Nuclear PDFs and quarkonia

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Synergies between LHC and EIC for quarkonium physics

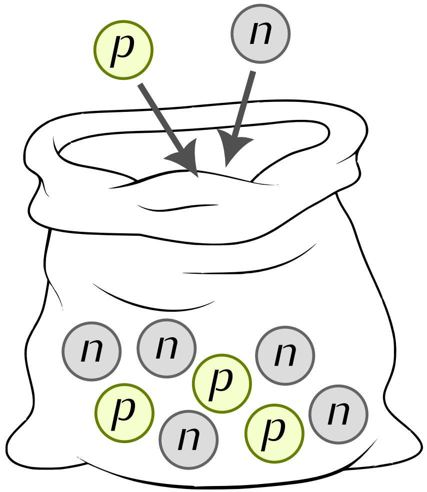
ECT* Trento

nCTEQ
nuclear parton distribution functions

08. July 2024

Structure of nuclei

- Nuclei made up of protons and neutrons ...

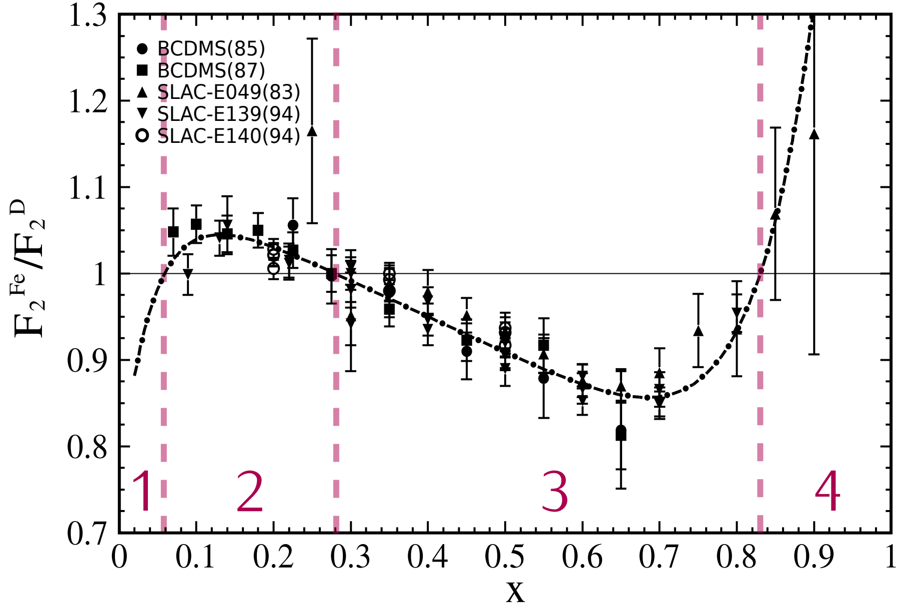


- Free nucleon approximation

$$Af^A \approx Zf^p + Nf^n$$

Structure of nuclei

- 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 nuclear structure determinations

Theoretical framework: collinear factorization

- We rely on collinear factorization

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

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

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

- Hard cross section $d\hat{\sigma}_{ab\to c}(\mu)$
  - 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] May involve second factorization scale and convolution with fragmentation functions.

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Theoretical framework: PDFs

- We rely on collinear factorization
- PDF 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

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

Theoretical framework: PDFs

- We rely on collinear factorization
- PDF x dependence not calculable in pQCD
- PDF μ dependence governed by DGLAP evolution equations

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

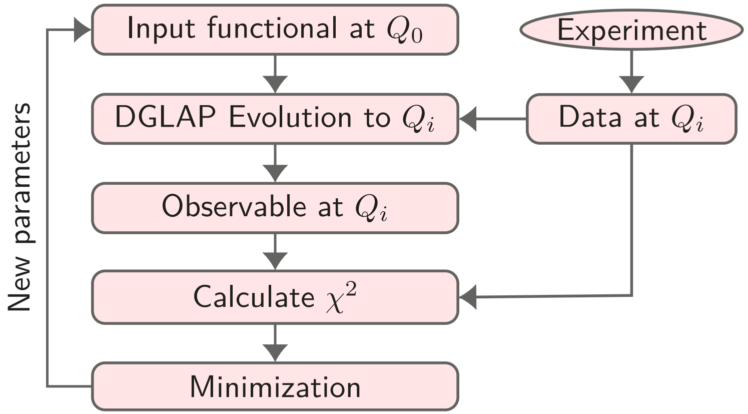
  - Describe violations of Bjorken x scaling
  - Flavours mix: set of $(2n_f+1)$ coupled integro-differential equations.

Theoretical framework: PDFs

- PDF x dependence extracted from data[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.

Theoretical framework: nuclear PDFs

- Nuclear modification can be incorporated into PDF determinations
  - Introduce the notion of bound PDF for flavour i: $f_i^{p/A}(x,\mu,A)$, with A-dependent x parametrization at Q_0
  - $x \in (0, A)$, 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. $f_{d,u}^{n/A} = f_{u,d}^{p/A}$

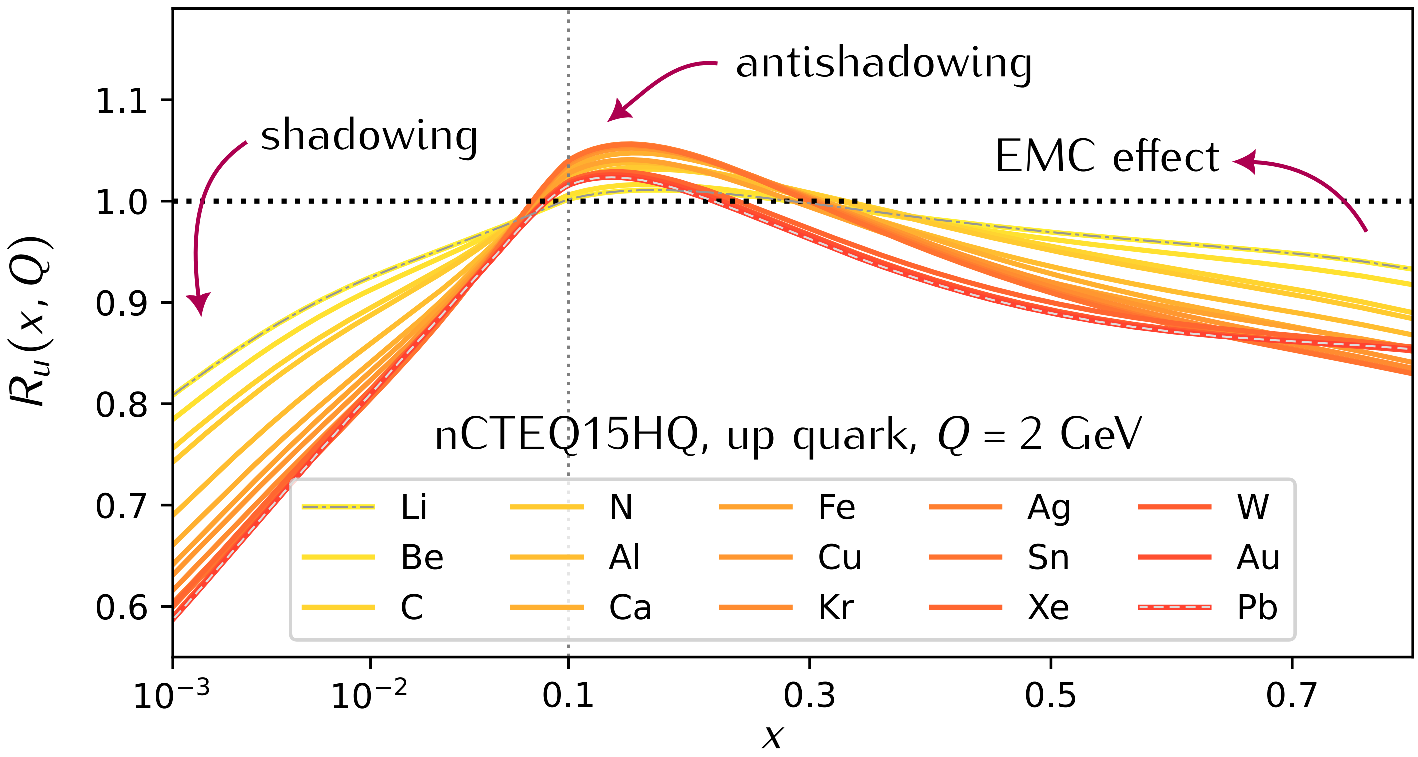
$$f_i^{(A,Z)}(x,\mu) = \frac{Z}{A} f_i^{p/A}(x,\mu,A) + \frac{A-Z}{A} f_i^{n/A}(x,\mu,A)$$

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

[a] Proof of factorization for collisions of nuclei not yet available.

