



nCTEQ15-HIX

Nuclear PDFs in valence region

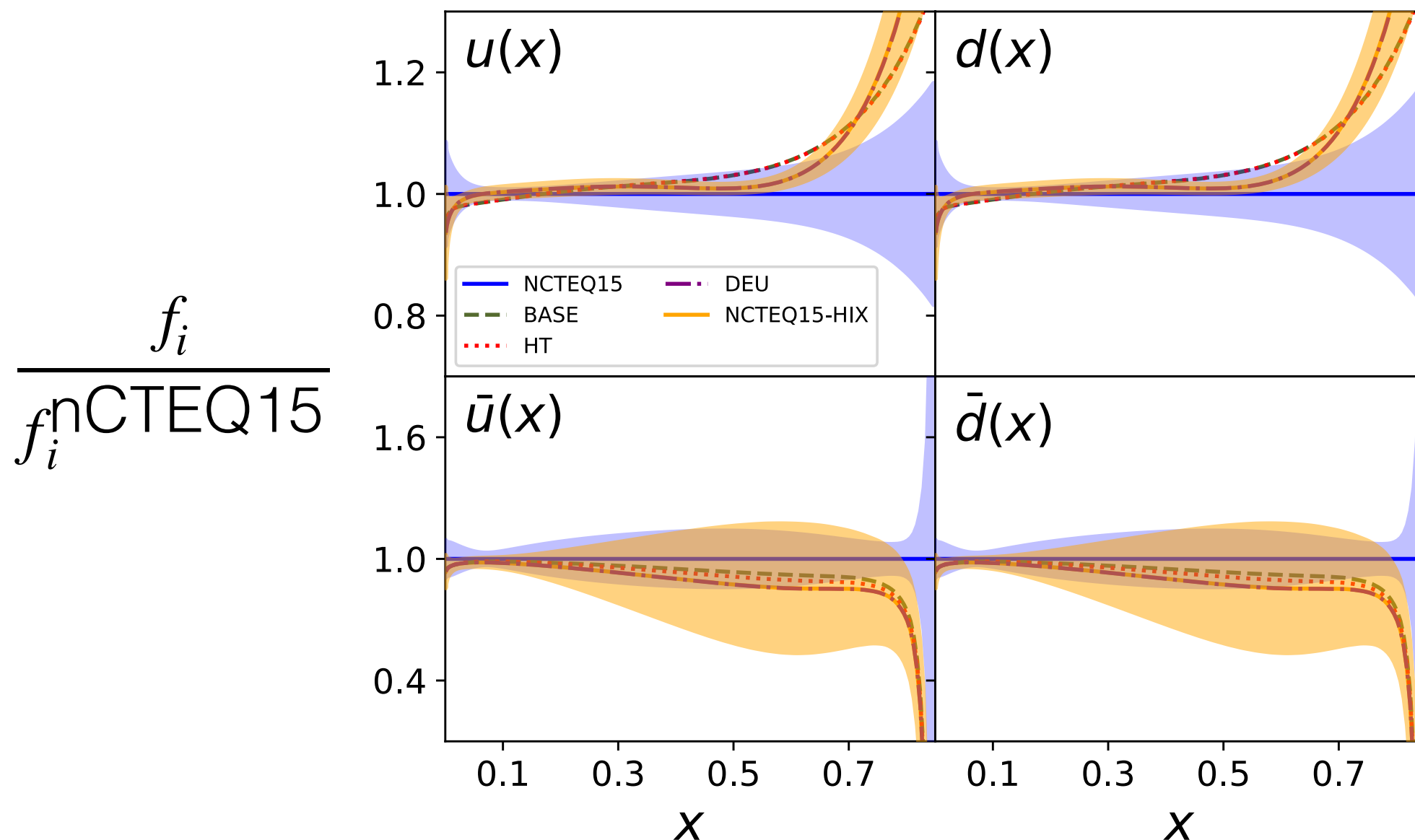
Efrain Segarra

In collaboration with T. Ježo, A. Accardi, P. Duwentäster,
O. Hen, T.J. Hobbs, C. Keppel, M. Klasen, K. Kovařík,
A. Kusina, J.G. Morfín, K.F. Muzakka, F.I. Olness,
I. Schienbein, J.Y. Yu



nPDFs in valence region

Important framework as we push towards the EIC and essential for valence analyses

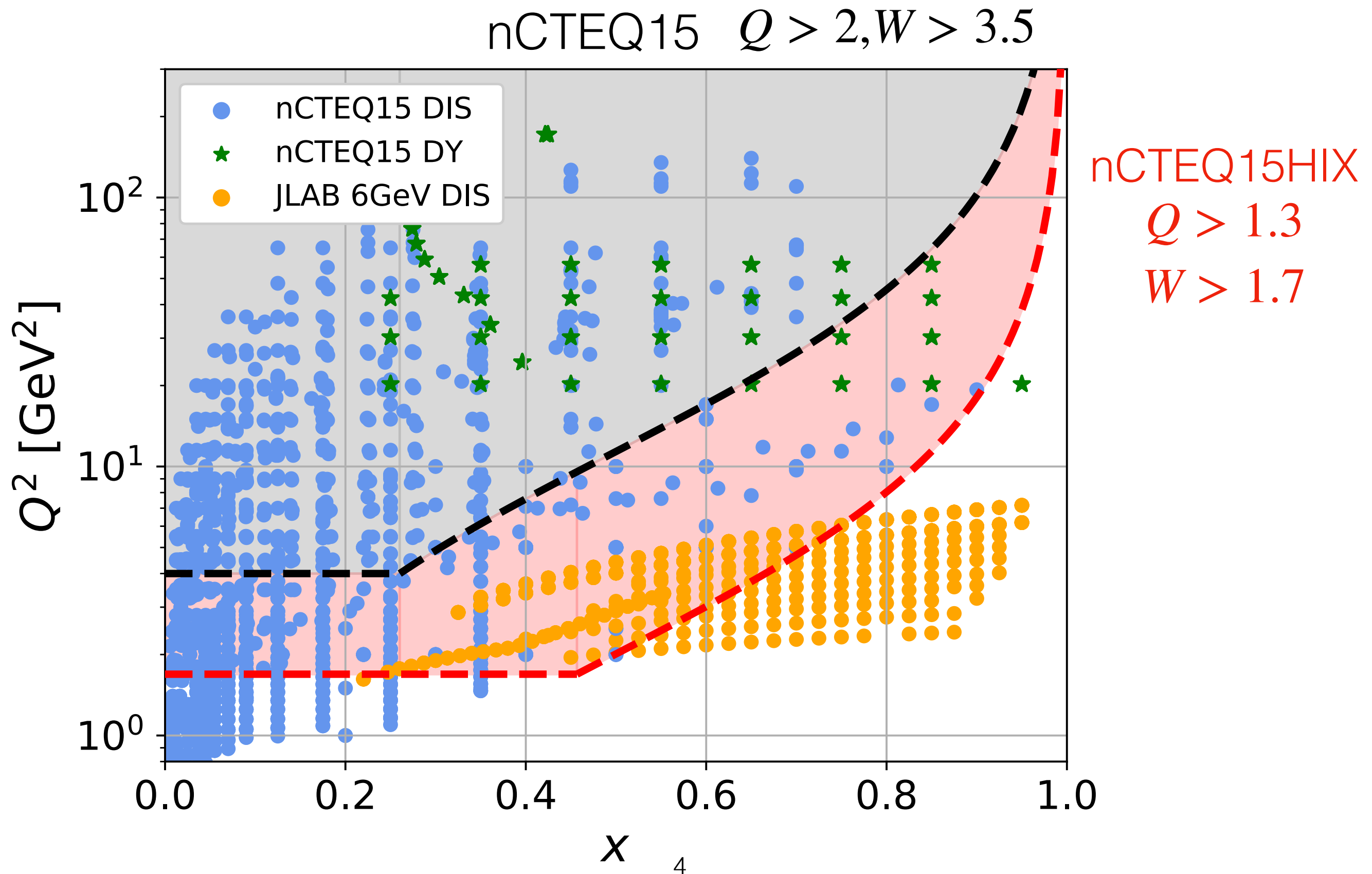


Outline

- Challenges in the valence region
- Resulting PDFs (**nCTEQ15HIX**)

arxiv 2012.11566 (under review)

Moving to valence region



Challenges in valence region

Requires lower (Q^2, W) cuts

- EMC Region and Fermi-Smearing
 - Flexible x -parameterization
 - Flexible A -dependence

Challenges in valence region

Requires lower (Q^2, W) cuts

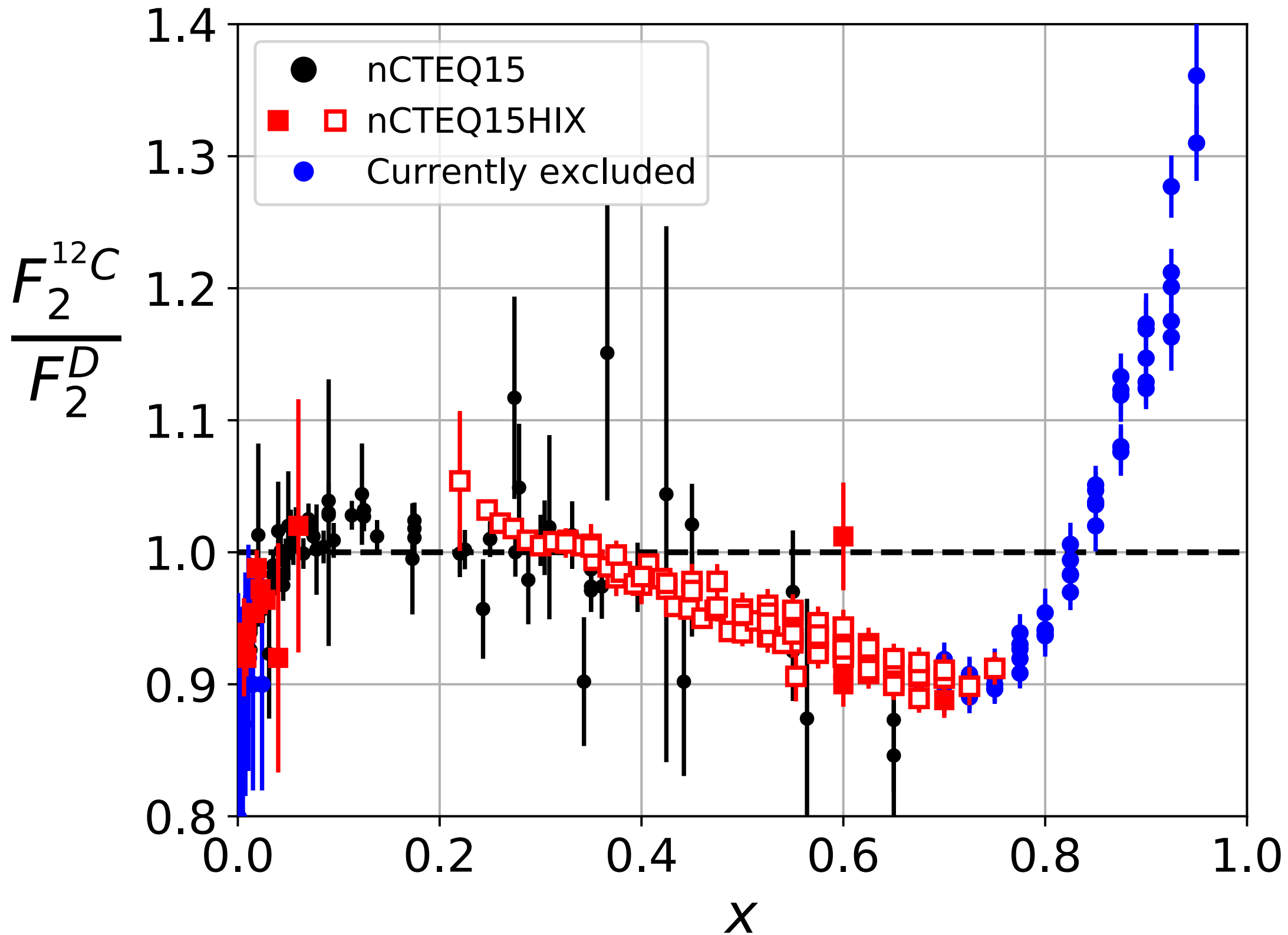
- EMC Region and Fermi-Smearing
 - Flexible x -parameterization
 - Flexible A -dependence
- Deuterium theory calculation

