UCLA Mani L. Bhaumik Institute for Theoretical Physics

Nuclear TMDs and 3D imaging in nuclei

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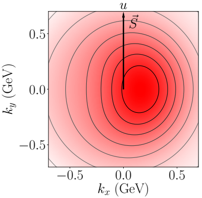
Success in 3D imaging in of spin-dependent TMDs

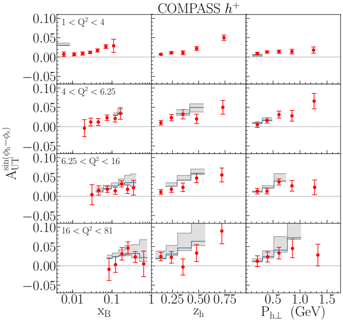
Spin-dependent TMDs

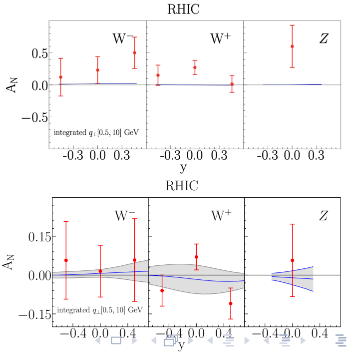
Quark Pol (columns) / Proton Pol (rows)

Φ	U	L	T
U	f		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1 \; h_{1T}^\perp$

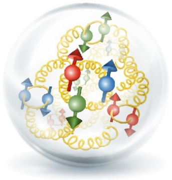


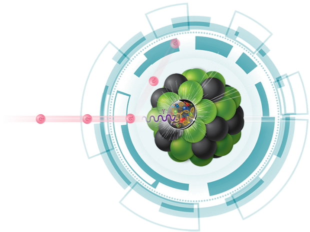
Recent results for the Sivers Echevarria, Kang, JT 2020





3D imaging in nuclei



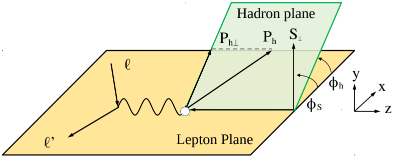


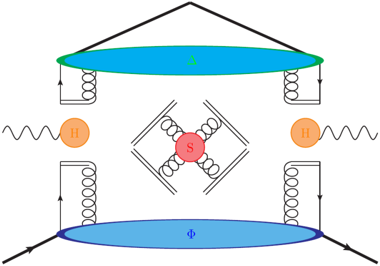
Recent community interest in nuclear modified distributions

- Recent measurements of the $q_\perp$ distribution for $\mathrm{p\,Pb}$ collisions for ATLAS and CMS.
- Preliminary PHENIX measurements for the $q_\perp$ distribution for $\mathrm{p\,Au}$ collisions.
- Recent measurements for hadron multiplicity with nuclear targets performed by CLAS collaboration at Jefferson Lab.
- “Nuclear TMDs in CLAS12" study approved by the PAC at Jefferson Lab.

3D imaging in nuclei

Factorization Theorems



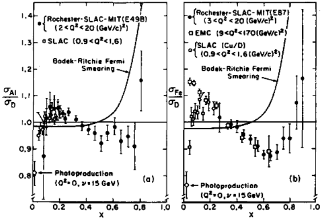


Central idea of a global analysis

- Calculate fixed order contributions to the differential cross section to a set precision.
- Resum large logarithms entering into the perturbative calculations to improve predictability in a large kinematic region.
- Use experimental data constrain parameterization.

Nuclear modified PDFs

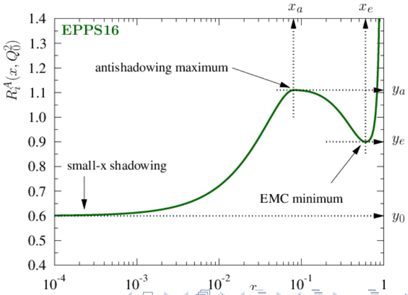
Four Decades of the EMC Effect



This effect is still not understood from first principles.

