Nuclear Cold QCD Review

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Nuclear Cold QCD White Paper

Outcome of CFNS workshop held in January 2025:

Cold Nuclear Matter Effects: from the LHC to the EIC

Organized by Francois Arleo, Charles Joseph Naim, Jen-Chieh Peng and RV

The primary objectives of this workshop include proposing a coherent, universal theoretical/phenomenological framework for interpreting all existing data, fostering dialogue between theorists and experimentalists, and highlighting the potential of future EIC data for advancing our understanding of Cold Nuclear Matter effects (CNM). At the conclusion of this workshop, we will identify the key CNM questions that remain unresolved, as well as the most suitable observables that can be employed to address them. An important outcome of the workshop will be a paper summarizing these key questions and proposing ways to answer them.

Key Questions

Three key questions were identified that need to be addressed by future data:

1. **What are the relative contributions of perturbative (gluon saturation) and non-perturbative (nPDF) QCD dynamics to the modification of nuclear structure functions and particle production spectra at small x?**
2. **How do parton energy loss mechanisms affect particle production in $h + A$ and $e + A$ collisions?**
3. **What other effects modify particle production and how do we distinguish among final-state interactions?**

To address these questions, we reviewed the state of the art and suggested observables that could help answer questions regarding the types of effects and how to distinguish among them.

Topics Covered in the White Paper

F. Arleo *et al.*, arXiv:2506.17454 (to be submitted to Phys. Rev C)

- **Current Data**
- **Leading-Twist nPDF Effects vs. Saturation**
- **Energy Loss in Cold Nuclear Matter**
- **Nuclear Absorption**
- **Other Effects**
  - **Comovers**
  - **Impact Parameter Dependence of nPDF Effects**
  - **Intrinsic Charm**
- **Future Experiments**

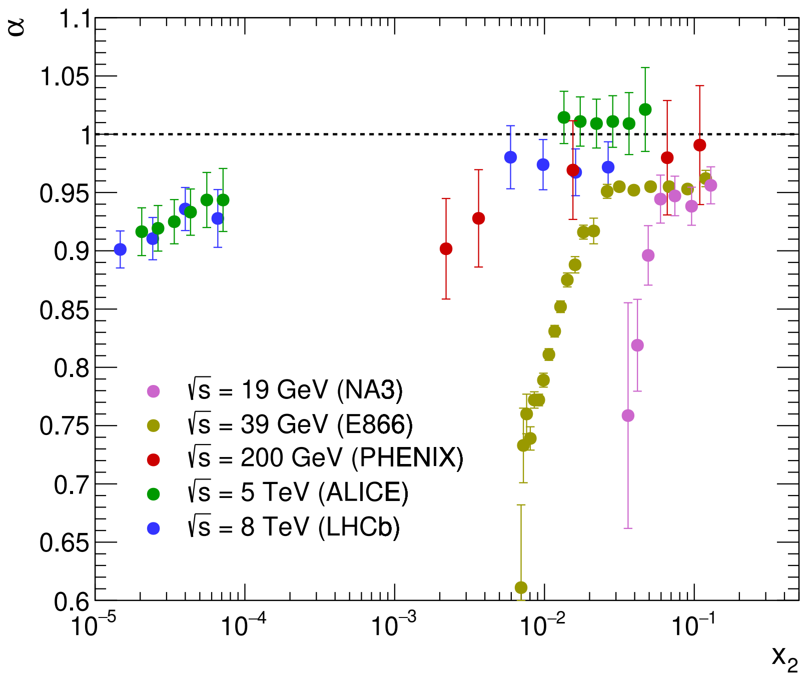
Some contributions from the paper are now discussed

