

Towards new release of nCTEQ nuclear PDFs

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J.G. Morfin, K.F. Muzakka, F.I. Olness, P. Risse, I. Schienbein, J.Y. Yu, ...



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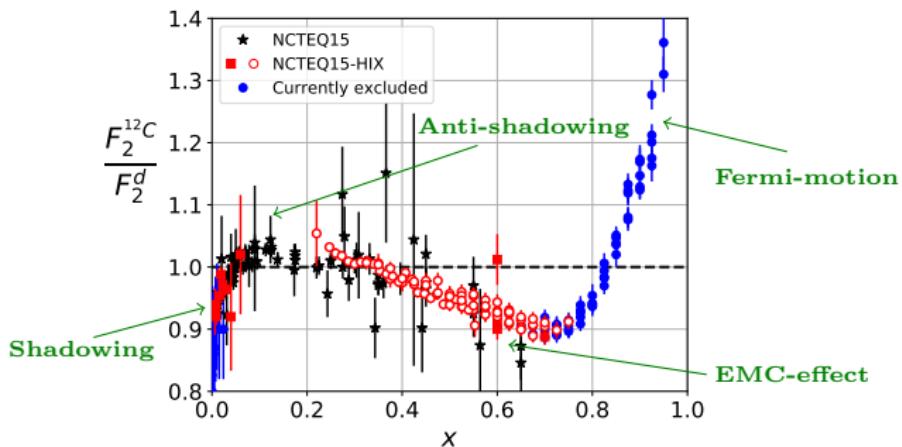
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Introduction

- ▶ Cross-sections in nuclear collisions are modified

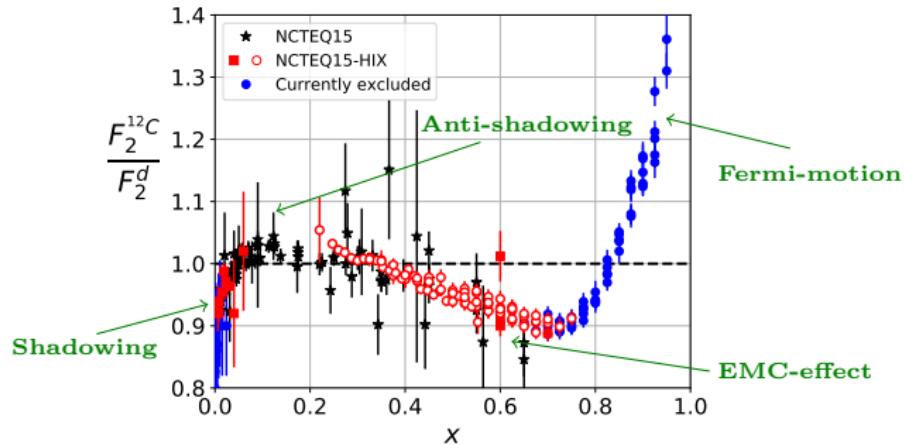
$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$



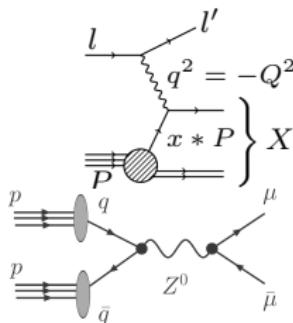
Introduction

- Cross-sections in nuclear collisions are modified

$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$



- Can we translate this modifications into ***universal*** nuclear PDFs?



$$\frac{d^2\sigma}{dx dQ^2} = \sum_{i=q,\bar{q},g} \int_x^1 \frac{dz}{z} f_i(z, \mu) d\hat{\sigma}_{il \rightarrow l'X} \left(\frac{x}{z}, \frac{Q}{\mu} \right) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{Q^2}\right)$$

$$\sigma_{pp \rightarrow l\bar{l}X} = \sum_{i,j=q,\bar{q},g} \int_{x_1}^1 dz_1 \int_{x_2}^1 dz_2 f_i(z_1, \mu) f_j(z_2, \mu) \hat{\sigma}_{ij \rightarrow l\bar{l}X} + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{Q^2}\right)$$

