

Nuclear PDFs: new results from global fits

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nCTEQ collaboration

ITP, WWU

SFB 1225 isoQuant



Nuclear structure at high energies

Periodic Table of the Elements

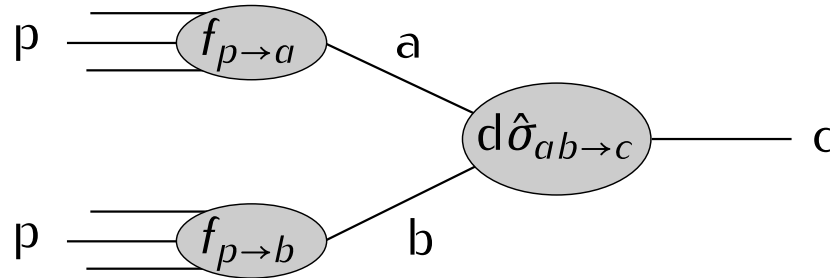
Nuclei with DIS data included in
nCTEQ15 (Fig. by E. Godat)

1 1A H Hydrogen 1.00794	2 2A He Helium 4.002602											13 3B B Boron 10.811	14 4A C Carbon 12.011	15 5A N Nitrogen 14.007	16 6A O Oxygen 15.999	17 7A F Fluorine 18.998	18 8A Ne Neon 20.180
3 3A Li Lithium 6.941	4 4A Be Beryllium 9.012											13 3B Al Aluminum 26.982	14 4A Si Silicon 28.086	15 5A P Phosphorus 30.974	16 6A S Sulfur 32.064	17 7A Cl Chlorine 35.453	18 8A Ar Argon 39.948
11 1A Na Sodium 22.990	12 2A Mg Magnesium 24.305	3 3B Sc Scandium 44.956	4 4B Ti Titanium 47.867	5 5B V Vanadium 50.942	6 6B Cr Chromium 51.996	7 7B Mn Manganese 54.938	8 8B Fe Iron 55.845	9 9B Co Cobalt 58.933	10 10B Ni Nickel 58.693	11 11B Cu Copper 63.546	12 12B Zn Zinc 65.38	13 3B Ga Gallium 69.723	14 4B Ge Germanium 72.630	15 5B As Arsenic 74.922	16 6B Se Selenium 78.972	17 7B Br Bromine 79.904	18 8B Kr Krypton 83.798
19 1A K Potassium 39.098	20 2A Ca Calcium 40.078	39 3B Y Yttrium 88.906	40 4B Zr Zirconium 91.224	41 5B Nb Niobium 92.906	42 6B Mo Molybdenum 95.94	43 7B Tc Technetium 98.907	44 8B Ru Ruthenium 101.07	45 9B Rh Rhodium 102.906	46 10B Pd Palladium 106.42	47 11B Ag Silver 107.868	48 12B Cd Cadmium 112.411	49 3B In Indium 114.818	50 4B Sn Tin 118.71	51 5B Sb Antimony 121.760	52 6B Te Tellurium 127.6	53 7B I Iodine 126.905	54 8B Xe Xenon 131.29
55 1A Cs Cesium 132.905	56 2A Ba Barium 137.327	57-71 3B La-Lu Lanthanum-Lutetium 138.905-175.053	72 4B Hf Hafnium 178.49	73 5B Ta Tantalum 180.948	74 6B W Tungsten 183.85	75 7B Re Rhenium 186.207	76 8B Os Osmium 190.23	77 9B Ir Iridium 192.22	78 10B Pt Platinum 195.08	79 11B Au Gold 196.967	80 12B Hg Mercury 200.59	81 3B Tl Thallium 204.383	82 4B Pb Lead 207.2	83 5B Bi Bismuth 208.980	84 6B Po Polonium [209]	85 7B At Astatine 209	86 8B Rn Radon 222.018
87 1A Fr Francium [223]	88 2A Ra Radium [226]	89-103 3B Ac-Lr Actinide-Lanthanide [227]-[261]	104 4B Rf Rutherfordium [261]	105 5B Db Dubnium [262]	106 6B Sg Seaborgium [263]	107 7B Bh Bohrium [264]	108 8B Hs Hassium [265]	109 9B Mt Meitnerium [266]	110 10B Ds Darmstadtium [267]	111 11B Rg Roentgenium [268]	112 12B Cn Copernicium [269]	113 3B Uut Ununtrium [270]	114 4B Fl Flerovium [279]	115 5B Uup Ununpentium [279]	116 6B Lv Livermorium [279]	117 7B Uus Ununseptium [279]	118 8B Uuo Ununoctium [279]

- Nuclear parton distribution functions: proxy for nuclear structure at high energies
 - ▶ Point to fundamental q, g dynamics of p, n bound in nuclei
 - ▶ Set the initial conditions in creation of new state of matter: Color-glass condensate \rightarrow Quark-gluon plasma

Theoretical framework

- Take for example proton-proton (pp) collisions in picture:



- Or in formula, in the collinear factorization framework:

$$d\sigma_{pp \rightarrow c} = \sum_{a,b} f_{p \rightarrow a}(x_a, \mu) \otimes f_{p \rightarrow b}(x_b, \mu) \otimes d\hat{\sigma}_{ab \rightarrow c}(\mu)$$
$$\mu \gtrsim 1 \text{ GeV}, x \in (0, 1)$$

- With μ : factorization scale, x : fraction of parton $a(b)$ momentum in proton p

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- With μ : factorization scale, x : fraction of parton $a(b)$ momentum in proton p
- Hard cross section $d\hat{\sigma}_{ab \rightarrow c}(\mu)$
 - ▶ Process specific
 - ▶ Calculable in perturbative QCD (pQCD)
- Parton Distribution Functions (PDFs) $f_{p \rightarrow a}(x, \mu)$
 - ▶ Universal
 - ▶ Not calculable from first principles (not yet)
- Similarly for lp , νp and one-particle inclusive^a processes

^aWhich involve second factorization scale and convolution with fragmentation functions.

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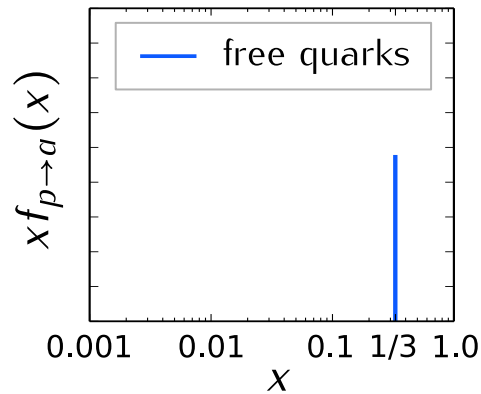
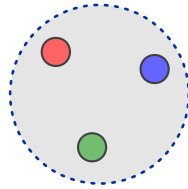
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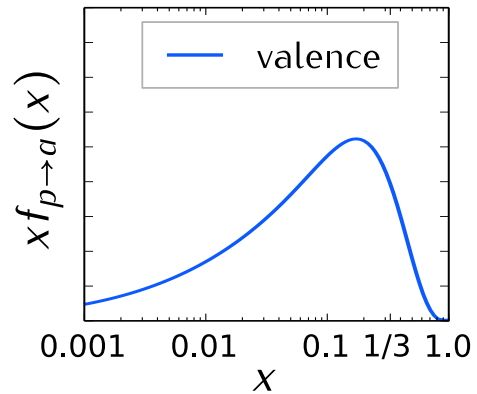
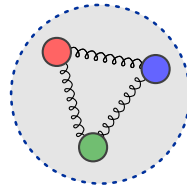
Parton Distribution Functions (PDFs)

- PDF[$f_{p \rightarrow a}(x, \mu)$]: probability that parton a carries fraction^a x of proton p momentum

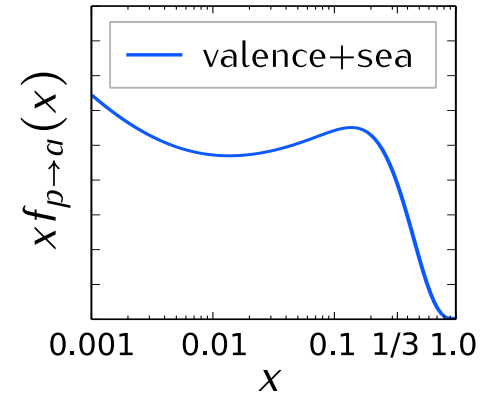
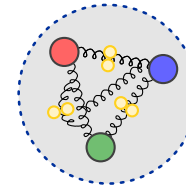
Free partons



Bound partons



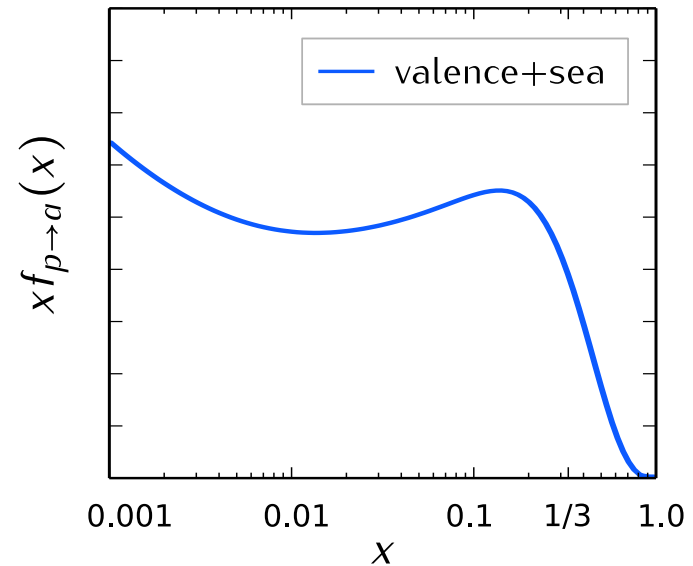
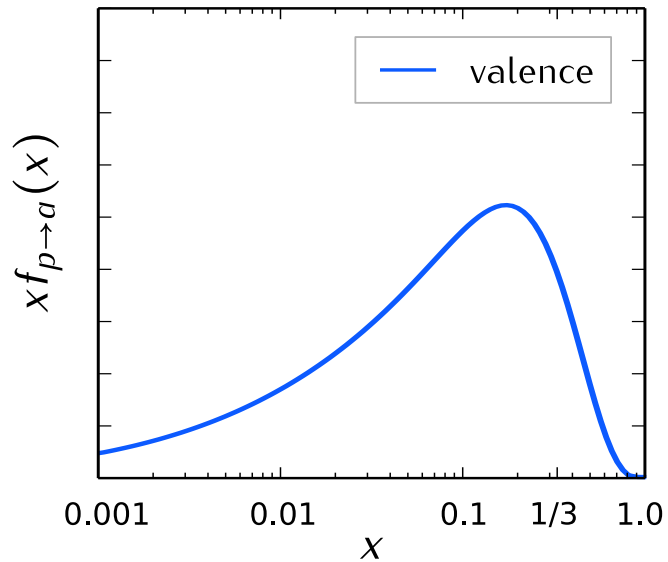
Bound partons
& QCD effects



^aLongitudinal.

