A Simultaneous Study of Nuclear Modifications of Hadrons, Jets, and Substructures (EEC)

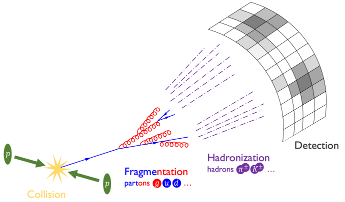
Lin Li

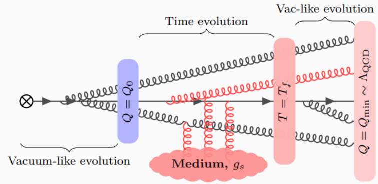
Central China Normal University
Collaborators: Yanru Bao, Weiyao Ke, Guang-You Qin

New opportunites in particle and nuclear physics with energy correlators, Wuhan, China
May 16 2025

Jet modifications in nuclear collisions

- Partons interact with quark-gluon plasma in AA.
- High-p_T hardons suppression are governed by parton energy loss. **While modifications of jets (as collection of particles) are more complicated**.
- This work: employ the LIDO partonic transport model + hydrodynamic description of QGP + simple medium response model to study **hadron, jets, and EEC at LHC and RHIC**.





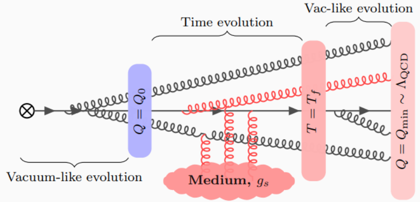
outline

LIDO Model: Jet Evolution Framework

PYTHIA8 Vacuum Shower $Q \sim p_T^{\text{hard}} \to Q_0$ → LIDO Transport Parton-Medium Interactions → PYTHIA8 Final Shower + Hadronization

Framework Components

- PYTHIA8: Initial jet production and Vacuum shower evolution
- LIDO: In-medium transport (Partons decouple below $T < T_f$)
- PYTHIA8: Vacuum shower + fragmentation.
- $2+1D$ Hydrodynamics: QGP background evolution



Reference: PRC 100(2019)064911

Reference: JHEP05(2021)041

Transport Equation in the Incoherent Limit

Combining all relevant processes, the semiclassical transport equation in the incoherent limit with independent collisions can be written as:

$$\frac{df}{dt} = D[f] + C_{1\to 2}[f] + C_{2\to 2}[f] + C_{2\to 3}[f]$$

The distribution function of a hard parton evolves under the influence of:

- Diffusion term: $D[f]$
- Large-q elastic collisions: $C_{2\to 2}[f]$
- Diffusion-induced small-q parton splitting/merging: $C_{1\to 2}[f]$
- Large-q inelastic collisions: $C_{2\to 3}[f]$

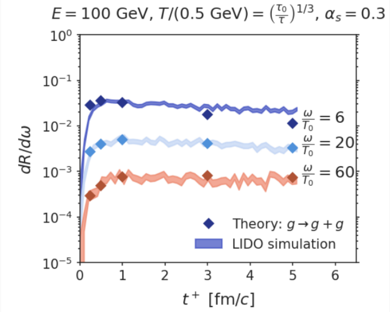
Including interference from multiple scattering (the LPM effect)

- Energetic splitting has long formation time $\tau_f \sim E/k_\perp^2$. All scatterings with medium wihtin τ_f contribute coherently.
- From theory calculation: the rate of medium-induced splittings is suppressed relative to the incoherent limit:

$$\frac{dP_{i\to jk}}{dtdx} \approx \langle\frac{\lambda}{\tau_f}\rangle \frac{dP^{\mathrm{incoh}}_{i\to jk}}{dtdx}$$

$\langle\frac{\lambda}{\tau_f}\rangle$ is estimate for each parton at run time.

- LIDO is fine tuned to reproduce NLL calculation of medium-induced radiation rates.