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

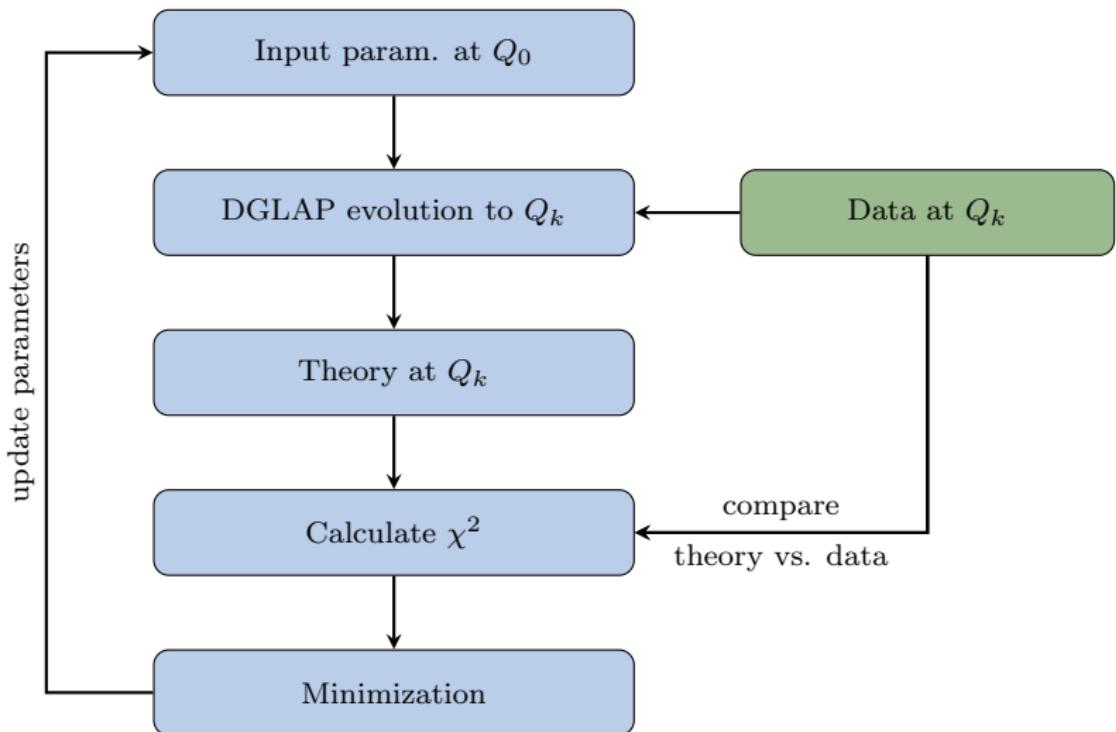
Isospin symmetry

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

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 $\mu = Q_0 \sim 1\text{GeV}$:

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

with $c_j = c_j(A) \stackrel{\text{nCTEQ}}{=} p_k + a_k (1 - A^{-b_k})$ 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 $\mu = Q_{\max}$.
4. Calculate theory predictions corresponding to the data (σ_{DIS} , σ_{DIS} , 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)

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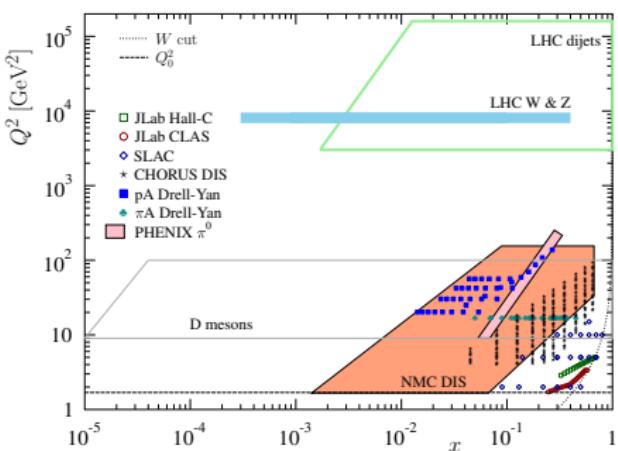
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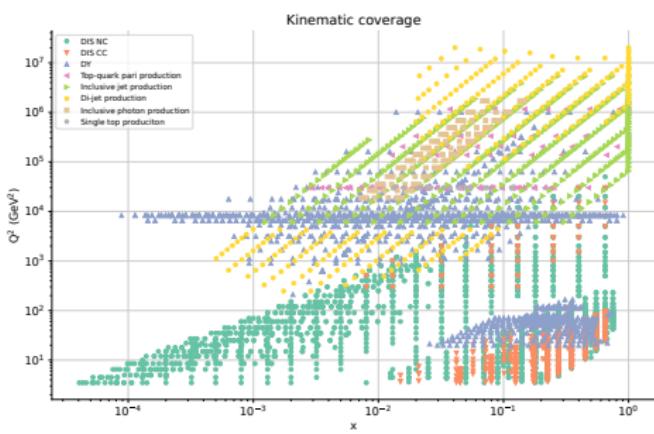
Differences with the free-proton PDFs

- Theoretical *status* of **Factorization** (no proof for pA or AA , final state effects)
- **Higher-twists** potentially enhanced
- Parametrization – more parameters to model **A -dependence**
- Fewer, less precise **data** with more restrictive kinematic coverage (no HERA, LHC very important):

