Pinning down nuclear PDFs with the LHC data

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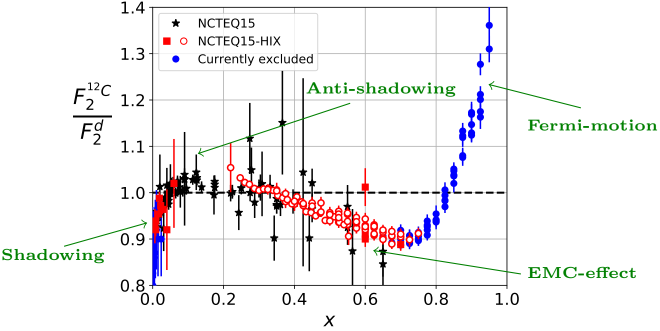
Structure of nuclei

- First approximation: nuclei consist of **free** protons and neutrons **does not work**

$$F_2^A(x) \neq Z F_2^p(x) + N F_2^n(x)$$

- Cross-sections in nuclear collisions are modified



- Can we translate this modifications into ***universal*** quantities – **nuclear PDFs** (nuclear Parton Distribution Functions)?

Collinear factorization

- Can we translate this modifications into ***universal* nuclear PDFs**?
- Natural theoretical framework: **collinear factorization**

DY-like processes

$$d\sigma_{pp\to l\bar{l}X} = \sum_{i,j=q,\bar{q},g} f_i(x_1,\mu) \otimes f_j(x_2,\mu) \otimes d\hat{\sigma}_{ij\to l\bar{l}X} + \mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{Q^2}\right)$$

DIS-like processes

$$\frac{d^2\sigma}{dx dQ^2} = \sum_{i=q,\bar{q},g} f_i(x,\mu) \otimes d\hat{\sigma}_{il\to l'X} + \mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{Q^2}\right)$$

- **Parton-level cross-section**
  - process-dependent
  - perturbative (calculable order by order in α_S)
- **Nuclear PDFs**
  - universal
  - non-perturbative (not calculable)

Properties of PDFs

- **Sum rules**
  - **Number sum rules** – connect partons to quarks from SU(3) flavour symmetry of hadrons; proton (uud), neutron (udd). For protons:

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

  - **Momentum sum rule** – momentum conservation connecting all flavours

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

- **Scale dependence**
  - x-dependence of PDFs is NOT calculable in pQCD
  - μ^2-dependence is calculable in pQCD – given by **DGLAP** equations

DGLAP evolution equations

$$\frac{d f_q(x,\mu^2)}{d\log\mu^2} = \frac{\alpha_S(\mu^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}\left(\frac{x}{y}\right) f_q(y,\mu^2) + P_{qg}\left(\frac{x}{y}\right) f_g(y,\mu^2)\right]$$

$$\frac{d f_g(x,\mu^2)}{d\log\mu^2} = \frac{\alpha_S(\mu^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{gg}\left(\frac{x}{y}\right) f_g(y,\mu^2) + P_{gq}\left(\frac{x}{y}\right) f_q(y,\mu^2)\right]$$

- Different PDFs mix – set of $(2n_f + 1)$ coupled integro-differential equations.
- Splitting functions are calculable in pQCD $P_{ij}(z) = P_{ij}^{(0)}(z) + \frac{\alpha_S}{2\pi} P_{ij}^{(1)}(z) + \cdots$

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  - x-dependence of PDFs is NOT calculable in pQCD
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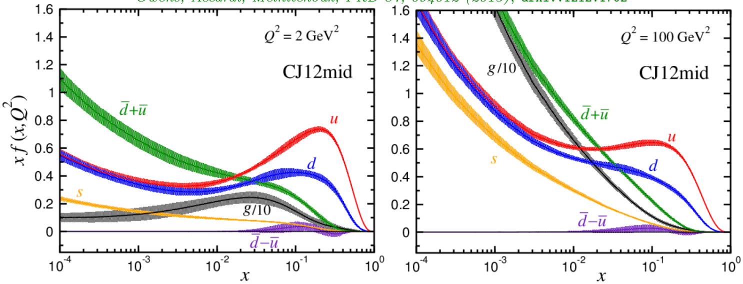
Owens, Accardi, Melnitchouk, PRD 87, 094012 (2013), arXiv:1212.1702



Schematics of Global Analysis

1. Choose experimental data (e.g. DIS, DY, inclusive jet prod., etc.)
2. Parametrize **nuclear PDFs** at low initial scale $\mu = Q_0 \sim 1\text{GeV}$:

$$f_i^{(A,Z)}(x,Q) = \frac{Z}{A} f_i^{p/A}(x,Q) + \frac{A-Z}{A} f_i^{n/A}(x,Q)$$
$$f_i^{p/A}(x,Q_0) = f_i^{p/A}(x; c_0, c_1, \dots) = c_0 x^{c_1} (1-x)^{c_2} P(x; c_3, \dots)$$

with $c_j = c_j(A) \overset{\text{nCTEQ}}{=} p_k + a_k \left(1 - A^{-b_k}\right)$ depending on the nuclei;
$f_i^{n/A}(x,Q)$ - from isospin symmetry.

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$f_i^{n/A}(x,Q)$ - from isospin symmetry.

3. Use DGLAP equation to evolve $f_i(x,\mu)$ from $\mu = Q_0$ to $\mu = Q_{\text{max}}$.
4. Calculate theory predictions corresponding to the data (σ_{DIS}, σ_{DY}, etc.).
5. Calculate appropriate χ^2 function – compare data and theory

$$\chi^2(\{c_i\}) = \sum_{\text{data points}} \left(\frac{\text{data} - \text{theory}(\{c_i\})}{\text{uncertainty}} \right)^2$$

6. Minimize χ^2 function with respect to parameters $c_0, c_1, \dots$
7. Compute uncertainties (Hessian, Monte Carlo)

nuclear PDFs in pre-LHC time

- **Multiplicative nuclear correction factors**

$$f_i^{p/A}(x_N, \mu_0) = R_i(x_N, \mu_0, A)\ f_i^{free\ proton}(x_N, \mu_0)$$

  - **HKN**: Hirai, Kumano, Nagai
    [PRC 76, 065207 (2007)]
  - **EPS**: Eskola, Paukkunen, Salgado
    [JHEP 04 (2009) 065]
  - **DSSZ**: de Florian, Sassot, Stratmann, Zurita
    [PRD 85, 074028 (2012)]

