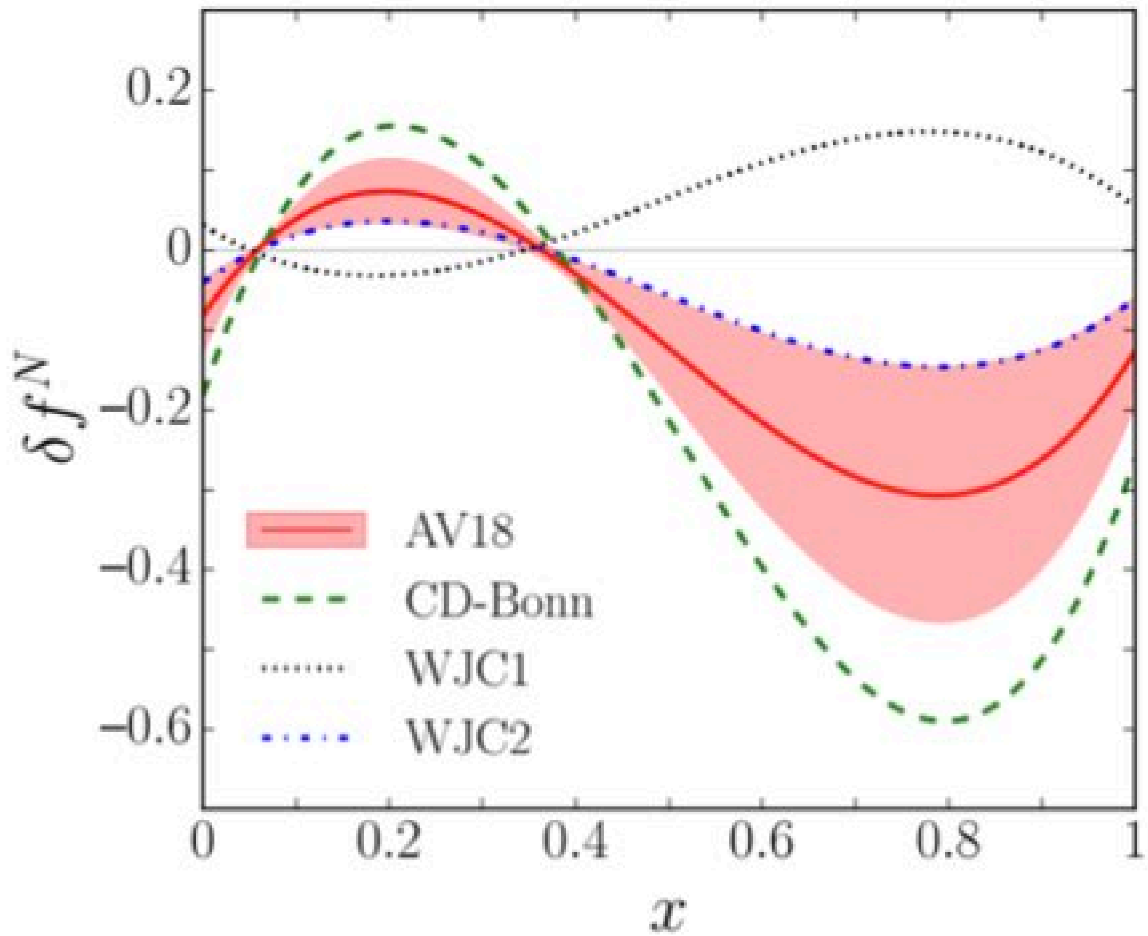
The most of the recent nuclear potentials does not introduce a bias on the fit



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CJ22 fit

Accardi, Jing, Owens et al., PRD 107 (2023)

Latest results from QCD fits in CJ framework

CJ22 fit

- Same off-shell parameterization
- More flexible parameterization of sea quarks (NuSea and SeaQuest data)

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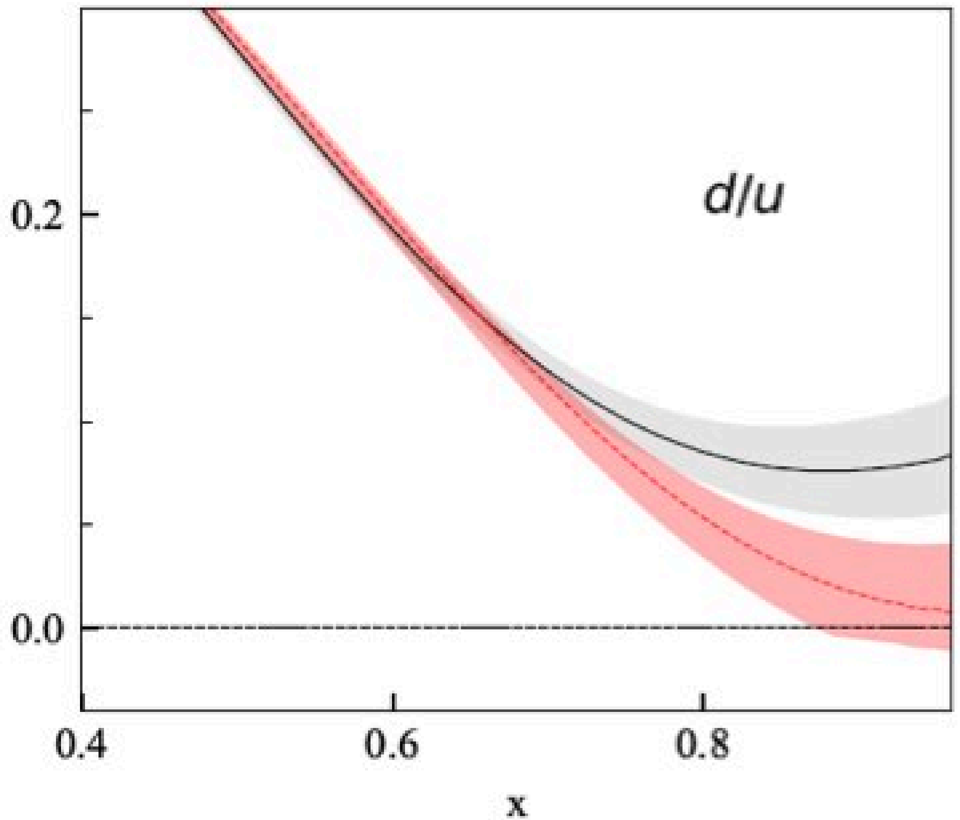

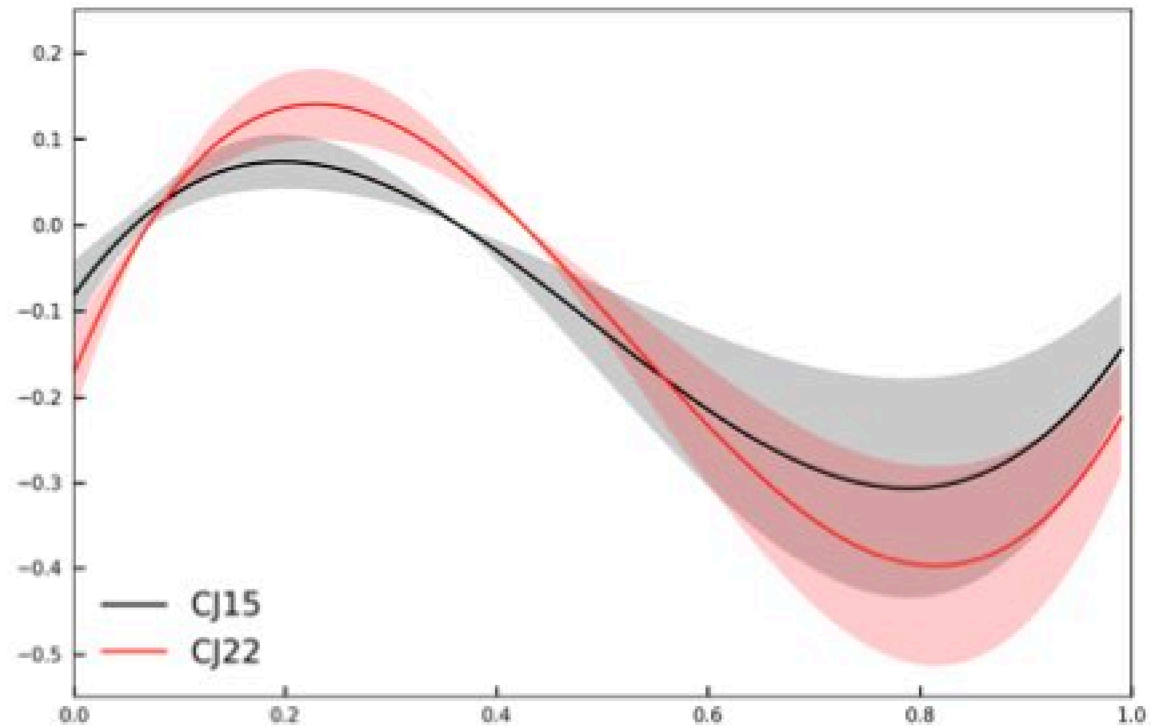

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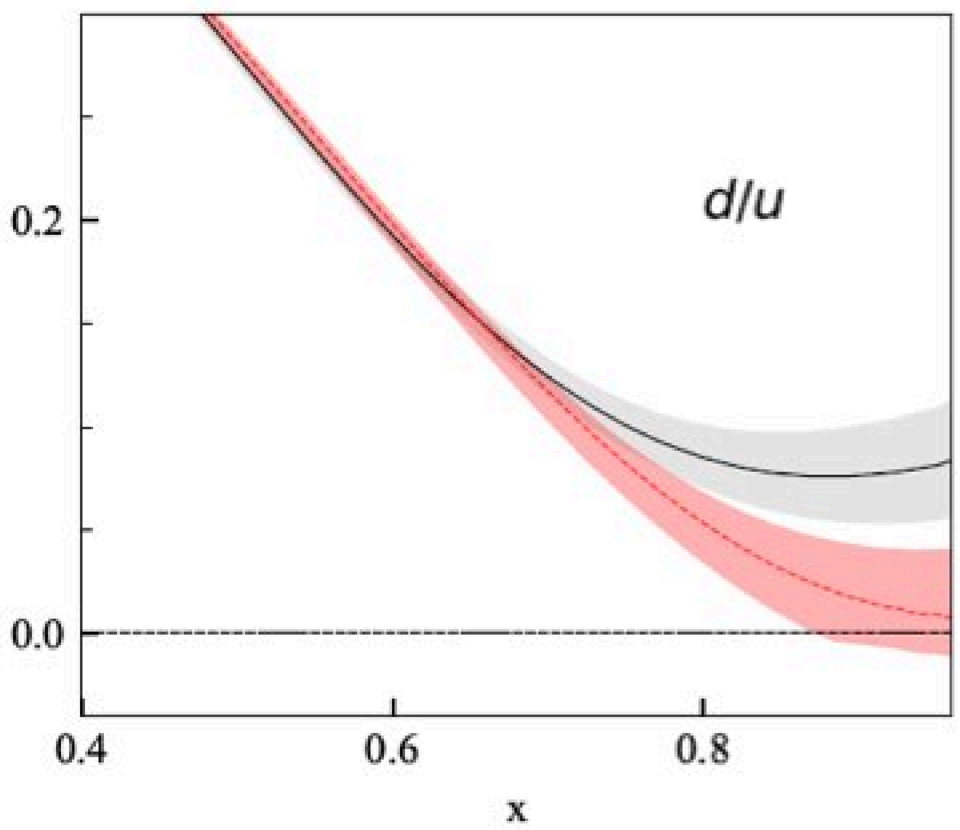

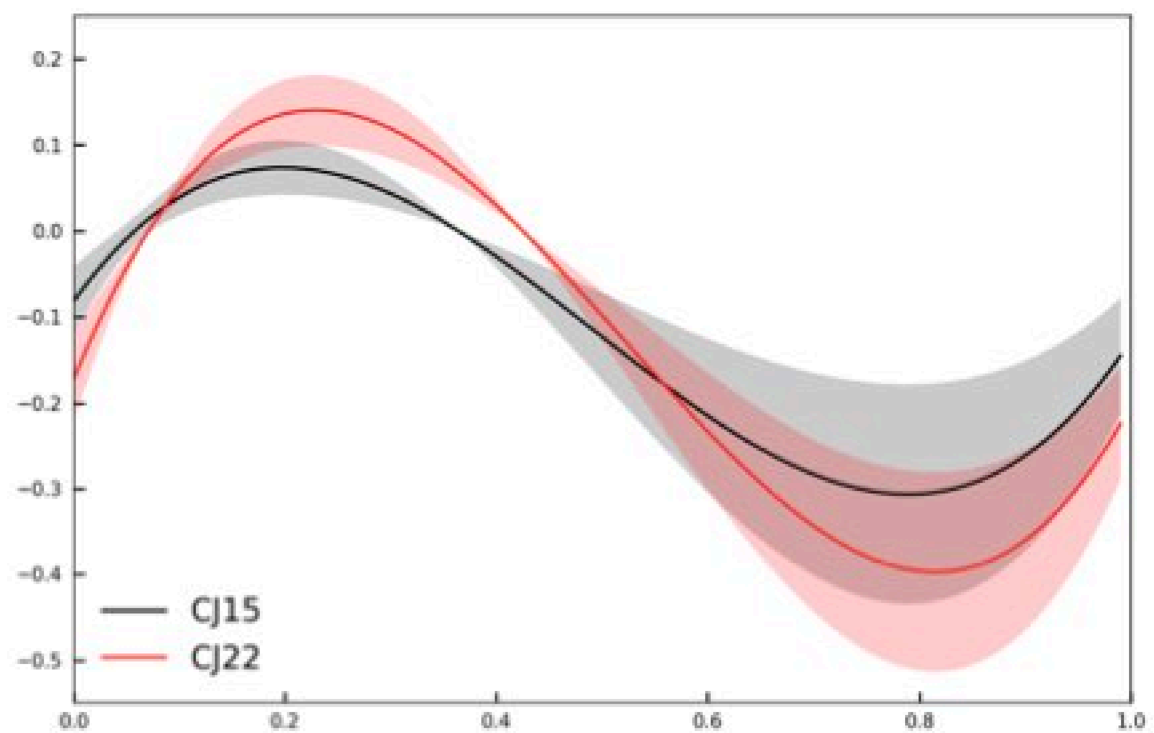

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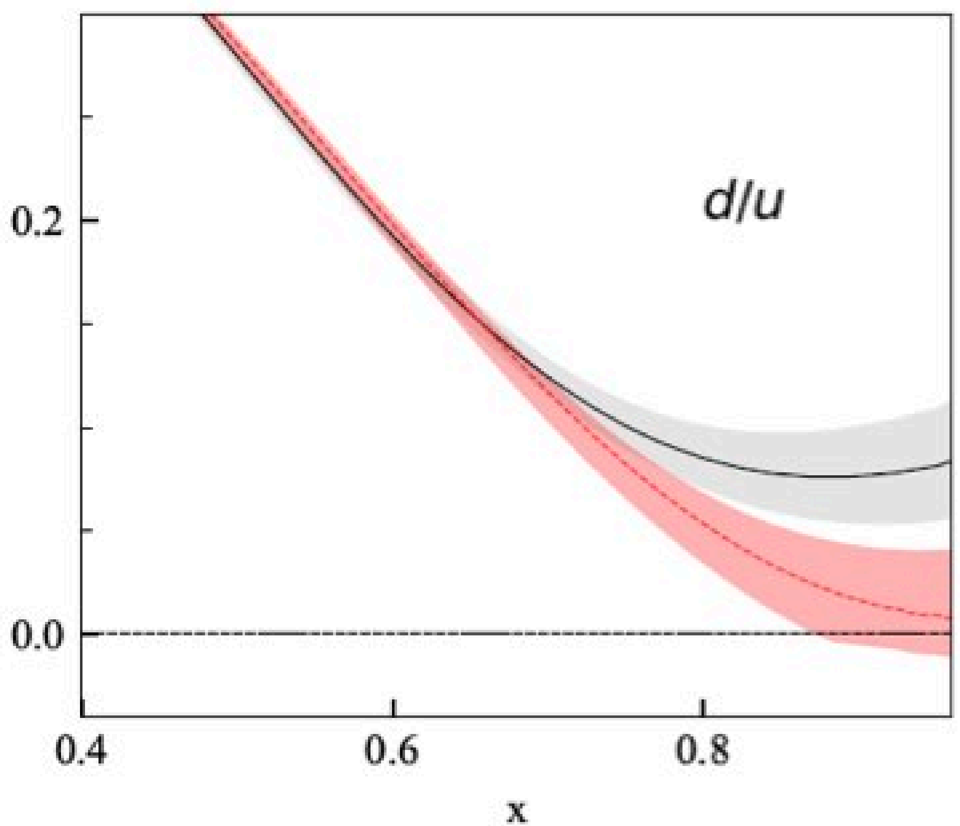

