eHIJING: jet-medium interactions and evolutions in e-A

CTEQ-EICUG-HSF-MCnet Workshop on MCEG for the EIC, online

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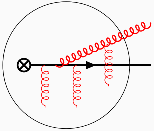
Nuclear effects in QCD hard processes

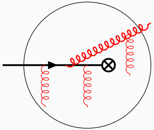
Dynamical effects:

- Medium-modified parton evolution/fragmentation
- Nuclear target evolution.
- Process dependent

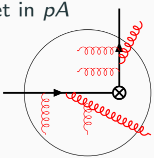
DIS in eA



Drell-Yan in pA



h/jet in pA



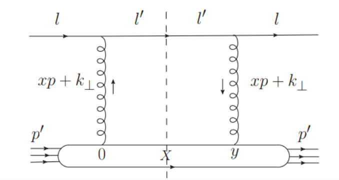
Nuclear non-perturbative input:

- Nuclear parton distribution.
- In-medium hadronization.
- Intrinsic to the medium.

Understand (perturbative) dynamical effects.

Separate from intrinsic nuclear properties.

Final-state interactions in nuclear & eA collisions



- Multiple ($\propto A^{1/3}$) interactions between jet partons and target.

- Mediated by Glauber gluons, $k^+ k^- \ll k_\perp^2$, carry small momentum fraction of the target.

- Relate an effective Glauber gluon density to the TMD gluon distribution at small x:

$$\phi_g(x, \mathbf{k}_\perp) = \int \frac{d\xi^+ d\vec{\xi}_T^2}{2\pi P^-} e^{-ixP^- \xi^+ - i\mathbf{k}_\perp \cdot \vec{xi}_T} \langle F^{i-}(0, \vec{0}) F_i^-(\xi^+, \vec{\xi}_T) \rangle .$$

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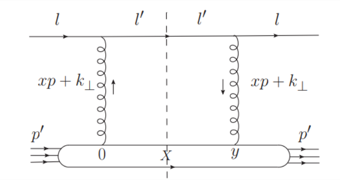
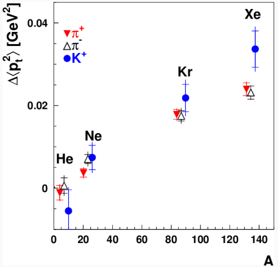
  - Collisional k_T broadening.





[HERMES]

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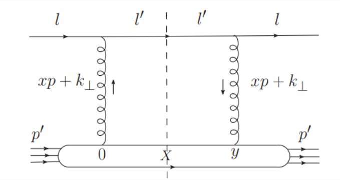
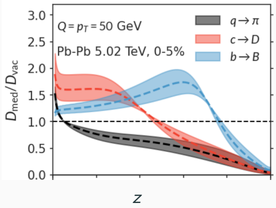
  - Collisional k_T broadening.
  - Modifies QCD splitting function: radiative broadening, modified fragmentation.





△ Huge effects in nuclear collisions, but direct measurement of FF is hard.

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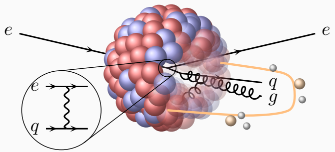
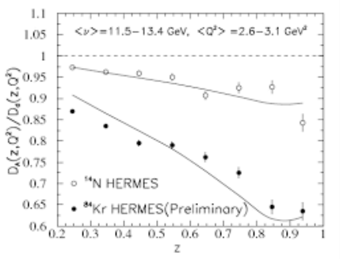
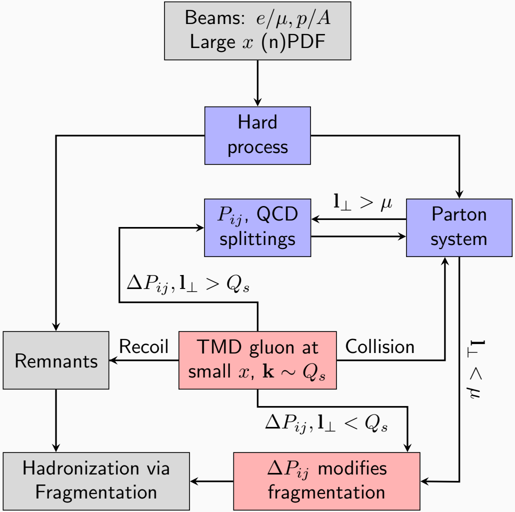




[E Wang, X-N Wang PRL89 162301]

Differential measurement of fragmentation at EIC has huge impact on theory and modeling.

eHIJING (electron-Heavy-Ion-Jet-INteraction-Generator)



A Monte Carlo model for jet shower modifications in *e*-*A*:

- *e*-*p* event generation from Pythia8.
- *e*-*A* (c++17, including modifications to Pythia8):
  1) multiple Glauber scatterings
  2) modified splitting functions
  3) in-medium parton shower
  4) hadronization

⋆ Recent progress to understand in-medium multiple emission.

