

Recent results on nPDFs

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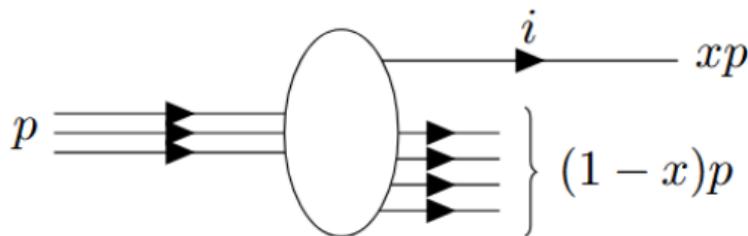
Quarkonia as Tools 2024



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PDFs

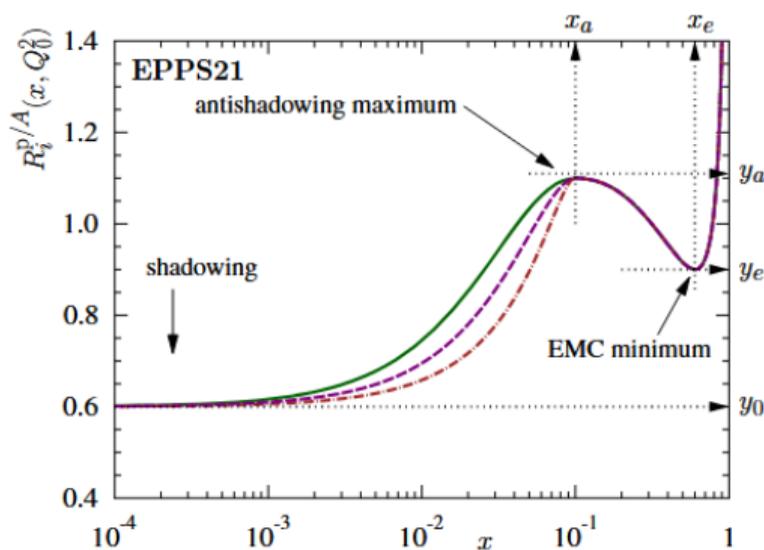
- ▶ Probability densities to find a parton with a momentum fraction x inside of a hadron of momentum p



- ▶ Enter calculations involving hadrons in the initial state
- ▶ Non-perturbative, Universal objects
- ▶ Fitted on experimental data

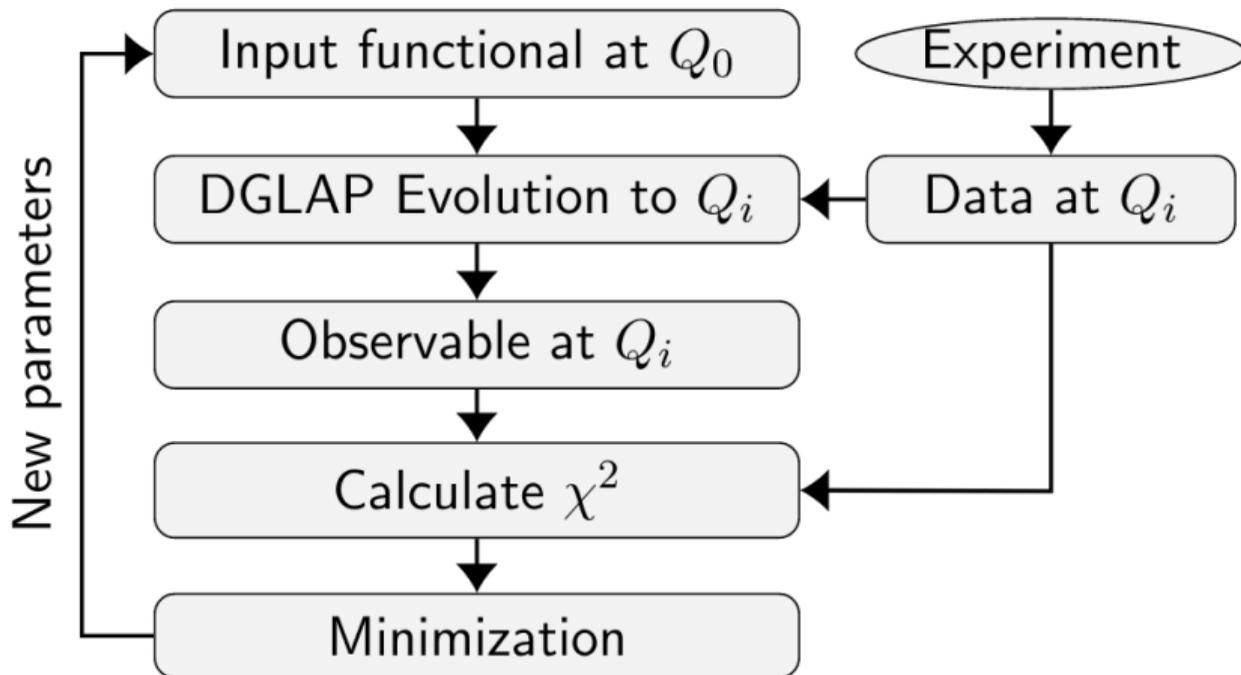
Nuclear PDFs

- ▶ PDFs are modified when nuclei are involved
- ▶ The nuclear PDF is not just Z times the proton PDF + N times the neutron PDF