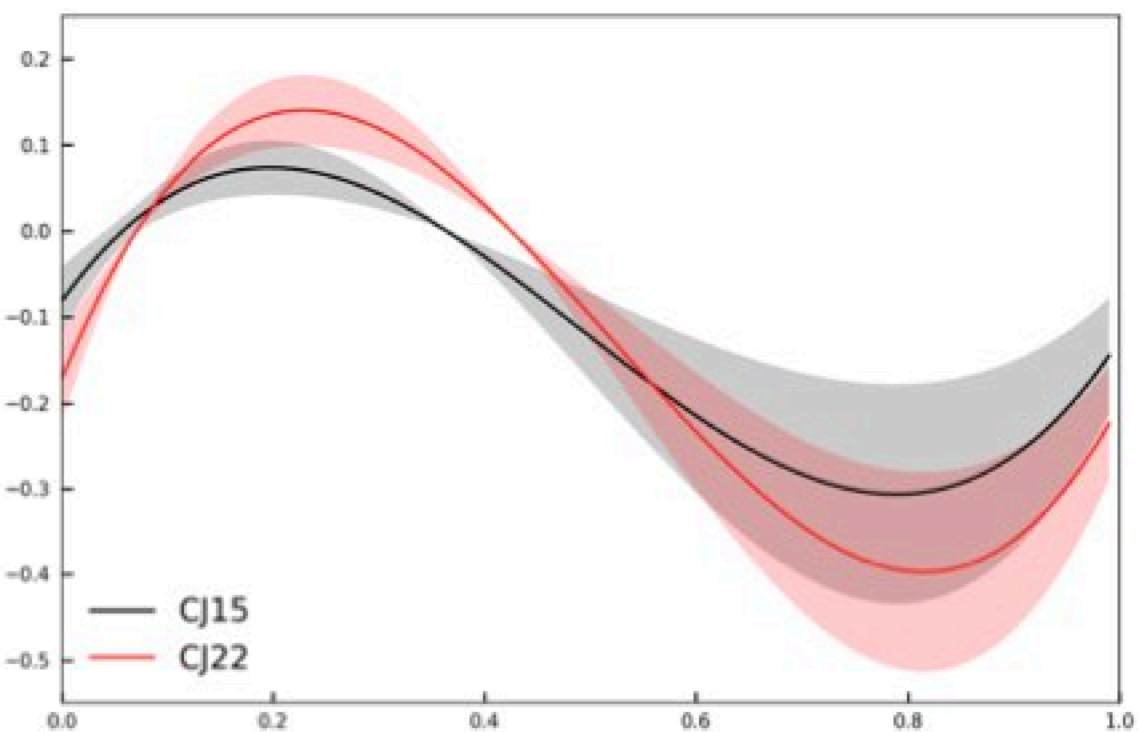

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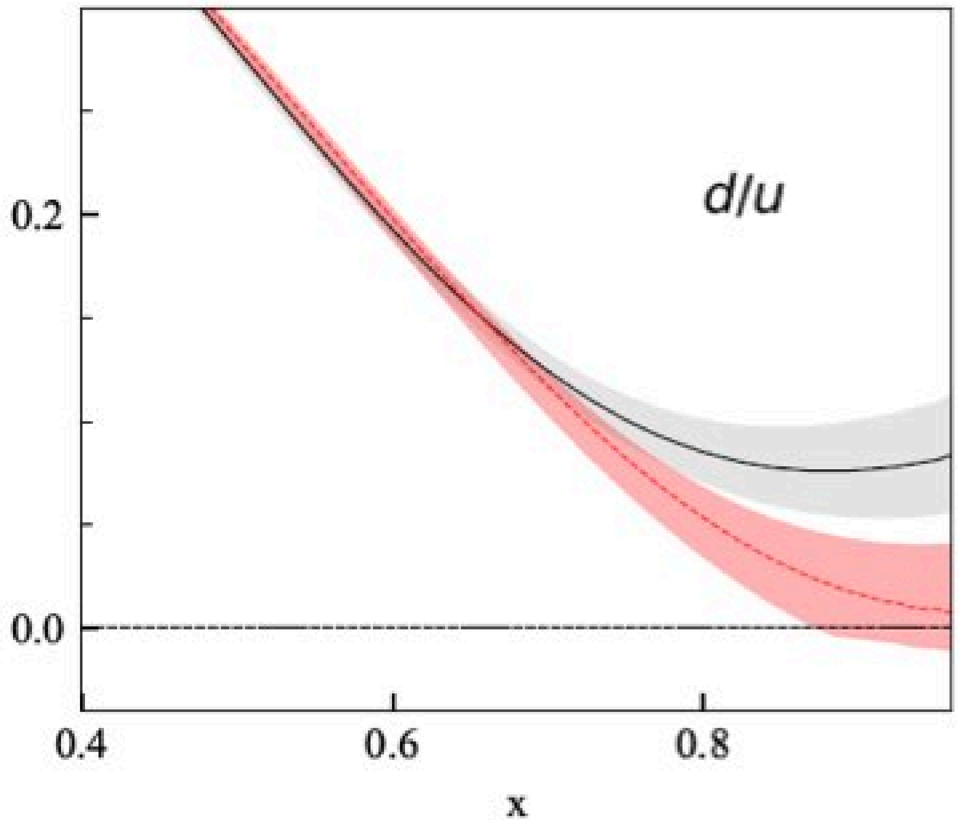

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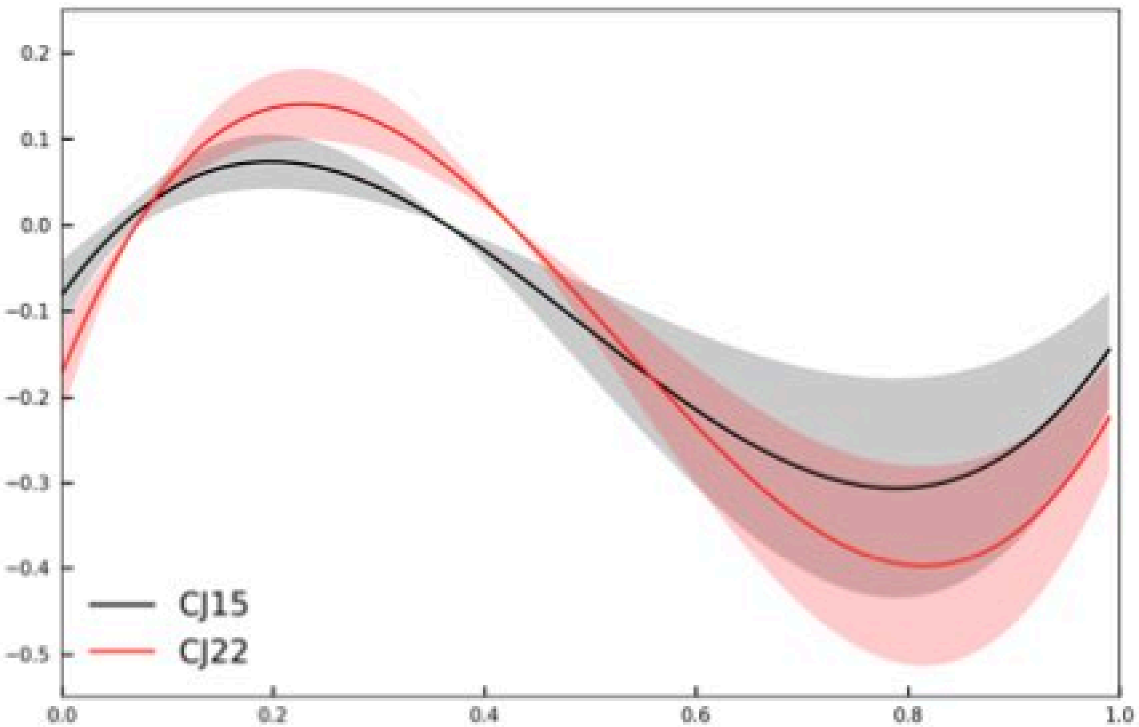

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Difference on d/u is absorbed in something else

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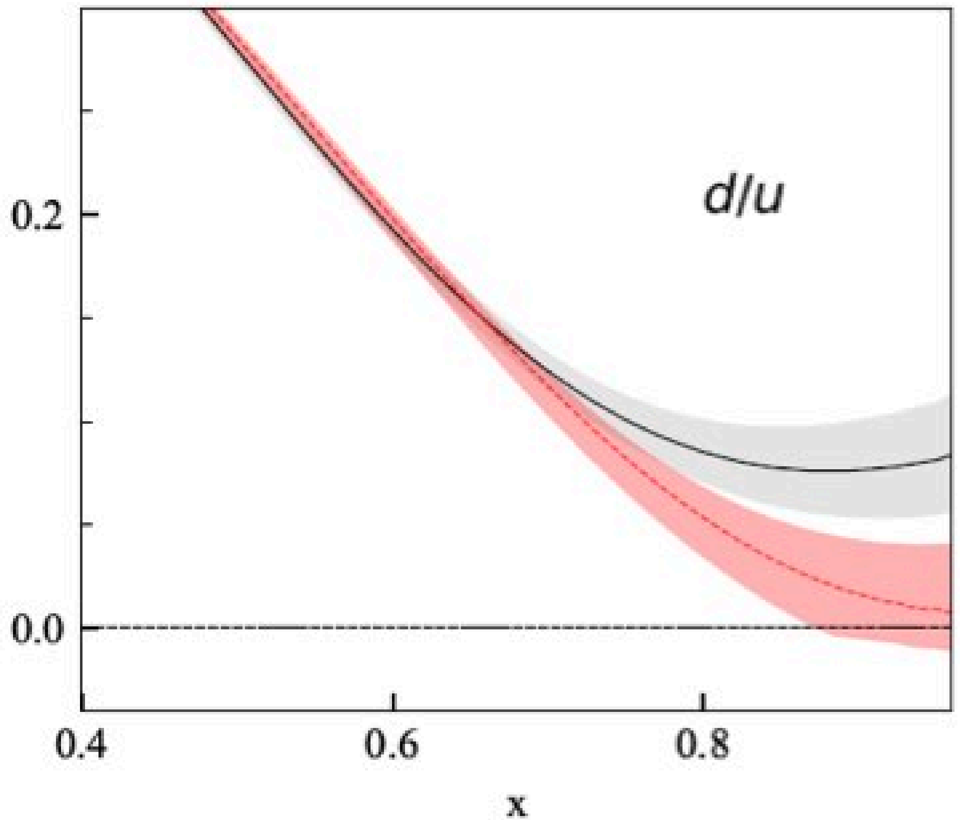

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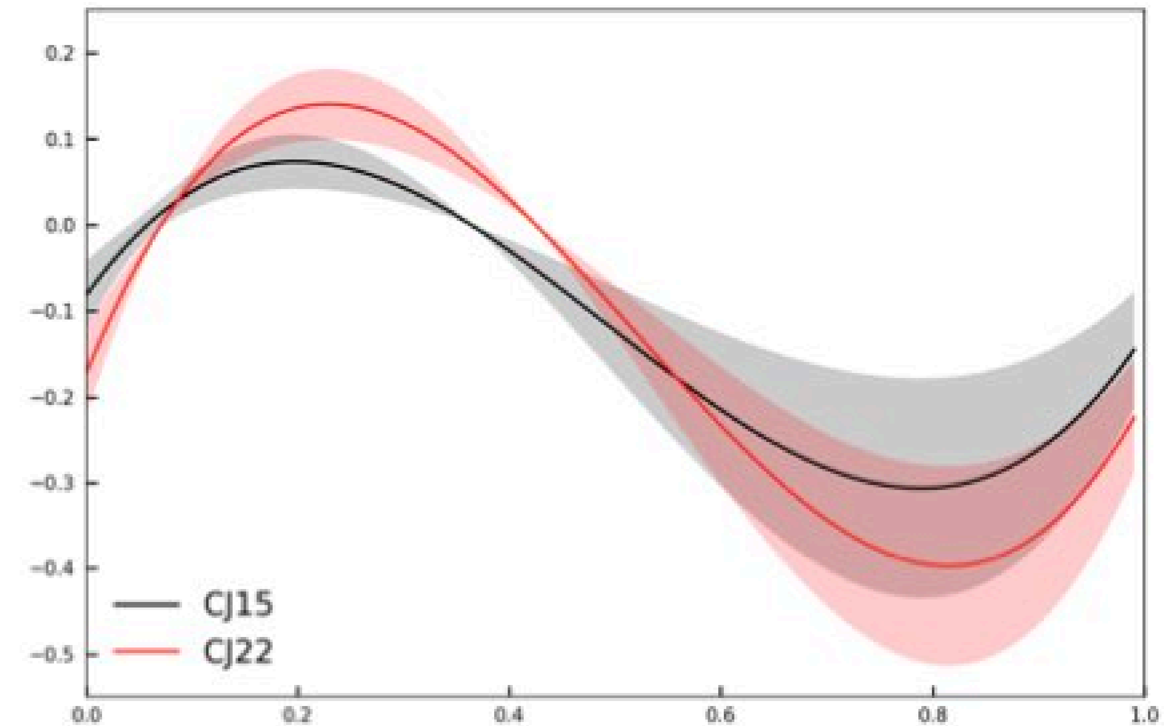

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Difference on d/u is absorbed in something else $\longrightarrow$ **Higher Twist**

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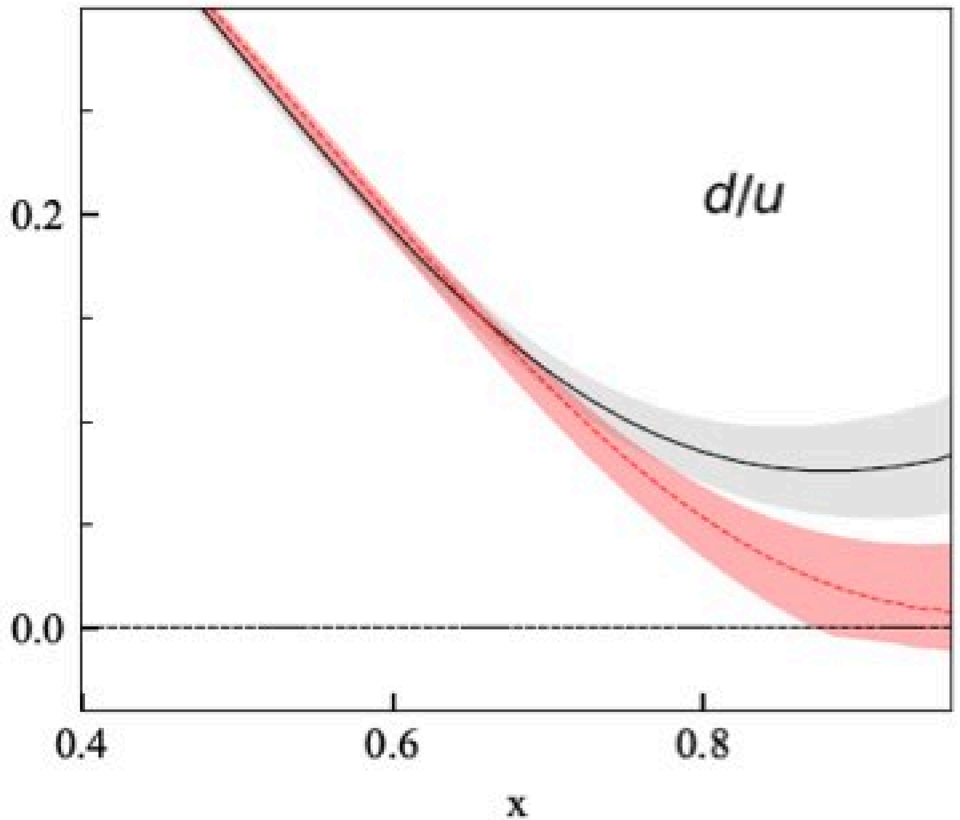