Effective understanding of the nuclear modifications.

- Eskola, Kolhinen, Ruuskanen 1998: Kept DGLAP evolution equations unchanged.
- Found that global experimental data can be described by modifying NP parameterization.
- Indication that nuclear modifications may be non-perturbative in nature.

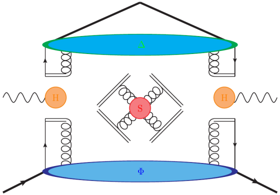


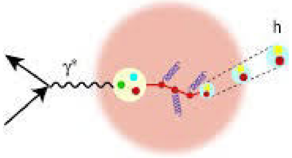
Nuclear modified FFs

Extractions

Sassot, Stratmann, Zurita 2009

Zurita 2020 (LIKEn)



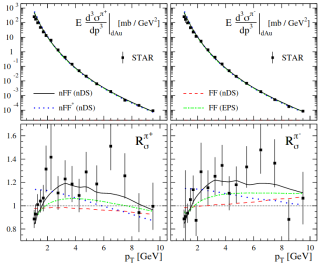


Data from SIDIS + p A → h collisions.

- No modification to the DGLAP evolution.
- Accounted for nuclear medium effects in the non-perturbative parameterization.

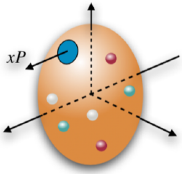
$$D^H_{i/A}\left(z, Q_0^2\right) = \left[W_i \otimes D^H_i\right]\left(z, Q_0^2\right)$$

$$W_q(y, A, Q_0^2) = n_q y^\alpha (1-y)^\beta + n'_q \delta(1-\epsilon-y)$$



Nuclear imaging in three-dimensions

From collinear distributions to TMDs



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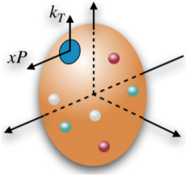
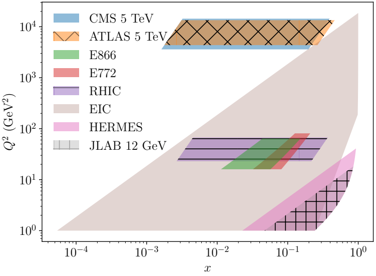


Drell-Yan Measurements

- $R_{\mathrm{AB}} = \frac{d\sigma_A}{dq_\perp} / \frac{d\sigma_B}{dq_\perp}$
  -E866
  -E772
  -Prelim. RHIC
- $d\sigma/dq_\perp$ (p Pb)
  ATLAS
  CMS

SIDIS Measurements

- Multiplicity ratio $R_h^A = M_h^A / M_h^D$.
  -HERMES 2007
  -JLab (released shortly after our analysis)
  -Planned JLab
  -Possible EIC.



Parameterization

Cross section

$$\frac{d\sigma^A}{dx\,dQ^2\,dz\,d^2P_{h\perp}} = \sigma_0\,H(Q)\sum_q e_q^2 \int_0^\infty \frac{b\,db}{2\pi} J_0\left(\frac{bP_{h\perp}}{z}\right) f^A_{q/n}(x,b;Q)\,D^A_{h/q}(z,b;Q)$$

TMDs

$$f^A_{q/n}(x,b;Q) = \left[C_{q\leftarrow i}\otimes f^A_{i/n}\right](x,\mu_{b_*})\exp\left[-S_{\text{pert}}(\mu_{b_*},Q) - S^f_{\text{NP}}(b,Q,A)\right]$$

$$D^A_{h/q}(z,b;Q) = \frac{1}{z^2}\left[\hat{C}_{i\leftarrow q}\otimes D^A_{h/i}\right](z,\mu_{b_*})\exp\left[-S_{\text{pert}}(\mu_{b_*},Q) - S^D_{\text{NP}}(b,z,Q,A)\right]$$

