nCTEQ15-HIX
Nuclear PDFs in valence region

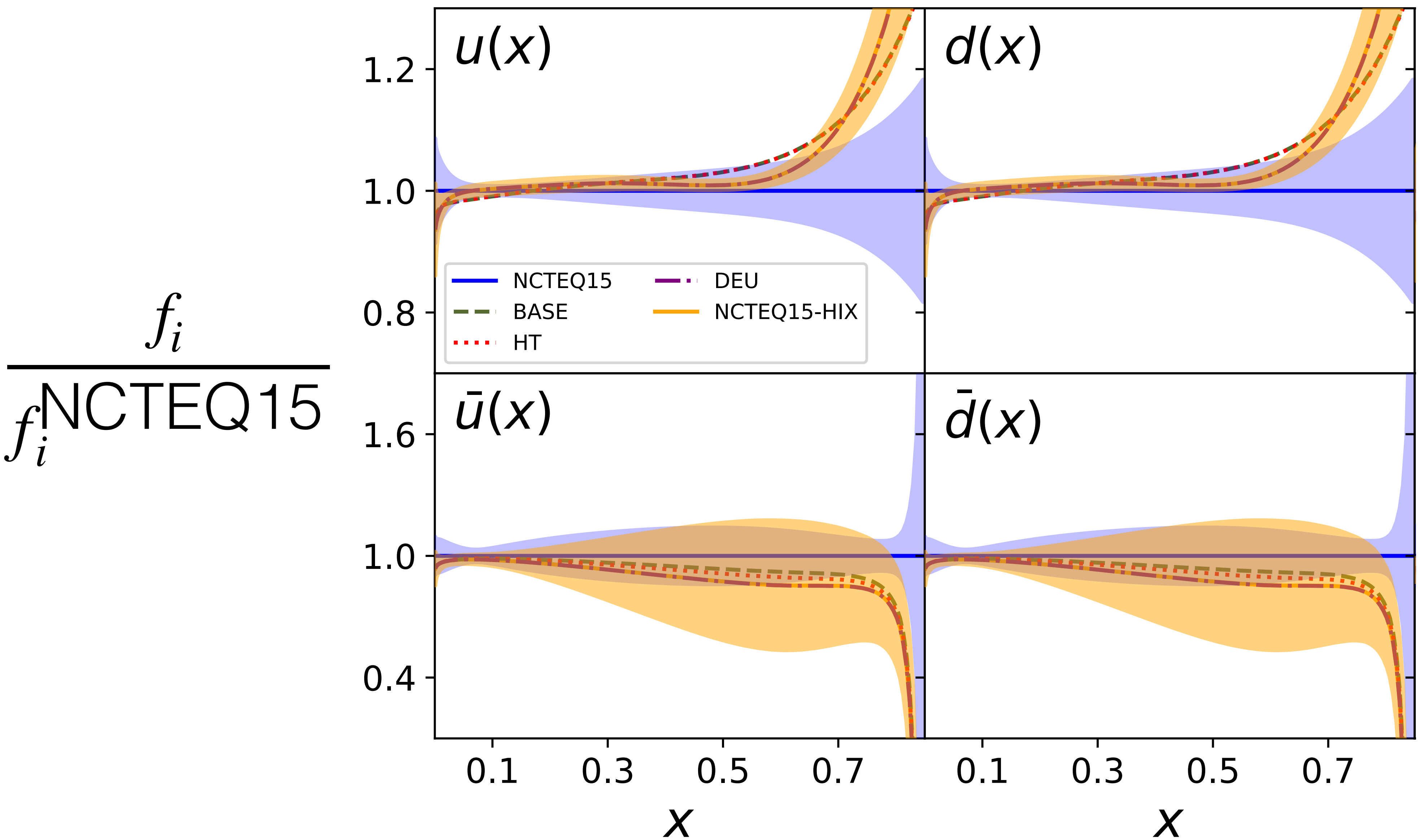
Efrain Segarra

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

arxiv 2012.11566 (under review)

nPDFs in valence region

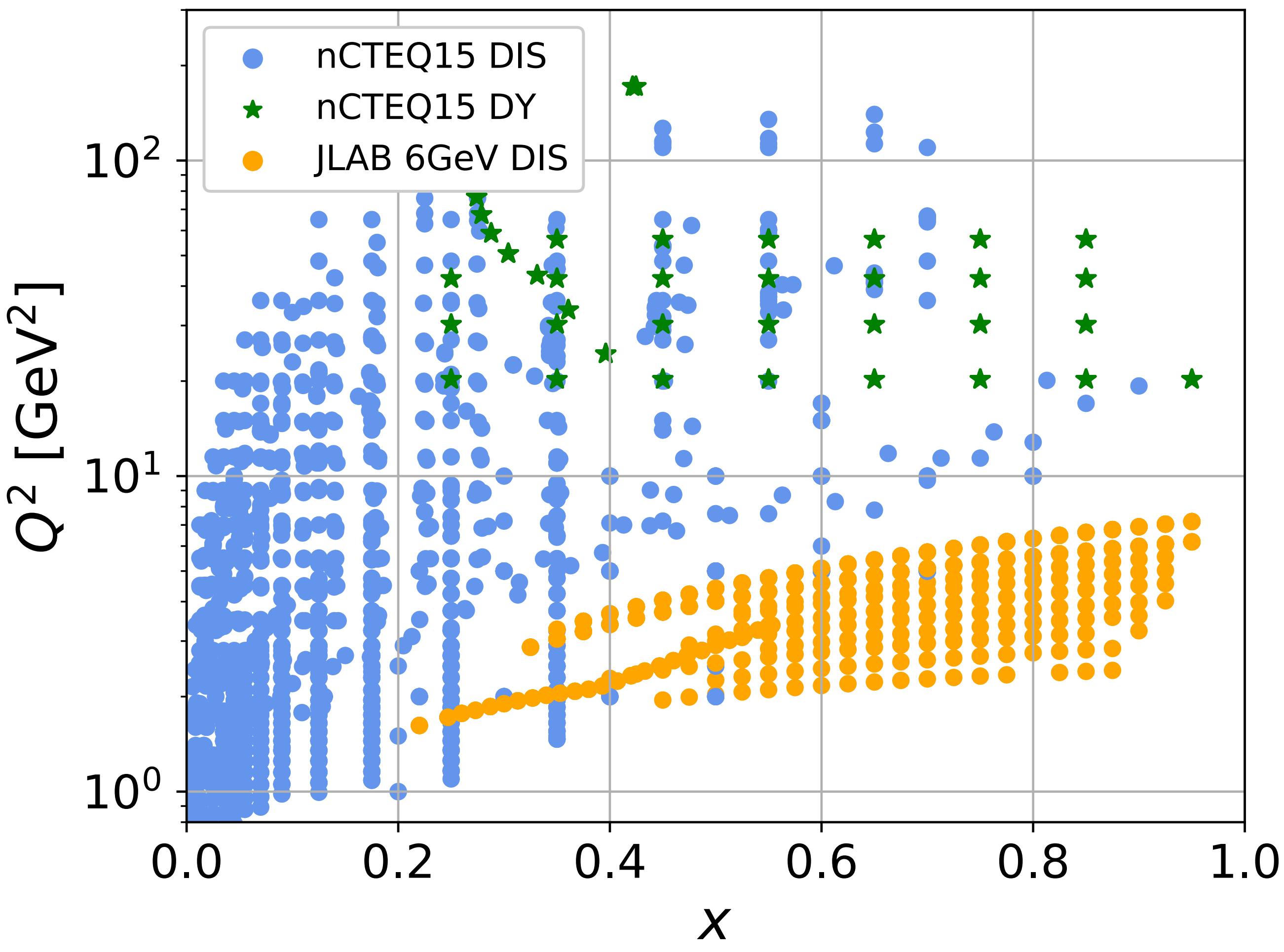
Important for neutrino DIS analyses in transition region ($W > 1.7$ GeV) & future experiments (like DUNE)



Outline

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

arxiv 2012.11566 (under review)



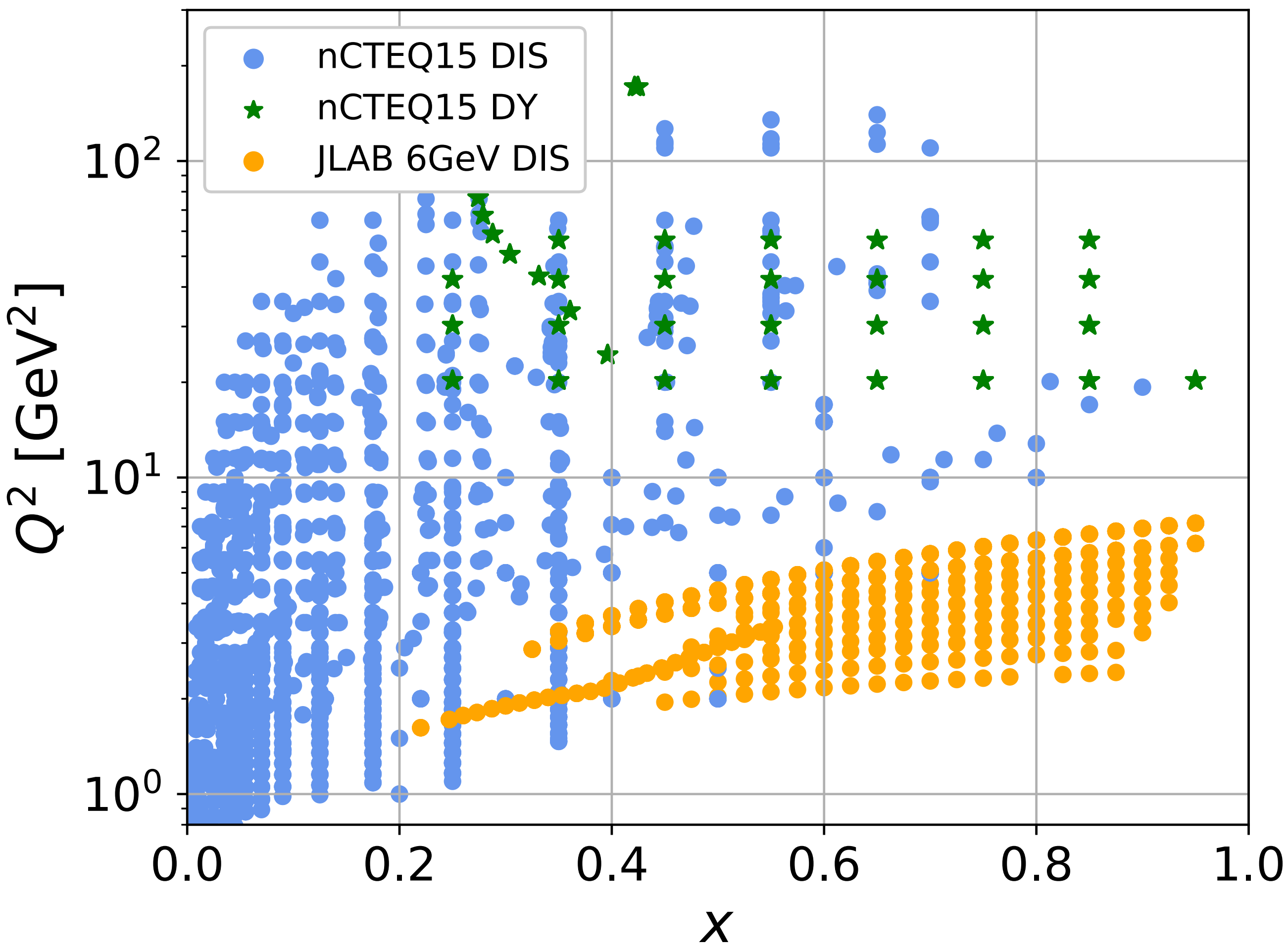
Extracting nPDFs

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)

