Unresolved Questions in Cold Nuclear Matter

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Stony Brook University

Proton-Proton Collisions

At large momentum transfer in pp, scale $Q \gg \Lambda_{\mathrm{QCD}} \approx 200$ MeV

$$\mathrm{pp} \to \gamma^\star / Z^0 \to \ell^+ \ell^- + \mathrm{X} \quad \text{(Drell-Yan)}$$

Factorization of cross section = approximation

$$\frac{\mathrm{d}\sigma_{\mathrm{pp}}}{\mathrm{d}y\,\mathrm{d}Q} = \sum_{i,j} \int \mathrm{d}x_1\, f_i^{\mathrm{p}}(x_1, \mu) \int \mathrm{d}x_2\, f_j^{\mathrm{p}}(x_2, \mu) \frac{\mathrm{d}\hat{\sigma}_{ij}(x_1, x_2, \mu')}{\mathrm{d}y\,\mathrm{d}Q} + \mathcal{O}\left(\frac{\Lambda_{\mathrm{p}}^n}{Q^n}\right)$$

- $\hat{\sigma}_{ij}$: Partonic cross section calculable in perturbation theory
- x_1, x_2 : Fraction of momentum carried by the parton in the proton
- $f_{i,j}$: Parton Distribution Function (PDF), **universal**

Proton-Nucleus Collisions

Cross section in pA collisions assuming collinear factorization:

$$\frac{\mathrm{d}\sigma_{\mathrm{pA}}}{\mathrm{d}y\,\mathrm{d}Q} = \sum_{i,j} \int \mathrm{d}x_1\, f_i^{\mathrm{p}}(x_1,\mu) \int \mathrm{d}x_2\, f_j^{\mathrm{A}}(x_2,\mu) \frac{\mathrm{d}\hat{\sigma}_{ij}(x_1,x_2,\mu')}{\mathrm{d}y\,\mathrm{d}Q} + \mathcal{O}\left(\frac{\Lambda_{\mathrm{A}}^n}{Q^n}\right)$$

- Probing the PDF of a nucleus (without nuclear effects):

$$f_i^{\mathrm{A}} = Z f_i^{\mathrm{p}} + (A - Z) f_i^{\mathrm{n}}$$

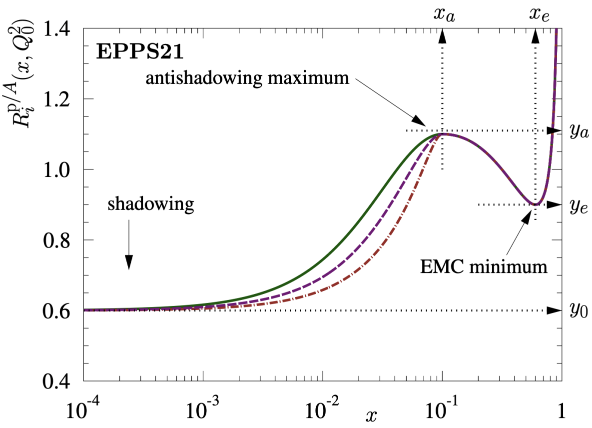
$$\sigma_{\mathrm{pA}} = Z\sigma_{\mathrm{pp}} + (A - Z)\sigma_{\mathrm{pn}} \approx A\sigma_{\mathrm{pp}}$$

- Investigating nuclear effects via:

$$R_{\mathrm{pA}} \equiv \frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}}{\mathrm{d}\sigma_{\mathrm{pp}}} \approx 1$$

Nuclear parton distribution functions (nPDF)

- EMC effect discovered in 1983 in DIS on nuclear targets
- **PDF is modified in nuclei** : $f_j^{p/A} \neq f_j^p$



- The nuclear modification factor depends on x

nPDF and data-sets

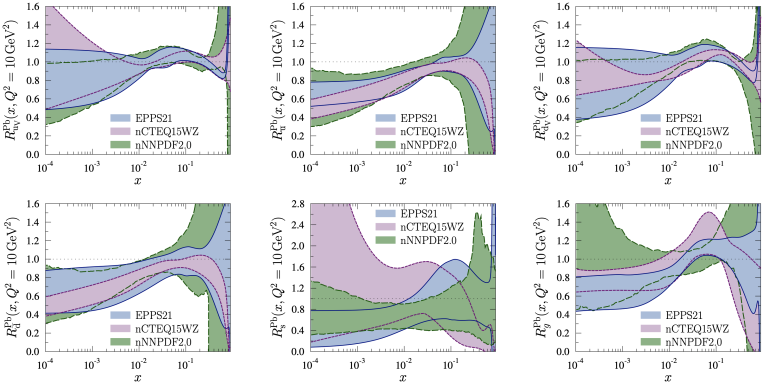
Historically, nPDFs were mainly extracted from DIS data