Our assumptions

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

Parameterization continued

TMDs

$$f_{q/n}^A(x,b;Q) = \left[C_{q\leftarrow i}\otimes f_{i/n}^A\right](x,\mu_{b_*})\exp\left[-S_{\rm pert}(\mu_{b_*},Q) - S_{\rm NP}^f(b,Q,A)\right]$$

$$D_{h/q}^A(z,b;Q) = \frac{1}{z^2}\left[\hat{C}_{i\leftarrow q}\otimes D_{h/i}^A\right](z,\mu_{b_*})\exp\left[-S_{\rm pert}(\mu_{b_*},Q) - S_{\rm NP}^D(b,z,Q,A)\right]$$

Collinear Distributions

We use the EPPS16 parameterization for $f_{i/n}^A$ (NLO) + CT14nlo.

We use the LIKEn parameterization for $D_{h/i}^A$ (NLO).

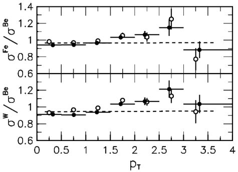
Perturbative order in our analysis

Work at NLO+NNLL for the TMDs.

Potentially can be done at N^{3}LO+N^{3}LL'. However, the collinear distributions have only been obtained at NLO.

We take the non-perturbative parameterization

TMD: Sun, Isaacson, Yuan, Yuan (2014), Modification: Liang, Wang, Zhou (2008)



$$S_{\rm NP}^f(b,Q,A) = S_{\rm NP}^f(b,Q) + a_N\left(A^{1/3}-1\right)b^2$$

$$S_{\rm NP}^D(z,b,Q,A) = S_{\rm NP}^D(z,b,Q) + b_N\left(A^{1/3}-1\right)\frac{b^2}{z^2}$$

Semi-Inclusive DIS cross section

Multiplicity ratio ($R_h^A = M_h^A / M_h^D$)

$$M_h^A = \frac{d\sigma^A / d\mathcal{PS} dz_h \, d^2 P_{h\perp}}{d\sigma^A / d\mathcal{PS}} \qquad d\mathcal{PS} = dx_B \, dQ^2$$

$$\frac{d\sigma^A}{d\mathcal{PS}} = \frac{\sigma_0^{DIS}}{x_B}\left[F_2(x_B, Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x_B, Q^2)\right] ,$$

Structure functions calculated with APFEL using nuclear modified collinear PDF.

Kinematic cuts on the transverse momentum

Usual TMD cuts on transverse momentum:

$$P_{h\perp}/z_h < 0.25\, Q$$

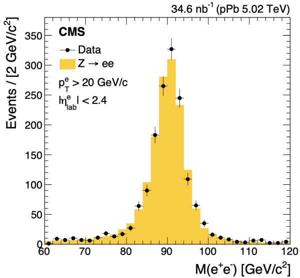
Due to low number of experimental data from HERMES, we use:

$$P_{h\perp} < 0.7\,\text{GeV} \qquad \text{z}_\text{h} < 0.7$$

See Echevarria, Idilbi, Kang, Vitev 2014, Bacchetta, Delcarro, Pisano, Radici, and Echevarria, Kang, Terry 2020.

Drell-Yan cross section

$$\frac{d\sigma^A}{d\mathcal{PS}} = \sigma_0 \, H(Q) \, \mathcal{P}\left(\eta, p_\perp^{\ell\ell}\right) \sum_q c_q(Q) \int_0^\infty \frac{b\,db}{2\pi} J_0\left(b\,q_\perp\right) \, f_{q/A}(x_1, b; Q) \, f_{\bar{q}/p}(x_2, b; Q) \,,$$



For LHC experimental data:

- We perform integration over the mass ranges for ATLAS and CMS, see Bertone, Scimemi, Vladimirov 2019, Bacchetta et al 2019, .
- Take into consideration mixing between γ^* / Z from the coupling constants.
- Fiducial cuts on the final-state leptons is performed using the Artemides package Bertone, Scimemi, Vladimirov 2019.

