Cold nuclear matter effects: from TMDs to EECs

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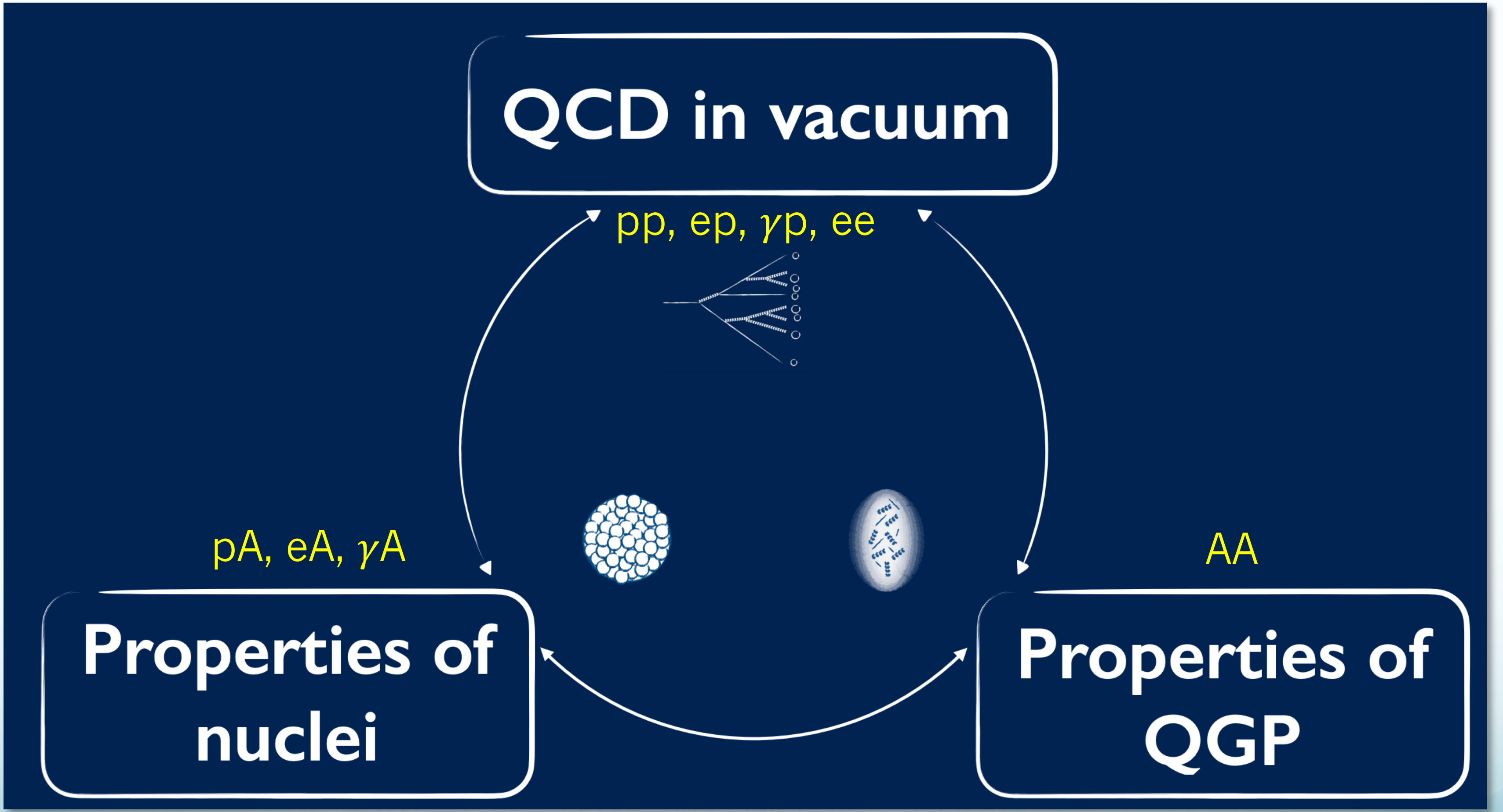
CFNS Workshop – Cold Nuclear Matter Effects: from the LHC to the EIC
January 13 - 16, 2025

High Energy Nuclear Collisions



Courtesy of James Mulligan, Hard Probe 2023

Traditional approach for probing cold nuclei

- For probing properties of cold nuclei vs proton
  - Replacing proton PDFs with nuclear PDFs
  - Assuming evolution is the same, only change the PDFs at the initial scale

At the heart of it all: Collinear factorisation of QCD

The cross section for producing an inclusive final state $k+X$ can be described as a convolution of...

...**C**oefficient **F**unctions $d\hat{\sigma}^{ij\to k+X'}$ which are calculable from perturbative QCD...

$$d\sigma^{AB\to k+X}(Q^2) \overset{Q\gg\Lambda_{\mathrm{QCD}}}{=} \sum_{i,j,X'} f_i^A(Q^2)\otimes d\hat{\sigma}^{ij\to k+X'}(Q^2)\otimes f_j^B(Q^2) + \mathcal{O}(1/Q^2)$$

...and **P**arton **D**istribution **F**unctions f_i^A, f_j^B which contain long-range physics and cannot be obtained by perturbative means...

...plus "**H**igher **T**wist" corrections which are suppressed at high enough momentum scale $Q \gg \Lambda_{\mathrm{QCD}}$

parent hadron or nucleus

factorisation scale

The PDFs $f_i^A(x,Q^2)$ are *universal*, process independent,

parton flavour

fraction of momentum carried by the parton

splitting functions

and obey the DGLAP equations $Q^2\dfrac{\partial f_i^A}{\partial Q^2} = \sum_j P_{ij}\otimes f_j^A$

Mellin conv.

...this is the framework which every PDF analysis and application relies on and tests!

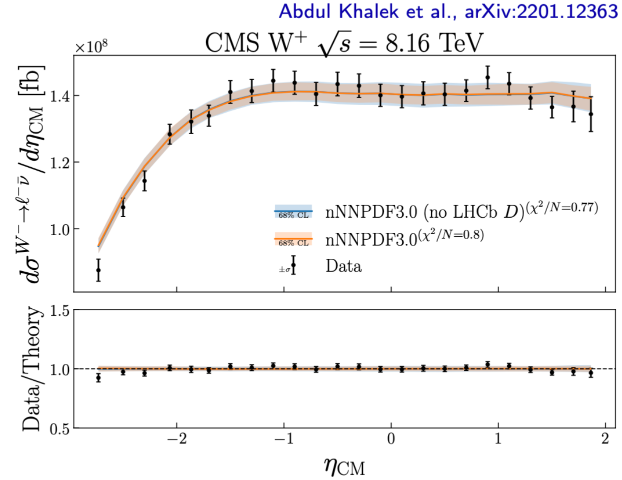
Courtesy of Petja Paakkinen, Quark Matter 2022

Very successful approach: nPDF global fits

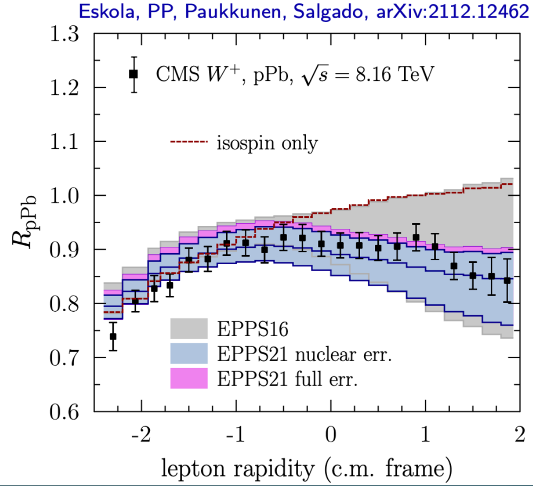
Recent nPDF global fits – all new since QM2019!

