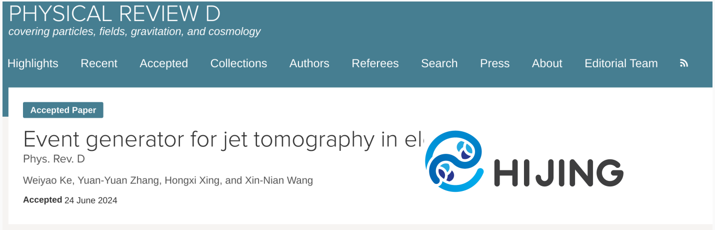
The eHIJING Event Generator for Jet Tomography in *eA*

The 4th EIC-ASIA Workshop, Fudan University, Shanghai, July 04, 2024

Weiyao Ke, Central China Normal University

Based on WK, Y. Zhang, H. Xing, X.-N. Wang 2304.10779 (accepted by PRD)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Accepted Paper

Event generator for jet tomography in el

Phys. Rev. D

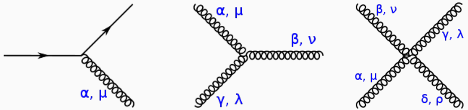
Weiyao Ke, Yuan-Yuan Zhang, Hongxi Xing, and Xin-Nian Wang

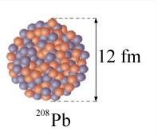
Accepted 24 June 2024

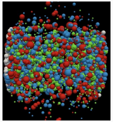
HIJING

Collider study of nuclear matter

- How can the perturbative understanding at short distances help the study of strongly-coupled & many body systems at large distances.



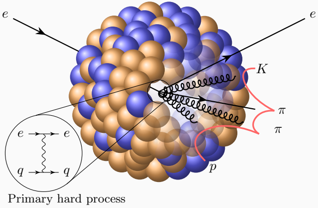




- For example, one utilizes hadron produced at small p_T in SIDIS (TMD region) to learn the partonic motion inside proton.

$$\frac{d\sigma_{e+p\to h+X}}{dxdydzd^2\mathbf{p}_T} = \frac{4\pi\alpha_{\rm em}^2}{Q^2}\frac{1+(1-y)^2}{y}\sum_q e_q^2 H_{qq}(Q^2,\mu)$$

$$\int \frac{d^2\mathbf{b}}{(2\pi)^2} e^{i\mathbf{b}\cdot\mathbf{p}_T}\tilde{f}_{q/p}(x,b,\mu,\frac{\zeta_1}{\nu^2})\tilde{D}_{h/q}(z,b,\mu,\frac{\zeta_2}{\nu^2})$$

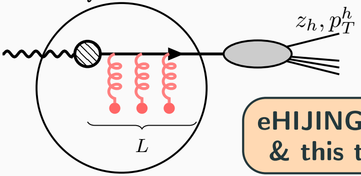


- From proton to a nucleus, what changes in $\tilde{f}_{q/p}$ and $\tilde{D}_{h/q}$. Are there any novel corrections?

Two limiting pictures of DIS with nucleus

Hard vertex localized to 1–2 nucleons

$$\frac{\nu}{Q^2} \ll L \sim r_0 A^{1/3}\,, \quad \text{or } x_B \gg \frac{0.1}{A^{1/3}}$$



eHIJING 1.0 & this talk

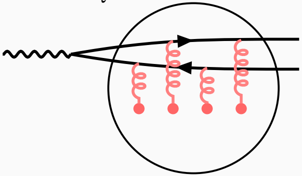
Tomography region

- How are parton structures of nucleons modified in nuclear environment.
- Partonic and hadronic transport phenomena in the cold nuclear matter.

$$\text{Modifications} = \text{Nucleon properties} \otimes \text{in-medium dynamics}$$

Coherent interactions with whole brick

$$\frac{\nu}{Q^2} \gg r_0 A^{1/3}\,, \quad \text{or } x_B \ll \frac{0.1}{A^{1/3}}$$



Small-x region

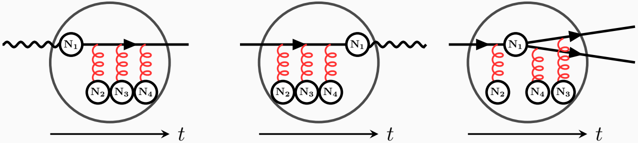
- Dipole approximation $\gamma^* + A \approx q + \bar{q} + A$.
- Dynamical generated scale (Q_s) becomes dominant. Interactions reveal gluonic dynamics of the nucleus.

The jet transport phenomena and Monte Carlo studies

- From a coarse-graining point of view, jet transport parameter $\hat{q}$ is a most direct quantification of the in-medium dynamics of parton:

$$\hat{q}_R = \frac{d\langle \Delta p_T^2 \rangle}{dL} \xrightarrow[\text{dilute medium}]{\text{weakly-coupled}} \sum_T \rho_T \int \mathbf{q}^2 \frac{d\sigma_{RT}}{d^2\mathbf{q}} d^2\mathbf{q}$$

- Determining the cold nuclear matter $\hat{q}_R$ facilitates many studies with a nuclear target.



$eA \to h + X$ $\quad pA \to \gamma^* + X$ $\quad pA \to h + X$

- Direct calculations of observables with medium effects is hard but under rapid developments. In many cases, Monte Carlo approach is still the only option for phenomenology.

