UCLA College | Physical Sciences
Physics & Astronomy

Global extraction of nuclear TMDs

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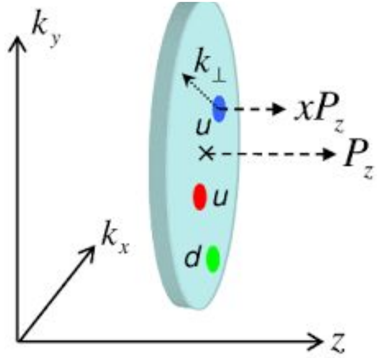
Introduction

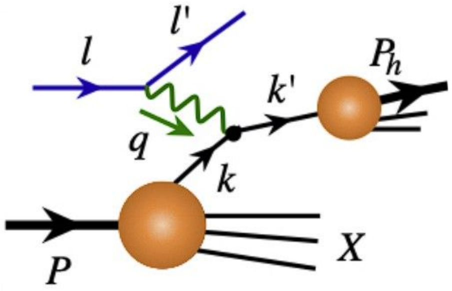
TMDs

TMD (Transverse Momentum Dependent) **PDF** (Parton Distribution Function)

$f_{i/h}(x, k_\perp)$: the probability of finding a parton(i) with collinear momentum xP and transverse momentum $k_\perp$ inside hadron(h).



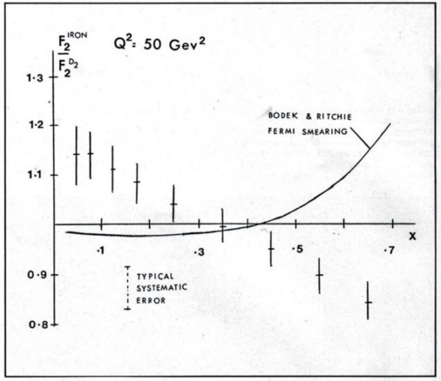
Collinear vs Transverse



TMDFF (Fragmentation function)

$D_{h/i}(z, p_\perp)$: the probability for a fragmenting parton(i) to produce a hadron(h) with momentum zk' and transverse momentum $p_\perp$.

Nuclear effect & transverse momentum broadening



1] Structural function ratio (nuclear/free) for DIS(deep inelastic scattering) at EMC. Measured ratio has opposite trend from prediction based on free PDF

EMC effect

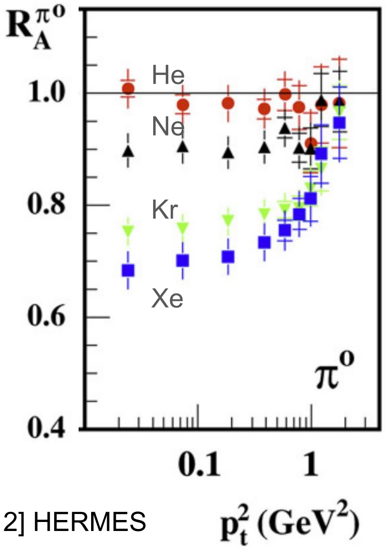
4 decades ago, physicists at EMC (European Muon Collaboration) collaboration discovered the PDF of nucleon bound inside nucleus is different from free nucleon.
We quantify this difference with nuclear modification ratio R:

$$f_{i/A}(x,Q) = R_i^A(x,Q)\ f_{i/p}(x,Q)$$

Today collinear PDF and nuclear modification ratio have been extraction with high precision (for example CT18NLO & EPPS21)

Transverse momentum broadening

Another important phenomenon is transverse momentum broadening. Due to multiple scattering of parton inside nuclear medium, nuclear PDF and FF are augmented at large transverse momentum. However, no one had quantified the nuclear broadening within the TMD framework.



2] HERMES

Stage I (2021)

Nuclear modification of TMDs (A-dependent)

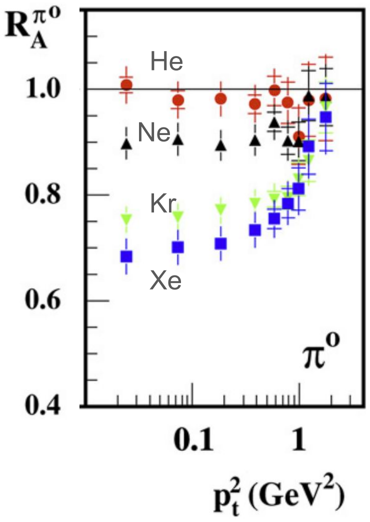
We assume the TMD functions can be related to its collinear counterpart with a gaussian distribution in transverse momentum.
To quantify the the nuclear broadening, our group proposed a nuclear weight dependent modification to the simple gaussian model:

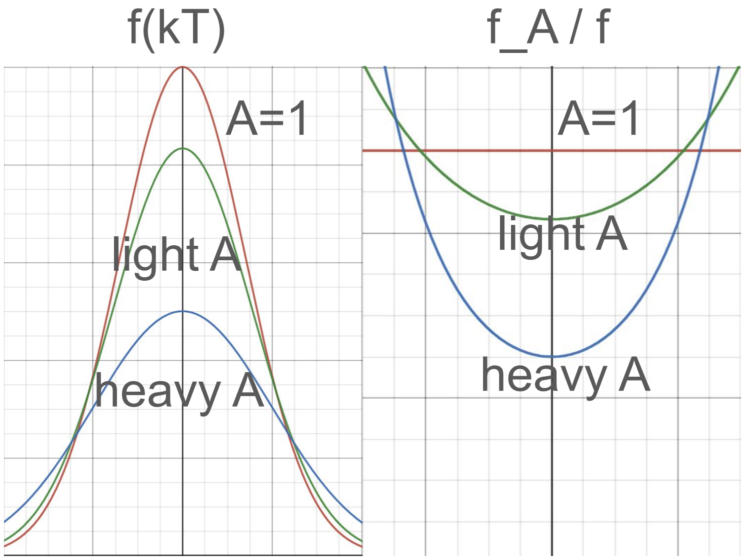
$$f_{i/h}(x, k_\perp) \propto f_{i/h}(x) \frac{e^{-k_\perp^2/\langle k_\perp^2 \rangle}}{\langle k_\perp^2 \rangle}$$

$$D_{h/i}(z, p_\perp) \propto D_{h/i}(z) \frac{e^{-p_\perp^2/\langle p_\perp^2 \rangle}}{\langle p_\perp^2 \rangle}$$

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

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





Parameterization of nTMDs

In the fourier transformed b space, the exact expression for nTMDPDF and nTMDFF are given by:

$$f_{i/h}^{A}(x,b,Q) = \left[C_{i\leftarrow j}\otimes f_{j/h}^{A}\right](x,\mu_{b_*})e^{-S_{\mathrm{pert}}-S_f^{\mathrm{NP,A}}}$$

$$D_{h/i}^{A}(z,b,Q) = \left[\hat{C}_{j\leftarrow i}\otimes D_{h/j}^{A}\right](z,\mu_{b_*})e^{-S_{\mathrm{pert}}-S_D^{\mathrm{NP,A}}}$$

The gaussian form is absorbed into the NP Sudokov form factors:

$$S_f^{\mathrm{NP,\ A}}(b,Q;Q_0) = S_f^{\mathrm{NP}}(b,Q;Q_0) + \boxed{a_N(A^{\frac{1}{3}}-1)b^2}$$

$$S_D^{\mathrm{NP,\ A}}(z,b,Q;Q_0) = S_D^{\mathrm{NP}}(z,b,Q;Q_0) + \boxed{b_N(A^{\frac{1}{3}}-1)\frac{b^2}{z^2}}$$