	KSASG20	nCTEQ15WZSIH	TUJU21	EPPS21	nNNPDF3.0
Order in α_s	NLO & NNLO	NLO	NLO & NNLO	NLO	NLO
lA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓		✓	✓	✓
pA DY	✓	✓		✓	✓
πA DY				✓	
RHIC dAu π^0,$\pi^\pm$		✓		✓	
LHC pPb π^0,$\pi^\pm$,$K^\pm$		✓			
LHC pPb dijets				✓	✓
LHC pPb D^0				✓	✓
LHC pPb W,Z		✓	✓	✓	✓
LHC pPb γ					✓
Q, W cut in DIS	1.3, 0.0 GeV	2.0, 3.5 GeV	1.87, 3.5 GeV	1.3, 1.8 GeV	1.87, 3.5 GeV
p_T cut in D^0,h-prod.	N/A	3.0 GeV	N/A	3.0 GeV	0.0 GeV
Data points	4353	940	2410	2077	2188
Free parameters	9	19	16	24	256
Error analysis	Hessian	Hessian	Hessian	Hessian	Monte Carlo
Free-proton PDFs	CT18	~CTEQ6M	own fit	CT18A	~NNPDF4.0
Free-proton corr.	no	no	no	yes	yes
HQ treatment	FONLL	S-ACOT	FONLL	S-ACOT	FONLL
Indep. flavours	3	5	4	6	6
Reference	PRD 104, 034010	PRD 104, 094005	arXiv:2112.11904	arXiv:2112.12462	arXiv:2201.12363

Abdul Khalek et al., arXiv:2201.12363



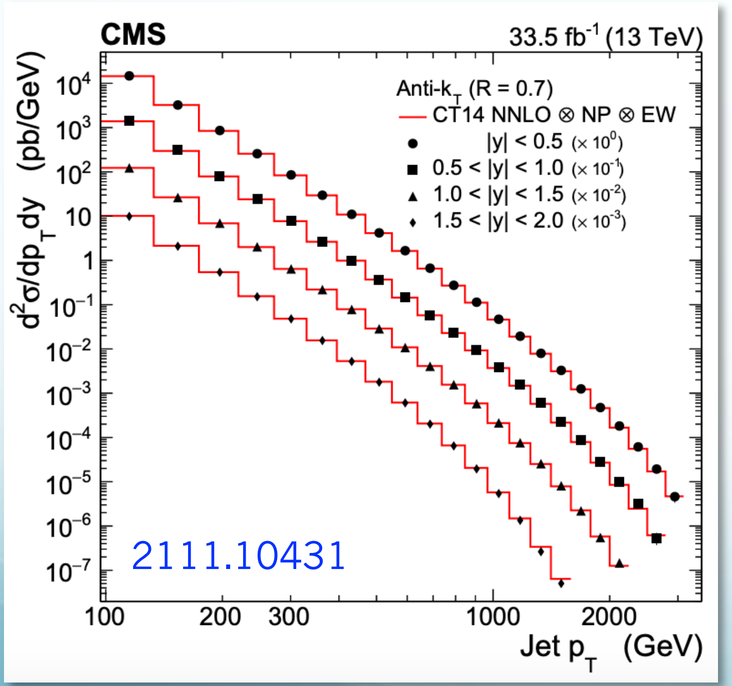
Eskola, PP, Paukkunen, Salgado, arXiv:2112.12462

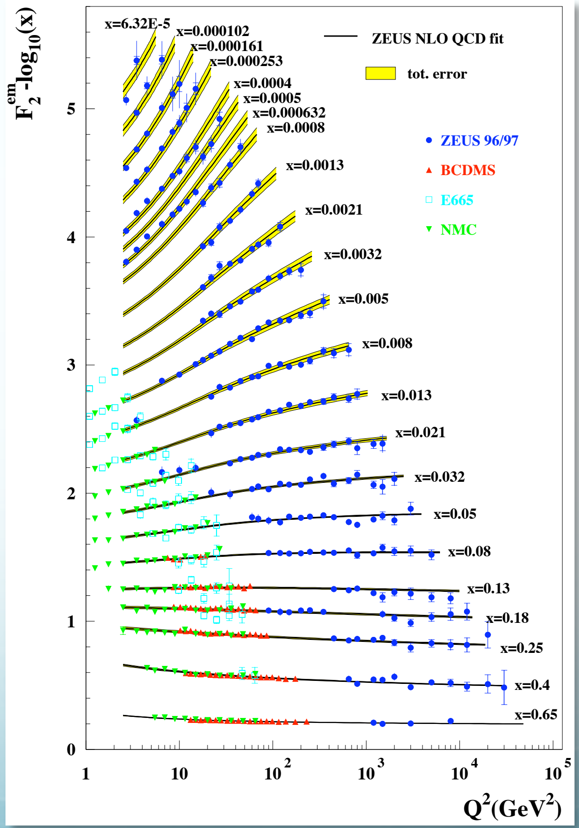


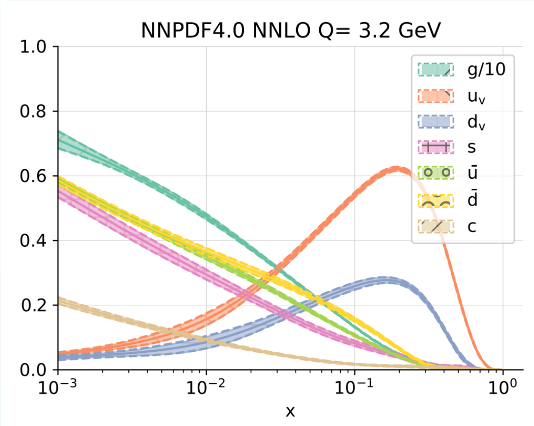
Courtesy of Petja Paakkinen, Quark Matter 2022

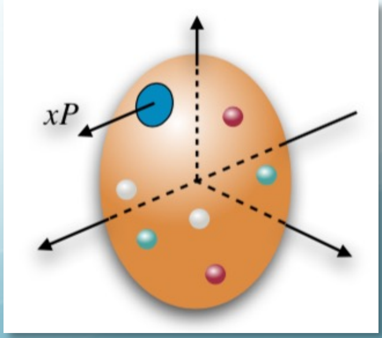
QCD factorization: collinear and TMD

- There are different types of QCD factorization, one should use them accordingly to include world data in different processes
  - **Collinear factorization**: process with ONE single hard scale
    - Single-inclusive hadron/jet in p+p collisions: pT is the hard scale
    - Inclusive deep inelastic scattering (DIS): Q is the hard scale



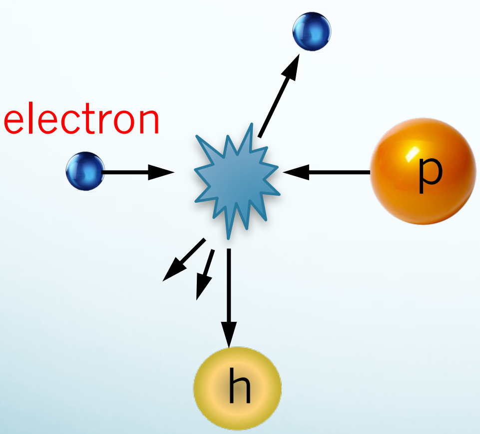


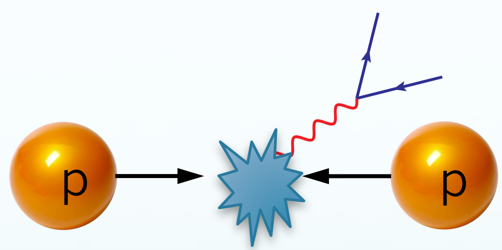


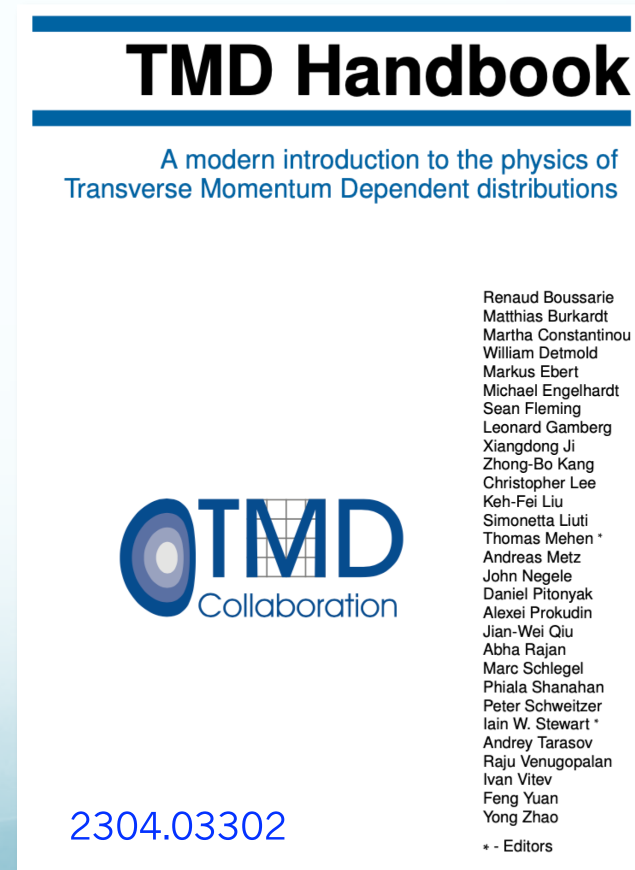


Another type: TMD factorization

- Transverse-momentum dependent (TMD) factorization, used for more differential processes
  - **TMD factorization**: process with TWO momentum scales (Q, qT) with qT << Q
    - Semi-inclusive hadron production in e+p collisions (SIDIS): qT, Q
    - Drell-Yan production in p+p collisions: qT, Q