A model for the Glauber gluon density

- A saturation-based model of $\phi_g(x, \mathbf{k}_\perp^2)$

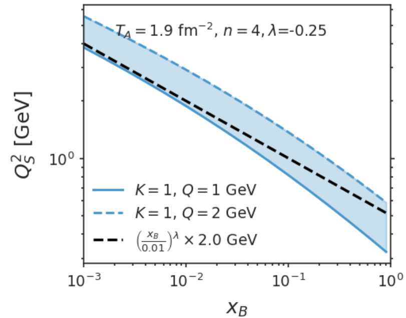
$$\phi_g(x, \mathbf{k}_\perp) = \frac{K}{\alpha_s} \frac{(1-x)^n x^\lambda}{\mathbf{k}_\perp^2 + Q_s^2(x_B, Q^2)}$$

- For a given nuclear thickness $T_A(\mathbf{b})$, Q_s is determined self-consistently [Y-Y Zhang, X-N Wang PRD105(2022)034015; A. Mueller NPB558(1999)285-303].

$$Q_s^2(x_B, Q^2) = T_A \frac{C_A}{d_A} \int_{\Lambda^2}^{Q^2/x_B} d^2\mathbf{k}_\perp \alpha_s \phi_g(x = x_B \frac{\mathbf{k}_\perp^2}{Q^2}, \mathbf{k}_\perp^2)$$

- Q_s acts as a screen mass to the Glauber scattering

$$\frac{d\sigma_G}{d\mathbf{k}_\perp^2} = \frac{C_R}{d_A} \frac{\alpha_s \phi_g(x, \mathbf{k}_\perp^2)}{\mathbf{k}_\perp^2}$$



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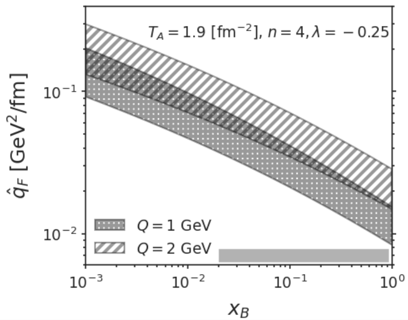
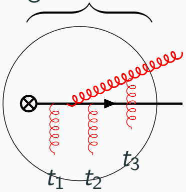


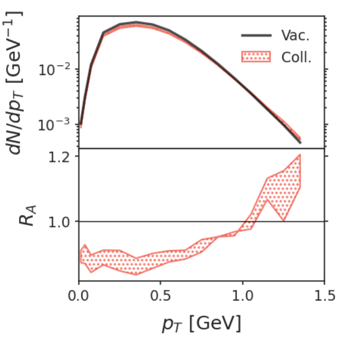
The jet transport parameter

$$\hat{q}_R \equiv \frac{d\langle \Delta p_\perp^2 \rangle}{dL} = \frac{C_R}{C_A} \frac{Q_s^2(x_B, Q^2, T_A)}{L}$$

Multiple collisions in eHIJING

- For each newly generated parton in the shower, compute the in-medium path length L. Currently only implemented for round nuclei.
- Compute average number of multiple collisions $\langle N \rangle = L/\lambda_G \approx \sigma_G \rho L$
- Number of collisions N follows a Poisson distribution $P(N) = \frac{\langle N \rangle^N e^{-\langle N \rangle}}{N!}$
- Sample the location and kinematics of collisions $(t_i, \mathbf{k}_{\perp i}, x_i)$



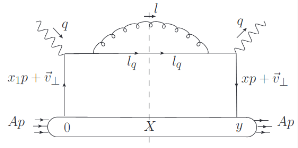


◁ **Collisional broadening of hadron transverse momentum distribution.**

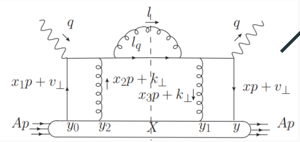
Medium-induced radiation will further modify R_A.

Medium-modified QCD splitting functions: $q \to q$

Theory inputs: higher-twist & generalized higher-twist calculations [Y-Y Zhang, X-N Wang PRD105(2022)034015].



$\hat{\sigma}_{\gamma^* N \to q} \otimes \frac{\alpha_s}{2\pi}\frac{1}{l_\perp^2} P_{qq}(z)$



$$\frac{d\sigma^D_{eA}}{dx_B dQ^2 dz d^2l_\perp d^2l_{q\perp}} = \frac{2\pi\alpha_{em}^2}{Q^4}\sum_q e_q^2[1+(1-\frac{Q^2}{x_B s})^2]\frac{\alpha_s}{2\pi}\frac{1+z^2}{1-z}\frac{2\pi\alpha_s}{N_c}\int\frac{d^2k_\perp}{(2\pi)^2}\int d^2b_\perp dy_0^- dy_1^-$$
$$\times\rho_A(y_0^-,b_\perp)\rho_A(y_1^-,b_\perp)q_N(x_B,\vec{v}_\perp,b_\perp)\frac{\phi_N(x_G,\vec{k}_\perp)}{k_\perp^2}\left[\mathcal{N}_g^{\rm qLPM}+\mathcal{N}_g^{\rm gLPM}+\mathcal{N}_g^{\rm nonLPM}\right]. \quad (19)$$