Reference(theory):PRC82(2010)064902
Reference(theory):PRC58(1998)1706

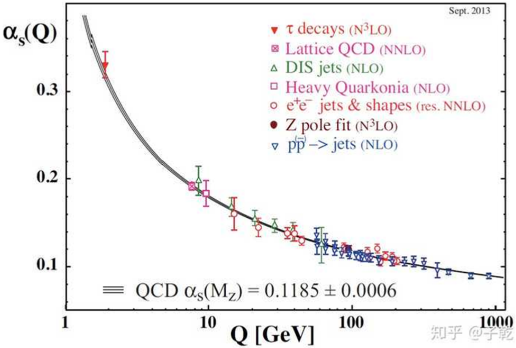
Temperature-Dependent Running Coupling

- At finite temperature, we stop the running of α_s below the thermal scale:

$$\mu_{\min} = C_M \times \pi T$$

- The $N_f = 3$ strong coupling constant is

$$\alpha_s(Q,T) = \frac{4\pi}{9} \cdot \frac{1}{\ln\left(\frac{\max\{Q^2, \mu^2_{\min}\}}{\Lambda^2_{\mathrm{QCD}}}\right)}$$



A simple model for medium response

- Energy-momentum deposition to soft sector:

$$\frac{d\delta p^\mu}{dt}(t,\mathbf{x}) = \int_p \Theta(p\cdot u < E_{\min}) p^\mu \frac{d}{dt} f_H(t,\mathbf{x},p)$$

- An ideal-hydro response (no transverse flow)

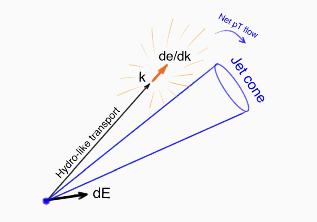
$$\frac{de}{d\Omega'_k} = \frac{\delta p^0 + \hat{k}'\cdot\delta\vec{p}/c_s}{4\pi}, \quad \frac{d\vec{p}}{d\Omega'_k} = \frac{3(c_s\delta p^0 + \hat{k}'\cdot\delta\vec{p})\hat{k}'}{4\pi}$$

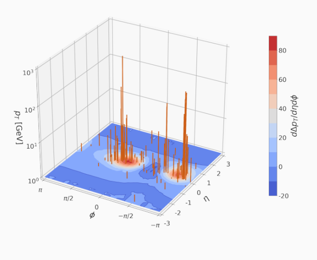
Requires $R_{\text{response}} \gg l_{\text{energy loss}}$.

- Freeze-out to massless particles under a radial transverse flow $v_\perp \Rightarrow$ corrects the momentum density in $\eta-\phi$ plane.

$$\frac{d\Delta p_T}{d\phi d\eta} = \int \frac{3}{4\pi} \frac{\frac{4}{3}\sigma u_\mu - \hat{p}_\mu}{\sigma^4} \delta p^\mu(\hat{k}) \frac{d\Omega_{\hat{k}}}{4\pi}$$

$$\sigma = \gamma_\perp[\cosh(\eta-\eta_s-\eta_{\hat{k}}) - v_\perp\cos(\phi-\phi_{\hat{k}})]$$



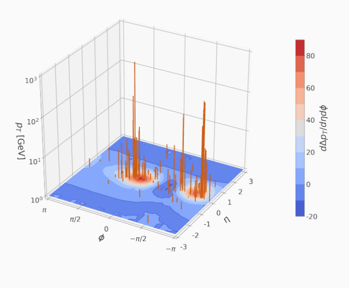


Jet Definition in LIDO with medium response

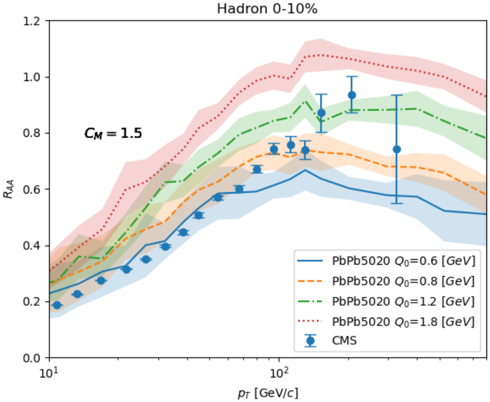
- Jets (anti-k_T) are reconstructed from energy bins $E_{T,ij}$, defined by:

$$E_{T,ij} = \underbrace{\frac{d\Delta p_T}{d\phi d\eta}(\eta_i, \phi_j)\Delta\eta\Delta\phi}_{\text{from medium response}} + \underbrace{\sum_{\substack{|\eta_k-\eta_i|<\Delta\eta/2 \\ |\phi_k-\phi_j|<\Delta\phi/2}} p_{T,k}}_{\text{from parton fragmentations}}$$

- Uncorrelated medium background are assumed to be perfectly subtracted.

