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Light and heavy meson production in small collision systems

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Los Alamos
NATIONAL LABORATORY

Outline of the Talk

SQM 2026

- Modelling of small systems
- Light and heavy flavor modification
- Comparison between p+Pb and O+O, from earlier measurements
- New results for O+O and Ne+Ne and comparison to recent measurements
- Energy correlators in small systems, O+O and Ne+Ne, recent measurements
- Conclusions

Credit for this work should be given to Weiyao Ke and Bianka Mecaj

Acknowledgment of support

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

U.S. DEPARTMENT OF ENERGY

HEFTY COLLABORATION

CNM implementation and results

Specific CNM effects we consider arise from the elastic, inelastic, and coherent re-scattering of partons in nuclei

M. Gyulassy et al. (2002)

- **Cronin effect (and of course isospin)**

$$g(\mathbf{k}) = \exp(-\mathbf{k}_T^2/\langle \mathbf{k}_T^2\rangle_{pp})/\pi\langle \mathbf{k}_T^2\rangle_{pp},$$

$$\langle k_T^2\rangle_{pA} \approx \langle k_T^2\rangle_{pp} + L_A \frac{\mu^2}{\lambda}\ln(1 + c\, p_T^2/\mu^2)$$

- **Coherent power corrections**

$$\Delta x_i/x_i \sim \mu^2 A^{1/3}/(-u)$$

$$\Delta x_j/x_j \sim \mu^2 B^{1/3}/(-t)$$

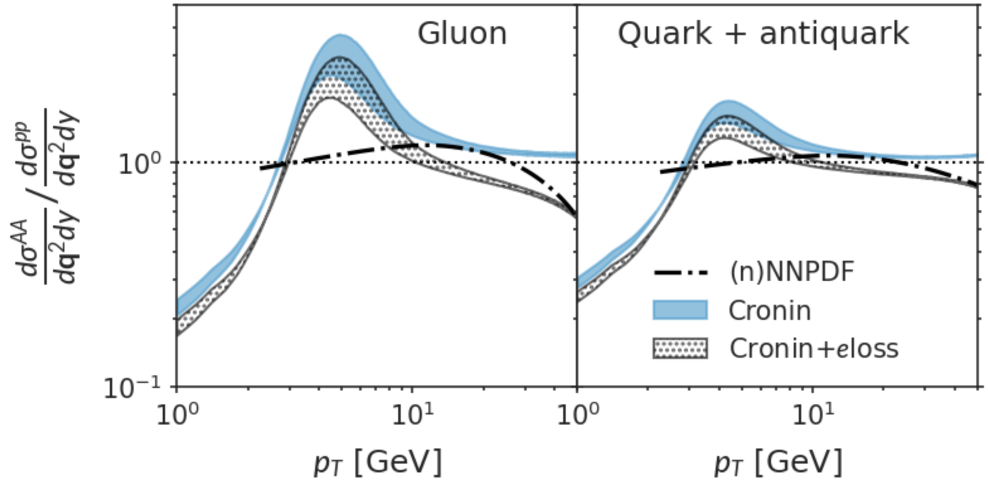
J. Qiu et al. (2005)

- **CNM energy loss**

I.V. (2007)

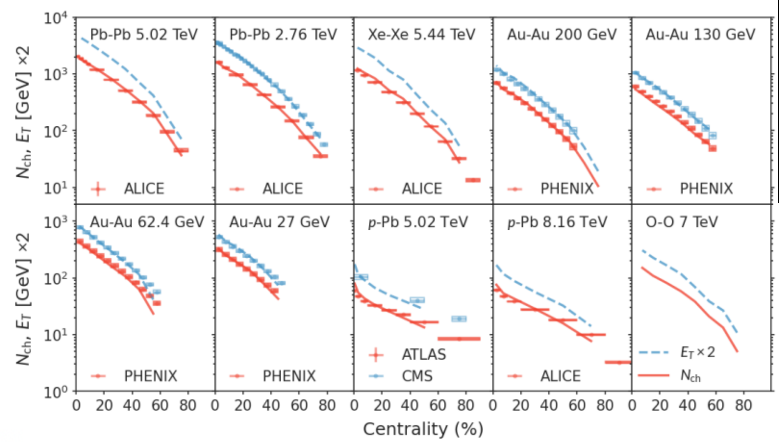
$$\Delta x/x = \epsilon_{\rm fl}\int_{m_N/p^+}^{1} dx \int_{x m_N \le |\mathbf{k}| \le x p^+} d^2\mathbf{k}\, x \frac{dN_{\rm IS}}{dx d^2\mathbf{k}}$$

Parton level results at RHIC compared to nPDF parameterization



For prospects for better (TMD based) description of the low p_T region Cronin effect, etc see W. Ke et al. (2005) (beyond this collinear factorization scope)

QGP effects



Hydro medium and TRENTO initial conditions

J. Bernhard (2018)

Final-state collisional and radiative processes

- **Collisional energy loss**

$$\frac{dE_{\rm el}}{d\Delta z} = \frac{C_F}{4}\left(1+\frac{N_f}{6}\right)\alpha_s(ET)g_s^2T^2\ln\left(\frac{ET}{m_D^2}\right)\left(\frac{1}{v}-\frac{1-v^2}{2v^2}\ln\frac{1+v}{1-v}\right)$$

- **In-medium splitting functions / radiative energy loss**

M. Sievert et al. (2019)

$$\mathbf{A}=\mathbf{k},\ \mathbf{B}=\mathbf{k}+x\mathbf{q},\ \mathbf{C}=\mathbf{k}-(1-x)\mathbf{q},\ \mathbf{D}=\mathbf{k}-\mathbf{q},$$
$$\omega_1=\frac{\mathbf{B}^2}{x(1-x)p^+},\quad \omega_2=\frac{\mathbf{C}^2}{x(1-x)p^+},$$
$$\omega_3=\frac{\mathbf{C}^2-\mathbf{B}^2}{x(1-x)p^+},\quad \omega_4=\frac{\mathbf{A}^2}{x(1-x)p^+},\quad \omega_5=\frac{\mathbf{A}^2-\mathbf{D}^2}{x(1-x)p^+}.$$

