Quarkonia in pA and nPDF

A. Kusina

Institute of Nuclear Physics PAN, Krakow, Poland

Joint session between:
Workshop on Double Parton Scattering and the 3D structure of hadrons (Aussois, France)
and
Cold Nuclear Matter Effects: from the LHC to the EIC
(Stony Brook, NY)

Work supported by:

NARODOWE CENTRUM NAUKI

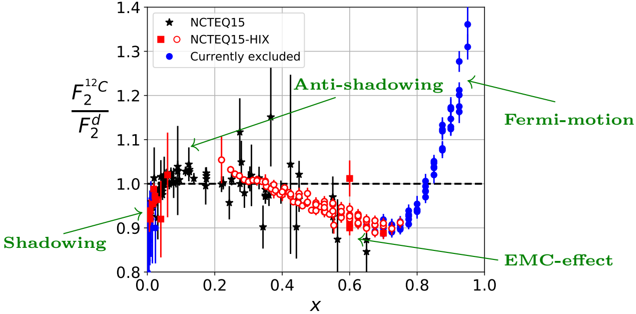
SONATA BIS grant No 2019/34/E/ST2/00186

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

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

DIS-like processes

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

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

Assumptions entering nuclear PDF analyses

Factorization

- allow for definition of **universal PDFs**
- **DGLAP** evolution equations
- make the formalism **predictive**
- needed even if it is broken

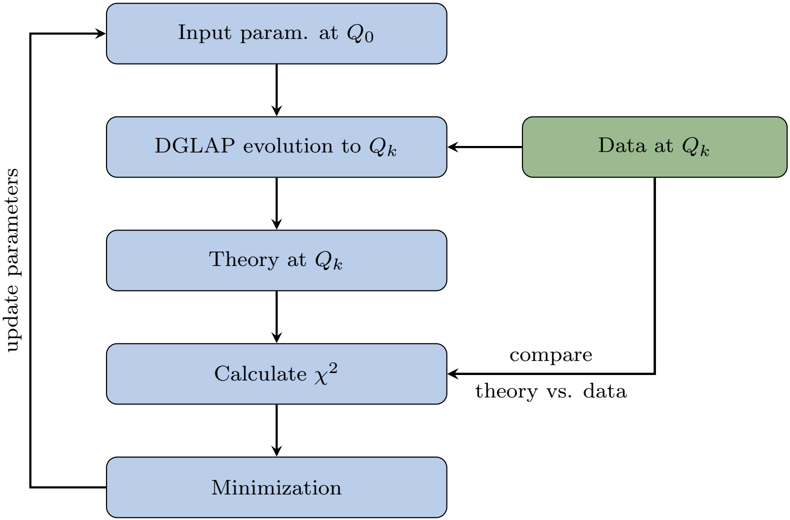
Isospin symmetry

$$\begin{cases} u^{n/A}(x) = d^{p/A}(x) \\ d^{n/A}(x) = u^{p/A}(x) \end{cases} \qquad \text{where} \qquad f_i^{(A,Z)} = \frac{Z}{A} f_i^{p/A} + \frac{A-Z}{A} f_i^{n/A}$$

Neglect contributions from $x > 1$

- same *evolution equations*
- *sum rules* as the free proton PDFs

Schematics of Global Analysis



Schematics of Global Analysis

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

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

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

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 $c_0, c_1, \ldots$
7. Compute uncertainties (Hessian, Monte Carlo)

Schematics of Global Analysis

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

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

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

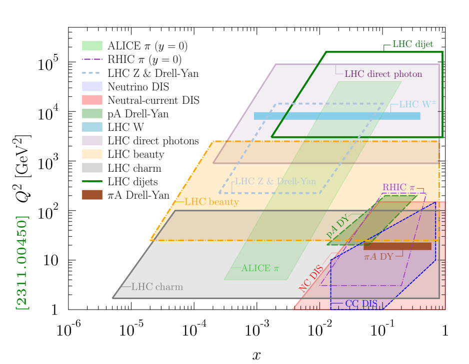
with $c_j = c_j(A) \overset{\text{nCTEQ}}{=} p_k + a_k \left(1 - A^{-b_k}\right)$ depending on the nuclei;
$f_i^{n/A}(x,Q)$ - from isospin symmetry.
3. Use DGLAP equation to evolve $f_i(x,\mu)$ from $\mu = Q_0$ to $\mu = Q_{\text{max}}$.
4. Calculate theory predictions corresponding to the data (σ_{DIS}, 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)

Comparison of 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	$Q > 1.3$ Ge				$Q > 2$GeV $W > 3.5$GeV $HQ(SIH) > 3$ GeV
No data points	4335				1496
No free param.	9				19
χ^2/dof	1.06(1.05)				0.86
Error analysis	Hessian				Hessian
$\Delta\chi^2$ tol.	20 (68% CI				35
Proton baseline	CT18				~CTEQ6.1
Q_0 ini. scale	1.3 GeV				1.3 GeV
No flavours	3				5
Deuteron treat.	fitted				free
QCD order	**NLO & NN**				**NLO**
HQ scheme	FONLL				S-ACOT



nPDF constrains

To better *constrain* (n)PDFs we need precise data for different process

- more process give access to more flavour combination - better flavour separation
- caveat: use processes where factorization works

nPDF constrains

To better *constrain* (n)PDFs we need precise data for different process

- more process give access to more flavour combination - better flavour separation
- caveat: use processes where factorization works

For nPDFs we generally lack good constraints on **gluon**:

- **DIS** (from Q^2 evolution): not large enough lever arm
- W/Z from pPb in LHC: clean but limited sensitivity ($x \geq 10^{-3}$)
- **Dijets** from pPb in LHC: problematic NLO doesn't work
- **Direct photon** from pPb in LHC: at the moment *not* precise enough
- **SIH** (Single Inclusive Hadron) from LHC & RHIC: FF-dependent + $x \geq 10^{-2}$

nPDF constrains

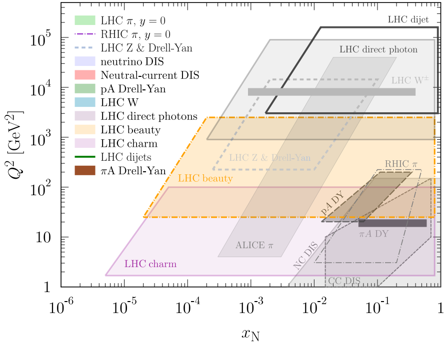
To better *constrain* (n)PDFs we need precise data for different process