Challenges in valence region

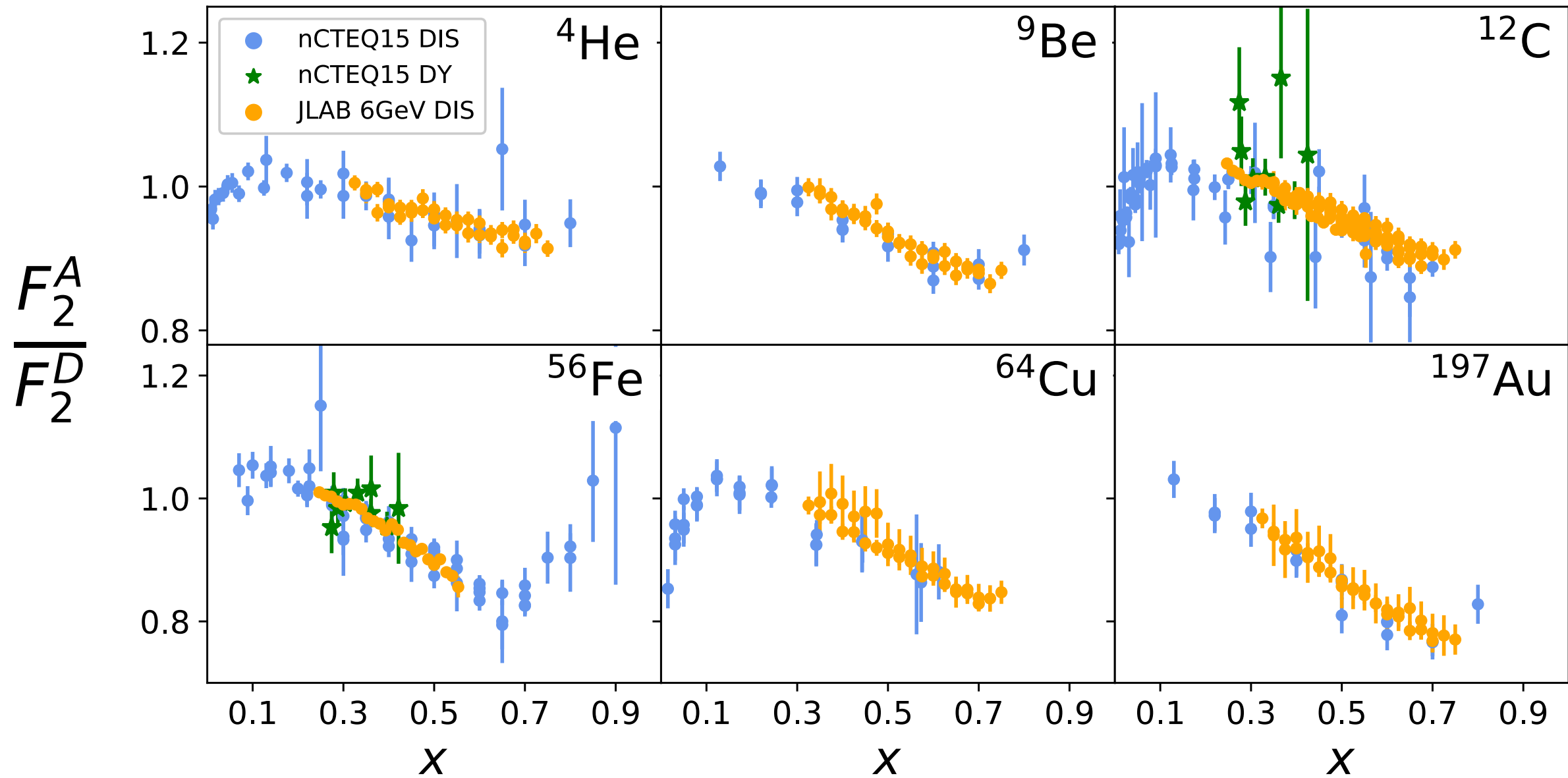
Requires lower (Q^2, W) cuts

- EMC Region and Fermi-Smearing
 - Flexible x -parameterization
 - Flexible A -dependence
- Deuterium theory calculation
- Target-mass and higher-twist effects become important in theory calculation

EMC region and Fermi smearing



JLab 6GeV has precise data over wide range of A



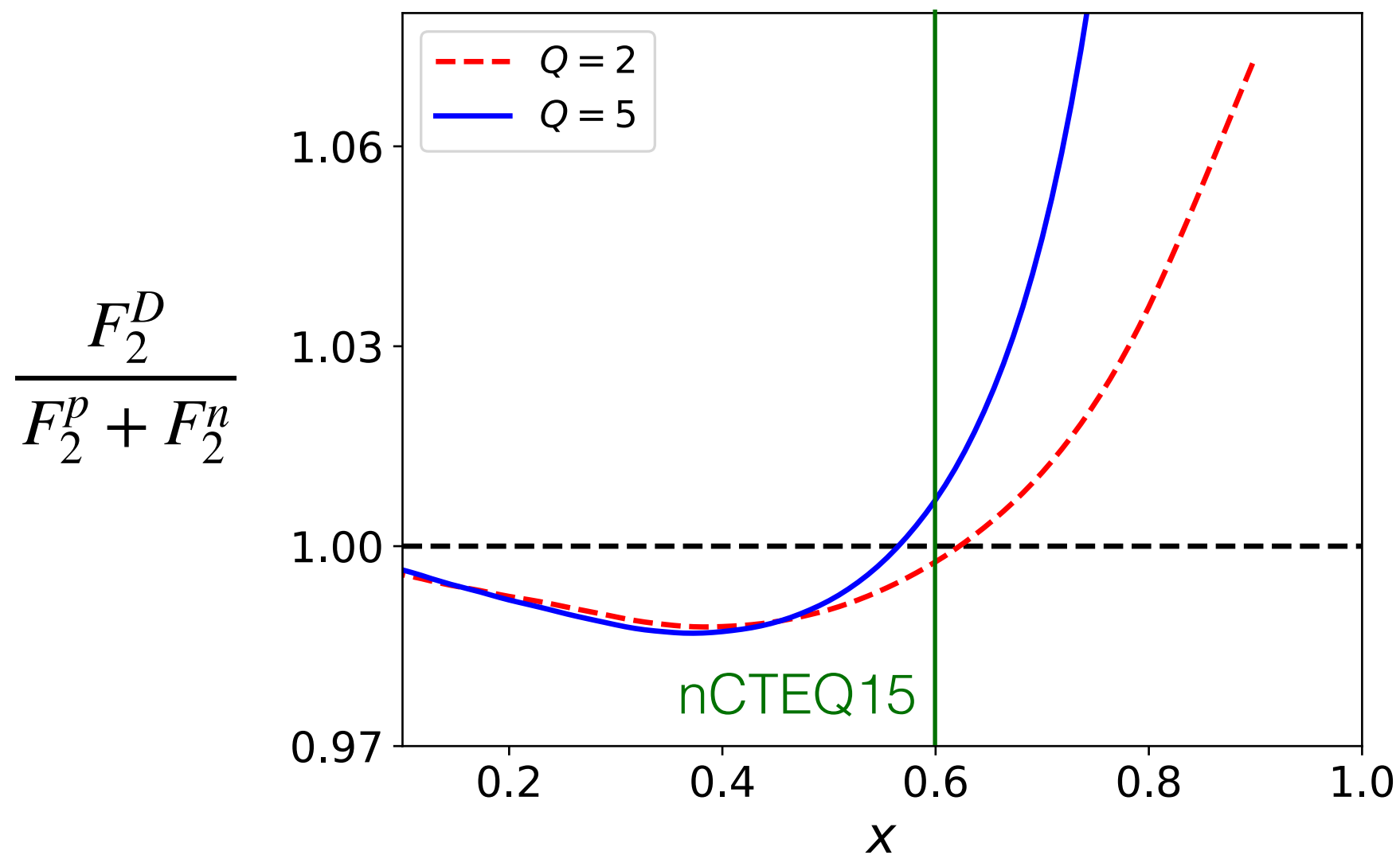
Deuterium at high- x

nCTEQ15
calculates

$$\frac{F_2^A}{F_2^p + F_2^n}$$

Data
reported as

$$\frac{F_2^A}{F_2^D}$$



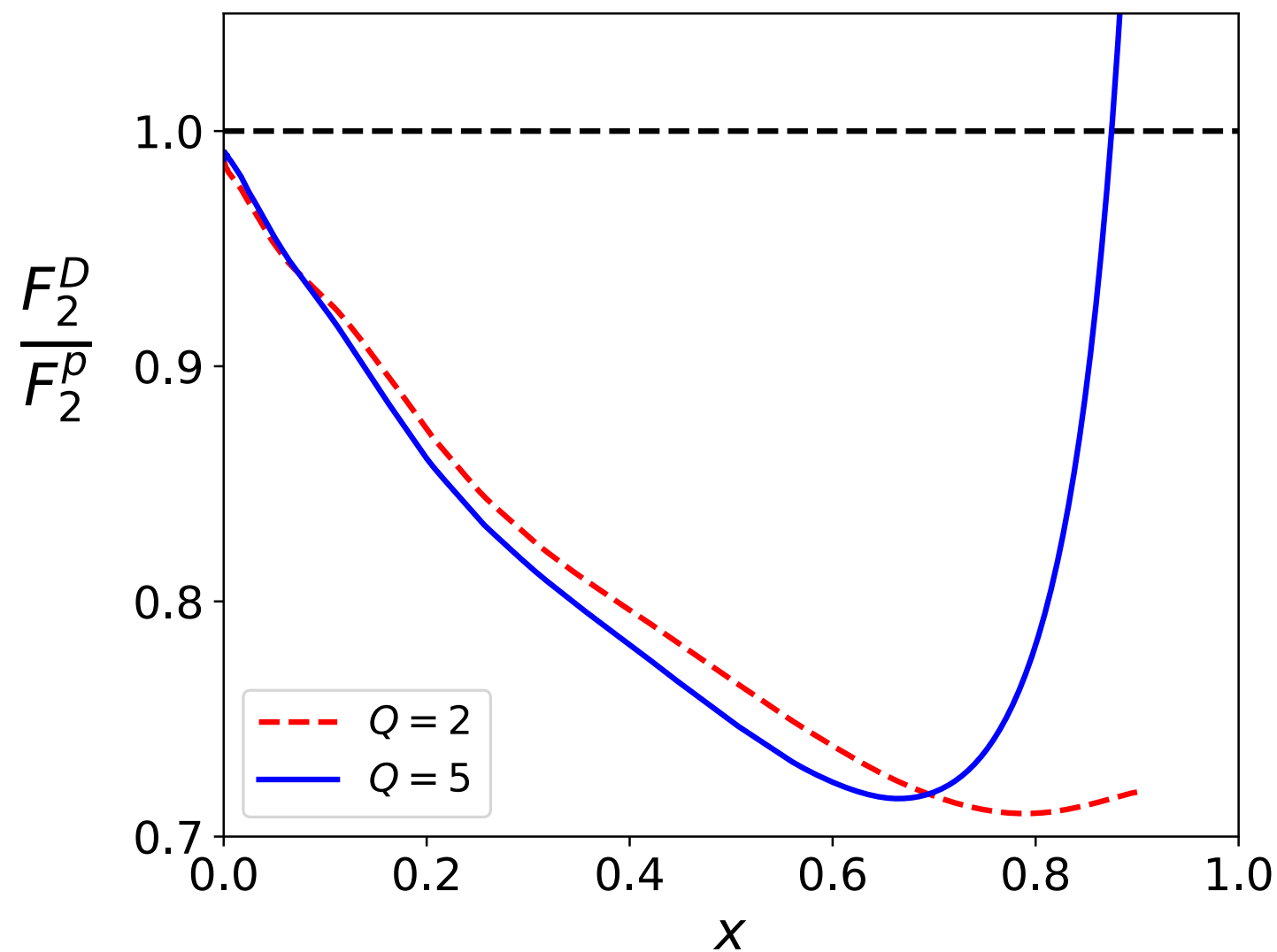
Deuterium at high- x

nCTEQ15HIX
calculates

$$\frac{F_2^A}{F_2^p} \quad (\text{Fixed free proton})$$

Data
“evolution”

$$\frac{F_2^A}{F_2^d} \cdot \left(\frac{F_2^d}{F_2^p} \right)_{CJ}$$



TMC & HT Corrections

TMC: Subleading M^2/Q^2 corrections to leading twist structure function

$$F_2^{TMC} \sim F_2^{(0)} + \frac{M^2}{Q^2} [\dots]$$

HT: Non-perturbative multi-quark interactions, theoretically not well understood, often parametrized and fitted

