DOE contracts:
DE-SC0007981
DE-AC05-06OR23177

CTEQ-Jefferson Lab Collaboration

Study of PDFs at large x from the CJ Collaboration

Matteo Cerutti

SoLID Opportunities and Challenges of Nuclear Physics at the Luminosity Frontier

June 19, 2024

CTEQ-JLab collaboration

Main focus: Investigate the internal structure of nucleons in their valence region

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collinear factorization

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

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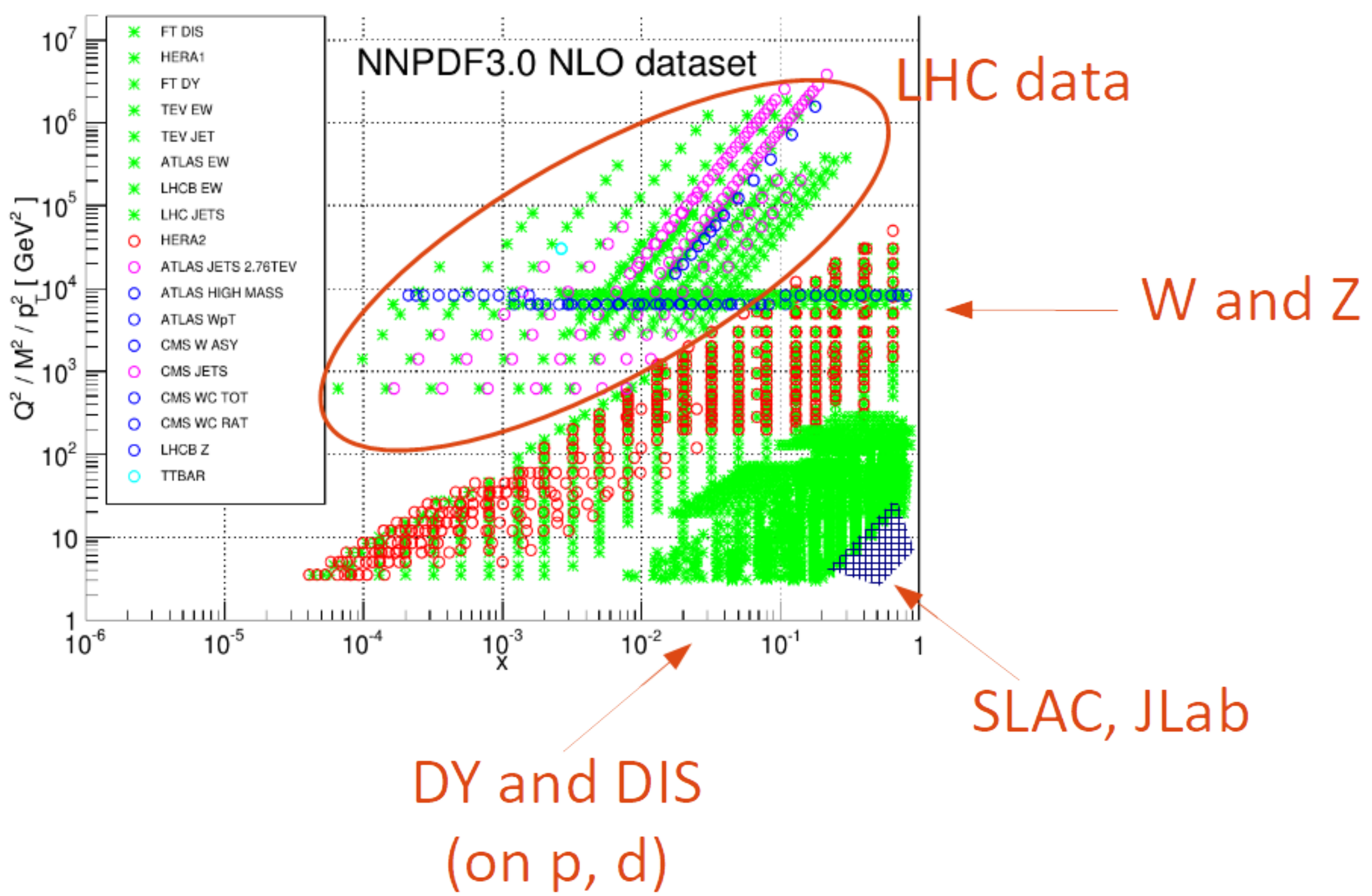
universality

- DIS — p, d targets
- pp collisions — Drell-Yan, W/Z boson production, Jets



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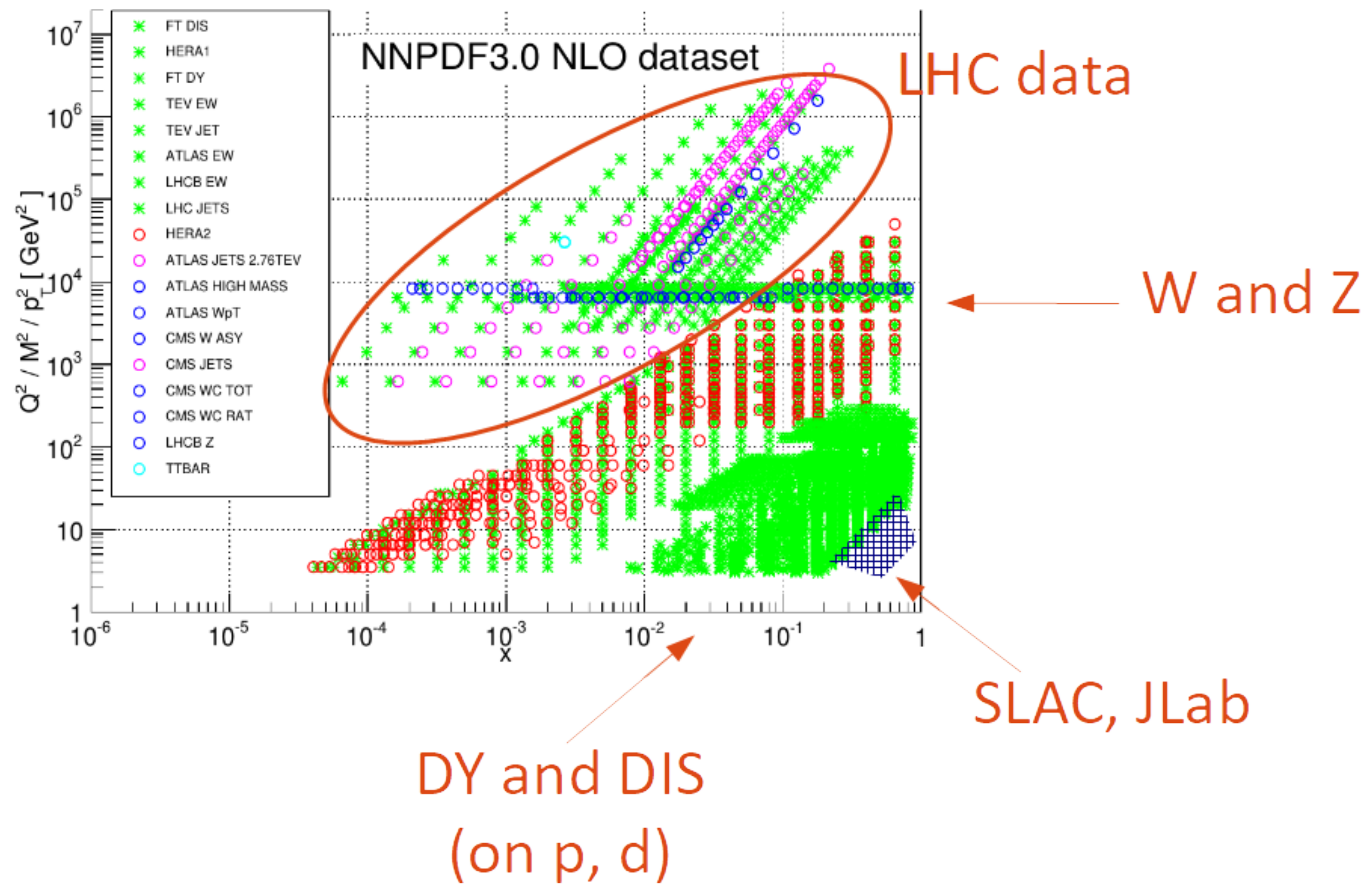

- DIS — p, d targets
- pp collisions — Drell-Yan
  - W/Z boson production
  - Jets

40+ years of experience

CTEQ-JLab collaboration

Coordinate theory+experiment effort within Jefferson Lab

- A. Accardi, MC, X. Jing, I. Fernando, W. Melnitchouk, J. F. Owens
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Recent works:

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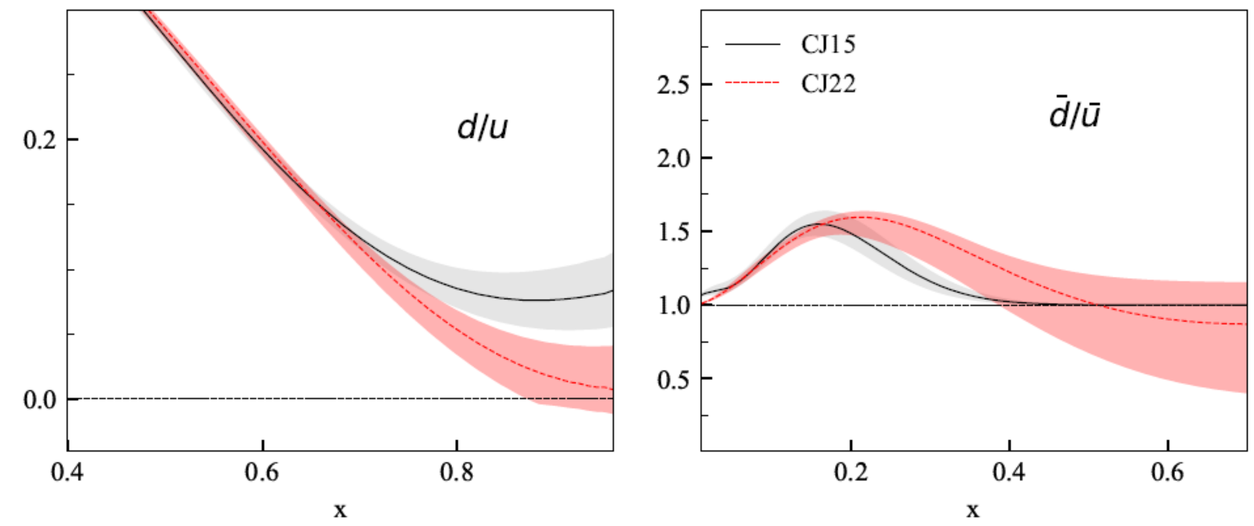

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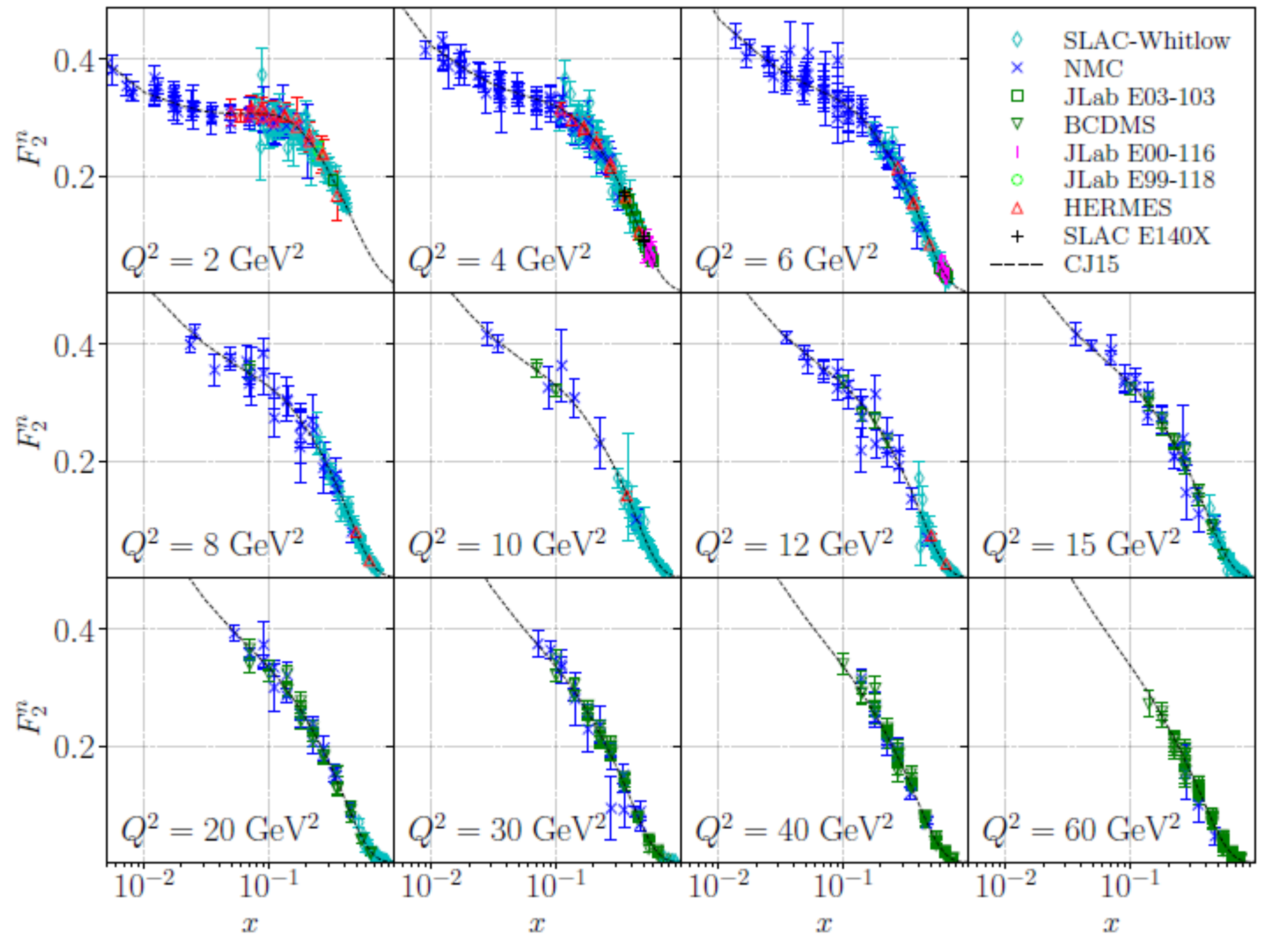

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- Extraction of neutron $F_2(x, Q^2)$

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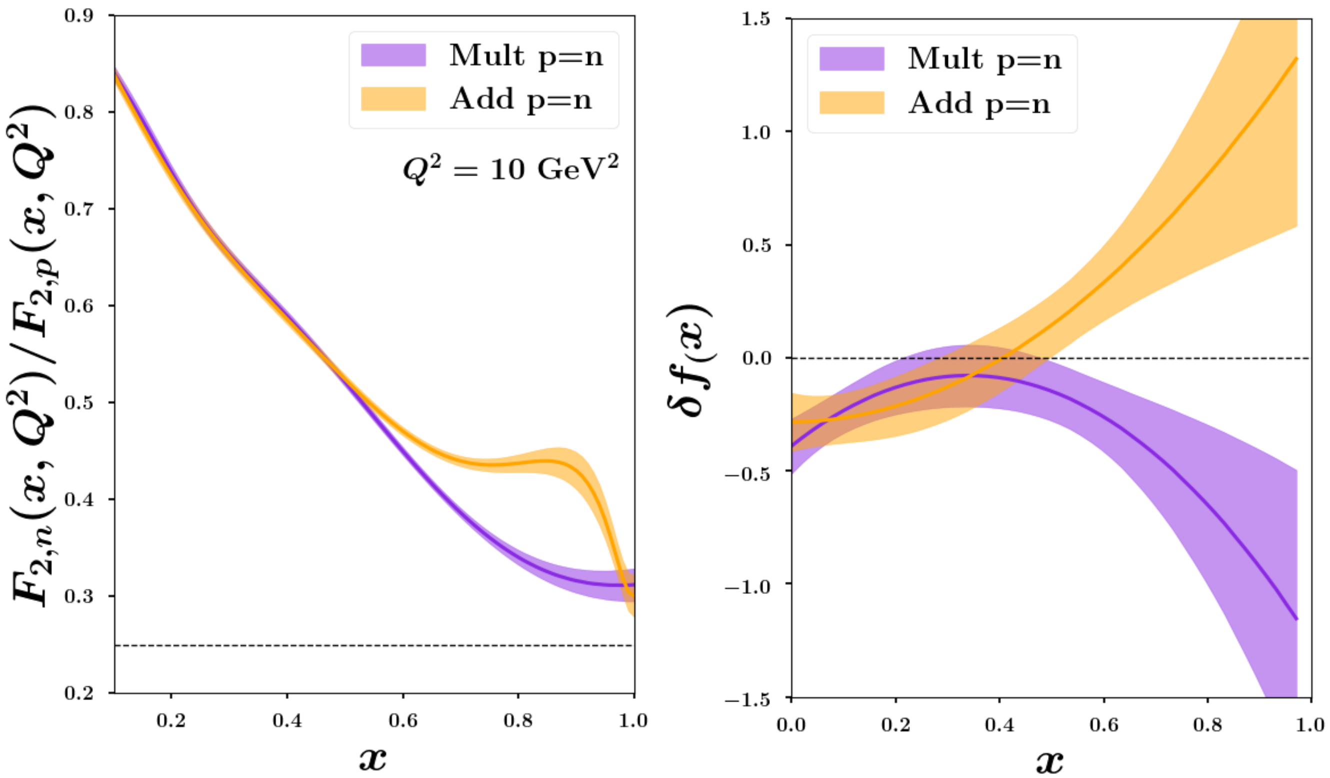
- Systematic uncertainties from HT and off-shell corrections

  HTvsOS In preparation (see DIS2024 talk)



HTvsOffshell

in preparation

Bias in the approach identified

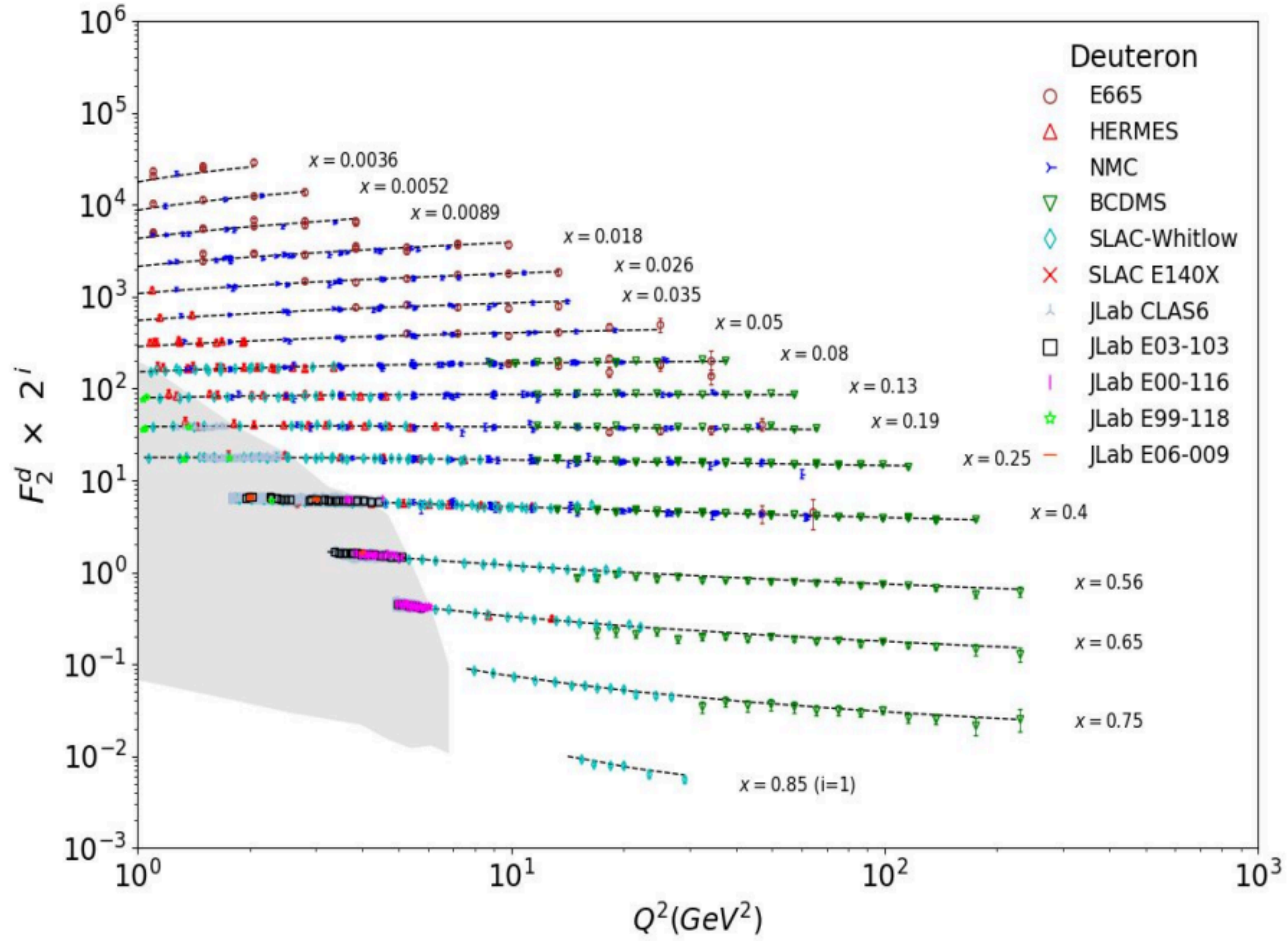
…and solved!

