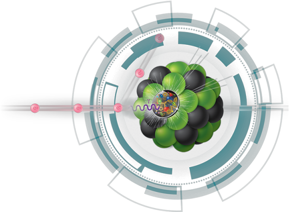
Nuclear TMDs and 3D imaging in nuclei

John Terry

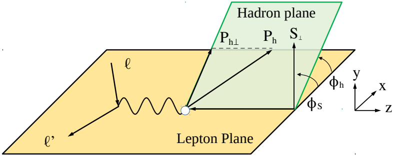
In collaboration with Mishary Alrashed, Daniele Paolo Anderle, Zhong-bo Kang, and Hongxi Xing

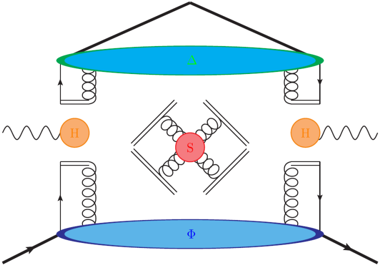
October 22, 2021



Overview of Global Analyses

Factorization Theorems

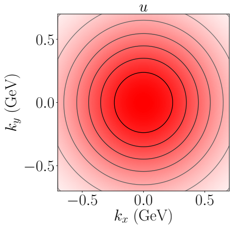




Central idea of a global analysis

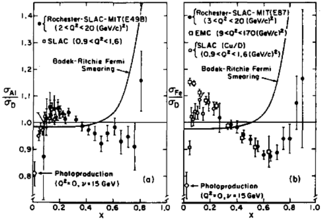
- Calculate the perturbative physics at high order.
- We take an ansatz for the NP physics.
- Use experimental data constrain parameterization.

→



Nuclear Modified PDFs

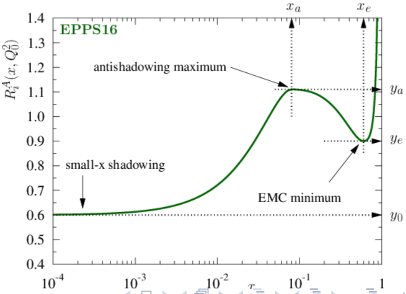
Four Decades of the EMC Effect



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.



Extractions for Nuclear Modified PDFs

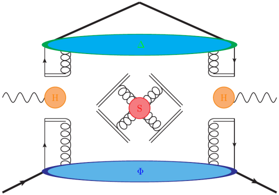
- **EKS:** K.J. Eskola, V.J. Kolhinen, C.A. Salgado, Eur. Phys. J. C9 (1999) 61. — FIRST EVER
- **HKM:** M. Hirai, S. Kumano, M. Miyama, Phys. Rev. D64 (2001) 034003.
- **nDS:** D. de Florian, R. Sassot, Phys. Rev. D69 (2004) 074028. — FIRST NLO
- **HKN07:** M. Hirai, S. Kumano, T.-H. Nagai, Phys. Rev. C76 (2007) 065207. — FIRST WITH THEORETICAL UNCERTAINTIES
- **EPS09:** K.J. Eskola, H. Paukkunen, C.A. Salgado, JHEP 0904 (2009) 065.
- **DSSZ:** D. de Florian, R. Sassot, M. Stratmann, PZ, Phys. Rev. D85 (2012), 074028. — FIRST WITH CC AND nFFs
- **nCTEQ15:** K. Kovarik, A. Kusina, T. Jezo, D. B. Clark, C. Keppel, F. Lyonnet, J. G. Morfin, F. I. Olness, J. F. Owens, I. Schienbein and J. Y. Yu, Phys. Rev. D93 (2016) no.8, 085037.
- **KA15:** H. Khanpour, S.A. Tehrani, Phys.Rev. D93 (2016) no.1, 014026. — FIRST NNLO
- **EPPS16:** K. J. Eskola, P. Paakkinen, H. Paukkunen, C. A. Salgado, Eur. Phys. J. C77 (2017) no.3, 163. — FIRST WITH LHC DATA
- **nNNPDF1.0:** R. A. Khalek, J. J. Ethier, J. Rojo, Eur. Phys. J. C79 (2019) no.6, 471. — FIRST WITH NEURAL NETWORKS
- **nTuJu:** M. Walt, I. Helenius, W. Vogelsang, Phys. Rev. D100 (2019) no.9, 096015. — FIRST OPEN SOURCE
- **nNNPDF2.0:** R. A. Khalek, J. J. Ethier, J. Rojo, G. van Weelden, arXiv: 2006.14629 [hep-ph].
- **nCTEQ15WZ:** A. Kusina, T. Ježo, D. B. Clark, P. Duwentäster, E. Godat, T. J. Hobbs, J. Kent, M. Klasen, K. Kovařík, F. Lyonnet, K. F. Muzakka, F. I. Olness, I. Schienbein and J. Y. Yu, arXiv:2007.09100 [hep-ph].