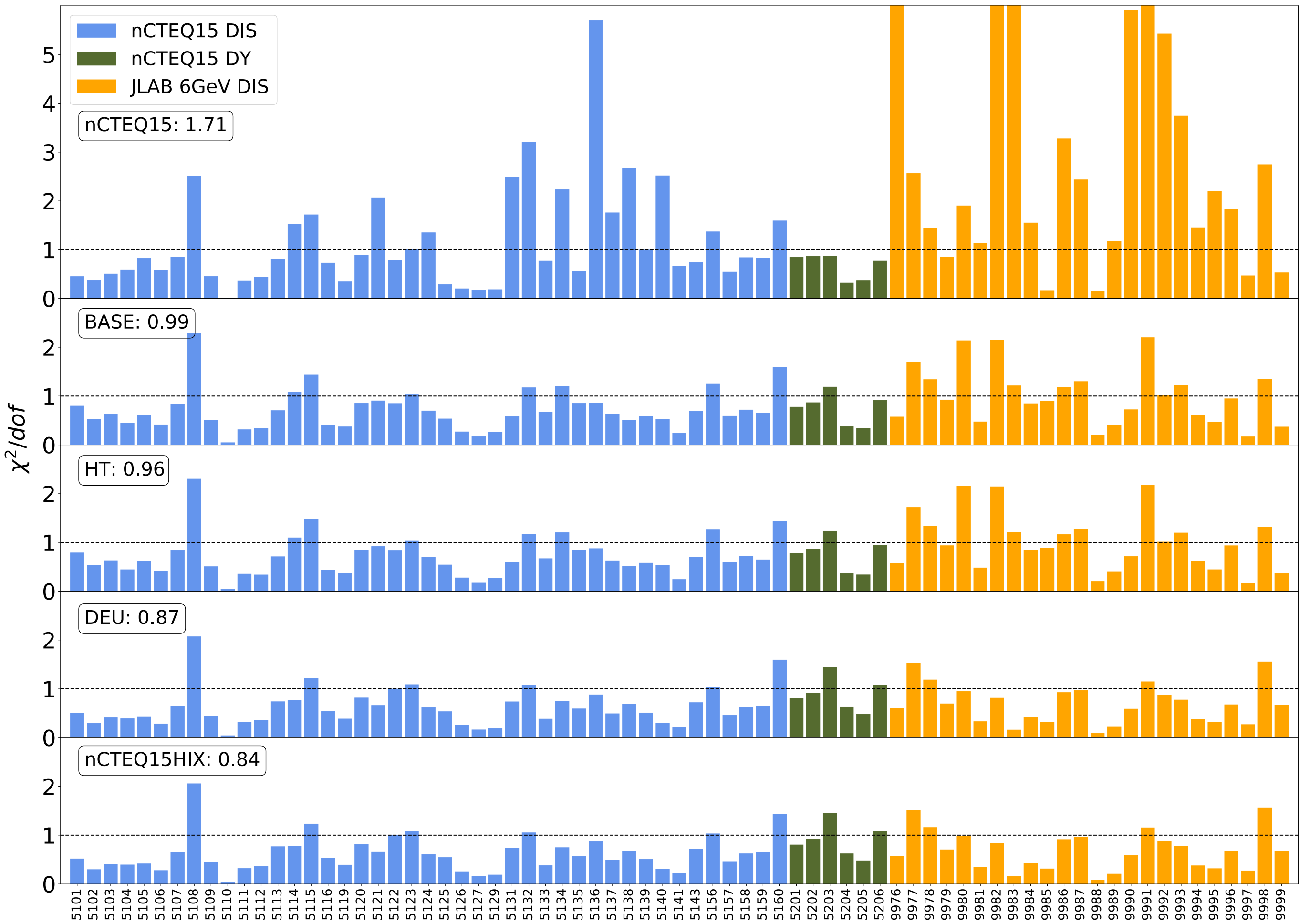
$$F_2^A \rightarrow F_2^A \left[1 + \frac{C_{HT}^A}{Q^2} \right]$$

*(often called dynamical higher-twist;
what are the dynamics that allow for
one quark to carry all momentum)*

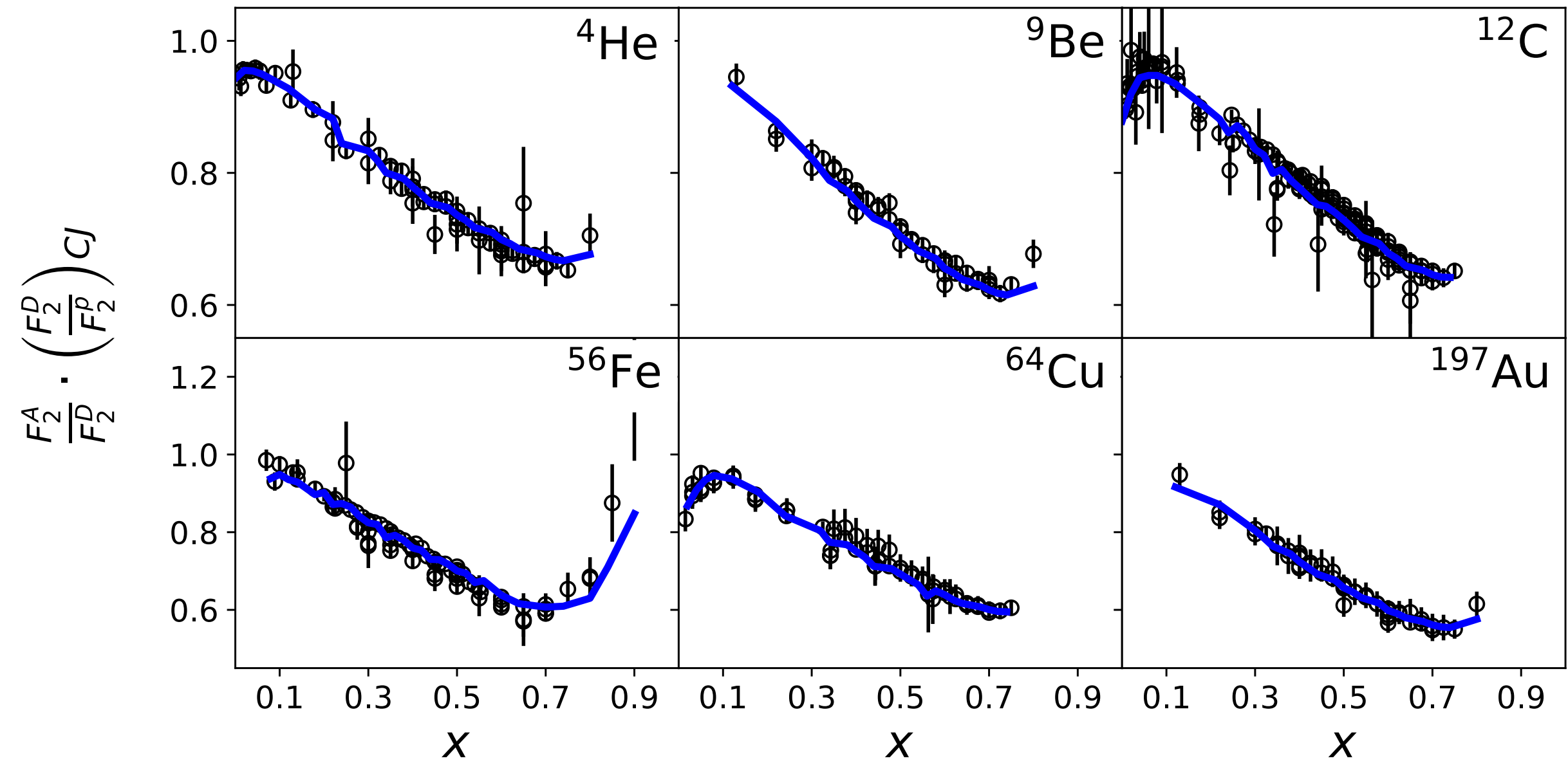
Approach to nCTEQ15HIX

Include JLab 6GeV DIS data & **remove all isoscalar corrections** from nCTEQ15 data with lowered (Q^2, W) cuts ($N_{data} = 740 \rightarrow 1564$)

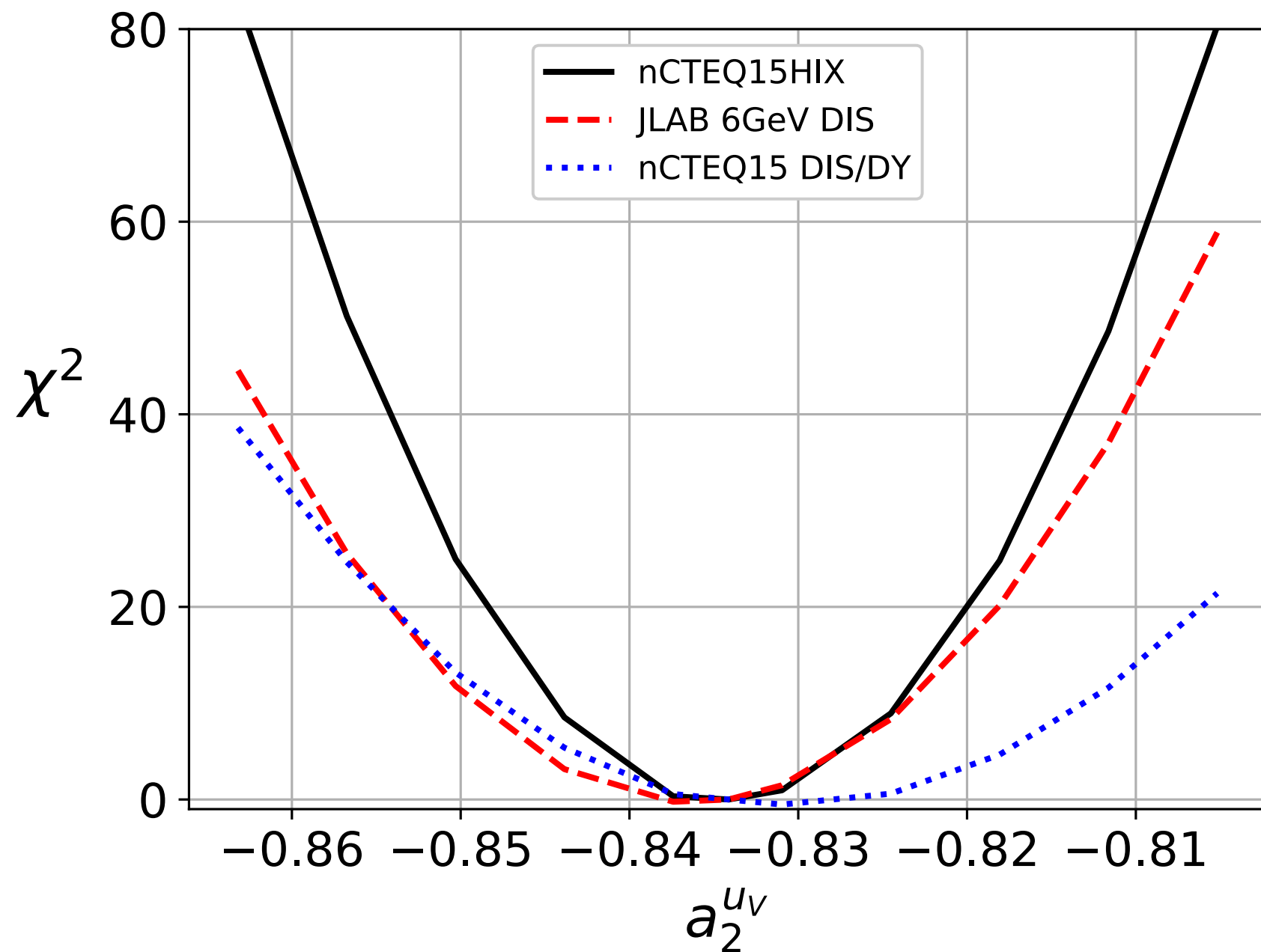
1. See how nCTEQ15 works out of the box (**nCTEQ15**)
2. Refit nCTEQ15 (**BASE**)
3. Include just HT & TMC corrections (**HT**)
4. Include just deuterium-to-proton evolution (**DEUT**)
5. Include all corrections (**nCTEQ15HIX**)



nCTEQ15HIX describes data well



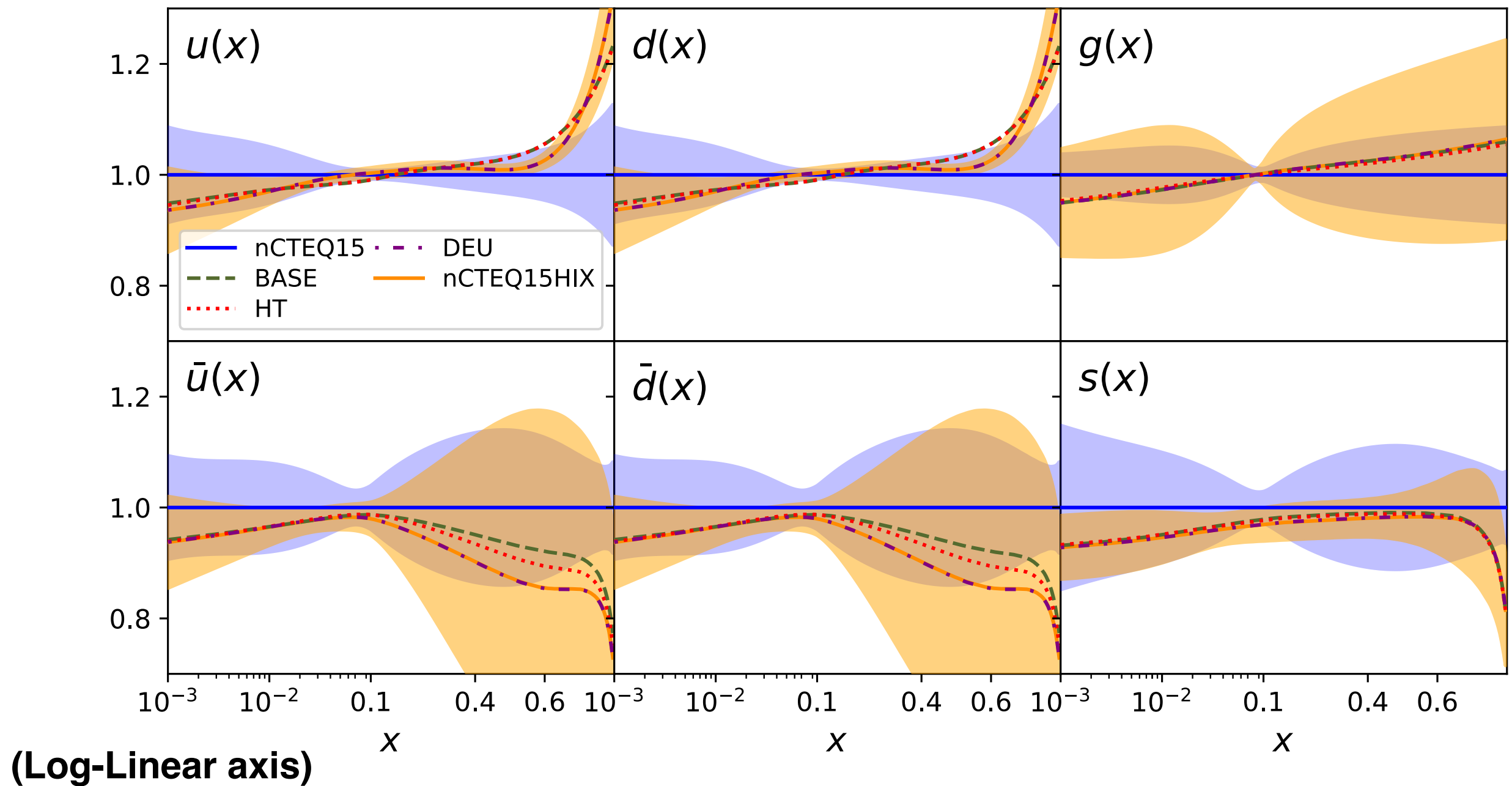
Added JLab 6GeV data adds tighter constraints
on u_V, d_V parameters