	EPS09	DSSZ	nCTEQ	EPPS16	EPPS21
e-DIS	✓	✓	✓	✓	✓
ν-DIS		✓		✓	✓
Drell-Yan pA	✓	✓	✓	✓	✓
RHIC hadrons	✓	✓	✓	✓	✓
LHC data pA (QED)				✓	✓
Drell-Yan πA				✓	✓
LHC data pA (D mesons)					✓

- Recent hA collision data included to:
  - Extend the explored x range
  - Access gluon nPDF more directly

$\rightarrow$ **Possible biases from additional nuclear effects**

nPDF and data-sets

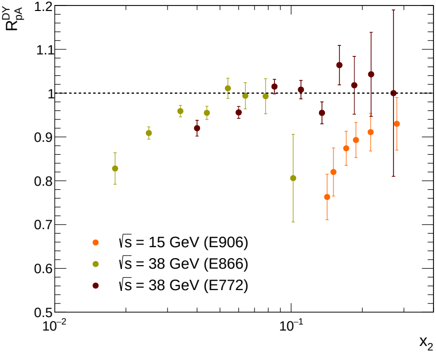


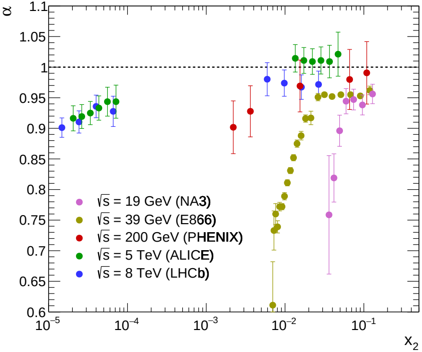
- nCTEQ15WZ and EPPS21 use heavy quark data in pA

$\rightarrow$ **Strongly impacting $R_g^{\mathbf{A}}$**

nPDF Scaling

$R_{pA}^{nPDF}(x, Q^2, \sqrt{s}) \equiv R_{pA}(x, Q^2)$ should scale as a function of x_2





- Nuclear dependence for J/ψ and Drell-Yan production

  Arleo Naïm Platchkov 1810.05120

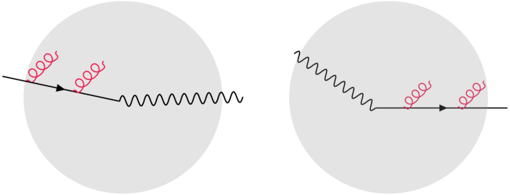
- No scaling as a function of $\sqrt{s}$ observed

$\rightarrow$ **Exploring beyond nPDF effects!**

Exploring beyond nPDF effects

The nuclear medium affects hard processes differently.

- $\mathrm{hA} \to \gamma^* + \mathrm{X}$ (DY)
  - **Initial-state interactions**
- $\mathrm{eA} \to e + h + \mathrm{X}$ (SIDIS)
  - **Final-state interactions**



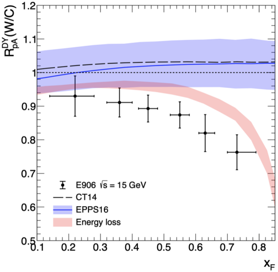
- $\mathrm{hA} \to c\bar{c}(\to J/\psi) + \mathrm{X}$ (Quarkonia)
  - **Initial- and final-state interactions**

How does the nuclear medium affect particle production?