EPPS21 ~ 2000 points



NNPDF4.0 ~ 5000 points



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 $p\text{Pb}$ π, K					✓
LHC $p\text{Pb}$ W/Z		✓	✓	✓	✓
LHC $p\text{Pb}$ dijet			✓	✓	
LHC $p\text{Pb}$ HQ			✓ GMVFNS	✓ FO+PS(rew)	✓ ME fit
LHC quarkonium					✓ ME fit
LHC $p\text{Pb}$ γ				✓	
Kinematic cuts	$Q > 1.3 \text{ GeV}$	$Q > 1.87 \text{ GeV}$ $W > 3.5 \text{ GeV}$	$Q > 1.3 \text{ GeV}$ $W > 1.8 \text{ GeV}$ $p_T^{HQ} > 3 \text{ GeV}$	$Q > 1.87 \text{ GeV}$ $W > 3.5 \text{ GeV}$	$Q > 2 \text{ GeV}$ $W > 3.5 \text{ GeV}$ $p_T^{HQ(SIH)} > 3 \text{ GeV}$
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	\sim NNPDF4.0	\sim 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

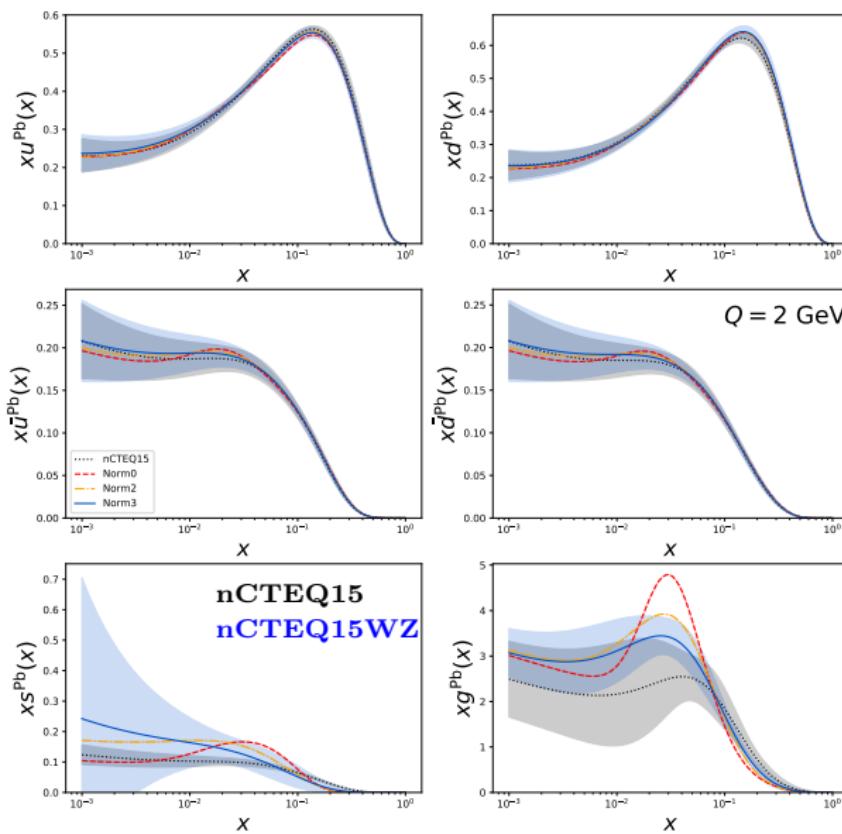
Recent nCTEQ results

- ▶ Last full nPDF release: **nCTEQ15** [PRD 93, 085037 (2016)]
 - ▶ DIS NC data
 - ▶ fixed-target DY data
 - ▶ pion data from RHIC
- ▶ Updates on the way to new release
 - ▶ **nCTEQ15WZ** [EPJC 80, 968 (2020)]
 - ▶ LHC W/Z data
 - ▶ constraints on *gluon* and *strange* nPDFs
 - ▶ **nCTEQ15HIX** [PRD 103, 114015 (2021)]
 - ▶ 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
 - ▶ currently in form of PDF-reweighting

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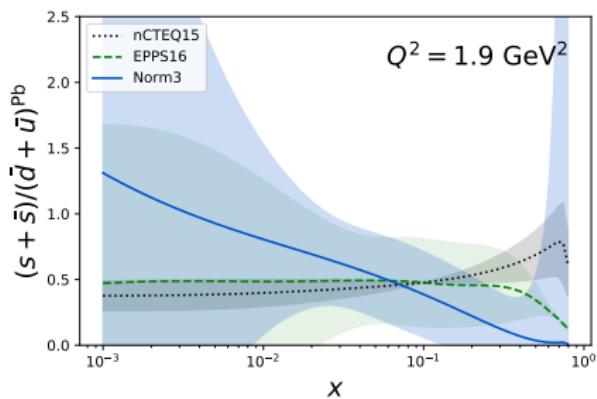
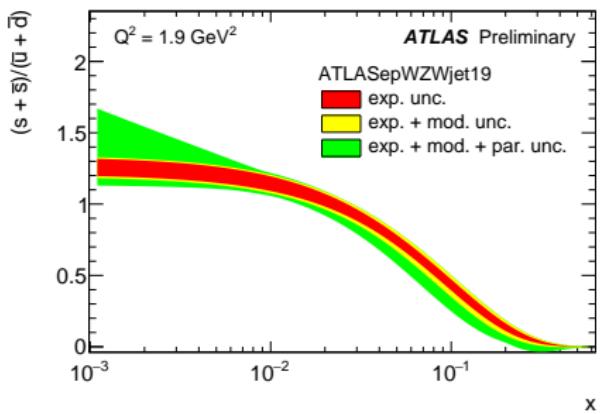
nuclear PDF analysis with $p\text{Pb}$ W/Z LHC data