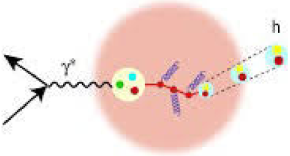
Nuclear Modified FFs

Extractions

Sassot, Stratmann, Zurita 2009 (SSZ)

Zurita 2020 (LIKEn)



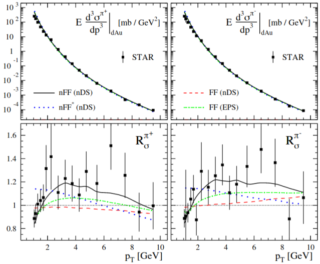


Data from SIDIS + p A → h collisions.

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

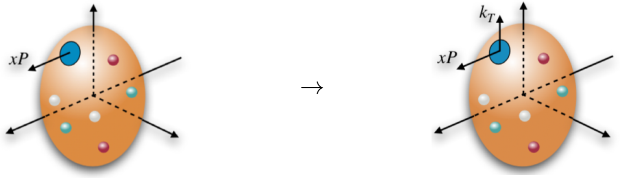
$$D^H_{i/A}\left(z, Q_0^2\right) = \left[W_i \otimes D^H_i\right]\left(z, Q_0^2\right)$$

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



Nuclear Holography in Three-Dimensions

From collinear distributions to TMDs

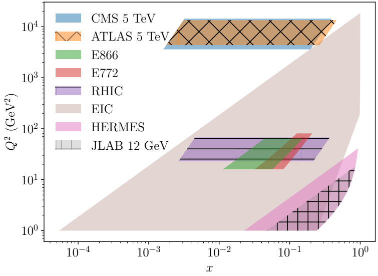


Drell-Yan Measurements

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

SIDIS Measurements

- Multiplicity ratio $R_h^A = M_h^A / M_h^D$.
  -HERMES 2007
  -Prelim. JLab
  -Planned JLab
  -Possible EIC.



Parameterization

Cross section

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

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.

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

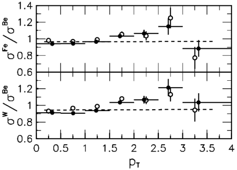
We use the EPPS16 parameterization for $f_{i/n}^{A}$ (NLO).

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

Perturbative order in our analysis

Work at NLO+NNLL for the TMDs.

We take the non-perturbative parameterization



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

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

Fitting Procedure and Data

Our definition of the χ^2

$$\chi^2 = \sum_{i=1}^{N} \left[\left(\frac{1 - \mathcal{N}_i}{\delta \mathcal{N}_i} \right)^2 + \sum_{j=1}^{N_i} \frac{(E_j - \mathcal{N}_i T_j)^2}{\delta E_j^2} \right]$$