$$\mathcal{N}_g^{\rm qLPM} = \frac{1}{N_c}\left(\frac{[\vec{l}_\perp-(1-z)\vec{v}_\perp]\cdot[\vec{l}_\perp-(1-z)(\vec{l}_\perp+\vec{l}_{q\perp})]}{[\vec{l}_\perp-(1-z)\vec{v}_\perp]^2[\vec{l}_\perp-(1-z)(\vec{l}_\perp+\vec{l}_{q\perp})]^2}-\frac{1}{[\vec{l}_\perp-(1-z)\vec{v}_\perp]^2}\right)$$
$$\times\left(1-\cos[(x_L+x_E-x_F)p^+(y_1^- - y_0^-)]\right), \quad (20)$$

$$\mathcal{N}_g^{\rm gLPM} = C_A\left(\frac{2}{[\vec{l}_\perp-(1-z)\vec{v}_\perp-\vec{k}_\perp]^2}-\frac{[\vec{l}_\perp-(1-z)\vec{v}_\perp-\vec{k}_\perp]\cdot[\vec{l}_\perp-(1-z)(\vec{l}_\perp+\vec{l}_{q\perp})]}{[\vec{l}_\perp-(1-z)\vec{v}_\perp-\vec{k}_\perp]^2[\vec{l}_\perp-(1-z)(\vec{l}_\perp+\vec{l}_{q\perp})]^2}\right.$$
$$\left.-\frac{[\vec{l}_\perp-(1-z)\vec{v}_\perp]\cdot[\vec{l}_\perp-(1-z)\vec{v}_\perp-\vec{k}_\perp]}{[\vec{l}_\perp-(1-z)\vec{v}_\perp]^2[\vec{l}_\perp-(1-z)\vec{v}_\perp-\vec{k}_\perp]^2}\right)\times\left(1-\cos[(x_L+\frac{z}{1-z}x_D+x_S-x_F)p^+(y_1^- - y_0^-)]\right), \quad (21)$$

$$\mathcal{N}_g^{\rm nonLPM} = C_F\left(\frac{1}{[\vec{l}_\perp-(1-z)(\vec{l}_\perp+\vec{l}_{q\perp})]^2}-\frac{1}{[\vec{l}_\perp-(1-z)\vec{v}_\perp]^2}\right), \quad (22)$$

twist four

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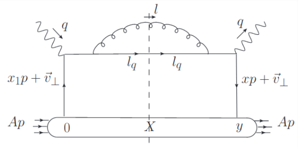

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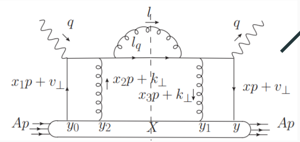

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$$\times\left(1-\cos[(x_L+x_E-x_F)p^+(y_1^--y_0^-)]\right), \quad (20)$$

Suppressed by $1/N_c^2$

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Main contributions

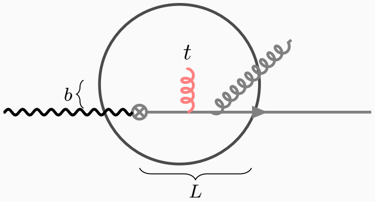
$$\mathcal{N}_g^{\rm nonLPM} = C_F\left(\frac{1}{[\vec{l}_\perp-(1-z)(\vec{l}_\perp+\vec{l}_{q\perp})]^2}-\frac{1}{[\vec{l}_\perp-(1-z)\vec{v}_\perp]^2}\right), \quad (22)$$

Power suppressed by UV cut off ($\sim\sqrt{\Lambda E}$)

Medium-modified QCD splitting functions: $q \to q$: soft-gluon limit

$$\Delta P_{qq}(x, \mathbf{l}_\perp) \supset \frac{\alpha_s C_F}{2\pi} \frac{P_{qq}(x)}{l_\perp^2} \int_0^L dt \rho_N(b,t) \int_{\mathbf{k}_\perp} \frac{C_A}{d_A} \frac{\alpha_s \phi_g(\mathbf{k}_\perp^2)}{\mathbf{k}_\perp^2} \frac{2\mathbf{k}_\perp \cdot \mathbf{l}_\perp}{(\mathbf{l}_\perp - \mathbf{k}_\perp)^2} \left[1 - \cos\frac{t}{\tau_f}\right]$$

- Impact parameter b, path length L.
- Nucleon density along the path $\rho_N(b,t)$.
- Formation time $\tau_f = \frac{2x(1-x)E}{(\mathbf{k}_\perp - \mathbf{l}_\perp)^2}$.