nCTEQ15 nuclear PDFs + W/Z $p\text{Pb}$ 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: $R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$



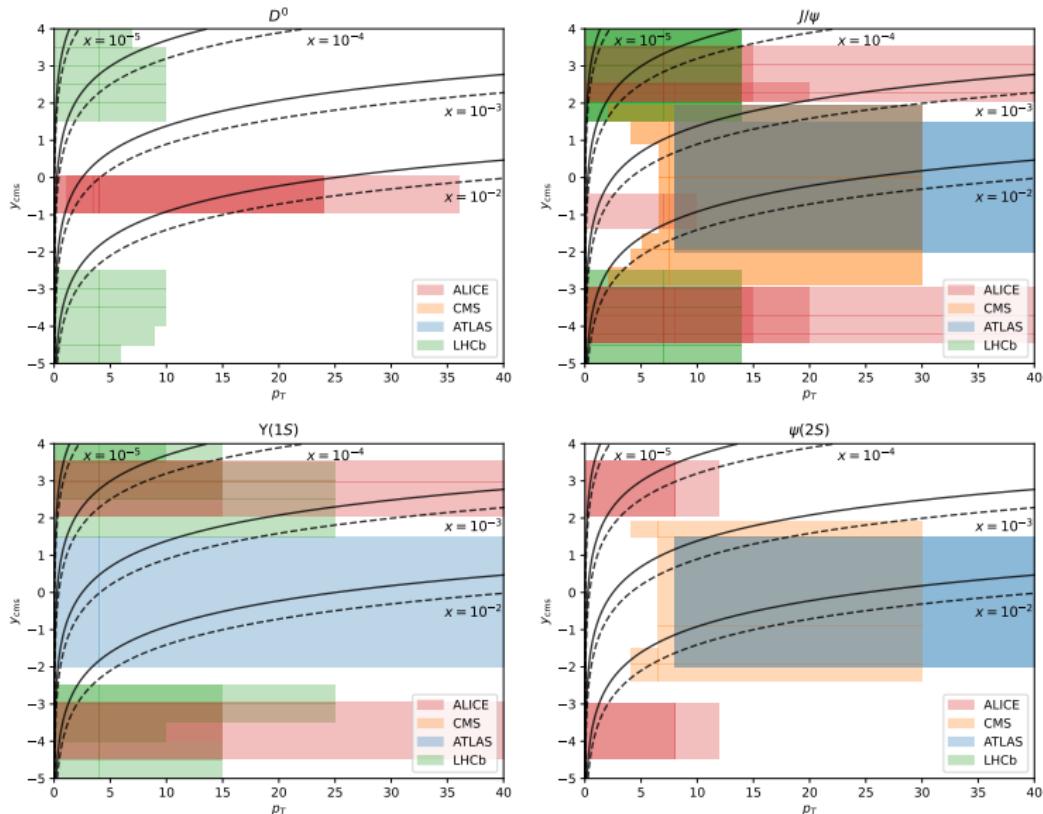
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Available nPDFs including heavy quark(onium) data

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

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



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

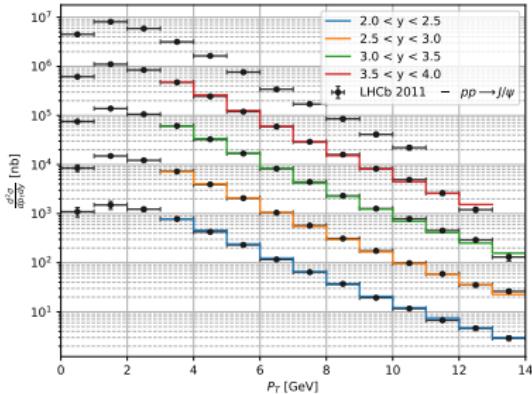
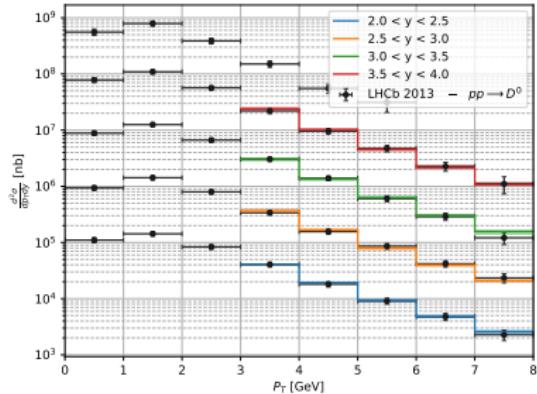
Heavy Quarks (HQ) - Data-driven Approach

$$\sigma(AB \rightarrow Q + X) = \int dx_1 \, dx_2 f_{1,g}(x_1) f_{2,g}(x_2) \frac{1}{2\hat{s}} |\mathcal{A}_{gg \rightarrow Q + X}|^2 d\text{LIPS}$$

