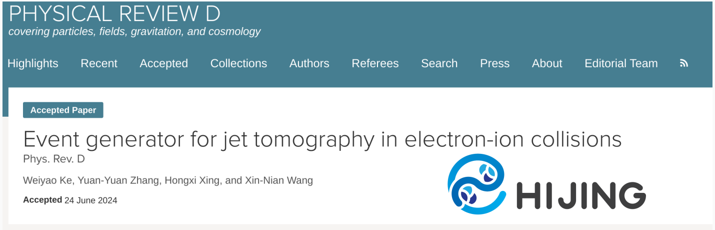
The eHIJING Event Generator for Jet Tomography in *eA*

EICUG Theory WG Meeting on Parton Showers, July 10, 2024 (online)

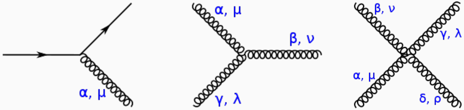
Weiyao Ke, Central China Normal University

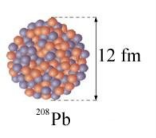
Based on WK, Y. Zhang, H. Xing, X.-N. Wang 2304.10779 (accepted by PRD)

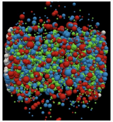


Collider study of nuclear matter & Monte Carlo models

- Utilize perturbative understanding at short distances to learn strongly-coupled & many body phenomena at large distances.







- For example, one can look at hadrons produced at small p_T in SIDIS to learn the partonic motion inside proton — the TMD region.

$$\frac{d\sigma_{e+p\to h+X}}{dxdydzd^2\mathbf{p}_T} = \frac{4\pi\alpha_{\rm em}^2}{Q^2}\frac{1+(1-y)^2}{y}\sum_q e_q^2 H_{qq}(Q^2,\mu)\int\frac{d^2\mathbf{b}}{(2\pi)^2}e^{i\mathbf{b}\cdot\mathbf{p}_T}\tilde{f}_{q/p}(x,b,\mu,\frac{\zeta_1}{\nu^2})\tilde{D}_{h/q}(z,b,\mu,\frac{\zeta_2}{\nu^2})$$

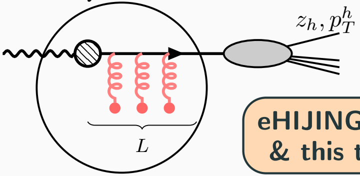
- With nuclear targets, some observables can be studied in *ep* framework in certain kinematics. Understanding of other phenomena still heavily relies on Monte-Carlo simulations and modeling.

Two limiting pictures of DIS with the nucleus

Tomography region

Hard vertex localized to 1–2 nucleons

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

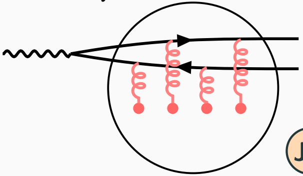


eHIJING 1.0 & this talk

Small-x region

Coherent interactions with whole brick

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

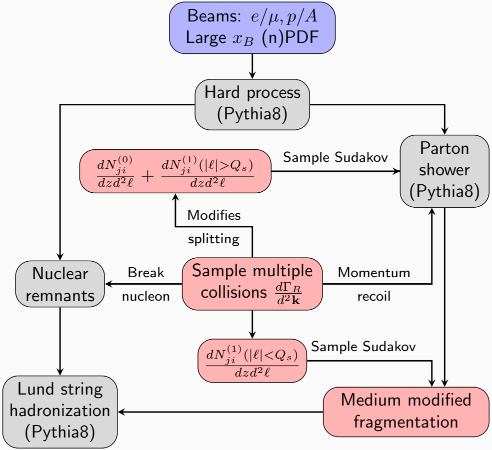


J. Zhou's talk

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.

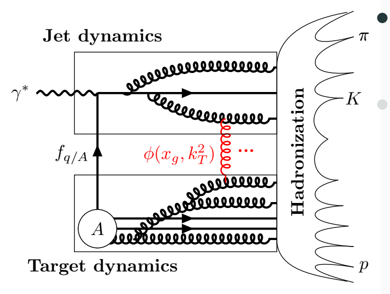


- **Almost the same** *ep* physics as Pythia8235.
- Multiple forward scatterings between jet partons and the cold nuclear medium.
- Nucleon remnants from multiple collisions.
- Modified parton shower algorithm with inputs from (generalized) higher-twist calculations.
- Lund string hadronization.