Leading-log behavior of medium-induced emissions

Important for a probabilistic picture for in-medium parton shower. There are many scales:

1. $Q/\Lambda \gg 1$.
2. In large and dense medium: $L \gg \lambda_g$, $\frac{E}{k_{T,\min}^2}\frac{1}{L} = \mathcal{O}(1)$.
3. Dilute medium: $L/\lambda_g = \mathcal{O}(1)$, but $\frac{E}{k_{T,\min}^2}\frac{1}{L} \gg 1$.

Consider (1) and (3) for e-A **jet tomography** [WK, I. Vitev, in preparation]

- $\Delta P_{qq}(x, \mathbf{l}_\perp) \sim \frac{\alpha_s C_R Q_s^2 L}{E}\frac{P_{qq}(x)}{x(1-x)}$. Fragmentation modified by strongly ordered medium-induced emissions $k_{T,\min}^2 < \mu^2 = \frac{\mathbf{k}_\perp^2}{x(1-x)} < \frac{2E}{L}$ from the endpoint $x \to 1$.

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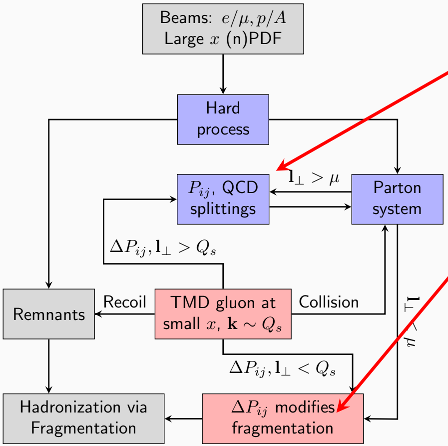
- For transverse momentum broadening: $\tau_f < L$, formed in medium.

Medium-modified parton shower in eHIJING

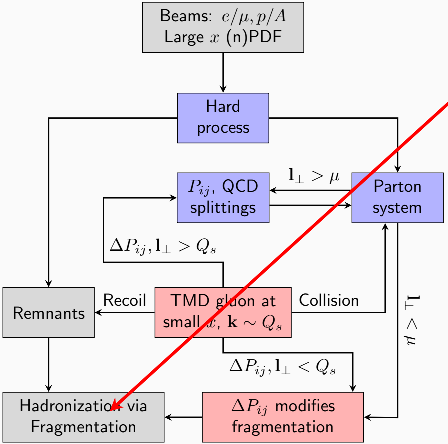


- For $Q_s < \mathbf{l}_\perp$, add medium-induced splittings to Pythia8, $P_{\rm vac}(x) + \Delta P_{\rm med}(x, \mathbf{l}_\perp)\Theta(\mathbf{l}_\perp - Q_s)$. Modifies the k_T-order parton shower.
- For $\mathbf{l}_\perp < Q_s$. Multiple **medium-induced** emissions in a formation-time picture

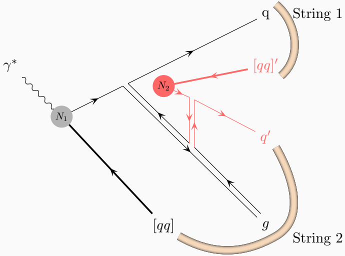
$$\underbrace{1/Q_s \sim \tau_{f,1} < \cdots}_{\text{Important for } D(z, k_T)} < L < \underbrace{\cdots < \tau_{f,n} < \frac{E}{\Lambda^2}}_{\text{Important for } D(z, k_T)}$$

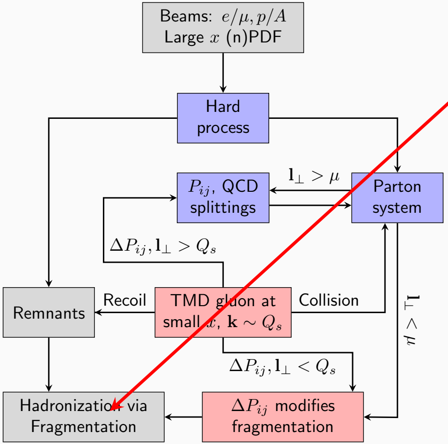
- Leading-log analysis suggests $\tau_f \sim L$ is the natural scale of medium-induced processes.

Hadronization



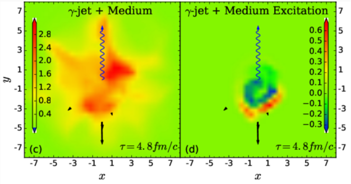
- Model hadronization with Lund string: jet shower + remnants.





- Model hadronization with Lund string: jet shower + remnants.
- This cannot handle very soft collisions & induced emissions.

  $\Rightarrow$ Soft energy-momentum deposition & medium excitation? Similar practices in heavy-ion collisions.