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

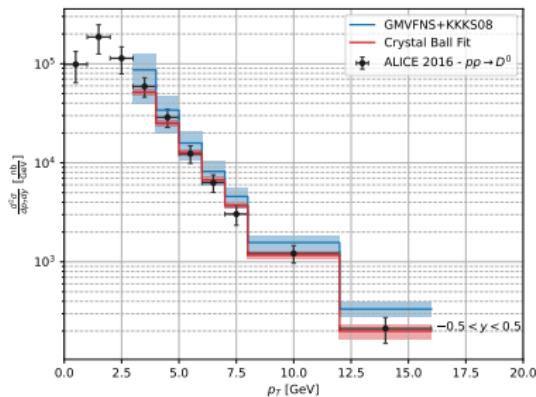
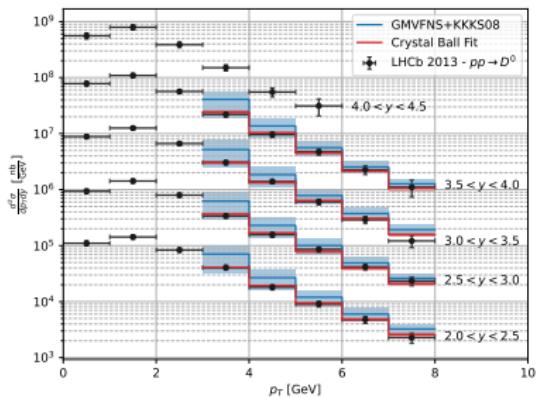
$$\overline{|\mathcal{A}_{gg \rightarrow Q + X}|^2} = \frac{\lambda^2 \kappa \hat{s}}{M_Q^2} \begin{cases} e^{-\kappa \frac{p_T^2}{M_Q^2} + a|y|} & \text{if } p_T \leq \langle p_T \rangle \\ e^{-\kappa \frac{\langle p_T \rangle^2}{M_Q^2} + a|y|} \left(1 + \frac{\kappa}{n} \frac{p_T^2 - \langle p_T \rangle^2}{M_Q^2}\right)^{-n}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

- Very good agreement between data and fitted theory



Baseline - comparison with GMVFNS for D^0

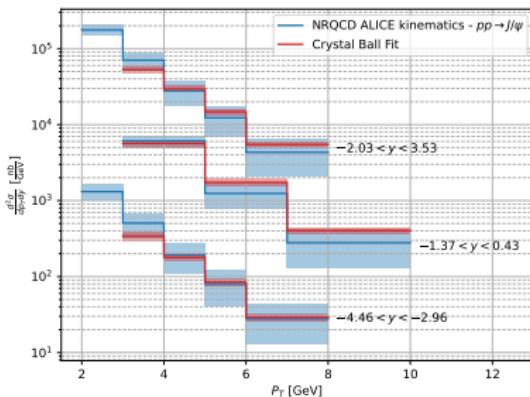
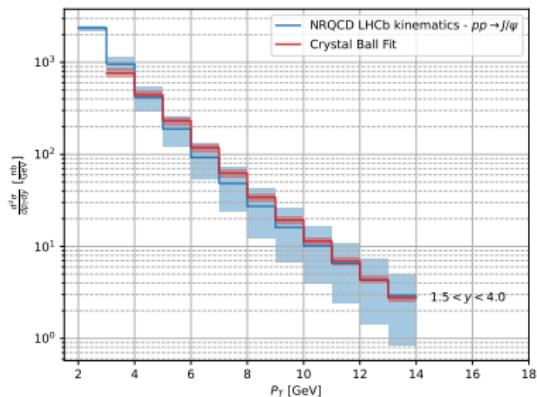
Calculations in the GMVFNS using KKKS08 fragmentation functions