$$\frac{dN_{qq}^{\rm med}}{dx d\mathbf{k}^2} \equiv P_{qq}(x,\mathbf{k}^2)\int_0^\infty d\Delta z\int d^2\mathbf{q}\frac{dR_g(\Delta z)}{d^2\mathbf{q}}$$
$$\left\{\left[\frac{\mathbf{B}}{\mathbf{B}^2}\cdot\left(\frac{\mathbf{B}}{\mathbf{B}^2}-\frac{\mathbf{C}}{\mathbf{C}^2}\right)+\frac{1}{N_c^2}\frac{\mathbf{B}}{\mathbf{B}^2}\cdot\left(\frac{\mathbf{A}}{\mathbf{A}^2}-\frac{\mathbf{B}}{\mathbf{B}^2}\right)\right][1-\cos(\omega_1\Delta z)]\right.$$
$$+\frac{\mathbf{C}}{\mathbf{C}^2}\cdot\left(2\frac{\mathbf{C}}{\mathbf{C}^2}-\frac{\mathbf{A}}{\mathbf{A}^2}-\frac{\mathbf{B}}{\mathbf{B}^2}\right)[1-\cos(\omega_2\Delta z)]+\frac{\mathbf{B}}{\mathbf{B}^2}\cdot\frac{\mathbf{C}}{\mathbf{C}^2}[1-\cos(\omega_3\Delta z)]$$
$$\left.-\frac{\mathbf{A}}{\mathbf{A}^2}\cdot\left(\frac{\mathbf{A}}{\mathbf{A}^2}-\frac{\mathbf{D}}{\mathbf{D}^2}\right)[1-\cos(\omega_4\Delta z)]-\frac{\mathbf{A}}{\mathbf{A}^2}\cdot\frac{\mathbf{D}}{\mathbf{D}^2}[1-\cos(\omega_5\Delta z)]\right\},$$

Also evaluated branching for heavy flavor and the energy loss limit

System size dependence (expanding QGP)

$$\frac{\Delta E_{\rm el}}{E}\propto\int_{\tau_0}^{\tau_0+L}\mu^2 d\Delta z\propto L^{1/3}\qquad \frac{\Delta E_{\rm rad}}{E}\propto\int_{\tau_0}^{\tau_0+L}\frac{\mu^2}{\lambda_g}\Delta z d\Delta z\propto L$$

Much weaker path length dependence of collisional vs radiative E-loss. Implies increased importance in small systems

Evolution of heavy flavor fragmentation functions

Heavy - Lund-Bowers FF

DGLAP evolution equations

$$D(z) = z^{-1-bM_\perp^2}(1-z)^a e^{-\frac{bM_\perp^2}{z}}$$

M. Bowers (1981)

V. Gribov et al. (1972)

Y. Dokshitzer (1977)

G. Altarelli et al. (1977)

$$\frac{\partial D^0_{h/i}(z,Q^2)}{\partial \ln Q^2} = \sum_j \int_z^1 \frac{dx}{x}\left[P'_{ji}(x \to 1-x, Q^2) + d_{ji}(Q^2)\delta(1-x)\right] D_{h/j}\left(\frac{z}{x}, Q^2\right)$$

Singular part coefficients

$$d_{qq}(Q^2) = \frac{\alpha_s(Q^2)}{2\pi} C_F \frac{3}{2},$$

$$d_{HH}(Q^2, r) = \frac{\alpha_s(Q^2)}{2\pi} C_F c_{HH}(r),$$

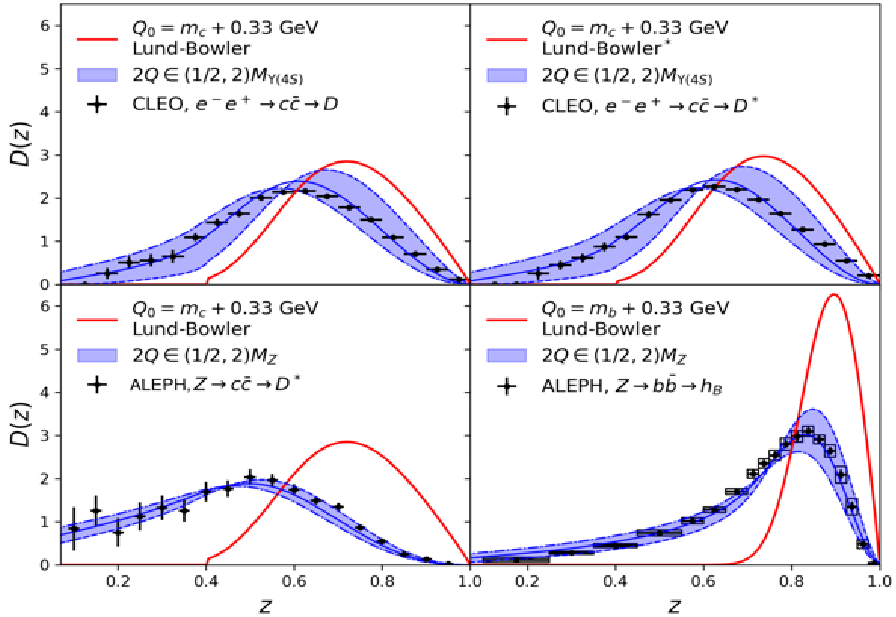
$$d_{gg}(Q^2, r) = \frac{\alpha_s(Q^2)}{2\pi}\left[\frac{11}{6}N_c - N_f T_F \frac{2}{3} + \sum_{H=c,b} T_F c_{gH}(r)\right]$$

$$c_{gH}(r) = F\left(\frac{1+\sqrt{1-4r^2}}{2}\right) - F\left(\frac{1-\sqrt{1-4r^2}}{2}\right) - 2r^2\sqrt{1-4r^2},$$