The Outline

eHIJING generator for *eA* in the jet tomography region

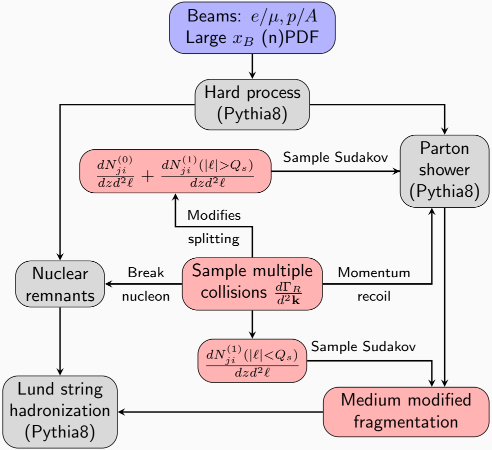
Comparison to SIDIS data

Known problems & future plan

eHIJING generator for *eA* in the jet tomography region

The eHIJING event generator 1.0

Electron-Heavy-Ion-Jet-INteraction-Generator a completely different (c++ & Pythia8) program from HIJING (fortran & Pythia6) in the heavy-ion community.

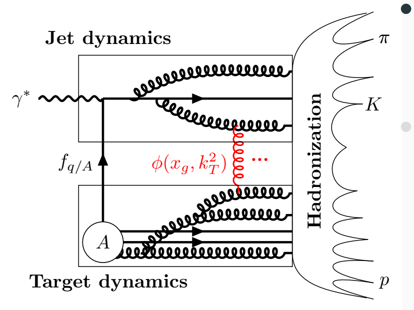


- **Almost the same** *ep* physics as Pythia8235.
- Multiple forward scatterings between jet partons and the cold nuclear medium.
- Nucleon remnants from multiple collisions.
- Modified parton shower algorithm with inputs from (generalized) higher-twist calculations.
- Lund string hadronization.

Forward scattering between jet parton and the target

- The differential scattering probability is proportional to the area density of nucleon ($\rho_N L$) times the differential cross-section

$$\frac{dP}{d^2\mathbf{k}} = \rho_N L \sum_T f_T \frac{d\sigma_{RT}}{d^2\mathbf{k}} \equiv \rho_N L \frac{C_R}{d_A} \frac{\alpha_s \phi_g(x_g, \mathbf{k})}{\mathbf{k}^2} \Theta(\mathbf{k} > \mathbf{k}_{T,\min})$$



- It is then related to the unintegrated gluon distribution function $\phi_g(x_g, \mathbf{k})$ J. Casalderrey-Solana, X.-N. Wang PRC77(2008)024902.
- EHIJING1.0 omits target dynamics and parametrize $\phi_g(x, \mathbf{k})$ with a saturation-motivated model KLN, NPB 594(2001)371.

$$\alpha_s \phi_g(x_g, \mathbf{k}) = K \frac{x_g^\lambda (1 - x_g)^n}{\mathbf{k}^2 + Q_s^2(x_g, Q^2)}, \quad x_g = \frac{\mathbf{k}^2}{Q^2} x_B$$

with self-consistent condition $Q_s^2 = \int \mathbf{k}^2 \frac{dP}{d^2\mathbf{k}} d^2\mathbf{k} \equiv \hat{q}_A L$

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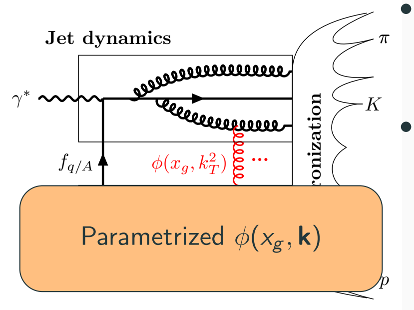

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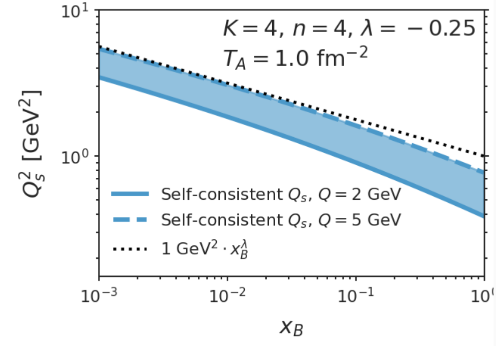
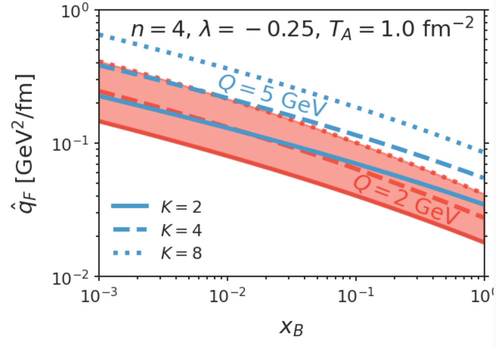
Jet transport parameter and the "screening scale" Q_s

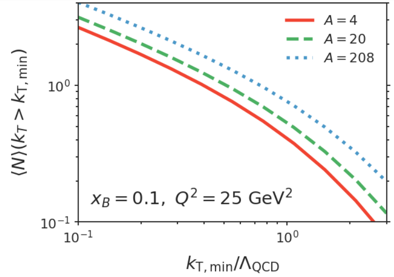




- Values of $n=4$ and $\lambda=-0.25$ taken the same as the original KLN model.
- Consider the tomography region of a nucleus $A\sim 100$, $x_B \gg 0.1/A^{1/3} \approx 0.02$. Q_s remains small compared to $Q \gg 1$ GeV.
- The range of K result in a $\hat{q}_F$ comparable to other phenomenological extractions.

