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

CTEQ-Jefferson Lab Collaboration

F_2 neutron data-driven extraction

update from CJ collaboration

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

Matteo Cerutti

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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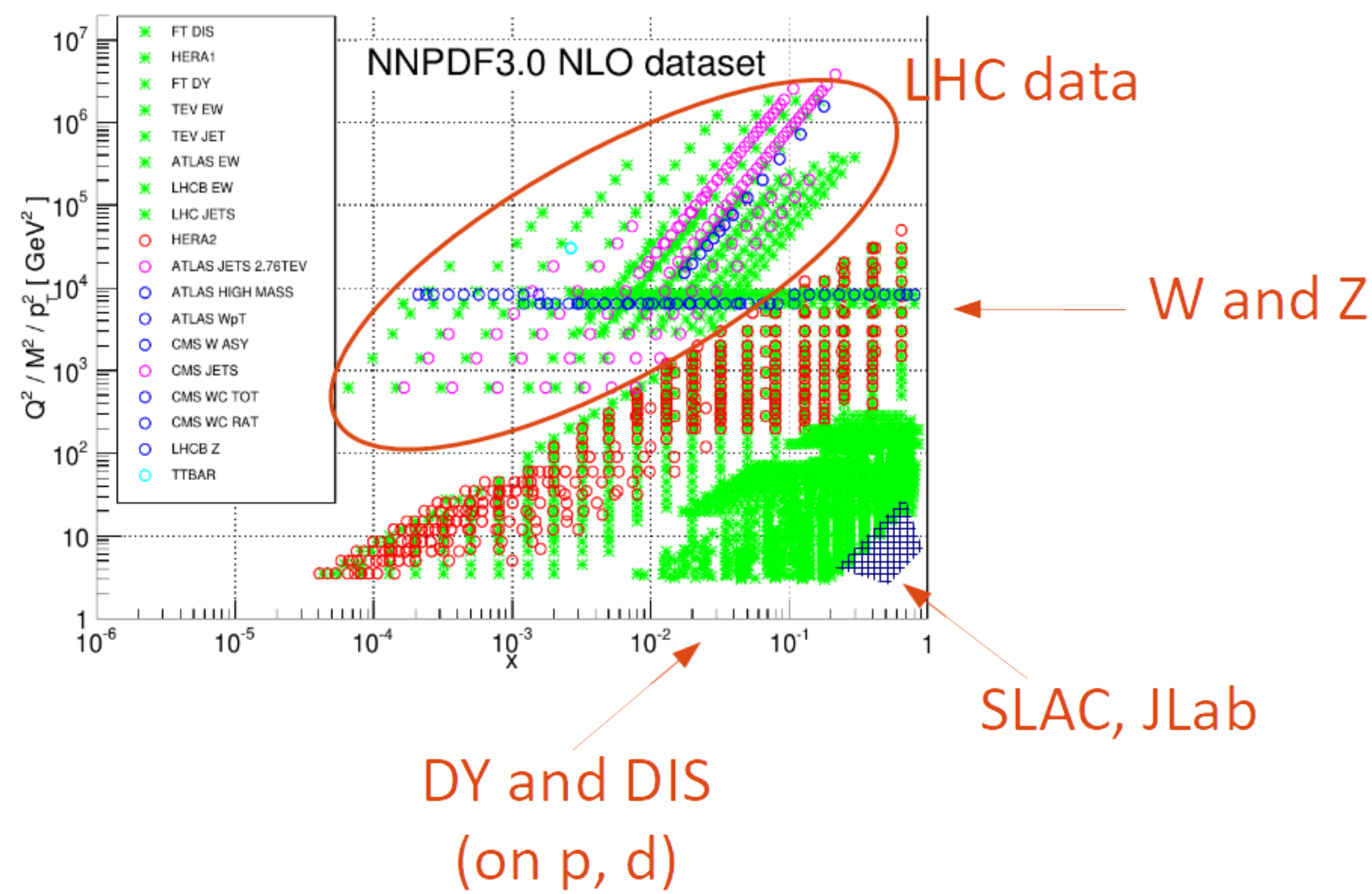
universality

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



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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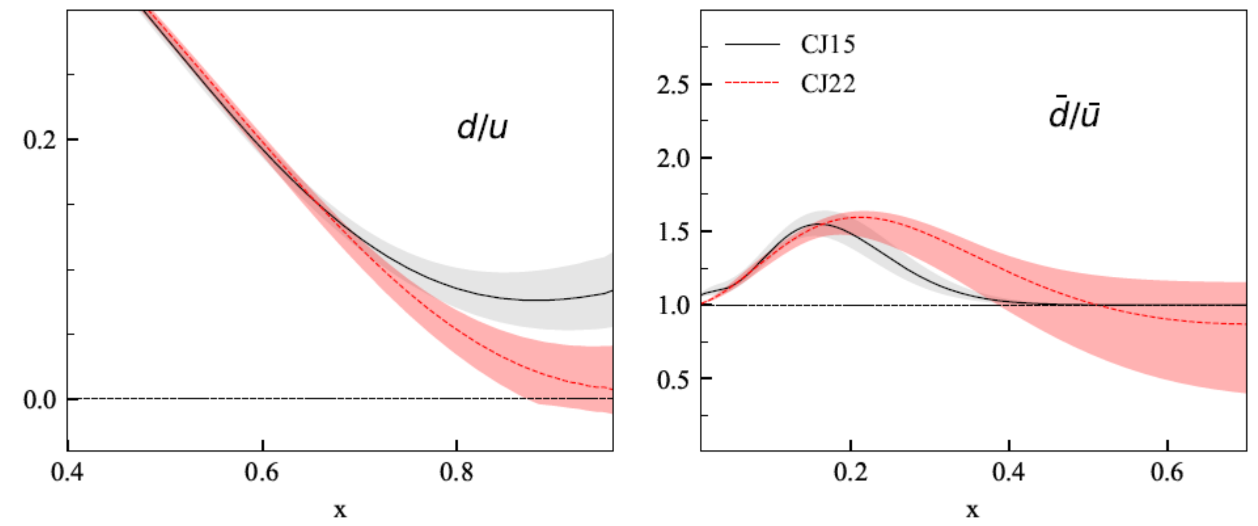
- Extraction of PDFs at large x

  CJ22 Accardi, Jing, Owens et al., PRD 107 (2023)



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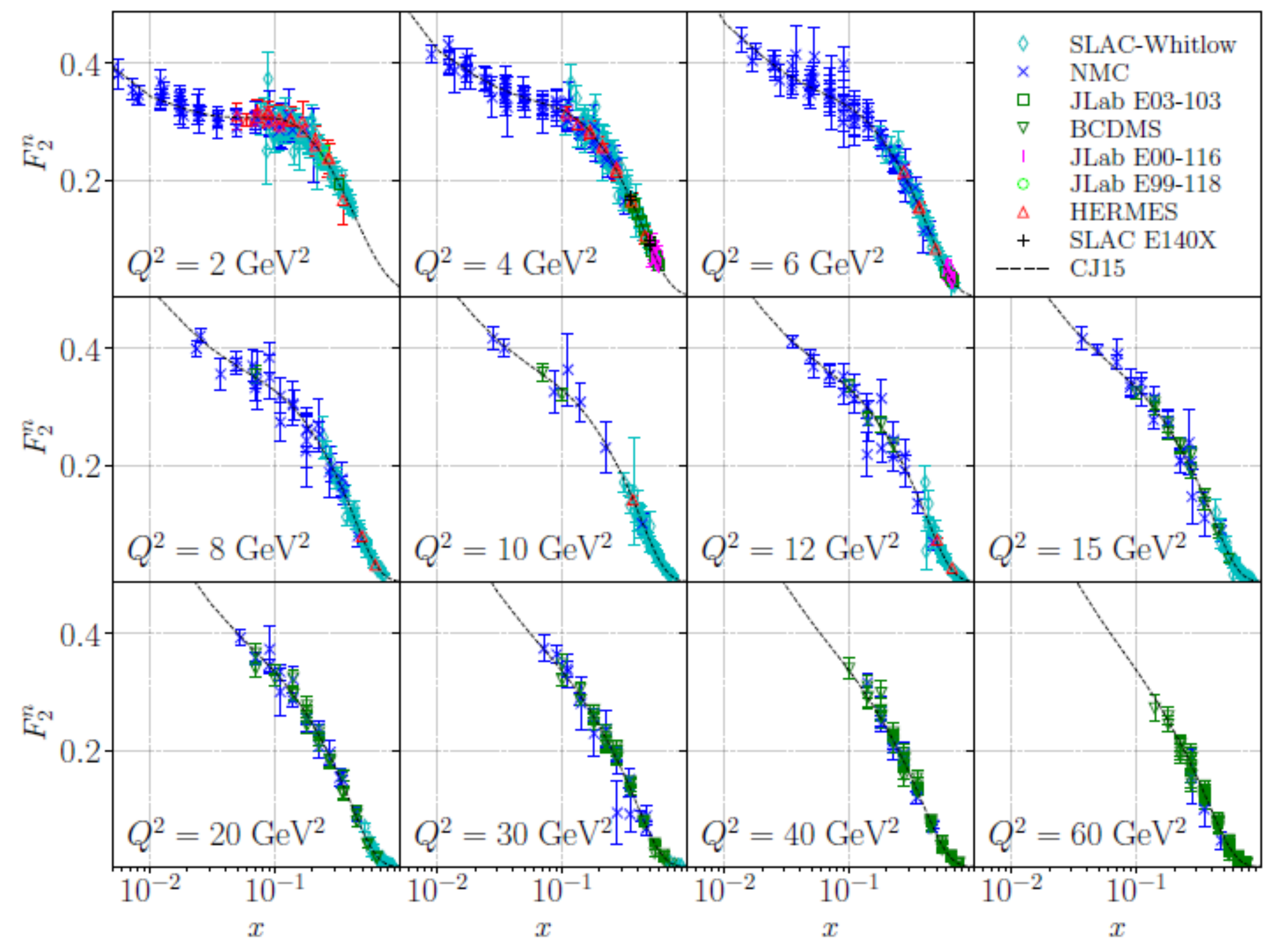

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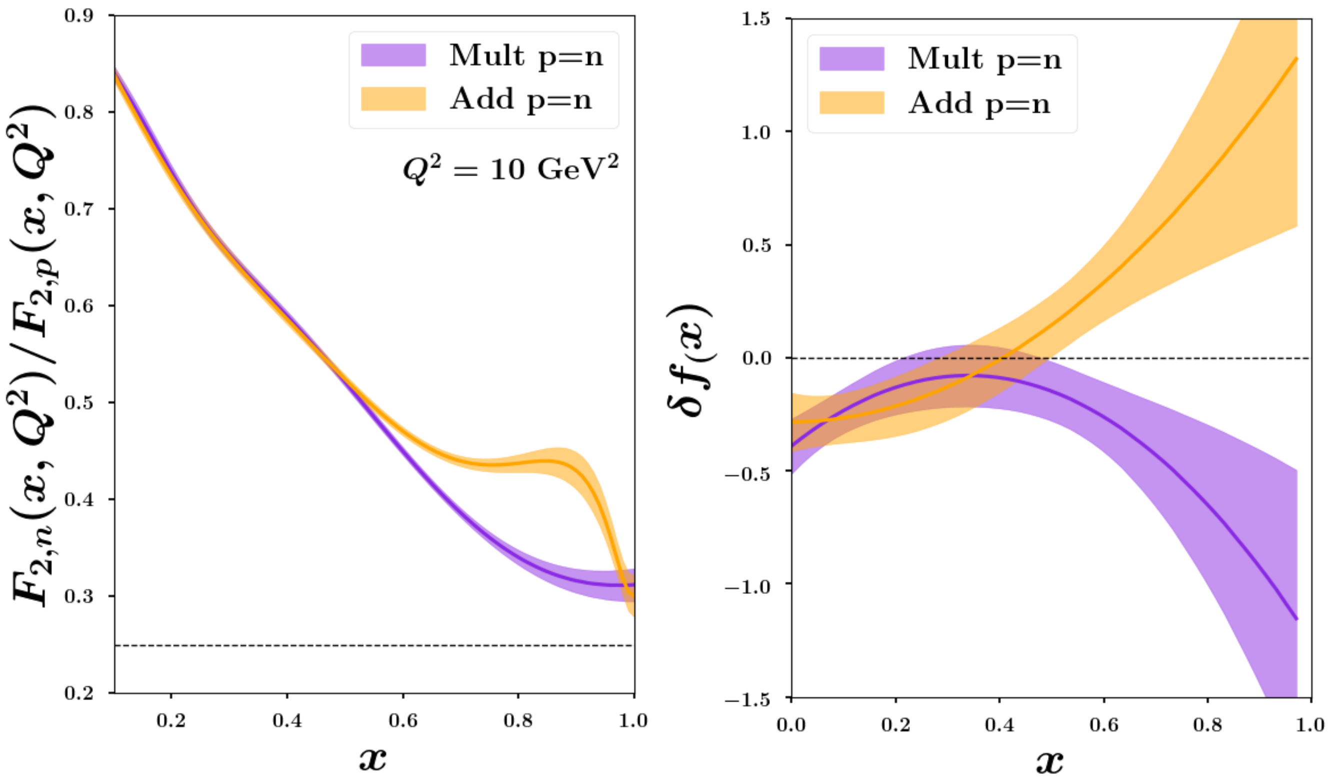

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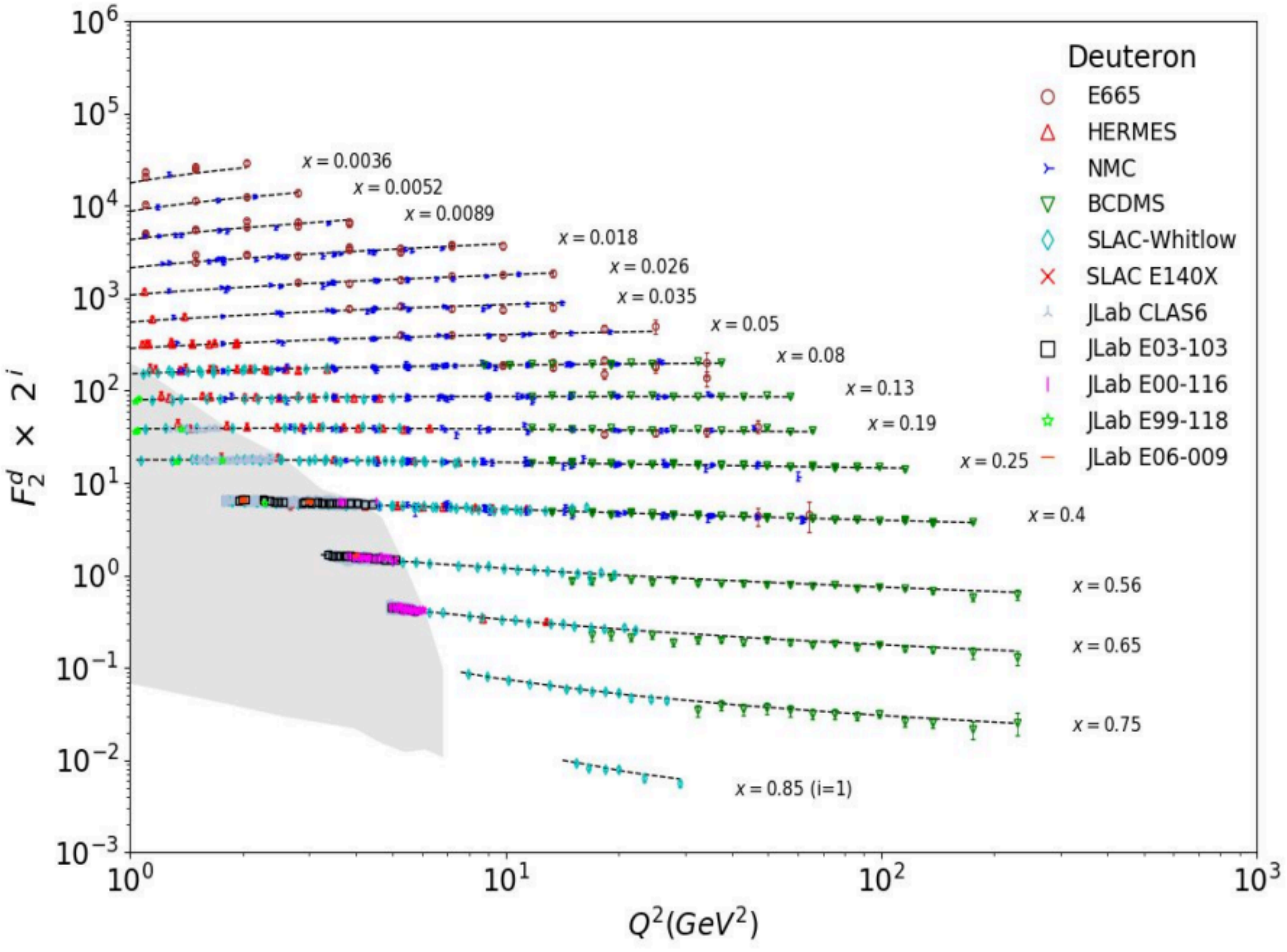
\+ ...

