Universität Münster

isoQuant SFB1225

nCTEQ
nuclear parton distribution functions

Nuclear PDF updates from nCTEQ

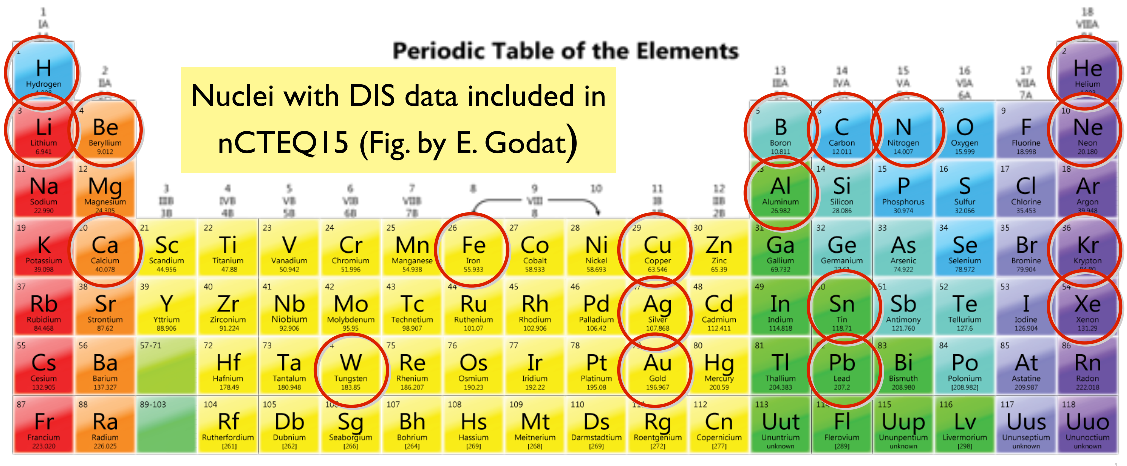
Tomáš Ježo
nCTEQ collaboration
ITP, University of Münster
SFB 1225 isoQuant

Forward Physics and QCD at the LHC and EIC
23 - 27. Oct. 2023

WILHELM UND ELSE HERAEUS-STIFTUNG

living.knowledge

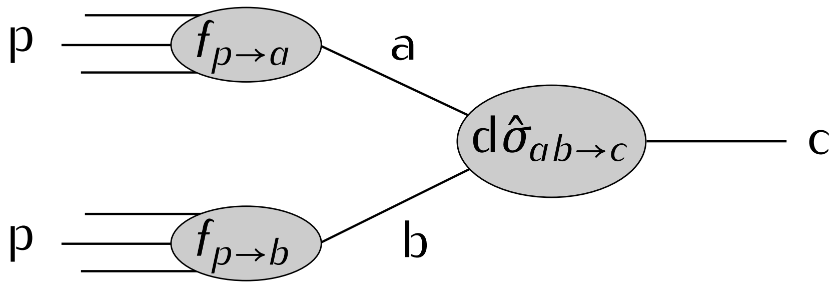
Nuclear structure at high energies



- 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 → Quark-gluon plasma

Theoretical famework

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



- Or in formula, in the collinear factorization framework:

$$\mathrm{d}\sigma_{pp\to c} = \sum_{a,b} f_{p\to a}(x_a,\mu) \otimes f_{p\to b}(x_b,\mu) \otimes \mathrm{d}\hat{\sigma}_{ab\to c}(\mu)$$

$$\mu \gtrsim 1\ \mathrm{GeV}, x \in (0,1)$$

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

Theoretical famework

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

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

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

- Hard cross section $\mathrm{d}\hat{\sigma}_{ab\to c}(\mu)$
  - Process specific
  - Calculable in perturbative QCD (pQCD)

- Parton Distribution Functions (PDFs) $f_{p\to a}(x,\mu)$
  - Universal
  - Not calculable from first principles (not yet)

- Similarly for lp, νp and one-particle inclusive[a] processes

---

[a] Which involve second factorization scale and convolution with fragmentation functions.

Theoretical famework

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

$$\mathrm{d}\sigma_{pp\to c} = \sum_{a,b} f_{p\to a}(x_a,\mu) \otimes f_{p\to b}(x_b,\mu) \otimes \mathrm{d}\hat{\sigma}_{ab\to c}(\mu)$$

$$\mu \gtrsim 1\ \mathrm{GeV}, x \in (0,1)$$

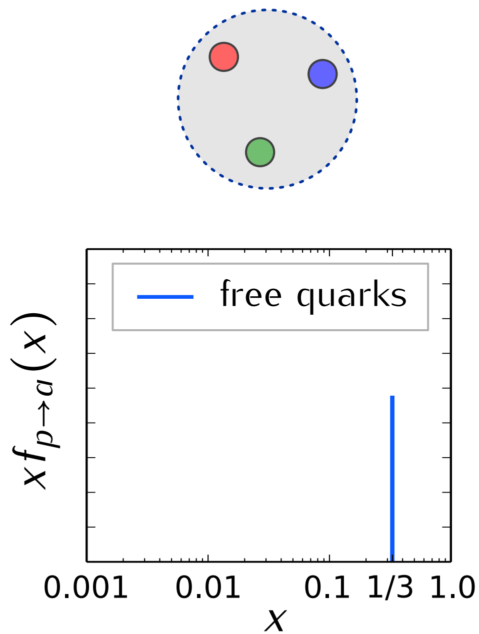
- With μ: factorization scale, x: fraction of parton $a(b)$ momentum in proton p
- Hard cross section $\mathrm{d}\hat{\sigma}_{ab\to c}(\mu)$
  - Process specific
  - Calculable in perturbative QCD (pQCD)
- Parton Distribution Functions (PDFs) $f_{p\to a}(x,\mu)$
  - Universal
  - Not calculable from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

[a] Which involve second factorization scale and convolution with fragmentation functions.

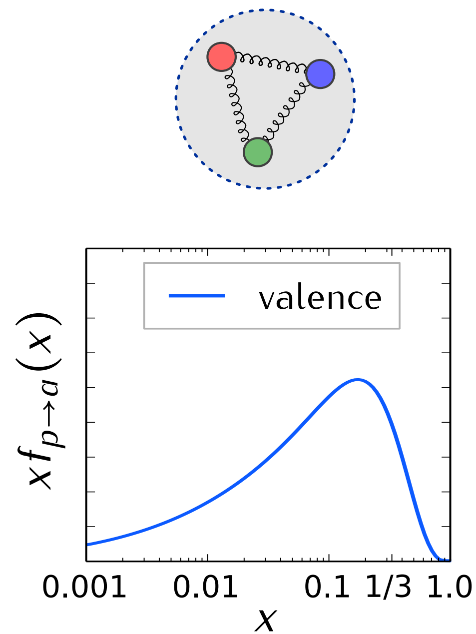
Parton Distribution Functions (PDFs)

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

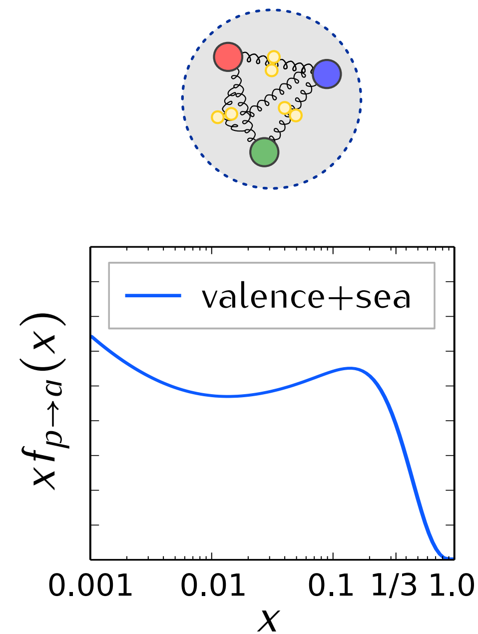
Free partons



Bound partons



Bound partons & QCD effects

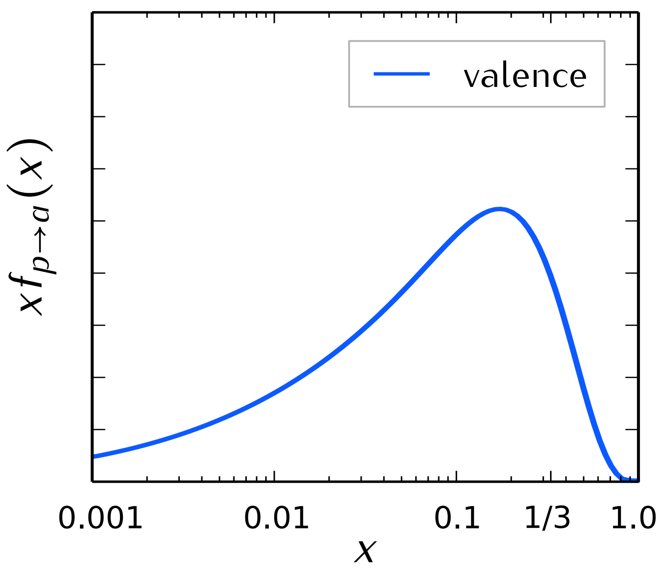


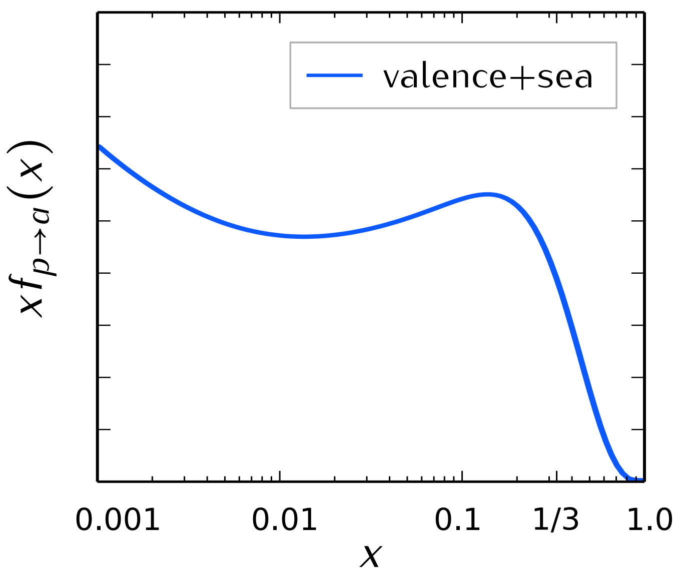
[a] Longitudinal.