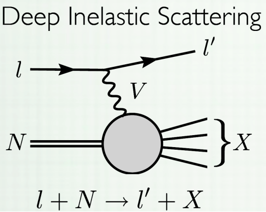
- **Native nuclear PDFs**
  - **nCTEQ**: Kovarik, Kusina, Jezo, Olness, ...
    [PRD 93, 085037 (2016)]

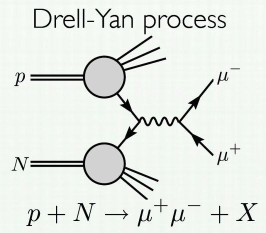
$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$

$$f_i(x_N, A = 1, \mu_0) \equiv f_i^{free\ proton}(x_N, \mu_0)$$

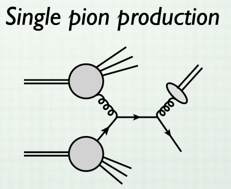
Data sets

- NC DIS & DY
  CERN BCDMS & EMC & NMC
  N = (D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W)
  FNAL E-665
  N = (D, C, Ca, Pb, Xe)
  DESY Hermes
  N = (D, He, N, Kr)
  SLAC E-139 & E-049
  N = (D, Ag, Al, Au, Be,C, Ca, Fe, He)
  FNAL E-772 & E-886
  N = (D, C, Ca, Fe,W)





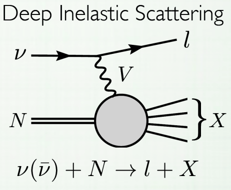
- Single pion production



RHIC - PHENIX & STAR

N = Au

- Neutrino DIS

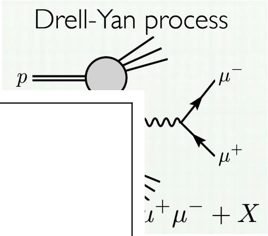


CHORUS CCFR & NuTeV

N = Pb N = Fe

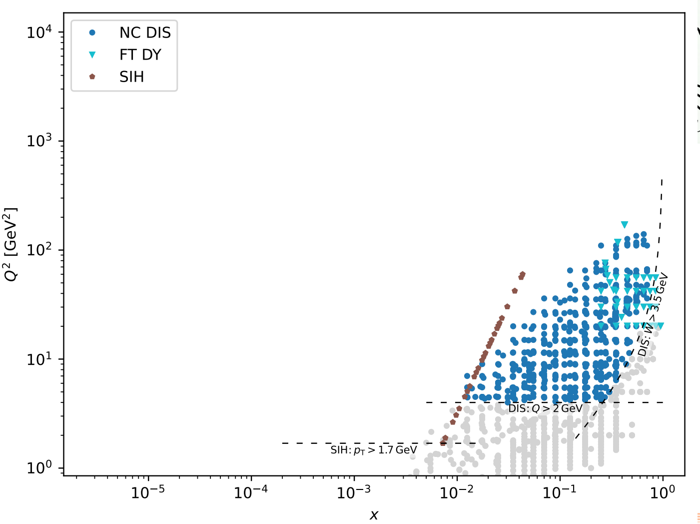
Data sets

- NC DIS & DY
  CERN BCDMS & EMC & NMC
  N = (D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W)
  FNAI
  N = (
  DESY
  N = (
  SLAC
  N = (
  FNAI
  N = (

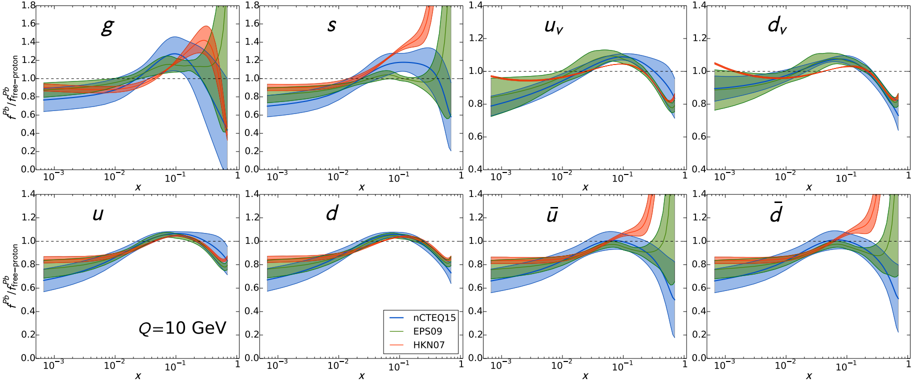


- Singl

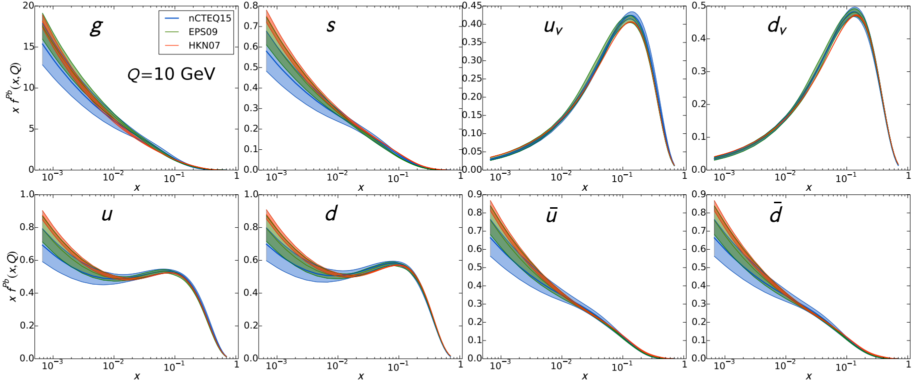
RHIC
N = A



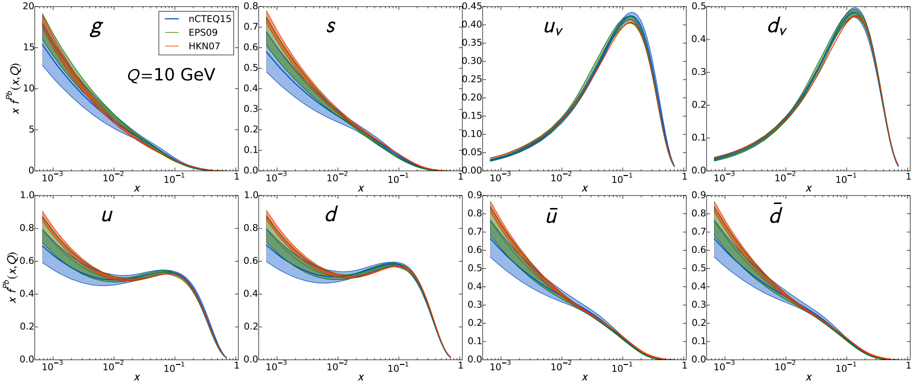
Nuclear modification for lead ($R_i(\mathrm{Pb}) = f_i^{\mathrm{Pb}}(x,Q) f_i^p(x,Q)$)