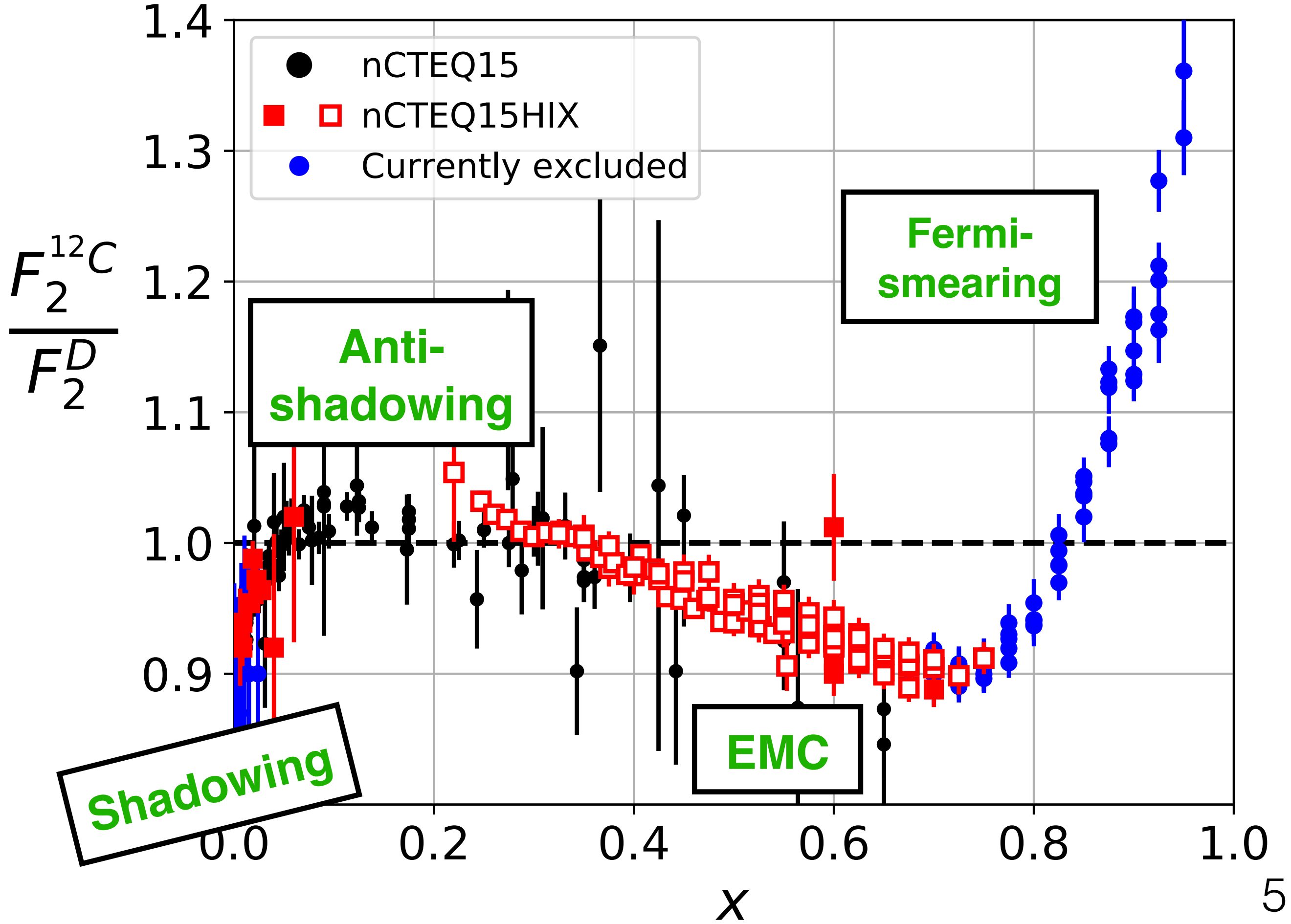
Challenge of nPDFs



Theory ⟷ Observables

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

(In reality, NLO calculation)



Parameterization

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

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

nCTEQ15 Framework

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

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

Phys.Rev.D80:094004,2009

nCTEQ15 Framework

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

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

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

Additional constraints due to baryon and momentum sum rules

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

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

Phys.Rev.D80:094004,2009

nCTEQ15 Framework

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

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

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

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

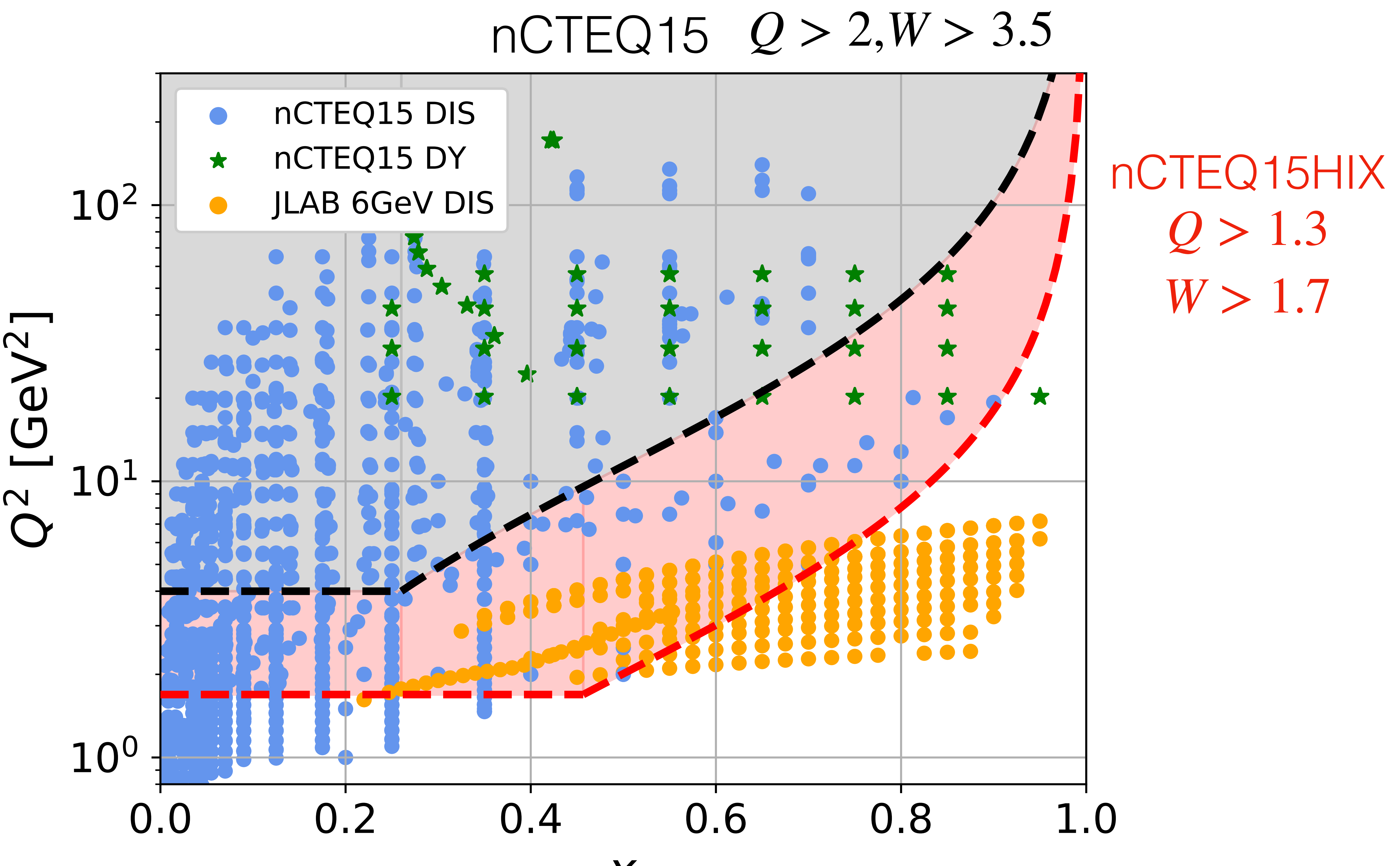
Additional constraints due to baryon and momentum sum rules

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

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

Phys.Rev.D80:094004,2009

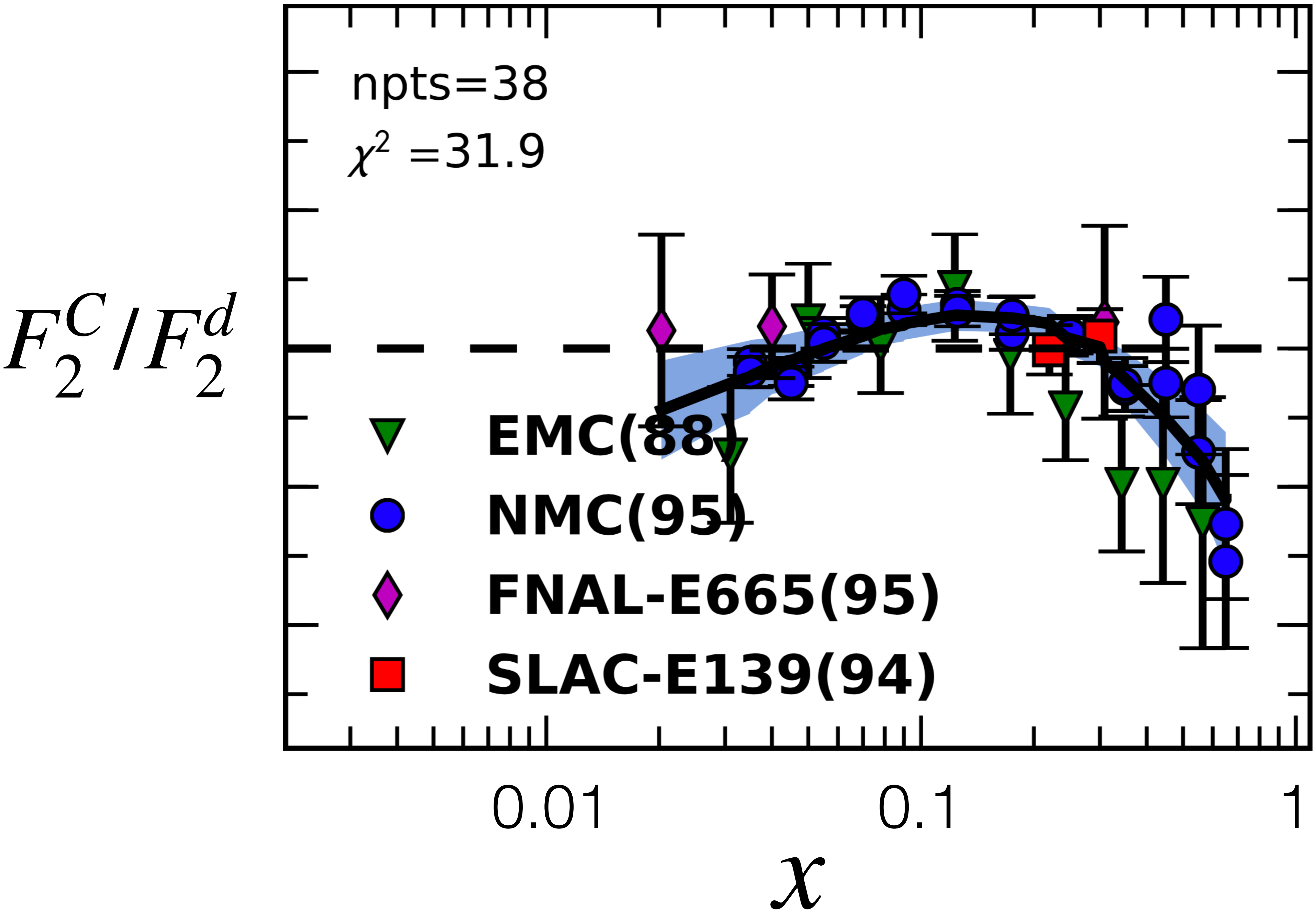
Data used



nCTEQ15 $Q > 2, W > 3.5$
nCTEQ15 DIS
nCTEQ15 DY
JLAB 6GeV DIS
Q^2 [GeV^2]
10^2
10^1
10^0
0.0
0.2
0.4
0.6
0.8
1.0
x
nCTEQ15HIX
$Q > 1.3$
$W > 1.7$