- more process give access to more flavour combination - better flavour separation
- caveat: use processes where factorization works

For nPDFs we generally lack good constraints on **gluon**:

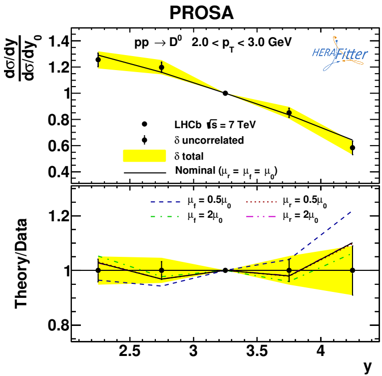
- **DIS** (from Q^2 evolution): not large enough lever arm
- W/Z from pPb in LHC: clean but limited sensitivity ($x \geq 10^{-3}$)
- **Dijets** from pPb in LHC: problematic NLO doesn't work
- **Direct photon** from pPb in LHC: at the moment *not* precise enough
- **SIH** (Single Inclusive Hadron) from LHC & RHIC: FF-dependent + $x \geq 10^{-2}$

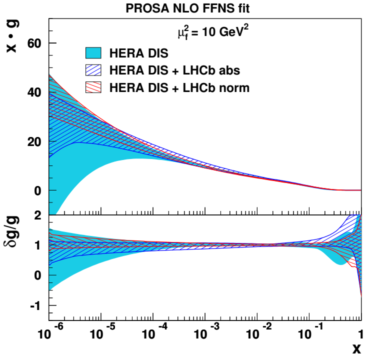
? **Heavy quark(onia)**: precise + access to very small $x \leq 10^{-5}$ but...



First use of HF data to constrain (n)PDFs

- PROSA [EPJC 75, 396 (2015)] first use of D and B data to constrain proton PDFs
  - use ratio to central bin to reduce scale uncertainty





First use of HF data to constrain (n)PDFs

- First use in nPDFs [PRL 121 (2018) 052004; PRD 104 (2021) 014010]: pPb data for D, B, J/ψ, Υ

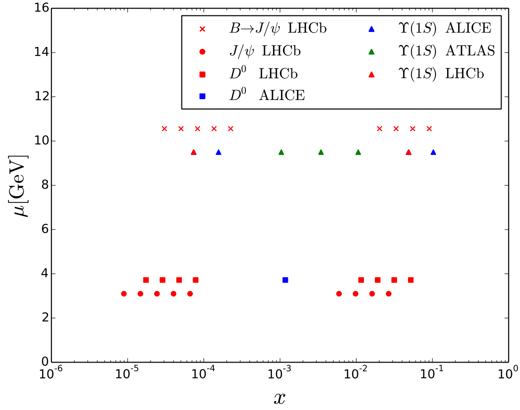
- Use PDF reweighting
- Data-driven approach for theory calculations [PRL107, 082002 (2011); EPJC77, 1 (2017)]

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

✓ removes model dependence
✓ fast to generate events
✗ currently limited to probes produced in $2\to 2$ partonic processes dominated by single partonic channel (gg, $q\bar{q}$, ...)
$\to$ In our case (D^0, J/ψ, $B\to J/\psi$, $\Upsilon(1S)$ production) gg dominated.
✗ not a fixed order calculation

pPb LHC heavy-flavour data [PRL 121 (2018) 052004; PRD 104 (2021) 014010]

	D^0	J/ψ	$B \to J/\psi$	$\Upsilon(1S)$
μ_0	$\sqrt{4M^2_{D^0} + P^2_{T,D^0}}$	$\sqrt{M^2_{J/\psi} + P^2_{T,J/\psi}}$	$\sqrt{4M^2_B + \left(\frac{M_B}{M_{J/\psi}} P_{T,J/\psi}\right)^2}$	$\sqrt{M^2_{\Upsilon(1S)} + P^2_{T,\Upsilon(1S)}}$
p+p data	LHCb [1]	LHCb [2,3]	LHCb [2,3]	ALICE [4], ATLAS [5], CMS [6], LHCb [7,8]
R_{pPb} data	ALICE [9], LHCb [15]	ALICE [10,11], LHCb [16,12]	LHCb [12]	ALICE [13], ATLAS [14], LHCb [17]

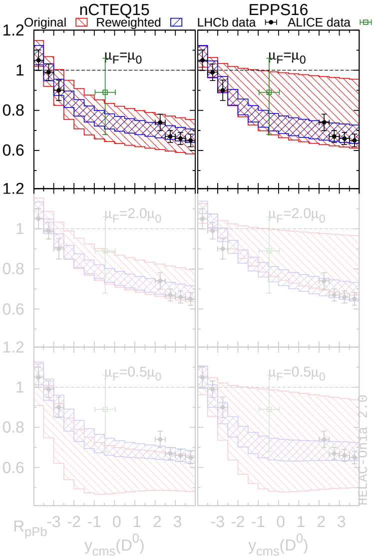


Expected nuclear effects on heavy quark(onium) production in pA collisions

- Nuclear modification of PDFs: initial-state effect
- Energy loss (w.r.t. pp collisions): initial-state or final-state effect
- Break up of the quarkonium in the nuclear matter: final-state effect
- Break up by comoving particles: final-state effect
- Colour filtering of intrinsic QQ pairs: initial-state effect
- ...

> - We assume leading twist factorization is valid – ONLY modifications of PDFs are present → "shadowing-only" hypothesis.

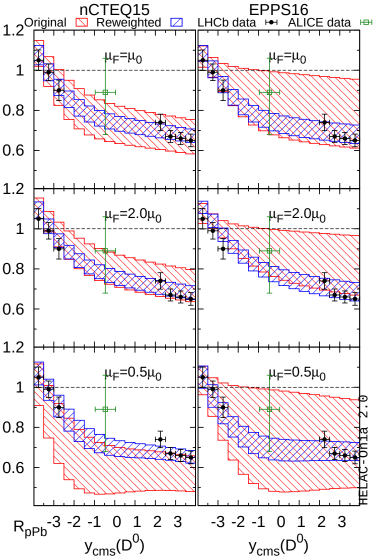
Reweighting with D^0 data



LHCb [JHEP 1710 (2017) 090, 1707.02750]
ALICE [PRL113, 232301 (2014), 1405.3452]

- Initial description of data is good for both nCTEQ15 and EPPS16.
- Substantial reduction of uncertainty especially for EPPS16.