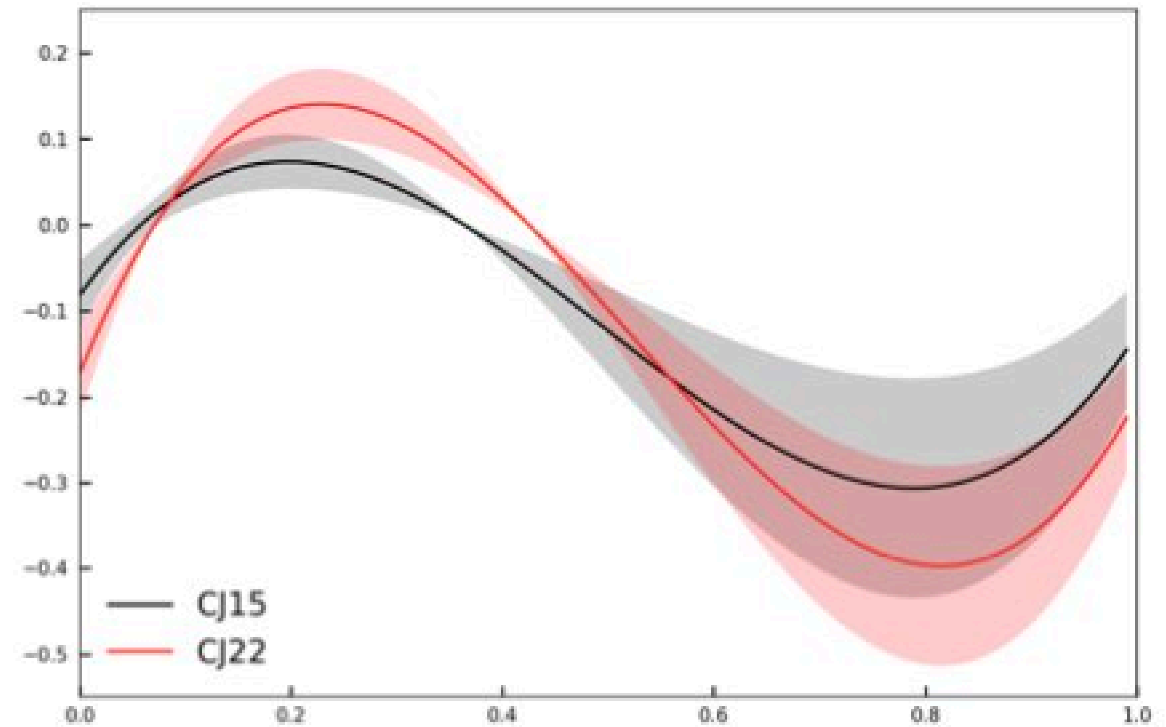

Different

Similar

Difference on d/u is absorbed in something else ⟶ **Higher Twist**

Is the model for off-shell correction enough flexible?

Polynomial off-shell function

Polynomial off-shell function

$$\delta f^N = C(x - x_0)(x - x_1)(1 + x_0 - x)$$ KP-like model

Kulagin and Petti, NPA 765 (2006)

Polynomial off-shell function

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

KP-like model

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+ valence sum rule

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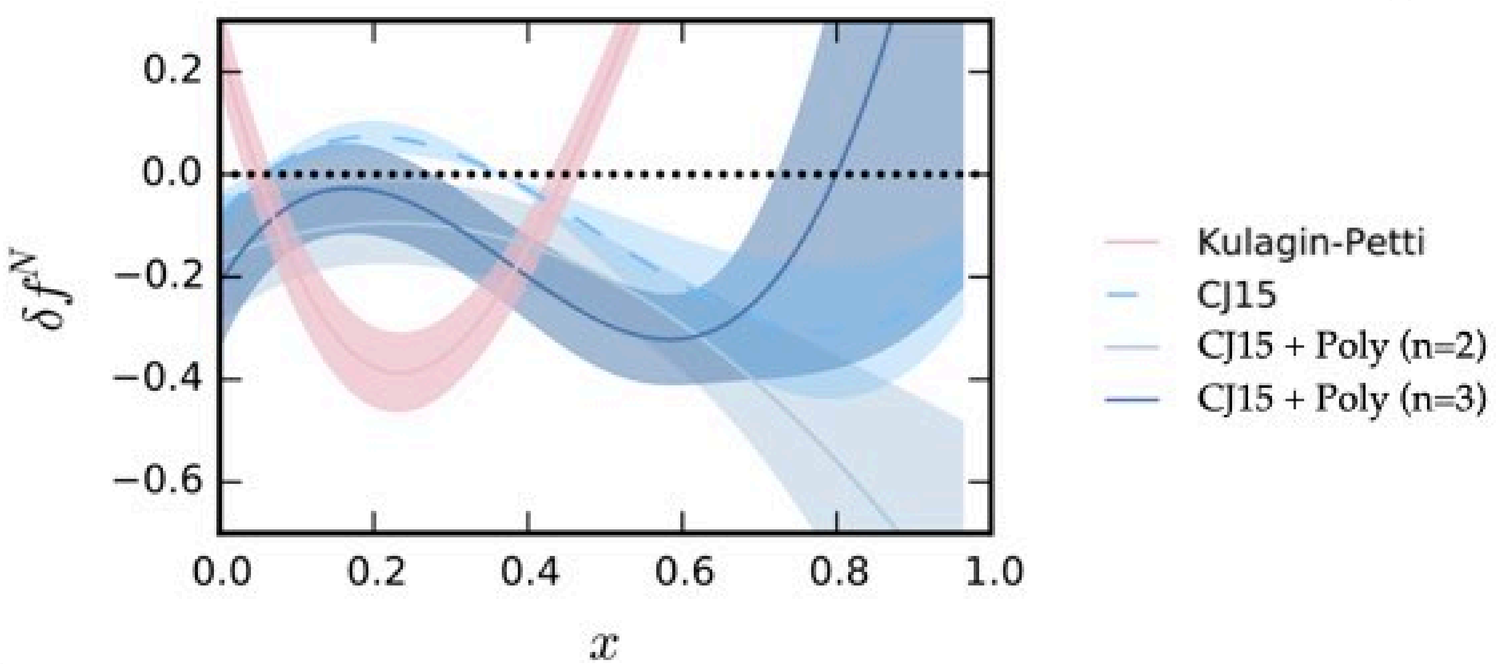

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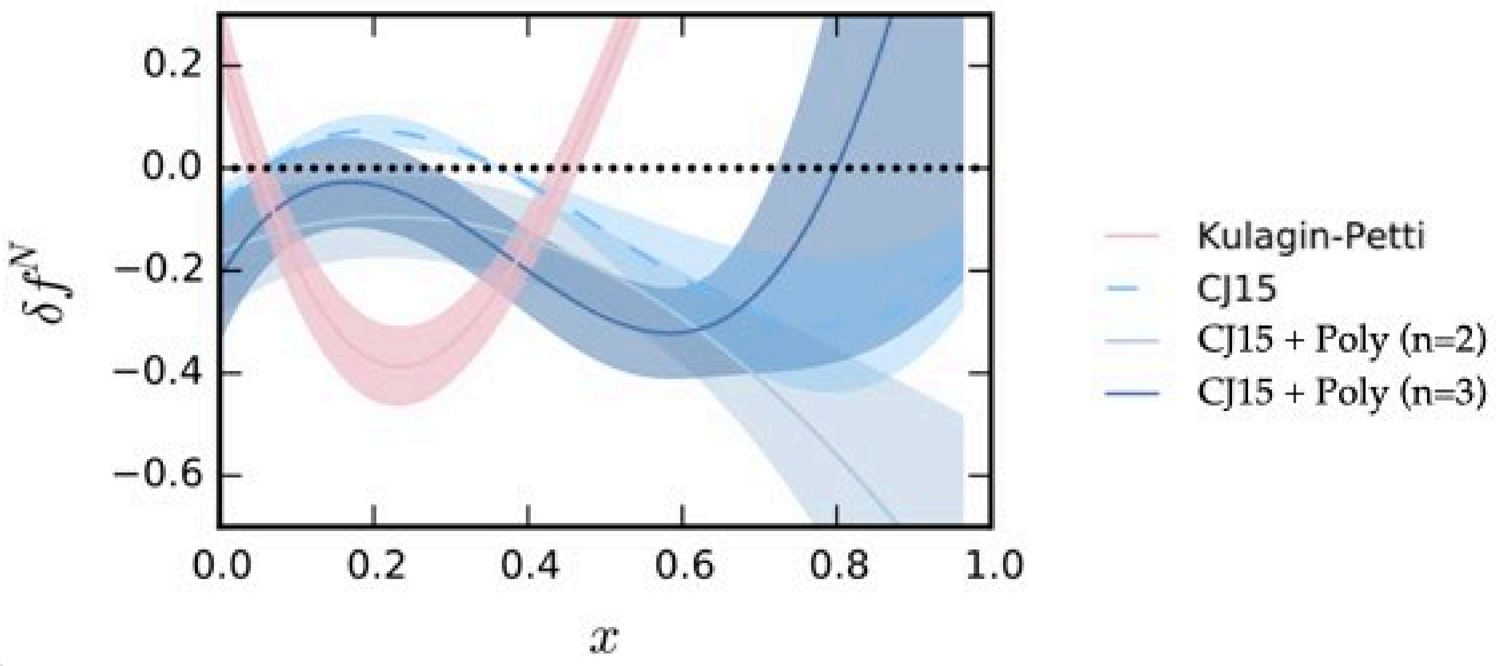

Better agreement with the data w/o imposing nodes a priori to the off-shell function

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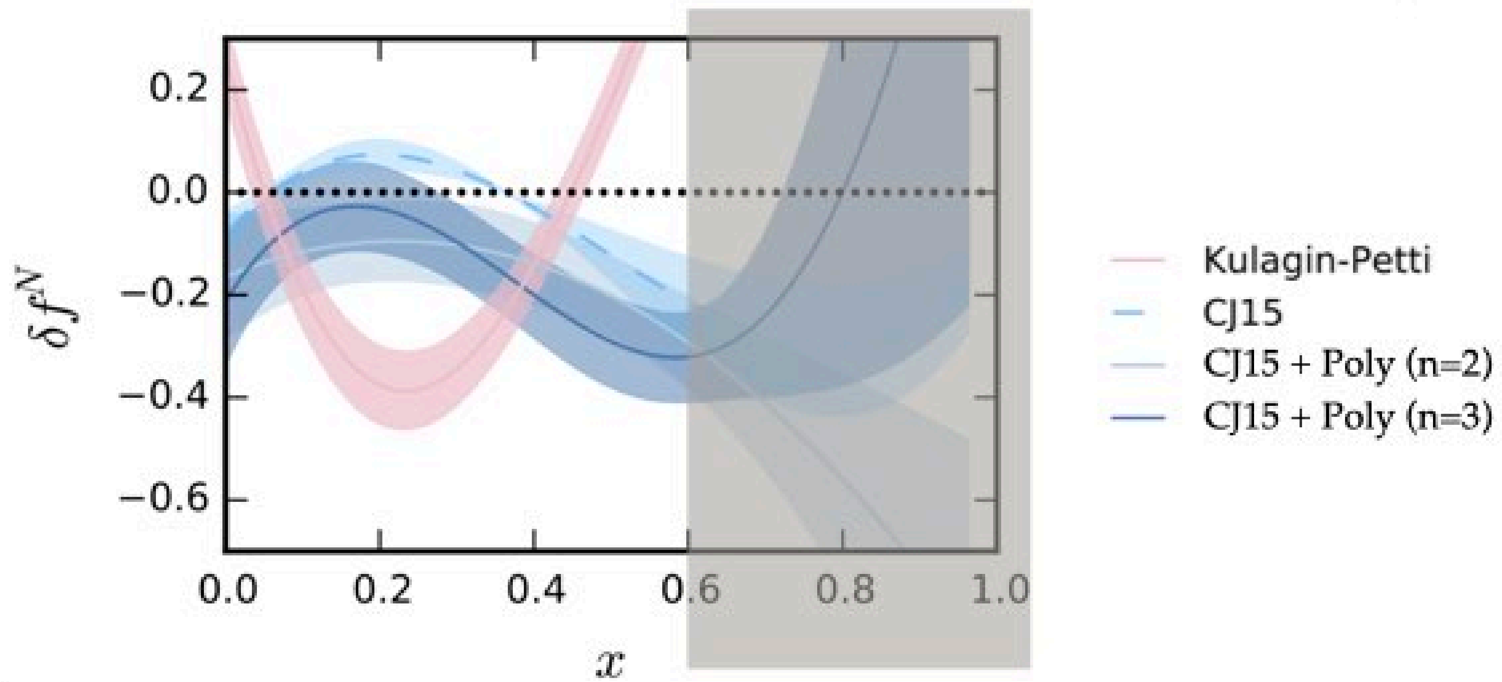

Better agreement with the data w/o imposing nodes a priori to the off-shell function

Constrain power of CJ15 dataset only up to x = 0.6

Higher-Twist function

Higher Twist correction

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Higher Twist correction

Multiplicative

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

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CJ fits

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Bias in n/p function

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structure function is smaller

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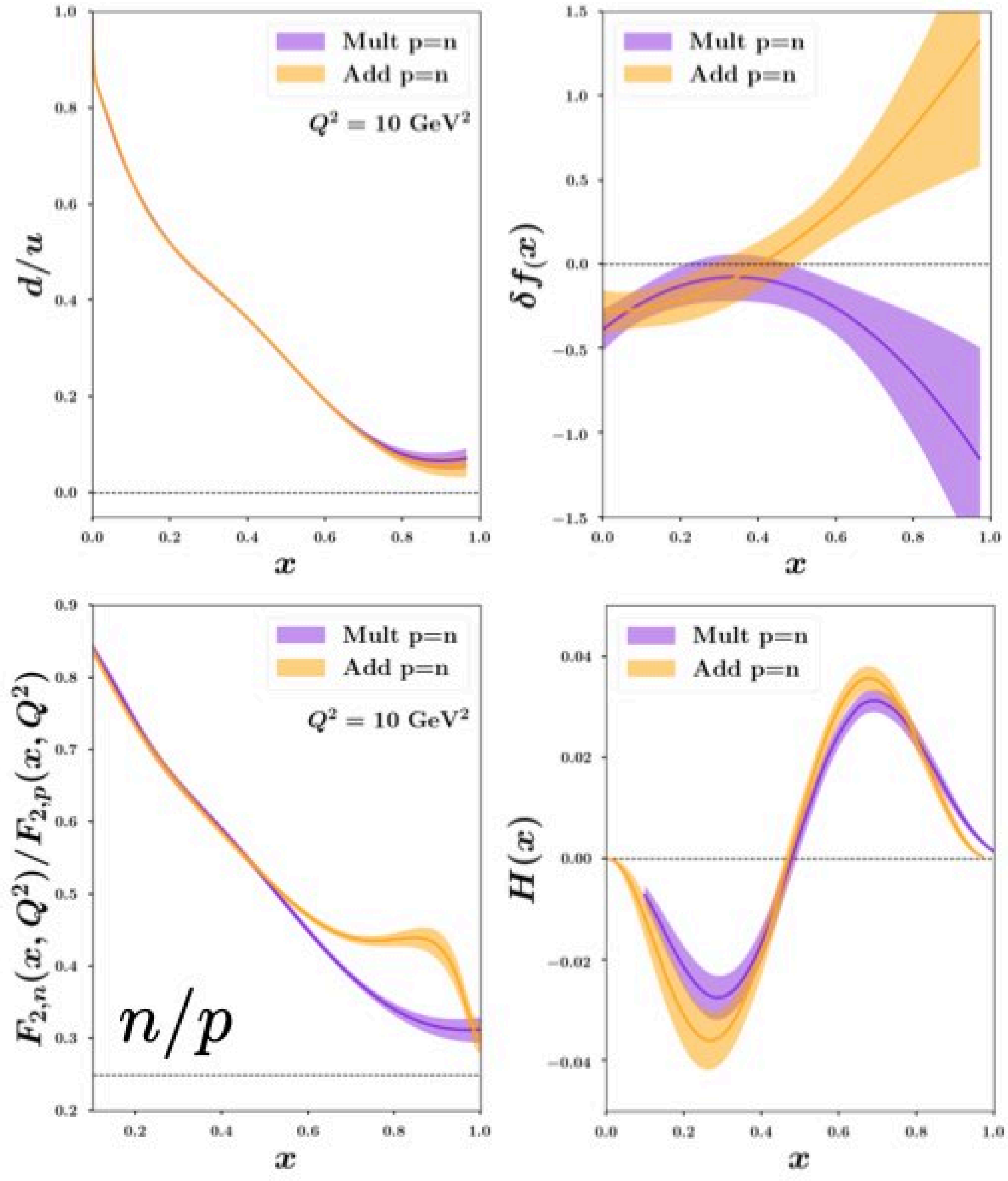
Bias not present!