Inspired by a slide from P. Risse

Parton Distribution Functions (PDFs)

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

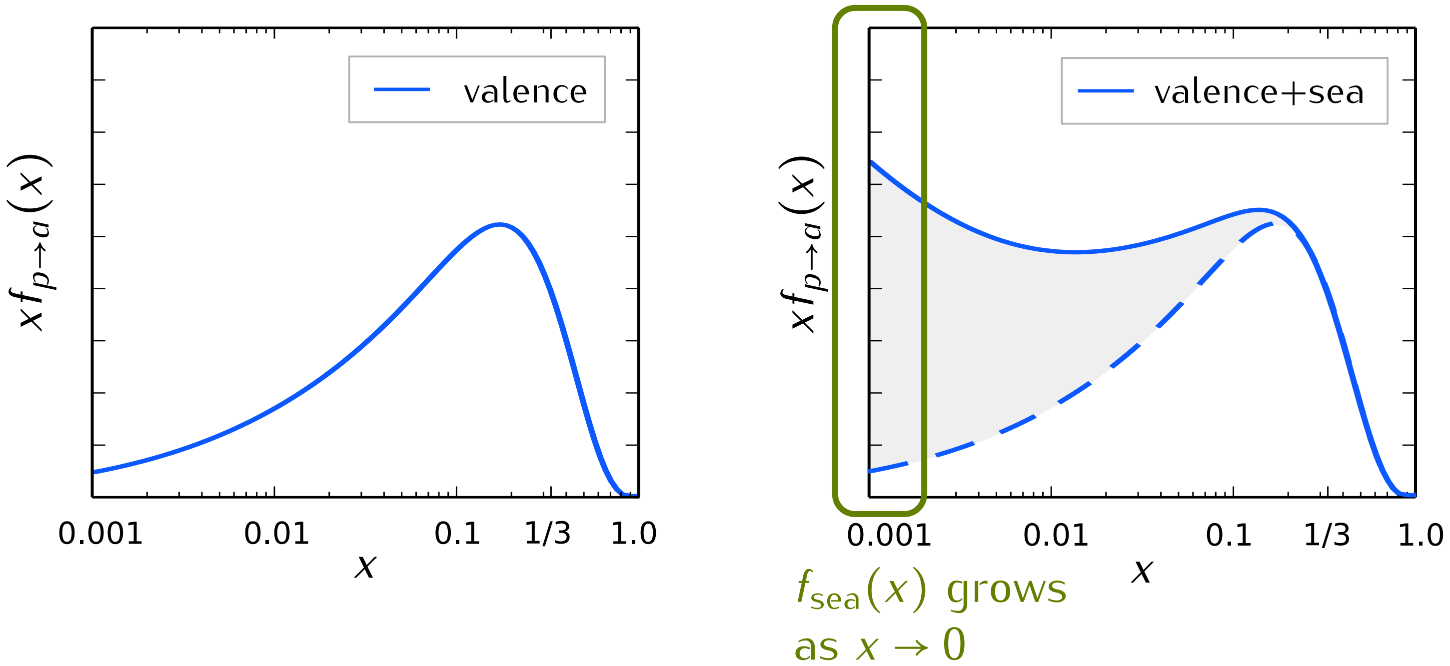




[a] Longitudinal.

Parton Distribution Functions (PDFs)

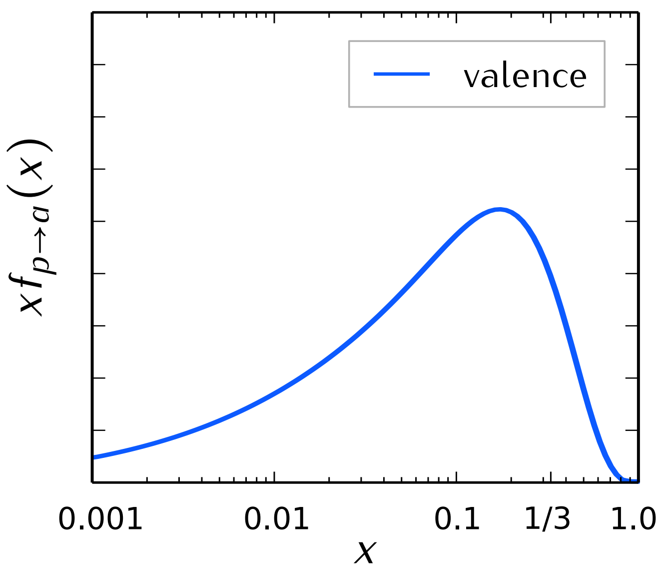
- PDF[$f_{p \to a}(x, \mu)$]: probability that parton a carries fraction[a] x of proton p momentum

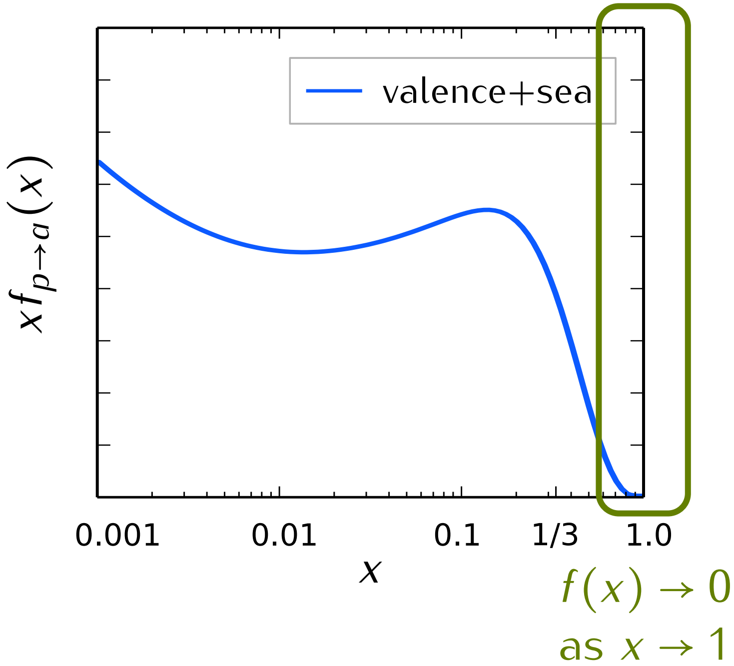


[a] Longitudinal.

Parton Distribution Functions (PDFs)

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





[a] Longitudinal.

Parton Distribution Functions (PDFs)

- Universal: same PDF enters different processes (DIS, DY, SIH, HQ, ...)
- x dependence not calculable in pQCD
  - Constrained through *number*...

$$\int_0^1 dx[\underbrace{f_u(x) - f_{\bar{u}}(x)}_{u-\text{valence distr.}}] = 2 \qquad \int_0^1 dx[\underbrace{f_d(x) - f_{\bar{d}}(x)}_{d-\text{valence distr.}}] = 1$$

$$\int_0^1 dx[f_s(x) - f_{\bar{s}}(x)] = \int_0^1 dx[f_c(x) - f_{\bar{c}}(x)] = 0$$

  - ...and *momentum* sum rules

$$\sum_{i=q,\bar{q},g} \int_0^1 dx\, x f_i(x) = 1$$

- μ dependence governed by DGLAP evolution equations

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

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

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

Parton Distribution Functions (PDFs)