Extraction of neutron F_2 structure function

DIS on deuteron target

CJ global data set:

- 1000+ data points
- high-x and low-Q^2
- $W^2 > 3$ GeV^2, $Q^2 > 1.69$ GeV^2



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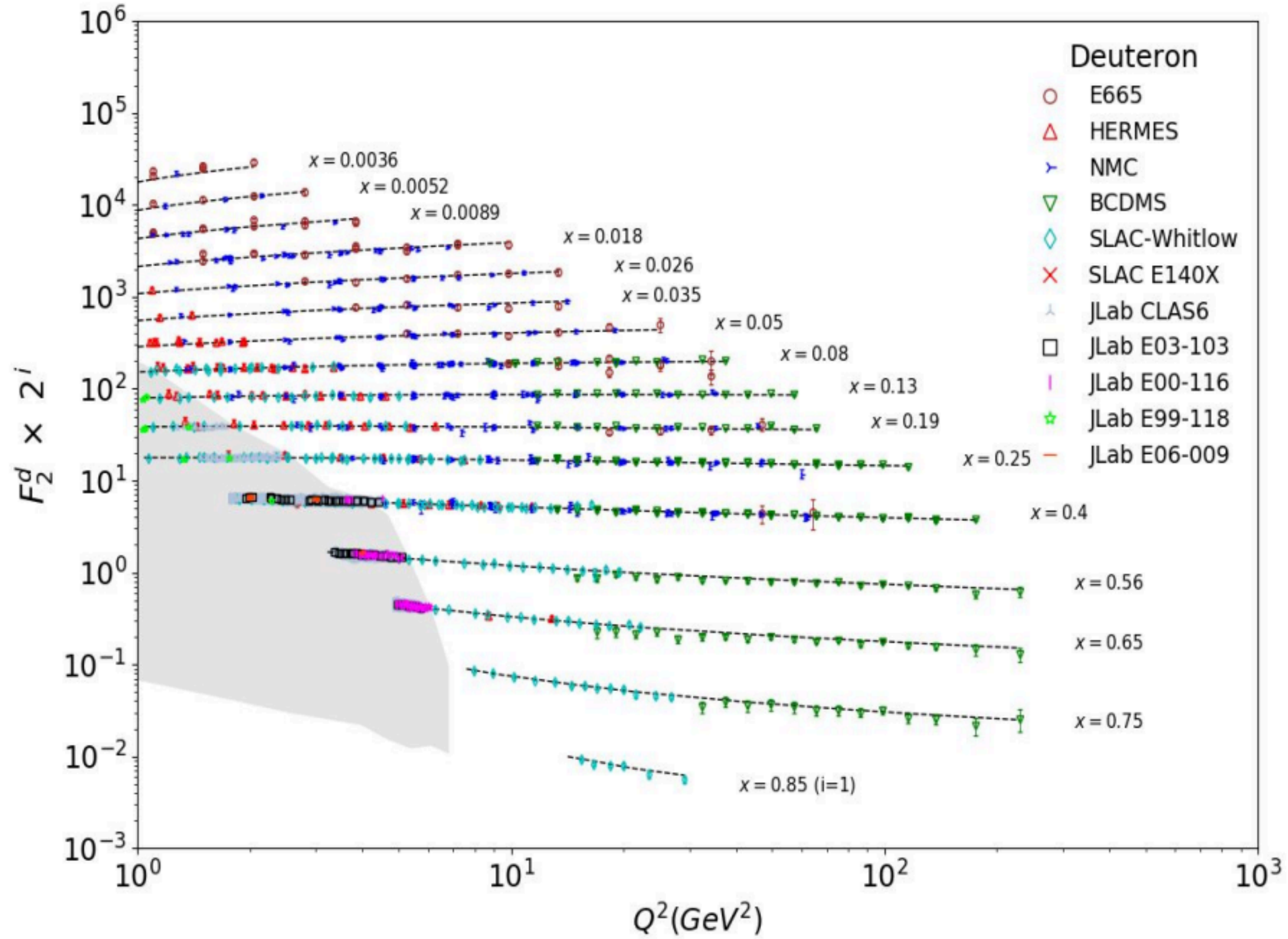
Full treatment of nuclear corrections

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



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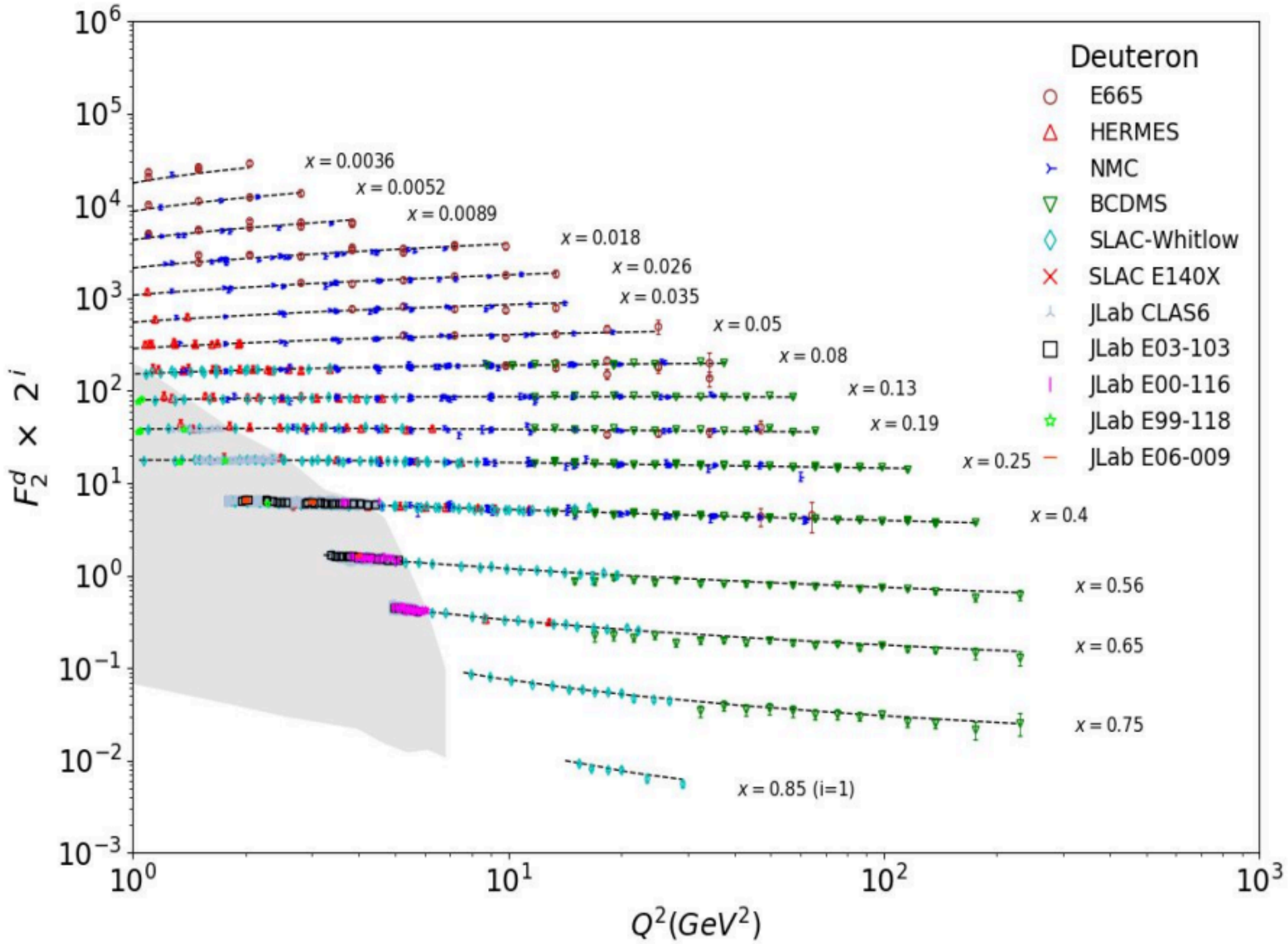

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$$F_{2,D}(x_D, Q^2) = \int_{y_{Dmin}}^{y_{Dmax}} dy_D dp_T^2 f_{N/D}(y_D, p_T^2; \gamma) F_{2,N}\left(\frac{x_D}{y_D}, Q^2, p^2\right)$$

Smearing function

Structure function of a bound, off-shell nucleon

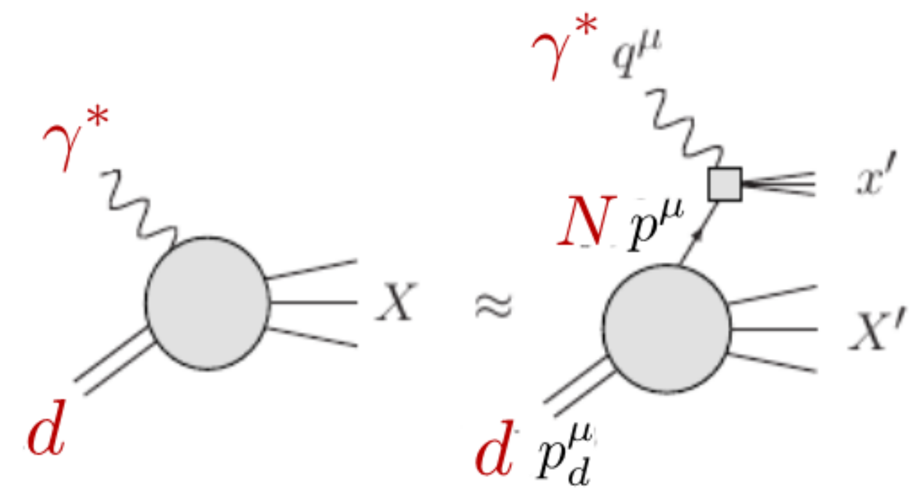
Deuterium: off-shell corrections

Deuterium: off-shell corrections

Bound, off-shell nucleon inside the deuteron

$$p^2 < m_N^2$$

Structure functions are deformed at large x



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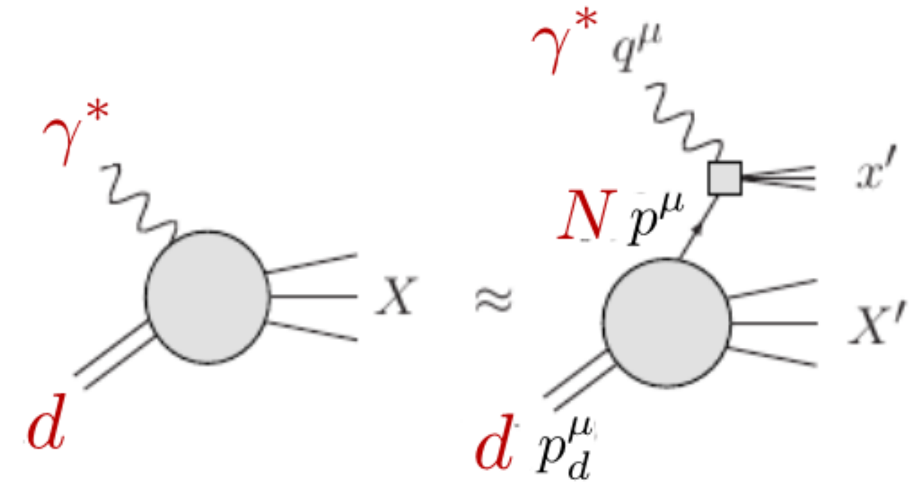

Off-shell expansion (in nucleon virtuality p^2)

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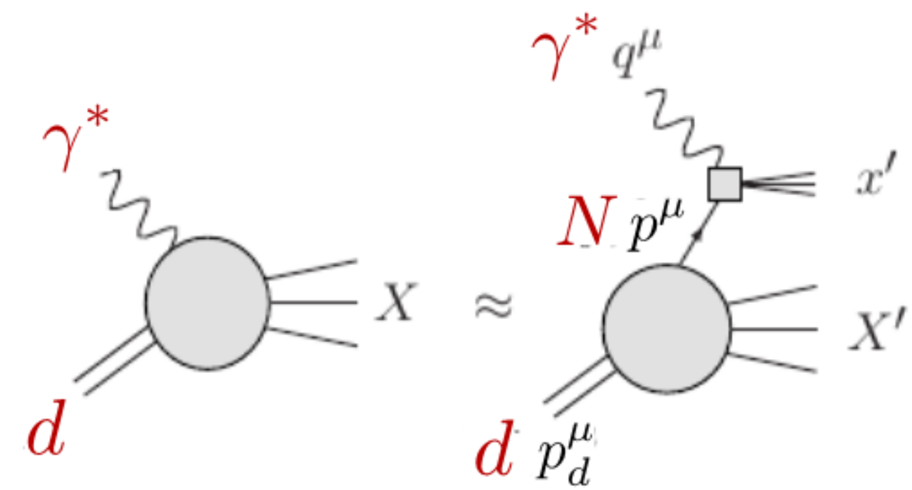

Off-shell expansion (in nucleon virtuality p^2)

parton level

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

Kulagin, Piller, Weise, PRC 50 (1994)
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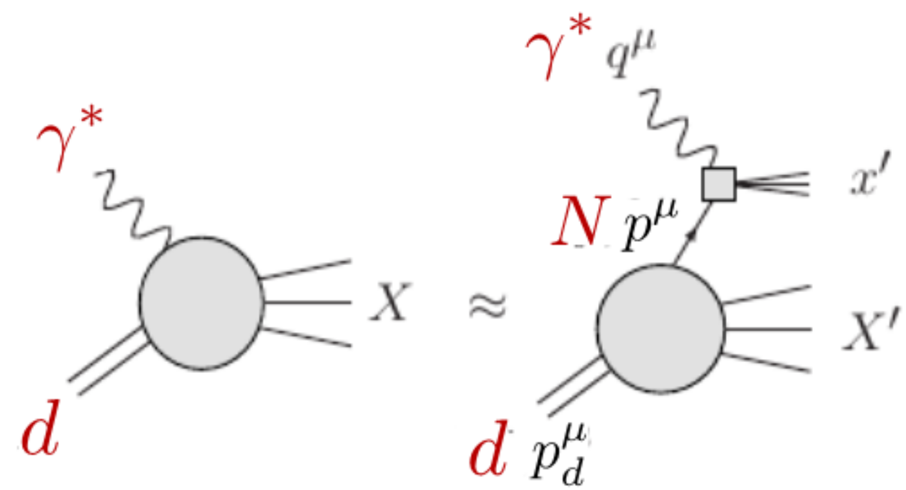

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struct. func level

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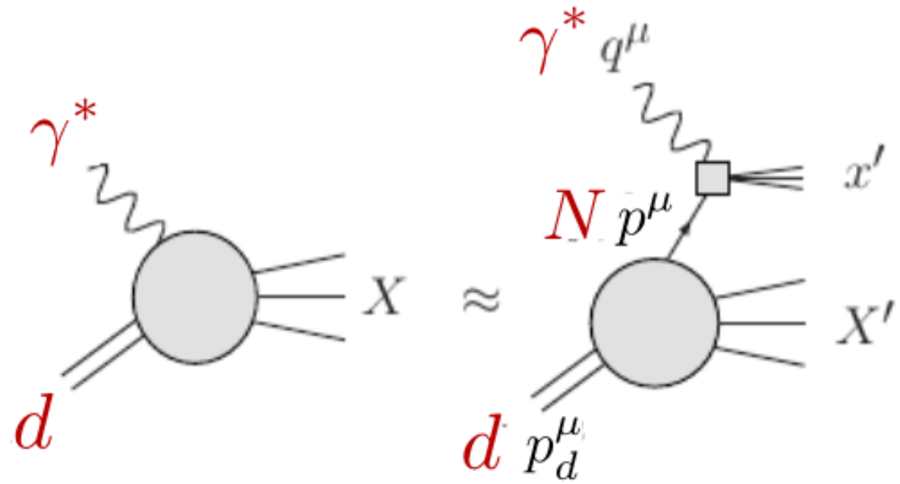

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Free nucleon pdfs/SFs

$p^2 = m_N^2$

Deuterium: off-shell corrections

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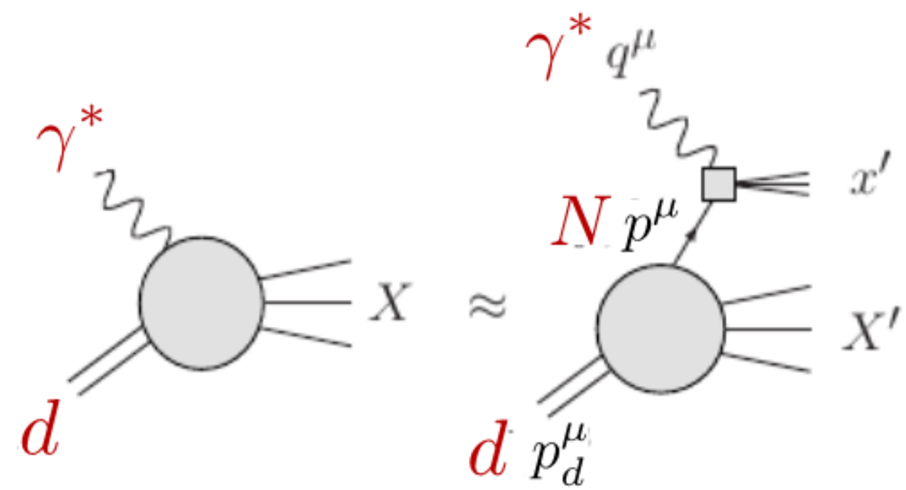

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Free nucleon pdfs/SFs
$p^2 = m_N^2$

Off-shell function
(To be fitted)

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)

\+ valence sum rule

$$\int_0^1 dx \, \delta f^N(x) \; [q(x) - \bar{q}(x)] \; = \; 0$$

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Alekhin, Kulagin, Petti, PRD 96 (2017)

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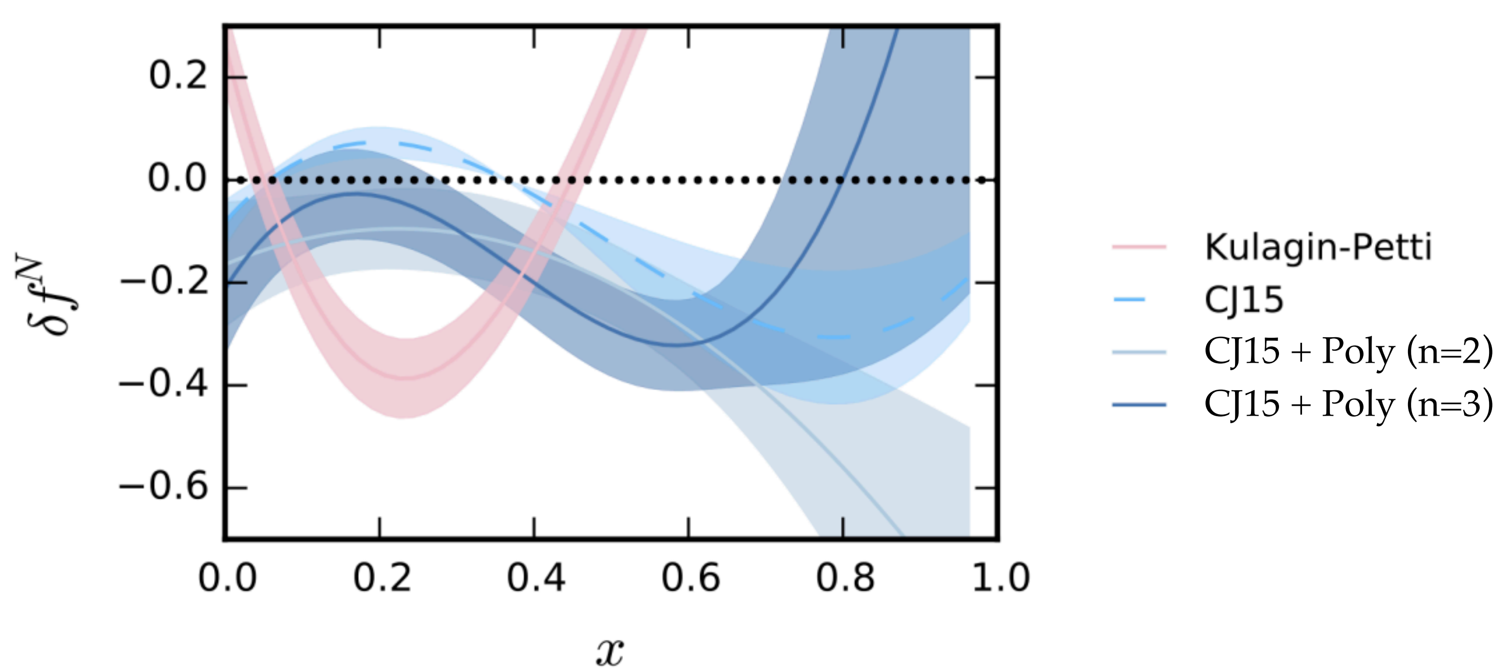