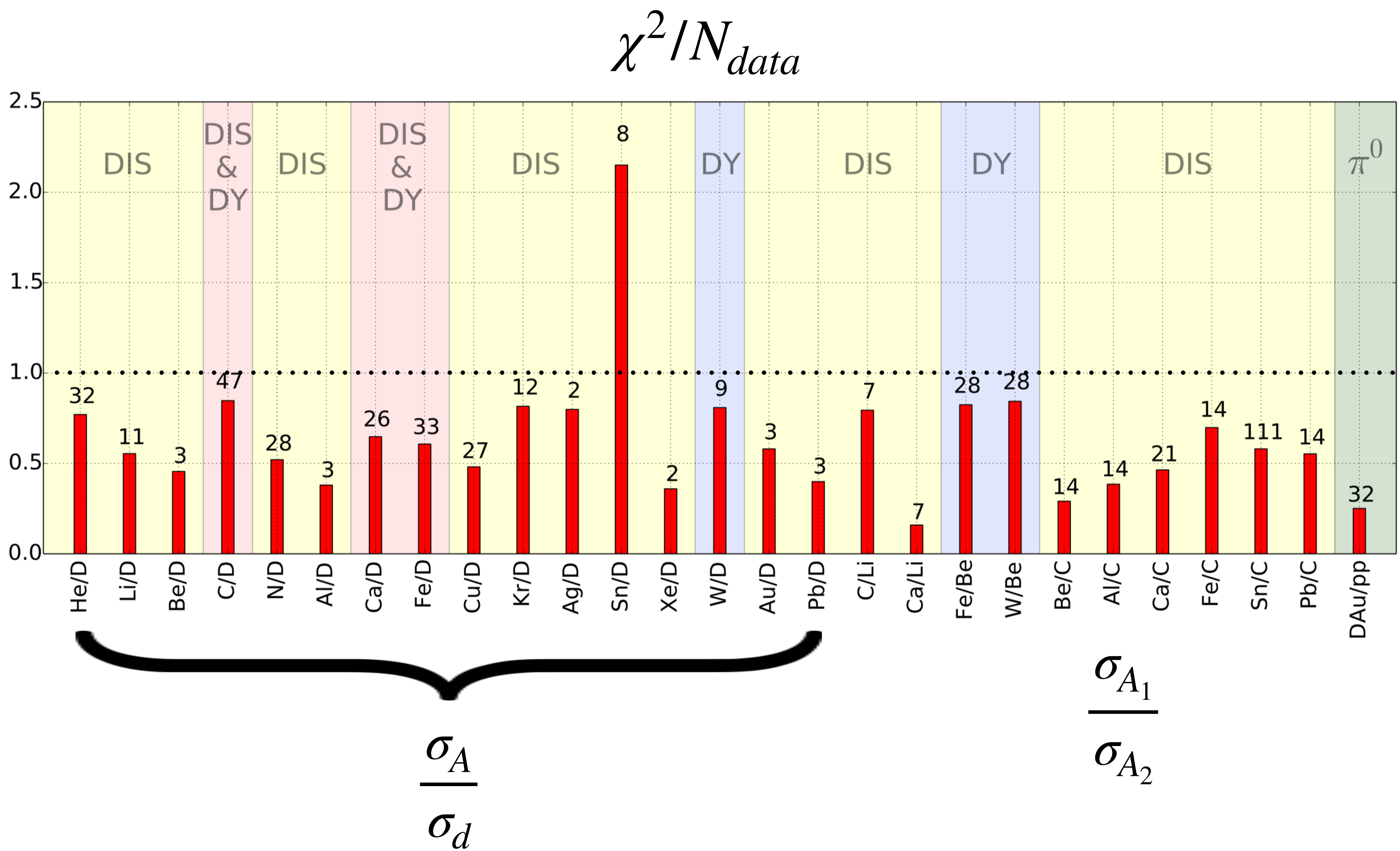
Extraction and assessment of fit

χ^2 minimization of ~ 16 parameters



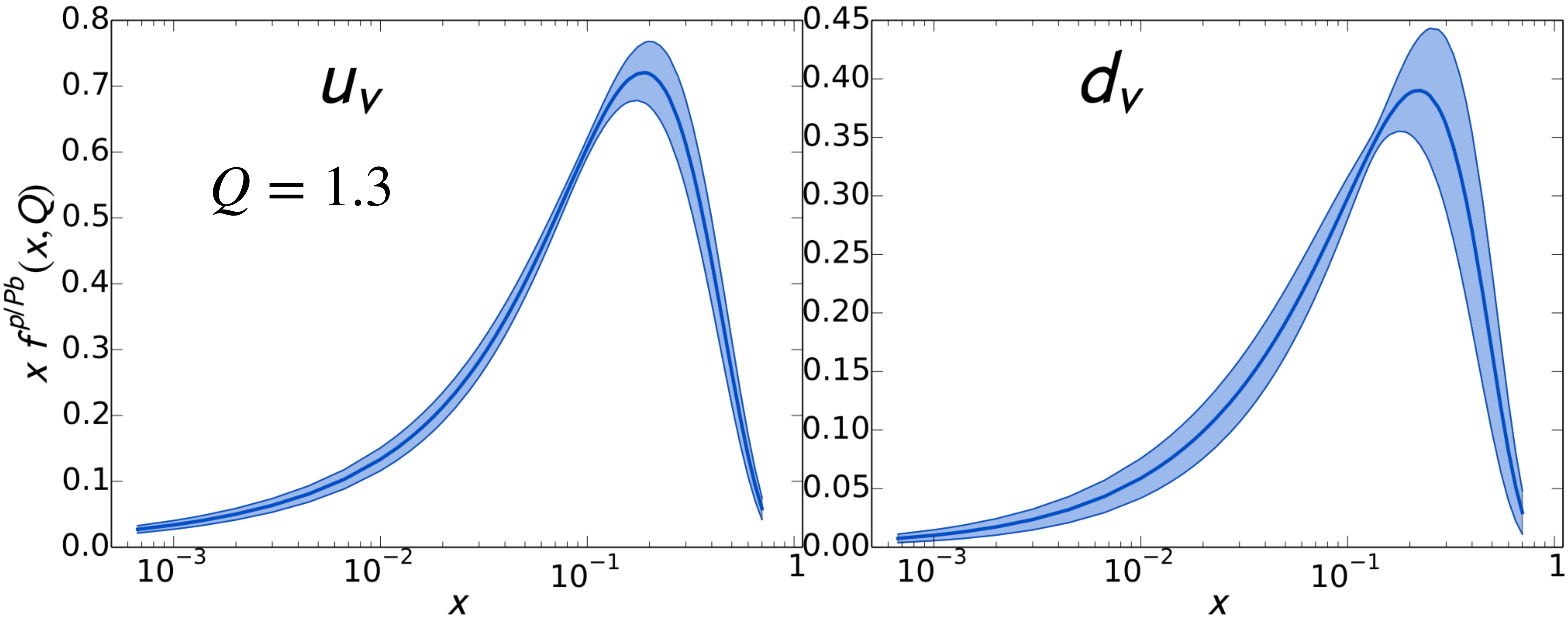
Phys.Rev.D80:094004,2009

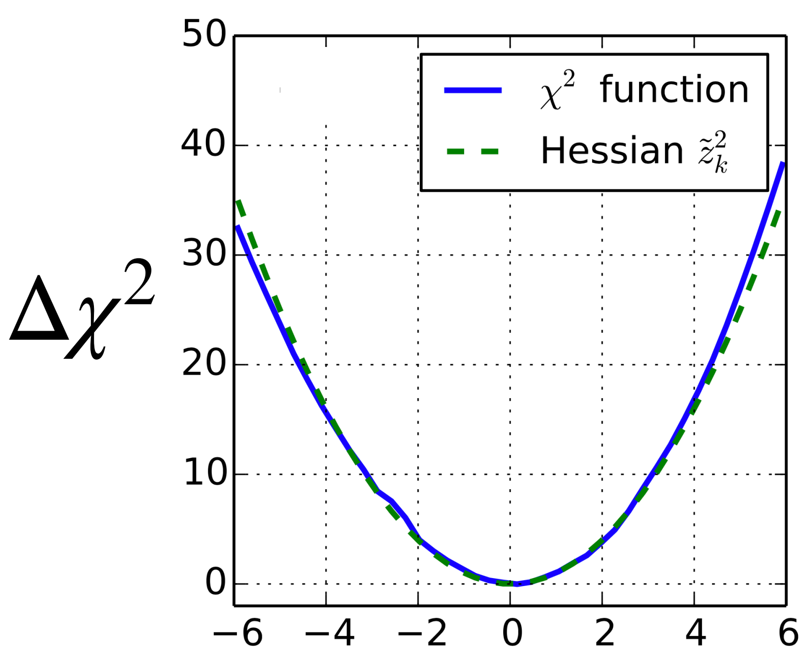
Assessing quality



Phys.Rev.D80:094004,2009

Resulting effective nPDFs

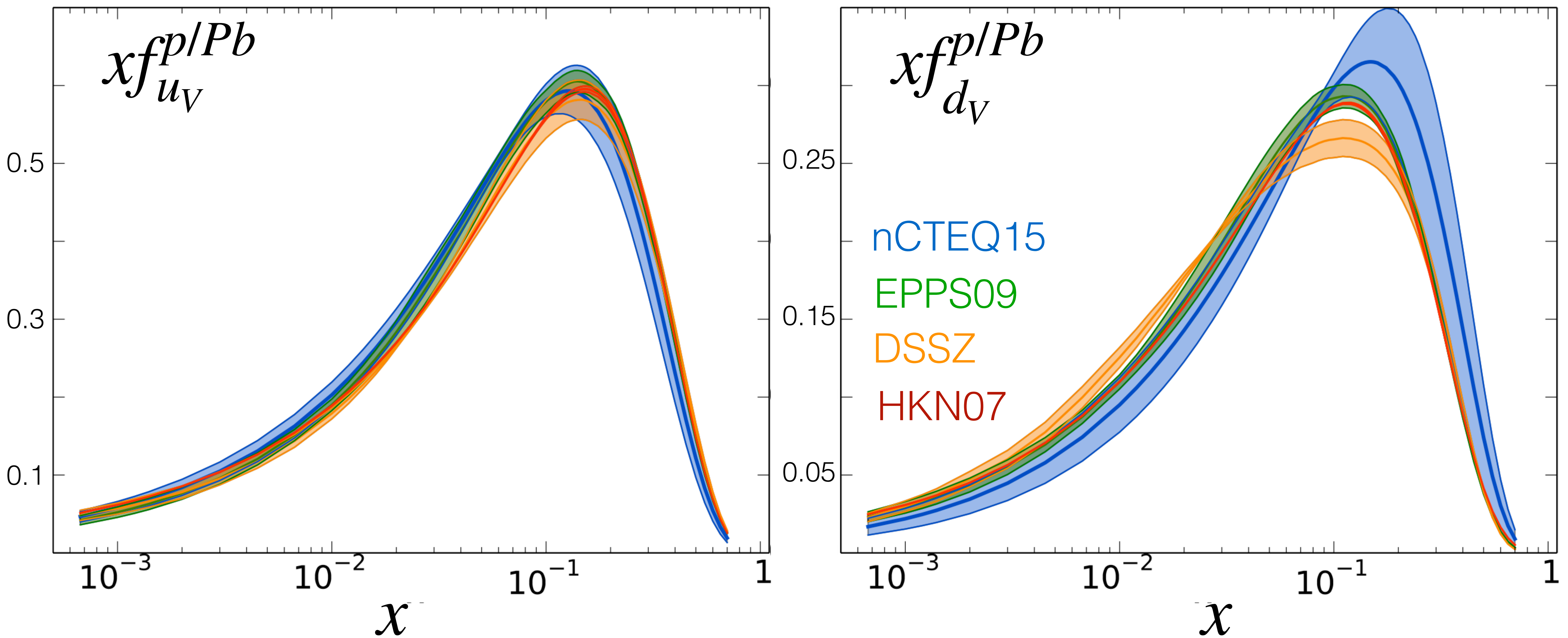




Uncertainty estimated via
Hessian method

Phys.Rev.D80:094004,2009

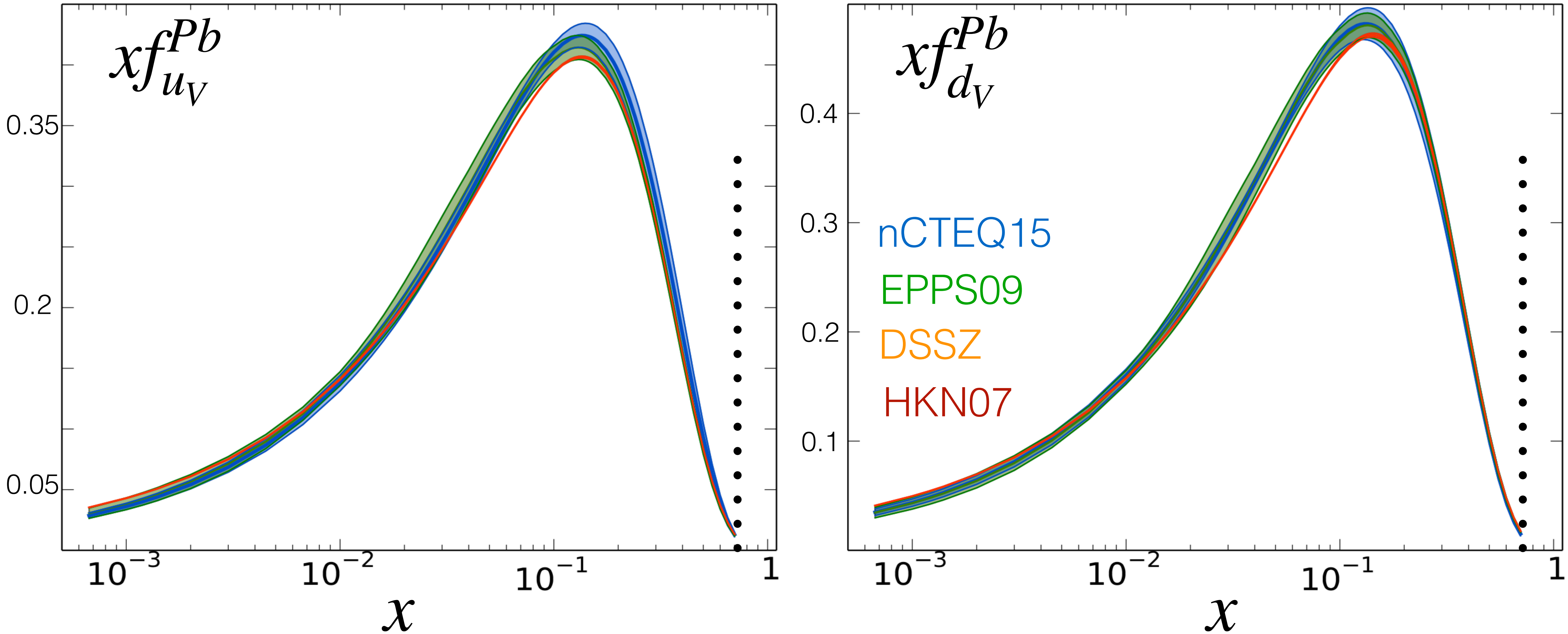
Average effective PDFs have some variance between groups



