WWU MÜNSTER

isoQuant SFB1225

nCTEQ
nuclear parton distribution functions

Nuclear PDFs: new results from global fits

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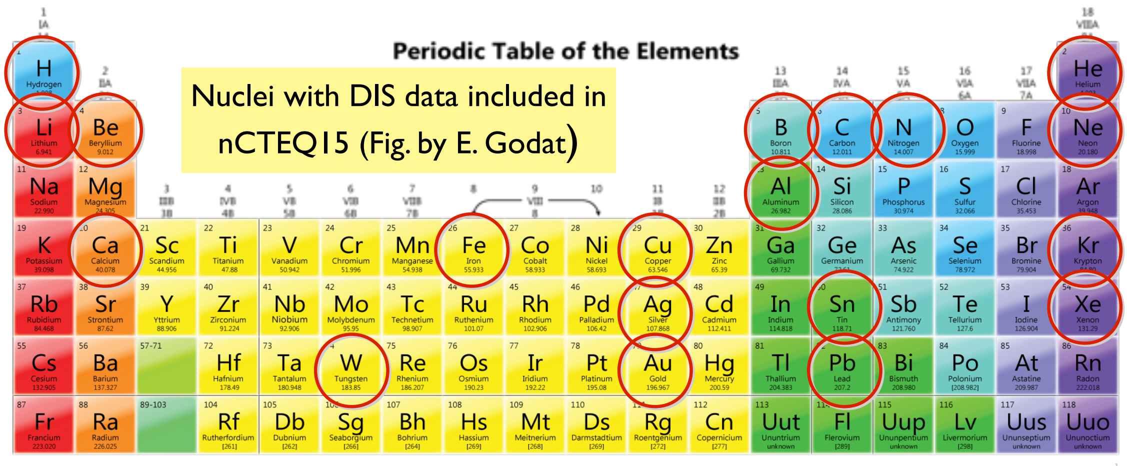
2023 HARD PROBES Aschaffenburg

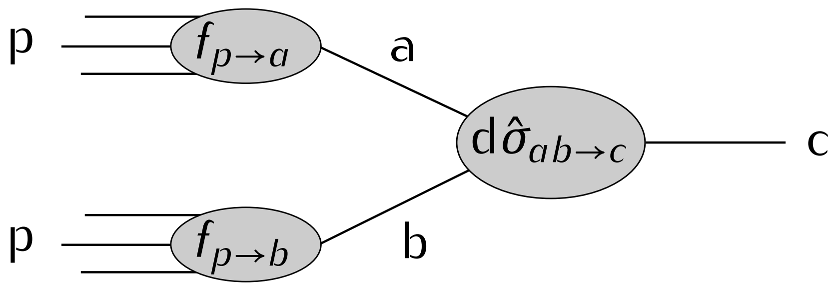
Nuclear structure at high energies



- 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:

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

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

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- 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.

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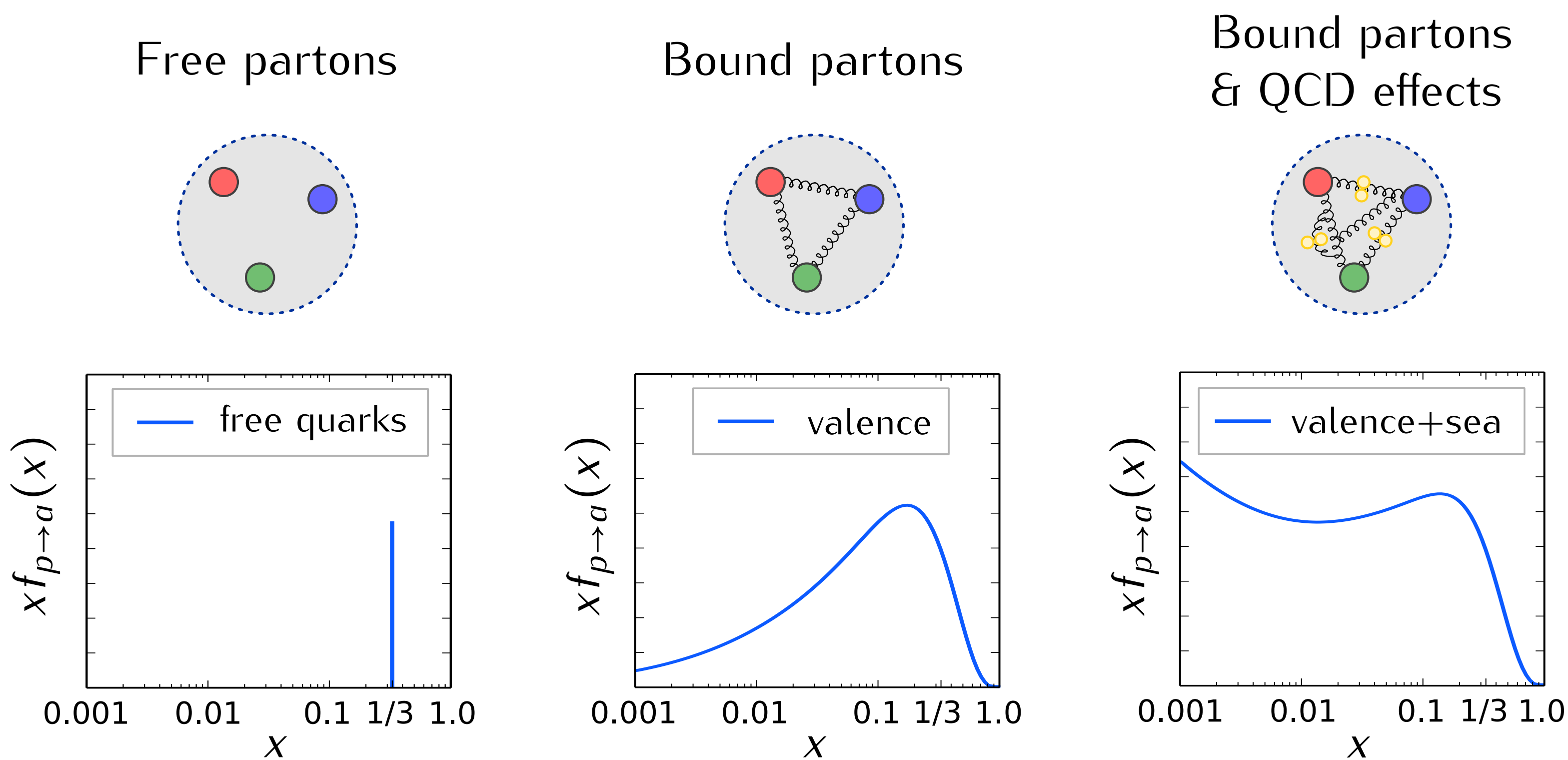
Parton Distribution Functions (PDFs)

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



[a] Longitudinal.

Inspired by a slide from P. Risse

Parton Distribution Functions (PDFs)

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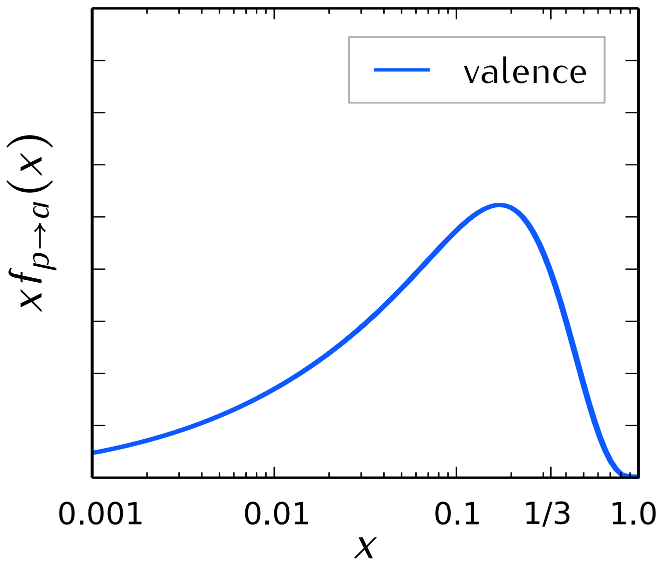

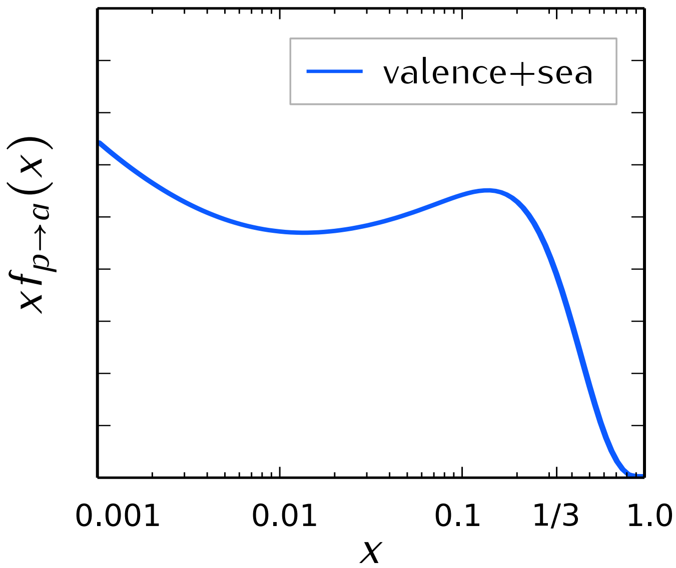

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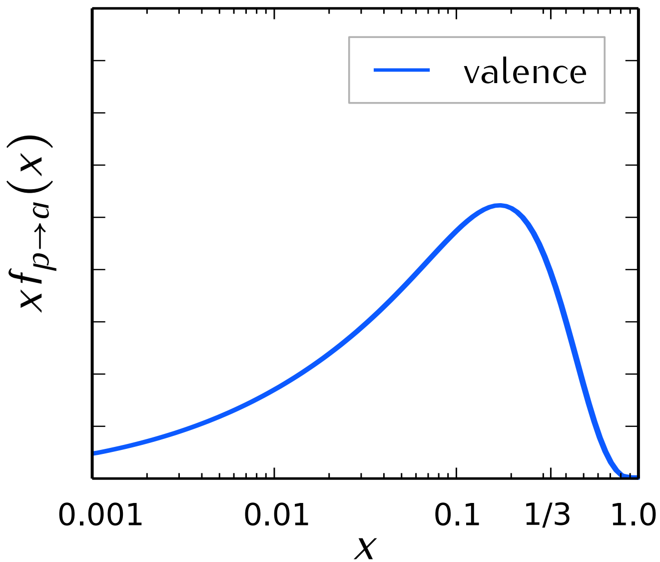