TMD Handbook

A modern introduction to the physics of
Transverse Momentum Dependent distributions

Renaud Boussarie
Matthias Burkardt
Martha Constantinou
William Detmold
Markus Ebert
Michael Engelhardt
Sean Fleming
Leonard Gamberg
Xiangdong Ji
Zhong-Bo Kang
Christopher Lee
Keh-Fei Liu
Simonetta Liuti
Thomas Mehen *
Andreas Metz
John Negele
Daniel Pitonyak
Alexei Prokudin
Jian-Wei Qiu
Abha Rajan
Marc Schlegel
Phiala Shanahan
Peter Schweitzer
Iain W. Stewart *
Andrey Tarasov
Raju Venugopalan
Ivan Vitev
Feng Yuan
Yong Zhao

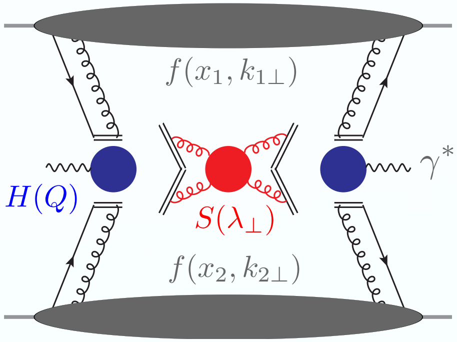
* - Editors

TMD Collaboration

2304.03302

TMD factorization in a nutshell

- Drell-Yan in pp collisions: $p + p \to [\gamma^* \to \ell^+ \ell^-] + X$



$$\frac{d\sigma}{dQ^2 dy d^2 q_\perp} \propto \int d^2 k_{1\perp}\, d^2 k_{2\perp}\, d^2 \lambda_\perp H(Q) f(x_1, k_{1\perp}) f(x_2, k_{2\perp}) S(\lambda_\perp) \delta^2(k_{1\perp} + k_{2\perp} + \lambda_\perp - q_\perp)$$

$$= \int \frac{d^2 b}{(2\pi)^2} e^{iq_\perp \cdot b} H(Q) f(x_1, b) f(x_2, b) S(b)$$

$$F(x, b) = f(x, b)\sqrt{S(b)}$$

$$= \int \frac{d^2 b}{(2\pi)^2} e^{iq_\perp \cdot b} H(Q) F(x_1, b) F(x_2, b)$$

mimic "parton model"

$$= \int d^2 k_{1\perp}\, d^2 k_{2\perp}\, H(Q) F(x_1, k_{1\perp}) F(x_2, k_{2\perp}) \delta^2(k_{1\perp} + k_{2\perp} - q_\perp)$$

TMD evolution: different from DGLAP

- TMD evolution

$$\frac{d\ln\tilde{f}_{i/p}(x,\mathbf{b}_T;\mu,\zeta)}{d\ln\mu} \overset{\text{CSS}}{=} \gamma_q[\alpha_s(\mu);\zeta/\mu^2]$$

$$\frac{\partial\ln\tilde{f}_{i/p}(x,\mathbf{b}_T;\mu,\zeta)}{\partial\ln\sqrt{\zeta}} = \tilde{K}(b_T;\mu)$$ Collins-Soper kernel

$$\frac{d\tilde{K}(b_T;\mu)}{d\ln\mu} = -\gamma_K[\alpha_s(\mu)]$$

- Solution of the above TMD evolution

$$\tilde{f}_{i/P}(x,\mathbf{b}_T,\mu,\zeta) = \tilde{f}_{i/P}(x,\mathbf{b}_T,\mu_0,\zeta_0)\,\exp\left\{\int_{\mu_0}^{\mu}\frac{d\mu'}{\mu'}\gamma_q\left[\alpha_s(\mu');\zeta_0/\mu'^2\right]\right\}\exp\left\{\tilde{K}(b_T;\mu)\ln\sqrt{\frac{\zeta}{\zeta_0}}\right\}$$

$$\mu = \sqrt{\zeta} = Q$$
$$\mu_0 = \sqrt{\zeta_0} = Q_0$$

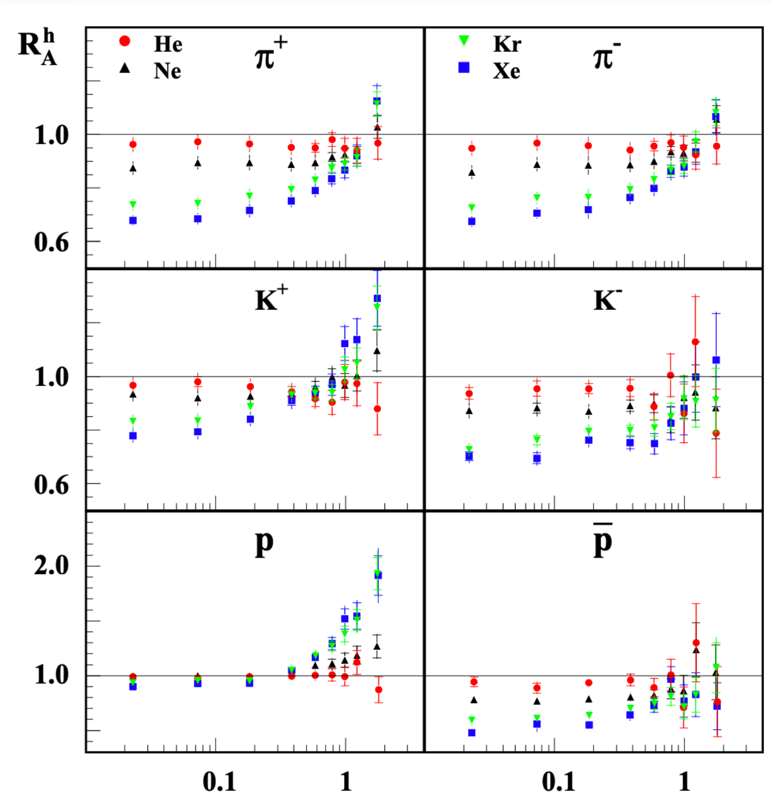
- One also has to include non-perturbative contribution

Using QCD factorization accordingly

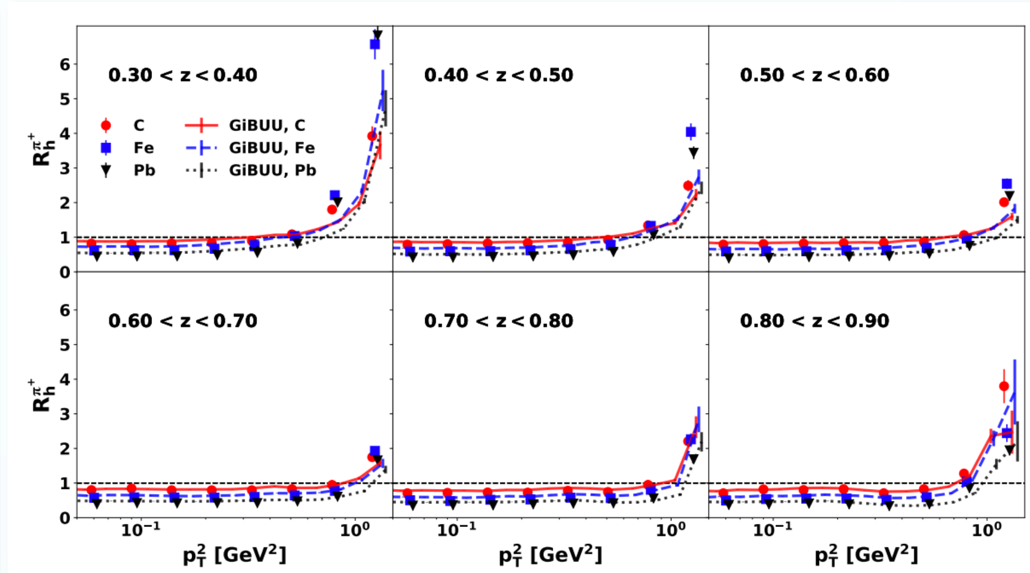
- Now we have two types of factorization, we should use them accordingly to extract the properties of cold nuclear matter consistently
  - For observables with **two** momentum scales: small pt distribution for SIDIS in e+A, Drell-Yan in p+A, we should use TMD factorization
  - For observables with **one** momentum scale: such as transverse-momentum broadening, we should use collinear factorization
  - These two approaches are also closely related to each other and thus could be used in a joint global fit in the future

Examples: TMD factorization in e+A and p+A

- SIDIS measurements in e+A: pt << Q, similar for Drell-Yan



HERMES, 0704.3270



CLAS @JLab, 2109.09951

$$R_A^h(\nu, Q^2, z, p_t^2) = \frac{\left(\frac{N^h(\nu,Q^2,z,p_t^2)}{N^e(\nu,Q^2)}\right)_A}{\left(\frac{N^h(\nu,Q^2,z,p_t^2)}{N^e(\nu,Q^2)}\right)_D}$$