2 parameters in total: a_N, b_N

Collinear nPDF: EPPS16
Collinear nFF: LIKEn21

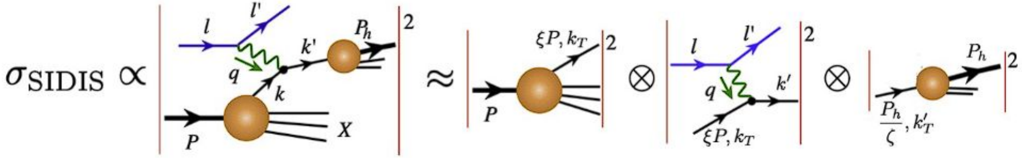
Extraction: data and framework

Drell-Yan: E772, E866, RHIC, CMS, ATLAS $\frac{q_\perp}{Q} < 0.3$

$$p + N \to [\gamma^*(q) \to]\ l^+ + l^- + X$$

SIDIS: HERMES $z < 0.7, P_{h\perp}^2 < 0.3$

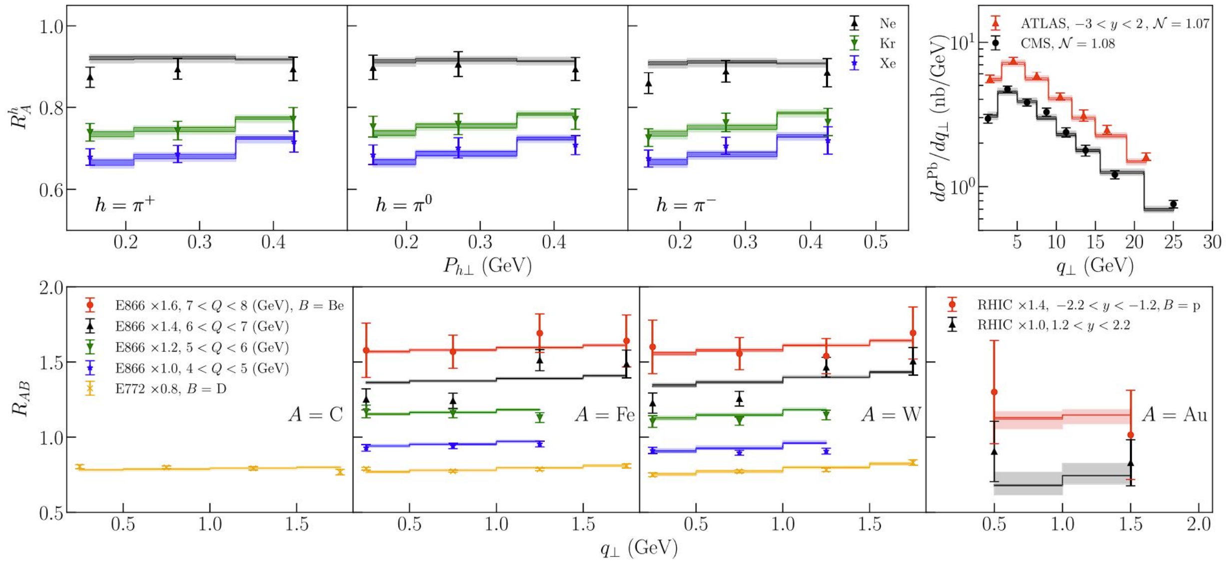
$$e^-(l) + N(P) \to e^-(l') + h(P_h) + X$$



Theoretical prediction for X-section is obtained with TMD factorization theorem:

$$\frac{d\sigma}{d\mathcal{PS}} = \sigma_0^{DIS}(y,Q) H^{DIS}(Q) \sum_i e_i^2 \int \frac{bdb}{2\pi}\ J_0(\frac{P_{h\perp}}{z} b) f_{i/h}^A(x,b,Q) D_{h/i}^A(z,b,Q)$$

Fit Result



$$R_A^h = \frac{M_A^h}{M_D^h}, \ M^h \simeq \frac{d\sigma_{\mathrm{SIDIS}}}{d\sigma_{\mathrm{DIS}}}$$

$$R_{AB} = \frac{d\sigma_A}{dq_\perp} / \frac{d\sigma_B}{dq_\perp}$$

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

$$a_N = 0.016, b_N = 0.0097$$

chi2/dof = **1.2**

arXiV:2107.12401

Stage II (2023)

Simultaneous fit of NP Sudakov and nFF

DEHSS vacuum collinear FF $$D_i(z, Q_0) = \tilde{N}_i z^{\alpha_i}(1-z)^{\beta_i}[1+\gamma_i(1-z)^{\delta_i}]$$