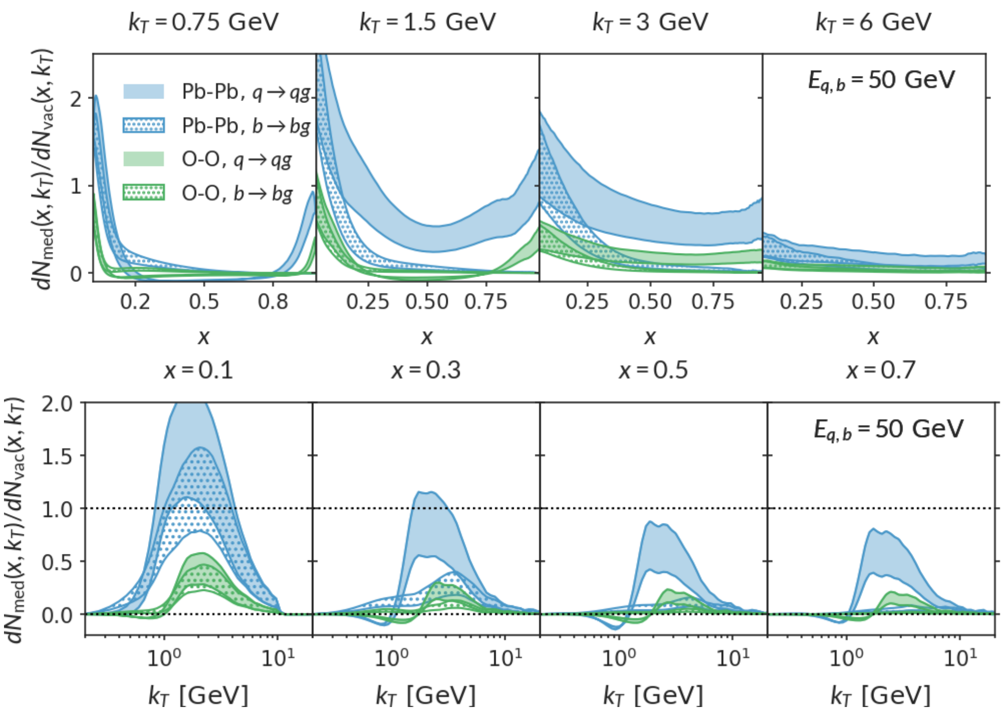
$$F(x) = -x^4 + \frac{4}{3}x^3 - x^2,$$

$$c_{HH}(r) = \frac{1}{1+r^2} + \frac{2r^2+1}{2(1+r^2)^2} + \frac{2r^2}{1+r^2} - 2\ln\frac{1}{1+r^2}.$$

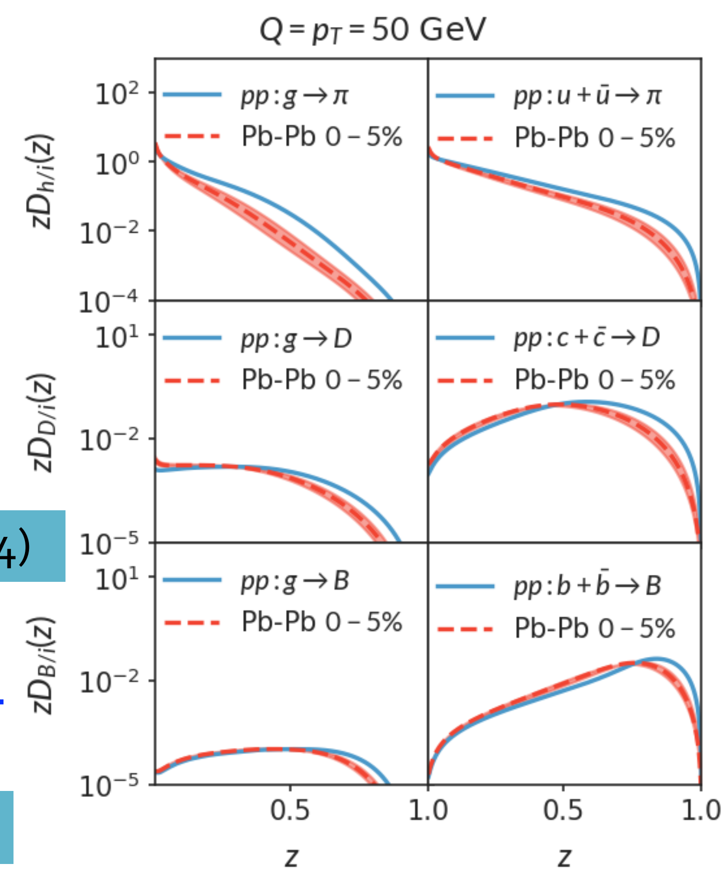
Heavy flavor specific $r = M/Q$



Light and heavy flavor fragmentation and evolution



Enhancement of soft branching and larger angle radiation



Z. Kang et al. (2014)

In-medium DGLAP evolution

$$P'_{ji} \to P'_{ji} + \mathbf{k}^2 \frac{dN^{\rm med\,\prime}_{ji}}{dx d\mathbf{k}^2} \quad \text{with } x \to 1 - x,$$

$$d_{ji}(Q^2) \to d_{ji}(Q^2) + d^{\rm med}_{ji}(Q^2)$$

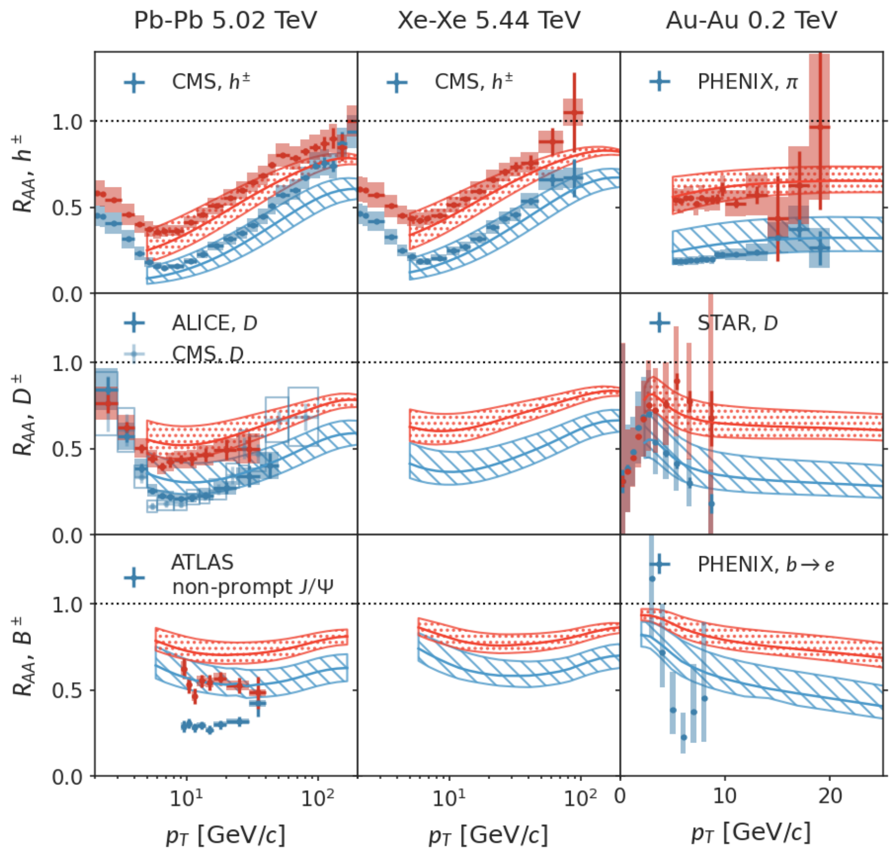
Additional medium-induced scaling violations. For analytic treatment