- 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

Baseline - comparison with NRQCD for J/ψ

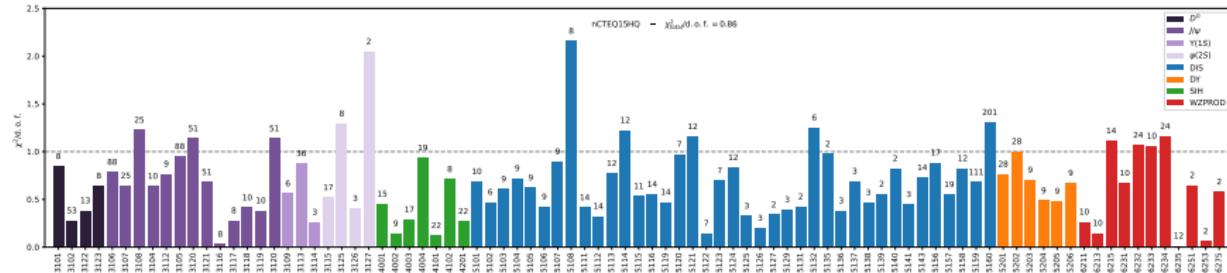
Calculations by Mathias Butenschoen, Bernd Kniehl [M. Butenschoen et al., Nucl.Phys.B Proc.Suppl. 222-224 (2012) 151-161]



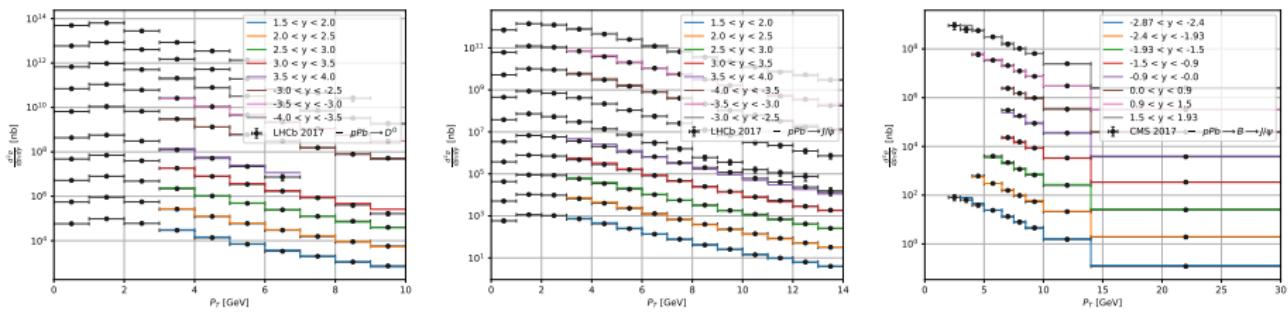
- ▶ NRQCD Uncertainties due to scale variations:
 $1/2 < \mu_r/\mu_{r,0} = \mu_i/\mu_{i,0} = \mu_{\text{NRQCD}}/\mu_{\text{NRQCD},0} < 2$
- ▶ Base scale $\mu_{r,0} = \mu_{i,0} = \sqrt{p_T^2 + 4m_c^2}$ and $m_{\text{NRQCD},0} = m_c$

nCTEQ15HQ $p\text{Pb}$ data description [PRD 105 (2022) 11, 114043]

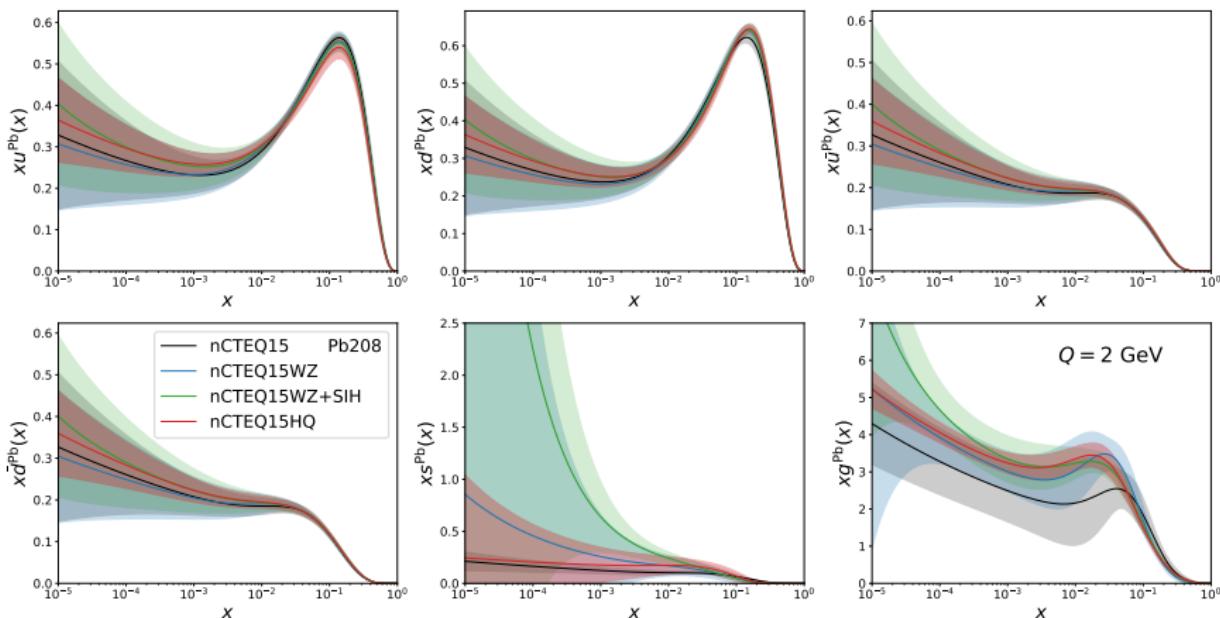
χ^2 for nCTEQ15HQ with 548 new HF data points:



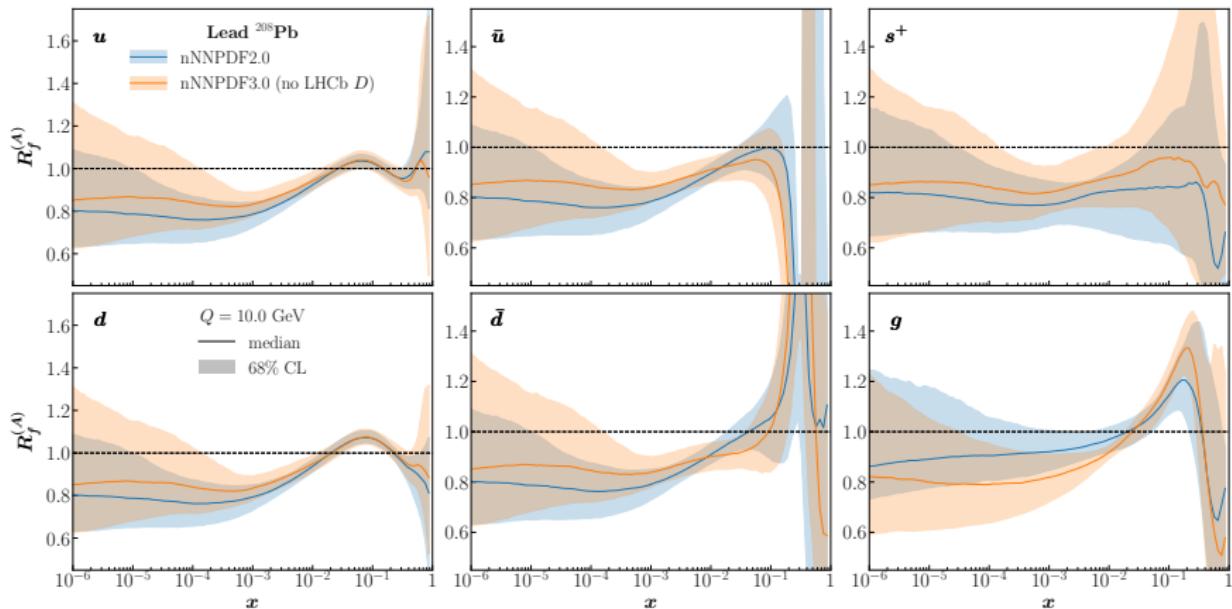
Example $p\text{Pb}$ data description:



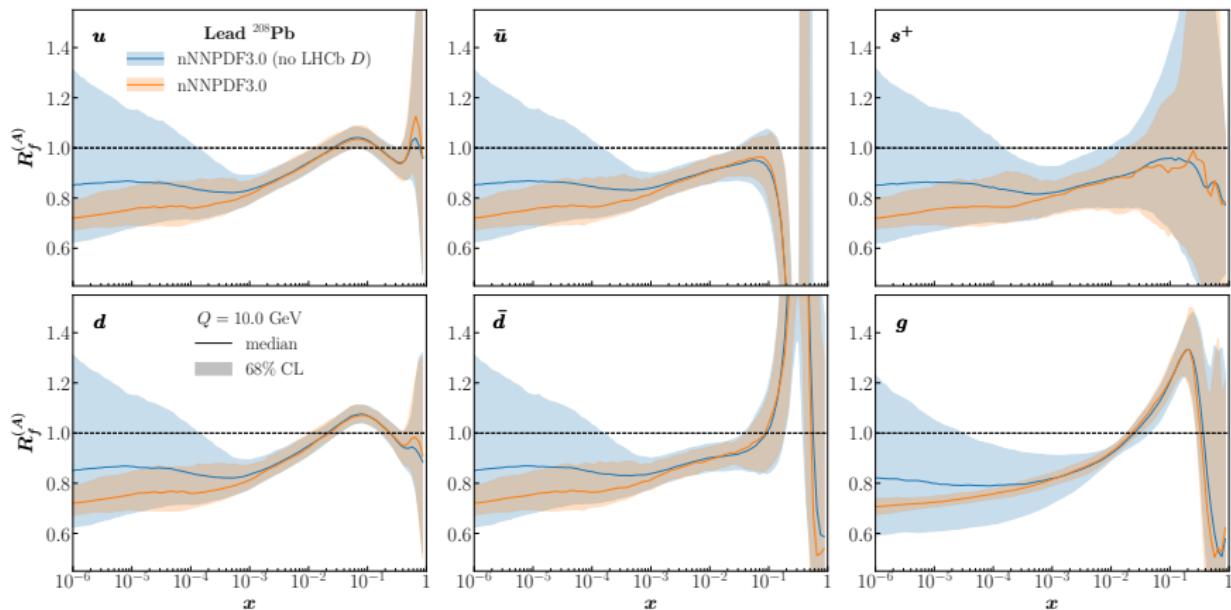
- ▶ New data compared to nCTEQ15WZ+SIH:
 D , J/ψ , $B \rightarrow J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \rightarrow \psi(2S)$
- ▶ Predictions for heavy quark(onium) data done with data-driven method [PRL 121 (2018) 052004; PRL107, 082002 (2011); EPJC77, 1 (2017)]