Forward scattering between jet parton and the target

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

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



- It is related to the unintegrated gluon distribution $\phi_g(x_g, \mathbf{k})$ of the matter J. Casalderrey-Solana, X.-N. Wang PRC77(2008)024902.
- EHIJING1.0 omits target dynamics and parametrize $\phi_g(x, \mathbf{k})$

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

The form is motivated by the saturation KLN model NPB594(2001)371 + self-consistent condition $Q_s^2 = \int \mathbf{k}^2 \frac{dP}{d^2\mathbf{k}} d^2\mathbf{k}$

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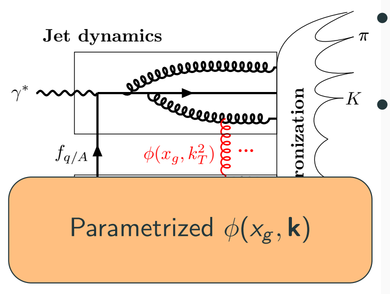

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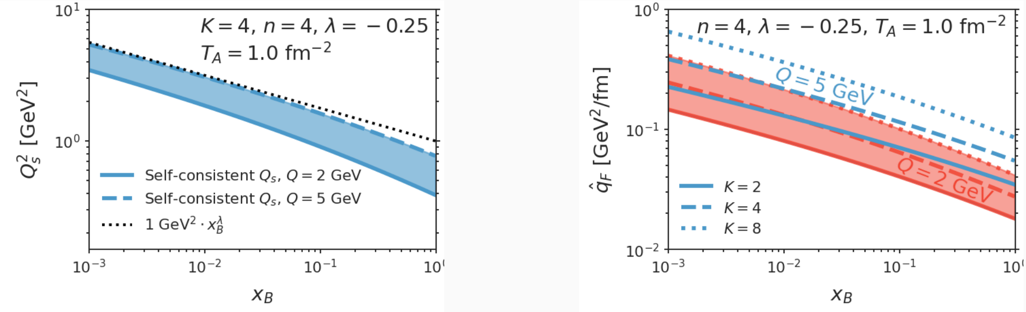
The "screening scale" Q_s and the jet transport parameter

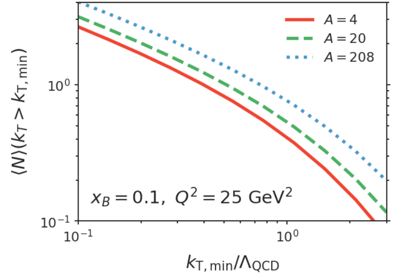


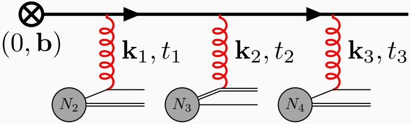
- $n = 4$ and $\lambda = -0.25$, same values as the KLN model NPB594(2001)371.
- The jet transport parameter $\hat{q}$ is directly related to Q_s

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

Poisson sampling of multiple collisions

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





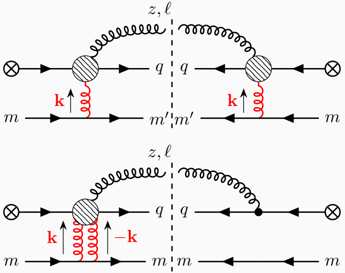
- The number of collisions follows a Poisson distribution

$$P(N) = \frac{\langle N \rangle^N}{N!} e^{-\langle N \rangle}$$

$$\langle N \rangle = \int \frac{dP}{d^2\mathbf{k}} d^2\mathbf{k}$$

- The time of the collision is uniformly sampled in $[0, L]$, the transverse position is the same as impact parameter **b**.
- **k** of each collision is sampled according to $\frac{dP}{d^2\mathbf{k}}$. k^+, k^- determined by on-shell conditions of the jet parton and the target parton.

Multiple scattering $\Longrightarrow$ additional radiative corrections.



