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The smallest QGP droplet

System-size dependence of hydrodynamization in kinetic theory

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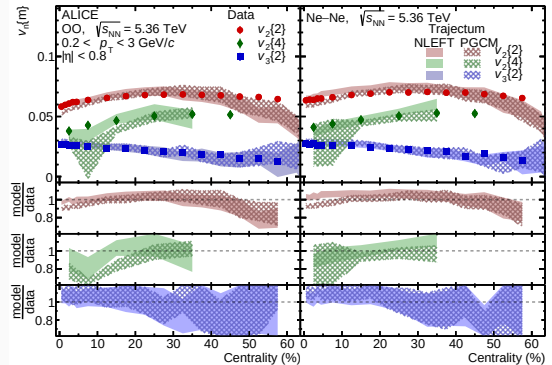
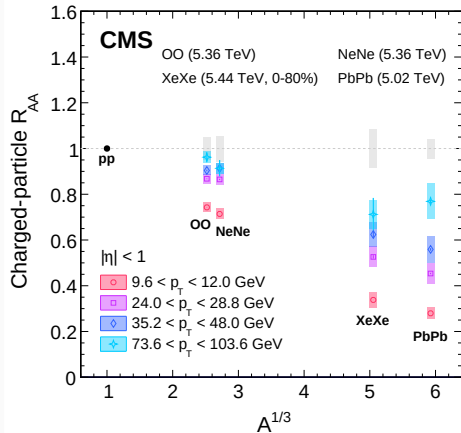
September 24, 2026

EMMI Workshop: Light-Ion Collisions

Institute for Theoretical Physics, Heidelberg University

In collaboration with: Aleksas Mazeliauskas, Sergio Barrera Cabodevila, Fabian Zhou

Light ions: a new handle on system size



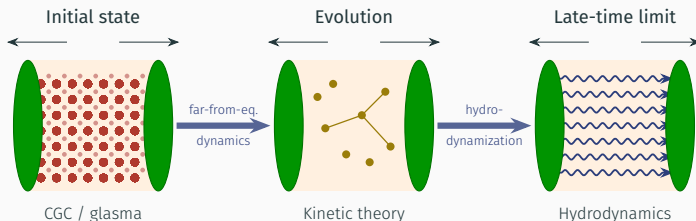
- **light-ion collisions:** strong evidence of collective flow and jet modification factor $\rightarrow$ **hydro-like** behavior

The main question

kinetic theory: **first-principles bridge** connecting initial stage to hydrodynamics. How much collectivity expected at each transverse size?

The Boltzmann equation applied to ion collisions

- Kinetic theory can evolve the **far-from-equilibrium** initial gluon distribution (CGC) into a **collective dynamical system**, behaving like a fluid



$$\underbrace{\partial_\tau f + \vec{v} \cdot \nabla_{\vec{x}} f}_{\text{expansion}} = - \underbrace{\mathcal{C}_{2 \leftrightarrow 2}[f]}_{g+g \leftrightarrow g+g} - \underbrace{\mathcal{C}_{1 \leftrightarrow 2}[f]}_{g \leftrightarrow g+g}, \quad f(\tau, \vec{x}; \vec{p}): \text{single-particle distribution}$$

About the collision kernels

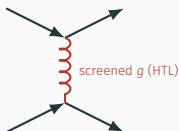
Collision kernels can be described using different models for gluon interactions: **EKT** (Kurkela, Zhu, Phys.Rev.Lett.115.18(2015)), **BEDA** (Barrera, Salgado, Wu, JHEP06(2024)) and **RTA** (Ambrus, Schlichting, Werthmann, Phys.Rev.Lett.130(2023))

Comparison between EKT, BEDA and RTA kernels

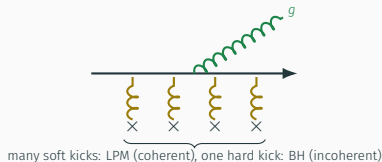
	EKT	BEDA	RTA
$\mathcal{C}_{2\leftrightarrow 2}$	full $2 \leftrightarrow 2$ QCD dynamics @LO	small-angle scatterings only	$-\frac{\mathbf{p} \cdot \mathbf{u}}{\tau_R} (f - f_{\text{eq}})$
$\mathcal{C}_{1\leftrightarrow 2}$	LPM + Bethe-Heitler (BH)	deep-LPM only	