Nuclear TMDs

- Following nuclear PDFs

Alrashed, Anderle, Kang, Terry, Xing, PRL, 2022

  - Assuming same TMD factorization formalism, replacing proton TMDs with nuclear TMDs
  - Assuming same TMD evolution, only replacing the TMDs at the initial scale

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

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

Intact since they are all from perturbative TMD evolution

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

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

- Change to nuclear PDFs (FFs): collinear dynamics
- Change non-perturbative Sudakov at initial scale: transverse dynamics

Status

- First work in this direction
  - Use nuclear PDFs from EPPS16 with CT14nlo, and nuclear FFs from LIKEn21 (P. Zurita, 2101.01088)
  - Modify non-perturbative Sudakov
    - Particle production in e+p or p+p

$$S_{\rm NP}^{f}(b,Q) = g_2(b)\ln(\sqrt{Q}/\sqrt{Q_0}) + g_q b^2,$$

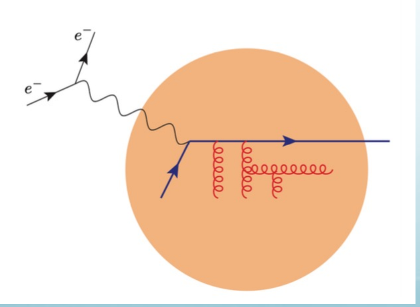
$$S_{\rm NP}^{D}(z,b,Q) = g_2(b)\ln(\sqrt{Q}/\sqrt{Q_0}) + g_h b^2/z^2,$$

Under Gaussian approximation, g_q is related to intrinsic momentum at the initial scale

$$g_q = \frac{\langle k_T^2\rangle|_{Q_0}}{4}$$

- Modification in e+A or p+A: due to parton multiple scattering

$$g_q^A(x,Q) = g_q + a_N L, \qquad g_h^A(z,Q) = g_h + b_N L, \qquad L = A^{1/3} - 1$$

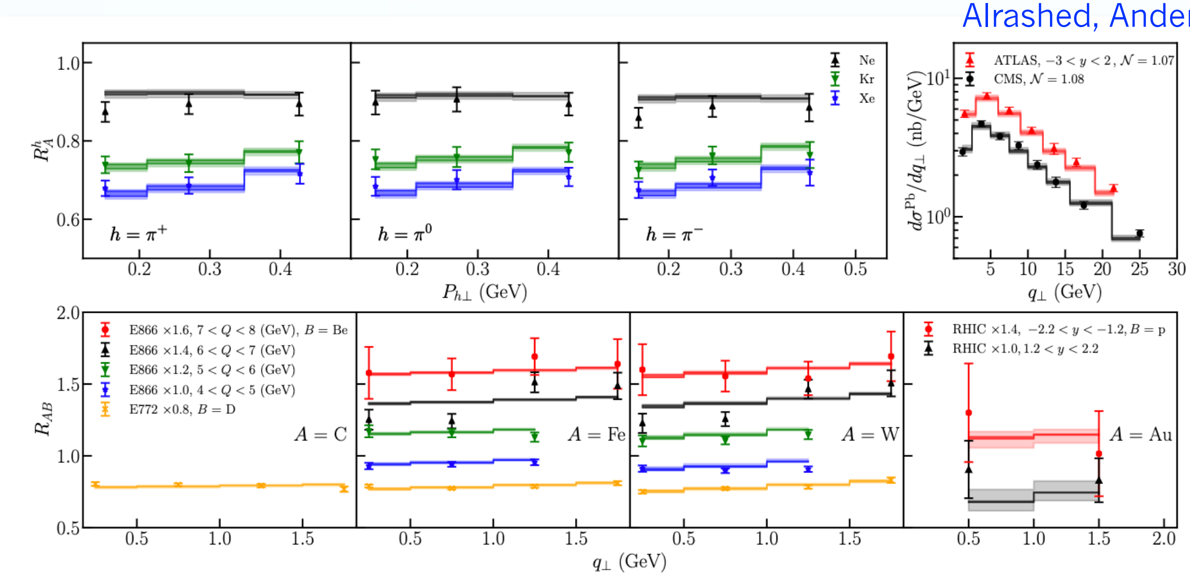


See similar work, e.g.
Jia, Wei, Xiao, Yuan, 1910.05290

Global fits of nuclear TMDs

- Nuclear TMD PDFs and TMD FFs (no Jlab data yet)

Alrashed, Anderle, Kang, Terry, Xing, PRL, 2022



$$a_N = 0.016 \pm 0.003\ \mathrm{GeV}^2$$
$$b_N = 0.0097 \pm 0.0007\ \mathrm{GeV}^2$$

Results.—The global analysis of these parameters results in a χ^2/d.o.f. of 1.196 where we have $a_N = 0.016 \pm 0.003\ \mathrm{GeV}^2$ and $b_N = 0.0097 \pm 0.0007\ \mathrm{GeV}^2$. We note that the χ^2/d.o.f. with $a_N = b_N = 0$ being 6.183. Thus, the

TABLE I. The χ^2 of the central fit for each data set in our fit. (NA represents not applicable.).

Collaboration	Process	Baseline	Nuclei	N_{dat}	χ^2
HERMES [36]	SIDIS (π)	D	Ne, Kr, Xe	27	16.3
RHIC [44]	DY	p	Au	4	2.0
E772 [42]	DY	D	C, Fe, W	16	20.1
E866 [43]	DY	Be	Fe, W	28	43.3
CMS [45]	γ^*/Z	NA	Pb	8	9.7
ATLAS [46]	γ^*/Z	NA	Pb	7	13.1
Total				90	105.2

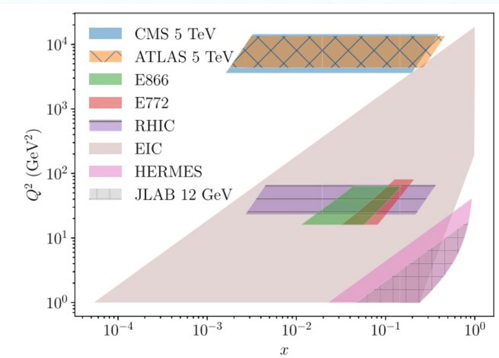


FIG. 1. Kinematic coverage for current experimental data and the projected coverage for JLab and the EIC.

Extracted nuclear TMD PDFs and TMD FFs

- Nuclear TMD PDFs and TMD FFs: 3D imaging of cold nuclear matter

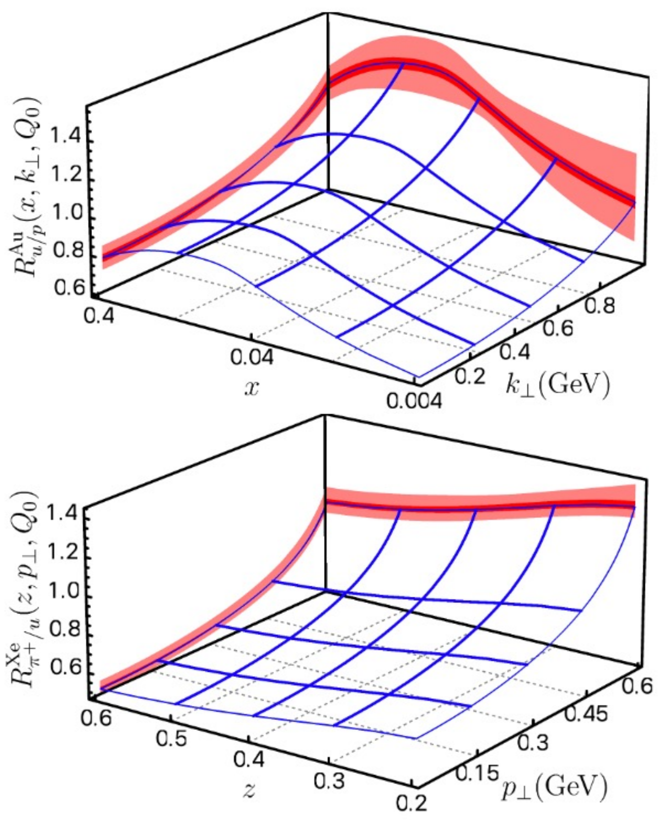


FIG. 3. The extracted nuclear ratio for the TMDPDF (top) and the TMDFF (bottom) at $Q_0 = \sqrt{2.4}$ GeV. The light and dark bands are the same as in Fig. 2.