Better agreement with the data w/o imposing nodes a priori to the off-shell function

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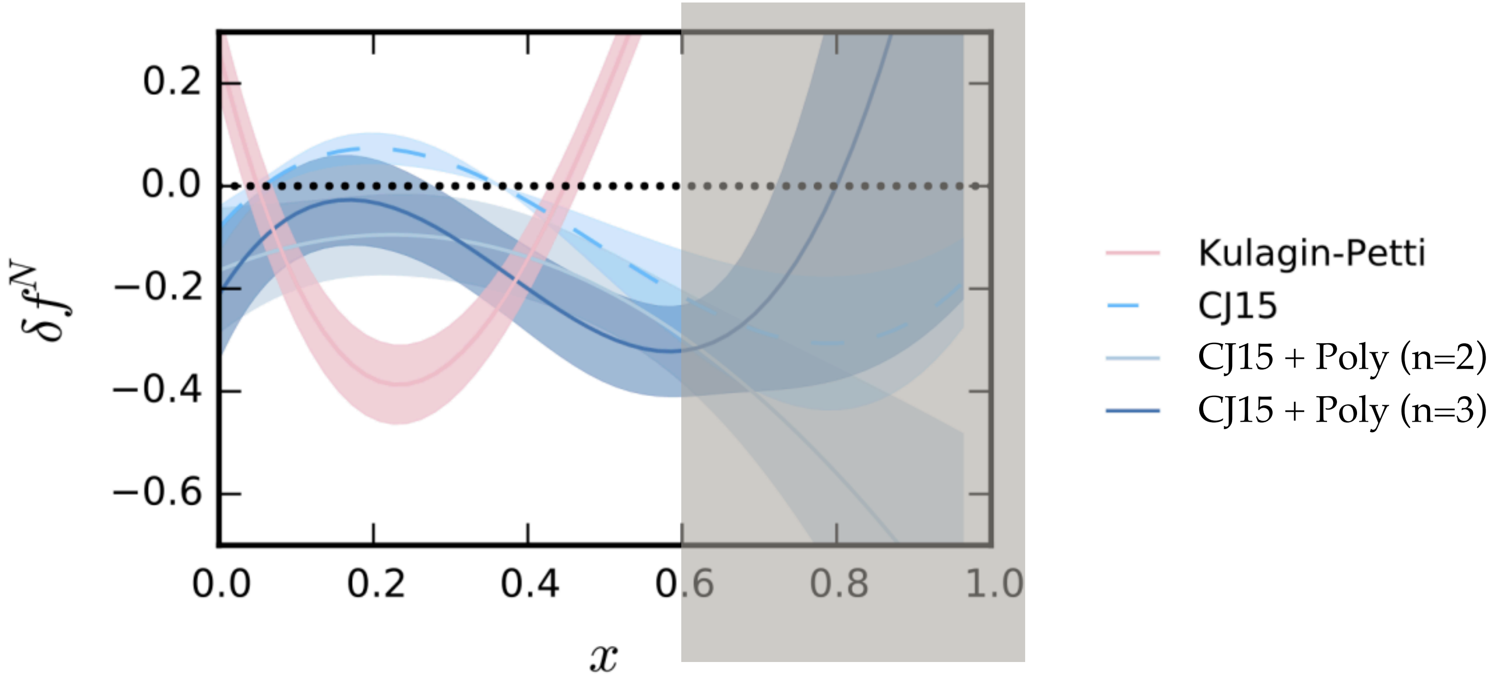

Better agreement with the data w/o imposing nodes a priori to the off-shell function

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

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

Higher-Twist function

Higher Twist correction

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

Additive

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

Higher-Twist function

Higher Twist correction

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

$$C(x) = a_{ht}^{(0)} x^{a_{ht}^{(1)}} (1 + a_{ht}^{(2)} x)$$

Additive

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

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they are related

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CJ fits

Additive

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Impact of HT on n/p ratio

Are experimental observables independent of the choice of the HT?

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Mult HT

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

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Add HT

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

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

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

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Bias in n/p function

Impact of HT on n/p ratio

Are experimental observables independent of the choice of the HT?

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

Impact of HT on n/p ratio

Are experimental observables independent of the choice of the HT?

$$\frac{n}{p} \xrightarrow{x \to 1} \frac{1}{4}$$

LT

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

Add HT

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

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

Impact of HT on n/p ratio

Are experimental observables independent of the choice of the HT?

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Impact of HT on n/p ratio

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$H_p(x) = H_n(x)$ → $\frac{1}{4} + 3\frac{H}{16uQ^2}$

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$H_p(x) = 2H_n(x)$: $\frac{1}{4} + \frac{H}{16uQ^2}$

Impact of HT on n/p ratio

Are experimental observables independent of the choice of the HT?

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

Add HT

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structure function is smaller

Impact of HT on n/p ratio

Are experimental observables independent of the choice of the HT?

$\frac{n}{p} \xrightarrow{x \to 1} \frac{1}{4}$ LT

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

Add HT

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

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

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

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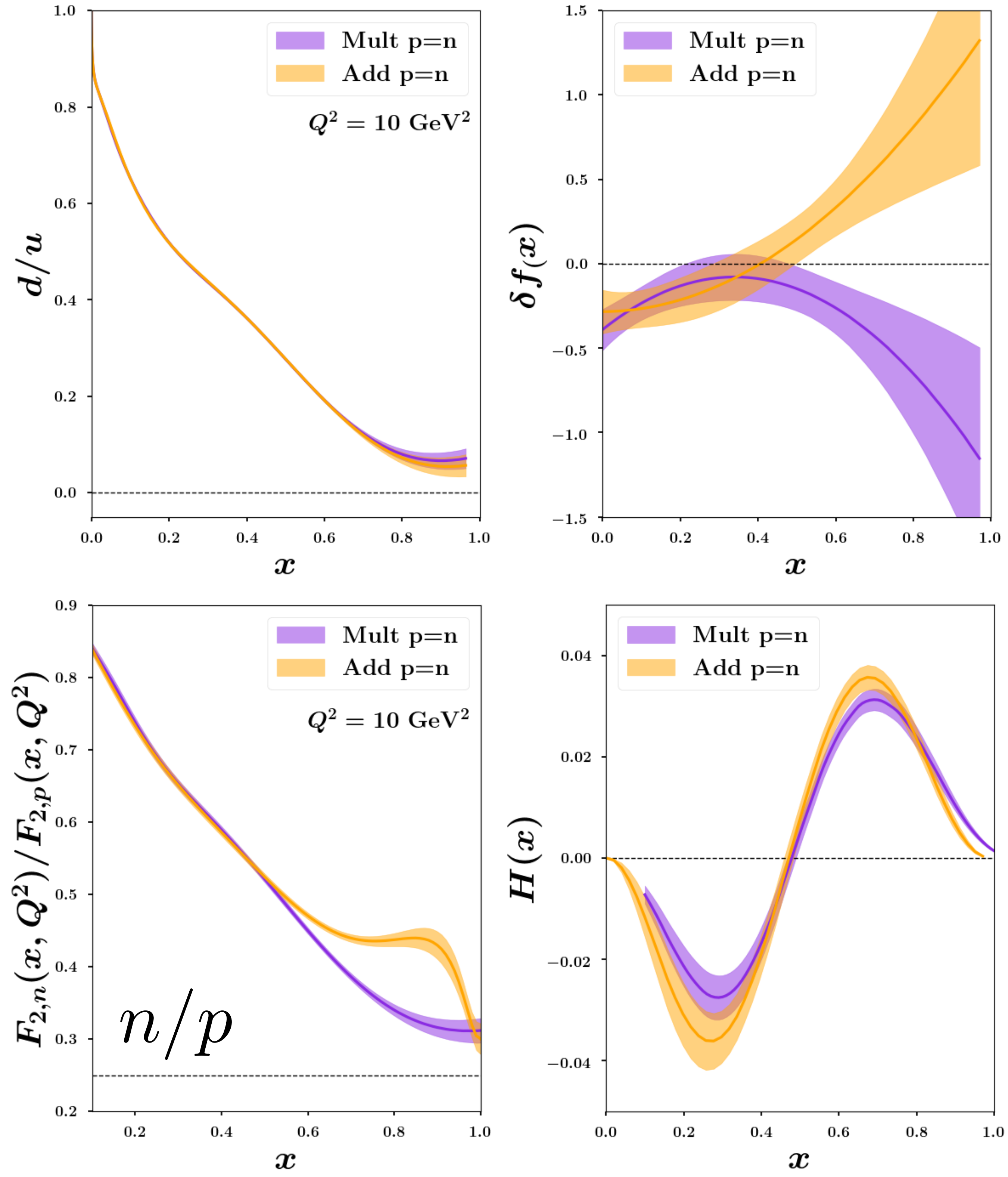
same as Add

Bias not present!

Results in the CJ fitting framework

Case 1: isospin symmetry



Results in the CJ fitting framework

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BUT smaller d/u than Mult

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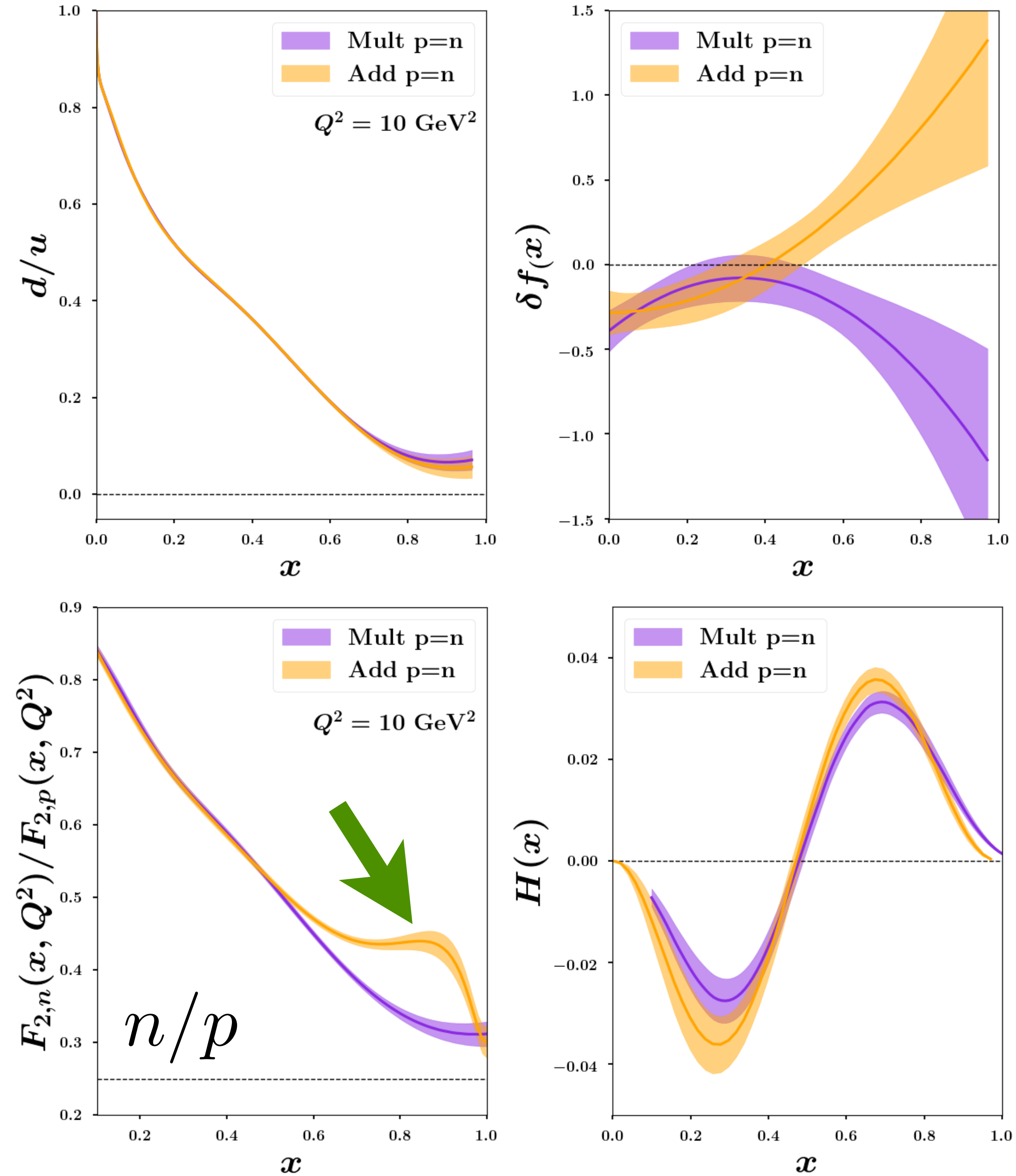

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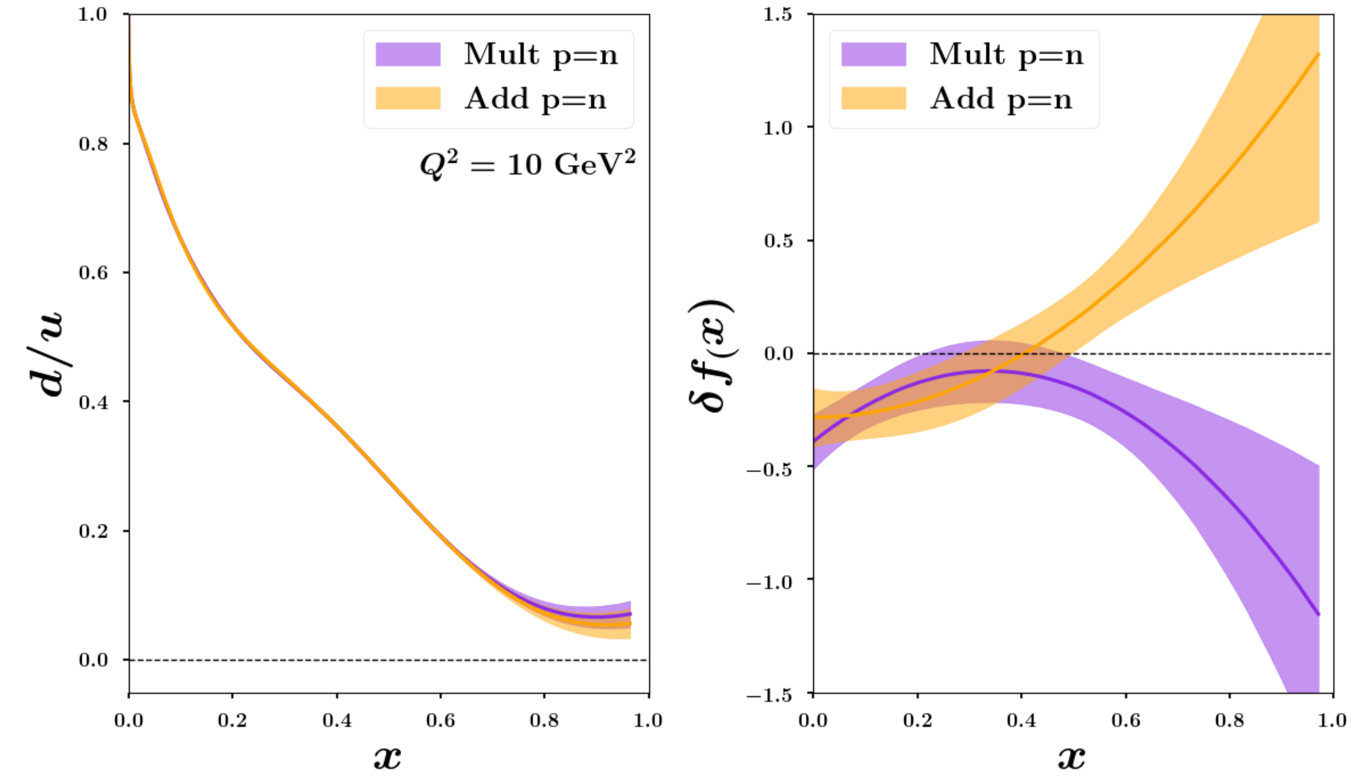
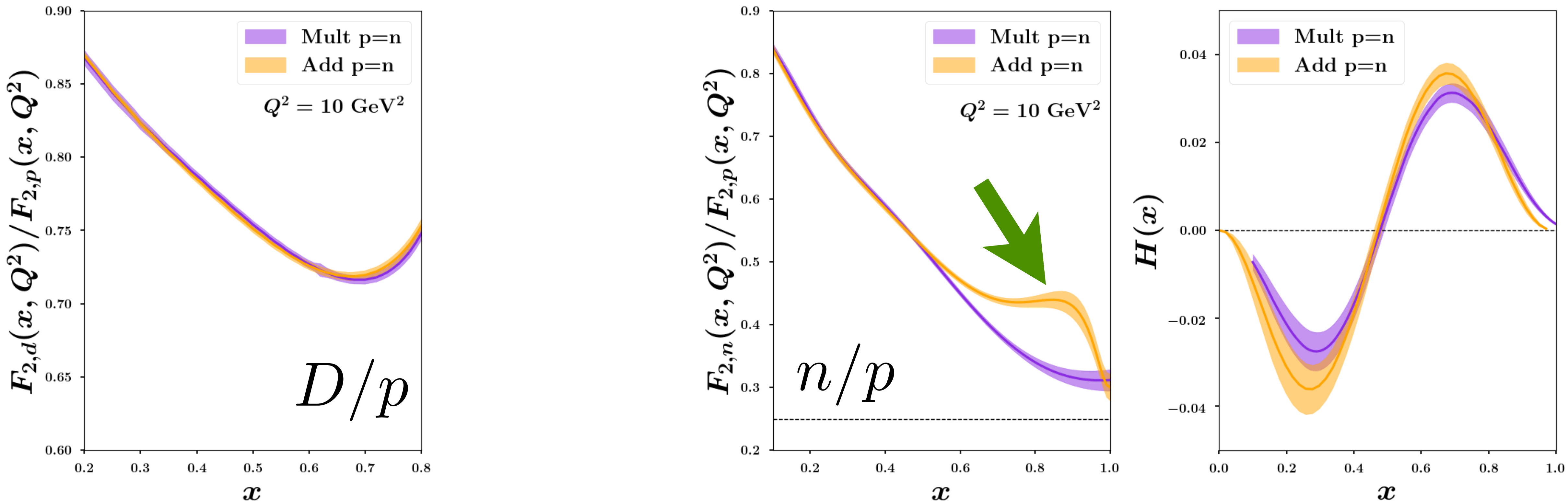
Bias identified

Off-shell compensates n/p bias





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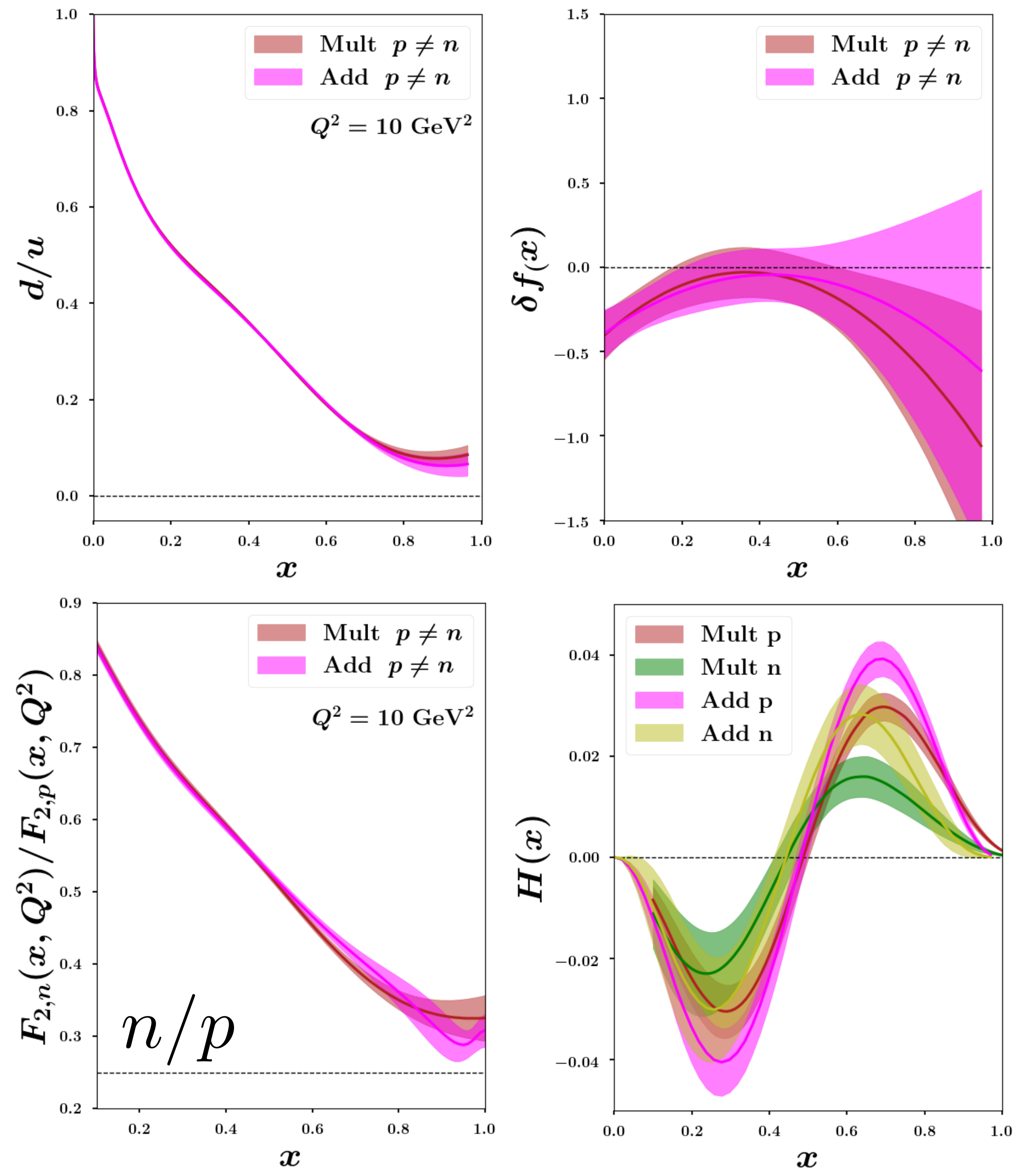
Case 2: isospin breaking