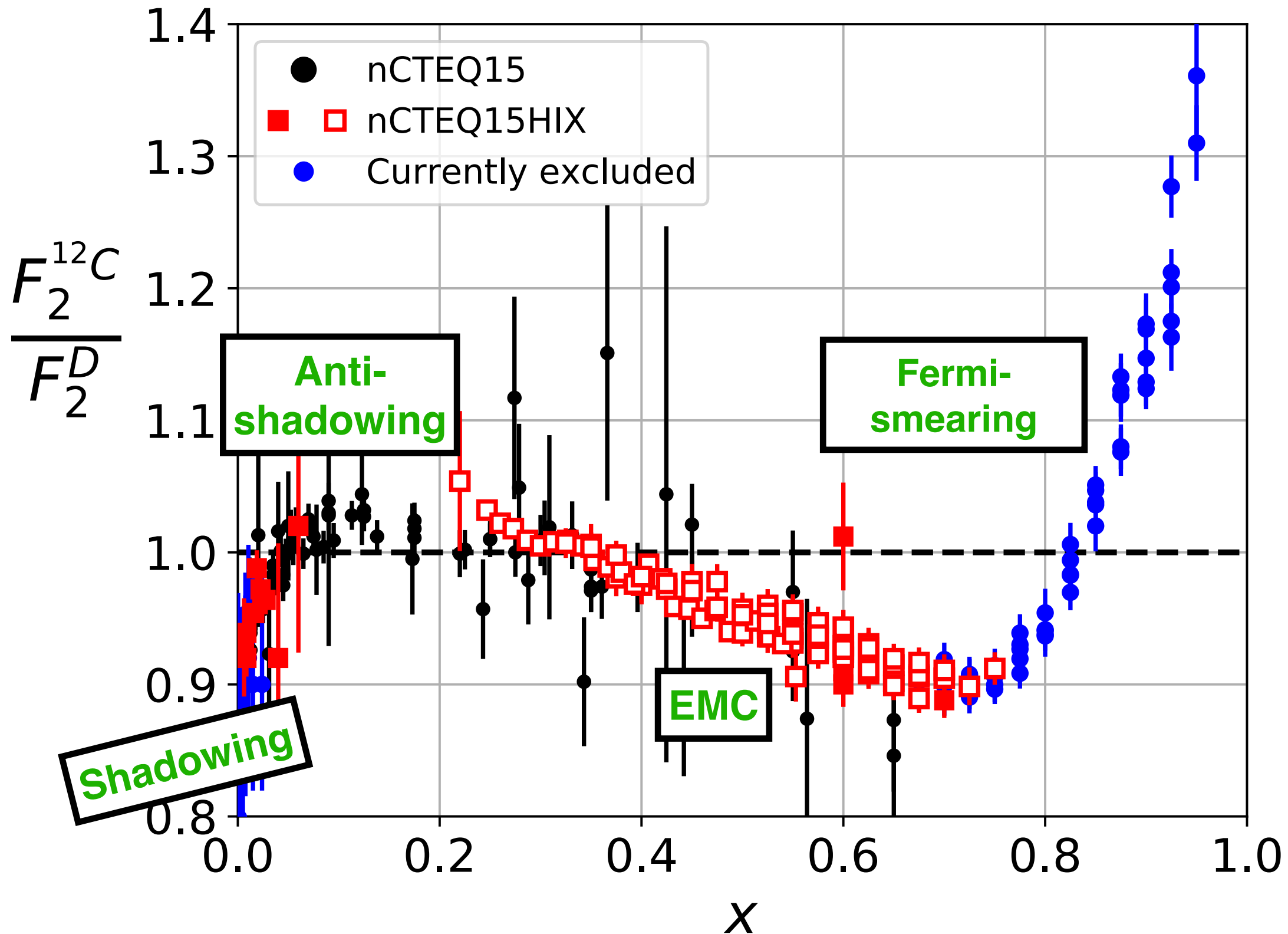
Resulting nPDFs have new behavior at high- x

$$\frac{f_i}{f_i^{\text{nCTEQ15}}}$$

Carbon PDF Ratios to nCTEQ15 ($Q = 2$ GeV)



...but we still don't use data much above $x \sim 0.7$

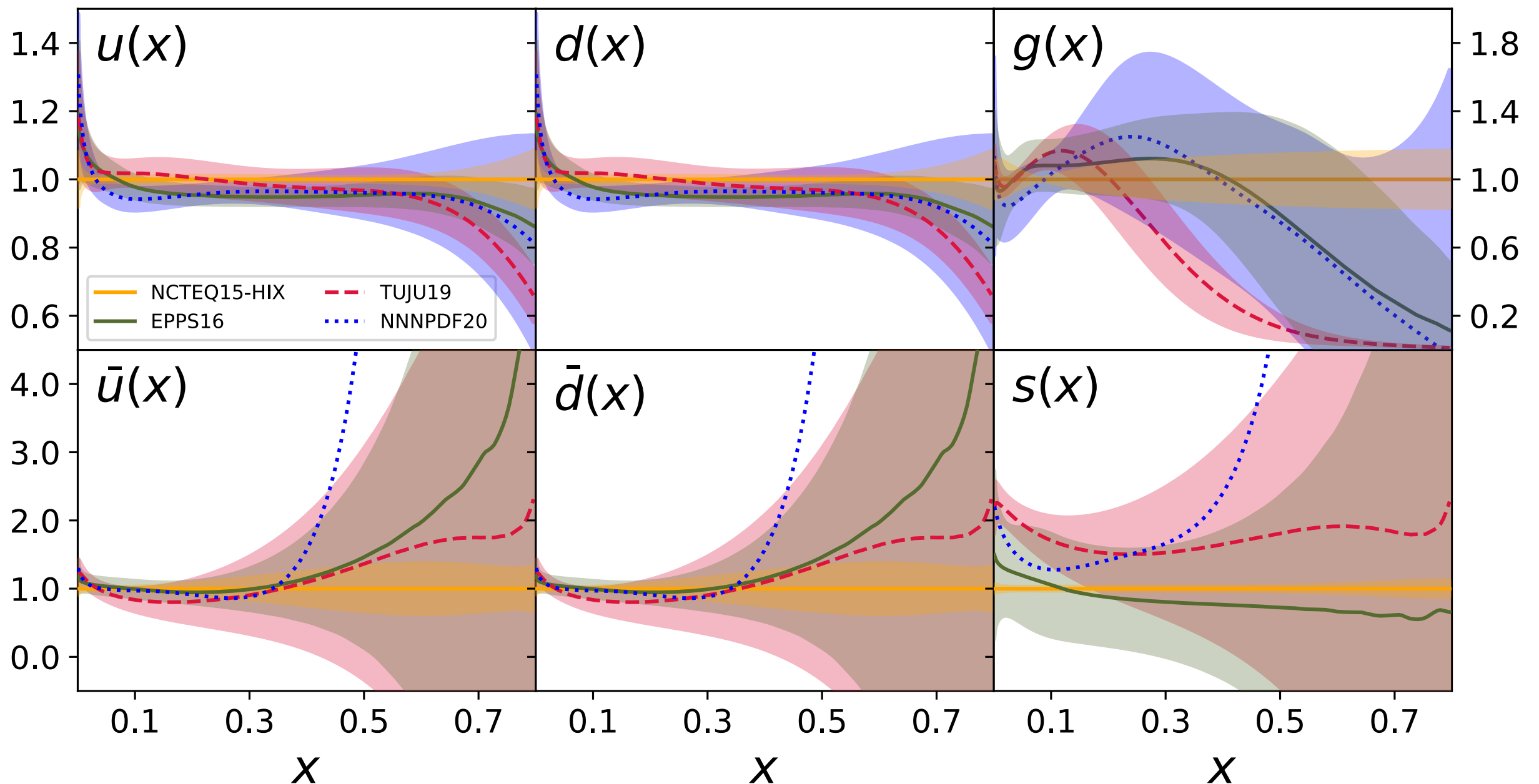


Stay tuned & check out our work

nCTEQ15HIX — Extending nPDF Analyses into
the High- x Region with New Jefferson Lab Data

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K. Kovařík,⁵ A. Kusina,⁷ J.G. Morfín,⁸ K.F. Muzakka,⁵ F.I. Olness,^{6,‡} I. Schienbein,⁹ and J.Y. Yu.⁹

Carbon PDF Ratios to NCTEQ15-HIX ($Q = 2$ GeV)

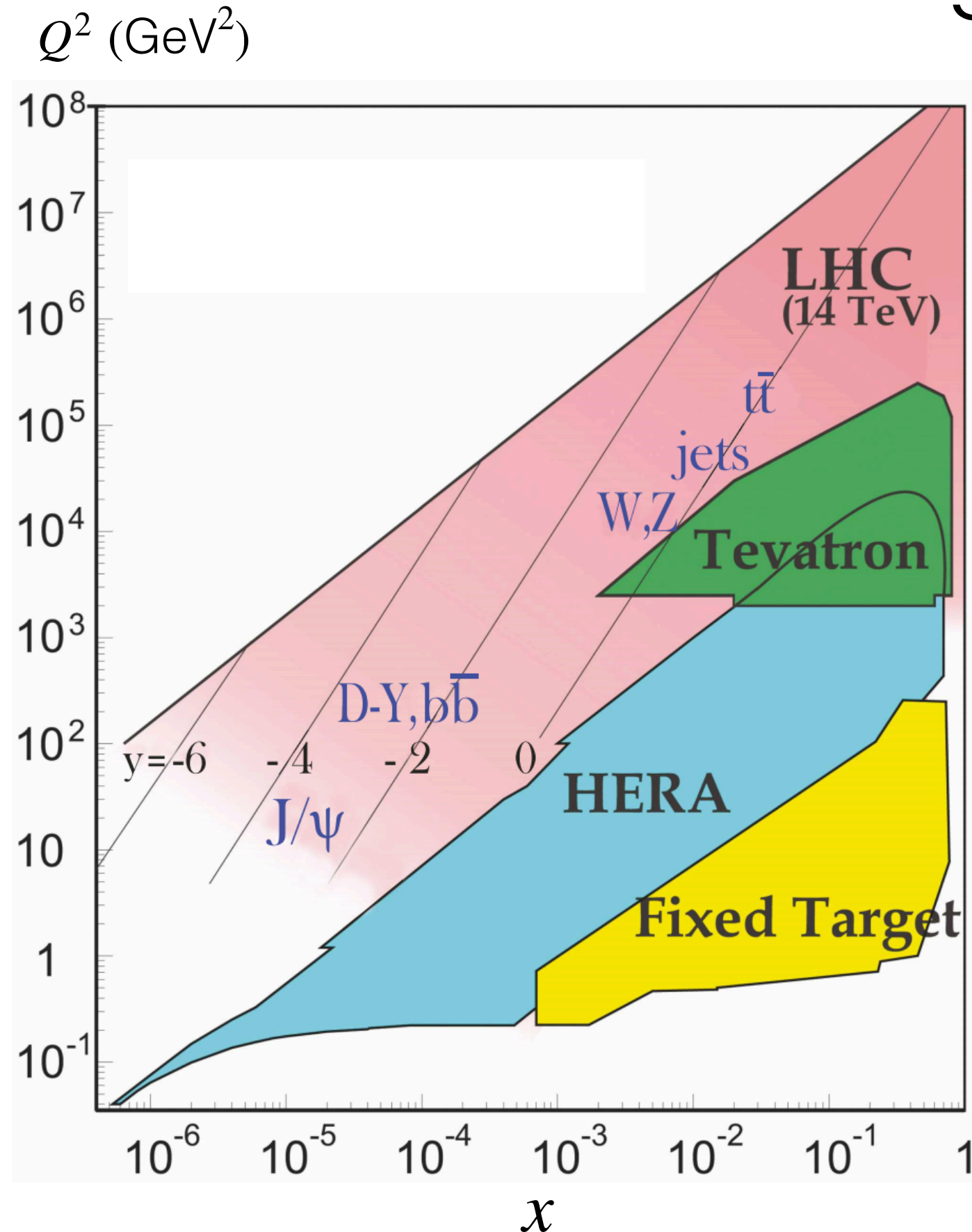


Thanks all!