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

Phys.Rev.D80:094004,2009

Full effective nPDFs are very similar



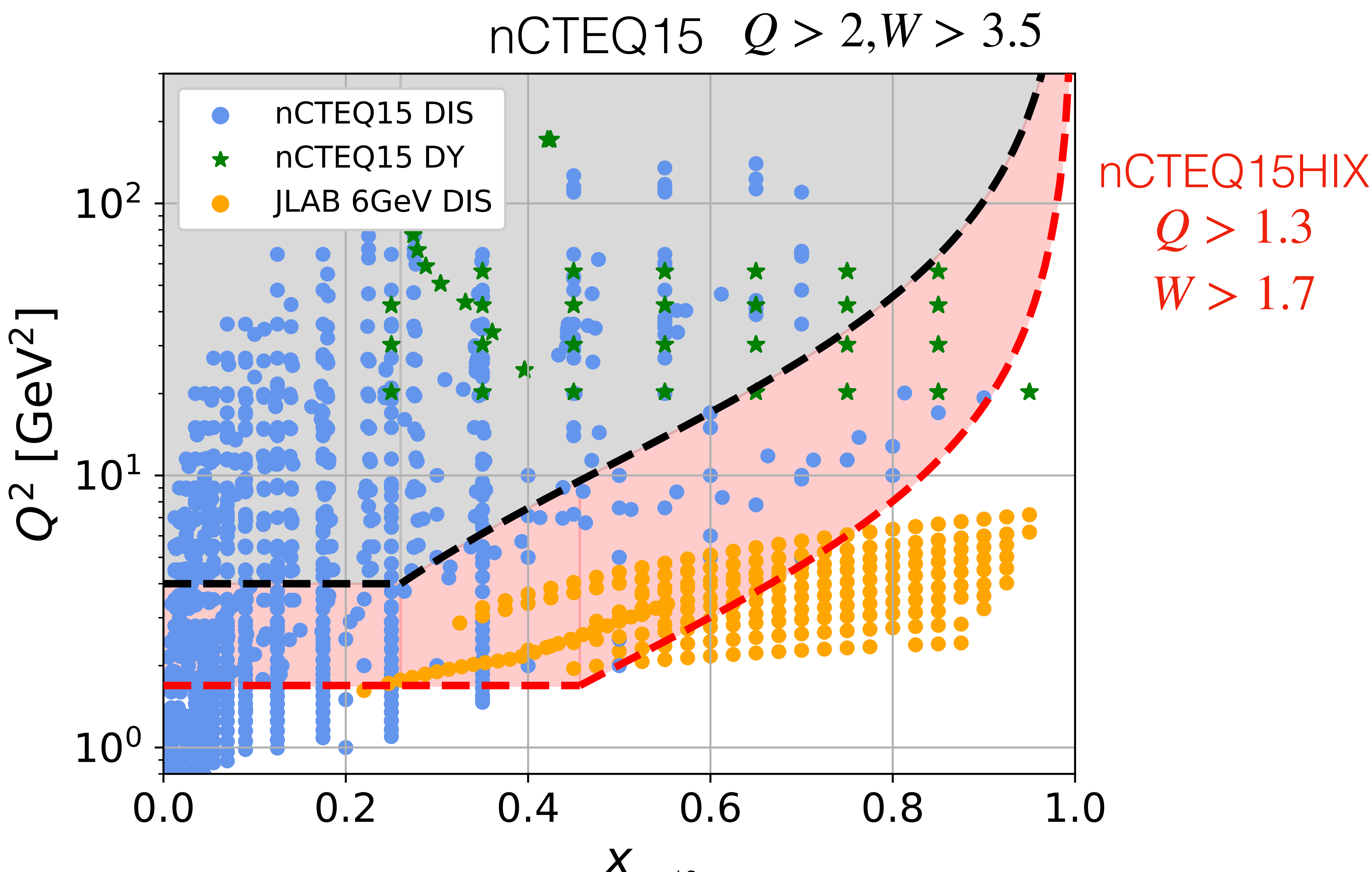
(which is great given completely different approaches)

Phys.Rev.D80:094004,2009

Outline

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

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

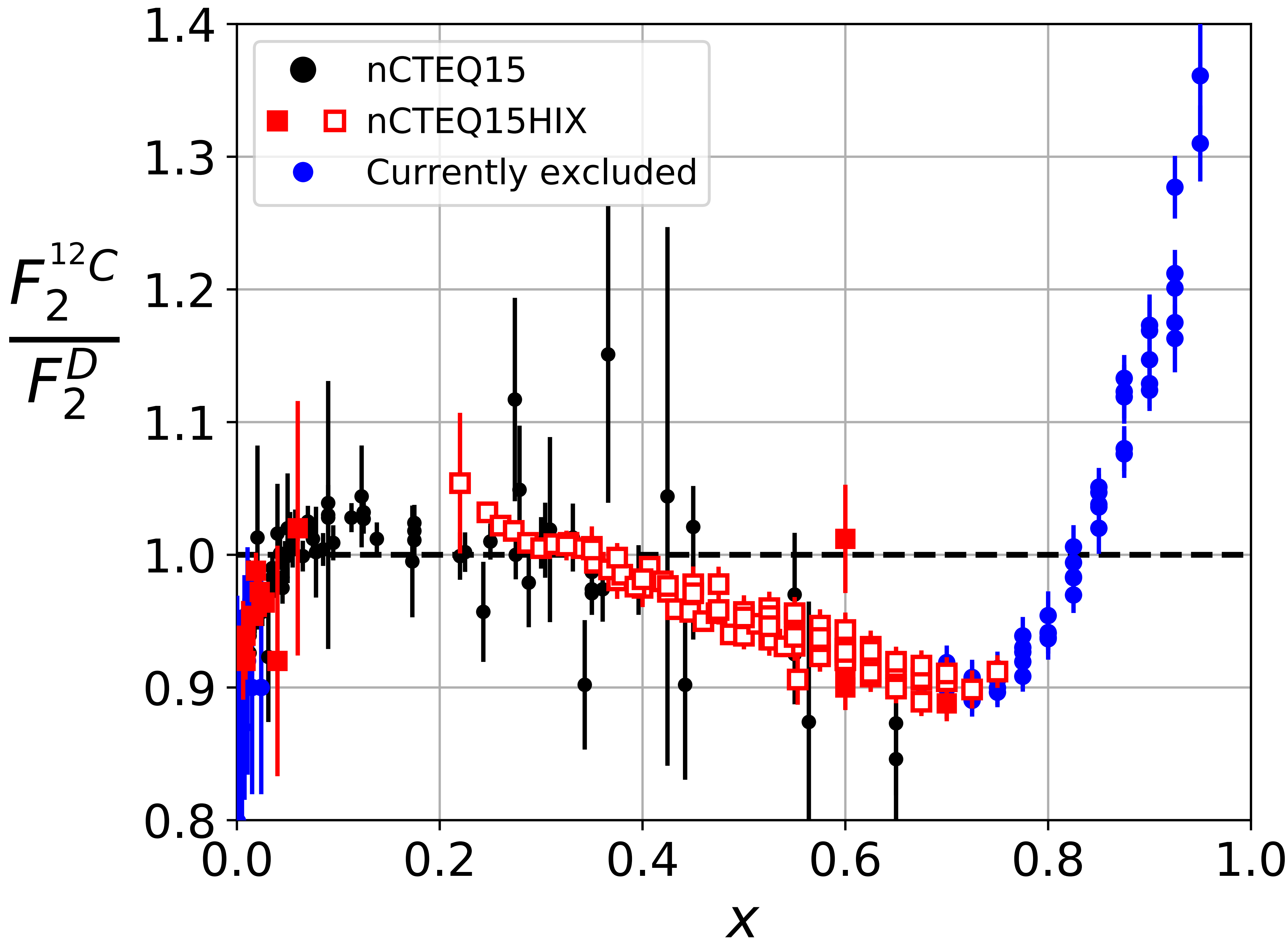
- EMC Region and Fermi-Smearing
  - Flexible x-parameterization
  - Flexible A-dependence
- Deuterium theory calculation