Nuclear modification $$\tilde{N}_q \to \tilde{N}_q[1 + N_{q1}(1 - A^{N_{q2}})]$$

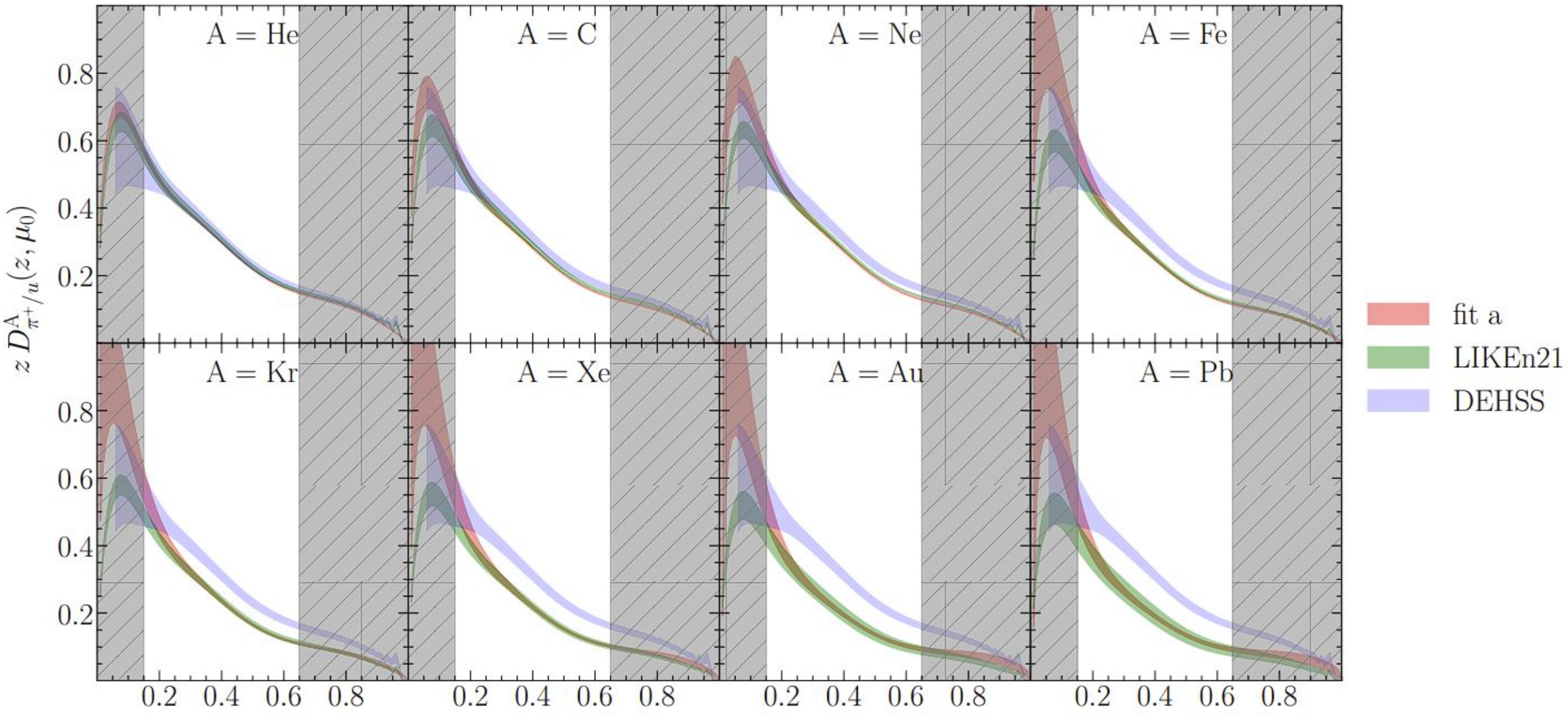
$$\alpha_q, \beta_q \to \alpha_q, \beta_q + \alpha_{q1}, \beta_{q1}(1 - A^{\alpha_{q2}, \beta_{q2}})$$

9 parameters in total: $\gamma \quad g_3^f \quad g_3^D \quad N_{q2} \quad \gamma_{q2} \quad \delta_{q2} \quad N_{q1} \quad \gamma_{q1} \quad \delta_{q1}$

$N_{q1} = 0.238^{+0.365}_{-0.0789}$	$\alpha_{q1} = 0.082^{+1.12}_{-0.0393}$	$\beta_{q1} = 0.00169^{+0.176}_{-0.283}$
$N_{q2} = 0.259^{+0.0772}_{-0.103}$	$\alpha_{q2} = 0.388^{+0.0799}_{-0.270}$	$\beta_{q2} = 1.030^{+0.512}_{-1.11}$
$a_N = 0.016^{+0.00187}_{-0.00189}$	$b_N = 0.013^{+0.0104}_{-0.00730}$	