W. Ke et al. (2025)

Phenomenological results

Large systems

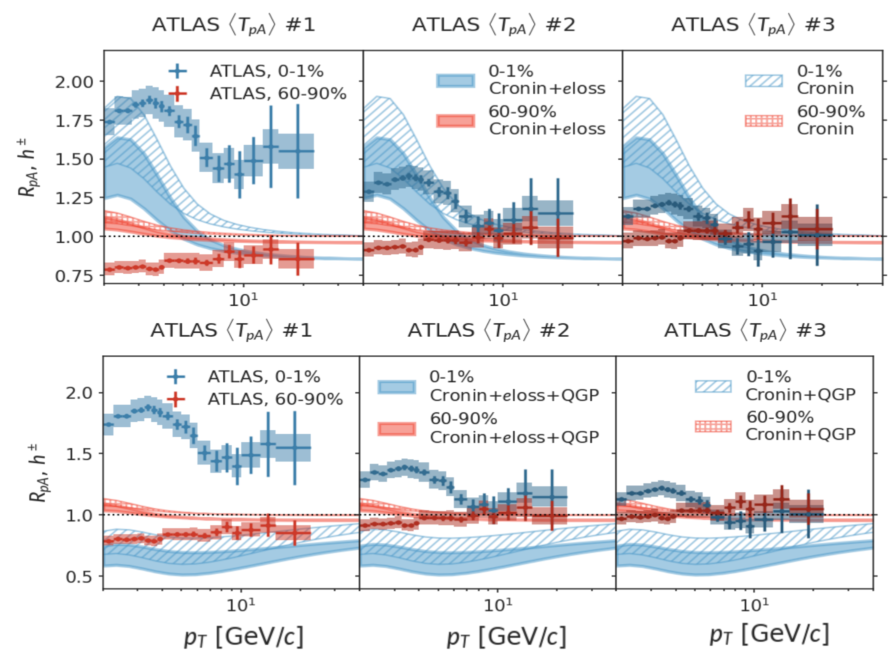
Radiative processes dominate



W. Ke et al. (2023)

- **Theoretical results agree with existing light hadron and D meson measurements at RHIC and LHC. True for both central and peripheral collisions**
- **There is tension with the B meson production (or non-prompt J/psi). May be dissociation?**

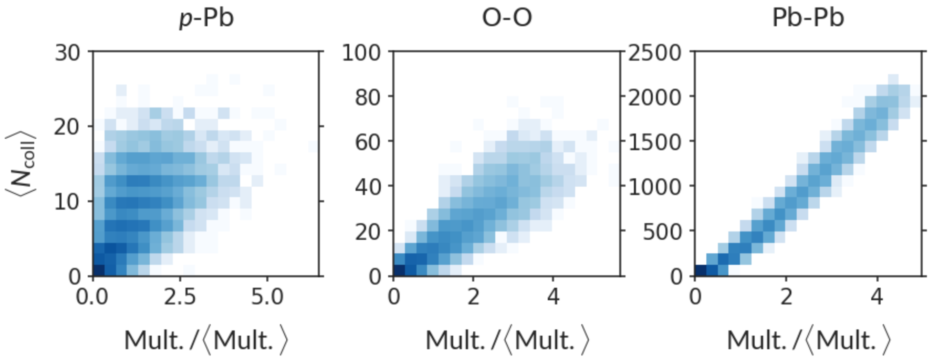
Small systems



Centrality determination in p/d+A challenging. No room for quenching effects in p+Pb from these measurements

QGP in small systems?

Correlation between multiplicity and number of collisions can be vastly improved in collisions of small nuclei (such as O+O, Ne+Ne)



Correlation between multiplicity and centrality

- From jet quenching perspective whether QGP is produced or not can be easily distinguished in small systems (assuming good determination of centrality)

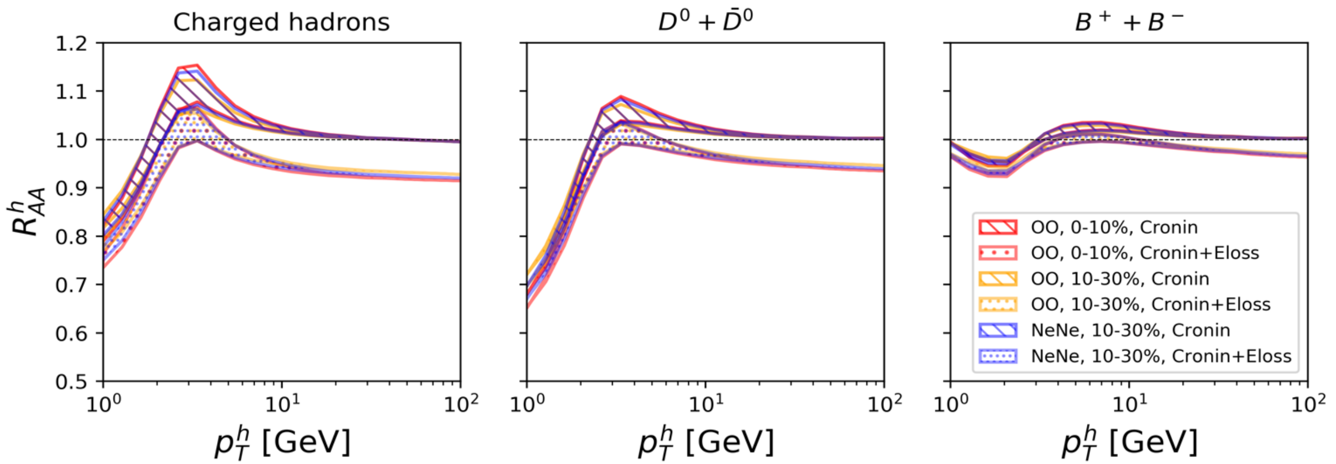
Form earlier comparisons such as p+Pb, we chose the smaller CNM effects. Still calculate with a and without cold nuclear matter energy loss.

Without QGP

Results presented:

- With CNM
- With CNM + Rad.
- With CNM + Rad. + Coll.