Extraction of neutron F_2 structure function

DIS on deuteron target

CJ global data set:

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



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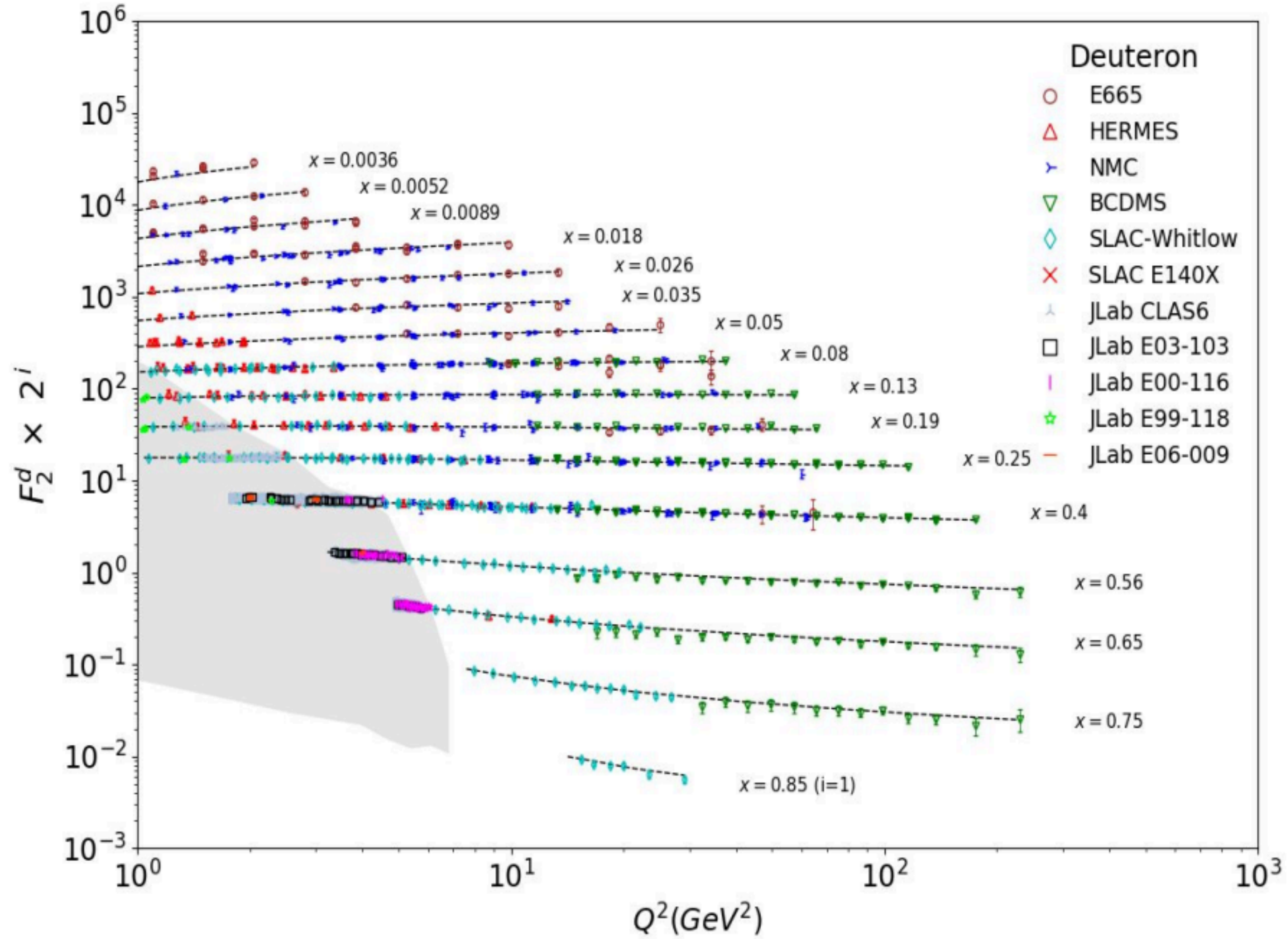


Full treatment of nuclear corrections

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

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

Smearing function

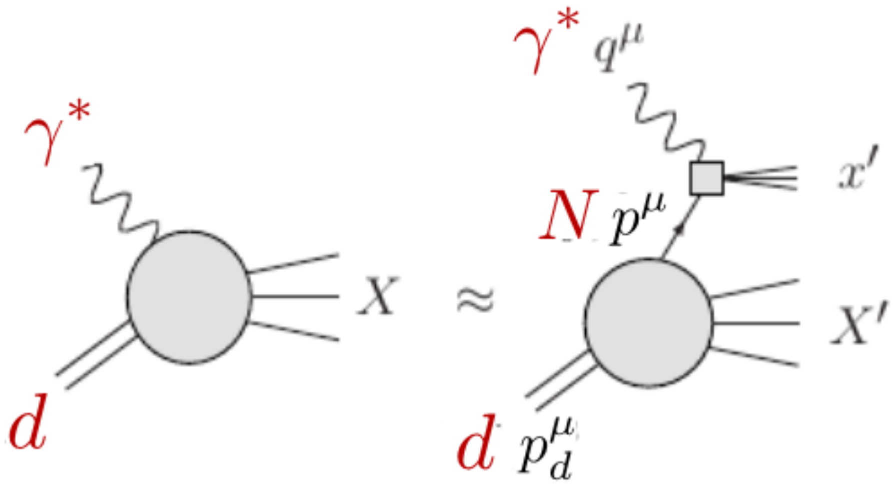
Structure function of a bound, off-shell nucleon

Deuterium: off-shell corrections

Bound, off-shell nucleon inside the deuteron

$$p^2 < m_N^2$$

Structure functions are deformed at large x



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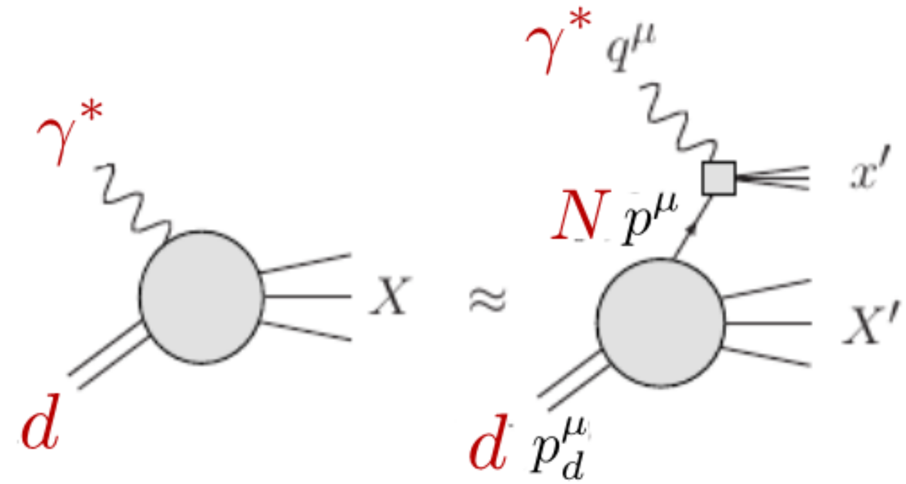

Off-shell expansion (in nucleon virtuality p^2)

parton level

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

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

struct. func level

Kulagin, Piller, Weise, PRC 50 (1994)
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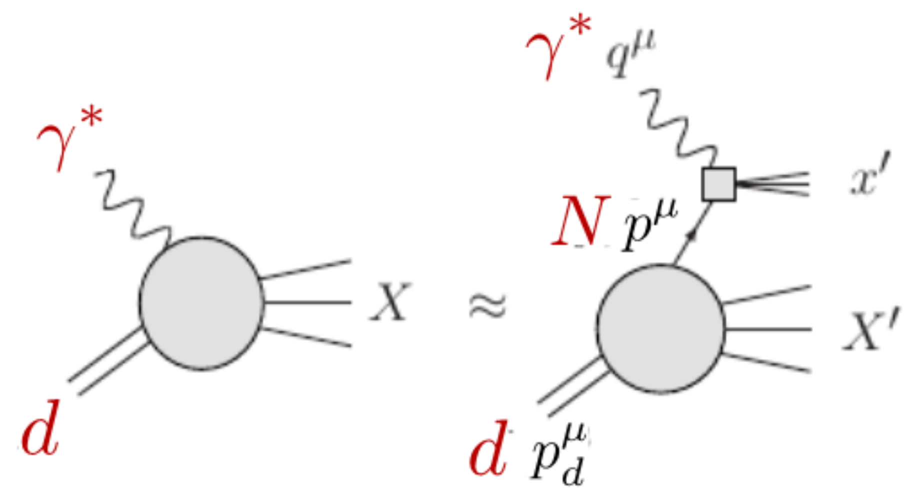

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Free nucleon pdfs/SFs
$p^2 = m_N^2$

Off-shell function
(To be fitted)

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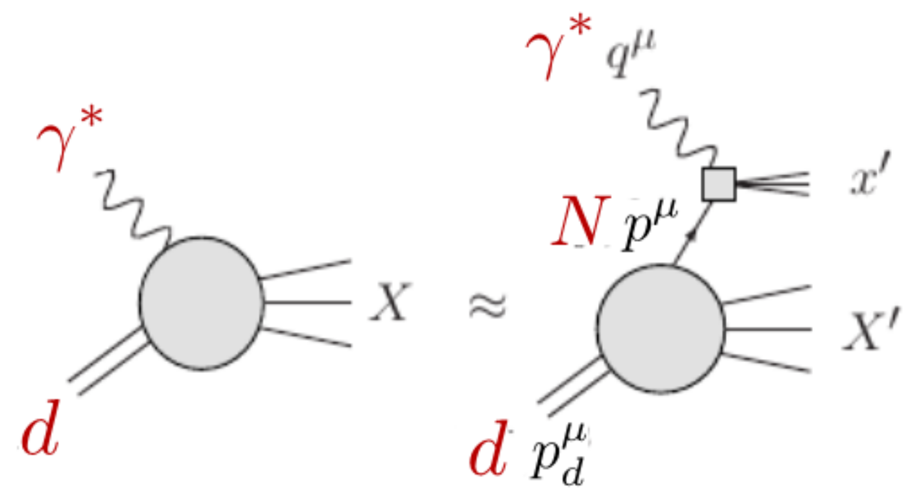

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KP-like model

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

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

Higher-Twist function

Higher Twist correction

Multiplicative

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

Additive

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

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they are related

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

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

Higher-Twist function

Higher Twist correction

Multiplicative

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

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

CJ fits

Additive

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

BIAS in isospin-symmetric case

MC, Accardi, Fernando, Li, arXiv:2407.03589

they are related

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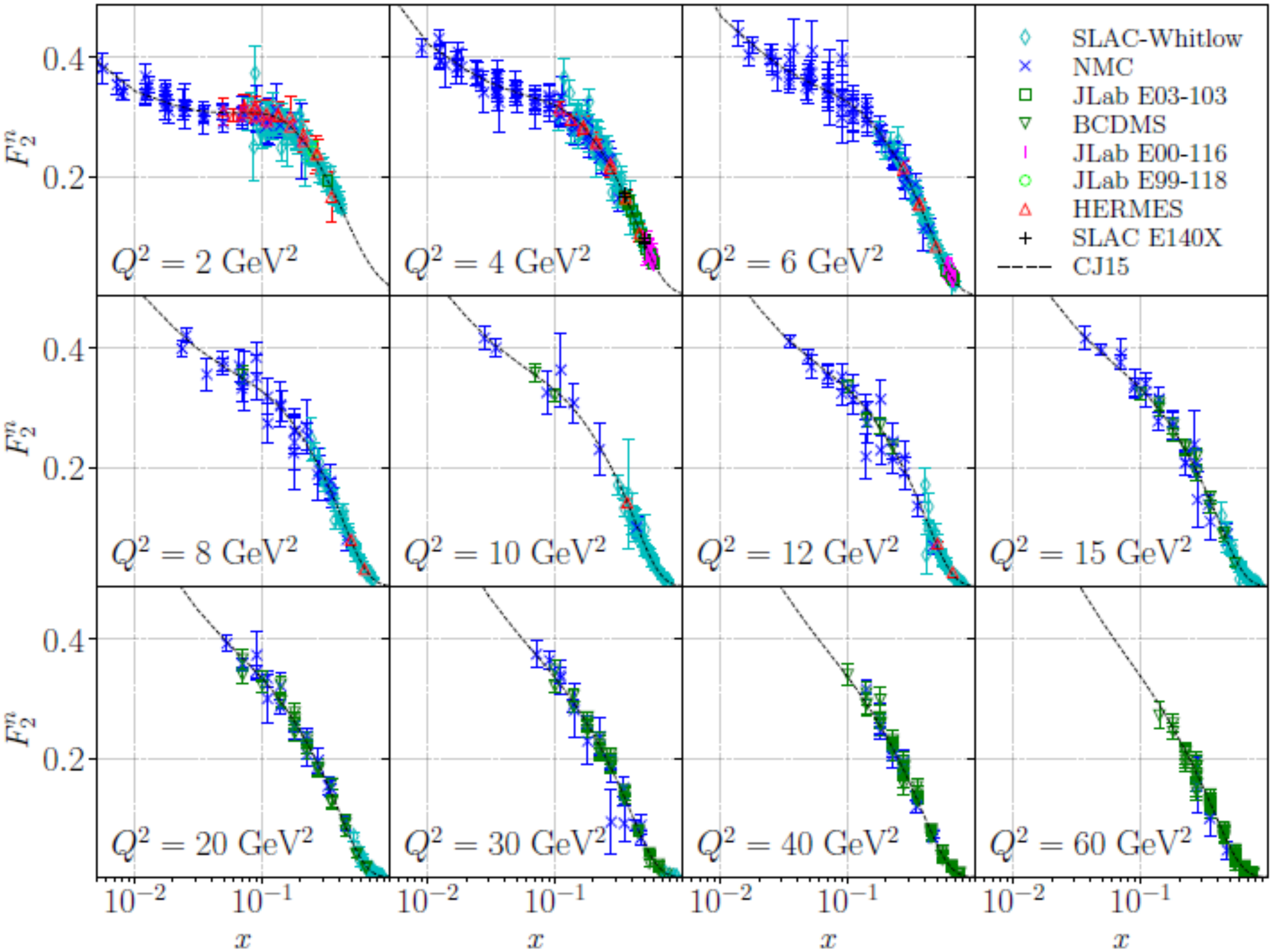
Extraction of neutron F_2 structure function

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

Basic idea

$F_{2,n}$

- p, d data matching
- data cross normalization
- results based on CJ15 analysis
- extracted experimental bins centered for applications



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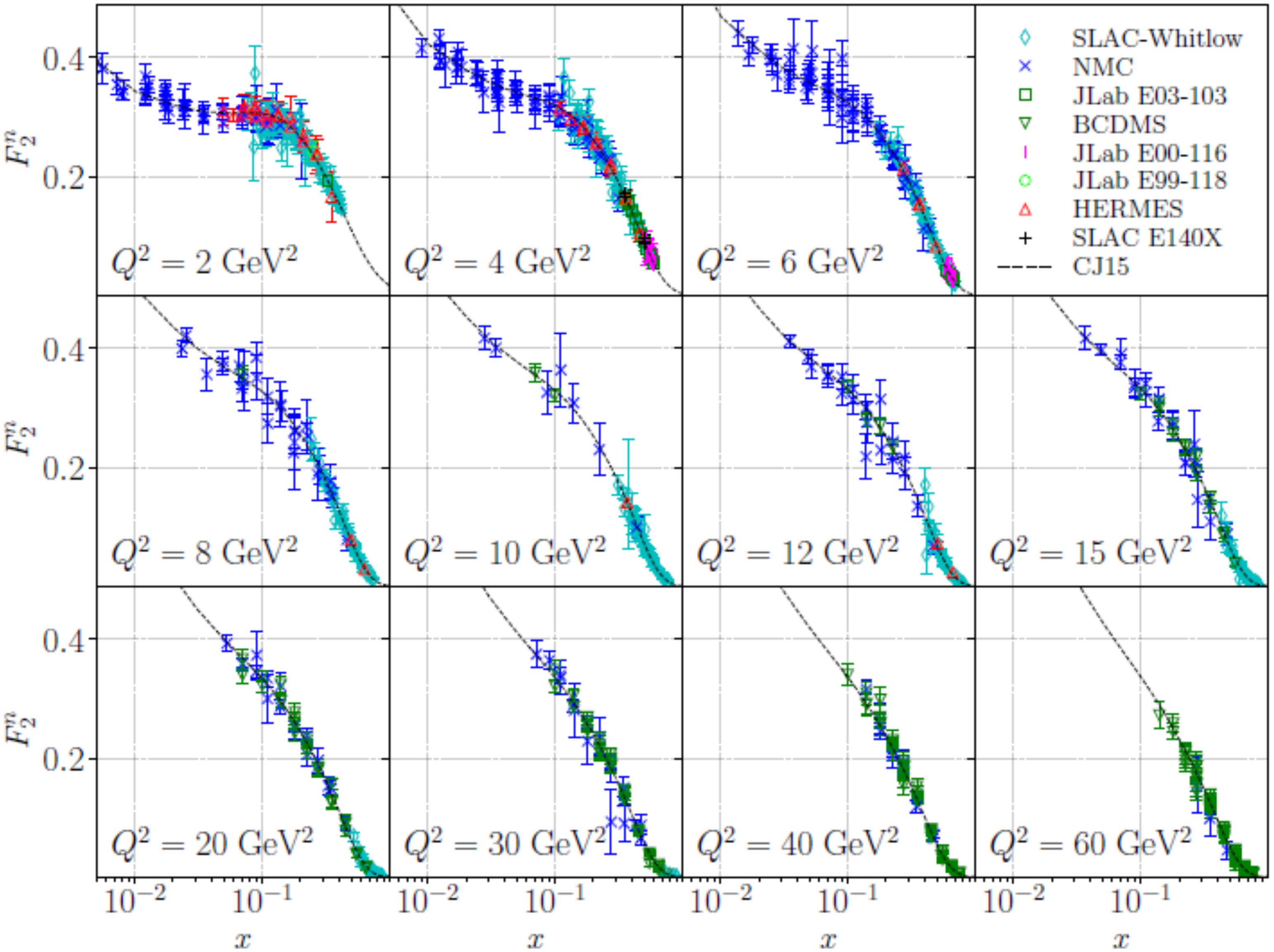