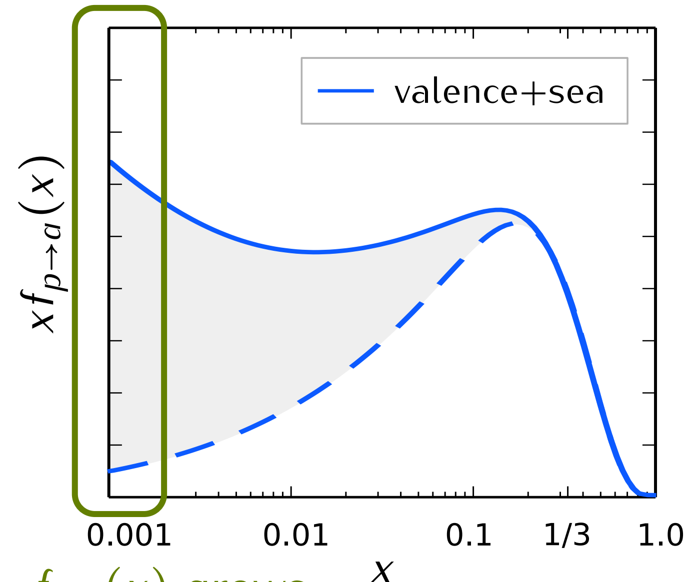

$f_{\text{sea}}(x)$ grows as $x \to 0$

[a] Longitudinal.

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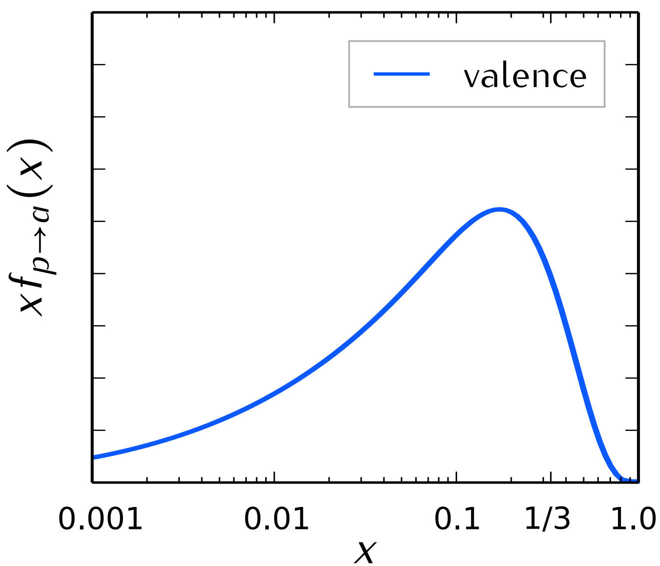

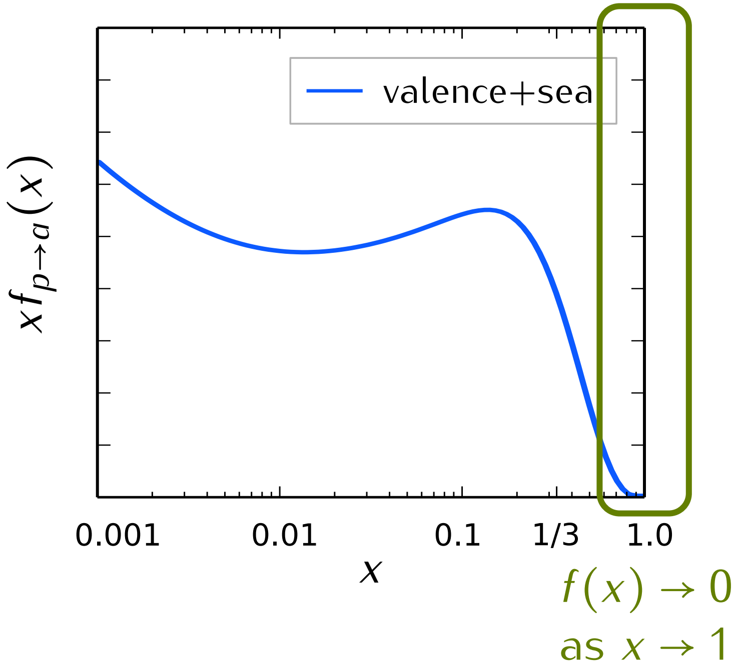

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Parton Distribution Functions (PDFs)

- 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

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

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

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$$\frac{\mathrm{d}}{\mathrm{d}\log\mu^2} f_{\boxed{q}}(x,\mu^2) \sim (P_{qq} \otimes f_{\boxed{q}})(x,\mu^2) + (P_{qg} \otimes f_{\boxed{g}})(x,\mu^2)$$

$$\frac{\mathrm{d}}{\mathrm{d}\log\mu^2} f_{\boxed{g}}(x,\mu^2) \sim (P_{gg} \otimes f_{\boxed{g}})(x,\mu^2) + (P_{gq} \otimes f_{\boxed{q}})(x,\mu^2)$$

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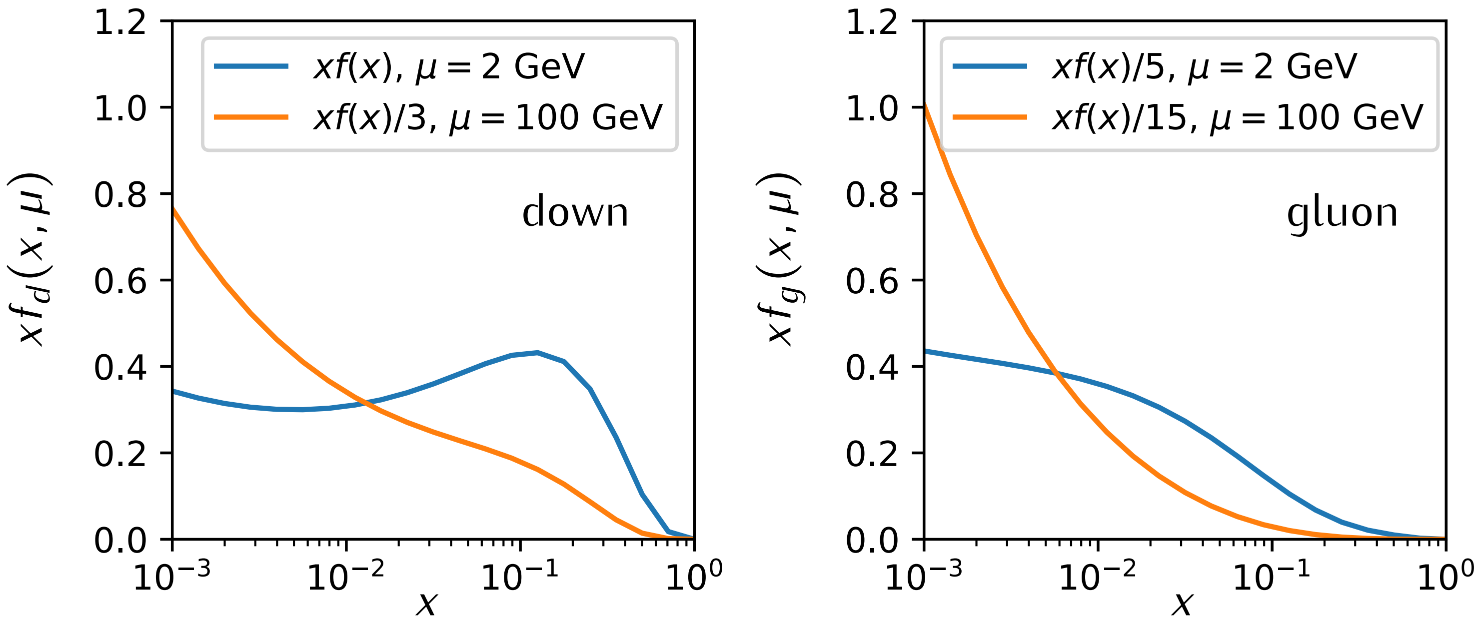
Parton Distribution Functions (PDFs)

- μ dependence governed by DGLAP evolution equations:



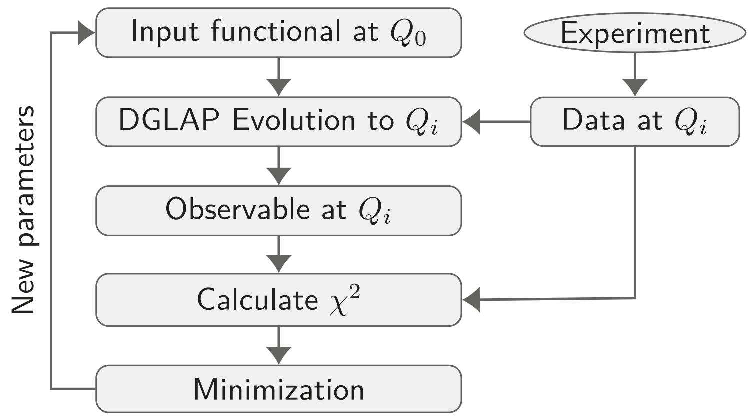
  - Reduces valence and increases sea
  - Mixes flavours

Parton Distribution Functions (PDFs)

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

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

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



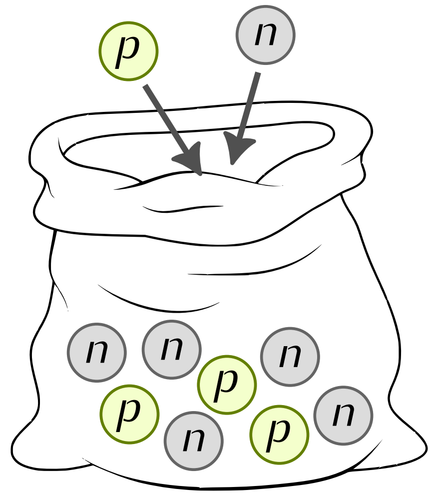
$$\chi^2 = \sum_{ij}^{N} (D_i - T_i)\,(C^{-1})_{ij}\,(D_j - T_j)$$

[a] Calculable in lattice QCD in near future?