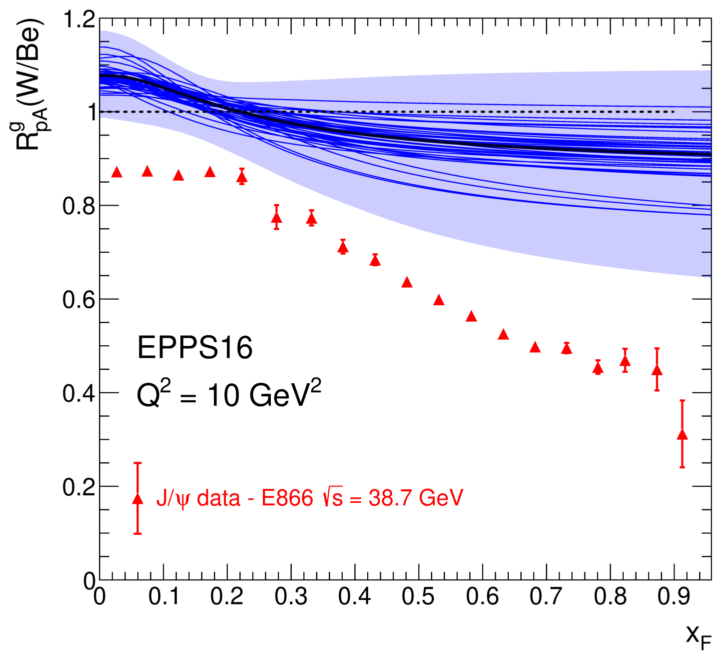
No x_2 Scaling of J/ψ Nuclear Dependence

If nuclear PDF modifications are sufficient to explain J/ψ data, then the results should be independent of $\sqrt{s_{NN}}$ and depend only on x_2

Left hand side shows J/ψ data from fixed-target energies to the LHC. The x_2 range is wide and results are very different, with experiments that reach large x_F showing the strongest modification

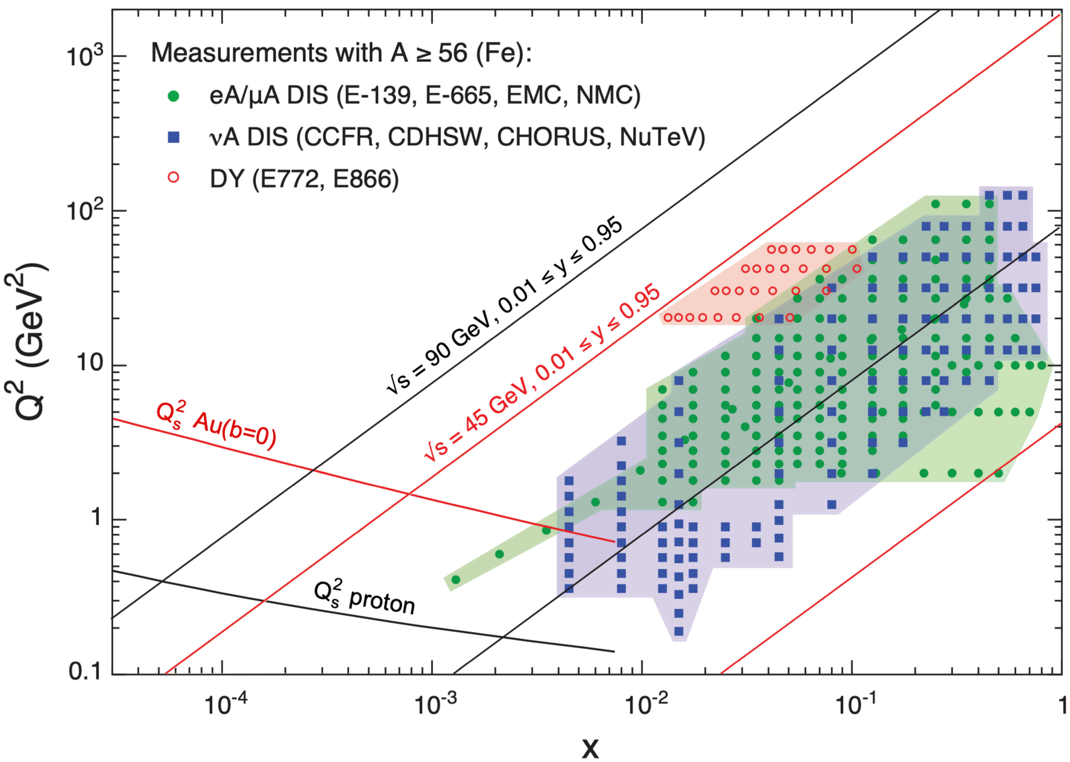
Right hand side shows the EPPS16 gluon ratio for W/Be compared to the E866 results from $\sqrt{s_{NN}} = 38.7$ GeV. The EPPS16 results lie consistently above the data.