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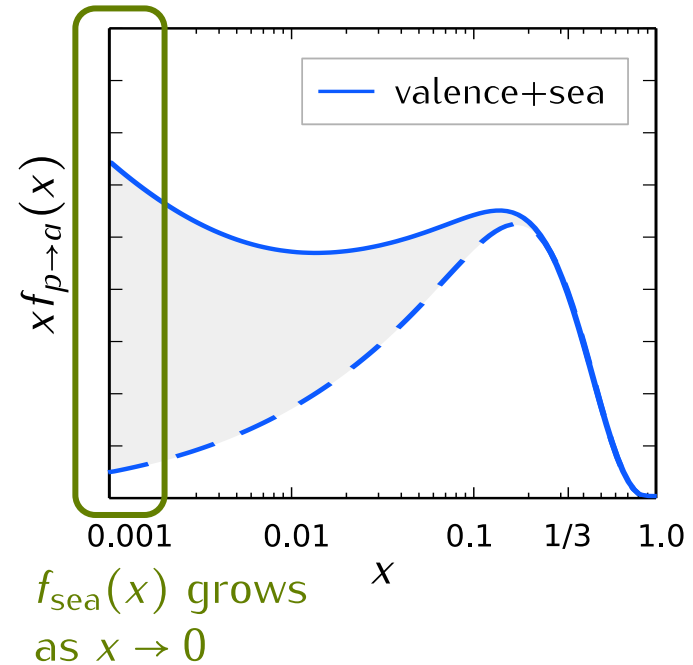
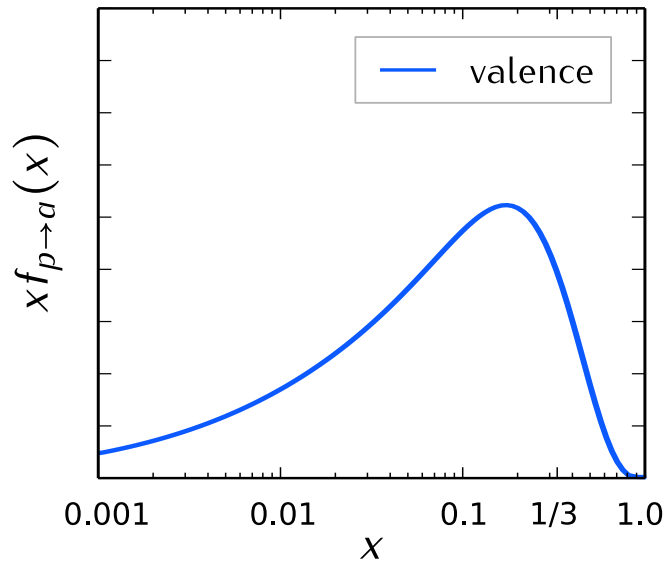
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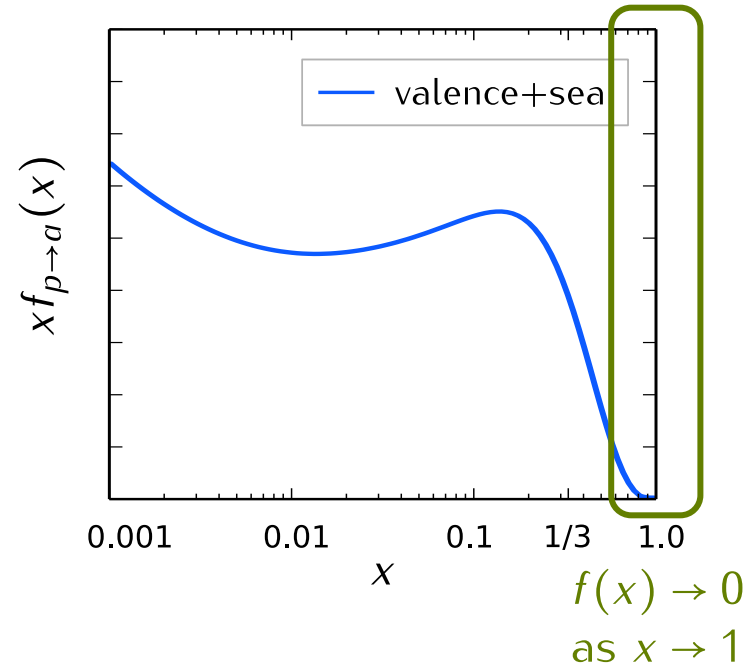
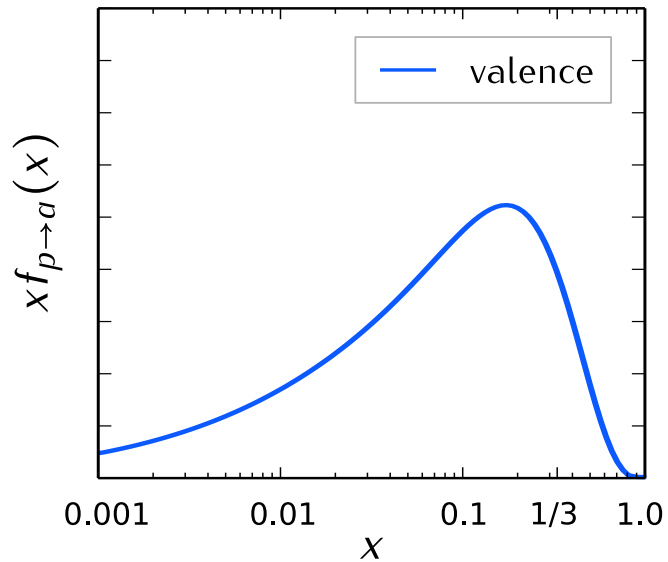
- PDF $[f_{p \rightarrow a}(x, \mu)]$: probability that parton a carries fraction^a x of proton p momentum



^aLongitudinal.

Parton Distribution Functions (PDFs)

- PDF[$f_{p \rightarrow a}(x, \mu)$]: probability that parton a carries fraction^a x of proton p momentum



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Parton Distribution Functions (PDFs)

- Universal: same PDF enters different processes (DIS, DY, SIH, HQ, ...)
- x dependence not calculable in pQCD
 - ▶ Constrained through number and momentum sum rules
- μ dependence governed by DGLAP evolution equations

$$\frac{d}{d \log \mu^2} f_q(x, \mu^2) \sim (P_{qq} \otimes f_q)(x, \mu^2) + (P_{qg} \otimes f_g)(x, \mu^2)$$
$$\frac{d}{d \log \mu^2} f_g(x, \mu^2) \sim (P_{gg} \otimes f_g)(x, \mu^2) + (P_{gq} \otimes f_q)(x, \mu^2)$$

- ▶ Describe violations of Bjorken x scaling
- ▶ Different PDFs mix: set of $(2n_f + 1)$ coupled integro-differential equations.

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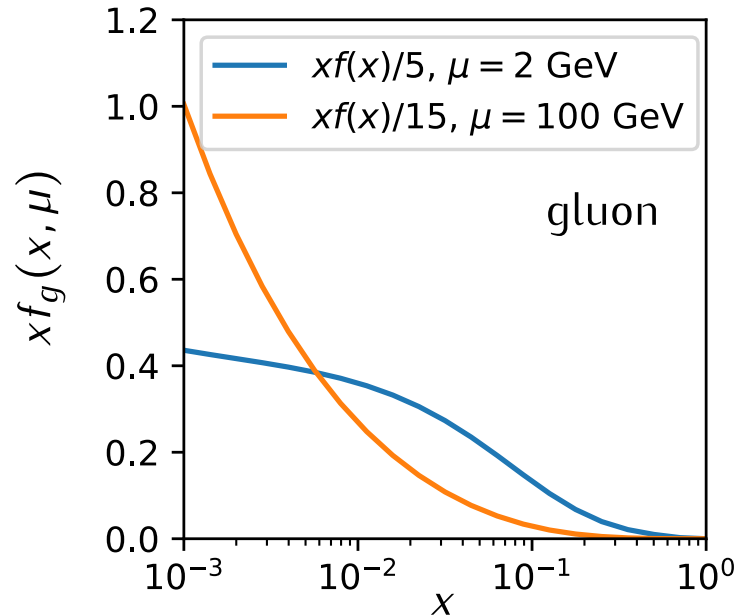
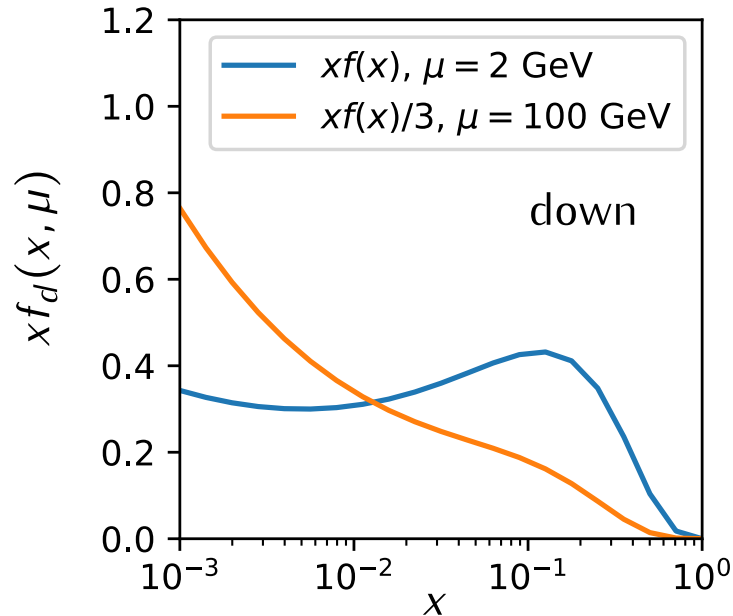
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Parton Distribution Functions (PDFs)

- μ dependence governed by DGLAP evolution equations:



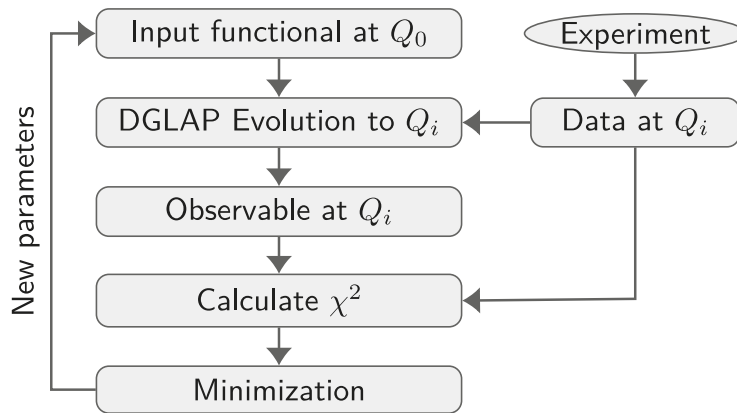
- ▶ Reduces valence and increases sea
- ▶ Mixes flavours

Parton Distribution Functions (PDFs)

- x dependence not calculable in pQCD:^a
 - ▶ assume parametrization^b in x at a chosen input scale Q_0 :

$$xf_i(x, Q_0) = N(1-x)^{p_{i,1}} x^{p_{i,2}} P(x, p_{i,3}, \dots)$$

- ▶ set $p_{i,j}$, calculate theoretical predictions, compare to data, iterate:



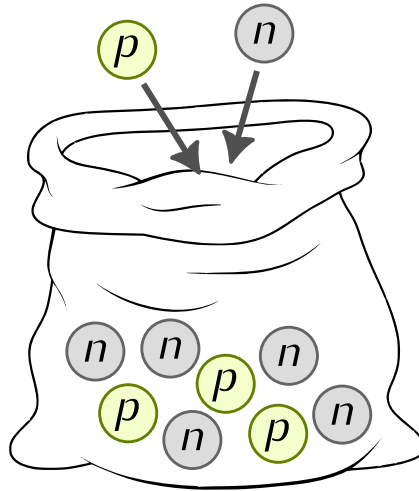
$$\chi^2 = \sum_{ij}^N (D_i - T_i) (C^{-1})_{ij} (D_j - T_j)$$

^aCalculable in lattice QCD in near future?