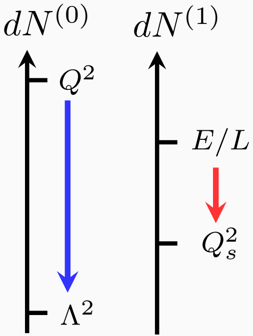
- For a thin medium, radiative correction can be organized in a twist expansion. A recent calculation at (generalized) twist-4, Y.-Y. Zhang, X.-N. Wang, PRD105(2022)034015
- eHIJING 1.0 only implements leading-nuclear-size (L^+) terms at (generalized) twist-4 in the soft-gluon limit ∇

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

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

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

Medium-modified parton shower



- Virtuality (ℓ_T) ordered parton shower. Large logs can come from: 1) vacuum emissions between $\Lambda^2 < \ell^2 < Q^2$. 2) induced emissions between $Q_s^2 < \ell^2 < p^+/L^+$ WK, I Vitev PLB854(2024)138751
- Multiple emissions sampled by inverting the Sudakov form factor

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

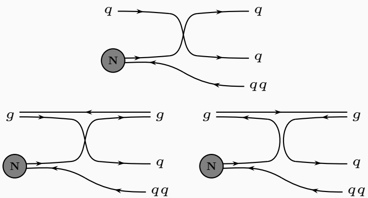
$$\langle N_{ji}(\ell_2,\ell_1)\rangle = \int_{z_{\min}(\ell_m)}^{z_{\max}(\ell_m)} dz \int_{\ell^2{}_2}^{\ell^2{}_1} d^2\ell \left[\frac{dN^{(0)}}{dzd^2\ell} + \frac{dN^{(1)}}{dzd^2\ell}\Theta(Q_s^2 < \ell^2)\right]$$

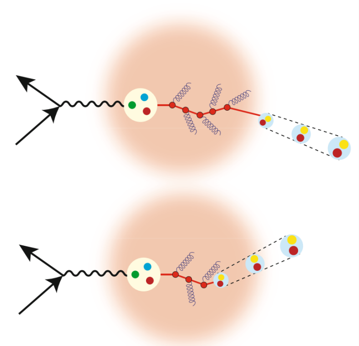
- Medium-induced radiations between $\Lambda^2 < \ell^2 < Q_s^2$ no longer gives large logs of energy scales. Multiple emissions are ordered in formation time.

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

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

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)

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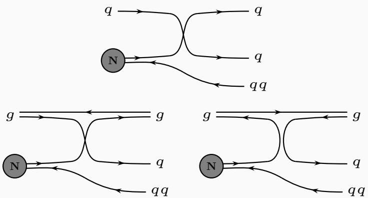

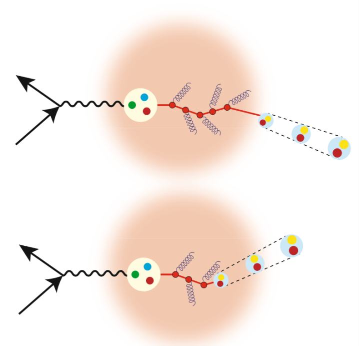

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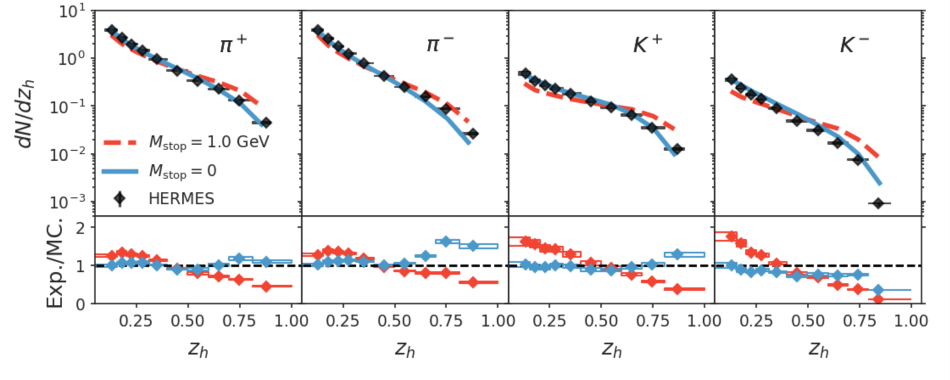
Comparison to SIDIS data