Kinematic cuts

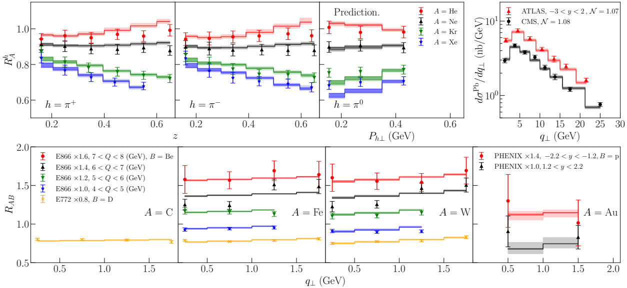
SIDIS

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

Drell-Yan

$q_\perp / Q < 0.3$

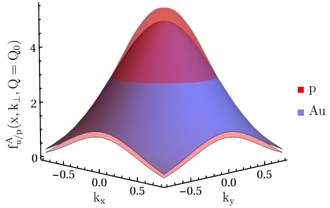
Description of the experimental data (Preliminary)



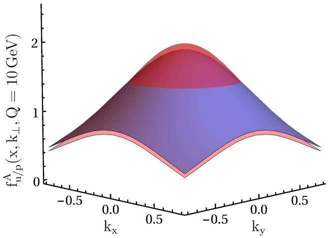
$\chi^2/d.o.f = 1.045$ 126 points with $a_N = 0.0171 \pm 0.003$ and $b_N = 0.0144 \pm 0.001$

3D imaging in the nucleus

$Q_0^2 = 2.4\mathrm{GeV}^2$

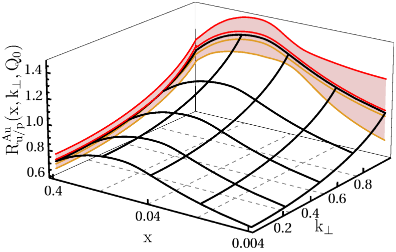


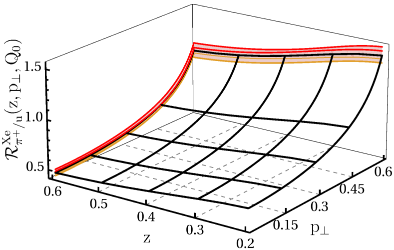
$Q^2 = 100\mathrm{GeV}^2$



$$R^{\mathrm{Au}}_{u/p}(x, k_\perp, Q_0) = \frac{f^{\mathrm{Au}}_{u/p}(x, k_\perp, Q_0)}{f_{u/p}(x, k_\perp, Q_0)}$$

$$\mathcal{R}^{\mathrm{Xe}}_{\pi^+/u}(z, p_\perp, Q_0) = \frac{D^{\mathrm{Xe}}_{\pi^+/u}(z, p_\perp, Q_0)}{D_{\pi^+/u}(z, p_\perp, Q_0)}$$

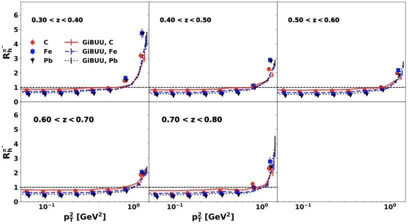




Recent data from Jefferson Lab (arXiv:2109.09951)

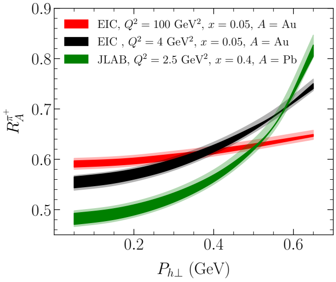
Measurement of charged-pion production in deep-inelastic scattering off nuclei with the CLAS detector