^bNNPDF collaboration use NN to avoid parametrization bias.

Nuclear Parton Distribution Functions (nPDFs)

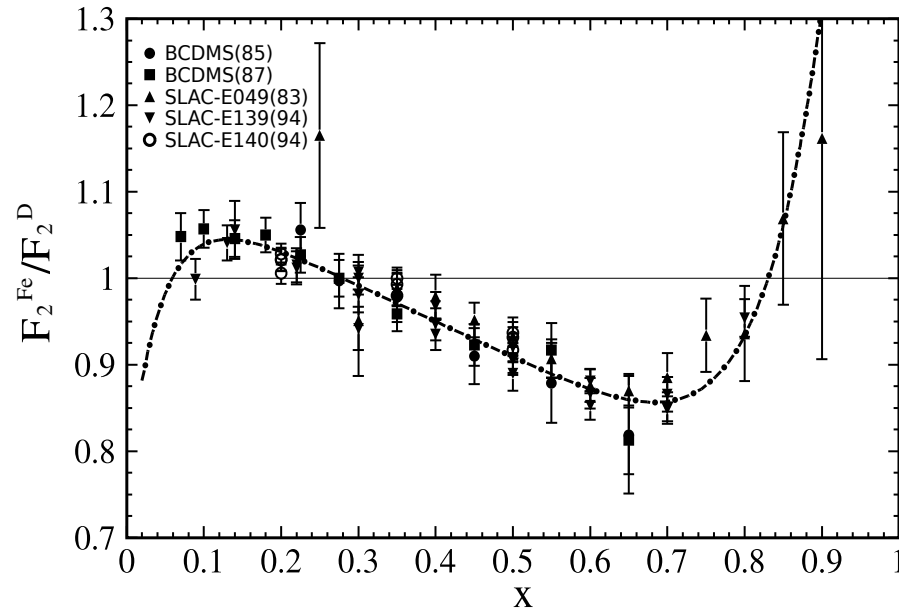
- Free nucleon approximation:



$$Af^A(x, \mu) \stackrel{?}{=} Zf^p(x, \mu) + Nf^n(x, \mu)$$

Nuclear Parton Distribution Functions (nPDFs)

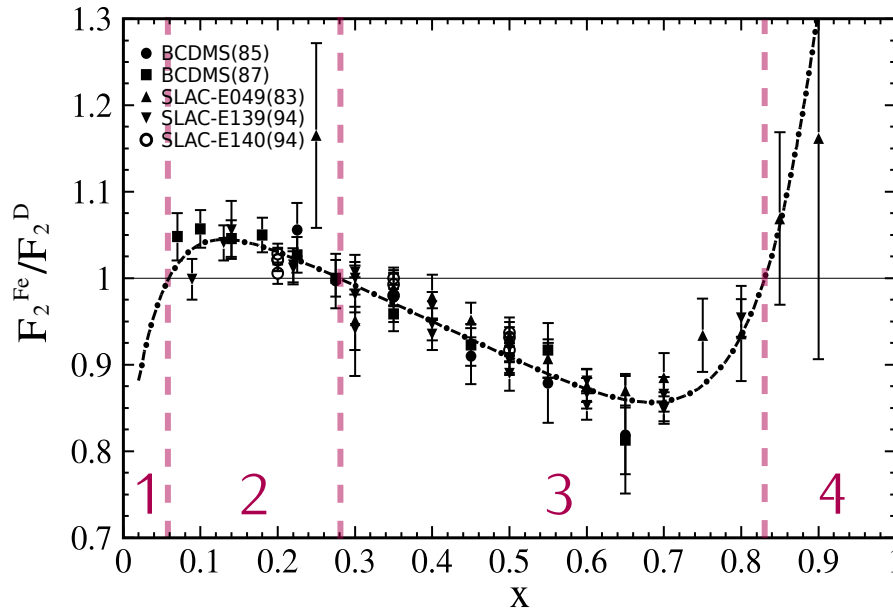
- Nuclear modification:



$$Af^A(x, \mu) \neq Zf^p(x, \mu) + Nf^n(x, \mu)$$

Nuclear Parton Distribution Functions (nPDFs)

- Nuclear modification:

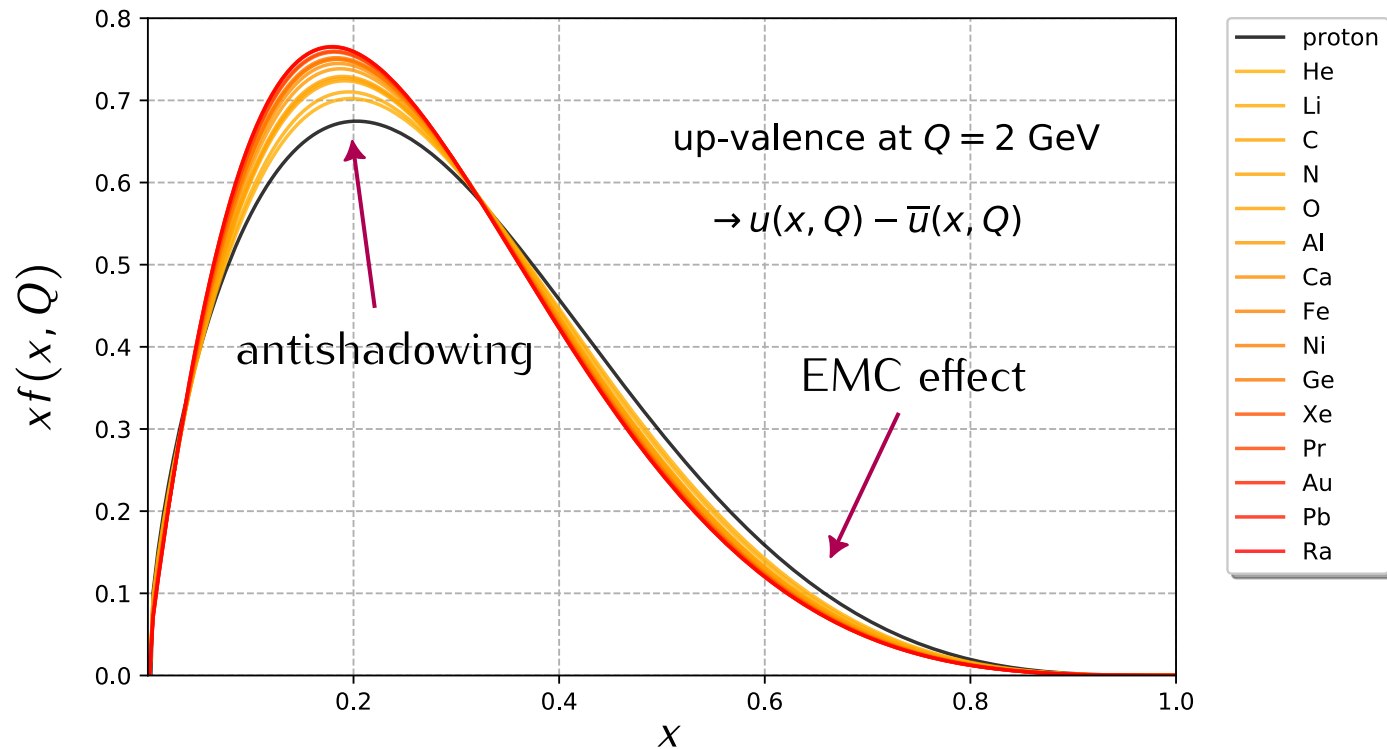


- ▶ 1 shadowing
- ▶ 2 anti-shadowing
- ▶ 3 EMC effect
- ▶ 4 Fermi motion

- ▶ Underlying dynamics still to be fully theoretically understood
- ▶ Can be parametrized and incorporated into nPDF fits

Nuclear Parton Distribution Functions (nPDFs)

- Nuclear modification:



Nuclear Parton Distribution Functions (nPDFs)

- Nuclear modification can be incorporated into the PDF framework:
 - ▶ Introduce the notion of bound proton PDF for flavour i : $f_i^{p/A}(x, \mu, A)$
 - ▶ $x \in (0, A)$, but $x > 1$ region typically negligible
 - ▶ $f_i^{p/A}$ fulfils the usual evolution equations and sum rules
 - ▶ $f_i^{n/A}$ from isospin symmetry, i.e. $f_{d,u}^{n/A} = f_{u,d}^{p/A}$

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

- ▶ $f_i^{(A,Z)}$ replaces f_i^p in the factorization formula^a

^aProof of factorization for collisions of nuclei not yet available.

Global analyses of nPDFs

● EPPS

- EKS98: [hep-ph/9807297](#)
- EKPS07: [hep-ph/0703104](#)
- EPS08: [0802.0139](#)
- EPS09: [0902.4154](#)
- EPPS16: [1612.05741](#)
- EPPS21: [2112.12462](#)

● nNNPDF

- nNNPDF1.0: [1904.00018](#)
- nNNPDF2.0: [2006.14629](#)
- nNNPDF3.0: [2201.12363](#)

● nCTEQ

- nCTEQ09: [0907.2357](#)
- nCTEQ15: [1509.00792](#)
- nCTEQ15WZ: [2007.09100](#)
- nCTEQ15HiX: [2012.11566](#)
- nCTEQ15WZSIH: [2105.09873](#)
- nCTEQ15HQ: [2204.09982](#)
- nCTEQ15WZSIHdeut: [2204.13157](#)
- BaseDimuChorus: [2204.13157](#)

● TUJU

- TUJU19: [1908.03355](#)
- TUJU21: [2112.11904](#)

● KA

- KA15: [1601.00939](#)
- KSASG20: [2010.00555](#)

● nDS

- nDS03: [hep-ph/0311227](#)
- DSSZ12: [1112.6324](#)

● HKM/HKN

- HKM01: [hep-ph/0103208](#)
- HKN04: [hep-ph/0404093](#)
- HKN07: [0709.3038](#)

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Global analyses of nPDFs

Extract from a table by P. Paakinen

	KSASG	nCTEQ	TUJU	EPPS	nNNPDF
Order in α	NLO & NNLO	NLO	NLO & NNLO	NLO	NLO
Error analysis	Hessian	Hessian	Hessian	Hessian	Monte Carlo
Free-proton PDFs	CT18	\sim CTEQ6M	own fit	CT18A	\sim NNPDF4.0
HQ treatment	FONLL	S-ACOT	FONLL	S-ACOT	FONLL

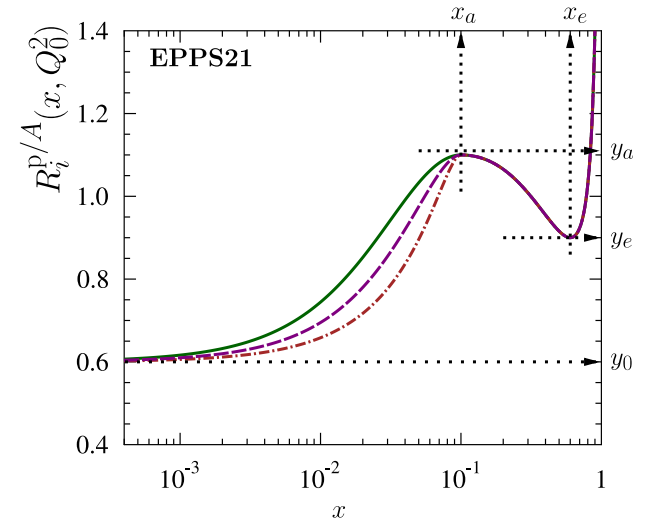
- Have in common: collinear factorisation, DGLAG evolution, sum rules, pQCD observables*, χ^2 minimization, isospin symmetry, $x > 1$ region neglected, ...
- Differ in:
 - ▶ **Parametrization:** R vs. f^A ; proton baseline; functional form vs. neural nets
 - ▶ **Data selection:** processes; cuts; correlations; normalisations
 - ▶ **Error analysis:** Hessian vs. monte carlo replicas; $\Delta\chi^2$ tolerance; **proton baseline uncertainties**
 - ▶ **Other:** inputs (m_c , m_b , $\alpha_S(M_Z)$, ...); heavy flavour scheme; deuteron treatment; target mass corrections; **perturbative order**; ...