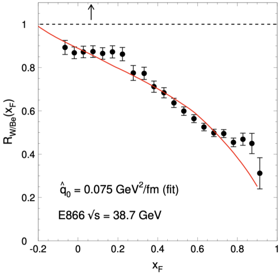
Energy loss effects

Energy loss effects have successfully described nuclear data

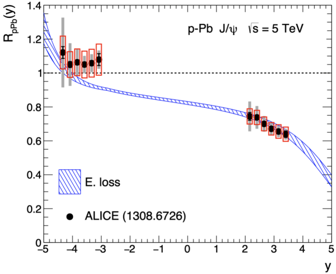
DY



J/ψ



J/ψ



- E866 and ALICE J/ψ suppression, $\langle\epsilon\rangle_{\text{FCEL}} \propto \sqrt{\hat{q}L}/M \cdot E$

  Arleo Peigné 1204.4609, 1212.0434, Arleo Kolevatov Peigné Rustamova 2003.06337

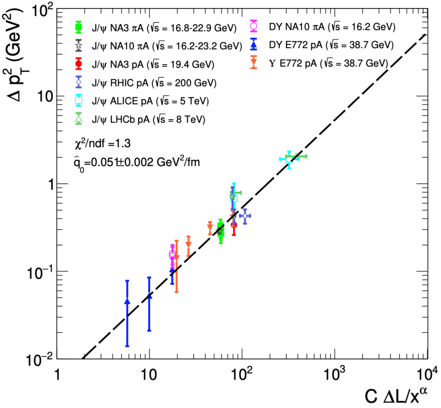
- E906 DY suppression, $\langle\epsilon\rangle_{\text{LPM}} \propto \alpha_s \hat{q}\, L^2$

  Arleo Naïm Platchkov 1810.05120

$\rightarrow$ What about other effects?

Transverse Momentum Broadening

Broadening effects have successfully described nuclear data

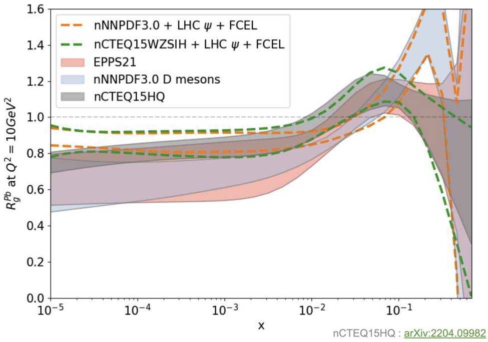


- J/ψ, ψ', Υ and DY data: a factor of 400 in beam energy!
- Broadening analysis reveals **universal scaling** across energies

Arleo Naïm 1810.05120

nPDF including the energy loss effect

A global exhaustive fit: the (only) future path?



Avez Arleo work ongoing

- Global fit including nPDF and energy loss from J/ψ suppression
- Significative impact on the shadowing amplitude

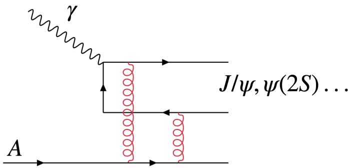
$\rightarrow$ Shadowing would be no more than 10-20% at $x \sim 10^{-5}$

Challenges in constraining gluon shadowing

Constraints on gluon shadowing from LHC pA data

- Limited experimental data for quarkonia and D-mesons
- Challenges in distinguishing shadowing from other nuclear effects
- Including energy loss in the global fit drastically reduces the shadowing amplitude by 10-20% at $x \sim 10^{-5}$

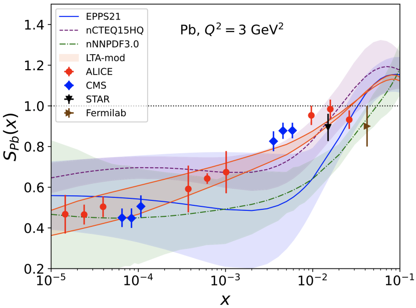
Ultra-peripheral collisions (UPC):



$\rightarrow J/\psi$ production in UPCs to probe gluon shadowing

Shadowing amplitude

J/ψ production in UPCs: a direct probe of R_g



Guzey CFNS cold QCD workshop (2025)

- Strong nuclear suppression of coherent J/ψ photoproduction in Pb-Pb UPC@LHC due to large gluon shadowing at small x

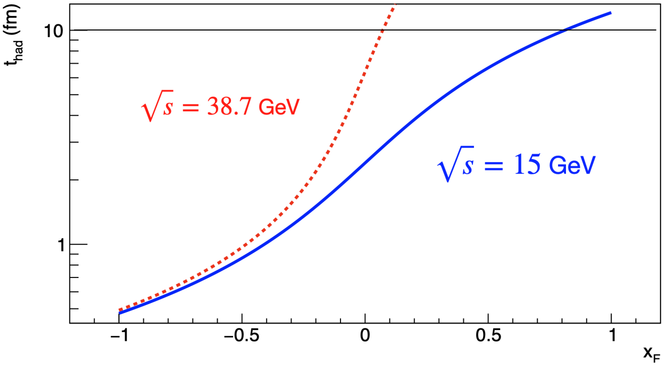
  Guzey Kryshen Strikman Zhalov 1305.1724, Guzey Zhalov 1307.4526

- EPPS21, nCTEQ15HQ, nNNPDF3.0 use heavy quarks in pPb

  $\rightarrow$ A shadowing amplitude up to 60% at $x \sim 10^{-5}$?