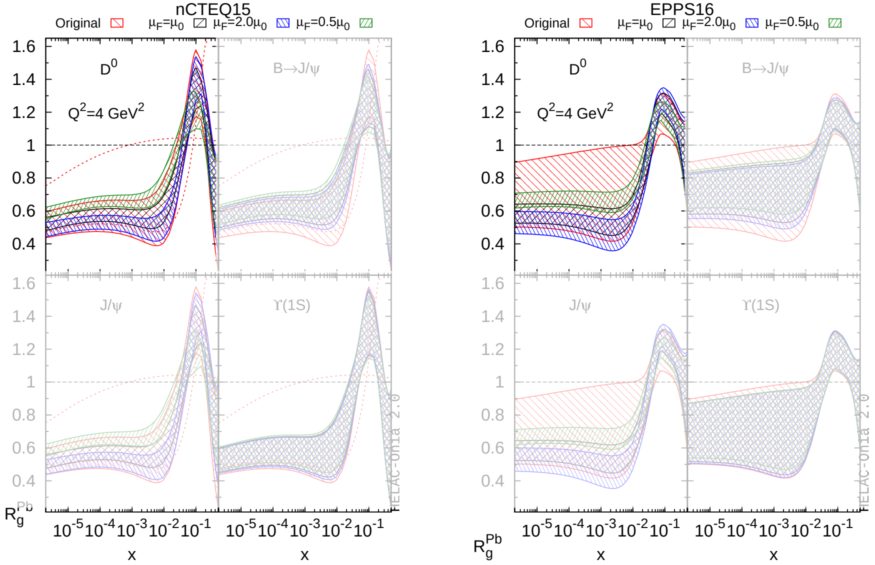
Reweighting with D^0 data



LHCb [JHEP 1710 (2017) 090, 1707.02750]
ALICE [PRL113, 232301 (2014), 1405.3452]

- Initial description of data is good for both nCTEQ15 and EPPS16.
- Substantial reduction of uncertainty especially for EPPS16.
- If we include factorization scale uncertainty errors increase and it can become the dominant uncertainty.

Reweighting results: $R_g^{\mathrm{Pb}} = f_g^{\mathrm{Pb}} / f_g^p$



Consistency with other data

We checked the consistency of the reweighted (**nCTEQ15**) nPDFs with other data sets entering global analysis:

- DIS data (the most precise set NMC Sn/C [NPB 481 (1996) 23]).
- LHC W/Z boson production data [EPJC 77, (2017) 488].
- PHENIX J/ψ $R_{d\mathrm{Au}}$ data [PRL 107 (2011) 142301; PRC 87, (2013) 034904].

This is very non-trivial and further confirms the “shadowing-only” hypothesis of leading twist factorization is valid within the current data precision!

Consistency with other data

- The results of the [PRL 121 (2018), 052004] study were successfully used e.g. to describe data at RHIC.

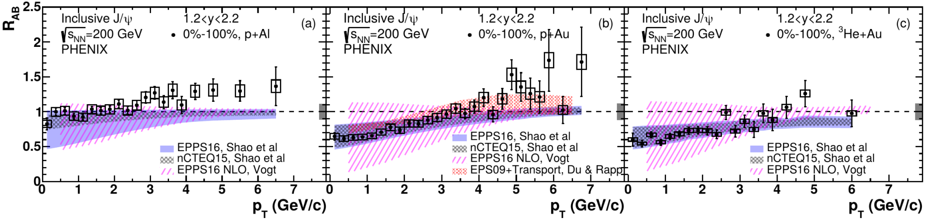


FIG. 10. Nuclear modification factor of inclusive J/ψ as a function of p_T at forward rapidity ($p/^3$He-going direction) for 0%–100% p+Al, p+Au, and ^{3}He+Au collisions. Bars (boxes) around data points represent point-to-point uncorrelated (correlated) uncertainties. The theory bands are discussed in the text.

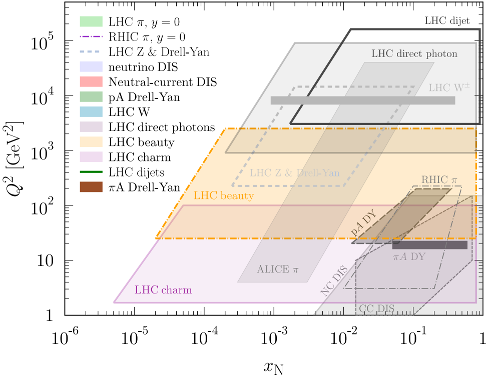
arXiv:1910.14487

see also: K. Smith, Quark Matter 2019

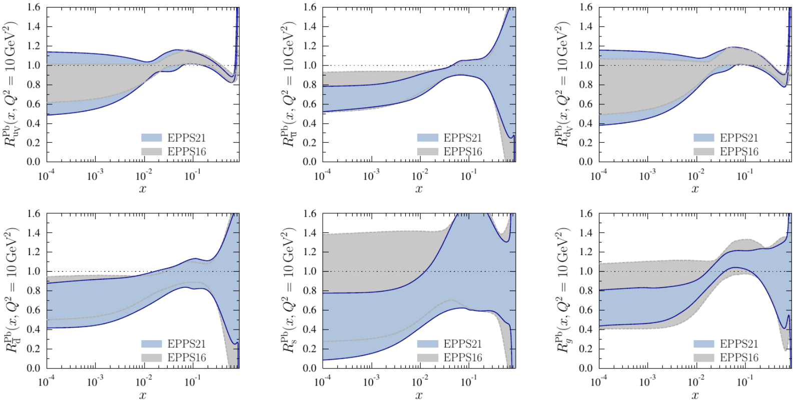
nPDF fits including heavy-quark(onium) data

Available nPDFs including heavy quark(onium) data

	N_{data}	N_{params}	Observables
EPPS21	2029+48	24	(ν)DIS, DY, SIH, W/Z, dijet, D
nNNPDF3.0	2151+37	256	(ν)DIS, DY, W/Z, dijet, γ, D
nCTEQ15HQ	936+548	19	DIS, DY, SIH, W/Z D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$