Poisson sampling of multiple collisions

$\langle N \rangle$ as function of A & IR cut off.

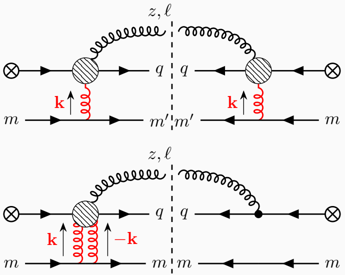


- The average number of multiple collisions $\langle N \rangle = \int \frac{dP}{d^2\mathbf{k}} d^2\mathbf{k}$.
- The number of collisions follows a Poisson distribution

$$P_N = \frac{\langle N \rangle^N}{N!} e^{-\langle N \rangle}$$

- The x^+ coordinate of the collision center is uniformly sampled on $[0, L^+]$, the transverse position aligns with the impact parameter **b**.
- **k** of each collision is sampled according to $\frac{dP}{d^2\mathbf{k}}$, which determines $k^- = x_g P_N^-$. k^+ is determined by the on-shell condition of the recoiled target parton.

Higher-twist splitting function



Multiple scattering induce additional radiative corrections.

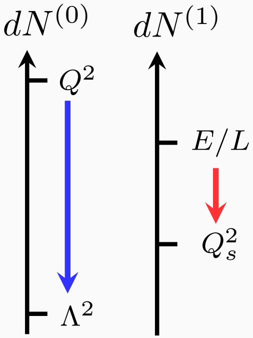
- For a thin medium, it can be analyzed in a twist expansion. A recent calculation at (generalized) twist-4, Y.-Y. Zhang, X.-N. Wang, PRD105(2022)034015
- eHIJING 1.0 only implements leading-nuclear-size (L^+) terms at (generalized) twist-4 in the soft-gluon limit ▽

$$\frac{d}{dzd^2\ell}\begin{Bmatrix} N_{gq}^{\mathrm{GHT}} \\ N_{gg}^{\mathrm{GHT}} \end{Bmatrix} = \begin{Bmatrix} P_{gq}^0(z) \\ P_{gg}^0(z) \end{Bmatrix} \left[\frac{1}{\ell^2} + \frac{1}{\ell^2}\rho_N L \int_0^{Q^2/x_B} \frac{C_A}{d_A}\frac{\alpha_s \phi_g(x_g, \mathbf{k}^2)}{\mathbf{k}^2}\frac{2\mathbf{k}\cdot\ell}{(\ell-\mathbf{k})^2}\left(1 - \frac{\sin(L^+/\tau_f)}{L^+/\tau_f}\right) d^2\mathbf{k}\right]$$

$$\tau_f = \frac{2x(1-x)p^+}{(\ell-\mathbf{k})^2} \quad \text{the radiation formation time}$$

- In earlier literature, the HT formula is further simplified assuming $\mathbf{k} \ll \ell$ under the integral. This is also implemented in eHIJING for comparison.

Medium-modified parton shower



The medium-induced functions contains multiple scales: p^+/L^+ and Q_s^2.

- Virtuality (k_T) ordered parton shower. Vacuum emissions between $\Lambda^2 < \ell^2 < Q^2$ + induced emissions between $Q_s^2 < \ell^2 < p^+/L^+$.
- Multiple branchings sampled using the inverse of Sudakov form factor

$$r = e^{-\langle N_{ji}(\ell_2,\ell_1)\rangle}, \quad r \sim U(0,1)$$

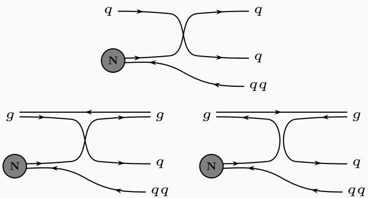
$$\langle N_{ji}(\ell_2,\ell_1)\rangle = \int_{z_{\min}(\ell_m)}^{z_{\max}(\ell_m)} dz \int_{\ell_2^2}^{\ell_1^2} d^2\ell \left[\frac{dN^{(0)}}{dzd^2\ell} + \frac{dN^{(1)}}{dzd^2\ell}\Theta(Q_s^2 < \ell^2)\right]$$

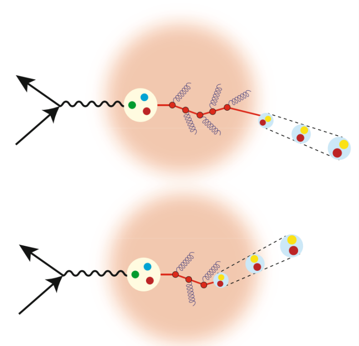
- Medium-induced radiations between $\Lambda^2 < \ell^2 < Q_s^2$ no longer gives large logs of energy scales. Multiple emissions are ordered in formation time.

$$r = e^{-\langle N_{ji}^{(1)}\rangle(\tau_2,\tau_1)}, \quad r \sim U(0,1)$$

$$\langle N_{ji}^{(1))}\rangle(\tau_2,\tau_1) = \int_{\Lambda^2}^{Q_s^2} \frac{d^2\ell}{\ell^2} \int_0^1 dz \frac{dN_{ji}^{(1)}}{dzd^2\ell}\Theta\left(\tau_1 < \tau_f < \tau_2\right).$$