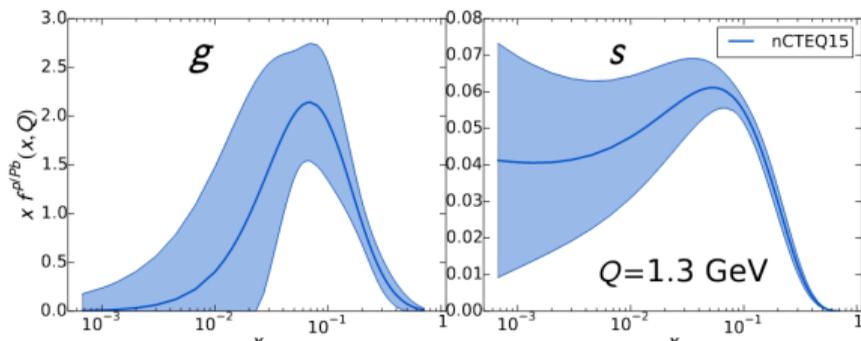
- ▶ $f_i^A(x, Q^2) = \frac{Z}{A} f_i^{p/A}(x, Q^2) + \frac{A-Z}{A} f_i^{n/A}(x, Q^2)$
- ▶ $f_i^{p/A}(x, Q^2) = R_i^A(x, Q^2) f_i^p(x, Q^2)$
- ▶ Isospin symmetry to obtain $f_i^{n/A}(x, Q^2)$

"Standard" fitting procedure



Current status of nPDFs

- ▶ More precise (n)PDFs → more precise predictions for observables measured at colliders (notably the future EIC)

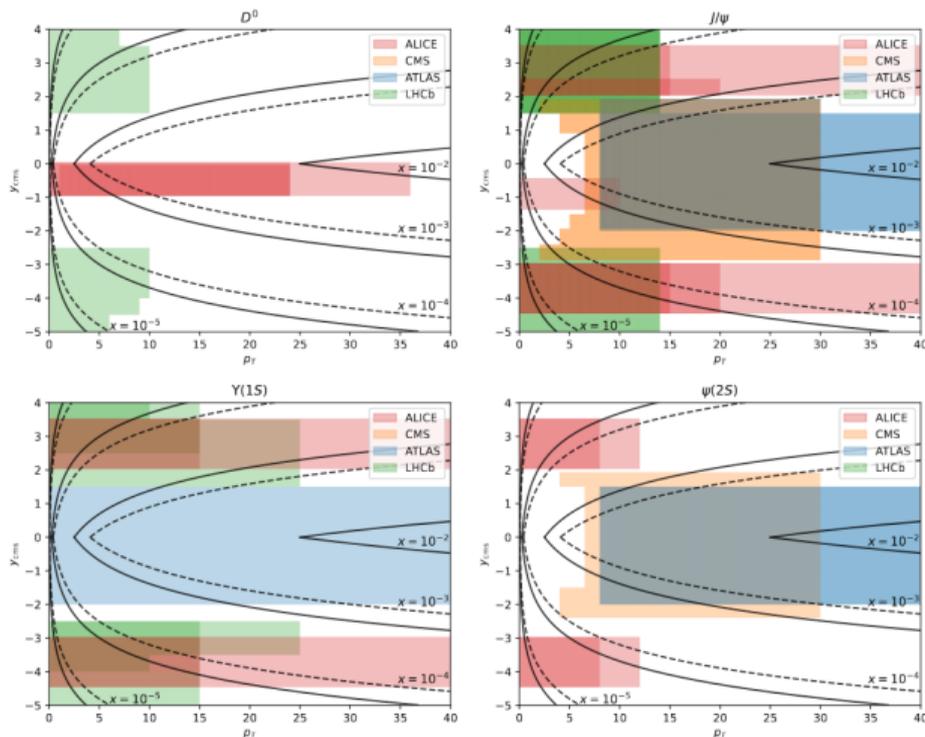


- ▶ Very large gluon uncertainties, especially at low x
→ large uncertainties on other flavors via DGLAP evolution

Won't be an exhaustive overview, only focus on nPDFs using heavy flavor data

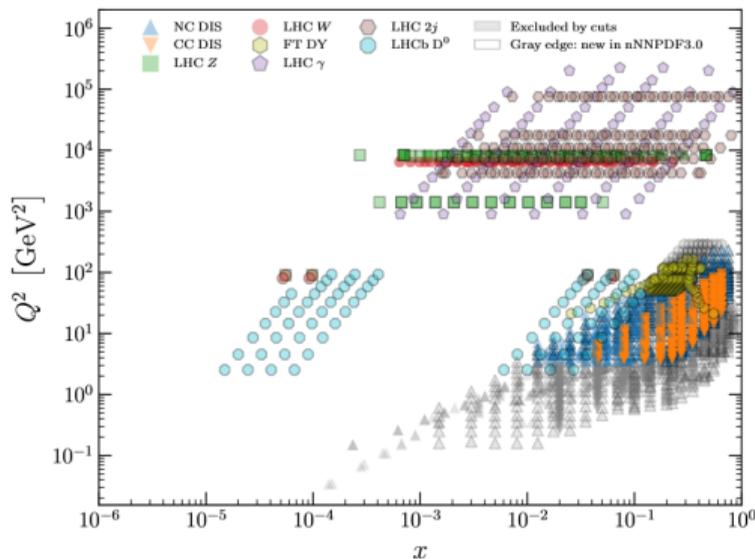
Why quarkonia? (And open heavy flavors)