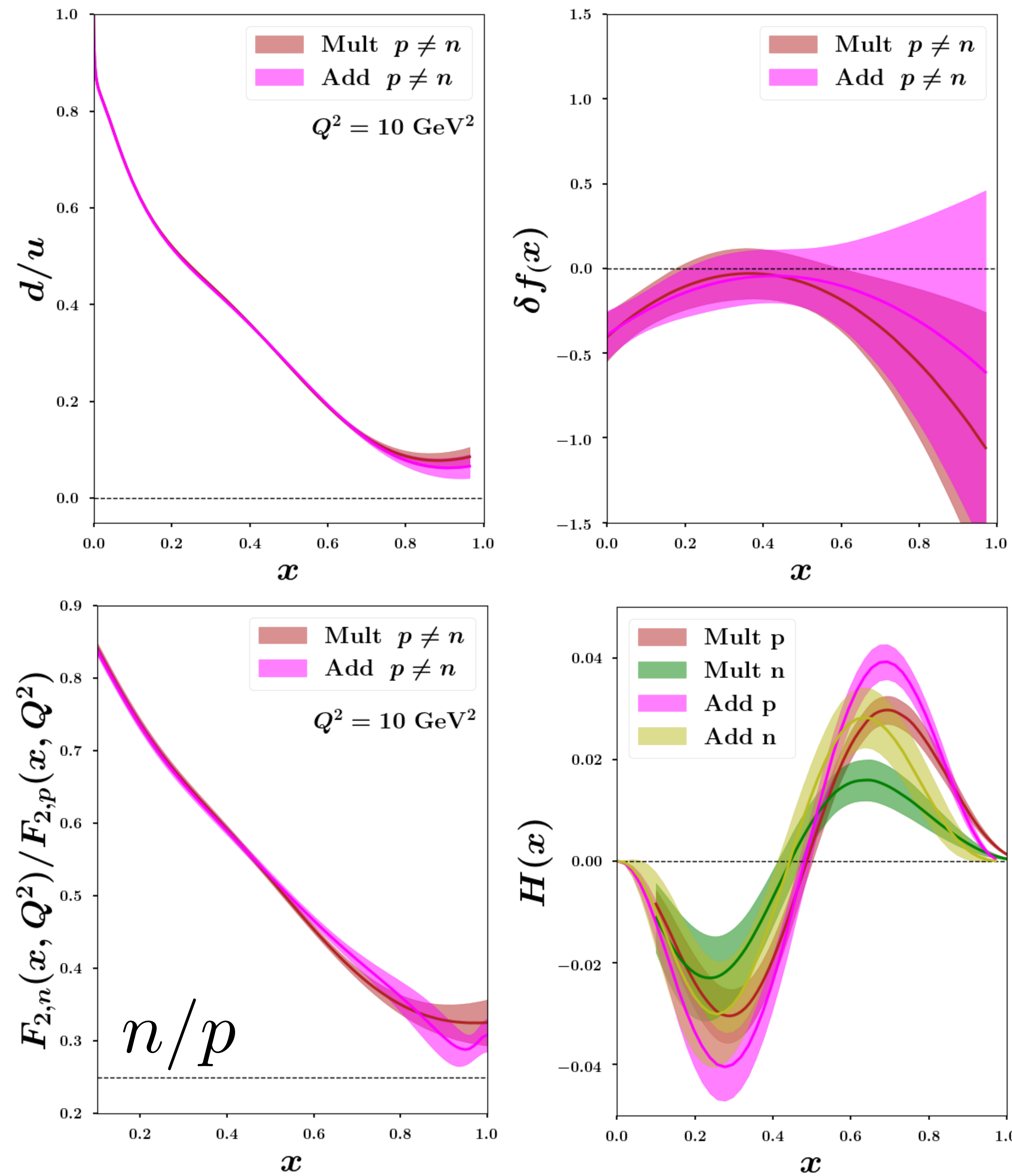


Results in the CJ fitting framework

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

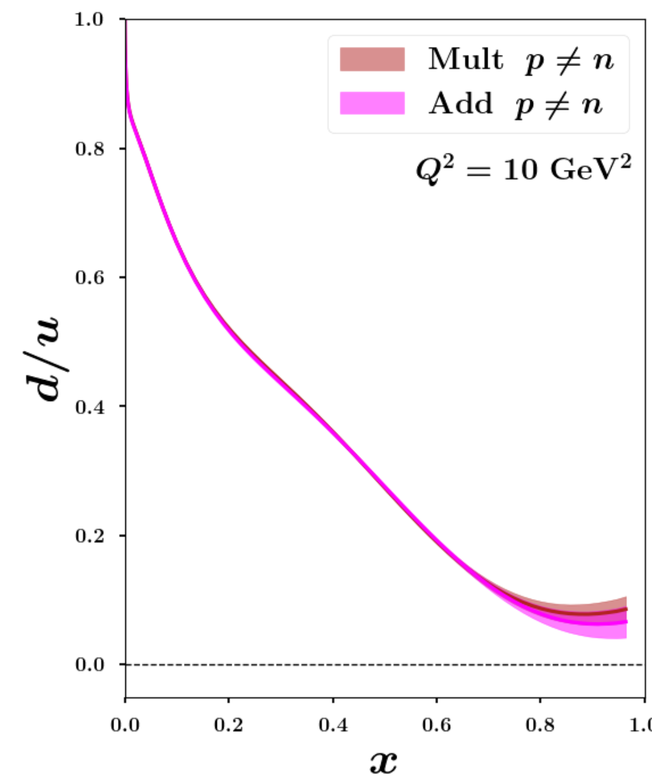
Compatible n/p

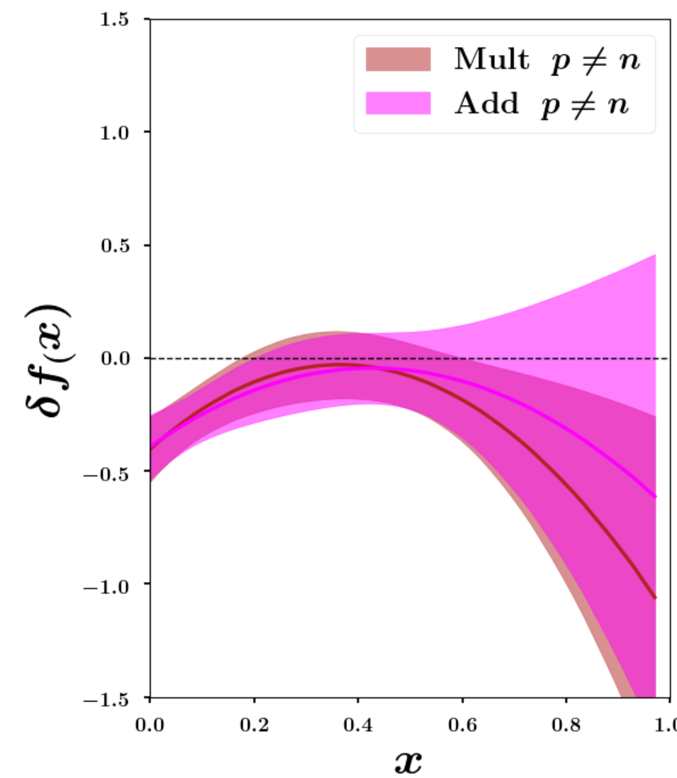
$$H_n(x) \simeq \frac{1}{2} H_p(x)$$

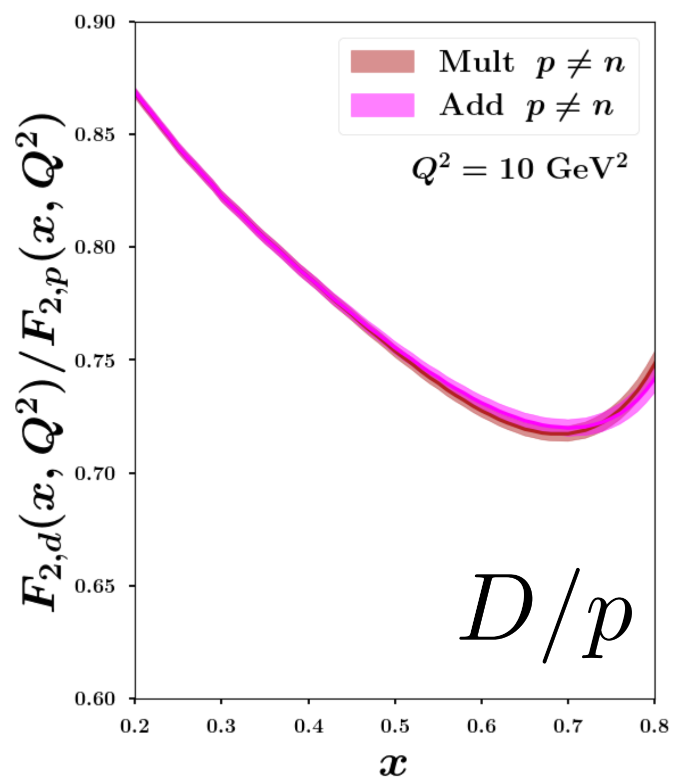
Bias removed

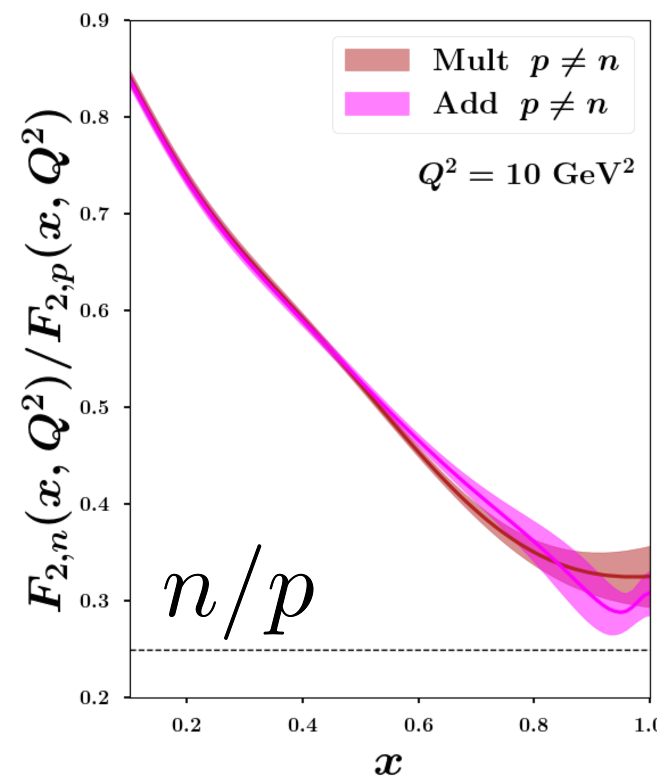
No need of compensation by off-shell

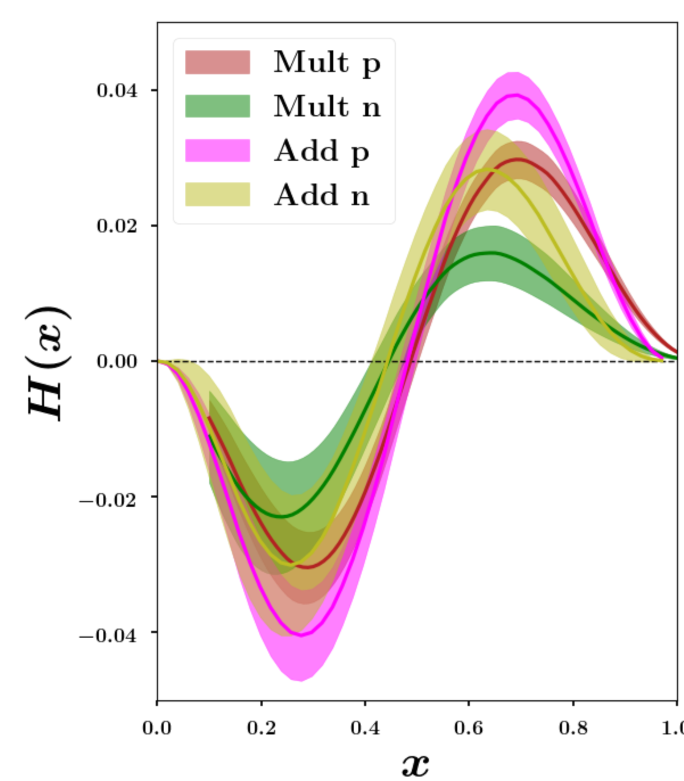
Theory calculation confirmed!





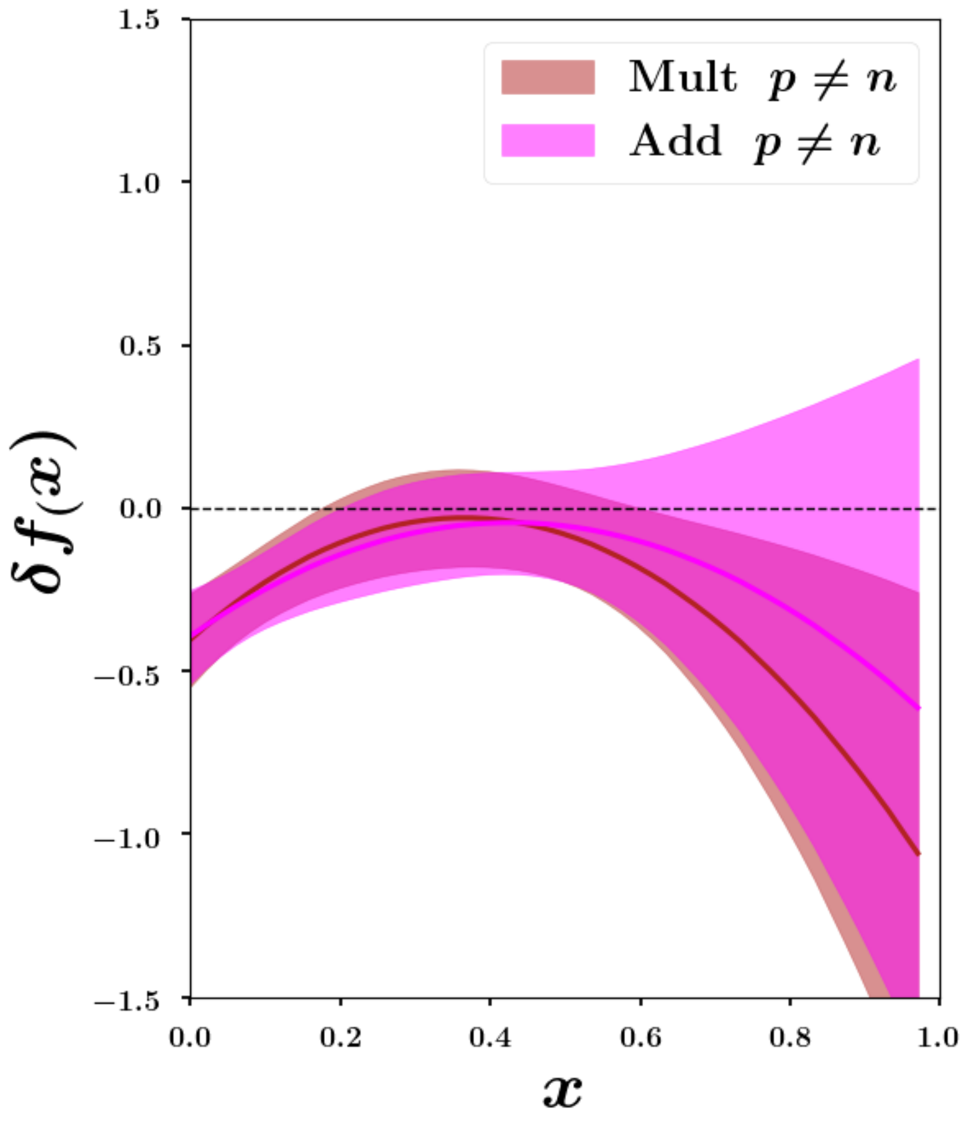






Results in the CJ fitting framework

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



Is the nucleon inside the deuterium almost on-shell?

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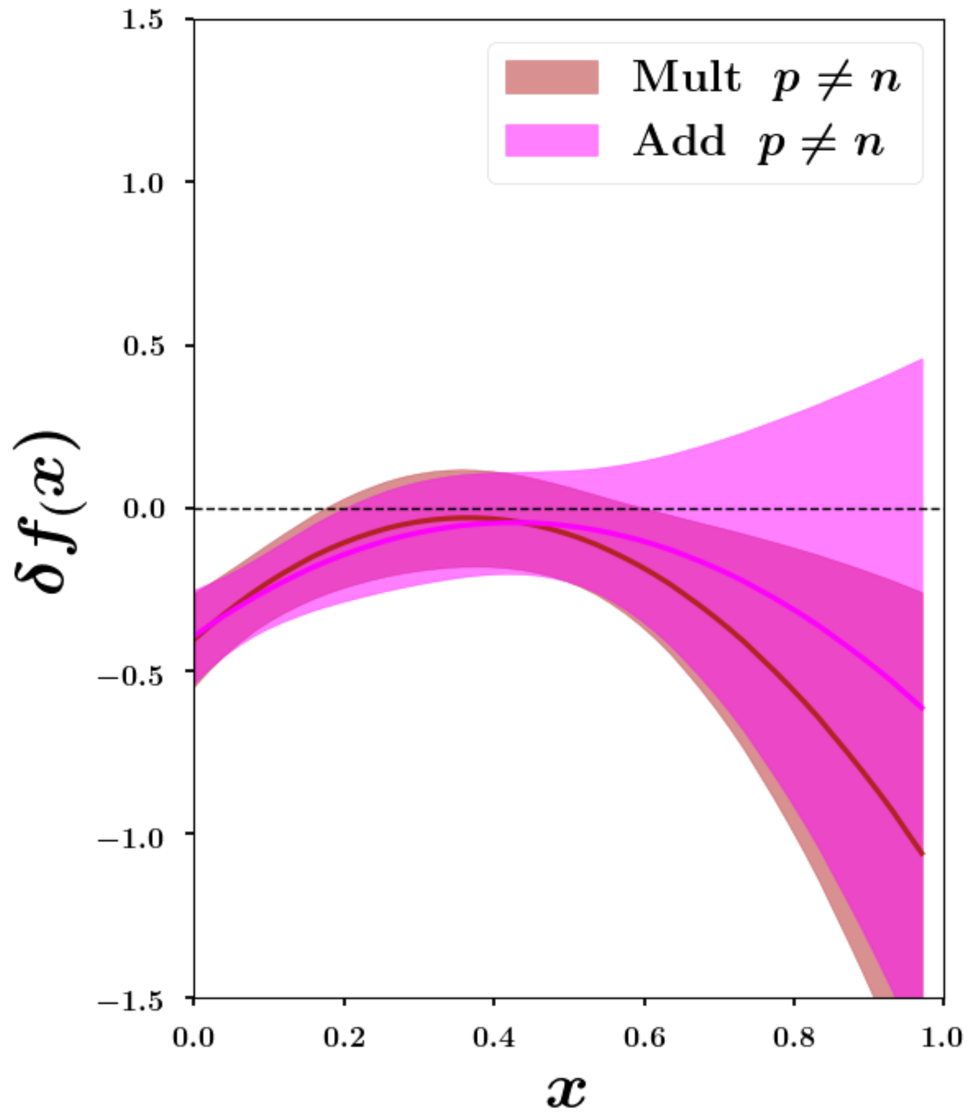

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Need A=3 data to assess flavour dependence of off-shell function

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: $\delta f_u(x) \neq \delta f_d(x)$

Need more information

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We **cannot directly compare** off-shell function at the pdfs level (δf) with the one at the structure function level (δF)

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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

CJ place in PVDIS physics

SoLID can help us
We can help SoLID

PVDIS process

PVDIS Asymmetry

$$A_{\mathrm{PV}} \equiv \frac{d\sigma(\lambda = 1) - d\sigma(\lambda = -1)}{d\sigma(\lambda = 1) + d\sigma(\lambda = -1)}$$

