Nuclear TMDs and Three Dimensional Imaging in Nuclei arXiV:2107.12401 (Published in PRL)

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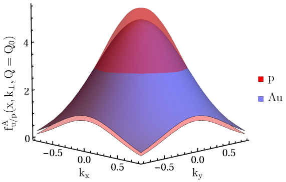
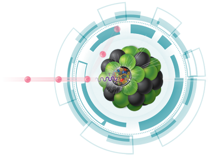
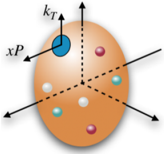




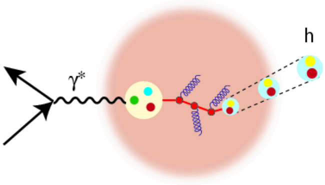
2023 California EIC Consortium Collaboration Meeting

Introduction – TMDs

Transverse Momentum Dependent (TMD) Parton Distribution Functions (PDFs) $f_{q/h}(x, k_T, Q^2)$ give the probability that a parton of type q inside a hadron h with momentum P has collinear momentum xP and transverse momentum k_T.



TMD Fragmentation Functions $D_{h/q}(z, p_T, Q^2)$ give the probability that a hadron h formed from a fragmentating parton q with momentum P will have a collinear momentum zP and a transverse momentum p_T.

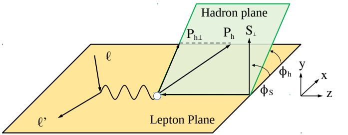


These functions provide pivotal information about the 3D structure of the nucleus and are indispensible tools for making predictions in perturbative QCD. Extracting these functions is one of the major goals of the EIC

Nuclear Medium Modifications

Since the early 1980s, Physicists have known that the PDFs and FFs for a nucleon bound to a nucleus must be different than the PDFs for a free nucleon. First observed experimentally by the EMC in 1983.

e.g. Semi Inclusive Deep-Inelastic Scattering (SIDIS) process $p + l \rightarrow h + X$:.



$$\sigma_{SIDIS} \simeq H \otimes f_q \otimes D_{h/q}$$

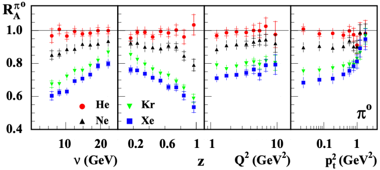


Fig. 5. Values of R_A^h for neutral pions as a function of ν, z, Q^2, and p_t^2. The data as a function of z are shown for $z > 0.1$. Error bars as in Fig. 2.

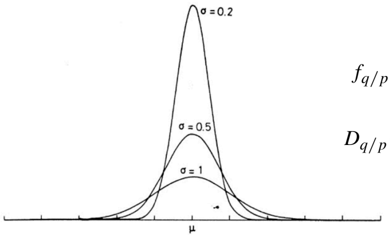
$$R_A^h \simeq \frac{\sigma_{SIDIS}^A}{\sigma_{SIDIS}^D}$$

Extractions of collinear nuclear PDFs (first done by EKS1999) have been successfully performed at ever increasing precision, while for the collinear nuclear FFs was done only at 2009 by Sassot, Stratmann, Zurita and in 2021 by Zurita (LIKEn)

$\rightarrow$ Accounted for nuclear medium effects in the non-perturbative parameterization (i.e. keep DGLAP the same, only the initial value is changed.)

Nuclear Broadening

TMD medium effects observed in SIDIS and DY. Nuclear modifications of the TMDPDF and TMDFF first extracted by us in arXiV:2107.12401.



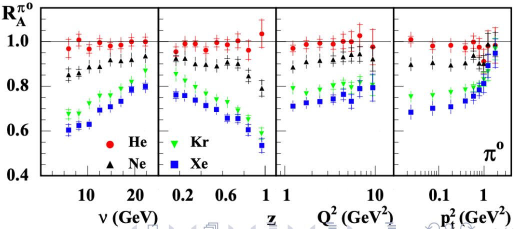
$$f_{q/p}(x, k_T, Q) \simeq \frac{1}{\pi\langle k_T^2\rangle} \exp(-\frac{k_T^2}{\langle k_T^2\rangle}) f_{q/p}(x, Q)$$

$$D_{q/p}(z, p_T, Q) \simeq \frac{1}{\pi\langle p_T^2\rangle} \exp(-\frac{p_T^2}{\langle p_T^2\rangle}) D_{q/p}(x, Q)$$