Results in the CJ fitting framework

Case 1: isospin symmetry



Results in the CJ fitting framework

Case 1: isospin symmetry

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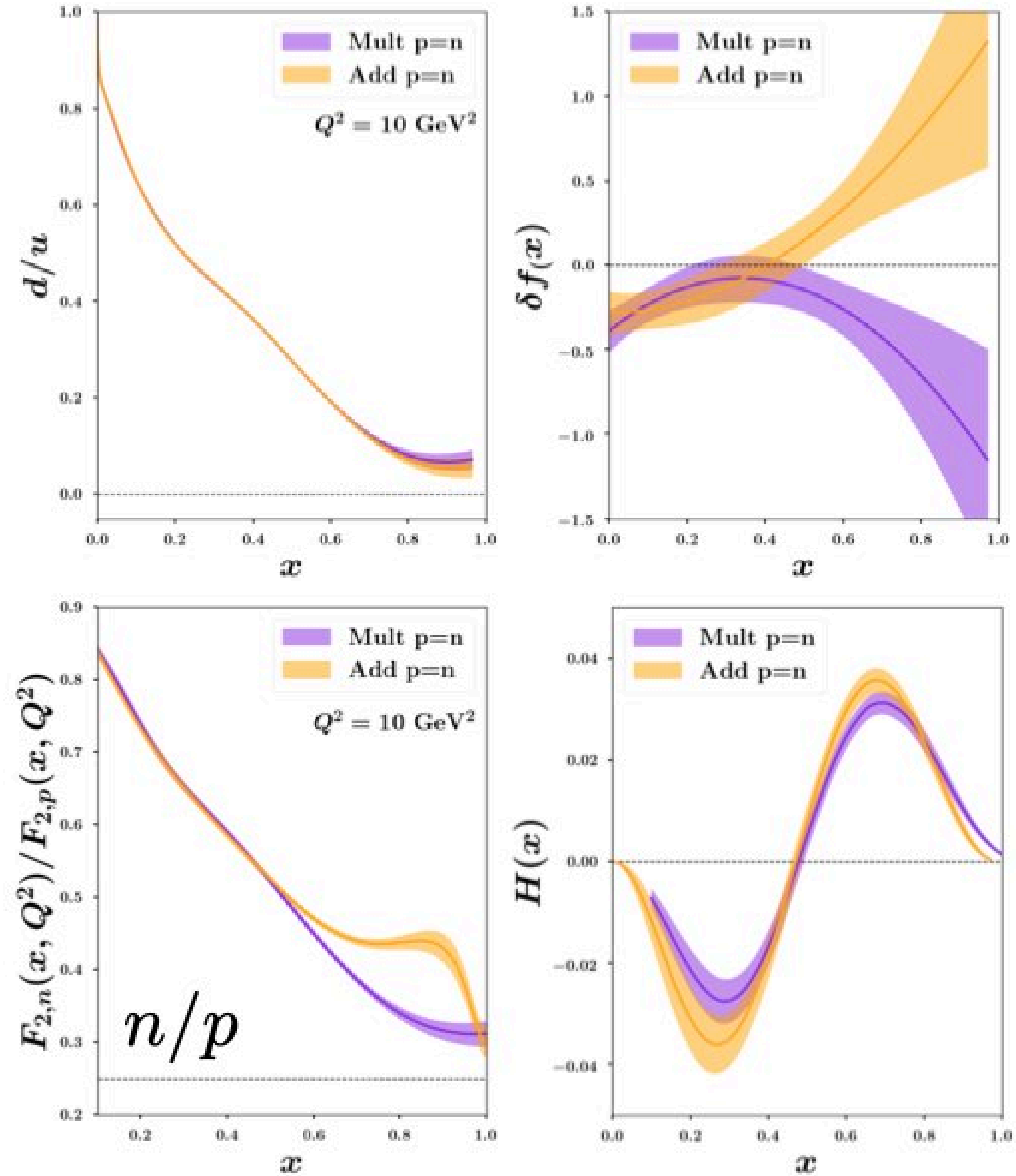
Unnaturally large n/p

BUT smaller d/u than Mult



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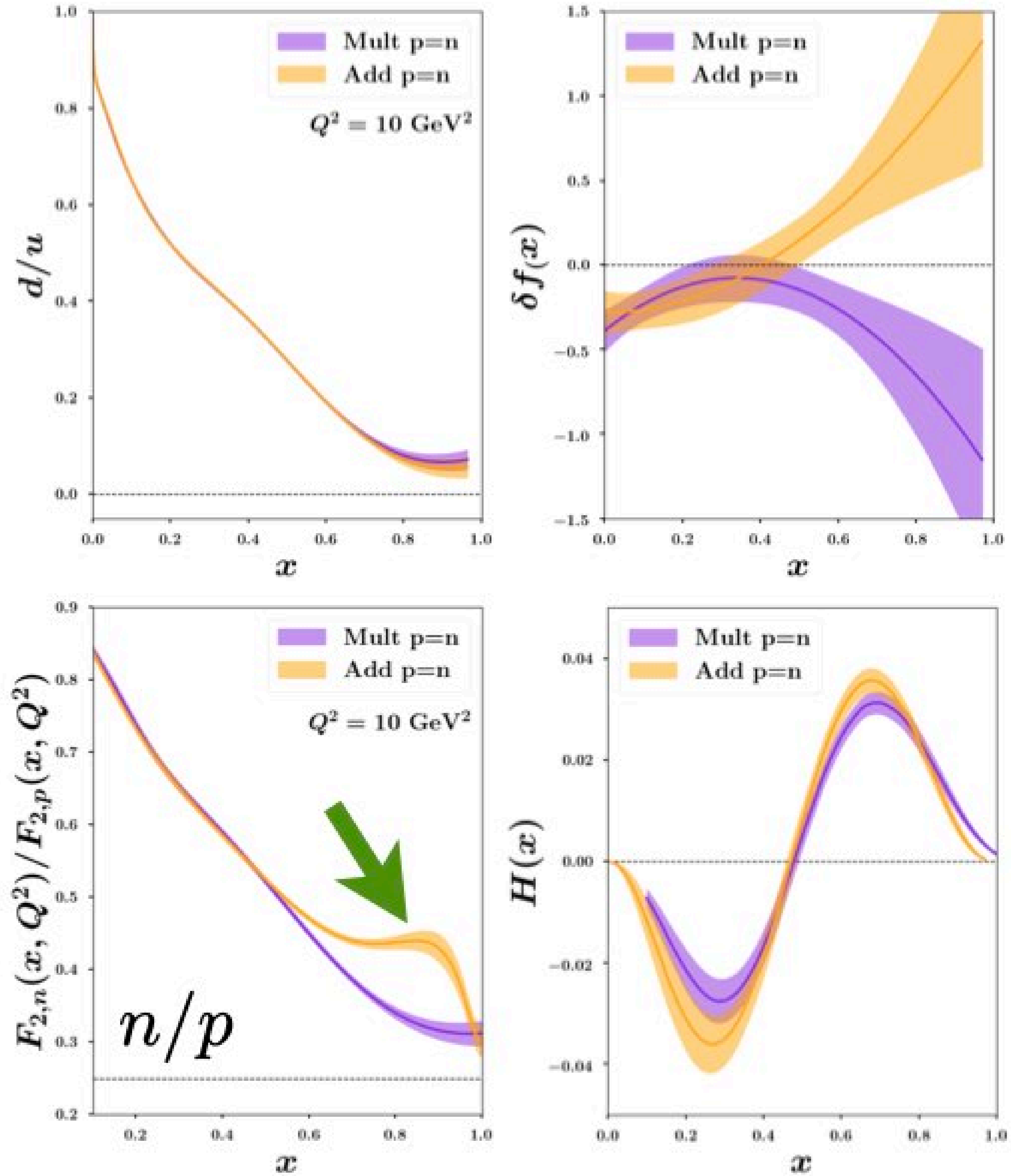

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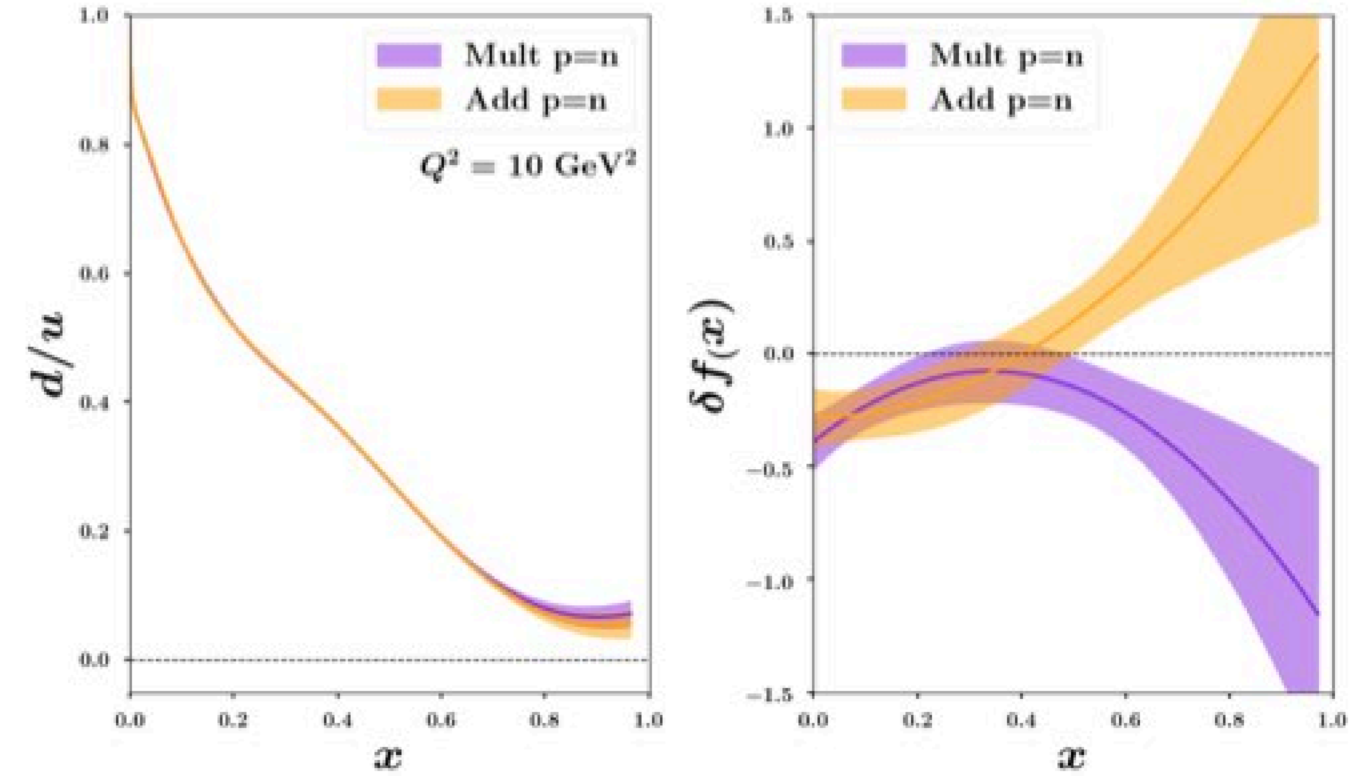
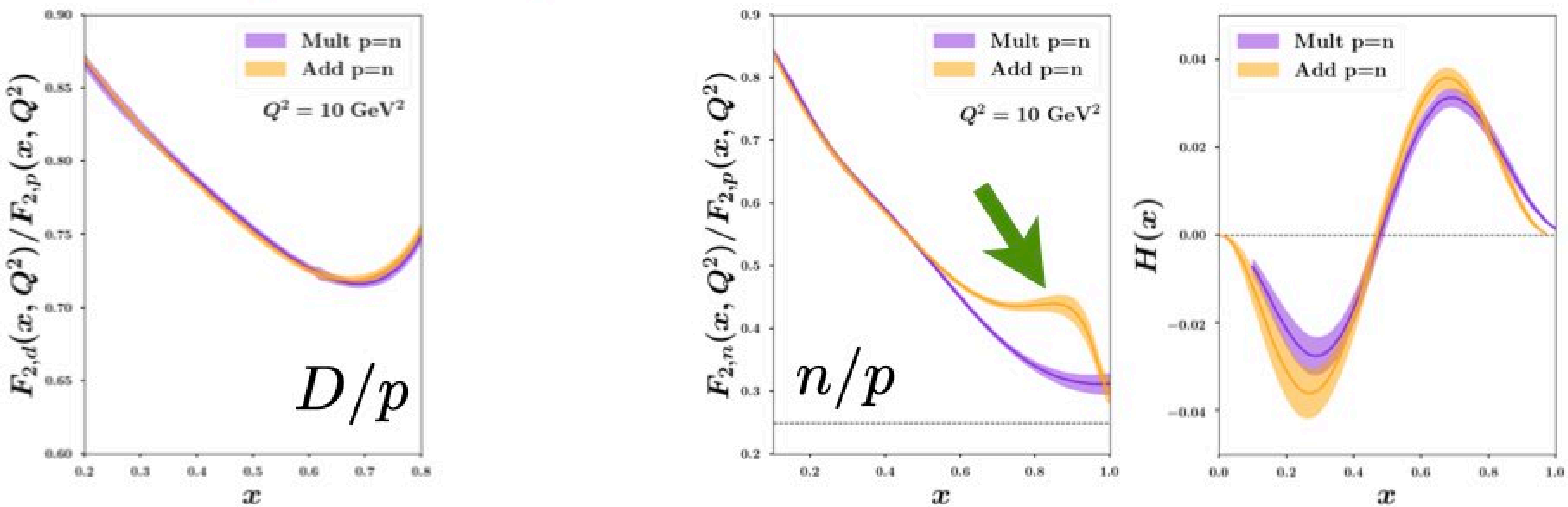
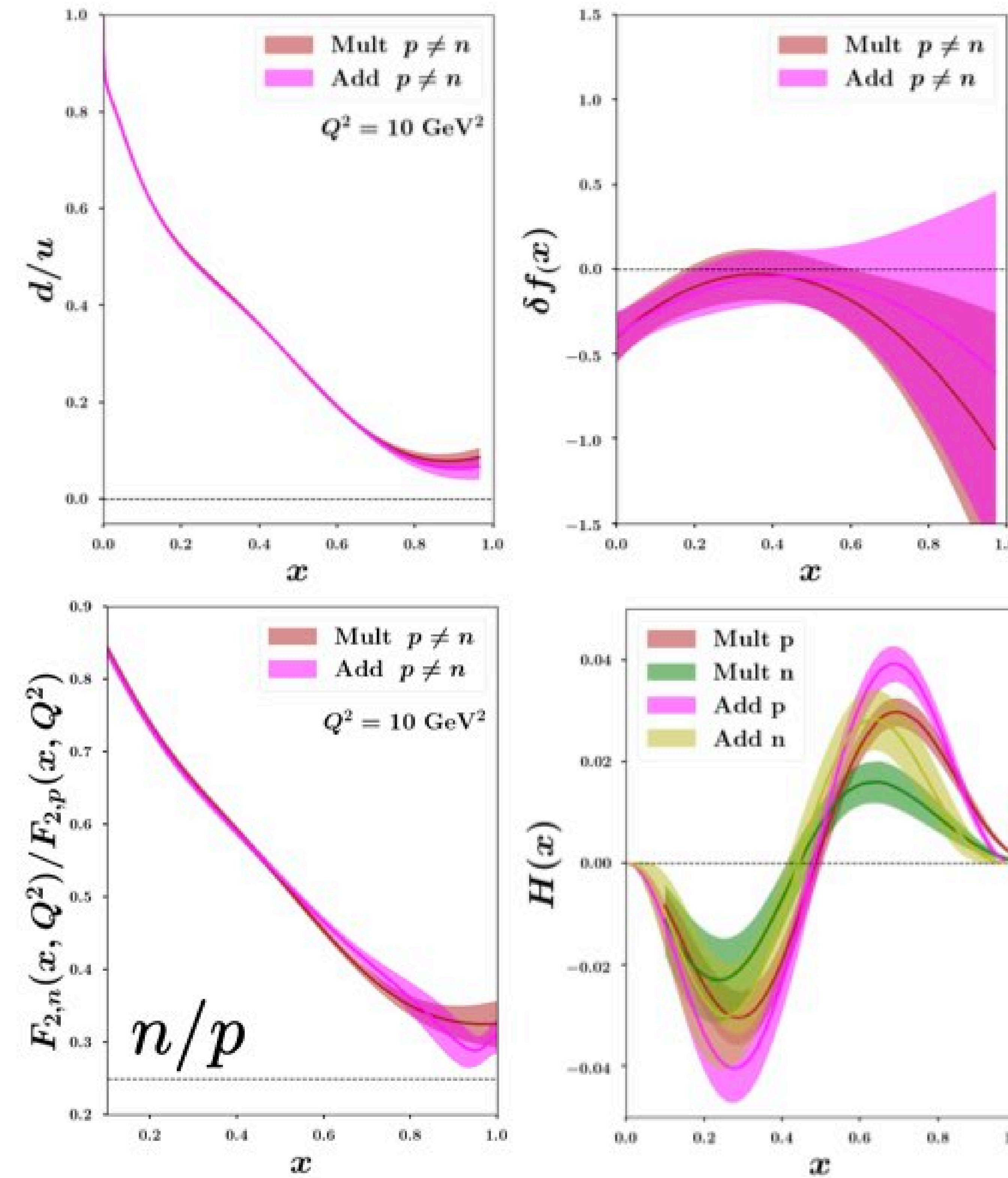
Off-shell compensates n/p bias