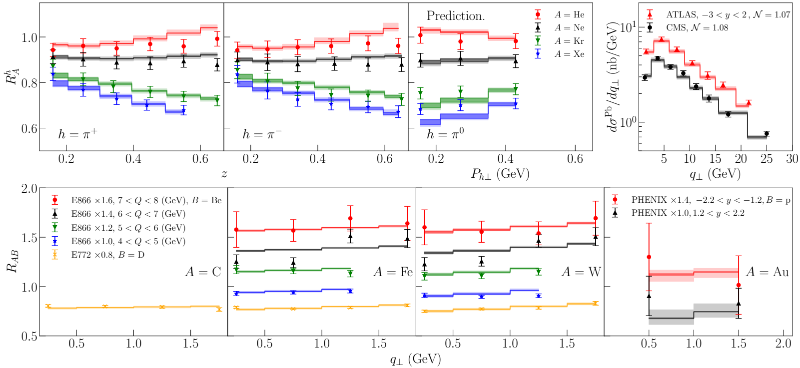
Cuts on transverse momentum
We use the usual cuts:

$$q_\perp < 0.3\,Q$$

Normalization All data are ratios except for the LHC data. We take the definition of the chi2

$$\chi_k^2(\mathbf{a}) = \left(\frac{1 - f_N}{\delta^{\text{norm.}}}\right)^2 + \sum_i \left[\frac{T_i(\mathbf{a}) - f_N D_i}{\delta_i^{\text{uncorr.}}}\right]^2$$

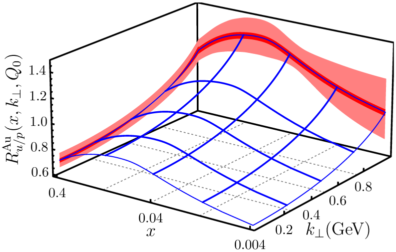
Description of experimental data



$\chi^2/d.o.f = 1.045$ 126 points with $a_N = 0.0171 \pm 0.003$ and $b_N = 0.0144 \pm 0.001$

Results for 3D imaging in nuclei

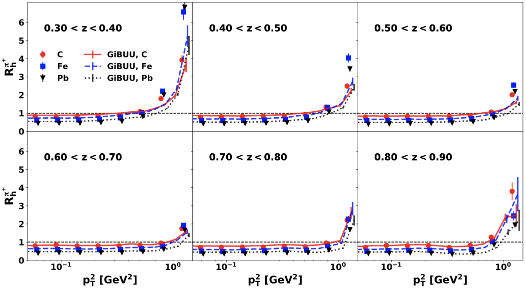
$$R_{u/p}^{\mathrm{Au}}(x, k_\perp, Q_0) = \frac{f_{u/p}^{\mathrm{Au}}(x, k_\perp, Q_0)}{f_{u/p}(x, k_\perp, Q_0)} \qquad \mathcal{R}_{\pi^+/u}^{\mathrm{Xe}}(z, p_\perp, Q_0) = \frac{D_{\pi^+/u}^{\mathrm{Xe}}(z, p_\perp, Q_0)}{D_{\pi^+/u}(z, p_\perp, Q_0)}$$



Moving forward

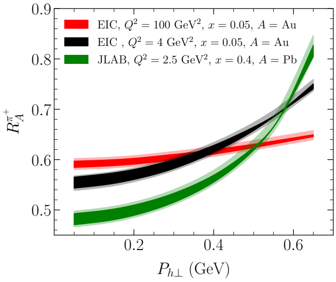
Analysis on-going to examine the contribution of the experimental data at Jefferson Lab.

Measurement of charged-pion production in deep-inelastic scattering off nuclei with the CLAS detector



Summary and Outlook

- There has been tremendous progress over the past few decades in extracting nuclear modified collinear distributions as well as spin-dependent TMDs.
- We present a procedure for extracting the nuclear modified TMDPDF and TMDFFs.
- 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 to the audience and the organizers!