Compatible with preliminary ALICE and CMS data, albeit on the upper edge



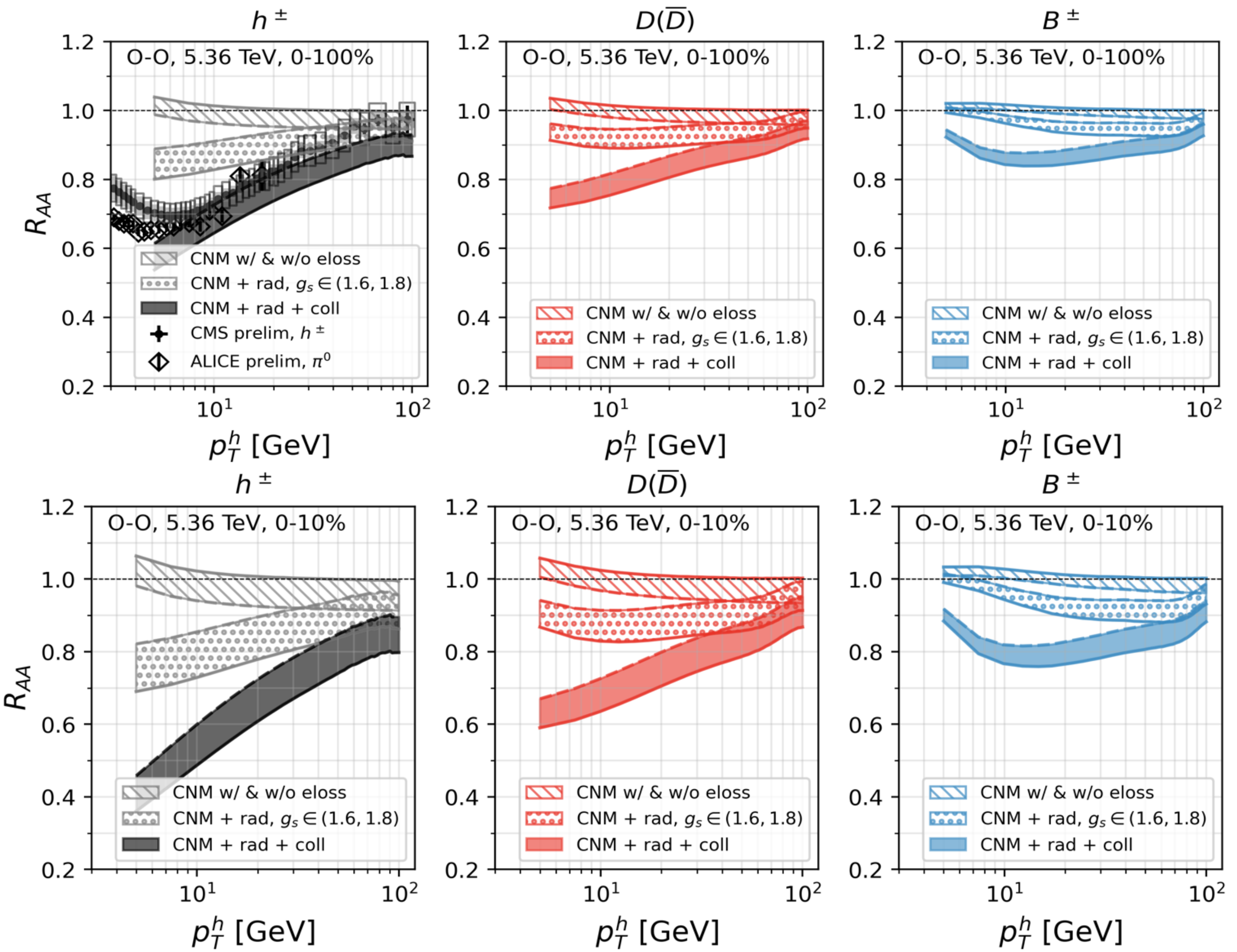
Predictions vs centrality for O+O

- Same trends seen as a function of centrality. No surprises in small but symmetric collisions systems

- For 10-30% pre modification is very, very similar to min-bias collisions
- For 0-10% the suppression is somewhat larger but not by much

Suggest smaller collisional energy losses

W. Ke et al. (2026) CMS (2025) ALICE (2025)

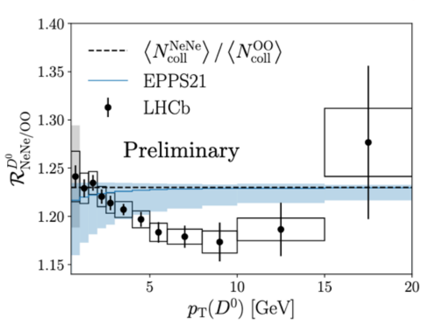


Additional predictions for Ne+Ne

- Ne+Ne/O+O within 5%, 10% at most. Differences mostly low to intermediate p_T

- **Reduction of QGP density at forward y taken into account**
- **Note that LHCb uses different normalization**

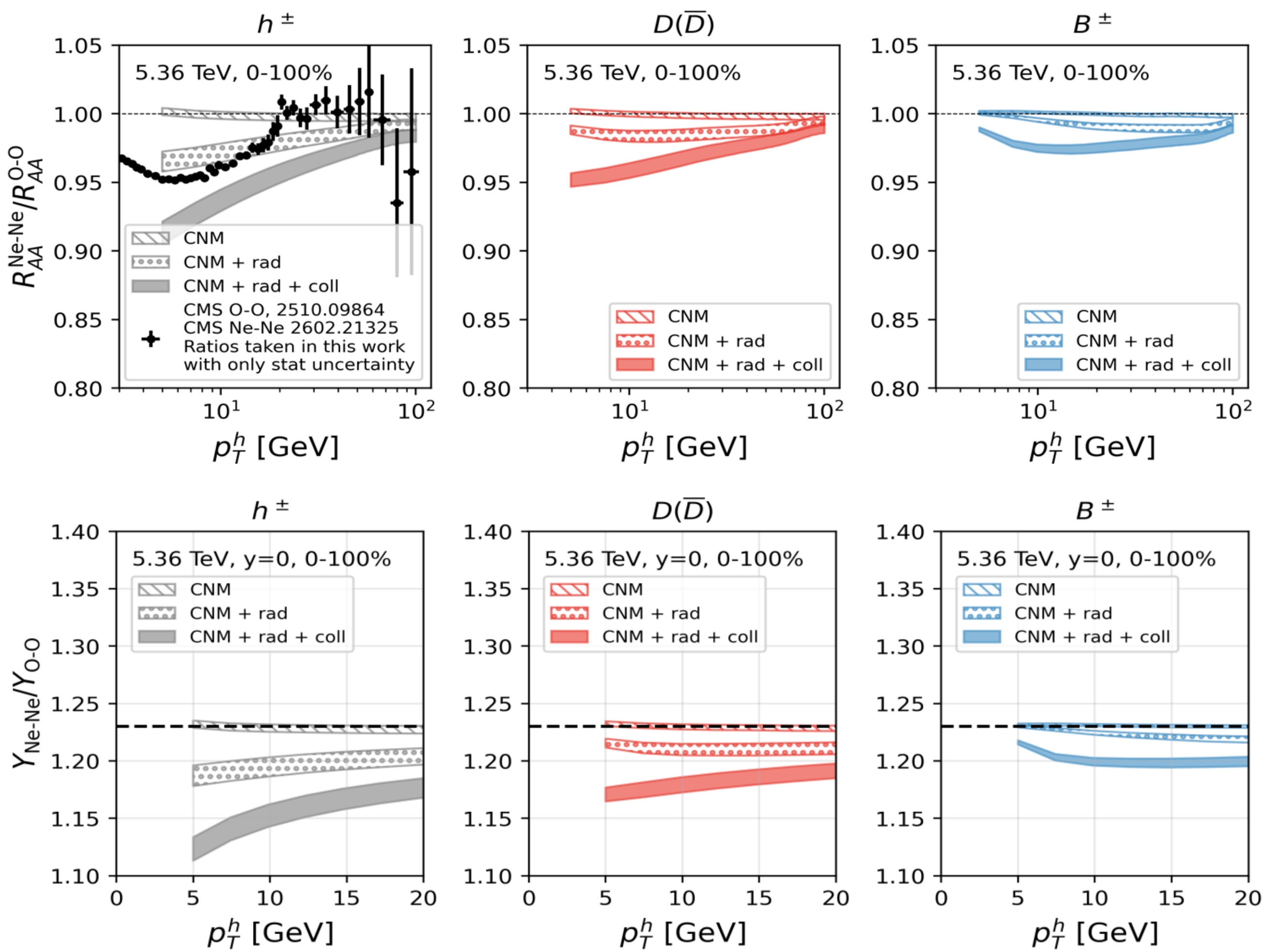
LHCb-PAPER-2026-008 (NEW!)