Global analyses of nPDFs

- Perturbative order:
 - ▶ Protons: wealth of Hera, LHC pp data → 1% accuracy, need NNLO
 - ▶ Nuclei: mostly FT, some LHC pA → 10% accuracy, NLO sufficient
- Parametrization: ideally, results should be independent of it
 - ▶ EPPS: nuclear modification ratio; A , x dependence mixing marginal

$$R_i^A(x, Q_0^2) = \begin{cases} a_0 + a_1(x - x_a) \left[e^{-x a_2/x_a} - e^{-a_2} \right], & x \leq x_a \\ b_0 x^{b_1} (1-x)^{b_2} e^{x b_3}, & x_a \leq x \leq x_e \\ c_0 + c_1(c_2 - x)(1-x)^{-\beta}, & x_e \leq x \leq 1 \end{cases}$$

$$y_i(A) = 1 + \left[y_i(A_{\text{ref}}) - 1 \right] \left(\frac{A}{A_{\text{ref}}} \right)^{\gamma_i}$$



Adapted from a figure by EPPS

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 - ▶ nNNPDF: nuclear PDF, NN parametrization; A, x dependence mix

$$xF(x, Q_0) = \mathcal{N}_F x^{\alpha_F} (1-x)^{\beta_F} \text{NN}_F(x, A)$$

$$F \in \{\Sigma^{(p/A)}, T_3^{(p/A)}, T_8^{(p/A)}, V^{(p/A)}, V_3^{(p/A)}, g^{(p/A)}\}$$

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 - ▶ KSASG, TUJU, nCTEQ: nuclear PDF, traditional parametrization; A , x mix

e.g. in nCTEQ15

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5}$$
$$c_k \rightarrow c_k(A) \equiv p_k + a_k (1 - A^{-b_k})$$

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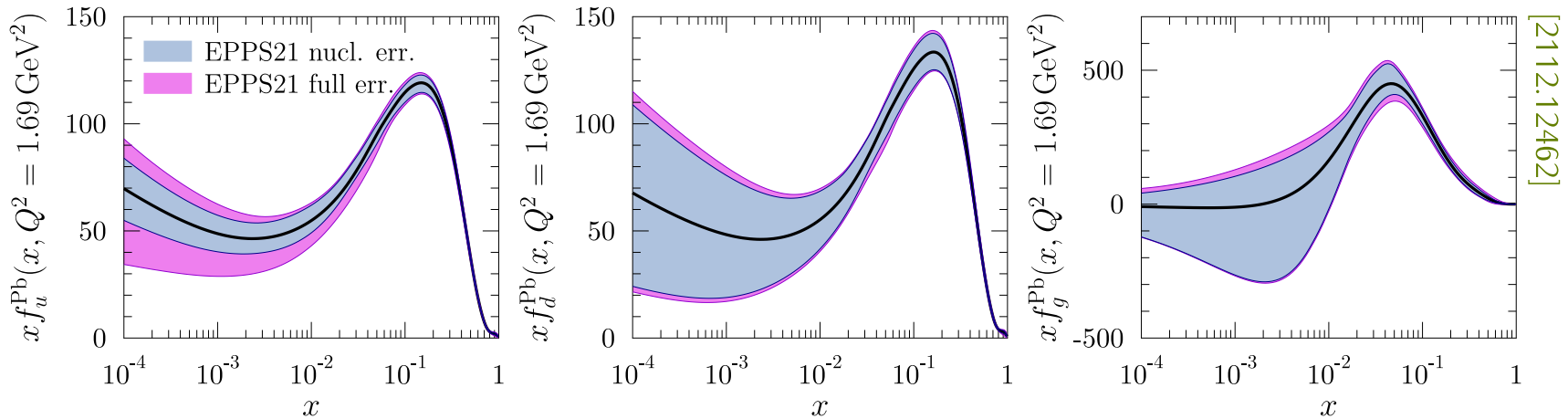
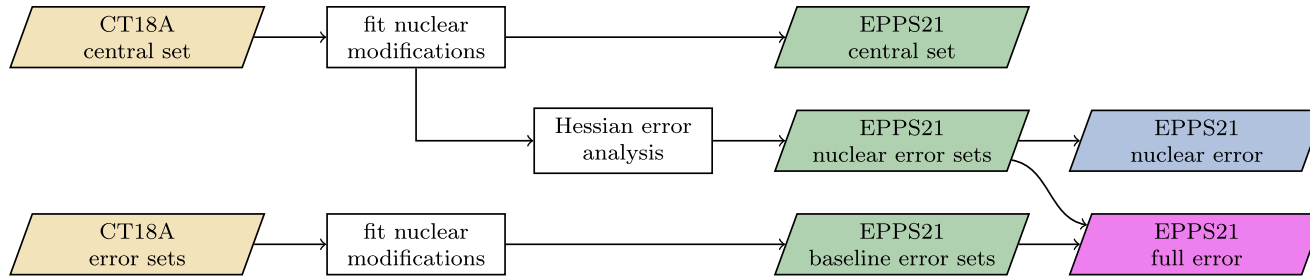
nCTEQ in parallel develops a framework which A and x dependences strictly factorize. See slides of A. Kusina from Wednesday!

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 - ▶ EPPS developed a prescription on how to take them into account

Global analyses of nPDFs

- Proton baseline uncertainties in EPPS:

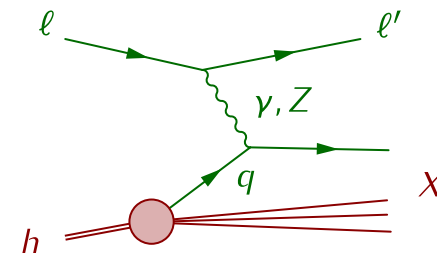


Global analyses of nPDFs

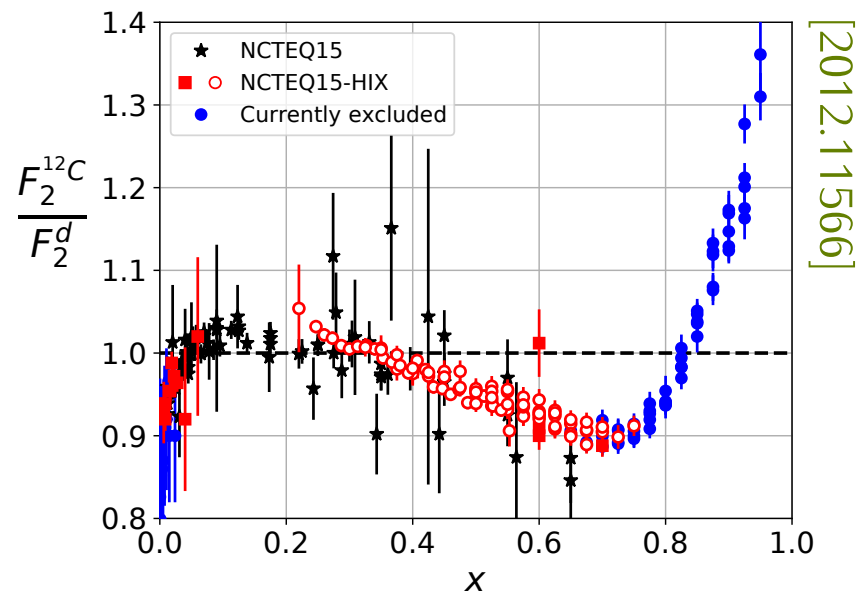
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- Data selection: guiding theme of the remainder of this talk

Data: Neutral current DIS

	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15HIX
NC DIS tot ^a	1274	459	1078	451	1227
JLAB only	199	-	160	-	336



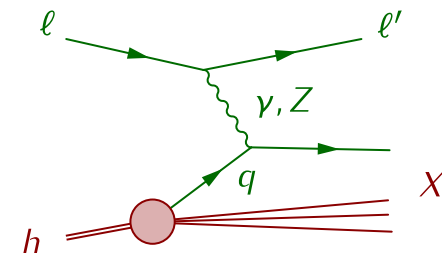
- Traditionally the bulk of data in nPDF analyses
- Constraints valence distributions across a broad x range
- NEW! JLab CLAS and Hall C data
 - ▶ Maps out the high- x EMC region very precisely



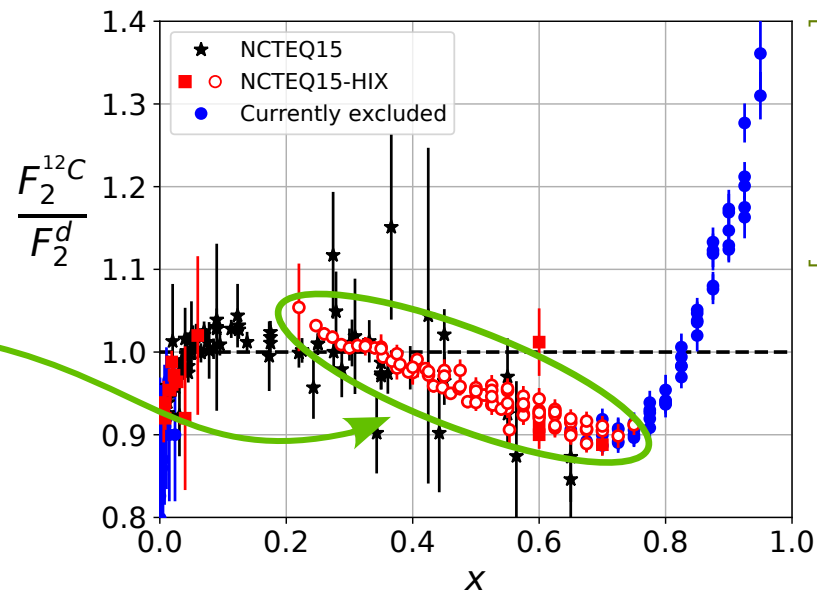
^aDeuteron data excluded.