Theoretical framework: nuclear PDFs

- Dependence on A



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 2202.01074
- **nNNPDF**
  - **nNNPDF1.0:** 1904.00018
  - **nNNPDF2.0:** 2006.14629
  - **nNNPDF3.0:** 2201.12363
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  - **nCTEQ09:** 0907.2357
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  - **nCTEQ15WZSIH:** 2105.09873
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  - **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

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Outdated

- nDS
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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**; ...

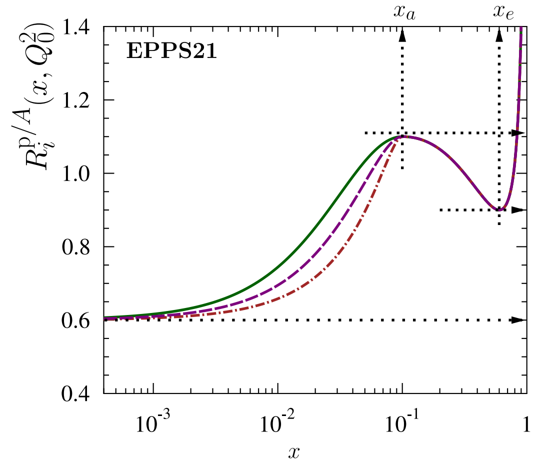
Global analyses of nPDFs

- 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

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

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



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: nPDF; analytic parametrization; A, x mix

e.g. in nCTEQ15

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

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

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- Data selection: discussed in the next few slides

Data: Neutral current DIS

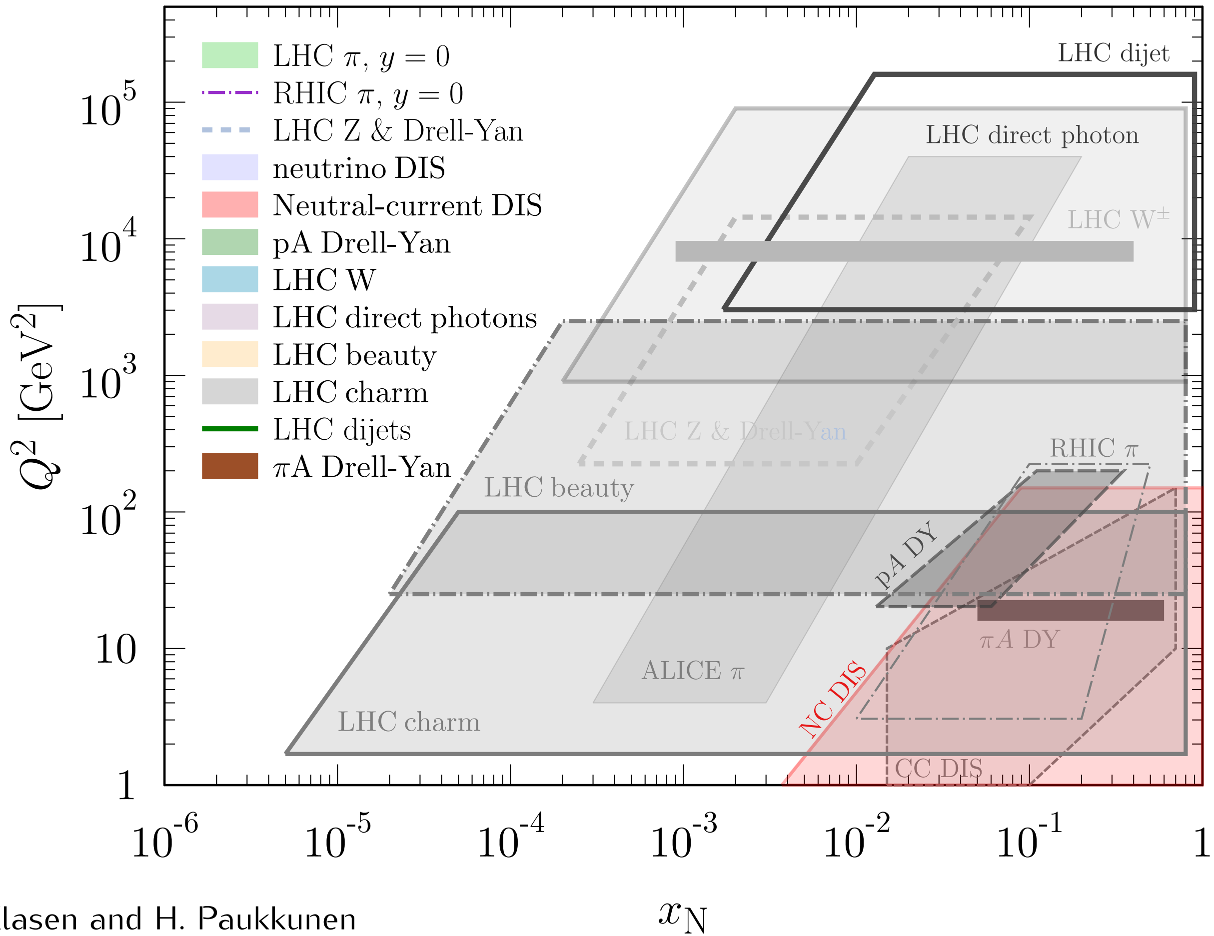
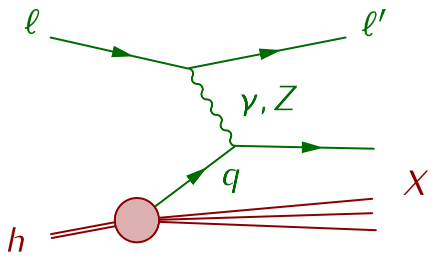


Figure from M. Klasen and H. Paukkunen

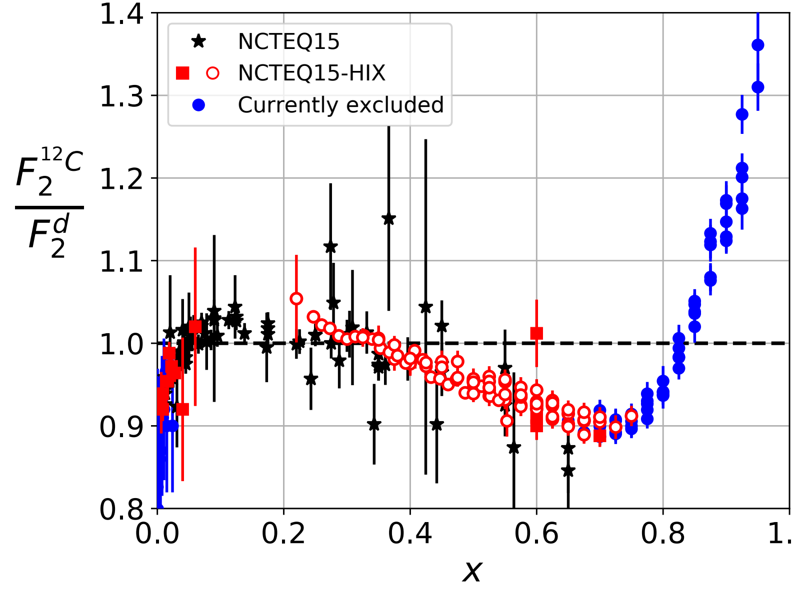
Data: Neutral current DIS

[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.