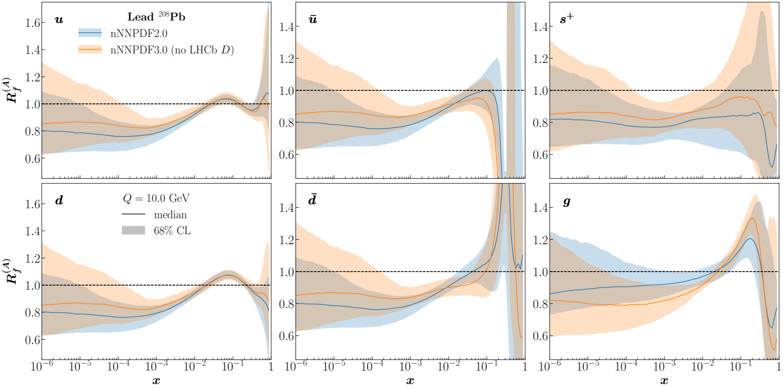


- New data compared to EPPS16:
  JLAB DIS, CMS W from pPb @8TeV, CMS dijet, LHCb D^0
- D meson data from LHCb at $\sqrt{s} = 5$ TeV [JHEP 1710 (2017) 090]
- Predictions for D meson (double differential in p_T and y) calculated in version of GM-VFNS scheme [JHEP 05 (2018) 196]



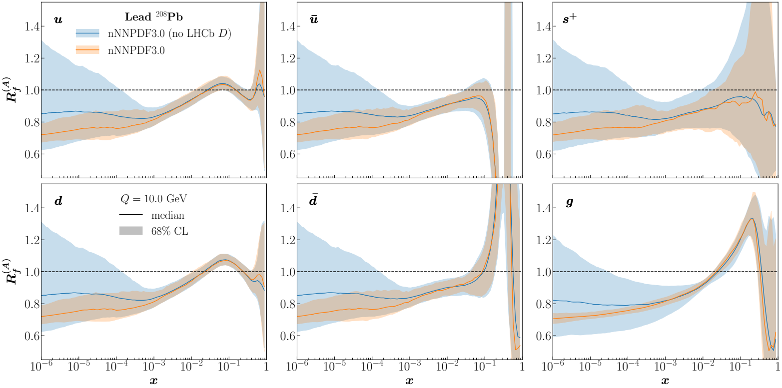
nNNPDF3.0 [EPJC 82 (2022) 6, 507]

- 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 done in POWHEG+PYTHIA included using **PDF reweighting**



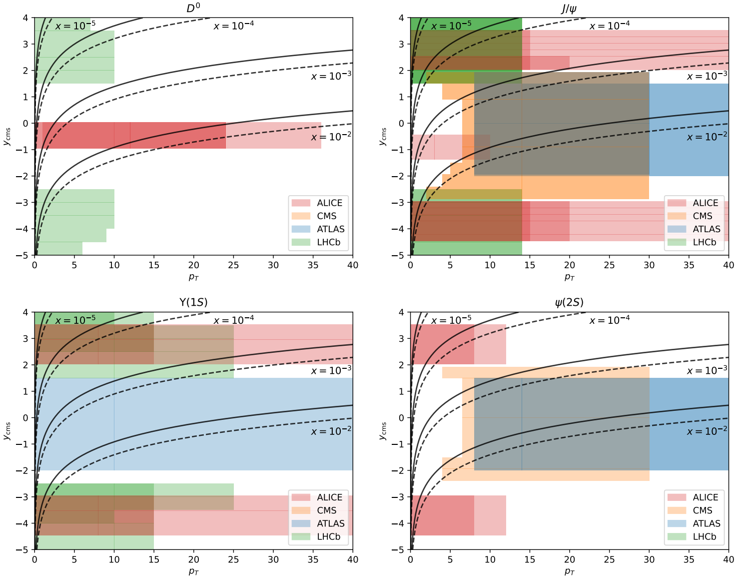
nNNPDF3.0 [EPJC 82 (2022) 6, 507]

- 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 done in POWHEG+PYTHIA included using **PDF reweighting**



nCTEQ15HQ [PRD 105 (2022) 11, 114043]

- New data compared to nCTEQ15WZ+SIH ($p_T > 3$ GeV):
  D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$



Heavy Quarks (HQ) - Theoretical approaches

Schemes for the calculation of **Open Heavy Quark** production (D, B mesons):

- **FFNS**: HQ present only in final state. Valid for small p_T.
- **ZM-VFNS**: HQ treated as massless, but included in PDFs. Valid at large p_T.
- Schemes interpolating between the two:
  - **FONLL**: $d\sigma_{\text{FONLL}} = d\sigma_{\text{FFNS}} + (d\sigma_{\text{ZMVFNS}} - d\sigma_{\text{FFNS},0}) \times G(m_Q, p_T)$,
  - **GM-VFNS**: Massive heavy quarks included in the PDFs for $\mu_f > \mu_T$.

Different schemes for the calculation of **Quarkonium** production:

- **Color-evaporation model**: hard scattering creates $Q\bar{Q}$-pair, which radiates gluons until it hadronizes
- **Color-singlet model**: Intermediate state is a color neutral $Q\bar{Q}$-pair
- **Non-relativistic QCD**: separation of short and long distance physics through expansion in velocity

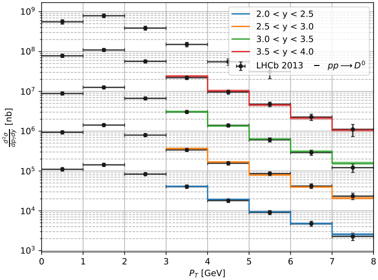
Heavy Quarks (HQ) - Data-driven Approach [PRL 121, 052004 (2018)]

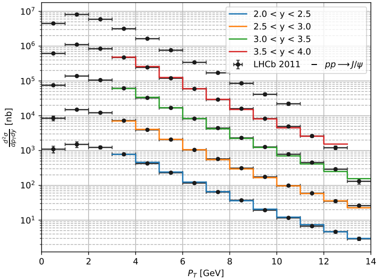
$$\sigma(AB \to \mathcal{Q} + X) = \int \mathrm{d}x_1 \, \mathrm{d}x_2 f_{1,g}(x_1) \, f_{2,g}(x_2) \, \frac{1}{2\hat{s}} \overline{\left|\mathcal{A}_{gg\to Q} + X\right|^2} \mathrm{dLIPS}$$

- Crystal-Ball parametrization extended to include rapidity dependence (a param.)