Data: Neutral current DIS

	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15HIX
NC DIS tot ^a	1274	459	1078	451	1227
JLAB only	199	-	160	-	336

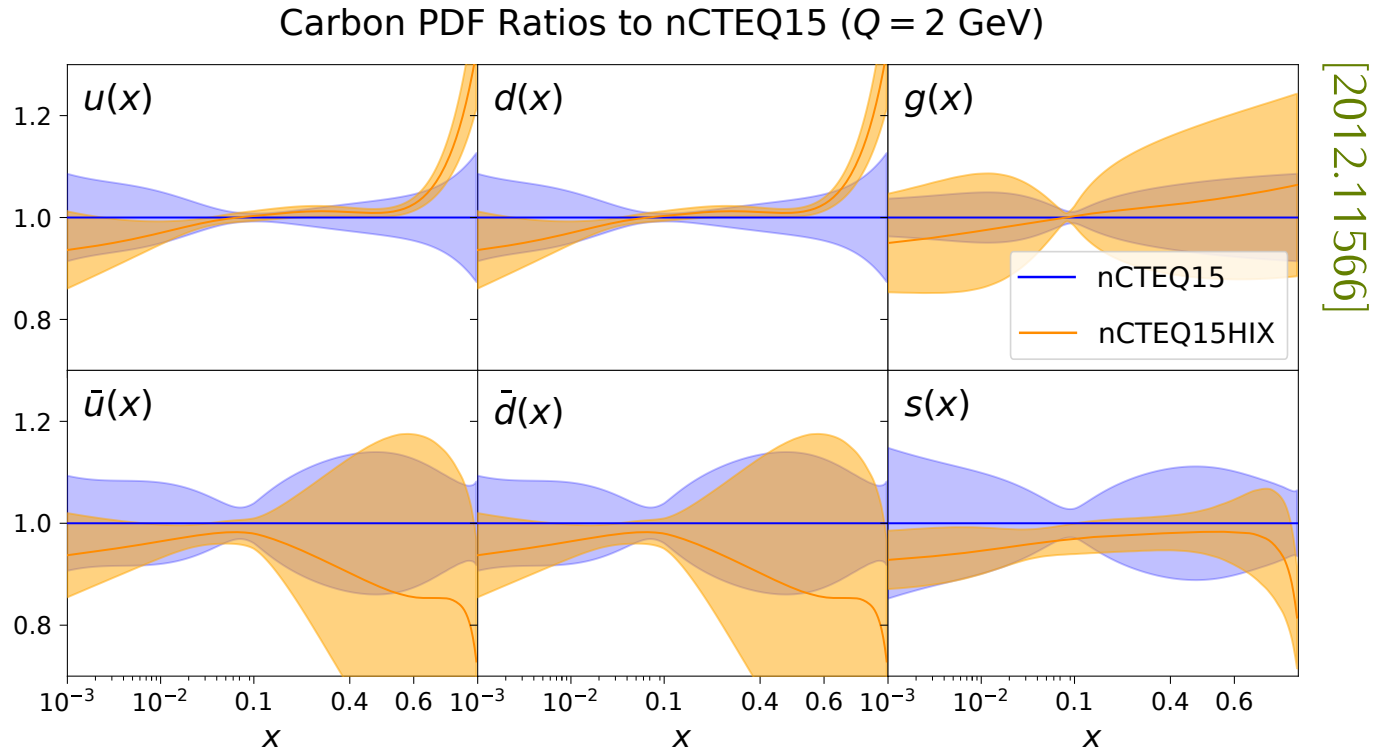


- Traditionally the bulk of data in nPDF analyses
- Constraints valence distributions across a broad x range
- NEW! JLab CLAS and Hall C data
 - ▶ Maps out the high- x EMC region very precisely



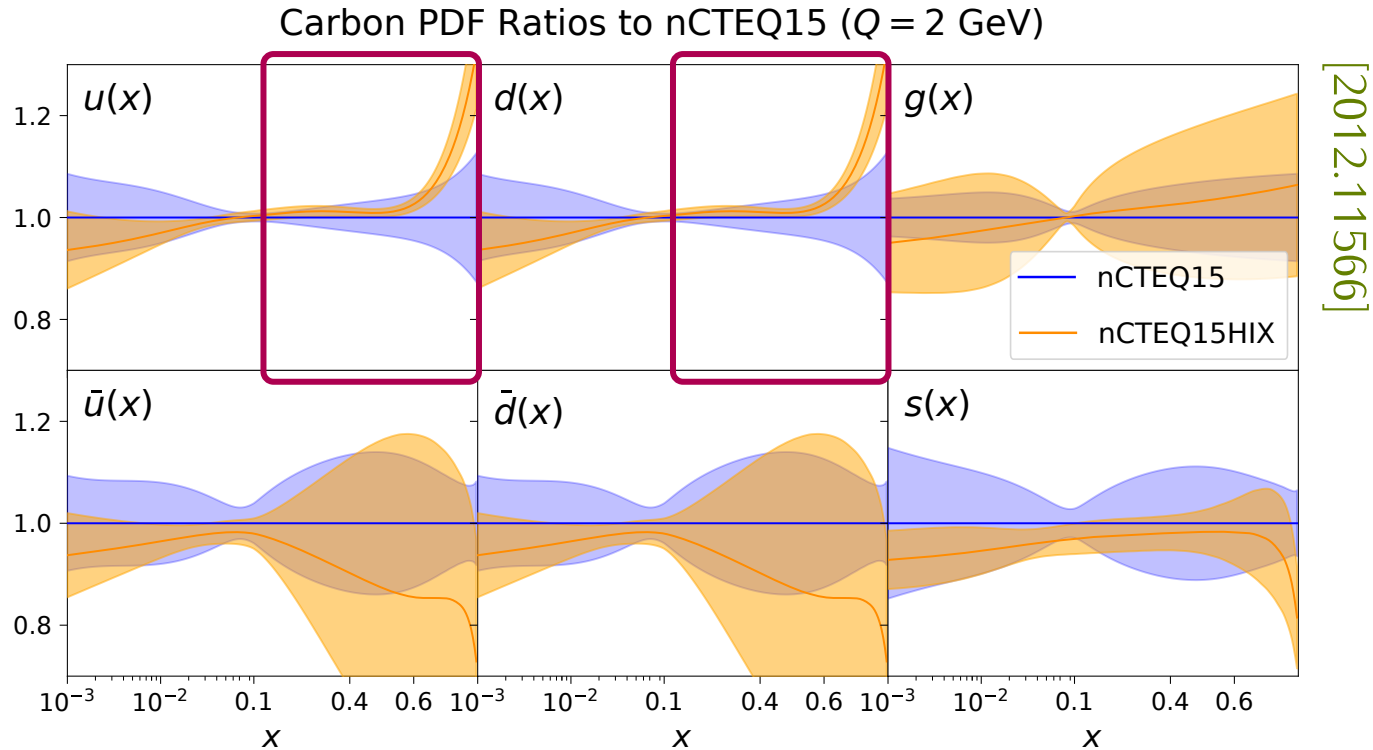
^aDeuteron data excluded.

Data: Neutral current DIS



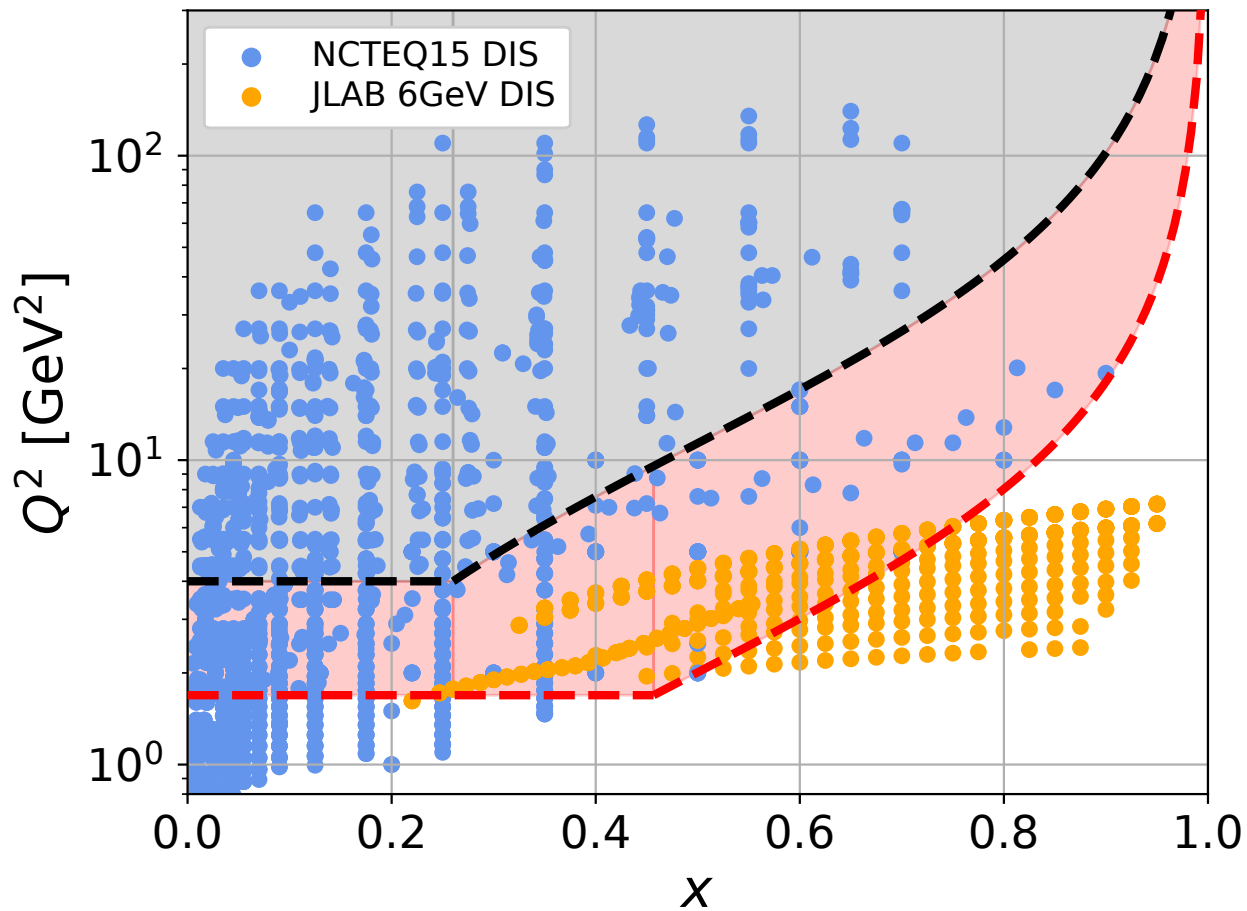
- Valence quark uncertainties strongly reduced!

Data: Neutral current DIS



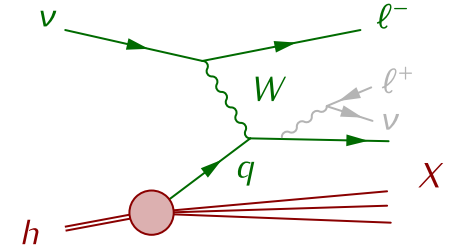
- Valence quark uncertainties strongly reduced!