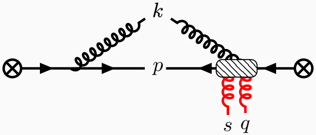


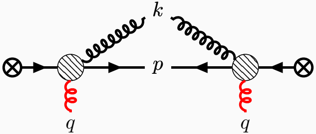
[Jet wake in HIC, Wei Chen et al PLB777(2018)86]

A more demanding question: the probabilistic picture of jet+target dyanmics

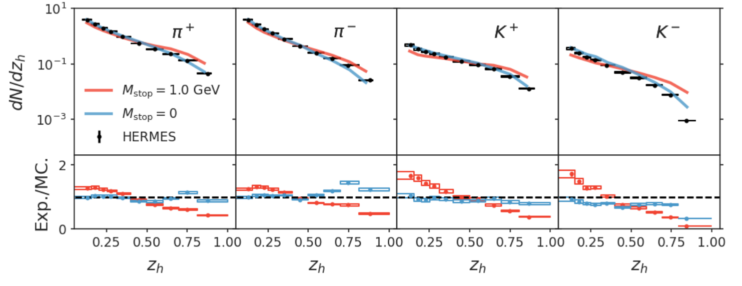
- The medium-modified QCD splitting functions are calculated by **summing over** medium final states.
- Currently, how to couple multiple collisions to modified parton shower heavily relies on modeling.
- Need new theoretical inputs!

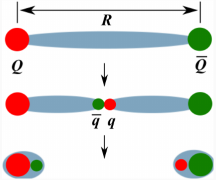
The modified splitting function contains:





The Lund string model in Pythia8: $D(z)$



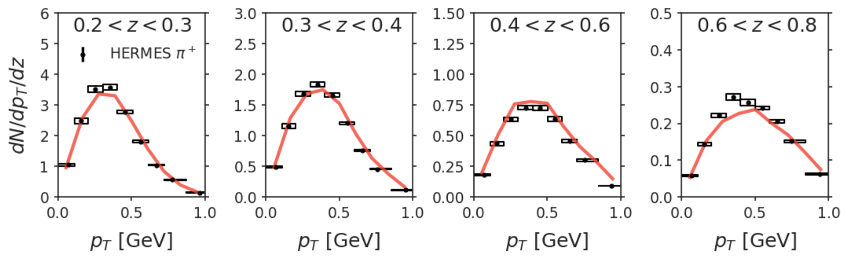


[HERMES, Phys Rev D 87, 074029 (2013)]

- Change a default Pythia8 fragmentation parameter $M_{\rm stop}$ from 1 GeV to 0 to fit π and K spectra in e-d collisions at HERMES energy.
- $M_{\rm stop}$ controls the minimum mass of string to break $W > m_q + m_{\bar{q}'} + M_{\rm stop}$.

The Lund string model in Pythia8: $d^2N_h/dz_h/dp_T$

$d^2N_h/dz_h/dp_T$

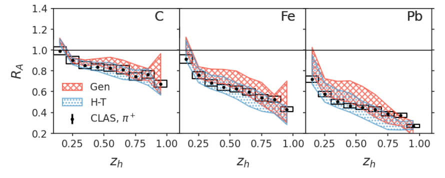


[HERMES, Phys Rev D 87, 074029 (2013)]

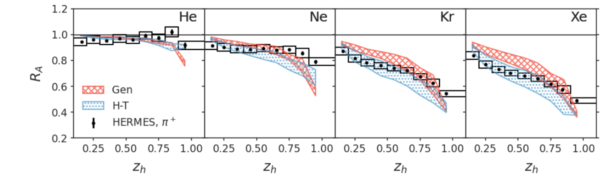
Reasonable agreement with Pythia8's non-perturbative modeling

- A primordial quark k_T, $k_T \sim e^{-k_T^2/2\sigma_1^2}$ with $\sigma_1 \propto (1 + Q_{1/2}/Q)^{-1}$ [T. Sjöstrand and P.Z. Skands, JHEP 03 (2004) 053].
- k_T from Lund string fragmentation, $k_T \sim e^{-k_T^2/2\sigma_2^2}$ with $\sigma_2 = 0.335$ GeV as default.

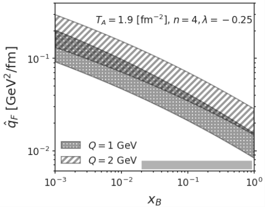
Test of medium-modified hadronization at CLAS and HERMES



[CLAS PRC105(2022)015201]



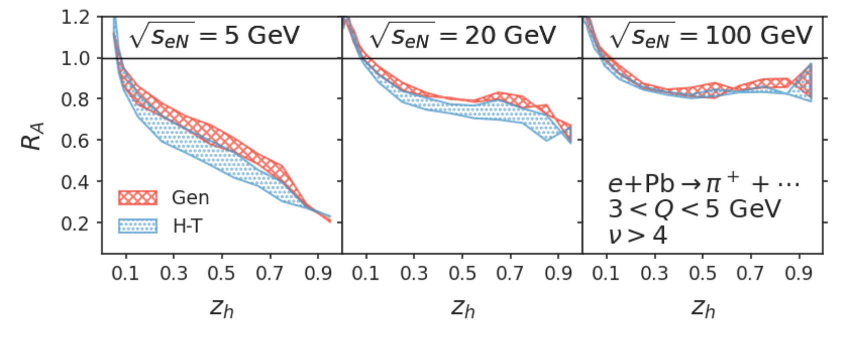
[HERMES, NPB 780, 24 (2007)]