W. Ke et al. (2026)

CMS (2026)

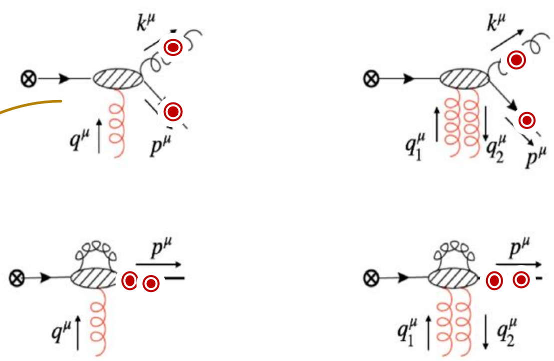
LHCb (2026)



Energy correlators in matter

B. Mecaj et al . (2025)

- EEC captures the redistribution of energy inside the jet caused by multiple scatterings in the medium.
- Medium interactions are described via medium induced splitting function at any order in opacity, SCET with Glauber gluons



The EEC in the medium becomes a weighted cross section using the TMD splitting functions

$$\frac{d\Sigma^{RR}}{d^{2-2\epsilon}\vec{\theta}} = \frac{g^2 C_F}{(2\pi)^3}\int dx P_{qq,\epsilon}(x) x(1-x)\int \frac{d^{2-2\epsilon}\mathbf{k}}{(2\pi)^{-2\epsilon}}\sum_T \int_0^\infty dz^+ \rho_T^-(z^+)\int \frac{d^{2-2\epsilon}\mathbf{q}}{(2\pi)^{2-2\epsilon}}\frac{g^2 C_T/d_A}{(\mathbf{q}^2+m^2)^2}$$
$$\delta^{(2-2\epsilon)}\left(\vec{\theta}-\frac{\mathbf{k}-(1-x)\mathbf{q}}{x(1-x)P^+/2}\right) g^2 \left\{\frac{C_F}{[\mathbf{k}-(1-x)\mathbf{q}]^2} + (2C_F - C_A)\left[\frac{1}{\mathbf{k}^2} - \frac{\mathbf{k}\cdot(\mathbf{k}-(1-x)\mathbf{q})}{\mathbf{k}^2(\mathbf{k}-(1-x)\mathbf{q})^2}\right]\phi\left(\frac{\mathbf{k}^2 z^+}{2x(1-x)P^+}\right)\right.$$
$$+ C_A\left[\frac{1}{(\mathbf{k}-\mathbf{q})^2} - \frac{(\mathbf{k}-\mathbf{q})\cdot(\mathbf{k}-(1-x)\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2(\mathbf{k}-(1-x)\mathbf{q})^2}\right]\phi\left(\frac{(\mathbf{k}-\mathbf{q})^2 z^+}{2x(1-x)P^+}\right) + C_A\left[\frac{1}{(\mathbf{k}-\mathbf{q})^2} - \frac{\mathbf{k}\cdot(\mathbf{k}-\mathbf{q})}{\mathbf{k}^2(\mathbf{k}-\mathbf{q})^2}\right]\phi\left(\frac{(\mathbf{k}-\mathbf{q})^2 z^+}{2x(1-x)P^+}\right)$$
$$\left.+ C_A\left[\frac{1}{\mathbf{k}^2} - \frac{(\mathbf{k}-\mathbf{q})\cdot\mathbf{k}}{(\mathbf{k}-\mathbf{q})^2\mathbf{k}^2}\right]\phi\left(\frac{\mathbf{k}^2 z^+}{2x(1-x)P^+}\right) + C_A\frac{\mathbf{k}\cdot(\mathbf{k}-\mathbf{q})}{\mathbf{k}^2(\mathbf{k}-\mathbf{q})^2}\phi\left(\frac{[\mathbf{k}^2-(\mathbf{k}-\mathbf{q})^2]z^+}{2x(1-x)P^+}\right)\right\}$$

Multiple scales that can be resolved through an in-medium factorization theorem.

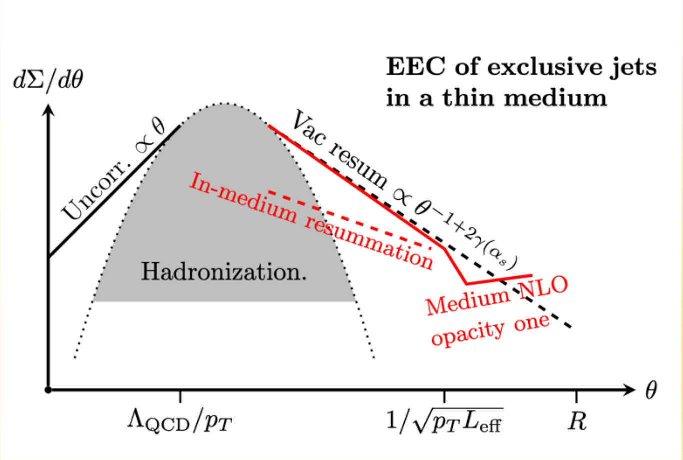
$$\Lambda_{\mathrm{QCD}} \ll \mu_{\mathrm{med}} \ll p_T\theta \ll Q$$

$$\frac{d\Sigma}{d\theta\, dp_T\, dy} = \sum_{a,b,c}\int dx_a\, dx_b\, dz_J\; f_{a/A}(x_a,\mu)\, f_{b/B}(x_b,\mu)\; H_{ab\to c}\left(\frac{p_T}{z_J},\, y;\mu\right)$$
$$\times\left[J^{\mathrm{vac}}(\theta;\, z_J,\, p_T R, m_Q,\mu) + J^{\mathrm{med}}(\theta;\, z_J,\, p_T R, m_Q,\mu;\, L, m_{\mathrm{eff}})\right]$$

Jet function: Encodes in-medium effects

The jet function in matter

- Describes **collinear radiation inside the jet** propagating through a QCD medium.
- Encodes how **multiple scattering and induced gluon emission** modify the jet substructure.