Data: Neutral current DIS



Data: Charged current DIS

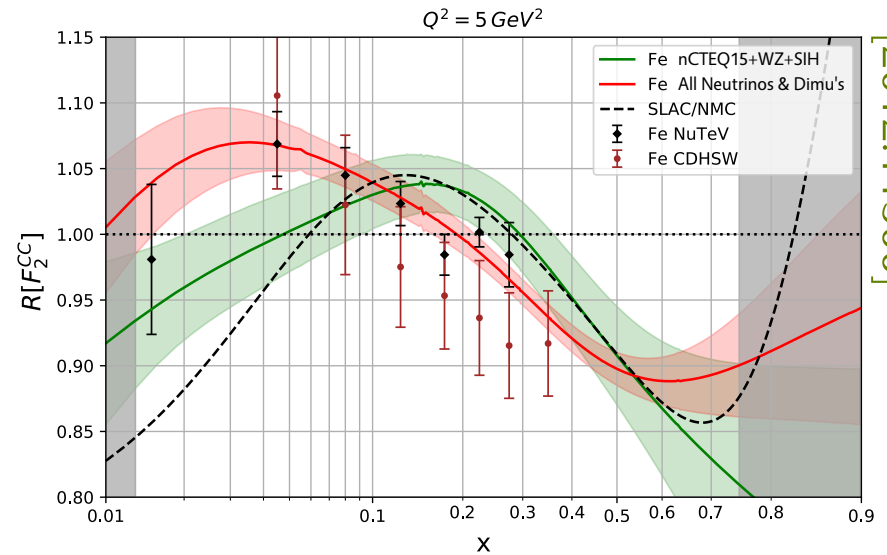
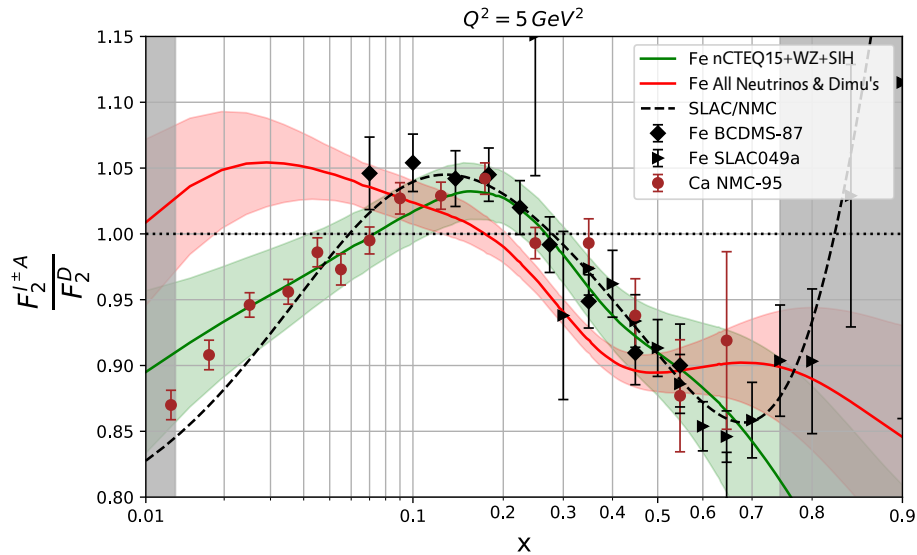
	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15BDC ^a
CC DIS	2458	1736	824	922	974
di-muon only	-	-	-	76	150



- Important for flavour separation
- Constrains strange distribution
- Remarkably abundant and precise, but not universally included
 - ▶ Chorus (824 pts): mostly included
 - ▶ CDHSW (930 pts): sometimes included
 - ▶ CCFR & NuTeV (4343 pts): mostly excluded

^anCTEQ15BaseDimuChorus

Data: Charged current DIS

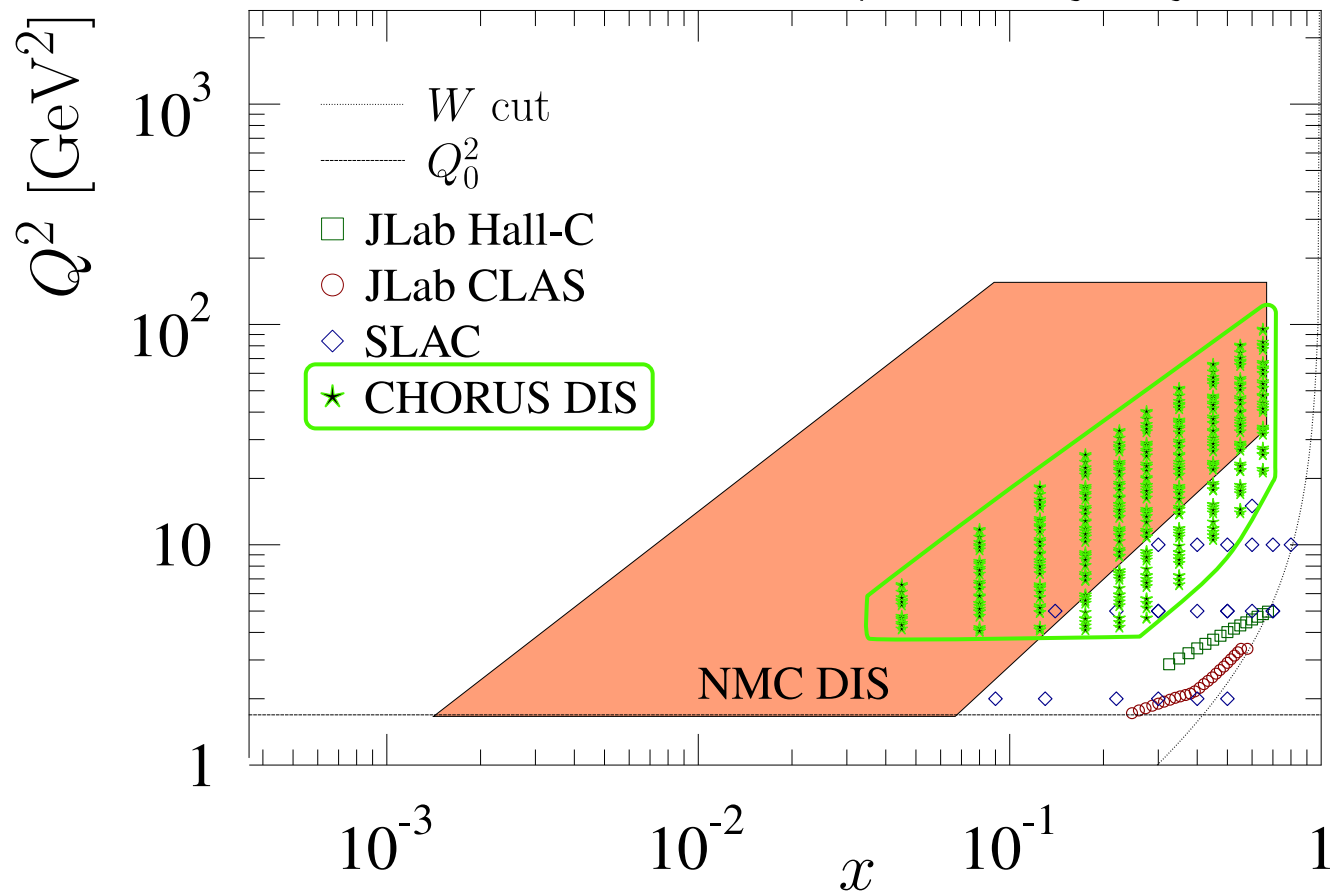


[2012.11566]

- Nutev, CCFR and CDHSW data in tension with NC DIS data. Dropping correlations alleviates the tension but doesn't resolve it.

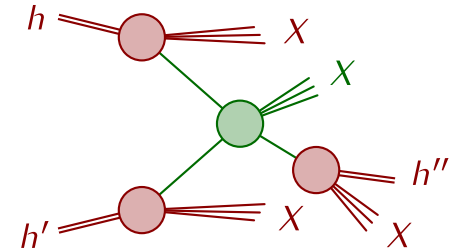
Data: Charged current DIS

Adapted from a figure by EPPS21



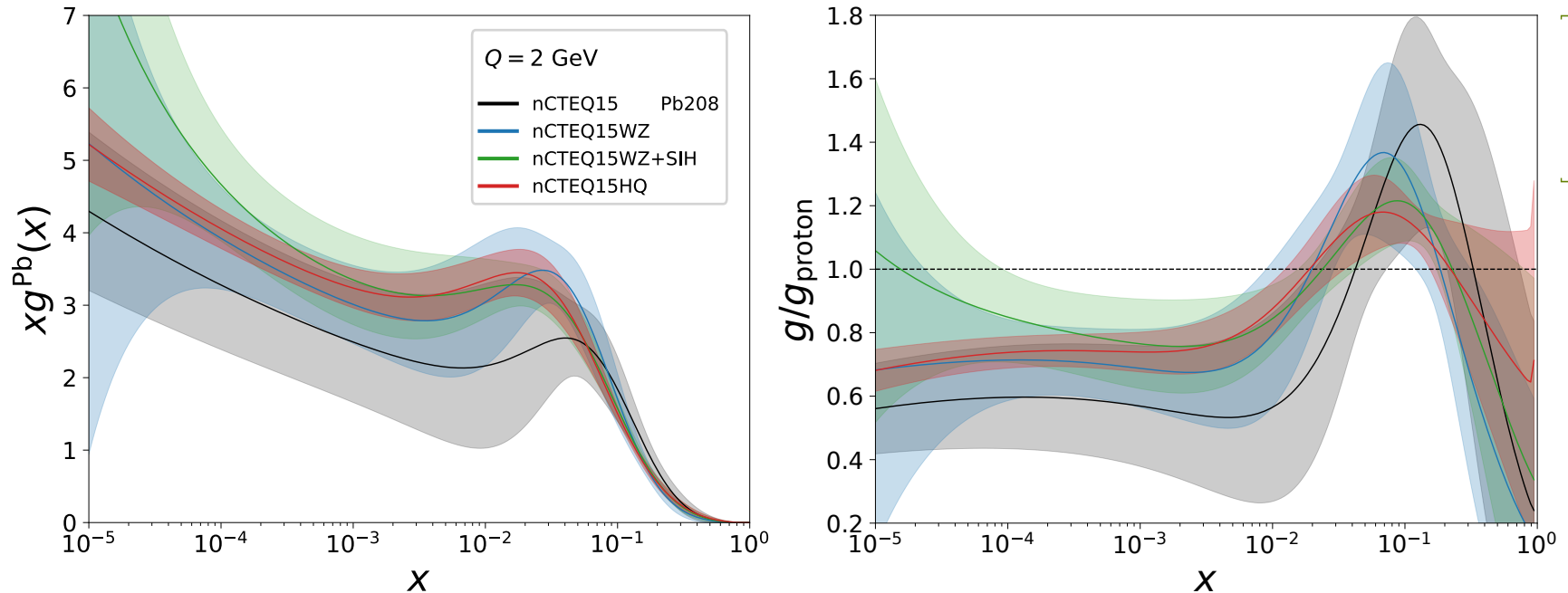
Data: Heavy quark production

	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15HQ
open HF	-	-	48	37	82
quarkonia	-	-	-	-	466



- Unprecedented low x reach
- Two very different production modes
 - ▶ Open heavy flavour production: D
 - ▶ Quarkonia production: $J/\psi, \Upsilon(1S), \psi(2S)$
- EPPS: only open HF, pQCD prediction with fragmentation
- nNNPDF: only open HF, pQCD prediction with GPMC hadronization
- nCTEQ: open HF and quarkonia, data driven approach based on a ME fit