Results in the CJ fitting framework

Case 2: isospin breaking



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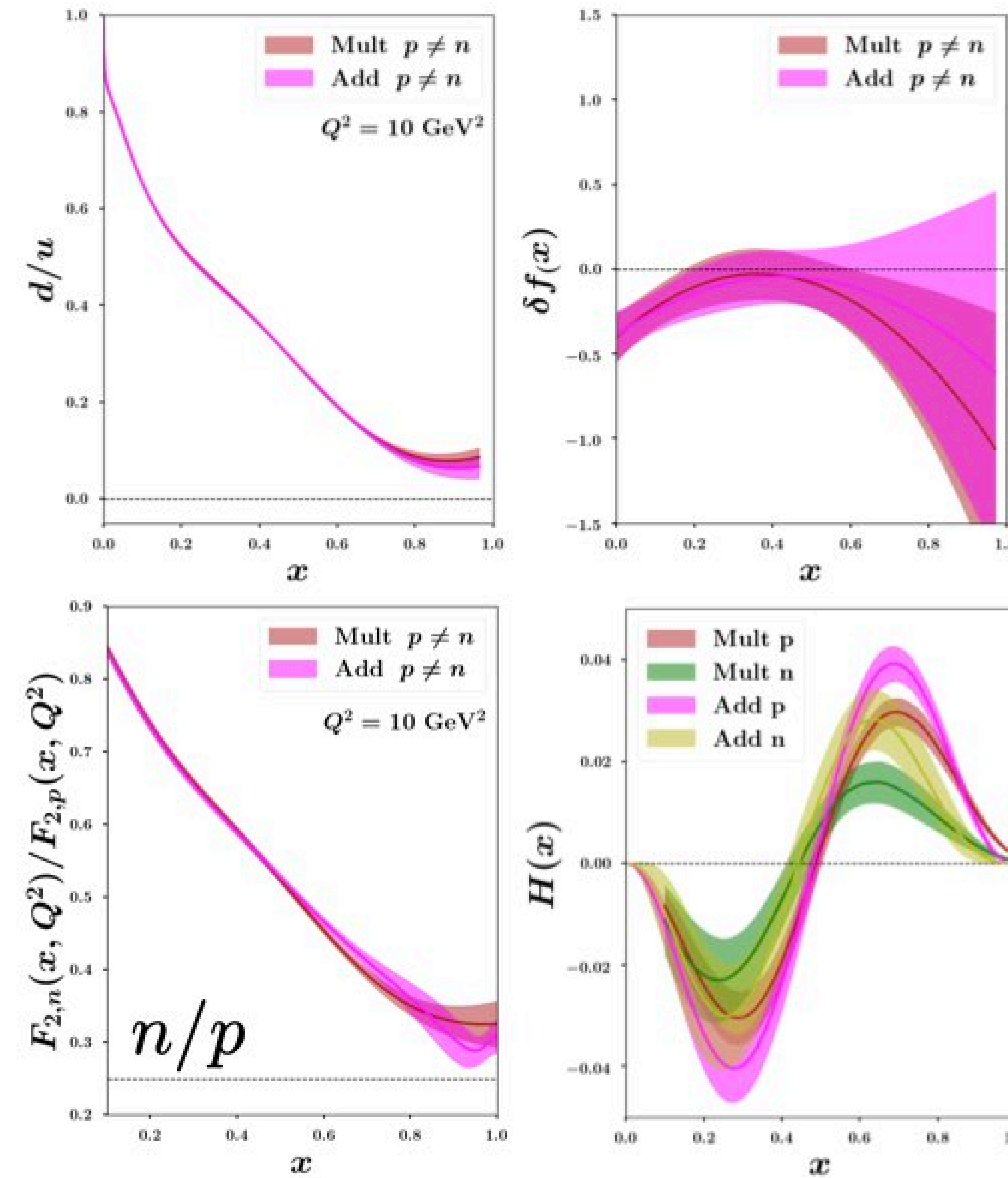
Case 2: isospin breaking

Compatible n/p

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



Results in the CJ fitting framework

Case 2: isospin breaking

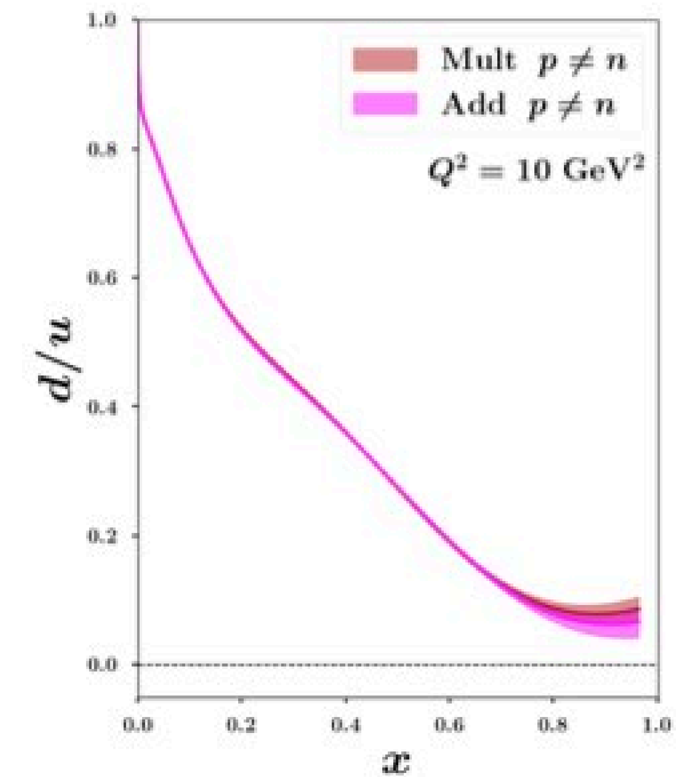
Compatible n/p

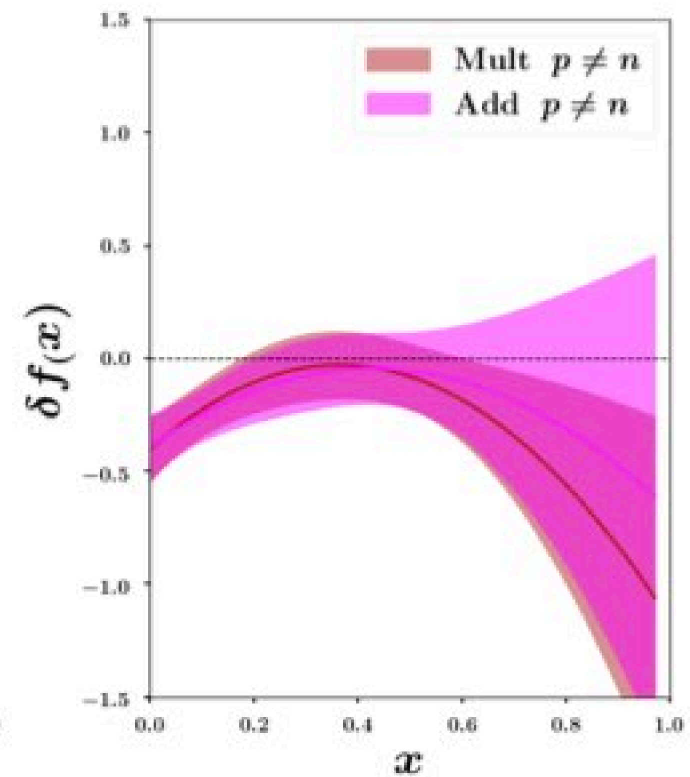
$$H_n(x) \simeq \frac{1}{2} H_p(x)$$

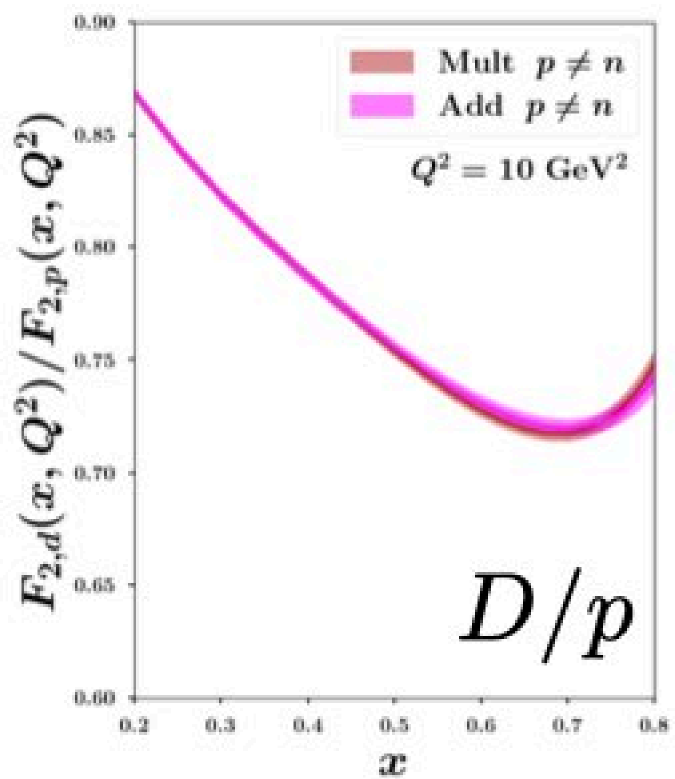
Bias removed

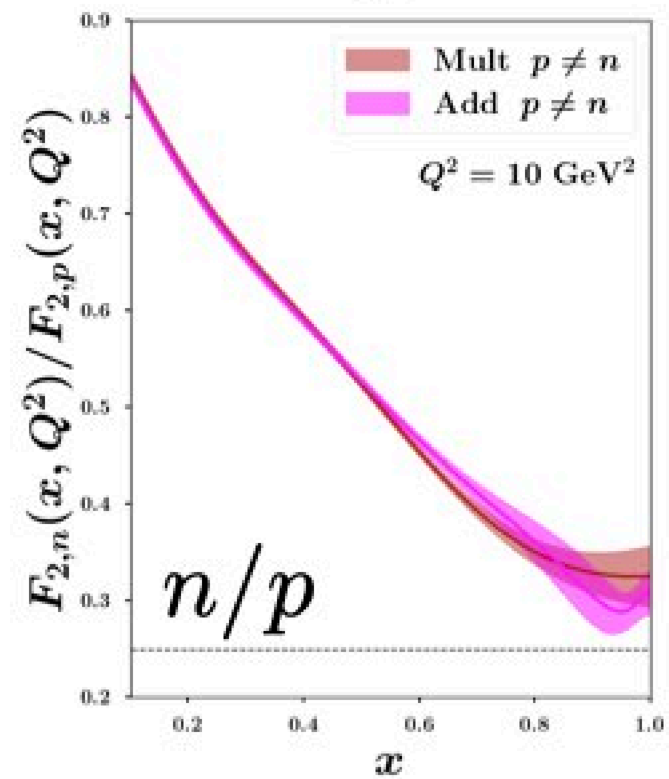
No need of compensation by off-shell

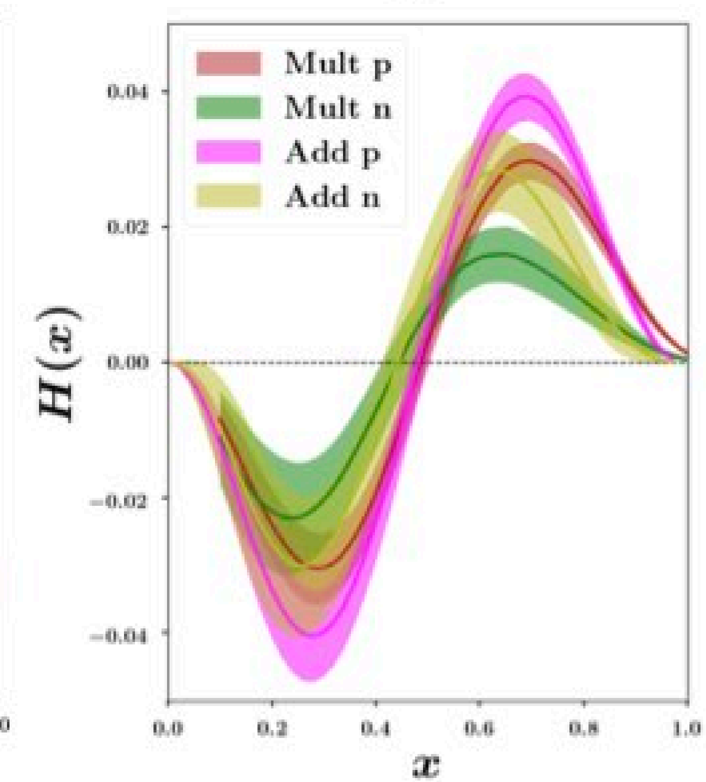
Theory calculation confirmed!