Shadowing vs. Saturation: x and Q^2 range

The current DIS and Drell-Yan data cover an x and Q^2 range that does not yet reach into the saturation regime. (LHC hadron production data reach lower x.) The EIC kinematic reach will be greater and reach higher Q^2, putting the saturation regime within reach for heavy nuclei, although not penetrating far into it.

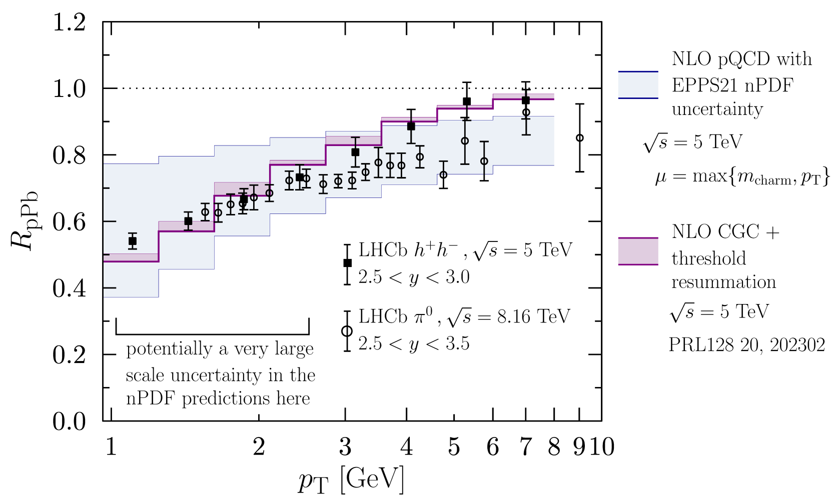


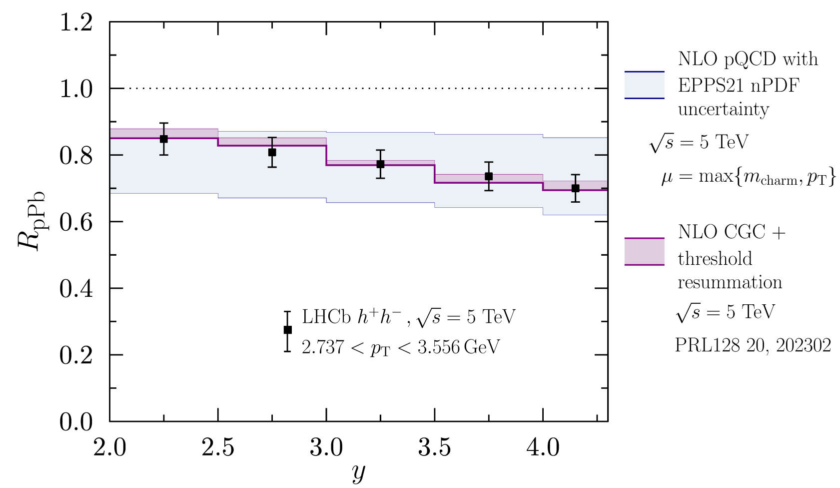
Shadowing vs. Saturation: Charged Hadron Production

At LHC energies, the CGC and nPDF predictions tend to exhibit different slopes but uncertainties make it hard to distinguish among them

CGC uncertainties include factorization and ancillary scale variations assuming that the $p + \mathrm{Pb}$ and $p + p$ cross sections are correlated

nPDF uncertainties are the variations of the parameters added in quadrature and reflect the precision of the available data





Shadowing vs. Saturation: Observables

Structure function measurements in DIS – CGC and leading-twist shadowing follow different trajectories in the (x, Q^2) plane due to differences in the underlying QCD dynamics. The differences between the two types of evolution are larger for the longitudinal structure function F_L and become larger for a heavy nucleus than in a proton.