Neutron F2 data sets and grids available!!!

https://github.com/JeffersonLab/CJ-database/

Extraction of neutron F_2 structure function

Experimental data sets *extension of CJ15 DIS included data set*

	Experiments	# of Proton F2 Data Points	# of Deuteron F2 Data Points
	SLAC-Whitlow[2]	564	582
	BCDMS	351 [3]	254 [4]
	HERMES [5]	45	45
	JLab E-00-116 [6]	136	136
	NMC [7]	275	275
+	SLAC-E140x [8]	9	13
+	JLab E-03-103 [9]	37	69
	JLab CLAS6	609 [10]	1723 [11]
	JLab E-94-110 [12]	112	0
	JLab E-06-009 [13]	0	79
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Matching conditions

- Same beam energy
- $|x_p - x_d| < 0.01$
- $|Q_p^2 - Q_d^2| < 1\,\%$

Extraction of neutron F_2 structure function

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extension of CJ15 DIS included data set

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	BCDMS	351 [3]	254 [4]	254
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1192 matched data points

Extraction of neutron F_2 structure function

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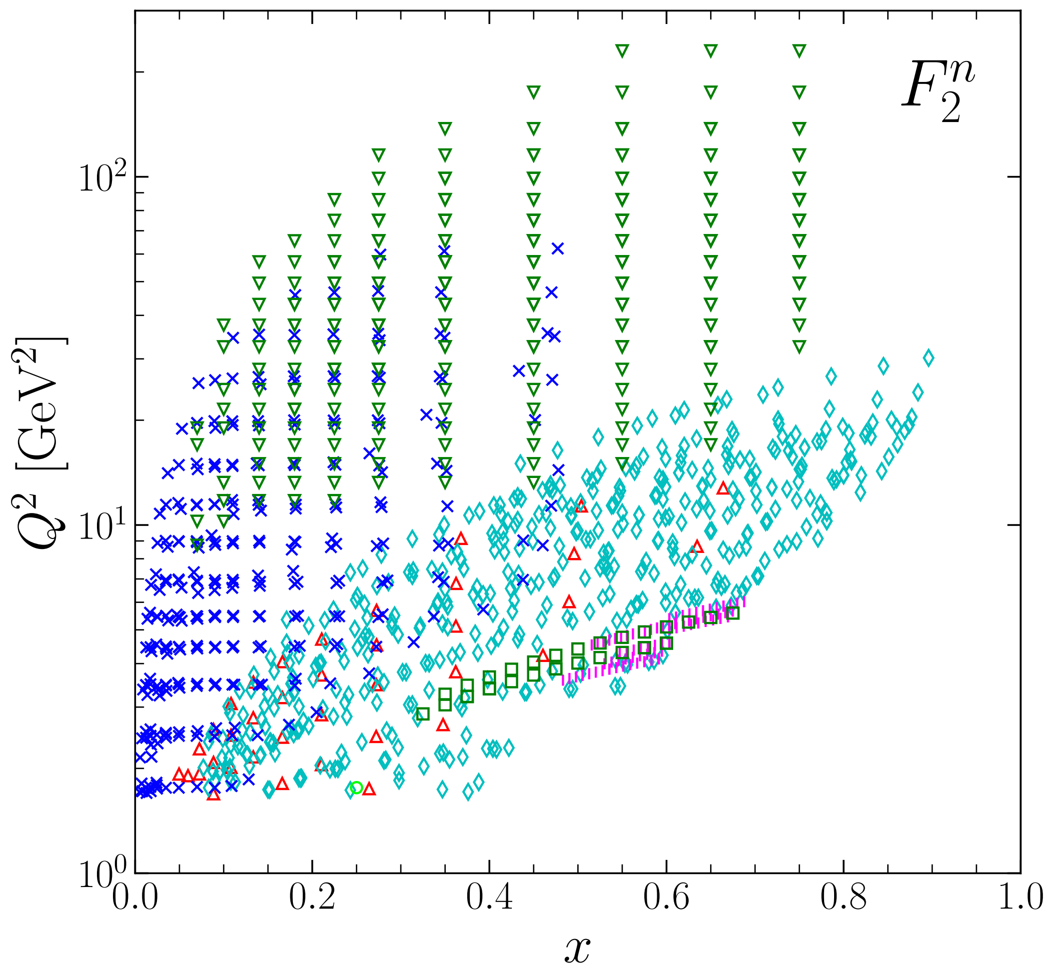
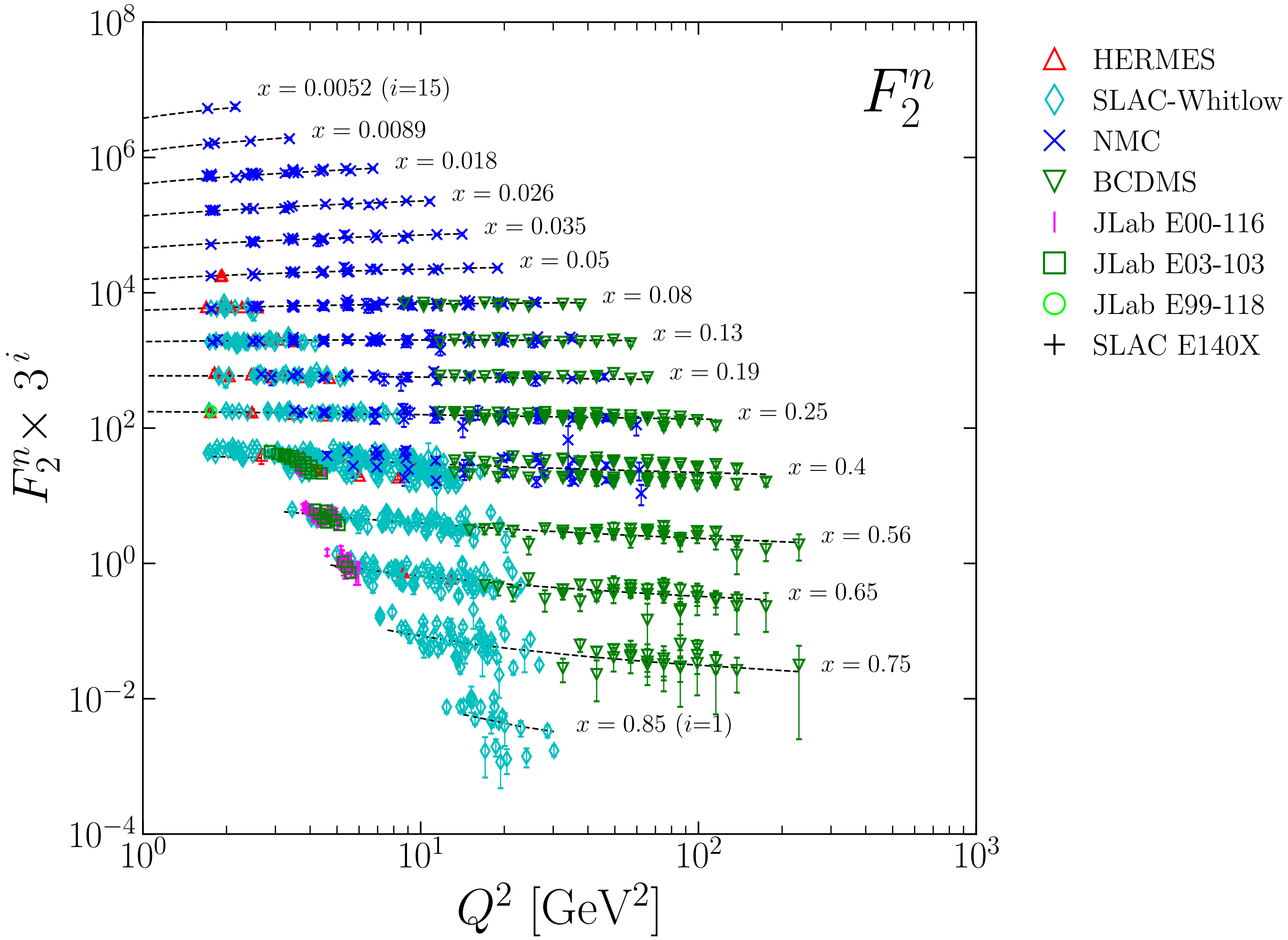
$W^2 > 3.5\ \text{GeV}^2$





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Avoid large fluctuations due to their relative systematic uncertainties

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Avoid large fluctuations due to their relative systematic uncertainties

Through CJ framework

$$\chi^2 = \sum_{\rm exp}\left[\sum_{i=1}^{N_{\rm data}}\left(\frac{D_i+\Delta_i-T_i/n}{\delta D_i}\right)^2 + \left(\lambda^{\rm norm}\right)^2 + \sum_{k=1}^{K}\lambda_k^2\right]_{\rm exp}$$

Uncorrelated error

Normalization error

$$n = 1 + \lambda^{\rm norm}\delta n$$

$$\Delta_i = \sum_k \lambda_k \beta_{k,i}$$

Correlated error

Extraction of neutron F_2 structure function

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Normalization error

$$n = 1 + \lambda^{\rm norm}\delta n$$

$$\Delta_i = \sum_k \lambda_k \beta_{k,i}$$

Correlated error

Fix theoretical prediction

Fit simultaneously the nuisance parameters λ

$$\widehat{D}_i^{(0)} = n^{(0)}\left(D_i + \Delta_i^{(0)}\right)$$

Extraction of neutron F_2 structure function

Uncertainties

$$\widehat{F}_2^n = \widehat{F}_2^{n(0)} \pm \delta \widehat{F}_2^n \pm \delta^{CJ} \widehat{F}_2^n$$

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

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Uncorrelated uncertainties $\Longrightarrow$ standard propagation from d, p data

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Uncorrelated uncertainties $\Longrightarrow$ standard propagation from d, p data

Procedural uncertainties:

Cross normalization $\Longrightarrow$ Hessian method with "error PDF sets"

Calculation of CJ ratio

`CJ15nlo_mod` $2^*N_{parameters} + 1 = 49$

(negligible)

$$\delta^{CJ}\lambda = \frac{1}{2}\sqrt{\sum_{j=1}^{24}\left[\lambda^{(2j-1)} - \lambda^{(2j)}\right]^2}$$

$$\delta^{CJ}\widehat{D}_i = \frac{1}{2}\sqrt{\sum_{j=1}^{24}\left[\widehat{D}^{(2j-1)} - \widehat{D}^{(2j)}\right]^2}$$

Extraction of neutron F_2 structure function

Bin centering

- Better visualization of data points
- Better evaluation of structure function moments - applications

Extraction of neutron F_2 structure function

Bin centering

Better visualization of data points

Better evaluation of structure function moments - applications

Use CJ framework

$$\widetilde{F}_2(x, Q_0^2) \equiv R_{\rm bc}(Q_0^2, Q^2)\, \widehat{F}_2(x, Q^2)$$

$$R_{\rm bc}(Q_0^2, Q^2) \equiv \left. \frac{F_2(x, Q_0^2)}{F_2(x, Q^2)} \right|_{CJ}$$

Procedural uncertainty: negligible

Extraction of neutron F_2 structure function

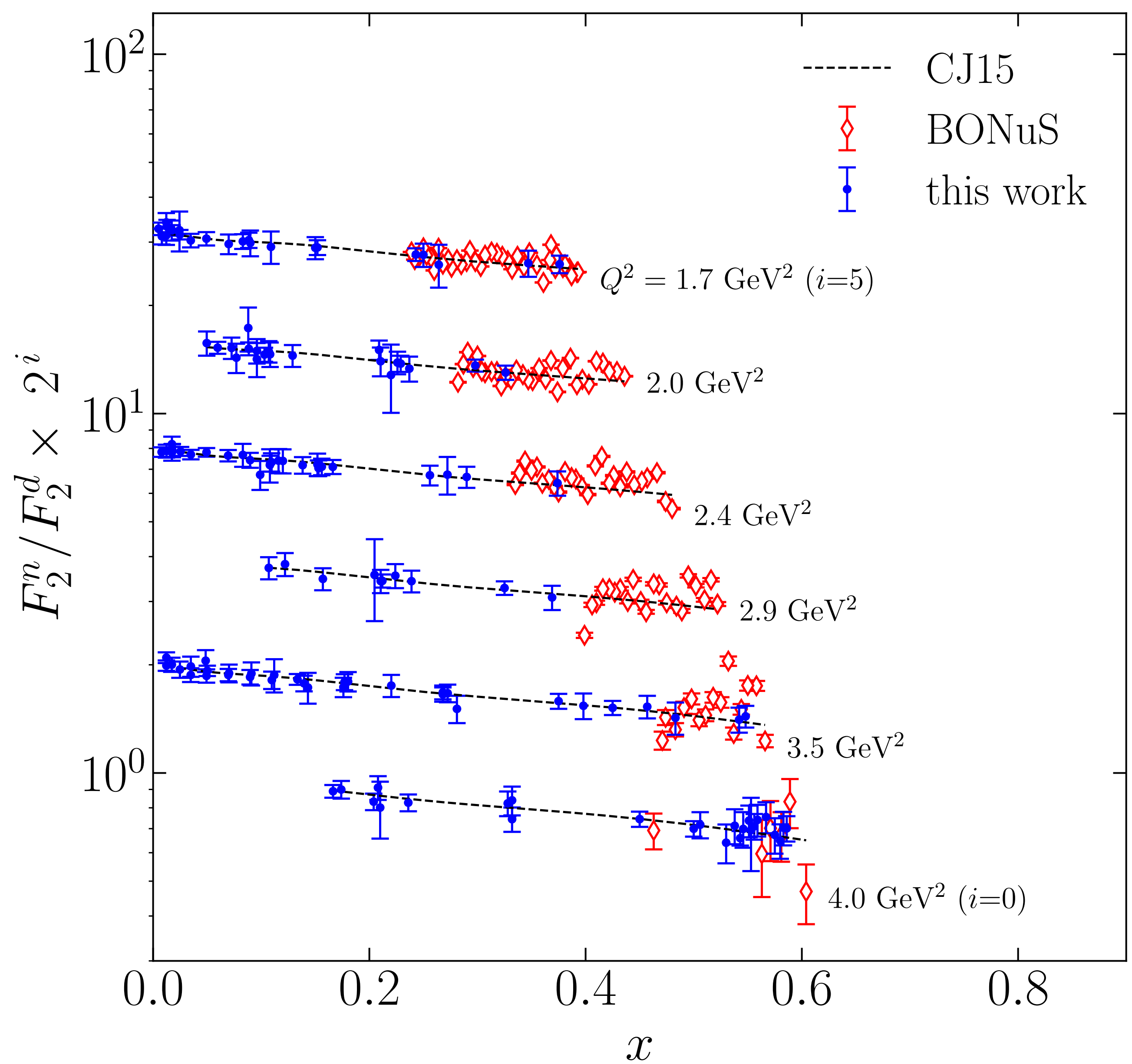
Comparison to BONuS data set

CLAS Collab., PRC 89 (2014)

$F_{2,n}/F_{2d}$ → Experimental data

↓

This extraction



GOOD AGREEMENT!