SIDIS in ep

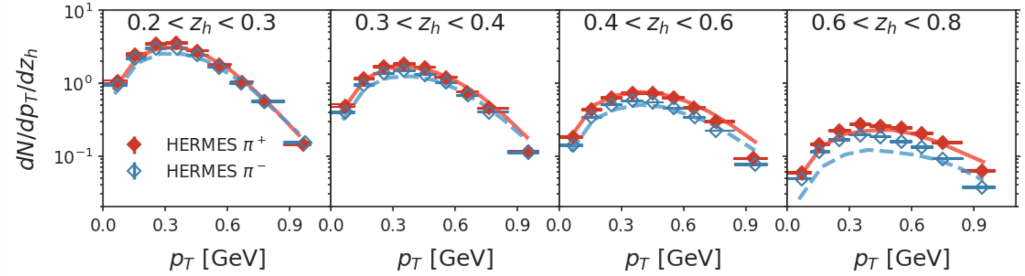
$$\frac{dN_h}{dz_h} = \frac{d\sigma_{ep\to h+X}/dz_h}{\sigma_{ep}}$$

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



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

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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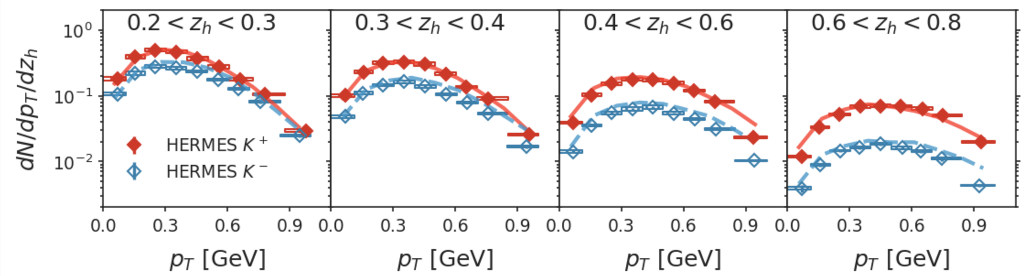
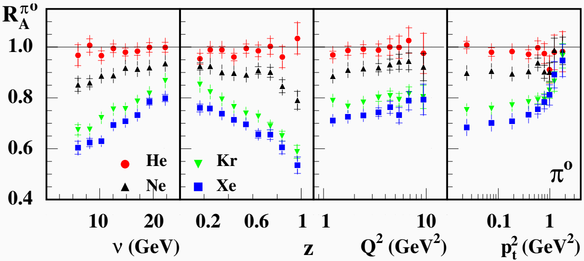


From *ep* to *eA* and the nuclear modification factor



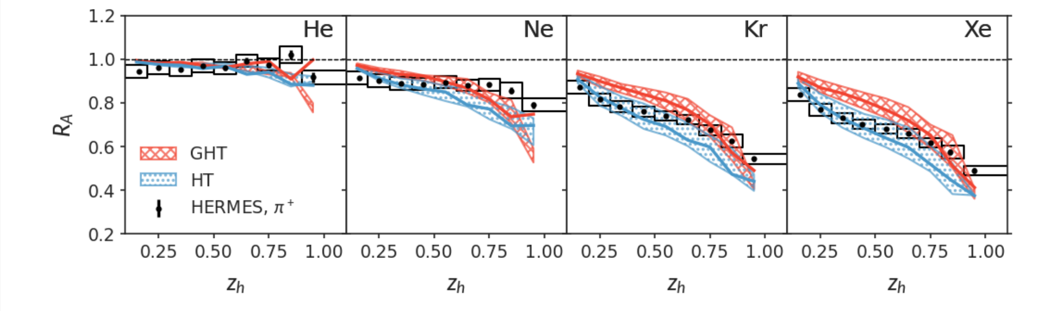
$$R_A = \frac{N_{eA\to\pi^0}(z_h, p_T^2; \nu, Q^2)}{N_{ed\to\pi^0}(z_h, p_T^2; \nu, Q^2)}$$

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

HERMES, NPB 780(2007)1-27

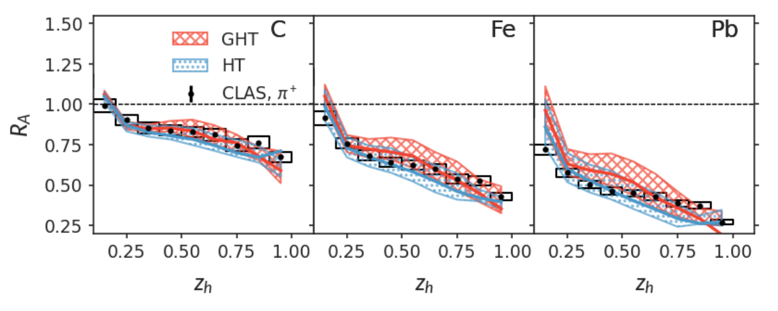
- R_A is defined as the ratio of the inclusive-normalized SIDIS cross-section.
- The inclusive normalization largely cancels collinear nuclear PDF effects.
  The normalization cannot cancel TMD nuclear PDF effects.
  eHIJING 1.0 uses empirical collinear nPDF without TMD nPDF modifications.