Lund string hadronization with jet-medium interactions



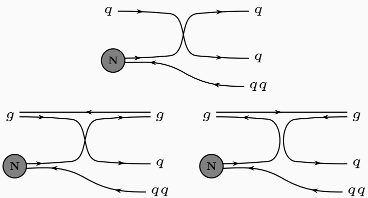


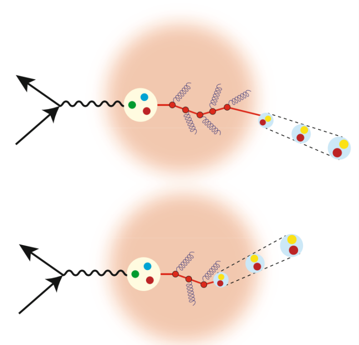
- Assume vacuum-like hadronization mechanism at a large hadron formation time

$$\tau_h = \frac{z_h \nu}{m_h} \frac{1}{\Lambda} \gg L$$

- Color exchanges of multiple scatterings implemented at the end of shower.
- Medium recoiled system is modeled by a quark + diquark.
- Apply Lund string fragmentation to the whole system of parton shower + remnant.
- Ongoing test to include hadronic transport for $\tau_h < L$ (from LBL & UIUC Collaborators)

Lund string hadronization with jet-medium interactions





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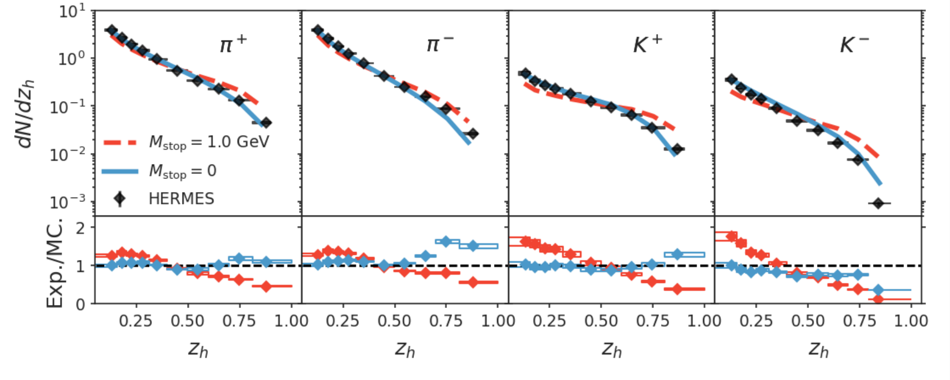
Comparison to SIDIS data

SIDIS in *ep*

$$\frac{dN_h}{dz_h} = \frac{d\sigma_{ep\to h+X}/dz_h}{\sigma_{ep}}$$

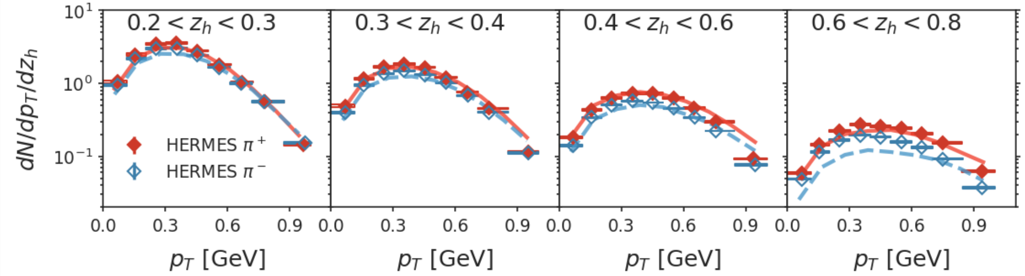
One of the default hadronization parameter in Pythia8 is changed to better described the z_h dependence.



SIDIS in *ep*

$$\frac{dN_h}{dz_h dp_T} = \frac{d\sigma_{ep\to h+X}/dz_h/dp_T}{\sigma_{ep}}$$

Good agreement in the TMD region of the p_T spectra.
But there are known problems for $p_T \gtrsim 1.5$ GeV.



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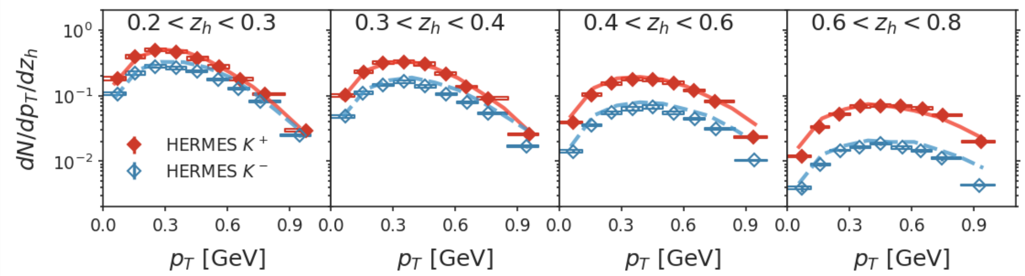
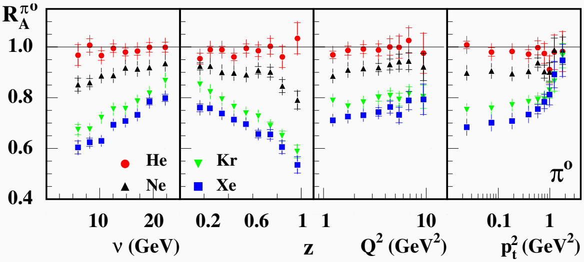