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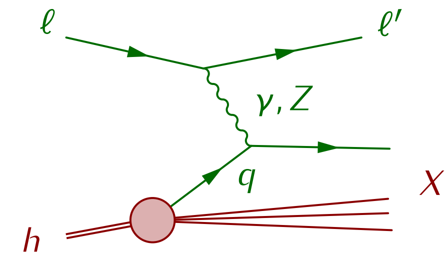

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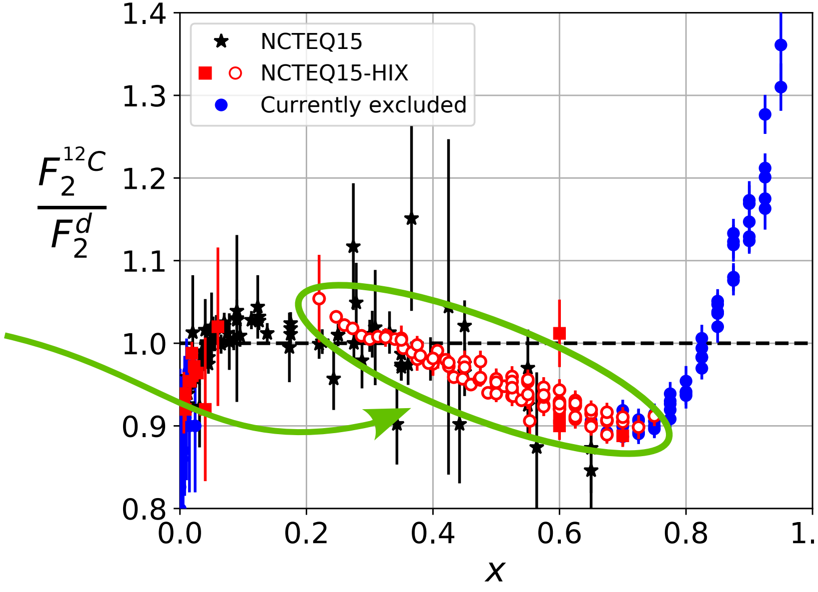

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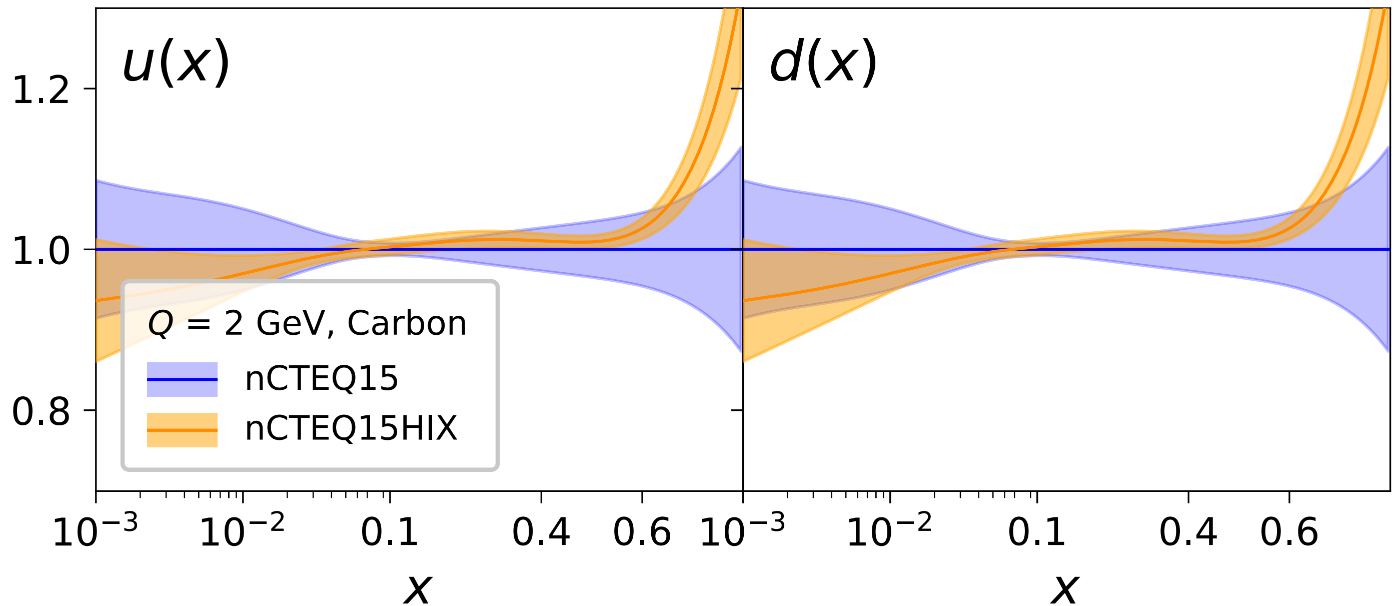

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- Valence quark uncertainties strongly reduced, in particular in high-x!

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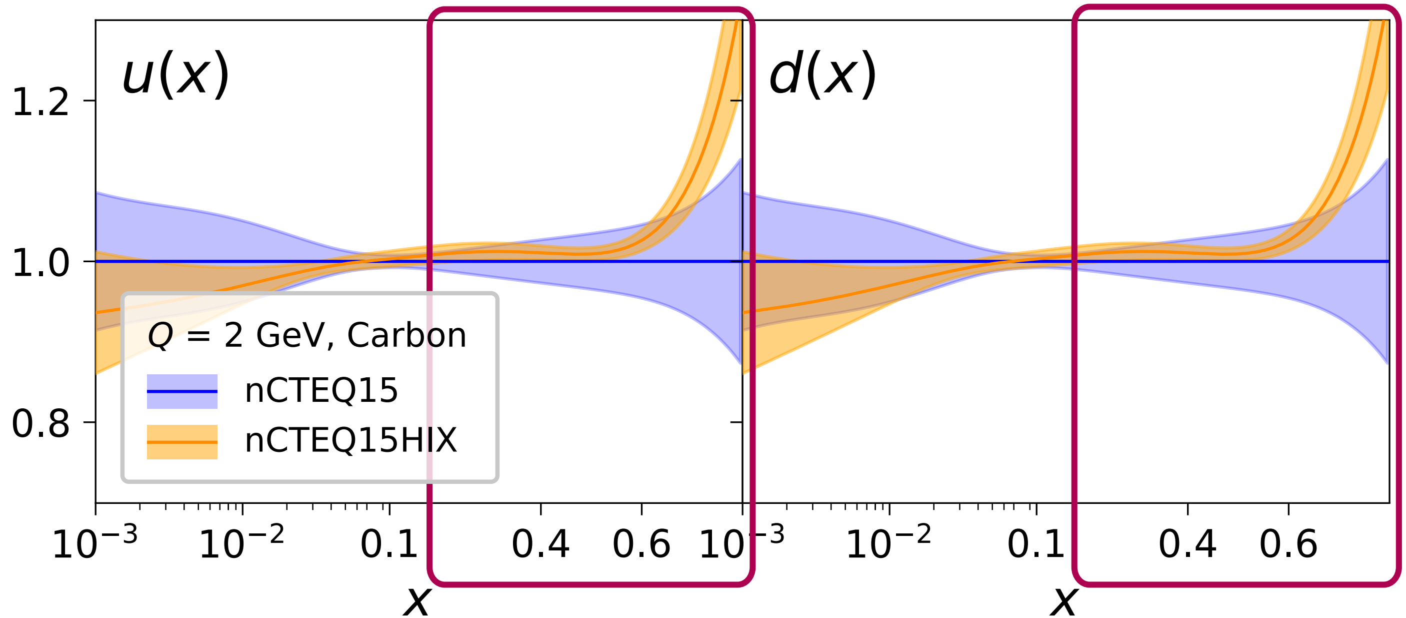