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.



CLAS PRC105(2022)015201

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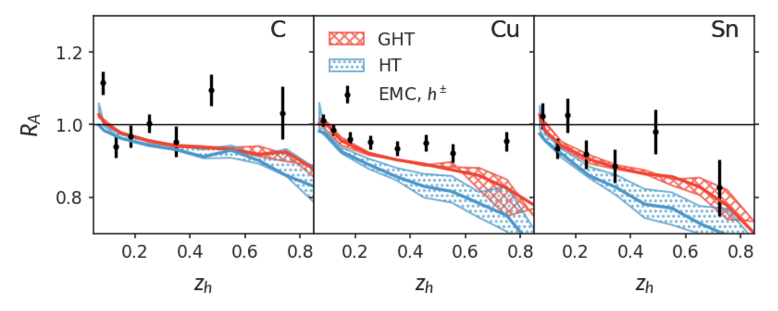

EMC ZPC52(1991)1 $\langle Q^2 \rangle \approx$ 10-12 GeV^2.

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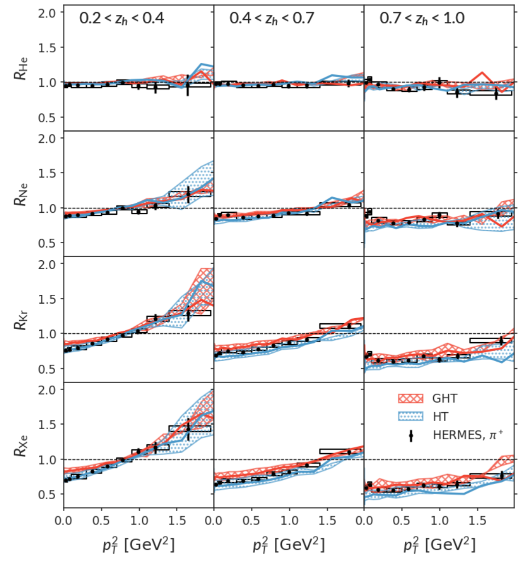
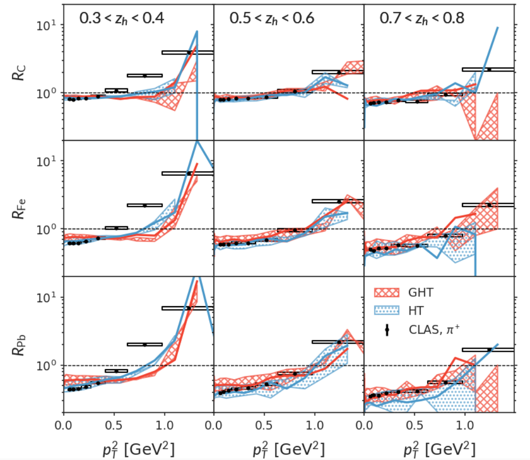
The TMD $R_A(z_h, p_T)$



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.