Nuclear absorption

Multiple scattering of $Q\bar{Q}$ bound state within the nucleons



- The typical size of a heavy nucleus is $L \sim 10$ fm
- J/ψ is mainly produced **outside** the nucleus at large y

$\rightarrow$ No J/ψ absorption at LHC forward data

Energy loss or nuclear absorption?

The absorption of quarkonia remains an open question

- $\sigma_{\text{abs}}^{J/\psi} \sim \mathbf{3} - 10$ mb: extracted using pA at $y \sim 0$
  $\rightarrow$ **probably overestimated**

  Lourenco Vogt Woehri 0901.3054, Arleo Tram 0612043
- **Energy loss alone coherently explains** J/ψ suppression in pA
- Possible shadowing effects in nuclear matter: 10%, 20% or more?
- What remains of the role of absorption, $\sigma_{\text{abs}}^{J/\psi} \ll 3$ mb?

$\rightarrow$ Comparison: J/ψ suppression in eA vs pA collisions
The suppression should not be universel

Nuclear Data Challenges

Numerous nuclear data available, from fixed-target to LHC

- Difficult to interpret due to **multiple effects**
- Need to isolate specific effects through **golden observables**
- Importance of **global approaches** (global fits)
- Critical to estimate the **precise contribution of shadowing**!

→ The cold QCD effects are the primary source of uncertainties in the interpretation of AA collisions

Golden observables?

- $\mathcal{R} = R_{\mathsf{pA}}^{J/\psi} / R_{\mathsf{pA}}^{\psi} \sim S\left(\sigma_{\rm abs}^{J/\psi}, \rm L_A\right) / S\left(\sigma_{\rm abs}^{\psi}, \rm L_A\right)$
    - Mid rapidity region, small $\sqrt{s}$
    - Independent of shadowing: $Q^2_{J/\psi} \sim Q^2_{\psi}$
    - Independent of FCEL: $\langle \epsilon \rangle_{\mathsf{FCEL}} \propto 1/M_\perp$

- $\mathcal{R} = R_{\mathsf{pA}}^{J/\psi} / R_{\mathsf{pA}}^{\Upsilon}$
    - Weak shadowing dependence, strong sets correlations
    - Probe of the mass dependence of FCEL

- Transverse momentum broadening $\Delta p_\perp^2$ in eA and pA collisions
    - Independent of shadowing
    - Independent of energy loss

- J/ψ production
    - Test the non-universality of J/ψ suppression in eA and pA
    - Strong test of $\langle \epsilon \rangle_{\mathsf{FCEL}}$ vs $\langle \epsilon \rangle_{\mathsf{LPM}}$, + possible nuclear abs.
    - In eA, $\langle \epsilon \rangle_{\mathsf{LPM}} \to 0$ at large $\sqrt{s}$

Key Questions in Nuclear Collisions

White paper in preparation:
Nuclear Cold QCD: Review and Future Strategy

1. **Energy Loss Mechanisms**
   - Initial-state (DY), final-state (SIDIS)
   - Initial/final-states (Quarkonia)

2. **Final-State Interactions**
   - Nuclear absorption, comovers

3. **Shadowing vs. Saturation**
   - Shadowing amplitude
   - Distinction between leading-twist shadowing and gluon saturation

CFNS Cold QCD workshop

Global Insights and Future Directions

- **Nuclear data reveal a scaling violation** as a function of x
  - R_{pA} is not universal
  - Collinear factorization is not satisfied
- **Shadowing uncertainty** impacts all data interpretation
- **Energy loss** is key to describing the data

- **Strategy to address the three questions:**
  - Assess the limitations of hA data for nPDF studies
  - Enhance global fits by incorporating nuclear effects
  - Strongly constrain shadowing using future EIC DIS data
  - Identify and measure the key observables

No need for more data, but better data AND stronger collaboration between phenomenologists and experimentalists