PVDIS process

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$$A_{\mathrm{PV}} \equiv \frac{d\sigma(\lambda = 1) - d\sigma(\lambda = -1)}{d\sigma(\lambda = 1) + d\sigma(\lambda = -1)}$$

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$$Y_\pm = 1 \pm (1-y)^2$$

PVDIS process

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$$F_{2UU}(x,Q^2) = F_2^{(\gamma)} - g_V^e \eta_{\gamma Z} F_2^{(\gamma Z)} + \left({g_V^e}^2 + {g_A^e}^2\right)\eta_Z F_2^{(Z)},$$

$$F_{2LU}^{\pm}(x,Q^2) = \mp g_A^e \eta_{\gamma Z} F_2^{(\gamma Z)} \pm 2 g_V^e g_A^e \eta_Z F_2^{(Z)},$$

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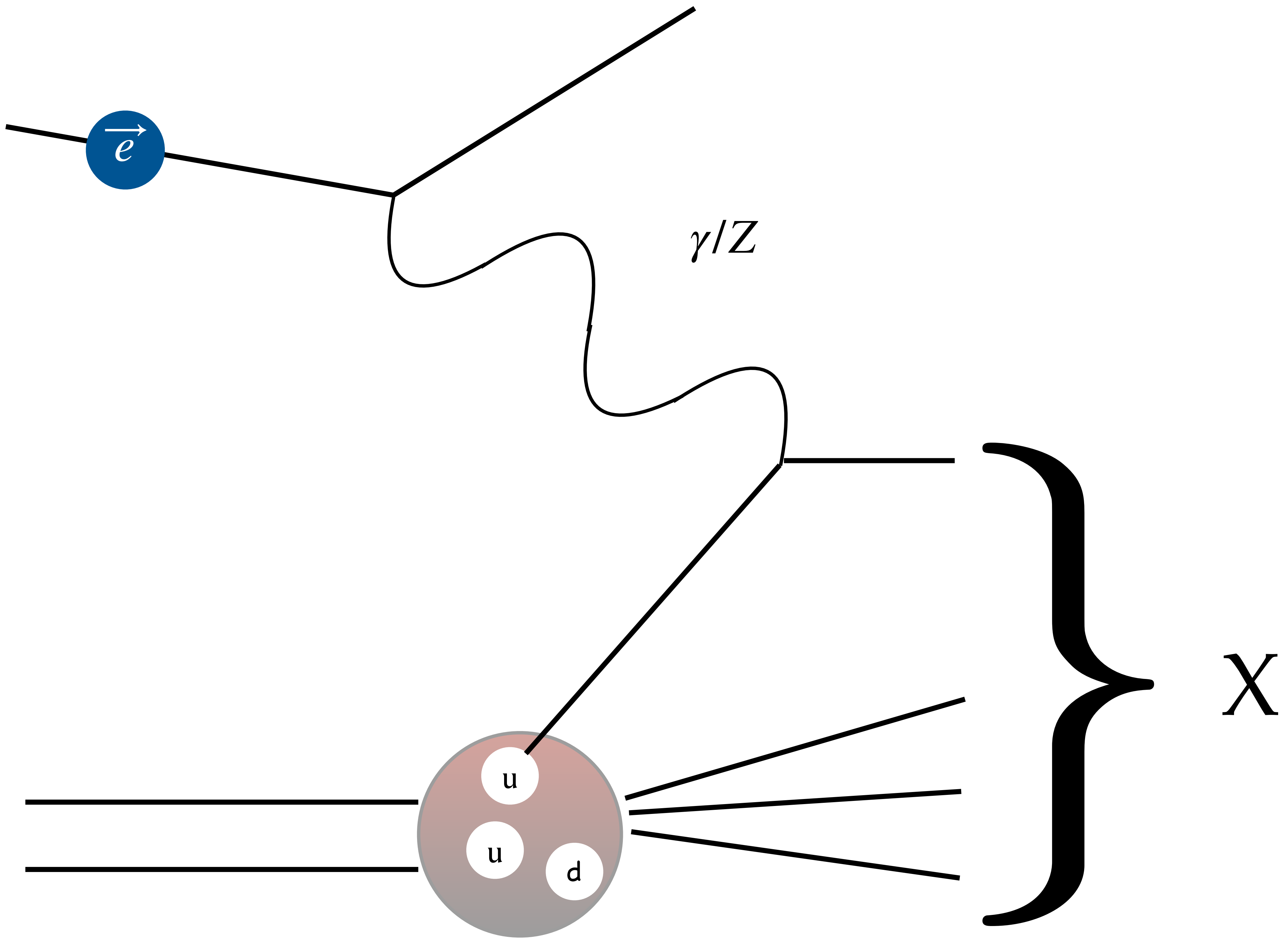
...but be careful

PVDIS process: proton target



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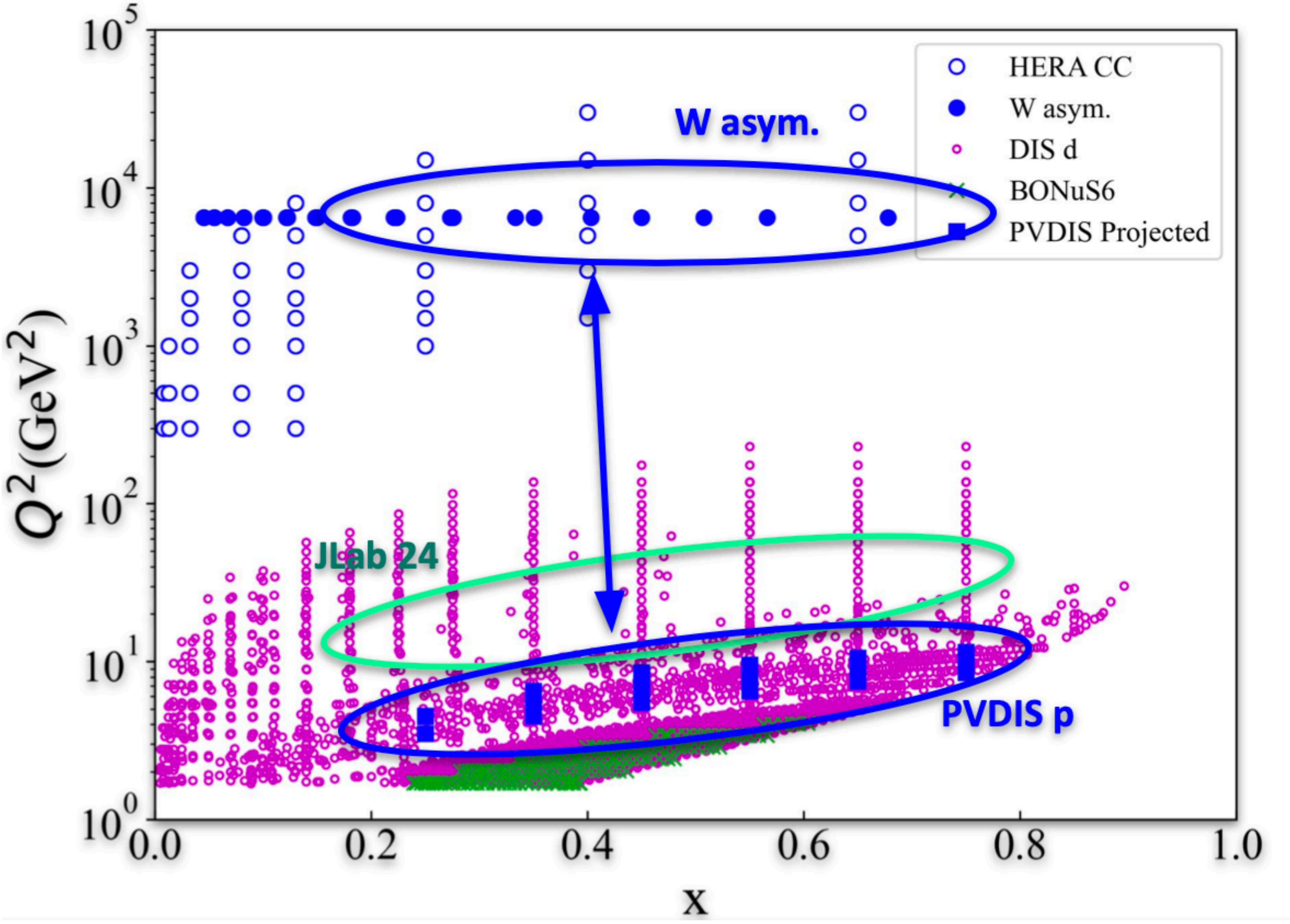

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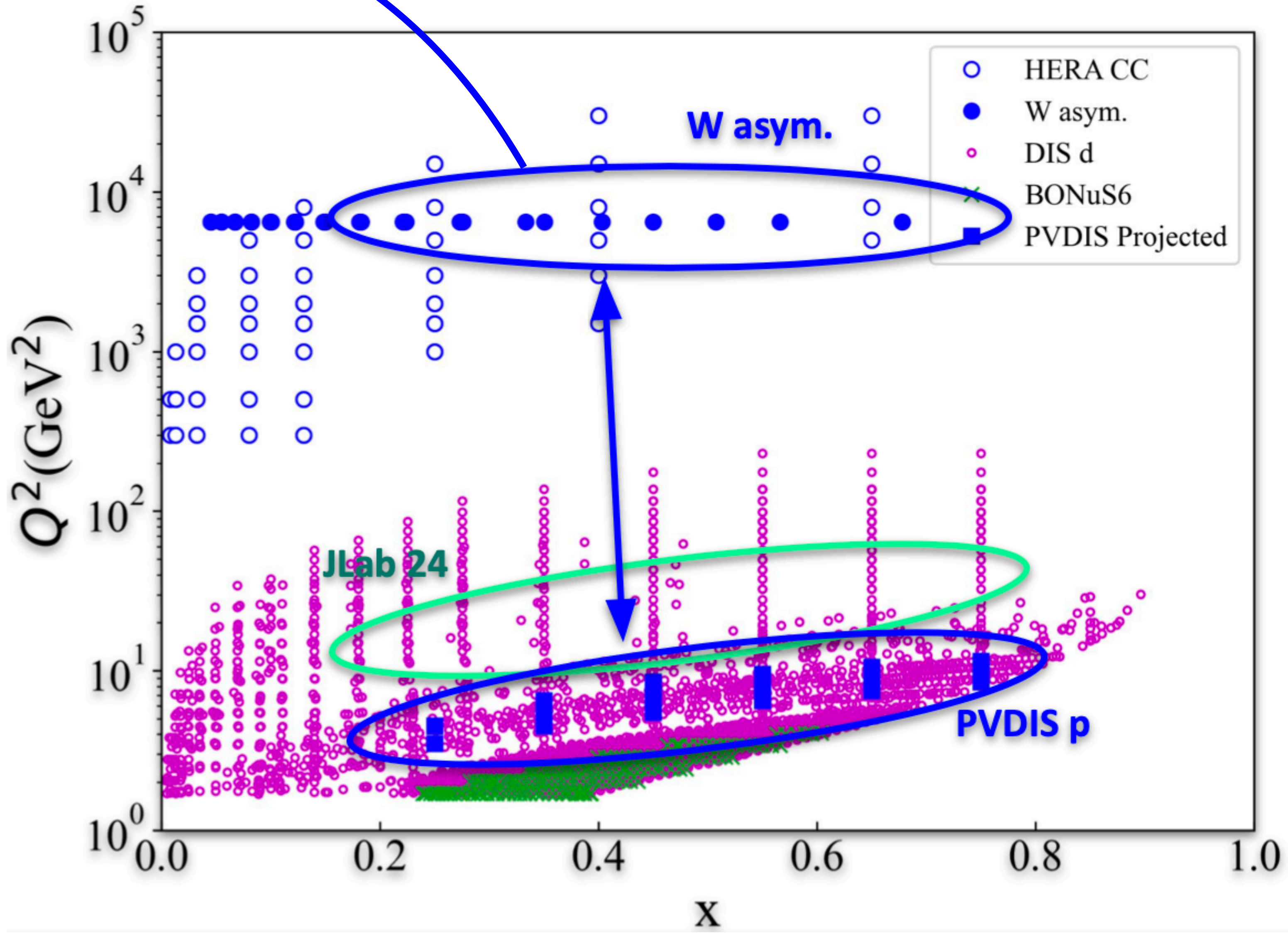
$$A_W \longrightarrow \frac{1 - d/u}{1 + d/u}$$



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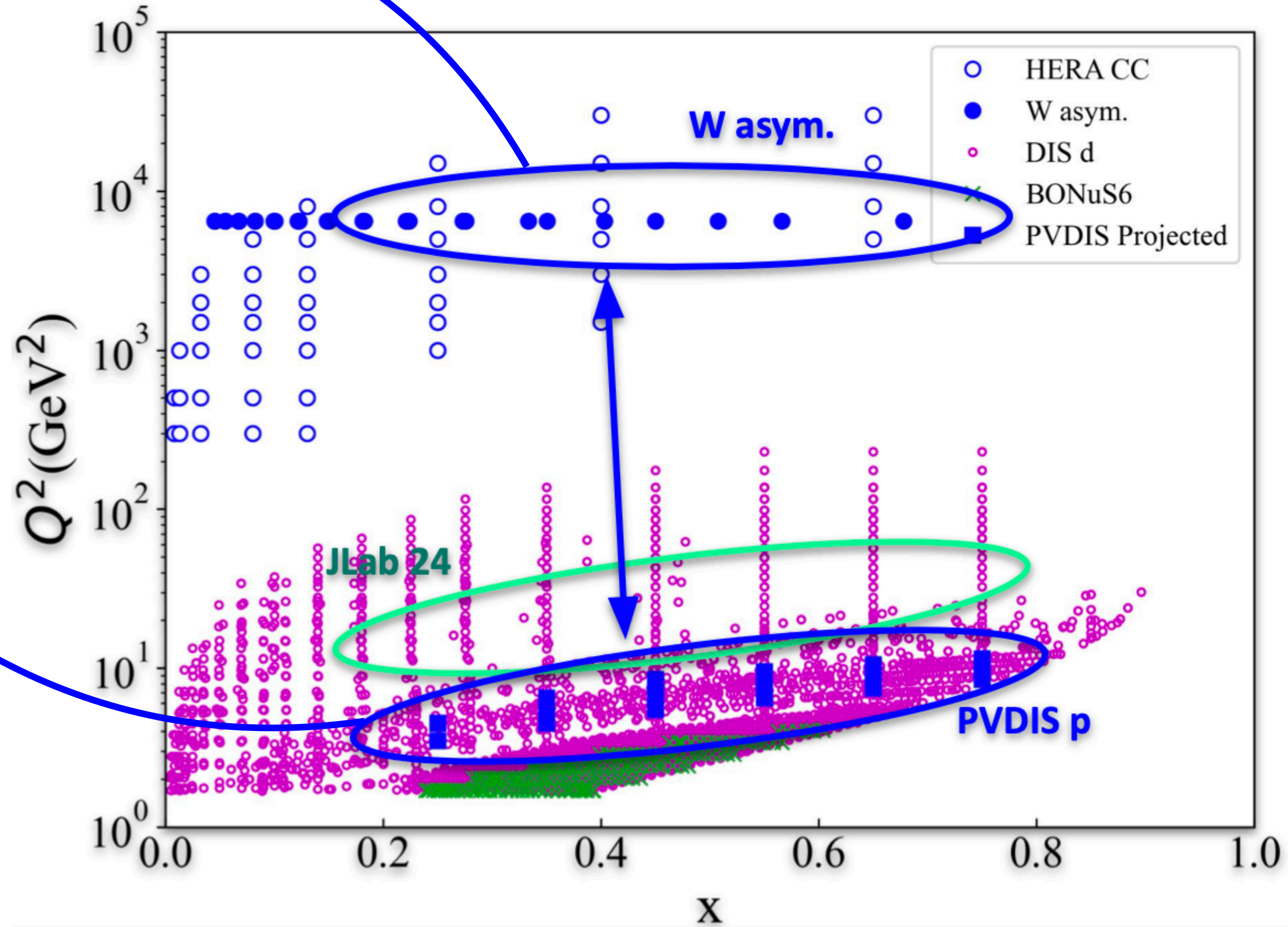
$\sin^2\theta_W$ fixed



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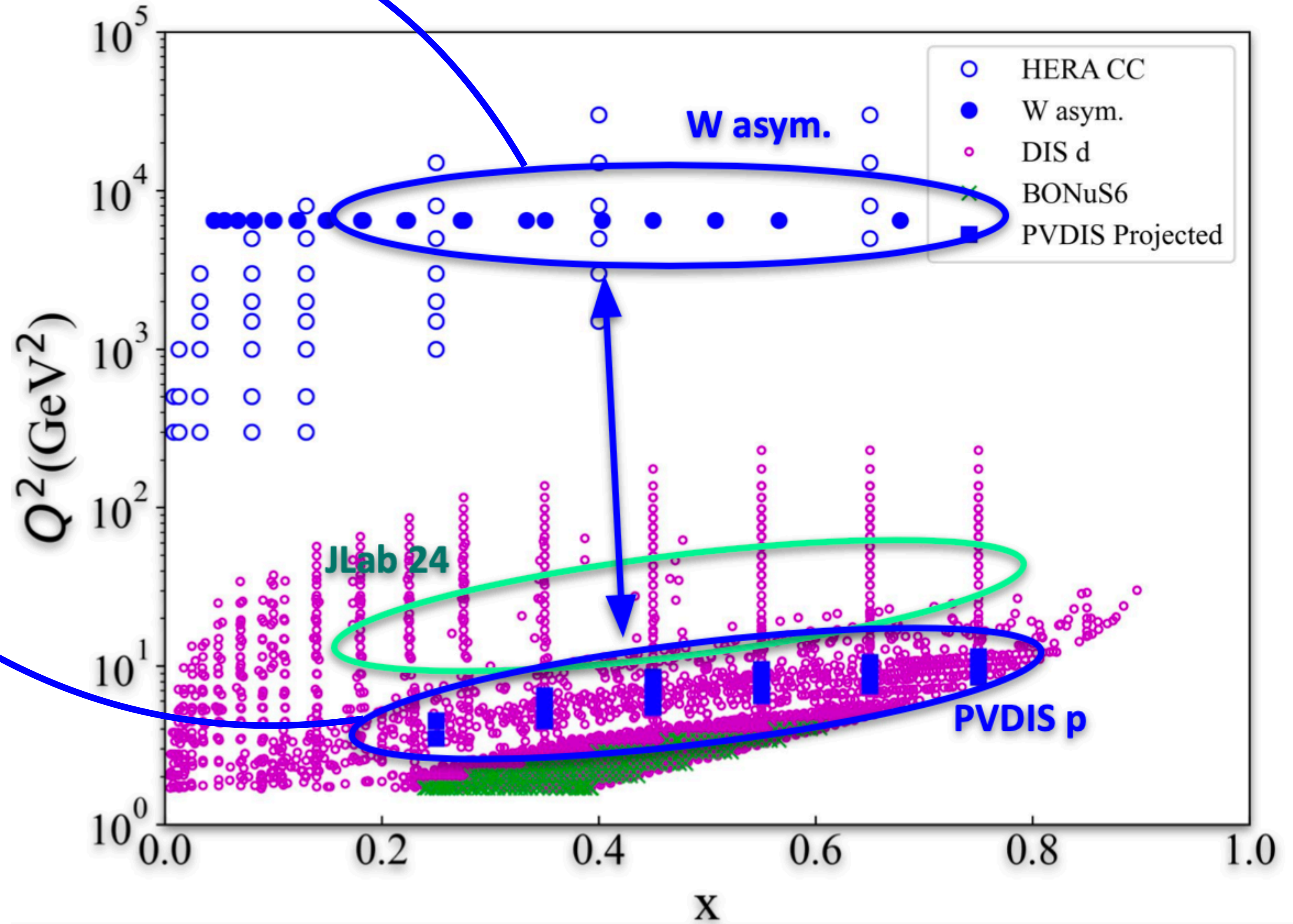
PVDIS on proton is sensitive to d/u at large x



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Be careful: experimental data with very high precision ($< 1\%$)

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Parton Model calculation (LO)

+ $O(\alpha_s)$ corrections

+ Target Mass corrections (TMC)