Alrashed, Anderle, Kang, Terry, Xing, PRL, 2022

Updated fit with Jlab data

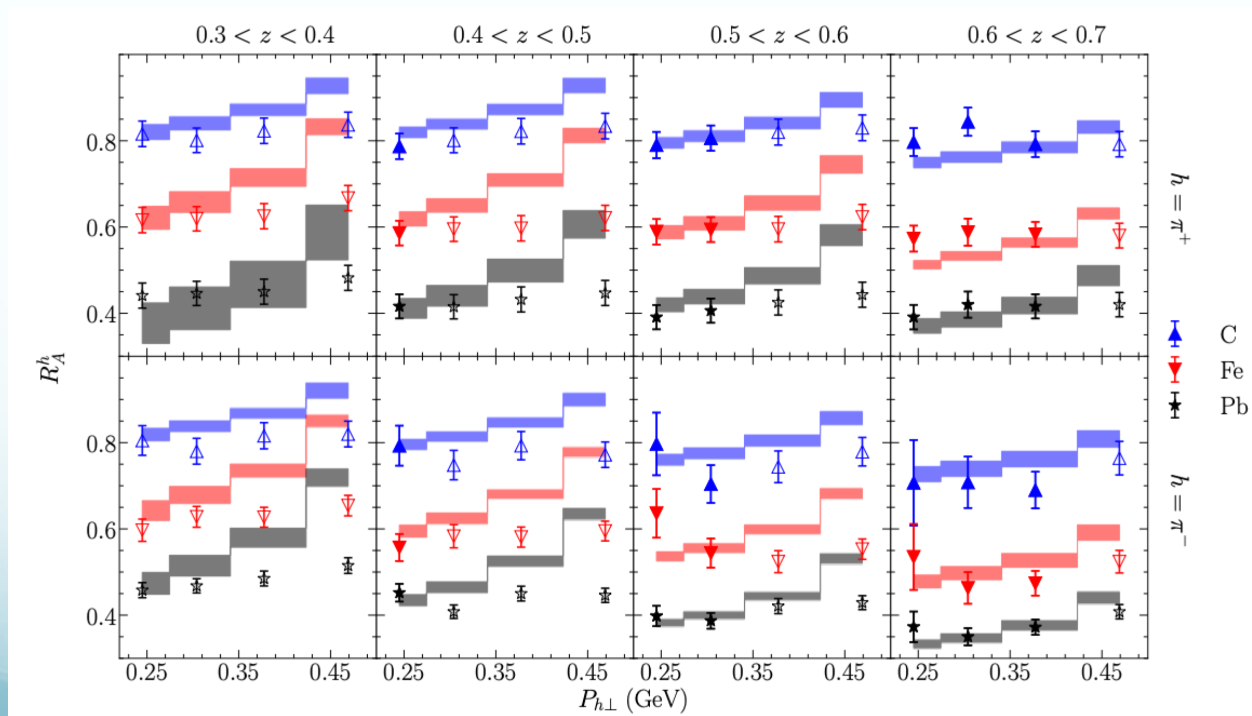
- Incorporate the collinear nuclear FFs into the fit by including CLAS@Jlab data

Alrashed, Anderle, Kang, Terry, Xing, Zhang, 2312.09226

$$S_f^{\mathrm{NP\ A}}(b, Q, Q_0) = S_f^{\mathrm{NP}}(b, Q, Q_0) + \frac{g_3^f}{2} L \left(\frac{Q_0^{\mathrm{NEW}}}{Q}\right)^{\gamma} b^2$$

$$S_D^{\mathrm{NP\ A}}(z, b, Q, Q_0) = S_D^{\mathrm{NP}}(z, b, Q, Q_0) + \frac{g_3^D}{2} L \left(\frac{Q_0^{\mathrm{NEW}}}{Q}\right)^{\gamma} \frac{b^2}{z^2}$$

$$\gamma = 2.200^{+0.135}_{-0.093}$$

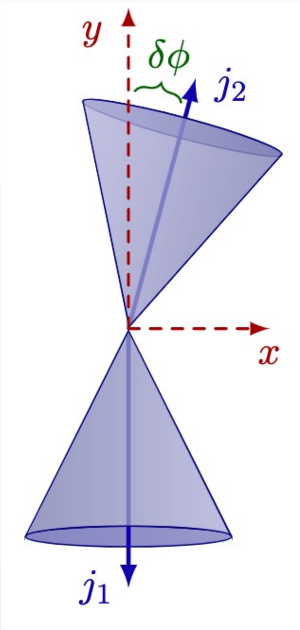


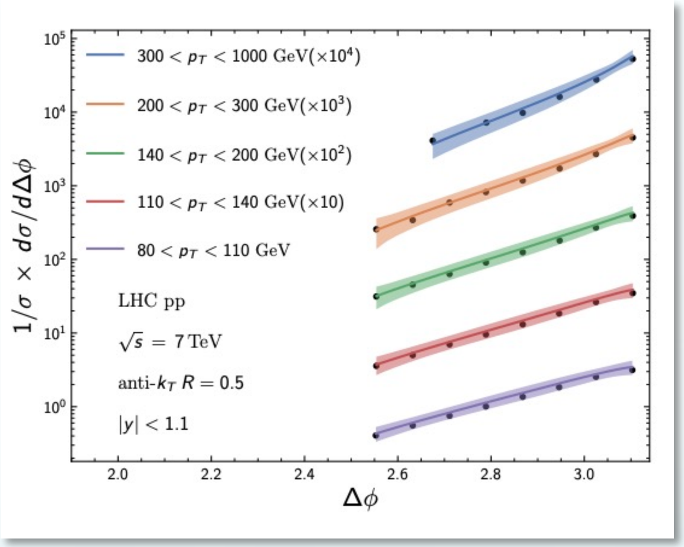
Application: TMDs in p+A collisions

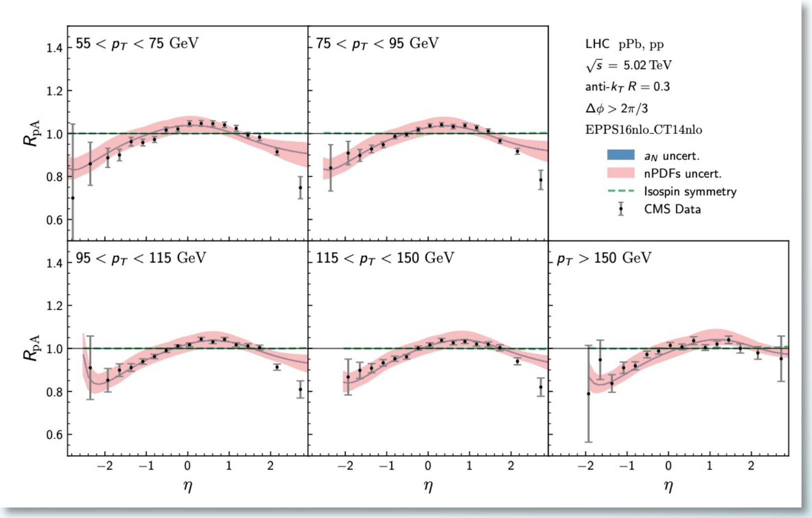
- Compare with other observables e.g. back-to-back dijet production in p+A collisions at the LHC

Gao, Kang, Shao, Terry, Zhang, 2306.09317, JHEP 2023

For dijet at p+p collisions, see also
Kang, Lee, Shao, Terry, JHEP 2021

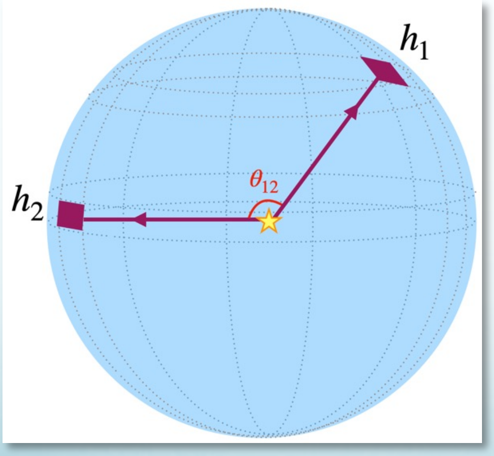


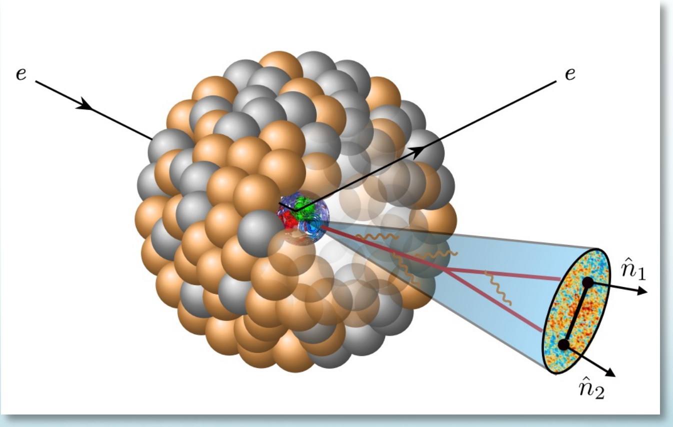




Energy Energy Correlator

- Two types
  - Global EEC
    - One of the earliest infrared safe event shape observables
    - Measure energy correlation as a function of the opening angle between pairs of particles
  - Local EEC
    - In-jet EEC: measure energy correlations for particles inside the jet



