eHIJING event generator for jet tomography at the EIC

RIKEN BNL Research Center Workshop: Small-x Physics in the EIC Era

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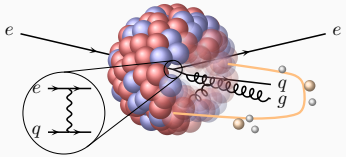
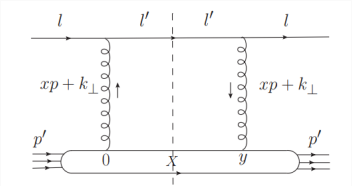
December 17, 2021, online

Final-state interactions in DIS of large nuclei

See X-N Wang's talk on Dec 16.





- This work: jet tomography at large x_B & high-Q^2
- Multiple collisions are mediated by small-x gluons. Cross-section $\leftrightarrow$ unintegrated gluon distribution

$$\frac{d\sigma_{qg}}{d\mathbf{k}_\perp^2} = \frac{\pi C_A}{d_A}\frac{\alpha_s}{\mathbf{k}_\perp^2}\phi_g(x_g, \mathbf{k}_\perp^2), \quad xG(x, Q^2) = \int \frac{d^2\mathbf{k}_\perp}{(2\pi)^2}\phi_g(x, \mathbf{k}_\perp^2)$$

- The first version takes a parametric ϕ_g motivated by [D Kharzeev, E Levin PLB 523 79-87]

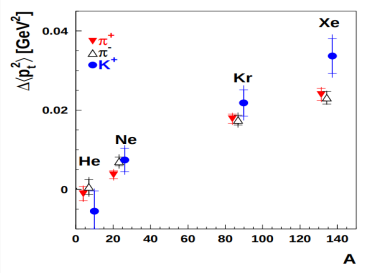
$$\alpha_s\phi_g(x, k_\perp^2; Q_s^2) = K\frac{(1-x)^n x^\lambda}{k_\perp^2 + Q_s^2}$$

- Self-consistently determine $Q_s^2 = \frac{4\pi^2 C_A}{d_A} T_A x_g G(x_g, Q^2/x_B)$ as probed by quark jet [Y-Y Zhang & X-N Wang, 2104.04520].

Modified fragmentation & momentum broadening

Momentum broadening in SIDIS

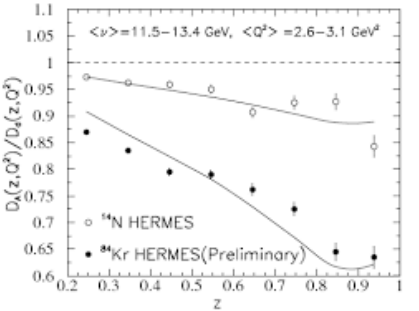
$$\Delta\langle p_T^2\rangle \equiv \langle p_T^2\rangle_{eA} - \langle p_T^2\rangle_{ed}(z_h; x_B, Q^2)$$
$$\approx z_h^2\langle \hat{q}_F(x_B, Q^2)L\rangle$$



[HERMES PLB 684, 114]

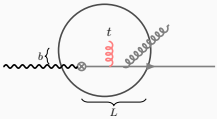
Medium modified fragmentation function

$D_h^A(z, Q^2)$ [E Wang & X-N Wang PRL 89, 162301]

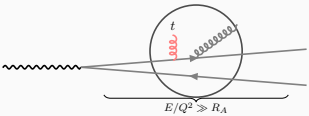


eHIJING (electron-Heavy-Ion Jet Interaction Generator)

Space-time picture at large x_B, Q^2:



Different from dominant contribution at small x_B



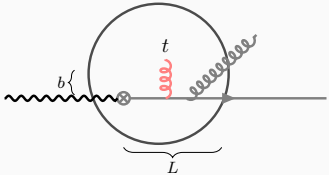
LO event generation ▽

To be considered in the future...

- Hard process
- Multiple collisions $\{(\mathbf{k}_\perp)_i, t_i^+\}, i = 1, 2, \cdots$ with Poisson fluctuation $\langle N \rangle = \sigma \rho_0 L$.
- Use $\{(\mathbf{k}_\perp)_i, t_i^+\}$ to modify gluon bremsstrahlung in the parton shower.
- Shower partons + recoiled remnants $(-\mathbf{k}_\perp) \to$ Lund string fragmentation.