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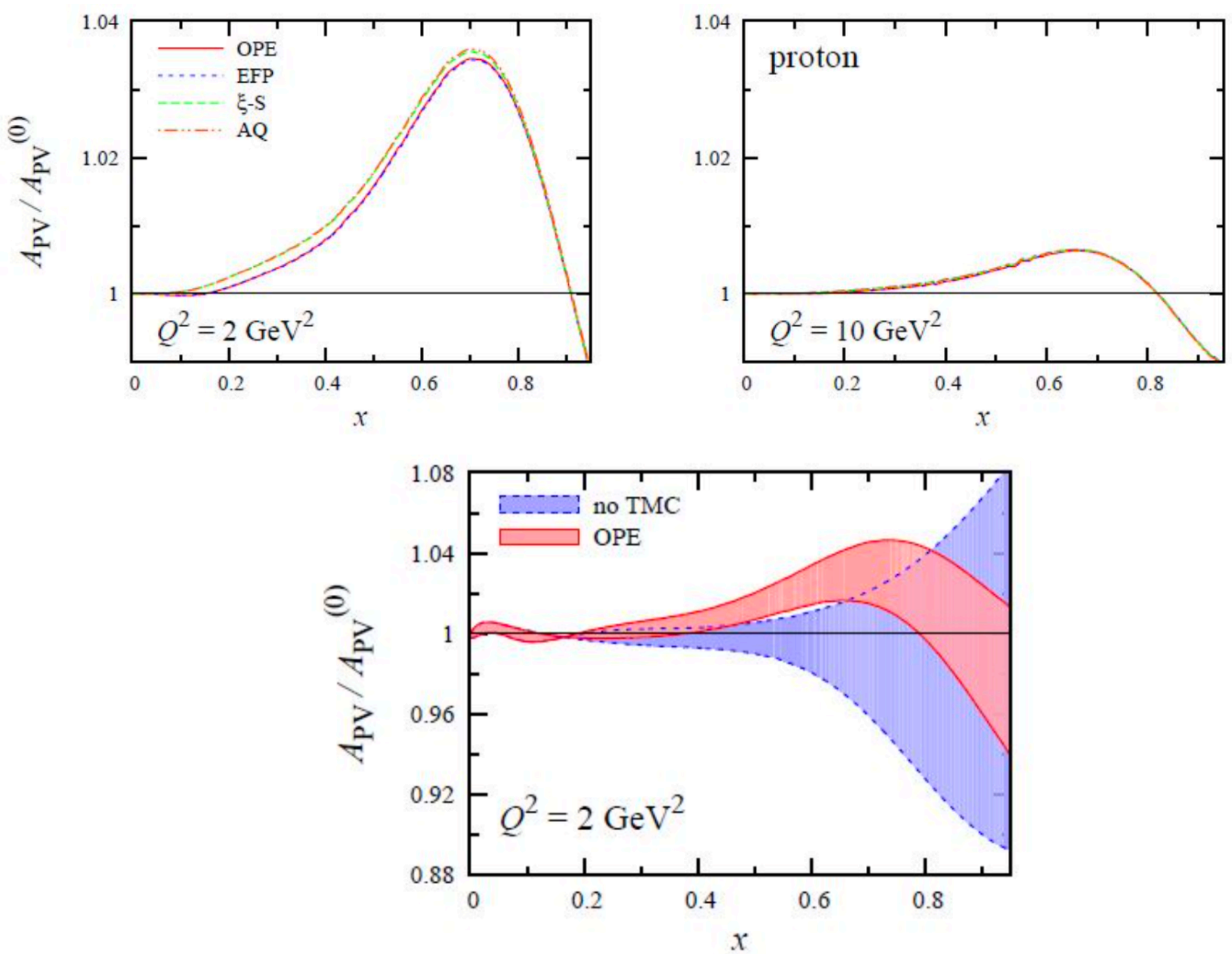

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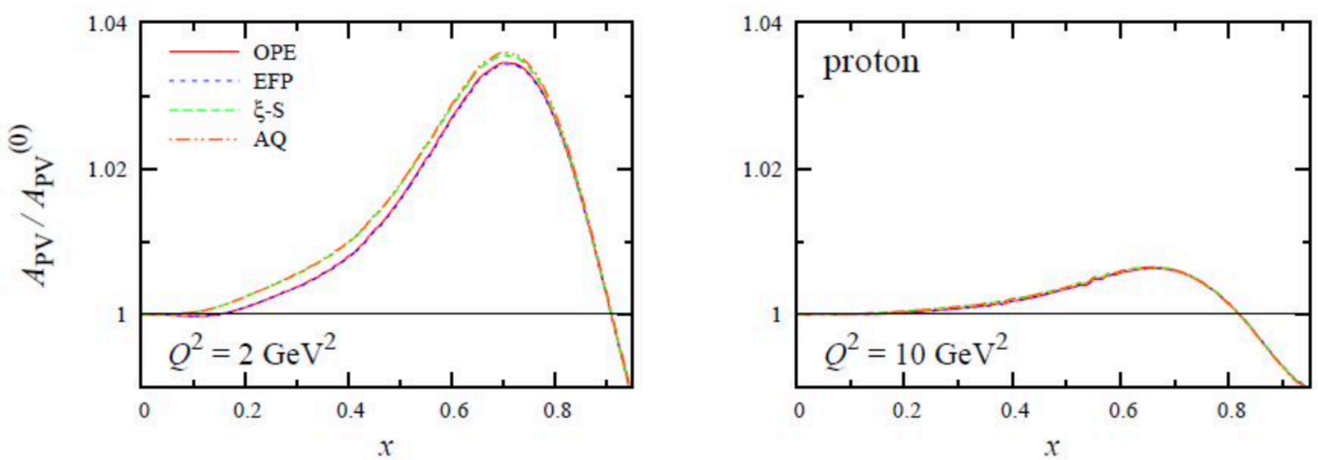
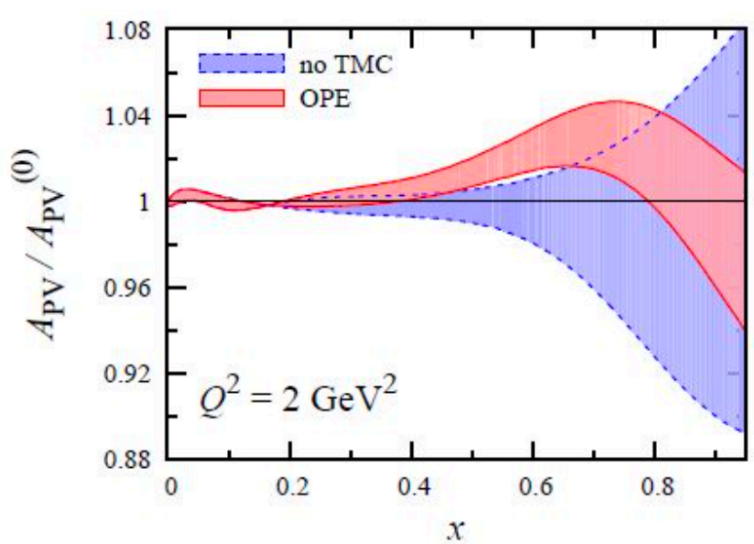


Non-negligible impact at low Q^2



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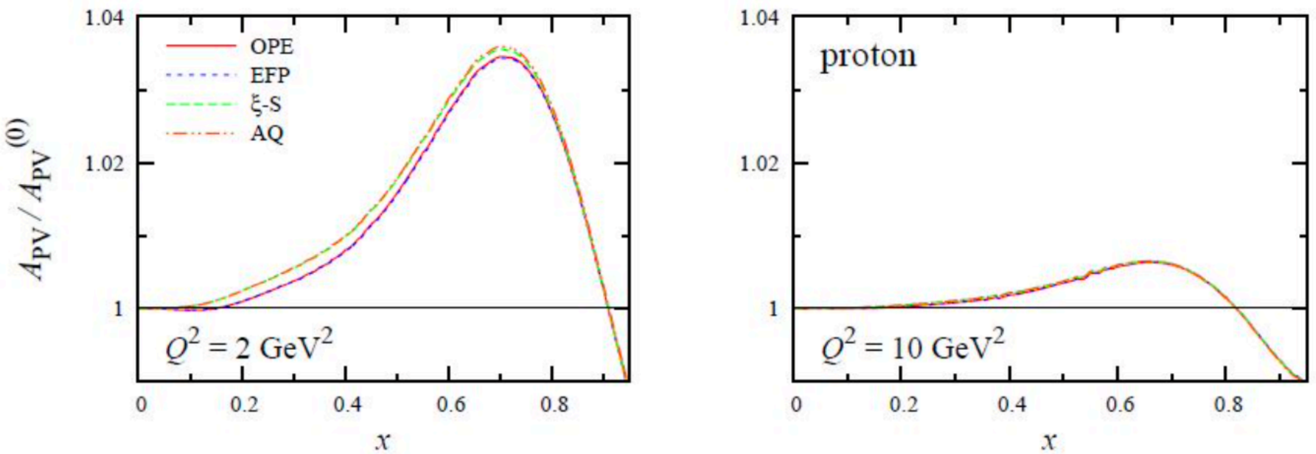

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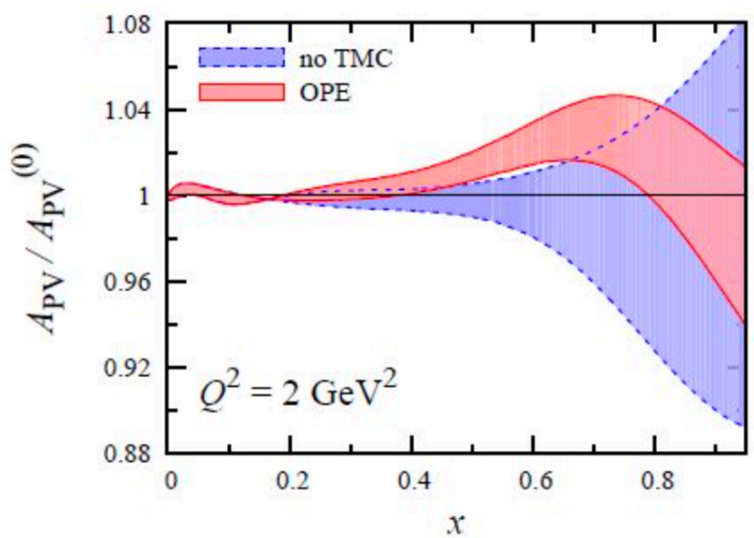
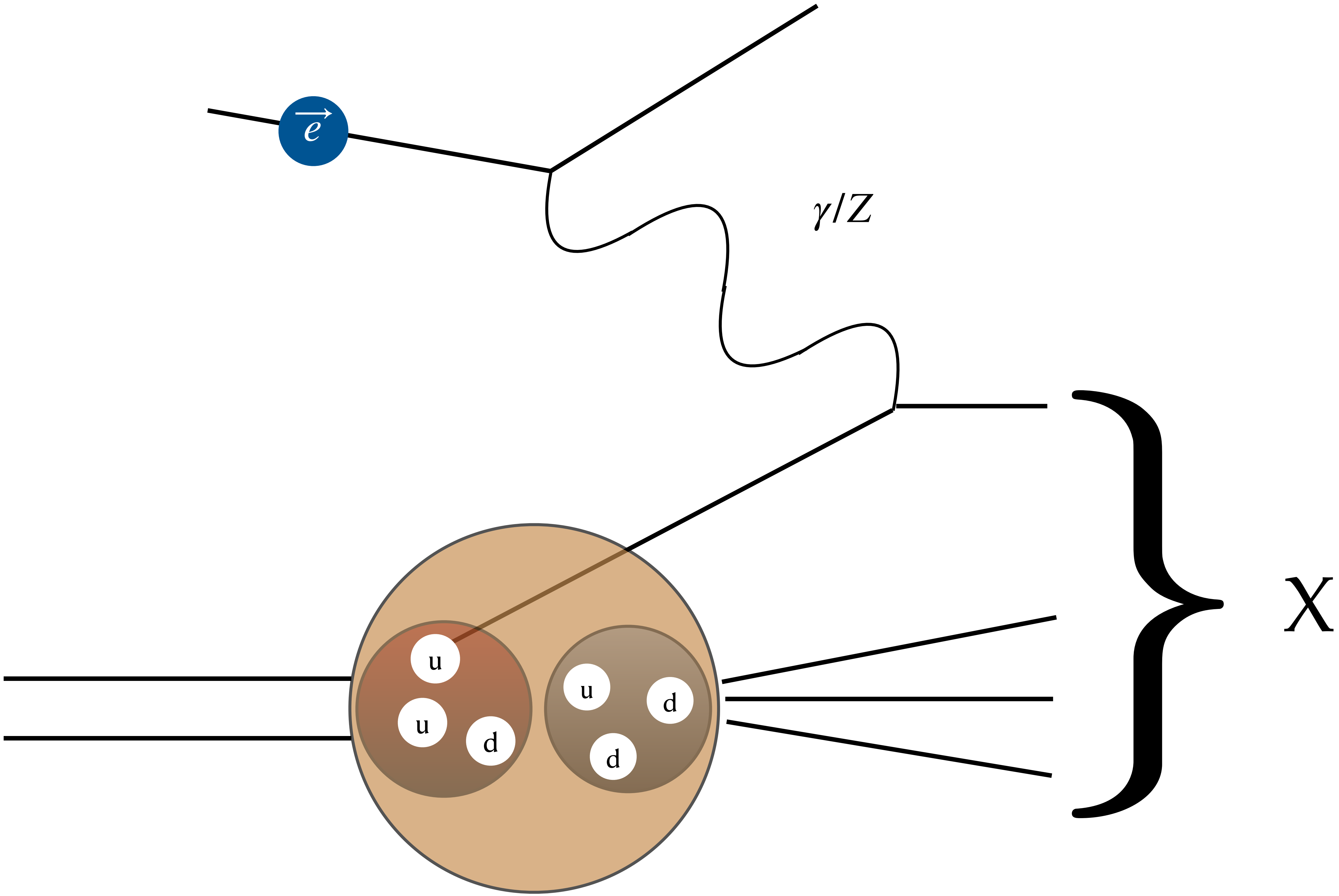


Even if subleading, it has to be considered

PVDIS process: deuteron target



PVDIS process: deuteron target

$$A_{PV} \sim \left(\frac{9}{5} - 4\sin^2\theta_W + C\frac{s+\bar{s}}{u+\bar{u}+d+\bar{d}} \right)$$

PVDIS process: deuteron target

$$A_{PV} \sim \left(\frac{9}{5} - 4\sin^2\theta_W + C\frac{s+\bar{s}}{u+\bar{u}+d+\bar{d}}\right)(1+\delta f) \; + \; HT \; + \; F_3^{\gamma Z}$$

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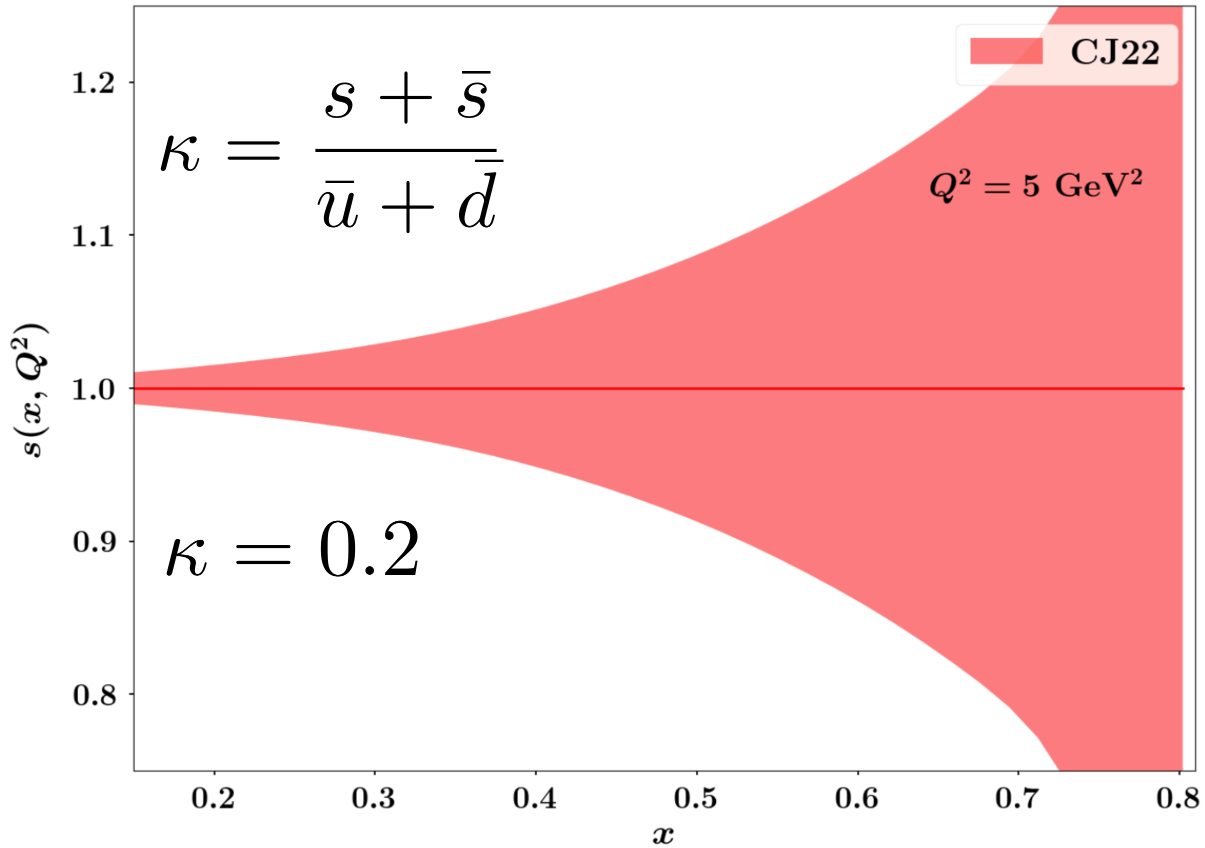
PVDIS on deuteron is sensitive to s-quark at large x



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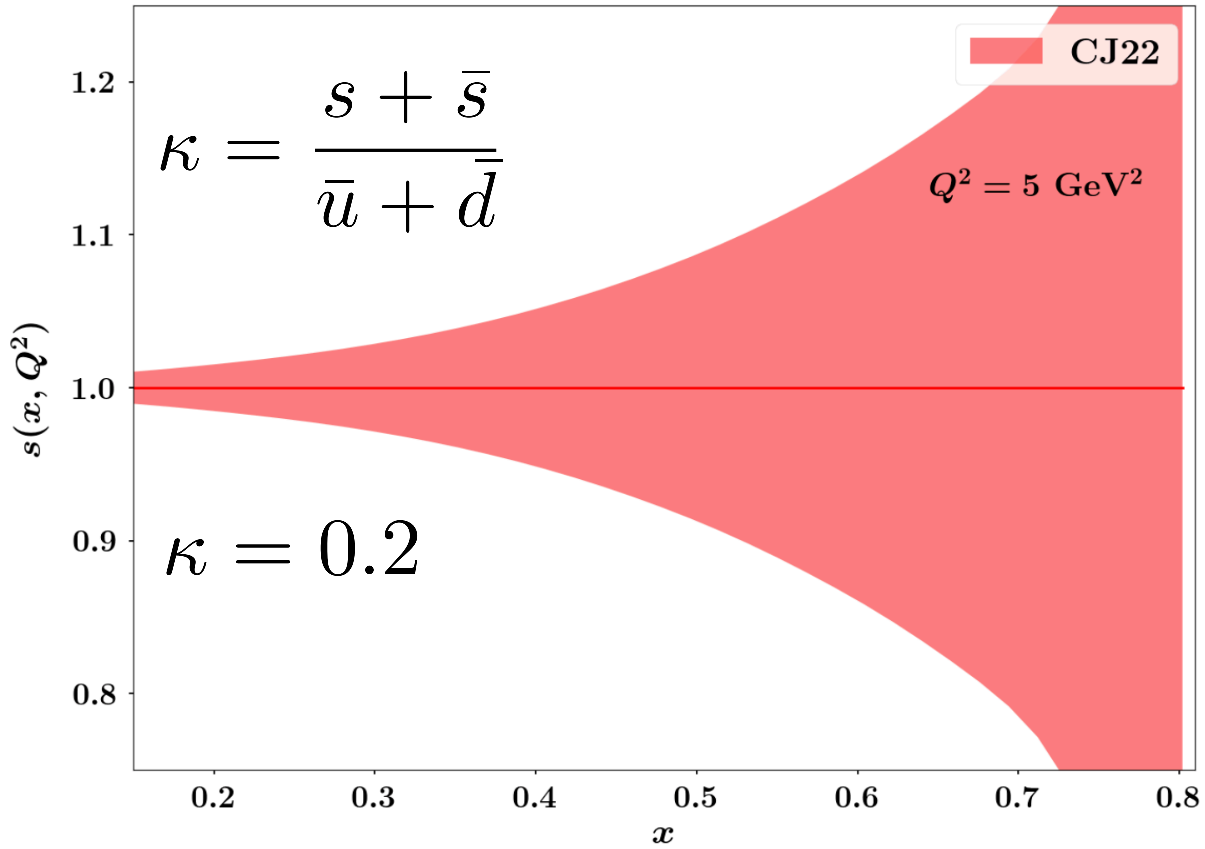
Nuclear corrections must be taken into account



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PVDIS process: deuteron target

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PVDIS on deuteron gives a direct access to EW mixing angle!

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$$q(x, Q^2)$$

$$\sin^2\theta_W$$

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$\sin^2\theta_W$

TMC

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$\sin^2\theta_W$

$\delta f(x)$

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Nucl. Corrections

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[Global fit]

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[Global fit]

If we find “anomaly”?

PVDIS process: deuteron target

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$q(x, Q^2)$

HT

$F_3^{\gamma Z}$

$\sin^2\theta_W$

$\delta f(x)$

TMC

Nucl. Corrections

[Global fit]

If we find "anomaly"?