Extraction of neutron F_2 structure function

Basic idea

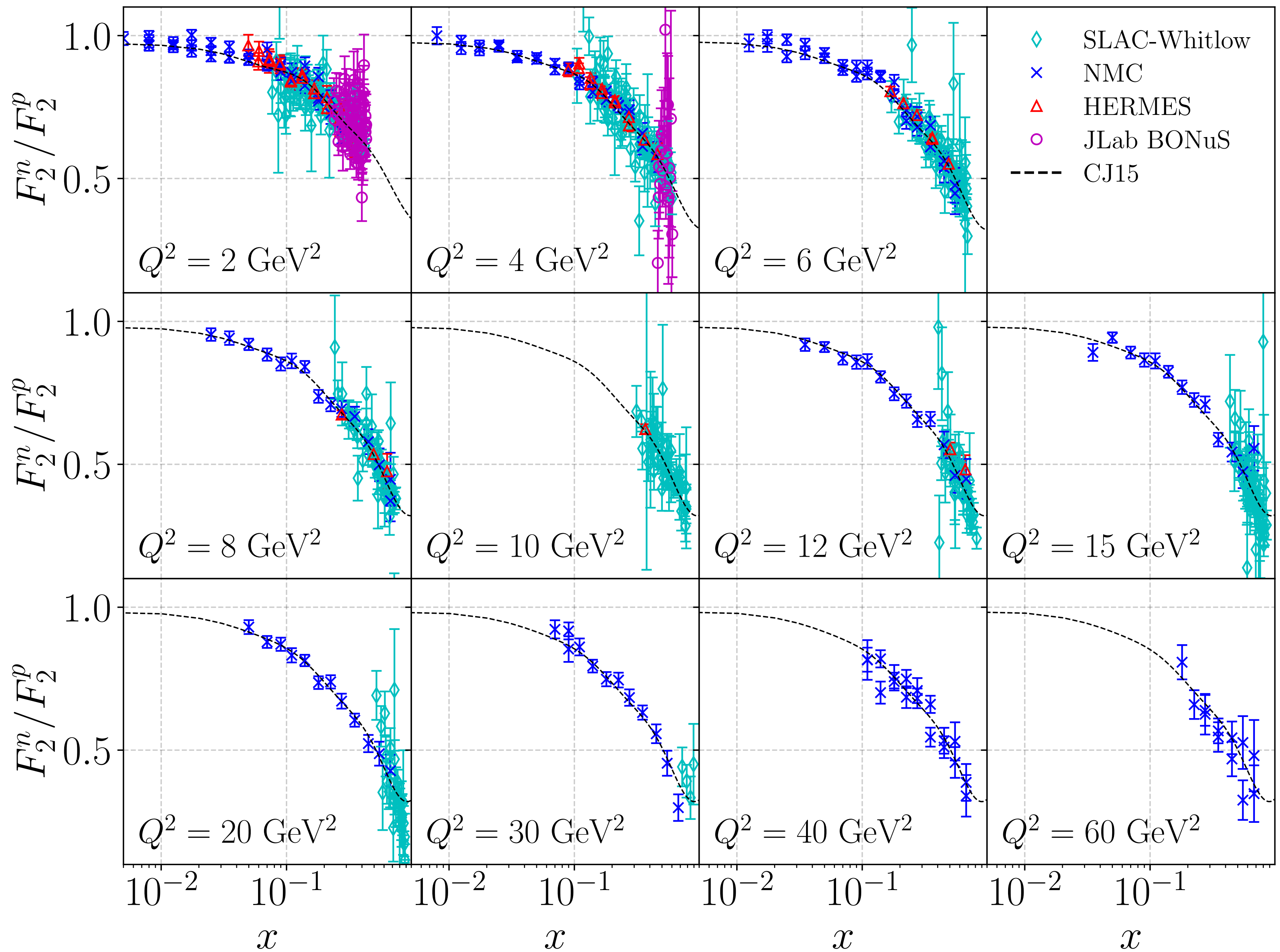
$F_{2,n}/F_{2p}$

Using d/p data

$$\widehat{R}^{(0)}_{n/p} = \frac{2\widehat{R}^{exp,(0)}_{d/p}}{R^{CJ}_{d/N}} - 1$$

Using n/d data (BoNUS)

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



Extraction of neutron F_2 structure function

$F_{2,n}/F_{2p}$

What about MARATHON data set?? Jefferson Lab Hall A Collab., PRL 128 (2022) 13

Extraction of neutron F_2 structure function

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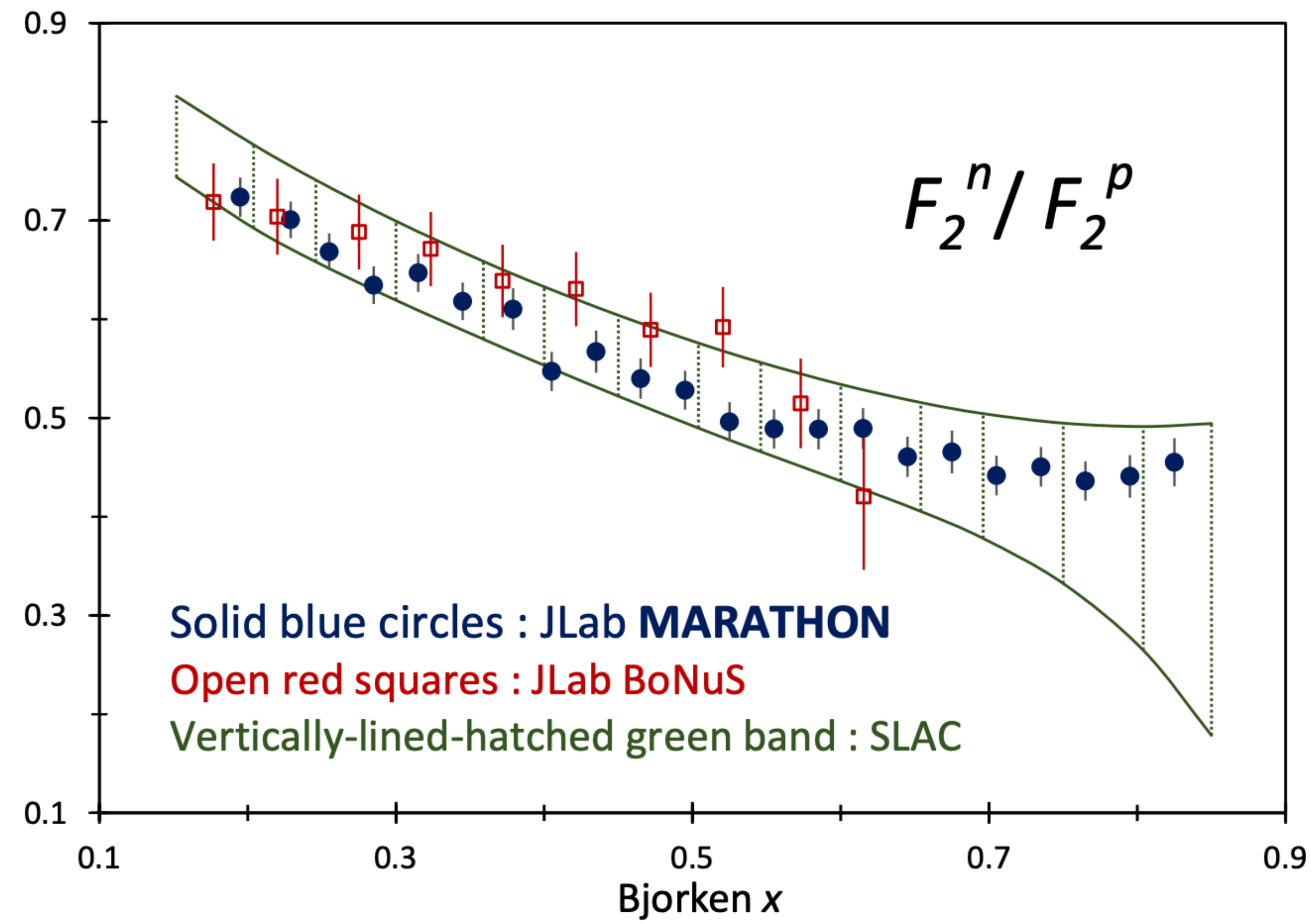
What about MARATHON data set??

Jefferson Lab Hall A Collab., PRL 128 (2022) 13

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R}_{ht} - F_2^h/F_2^t}{2F_2^h/F_2^t - \mathcal{R}_{ht}}$$

- A=3 not available in CJ framework
- Experimental analysis based on AKP framework



Extraction of neutron F_2 structure function

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Jefferson Lab Hall A Collab., PRL 128 (2022) 13

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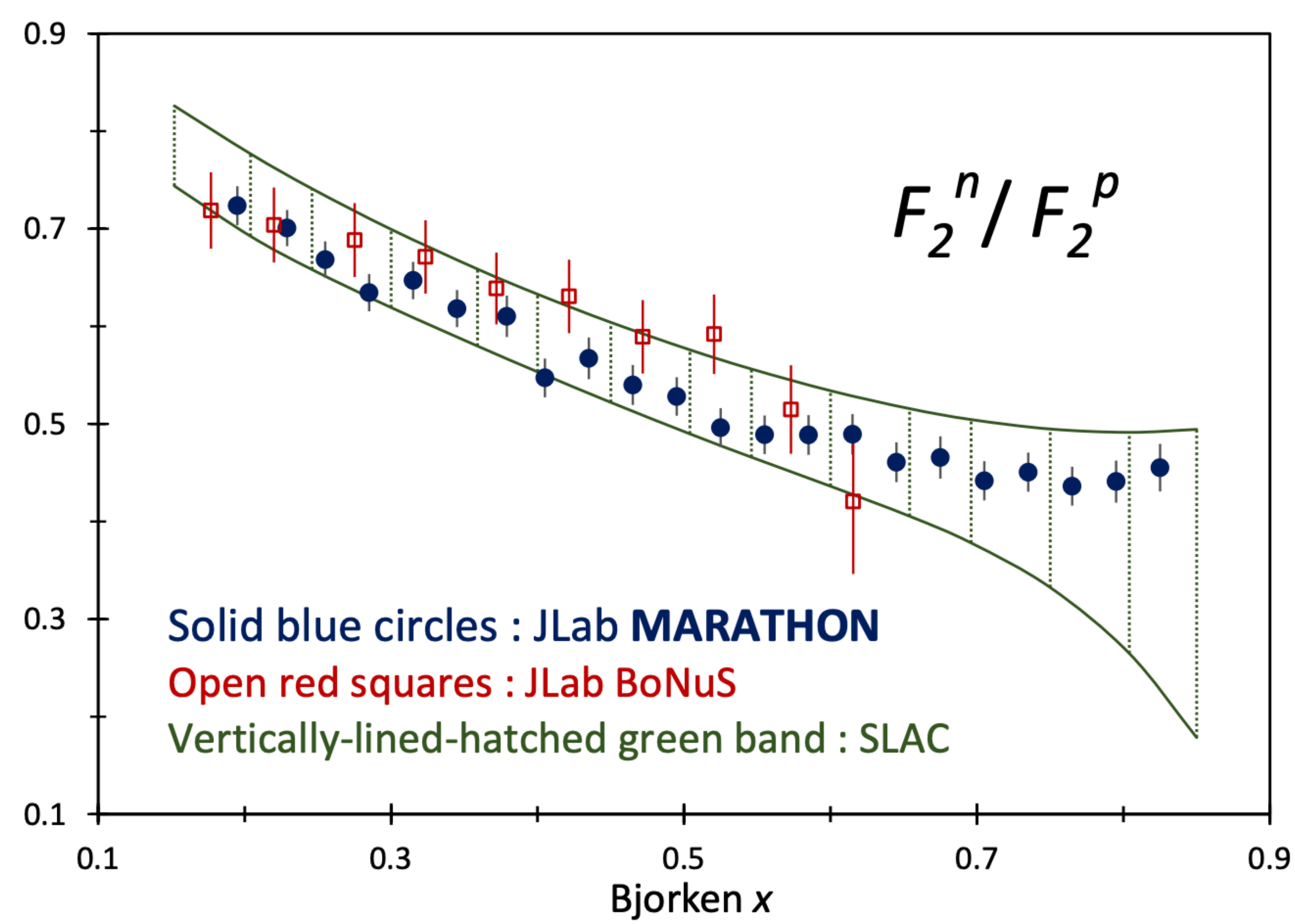
Be careful!