Nuclear lead PDFs ($f^{\mathrm{Pb}} = \frac{Z}{A} f^{p/A} + \frac{A-Z}{A} f^{n/A}$)



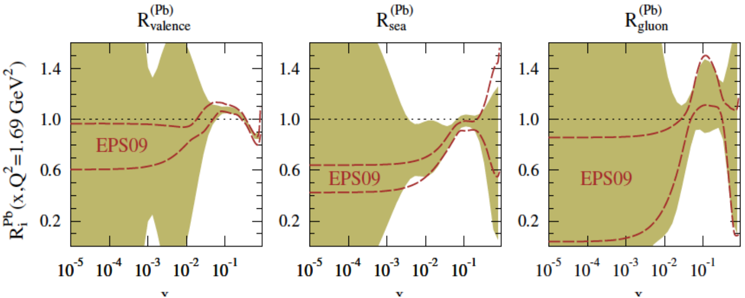
Nuclear lead PDFs ($f^{\rm Pb} = \frac{Z}{A} f^{p/A} + \frac{A-Z}{A} f^{n/A}$)



- Seems like a relativley good agreement between different groups, also the uncertainties looks reasonable but...
- Lack of data constraints resulted in many assumptions:
  - no flavour differentation between $\bar{u}$ and $\bar{d}$,
  - fixed strange,
  - hardly any constraints on gluon,
  - no information about low-x.

New fit framework:

The baseline fit using the new fit functions: no control over small x!



The lower bound restricted here by $F_L(Q^2 = 2\,\mathrm{GeV}^2, x > 10^{-5}) > 0$

Maybe against "physical intuition" (small-x theory predicts shadowing, $R_i < 1$), but consistent with the data.

E.g. in EPS09, small-x shadowing was essentially built in

[N. Armesto, 2015 LHeC Workshop, Chavannes-de-Bogis, June 26th 2015]

Currently available nPDFs

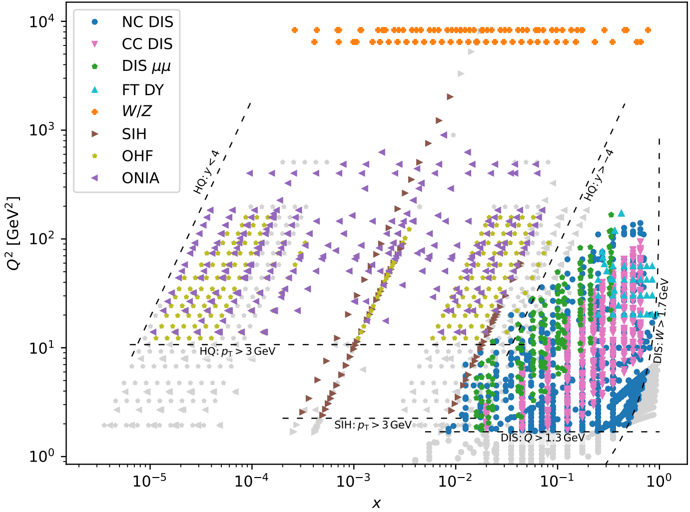
	KSASG20 PRD 104, 034010	**TUJU21** PRD 105, 094031	**EPPS21** EPJC 82, 413	**nNNPDF3.0** EPJC 82, 507	**nCTEQ15HQ** PRD 105, 114043
lA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓	✓	✓	✓	
pA Drell-Yan	✓		✓	✓	✓
πA Drell-Yan			✓		
RHIC dAu π			✓		✓
LHC pPb π, K					✓
LHC pPb W/Z		✓	✓	✓	✓
LHC pPb dijet			✓	✓	
LHC pPb HQ			✓ GMVFNS	✓ FO+PS(rew)	✓ ME fit
LHC quarkonium					✓ ME fit
LHC pPb γ				✓	
Kinematic cuts	$Q > 1.3$ GeV	$Q > 1.87$ GeV $W > 3.5$ GeV	$Q > 1.3$ GeV $W > 1.8$ GeV $p_T^{HQ} > 3$ GeV	$Q > 1.87$ GeV $W > 3.5$ GeV	$Q > 2$GeV $W > 3.5$GeV $p_T^{HQ(SIH)} > 3$ GeV
No data points	4335	2410	2077	2188	1496
No free param.	9	16	24	256 (NN)	19
χ^2/dof	1.06(1.05)	0.94(0.84)	1.00	1.10	0.86
Error analysis	Hessian	Hessian	Hessian	Monte Carlo	Hessian
$\Delta\chi^2$ tol.	20 (68% CL)	50	35	N/A	35
Proton baseline	CT18	custom	CT18A	∼NNPDF4.0	∼CTEQ6.1
Q_0 ini. scale	1.3 GeV	1.3 GeV	1.3 GeV	1.0 GeV	1.3 GeV
No flavours	3	4	6	6	5
Deuteron treat.	fitted	fitted	free	fitted	free
QCD order	**NLO & NNLO**	**NLO & NNLO**	**NLO**	**NLO**	**NLO**
HQ scheme	FONLL	FONLL	S-ACOT	FONLL	S-ACOT