Single particle and correlated pair production in $e + A$ and $p + A$

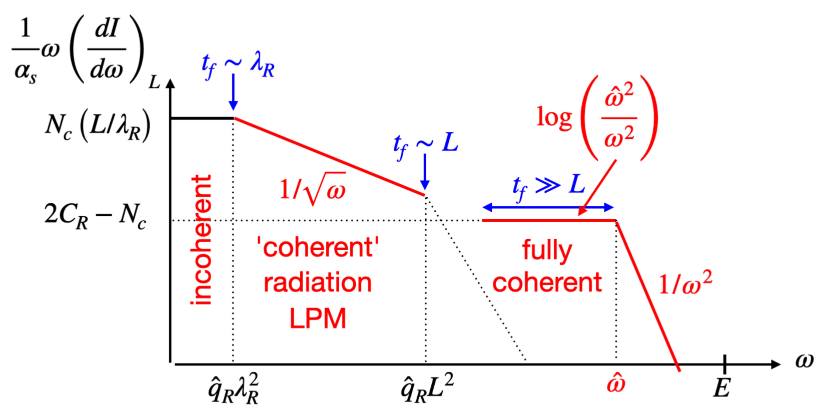
- **Two-particle azimuthal correlations – disappearance of the peak at 180° as a function of azimuthal angle in the CGC. Complications: NLO correlations already decorrelate the peak and momentum broadening can remove it (CGC effects also include suppression as well as broadening, different from NLO DGLAP; heavy flavor correlations may be most relevant**
- **Single-inclusive hadron production in $p+A$ – CGC and nPDF calculations predict different slopes of R_{pA} as a function of y and p_T; limited by typically large nPDF uncertainties**
- **Single inclusive hadron/jet production in $e+A$ – single inclusive DIS (SIDIS) can probe saturated sea quark distributions for $p_T \sim Q_s \ll Q$; fragmentation can be a complication that can be removed by studying single-inclusive jet production**

Diffractive vector meson production in $\gamma+A$ – UPCs probe low x gluon distributions, particularly for J/ψ production

Energy loss in medium

Based on the relative size of the formation time of a soft radiated gluon compared to the medium it travels through, the matter the gluon scatters with can be seen as incoherent scattering centers (Bethe-Heitler); partially coherent, with a group of scattering centers acts like a single radiator (LPM regime); full coherent (FCEL) where all scattering centers acts like a radiation source; and Bertsch-Gunion regime (BG-like) where initial state interactions can partially cancel radiation effects

	ΔE	Observables	Systems	Facilities
Initial state LPM	$\hat{q}\, L^2\, \ln E$	Drell-Yan	$h + A$	E906, COMPASS
Final state LPM	$\hat{q}\, L^2\, \ln E$	h, jets	$e + A$	CLAS, HERMES, EIC
FCEL	$(\hat{q}\, L)^{1/2}\, (E/M_T)$	h, jets	$h + A$	SPS, FNAL, RHIC, LHC
BG-like	$f(\hat{q}\, L) L\, E$	high x_F Drell-Yan, h, jets	$h + A$	FNAL, RHIC, LHC