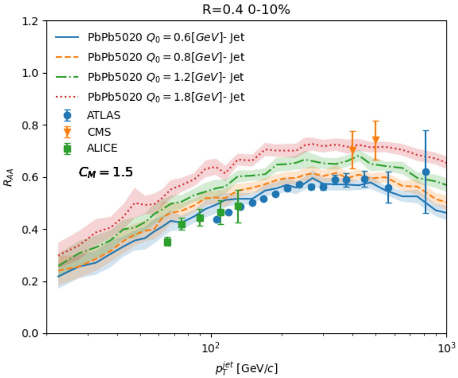


Effect of Q_0 (scale for transport initalization) on hadrons R_{AA}



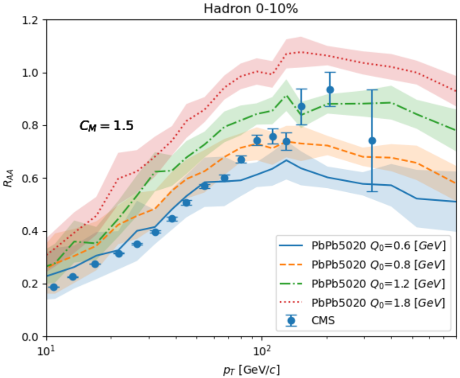
Increasing Q_0 leads to higher R_{AA}

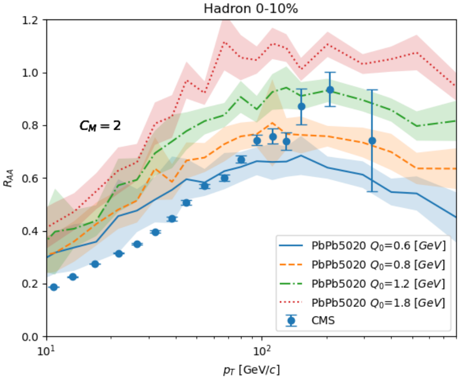
Effect of Q_0 (scale for transport initalization) on jet R_{AA}



Increasing Q_0 leads to higher R_{AA}

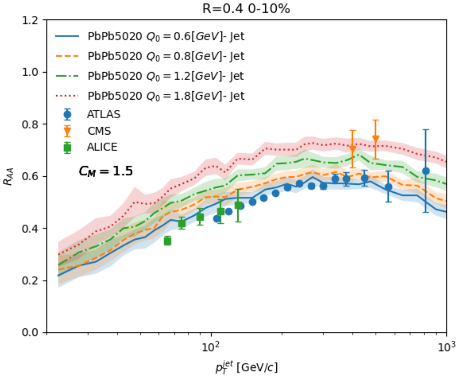
Effect of α_s on Hadrons R_{AA}

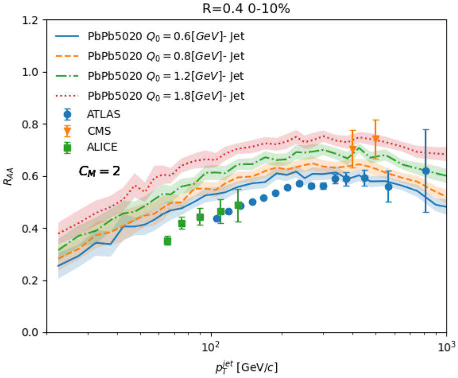




Increasing $C_M \Rightarrow$ decreasing jet-medium coupling at $T \Rightarrow$ less suppression

Sensitivity to effective jet-medium coupling





Increasing $C_M \Rightarrow$ decreasing jet-medium coupling at $T \Rightarrow$ less suppression