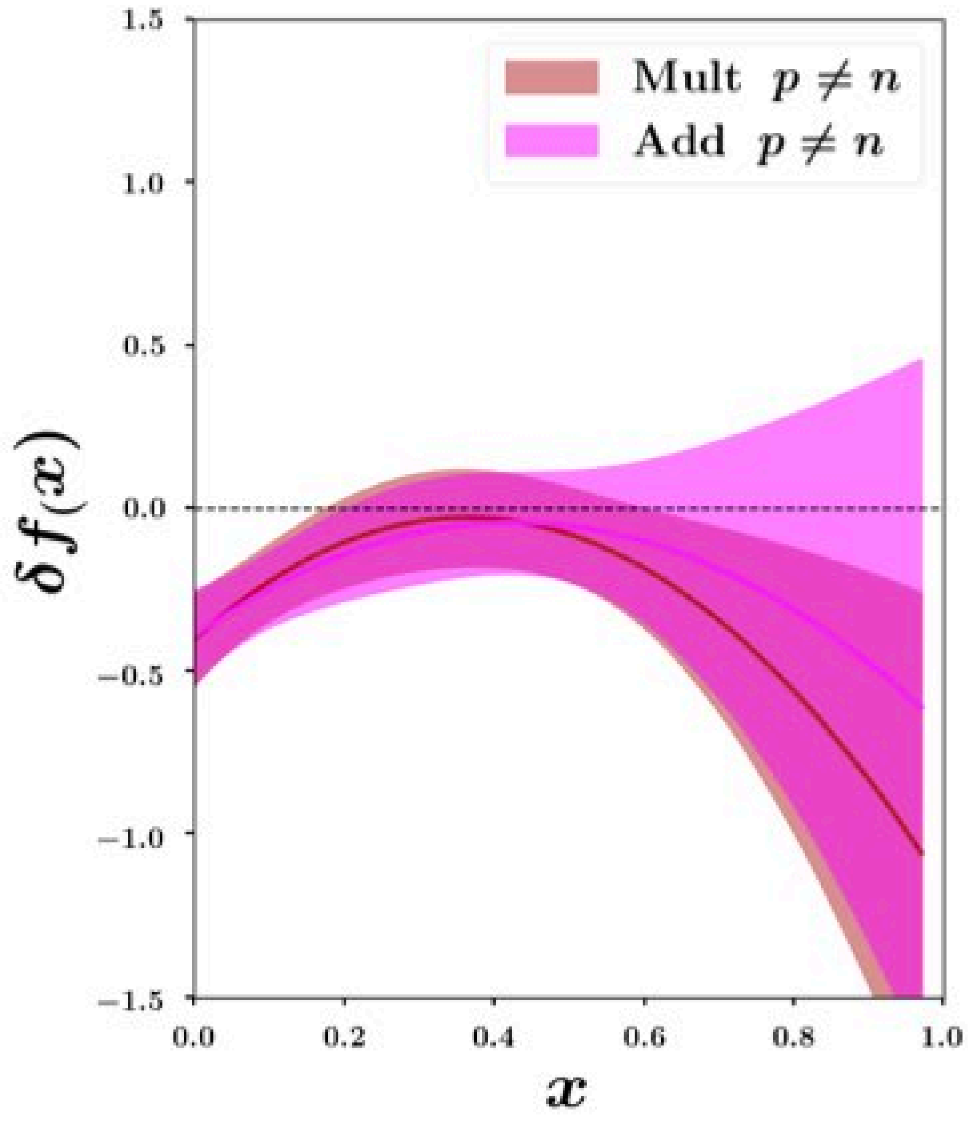






Results in the CJ fitting framework

After removing the bias $\delta f(x) \simeq 0$



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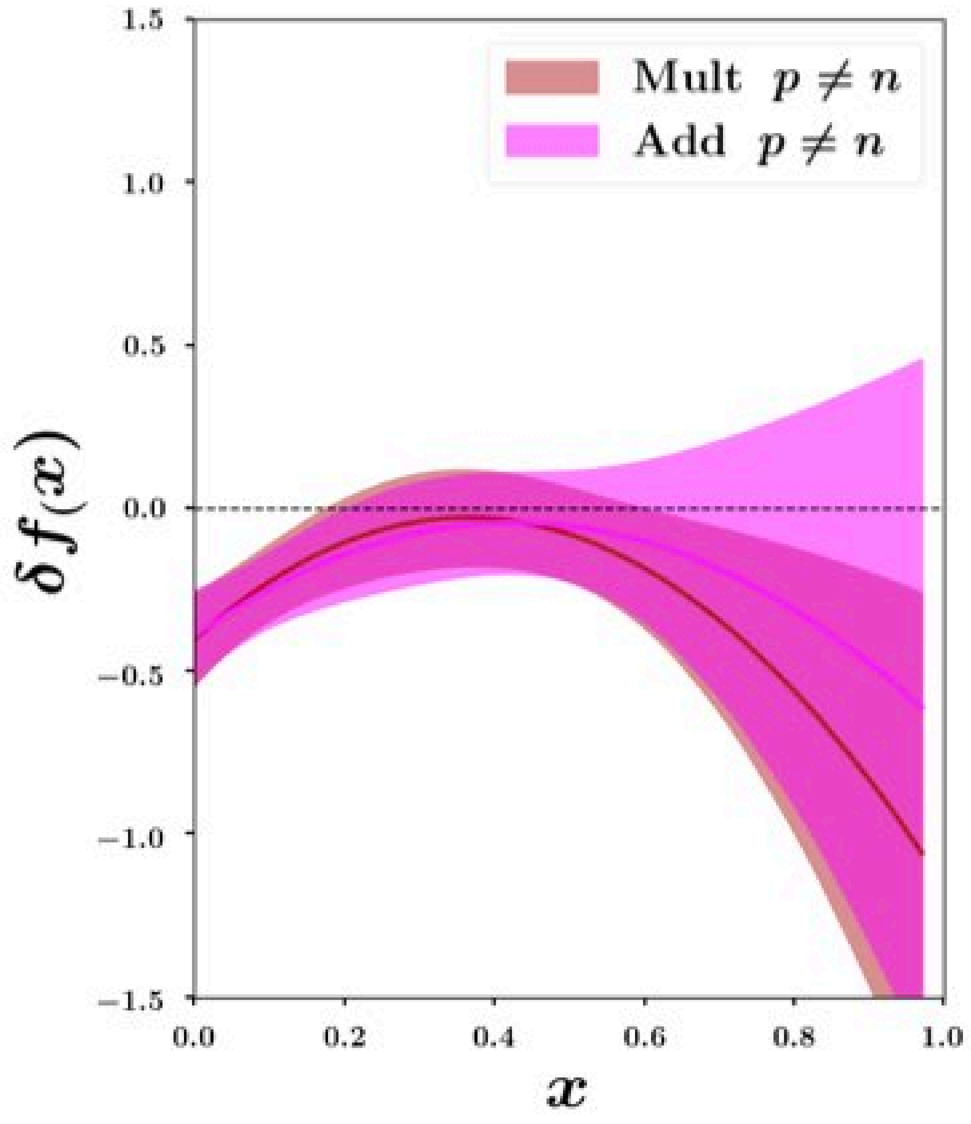

Is the nucleon inside the deuterium almost on-shell?

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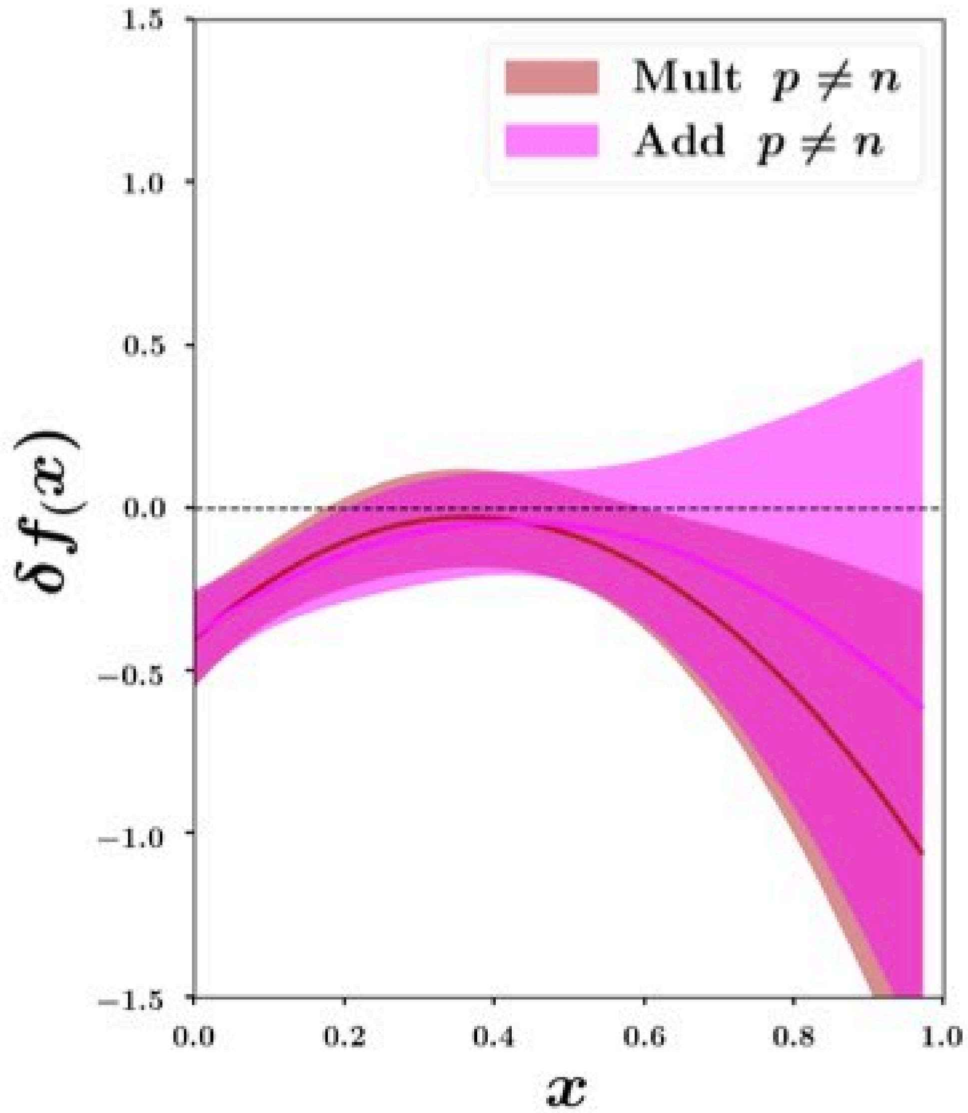

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Need A=3 data to assess flavour dependence of off-shell function

MARATHON data
Adams, et al., PRL 128 (2022)

Other extractions of the off-shell correction

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AKP Alekhin, Kulagin, Petti, PRD 107 (2023)

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Fit to A=3 data: $\delta f_u(x) \neq \delta f_d(x)$

AKP results

AKP Alekhin, Kulagin, Petti, PRD 107 (2023)

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AKP Alekhin, Kulagin, Petti, PRD 107 (2023)

Add HT (p=n) as baseline choice

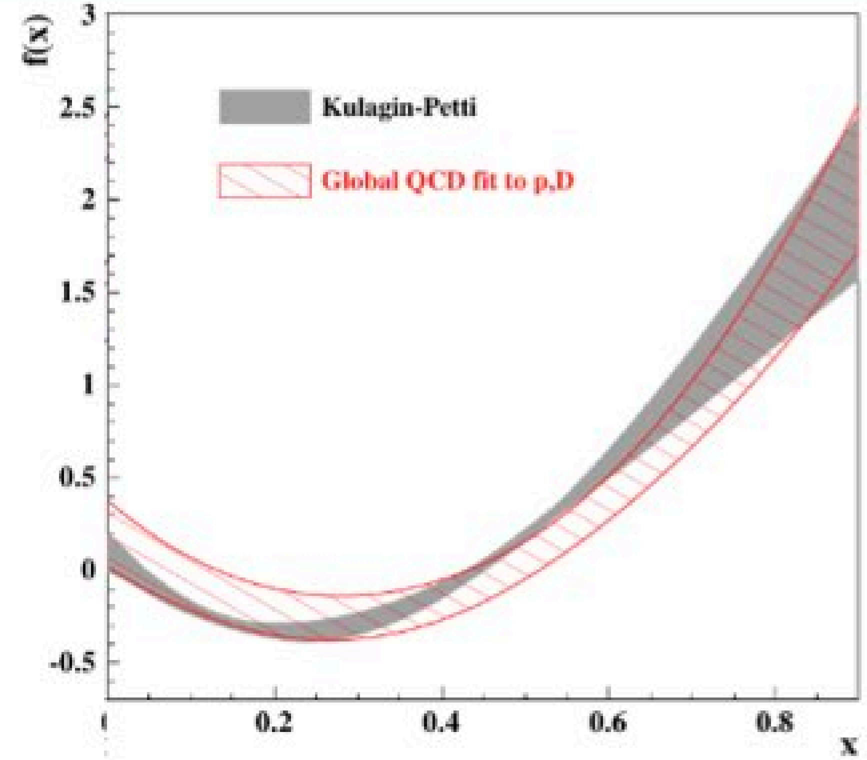
H_2, H_T parametrized

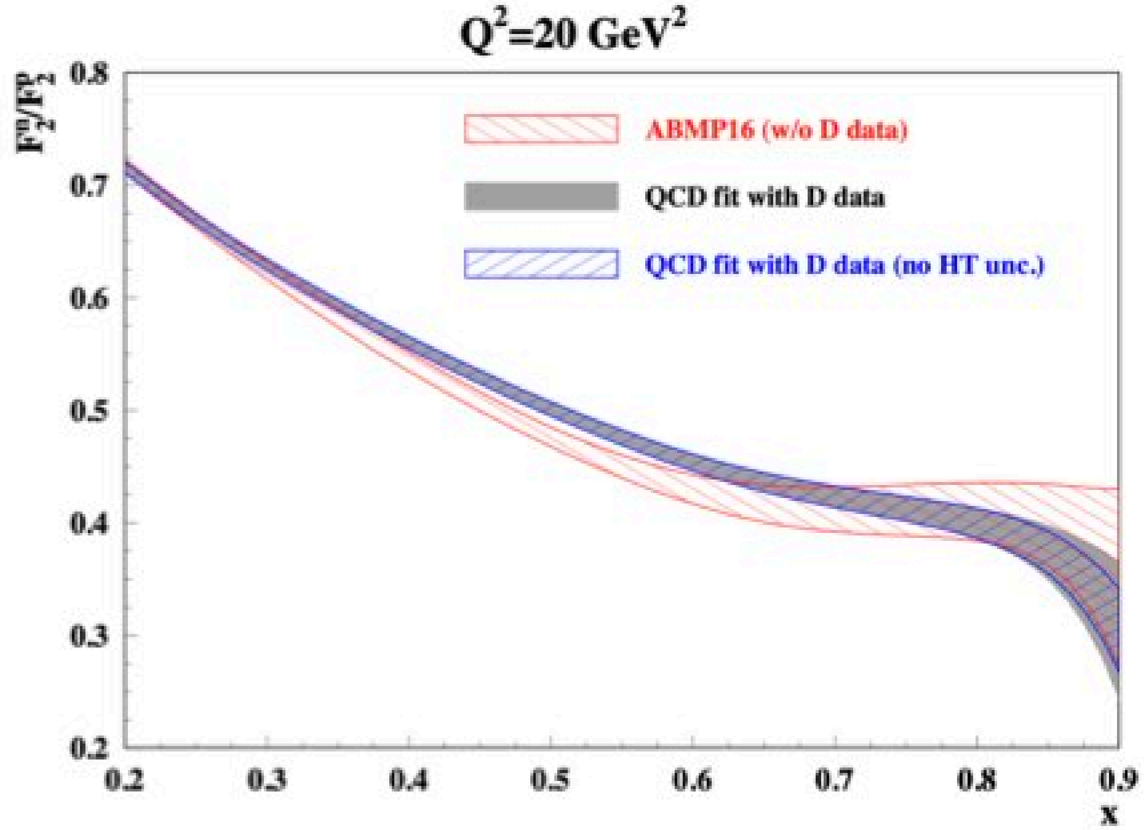
AKP results

AKP Alekhin, Kulagin, Petti, PRD 107 (2023)

Add HT (p=n) as baseline choice

H_2, H_T parametrized





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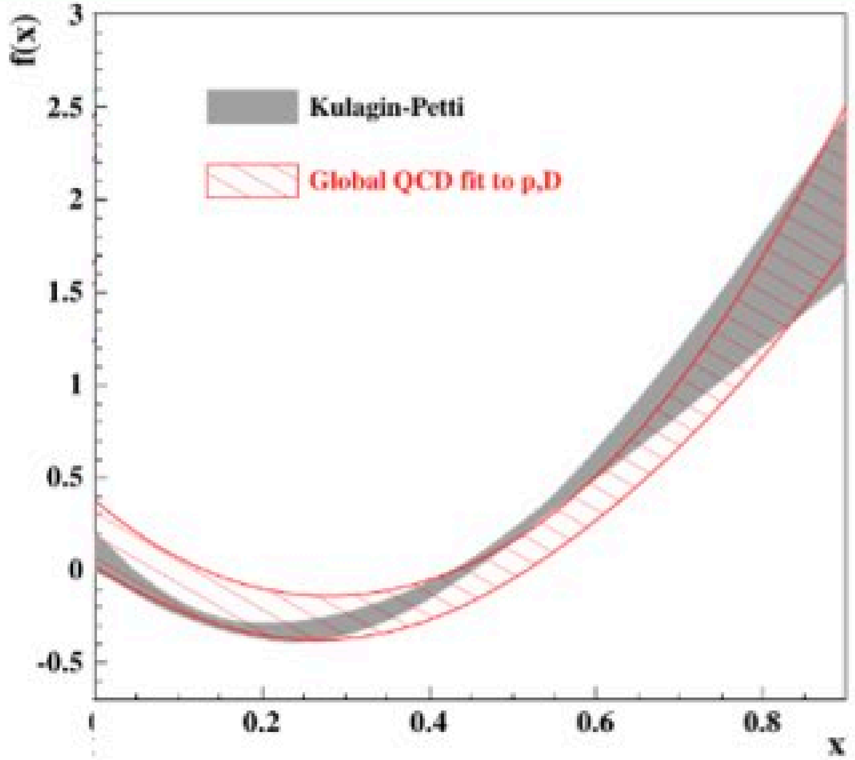