Medium correction of gluon bremsstrahlung

quark: $x_B, \mathbf{v}_\perp = (\mathbf{v}_\perp)_0 + \sum_i (\mathbf{k}_\perp)_i$
radiated gluon: $z_g, \mathbf{l}_\perp$
Formation time: $\tau_f = \frac{2(1-z_g)z_g E}{(\mathbf{l}_\perp - \mathbf{k}_\perp)^2}$



Full opacity-1 correction in DIS [Y-Y Zhang, X-N Wang 2104.04520].

$$\frac{dP}{dz_g d\mathbf{l}_\perp^2} = \frac{\alpha_s(\mathbf{l}_\perp^2)}{2\pi} \frac{P_0(z_g)}{\mathbf{l}_\perp^2} \left[1 + \Delta_1(L; z_g, \mathbf{l}_\perp; x_B, z_g \mathbf{v}_\perp)\right]$$

We take soft gluon and small-x: $z_g, x_g \ll 1$

$$\Delta_1 \approx \int_0^L dt^+ \frac{C_F \rho_0}{d_A} \int d^2\mathbf{k}_\perp \frac{\alpha_s \phi_g}{\mathbf{k}_\perp^2} \frac{C_A}{C_F} \frac{2\mathbf{k}_\perp \cdot \mathbf{l}_\perp}{(\mathbf{l}_\perp - \mathbf{k}_\perp)^2} \left(1 - \cos\frac{t}{\tau_f}\right)$$

$$\to \sum_i \frac{C_A}{C_F} \frac{2(\mathbf{k}_\perp)_i \cdot \mathbf{l}_\perp}{[\mathbf{l}_\perp - (\mathbf{k}_\perp)_i]^2} \left(1 - \cos\frac{t_i}{(\tau_f)_i}\right)$$

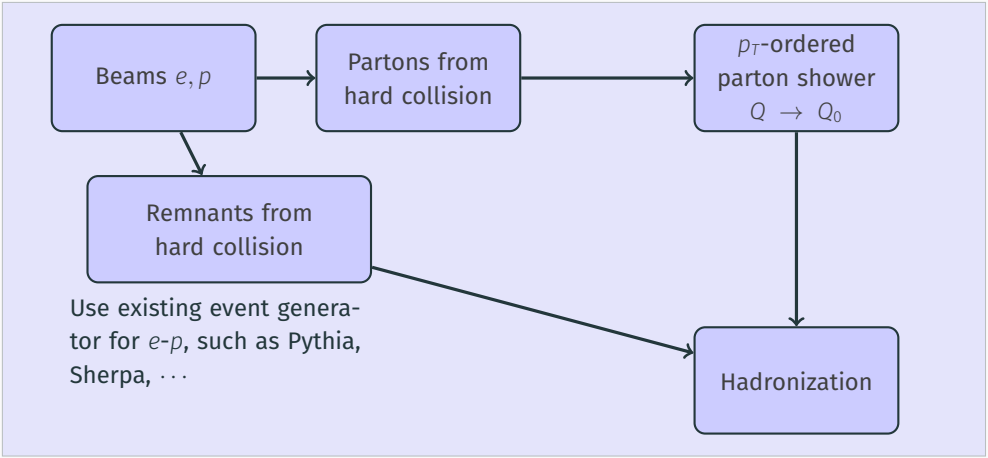
Multiple emissions and fragmentation model in the medium

- $l_\perp^2 > Q_s^2$: medium-modified p_T-ordered shower.
- $l_\perp^2 < Q_s^2$: model low-Q^2 medium-modified fragmentation [N-B Chang, W-T Deng, and X-N Wang PRC 89, 034911 (2014)]:

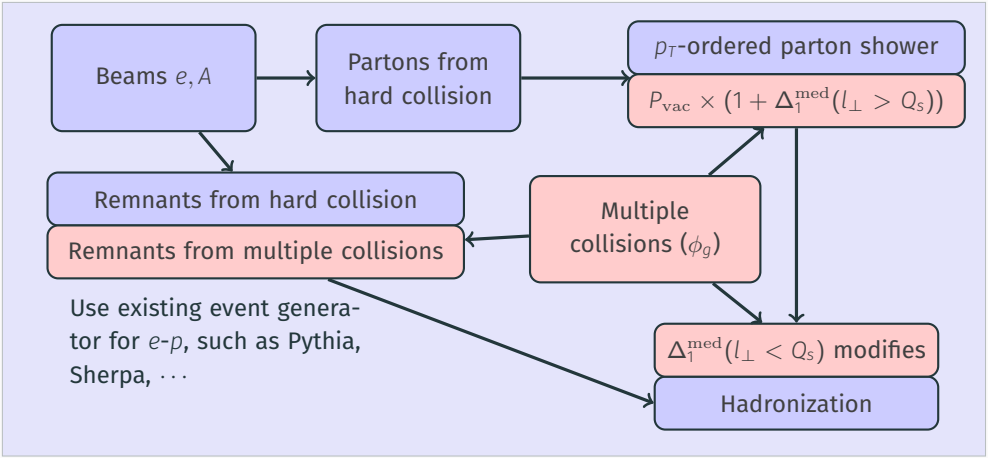
$$
\begin{aligned}
D^{\mathrm{A}}_{h/q}(x,\mu_0) &= \int_x^1 \frac{dz}{z} D^{\mathrm{vac}}_{h/q}\left(\frac{x}{z},\mu_0\right)\left[\delta(1-z)+\bar{\alpha}_s(Q_s^2)\left(\int_0^{Q_s^2}\frac{d\mathbf{l}_\perp^2}{\mathbf{l}_\perp^2}\left[P_0\Delta_1\right]_{qq}\right)_+\right] \\
&+ \bar{\alpha}_s(Q_s^2)\int_x^1 \frac{dz}{z} D^{\mathrm{vac}}_{h/g}\left(\frac{x}{z},\mu_0\right)\int \frac{d\mathbf{l}_\perp^2}{\mathbf{l}_\perp^2}\left[P_0\Delta_1\right]_{qg}
\end{aligned}
$$

In MC: τ_f-ordered gluon emissions from quark + transverse-momentum recoil

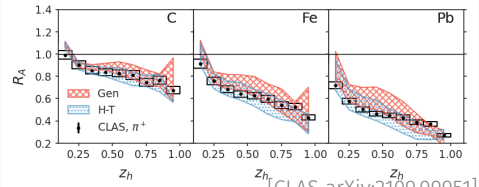
Modify Pythia8 for jet shower in medium in eHIJING



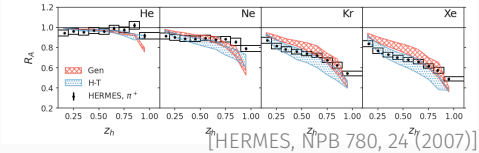
Modify Pythia8 for jet shower in medium in eHIJING



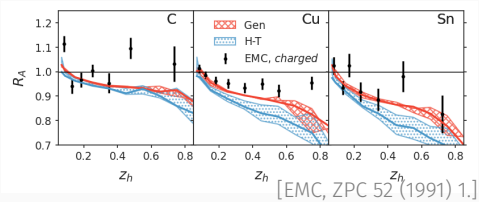
Nuclear modified fragmentation



[CLAS arXiv:2109.09951]



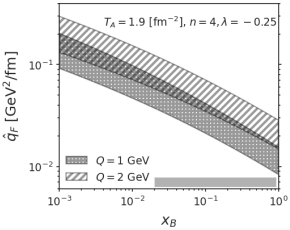
[HERMES, NPB 780, 24 (2007)]