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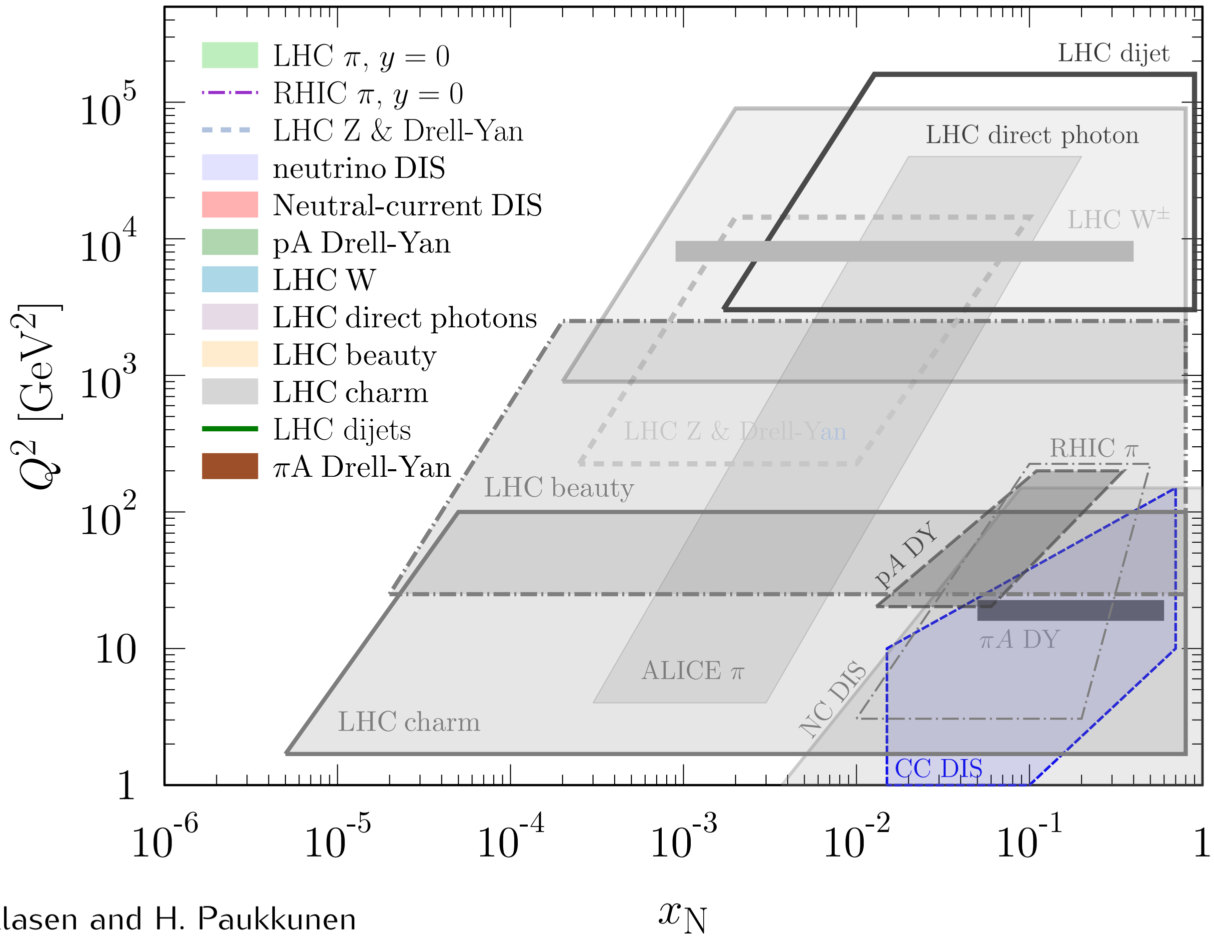
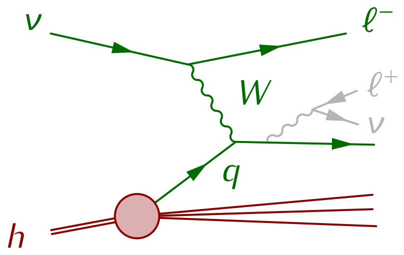


Figure from M. Klasen and H. Paukkunen

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

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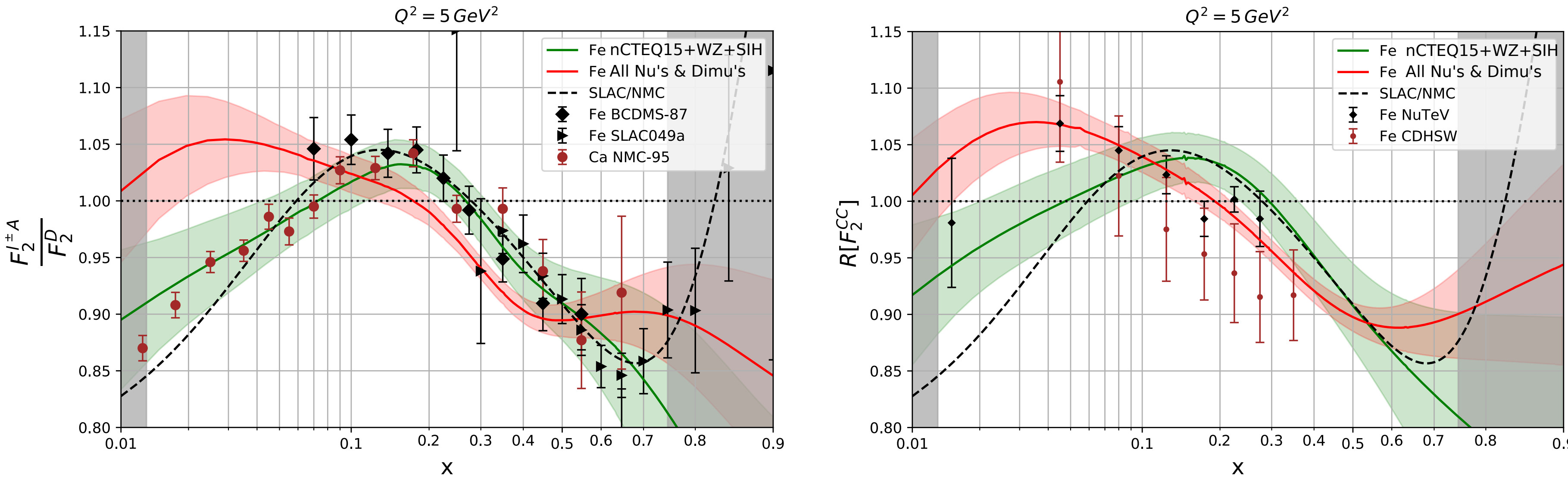


- NuTev, CCFR and CDHSW data in tension with NC DIS data. Dropping correlations alleviates the tension but doesn't resolve it.