The heavier the nucleus, the wider the TMD gaussian width (Nuclear Broadening)

$$\langle k_T^2\rangle_A = \langle k_T^2\rangle + a_N(A^{1/3} - 1)$$

$$\langle p_T^2\rangle_A = \langle p_T^2\rangle + b_N(A^{1/3} - 1)$$



Parametrization for the Nuclear TMDs (NLO + NNLL)

TMDs

$$f^A_{q/n}(x,b,Q) = [C_{q\leftarrow i} \otimes f^A_{i/n}](x,\mu_{b*})\exp(-S_{pert}(\mu_{b*},Q) - S^f_{NP}(b,Q,A))$$
$$D^A_{h/q}(x,b,Q) = [\hat{C}_{i\leftarrow q} \otimes D^A_{h/i}](z\mu_{b*})\exp(-S_{pert}(\mu_{b*},Q) - S^D_{NP}(b,z,Q,A))$$

Our assumptions

- Perturbative information is left unchanged by the nuclear medium. $C_{q\leftarrow i}, \hat{C}_{i\leftarrow q}, S_{pert}$ unchanged.
- Non-perturbative information is modified. $f^A_{i/n}, D^A_{h/i}, S^D_{NP}, S^f_{NP}$ are modified.

Collinear distributions

- We use the EPPS16 parameterization for $f^A_{i/n}$ (NLO)
- We use the LIKEn parameterization for $D^A_{h/i}$ (NLO)

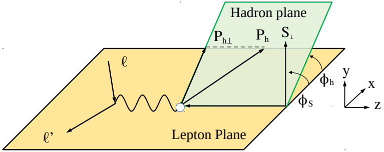
$$D^A_{\pi^+/i}(z,Q_0) = N_i \frac{z^{\alpha_i}(1-z)^{\beta_i}[1+\gamma_i(1-z)^{\delta_i}]}{B[2+\alpha_i+1+\beta_i]+\gamma_i B[2+\alpha_i,1+\beta_i+\delta_i]}$$
$$\tilde{N}_i \to \tilde{N}_i[1+N_{i_1}(1-A^{N_{i_2}})], c_i \to c_i + c_{i,1}(1-A^{c_{i,2}})$$

Nonperturbative Sudakov

- $S^f_{NP}(b,Q,A) = S^f_{NP}(b,Q,1) + a_N(A^{1/3}-1)b^2$
- $S^D_{NP}(b,z,Q,A) = S^D_{NP}(b,z,Q,A) + b_N(A^{1/3}-1)\frac{b^2}{z^2}$

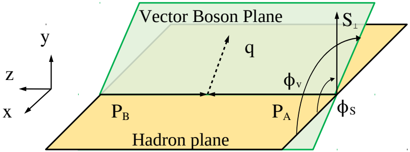
Observables and Currently Available Data

SIDIS (e+A $\rightarrow$ h+X) Measurements



- Multiplicity Ratio $R_A^h = M_h^A / M_h^D$
  - HERMES
  - JLAB (new)

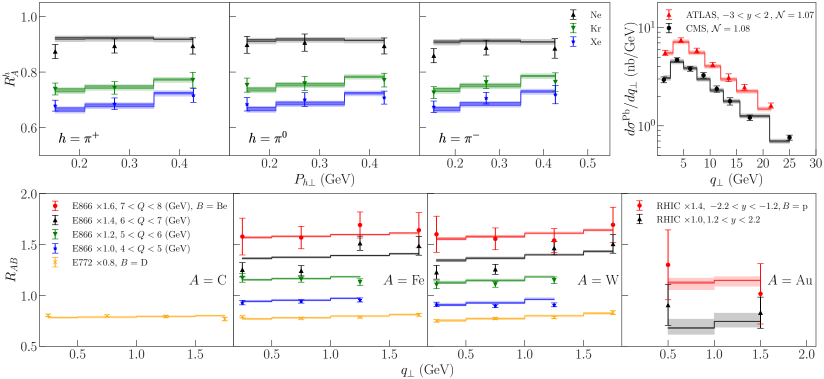
Drell-Yan (p+A $\rightarrow$ q) Measurements



- $R_{AB} = \frac{d\sigma^A}{dq_\perp} / \frac{d\sigma^B}{dq_\perp}$
  - E886
  - E772
  - RHIC (preliminary)
- $\frac{d\sigma}{dq_\perp}$
  - CMS (p Pb)
  - ATLAS (p Pb)

Fitting Procedure and Results

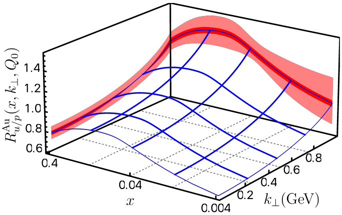
Data cuts: For SIDIS $P_{h\perp} < 0.7$ GeV , $z < 0.7$. For DY $q_\perp/Q < 0.3$.
(126 data points total)

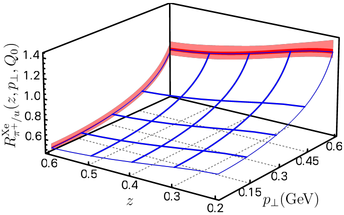


$\chi^2/dof = 1.196$ with fit paramaters:
$a_N = 0.016 \pm 0.003$
$b_N = 0.0097 \pm 0.0007$.