- ▶ Large data sets from LHC experiments
- ▶ Sensitivity to gluon nPDFs down to very low x ($\approx 10^{-4.5}$)

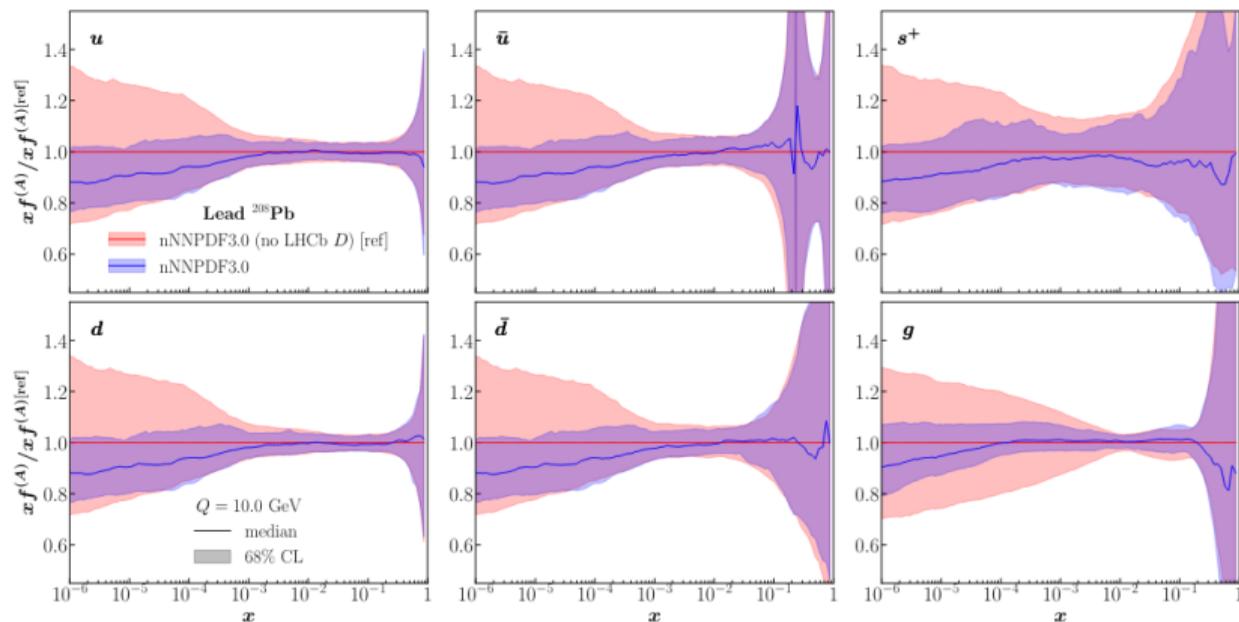


nNNPDF3.0 (2201.12363)

- ▶ Parametrization of the bound proton PDFs $f_i^{p/A}$ using neural networks at scale $Q_0 = 1 \text{ GeV}$
- ▶ 256 parameters
- ▶ 2188 data points (1467 old, 721 new)
- ▶ Processes:
 - (ν) DIS (411 new points)
 - DY (146 new points)
 - WZ
 - γ prompt production from ATLAS 8 TeV
 - Dijet (New data from CMS 5 TeV)
 - D meson data from LHCb 5 TeVIncluded via Bayesian reweighting (not fitted)