- EKT: full LO QCD kernels (Arnold, Moore, Yaffe, JHEP01(2003))

$2 \leftrightarrow 2$ elastic scattering



$1 \leftrightarrow 2$ splitting

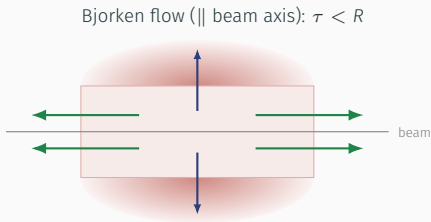


- BEDA: soft/collinear *limits* of the LO kernels, qualitatively EKT-like
- RTA: still able to qualitatively capture some characteristic features

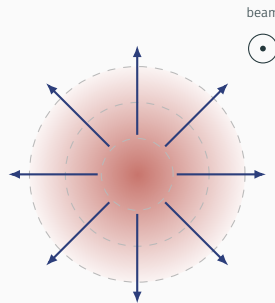
Kinetic-theory setup: the expansion

- longitudinal **Bjorken flow** + azimuthally symmetric **transverse expansion**

$$f = f(\tau, r; \vec{p}) \rightarrow \text{genuine (1+1)D expansion}$$



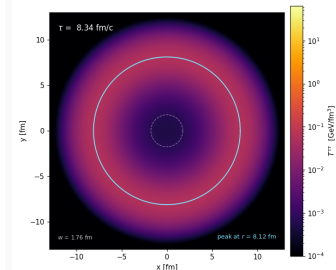
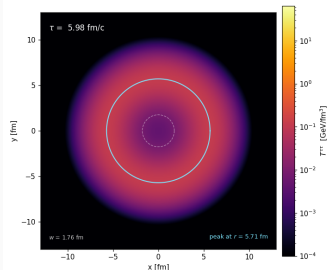
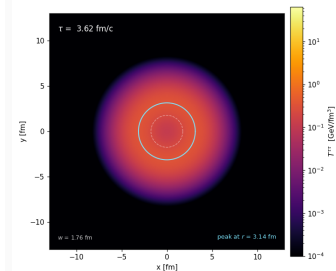
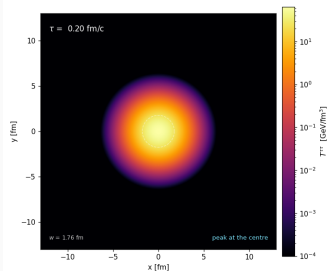
radial expansion ($\perp$ beam axis): $\tau \gtrsim R$



Our purpose

Study of the equilibration process in relation to the transverse size R , using **QCD-based kinetic theory**

How does the transverse expansion look like? The RTA case



central collisions

Gluon-only (conformal EoS) RTA simulation, corresponding to a O-O like expanding system¹

- $\tau < R$: Bjorken flow
- $\tau \gtrsim R$: radial expansion



outward energy transport

¹Kurkela, Mazeliauskas, Törnkvist, JHEP11(2021)

How to locally quantify isotropization? The BEDA case

- Inverse Reynolds number: ratio between shear stresses and energy density

$$\text{Re}_{\pi,0}^{-1} \equiv \frac{\sqrt{\pi^{\mu\nu}\pi_{\mu\nu}}}{\varepsilon} \quad , \quad \pi^{\mu\nu} \equiv T^{\mu\nu} - T_{\text{ideal}}^{\mu\nu} \quad (\text{shear-stress tensor})$$

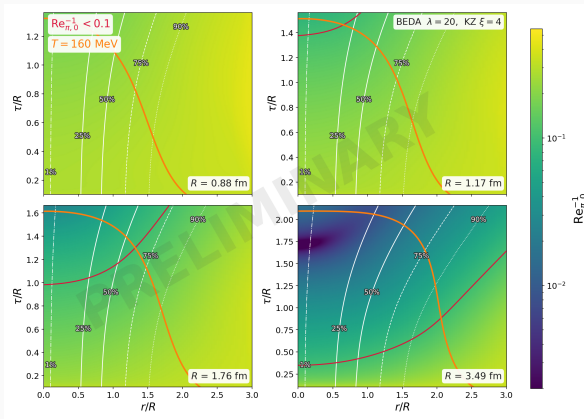
How much isotropic?