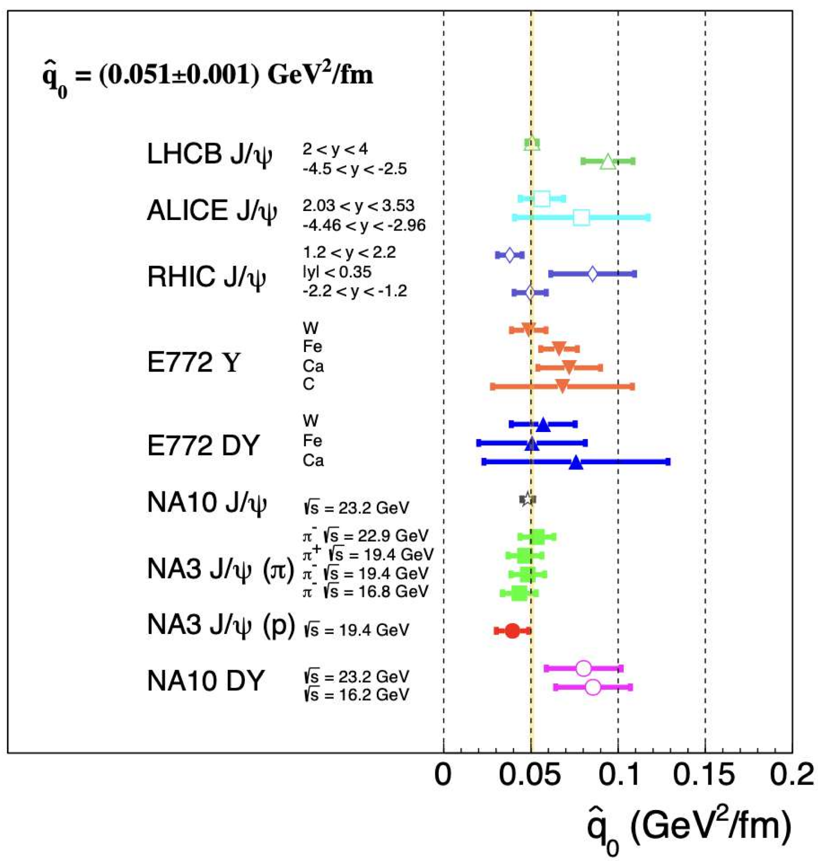


Transport Coefficient $\hat{q}$

Strength of induced gluon radiation governed by transport coefficient $\hat{q}$, related to the gluon distribution evaluated at the momentum scale $Q^2 \sim \Delta p_T^2$.

$$\hat{q} \equiv \frac{\tilde{\mu}^2}{\lambda} = \frac{4\pi^2\,\alpha_s\,C_R}{N_c^2-1}\,\rho\,xg\big(x,Q^2\big)$$

$\hat{q}$ can be determined from analyses of transverse momentum broadening, $\Delta p_T^2 = \left\langle p_T^2 \right\rangle_{hA} - \left\langle p_T^2 \right\rangle_{hp}$, related to multiple parton scattering

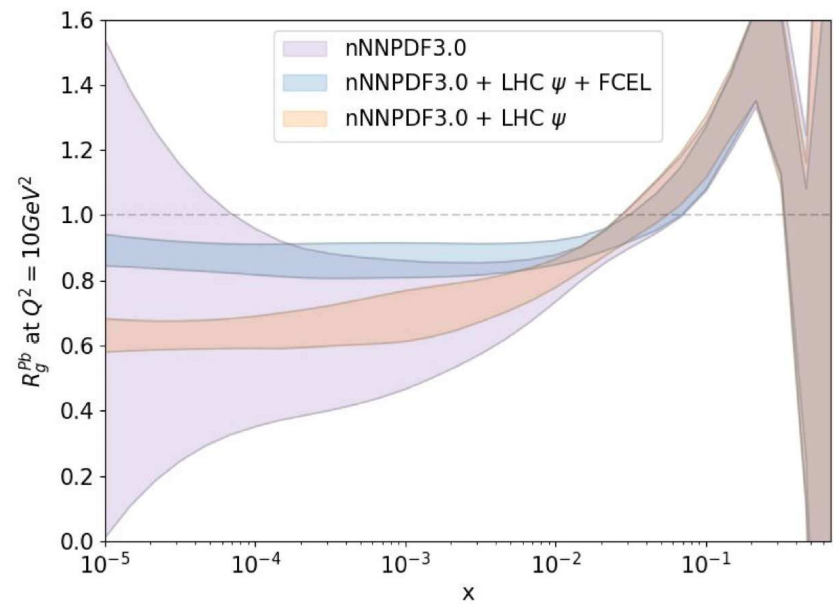


Using J/ψ Data to Pin down Nuclear Gluon PDF

The nPDF uncertainty on the low x gluon distribution can be large just based on DIS and DY data

The J/ψ is predominantly produced by gluons but is subject to other effects

Including J/ψ data can significantly reduce the uncertainties but the amount of low x shadowing depends on whether or not energy loss is taken into account



Energy Loss: Observables

Drell-Yan at high x_F – well suited for studies of LPM energy loss

J/ψ production in $e+A$ and $p+A$ – FCEL depends on the color structure of the partonic process and is thus not universal; comparison of $e+A$ and $p+A$ J/ψ production could test this non-universality

$$\begin{aligned} R_{eA}^{J/\psi}(x) &\simeq R_{eA}^{\mathbf{nPDF}}(x) \approx R_g^A(x); \\ R_{pA}^{J/\psi}(y,x_2) &\simeq R_{pA}^{\mathbf{nPDF+FCEL}}(y,x_2) \\ &\approx R_g^{\mathbf{A}}(x_2) \times R_{pA}^{\mathbf{FCEL}}(y,x_2)\,. \end{aligned}$$