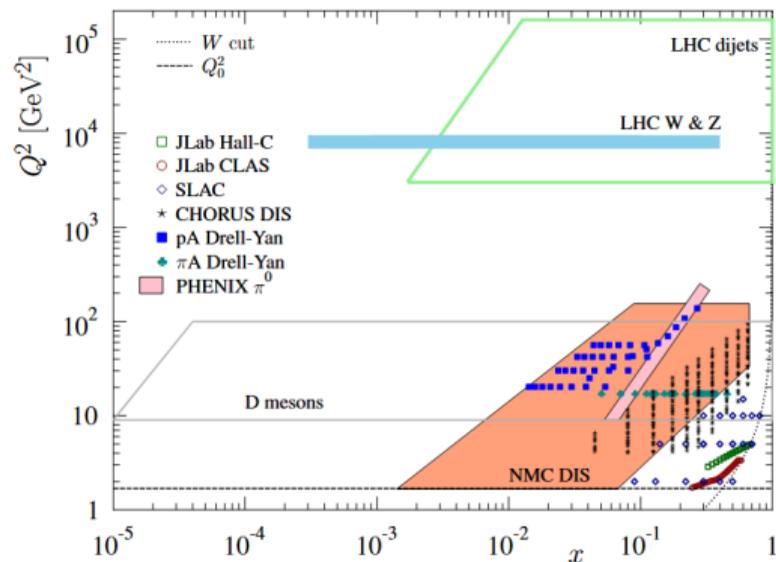
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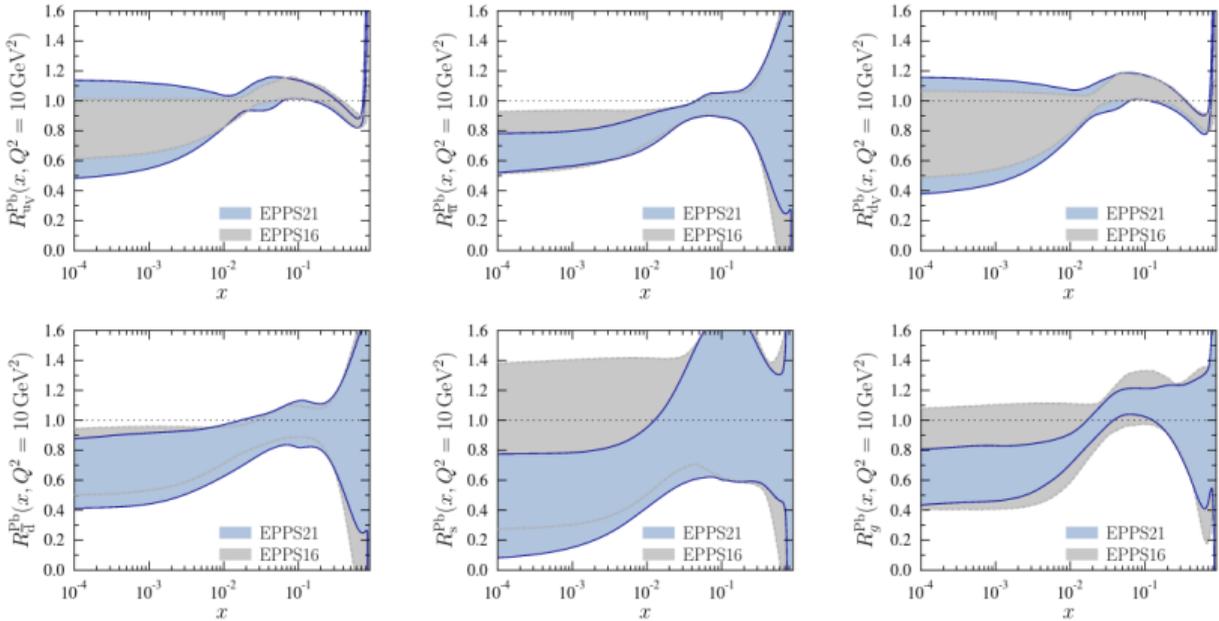
- Large reduction of gluon uncertainties thanks to LHCb D meson data.

EPPS21 (Eur. Phys. J. C 82, 413 (2022))

- ▶ Parametrization of the nuclear modification factor $R_i^{p/A}$ at $Q_0 = 1.3$ GeV
- ▶ 24 free parameters (from 20 in EPPS16)
- ▶ 2077 data points (1742 old, 335 new)
- ▶ Processes:
 - (ν)DIS (New data from JLAB)
 - DY
 - SIH
 - WZ (New W^\pm data from CMS 8 TeV)
 - Dijet (New data from CMS 5 TeV)
 - D meson data from LHCb 5 TeV



EPPS21 (Eur. Phys. J. C 82, 413 (2022))



► Important reduction of gluon and strange quark uncertainties. Due to D meson data for the gluon and due to W data and gluon uncertainty reduction for the strange quark

nCTEQ15HQ (Phys. Rev. D 105, 114043)

- ▶ Data-driven approach to include D/quarkonium data (implemented from [Phys. Rev. Lett. 121, 052004](#), [Phys. Rev. D 104, 014010](#))
- ▶ Parametrization of the nPDFs at $Q_0 = 1.3 \text{ GeV}$
- ▶ 19 parameters
- ▶ 1484 data points (936 old, 548 new)
- ▶ Processes:
 - DIS
 - DY
 - WZ
 - SIH
 - D_0 data from LHCb
 - J/ψ , $\psi(2S)$ and $\Upsilon(1S)$ data from LHC

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

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

Heavy flavor fitting procedure

- ▶ Cross-section parametrized as:

$$\sigma(AB \rightarrow \Phi + X) = \int dx_1 dx_2 f_{1,g}(x_1, \mu) f_{2,g}(x_2, \mu) \frac{1}{2\hat{s}} \overline{|\mathcal{A}(gg \rightarrow \Phi + X)|^2} dPS$$