Challenges in valence region

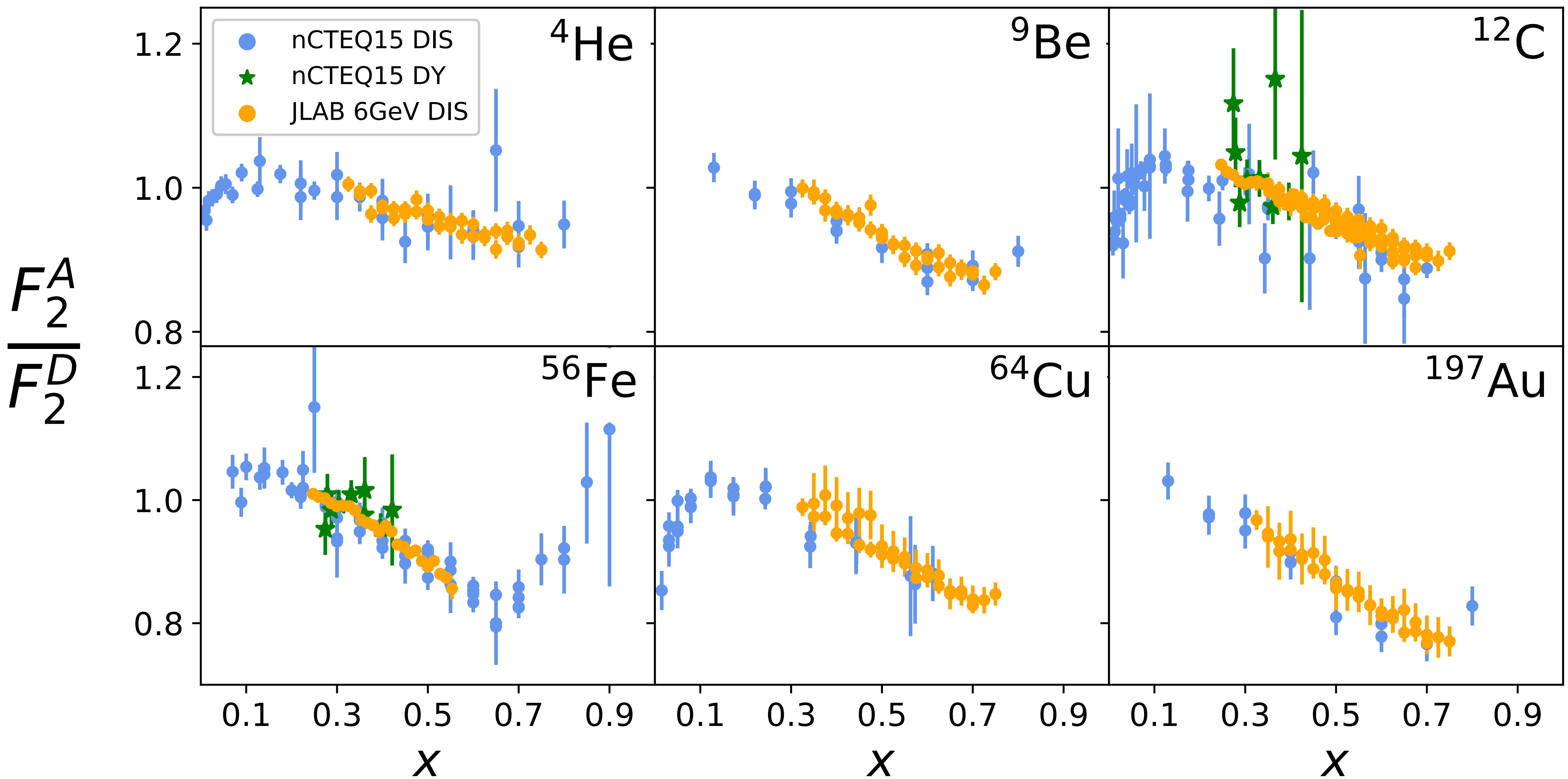
Requires lower (Q^2,W) cuts

- 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*

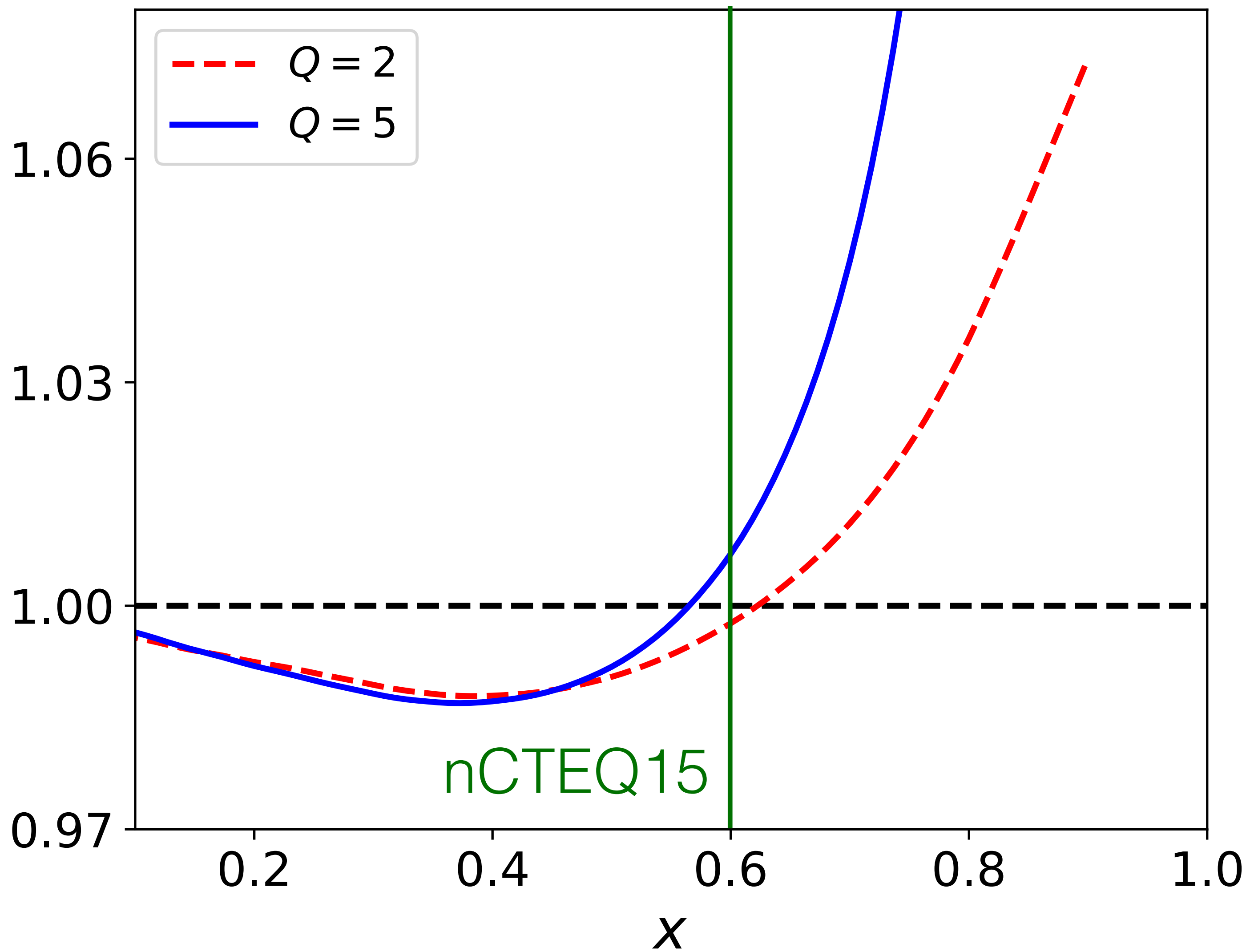
nCTEQ15 calculates

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

Data reported as

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

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



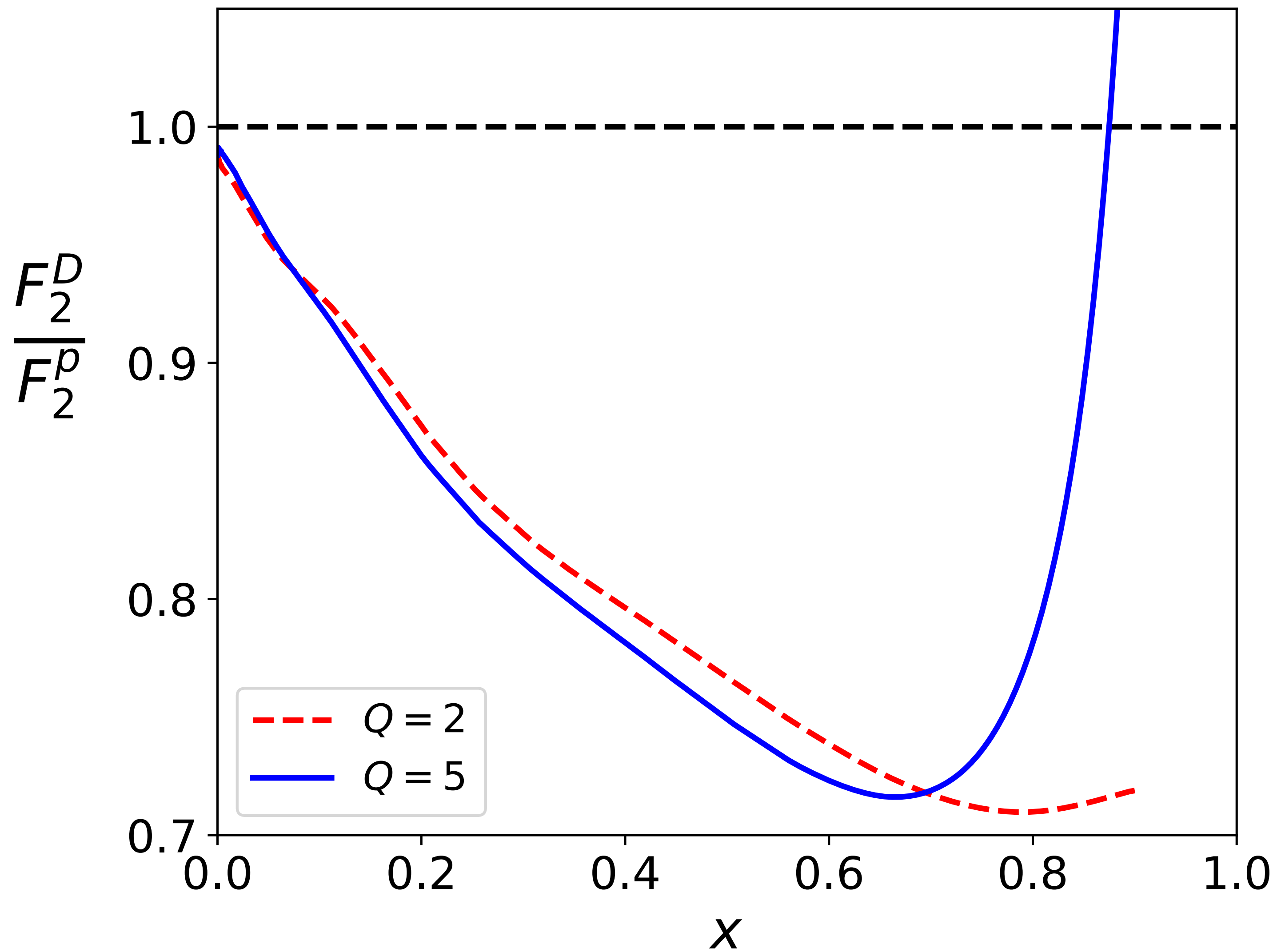
Deuterium at high-x

nCTEQ15HIX calculates

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

Data "correction"

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



TMC & HT Corrections

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

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

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

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

(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 ($N_{data} = 740 \rightarrow 1564$)

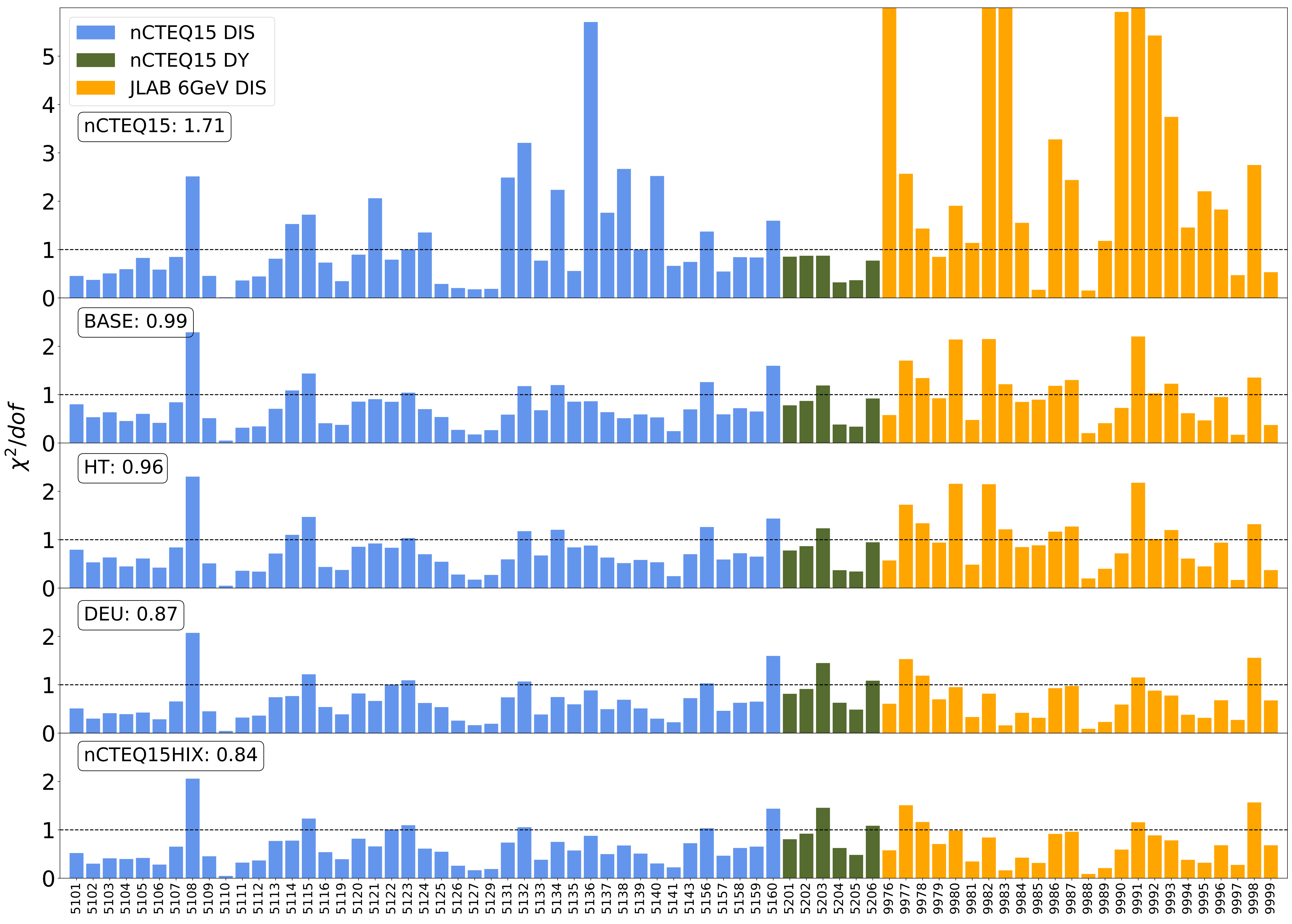
1. See how nCTEQ15 works out of the box (**nCTEQ15**)

2. Refit nCTEQ15 (**BASE**)

3. Include just HT & TMC corrections (**HT**)

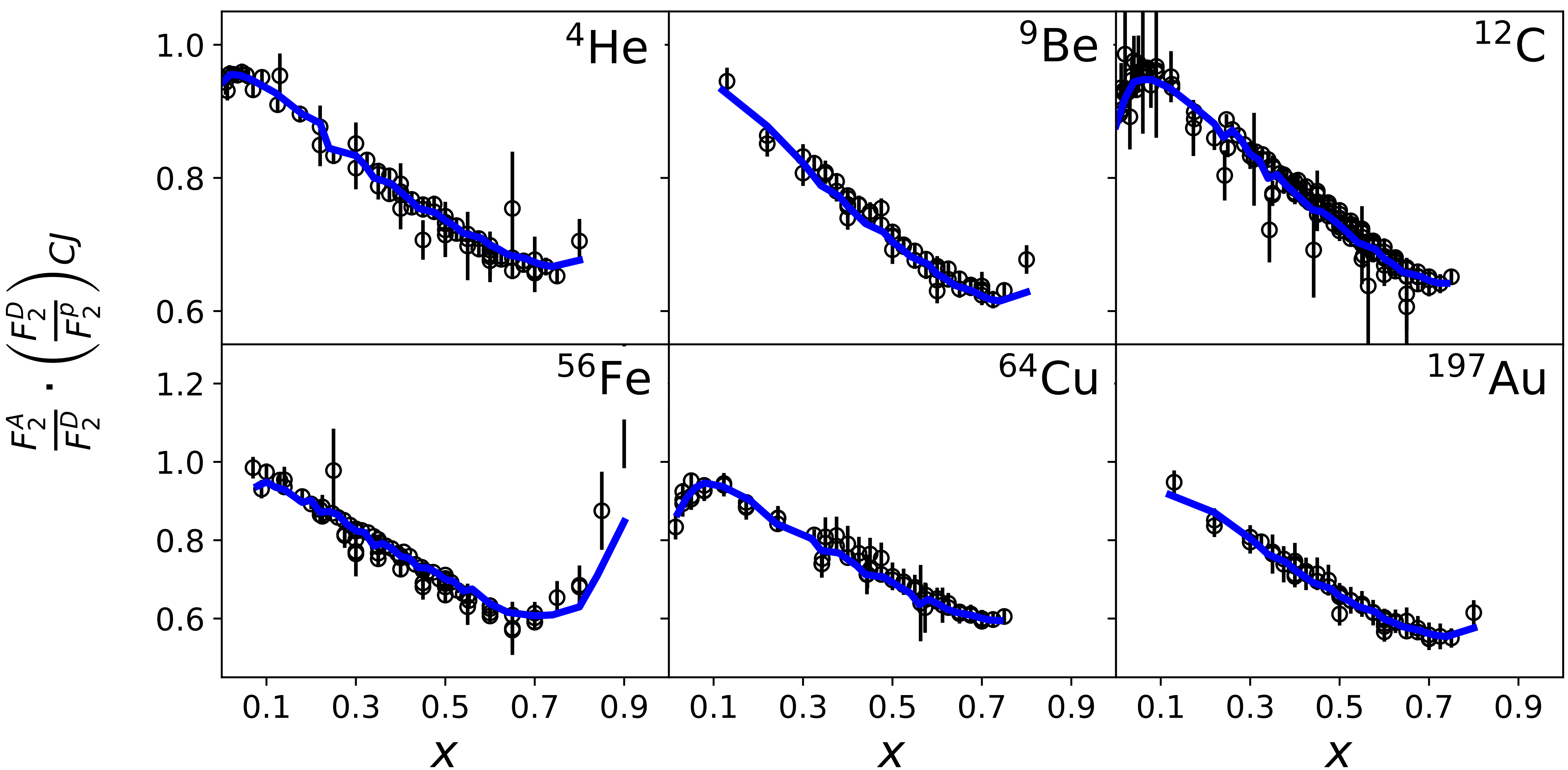
4. Include just deuterium-to-proton evolution (**DEUT**)