The TMD $R_A(z_h, p_T)$



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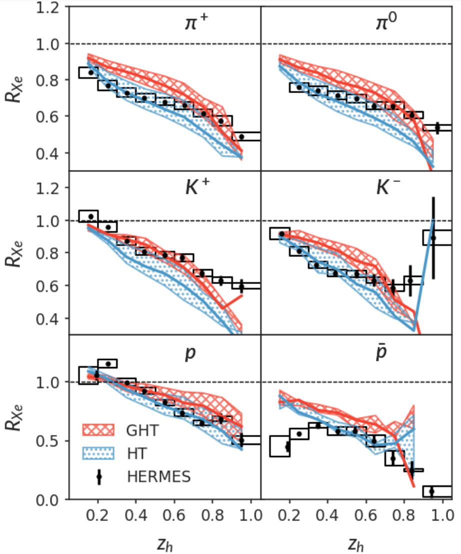
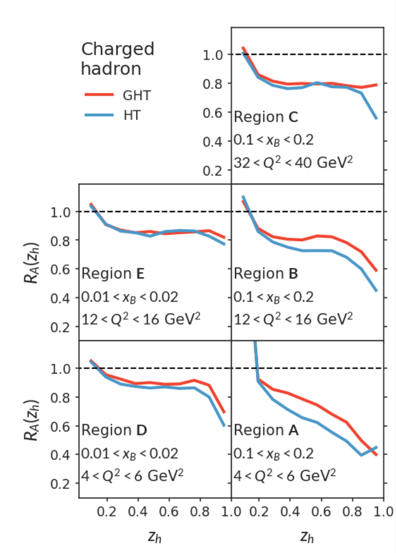
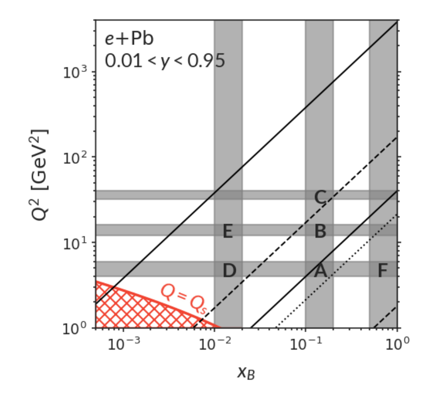
Flavor dependence



- Flavor dependence of R_A qualitatively captured.
- Clearly difference of R_A between K^+ and K^-, and between p and $\bar{p}$. Not captured 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





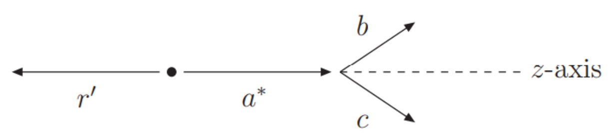
- Regions at various x_B and Q^2 with $Q \gg Q_s$.
- A highly differential test of the Q^2 and $\nu = Q^2/2x_B m_N$ dependence of the cold nuclear matter effects.

Some known problems

Global recoil versus dipole recoil schemes

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

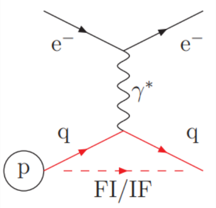
- In parton branching $p_a \to p_b + p_c$, the four-momentum conservation cannot be fulfilled with on-shell conditions for a, b, c.
- A recoiler system p_r is added so that $p_a^\mu + p_r^\mu = (p_a^*)^\mu + (p_r')^\mu = p_b^\mu + p_c^\mu + (p_r')^\mu$ is always satisfied.



B.Cabouat, T. Sjöstrand EPJC78(2018)226

Global recoil versus dipole recoil schemes

- **Global recoil** : recoil system is the rest of the event. Not used in Pythia8 default DIS. Because It affects $Q^2 = -(p_e - p'_e)^2$.
- **Dipole recoil**: the recoiler is the parton that form the color dipole with radiator a.



In DIS, the color dipole stretch from initial to final-state. Two possibilities:

- FI: final parton is the radiator, initial parton is the recoiler.
- IF: initial parton is the radiator, final parton is the recoiler.

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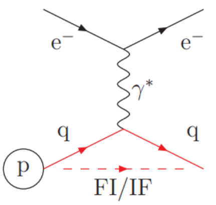

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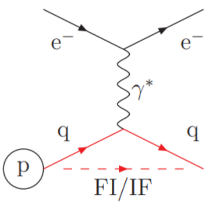
- FI: final parton is the radiator, initial parton is the recoiler.
- IF: initial parton is the radiator, final parton is the recoiler.

⋆ Pythia8 default DIS mode *only* implements IF radiation, because IF alone already reproduces the singular structure of the NLO matrix-element calculations! B.Cabouat, T. Sjöstrand EPJC78(2018)226

Global recoil versus dipole recoil schemes

- **Global recoil** : recoil system is the rest of the event. Not used in Pythia8 default DIS. Because It affects $Q^2 = -(p_e - p'_e)^2$.
- **Dipole recoil**: the recoiler is the parton that form the color dipole with radiator a.



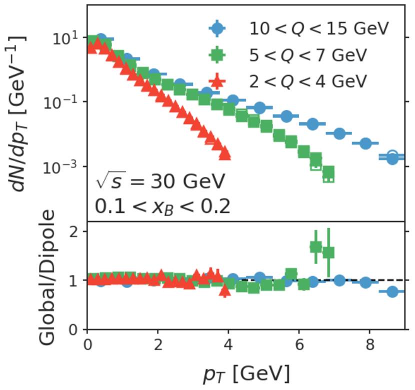
In DIS, the color dipole stretch from initial to final-state. Two possibilities:

- FI: final parton is the radiator, initial parton is the recoiler.
- IF: initial parton is the radiator, final parton is the recoiler.