chi2/dof = **0.88**

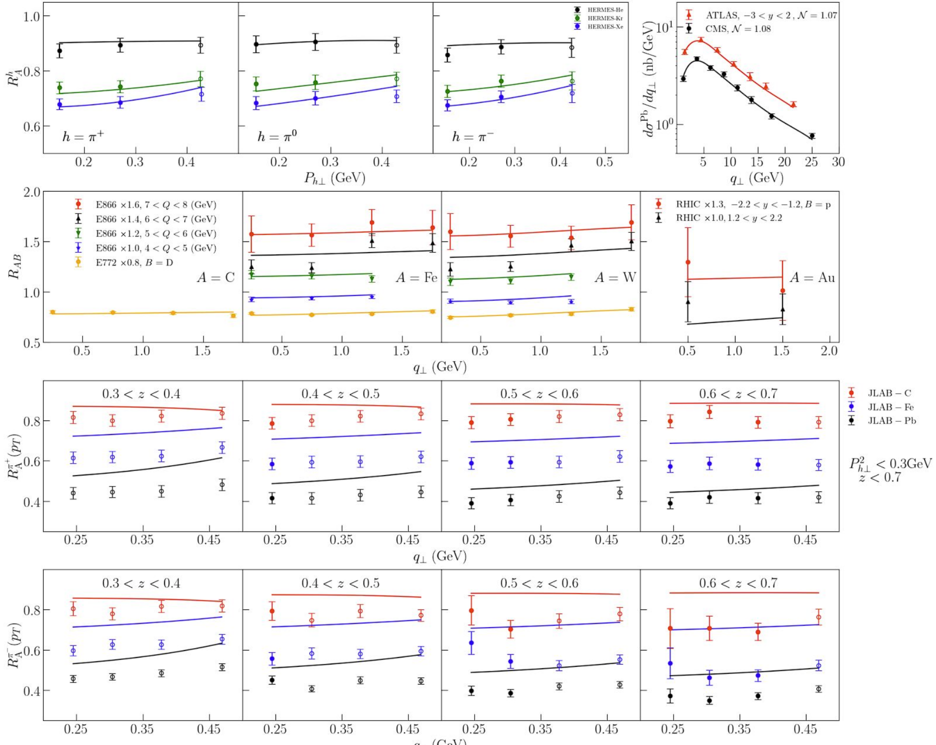
Fitted nFF vs LIKEn21



JLab

After the 1st stage extraction was published, new JLAB data came out; our previous parameterization for nTMDs was unable to capture the large non-perturbative effect of JLAB due at low Q

chi2/dof > 5



HERMES Q^2 ~ 2.6
JLab Q^2 ~ 1.6

Nuclear modification of TMDs (A,Q-dependent)

Sudakov

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

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

$$L = (A^{\frac{1}{3}} - 1)$$

DEHSS vacuum collinear FF

$$D_i(z,Q_0) = \tilde{N}_i z^{\alpha_i}(1-z)^{\beta_i}[1+\gamma_i(1-z)^{\delta_i}]$$

Nuclear modification

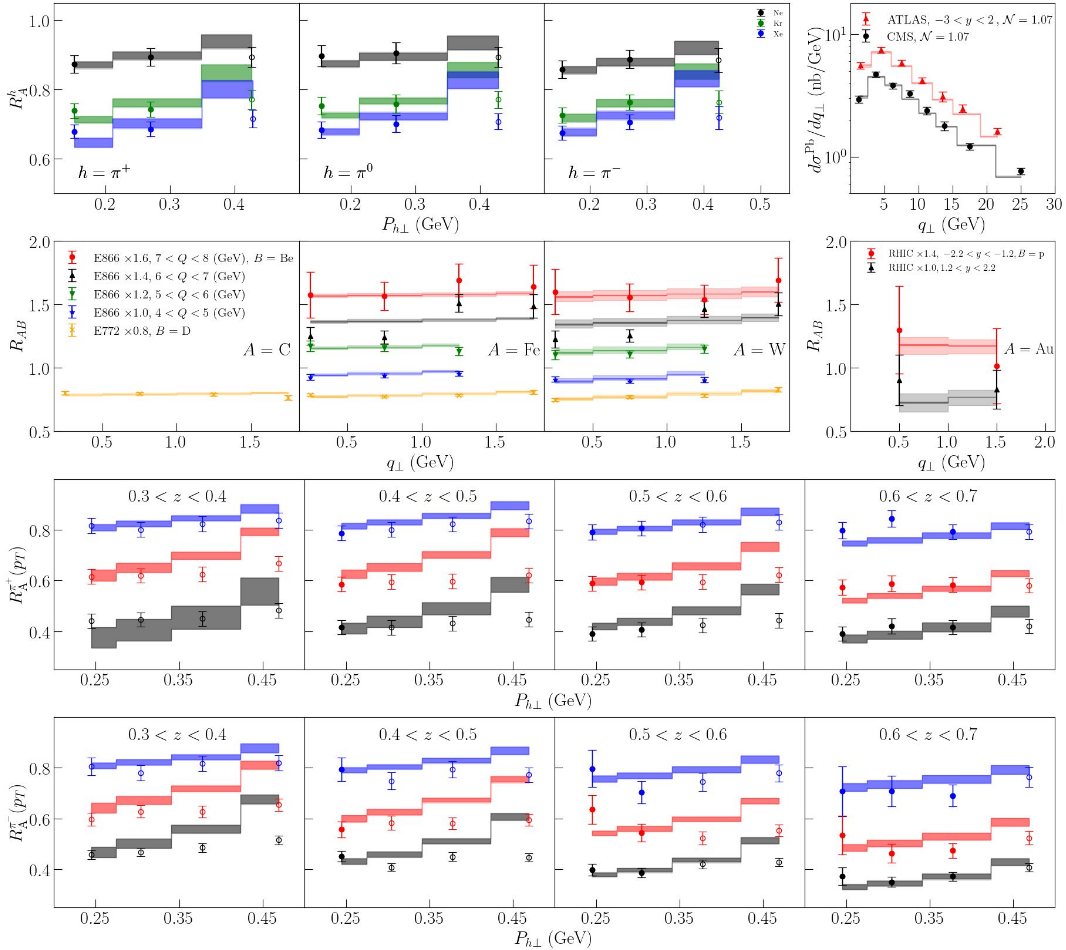
$$\tilde{N}_q \to \tilde{N}_q[1+N_{q1}(1-A^{N_{q2}})]$$

$$\gamma_q, \delta_q \to \gamma_q, \delta_q + \gamma_{q1}, \delta_{q1}(1-A^{\gamma_{q2},\delta_{q2}})$$