From ep to eA, the nuclear modification factor



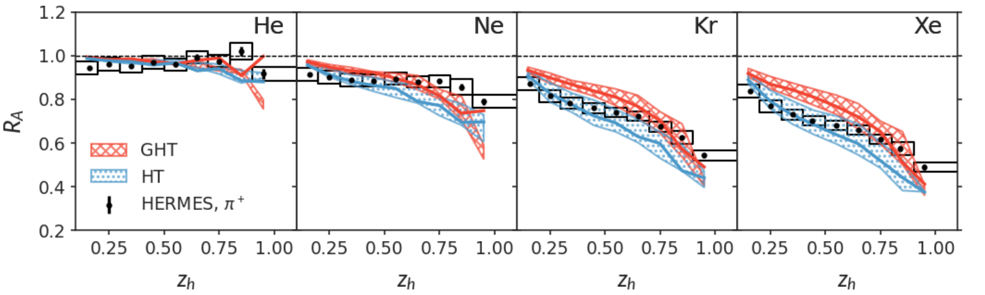
$$R_A = \frac{N_{eA\to\pi^0}(z_h, p_T^2; \nu, Q^2)}{N_{ed\to\pi^0}(z_h, p_T^2; \nu, Q^2)}$$

$$N_{eA\to\pi^0} = \frac{d\sigma_{eA\to\pi^0}}{d\nu dQ^2 dz_h dp_T^2} \Big/ \frac{d\sigma_{eA}}{d\nu dQ^2}$$

HERMES, NPB 780(2007)1-27

- R_A is defined as the ratio of the inclusive-normalized SIDIS cross-section.
- The inclusive normalization largely cancels collinear nuclear PDF effects.
  The normalization cannot cancel TMD nuclear PDF effects.
  eHIJING 1.0 uses empirical collinear nPDF without TMD nPDF modifications.

Modifications of the collinear distribution of hadrons in eA



HERMES, NPB 780(2007)1-27 $\langle Q^2 \rangle \approx$ 2-2.5 GeV^2.

- R_A is suppressed at large z_h as expected from the parton energy loss in matter.
- The systemic dependence on nuclear size is reproduced.
- With the same input on $\phi_g(x_g, \mathbf{k})$, the HT formula in past literature X.-f. Guo, E. Wang, X.-N. Wang, et al results in a larger suppression than the generalized HT (GHT) result Y.-Y. Zhang, G.-Y. Qin, X.-N. Wang. Cause of difference is also well understood now 2304.10779.

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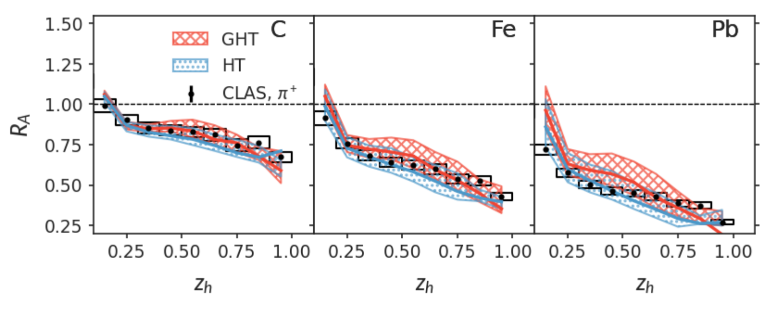

CLAS PRC105(2022)015201

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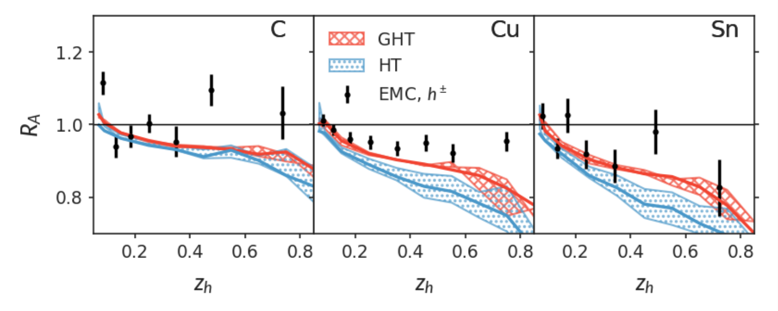

EMC ZPC52(1991)1 $\langle Q^2 \rangle \approx$ 10-12 GeV^2.

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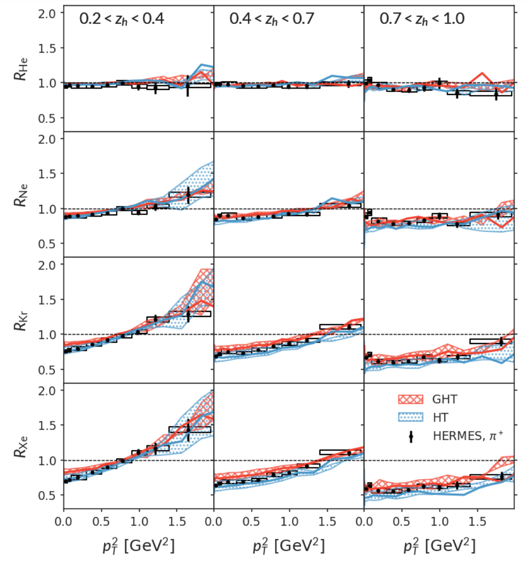
The TMD $R_A(z_h, p_T)$



HERMES, NPB 780(2007)1-27

- Modifications of the double differential spectra $dN/dz/dp_T$ are reproduced with the final-state medium effects.
- Note that TMD nPDF effects can also contribute to $R_A(p_T) \neq 1$ but this effect is not included in eHIJING 1.0.