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

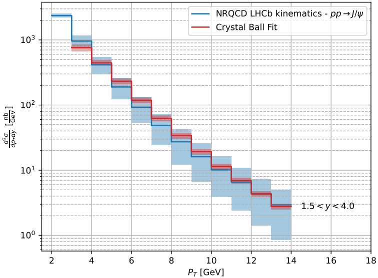
- Very good agreement between data and fitted theory (pp-baseline)

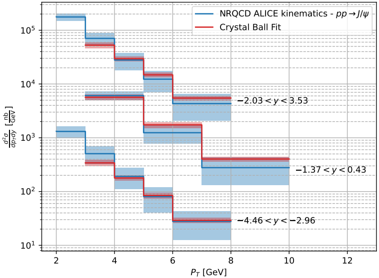




Baseline - comparison with NRQCD for J/ψ

Calculations by Mathias Butenschoen, Bernd Kniehl [M. Butenschoen et al., Nucl.Phys.B Proc.Suppl. 222-224 (2012) 151-161]

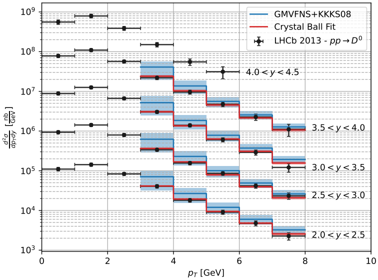


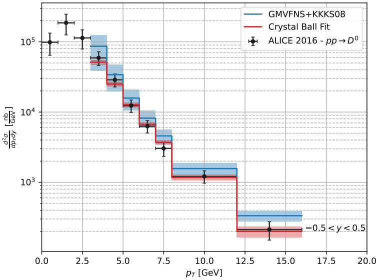


- NRQCD Uncertainties due to scale variations: $1/2 < \mu_r/\mu_{r,0} = \mu_i/\mu_{i,0} = \mu_{\text{NRQCD}}/\mu_{\text{NRQCD},0} < 2$
- Base scale $\mu_{r,0} = \mu_{i,0} = \sqrt{p_T^2 + 4m_c^2}$ and $m_{\text{NRQCD},0} = m_c$

Baseline - comparison with GMVFNS for D^0

Calculations in the GMVFNS using KKKS08 fragmentation functions





- GMVFNS Uncertainties due to scale variations: $1/2 < \mu_r/\mu_{r,0}, \mu_i/\mu_{i,0}, \mu_f/\mu_{f,0} < 2$
- Base scale $\mu_{r,0} = \mu_{i,0} = \mu_{f,0} = \sqrt{p_T^2 + 4m_c^2}$ and $m_c = 1.3$ GeV

nCTEQ15HQ fit setup [PRD 105 (2022) 11, 114043]

- Include all data from nCTEQ15WZ+SIH (936 points) [PRD 104 (2021) 094005] + 548 Heavy Quark(onia) data points

- Use the same open parameters and settings as nCTEQ15WZ+SIH

PDF of nucleus:

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

bound proton PDFs:

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

A-dependence:

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

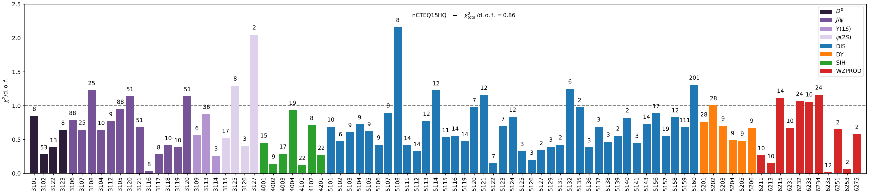
19 free parameters: $\{a_1^{u_v},\ a_2^{u_v},\ a_4^{u_v},\ a_5^{u_v},\ a_1^{d_v},\ a_2^{d_v},\ a_5^{d_v},\ a_1^{\bar{u}+\bar{d}},\ a_5^{\bar{u}+\bar{d}},$ $a_1^g,\ a_4^g,\ a_5^g,\ b_0^g,\ b_1^g,\ b_4^g,\ b_5^g,\ a_0^{s+\bar{s}},\ a_1^{s+\bar{s}},\ a_2^{s+\bar{s}}\}$

- Add uncertainties of the CB fit to data systematic uncertainties

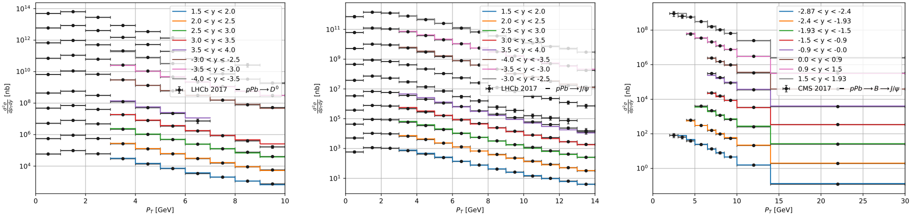
- Repeat full procedure with different scale choices $\mu_f/\mu_{f,0} = \{\frac{1}{2}, 1, 2\}$

nCTEQ15HQ pPb data description [PRD 105 (2022) 11, 114043]

χ^2 for nCTEQ15HQ with 548 new HF data points:

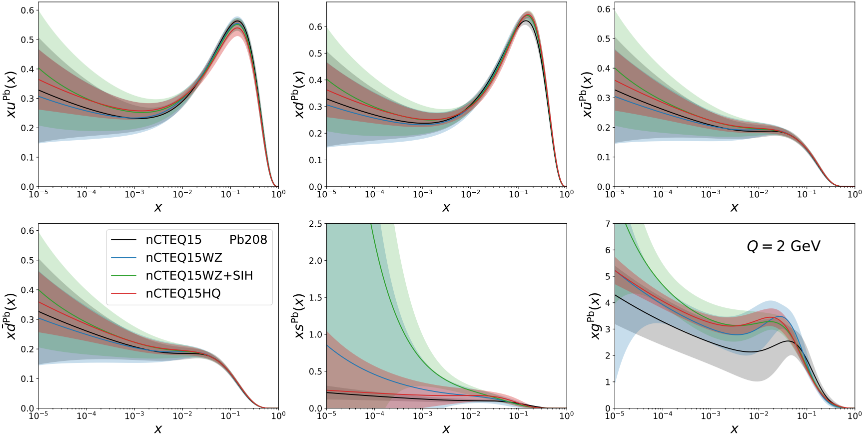


Example pPb data description:



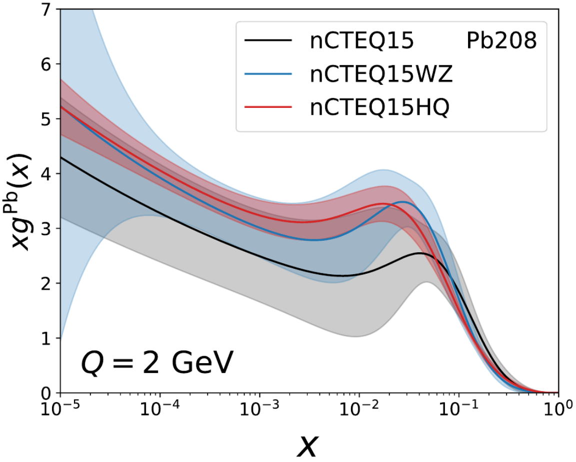
nCTEQ15HQ nPDFs [PRD 105 (2022) 11, 114043]