5. Include all corrections (**nCTEQ15HIX**)

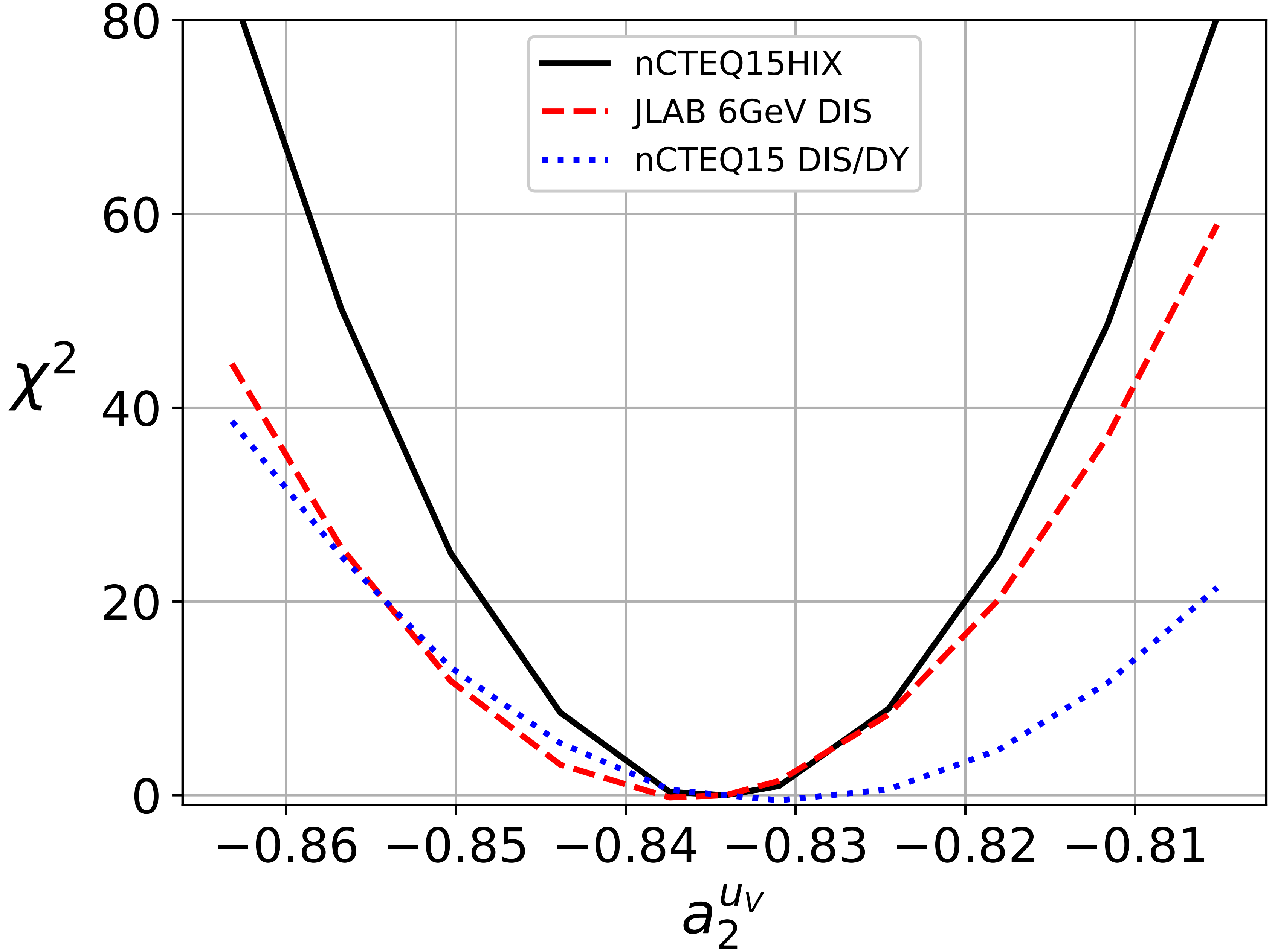


nCTEQ15 DIS
nCTEQ15 DY
JLAB 6GeV DIS
nCTEQ15: 1.71
BASE: 0.99
HT: 0.96
DEU: 0.87
nCTEQ15HIX: 0.84
χ^2/dof

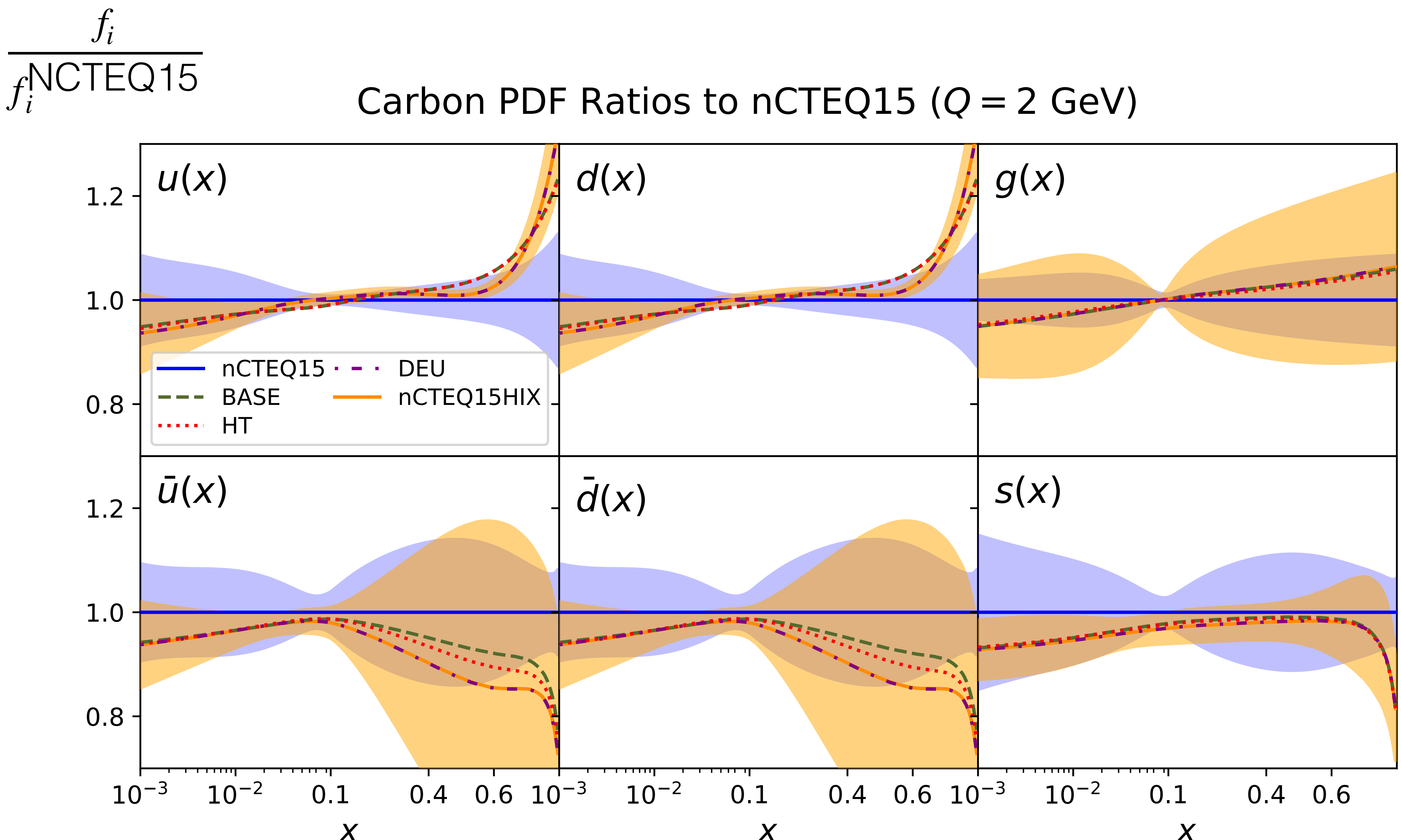
nCTEQ15HIX describes data well



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

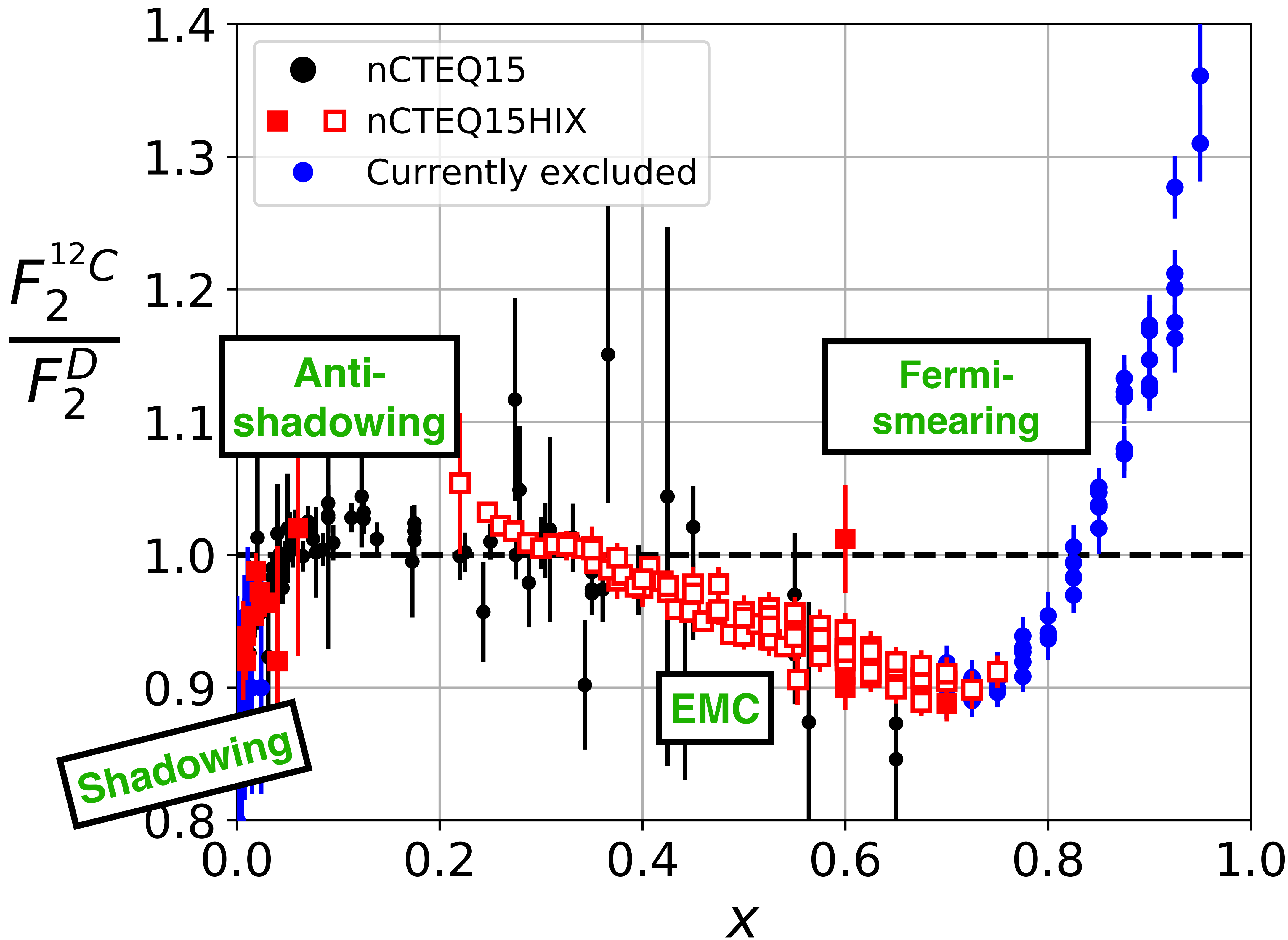


Resulting nPDFs have new behavior at high-x

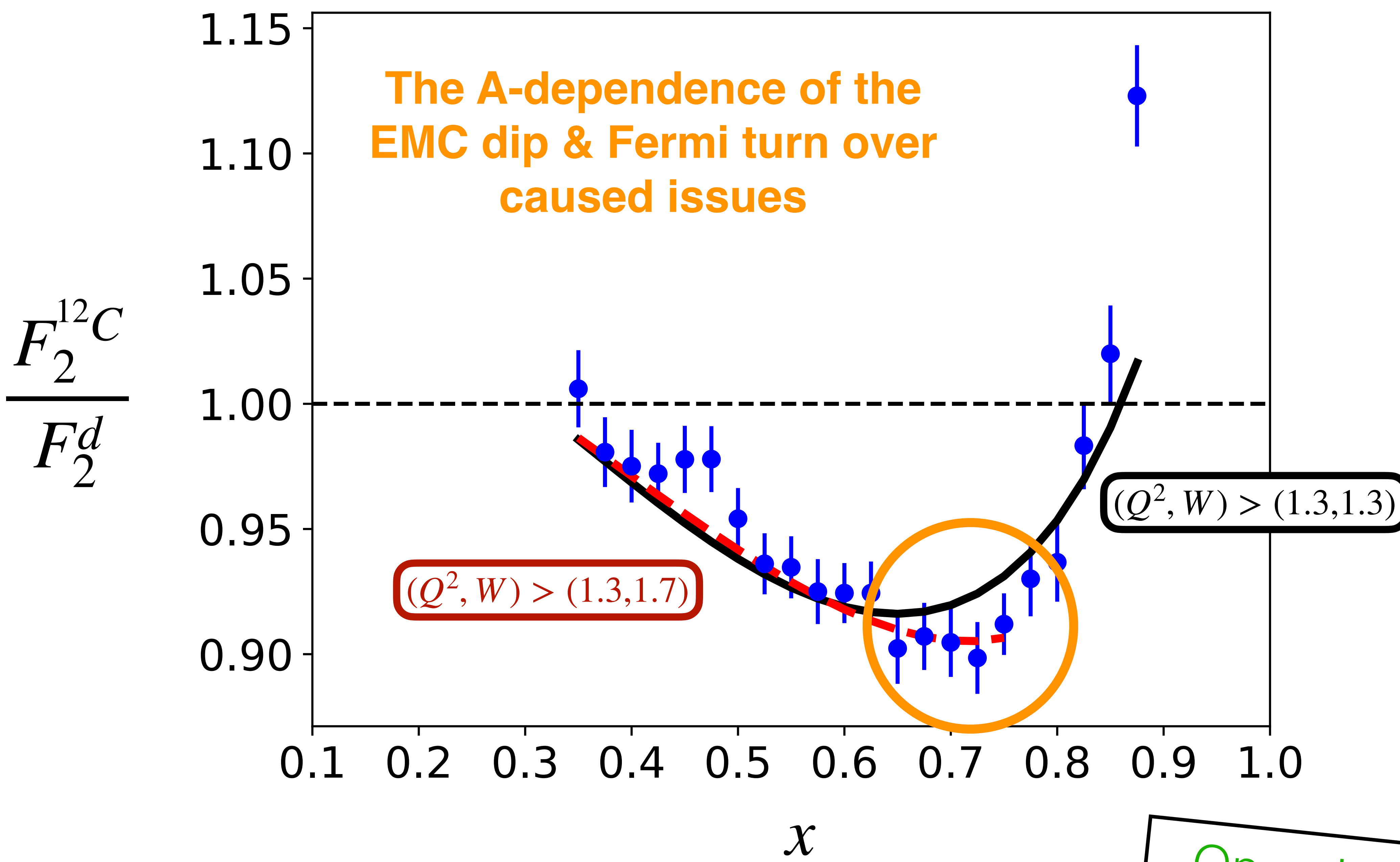


(Log-Linear axis)

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



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



On-going project for future nPDFs

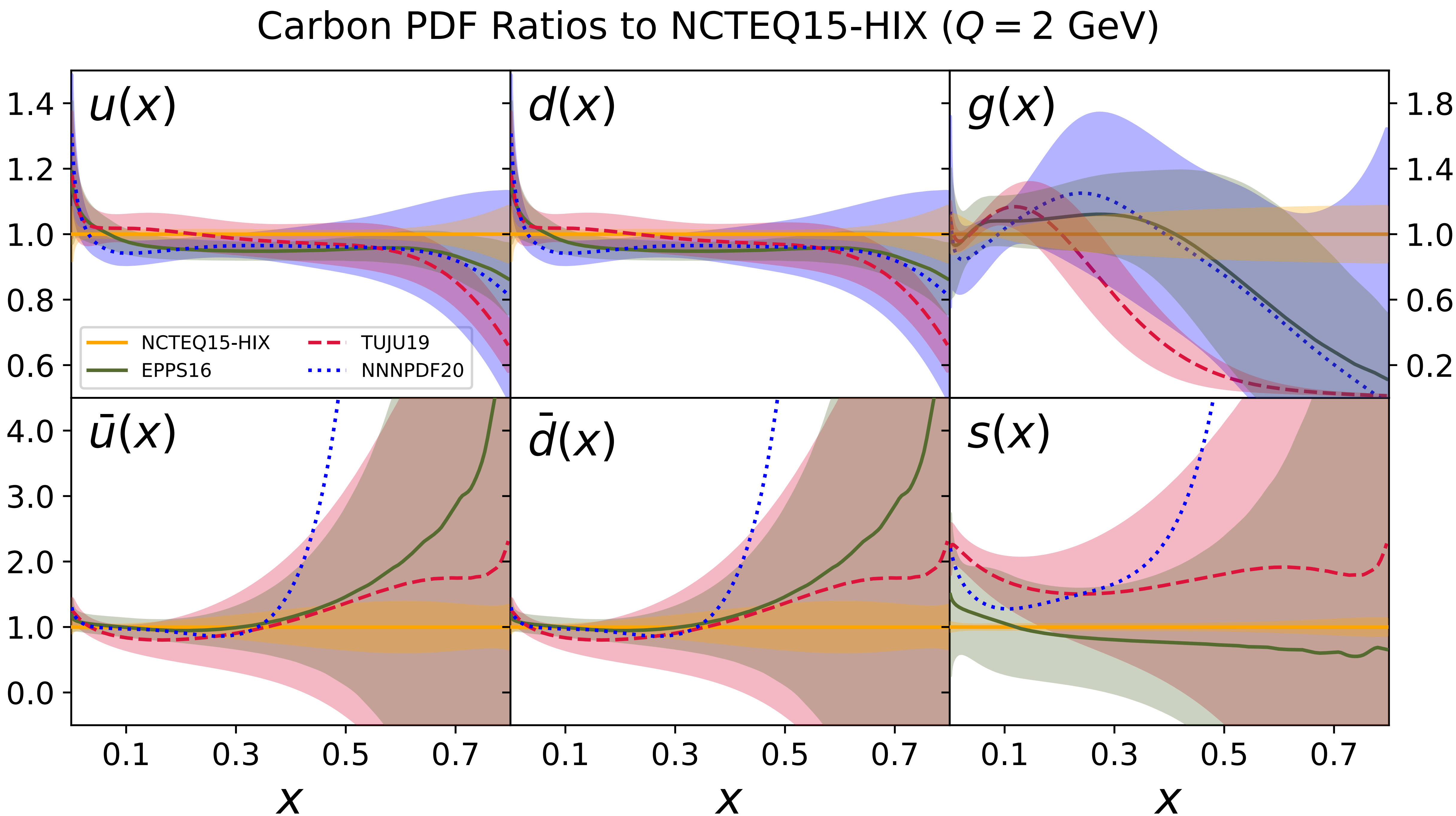
One approach:

$$f_i(x_1, Q_1^2) \to f_i^{new}(x_1, Q_1^2) = \int_{x_1}^{A} f_i(\frac{x_1}{\alpha}, Q_1^2)\mathscr{F}^A(\alpha)d\alpha$$