- Nuclear modification
  $$R_A = \left(N_h(\nu, Q^2; z_h, p_t)/N_\gamma\right)_{eA} / \left(N_h(\nu, Q^2; z_h, p_t)/N_\gamma\right)_{ed}.$$
- HT (red) & generalized HT (blue). Bands: $\hat{q}_F$ variation ▷.
- Consistent with the A dependence of data.
- Nuclear PDF EPPS16 [EPJC 77, 163 (2017)] used for hard process.

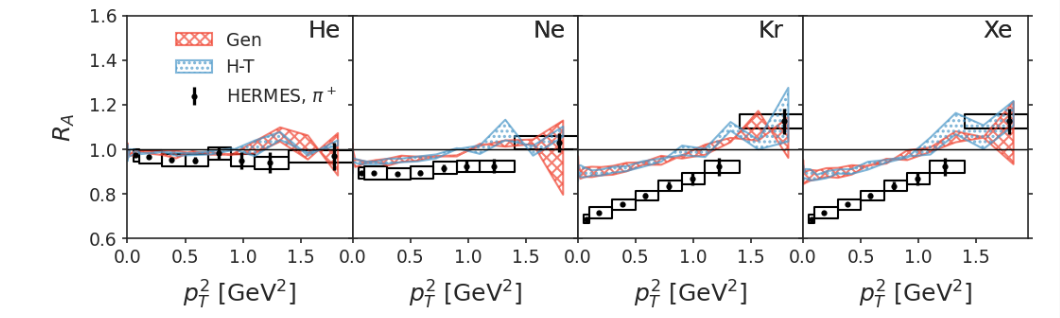
From fixed target to collider energies

Effects of modified fragmentation decrease with increasing jet energy. Still expect sizable correction if one aims for processes with large Q^2 and x_B.



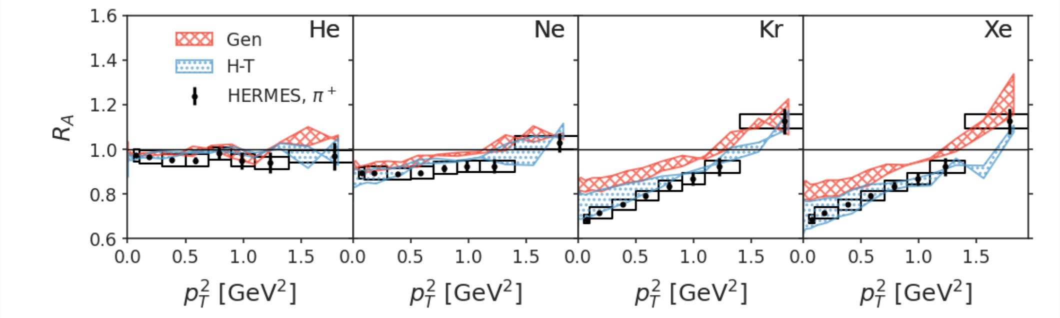
Collisional & radiative contribution to momentum broadening

Collisional broadening of the parton shower



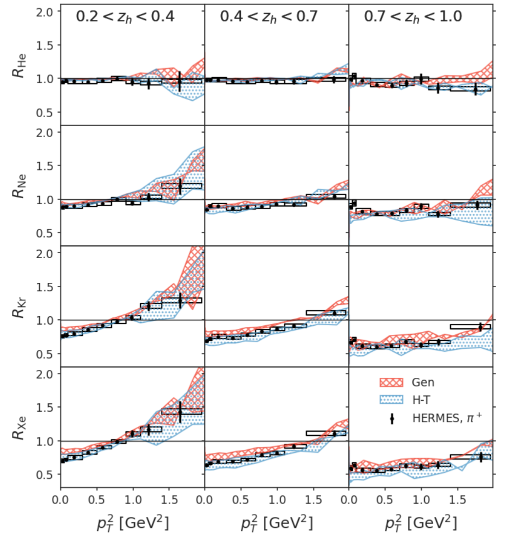
Collisional & radiative contribution to momentum broadening

Broadening from both collisions & induced radiations



- Broadening due to medium-induced radiation is important in large nuclei!
- Sensitive to the calculation of details of the in-medium splitting functions.