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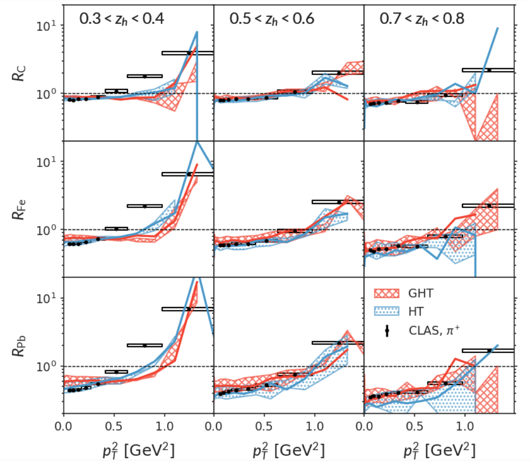

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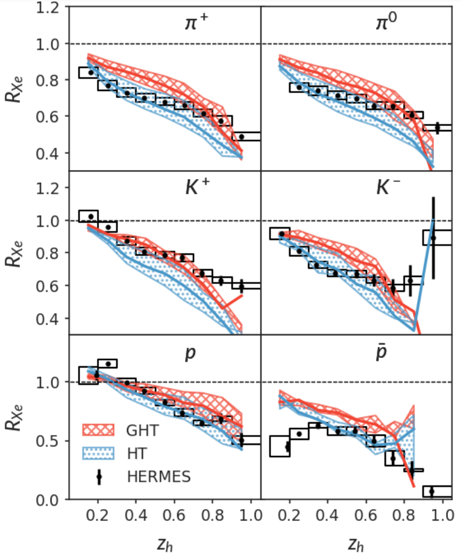
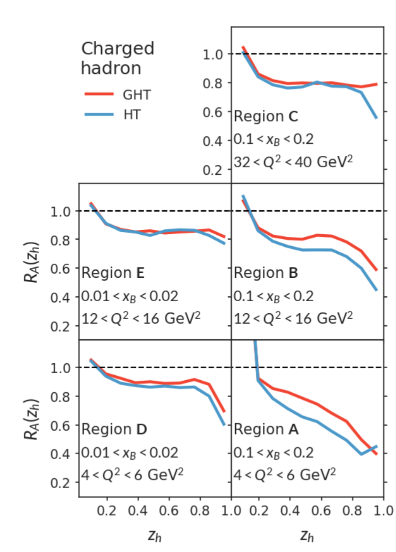
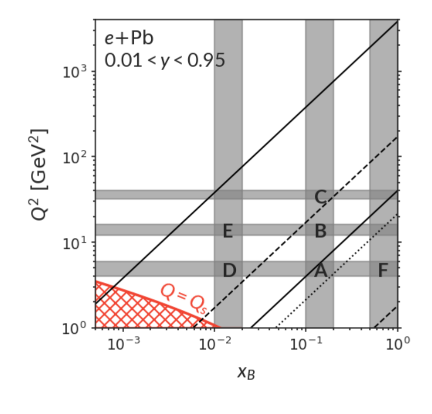
Flavor dependence



- Flavor dependence of R_A qualitatively captured.
- Clearly difference of R_A between K^+ and K^-, and between p and $\bar{p}$. Not capture by eHIJING 1.0.
- Possible reason 1: missing medium-induced flavor excitation and flavor conversion.
- Possible reason 2: missing hadronic interactions. Especially important for proton and low z_h hadrons.

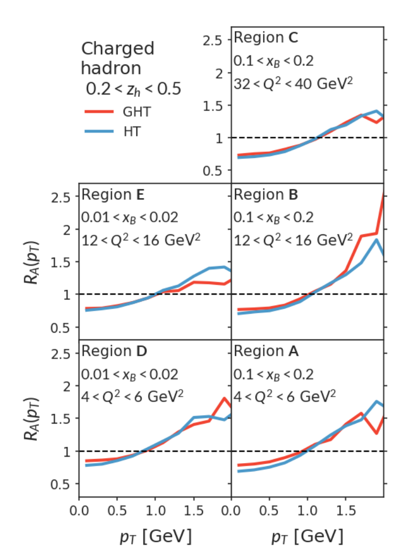
Projection for EIC/EicC

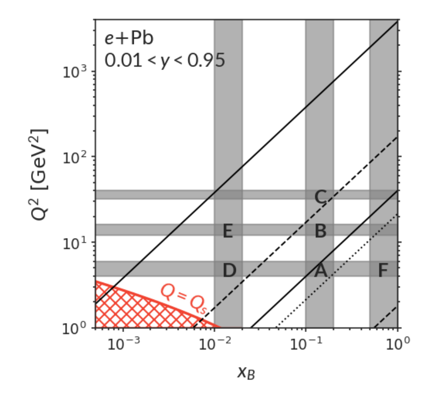




- Regions at various x_B and Q^2 with $Q \gg Q_s$.
- A highly differential test of the Q^2 and $\nu = Q^2/2x_B m_N$ dependence of the cold nuclear matter effects.

Projection for EIC/EicC





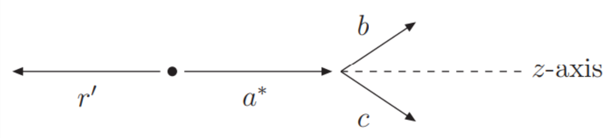
- Regions at various x_B and Q^2 with $Q \gg Q_s$.
- A highly differential test of the Q^2 and $\nu = Q^2/2x_B m_N$ dependence of the cold nuclear matter effects.

Known problems & future plan

Global recoil versus dipole recoil schemes

A subtle but important issue as pointed out by one of the referees.