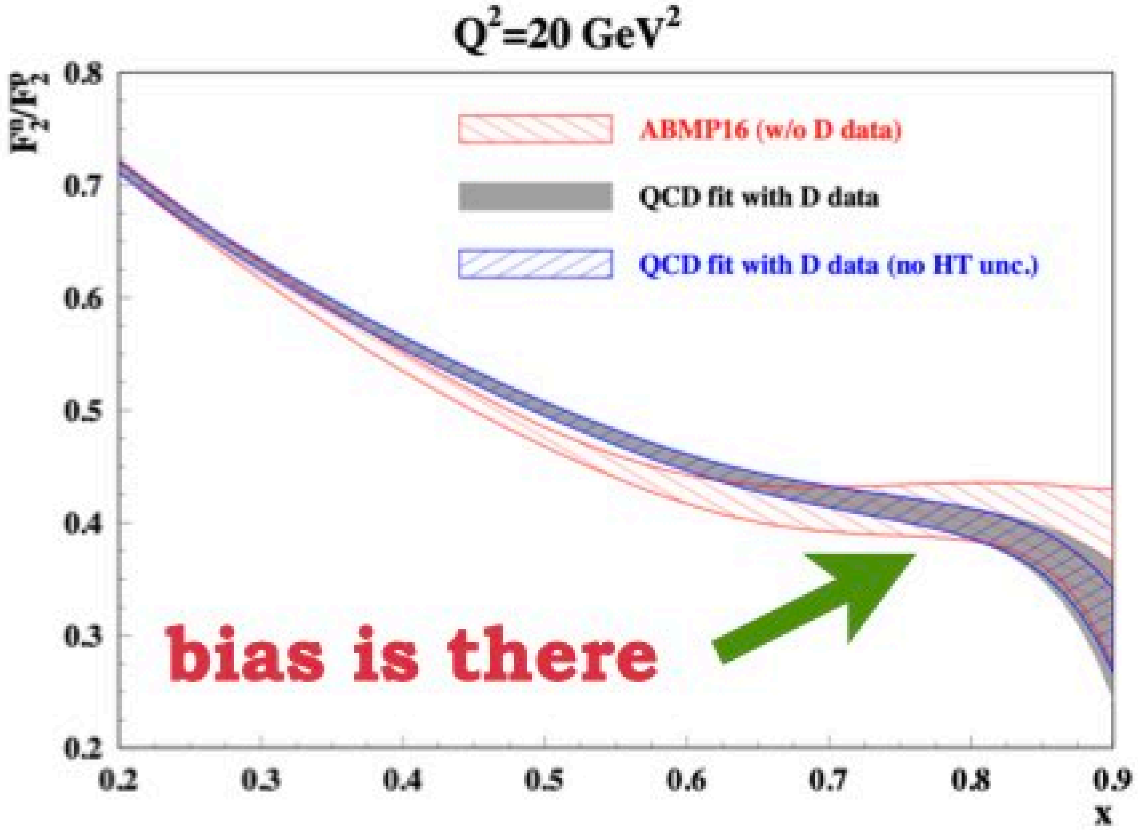

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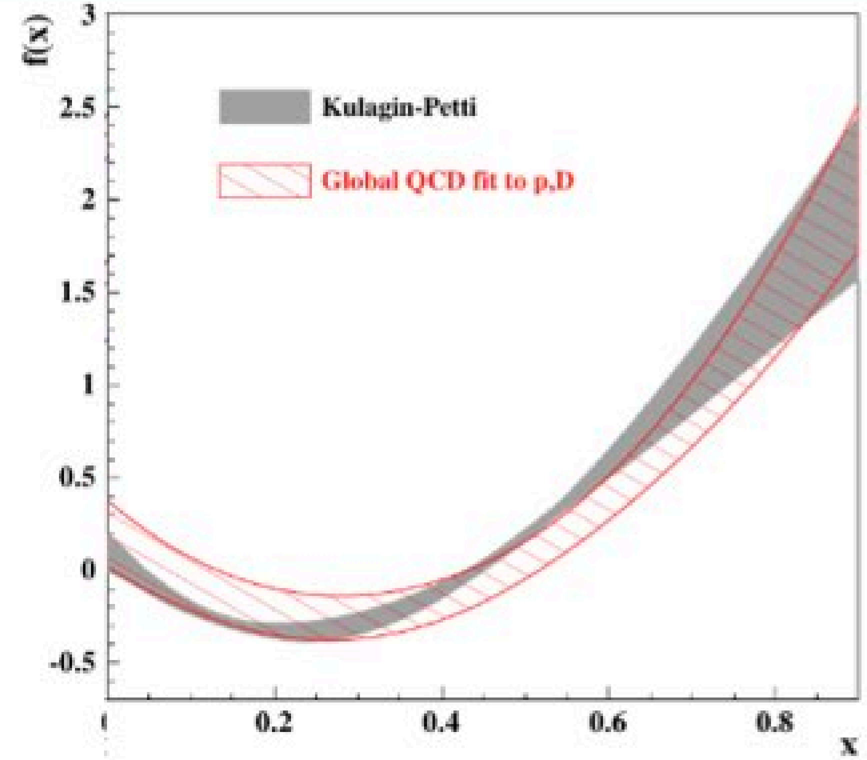
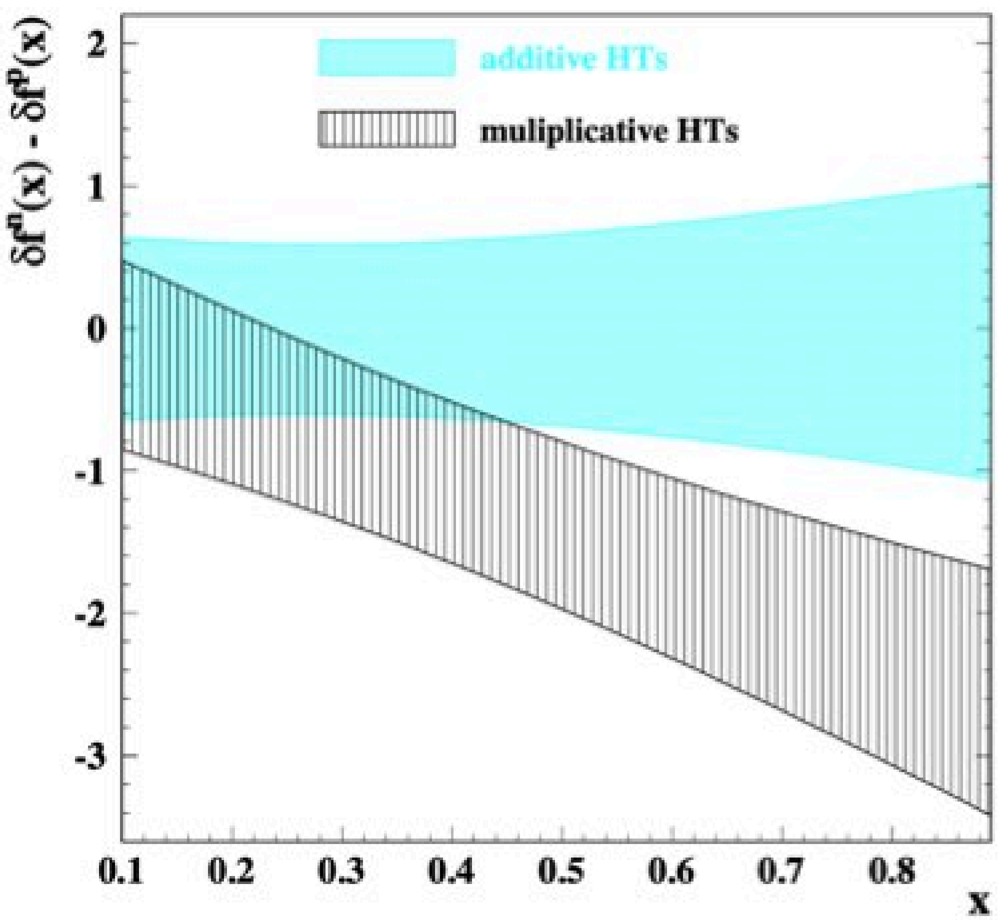
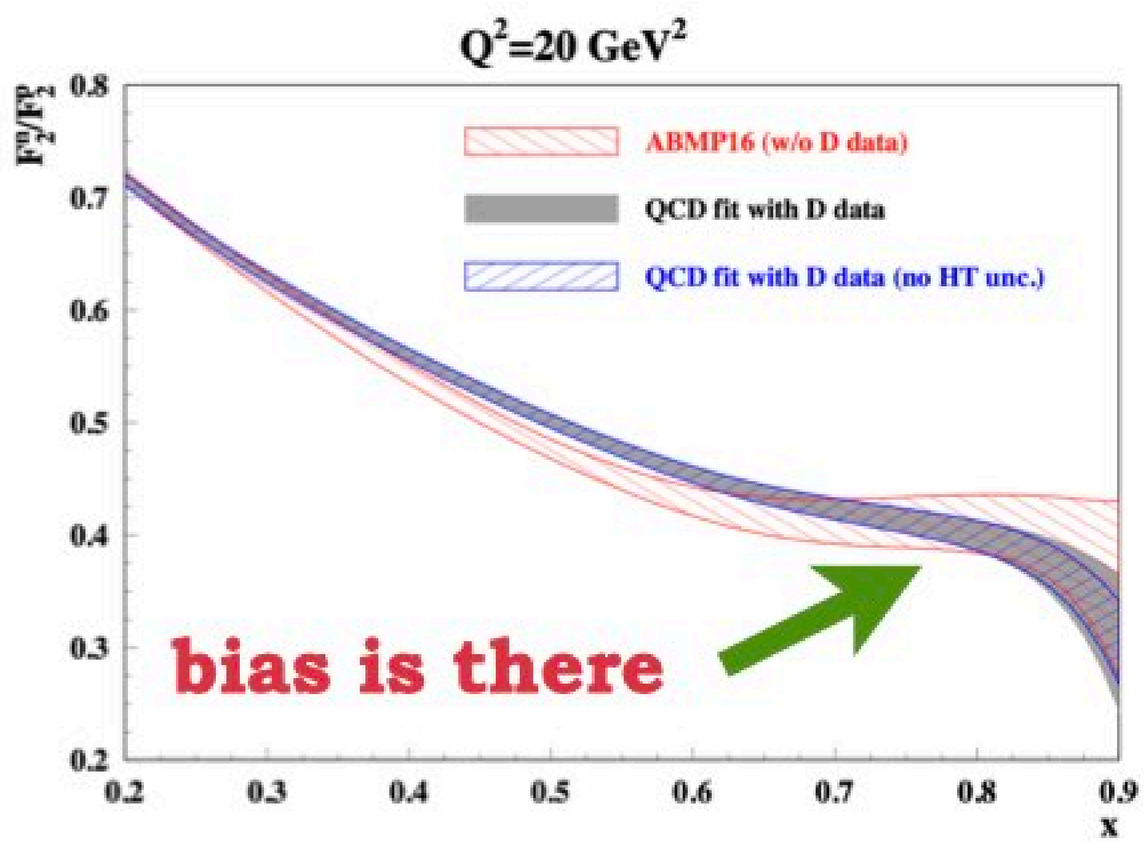


Fit to A=3 data δF_p δF_n





JAM results

JAM results

JAM *Fit including A=3 data* δf_u δf_d

JAM Collaboration, PRL 127 (2021)

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Mult HT (p=n) as default choice

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JAM Collaboration, PRL 127 (2021)

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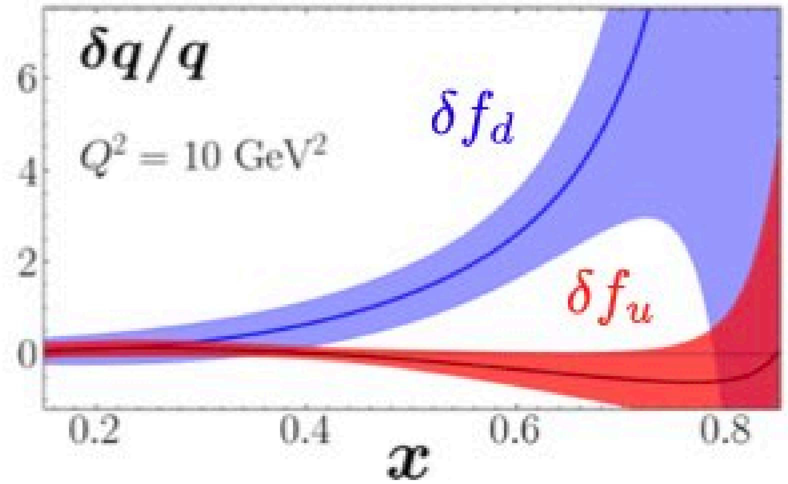
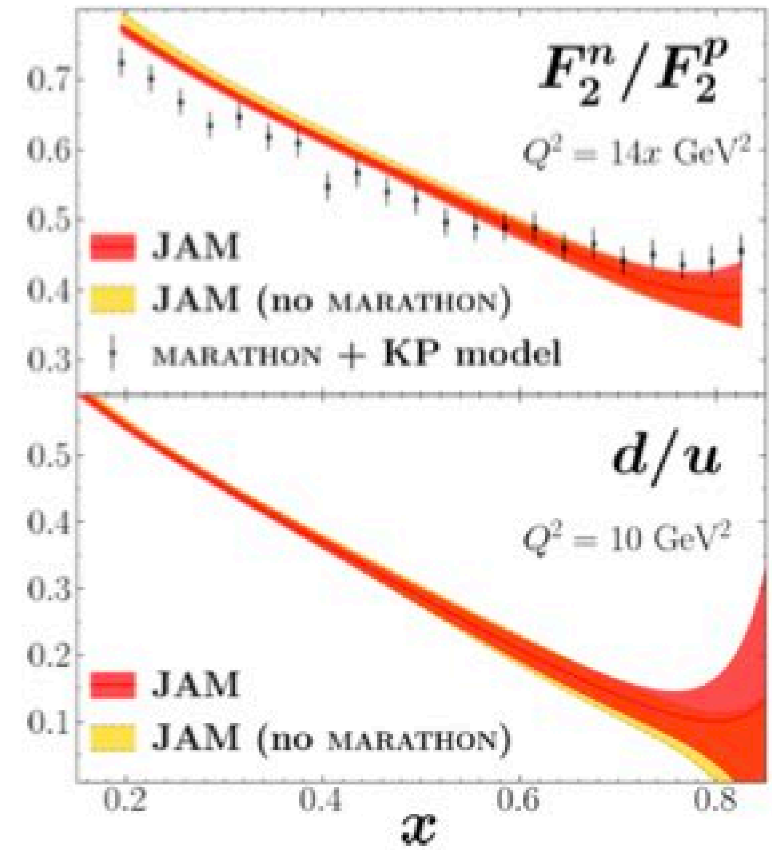