Questions, comments?



Extracting PDFs

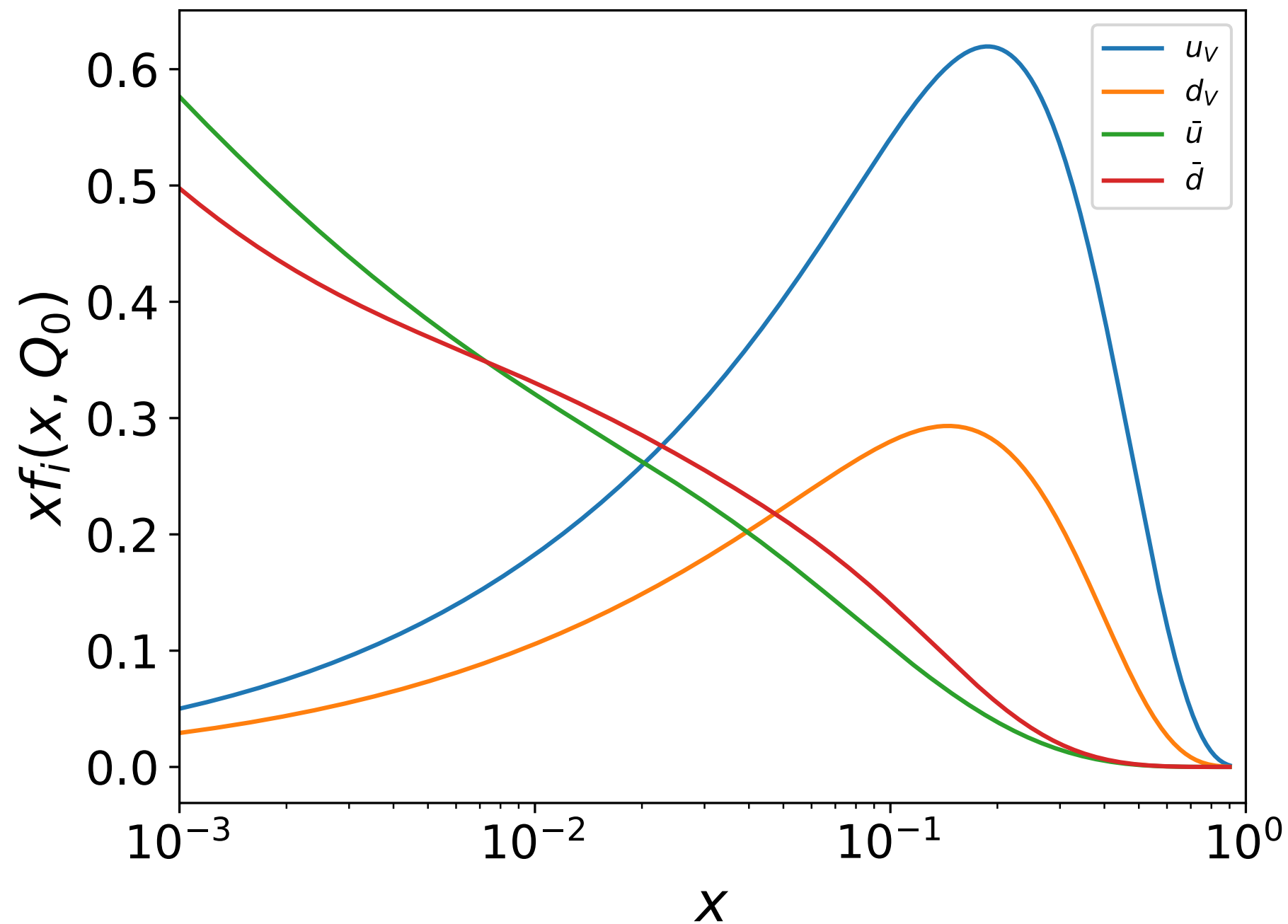


Finer points of debate

- how reliable is theory in all (Q^2, W)
- how reliable is the data
- are all data treated the same
- how to handle data uncertainty
- how to calculate PDF uncertainty
- ...

Inference results for free proton

CTEQ14 Proton PDFs

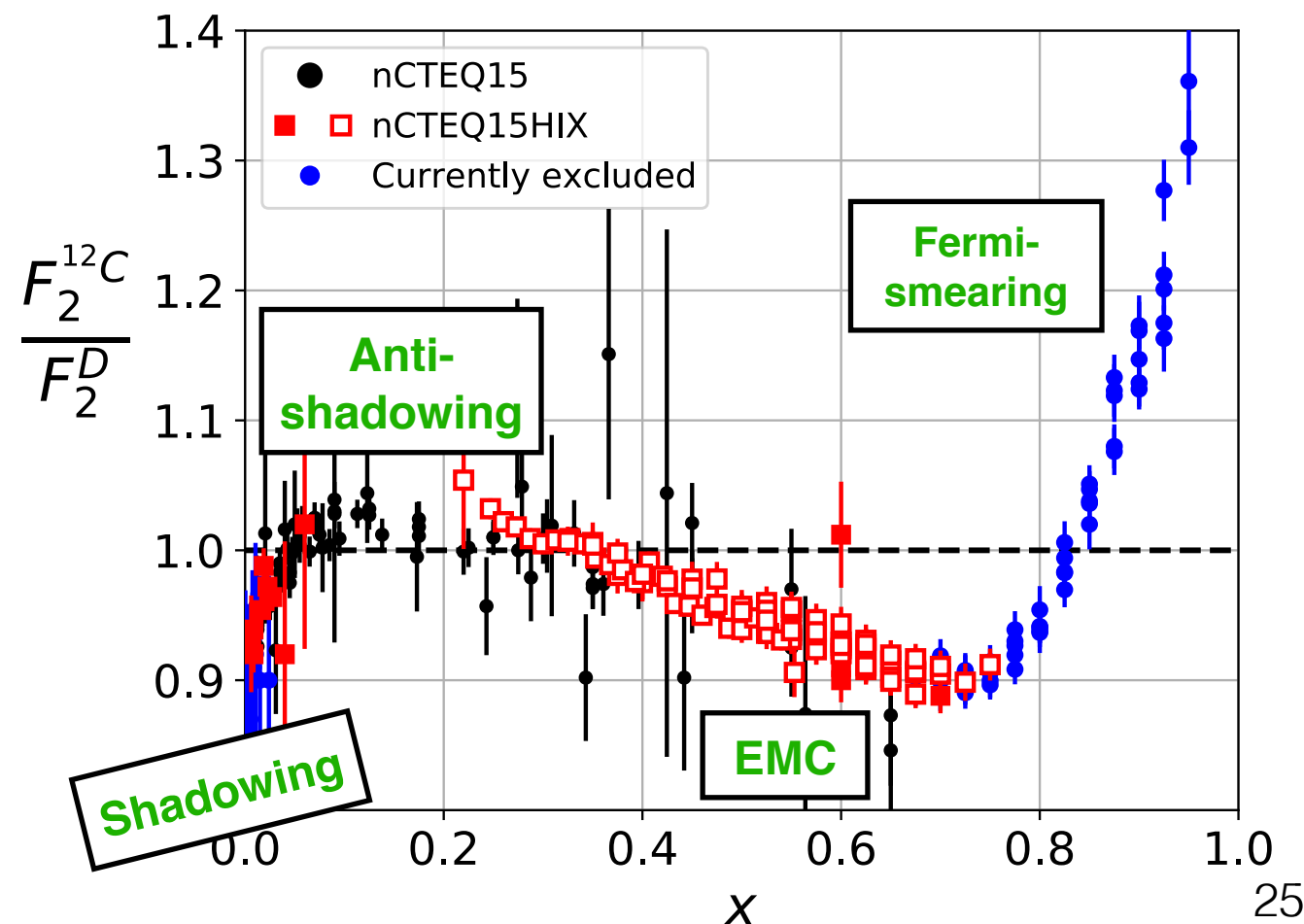
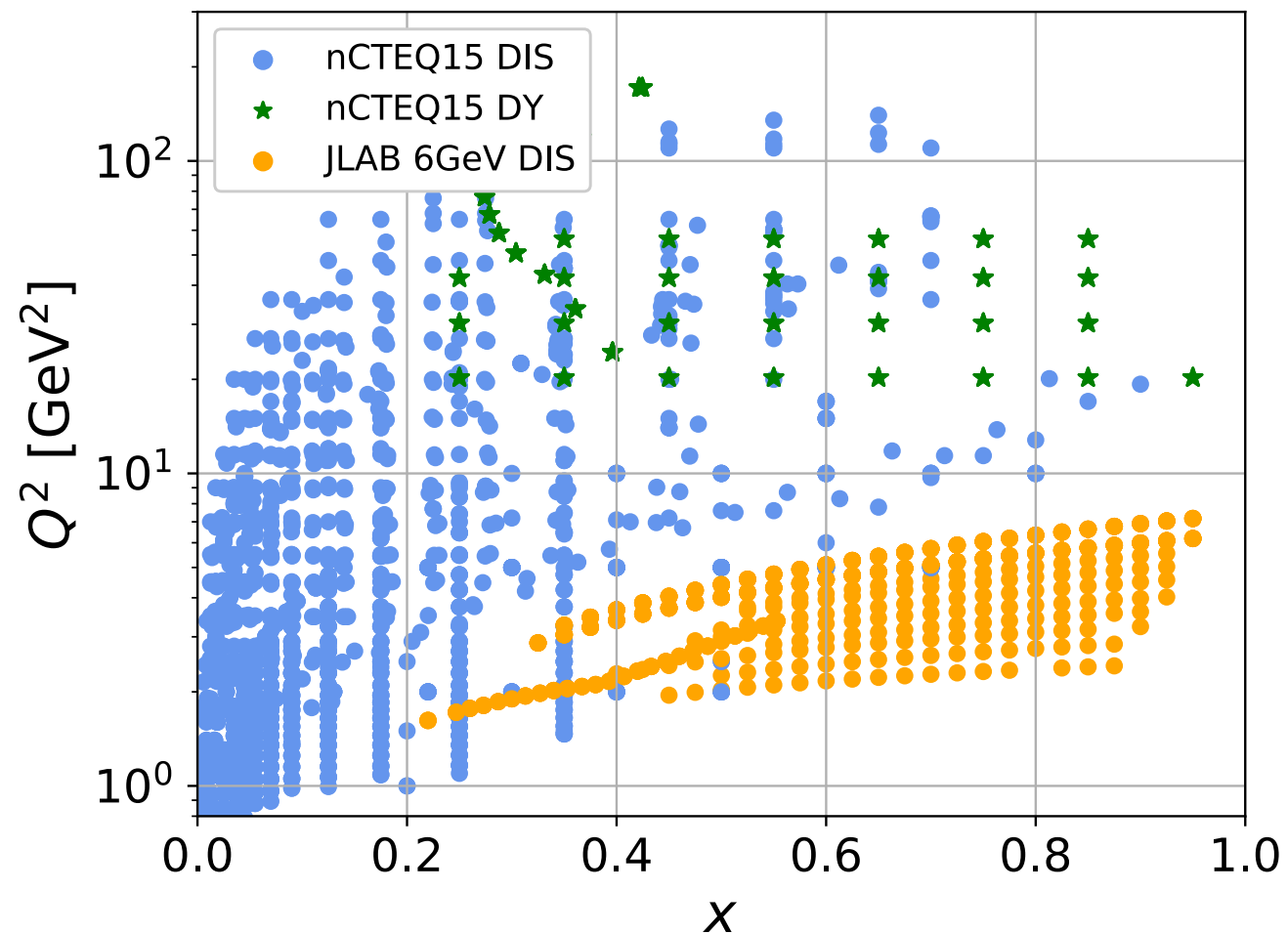


Challenge of nPDFs

Theory $\longleftrightarrow$ **Observables**

$$F_2^A(x, Q) \sim x \sum_i Q_{q,i}^2 f_i^A(x, Q)$$

(In reality, NLO calculation)