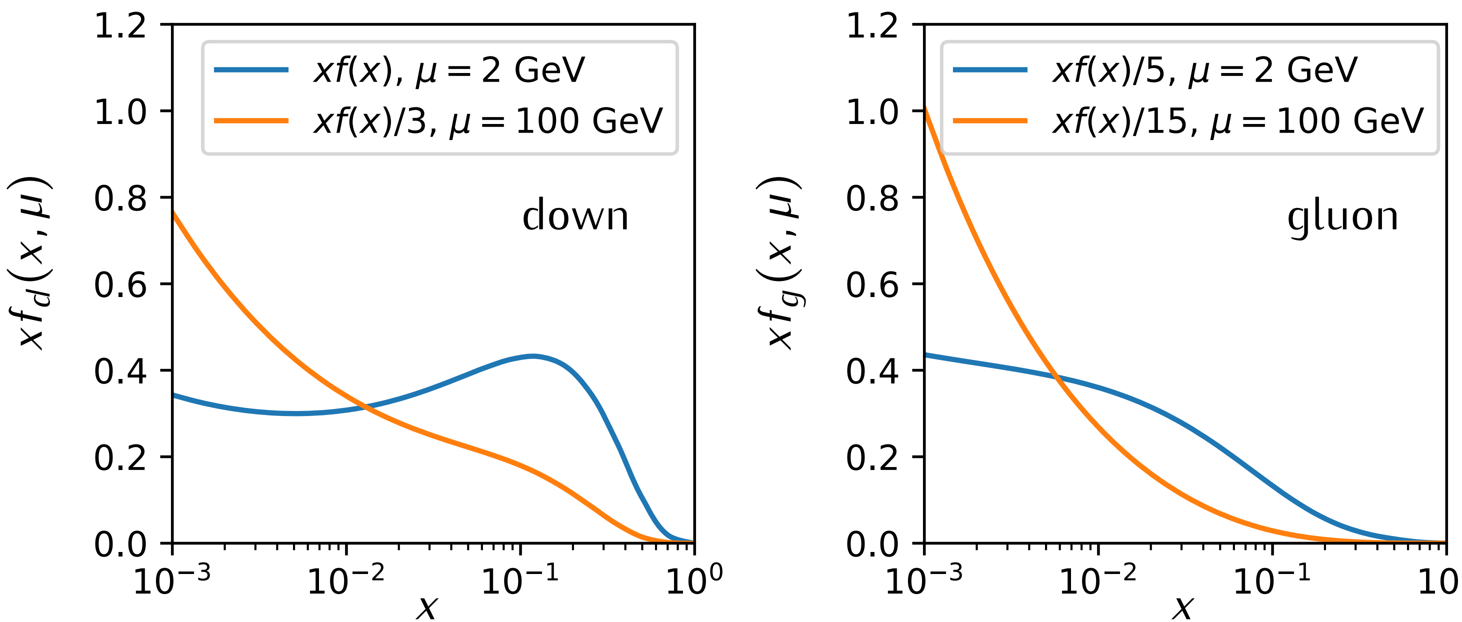
- Universal: same PDF enters different processes (DIS, DY, SIH, HQ, ...)
- x dependence not calculable in pQCD
  - Constrained through number and momentum sum rules
- μ dependence governed by DGLAP evolution equations

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

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

Parton Distribution Functions (PDFs)

- μ dependence governed by DGLAP evolution equations:



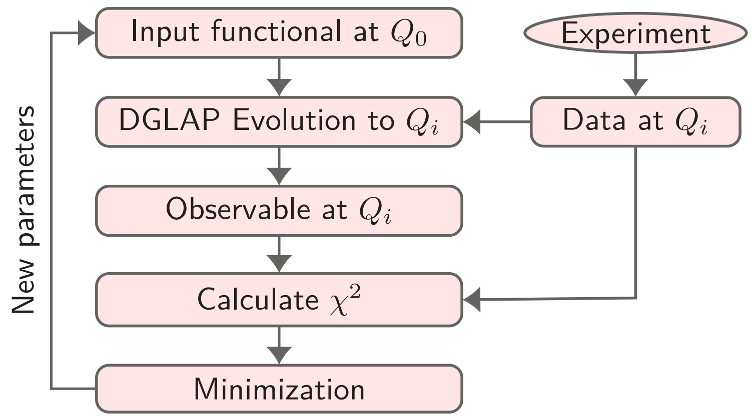
  - Reduces valence and increases sea
  - Mixes flavours

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:

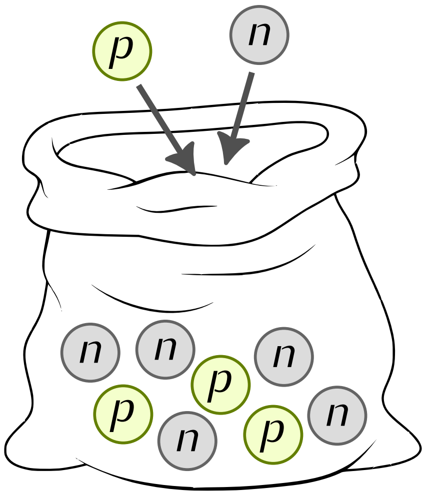


$$\chi^2 = \sum_{ij}^{N} (D_i - T_i)(C^{-1})_{ij}(D_j - T_j)$$

[a] Calculable in lattice QCD in near future?
[b] NNPDF collaboration use NN to avoid parametrization bias.

Nuclear Parton Distribution Functions (nPDFs)

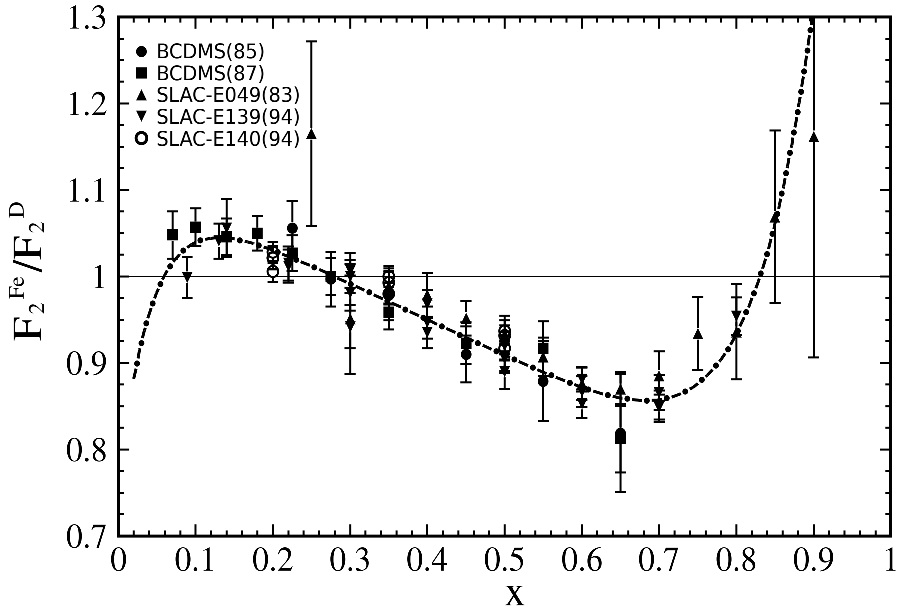
- Free nucleon approximation:



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

Nuclear Parton Distribution Functions (nPDFs)

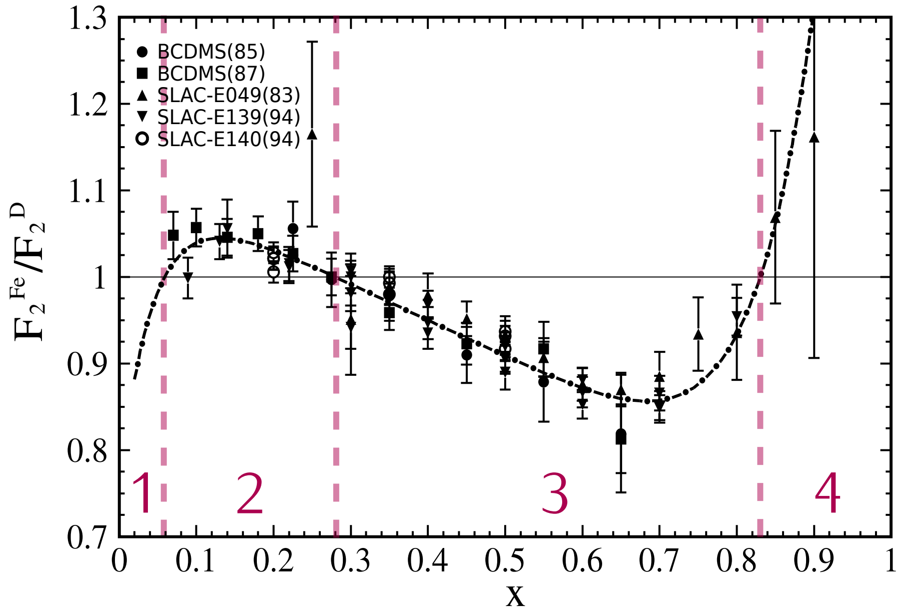
- Nuclear modification:



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

Nuclear Parton Distribution Functions (nPDFs)

- Nuclear modification:

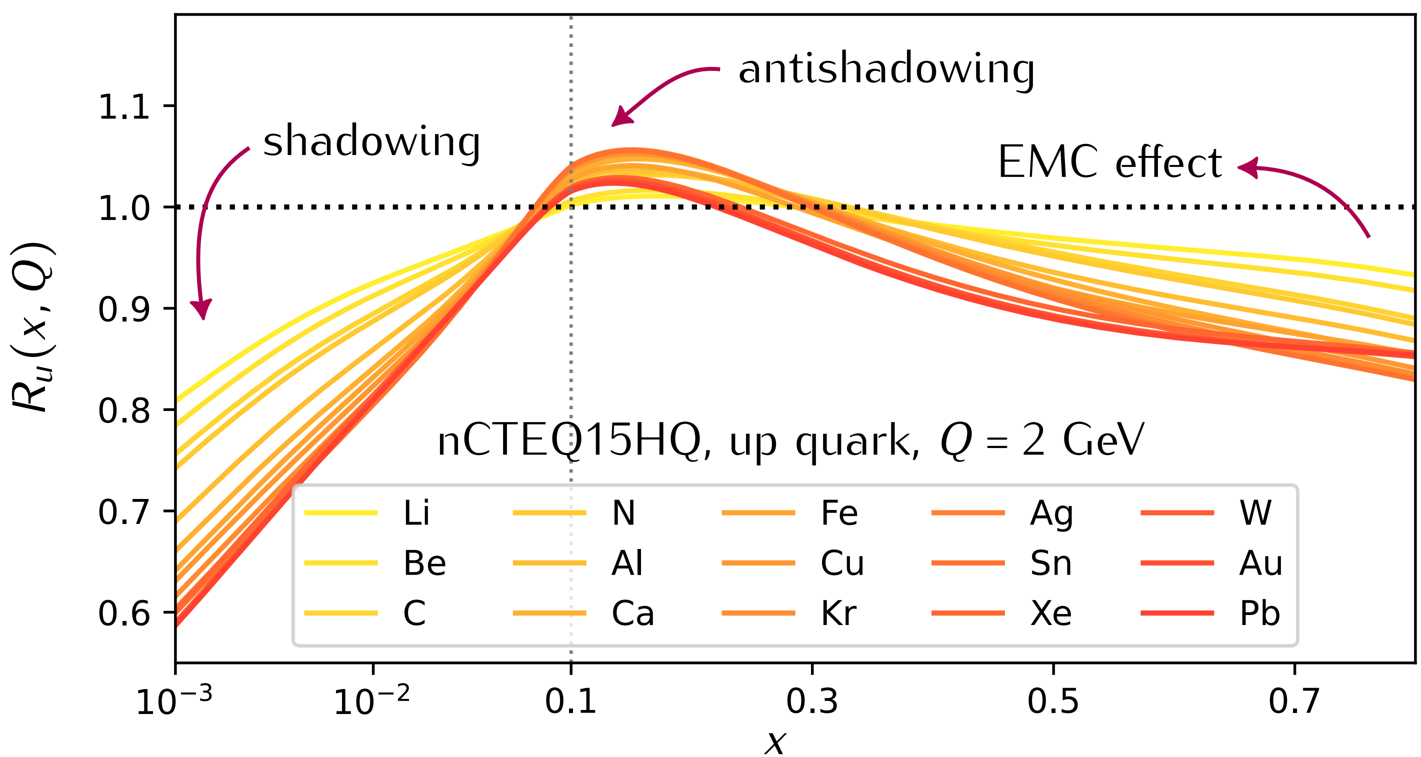


- 1 shadowing
- 2 anti-shadowing
- 3 EMC effect
- 4 Fermi motion

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

Nuclear Parton Distribution Functions (nPDFs)

- Nuclear modification, A dependence:



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]

[a] Proof 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

Adapted from a slide by I. Schienbein

Global analyses of nPDFs

Recent

- 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

Outdated

- nDS
  - nDS03: hep-ph/0311227
  - DSSZ12: 1112.6324
- HKM/HKN
  - HKM01: hep-ph/0103208
  - HKN04: hep-ph/0404093
  - HKN07: 0709.3038

Adapted from a slide by I. Schienbein

Global analyses of nPDFs

Extract from a table by P. Paakkinen

	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	~CTEQ6M	own fit	CT18A	~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**; ...

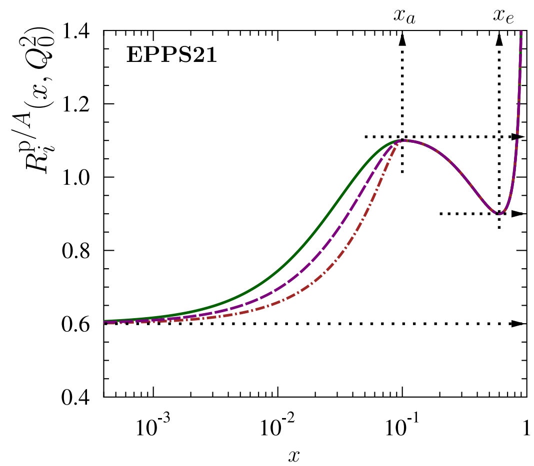
Global analyses of nPDFs

- 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: $R^{p/A}$; analytic parametrization; A, x dependence mixing marginal

$$R_i^A(x,Q_0^2) = \begin{cases} a_0 + a_1(x-x_a)\left[e^{-xa_2/x_a} - e^{-a_2}\right], & x \le x_a \\ b_0 x^{b_1}(1-x)^{b_2} e^{xb_3}, & x_a \le x \le x_e \\ c_0 + c_1(c_2 - x)(1-x)^{-\beta}, & x_e \le x \le 1 \end{cases}$$

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



Adapted from a figure by EPPS

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: $R^{p/A}$; analytic parametrization; A, x dependence mixing marginal
  - nNNPDF: nPDF; NN parametrization; A, x dependence mix

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

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

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: $R^{p/A}$; analytic parametrization; A, x dependence mixing marginal
  - nNNPDF: nPDF; NN parametrization; A, x dependence mix
  - KSASG, TUJU, nCTEQ: nPDF; analytic parametrization; A, x mix

e.g. in nCTEQ15

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5}$$

$$c_k \to c_k(A) \equiv p_k + a_k \left(1 - A^{-b_k}\right)$$

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

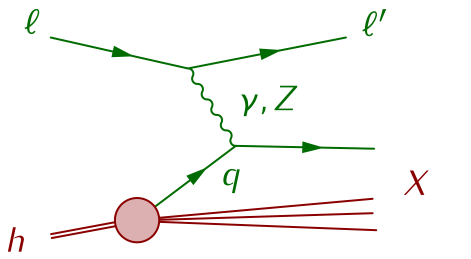
- Parametrization: ideally, results should be independent of it
  - EPPS: $R^{p/A}$; analytic parametrization; A, x dependence mixing marginal
  - nNNPDF: nPDF; NN parametrization; A, x dependence mix
  - KSASG, TUJU, nCTEQ: nPDF; analytic parametrization; A, x mix

- Data selection: discussed in the next few slides

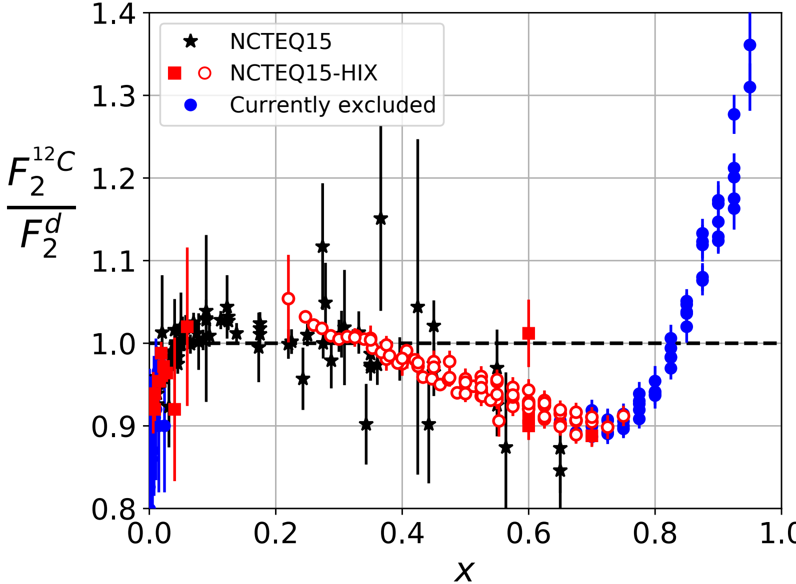
Data: Neutral current DIS

[nCTEQ coll., Phys.Rev.D 103 (2021) 11, 114015]

	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 accross a broad x range
- NEW! JLab CLAS and Hall C data
  - Maps out the high-x EMC region very precisely



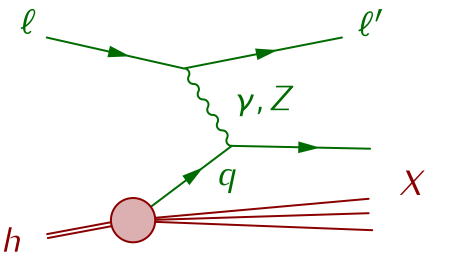
[2012.11566]

[a] Deuteron data excluded.

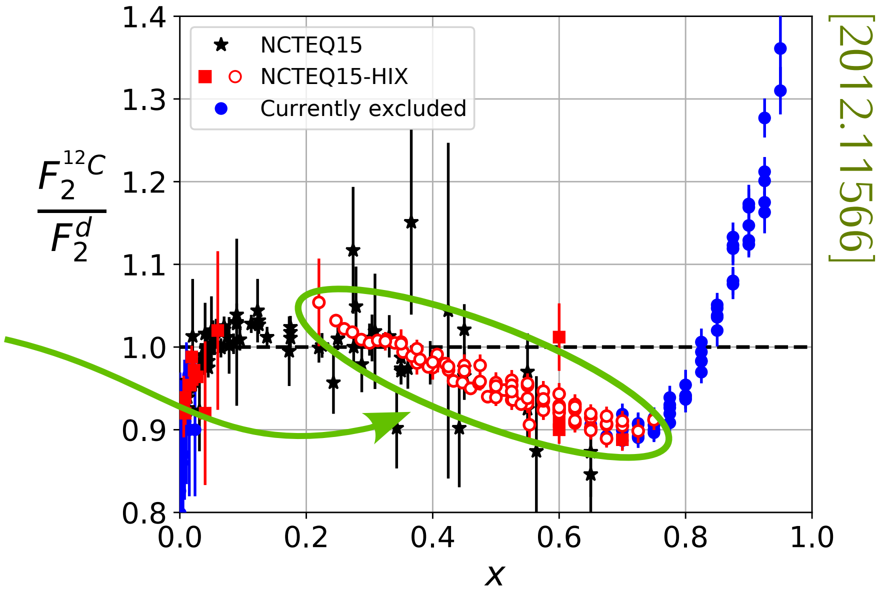
Data: Neutral current DIS

[nCTEQ coll., Phys.Rev.D 103 (2021) 11, 114015]