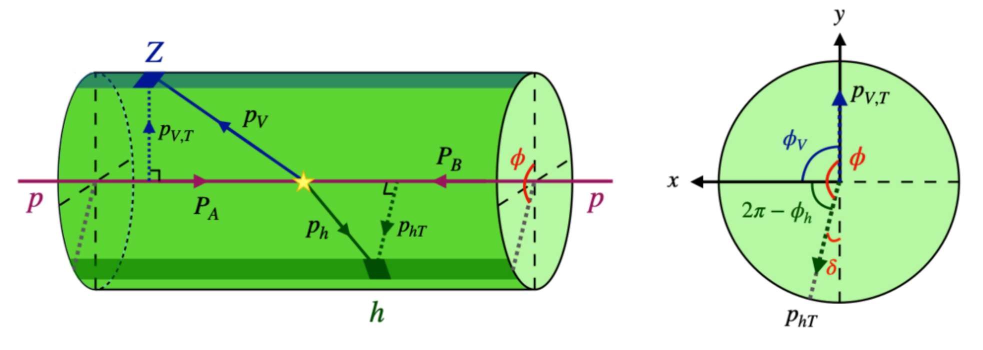


Energy-Energy Correlator

- In the back-to-back region, EEC follows a TMD factorization
  - EEC jet function is closely related to TMD FFs

Kang, Lee, Penttala, Zhao, Zhou, 2410.02747

- Transverse EEC (TEEC) for Z+hadron production in p+p and p+A



$$\mathbf{TEEC} = \sum_h \int d\sigma \frac{E_{T,V} E_{T,h}}{E_{T,V} \sum_{h'} E_{T,h'}} \delta\left(\tau - \frac{1+\cos\phi}{2}\right)$$

$$= \sum_h \int d\sigma \frac{E_{T,h}}{\sum_{h'} E_{T,h'}} \delta\left(\tau - \frac{1+\cos\phi}{2}\right). \quad (2)$$

$$\frac{d\Sigma}{d\tau\, dy_V\, dp_{V,T}} = \sum_{a,b,c} \frac{p_{V,T}}{\sqrt{\tau}} \int_{-\infty}^{\infty} \frac{db}{2\pi} e^{-2ib\sqrt{\tau} p_{V,T}} \int dy_c\, H_{ab\to Vc}(y_V, p_{V,T}, m_V, \mu)$$
$$\times\, x_a\, f_{1,a/p}^{(u)}\left(x_a, b, \mu, \frac{\zeta_a}{\nu^2}\right) x_b\, f_{1,b/p}^{(u)}\left(x_b, b, \mu, \frac{\zeta_b}{\nu^2}\right) J_c^{(u)}\left(b, \mu, \frac{\zeta_c}{\nu^2}\right) S_{abc}(b, \mu, \nu)$$

Nuclear modification in TEEC

- Relationship between TEEC jet function and TMD FFs

$$J_c(b,\mu,\zeta_c) \equiv \sum_h \int_0^1 \mathrm{d}z\, z D_{1,h/c}(z,b,\mu,\zeta_c)$$

$$\begin{aligned} D_{1,h/c}(z,b,\mu,\zeta_c) = \sum_i \int_z^1 \frac{\mathrm{d}y}{y} \hat{C}_{i\leftarrow c}\left(\frac{z}{y},b\right) D_{h/i}(y,\mu_{b_*}) \\ \times \exp[-S_{\text{pert}}(\mu,\mu_{b_*},\zeta_c)] \\ \times \exp[-S^c_{\text{NP}}(z,b,Q_0,\zeta_c)]\,, \end{aligned} \quad (45)$$

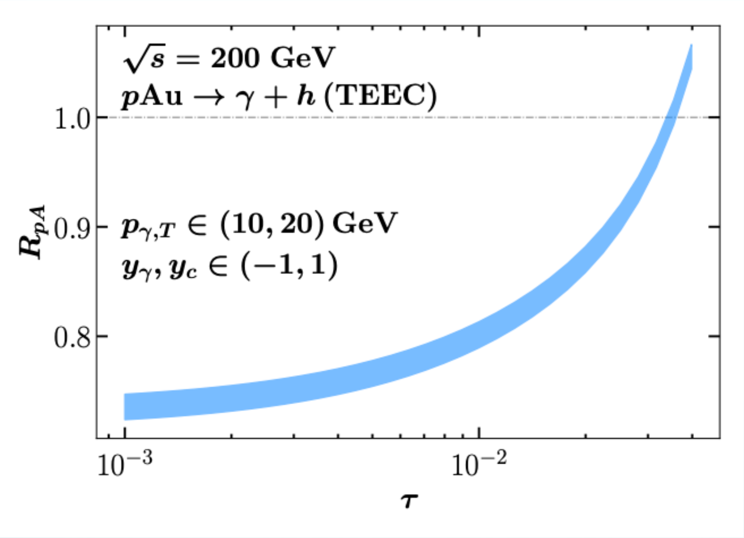
$$\begin{aligned} &\sum_h \int_0^1 \mathrm{d}z\, z D_{h/i}(z,\mu_{b_*}) \exp\left(-g_1^D \frac{b^2}{z^2}\right) \\ &\equiv \exp\left[-S_{\text{NP}}^{\text{TEEC}}(b)\right]\,, \end{aligned}$$

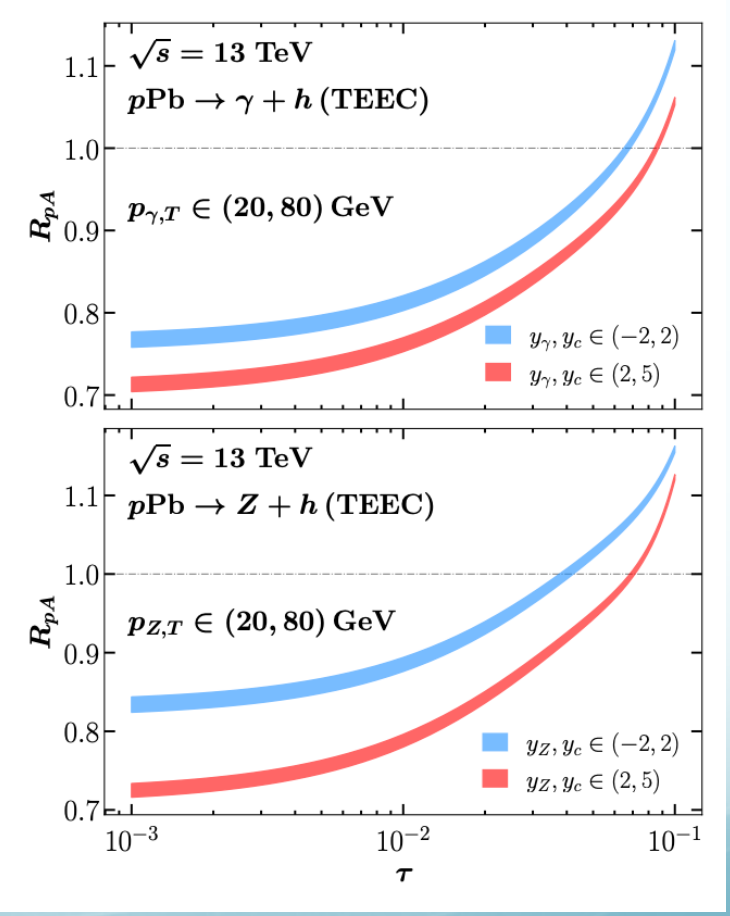
$$S_{\text{NP}}^{\text{TEEC}}(b) = N_1 b^{\alpha_1} + N_2 b^{\alpha_2}$$

$$\begin{aligned} J_q(b,\mu,\zeta_c) &= \exp[-S_{\text{pert}}(\mu,\mu_{b_*},\zeta_c)] \quad (50)\\ &\times \exp\left[-\frac{g_2}{2}\ln\left(\frac{b}{b_*}\right)\ln\left(\frac{\sqrt{\zeta_c}}{Q_0}\right) - S_{\text{NP}}^{\text{TEEC}}(b)\right]\,, \\ J_g(b,\mu,\zeta_c) &= \exp[-S_{\text{pert}}(\mu,\mu_{b_*},\zeta_c)] \quad (51)\\ &\times \exp\left[-\frac{C_A}{C_F}\frac{g_2}{2}\ln\left(\frac{b}{b_*}\right)\ln\left(\frac{\sqrt{\zeta_c}}{Q_0}\right) - S_{\text{NP}}^{\text{TEEC}}(b)\right]\,. \end{aligned}$$