→ **Strong PV!**

See my talk of this morning

SoLID can help us

- Good number of very precise experimental data
- PVDIS on proton: d/u ratio at large x
- PVDIS on deuteron: s-quark at large x

SoLID can help us

- Good number of very precise experimental data
- PVDIS on proton: d/u ratio at large x
- PVDIS on deuteron: s-quark at large x
- **Improve our knowledge on PDFs at large x**

SoLID can help us
We can help SoLID

- We have the knowledge to treat the corrections needed
- TMC + HT
  (PVDIS on proton)
- Nuclear corrections
  (PVDIS on deuteron)

SoLID can help us
We can help SoLID

- We have the knowledge to treat the corrections needed
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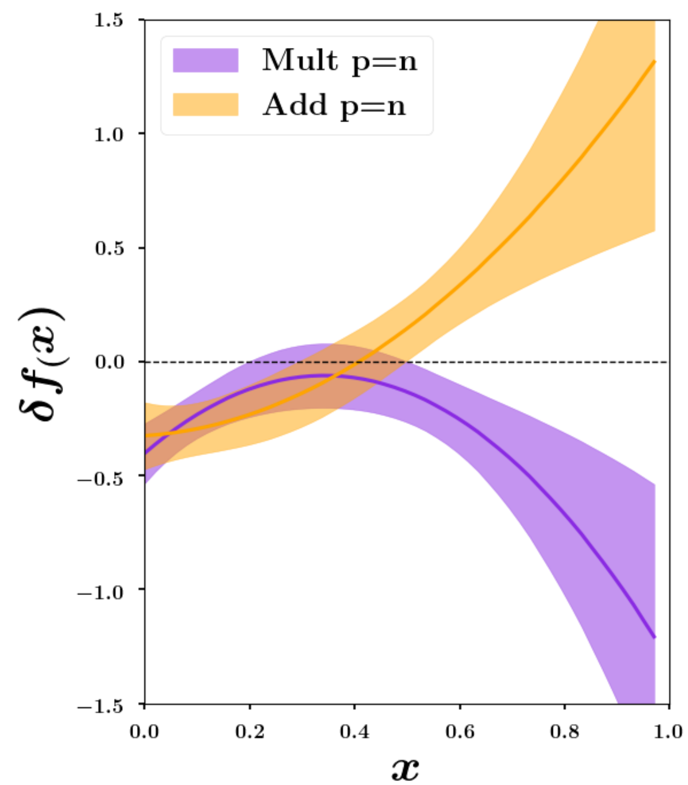
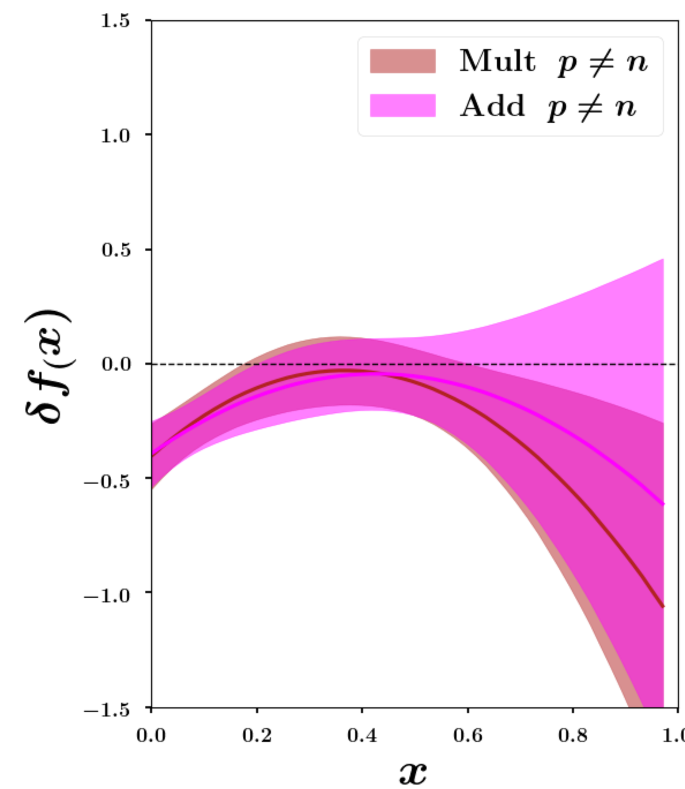
  (PVDIS on proton)
- Nuclear corrections
  (PVDIS on deuteron)
- **More refined test of SM physics**

Backup

Off-shell table

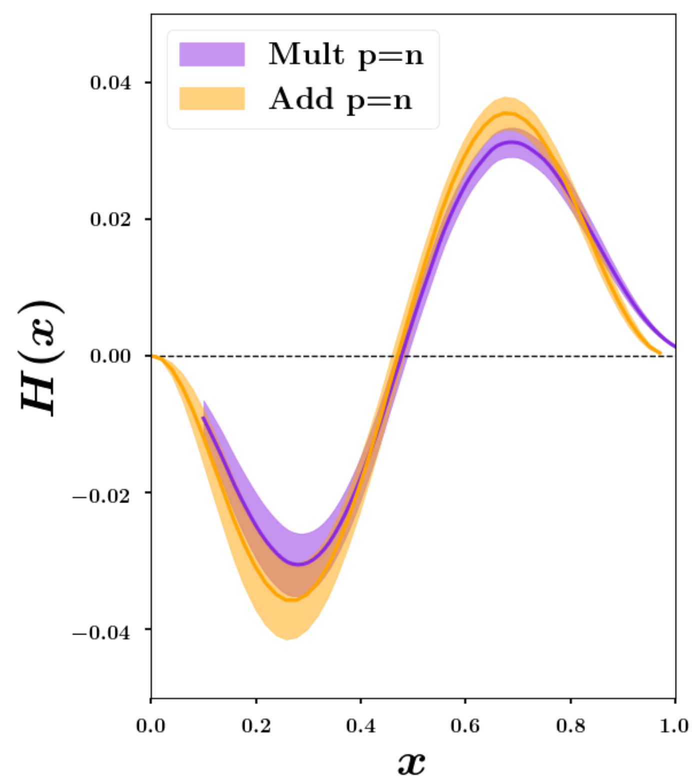
higher-twist \ isospin	Symmetric	Non symmetric
Multiplicative		
Additive		

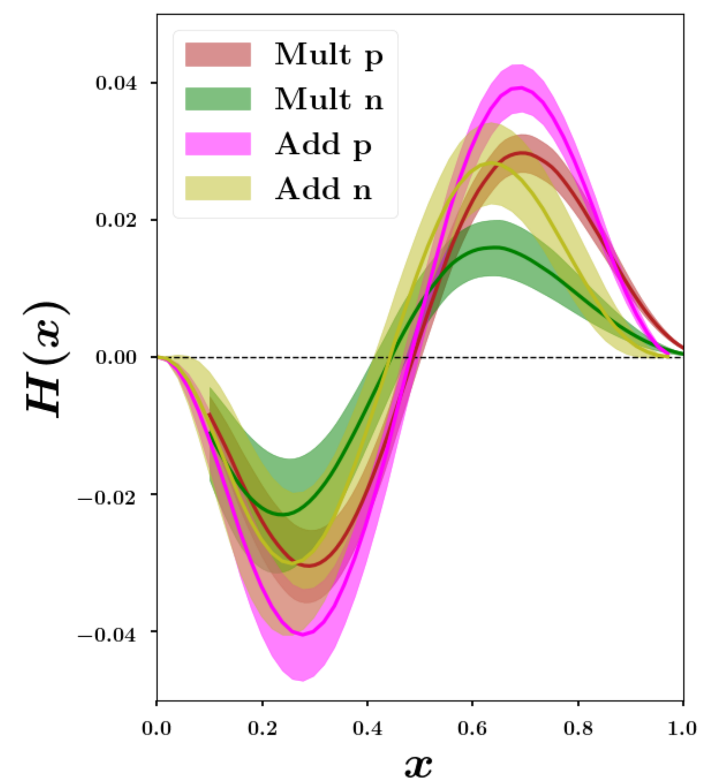




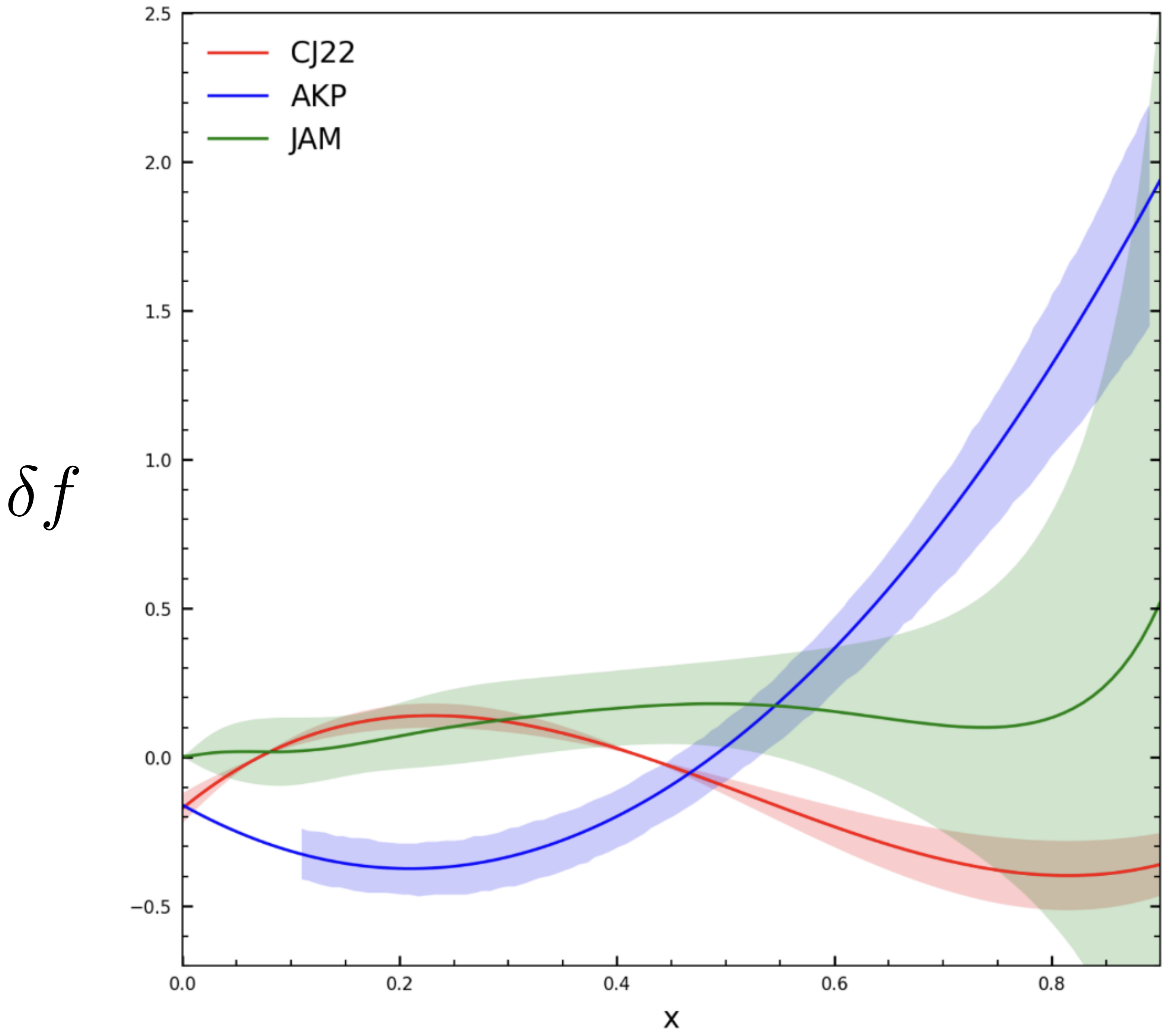
Higher-Twist table

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





AKP vs CJ



AKP results

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

AKP results

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

Add HT (p=n) as baseline choice

H_2, H_T parametrized

AKP results

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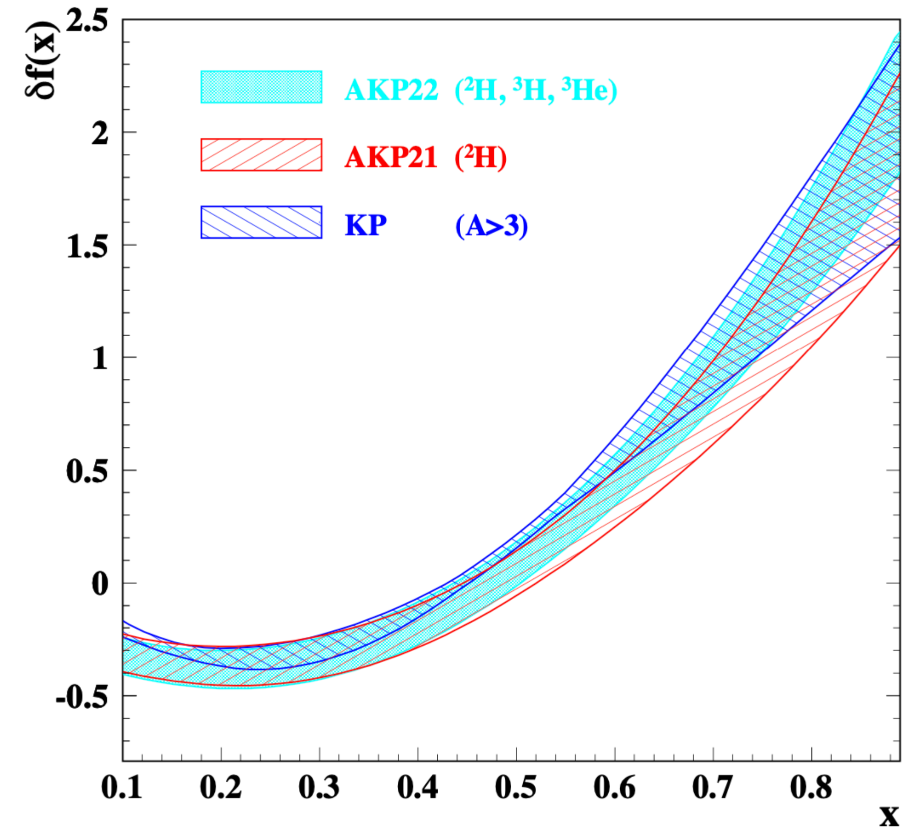
H_2, H_T parametrized



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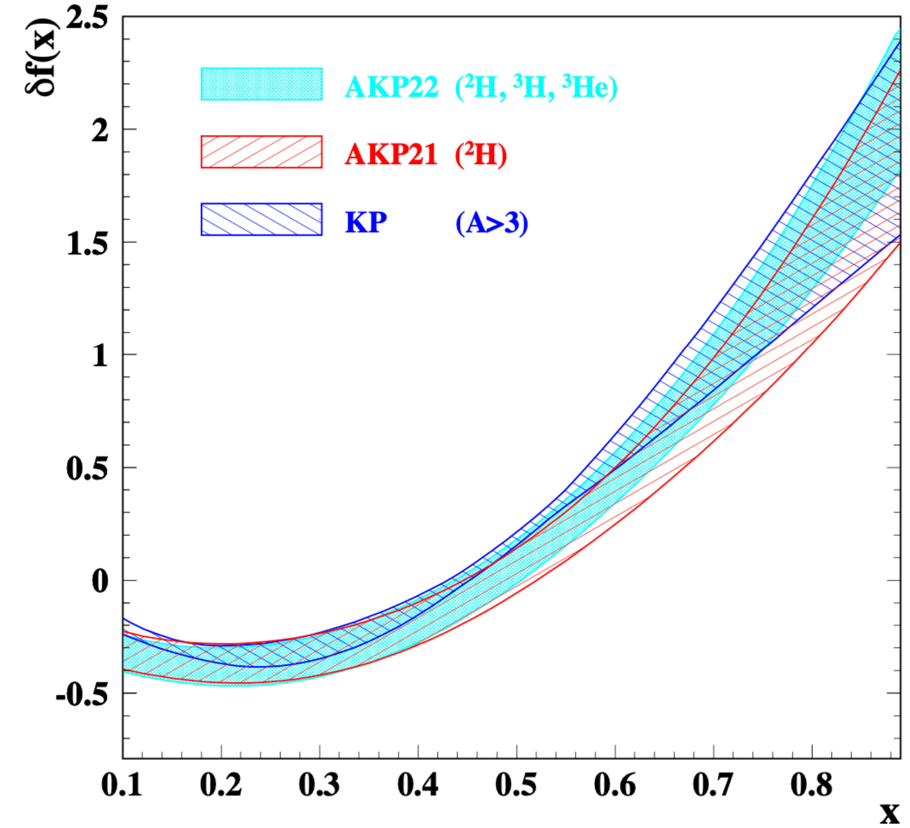