Currently available nPDFs

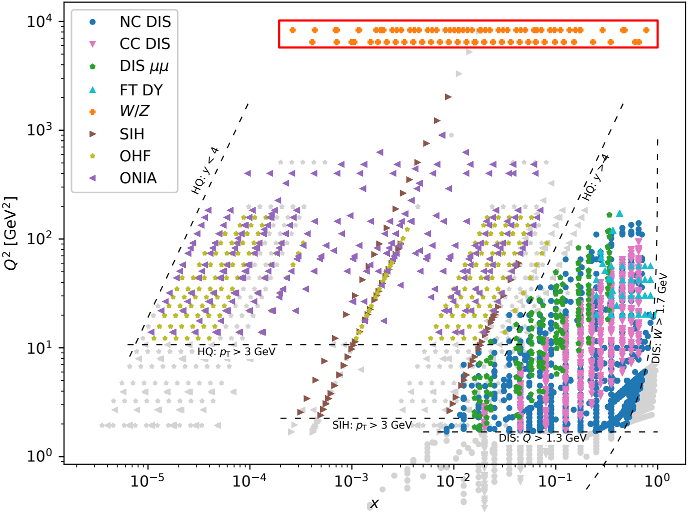
	KSASG20 PRD 104, 034010	**TUJU21** PRD 105, 094031	**EPPS21** EPJC 82, 413	**nNNPDF3.0** EPJC 82, 507	**nCTEQ25** arXiv:25XX.XXXX
lA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓	✓	✓	✓	✓
pA Drell-Yan	✓		✓	✓	✓
πA Drell-Yan			✓		
RHIC dAu π			✓		✓
LHC pPb π, K					✓
LHC pPb W/Z		✓	✓	✓	✓
LHC pPb dijet			✓	✓	
LHC pPb HQ			✓ GMVFNS	✓ FO+PS(rew)	✓ ME fit/GMVFNS
LHC quarkonium					✓ ME fit
LHC pPb γ				✓	
Kinematic cuts	$Q > 1.3$ GeV	$Q > 1.87$ GeV $W > 3.5$ GeV	$Q > 1.3$ GeV $W > 1.8$ GeV $p_T^{HQ} > 3$ GeV	$Q > 1.87$ GeV $W > 3.5$ GeV	$Q > 1.3$GeV $W > 1.7$GeV $p_T^{HQ(SIH)} > 3$ GeV
No data points	4335	2410	2077	2188	3518
No free param.	9	16	24	256 (NN)	36
χ^2/dof	1.06(1.05)	0.94(0.84)	1.00	1.10	0.978
Error analysis	Hessian	Hessian	Hessian	Monte Carlo	Hessian
$\Delta\chi^2$ tol.	20 (68% CL)	50	35	N/A	40
Proton baseline	CT18	custom	CT18A	~NNPDF4.0	CJ15
Q_0 ini. scale	1.3 GeV	1.3 GeV	1.3 GeV	1.0 GeV	1.3 GeV
No flavours	3	4	6	6	5
Deuteron treat.	fitted	fitted	free	fitted	CJ15 correction
QCD order	**NLO & NNLO**	**NLO & NNLO**	**NLO**	**NLO**	**NLO**
HQ scheme	FONLL	FONLL	S-ACOT	FONLL	S-ACOT

Currently available nPDFs

	KSASG20 PRD 104, 034010	**TUJU21** PRD 105, 094031	**EPPS21** EPJC 82, 413	**nNNPDF3.0** EPJC 82, 507	**nCTEQ25** arXiv:25XX.XXXX
lA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓	✓	✓	✓	✓
pA Drell-Yan	✓		✓	✓	✓
πA Dre					
RHIC					✓
LHC pI					✓
LHC pF					✓
LHC pI					
LHC p					E fit/GMVFNS
LHC qua					✓ ME fit
LHC					
Kinema					) > 1.3GeV ' > 1.7GeV (SIH) > 3 GeV
No data					3518
No free					36
$\chi^2/$					0.978
Error a					Hessian
$\Delta\chi^2$					40
Proton					CJ15
Q_0 ini					1.3 GeV
No fla					5
Deutero					15 correction
QCD					**NLO**
HQ sc					S-ACOT



Impact of pPb LHC W and Z data [EPJC 80, 968 (2020)]



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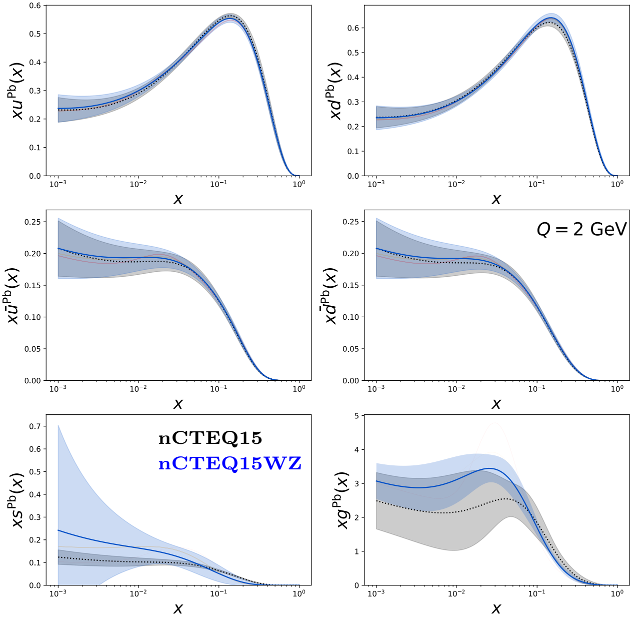
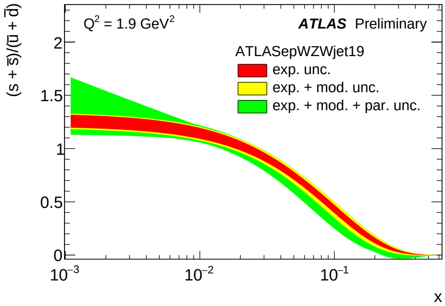
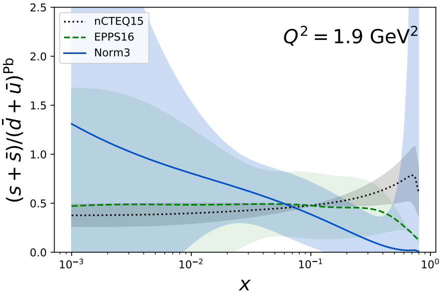