Data: Open heavy quarks and quarkonia

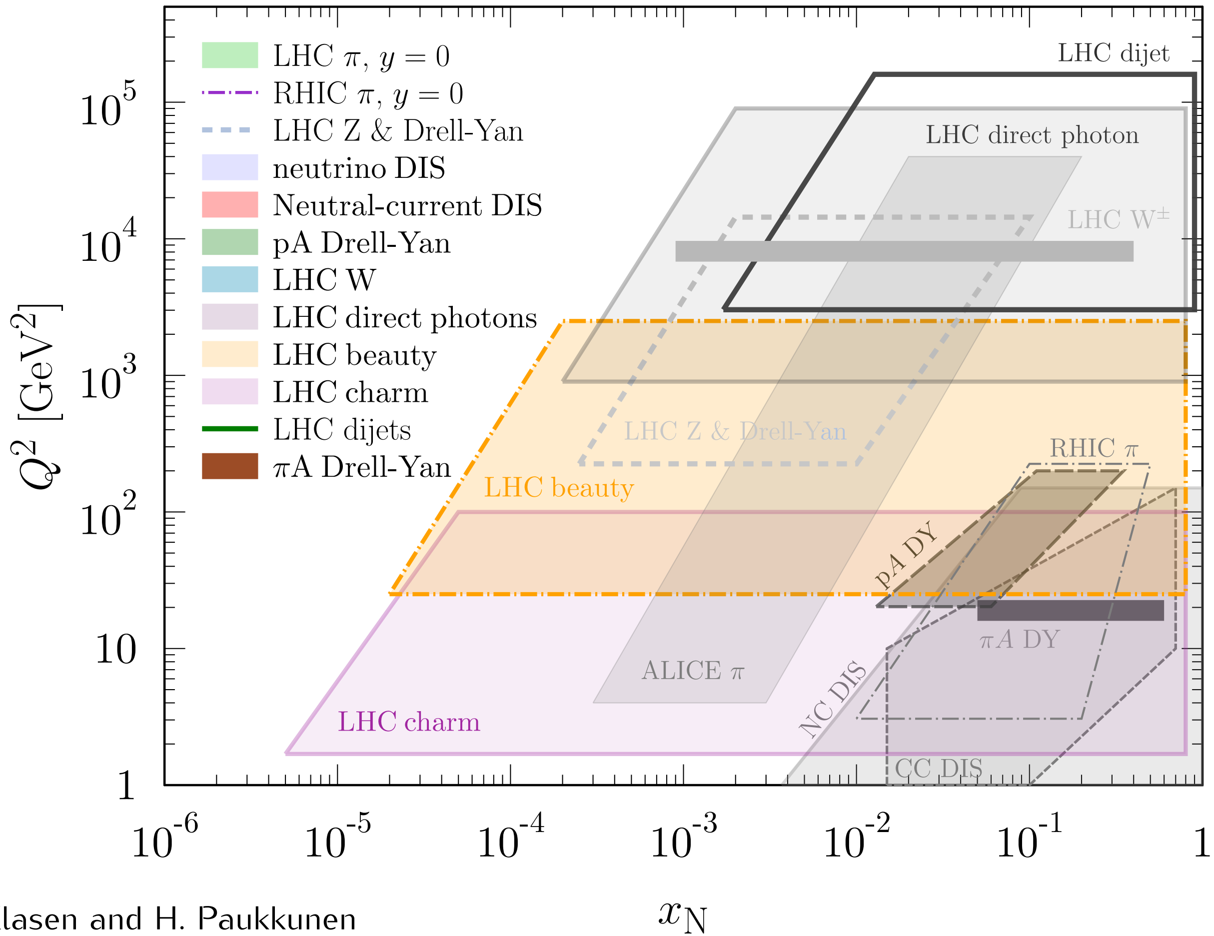
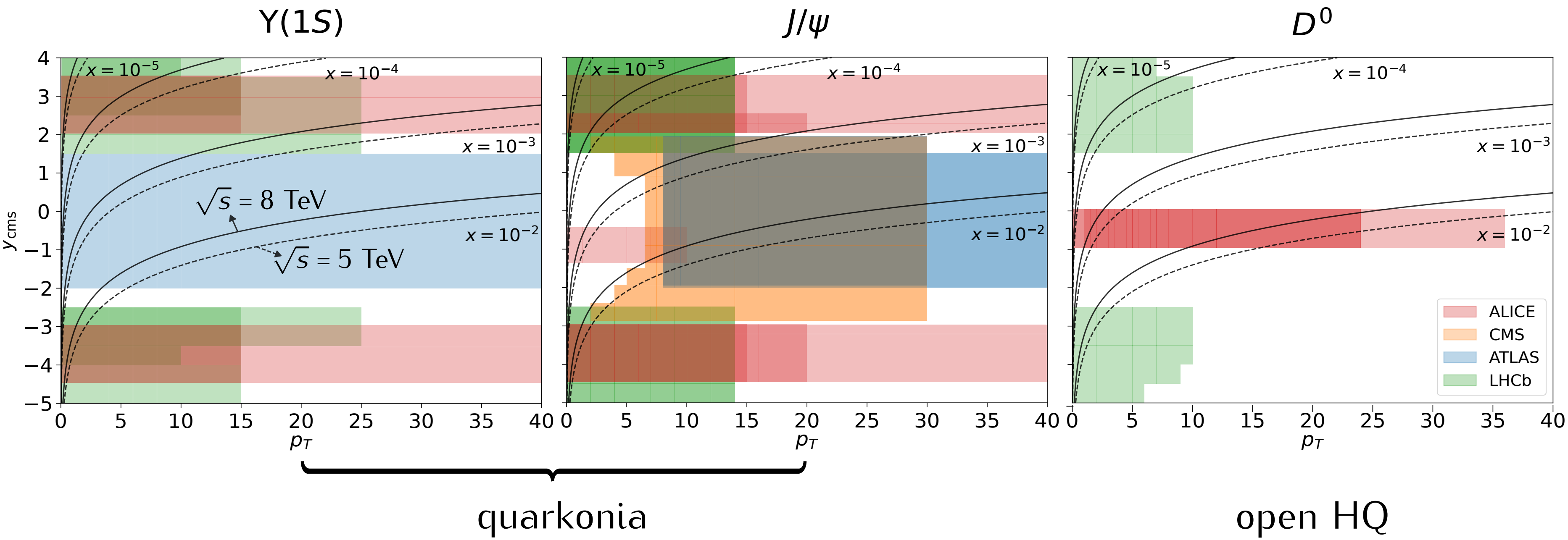


Figure from M. Klasen and H. Paukkunen

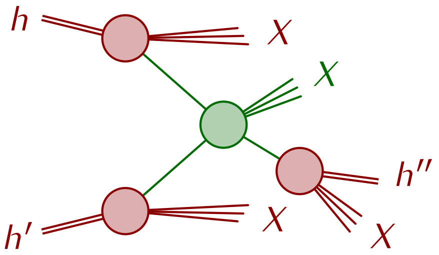
Data: Open heavy quarks and quarkonia

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



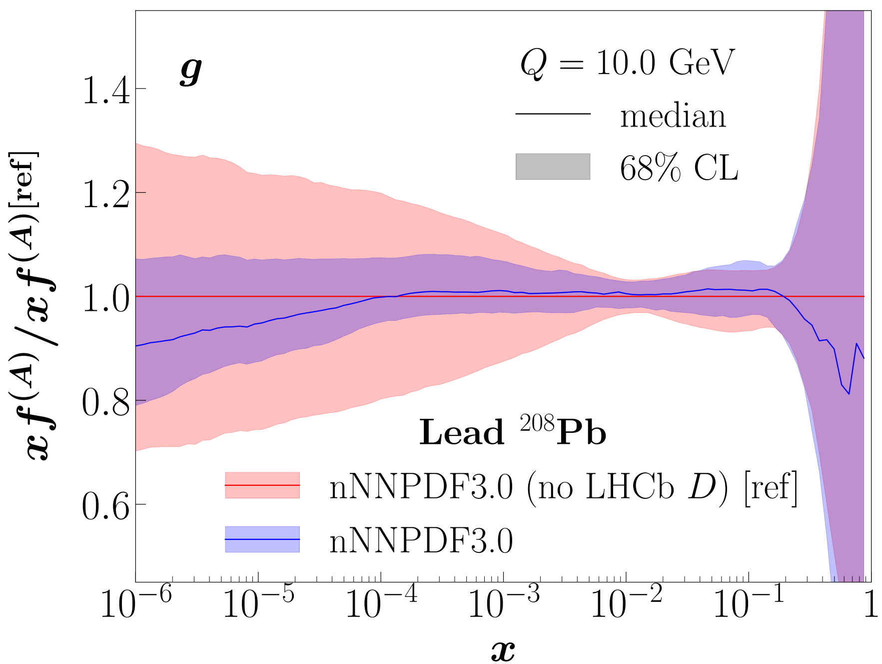
Data: Open heavy quarks and quarkonia

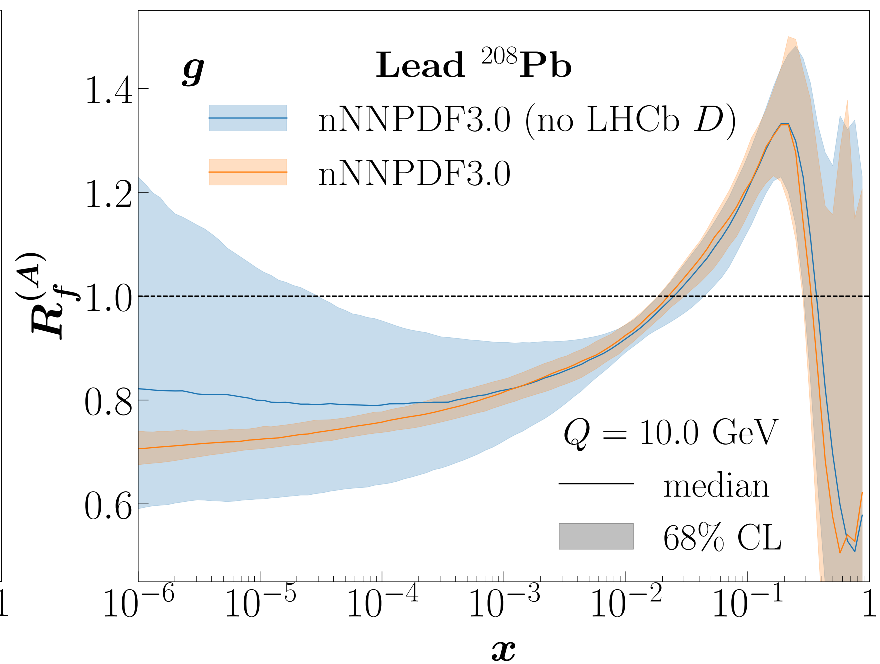
	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15HQ
open HF	-	-	48	37	82
quarkonia	-	-	-	-	466



- 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: Open heavy quarks





[2201.12363]

- nNNPDF reweights with open HQ: impressive reduction of uncertainties down to very low $x \sim 10^{-6}$

Data: Quarkonia

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

- We employ a data driven approach[a]
  - Rely on gg dominance and fit the matrix element:

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

parametrized with extended Crystall ball, 5 free parameters

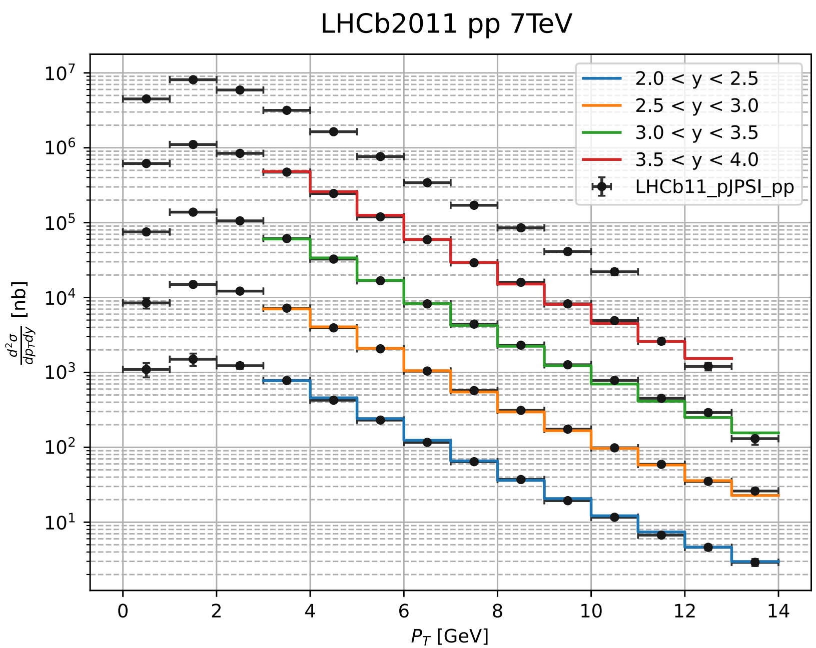
  - in pp data (different ME for each final state)
  - and use it to determine nPDFs in pA data

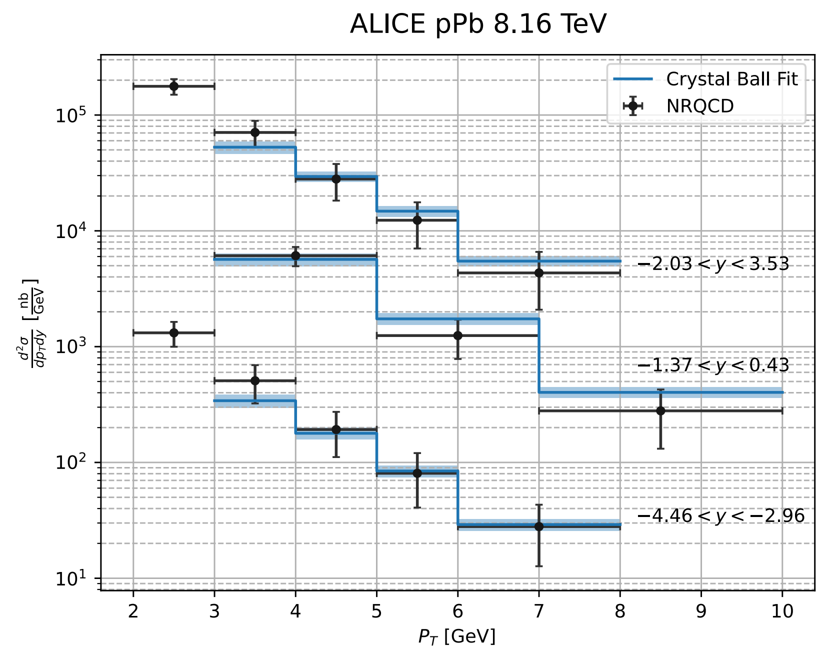
[a][PRL 107 (2011) 082002, PRL 121 (2018) 052004, PRD 104 (2021) 014010]

Data: Quarkonia

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

- Matrix element fit: pp data above $p_T > 3$ GeV[a]
  - J/ψ: $\chi^2/n_{\text{dof}} = 0.88$, $n_{\text{dat}} = 501$
  - $\psi(2S)$: $\chi^2/n_{\text{dof}} = 0.77$, $n_{\text{dat}} = 55$
  - $\Upsilon(1S)$: $\chi^2/n_{\text{dof}} = 0.92$, $n_{\text{dat}} = 375$





[a] The cut removes ~ 15% of data.

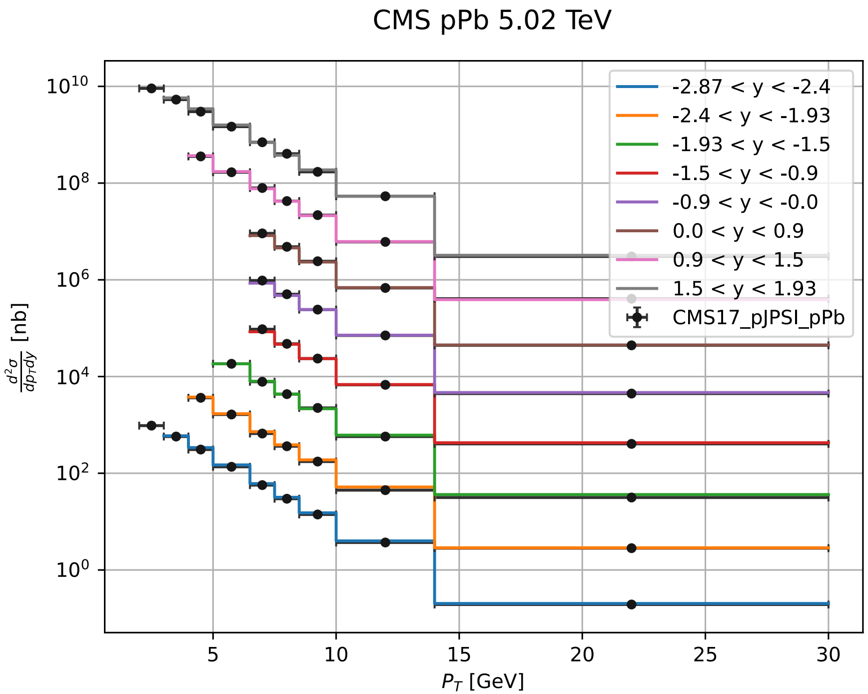
Data: Quarkonia

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

- nPDF fit: pPb data above $p_T > 3$ GeV[a]

	D^0	J/ψ	$\Upsilon(1S)$	$\psi(2S)$
nCTEQ15	(0.56)	(2.50)	(0.82)	(1.06)
nCTEQ15WZ	(0.32)	(1.04)	(0.76)	(1.02)
nCTEQ15WZ+SIH	(0.46)	(0.84)	(0.90)	(1.07)
nCTEQ15HQ	0.35	0.79	0.79	1.06

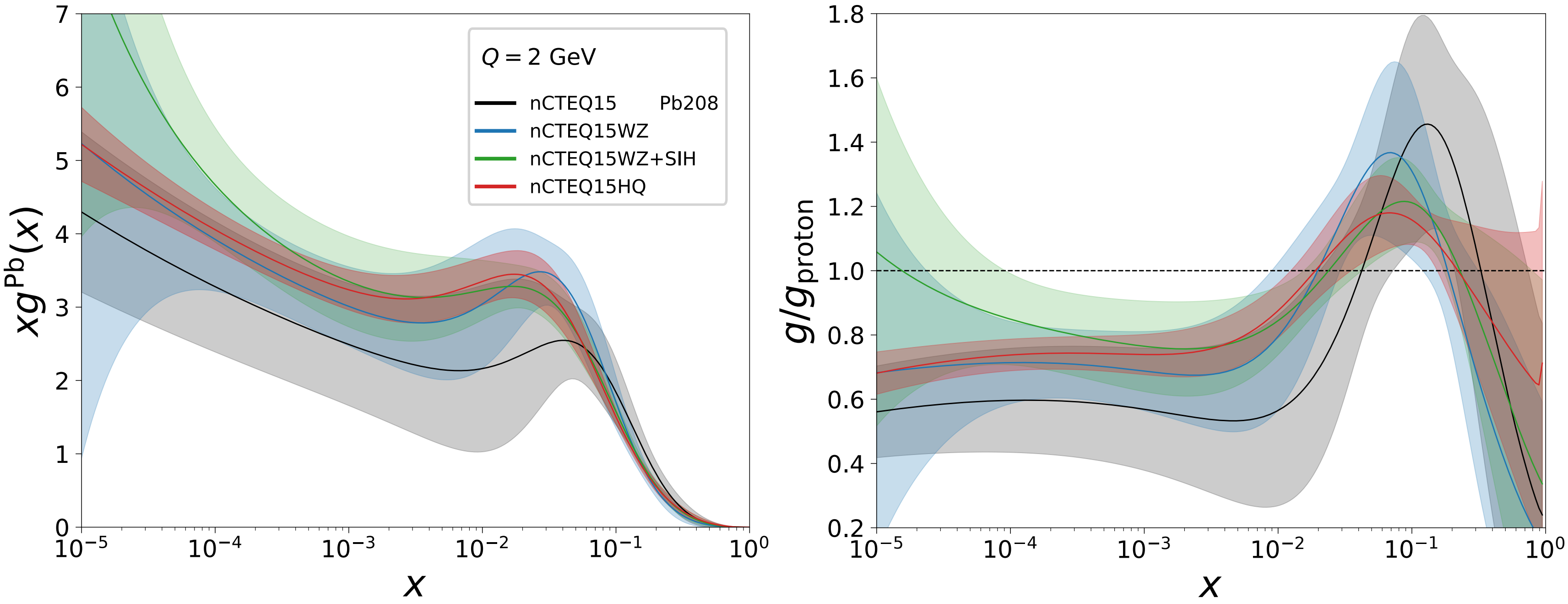
	DIS	DY	WZ	SIH	HQ	**Total**
nCTEQ15	0.86	0.78	(2.19)	(0.78)	(1.96)	**1.23**
nCTEQ15WZ	0.91	0.77	0.63	(0.47)	(0.92)	**0.90**
nCTEQ15WZ+SIH	0.91	0.77	0.72	0.40	(0.93)	**0.92**
nCTEQ15HQ	0.93	0.77	0.78	0.40	0.77	**0.86**