Stay tuned & check out our work

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

E.P. Segarra,[1,*] T. Ježo,[2,†] A. Accardi,[3,4] P. Duwentäster,[5] O. Hen,[1] T .J. Hobbs,[6,4] C. Keppel,[4] M. Klasen,[5] 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]

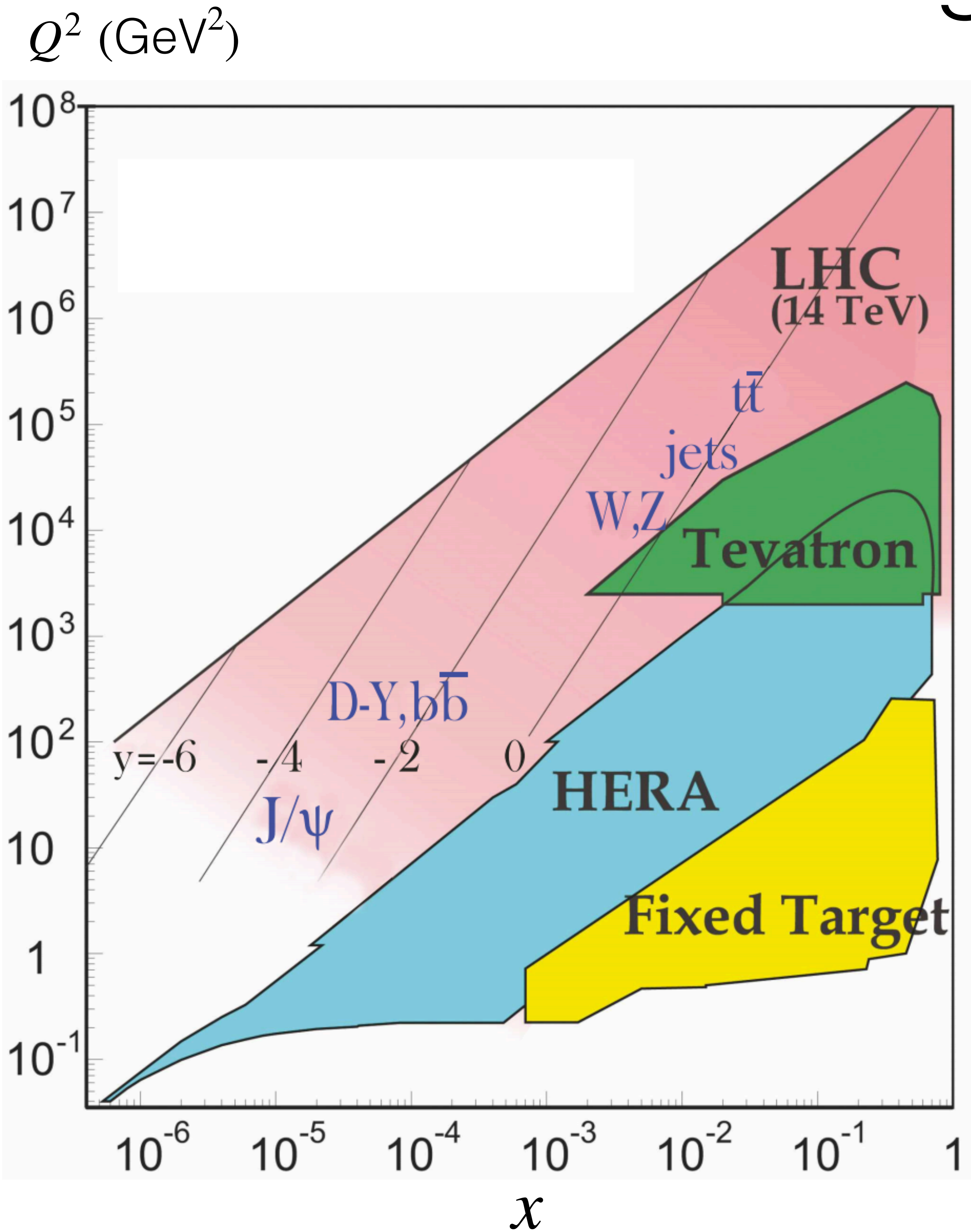


arxiv 2012.11566 (under review)

Thanks all!

Questions, comments?

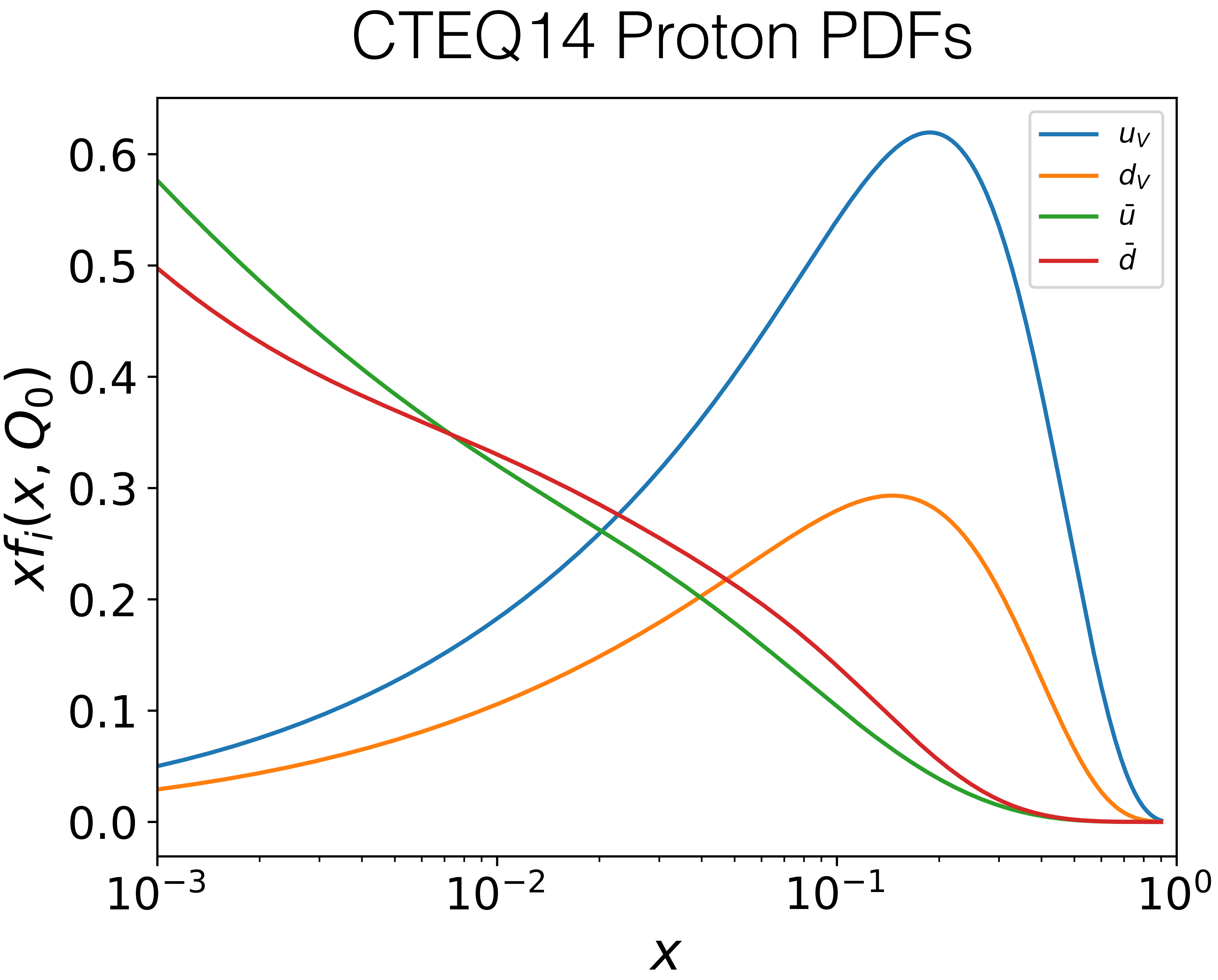
Extracting PDFs



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



https://lhapdf.hepforge.org/

nCTEQ15 Framework

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

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

This is pretty inconvenient to think about when comparing free proton PDFs to "modified" PDFs.