Direct and resolved photoproduction of forward jets and hadrons – resolved photoproduction would be sensitive to FCEL while direct photoproduction is not

$R_{pA}^{J/\psi}/R_{pA}^{\rm DY}$ at forward rapidity or large x_F – this ratio should be above unity for nPDF effects alone but smaller than unity for FCEL

$R_{pA}^{J/\psi}/R_{pA}^{\Upsilon}$ – FCEL is mass dependent, scaling like $1/m_T$, while nPDF evolution reduces the mass dependence of this effect

p_T broadening – useful for extracting $\hat{q}$ and constraining energy loss in Drell-Yan, quarkonium production, or SIDIS

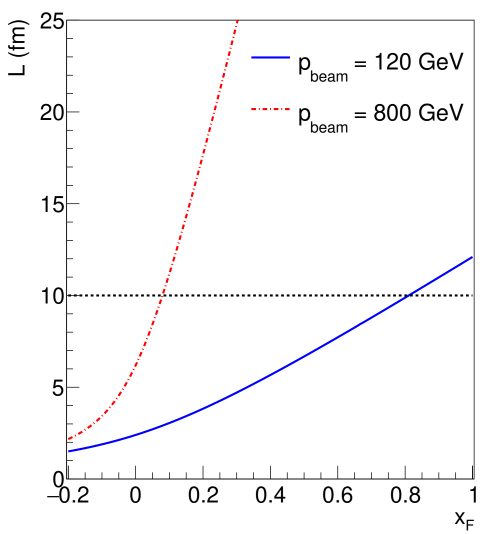
Light hadrons and heavy flavors at large x_F – Bertsch-Gunion type energy loss can suppress energetic final-states at large x_F

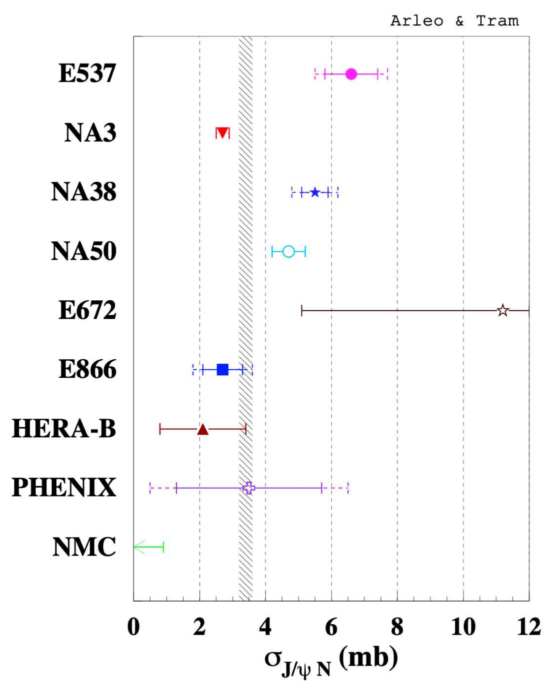
Is Absorption Important for J/ψ Production?

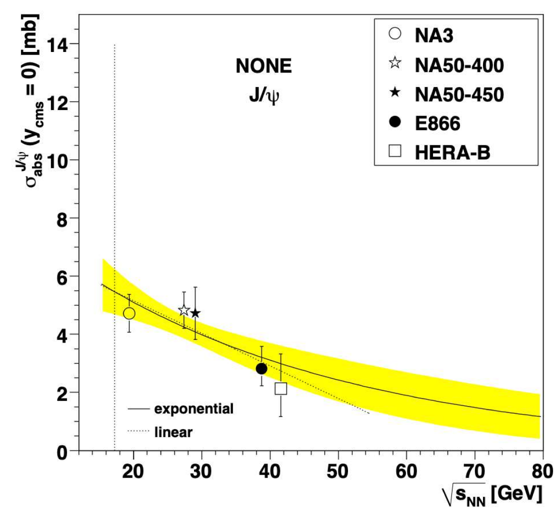
Whether the J/ψ can be absorbed depends on how far it travels through the medium before forming the final state (depending on the production mechanism)