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

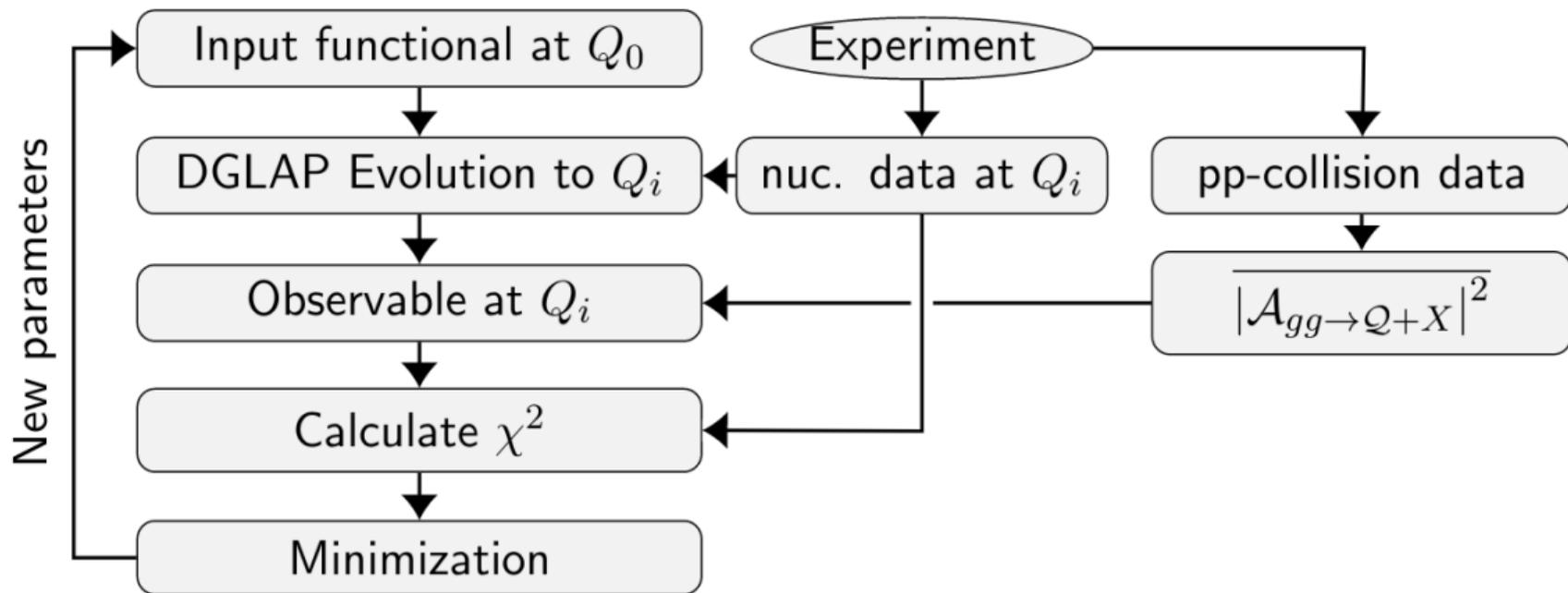
- ▶ 2 assumptions:

- gg-channel dominant
- Only consider 2→2 kinematics

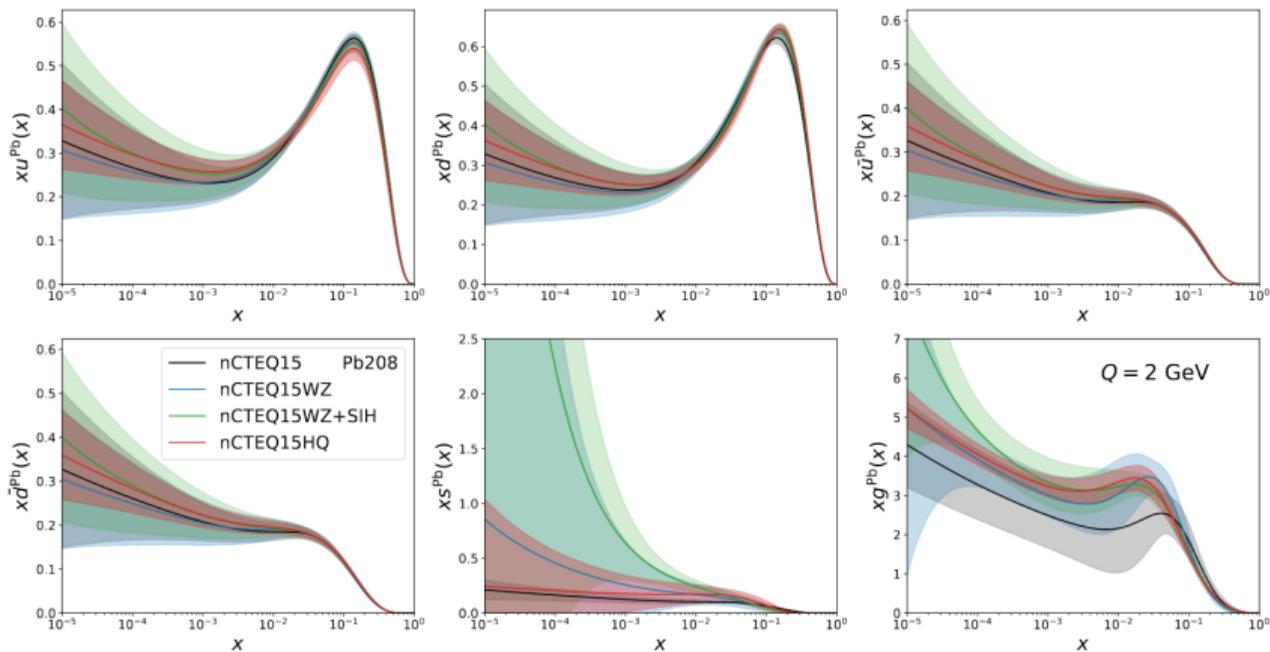
- ▶ 5 additional parameters

- ▶ a parameter added to include rapidity dependence

Heavy flavor fitting procedure

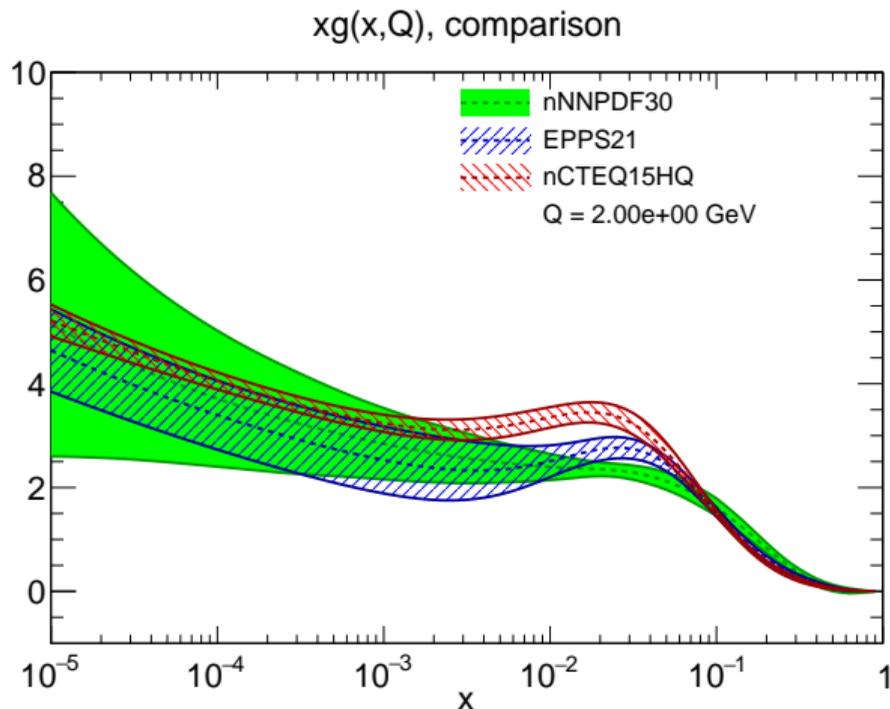


nCTEQ15HQ



► Gluon uncertainties greatly reduced, especially at very low x

Comparison



- ▶ Gluon nPDFs in Pb at 2 GeV
- ▶ Same distribution shapes, but different uncertainties at very low x
- ▶ nCTEQ15HQ has the lowest uncertainties
⇒ effect of quarkonia data?

Spatial dependence of nPDFs

- ▶ Traditionnal nPDFs are fitted on minimum bias data
⇒ **spatially averaged**
- ▶ Essential to understand the **spatial dependence** to interpret data in **different centrality classes**
- ▶ So far only one attempt to study impact parameter dependent nPDFs: EPS09s/EKS98s
- ▶ Valuable to have a second independent study, with a different methodology

EPS09s (J. High Energ. Phys. 2012, 73 (2012))

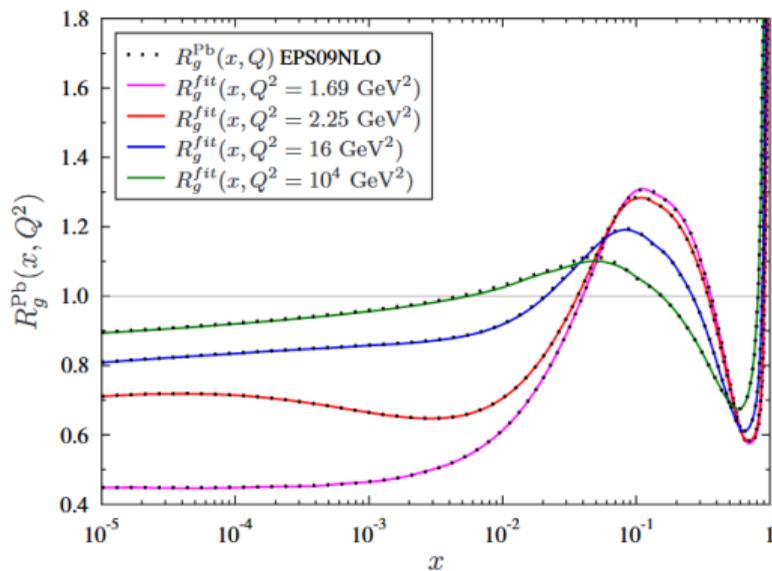
- ▶ Parametrization of the spatially dependent nuclear modification by the 2D local nucleon number density (thickness function)

$$R_i^A(x, Q^2) = \frac{1}{A} \int d^2\mathbf{s} T_A(\mathbf{s}) r_i^A(x, Q^2, \mathbf{s}) ; \quad r_i^A(x, Q^2, \mathbf{s}) = 1 + \sum_{j=1}^4 c_i^j(x, Q^2) [T_A(\mathbf{s})]^j$$

$$\int d^2\mathbf{s} T_A(\mathbf{s}) = A$$

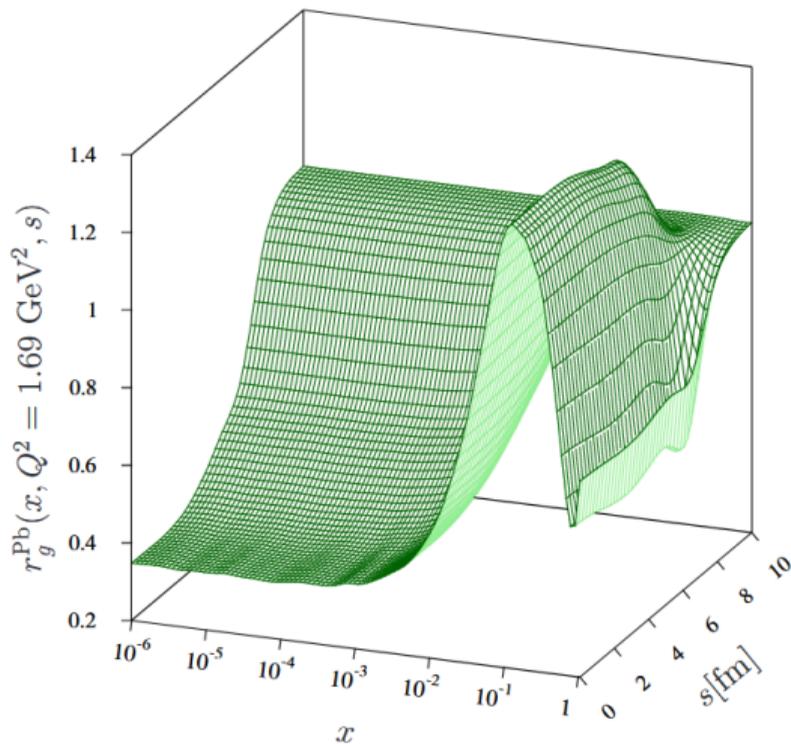
- ▶ c_i^j coefficients to be fitted on the nuclear modification factors
- ▶ Fit on a wide range of nuclei: $A = 16, 20, 27, 40, 56, 64, 84, 108, 115, 117, 131, 184, 195, 197, 208, 238 \Rightarrow$ Very different nucleon densities