(follow-up work on changing parameterization)

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

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

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

(Bit out of date comparison)

	nNNPDF1.0 EPJC79(2019471	EPPS16 EPJC77(2017)163	nCTEQ15 PRD93(2016)085037	KA15 PRD93(2016)014036	DSSZ12 PRD85(2012)074028	EPS09 JHEP0904(2009)065
lA DIS	✔	✔	✔	✔	✔	✔
DY in p+A	✘	✔	✔	✔	✔	✔
RHIC π d+Au	✘	✔	✔	✘	✔	✔
νA 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:

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

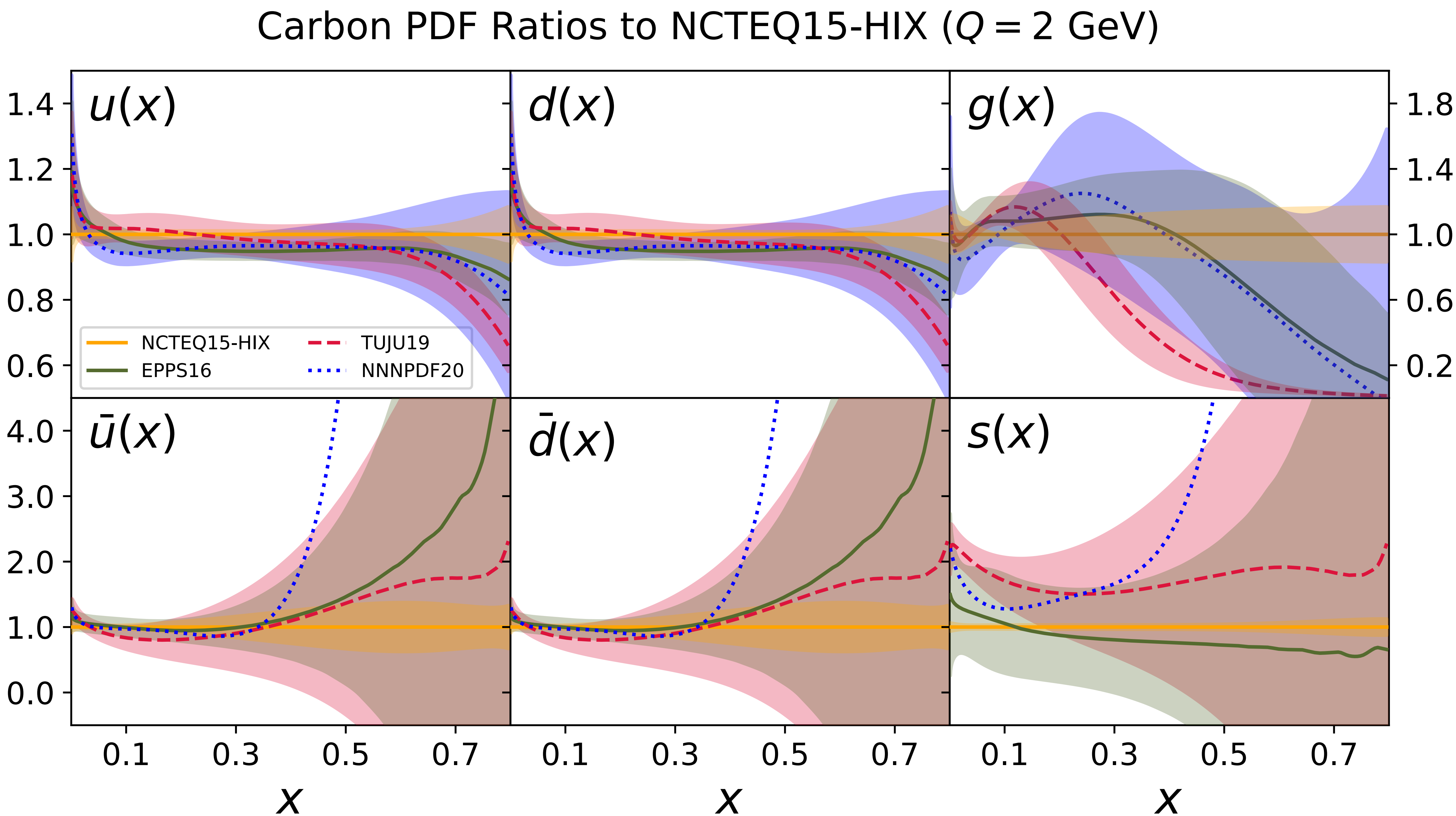
uses some assumption on F_2^n and results in degeneracy of isospin-symmetric PDFs: $f_u^A = f_d^A$

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



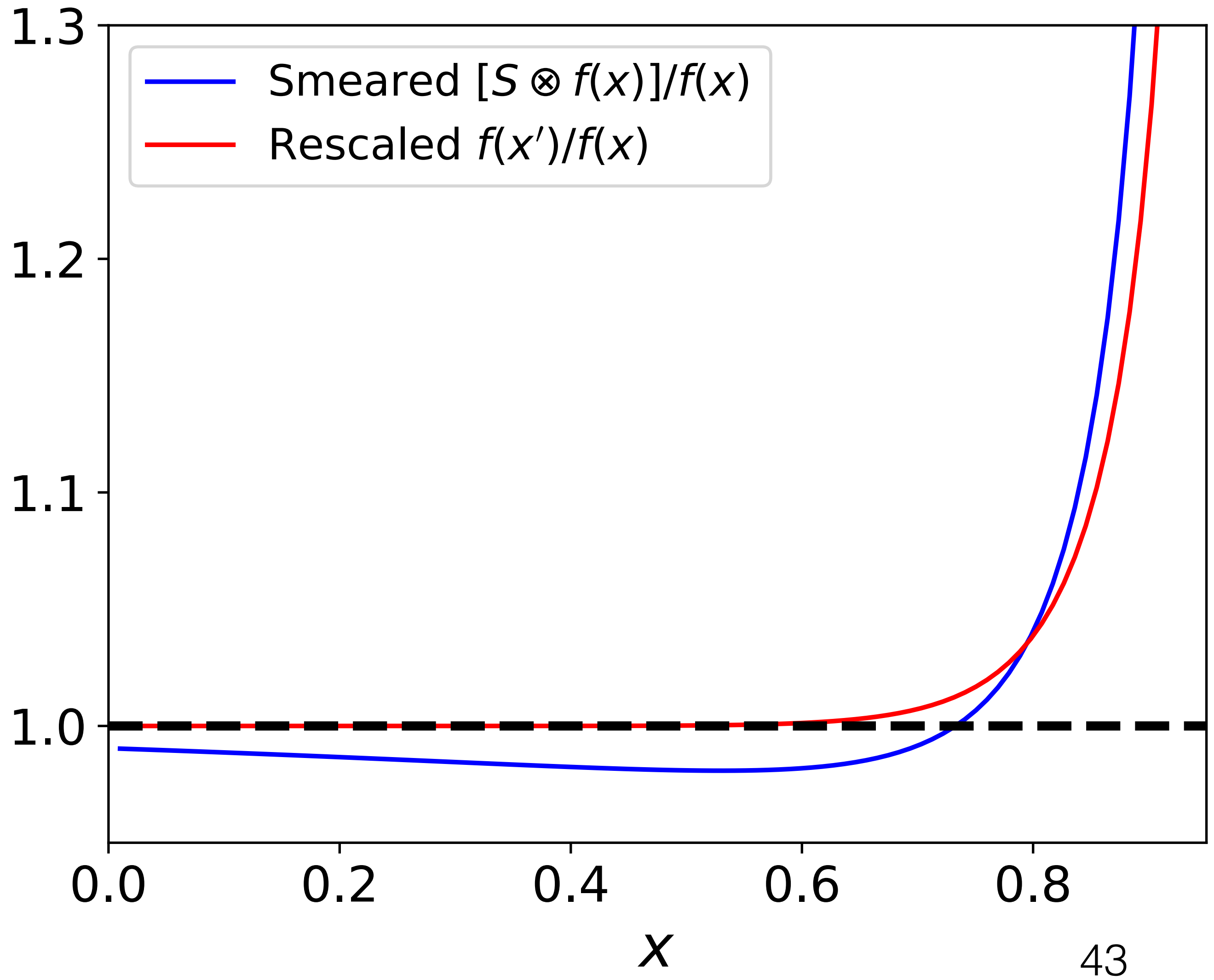
One way to address Fermi-smearing

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

One way to address Fermi-smearing

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

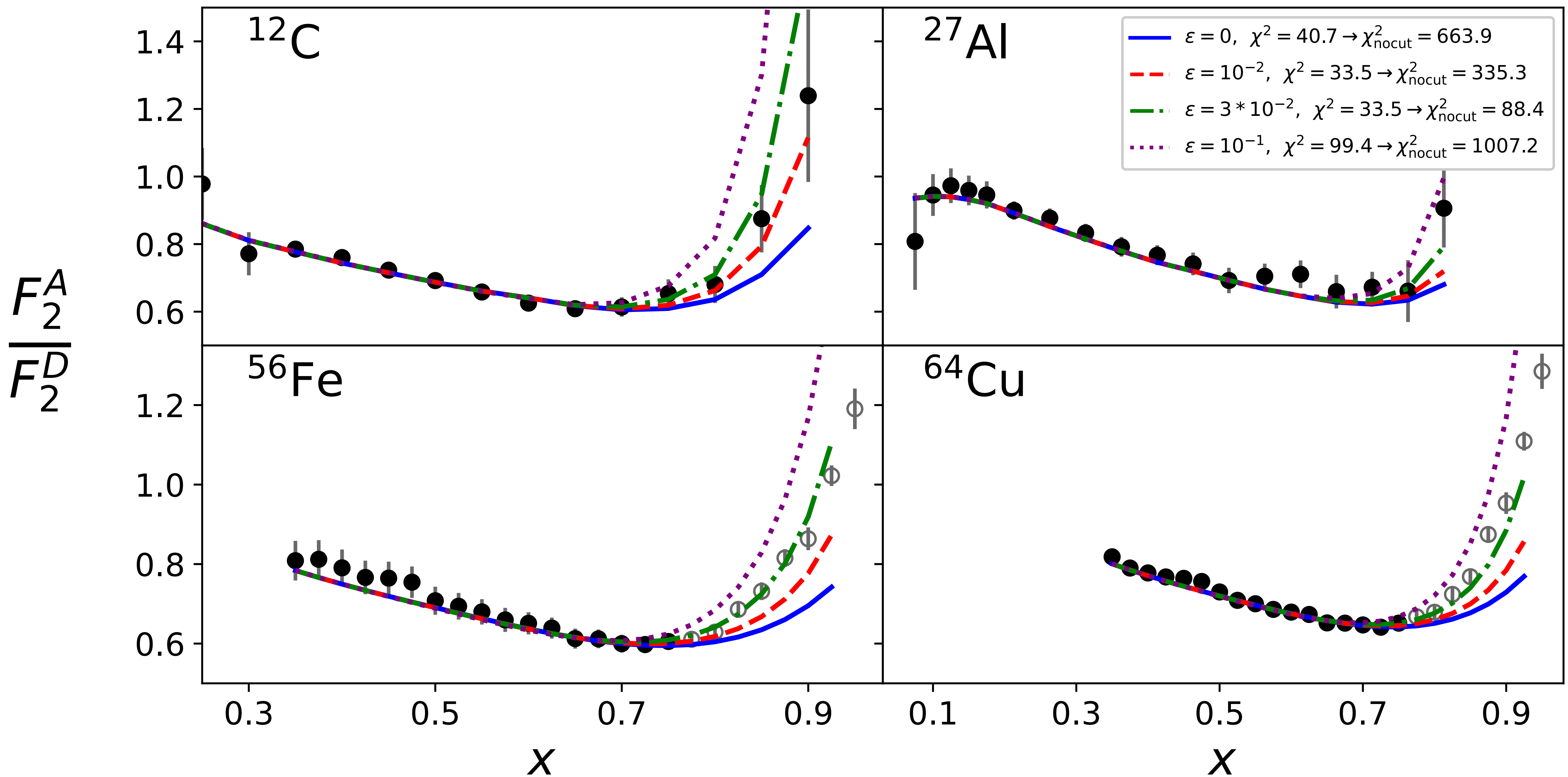
is computational expensive… but we developed a “trick”



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

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

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

This is pretty inconvenient to think about when comparing free proton PDFs to “modified” PDFs.

(follow-up work on changing parameterization)

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

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

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