Systematic uncertainties in treatment of HT and off-shell corrections

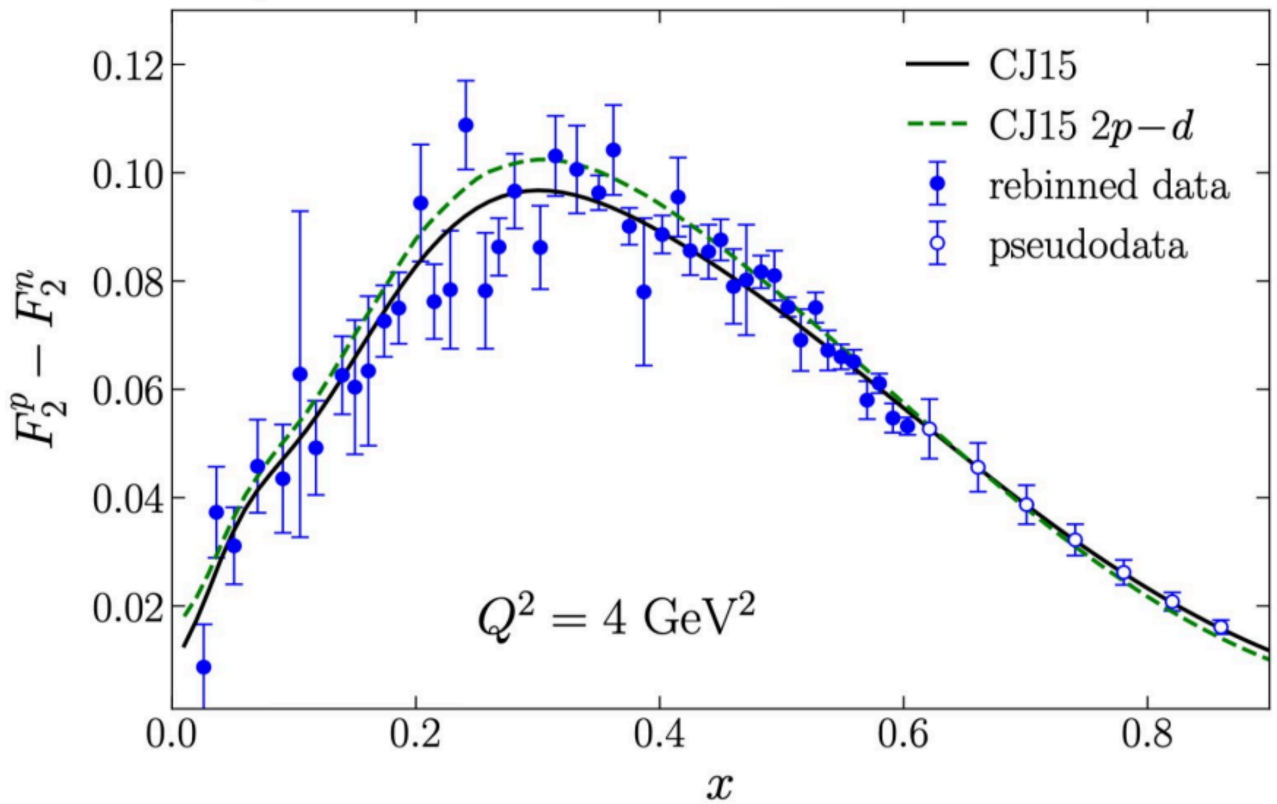


MC, Accardi, Fernando, Li, arXiv:2407.03589

Application: GSR

Gottfried sum rule

$$S_G(Q^2) = \int_0^1 \frac{dx}{x} \left[F_2^p(x, Q^2) - F_2^n(x, Q^2) \right]$$

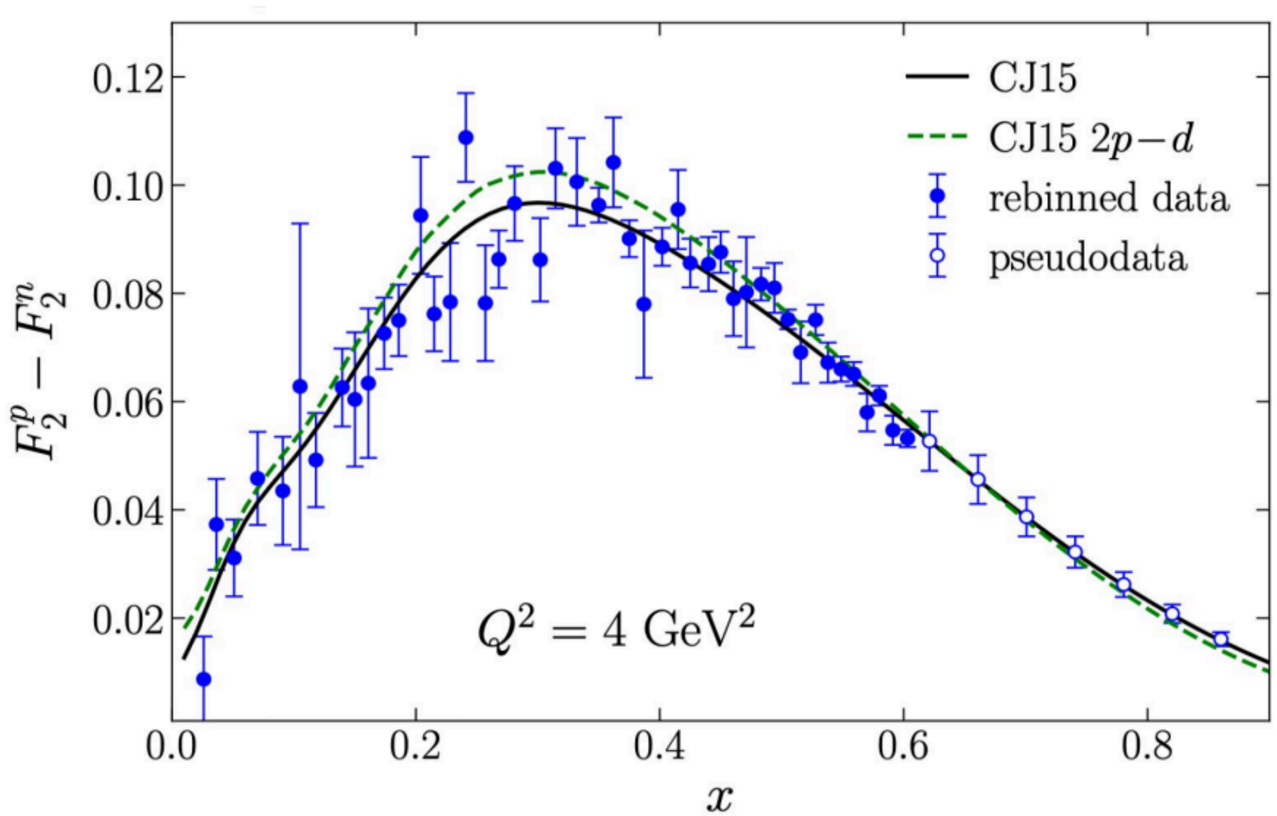


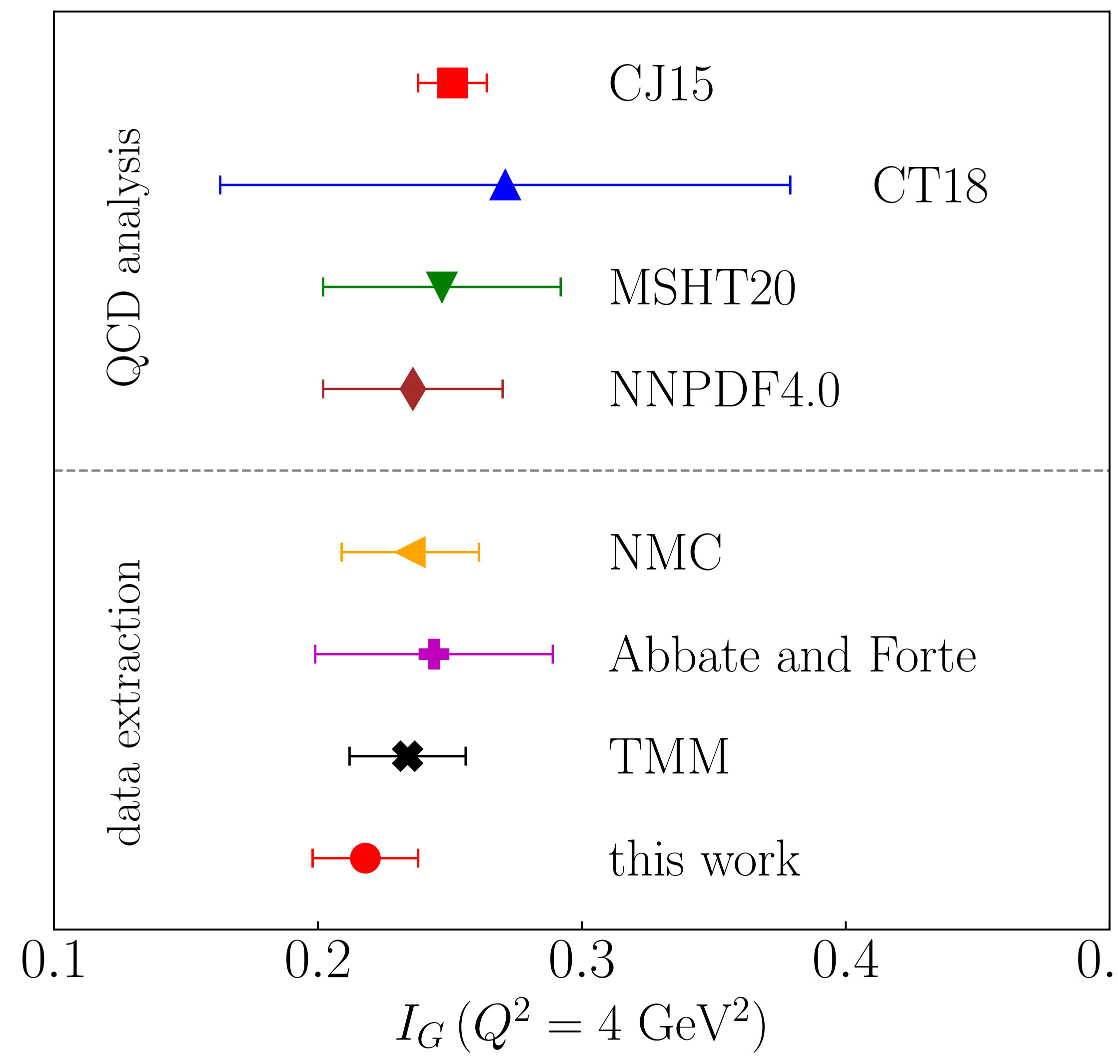
- **x<0.01**: Regge theory
- **0.01<x<0.6**: Exp. data
- **x>0.6**: CJ15 model

Application: GSR

Gottfried sum rule

$$S_G(Q^2) = \int_0^1 \frac{dx}{x} \left[F_2^p(x,Q^2) - F_2^n(x,Q^2)\right]$$





- **x<0.01**: Regge theory
- **0.01<x<0.6**: Exp. data
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GOOD AGREEMENT!

Application: non-singlet moments

Nachtmann moment

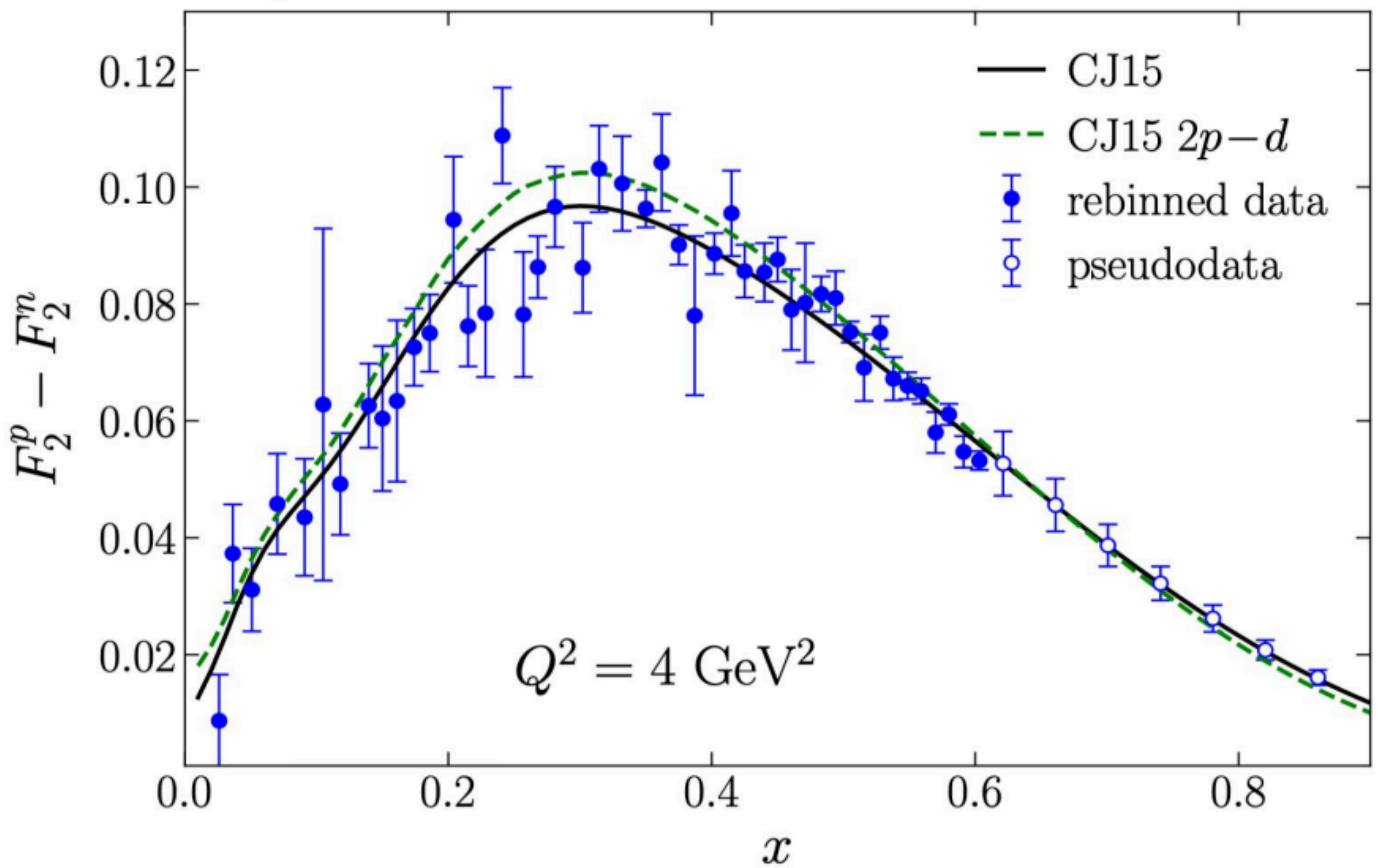
$$M_2^{p-n}(Q^2) = \int_0^1 dx \frac{\xi^3}{x^3}\left[\frac{3+9r+8r^2}{20}\right] F_2^{p-n}(x,Q^2)$$

ξ = Nachtmann variable

$$r = \sqrt{1 + 4x^2\frac{M_N^2}{Q^2}}$$

- Accounts for TMC
- Isoscalar F_2 from exp. data
- Relation to the non-singlet moment

$$\frac{3}{C_2} M_2^{p-n} = \langle x \rangle_{u^+ - d^+} + \text{ HT}$$



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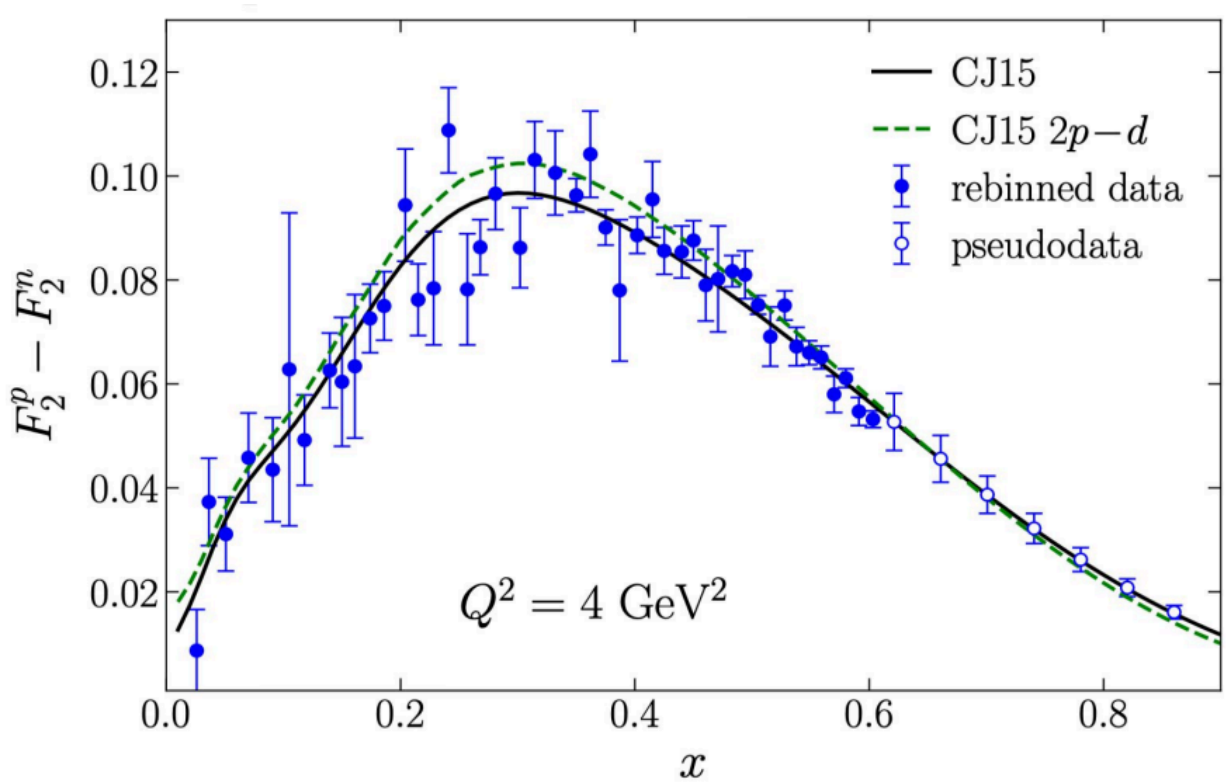

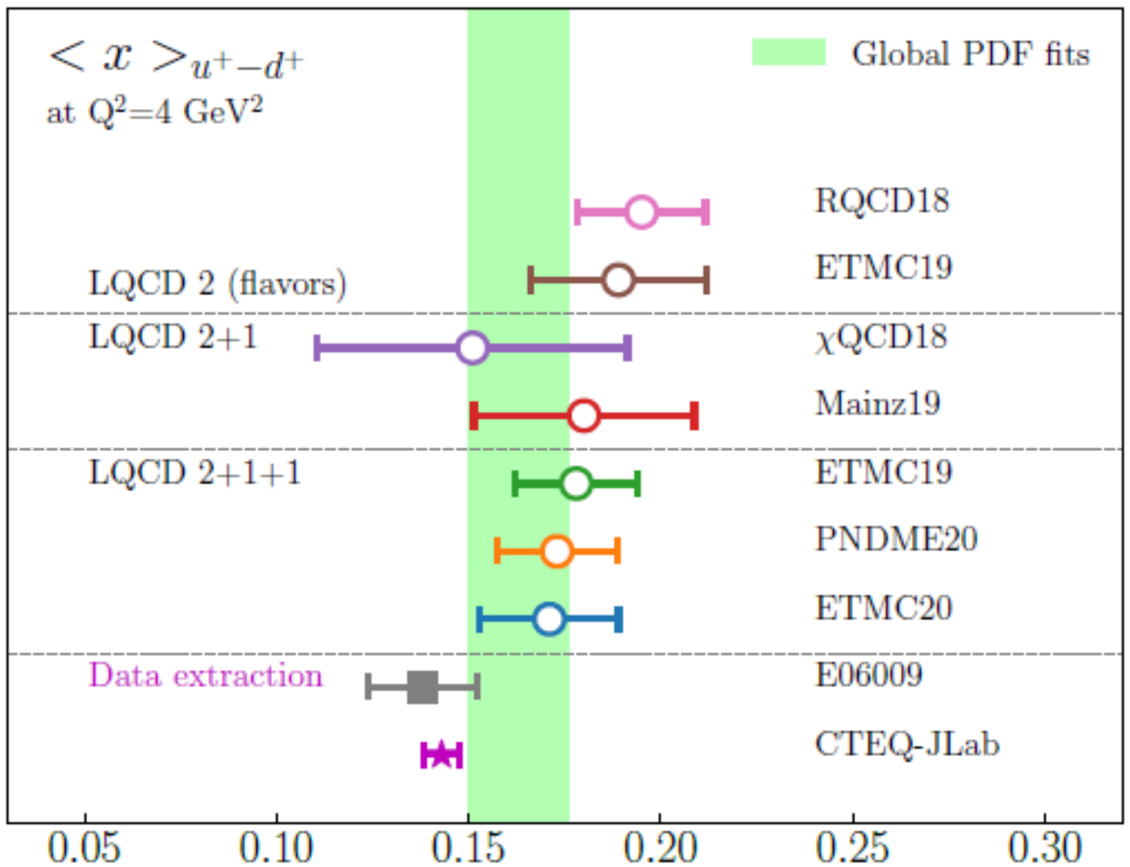

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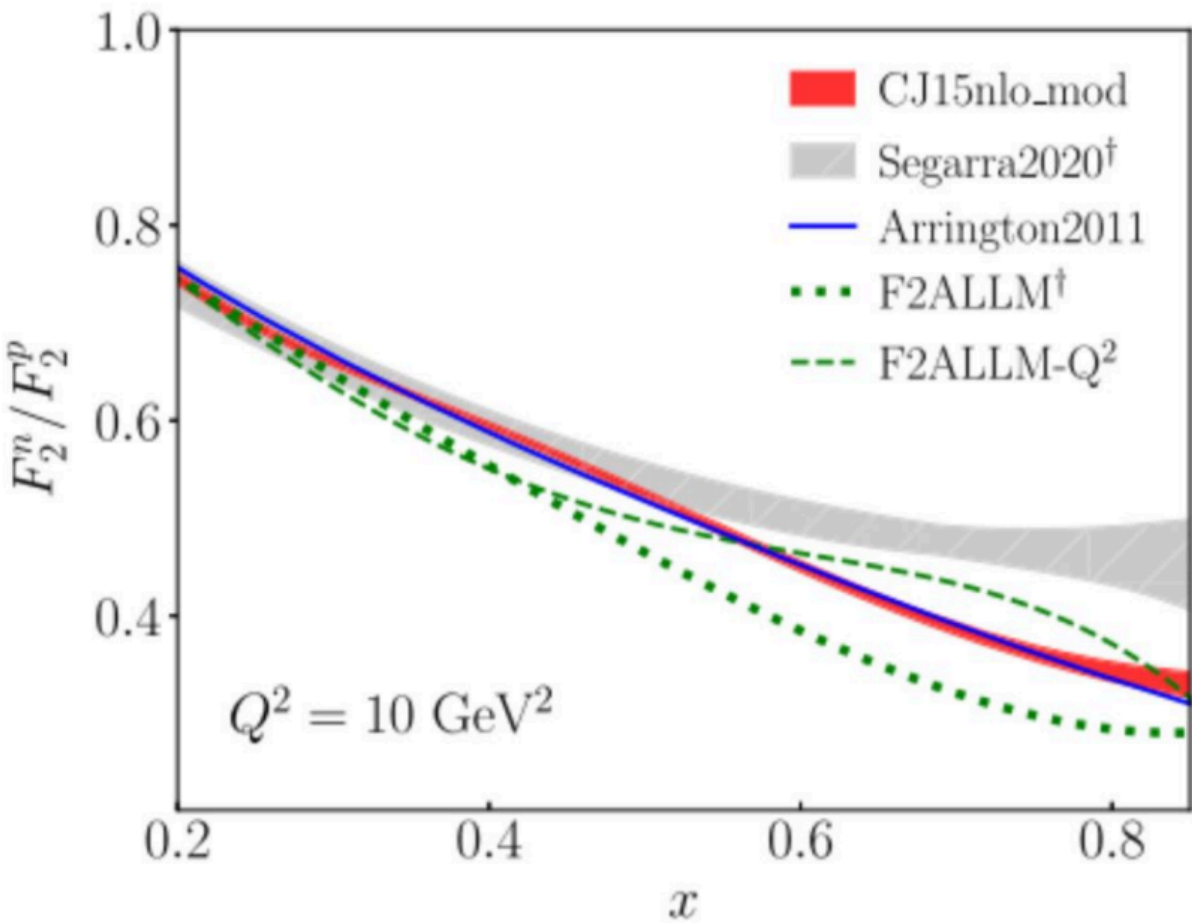
$$\langle x \rangle_{u^+ - d^+} = \int_0^1 dx x[u(x) + \bar{u}(x) - d(x) - \bar{d}(x)]$$