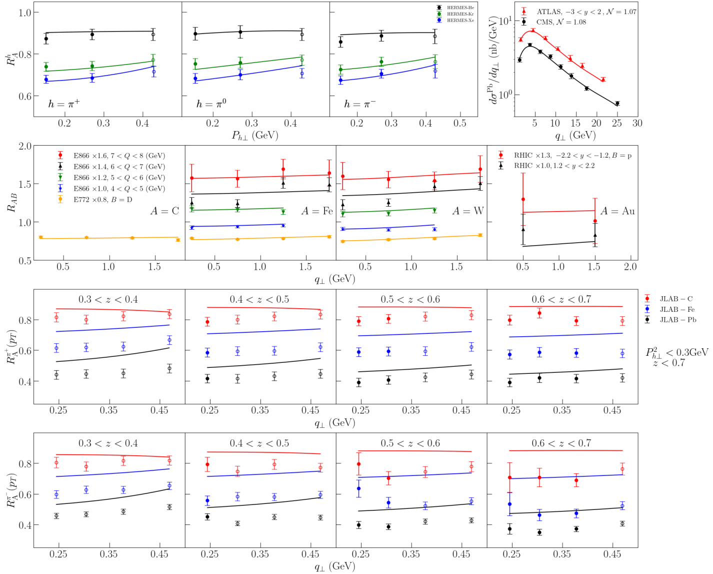
Nuclear Broadening: Quantified

$$R^{\mathrm{Au}}_{u/p}(x,k_\perp,Q_0)=\frac{f^{\mathrm{Au}}_{u/p}(x,k_\perp,Q_0)}{f_{u/p}(x,k_\perp,Q_0)}\qquad \mathcal{R}^{\mathrm{Xe}}_{\pi^+/u}(x,k_\perp,Q_0)=\frac{D^{\mathrm{Xe}}_{\pi^+/p}(z,p_\perp,Q_0)}{D_{\pi^+/u}(z,p_\perp,Q_0)}$$





New Data from JLAB



The χ^2/dof is 5.542 with JLAB. JLAB Q^2 typically 1.60-1.65 GeV^2. HERMES Q^2 typically $2.3 - 2.8$ GeV^2

Parametrization for the Nuclear TMDs (NLO + NNLL)

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$$\tilde{N}_i \to \tilde{N}_i[1+N_{i_1}(1-A^{N_{i_2}})],\, c_i \to c_i + c_{i,1}(1-A^{c_{i,2}})$$

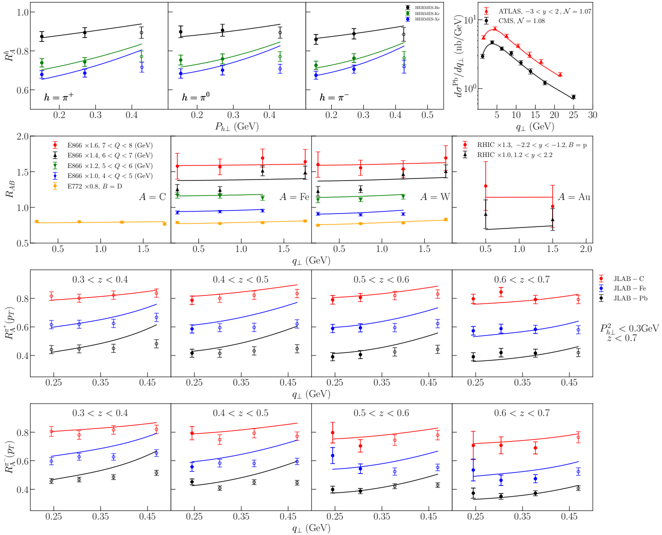
- Approximation: Only quarks are modified. N_{q_1} and N_{q_2} is the same for all quark flavors.
- α unmodified. $N_{q_2} = \beta_{q_2} = \delta_{q2} = \gamma_{q2}$