Parameterization

$$xf_i^{p/A}(x, Q_0) \sim x^{a_i(A)} (\dots) (1-x)^{b_i(A)}$$

$$a_i(A) \sim a_{i,1} + a_{i,2}(1 - A^{-a_{i,3}})$$

nCTEQ15 Framework

$$xf_i^{p/A}(x, Q_0) \sim a_{0,i}(A) x^{a_{1,i}(A)} (1-x)^{a_{2,i}(A)} e^{a_{3,i}(A)x} \left(1 + e^{a_{4,i}(A)}x\right)^{a_{5,i}(A)}$$

$$i = u_v, d_v, (\bar{u} + \bar{d}), \bar{d}/\bar{u}, s, g$$

nCTEQ15 Framework

$$xf_i^{p/A}(x, Q_0) \sim a_{0,i}(A) x^{a_{1,i}(A)} (1-x)^{a_{2,i}(A)} e^{a_{3,i}(A)x} (1 + e^{a_{4,i}(A)x})^{a_{5,i}(A)}$$



$$a_{j,i}(A) = p_{j,i} + m_{j,i}(1 - A^{-n_{j,i}})$$

$p_{j,i}$ are fixed free proton parameters from CTEQ

Additional constraints due to baryon and momentum sum rules

$$i = u_v, d_v, (\bar{u} + \bar{d}), \bar{d}/\bar{u}, s, g$$

$$j = \{0, \dots, 5\}$$

nCTEQ15 Framework

$$xf_i^{p/A}(x, Q_0) \sim a_{0,i}(A) x^{a_{1,i}(A)} (1-x)^{a_{2,i}(A)} e^{a_{3,i}(A)x} (1 + e^{a_{4,i}(A)}x)^{a_{5,i}(A)}$$



$$a_{j,i}(A) = p_{j,i} + m_{j,i}(1 - A^{-n_{j,i}})$$

$p_{j,i}$ are fixed free proton parameters from CTEQ

$$f_i^{(A,Z)}(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{A-Z}{A} f_i^{n/A}(x, Q)$$

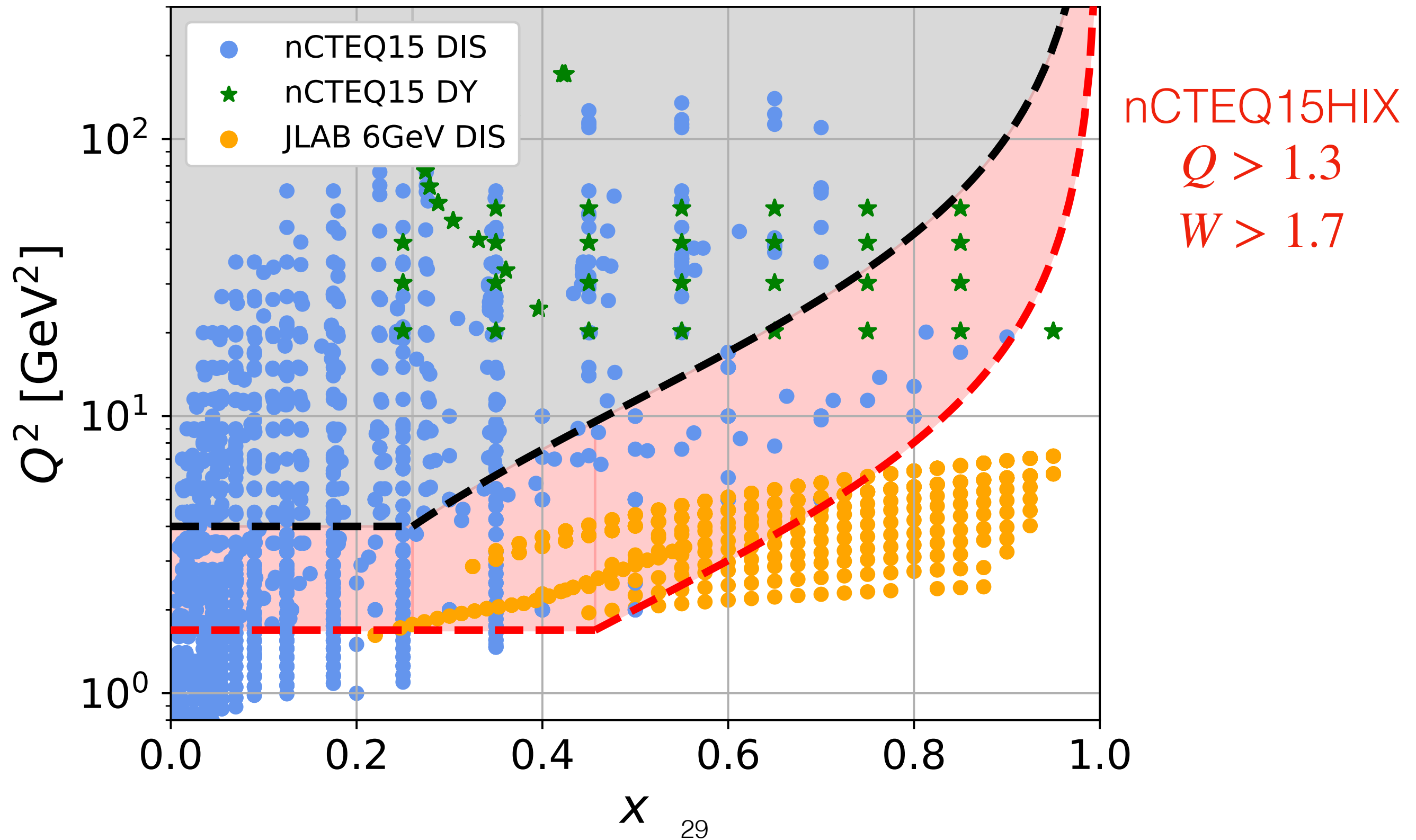
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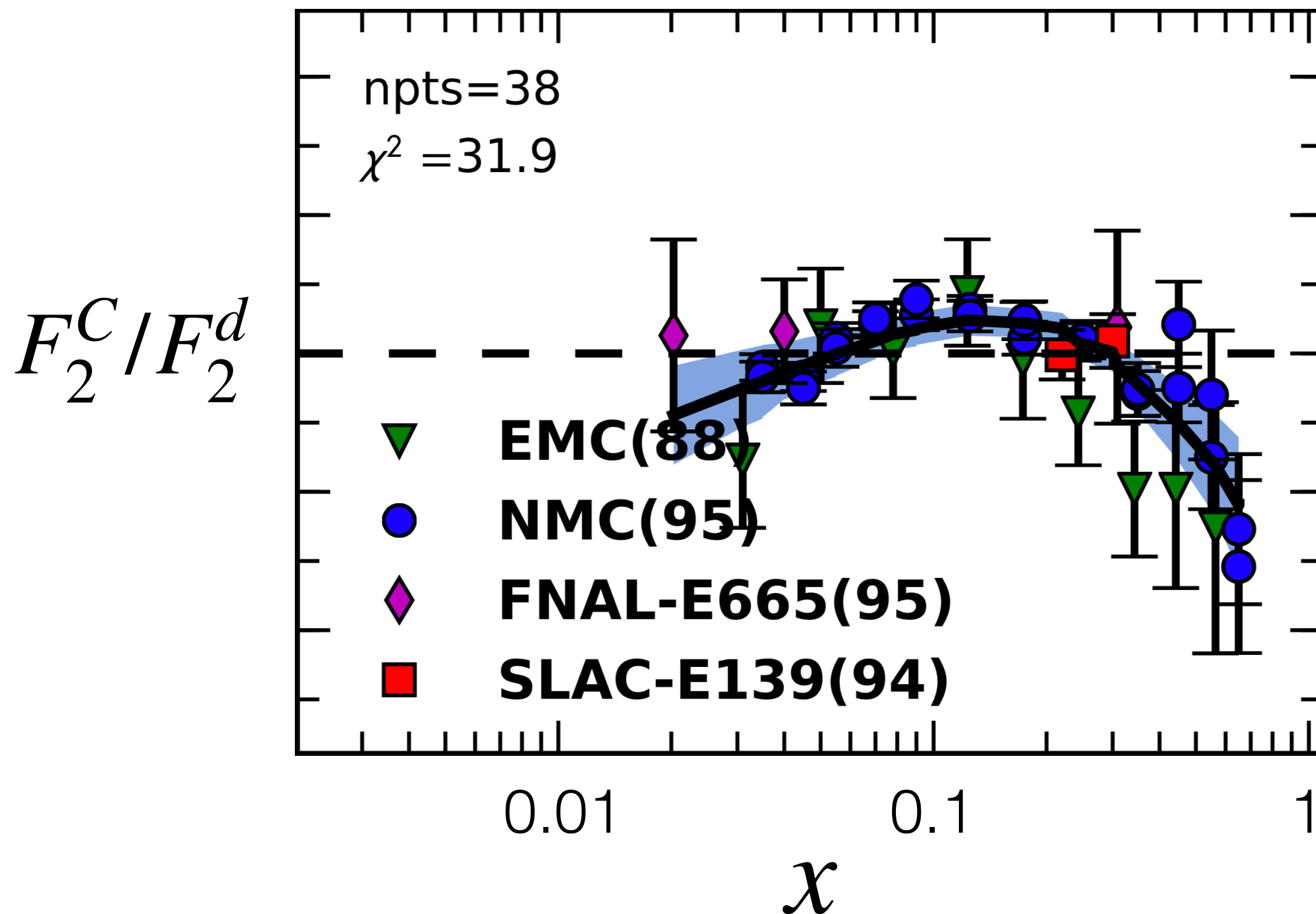
Data used