[b] NNPDF collaboration use NN to avoid parametrization bias.

Nuclear Parton Distribution Functions (nPDFs)

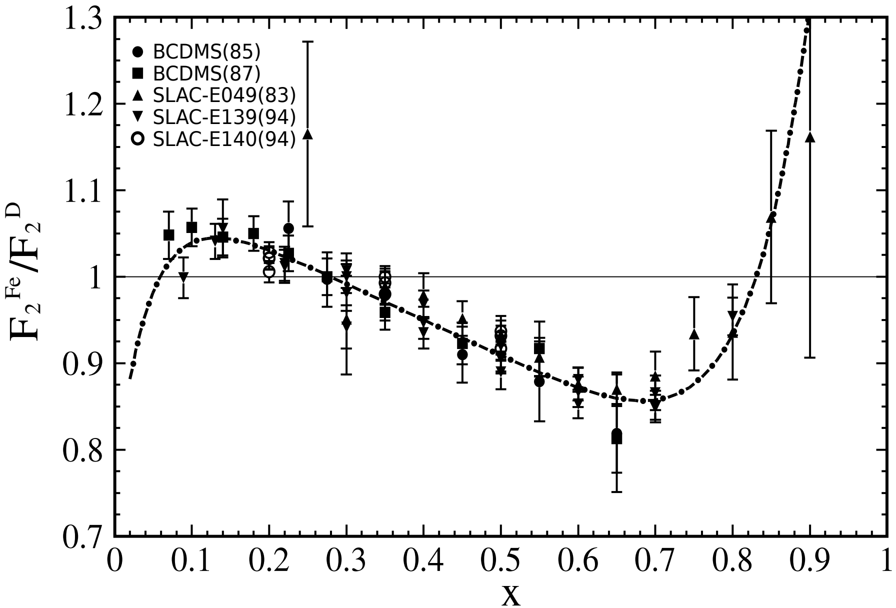
- Free nucleon approximation:



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

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)

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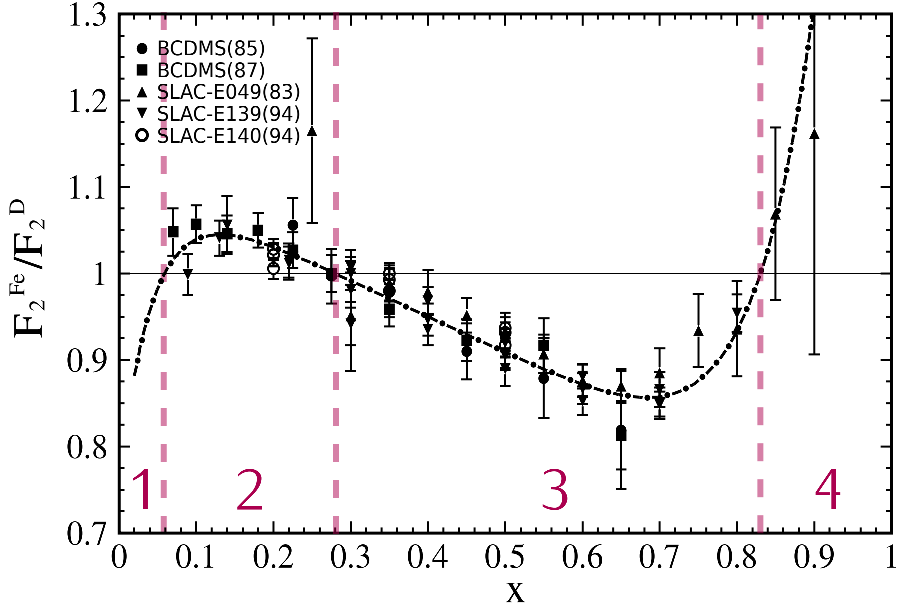
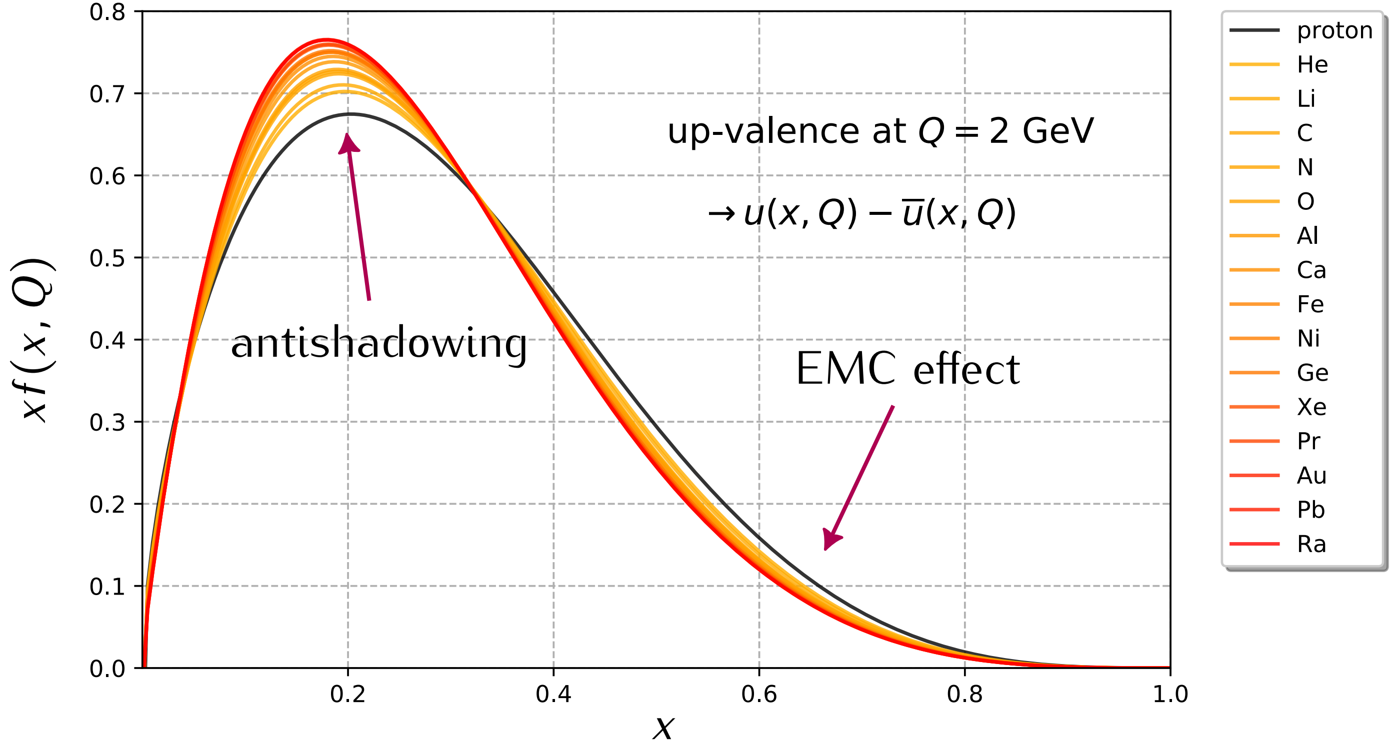


  - 1 shadowing
  - 2 anti-shadowing
  - 3 EMC effect
  - 4 Fermi motion

  - 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]

[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
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  - **nCTEQ09:** 0907.2357
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  - **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

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Outdated

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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	$\sim$CTEQ6M	own fit	CT18A	$\sim$NNPDF4.0
HQ treatment	FONLL	S-ACOT	FONLL	S-ACOT	FONLL

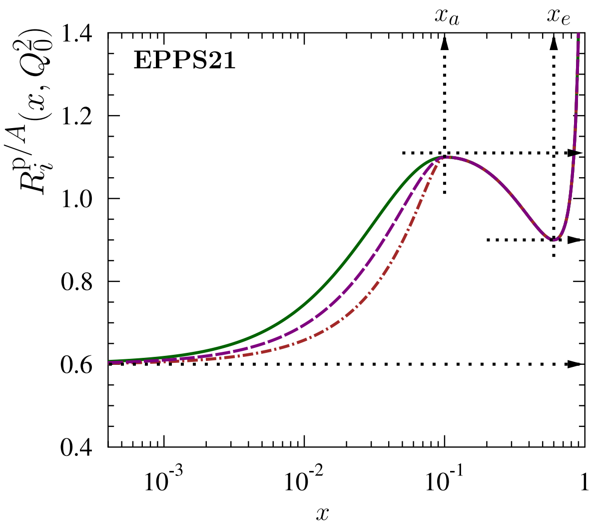
- Have in common: collinear factorisation, DGLAG evolution, sum rules, pQCD observables*, χ^2 minimization, isospin symmetry, $x > 1$ region neglected, ...
- Differ in:
  - **Parametrization**: R vs. f^A; proton baseline; functional form vs. neural nets
  - **Data selection**: processes; cuts; correlations; 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