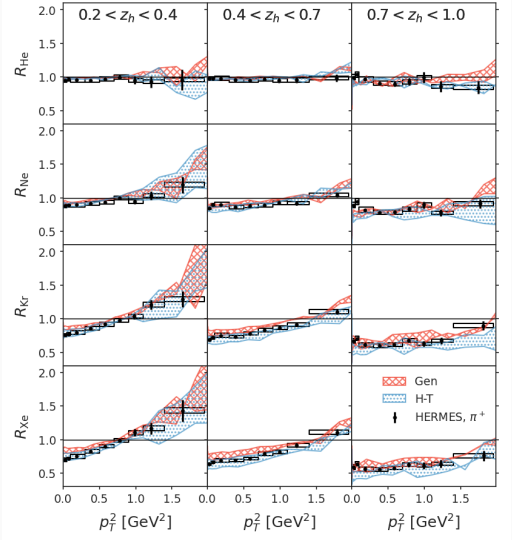
[EMC, ZPC 52 (1991) 1.]

$$R_A = \frac{(N_h(\nu, Q^2; z_h, p_t)/N_\gamma)_{eA}}{(N_h(\nu, Q^2; z_h, p_t)/N_\gamma)_{ed}}$$

- Higher-twist expansion (red) & generalized approach (blue).
- Bands: variation of Q_s or $\hat{q}_F$



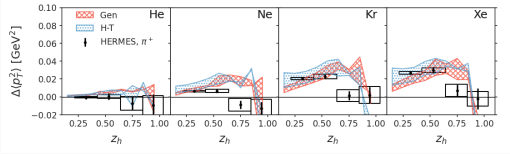
p_T-dependence $D(z_h, p_T)$



[HERMES, Nuclear Physics B 780, 24 (2007)]

$$R_A = \frac{\left(N_h(\nu, Q^2; z_h, p_t)/N_\gamma\right)_{eA}}{\left(N_h(\nu, Q^2; z_h, p_t)/N_\gamma\right)_{ed}}$$

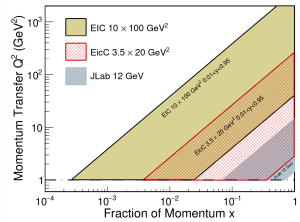
Interplay of parton energy loss and momentum broadening.

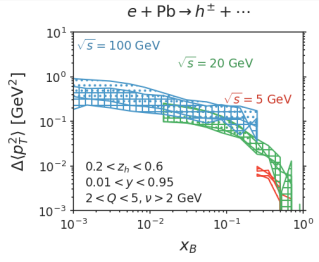


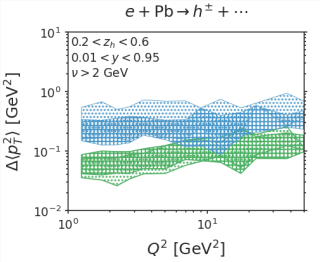
Large z: "survival bias" $\Delta p_T^2(z \to 1) = 0$; small z: $\Delta p_T^2 \sim z_h^2 \hat{q}_F L$.

Jet tomography at EIC

JLab 12 GeV beam / EicC / EIC ▽







The exact x_B, Q^2 dependence of $\Delta\langle p_T^2\rangle$ will be sensitive to the model for $\phi_g(x, \mathbf{k}_\perp)$.

Summary

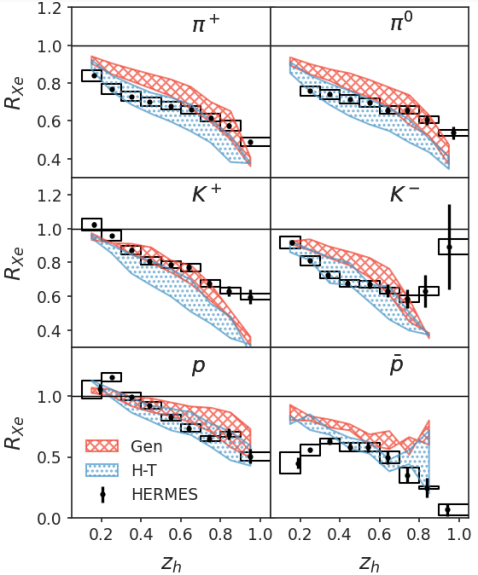
- eHIJING event generator approach jet tomography e-A: interplay of multiple collision, nuclear-modified parton shower and hadronization.
- Sensitivity analysis on Q_s^2, ϕ_g with modified fragmentation in SIDIS ($R_A(\nu, Q^2, z, p_t)$).