Substructure: Energy-Energy Correlator

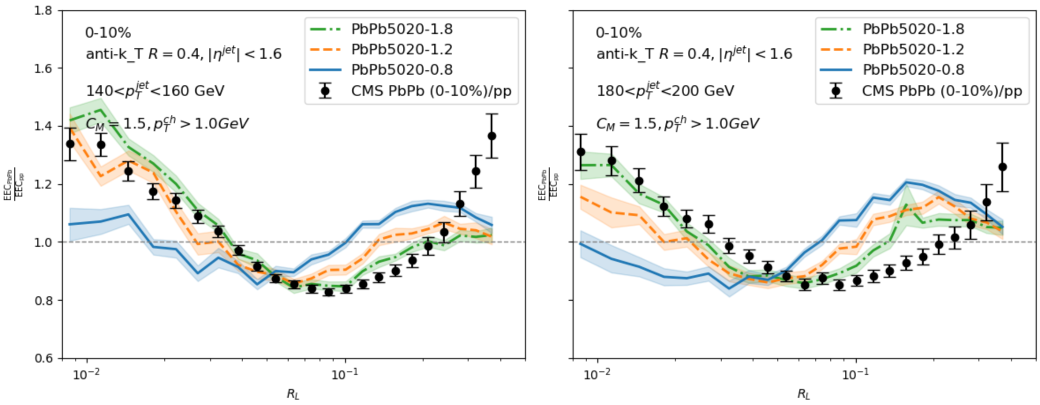
$$\frac{d\Sigma}{d\theta} = \int d\vec{n}_1\, d\vec{n}_2 \frac{\langle \epsilon(\vec{n}_1)\epsilon(\vec{n}_2)\rangle}{Q^2} \delta^2(\vec{n}_1 \cdot \vec{n}_2 - \cos(\theta))$$

$$\text{EEC}(\Delta r) = \frac{1}{W_{\text{pairs}}} \frac{1}{\delta r} \sum_{\text{jets}\in[p_{T,1}, p_{T,2}]} \sum_{\text{pairs}\in[\Delta r_a, \Delta r_b]} (p_{T,i} p_{T,j})^n$$

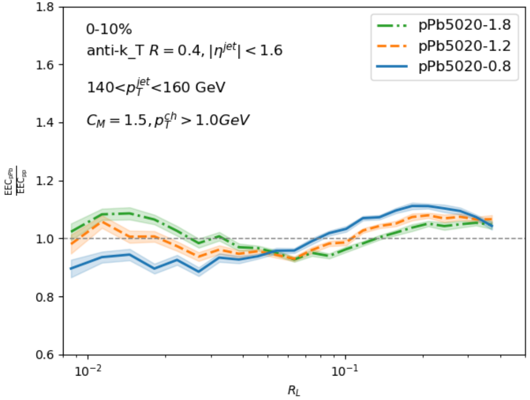
1. Normalize with weighted number of pairs W_{pairs}
2. Bin width normalization: $\delta r = \Delta r_b - \Delta r_a$
3. Exponent values n = 1 used in this analysis

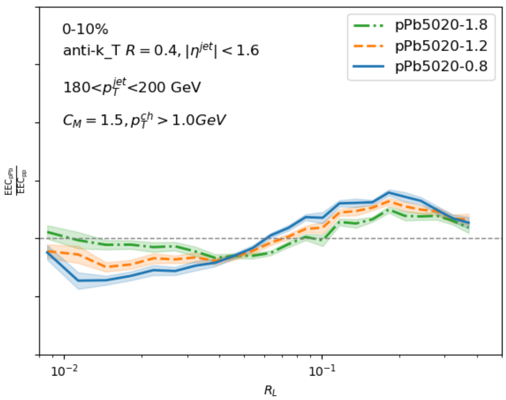
Energy-Energy Correlator Pb+Pb

The medium response contribution $d\Delta p_T/d\phi/d\eta$ has not yet included in the current EEC result (may change large angle behavior)!



Energy-Energy Correlator p+Pb





Summary

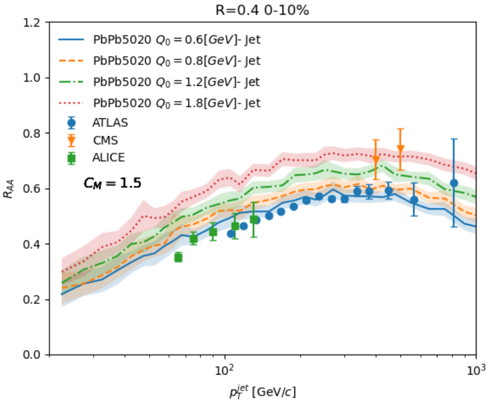
- Investigated jet and hadron nuclear modification factor R_{AA} in heavy-ion collisions at the LHC using the partonic transport model **LIDO**.
- Highlighted the importance of the correlation between **virtuality evolution** and the **space-time development** of in-medium jet showers.
- Analyzed the **Energy-Energy Correlator (EEC)** in PbPb and pPb collisions, and compared results with **CMS** experimental data.
- **Outlook:** Medium response effects need to be included explicitly for accurate EEC calculations.