$\text{Re}_{\pi,0}^{-1}$: deviations from local isotropy

$\text{Re}_{\pi,0}^{-1} < 0.1 \rightarrow$ negligible viscous shear-stress effects

- Outward motion of matter: energy fraction

$$F \equiv \frac{\text{energy shell } (0, r) \text{ at } \tau}{\text{total fireball energy at } \tau}$$



- amount of gluons near isotropy: increasing with size R

How to locally quantify hydrodynamization? The BEDA case

- introduce ratio between relative shear stress (KIN - NS) and energy density³

$$\text{Re}_{\pi,1}^{-1} \equiv \frac{\sqrt{(\pi - \pi_{\text{NS}})^{\mu\nu} (\pi - \pi_{\text{NS}})_{\mu\nu}}}{\varepsilon}, \quad \pi_{\text{NS}}^{\mu\nu} \equiv -\eta \sigma^{\mu\nu}$$

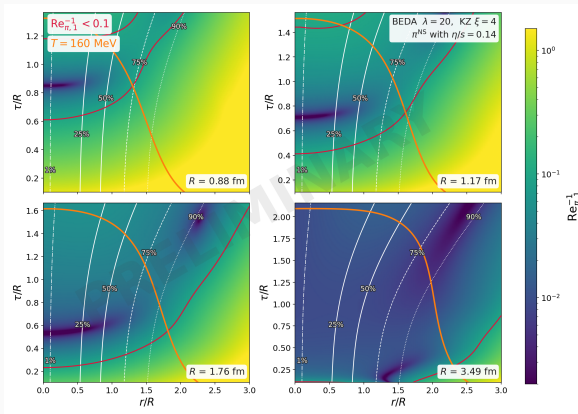
How close to viscous hydro?

$\text{Re}_{\pi,1}^{-1}$: deviations from NS theory

$\text{Re}_{\pi,1}^{-1} < 0.1 \rightarrow$ NS shear-stress captures the dynamics

- Outward motion of matter: energy fraction $F(\tau, r)$

³Kurkela, Wiedemann, Wu,
Eur.Phys.J.C79(2019)

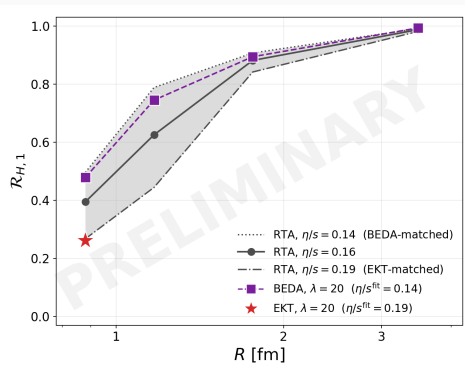
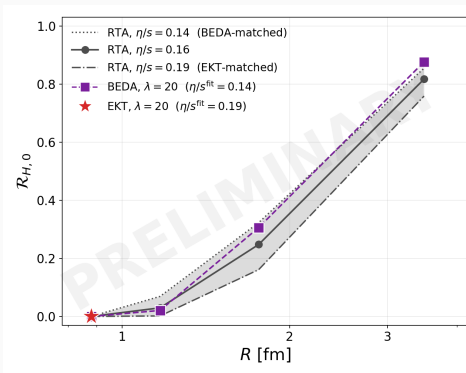


- percentage of **gluons NS-like**: increasing with size R

A global hydrodynamic quantifier? RTA vs BEDA vs EKT

Describe the **global properties** of the system during its whole evolution ($T_{FO} = 160$ MeV)