EPS09s (J. High Energ. Phys. 2012, 73 (2012))



- ▶ $\chi^2(x, Q^2) \equiv \sum_A \left[\frac{R_i^A(x, Q^2) - \frac{1}{A} \int d^2\mathbf{s} T_A(\mathbf{s}) r_i^A(x, Q^2, \mathbf{s})}{W_i^A(x, Q^2)} \right]^2$
- ▶ $A \geq 16$ and $W_i^A(x, Q^2) = 1$
- ▶ Nuclear modification well reproduced from the spatially dependent ones, at very different scales

EPS09s (J. High Energ. Phys. 2012, 73 (2012))



- ▶ Away from the nucleus edge, x-distribution similar to the input distribution
- ▶ Nuclear modification dies out when $|\mathbf{s}| > R_A$ as expected

Different ansatz

- ▶ Assumption that the spatially dependent nuclear modification can be determined by the thickness function

$$R^A(\mathbf{b}, x, \mu_F) - 1 = (R^A(x, \mu_F) - 1)G\left(\frac{T_A(\mathbf{b})}{T_A(0)}\right),$$

with

$$\int T_A(\mathbf{b})G\left(\frac{T_A(\mathbf{b})}{T_A(0)}\right)d^2\mathbf{b} = A.$$

We take (simplest test example):

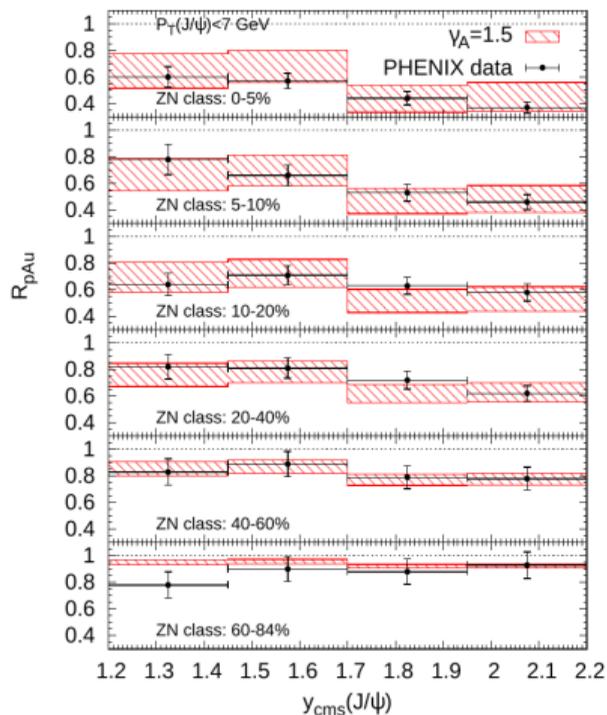
$$G\left(\frac{T_A(\mathbf{b})}{T_A(0)}\right) \propto \left(\frac{T_A(\mathbf{b})}{T_A(0)}\right)^{\gamma_A},$$

with γ_A to be determined ($\gamma_A = 0$ means no spatial dependence)

Observables used

- ▶ Direct fit on experimental data
- ▶ 2 types of data are used:
 - Centrality dependent R_{pA} for single inclusive particle production (in our case $pAu \rightarrow J/\Psi$ forward data from PHENIX (RHIC) at $\sqrt{s_{NN}} = 200$ GeV)
 - ★ forward: tension between nPDFs and backwards data
 - ★ J/Ψ : Comover effect may be important for excited states like $\Psi(2S)$
 - ★ RHIC: Large event-by-event fluctuations for LHC data.
 - Double Parton Scattering (DPS) in minimum bias pA collisions.
 - ★ Choice of $pPb \rightarrow D^0 D^0$ LHCb data
 - ★ $pPb \rightarrow J/\Psi D^0$ data also available but suffer from large SPS contamination.