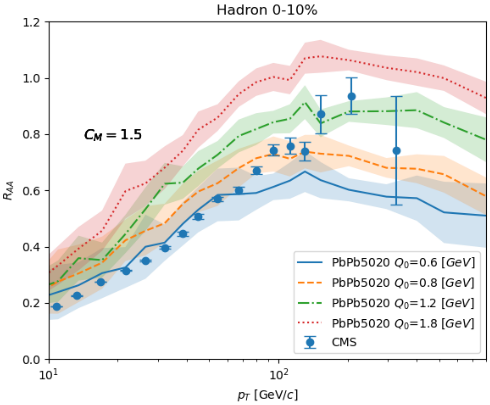
Backup

Impact of Q_0 on Nuclear Modification Factor R_{AA}

The infrared cutoff Q_0 affects leading-hadron R_{AA} more than jet R_{AA}:

- **Jet** R_{AA}**:** Multi-particle jets retain soft radiation inside the cone. Less sensitive to Q_0.
- **Hadron** R_{AA}**:** Single-particle energy loss is directly linked to Q_0. More sensitive.





Introduction for LIDO model

We categorize interactions into elastic (hard particle number conserving) and inelastic collisions (hard particle number non-conserving). The inelastic processes are further divided into parton-splitting and parton-fusion contributions.

Elastic collision

- $q_\perp < Q_{cut}$

$$D[f] = (\eta_{DP} + \frac{\hat{q}_s}{4}\frac{\partial^2}{\partial p^2})f$$

- $q_\perp > Q_{cut}$

$$C^a_{2\leftrightarrow 2}(p_a) = \sum_{bcde} \nu_c \int_{q_\perp > Q_{\rm cut}} d\Pi^{p_b p_c}_{p_d p_e} |M|^2_{p_b p_c; p_d p_e} f_b(p_b) f_0(p_c) (2\pi)^3 \left[-\delta^{(3)}(p_a - p_b)\delta^{ab} + \sum_{i=d,e} \delta^{(3)}(p_a - p_i)\delta^{ai} \right]$$

$$Q_{cut} = min(\{2m_D, \sqrt{6ET}\})$$

Introduction for LIDO model

Incoherent inelastic processes are divided into small-Q diffusion induced radiation/absorption $(1 \leftrightarrow 2)$, and large-Q $2 \leftrightarrow 3$ processes.

Inelastic collision $(1 \leftrightarrow 2)$

$|q| < Q_{cut}$

$$C^a_{1\leftrightarrow 2}(p) = \sum_{bcd} \int dx d\mathbf{k}_\perp^2 \frac{\alpha_s(k_\perp) P^b_{cd}(x)}{(2\pi)(\mathbf{k}_\perp^2 + m_\infty^2)^2} \left[-\hat{q}_{g,s}(p) f_b(p) \delta^{ab} + \frac{\hat{q}_{g,s}\left(\frac{p}{1-x}\right) f_b\left(\frac{p}{1-x}\right)}{1-x} \delta^{ac} + \frac{\hat{q}_{g,s}\left(\frac{p}{x}\right) f_b\left(\frac{p}{x}\right)}{x} \delta^{ad} \right]$$

Inelastic collision $(2 \leftrightarrow 3)$

$|q| > Q_{cut}$

$$C^a_{2\leftrightarrow 3}(p_a) = \sum_{bcdef} \nu_c \int_{q_\perp > Q_{\rm cut}} d\Pi^{p_b p_c}_{p_d p_e p_f} |M|^2_{p_b p_c, p_d p_e p_f} f_b(p_b) f_0(p_c) (2\pi)^3 \left[-\delta^{(3)}(p_a - p_b)\delta^{ab} + \sum_{f=d,e,f} \delta^{(3)}(p_a - p_i)\delta^{ai} \right]$$
$$+ \left[\text{Absorption term}\right]$$