- 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)]



nCTEQ15HQ nPDFs [PRD 105 (2022) 11, 114043]

- 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)]

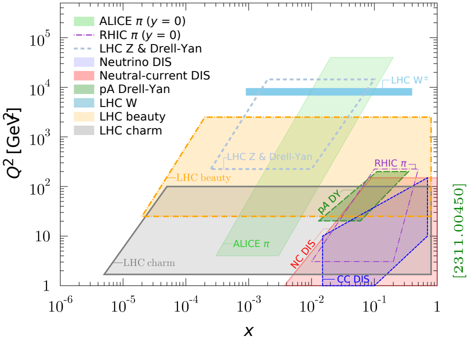


Towards nCTEQ24/25

- New nPDF release: **nCTEQ24/25** will combine 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

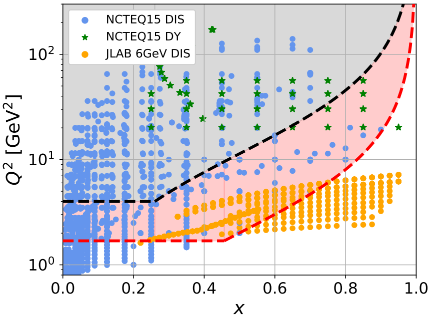
Towards nCTEQ24/25

- Data: NC DIS, CC DIS (+dimuon), FT DY, pPb LHC: W/Z, SIH, HQ, RHIC SIH ($\sim$ 3500 data points)



Towards nCTEQ24/25

- Data: NC DIS, CC DIS (+dimuon), FT DY, pPb LHC: W/Z, SIH, HQ, RHIC SIH (~ 3500 data points)
- Extended kinematic cuts on Q^2 & $W^2 = Q^2\frac{1-x}{x} + M_N^2$: $Q > 1.3$ GeV $W > 1.7$ GeV (earlier cuts: $Q > 2$ GeV $W > 3.5$ GeV)



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**

Towards nCTEQ24/25

- Data: NC DIS, CC DIS (+dimuon), FT DY, pPb LHC: W/Z, SIH, HQ, RHIC SIH ($\sim$ 3500 data points)

- Extended kinematic cuts on Q^2 & $W^2 = Q^2 \frac{1-x}{x} + M_N^2$: $Q > 1.3$ GeV $W > 1.7$ GeV (earlier cuts: $Q > 2$ GeV $W > 3.5$ GeV)

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

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

- New PDF parametrization:

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

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

Towards nCTEQ24/25

- Data: NC DIS, CC DIS (+dimuon), FT DY, pPb LHC: W/Z, SIH, HQ, RHIC SIH ($\sim$ 3500 data points)
- Extended kinematic cuts on Q^2 & $W^2 = Q^2 \frac{1-x}{x} + M_N^2$: $Q > 1.3$ GeV $W > 1.7$ GeV (earlier cuts: $Q > 2$ GeV $W > 3.5$ GeV)

  Requires proper treatment of:
  - **deuteron corrections**
  - **target mass corrections** (TMCs) [Prog.Part.Nucl.Phys. 136 (2024) 104096]
  - **higher twist effects**
- New proton baseline from CJ15 PDFs [PRD 93, 114017 (2016)]
- New PDF parametrization:

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

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

  with updated A-dependence:

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

$$\Downarrow$$

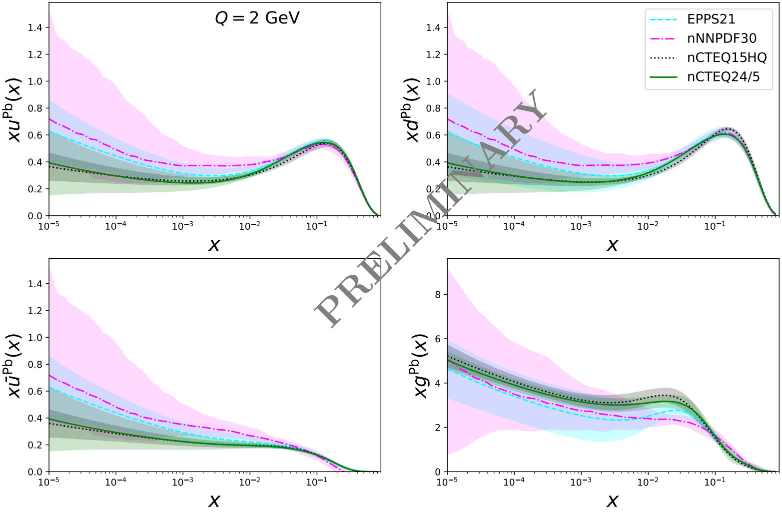
NEW: $c_k(A) \equiv p_k + a_k \ln(A) \; + \; b_k \ln^2(A)$

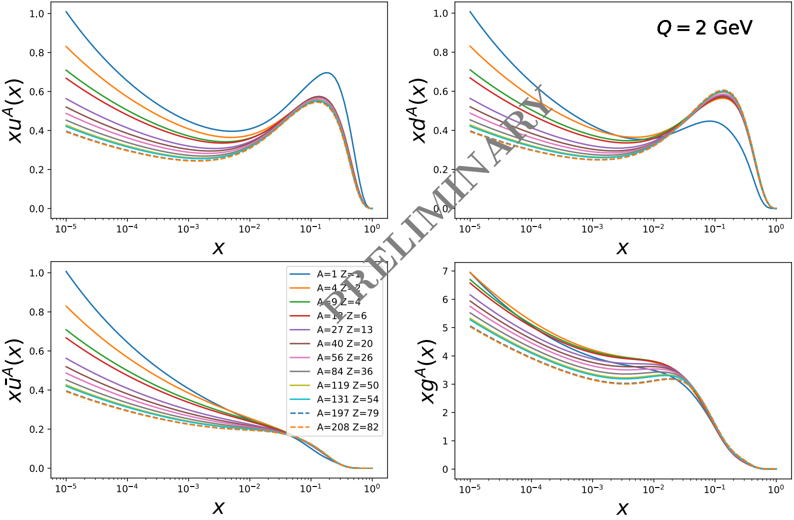
- Other details

  order: NLO QCD, HQ scheme: SACOT-χ, 30 free parameters, errors: Hessian

Preliminary results: PDFs

- Good agreement with previous nCTEQ PDFs and with EPPS21 & nNNPDF3.0 in the data region.
- Reduced gluon uncertainty (HQ data).