[a]The cut removes ~ 35% of data (714 pts).

Data: Quarkonia

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



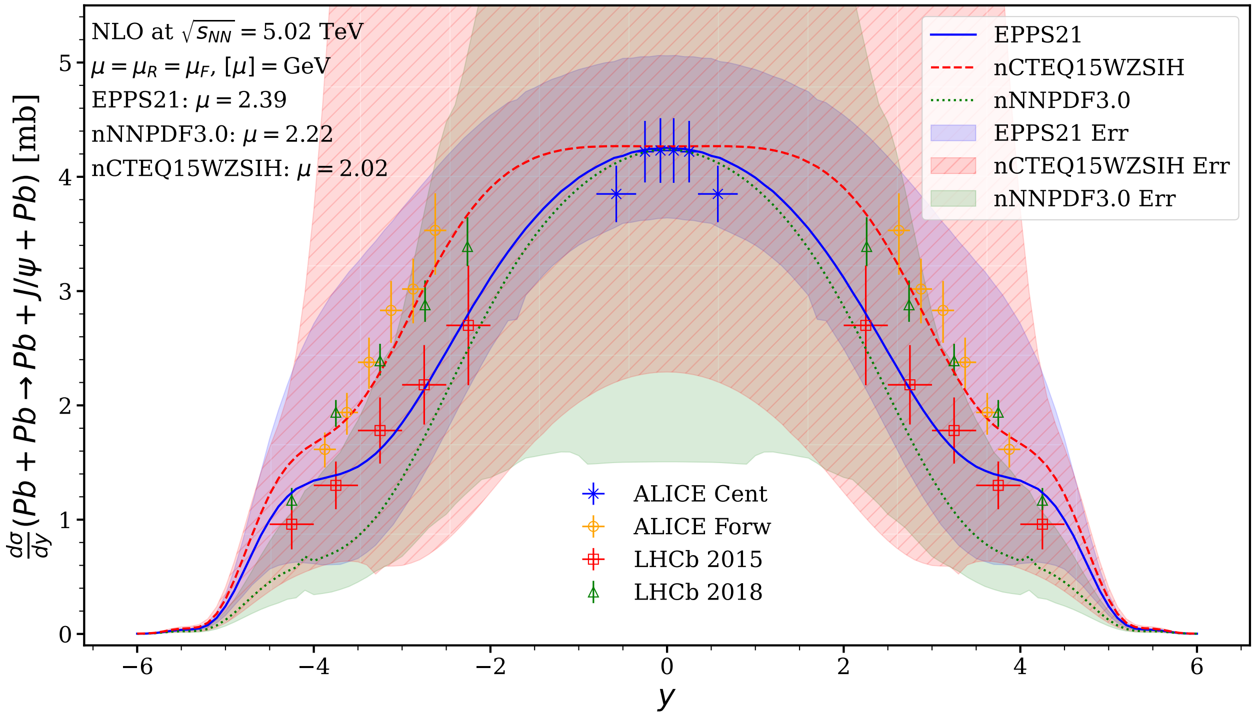
- Impressive reduction of uncertainties down to $x \sim 10^{-5}$

Data: other

- Fixed Target DY ($n_{\text{dat}} \sim 100$) [all but TUJU] and LHC W, Z ($n_{\text{dat}} \sim 150$) production [all but KSASG]
  - Useful for strange distribution, but also for gluon
- Dijets ($n_{\text{dat}} \sim 100$) [EPPS, nNNPDF]
  - Important for low-x gluon
  - pPb/pp ratio described well, absolute pPb no that well
- Single inclusive light flavours ($n_{\text{dat}} \sim 300$) [EPPS, nCTEQ])
  - Constrains gluon
  - Almost 2/3 points in a very low p_T difficult to describe
- Direct photon production ($n_{\text{dat}} \sim 50$) [nNNPDF]
  - Extra handle on gluon
  - pPb/pp ratio described well, absolute pPb no that well

Data: other

- Quarkonia from UPC PbPb collisions at LHC very promising[a]



[a][2203.11613, 2210.16048, 2303.03007]

Data: Future Neutral current DIS @ EIC

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

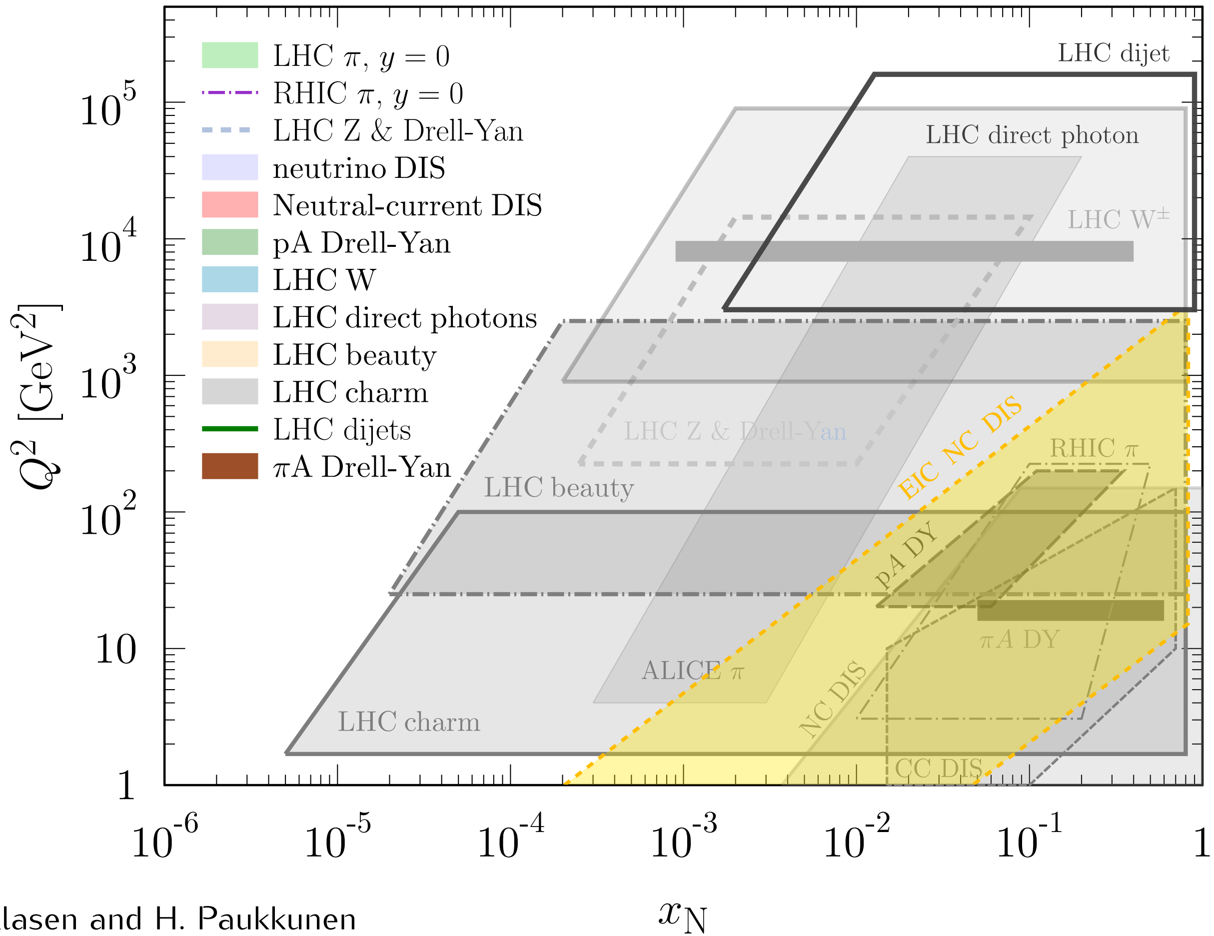
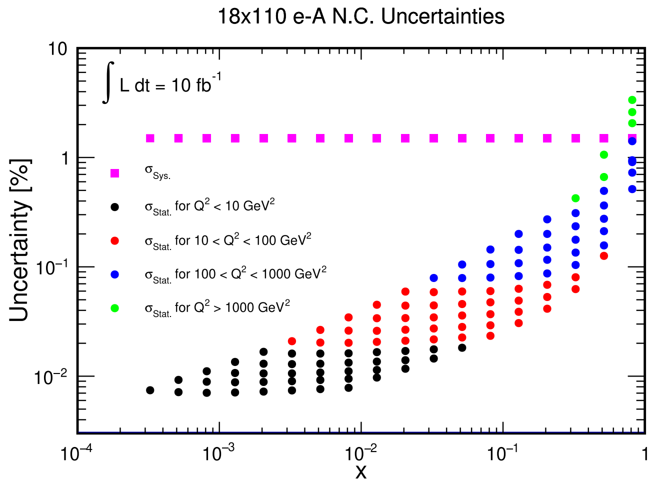