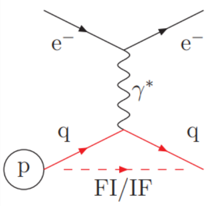
- In the parton branching program, the four-momentum conservation cannot be fulfilled by the generic $p_a \to p_b + p_c$ splitting with on-shell conditions for a, b, c.
- A recoiler system p_r is added such that $p_a + p_r = p_a^* + p_r' = p_b + p_c + p_r'$ is always satisfied.



B.Cabouat, TSjöstrand EPJC78(2018)226

Global recoil versus dipole recoil schemes

- **Global recoil** : recoil system is the rest of the event. Not used by default Pythia8 DIS mode $\Longrightarrow$ because it affects triggering of hard events $Q^2 = -(p_e - p'_e)^2$.
- **Dipole recoil**: the recoiler is the parton that form the color dipole with parton *a* before the branching. In DIS, the color dipole stretch from initial to final-state.



- FI: radiator in the final state, recoiler in the initial state.
- IF: radiator in the initial state, recoiler in the final state.
- Pythia8 default DIS mode only uses IF type radiation.
  Because it already reproduces the matrix-element calculations!
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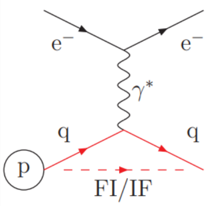

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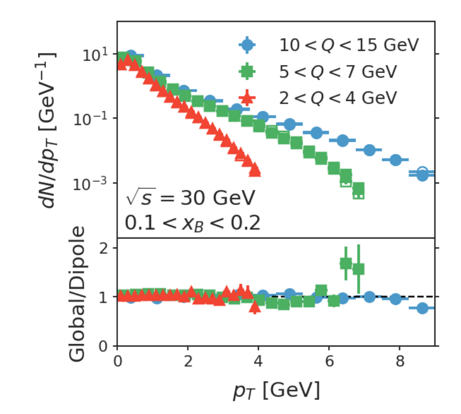
eHIJING 1.0 uses the non-standard global recoil. We **cannot directly use dipole recoil**, because in $P(z) = P^{\text{vac}}(z) + P^{\text{med}}(z)$, medium-induced radiation is a final-state effect.
A lot more technical problems to be solved!

What is the impact of using Global recoil

Drawback of using global recoil in DIS event generations:

- Q^2 can be changed by recoil. Should be negligible at large Q^2.
- The direction of virtual photon is affected by recoil ⇒ may affect TMD observable!



- In the lab frame, the difference between global/dipole recoil is small. Because p_T is dominated by the hard scattering.
- In the Breit frame, evident discrepancy between different recoiling scheme beyond $p_T = 1$-2 GeV.

> Be careful when interpreting nuclaer modifications at large $p_{T,\mathrm{Breit}}$ in EHIJING 1.0.

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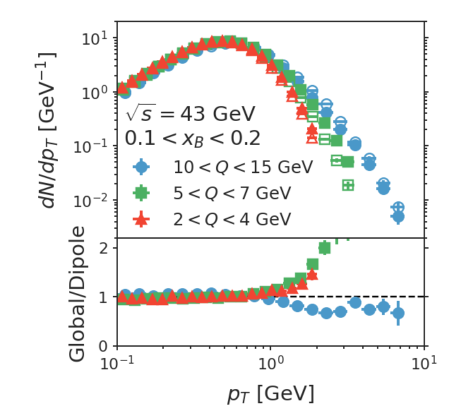

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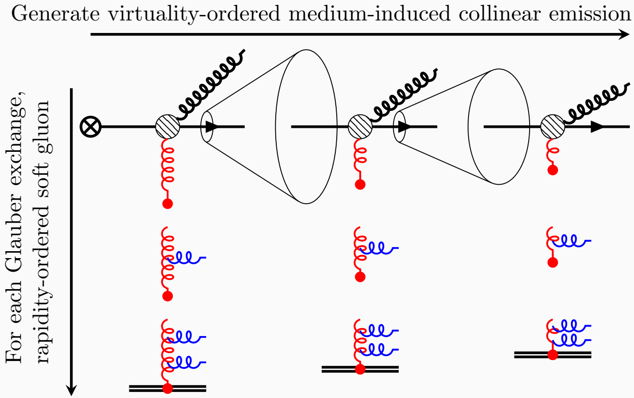
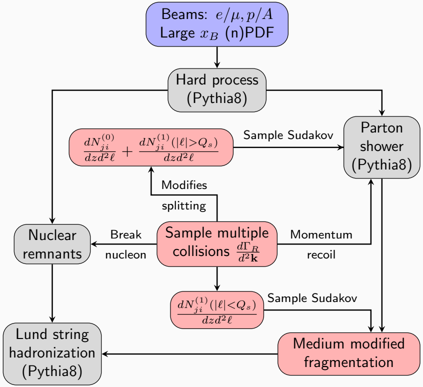
From a parametrized $\phi_g(x_g, k)$ to a dynamical target



- EHIJING 1.0 only consider the dynamics of the jet parton (multiple collisions + induced radiations).
- Recent works suggest that jet-medium scattering are renormalized by soft gluon emissions as described by BFKL. Varun Vaidya 2020, 2021. WK, I Vitev, in preparation.
- It is possible to include such dynamics into the event generation.

Summary and prospects



- The first publication of eHIJING 1.0. Aims at DIS in the tomography region.
- The physics: multiple collisions, modified splitting functions and parton shower, Lund string hadronization.
- Systematic comparison to SIDIS data at EMC, HERMES, and CLAS, with projects at EIC and EicC.
- Known problems with gloabl recoil in DIS. Lack target dynamics and hadronic interactions. A lot works & opportunities ahead.
- Collaboration with SDU to interpolate event generation from tomography region to small -x region.