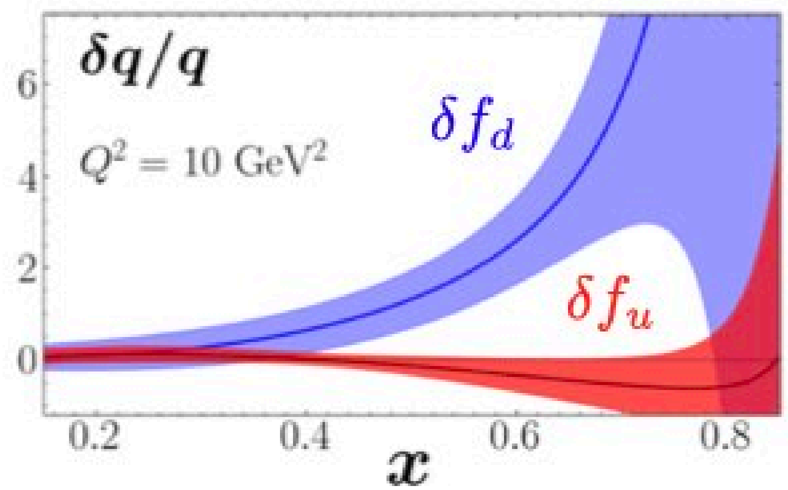


JAM results

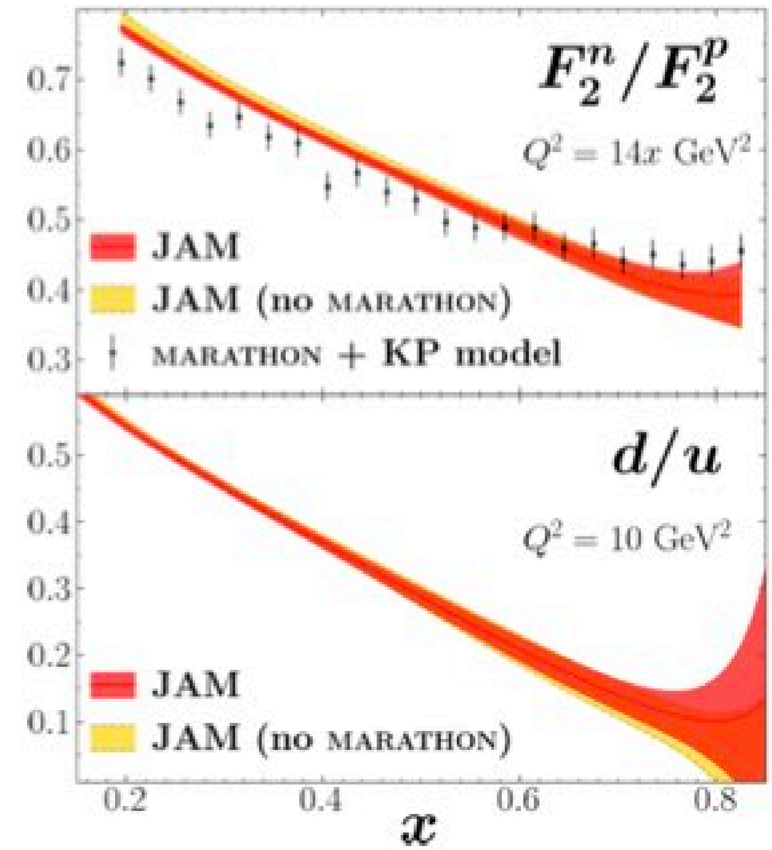
JAM *Fit including A=3 data* $\delta f_u\ \delta f_d$

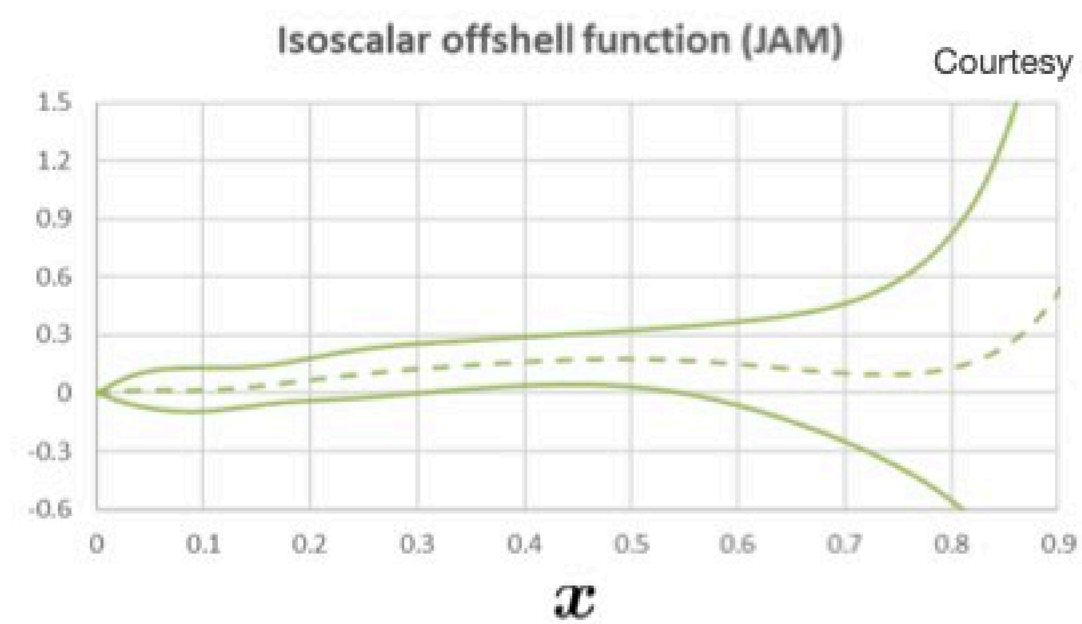
JAM Collaboration, PRL 127 (2021)

Mult HT (p=n) as default choice



$$\delta f(x)|_{\text{CJ-like}} = \frac{u\delta f_u + d\delta f_d}{u+d}$$





Courtesy of C. Cocuzza

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Experimental data differential on the off-shell proton virtuality p^2 would allow us to pin down the off-shell correction in a more clean way

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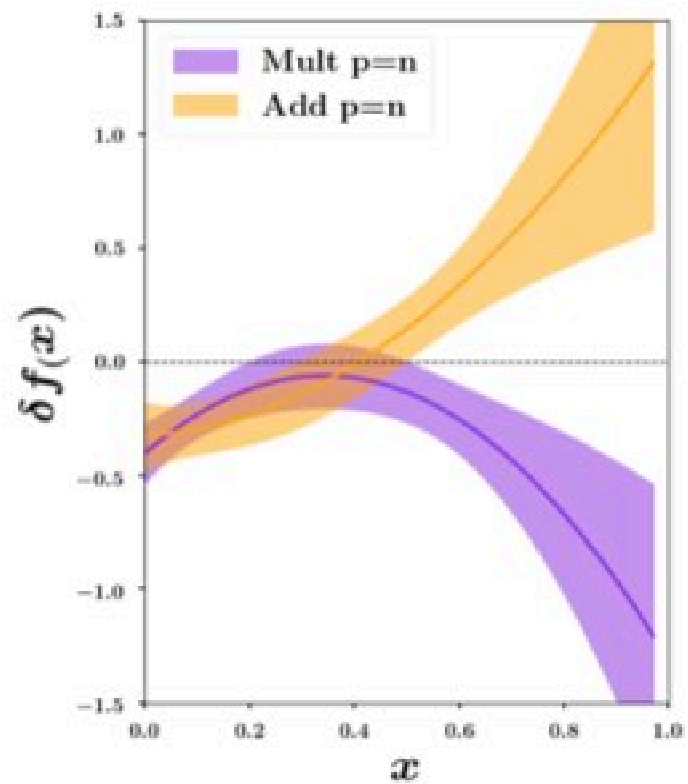
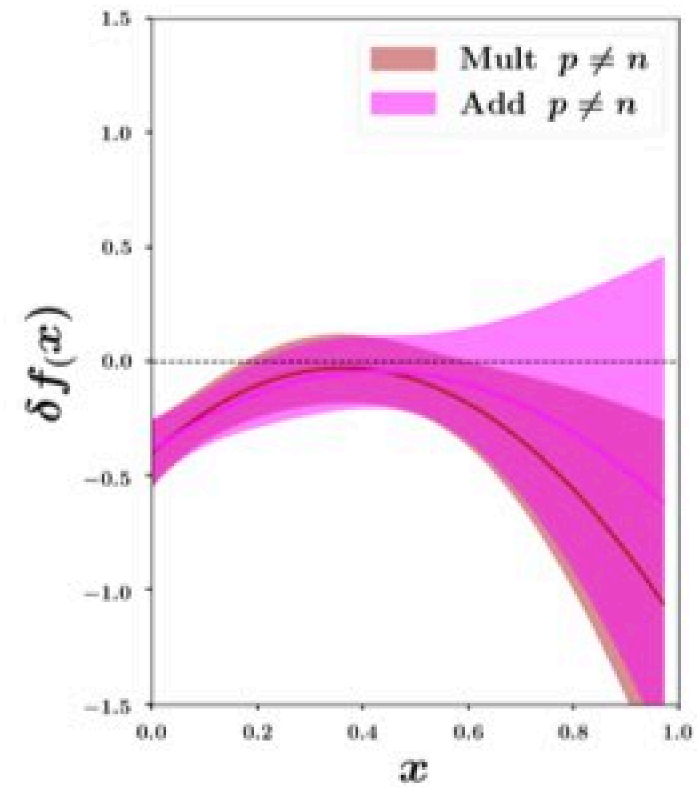
JAM A=3 fit not in agreement with AKP. Average result compatible with CJ

Backup

Off-shell table

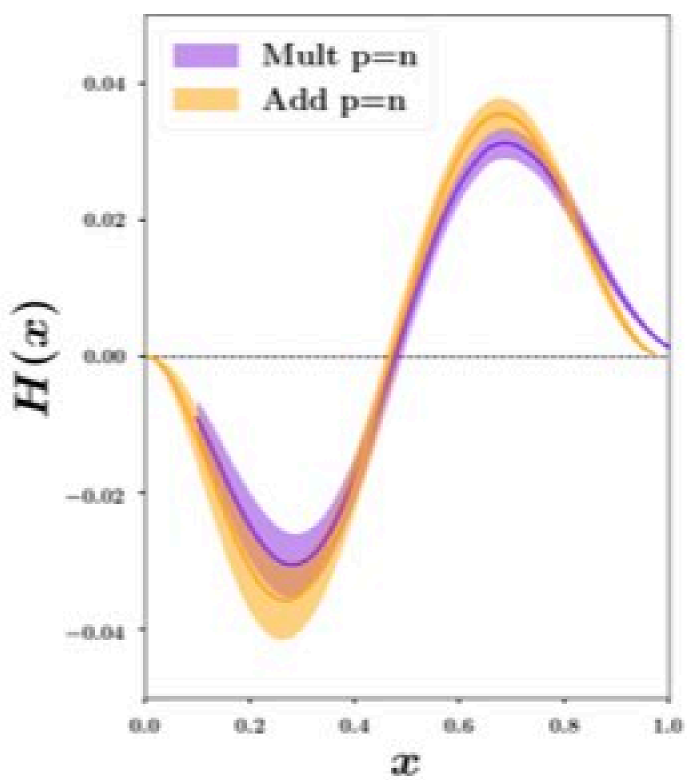
isospin / higher-twist	Symmetric	Non symmetric
Multiplicative		
Additive		

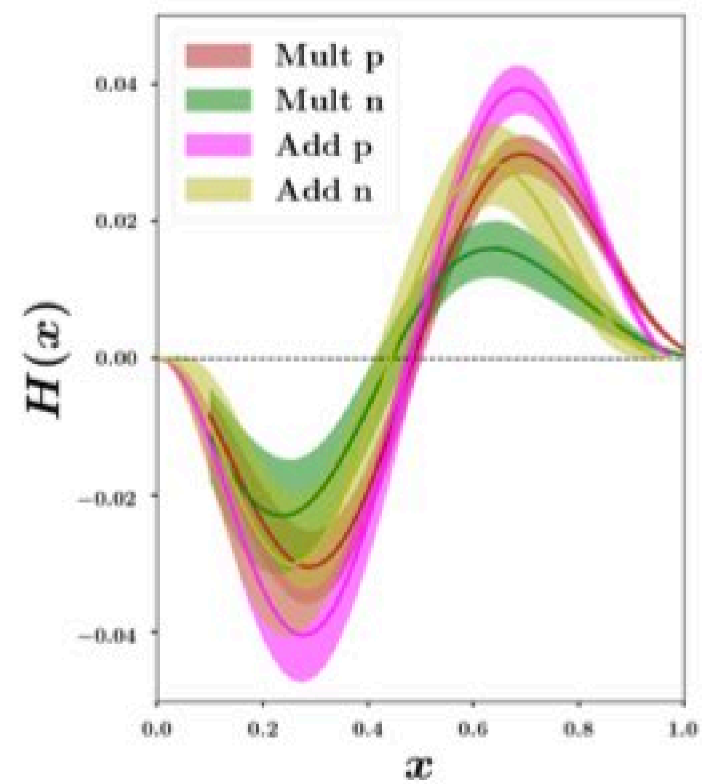




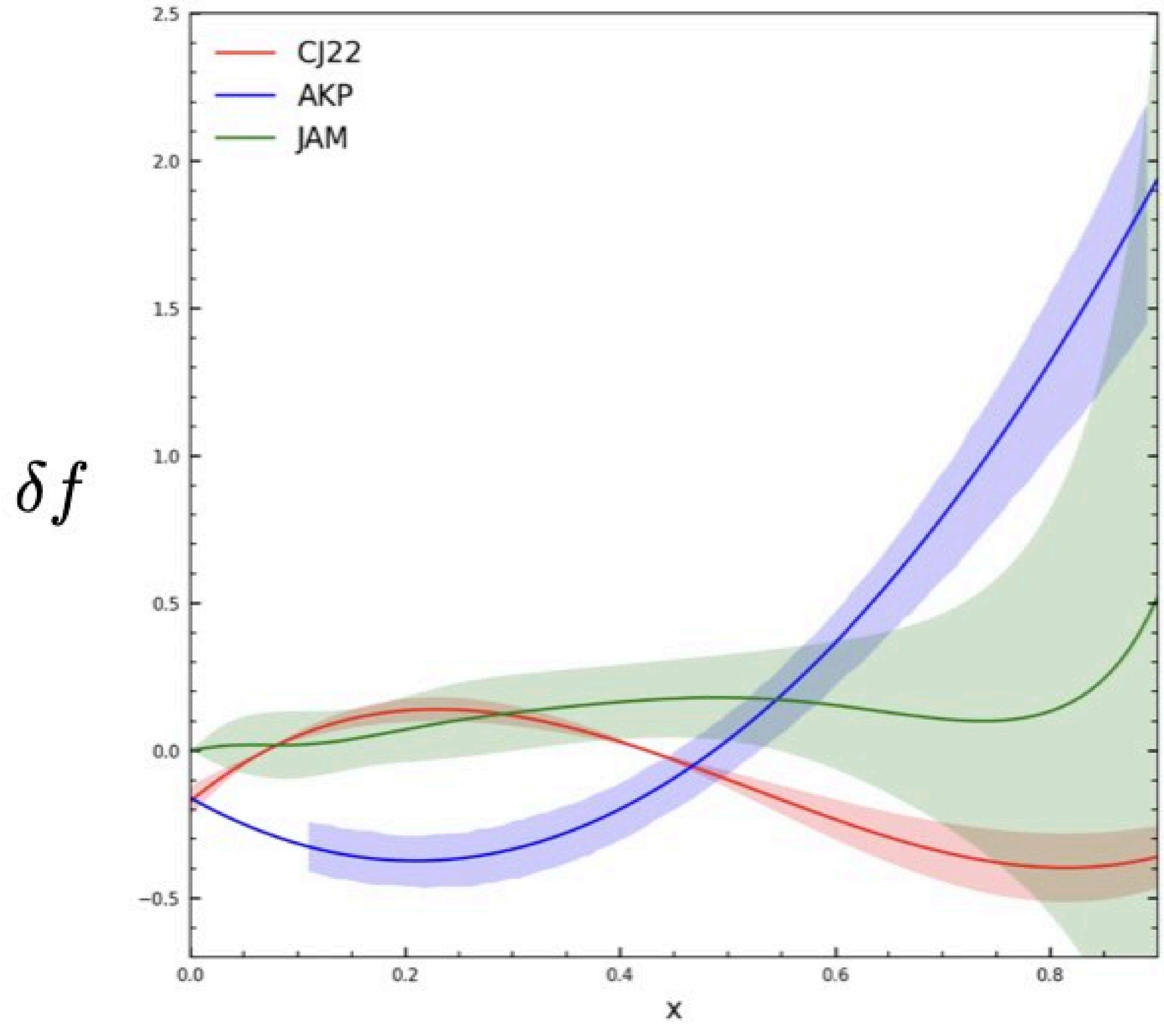
Higher-Twist table

higher-twist \ isospin	Symmetric	Non symmetric
Multiplicative	$\tilde{H} = F_{2,N}(x, Q^2) H_{\mathrm{Mult}}(x)$	$\delta\tilde{H} = F_{2,N}(x, Q^2) \delta H_{\mathrm{Mult}}(x)$
Additive		





AKP vs CJ



Some implementation differences

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	----	----