9 parameters in total: $\gamma \quad g_3^f \quad g_3^D \quad N_{q2} \quad \gamma_{q2} \quad \delta_{q2} \quad N_{q1} \quad \gamma_{q1} \quad \delta_{q1}$

Fit result

$$\text{TMD region}: z < 0.7, P_{h\perp}^2 < 0.3, \frac{P_{h\perp}}{Qz} < 0.5$$



chi2/dof = **1.275**

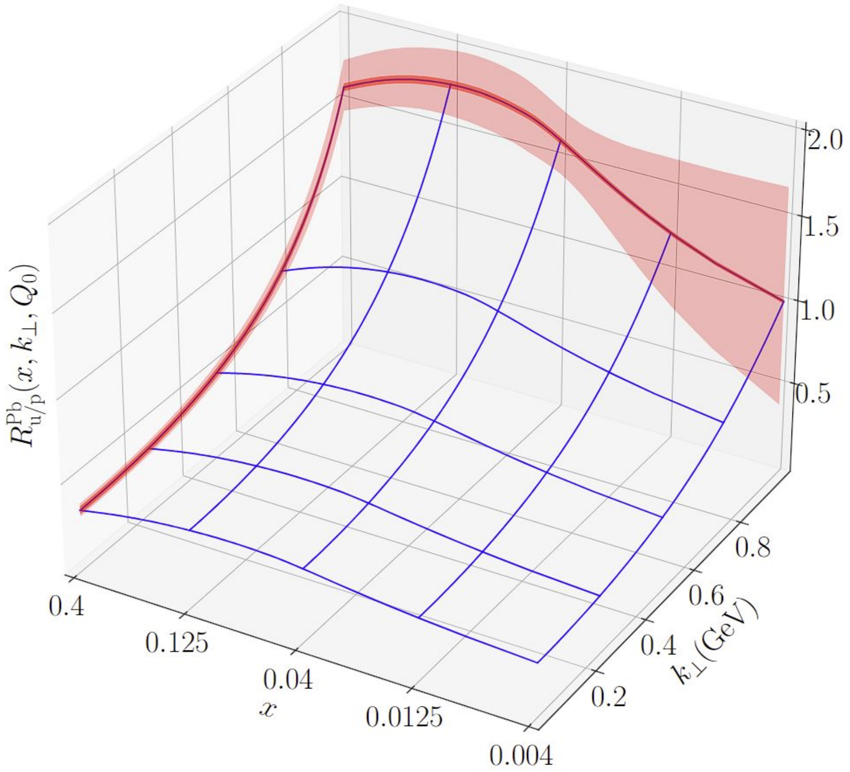
Collaboration	Process	Baseline	Nuclei	N_{data}	χ^2
JLAB [49]	SIDIS(π)	D	C, Fe, Pb	36	41.7
HERMES [40]	SIDIS(π)	D	Ne, Kr, Xe	18	10.2
RHIC [43]	DY	p	Au	4	1.3
E772 [41]	DY	D	C, Fe, W	16	40.2
E866 [42]	DY	Be	Fe, W	28	20.6
CMS [63]	γ^*/Z	N/A	Pb	8	10.4
ATLAS [83]	γ^*/Z	N/A	Pb	7	13.3
Total				117	137.8

$N_{q1} = 0.256^{+1.07}_{-0.194}$	$\gamma_{q1} = 0.006^{+0.727}_{-0.873}$	$\delta_{q1} = 0.184^{+0.883}_{-0.340}$
$N_{q2} = 0.156^{+0.137}_{-0.0906}$	$\gamma_{q2} = 1.150^{+0.334}_{-0.783}$	$\delta_{q2} = 0.474^{+0.144}_{-0.232}$
$\gamma = 2.200^{+0.135}_{-0.0925}$	$g_q^A = 0.440^{+0.0461}_{-0.0323}$	$g_h^A = 0.038^{+0.0157}_{-0.0150}$