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

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



Adapted from a figure by EPPS

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

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

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

e.g. in nCTEQ15

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

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

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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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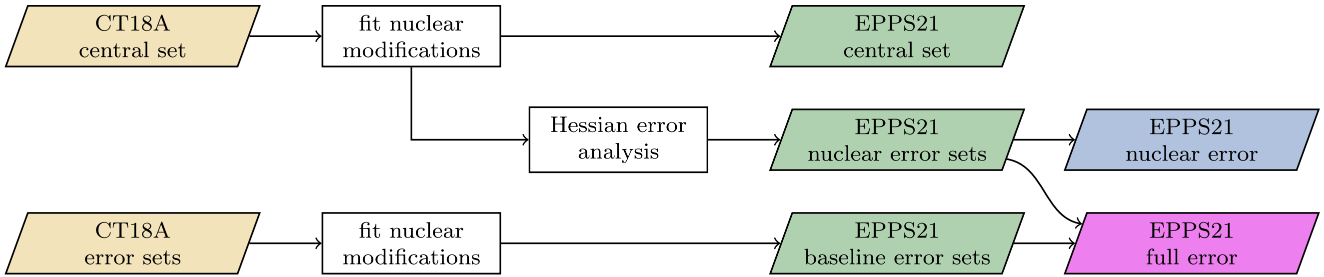
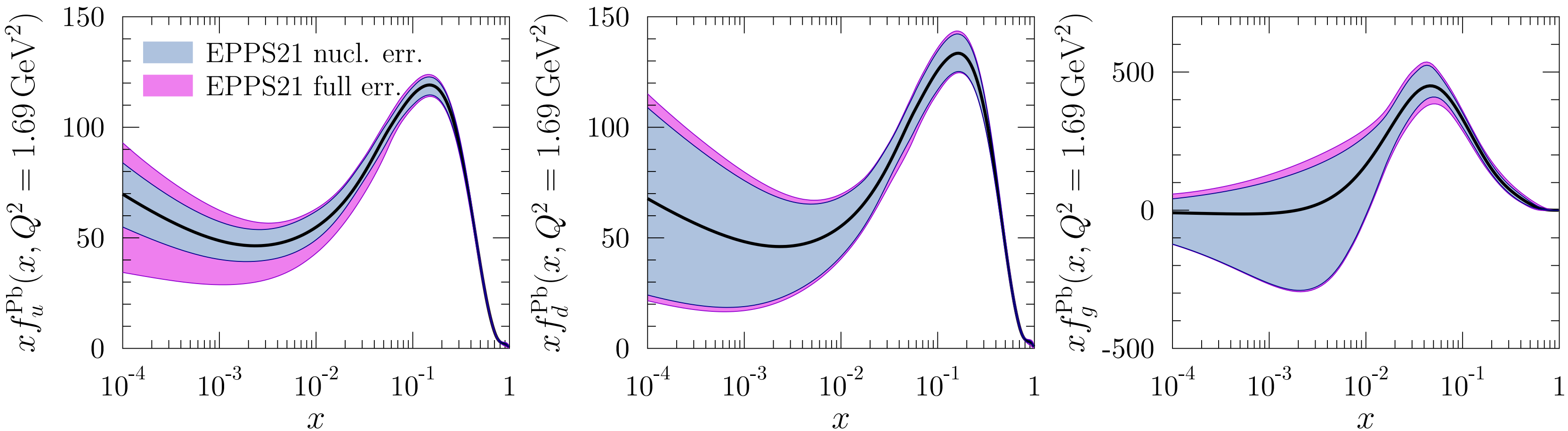
- Proton baseline uncertainties
  - EPPS developped a prescription on how to take them into account

Global analyses of nPDFs

- Proton baseline uncertainties in EPPS:





[2112.12462]

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- Proton baseline uncertainties
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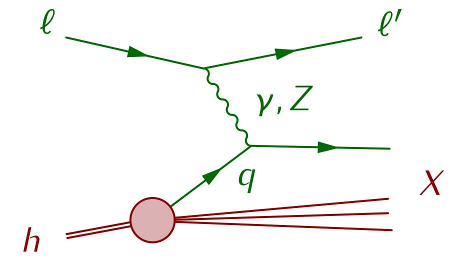
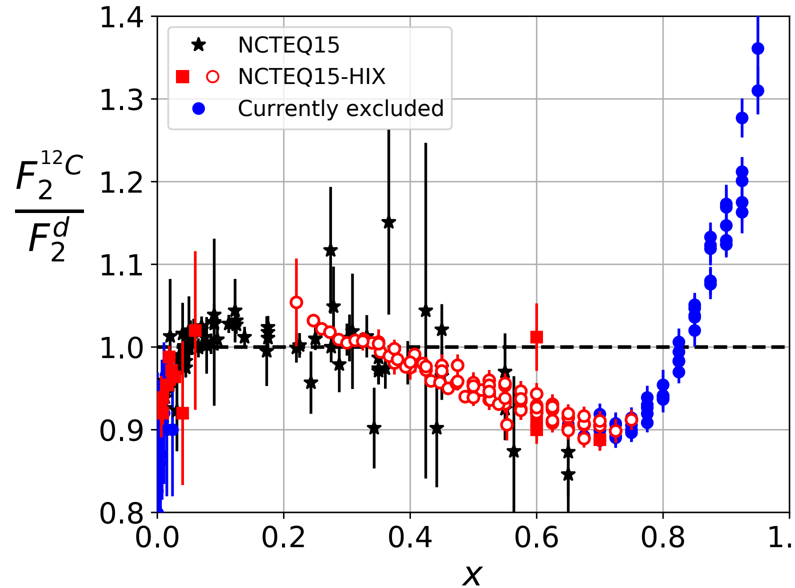
- Data selection: guiding theme of the remainder of this talk

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 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.

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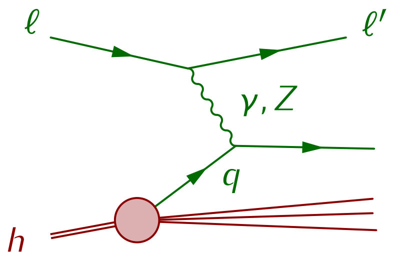

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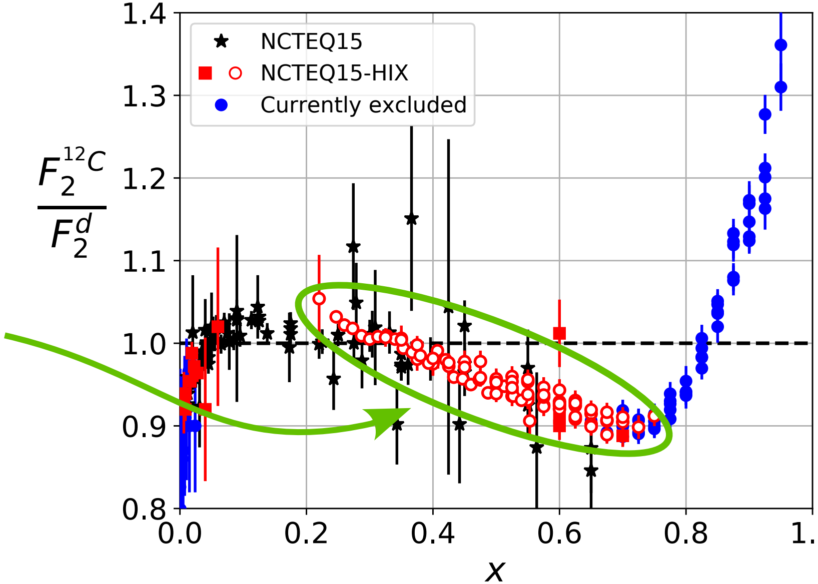

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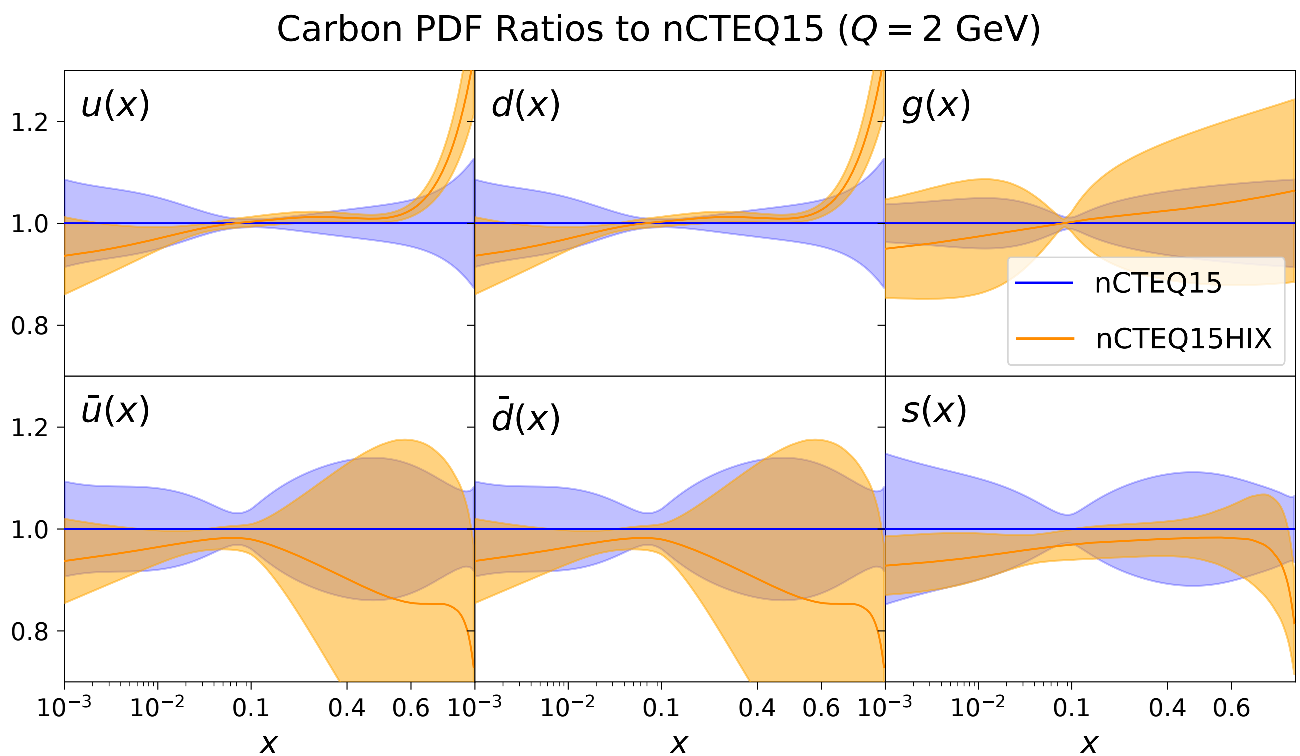

[2012.11566]

- Valence quark uncertainties strongly reduced!