nCTEQ15 $Q > 2, W > 3.5$

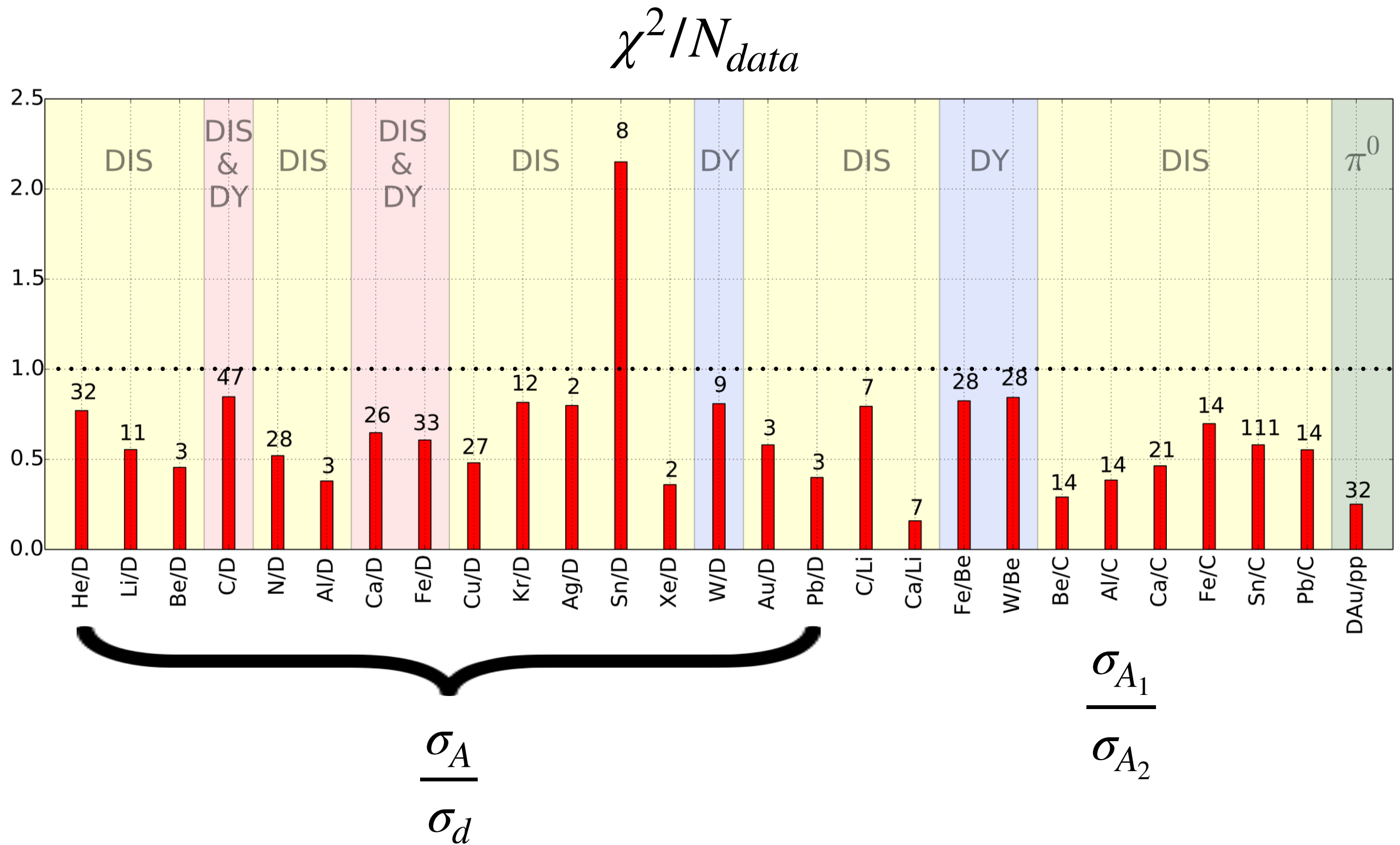


Extraction and assessment of fit

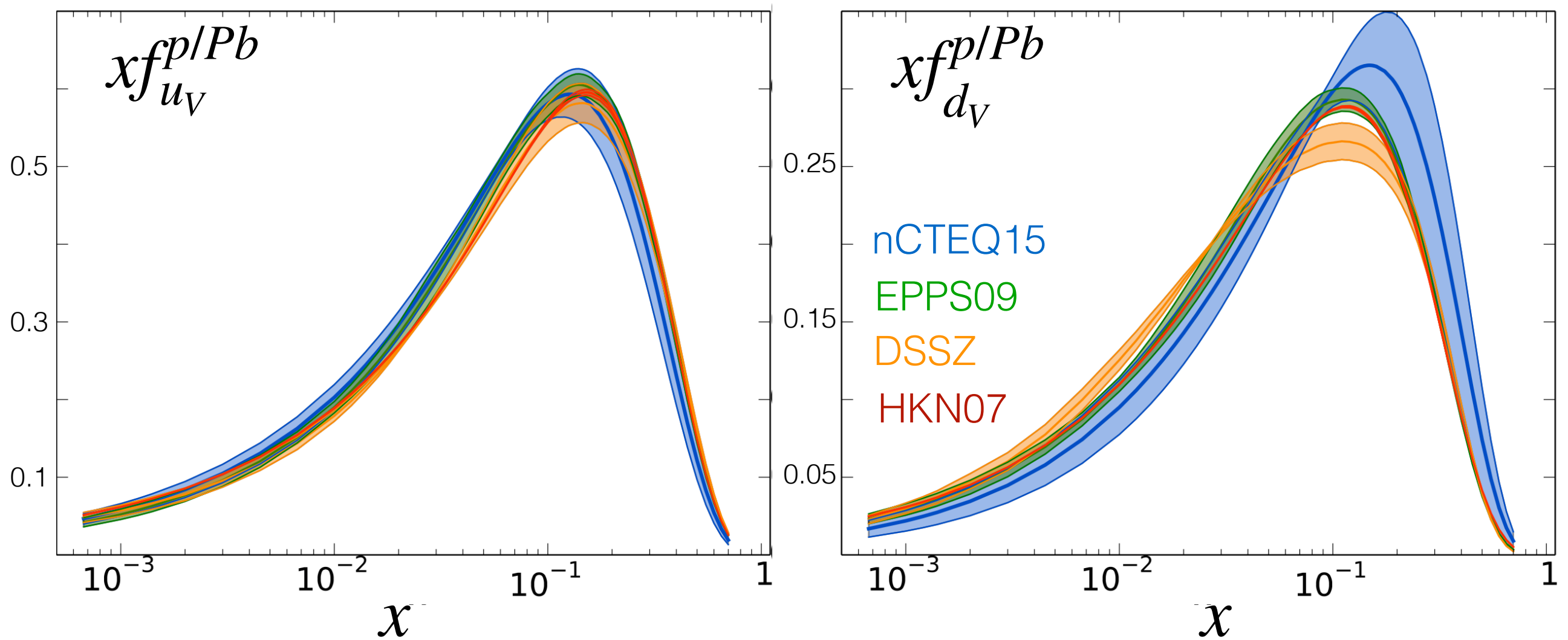
χ^2 minimization of ~ 16 parameters



Assessing quality

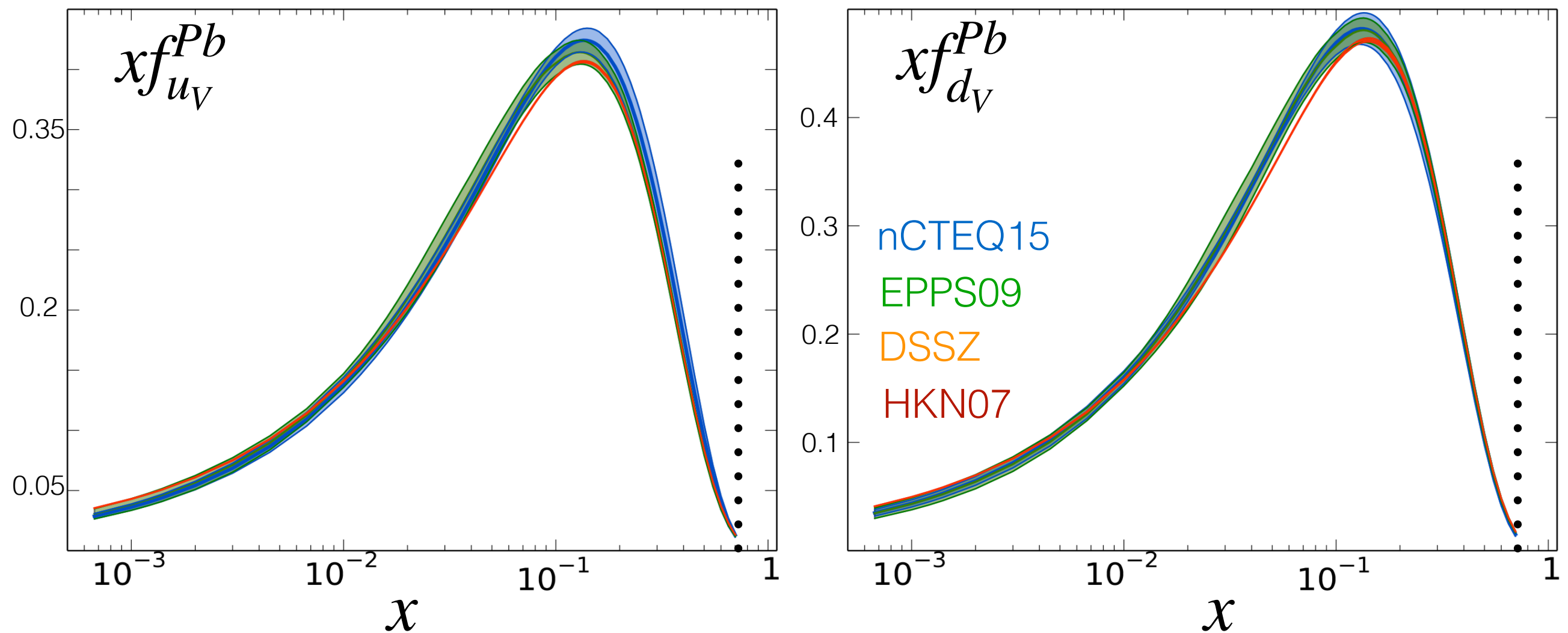


Average effective PDFs have some variance between groups



$$f_i^{(A,Z)}(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{A-Z}{A} f_i^{n/A}(x, Q)$$

Full effective nPDFs are very similar



(which is great given completely different approaches)

Outline

- nCTEQ framework (**nCTEQ15**)
- Challenges in the valence region
- Resulting PDFs (**nCTEQ15HIX**)

nCTEQ15 Framework

$$xf_i^{p/A}(x, Q_0) \sim a_{0,i}(A) x^{a_{1,i}(A)} (1-x)^{a_{2,i}(A)} e^{a_{3,i}(A)x} (1 + e^{a_{4,i}(A)}x)^{a_{5,i}(A)}$$



$$a_{j,i}(A) = p_{j,i} + m_{j,i}(1 - A^{-n_{j,i}})$$

This is pretty inconvenient to think about when comparing free proton PDFs to “modified” PDFs.
(follow-up work on changing parameterization)

$$f_i^A \sim f_i^p + c(A) f_i'$$

$$i = u_v, d_v, (\bar{u} + \bar{d}), \bar{d}/\bar{u}, s, g$$

$$j = \{0, \dots, 5\}$$

(Bit out of date comparison)

	nNNPDF1.0 EPJC79(2019)471	EPPS16 EPJC77(2017)163	nCTEQ15 PRD93(2016)085037	KA15 PRD93(2016)014036	DSSZ12 PRD85(2012)074028	EPS09 JHEP0904(2009)065
IA DIS	✓	✓	✓	✓	✓	✓
DY in p+A	✗	✓	✓	✓	✓	✓
RHIC π d+Au	✗	✓	✓	✗	✓	✓
ν A DIS	✗	✓	✗	✗	✓	✗
DY in π +A	✗	✓	✗	✗	✗	✗
LHC p+Pb dijets	✗	✓	✗	✗	✗	✗
LHC p+Pb W,Z	✗	✓	✗	✗	✗	✗

Order in α_s	NNLO	NLO	NLO	NNLO	NLO	NLO
Q-cut in DIS	1.87 GeV	1.3 GeV	2 GeV	1 GeV	1 GeV	1.3 GeV
W-cut	3.53 GeV	-	3.5 GeV	-	-	-
Data points	451	1811	708	1479	1579	929
Free parameters	Neural Net	20	16	16	25	15
Error tolerance	MC replica	52	35	N.N.	30	50
Proton baseline	NNPDF3.1	CT14NLO	~CTEQ6.1	JR09	MSTW08	CTEQ6.1
Mass scheme	FONLL-B	GM-VFNS	GM-VFNS	ZM-VFNS	GM-VFNS	ZM-VFNS
Flavour sep.	-	val.+sea	valence	-	-	-

Isoscalar corrected data

**Measured
data:**

$$\frac{F_2^A}{F_2^d} \rightarrow \frac{F_2^A}{F_2^d} \cdot \frac{F_2^p + F_2^n}{ZF_2^p + NF_2^n}$$

uses some
assumption on F_2^n
and results in
degeneracy of
isospin-symmetric
PDFs: $f_u^A = f_d^A$