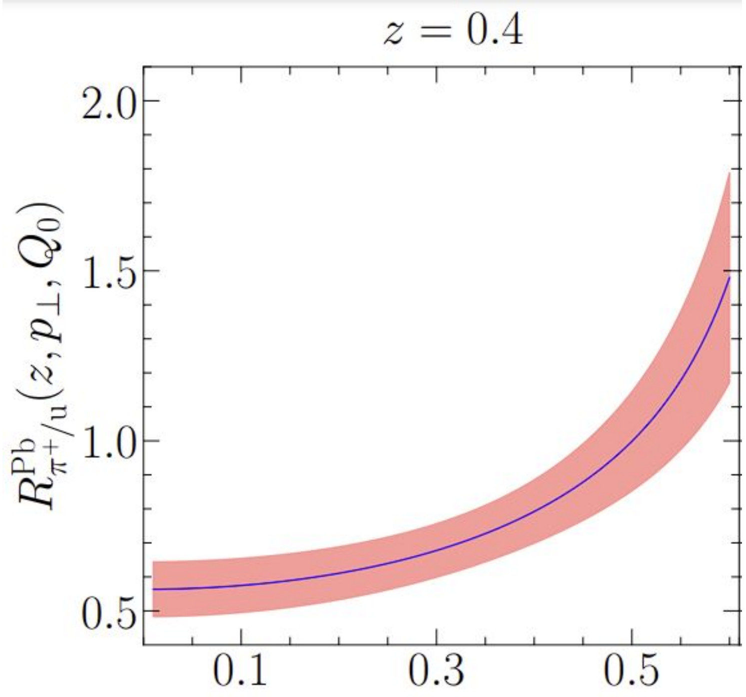
nTMDs ratio

TMDPDF

$$R^A(x, k_\perp, Q_0) = \frac{f^A(x, k_\perp, Q_0)}{f(x, k_\perp, Q_0)}$$



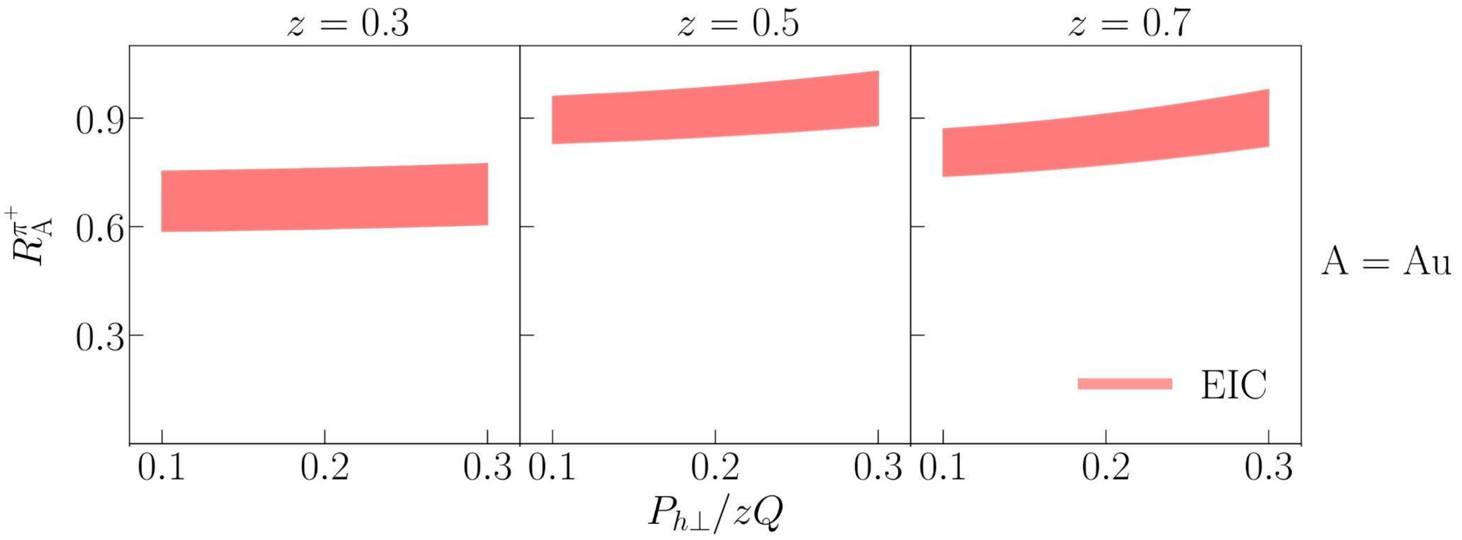
TMDFF



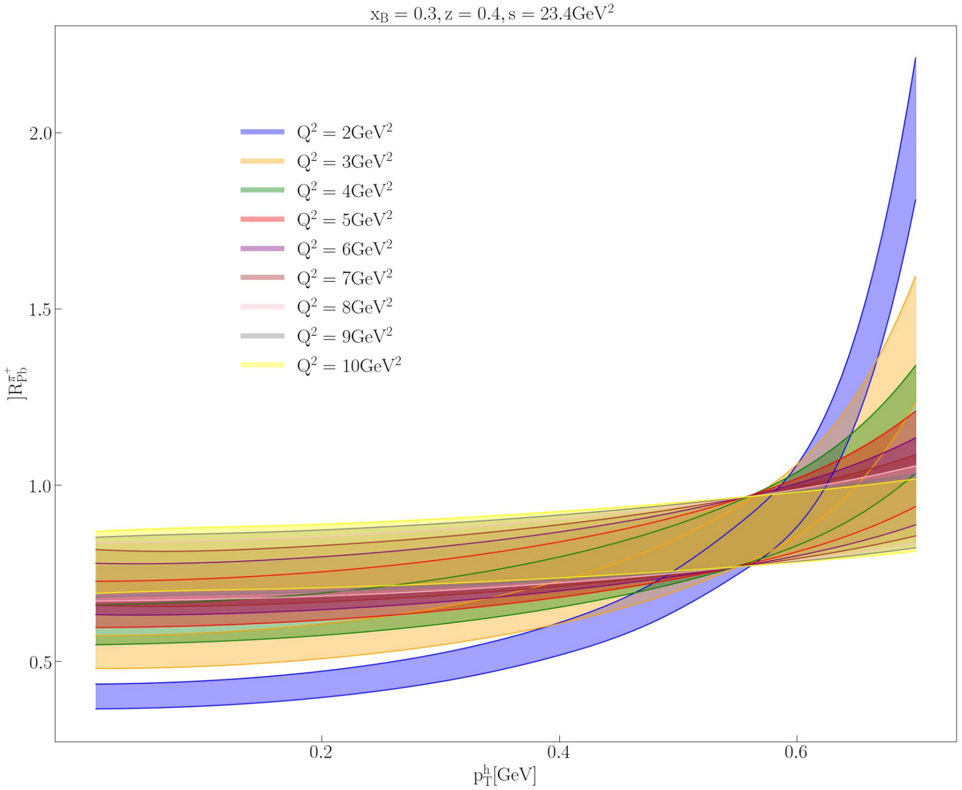
EIC prediction

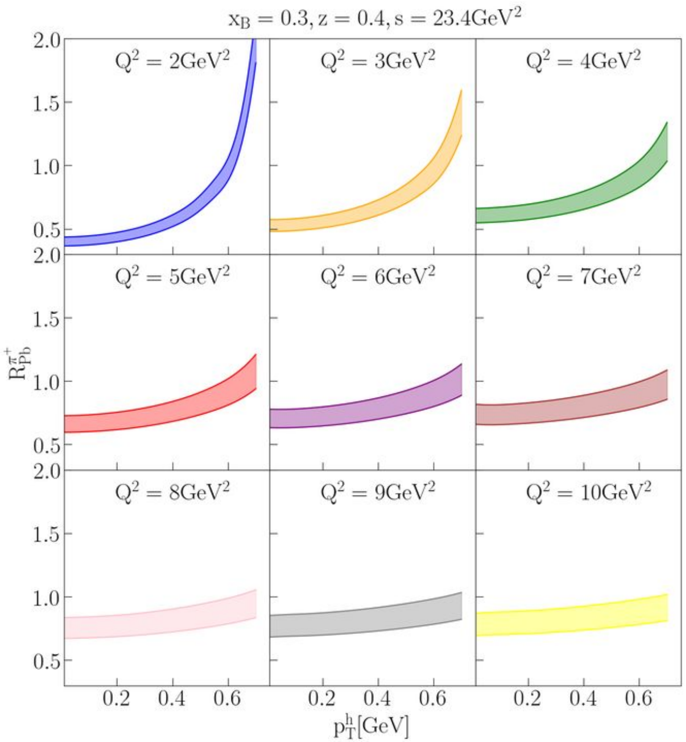
$$e^-(l) + N(P) \rightarrow e^-(l') + h(P_h) + X$$

x=0.1,Q^2=6.58 GeV^2, s = 328.832 GeV^2



JLab prediction





Summary

- Nuclear broadening can be described by nuclear modification to TMDs

$$S_f^{\mathrm{NP,\ A}}(b, Q; Q_0) = S_f^{\mathrm{NP}}(b, Q; Q_0) + a_N(A^{\frac{1}{3}} - 1)b^2$$

- Simultaneous description of Low Q JLab and HERMES SIDIS data can be achieved by the following Q dependent modification to TMDs

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

- This parameterization predicts a strong inverse relationship between nuclear broadening and Q

Thank you!

References

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