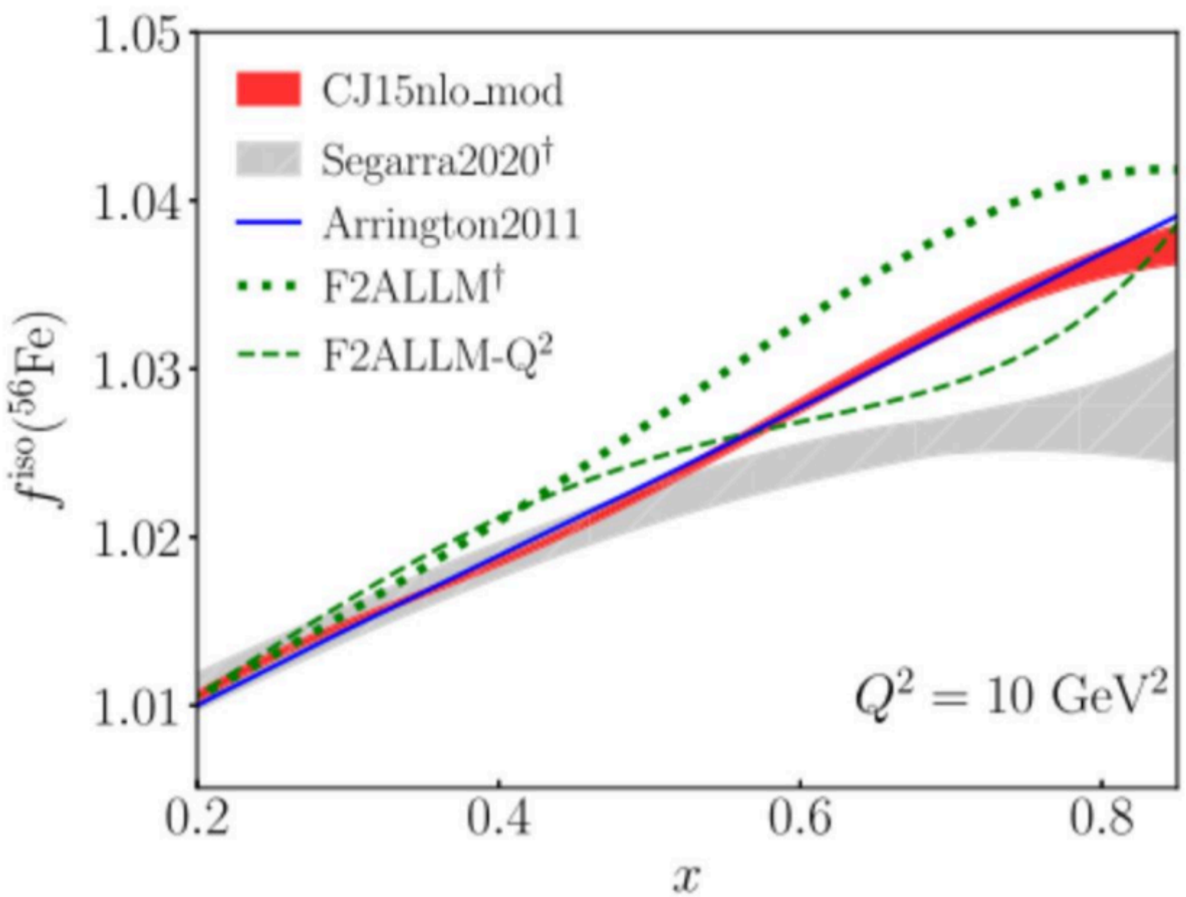
Application: isoscalar corrections

$$f_A^{iso}(x, Q^2) \simeq \left(\frac{A}{2}\right) \frac{1 + F_2^n/F_2^p}{Z + N F_2^n/F_2^p}$$

EMC effect

`CJ15nlo_mod`





Open database on GitHub

https://github.com/JeffersonLab/CJ-database/

CJ Unpolarized DIS Database Homepage

Reference: arXiv:2309.16851.

See also

- CTEQ-JLab collaboration website.
- note for reduced cross section and F2 calculation.

World DIS data tables

World **proton** and **deuteron** data of unploarized DIS cross sections, F2 structure functions, and the longitudinal to transverse cross section ratio R are collected or extracted from various experiments. Data were collected for the CJ global fit and related analysis. Now open for general use. See details under the data directory.

Neutron F2 extraction

Based on the collected F2 data, we performed a data-driven extraction of **neutron F2** and **neutron-to-proton F2n/F2p ratio** within the CJ15 framework (see eq. 7-9 in reference for details). Data from all experiemnts are cross-normalized and combined into a single Excel file, both in the original kineamtics, as well as rebinned in Q^2. Check the f2n directory.

Structure function grids

Within CJ framework, we calculated various structure functions (F2, F3, FL, etc) at given x, Q^2 grids. Results are provided under folder SFN_grids in the LHAPDF format. An example plotting script is available at `src/plot_sfn.py`

Experiment	σ_r	F2	R
SLAC-Whitlow	p: 10014	p: 10010	p: 10064
	d: 10015	d: 10011	d: 10065
	d/p: 10034	d/p (*): 10034	
SLAC-Whitlow(rebinned)		rebinned p: 10012	
		rebinned d: 10013	
SLAC-E140			d: 10066
SLAC-E140x	p: 10037	p: 10035	p: 10067
	d: 10038	d: 10036	d: 10068
NMC	p: 10022	p: 10020	
	d: 10040	d: 10039	
	d/p:10021	d/p (*):10021	
BCDMS	p: 10018	p: 10016	p: 10069
	d: 10019	d: 10017	d: 10070
JLab E06-009	d: 10042	d: 10041	d: 10071
(includes E04-001, E02-109)			
JLab E94-110	p: 10044	p: 10043	p: 10074
JLab E03-103	p:10047	p:10045	
	d:10048	d:10046	
JLab E99-118	p:10052	p:10049	p: (A)
	d:10053	d:10050	p-d: (A)
	d/p:10054	d/p:10051	
JLab JLCEE96	p: 10055	p: 10072	
	d: 10056	d: 10073	
JLab E00-116	p: 10003	p: 10001	
	d: 10004	p: 10002	
CLAS6	p: 10059	p: 10057	
	d: 10060	d: 10058	
BONUS		n: 10061	
		n/d: 10033	
HERA I+II	p: 10026 - 10032		
HERMES	p: 10007	p: 10005	
	d: 10008	d: 10006	
	d/p: 10009		
E665		p: 10062	
		d: 10063	

LHAPDF grids

F_2, F_L, F_3 $\gamma, \gamma Z, Z$

w/, w/o HT

Conclusions and Outlook

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- The F2n data set has been used for different applications

Backup

Impact of HT on n/p ratio

Are experimental observables independent of the choice of the HT?

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

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

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

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

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?