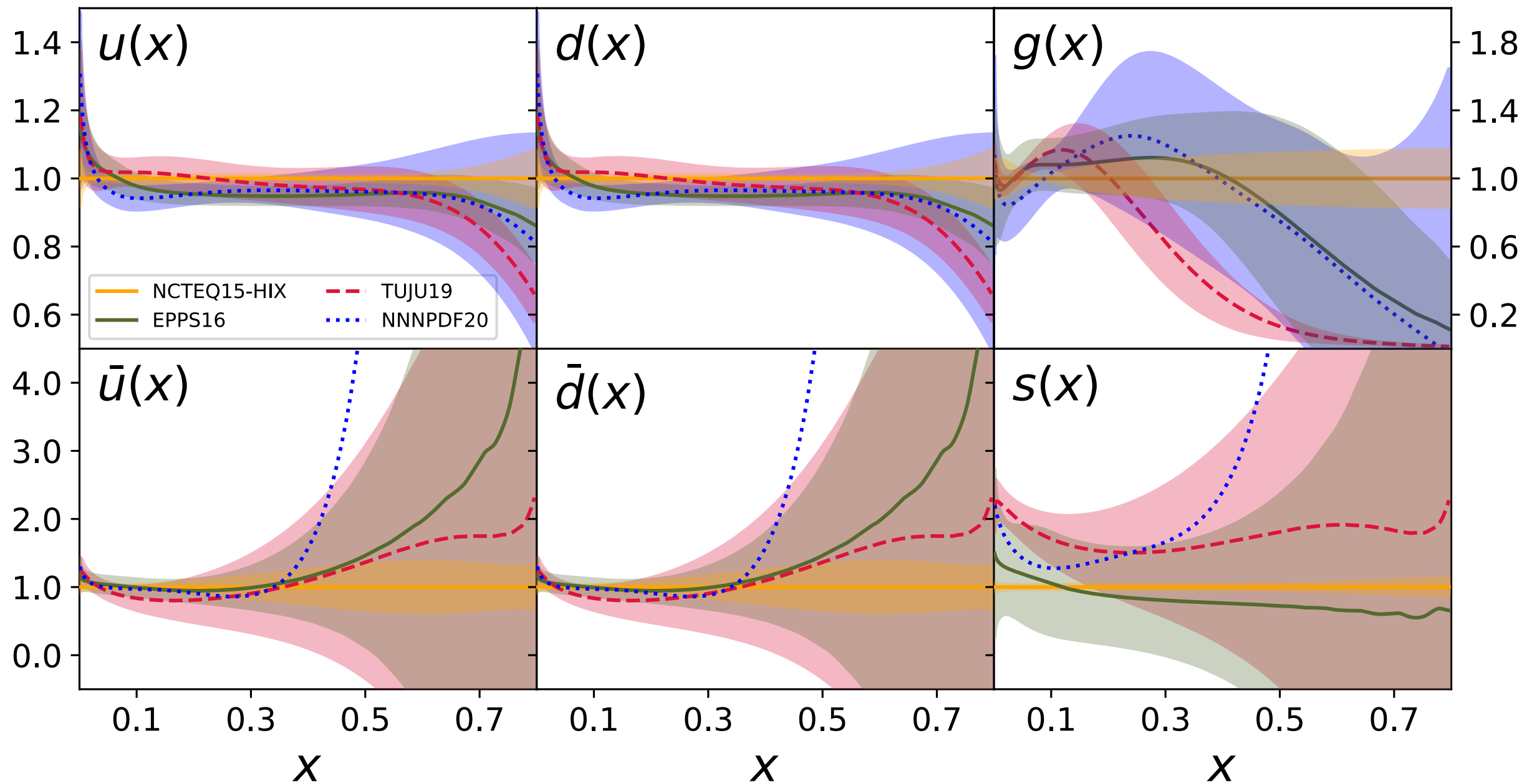
**nCTEQ15
theory:**

$$\frac{F_2^A}{F_2^p + F_2^n}$$

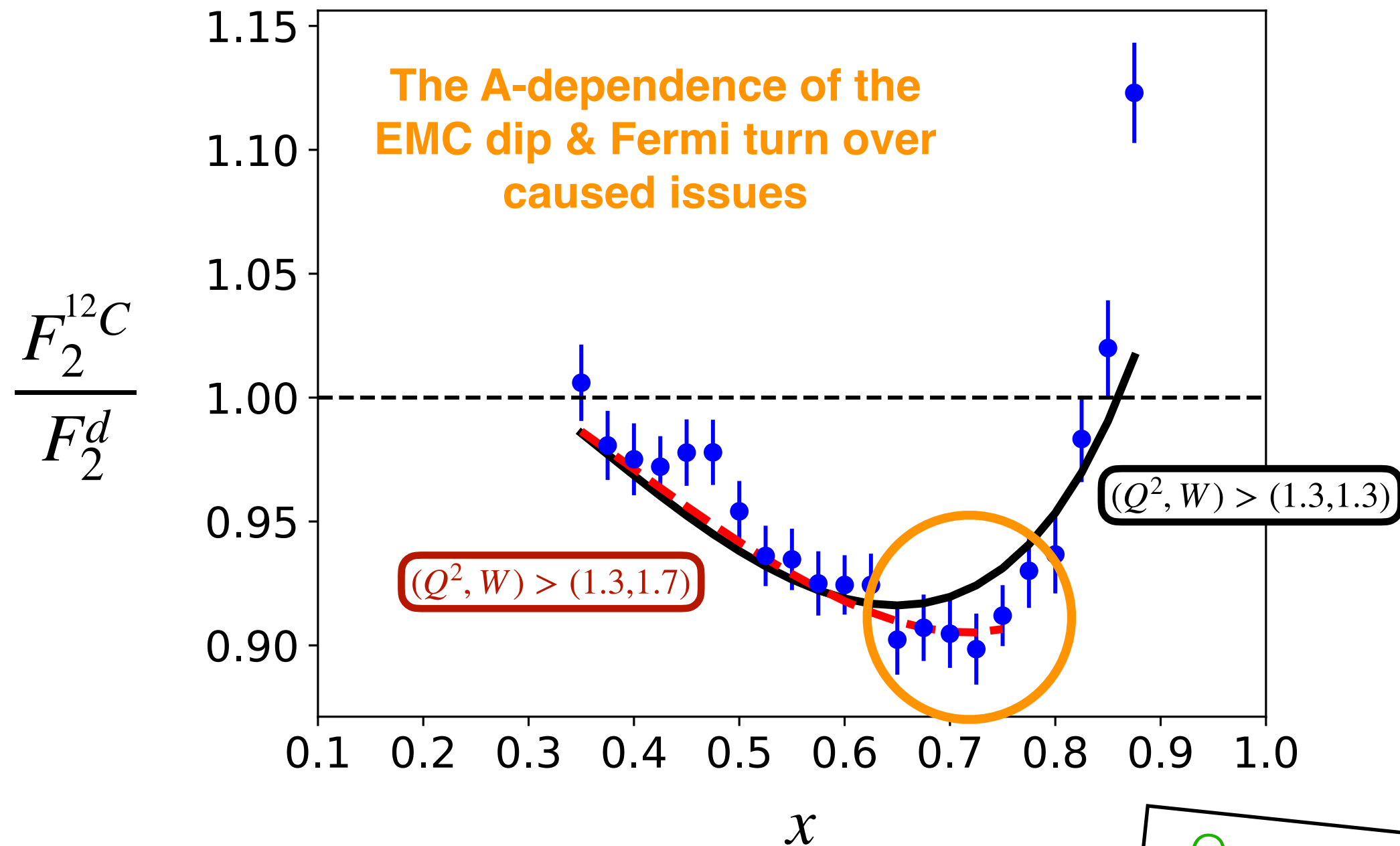
This is wrong to the
level of $F_2^d / (F_2^p + F_2^n)$

Similar behavior as compared to other groups

Carbon PDF Ratios to NCTEQ15-HIX ($Q = 2$ GeV)



We spent a long time trying to address very-high x



On-going project for future nPDFs

One approach:

$$f_i(x_1, Q_1^2) \rightarrow f_i^{new}(x_1, Q_1^2) = \int_{x_1}^A f_i\left(\frac{x_1}{\alpha}, Q_1^2\right) \mathcal{F}^A(\alpha) d\alpha$$

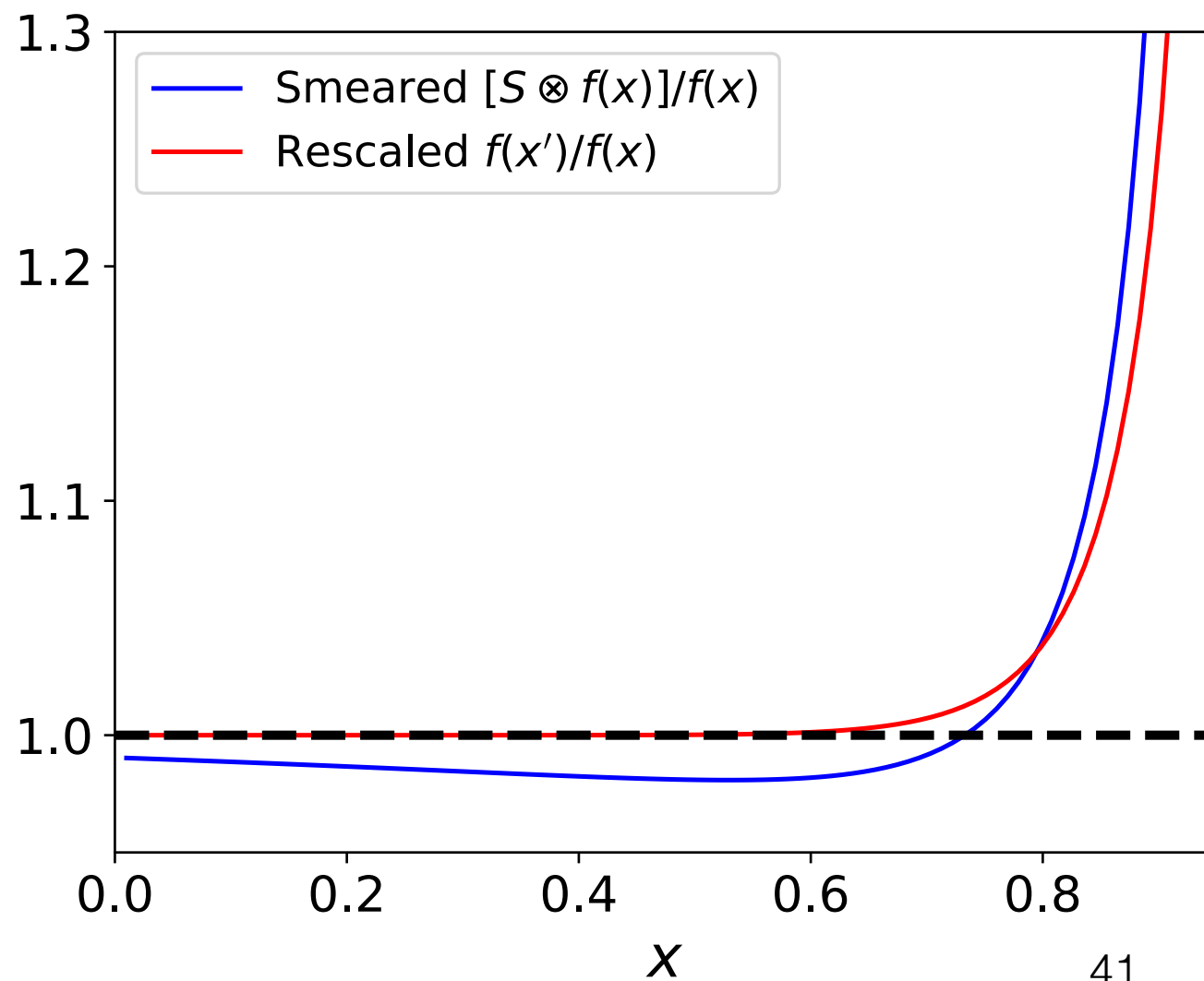
One way to address Fermi-smearing

$$f_i(x_1, Q_1^2) \rightarrow f_i^{new}(x_1, Q_1^2) = \int_{x_1}^A f_i\left(\frac{x_1}{\alpha}, Q_1^2\right) \mathcal{F}^A(\alpha) d\alpha$$

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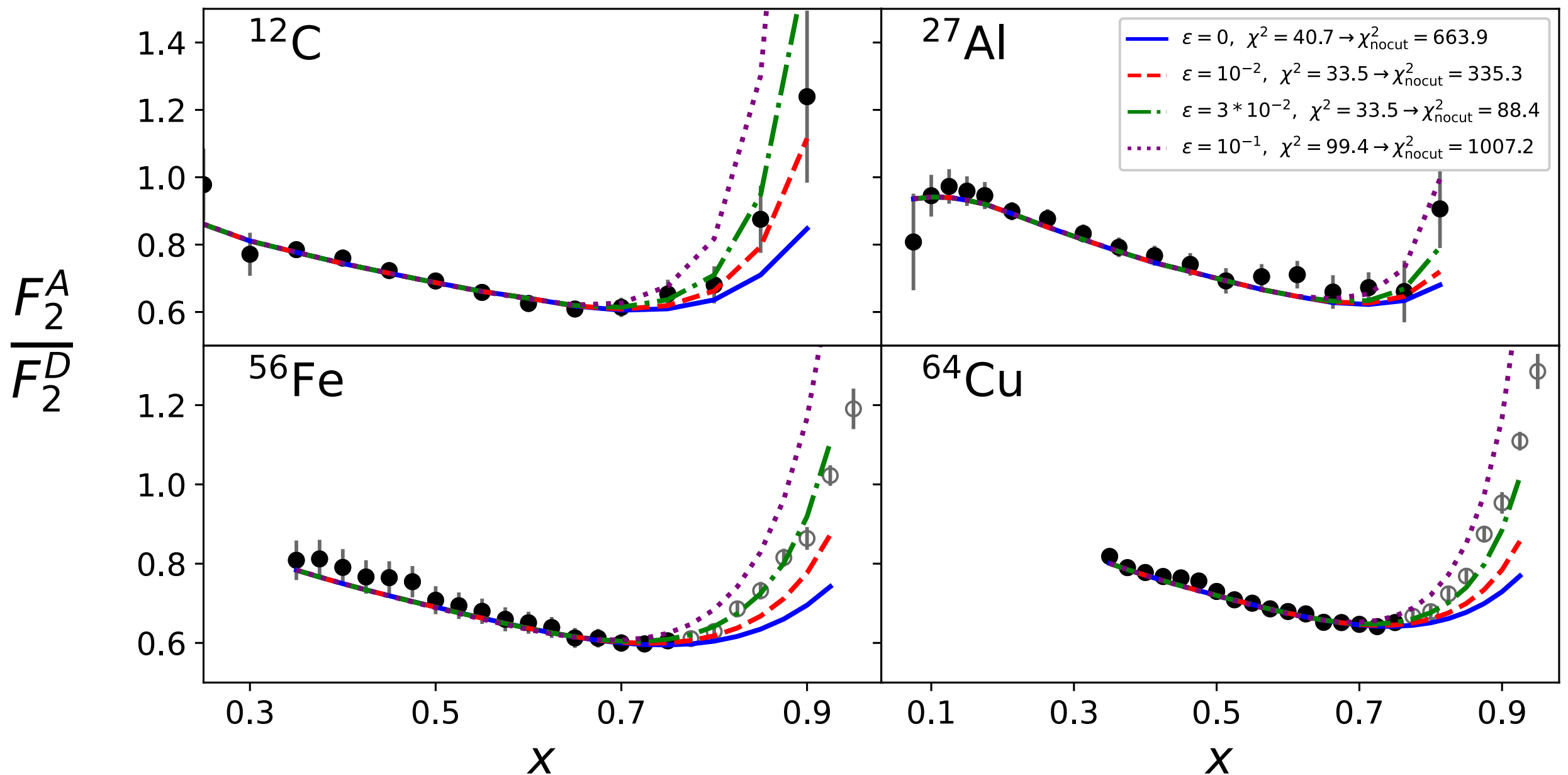
is computational expensive... but we developed a “trick”



Instead of calling
 $f_i(x, Q^2)$, rescale
 $x \rightarrow x' = x - \epsilon x^\kappa \log_{10} A$

Rescaling works quite well but issues of A-dependence remain

Fit only to black points and rescale resulting PDFs to check quality at high-x



Future work of overhauling A-dependence

$$xf_i^{p/A}(x, Q_0) \sim a_{0,i}(A) x^{a_{1,i}(A)} (1-x)^{a_{2,i}(A)} e^{a_{3,i}(A)x} (1 + e^{a_{4,i}(A)}x)^{a_{5,i}(A)}$$



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