TEEC and nuclear modification

- Compare with other observables e.g. back-to-back dijet production in p+A collisions at the LHC

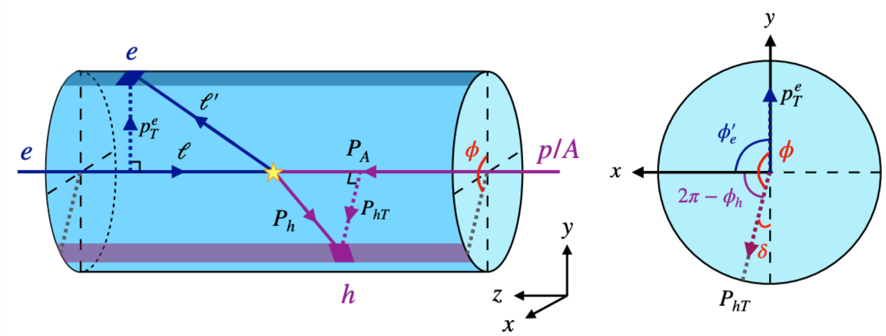




TEEC in small x regime at EIC

- Lepton-hadron TEEC in e+A collisions

Kang, Penttala, Zhao, Zhou, 2311.17142, PRD

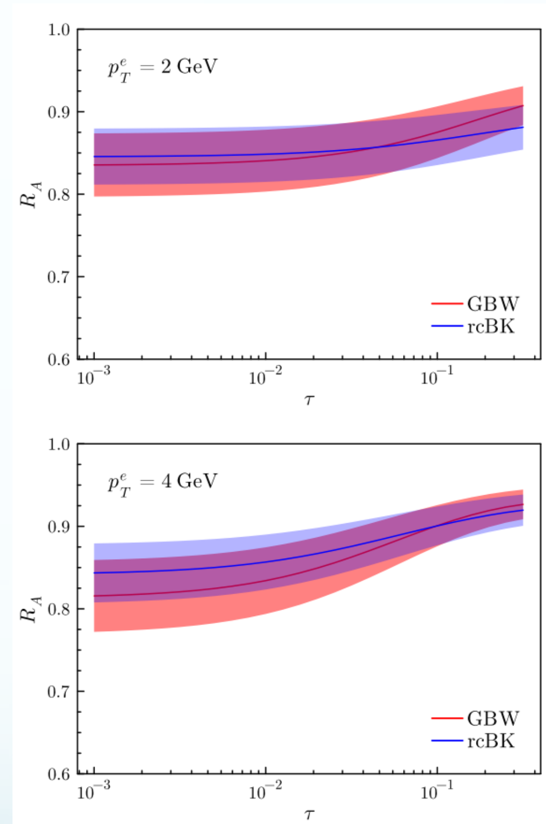


$$\textbf{TEEC} \equiv \frac{d\sigma}{d\tau\, dy_e\, d^2\boldsymbol{p}_T^e} = \sigma_0 H(Q,\mu) \sum_q e_q^2 \frac{p_T^e}{\sqrt{\tau}} \int_{-\infty}^{\infty} \frac{db}{2\pi} e^{-2ib\sqrt{\tau}p_T^e} f_q^{(u)}(x,b,\mu,\zeta/\nu^2) S_{nn_h}(b,\mu,\nu) J_q^{(u)}(b,\mu,\zeta'/\nu^2) \quad (4)$$

$$= \sigma_0 H(Q,\mu) \sum_q e_q^2 \frac{p_T^e}{\sqrt{\tau}} \int_0^{\infty} \frac{db}{\pi} \cos(2b\sqrt{\tau}p_T^e) f_q^{(u)}(x,b,\mu,\zeta/\nu^2) S_{nn_h}(b,\mu,\nu) J_q^{(u)}(b,\mu,\zeta'/\nu^2)\,.$$

$$x f_q(x,b,\mu_{b_*},\mu_{b_*}^2) = \frac{N_c S_\perp}{8\pi^4} \int d\epsilon_f^2\, d^2\boldsymbol{r}\, \frac{(\boldsymbol{b}+\boldsymbol{r})\cdot\boldsymbol{r}}{|\boldsymbol{b}+\boldsymbol{r}||\boldsymbol{r}|} \epsilon_f^2 K_1(\epsilon_f|\boldsymbol{b}+\boldsymbol{r}|) K_1(\epsilon_f|\boldsymbol{r}|) \times \Big[1 + \mathcal{S}_x(|\boldsymbol{b}|) - \mathcal{S}_x(|\boldsymbol{b}+\boldsymbol{r}|) - \mathcal{S}_x(|\boldsymbol{r}|)\Big], \quad (24)$$

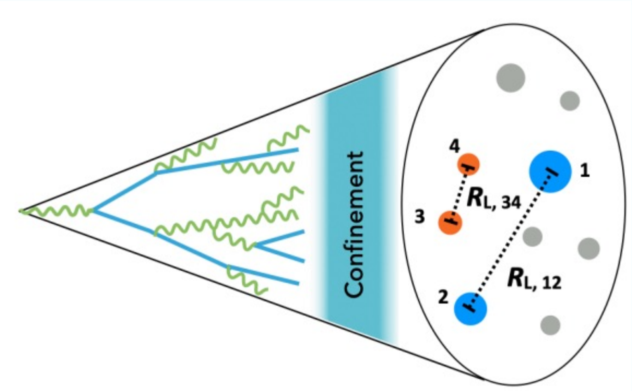
Marquet, Xiao, Yuan, PLB 09

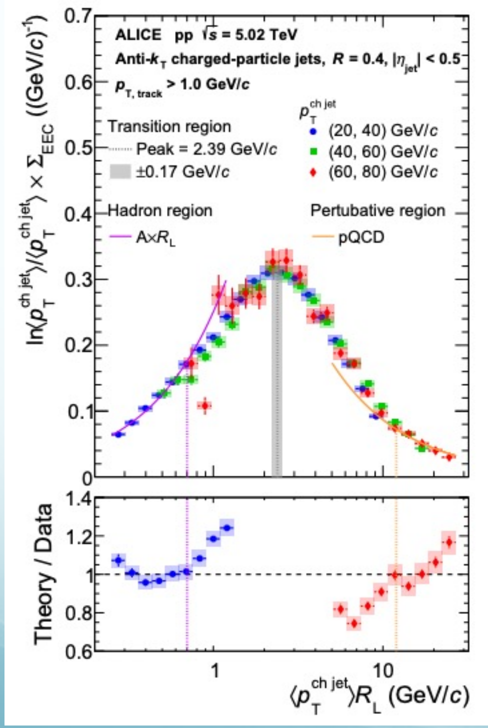


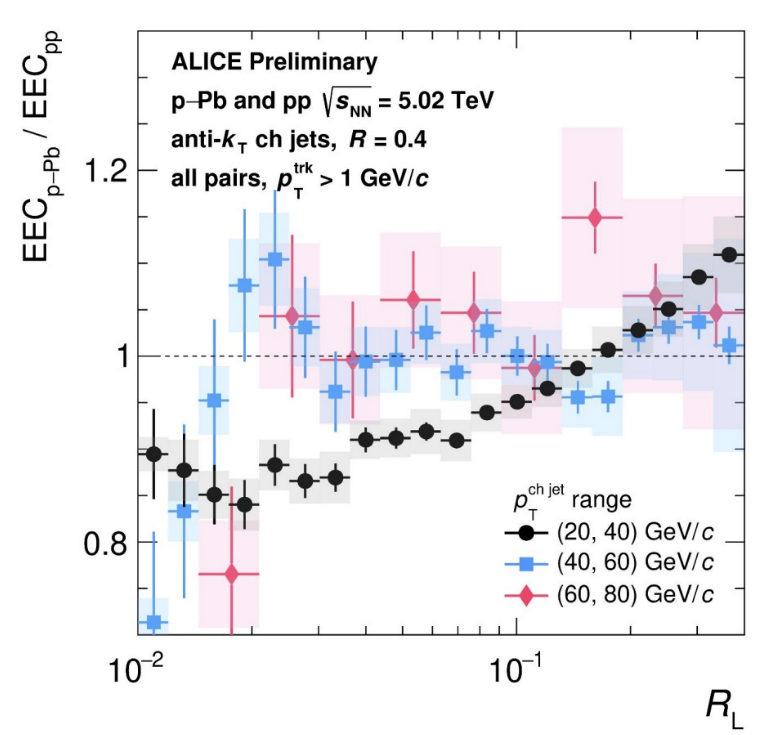
EEC in the collinear limit

- EEC for particles in jets

ALICE measurements







EEC in the collinear limit

- In order to describe the nuclear modification, one needs a model to describe the entire angular region (both small and large)