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

Add HT

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

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

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

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

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

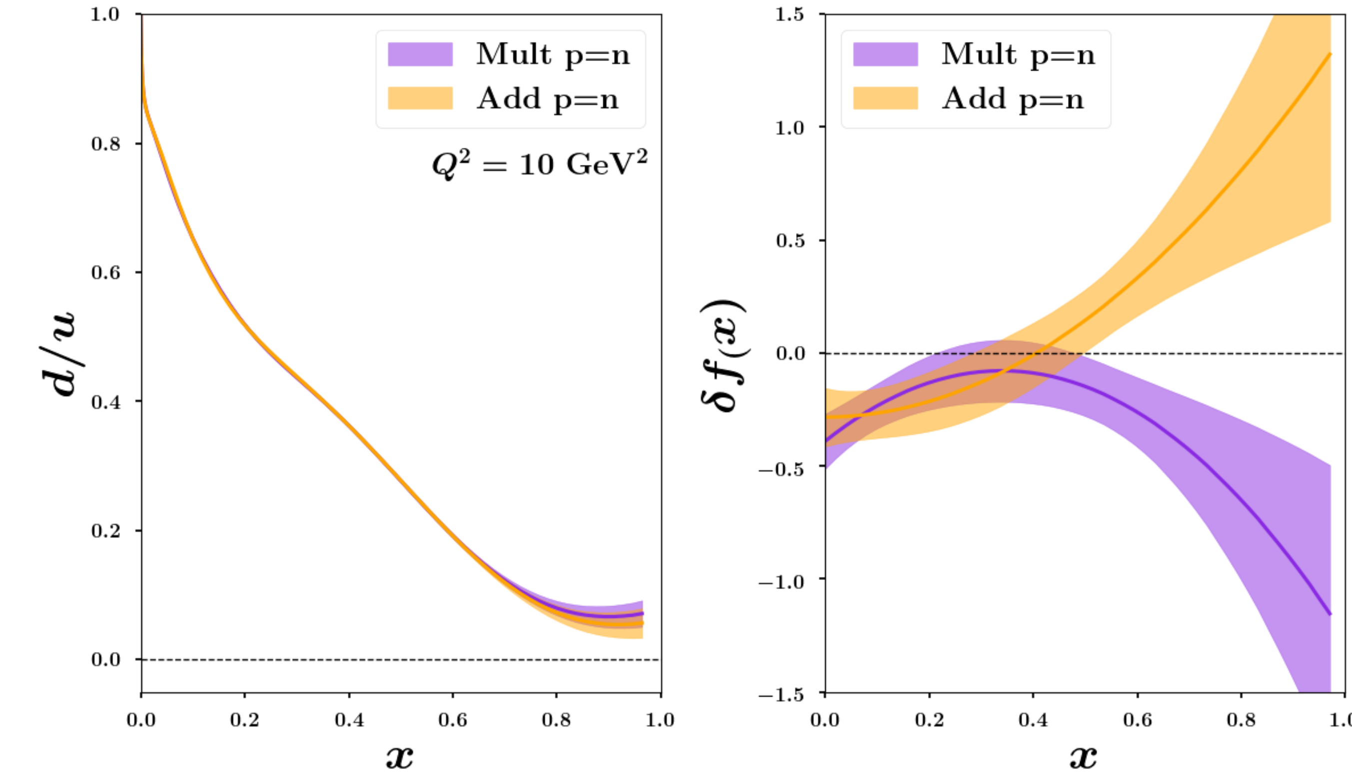
Add HT

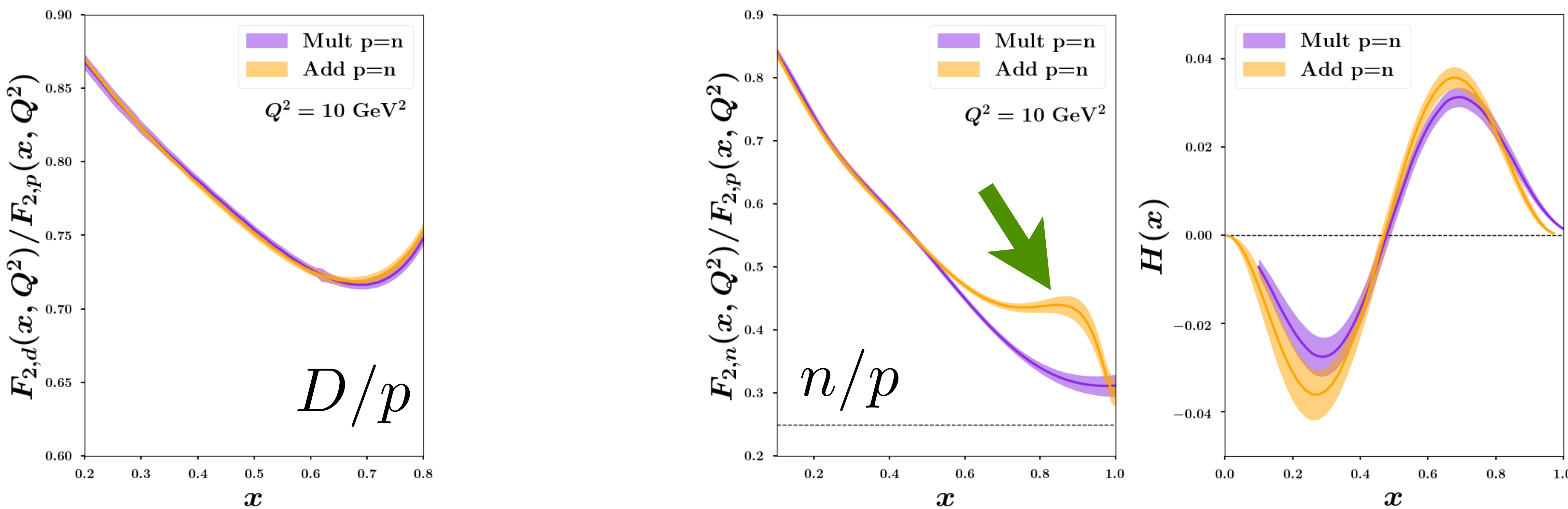
Unnaturally large n/p

BUT smaller d/u than Mult

Bias identified

Off-shell compensates n/p bias





Results in the CJ fitting framework

Case 2: isospin breaking

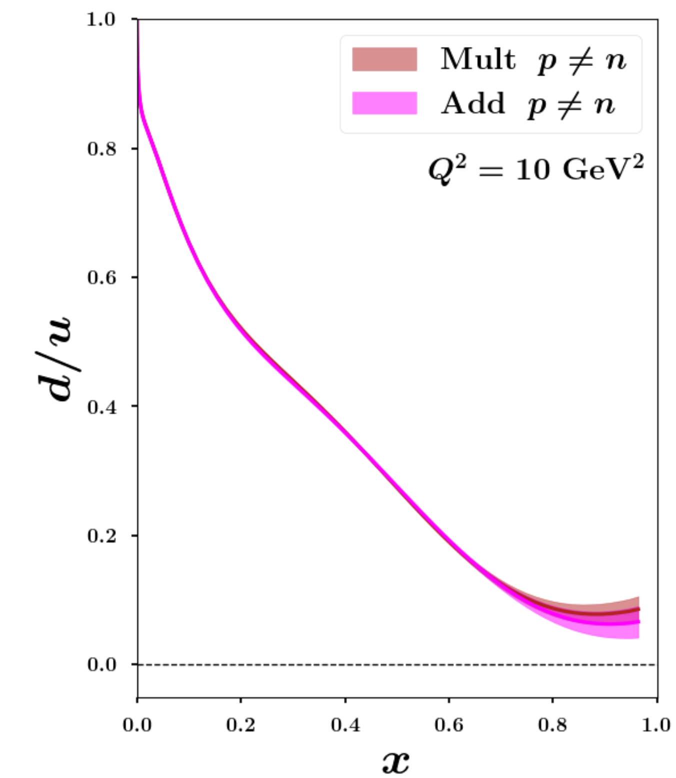
Compatible n/p

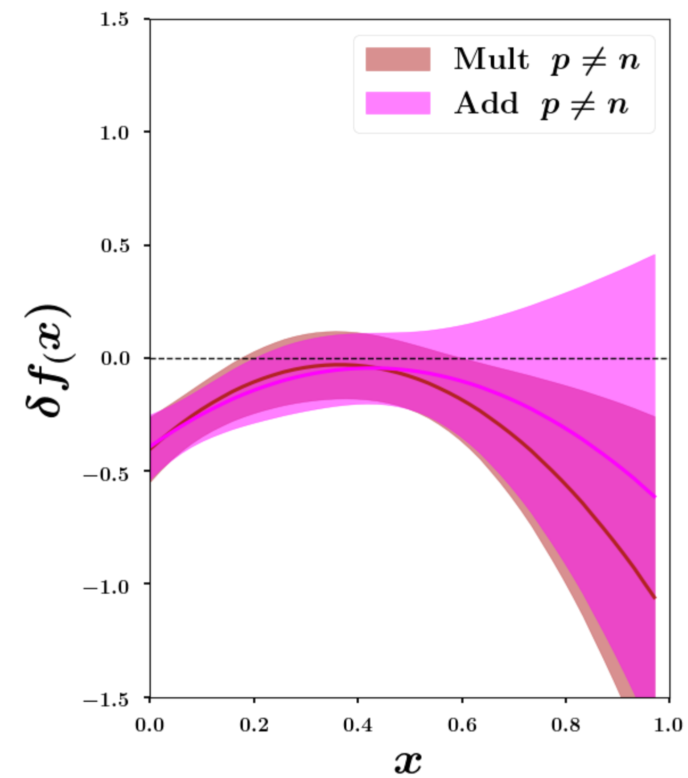
$$H_n(x) \simeq \frac{1}{2} H_p(x)$$

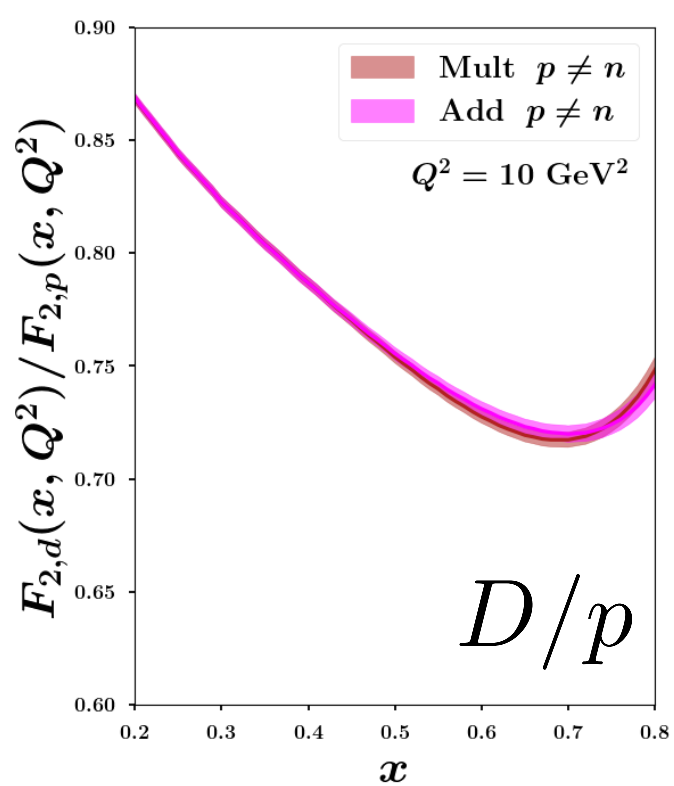
Bias removed

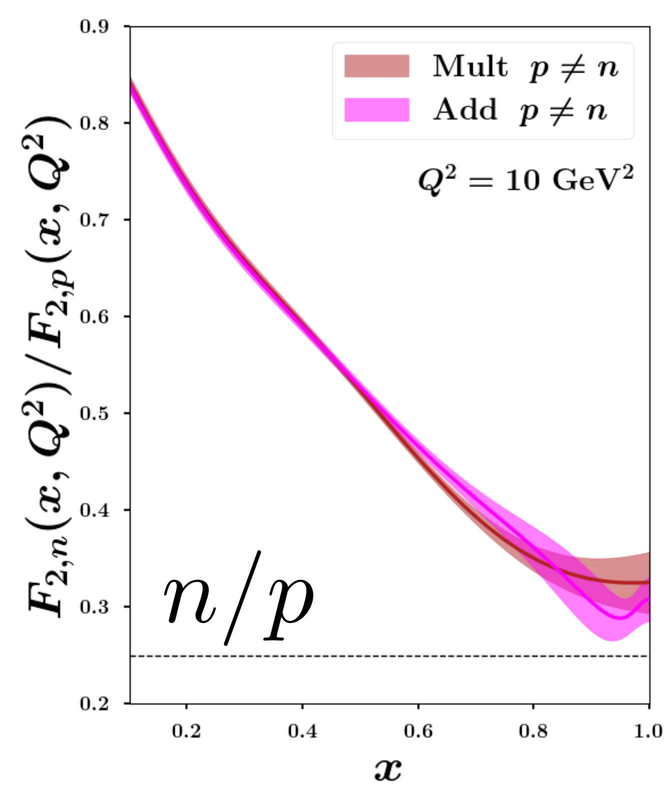
No need of compensation by off-shell

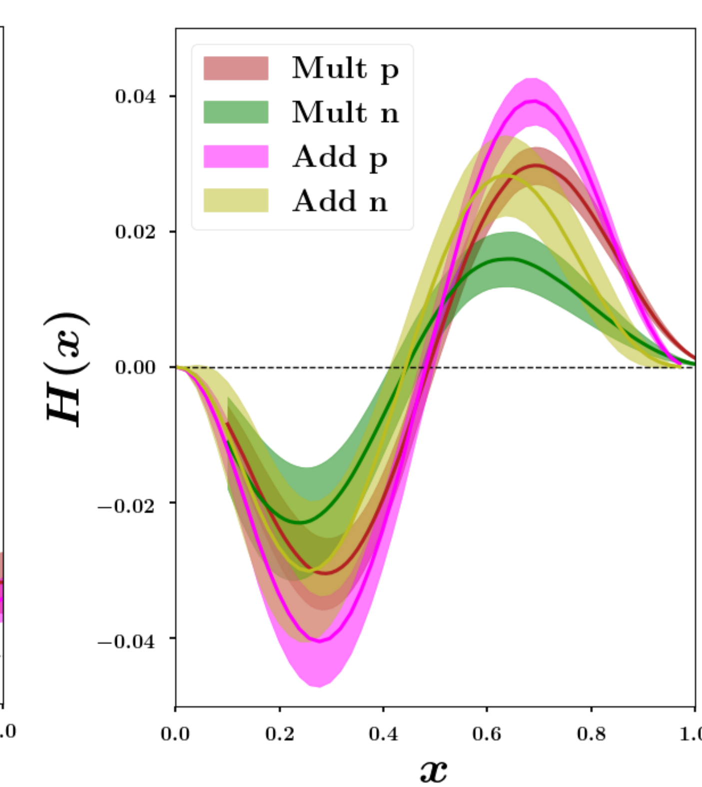
Theory calculation confirmed!





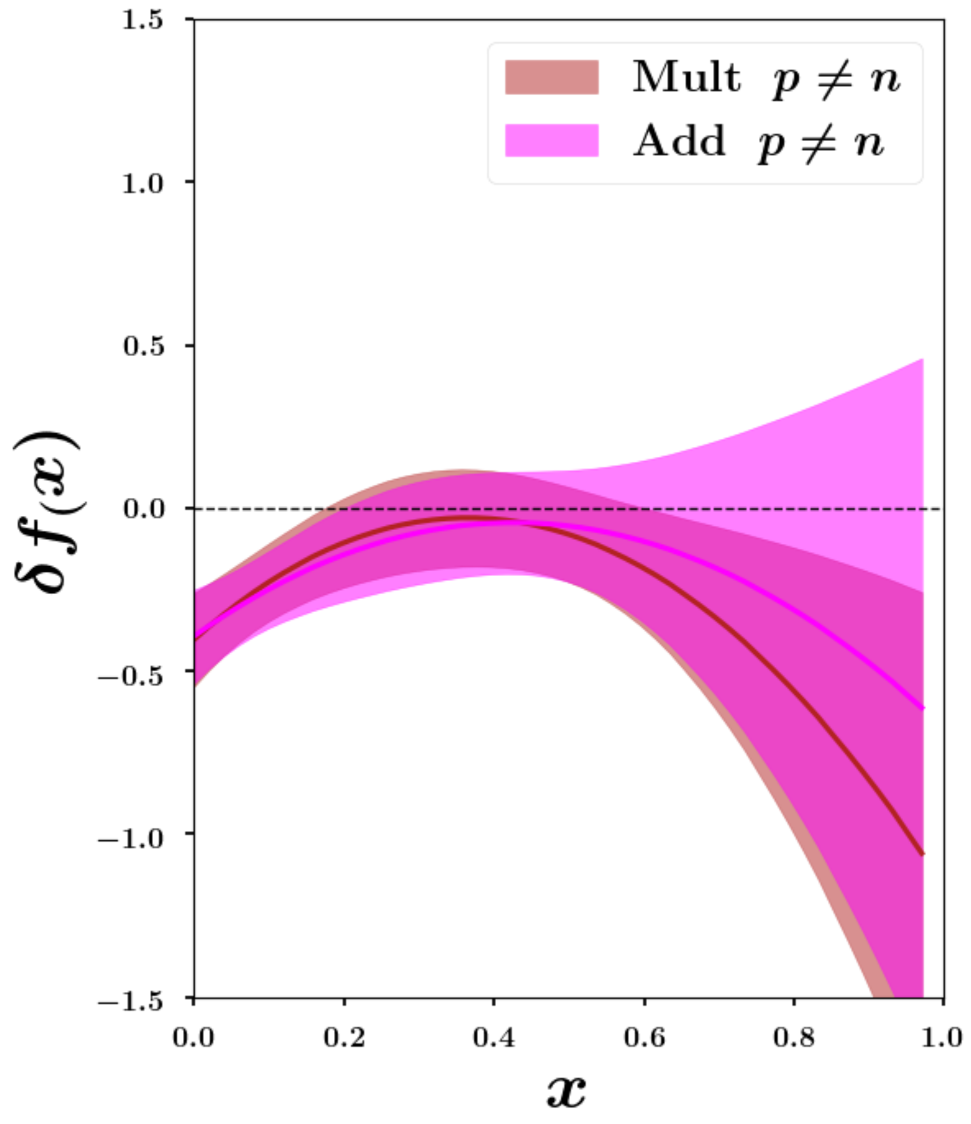






Results in the CJ fitting framework

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



Is the nucleon inside the deuterium almost on-shell?

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

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

No significant differences seen between HT Add and Mult

DISCLAIMER: off-shell function parametrized at the structure function level (δF)
and many other differences in the implementation

Fit to A=3 data: $\delta F_p(x) \simeq \delta F_n(x)$ (baseline)

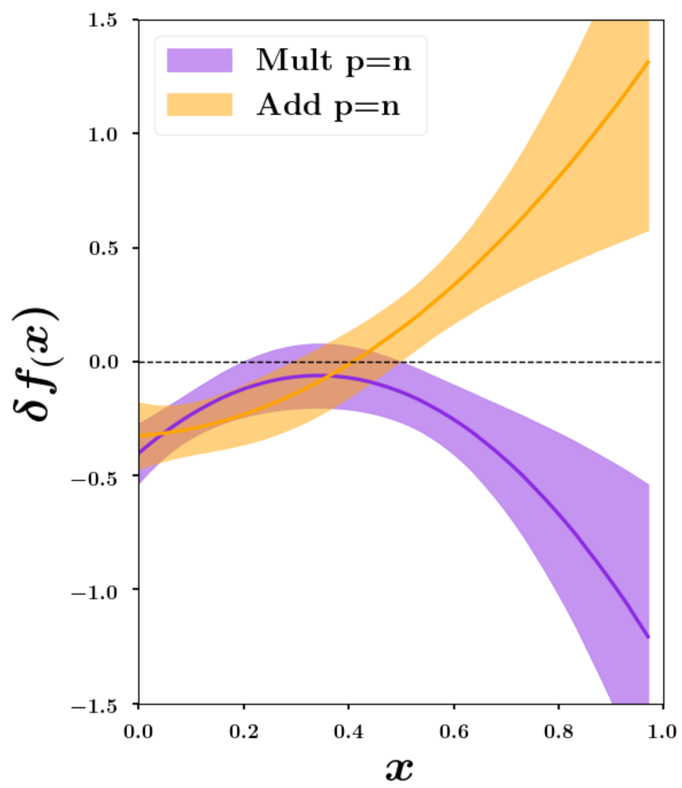
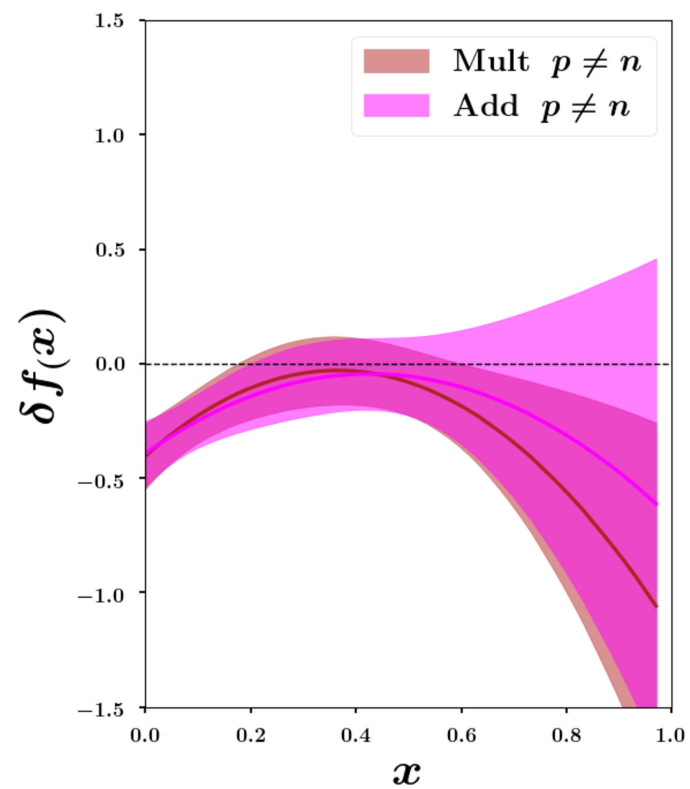
JAM JAM Collaboration, PRL 127 (2021)

Only multiplicative HT considered

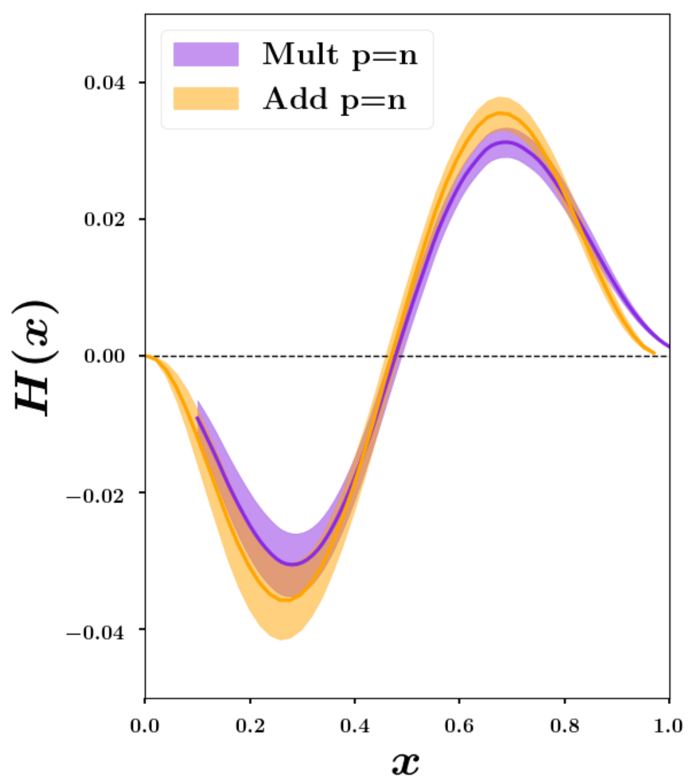
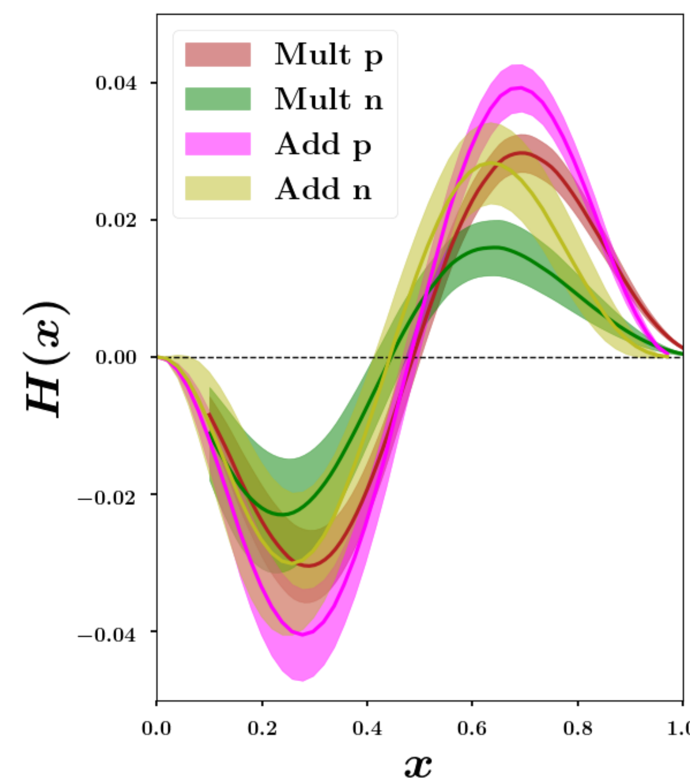
DISCLAIMER: off-shell function parametrized at the pdf level (δf)
but many differences in the implementation