One can obtain semi-analytic results suitable for RG evolution

W. Ke et al. (2023)

Example: The quark medium jet function

$$F_\epsilon^{q\to qg}(x) \times \kappa_\epsilon^{\text{med}} \times T_\epsilon\left(\frac{\mu^2}{2P^+/L_{\text{eff}}^+}\right)$$

Jet function: Encodes in-medium effects

Medium properties

$$\kappa^{\text{med}} = \frac{\rho_{\text{eff}}^- L_{\text{eff}}^+}{2P^+/L_{\text{eff}}^+}$$

Medium properties + EEC kinematics

$$T_\epsilon\left(\frac{\mu^2}{2P^+/L_{\text{eff}}^+}\right) = \alpha_s^2(\mu^2)\frac{1}{2}\left[\frac{\mu^2 e^{\gamma_E - 1}}{2P^+/L_{\text{eff}}^+}\right]^{2\epsilon}\left(1 + \mathcal{O}(\epsilon^2)\right)$$

Weighting effects: EEC kinematics

$$F_\epsilon^{q\to qg}(x) = C_F P_{qq,\epsilon}(x)\frac{1}{[x(1-x)]^{1+2\epsilon}}\left[(1-x)^{2+2\epsilon}(2C_F - C_A) + x^{2+2\epsilon}C_A + C_A\right]$$

Formally the in-medium jet function tests the **structure of medium-induced splitting** functions probe the medium modifications of QCD splitting functions.

In-medium EEC evolution

The factorization theorem enables a clean separation of scales as well as separation of medium and vacuum effects: **track down evolution effects due to medium and scales in the medium.**

- RGE describes how collinear radiation evolves the observable as the jet traverses the QCD medium.

$$\frac{d\Sigma}{d\theta^2} = \frac{d\Sigma^{vac}}{d\theta^2} + \frac{d\Sigma^{med}}{d\theta^2}$$

$$\frac{\partial}{\partial \ln \mu^2}\begin{bmatrix}\Sigma_q \\ \Sigma_g\end{bmatrix} = \frac{\alpha_s(\mu^2)}{2\pi}\begin{bmatrix}\gamma_{qq}^{\rm vac} + \Delta\gamma_{qq}^{\rm N=1} & \gamma_{gq}^{\rm vac} + \Delta\gamma_{gq}^{\rm N=1} \\ \gamma_{qg}^{\rm vac} + \Delta\gamma_{qg}^{\rm N=1} & \gamma_{gg}^{\rm vac} + \Delta\gamma_{gg}^{\rm N=1}\end{bmatrix}$$

Modifications to the anomalous dimensions due to medium effects.

N=3 two point
N=4 three point
...
(different N)

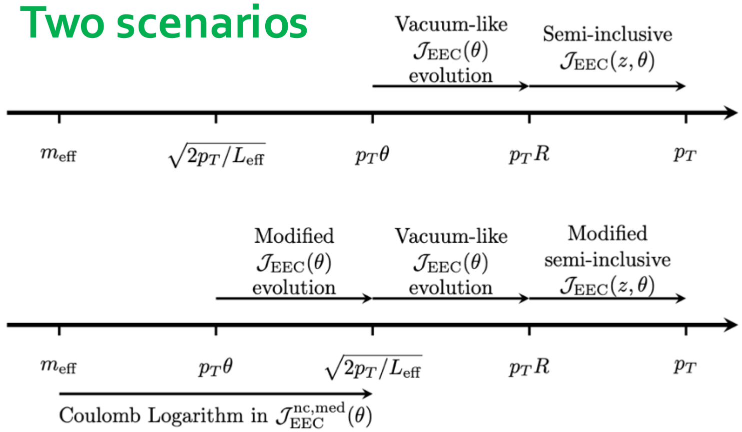
$$\Delta\gamma_{qq}^{\rm med}(N) = w_{\rm med} \times \left(2(N-1)C_F C_A + C_F^2\right) ,$$
$$\Delta\gamma_{gq}^{\rm med}(N) = w_{\rm med} \times \left(-C_F^2\right) ,$$
$$\Delta\gamma_{gg}^{\rm med}(N) = w_{\rm med} \times \left(2(N-1)C_A^2 + 2N_f T_F C_F\right) ,$$
$$\Delta\gamma_{qg}^{\rm N=1}(N) = w_{\rm med} \times \left(-2N_f T_F C_F\right) ,$$

with

$$w_{\rm med} \equiv 4\pi\alpha_s(\mu^2)\kappa^{\rm med} = \frac{4\pi\alpha_s(\mu^2)\rho_{\rm eff}L_{\rm eff}}{2p_T/L_{\rm eff}} \ll 1$$

Different types of logarithms: Coulomb + medium modified EEC kinematics

Two scenarios

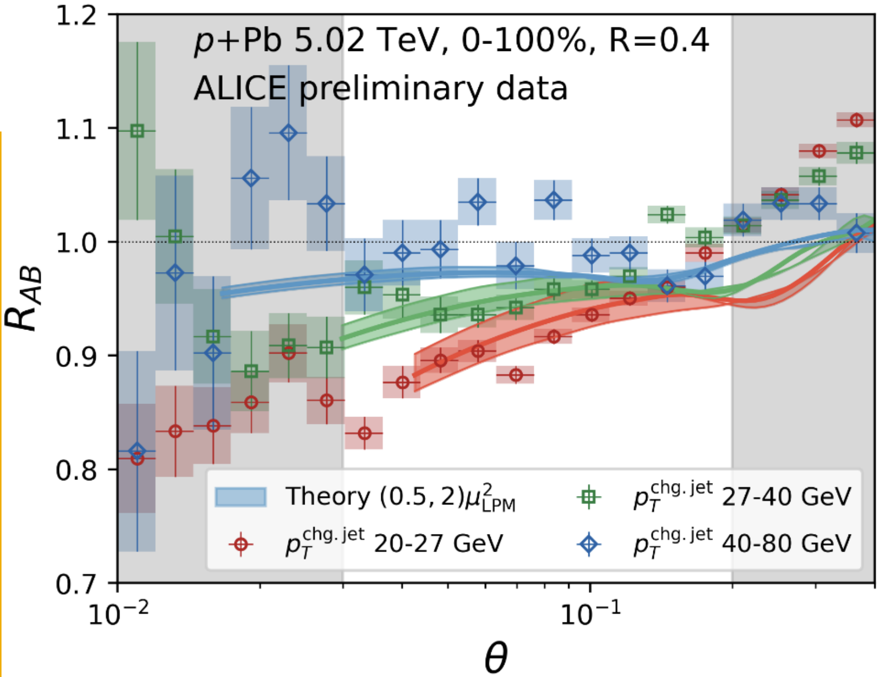


Energy correlators in matter

The observable $R_{pA}(\theta) = \frac{(d\Sigma/d\theta^2)_{pA}}{(d\Sigma/d\theta^2)_{pp}}$

- Reproduction of the small-angle **suppression** and the **large angle bump** demonstrates that sensitivity to the microscopic structure of the QGP and its space–time evolution.
- Even in small systems, the QGP induces ~ 10-20% effects, angular redistribution of jet energy: **probe of its microscopic and collective dynamics**.