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



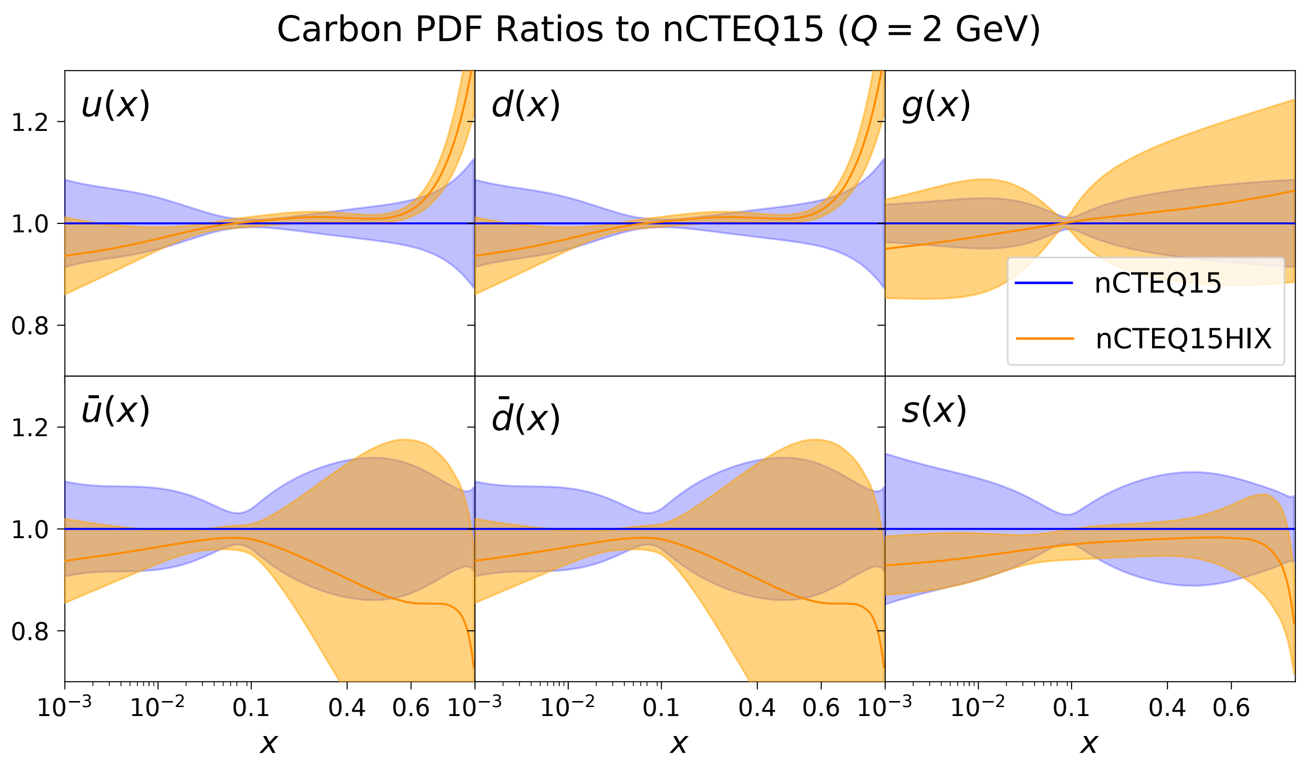
- Traditionally the bulk of data in nPDF analyses
- Constraints valence distributions accross a broad x range
- NEW! JLab CLAS and Hall C data
    - Maps out the high-x EMC region very precisely



[a]Deuteron data excluded.

Data: Neutral current DIS

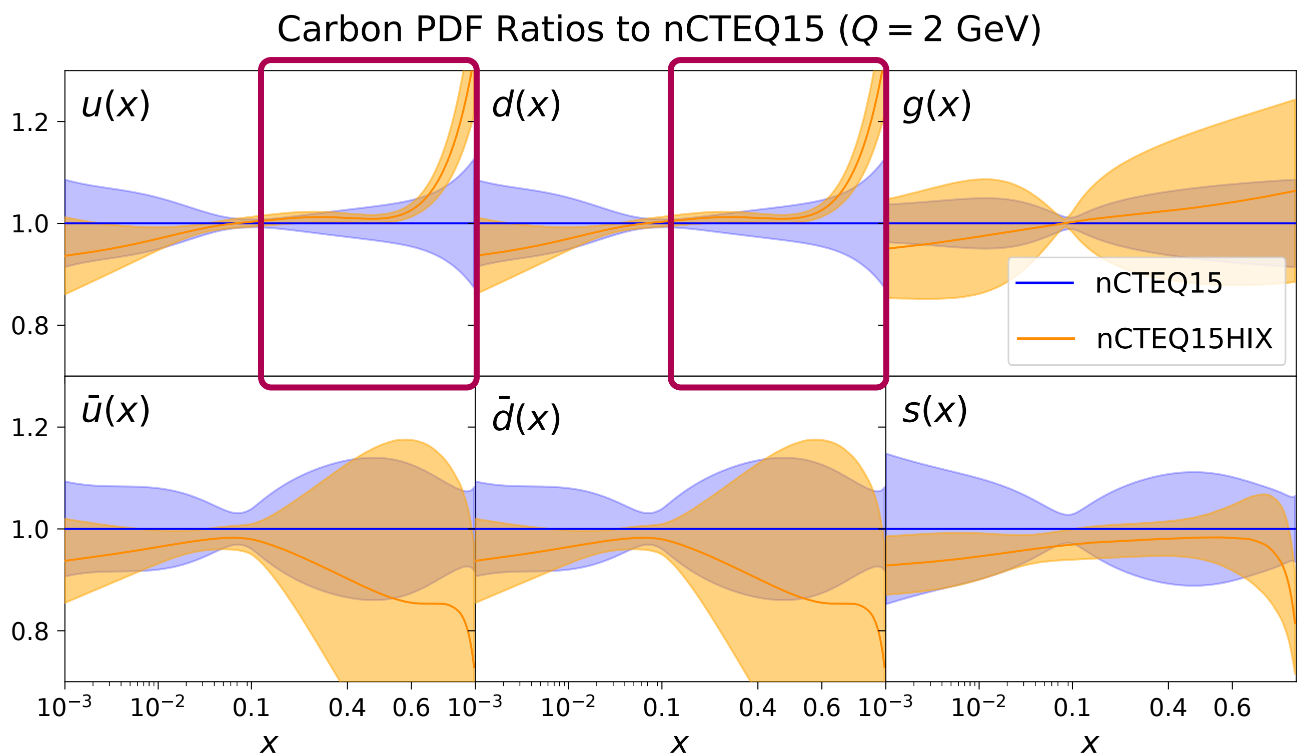
[nCTEQ coll., Phys.Rev.D 103 (2021) 11, 114015]



- Valence quark uncertainties strongly reduced!

Data: Neutral current DIS

[nCTEQ coll., Phys.Rev.D 103 (2021) 11, 114015]

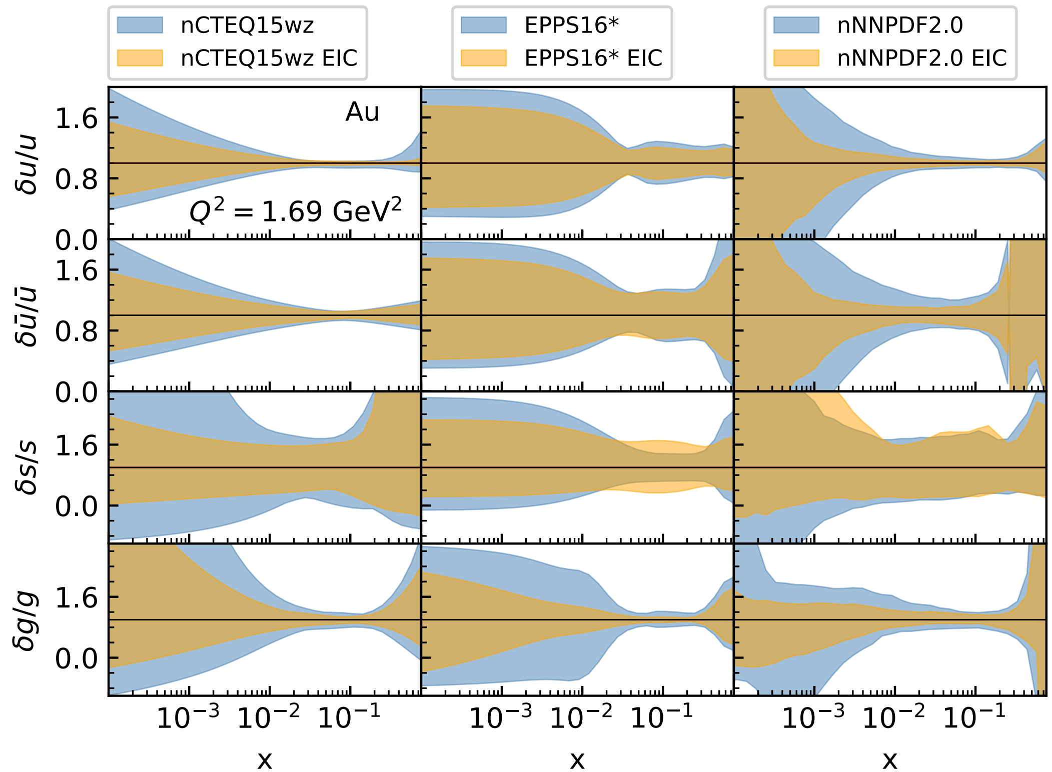


- Valence quark uncertainties strongly reduced!