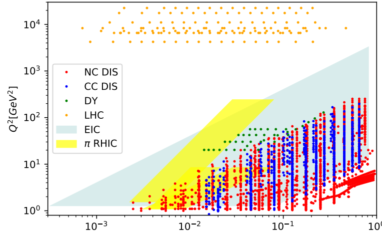




$Q = 2$ GeV
$xu^A(x)$
$xd^A(x)$
$x\bar{u}^A(x)$
$xg^A(x)$
x
A=1 Z=1
A=4 Z=2
A=9 Z=4
A=12 Z=6
A=27 Z=13
A=40 Z=20
A=56 Z=26
A=84 Z=36
A=119 Z=50
A=131 Z=54
A=197 Z=79
A=208 Z=82
PRELIMINARY

Summary

- The pPb LHC data have provided crucial information about nPDFs (kinematic coverage, gluon, flavour separation, strange)
- **Heavy Quark(onia)** data can constrain low-x gluon nPDFs in a region unconstrained by any other data but should we use them???
  - ✓ data-driven approach reduces uncertainties
  - ✓ compatible with data of other processes
  - ✗ but does it mean the factorization works?
  - ✗ possible other effects like energy loss
  - ✗ large scale uncertainties for charm
  - ✗ very low-x possible saturation region
  - ✗ dependence on fragmentation functions
- Maybe better to restrict to open heavy flavour especially B meson?
  - ✓ pQCD calculations should be reliable
  - ✓ scale uncertainties reduced compared to charm
  - ✗ there still can be other effects [JHEP 01 (2022) 164] (could be removed by cuts?)
  - ✗ removes a lot of data
- EIC will give opportunity to test what we learn at the LHC

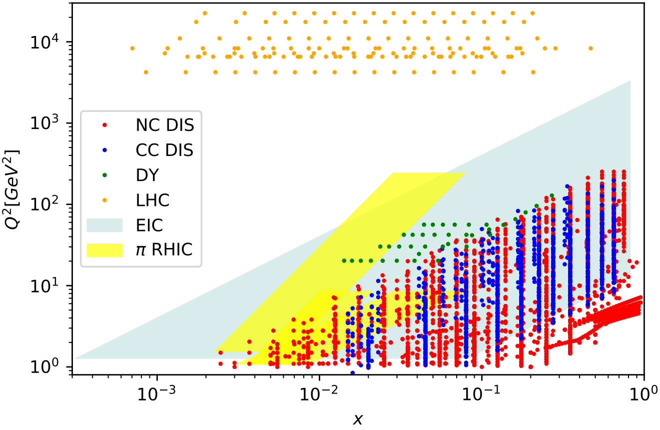


[NPA 1026 (2022) 122447]

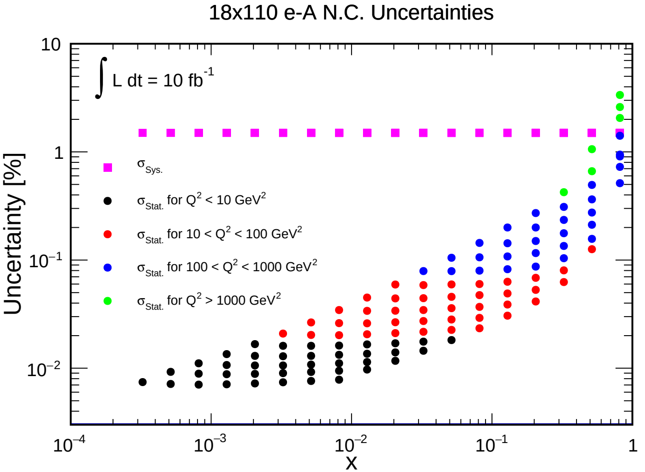
BACKUP SLIDES

Electron-Ion Collider opportunities for nPDFs [Nucl.Phys.A 1026 (2022) 122447]

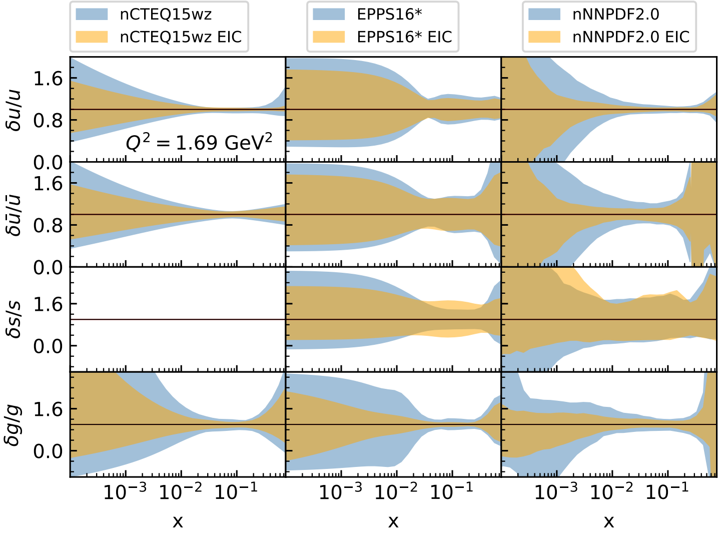
- Range of nuclei: Au, Cu, Fe, C, He, ...
- CM energy $\sqrt{s} \sim 40 - 140\sqrt{Z/A}$ GeV
- Very large luminosity $\sim 10^{33} - 10^{34}$ cm^{-2} s^{-1}
  ($\sim 100 - 1000$ times higher than HERA)
- Wide kinematic coverage