Uncertainties studied, CNM effects can be explored more. Overall shape and magnitude consistent with final-state QGP-like modification



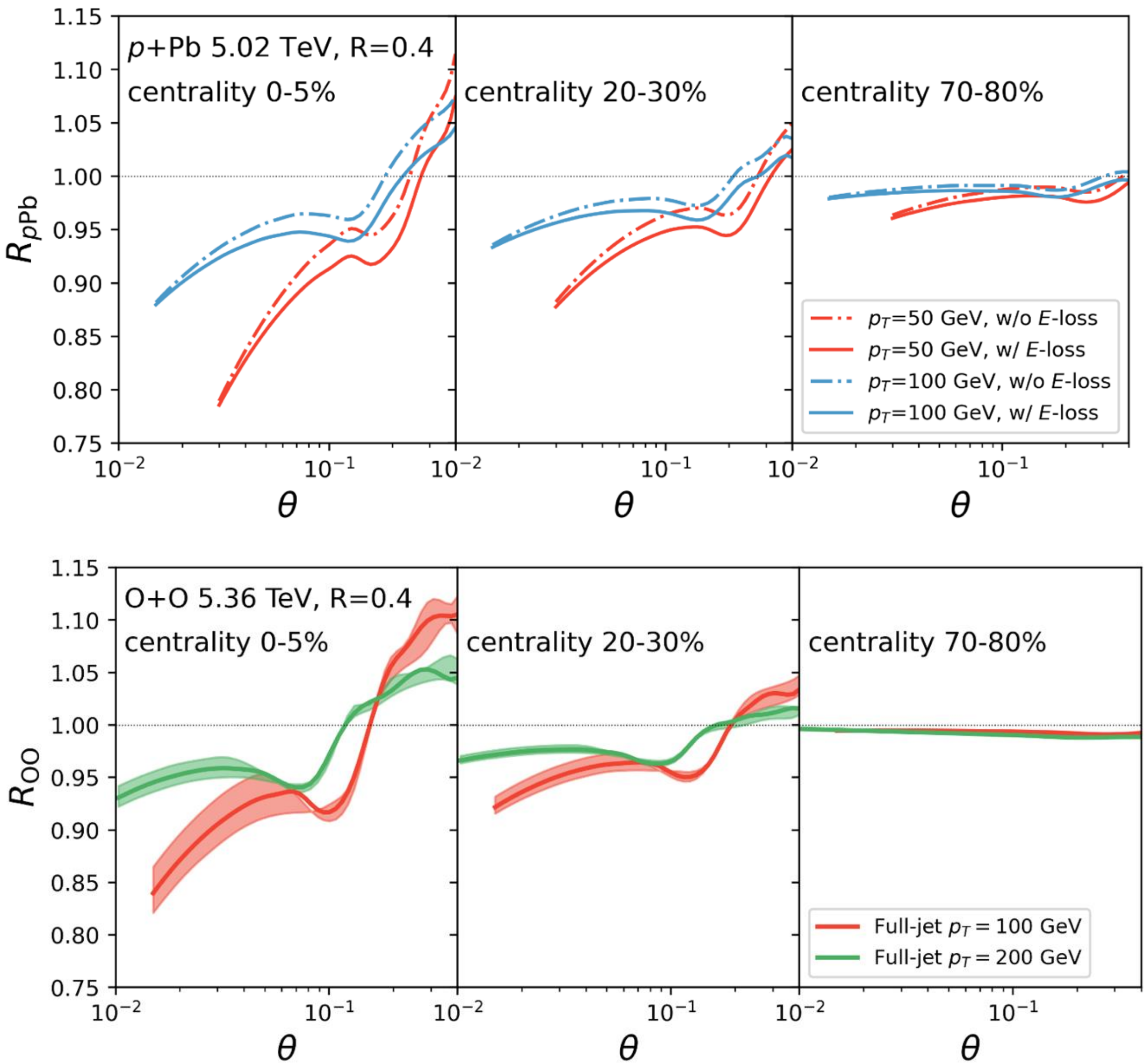
Describes the qualitative features of the preliminary ALICE data across the entire angular range.

Initial time τ_0	Decoupling T_d	g_s^{med}	$p_{T,cut}$	Screening	Glauber UV cut
0.1 fm/c	0.155 GeV	2.0	0.0 GeV	$\frac{1}{q^2} \to \frac{1}{q^2+m^2_{eff}}$	$\sqrt{3ET}$

D. Perepelitsa (2024)

B. Mecaj et al . (2025)

Comparison in small systems



p-Pb collisions on - top
O-O collisions - bottom

- To avoid some of the issues with current measurements going to higher jet p_T will be useful
- Very similar behavior between p-Pb and O-O for the correlator modification
- Attempt EEC anomalous dimension or opacity extraction from different systems

B. Mecaj et al . (2025)

Conclusions

- An important question is whether QGP can be produced in small ~ p-sized but elongated systems versus small but spherical systems with roughly the same soft particle multiplicity
- We addressed this question with inclusive hadron production in p+Pb and O+O/Ne+Ne, considering cold nuclear matter and QGP effects. The analysis accounts for heavy quark mass effects, solves mDGLAP with full in-medium splitting functions
- At the LHC p+A results are not incompatible with the QGP assumption in but uncertainties on centrality determination remain (various scenarios). In O+O results are perfectly consistent with the QGP formation scenario. Ne+Ne/O+O informative at low to intermediate $p_{T.}$ Suggestive of smaller collisional e-losses than in the calculation
- We further performed a first principles calculation of energy correlators. Derived and RG equations for the observable and presented phenomenological applications. The modification of EEC is consistent with QGP formation in small asymmetric systems p+Pb (and is similar for O+O)
- From the point of view of jet quenching, there isn't a clear conclusion in p+Pb (and d+Au). Inclusive hadron suppression at LHC – NO, EEC modification YES. Both measurements have their uncertainties, additional observables, both inclusive and differential, in p+Pb can help.