Data: Future Neutral current DIS @ EIC

[Nucl.Phys.A 1026 (2022) 122447]

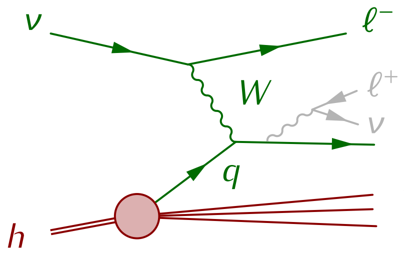
- A reweighting study: remarkable reduction of uncertainties accross the board



Data: Charged current DIS

[nCTEQ coll., Phys.Rev.D 106 (2022) 7, 074004]

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

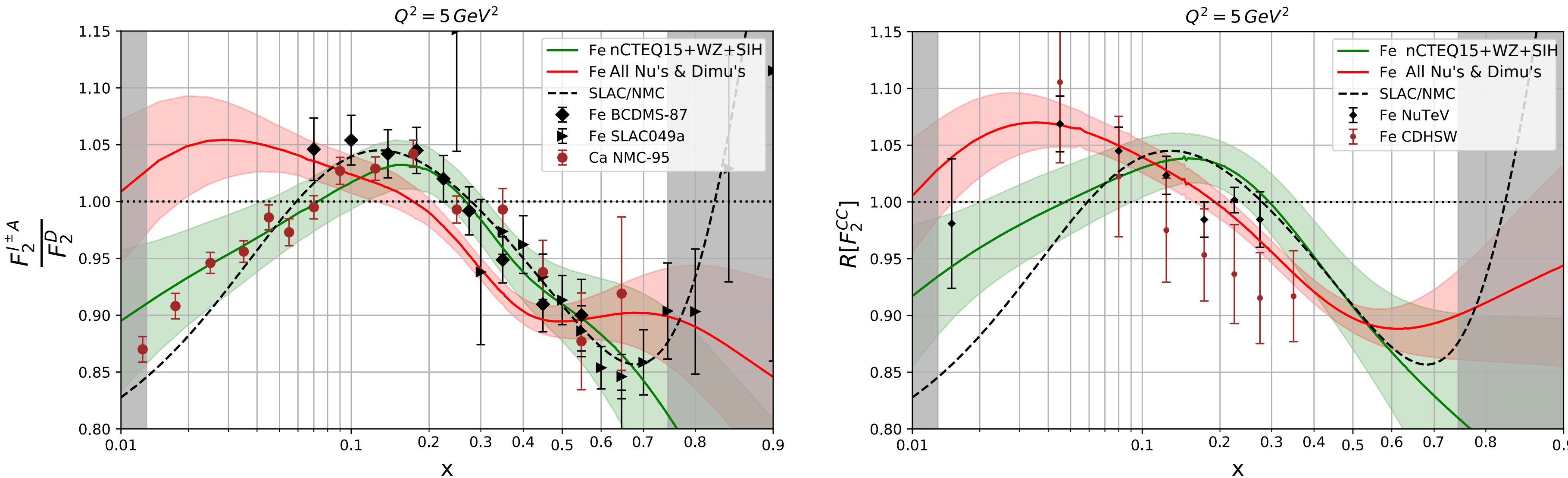


- Important for flavour separation
- Constrains strange distribution
- Remarkably abundant and precise, but not universally included
  - Chorus (824 pts): mostly included
  - CDHSW (930 pts): sometimes included
  - CCFR & NuTeV (4343 pts): mostly excluded

[a] nCTEQ15BaseDimuChorus

Data: Charged current DIS

[nCTEQ coll., Phys.Rev.D 106 (2022) 7, 074004]

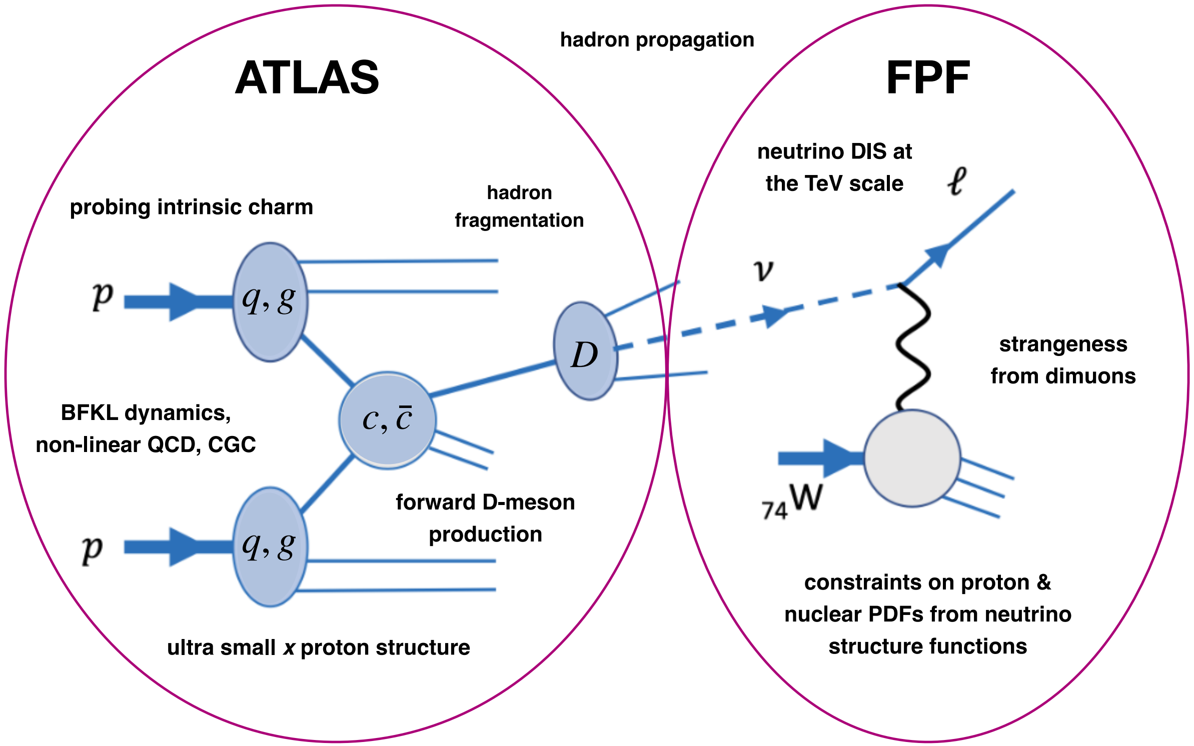


- NuTev, CCFR and CDHSW data in tension with NC DIS data. Dropping correlations alleviates the tension but doesn't resolve it.

Data: Future Charged current DIS @ FPF

[J.Phys.G 50 (2023) 3, 030501]

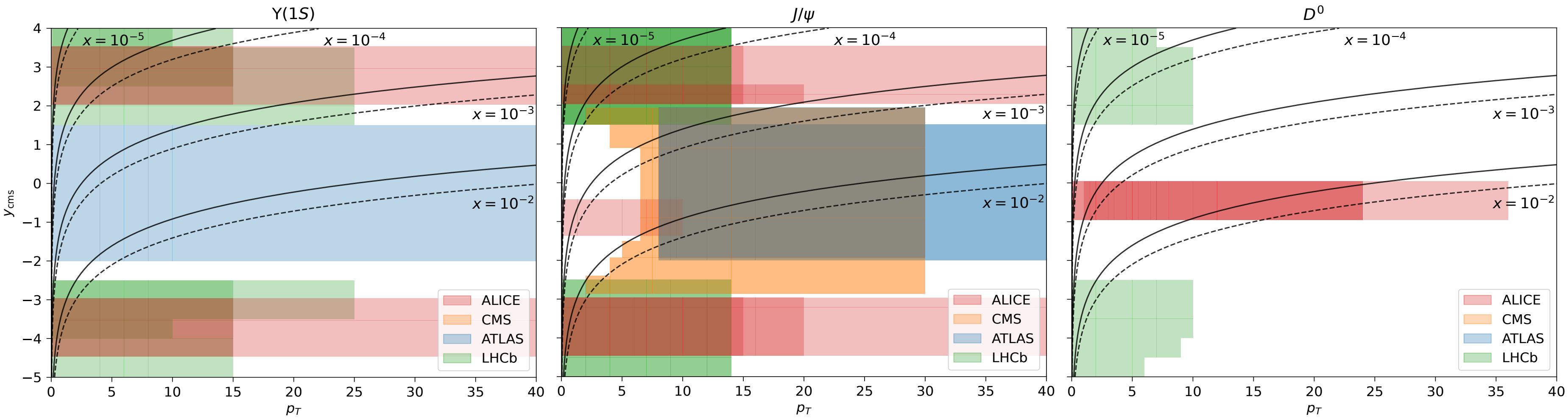
- Neutrino DIS with a biproduct neutrino beam from ATLAS



Data: Heavy quark production

[nCTEQ Coll., Phys.Rev.D 105 (2022) 11, 114043]

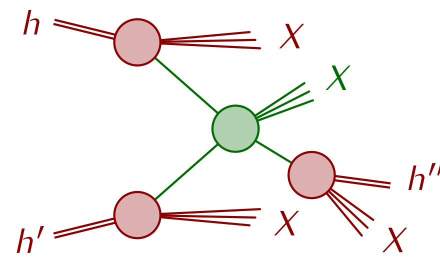
- In $y - p_T$ plane, $x \sim 2p_T \exp(-y)/\sqrt{s}$:



Data: Heavy quark production

[nCTEQ Coll., Phys.Rev.D 105 (2022) 11, 114043]