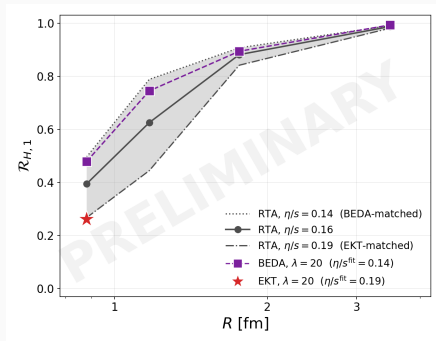
$$\mathcal{R}_{H,a} \equiv \frac{\text{4-volume with } Re_{\pi,a}^{-1} < 0.1 \text{ inside FO surface}}{\text{4-volume enclosed by FO surface}}, \quad \text{with } a = 0, 1$$



- fraction of **deconfined matter hydrodynamic** during the expansion (QGP formation)

Summary and outlook

- $\mathcal{R}_{H,q}$ keeps track of whole system history: how much deconfined matter had the possibility to **isotropize/hydrodynamize** until **freeze-out**?
- assuming the validity of kinetic theory: considerable **fraction hydro-like** for sufficiently large couplings ($\lambda \gtrsim 20 \leftrightarrow \eta/s \lesssim 0.16$) even for **small systems** ($R \lesssim 2$ fm)
- BEDA & EKT results: work in progress $\rightarrow$ study **hydrodynamization with QCD tools**



Thank you!

Opacity: the other control parameter for hydrodynamization

For a **conformal** system with **Gaussian IC** the whole dynamics depends on one dimensionless number:

$$\hat{\gamma} = \left(\frac{\varepsilon_0 \tau_0}{\nu_g \pi^2/30} \right)^{\frac{1}{4}} \frac{R^{3/4}}{5(\eta/s)} \quad , \quad \varepsilon_0 \equiv \varepsilon(\tau = \tau_0, r = 0)$$

for initial time $\tau_0 = 0.2 \text{ fm}/c$ and $\eta/s \approx 0.25$ (set by λ)⁴

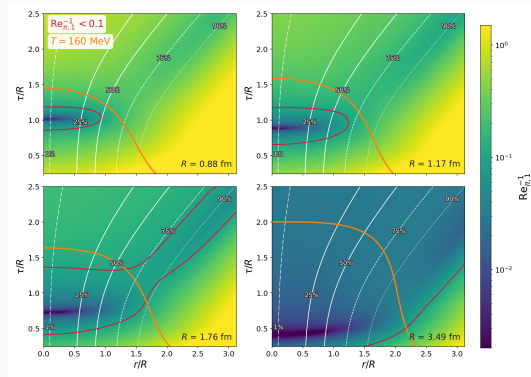
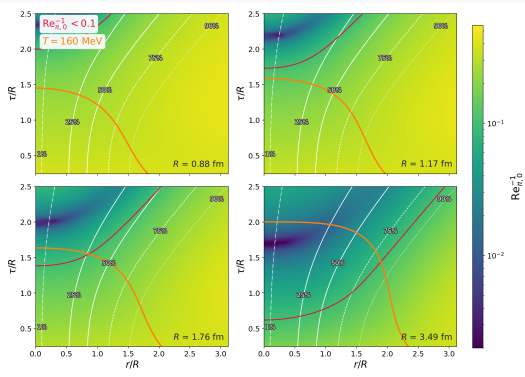
system	R [fm]	$(\varepsilon\tau)_0$ [GeV ³]	$\hat{\gamma}$	regime
pp (0–10%)	0.88	0.1023	≈ 0.9	FS dominated
p–Pb (0–10%)	1.17	0.2384	≈ 1.4	FS dominated
O–O (0–10%)	1.76	0.4972	≈ 2.3	transition
Pb–Pb (0–10%)	3.49	3.5803	≈ 6.2	hydro-like

- **opacity** provides a quick intuition on the expected behavior for the system (Kurkela, Wiedemann, Wu, Eur.Phys.J.C79(2019))