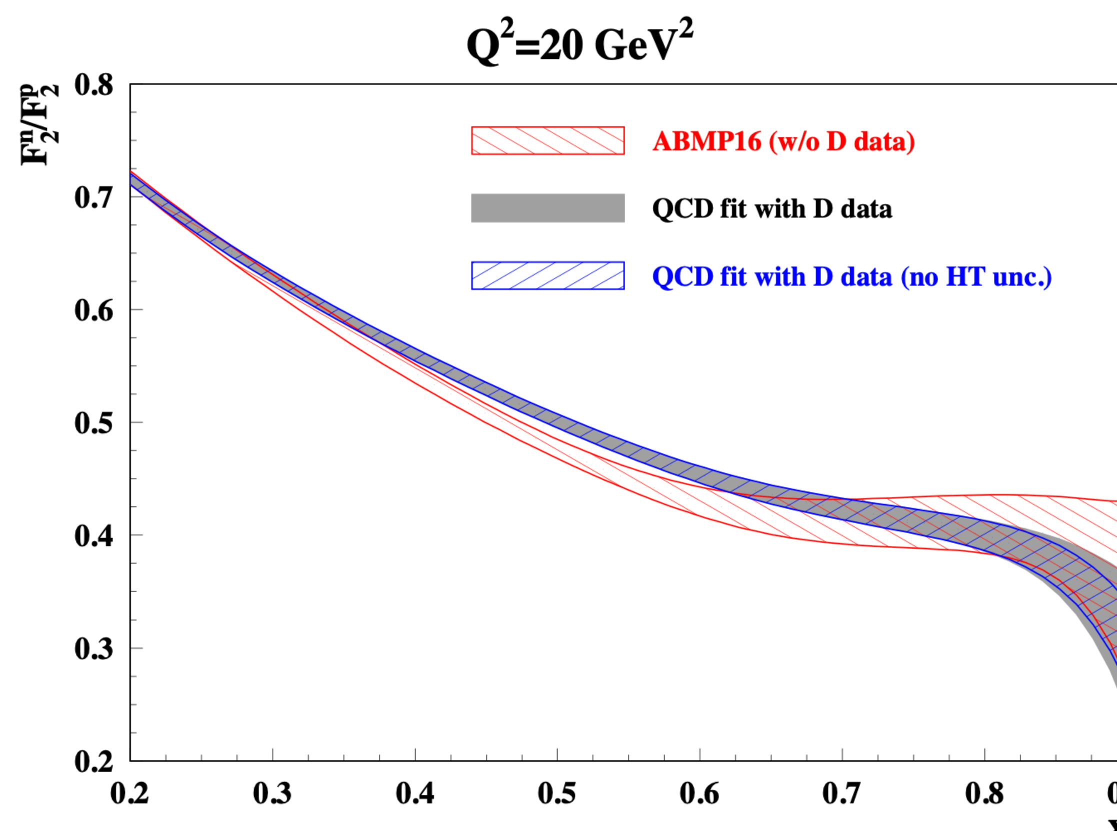

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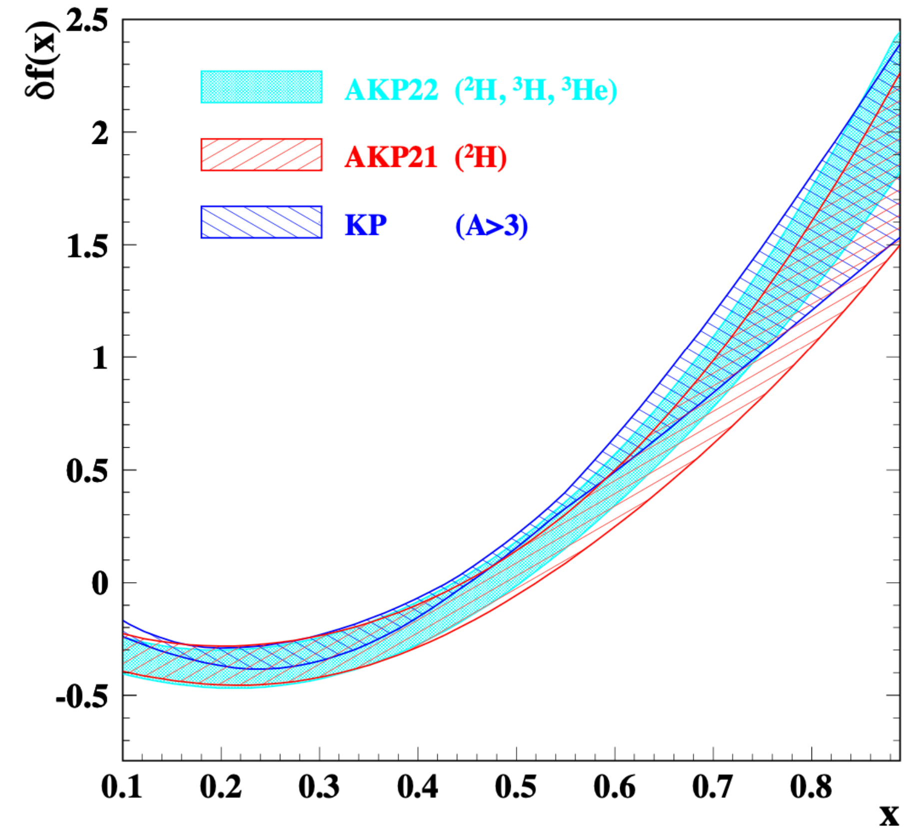
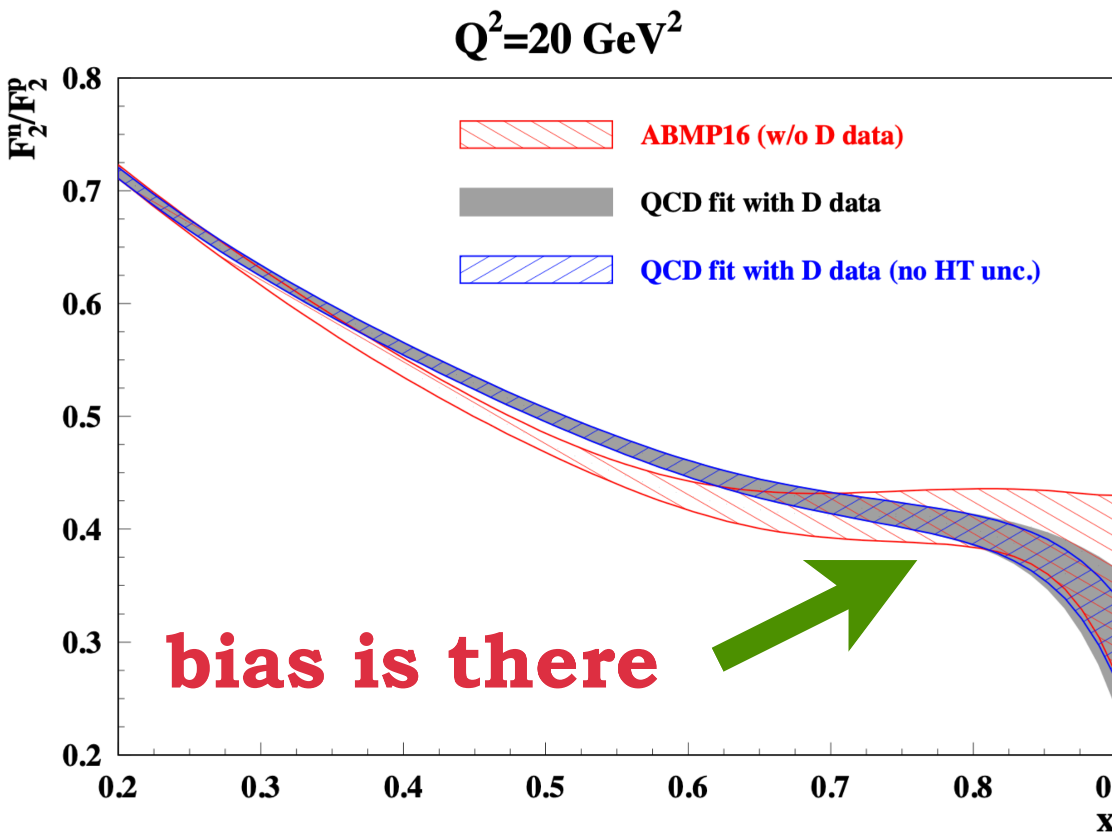




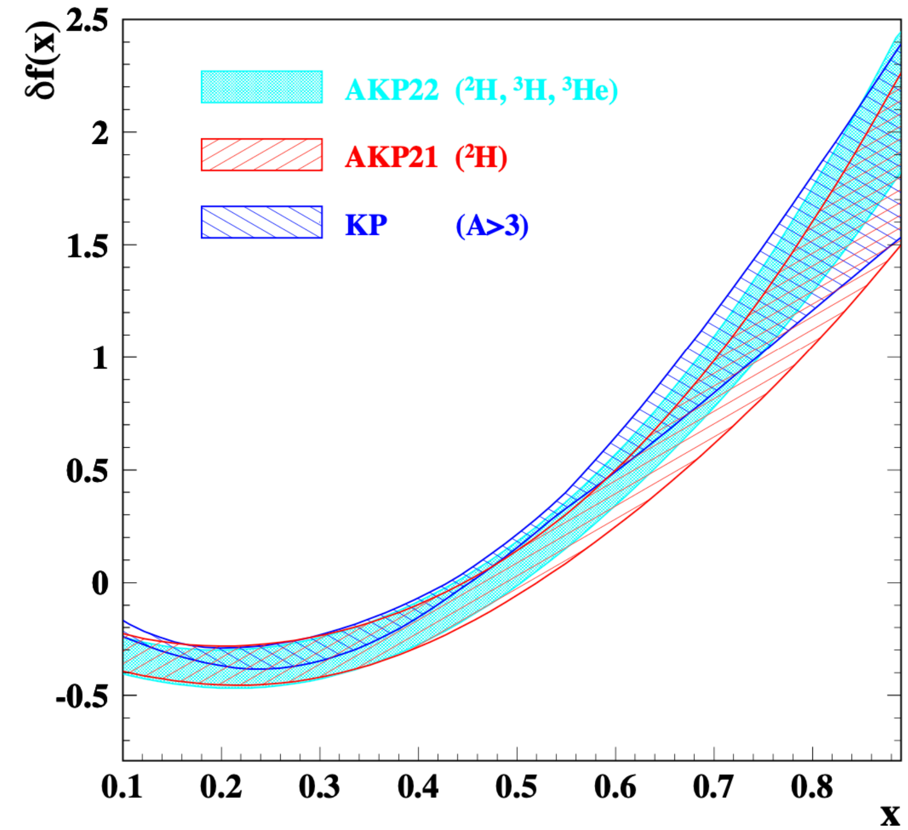
AKP results

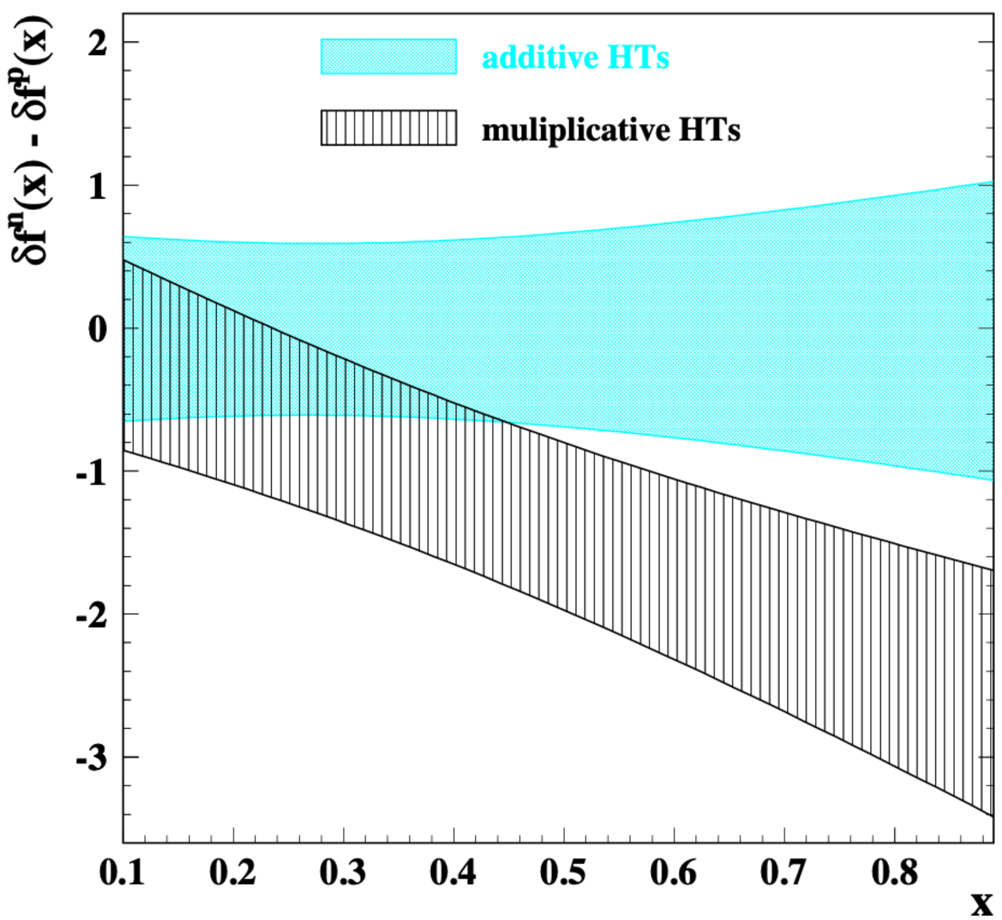
AKP Alekhin, Kulagin, Petti, PRD 107 (2023)

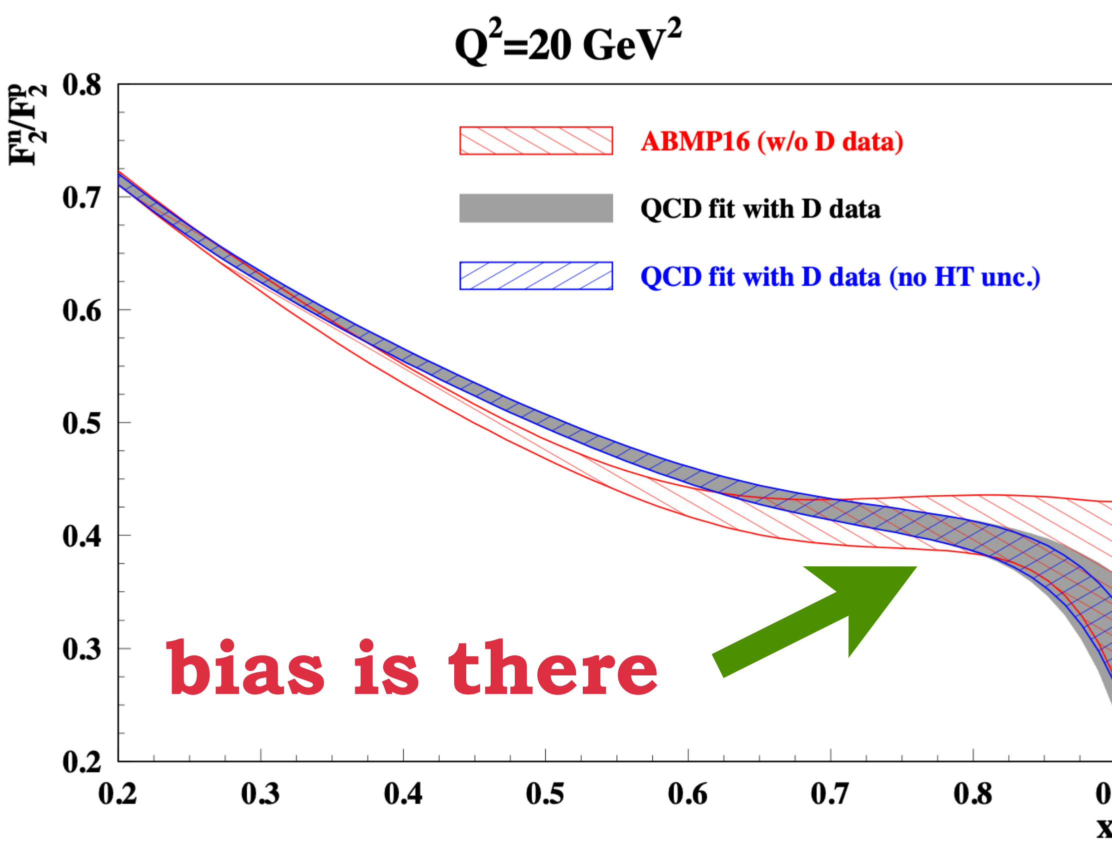
Add HT (p=n) as baseline choice

H_2, H_T parametrized

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)

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

JAM results

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

JAM Collaboration, PRL 127 (2021)

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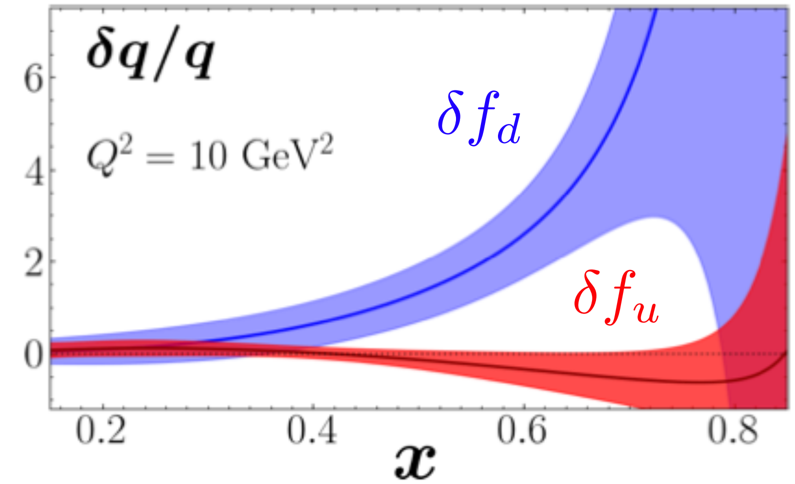

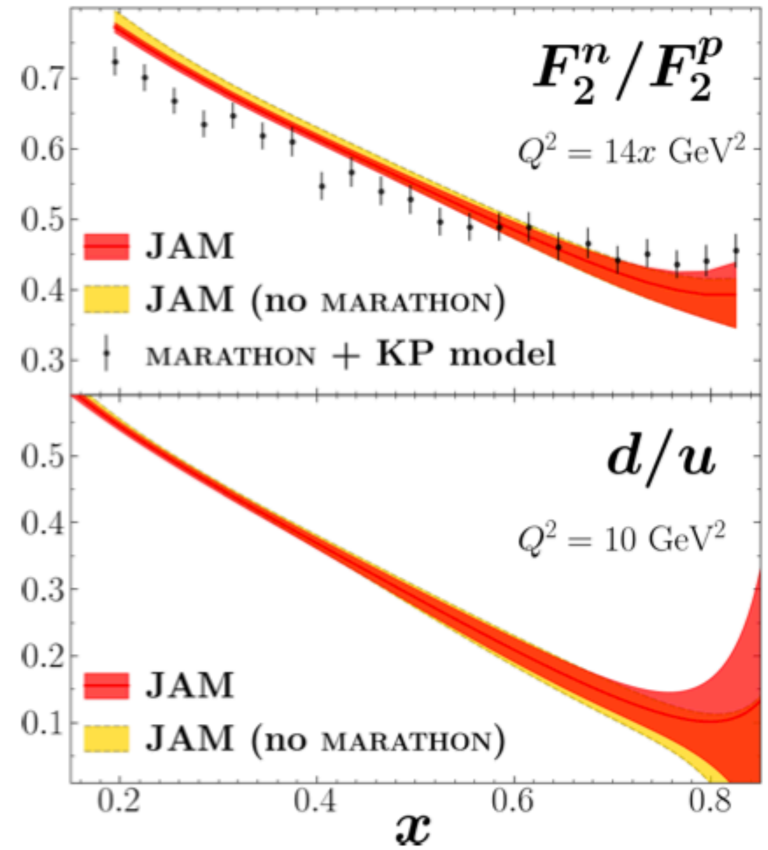

JAM results

JAM *Fit including A=3 data* δf_u δf_d

JAM Collaboration, PRL 127 (2021)

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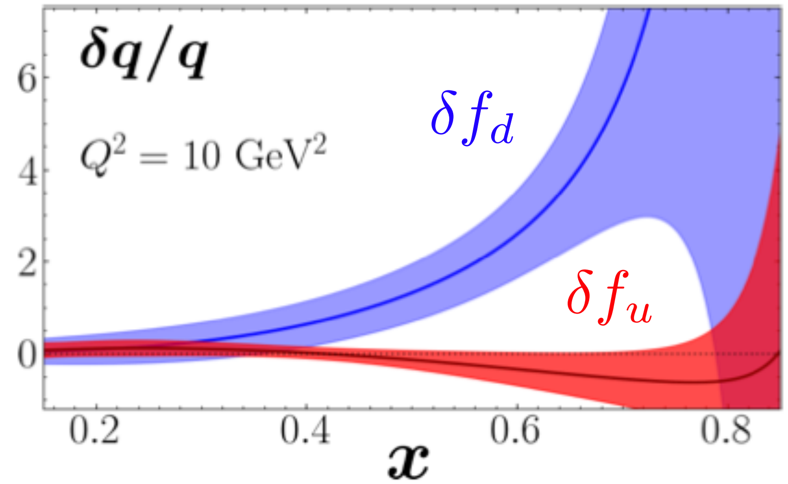
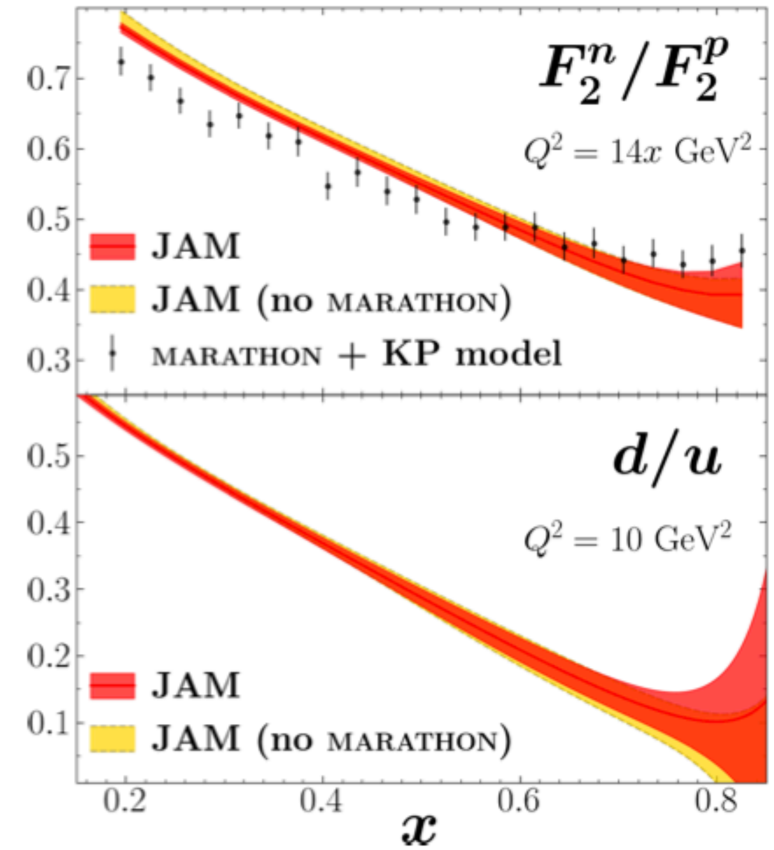
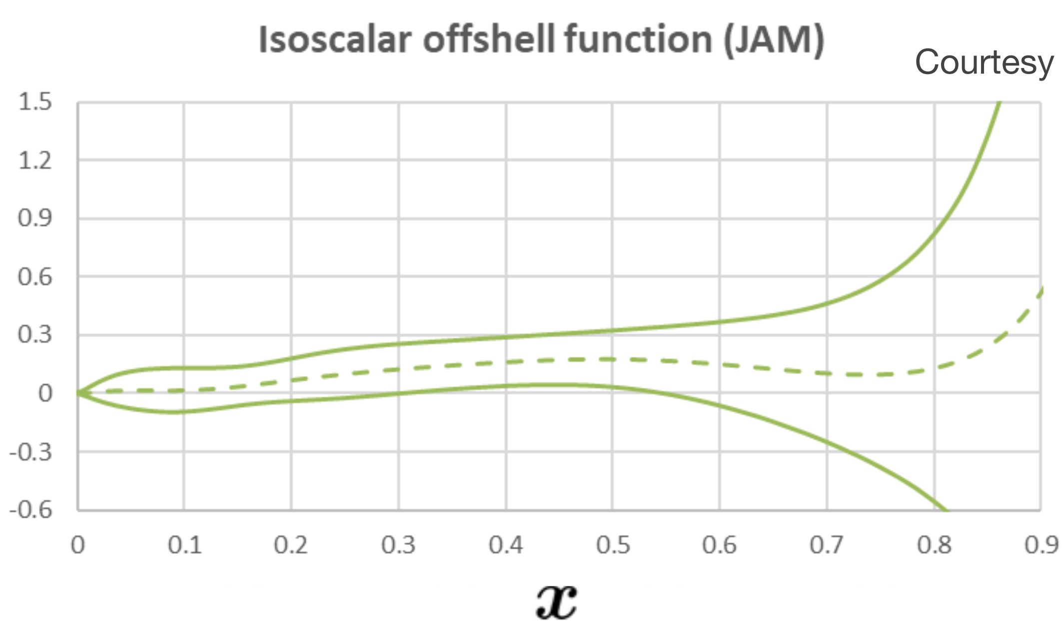


$$\delta f(x)|_{\text{CJ-like}} = \frac{u\delta f_u + d\delta f_d}{u+d}$$





Courtesy of C. Cocuzza

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	----	----