Centrality dependent R_{pA}

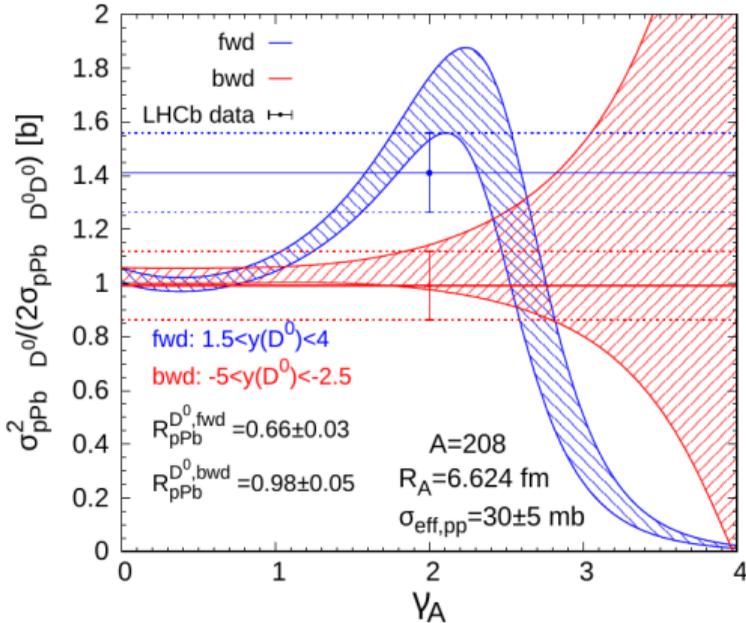


- ▶ With the Glauber model and assuming the only nuclear effect comes from the nPDFs:

$$R_{pAu}(b_{min} < b < b_{max}) = 1 - r + rR_{pAu}$$
- ▶
$$r = \frac{\int_{b_{min}}^{b_{max}} T_A(\mathbf{b}) G\left(\frac{T_A(\mathbf{b})}{T_A(0)}\right) d^2\mathbf{b}}{\int_{b_{min}}^{b_{max}} T_A(\mathbf{b}) d^2\mathbf{b}}$$
- ▶ R_{pAu} obtained from experiment (0-100% centrality)
- ▶ Best fit gives $\gamma_A = 1.50 \pm 0.10$ with $\chi^2/\text{ndf} = 0.64$. (24 data points vs $y_{cms}(J/\psi)$ and 96 vs $p_T(J/\psi)$)
- ▶ **Caveat:** "Naive" correspondence between \mathbf{b} and the centrality classes

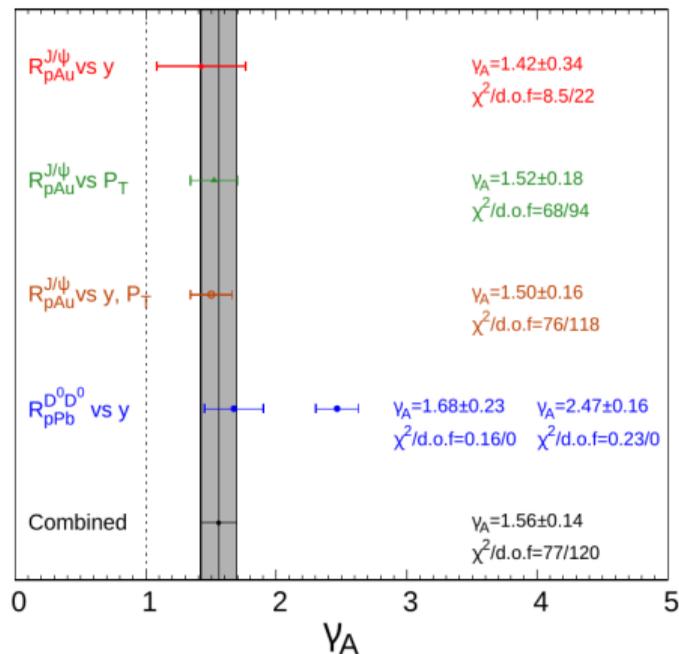
Minimum bias DPS

H.S. Shao, Phys. Rev. D 101 (2020) 5, 054036



- $R_{pPb \rightarrow D_0 D_0}^{DPS} = \frac{\sigma_{pPb \rightarrow D_0 D_0}^{DPS}}{A \sigma_{pp \rightarrow D_0 D_0}^{DPS}}$
 $= \sum_{i,j=1}^2 \left(\hat{T}_{A,ij} + (A-1) \sigma_{eff,pp} \hat{T}_{A,ij}^{(2)} \right) \times$
 $\left(R_{pPb}^{D_0} \right)^{2-i} \left(R_{pPb}^{D_0} \right)^{2-j}$
- $\sigma_{eff,pp}$: effective pp cross-section without initial parton-parton correlations, measured from DPS in pp collisions
- $R_{pPb}^{D_0}$: Nuclear modification of single inclusive D_0 production (measured)
- $2 \chi^2$ minima: $\gamma_A = 1.68 \pm 0.23$ and $\gamma_A = 2.47 \pm 0.16$

Combined results



- ▶ 2 very different observables but compatible results
- ▶ Atomic numbers of lead and gold are close
⇒ combination of fits
- ▶ Global fit gives $\gamma_A = 1.56 \pm 0.14$
(less than 10% relative uncertainty)
⇒ Highly disfavors $\gamma_A = 0$
- ▶ **Preliminary study**, work still under way

Conclusions

- ▶ Global effort towards the determination of more precise (n)PDFs
- ▶ Heavy flavor data help constrain the gluon nPDFs at very low x

- ▶ Spatial dependence shouldn't be neglected
- ▶ Parametrization of the nuclear modification with the thickness function
- ▶ Preliminary study with fitting on experimental data

- ▶ Correct the impact parameter/centrality correspondance
- ▶ Fit on more data?