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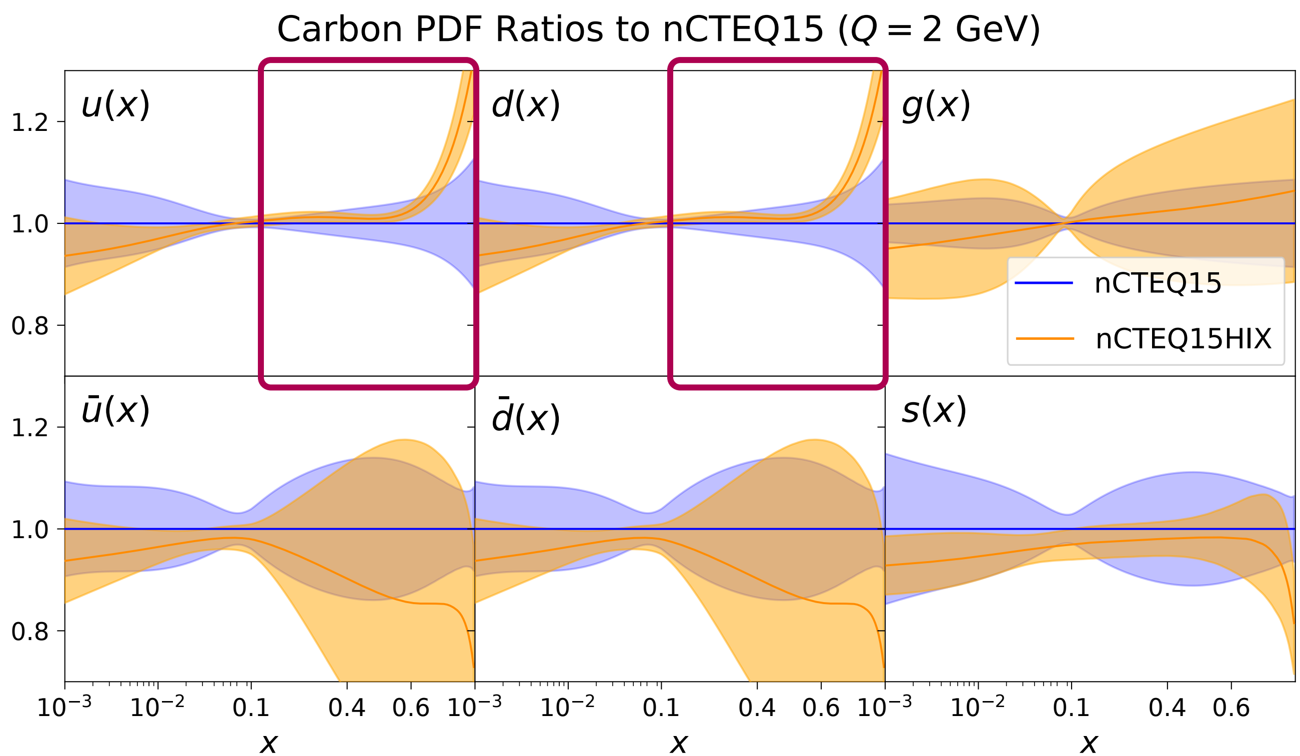

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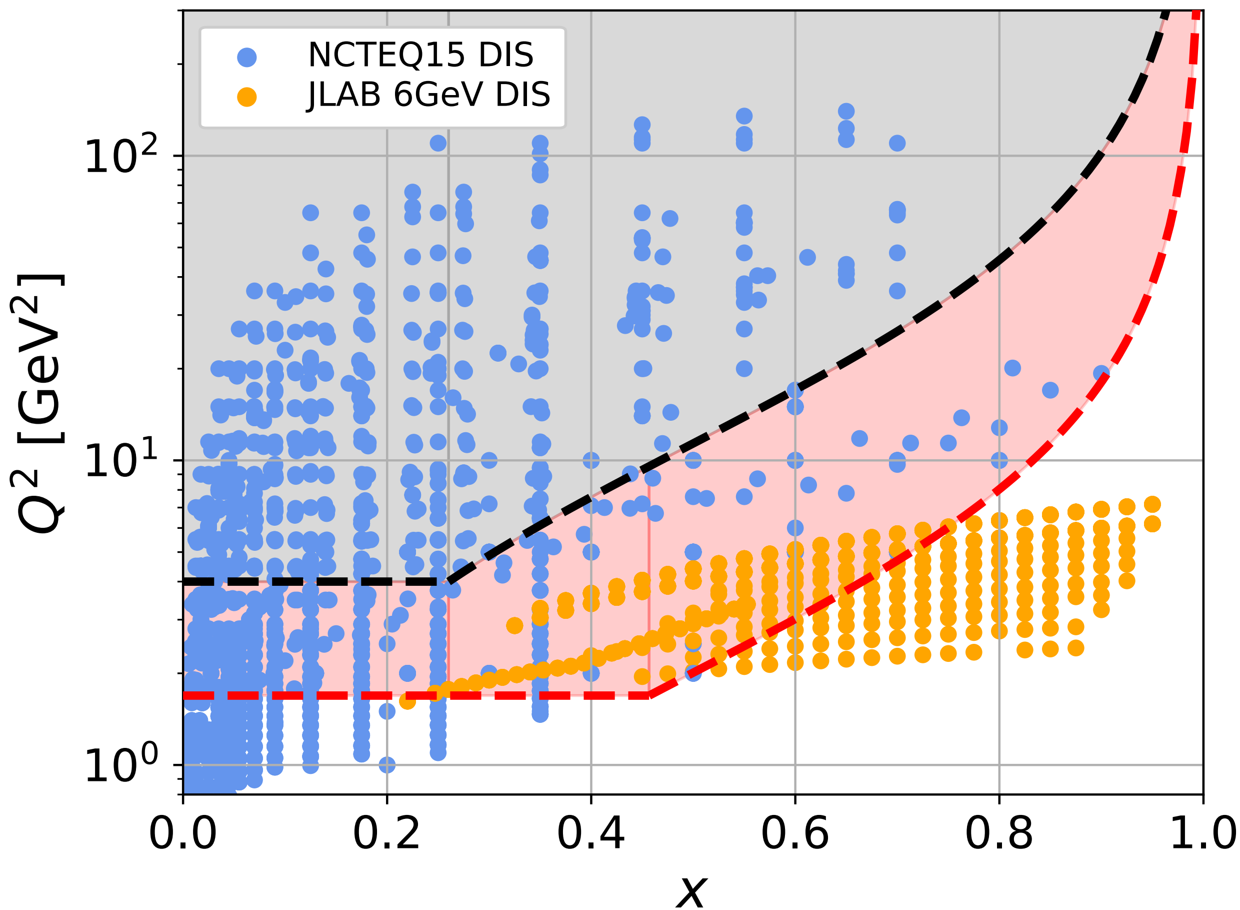
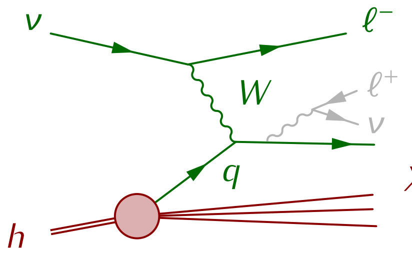


Data: Charged current DIS

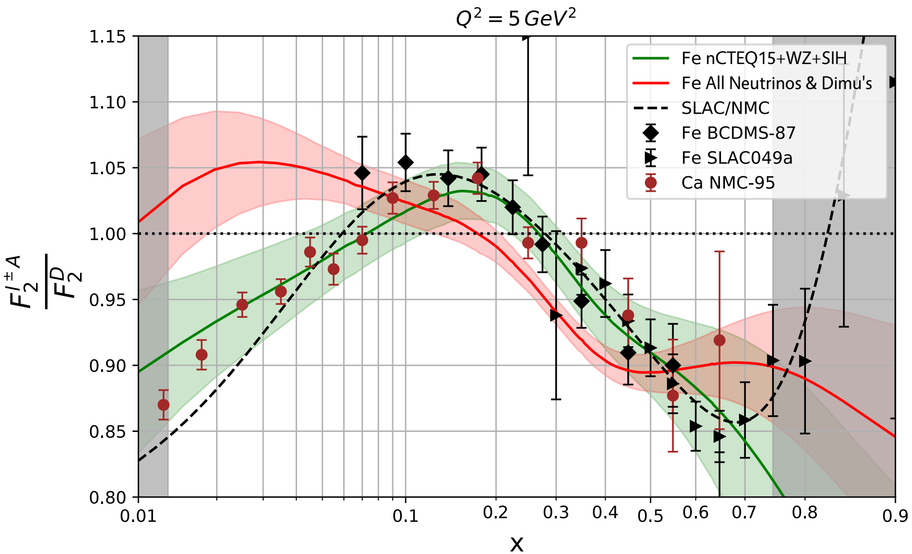
	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15BDC[a]
CC DIS	2458	1736	824	922	974
di-muon only	-	-	-	76	150