nCTEQ15 nuclear PDFs + W/Z pPb LHC data

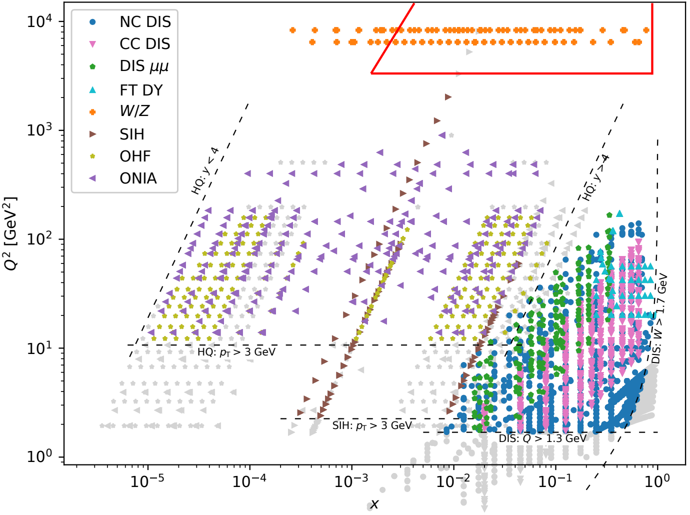
- Compare gray (nCTEQ15) with blue (new nCTEQ15WZ PDFs)
- u and d PDFs mostly unchanged
- Main impact on strange and gluon PDFs

Strange to light-sea ratio: $R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$





Impact of pPb LHC **dijet** data [Eur.Phys.J.C 79 (2019) 6, 511]



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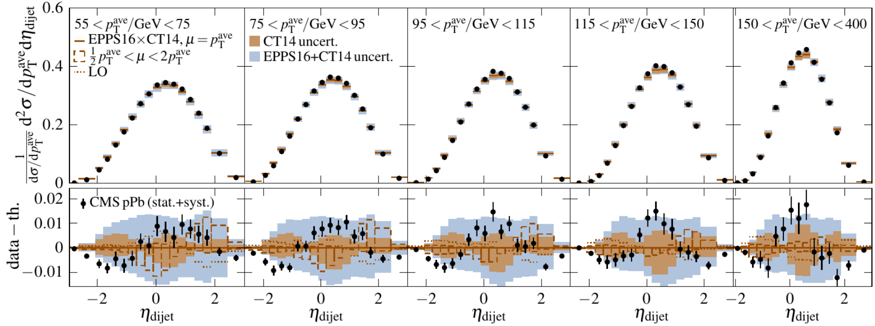


Fig. 7 As Fig. 2 but now with pPb data and predictions with EPPS16 nuclear modifications imposed on the CT14 NLO proton PDFs and omitting the results with $\mu = M_{dijet}$ for clarity. Light blue boxes show the combined uncertainty from the CT14 and EPPS16 PDFs.

Impact of pPb LHC **dijet** data [Eur.Phys.J.C 79 (2019) 6, 511]

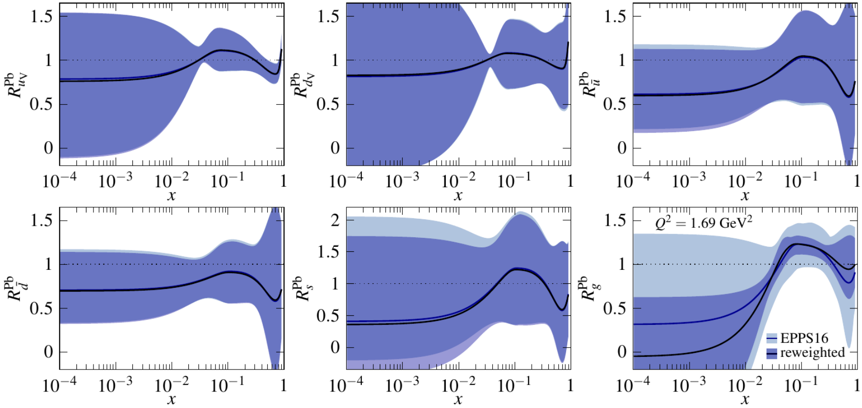
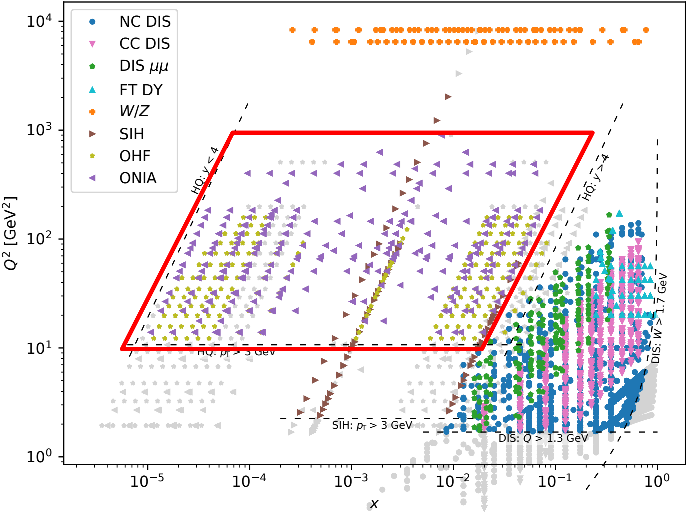


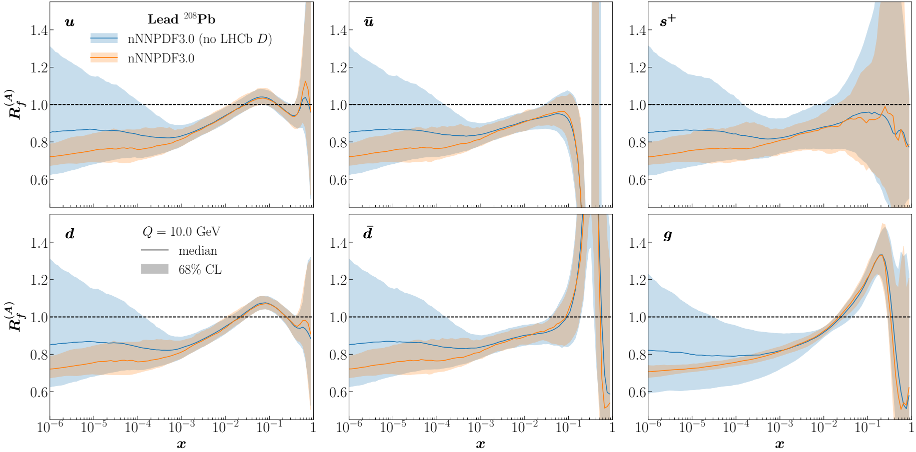
Fig. 11 The impact of reweighting the EPPS16 nPDFs with the data on the nuclear modification ratio of the dijet spectra. The original and reweighted EPPS16 nuclear modifications for the lead nucleus are presented at the parametrization scale $Q^2 = 1.69$ GeV^2. For better visibility, the s-quark modifications are presented with a different vertical axis scaling.