Different methods used to extract an absorption cross section reach different conclusions about the size of $\sigma_{\rm abs}$

Comovers have a similar A dependence but can better distinguish between final-state quarkonium production, *e.g.* between J/ψ and $\psi(2S)$







Absorption and Comovers: Observables

Double ratios of quarkonium states, $R^{Q\overline{Q}_i}/R^{Q\overline{Q}_j}$ – this ratio should be independent of nPDF and energy loss effects and so could isolate absorption effects for $t_{\rm form} \leq L$ where there are few comovers

Double ratios of quarkonium states, $R^{Q\overline{Q}_i}/R^{Q\overline{Q}_j}$ – in high energy collisions, $t_{\rm form} \gg L$ and absorption is negligible, this double ratio could then isolate comover effects; comparison between the double ratios for quarkonium and open heavy flavor mesons could further separate comovers from other effects

$R^{J/\psi}$ vs. R^{χ_c} – differences in the color state at production could result in different absorption cross sections

Hadron production in SIDIS in $e+p$ vs. $e+A$ – absorption effects can be isolated in regions were energy loss and nPDF effects are small

Other Effects: Observables

Impact parameter dependence of nPDFs – is the nucleus made up of shadowing hot spots or is shadowing uniform throughout the nucleus? PHENIX d+Au data suggested the former while ALICE data may suggest the latter. The EIC should study $e + A$ DIS as a function of impact parameter/event multiplicity.

Intrinsic charm – $e + p$ EIC measurements could be decisive

Proposal for Fixed-Target Program at the EIC

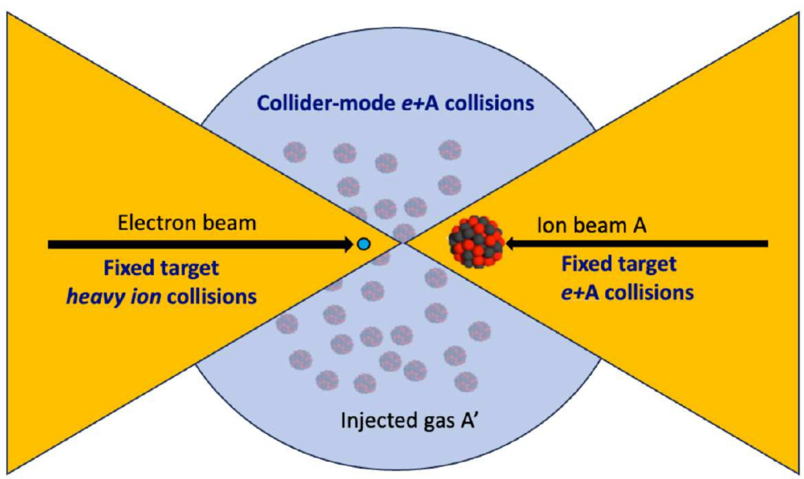
Conceptual notion of the EIC collision region with a fixed target

Collider $e + A$ collisions, the principle EIC design, will produce particles across all angles

In the A-going direction (left) particle from fixed target $A + A'$ collisions can be measured, with $\sqrt{s_{NN}} \sim 14$ GeV for a 100 GeV/nucleon beam

In the e-going direction (right) lower energy $e + A'$ collisions can be studied with an 18 GeV electron beam, just below the 22 GeV proposed in the JLab upgrade.

Either a gas jet target (like SMOG@LHCb) or target wires (like STAR BES II) can be used



Follow up Workshop

CFNS workshop,

Exploring a Fixed-Target Program at the EIC:
***Feasibility and Physics Opportunities*,**

to be held September 29-30

Organized by Daniel Cebra, Matt Durham, Charles Joseph Naim and RV

Already 16 registered participants after it was recently approved

Challenges in Disentangling CNM Effects

Difficult to interpret multiple effects

Need to isolate specific effects through carefully chosen observables

Global approaches are important

Cold QCD effects are a primary source of uncertainty in the interpretation of $A + A$ ***data***