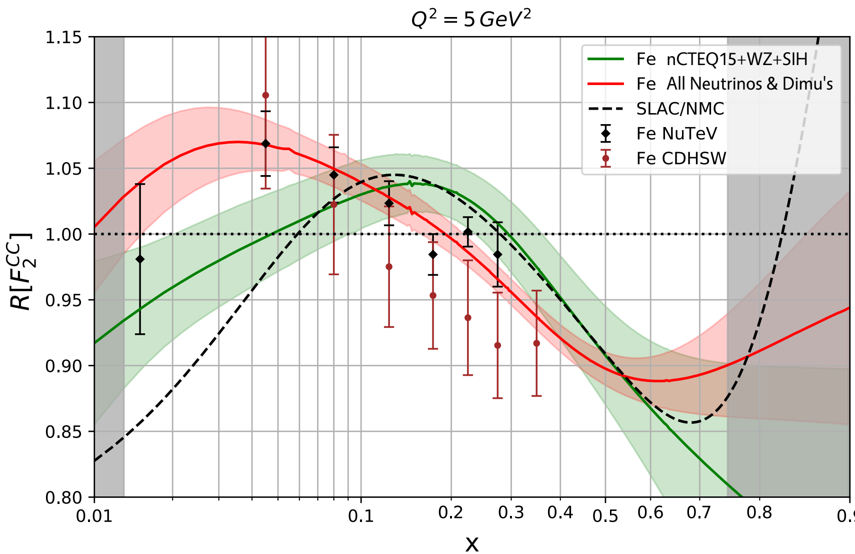


- Important for flavour separation
- Constrains strange distribution
- Remarkably abundant and precise, but not universally included
    - Chorus (824 pts): mostly included
    - CDHSW (930 pts): sometimes included
    - CCFR & NuTeV (4343 pts): mostly excluded

[a] nCTEQ15BaseDimuChorus

Data: Charged current DIS



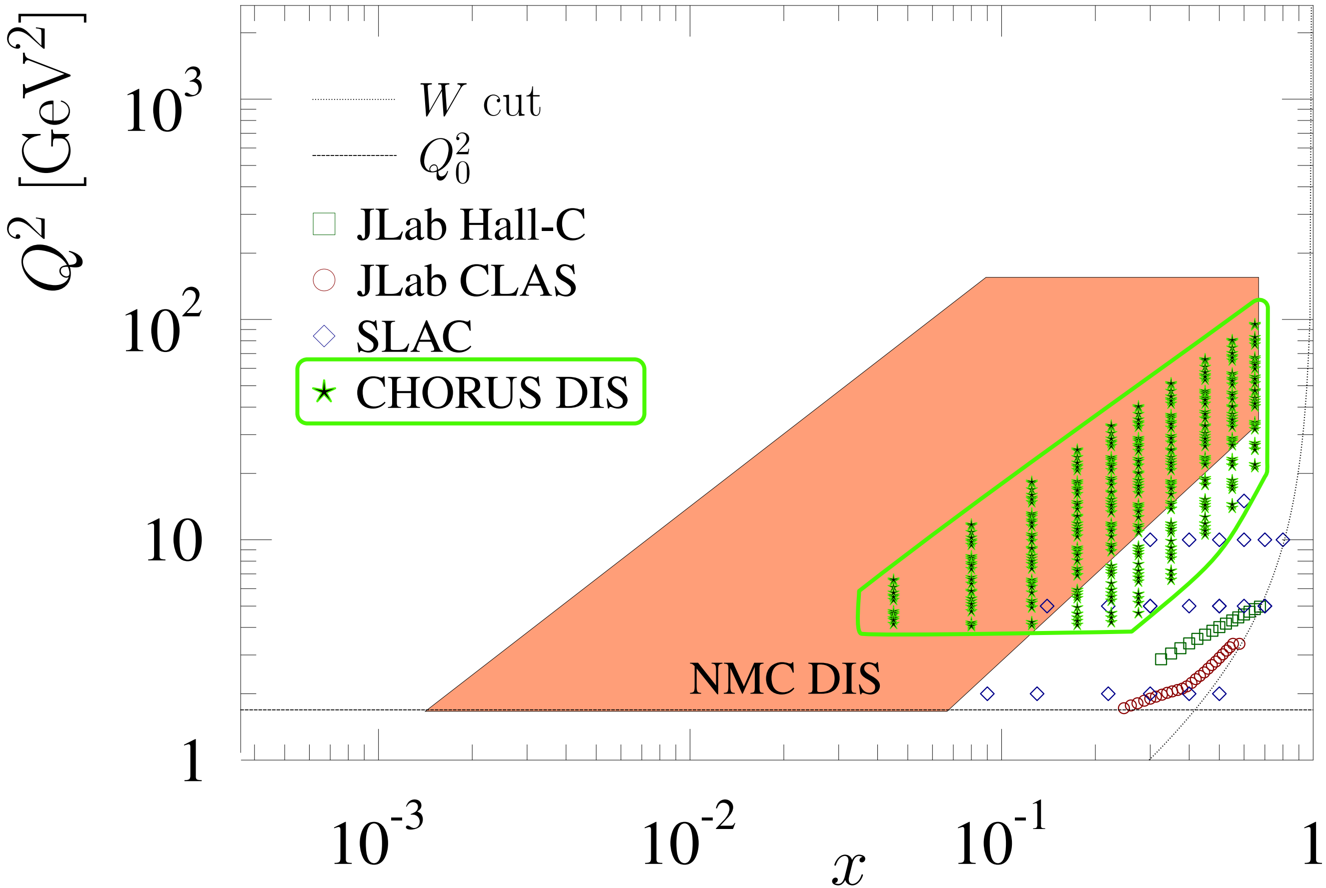


[2012.11566]