!!! But eHIJING 1.0 uses the non-standard global recoil. This is because in the modified splitting function $P(z) = P^{\mathrm{vac}}(z) + P^{\mathrm{med}}(z)$, $P^{\mathrm{med}}(z)$ is a final-state effect, which cannot be treated as IF-type radiation. **A lot more technical problems to be solved!**

The impact of using Global versus dipole recoil in *ep*

- Q^2 can be changed by global recoil. Should be negligible at large Q^2.
- Global recoil affects TMD observables and the match to fixed-order calculation.



- 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 nuclear modifications at large $p_{T,\mathrm{Breit}}$ in EHIJING 1.0.

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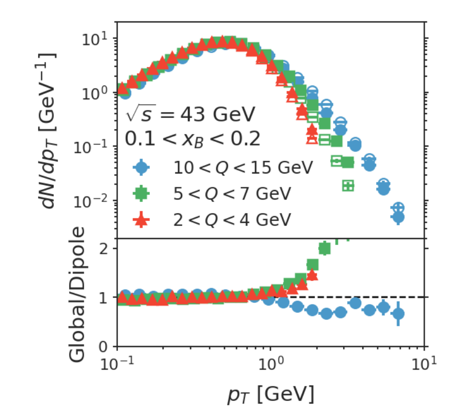

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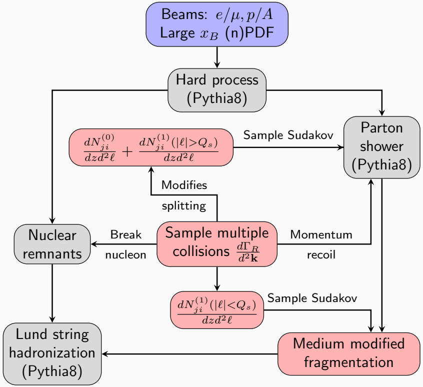
Summary and prospects



- 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 projections at EIC and EicC.
- Known problems with gloabl recoil in DIS. Lack target dynamics and hadronic interactions.
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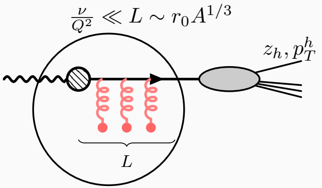

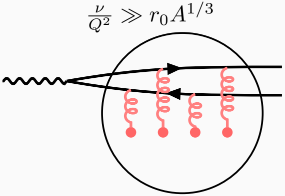

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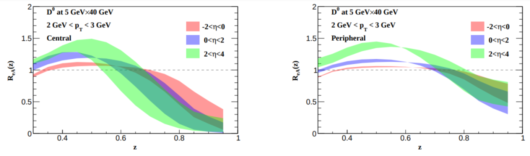
Questions

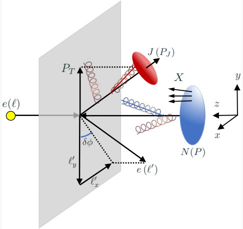
Things to look at in eHIJING

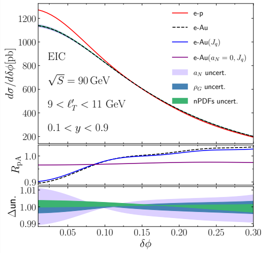
- Use target neutron emission to select on different path length of jet propagation in the cold nuclear matter Li, Liu Vitev, 2303.14201

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



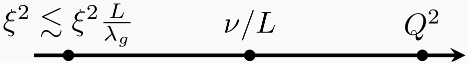
- Lepton-jet correlation (high precision *ep* baseline to study nuclear effects), Fang, Ke, Shao, Terry 2311.02150.



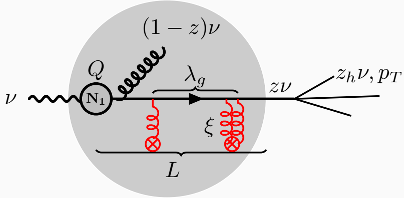


The ideal region for studying parton transport in matter

- 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.