p_T-dependent modified fragmentation function $D(z_h, p_T)$

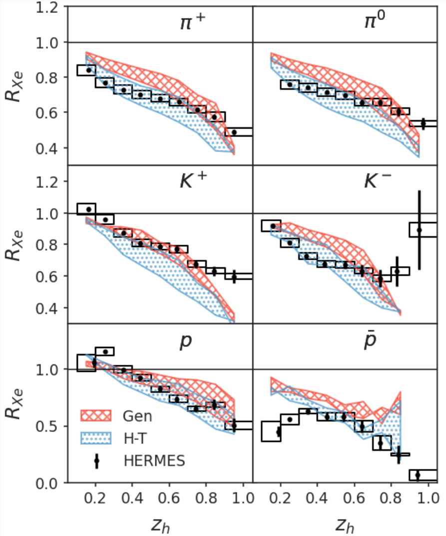


[HERMES, Nuclear Physics B 780, 24 (2007)]

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

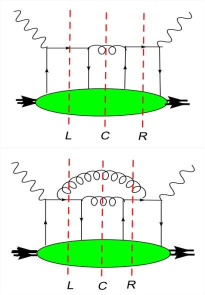
- Large z: suppression due to parton energy loss of leading particles.
- Small z: interplay of k_T broadening and the parton shower evolution.
- Partons that stays at large z likely to undergo less collisions, $\Rightarrow$ a “survival bias” due to the large fluctuation of the number of collisions.

Hadron specie dependence: $\pi^{\pm}$, π^{0}, $K^{\pm}$, p, $\bar{p}$

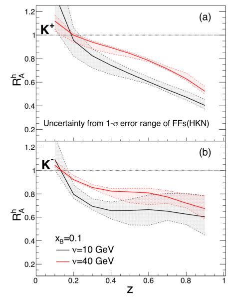


[HERMES, Nuclear Physics B 780, 24 (2007)]

- Notable difference between $R_A(K^+)$ vs $R_A(K^-)$, and $R_A(p)$ vs $R_A(\bar{p})$.
- Importance of medium-induced conversion of $g \to q$ and hadronic transport for future.



[BW Zhang, XN Wang, A Schaefer]



[NB Chang, WT Deng, XN Wang PRC 92 055207]

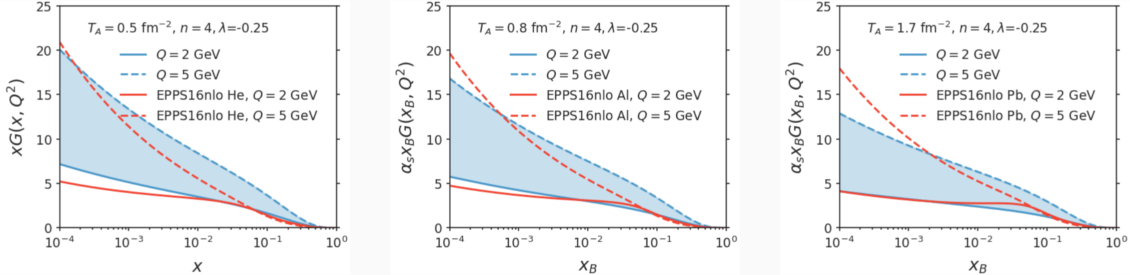
Summary and outlook

- Final-state jet-nucleus interactions lead to modified jet fragmentation. Measurements of fragmentation in e-A provide strong constraints to theory and models.
- eHIJING Monte Carlo: Glauber interactions, modified splitting functions, in-medium parton shower, and modified fragmentation.
- Understanding the leading-log behavior of medium-induced multiple emissions in dilute medium $\Rightarrow$ formation time ordering with natural scale L. Already partly used in eHIJING.
- First paper & github (eHIJING + a modified version of Pythia8) to come.
- How to build a probabilistic picture for jet+medium evolution? Important for in-medium hadronization & describing correlations between jet and target.

Questions?

Backup slides: compared to phenomenological nuclear PDF

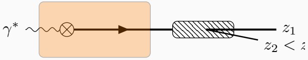
$$xG(x, Q^2) = \int_0^{Q^2} \frac{d^2\mathbf{k}_\perp}{(2\pi)^2} \phi_g(x, \mathbf{k}_\perp^2)$$



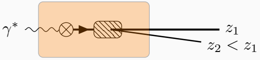
- Choice of parameters result in similar $xG(x, Q)$ at low Q^2.
- But lack proper evolution compared to realistic PDF.

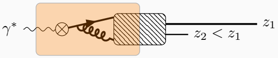
$$D_{2h} = \frac{d^2 N_h}{dz_1 dz_2}, z_1 > z_2; \qquad R_{2h} = \frac{D_{2h}^{eA}/D^{eA}}{D_{2h}^{ed}/D^{ed}}$$

Different space-time picture of hadronization:



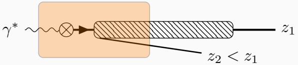
v.s.