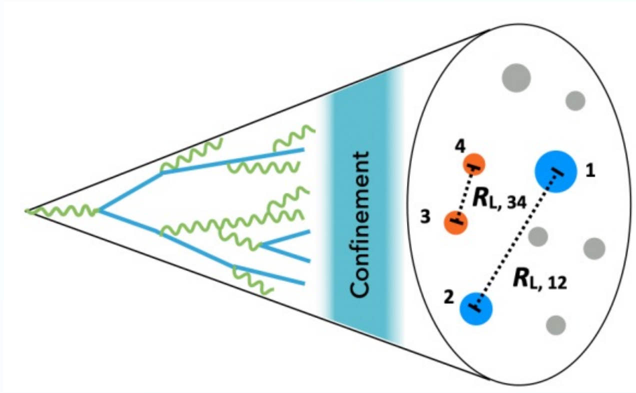
Relative transverse momentum between the pair:

$k_T \sim p_T R_L$

- p_T = jet transverse momentum

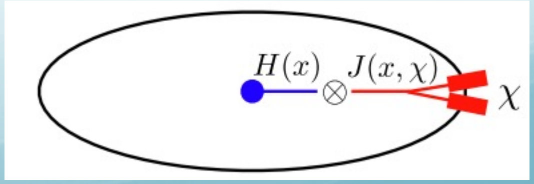
Different regions:

- $k_T \gg \Lambda_{\mathrm{QCD}}$: perturbative
  - Probes jet formation
- $k_T \sim \Lambda_{\mathrm{QCD}}$: nonperturbative
  - Effects from confinement and hadronization



- The perturbative region follows a collinear factorization
- The non-perturbative region could take some insights from TMD physics
  - Non-perturbative hadronization

Dixon, Moult, Zhu, 1905.01310



EEC in p+p: description of the data

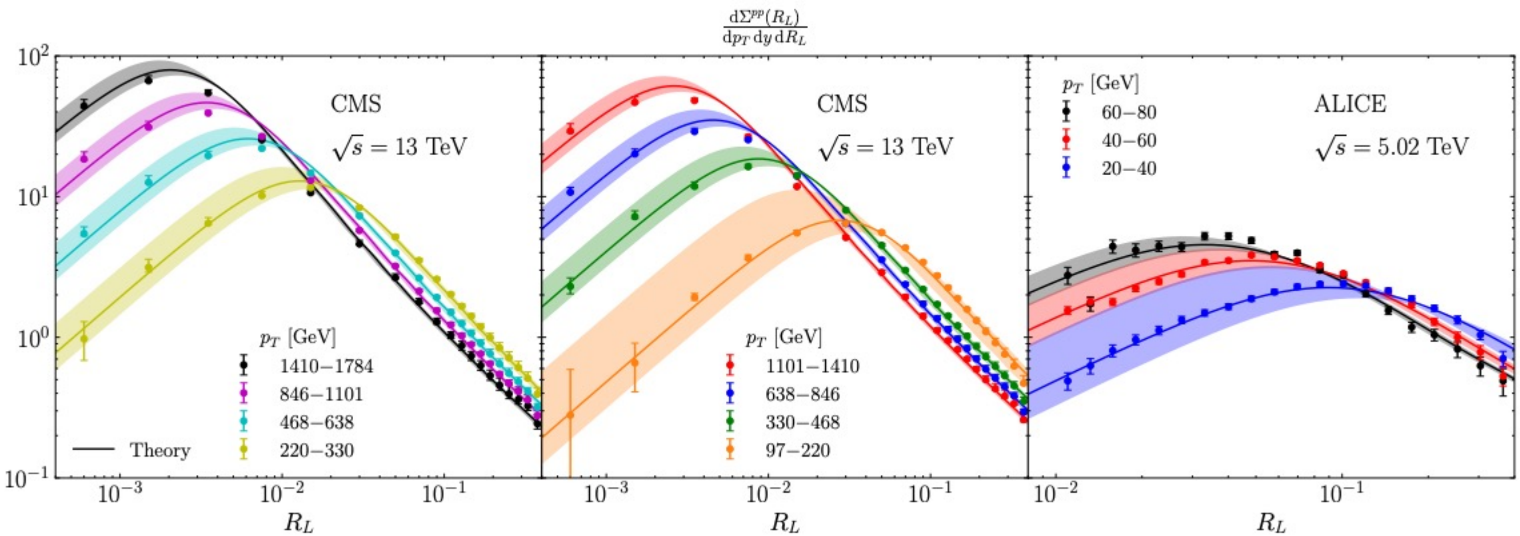
- EEC in p+p collisions

Barata, Kang, Lopez, Penttala, 2411.11782

$$\frac{d\Sigma^{pp}}{dp_T\, dy\, dR_L} = R_L p_T^2 \int_0^\infty db\, b\, J_0(R_L p_T b)\, j_{np}(b)\, \widetilde{\Sigma}(b)$$

$$j_{np}(b) \equiv \exp(-a_0 b)$$

$$\widetilde{\Sigma}(b) = (1,1) \cdot \left(\frac{\alpha_s(Rp_T)}{\alpha_s(\mu_{b_*})}\right)^{\frac{\gamma(3)}{\beta_0}} \cdot H(p_T)$$



- a_0 fitted to data: CMS: $a_0 = 3.8$ GeV, ALICE: $a_0 = 2.5$ GeV
  - Difference in measurements: CMS inclusive jets, ALICE charged jets

EEC in p+A collisions

- In the small angular region: transverse momentum broadening (TMB) for the pair due to multiple scattering

$$j_{np}(b) = \exp(-a_0 b) \Rightarrow j_{np}(b) = \exp(-a_0 b - a_1 b^2)$$

  - TMB for the pair: $a_1 \sim \frac{\langle k_T^2 \rangle}{4} \sim 0.25 \text{ GeV}^2$

- In the large angular region: medium-induced contribution to the EEC jet function from induced splitting in medium

$$\frac{dJ^{\text{med}}}{dR_L} = \frac{\alpha_s}{\pi R_L} \int_0^1 dz z(1-z) P^{\text{med}}(z, p_T, R_L)$$

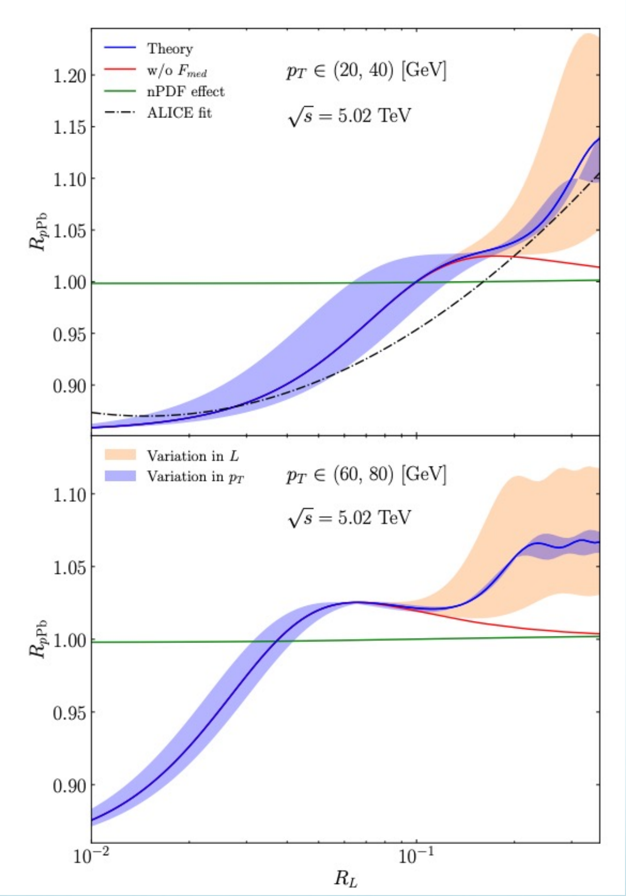
  - Jet quenching parameter in cold nuclear matter: $\hat{q} \approx 0.02 \text{ GeV}^2/\text{fm}$
  - Medium length L ~ 3 fm

Ru, Kang, Wang, Xing, Zhang, 1907.11808, PRD

EEC in p+A collisions

- Reasonably describe the nuclear modification observed in ALICE

Barata, Kang, Lopez, Penttala, 2411.11782



Summary

- Nuclear PDFs and nuclear FFs have played important roles in quantifying parton dynamics and modification in nuclei
- New paradigm: with new tools available, one could start to perform 3D imaging in nuclei via more advanced factorization formalism such as TMD factorization
- Through the relationship between TMDs and EEC, one could study TEEC in p+A collisions in the back-to-back region where a TMD factorization for TEEC can be applied
- Exciting new opportunities in the collinear limit of the EEC for particles inside jets: the community starts to measure and understand the nontrivial nuclear modifications
- Looking forward to the bright future

Thank you!