Nonperturbative Sudakov

- $S^f_{NP}(b,Q,A) = S^f_{NP}(b,Q,1) + g^f_3(\frac{Q_0^{\text{new}}}{Q})^\gamma(A^{1/3}-1)b^2$
- $S^D_{NP}(b,z,Q,A) = S^D_{NP}(b,z,Q,A) + g^D_3(\frac{Q_0^{\text{new}}}{Q})^\gamma(A^{1/3}-1)\frac{b^2}{z^2}$ $Q_0^{\text{new}} = 1$ GeV

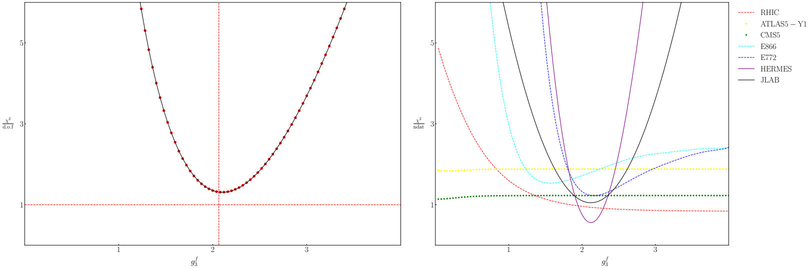
In total 8 parameters ($N_{q1}, N_{q2}, \beta_{q1}, \gamma_{q1}, \delta_{q1}, g_{3f}, g_{3D}, \gamma$)

Preliminary result



Achieved a global χ^2/dof of 1.315.
The optimal parameters are: $N_{q1} = 1.449$, $N_{q2} = 0.048$,
$\beta_{q1} = 0.386, \gamma_{q1} = 4.680, \delta_{q1} = 5.520, g_{3f} = 0.180, g_{3D} = 0.010, \gamma = 2.065$

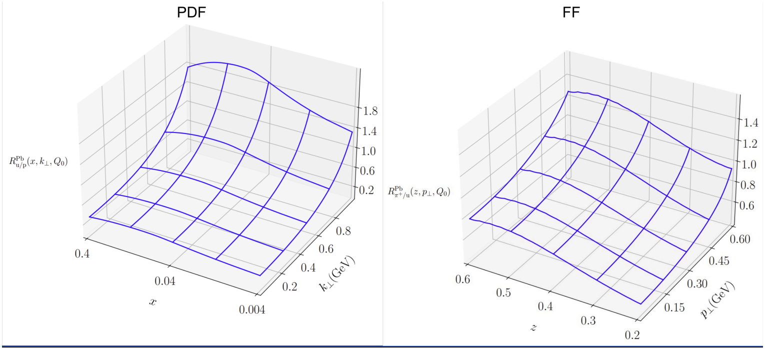
Constraint on γ (Preliminary)



Achieved a global χ^2/dof of 1.315.
The optimal parameters are: $N_{q_1} = 1.449$, $N_{q_2} = 0.048$,
$\beta_{q_1} = 0.386, \gamma_{q_1} = 4.680, \delta_{q_1} = 5.520, g_{3f} = 0.180, g_{3D} = 0.010, \gamma = 2.065$

Nuclear TMDs (Preliminary)

$$R_{u/p}^{\mathrm{Pb}}(x, k_\perp, Q_0) = \frac{f_{u/p}^{\mathrm{Pb}}(x, k_\perp, Q_0)}{f_{u/p}(x, k_\perp, Q_0)} \qquad \mathcal{R}_{\pi^+/u}^{\mathrm{Pb}}(x, k_\perp, Q_0) = \frac{D_{\pi^+/p}^{\mathrm{Pb}}(z, p_\perp, Q_0)}{D_{\pi^+/u}(z, p_\perp, Q_0)}$$



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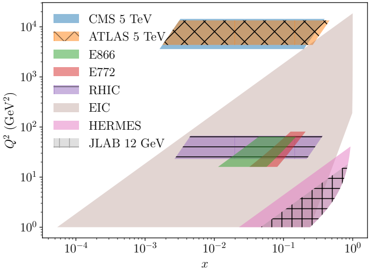
Summary and Outlook

- Nuclear TMDPDFs provide a 3D imaging of the nucleus
- Nuclear TMDFFs provide information about the fragmentation process in nuclei.
- At NLO+NNLL, we have performed the first extraction of nuclear modified TMDPDFs and TMDFFs.
- We quantify for the first time the nuclear broadening of the TMDs.
- We expect that additional data from JLab, RHIC, the LHC, as well as future measurements at the EIC could help further constrain these distributions.



Thank You!