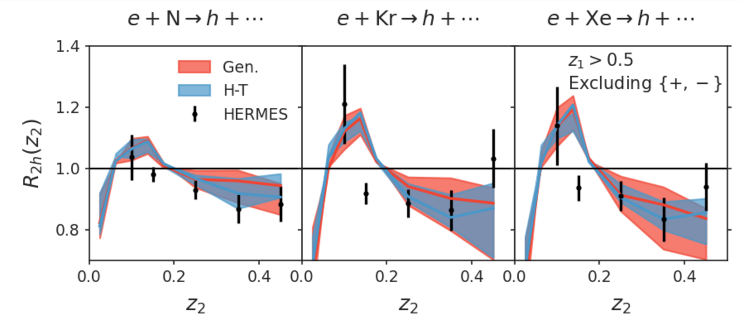
(Modified) radiation

[A. Majumder & X-N Wang]



Hadron formation time

Medium modified double hadron fragmentation



[HERMES, PRL 96 (2006) 162301]

- Reasonable agreement with double-hadron modifications.
- There is still room for hadronic transport at small z_2. ($z_2 = 0.1$, $E \sim 1$ GeV in target frame).

Stochastic version of the medium-modified splitting functions

With a large fluctuation in the number of collisions, we constructed fluctuating in-medium splitting functions

$$P_{qq}(x, \mathbf{l}_\perp) = \frac{\alpha_s C_F}{2\pi} \frac{P_{qq}(x)}{l_\perp^2} \left\{ 1 + \int dL \rho(L) \int_{\mathbf{k}_\perp} \frac{C_F}{d_A} \frac{\alpha_s \phi_g(x, \mathbf{k}_\perp^2)}{\mathbf{k}_\perp^2} \frac{C_A}{C_F} \frac{2\mathbf{k}_\perp \cdot \mathbf{l}_\perp}{(\mathbf{l}_\perp - \mathbf{k}_\perp)^2} \left[1 - \cos \frac{L}{\tau_f} \right] \right\}$$

$$\Longrightarrow \frac{\alpha_s C_F}{2\pi} \frac{P_{qq}(x)}{l_\perp^2} \left\{ 1 + \sum_i \frac{C_A}{C_F} \frac{2(\mathbf{k}_\perp)_i \cdot \mathbf{l}_\perp}{[\mathbf{l}_\perp - (\mathbf{k}_\perp)_i]^2} \left[1 - \cos \frac{L_i}{(\tau_f)_i} \right] \right\}$$

The usual average over the medium sources is replaced by the summation over the multiple collisions of the shower parton.

To test the sensitivity of observables to different "theories"

eHIJING implemented two versions of medium-modified splitting functions:

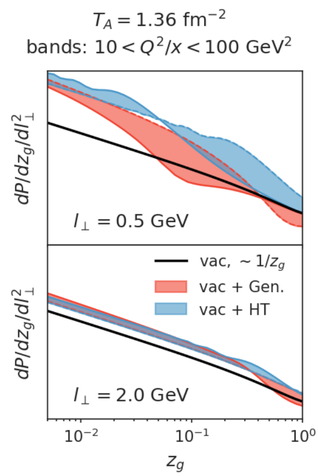
The generalized formula:

$$\int_0^L dt \int \frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2}\alpha_s \frac{C_A\rho_0\phi_g(x_g,\mathbf{k}_\perp^2)}{d_A}\frac{2\mathbf{k}_\perp\cdot\mathbf{l}_\perp}{(\mathbf{l}_\perp-\mathbf{k}_\perp)^2}\left(1-\cos\frac{(\mathbf{l}_\perp-\mathbf{k}_\perp)^2 t}{2(1-z)zE}\right)$$

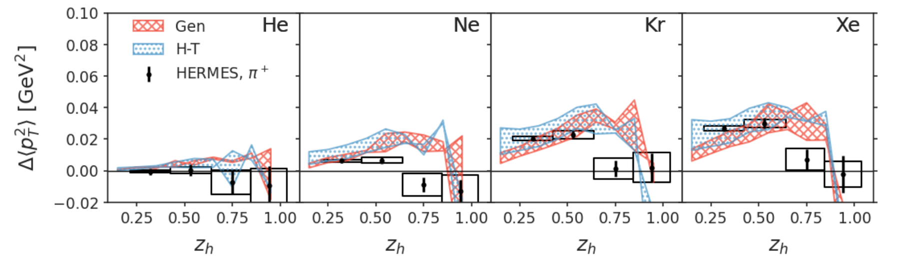
Collinear expanded formula (higher-twist): expand in powers of $\mathbf{k}_\perp^2/\mathbf{l}_\perp^2$ [X-N Wang, X Guo, A. Majumder, etc].

$$\int dL \frac{2\hat{q}'_A}{\mathbf{l}_\perp^2}\left[1-\cos\frac{\mathbf{l}_\perp^2 L}{2(1-z)zE}\right]$$

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



The net broadening $\Delta\langle p_T^2\rangle = \langle p_T^2\rangle_{eA} - \langle p_T^2\rangle_{ed}$



[HERMES, PLB 684 (2010) 114-118]

- Qualitatively similar z-dependence from simulation.
- Data drop more abruptly for $z_h > 0.7$. This region shrinks at higher colliding energies.