Impact of pPb LHC **heavy-quark(onia)** data [EPJC 82 (2022) 6, 507]

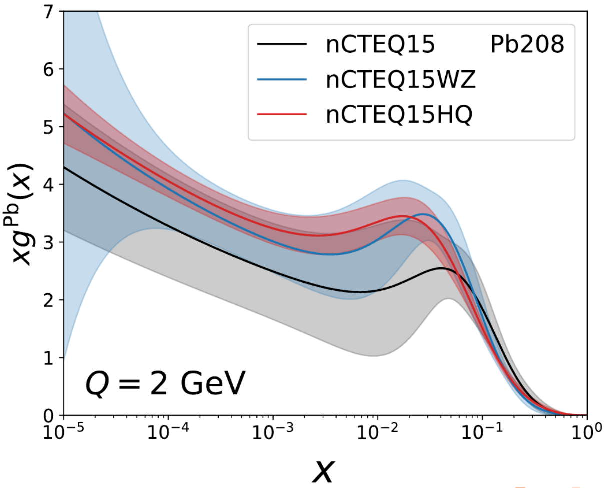


Impact of pPb LHC **heavy-quark(onia)** data [EPJC 82 (2022) 6, 507]

- New data compared to nNNPDF2.0:
  pPb data from LHC: ALICE W @5TeV, LHCb Z @5TeV, ALICE Z @8TeV, CMS Z @8TeV, CMS dijet, prompt photon ATLAS @8TeV, LHCb D^0
- D meson data from LHCb at $\sqrt{s} = 5$ TeV [JHEP 1710 (2017) 090]
- Predictions for D meson in FFNS (POWHEG+Pythia) included via **PDF reweighting**



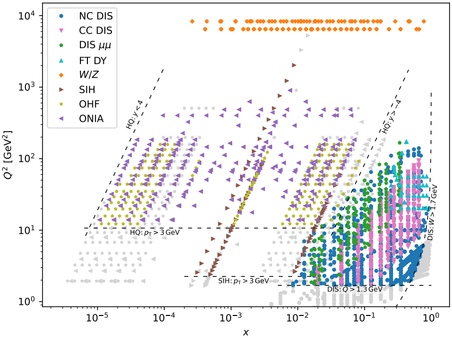
- New data compared to nCTEQ15WZ+SIH:
  D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$
- Predictions for heavy quark(onium) data done with data-driven method [PRL 121 (2018) 052004; PRL107, 082002 (2011); EPJC77, 1 (2017)]



Towards nCTEQ25

- New nPDF release: **nCTEQ25** combines the previous analyses:
  - **nCTEQ15** [PRD 93, 085037 (2016)]
    - DIS NC data
    - fixed-target DY data
    - pion data from RHIC
  - **nCTEQ15WZ** [EPJC 80, 968 (2020)]
    - LHC W/Z data
    - constraints on *gluon* and *strange* nPDFs
  - **nCTEQ15HIX** [PRD 103, 114015 (2021); Prog.Part.Nucl.Phys. 136 (2024) 104096]
    - JLAB DIS data
    - constraints at high-x
    - theoretical corrections: TMC, HT, deuteron
  - **nCTEQ15SIH** [PRD 104 (2021) 9, 094005]
    - LHC & RHIC SIH data
    - constraints on *gluon* nPDF
  - **nCTEQ15neutrino** [PRD 106 (2022) 7, 074004]
    - DIS neutrino data (NuTeV, CHORUS, CDHSW, dimuons)
    - compatibility of NC & CC DIS
    - flavour separation
  - **nCTEQ15HQ** [PRL 121, 052004 (2018); PRD 105 (2022) 11, 114043]
    - LHC & RHIC HF data
    - constraints on low-x *gluon* nPDF
    - PDF-reweighting + full analysis

- Data: NC DIS (+JLAB), CC DIS (+dimuon), FT DY, *p*Pb LHC: W/Z, SIH, HQ, RHIC SIH (**3518** data points)



nCTEQ25 – preliminary results

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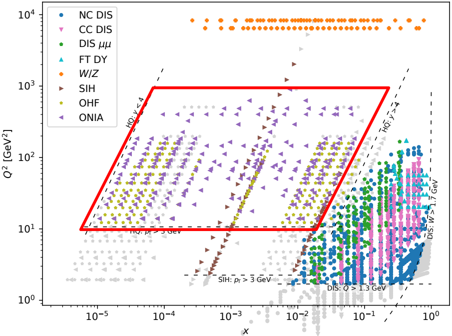

- Included heavy quark (HQ) data

	HQ data	No data points
nCTEQ25	D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$	548
EPPS21	D	48
nNNPDF3.0	D	37

- Predictions for HQ data done with data-driven method [PRL 121 (2018) 052004]

nCTEQ25 – preliminary results

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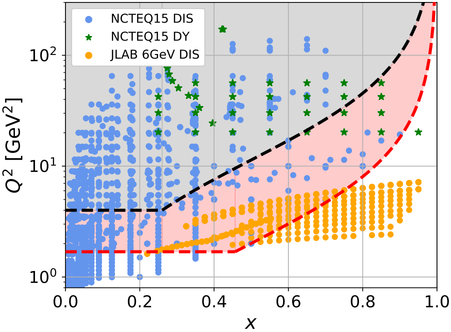
- Extended kinematic cuts on Q^2 and $W^2 = Q^2 \frac{1-x}{x} + M_N^2$: $Q > 1.3$ GeV $W > 1.7$ GeV (earlier cuts: $Q > 2$ GeV $W > 3.5$ GeV, additional **971** NC & **268** CC DIS data points)



nCTEQ15
$Q > 2$ GeV $W > 3.5$ GeV
$N_{\text{data}} = 708$

nCTEQ15HIX
$Q > 1.3$ GeV $W > 1.7$ GeV
$N_{\text{data}} = 1679$

Requires proper treatment of:

- **deuteron corrections**
- **target mass corrections** (TMCs) [Prog.Part.Nucl.Phys. 136 (2024) 104096]
- **higher twist effects**

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  Requires proper treatment of:
  - **deuteron corrections**
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  - **higher twist effects**

- New proton baseline from CJ15 PDFs [PRD 93, 114017 (2016)]

- New PDF parametrization: (36 free parameters):

$$x f_i(x, Q_0^2) = c_0 x^{c_1} (1-x)^{c_2} \left(1 + c_3\sqrt{x} + c_4 x + c_5 \sqrt{x}^3\right) \qquad i = u_v, d_v, g, \bar{u} + \bar{d}$$

$$\bar{d}/\bar{u}(x, Q_0) = a_0 x^{c_1} (1-x)^{c_2} + 1 + c_3 x (1-x)^{c_4}$$

  with updated A-dependence:

$$\textbf{OLD:} \quad c_k(A) \equiv p_k + a_k \left(1 - A^{-b_k}\right)$$

$$\Downarrow$$

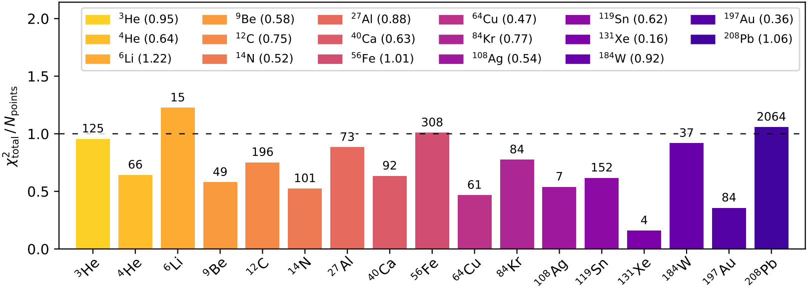
$$\textbf{NEW:} \quad c_k(A) \equiv p_k + a_k \ln(A) + b_k \ln^2(A)$$

- Other details

  order: NLO QCD, HQ scheme: SACOT-χ, 36 free parameters, errors: Hessian ($T = 40$)

Preliminary results: fit quality: χ^2

Fit quality: $\chi^2/N_{\text{dof}} = 0.979$ ($\chi^2 = 3408$ for $N_{\text{data}} = 3518$)



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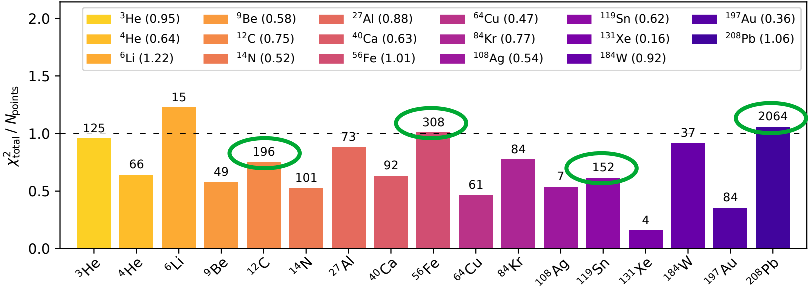

- Most of the data are for Pb
- Basically all constraints on gluon come from Pb data
- Limited information about A-dependence

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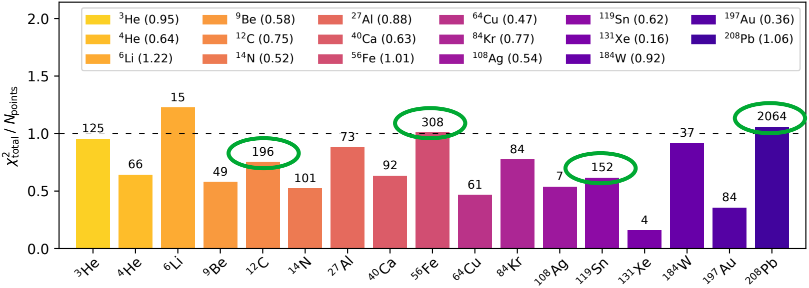
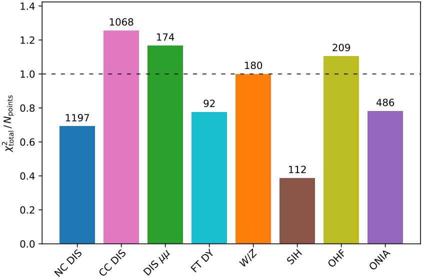
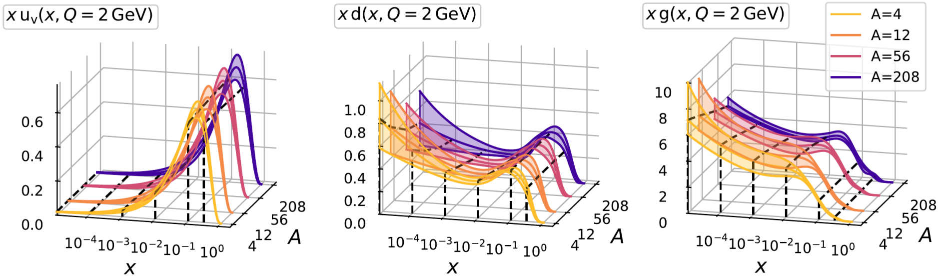