⁴ Kurkela, Mazeliauskas, Törnkvist, JHEP11(2021)

Isotropization and hydrodynamization in RTA (local)

Spacetime diagrams for $\text{Re}_{\pi,a}^{-1}$ in the RTA model (KZ, $\xi = 10$, $\eta/s = 0.25$)

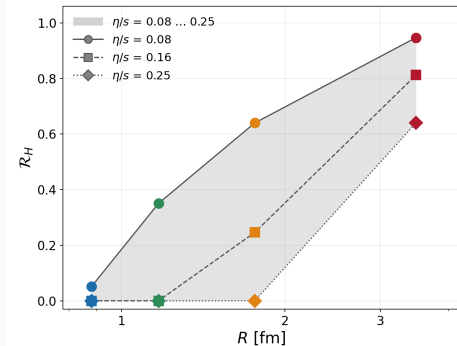
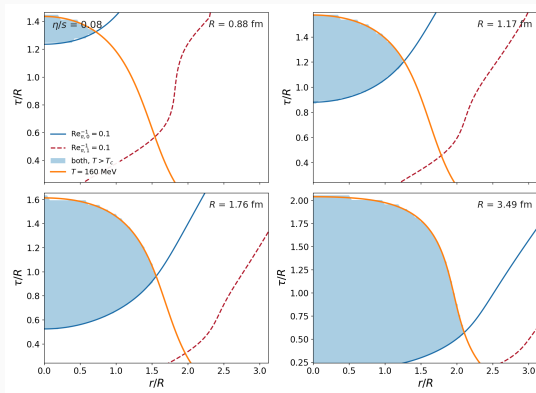


- RTA qualitatively similar to BEDA for these two Lorentz-invariant quantities

A global quantifier for thermalization? The RTA case

Near-equilibrium regions: local isotropy + NS-like $\rightarrow$ gradient expansion allowed

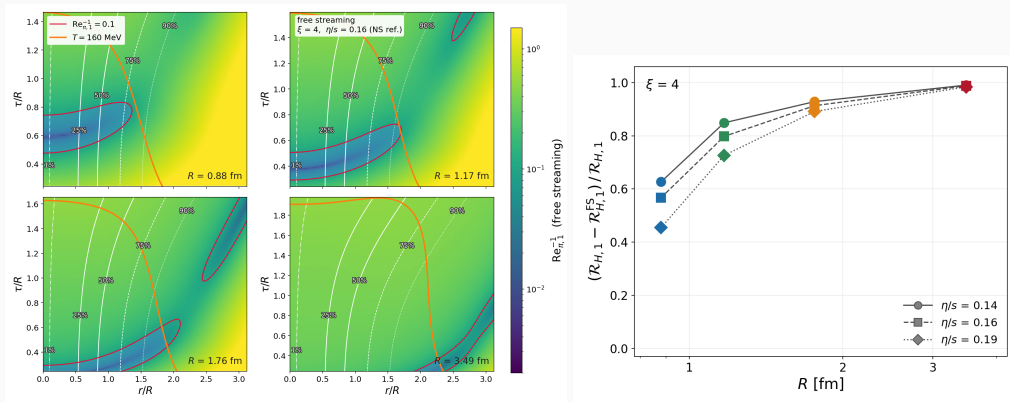
$$\mathcal{R}_H \equiv \frac{\text{4-volume with } Re_{\pi,0}^{-1} < 0.1 \text{ \& } Re_{\pi,1}^{-1} < 0.1 \text{ inside FO surface}}{\text{4-volume enclosed by FO surface}}$$



- fraction of matter with **convergent gradient expansion** (close to both eq and NS)

One observation about free streaming vs RTA

- small systems: FS → regions behaving NS-like → non-convergent gradient expansion
- how much larger is the near-NS volume than what free streaming produces?



- interactions responsible for roughly 50% ($R = 0.88$ fm), 80% ($R = 1.17$ fm), 90% ($R = 1.76$ fm), 99% ($R = 3.49$ fm) of the near-NS volume