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

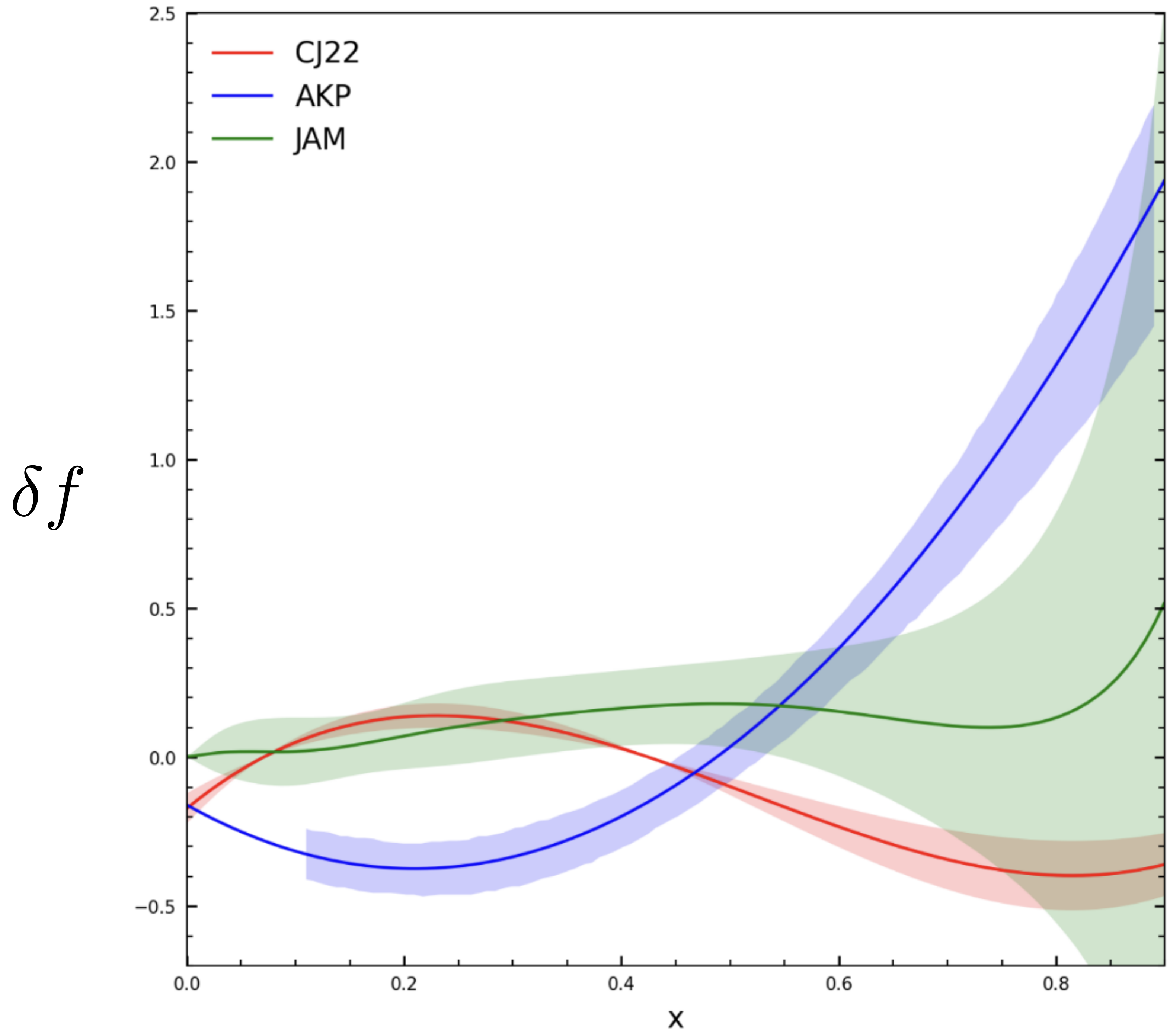
Off-shell table

isospin / higher-twist	Symmetric	Non symmetric
Multiplicative		
Additive		

Higher-Twist table

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

AKP vs CJ



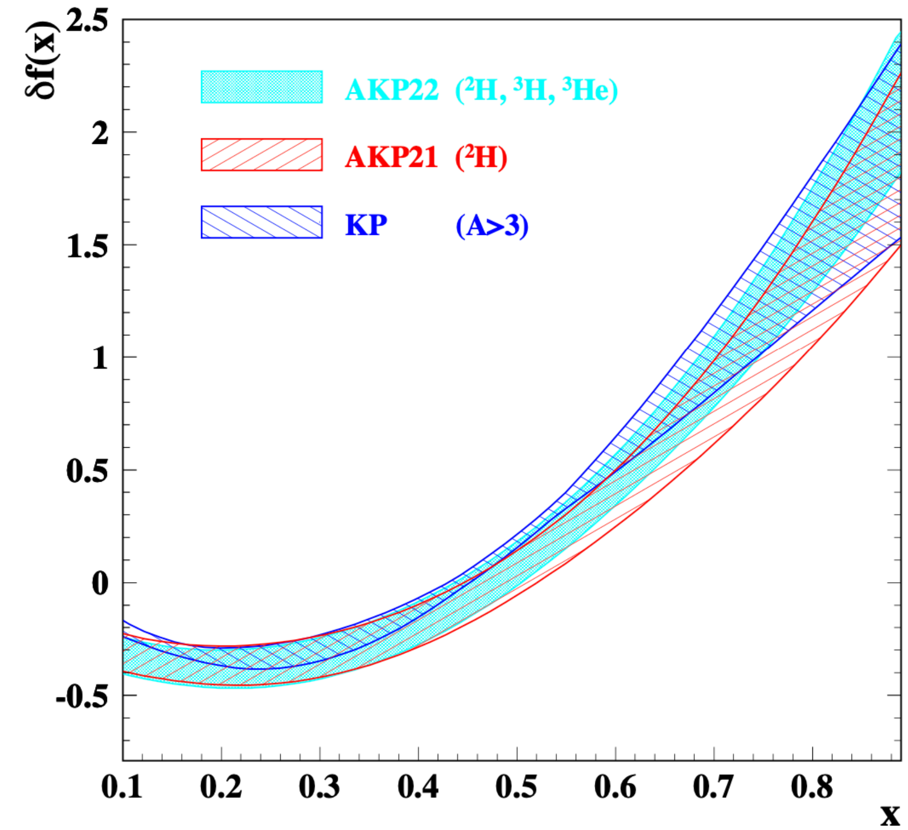
AKP results

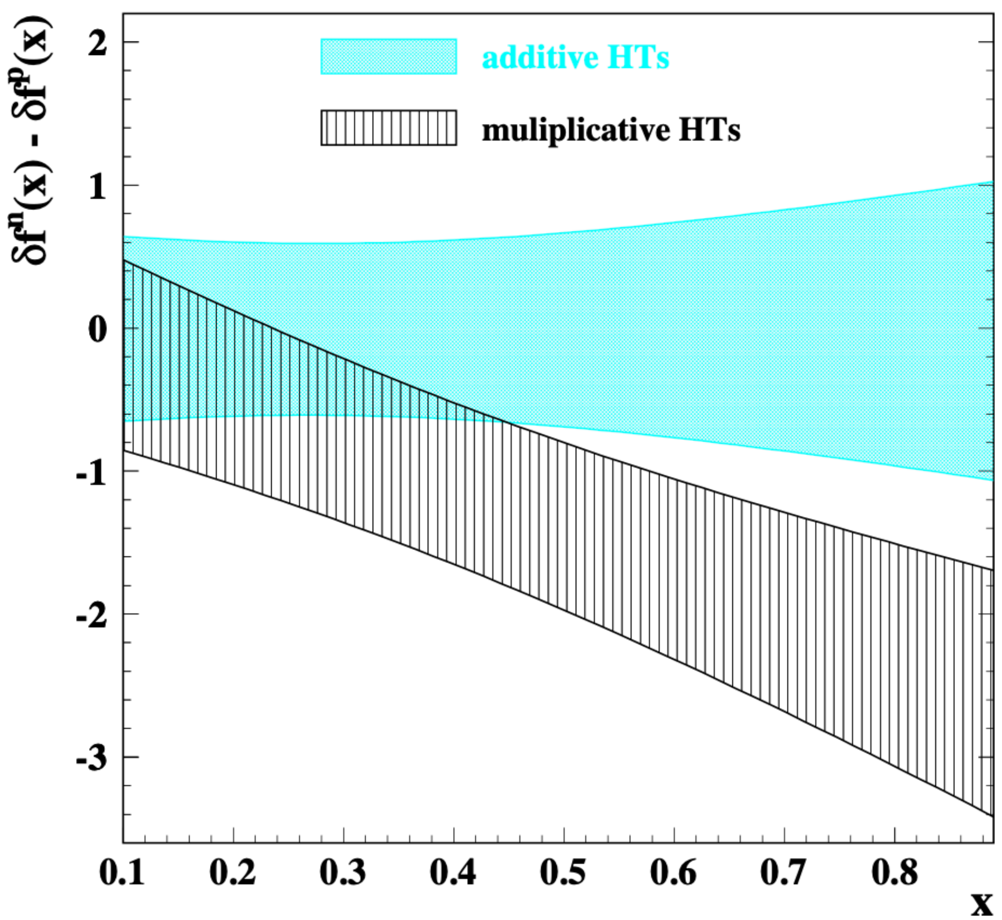
AKP Alekhin, Kulagin, Petti, PRD 107 (2023)

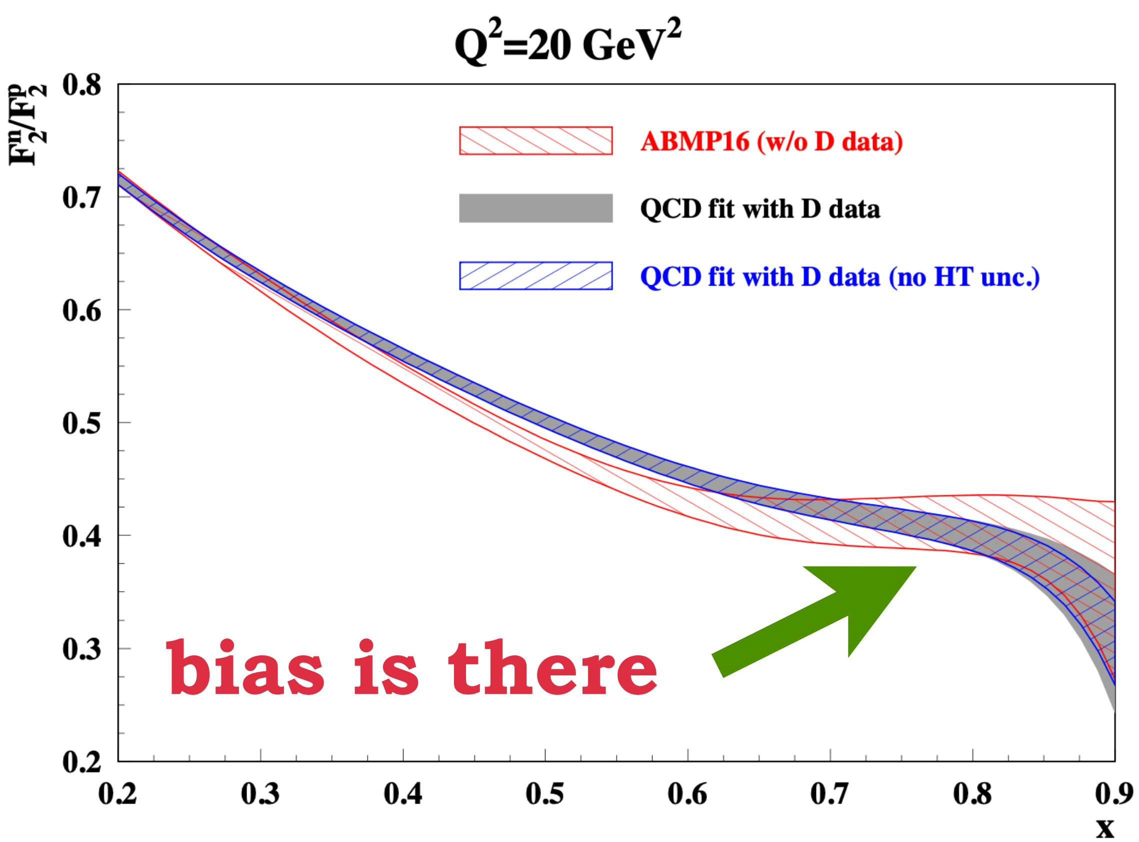
Add HT (p=n) as baseline choice

H_2, H_T parametrized

Fit to A=3 data δF_p δF_n





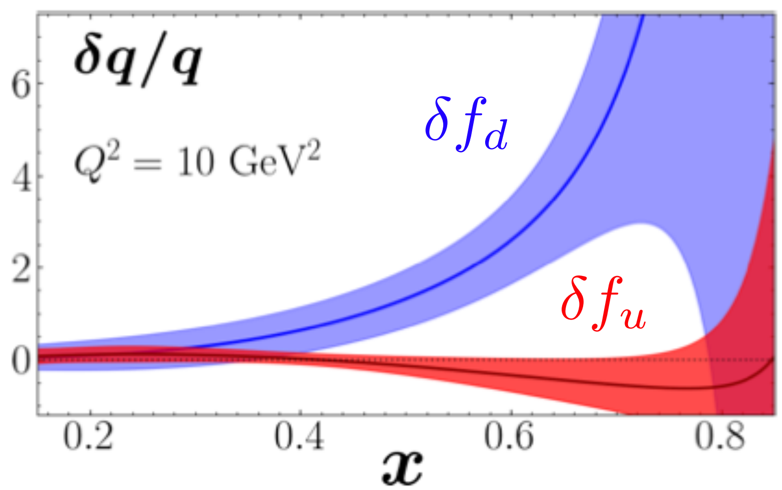


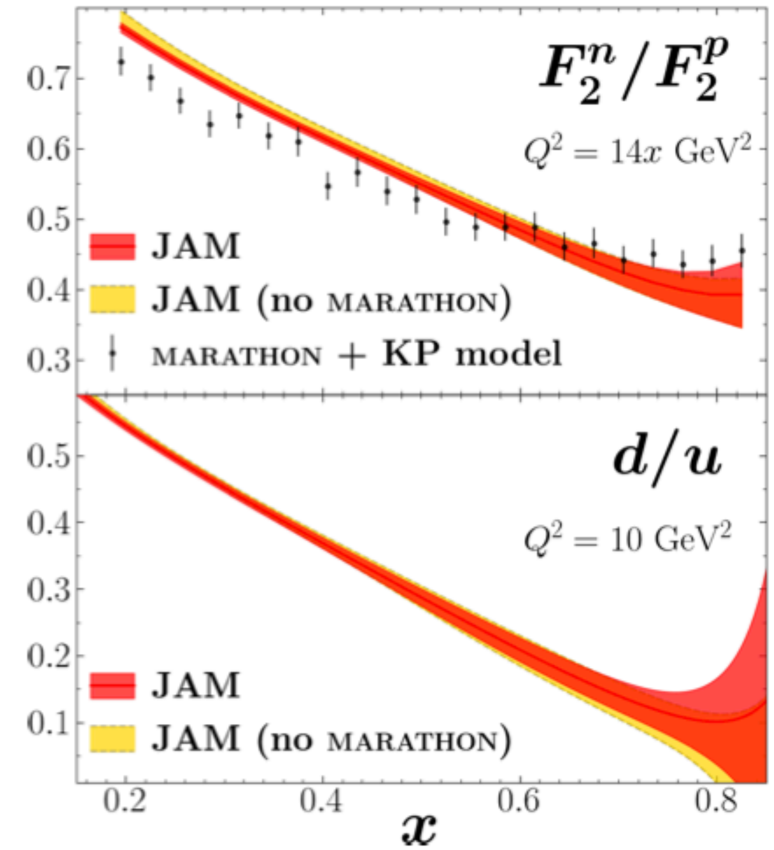
JAM results

JAM *Fit including A=3 data* δf_u δf_d

JAM Collaboration, PRL 127 (2021)

Mult HT (p=n) as default choice

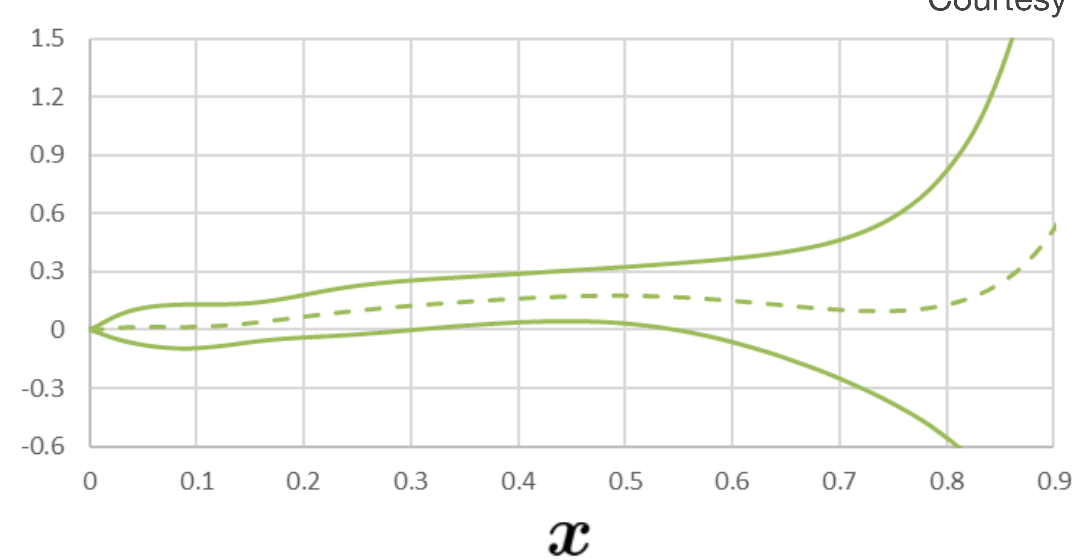




$$\delta f(x)|_{\text{CJ-like}} = \frac{u\delta f_u + d\delta f_d}{u+d}$$

Isoscalar offshell function (JAM)

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	----	----