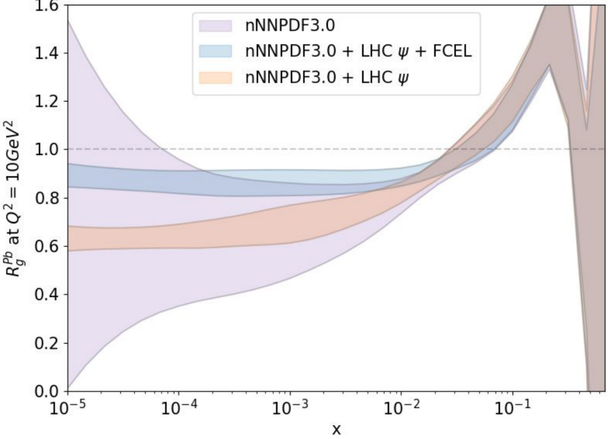
- Small uncertainties



- Great prospects for understanding nuclear structure in particular nPDFs

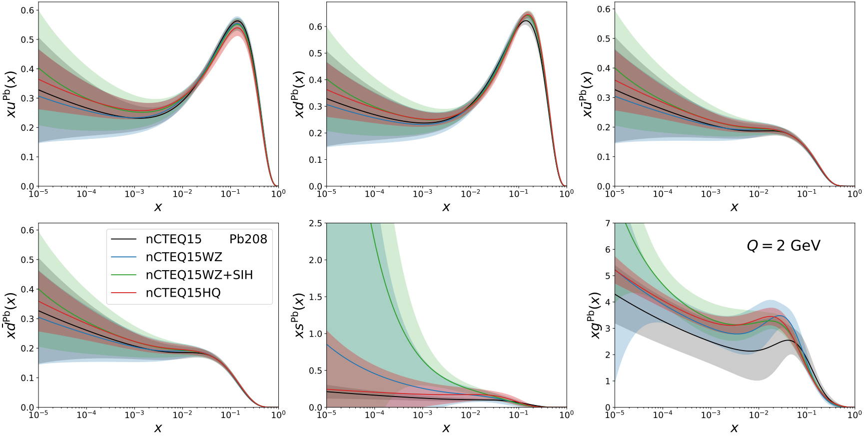


T. Avez Hard Probes 2023

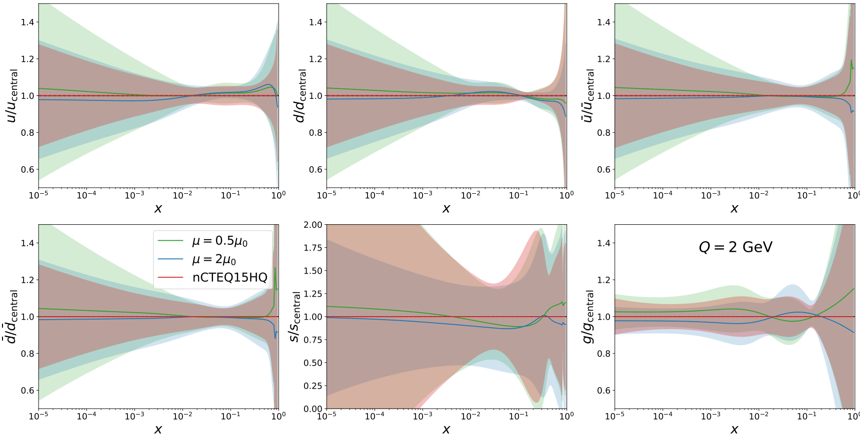


nCTEQ15HQ nPDFs [PRD 105 (2022) 11, 114043]

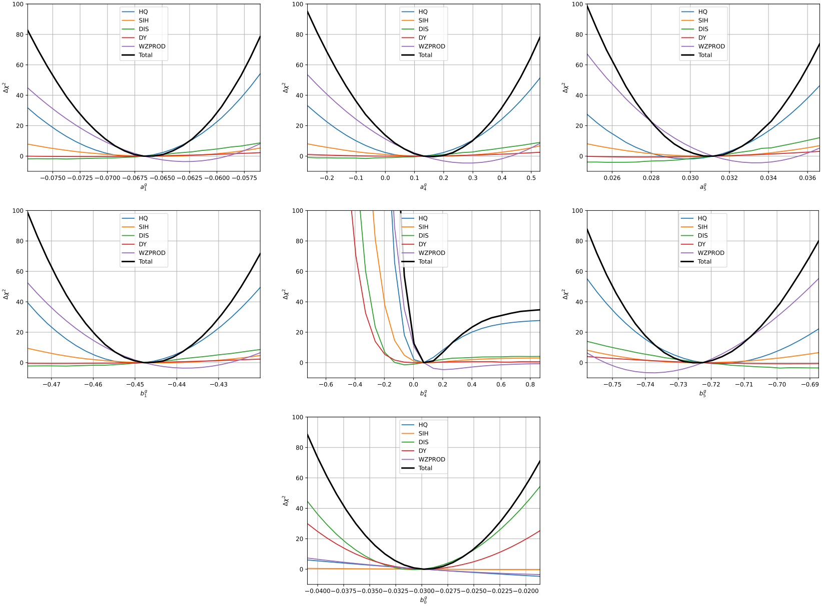
- New data compared to nCTEQ15WZ+SIH:
  D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$
- Predictions for heavy quark(onium) data done with data-driven method [PRL 121 (2018) 052004; PRL107, 082002 (2011); EPJC77, 1 (2017)]



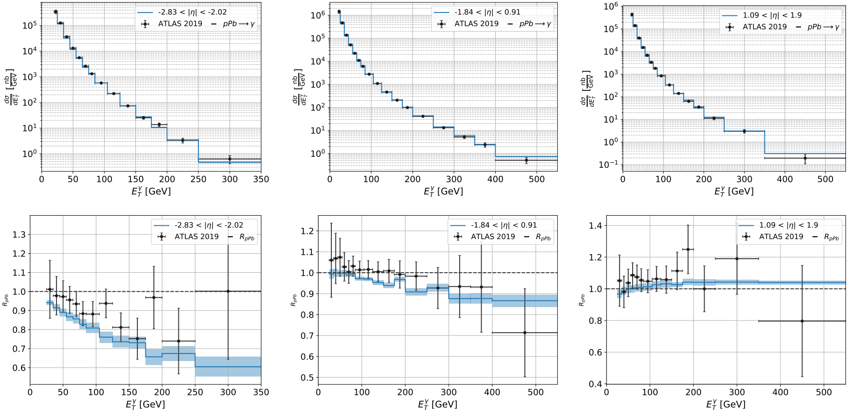
nCTEQ15HQ nPDFs scale dependence [PRD 105 (2022) 11, 114043]



nCTEQ15HQ: gluon parameters χ^2 scans



nCTEQ15HQ: description of prompt photons (NOT fitted)



- $\frac{d\sigma}{dE_T}$: $\chi^2/N_{dof} = 1.66$ (0.99 with free normalization)
- R_{pPb}: $\chi^2/N_{dof} = 0.53$