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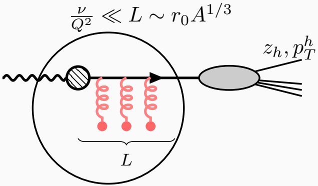

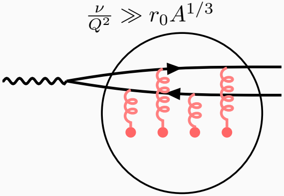

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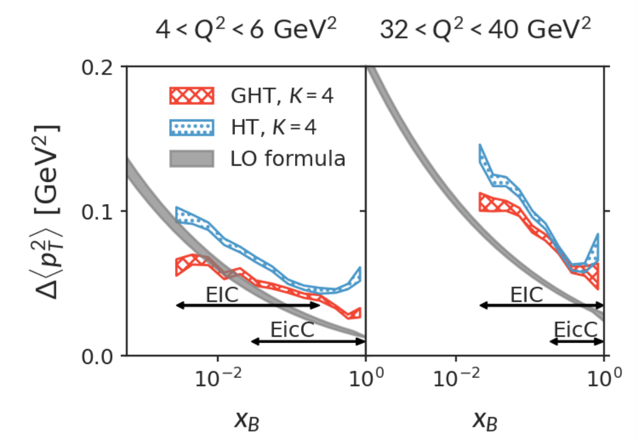
Questions

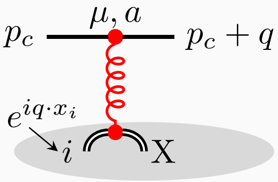
Projection for EIC/EicC: $\Delta\langle p_T^2\rangle$



A crude estimate of radiative broadening effect to $\Delta\langle p_T^2\rangle$.

Introduce parton-medium interactions

- Interaction of collinear jet partons and anti-collinear medium constituents mediated by Glauber gluon $q \sim (\lambda^2, \lambda^2, \lambda)E$



$$A_G^{a-}(q^-, \mathbf{q}) = ig_s \int dx^+ d^2\mathbf{x} \frac{ie^{iq^- x^+} e^{-i\mathbf{q}\cdot\mathbf{x}}}{\mathbf{q}^2 + \xi^2} J^{a-}(x^- = 0, x^+, \mathbf{x}).$$

- At the level of cross-section, take ensemble average of a color-neutral medium

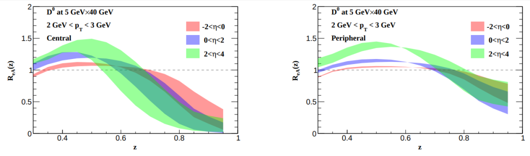
$$\int_{x,y} \langle\langle g_s A_G^a(q) e^{iq\cdot x} g_s A_G^b(k) e^{ik\cdot y} \rangle\rangle \propto \frac{\delta^{ab}\delta^{(2)}(\mathbf{k}+\mathbf{q})}{(\mathbf{q}^2+\xi^2)^2} \int dx^+ \rho_G(x^+) e^{i(q^- + k^-)x^+}$$

- In a weakly-coupled medium, $\rho_G = \sum_{T=F,A} g_s^2 \frac{C_T}{d_A} \rho_T$. ρ_T is medium color density.

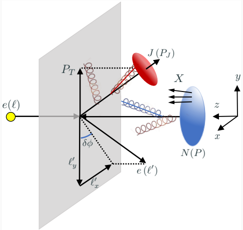
Things to look at in eHIJING

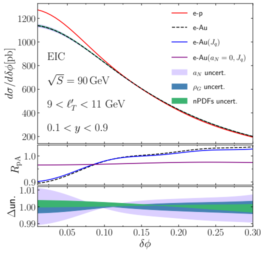
- Use target neutron emission to select on different path length of jet propagation in the cold nuclear matter Li, Liu Vitev, 2303.14201

Centrality	$0-1\%$	$0-3\ \%$	$0-10\ \%$	$60-100\ \%$	$80-100\ \%$	$90-100\ \%$	$0-100\ \%$
$\langle d\rangle[fm]$	9.09	8.48	7.61	2.88	2.71	2.71	4.40
$\langle d\rangle/\langle d\rangle_{\mathrm{min.bias}}$	2.07	1.93	1.73	0.65	0.62	0.62	1.00



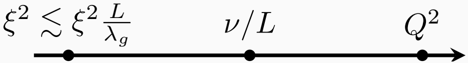
- Lepton-jet correlation (high precision *ep* baseline to study nuclear effects), Fang, Ke, Shao, Terry 2311.02150.



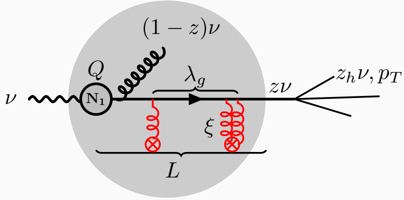


The ideal region for studying parton transport in matter

- Hard vertex is localized $\tau_H \sim \nu/Q^2 \ll L$ (large x_B).
- Hadronization outside the nucleus: $\tau_h \sim z_h\nu/\xi^2 \gg L$.
- Naturally set the scale sepration for an EFT



Semi-inclusive DIS in eA



⋆ To suppress hadronic final-state interactions, we want $z_h\nu \gg \xi^2 L \sim 3...4$ GeV for Pb.
Collider experiment has a larger ν, and is cleaner for studying partonic transport.