S. Morán,[1,3] R. Dupre,[2] H. Hakobyan,[1,52] M. Arratia,[3] W.K. Brooks,[1] A. Bórquez,[1] A. El Alaoui,[1] L. El Fassi,[4,5] K. Hafidi,[5] R. Mendez,[1] T. Mineeva,[1] S.J. Paul,[3] M.J. Amaryan,[36] Giovanni Angelini,[19] Whitney R. Armstrong,[5] H. Atac,[43] N.A. Baltzell,[44] L. Barion,[20] M. Bashkanov,[49] M. Battaglieri,[44,22] I. Bedlinskiy,[31] Fatiha Benmokhtar,[14] A. Bianconi,[46,26] L. Biondo,[22,25,47] A.S. Biselli,[15,8] F. Bossù,[10] S. Boiarinov,[44] W.J. Briscoe,[19] D. Bulumulla,[36] V.D. Burkert,[44] D.S. Carman,[44] P. Chatagnon,[2] V. Chesnokov,[41] T. Chetry,[4] G. Ciullo,[20,16] P.L. Cole,[30,9,44] M. Contalbrigo,[20] G. Costantini,[46,26] A. D'Angelo,[23,40] N. Dashyan,[52] R. De Vita,[22] M. Defurne,[10] A. Deur,[44] S. Diehl,[37,12] C. Djalali,[35,42] H. Egiyan,[44] L. Elouadrhiri,[44] P. Eugenio,[18] R. Fersch,[11,51] A. Filippi,[24] G. Gavalian,[44,32] Y. Ghandilyan,[52] G.P. Gilfoyle,[39] A.A. Golubenko,[41] R.W. Gothe,[42] K.A. Griffioen,[51] M. Guidal,[2] M. Hattawy,[36] F. Hauenstein,[36] T.B. Hayward,[12] D. Heddle,[11,44] K. Hicks,[35] A. Hobart,[2] M. Holtrop,[32] Y. Ilieva,[42] D.G. Ireland,[48] E.L. Isupov,[41] H.S. Jo,[29] D. Keller,[50] A. Khanal,[17] M. Khandaker,[34,*] W. Kim,[29] F.J. Klein,[9] A. Kripko,[37] V. Kubarovsky,[44,38] S.E. Kuhn,[36] L. Lanza,[23] M. Leali,[46,26] P. Lenisa,[20,16] K. Livingston,[48] I .J .D. MacGregor,[48] D. Marchand,[2] L. Marsicano,[22] V. Mascagna,[45,26] B. McKinnon,[48] C. McLauchlin,[42] Z.E. Meziani,[5] S. Migliorati,[46,26] M. Mirazita,[21] V. Mokeev,[44,41] C. Munoz Camacho,[2] P. Nadel-Turonski,[44] K. Neupane,[42] S. Niccolai,[2] G. Niculescu,[28] T. R. O'Connell,[12] M. Osipenko,[22] A.I. Ostrovidov,[18] M. Ouillon,[2] P. Pandey,[36] M. Paolone,[33] L.L. Pappalardo,[20,16] E. Pasyuk,[44] W. Phelps,[11,19] O. Pogorelko,[31] J. Poudel,[36] J.W. Price,[6] Y. Prok,[36,50] B.A. Raue,[17] Trevor Reed,[17] M. Ripani,[22] J. Ritman,[27] A. Rizzo,[23,40] G. Rosner,[48] J. Rowley,[35] F. Sabatié,[10] C. Salgado,[34] A. Schmidt,[19] R.A. Schumacher,[8] Y.G. Sharabian,[44] E.V. Shirokov,[41] U. Shrestha,[12] D. Sokhan,[10,48] O. Soto,[21] N. Sparveris,[43] S. Stepanyan,[44] I.I. Strakovsky,[19] S. Strauch,[42,19] R. Tyson,[48] M. Ungaro,[44,38] L. Venturelli,[46,26] H. Voskanyan,[52] A. Vossen,[13,44] E. Voutier,[2] D.P. Watts,[49] Kevin Wei,[12] X. Wei,[44] L.B. Weinstein,[36] R. Wishart,[48] M.H. Wood,[7,42] B. Yale,[51] N. Zachariou,[49] J. Zhang,[50] and Z.W. Zhao[13]
(The CLAS Collaboration)



Summary and Outlook

- There has been tremendous progress over the past few decades in extracting nuclear modified collinear distributions.
- We have performed the first extractions of the nuclear modified TMDPDF and TMDFFs.
- This allows us to quantify for the first time the nuclear broadening of these distributions.
- 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!