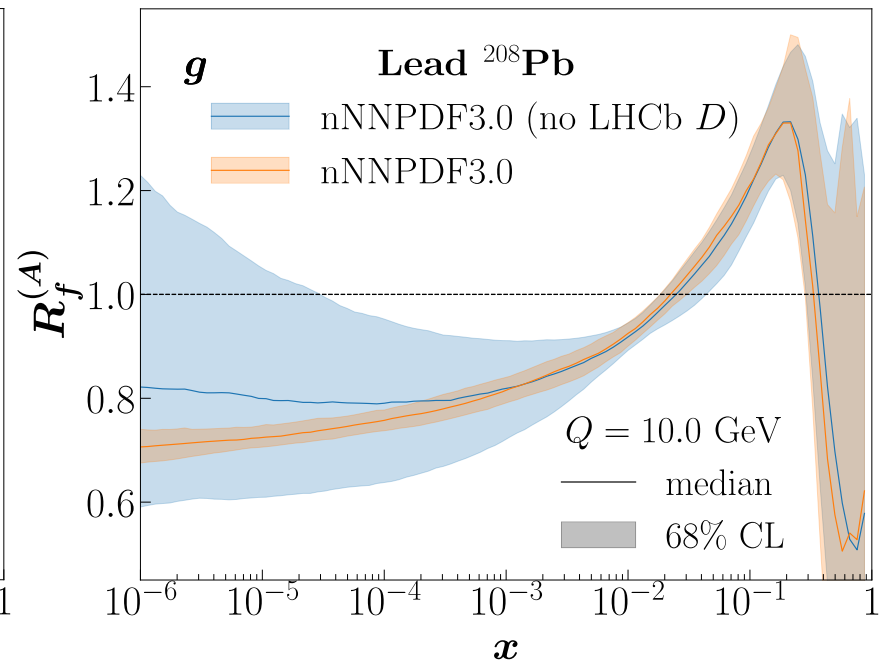
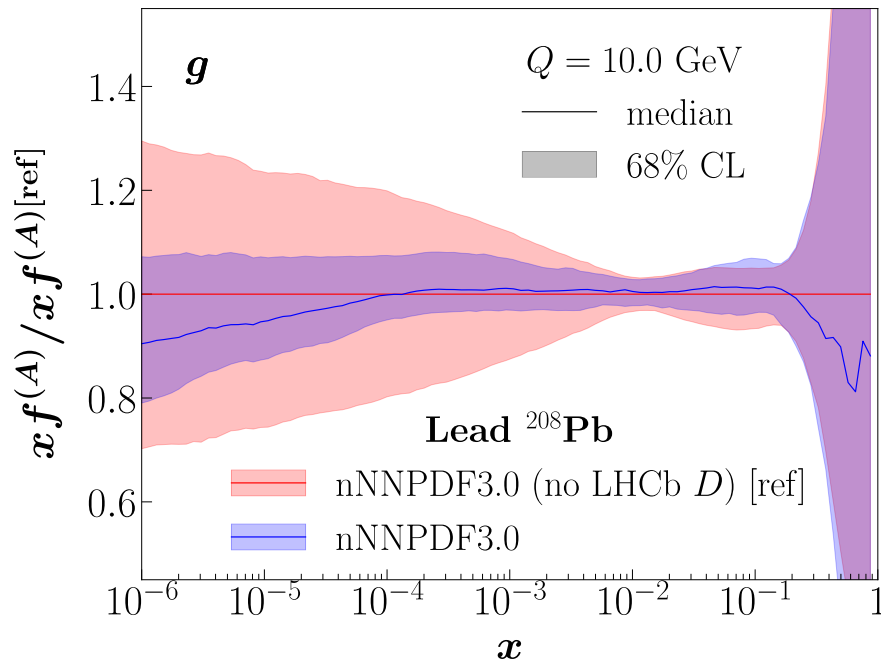
Data: Heavy quark production



[2204.09982]

- Impressive reduction of uncertainties down to $x \sim 10^{-5}$

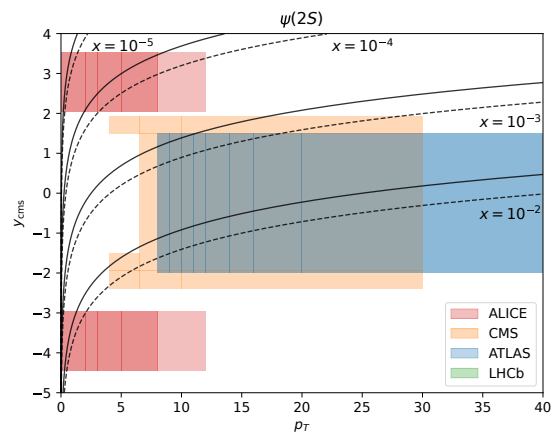
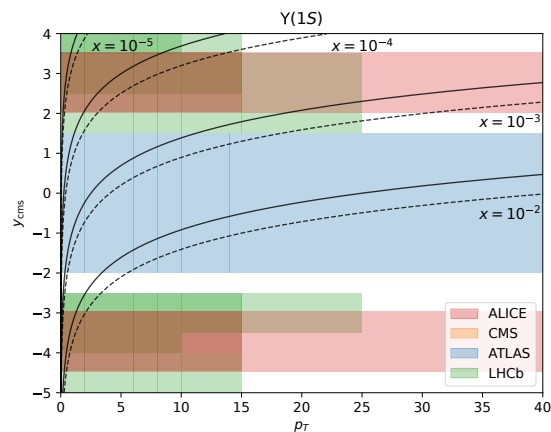
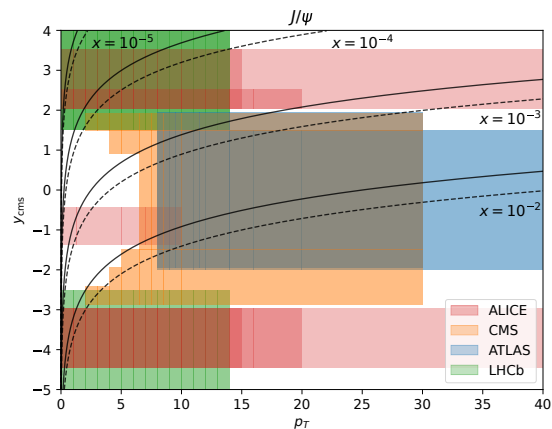
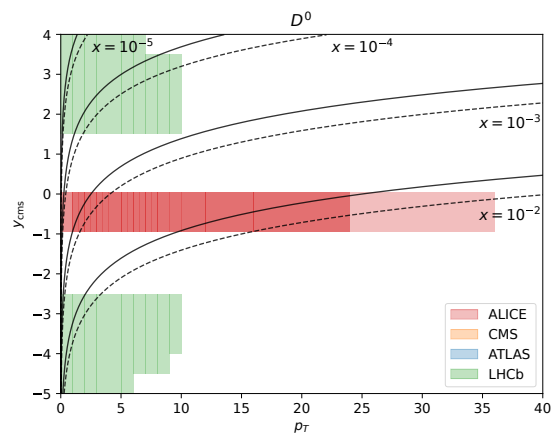
Data: Heavy quark production



[2201.12363]

- Impressive reduction of uncertainties down to $x \sim 10^{-6}$

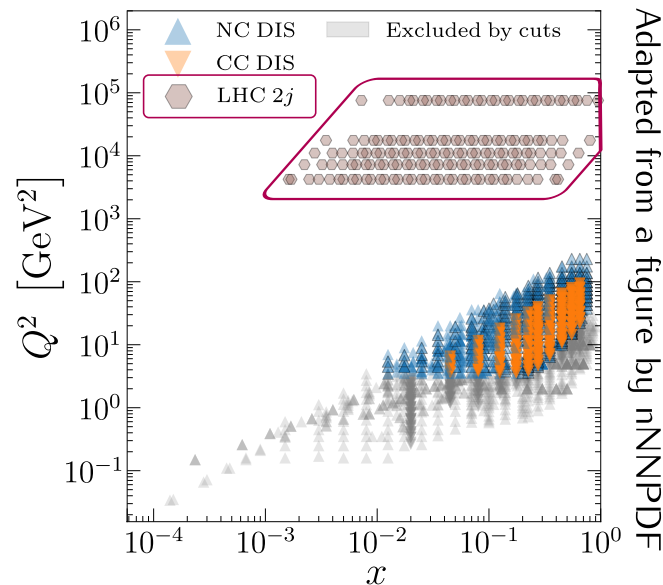
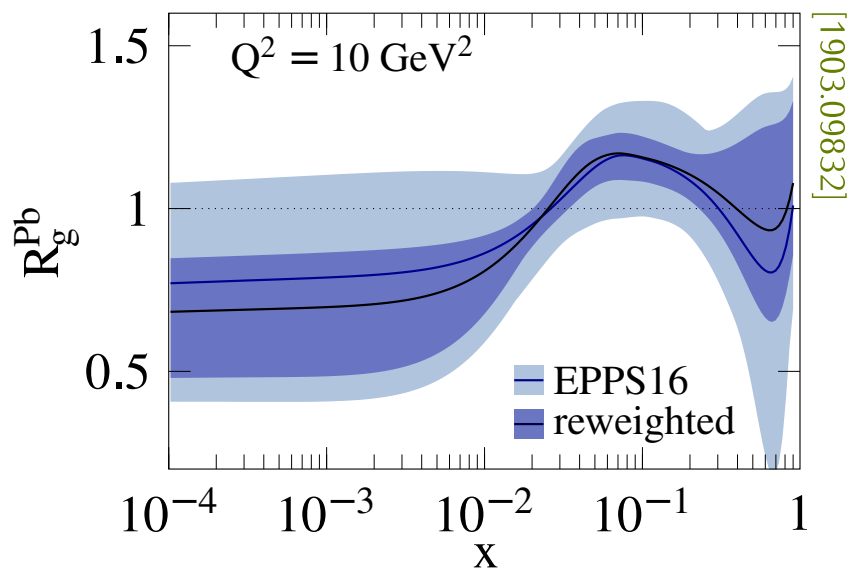
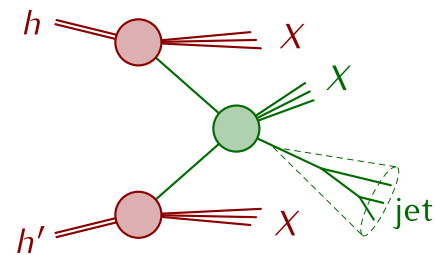
Data: Heavy quark production



Data: Jet production

	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15HQ
dijet	-	-	83	84	-

- Great potential to constrain gluon distribution at low x



Adapted from a figure by nNNPDF

Data: Jet production

- pPb/pp ratios described well

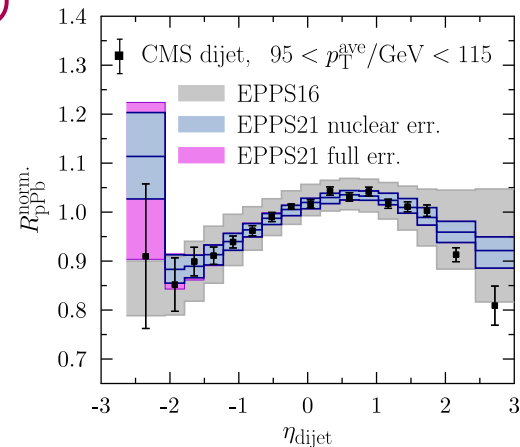
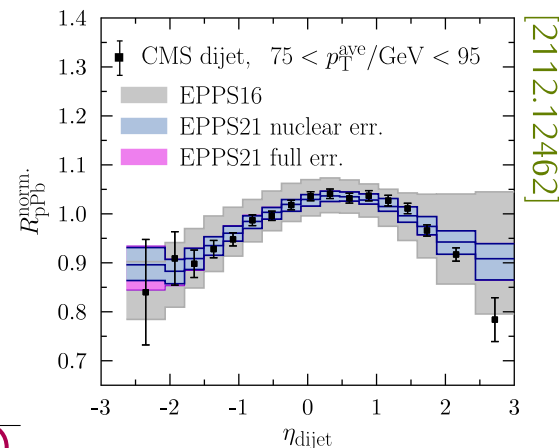
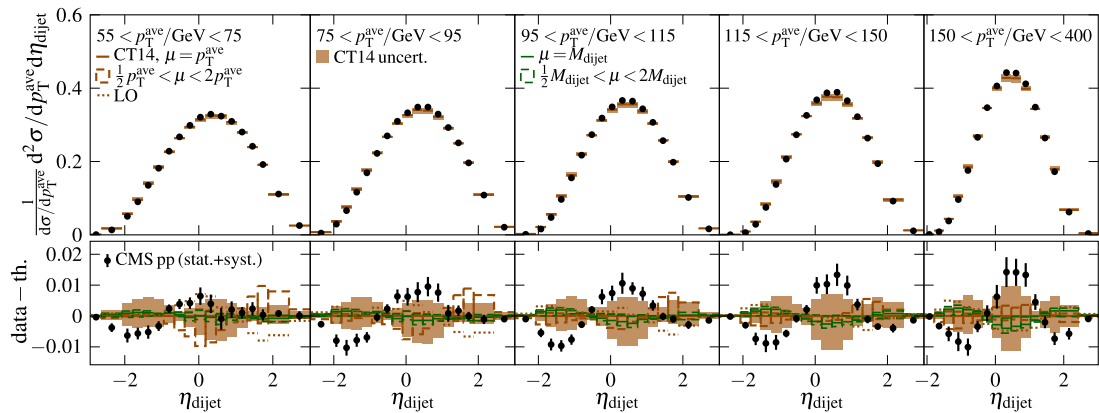
Experiment	Observable	Collisions	Data points	χ^2
CERN CMS	dijet	pPb(208)	83	123.81