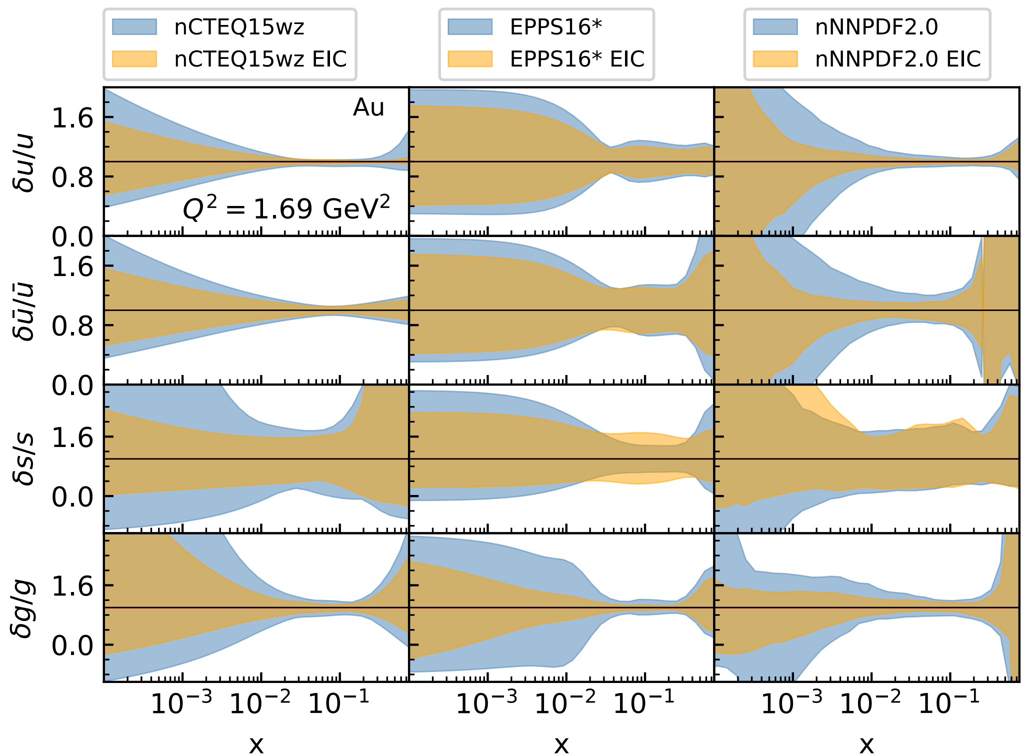
Figure from M. Klasen and H. Paukkunen

Data: Future Neutral current DIS @ EIC

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

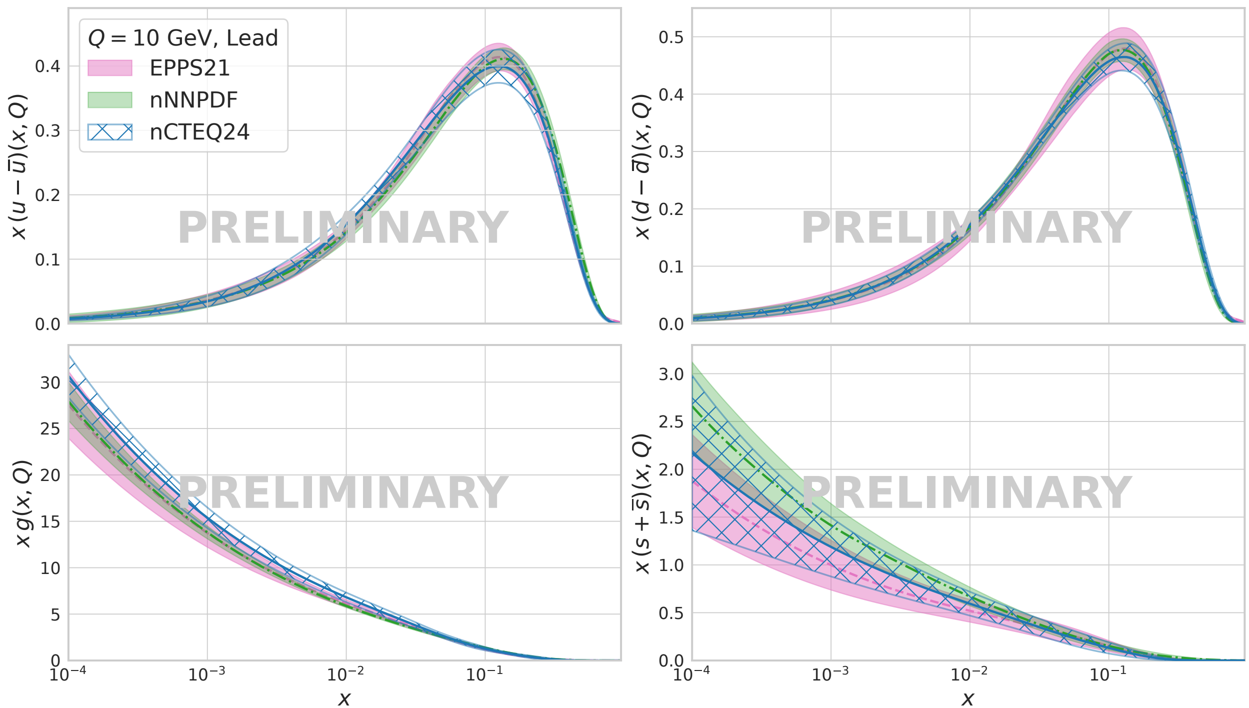
- A reweighting study: remarkable reduction of uncertainties accross the board





Comparison of nPDFs

- New global release from nCTEQ (work in progress)
  - Good agreement between EPPS, nNNPDF and nCTEQ (new global release)
  - nCTEQ: slightly different valence uncertainties and a higher gluon



Summary and outlook

- I reviewed:
  - The frameworks used in most recent global analyses of nPDFs
  - Status on data inclusion, with focus on quarkonia at LHC
    - Excellent description of over pPb with ME fitted in pp data
- Expected impact of selection of future data: EIC
- Overall: nPDF extraction is a very active field with a rich future ahead

- We're working on a new global release:
  - Modern proton baseline
  - Extended cuts (TMCs, HT)
  - Combine all recent data: NC DIS JLAB, CC DIS, HQ, ...