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

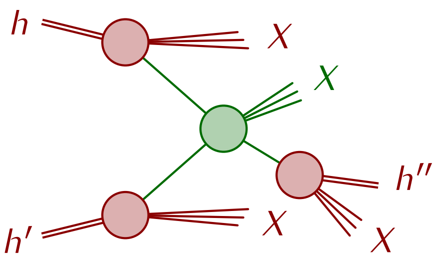
Data: Charged current DIS

Adapted from a figure by EPPS21



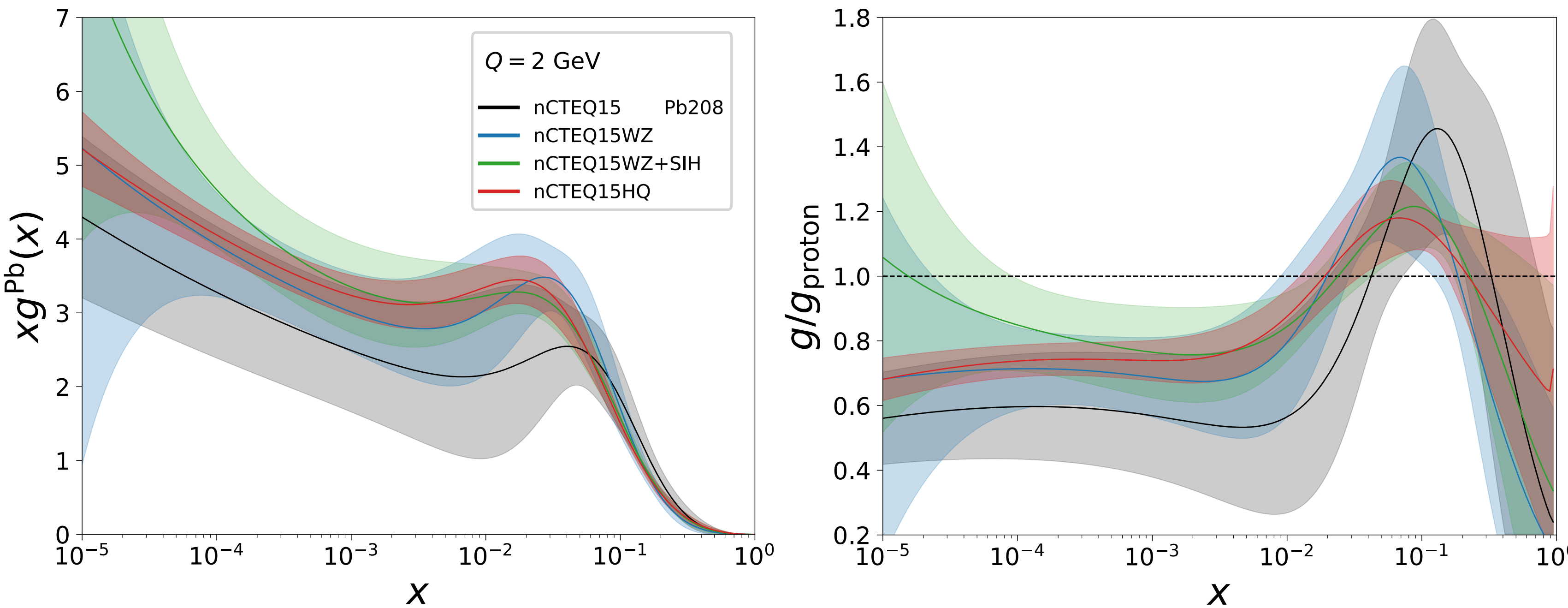
Data: Heavy quark production

	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

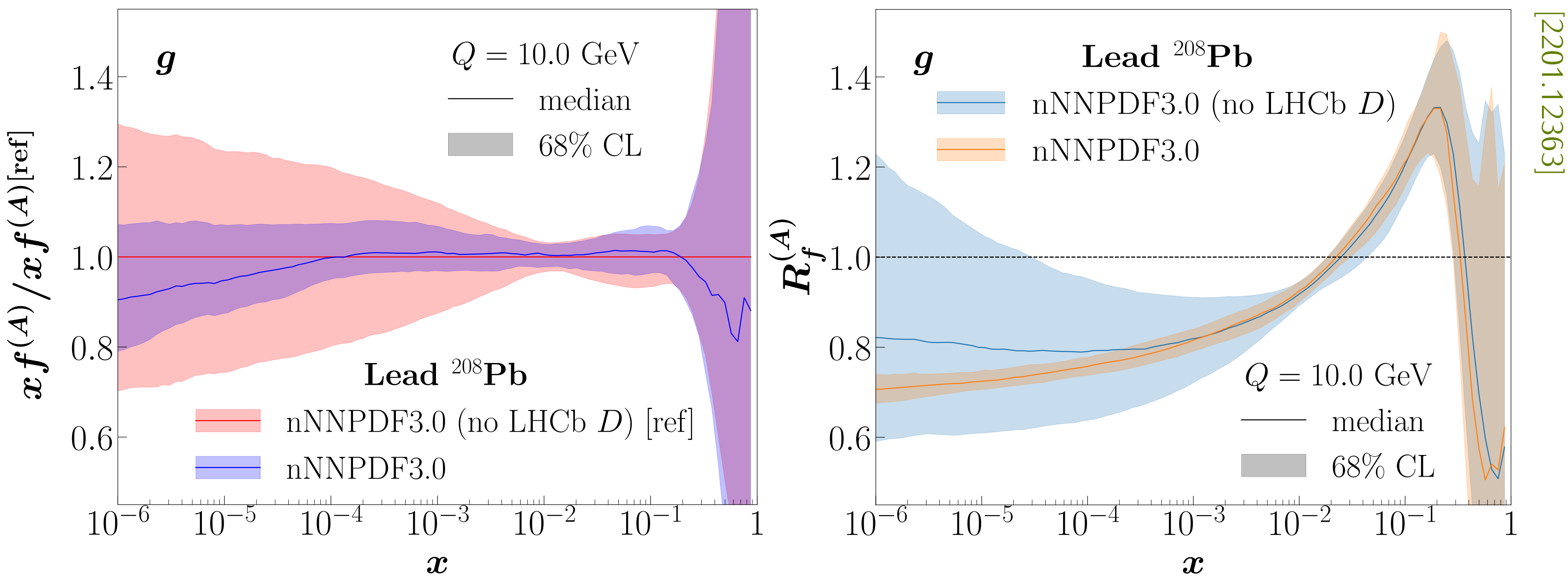
Data: Heavy quark production



[2204.09982]

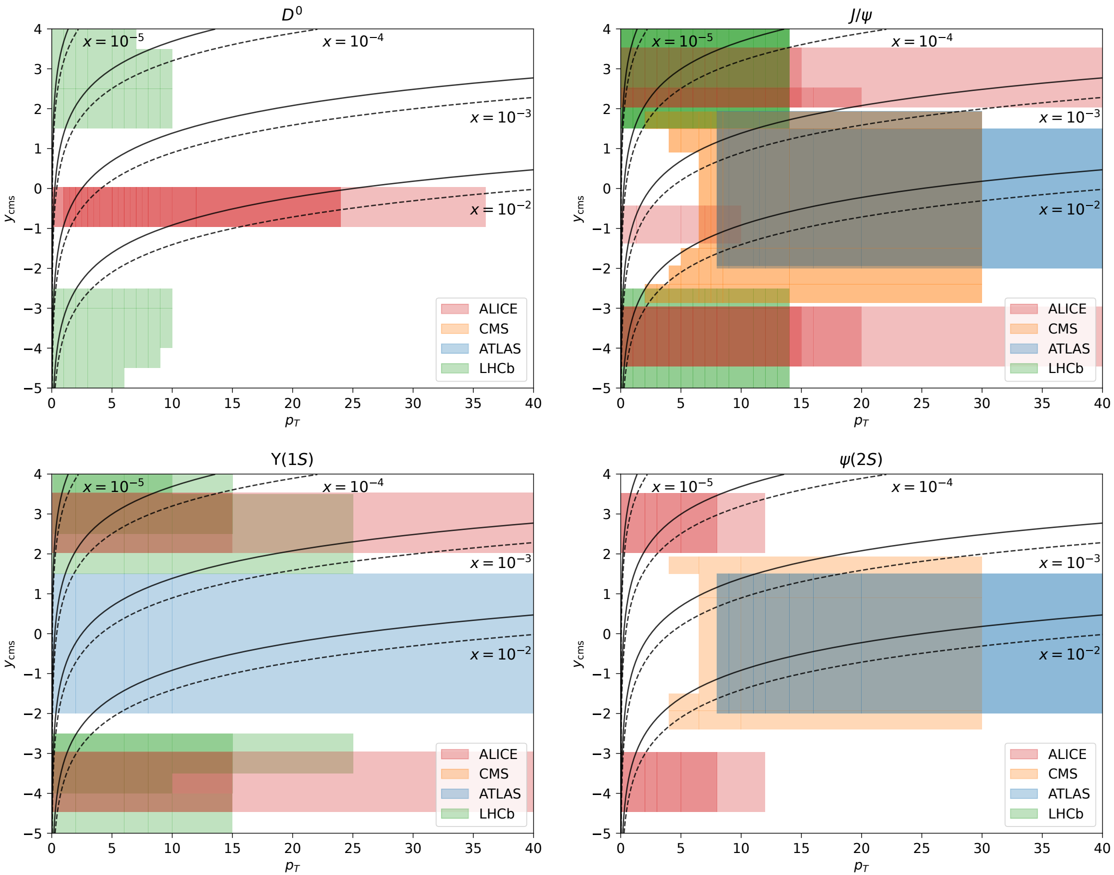
- Impressive reduction of uncertainties down to $x \sim 10^{-5}$

Data: Heavy quark production



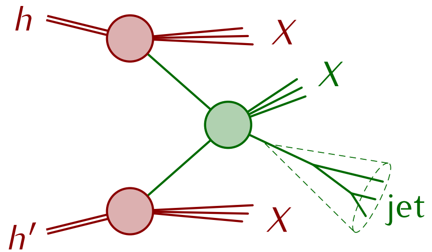
- Impressive reduction of uncertainties down to $x \sim 10^{-6}$

Data: Heavy quark production

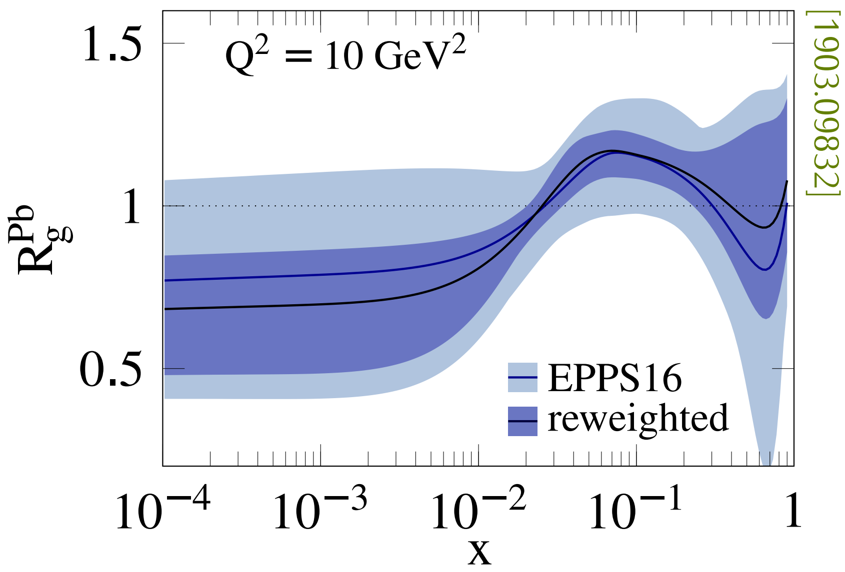


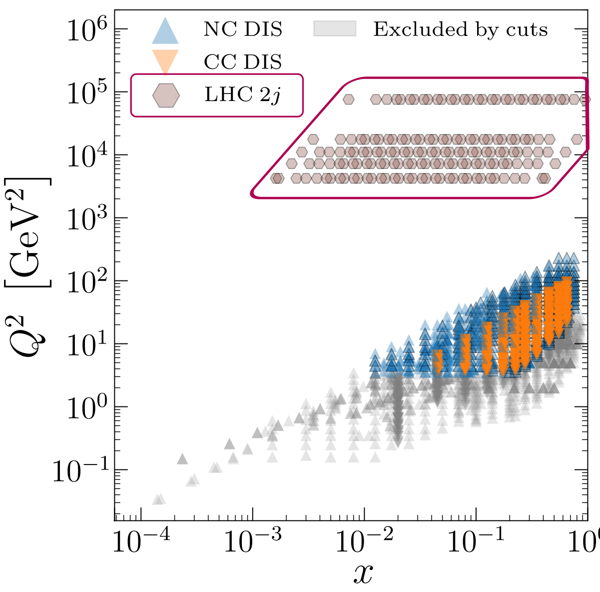
Data: Jet production

	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
  - EPPS:

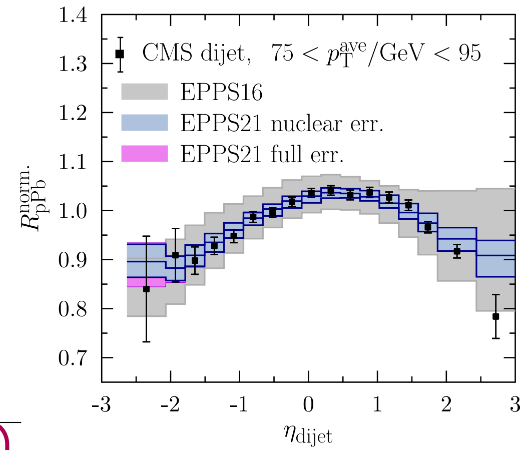
Experiment	Observable	Collisions	Data points	χ^2
CERN CMS	dijet	pPb(208)	83	123.81

  - nNNPDF:

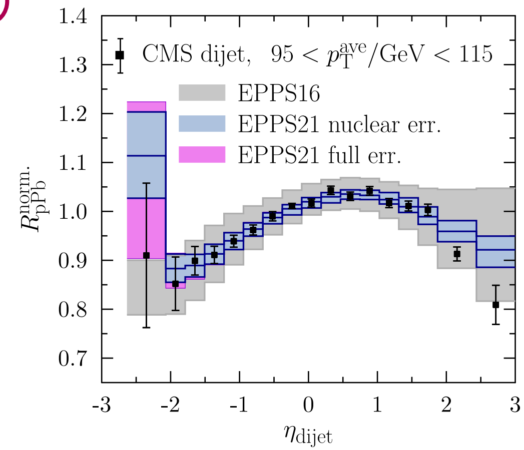
Dataset	n_{dat}	χ^2/n_{dat}
CMS dijet pPb/pp $\sqrt{s} = 5.02$ TeV	84	1.75

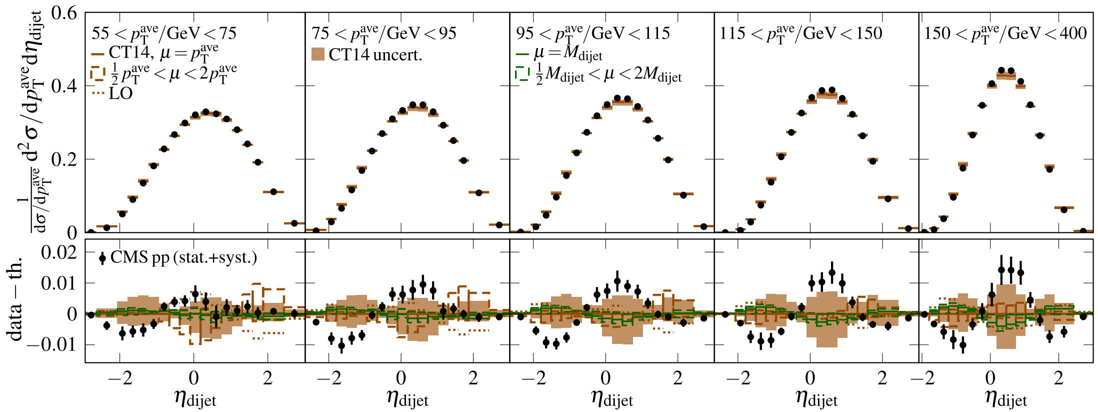
- Not pp, pPb separately

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



[2112.12462]





[1903.09832]

Data: Jet production

- pPb/pp ratios described well
  - EPPS:

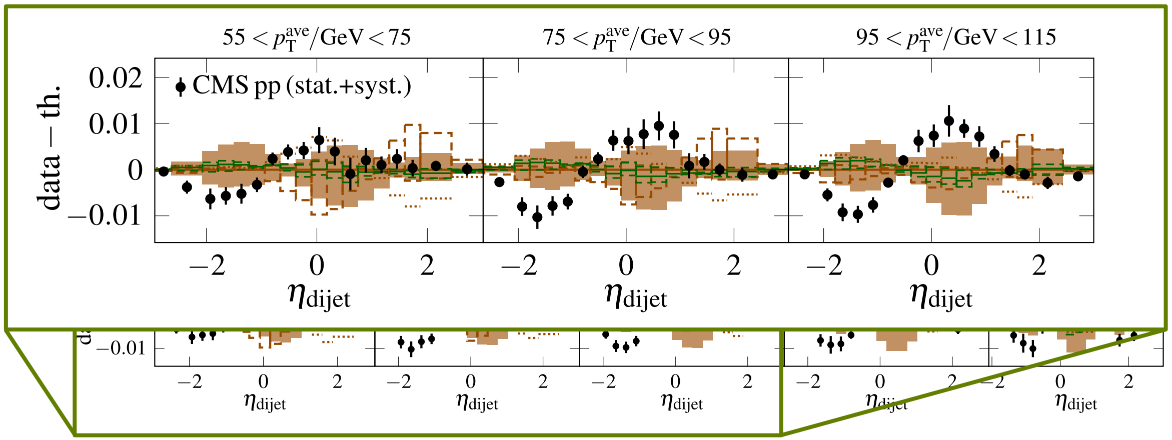
Experiment	Observable	Collisions	Data points	χ^2
CERN CMS	dijet	pPb(208)	83	123.81

  - nNNPDF:

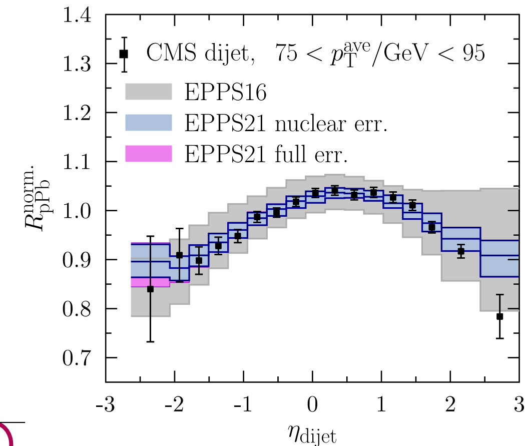
Dataset	n_{dat}	χ^2/n_{dat}
CMS dijet pPb/pp $\sqrt{s} = 5.02$ TeV	84	1.75

- Not pp, pPb separately

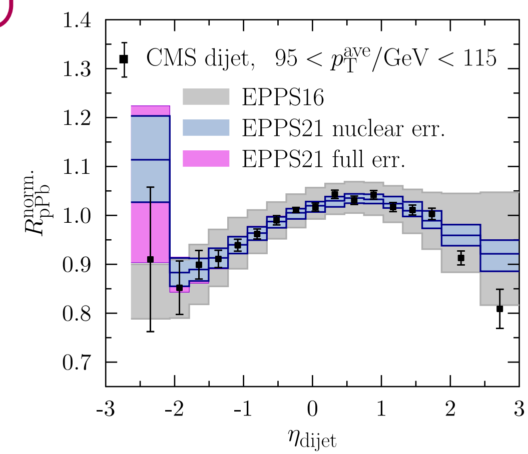
Dataset	n_{dat}	χ^2/n_{dat}
CMS dijet pPb $\sqrt{s} = 5.02$ TeV	85	[13.96]



[1903.09832]



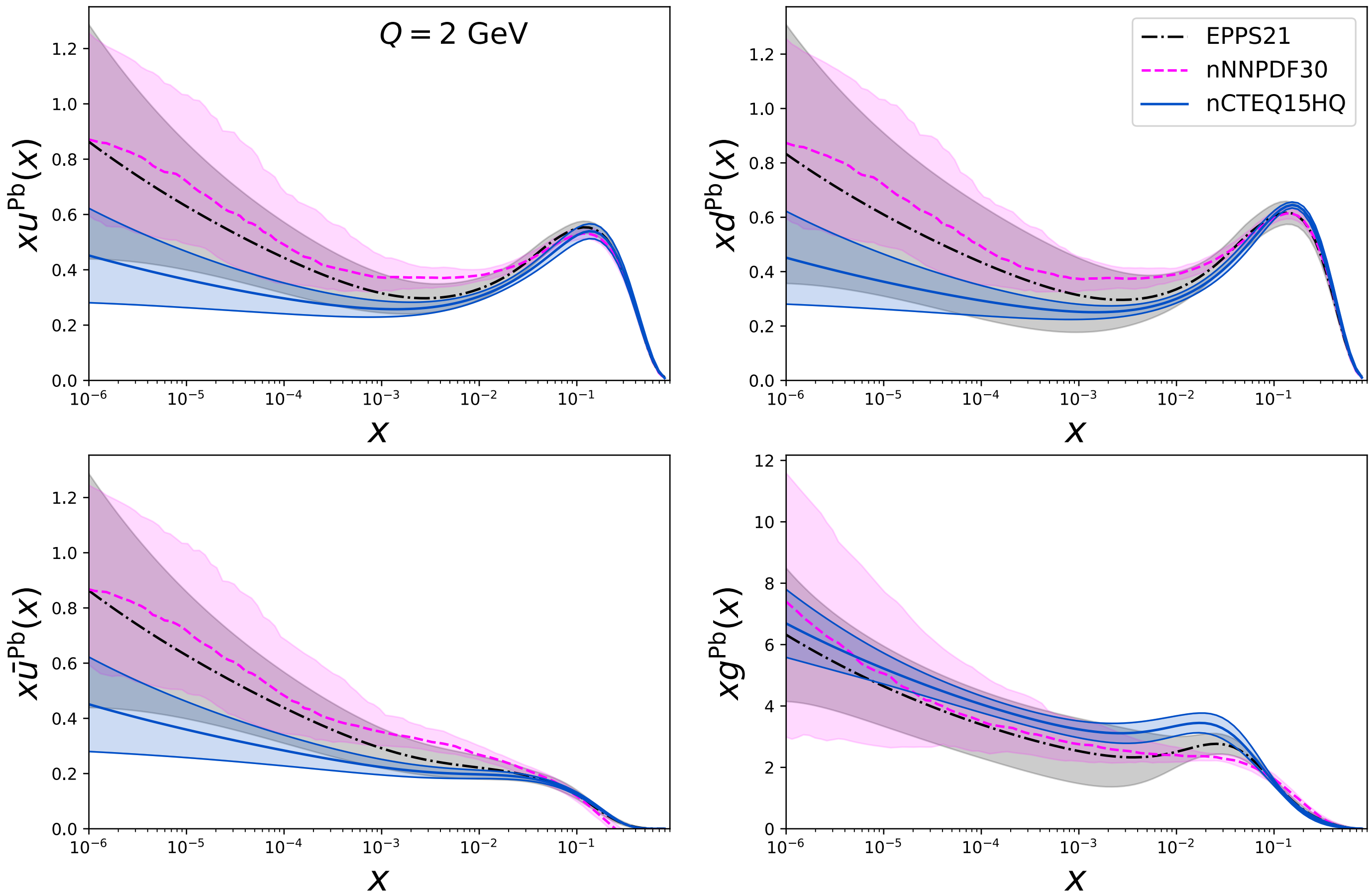
[2112.12462]



Data: not covered today

- Fixed Target DY ($n_{\text{dat}} \sim 100$) 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