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

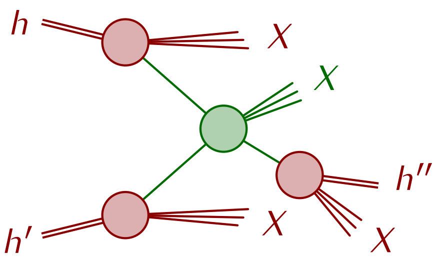


- Unprecedented low x reach
- Two very different production modes
  - Open heavy flavour production: D
  - Quarkonia production: $J/\psi, \Upsilon(1S), \psi(2S)$
- EPPS: only open HF, pQCD prediction with fragmentation
- nNNPDF: only open HF, rwgt using pQCD prediction with GPMC hadronization
- nCTEQ: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

Data: Heavy quark production

[nCTEQ Coll., Phys.Rev.D 105 (2022) 11, 114043]

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



Data-driven approach (Crystal Ball function):

$$\overline{|\mathcal{A}_{gg\to\mathcal{Q}+X}|^2} = \frac{\lambda^2\kappa\hat{s}}{M_{\mathcal{Q}}^2} e^{a|y|} \times \begin{cases} e^{-\kappa\frac{p_T^2}{M_{\mathcal{Q}}^2}} & \text{if } p_T \le \langle p_T \rangle \\ e^{-\kappa\frac{\langle p_T\rangle^2}{M_{\mathcal{Q}}^2}} \left(1 + \frac{\kappa}{n}\frac{p_T^2 - \langle p_T\rangle^2}{M_{\mathcal{Q}}^2}\right)^{-n} & \text{if } p_T > \langle p_T \rangle \end{cases}$$

- Originally proposed for J/Ψ pairs and double parton scattering

  [C.H. Kom, A. Kulesza, J. Stirling, PRL 107 (2011) 082002]

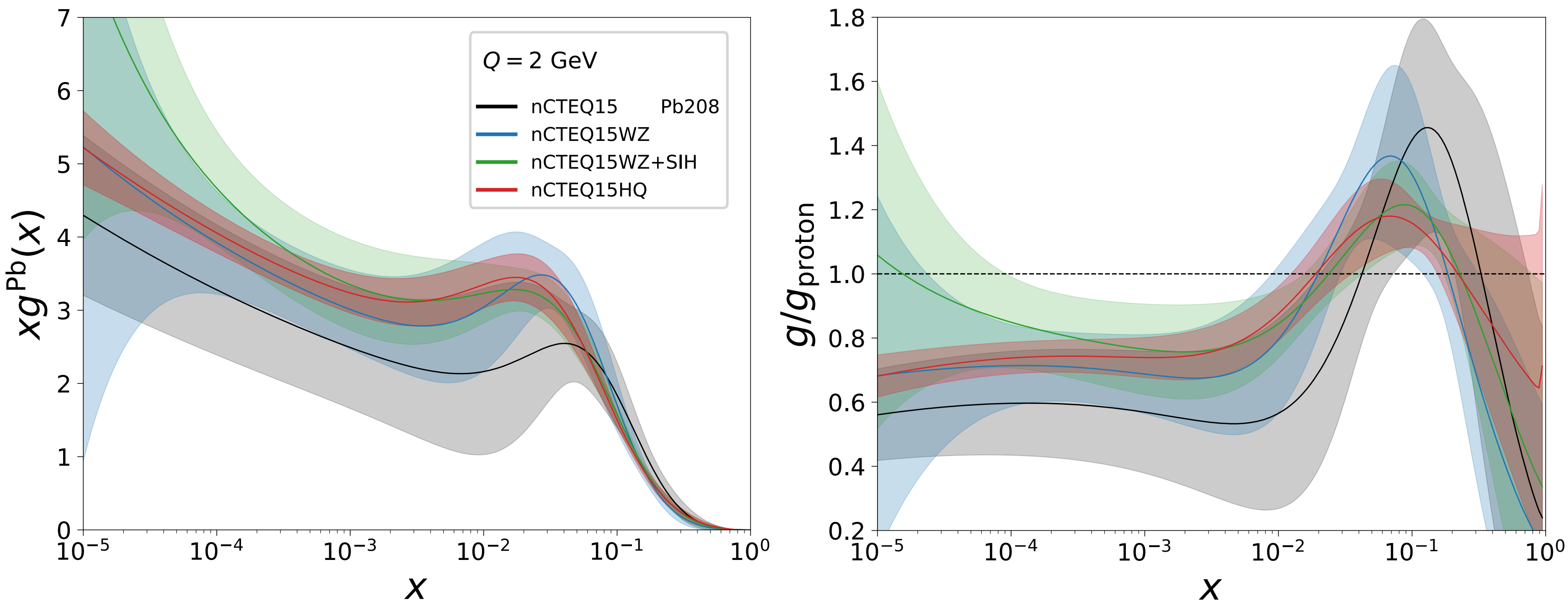
- Impact on nPDFs demonstrated with reweighting studies

  [A. Kusina, J.P. Lansberg, I. Schienbein, H.S. Shao, PRL 121 (2018) 052004 and PRD 104 (2021) 014010]

- New rapidity dependence allows to cover also LHCb data

Data: Heavy quark production

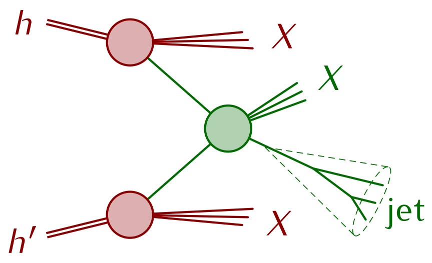
[nCTEQ Coll., Phys.Rev.D 105 (2022) 11, 114043]



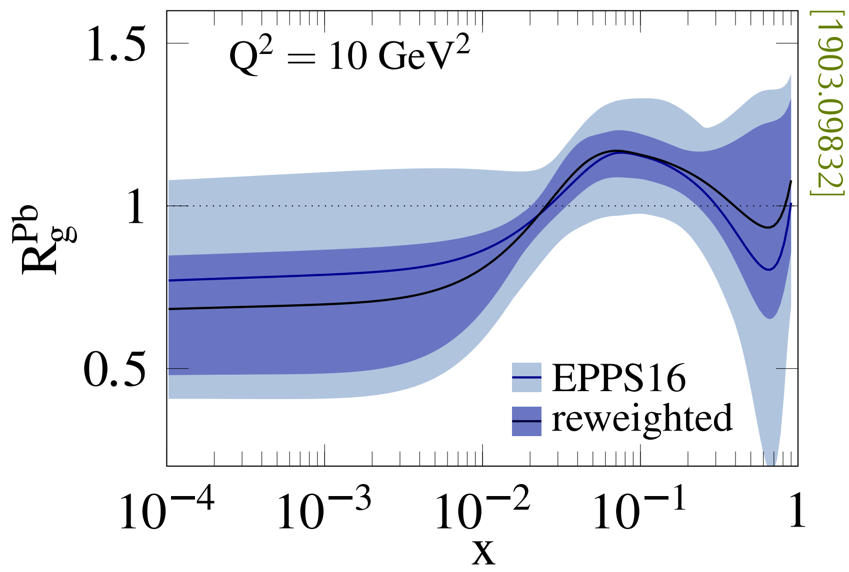
- Impressive reduction of uncertainties down to $x \sim 10^{-5}$

Data: Jet production

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



- Great potential to constrain gluon distribution at low x



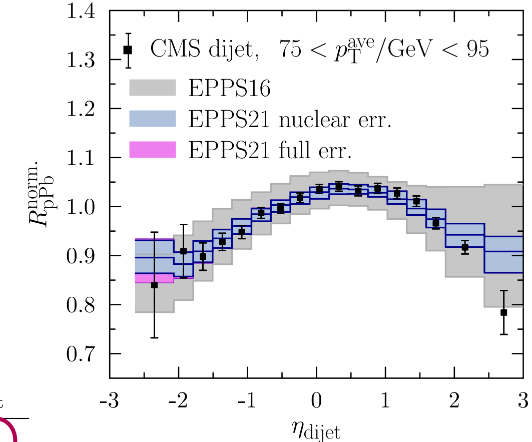
Data: Jet production

- pPb/pp ratios described well
  - EPPS:

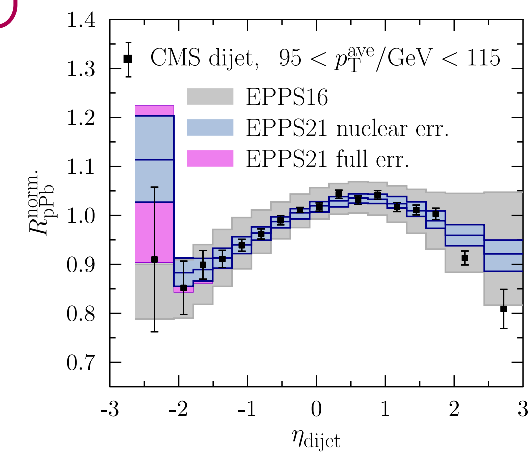
Experiment	Observable	Collisions	Data points	χ^2
CERN CMS	dijet	pPb(208)	83	123.81

  - nNNPDF:

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

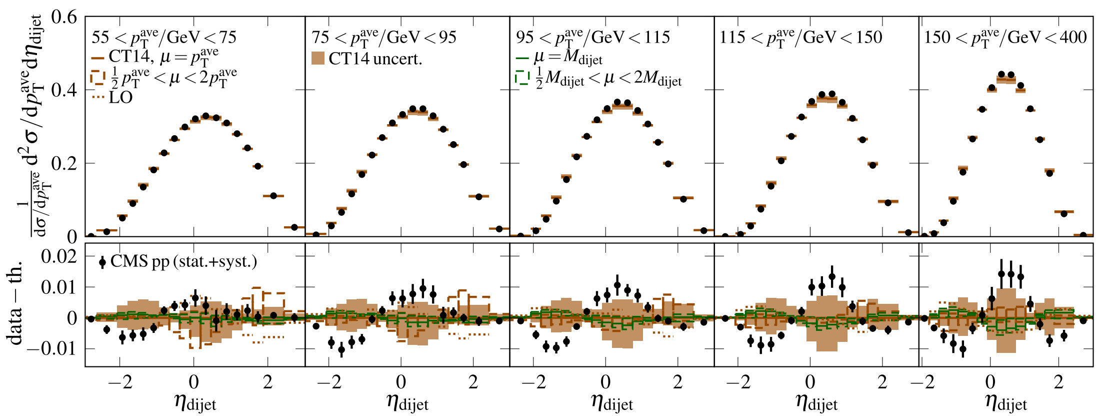


[2112.12462]



- Not pp, pPb separately

Dataset	n_{dat}	χ^2/n_{dat}
CMS dijet pPb $\sqrt{s} = 5.02$ TeV	85	[13.96]



[1903.09832]

Data: Jet production

- pPb/pp ratios described well
  - EPPS:

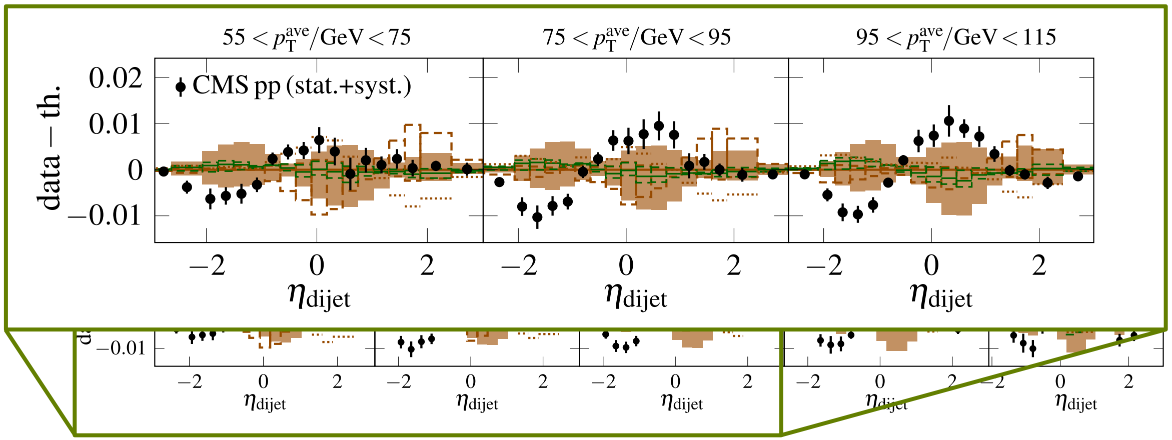
Experiment	Observable	Collisions	Data points	χ^2
CERN CMS	dijet	pPb(208)	83	123.81

  - nNNPDF:

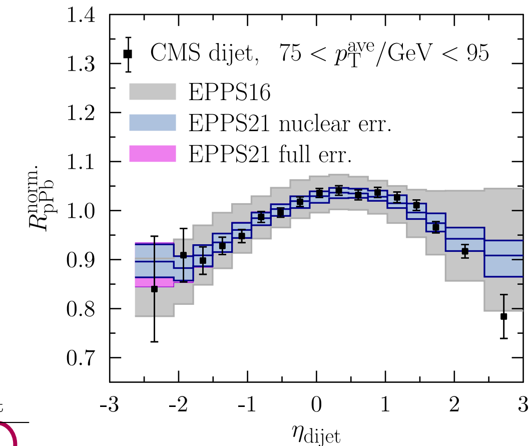
Dataset	n_{dat}	χ^2/n_{dat}
CMS dijet pPb/pp $\sqrt{s} = 5.02$ TeV	84	1.75

- Not pp, pPb separately

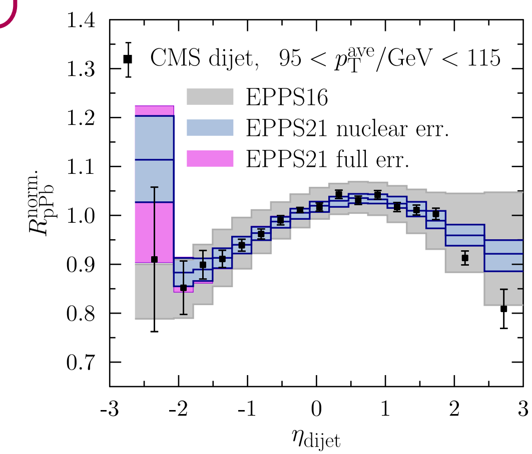
Dataset	n_{dat}	χ^2/n_{dat}
CMS dijet pPb $\sqrt{s} = 5.02$ TeV	85	[13.96]



[1903.09832]



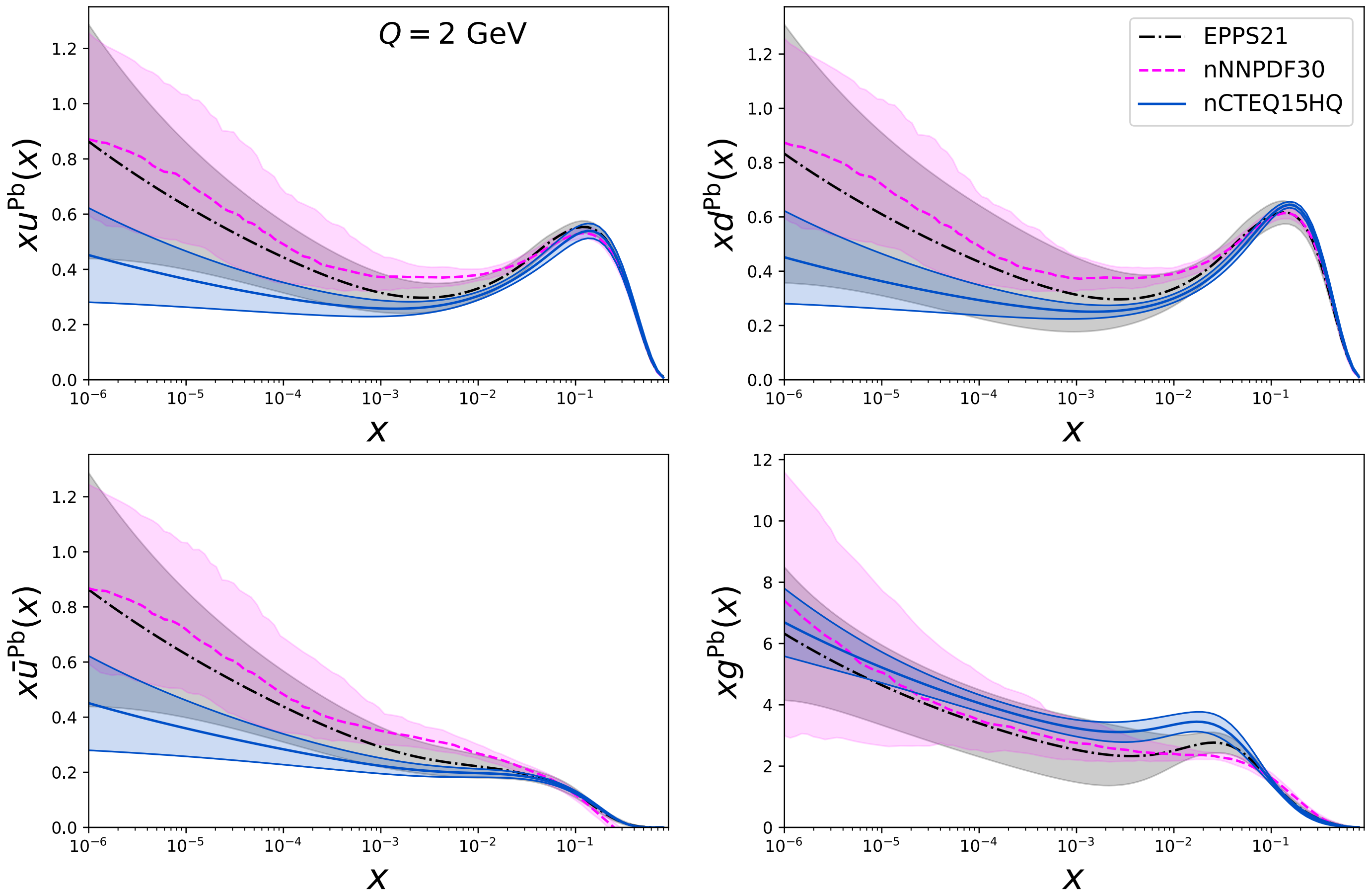
[2112.12462]



Data: not covered today

- Fixed Target DY ($n_{\rm dat} \sim 100$) and LHC W, Z ($n_{\rm dat} \sim 150$) production
  - Important for strange distribution, also constrains gluon
  - Included in most analyses
- Single inclusive light flavours ($n_{\rm dat} \sim 300$)
  - 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 ($n_{\rm dat} \sim 50$)
  - 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
  - NC DIS: New JLAB CLASS and Hall-C data
  - CC DIS: Reanalysis confirms unreconcilable tension
  - New processes useful for gluon and low x:
    - Heavy quarks
    - Dijets
    - Direct photons
- Expected impact of selection of future data: EIC, FPF
- Overall: nPDF extraction is a very active field with a rich future ahead