- ▶ 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**



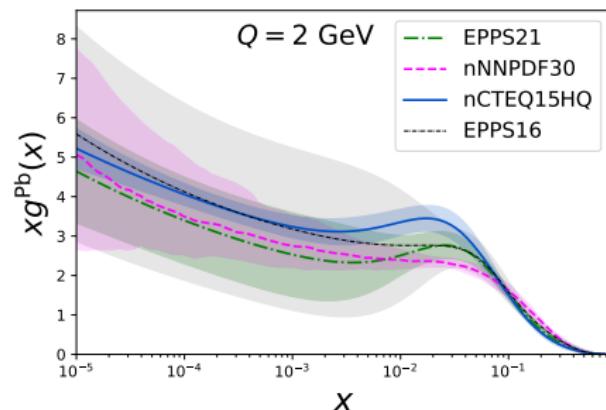
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Summary

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- ▶ I presented selected nCTEQ results on nuclear PDFs which will be combined into a next nCTEQ release.
- ▶ The $p\text{Pb}$ 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)
 - ▶ **strange quark** (W/Z)
- ▶ There is also a lot of progress from other groups: NNPDF3.0, EPPS21, TUJU19, KSASG20.



Summary

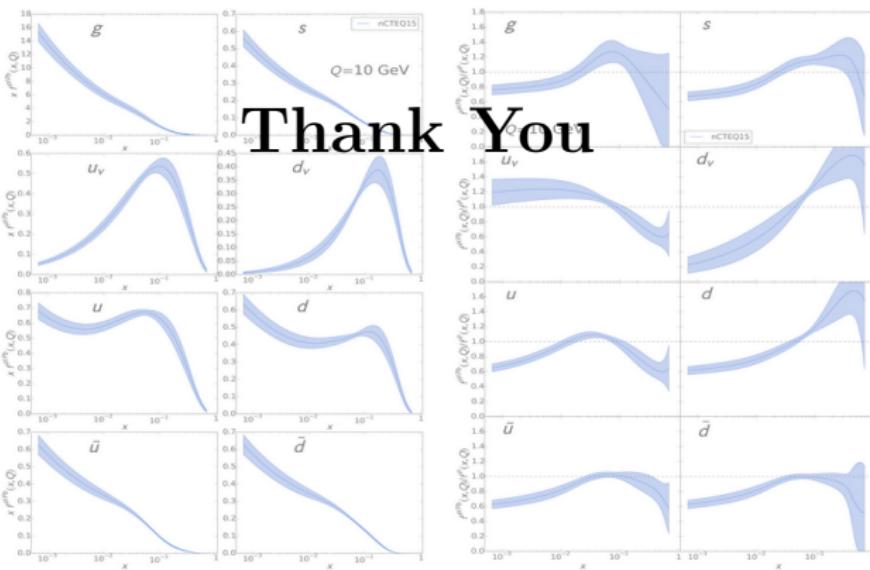
- ▶ Nevertheless we are still far away from the precision of proton PDFs and there are additional questions
 - ▶ factorization in pA collisions is not proven
 - ▶ A -dependence needs to be tested
 - ▶ there can be other effects like energy loss [JHEP 01 (2022) 164]
- ▶ What we still don't know:
 - ▶ **strange** distribution
 - ▶ we would like to know more about **gluon**
(test what we learned against data for colorless final states)
 - ▶ **low- x u & d** quark distributions
 - ▶ **intrinsic charm?**

nCTEQ

nuclear parton distribution functions

- Home
- PDF grids & code
 - nCTEQ15
 - previous PDF grids
- Papers & Talks
- Subversion
- Tracker
- Wiki

nCTEQ project is an extension of the CTEQ collaborative effort to determine parton distribution functions inside of a free proton. It generalizes the free-proton PDF framework to determine densities of partons in bound protons (hence nCTEQ which stands for nuclear CTEQ). All details on the framework and the first complete results can be found in arXiv:15????? [hep-ph]. The effects of the nuclear environment on the parton densities can be shown as modified parton densities or nuclear correction factors (for example for lead as shown below)



Thank You