▶ EPPS:

Dataset	n_{dat}	χ^2/n_{dat}
CMS dijet pPb/pp $\sqrt{s} = 5.02$ TeV	84	1.75

▶ nNNPDF:

- Not pp, pPb separately
- | Dataset | n_{dat} | χ^2/n_{dat} |
|-------------------------------------|------------------|-------------------------|
| CMS dijet pPb $\sqrt{s} = 5.02$ TeV | 85 | [13.96] |



Data: Jet production

- pPb/pp ratios described well

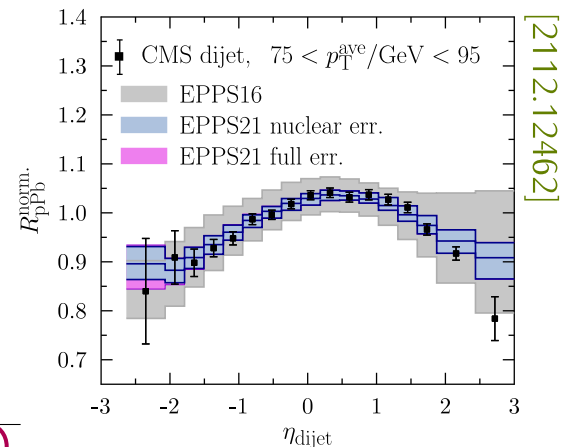
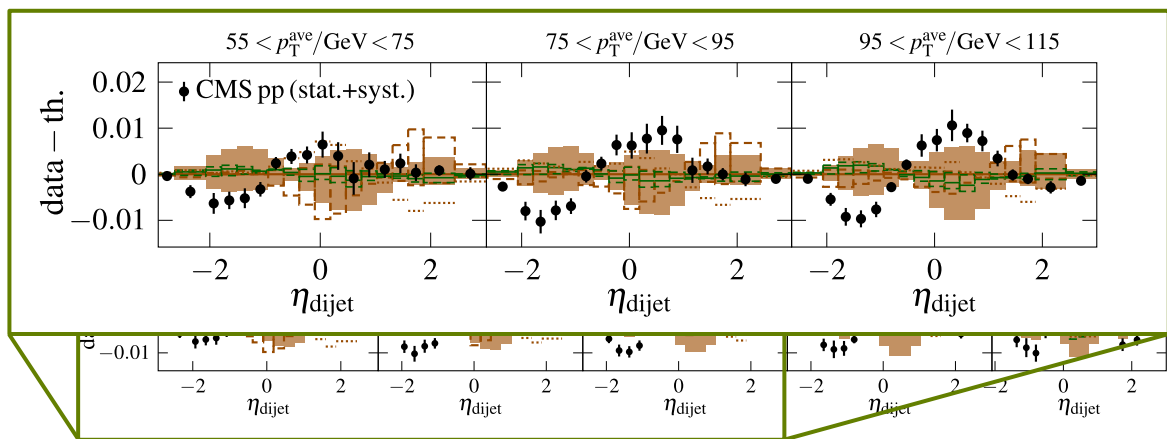
Experiment	Observable	Collisions	Data points	χ^2
CERN CMS	dijet	pPb(208)	83	123.81

► EPPS:

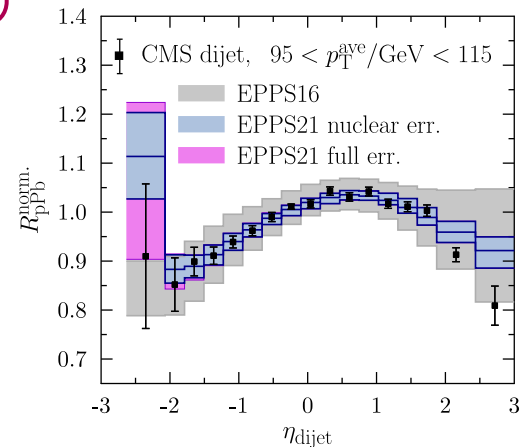
Dataset	n_{dat}	χ^2/n_{dat}
CMS dijet pPb/pp $\sqrt{s} = 5.02$ TeV	84	1.75

► nNNPDF:

- Not pp, pPb separately
- | Dataset | n_{dat} | χ^2/n_{dat} |
|-------------------------------------|------------------|-------------------------|
| CMS dijet pPb $\sqrt{s} = 5.02$ TeV | 85 | [13.96] |



[2112.12462]

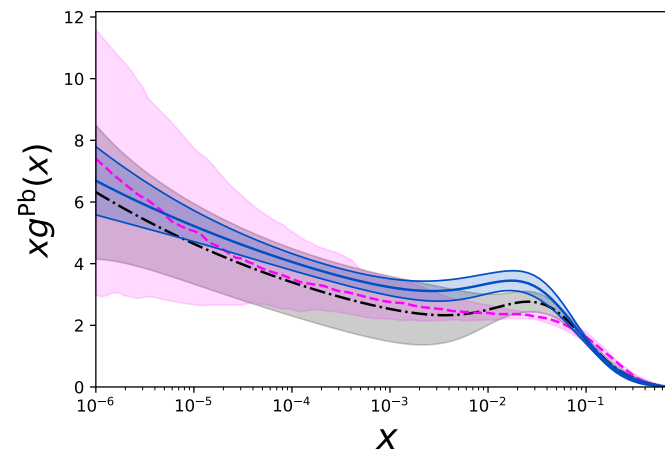
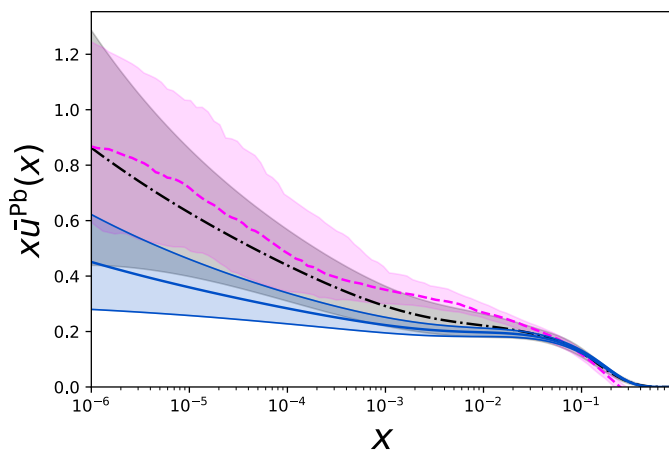
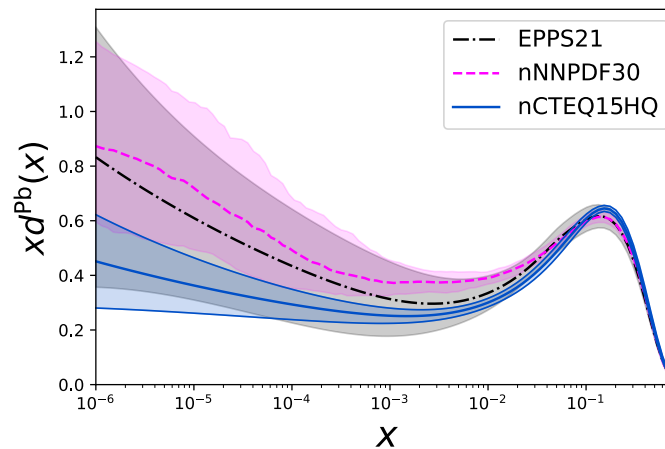
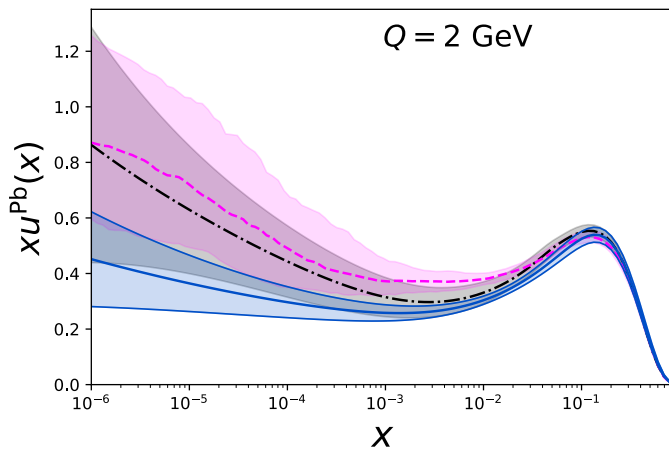


[1903.09832]

Data: not covered today

- Fixed Target DY ($n_{\text{dat}} \sim 100$) and LHC W, Z ($n_{\text{dat}} \sim 150$) production
 - ▶ Important for strange distribution, also constrains gluon
 - ▶ Included in most analyses
- Single inclusive light flavours ($n_{\text{dat}} \sim 300$)
 - ▶ Gluon dominated at LHC
 - ▶ Almost 2/3 points in a very low p_T difficult to describe
 - ▶ Analysed by nCTEQ and also partly by EPPS
- Direct photon production ($n_{\text{dat}} \sim 50$)
 - ▶ Should provide extra handle on gluon
 - ▶ pPb/pp ratio described well, absolute pPb no that well
 - ▶ Included so far only in nNNPDF

Comparison of nPDFs



Summary and outlook

- I reviewed:
 - ▶ The frameworks used in most recent global analyses of nPDFs
 - ▶ Status on data inclusion
- New developments in the last ~two years:
 - ▶ Relaxed cuts (EPPS, KSASG, nCTEQ)
 - ▶ NC DIS: New JLAB CLASS and Hall-C data (EPPS, KSASG, nCTEQ)
 - ▶ CC DIS: Reanalysis confirms unreconcilable tension (nCTEQ)
 - ▶ New processes useful for gluon and low x :
 - ▷ Heavy quarks (EPPS, nCTEQ, nNNPDF)
 - ▷ Dijets (EPPS, nNNPDF)
 - ▷ Direct photons (nNNPDF)
- Personal wish list: (di-)jets, direct photons, $t\bar{t}$, low mass DY/W/Z, light hadrons
- Overall: nPDF extraction is a very active field with a rich future ahead