Outlook

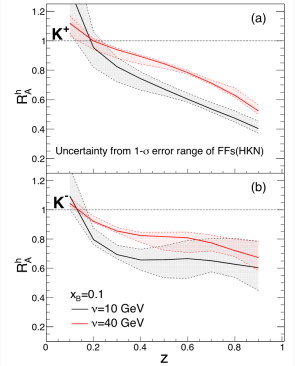
- Finalize and release
- Hadronic interactions / remnant dynamics
- Heavy flavor, flavor conversion.
- NLO event generation?

Questions?

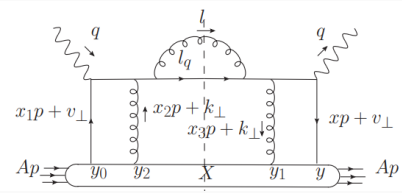
Flavor dependence



- Hadronic absorption at small z_h? $p/\bar{p}$.
- Need to consider medium-induced flavor production $g \to s\bar{s}$ for $R_A[K]$ at large z_h.



Back up: interplay of initial-state transverse momentum and final-state effects



[Double scattering term with radiative correction + finite transverse momentum of quark and gluon: Y-Y Zhang and X-N Wang]

- $v_\perp$ primordial k_T of quark + initial-state radiation broadening.
- Taking soft gluon limit: $z_g \ll 1$, $(1 - z_g)\mathbf{v}_\perp$ drops from the splitting function and does not affect final-state evolution other than momentum shift.

Medium-induced radiative correction in the collinear limit

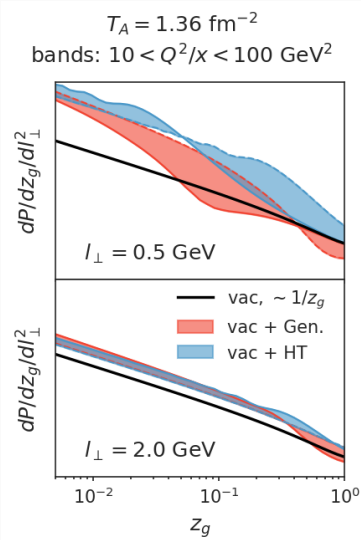
Collinear radiators $\tau_f' \equiv \frac{2z(1-z)E}{\mathbf{l}_\perp^2} \gg t \sim L$.

Expand in $\frac{|\mathbf{k}_\perp|}{|\mathbf{l}_\perp|} \ll 1$ [X-N Wang, X Guo, A. Majumder]

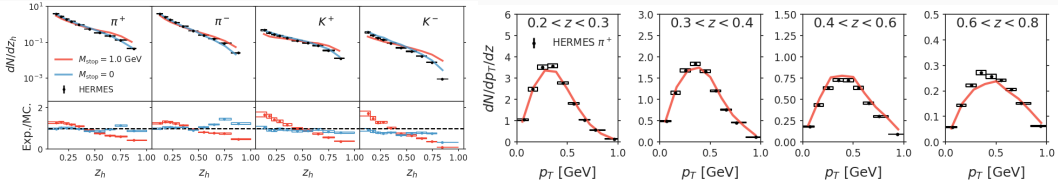
$$\Delta_1^{\mathrm{HT}} = \int_0^L dt \frac{2\hat{q}_A^{\mathrm{rad}}}{\mathbf{l}_\perp^2}\left(1-\cos\frac{t}{\tau_f'}\right),$$

$$\hat{q}_A^{\mathrm{rad}} = \int_0^{\mathbf{l}_\perp^2} \alpha_s(\mathbf{k}_\perp^2)\frac{C_A}{d_A}\rho_0\phi_g(x_g,\mathbf{k}_\perp^2)$$

$\hat{q}_A^{\mathrm{rad}}$: transport parameter for radiative correction.



Baseline: $e + d \to e + h + \cdots$



[HERMES, Phys Rev D 87, 074029 (2013)]

- Minimum invariant mass for string breaking in Pythia8: $W_{\text{min}} = m_q + m_{\bar{q}'} + M_{\text{stop}}$.
- Change of default Pythia8 M_{stop} from 1 GeV to 0: better fits π and K fragmentation.