Preliminary results: *A*-dependence

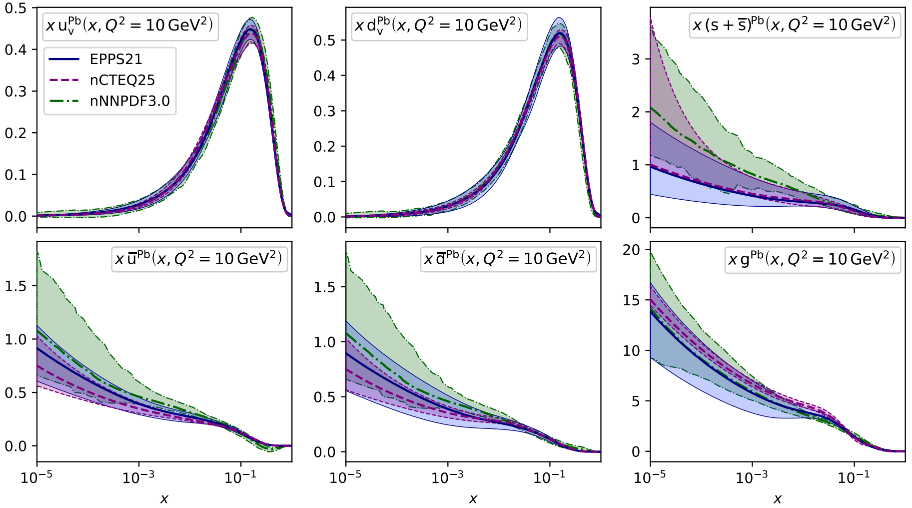
PDFs for selected nuclei: He, C, Fe, and Pb.



- Rather mild *A*-dependence
- For gluon and light-sea quarks visible shadowing at low-x

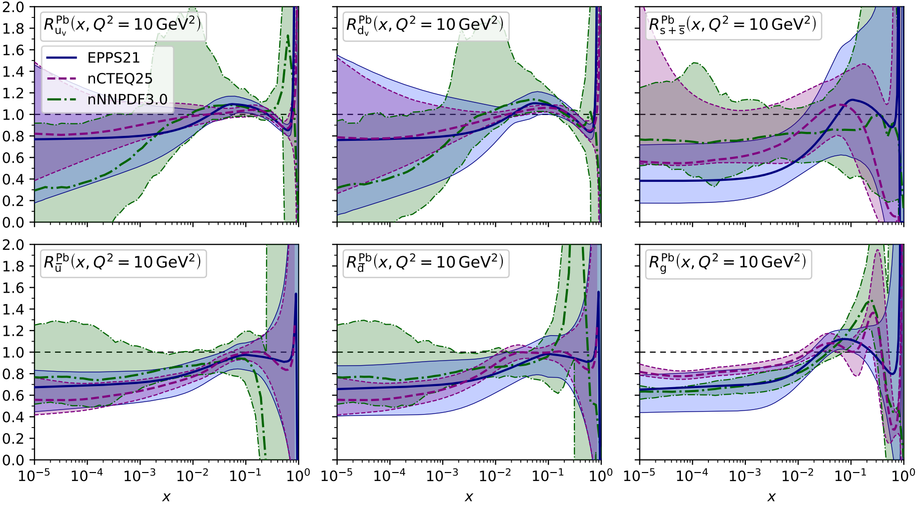
Preliminary results: Comparison with other global analyses

PDFs for lead



Preliminary results: Comparison with other global analyses

Nuclear modification for lead



Current status

- The pPb LHC data have provided crucial information about nPDFs
  - extending kinematic coverage down to $x \sim 10^{-5}$ (before $x \gtrsim 10^{-2}$)
  - gluon distribution (HQ(-onium), dijets, prompt photon, W/Z)
  - flavour separation (W/Z)
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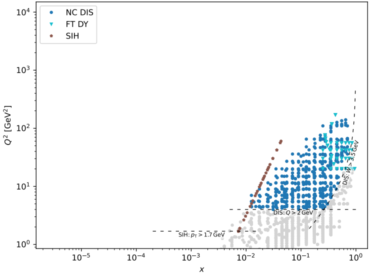

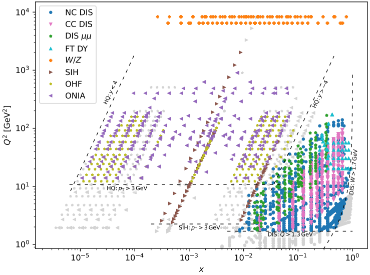

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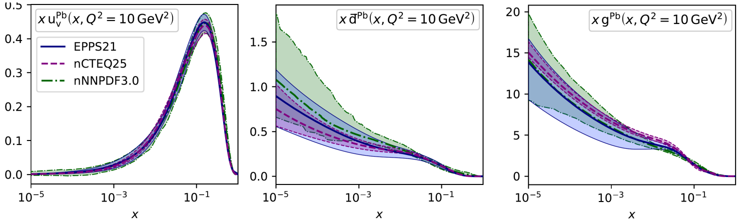

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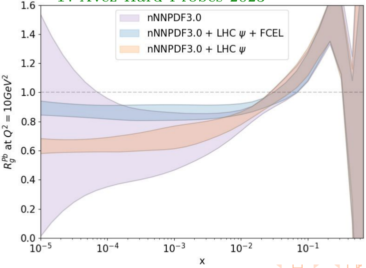
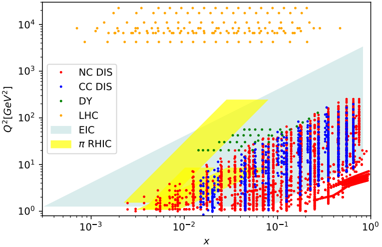
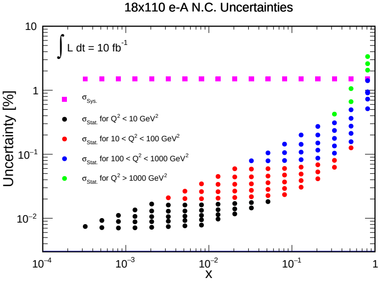
- Good starting point for EIC: nPDFs from different groups are in relatively good agreement
- Nevertheless we are still far away from the precision of proton PDFs and there are additional questions
  - connection between saturation and shadowing
  - factorization in pA is not clear, possible other effects e.g. energy loss [JHEP 01 (2022) 164]

T. Avez Hard Probes 2023



- Range of nuclei: Au, Cu, Fe, C, He, ...
- CM energy $\sqrt{s} \sim 40 - 140\sqrt{Z/A}$ GeV
- Very large luminosity $\sim 10^{33} - 10^{34}$ cm^{-2} s^{-1} ($\sim 100 - 1000$ times higher than HERA)
- Wide kinematic coverage
- Will allow to test what we have learned at LHC





Opportunities Electron-Ion Collider [Nucl.Phys.A 1026 (2022) 122447]

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