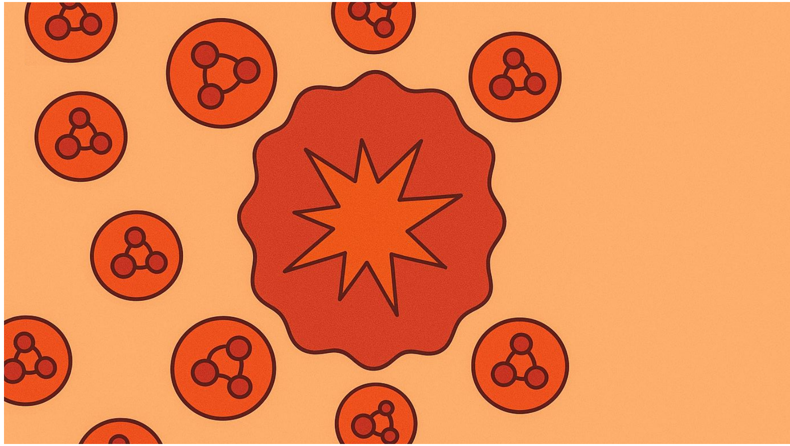
INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS

EMFCSC - Erice, Sicily

NEW RTA-BASED PARTICLIZATION AND FINAL STATE OBSERVABLES



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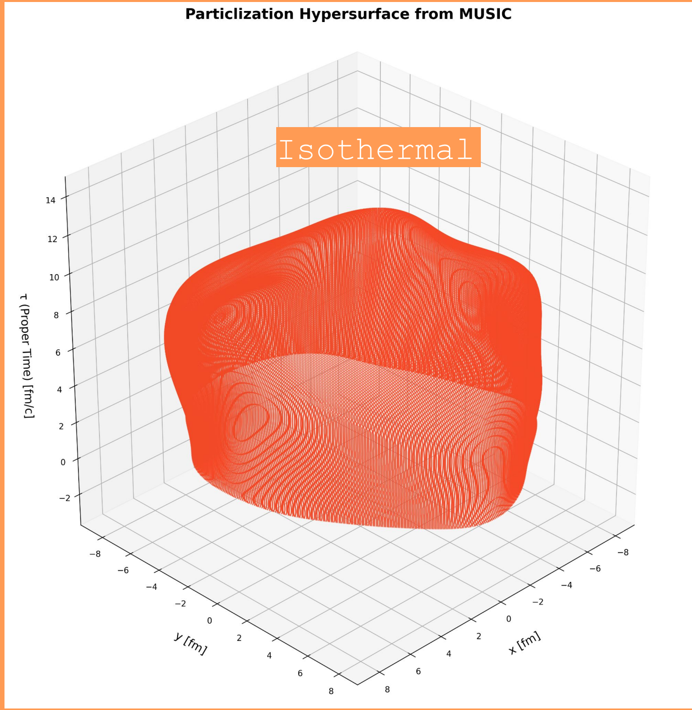
The particlization scheme

Numerical description of QGP formation process:

Relativistic viscous hydrodynamics — HRG model

Particlization



Cooper-Frye formula:

$$E_p \frac{dN_n}{d^3p} = \frac{1}{(2\pi\hbar)^3} \int_\Sigma p \cdot d^3\sigma \, f_n(x,p)$$

$$\left[f_{eq,n}(x,p) \; + \; \delta f_n(x,p) \right]$$

Samples discrete hadrons of a given species n.

Encode the effects of non-equilibrium dynamics.

$$f_{eq,n}(x,p) = g_n \left[\exp\left(\frac{p_n^\mu u_\mu}{T} \right) + a_n \right]^{-1}$$

Kinetic description

f_n describe the microscopic state of the system.

Relativistic Boltzmann equation:

$$p_n^\mu \partial_\mu f_n = C_n[f]$$

Accounts for particle interactions and how deviations relax towards equilibrium.

Hydrodynamics :

- Emerges from this framework as a consequence of energy and momentum conservation.
- Local temperature and velocity fields are defined through Landau matching.
- Out of equilibrium, the $T^{\mu\nu}$ splits in equilibrium contributions plus Π and $\pi^{\mu\nu}$ viscous corrections.

Hydro description

Macroscopic currents can be connected with microscopic deviations through Chapman-Enskog expansion.

Constitutive relations:

$$\Pi \simeq -\zeta\theta \qquad \pi^{\mu\nu} \simeq 2\eta\sigma^{\mu\nu}$$

Commonly used in particlization models.

Anderson-Witting ansatz:

$$f_{eq,n}\hat{L}_n\phi_n \simeq -\frac{E_{p,n}}{\tau_R}\delta f_n = -\frac{E_{p,n}}{\tau_R} f_{eq,n}\bar{f}_{eq,n}\phi_n$$

Deviations from equilibrium relax with a single time scale, τ_R.

RTA: Works if τ_R doesn't depend on the particle type or momentum.

New RTA ansatz:

$$f_{\mathrm{eq},n}\hat{L}_n\phi_n \simeq -\frac{E_{p,n}}{\tau_{R,n}} f_{\mathrm{eq},n}\bar{f}_{\mathrm{eq},n}\left[\phi_n - \frac{\sum_m \langle \phi_m, E_{p,m}\rangle}{\sum_m \langle E_{p,m}, E_{p,m}\rangle} E_{p,n} - \frac{\sum_m \left\langle \phi_m, p_m^{\langle\mu\rangle}\right\rangle}{\frac{1}{3}\sum_m \left\langle p_m^{\langle\nu\rangle}, p_{m\langle\nu\rangle}\right\rangle} p_{n\langle\mu\rangle}\right]$$

New RTA: Counter-terms constructed from the conserved quantities of the system. The phenomenological parameter γ summarize microscopic interactions.

$$\tau_{R,n} = t_R\left(\frac{E_p}{T}\right)^{\gamma}$$

Numerical implementation

corrections in terms of dissipative currents:

$$\phi_{p,n}\Big|_{\text{bulk}} = \left[\varphi(T)\frac{E_{\mathbf{p},i}}{T} - \frac{m_i^2}{3T^2}\left(\frac{E_{\mathbf{p},i}}{T}\right)^{\gamma-1} + \left(\frac{1}{3} - c_s^2\right)\left(\frac{E_{\mathbf{p},i}}{T}\right)^{\gamma+1}\right]\frac{\Pi}{\beta_\Pi}$$

$$\phi_{p,n}\Big|_{\text{shear}} = \frac{1}{T^2}\left(\frac{E_{\mathbf{p},i}}{T}\right)^{\gamma-1} p_i^{\langle\mu}p_i^{\nu\rangle}\frac{\pi_{\mu\nu}}{2\beta_\pi}$$

Precomputed tables			
$\beta_{\square}$	β_Π	c_s^2	φ(T)

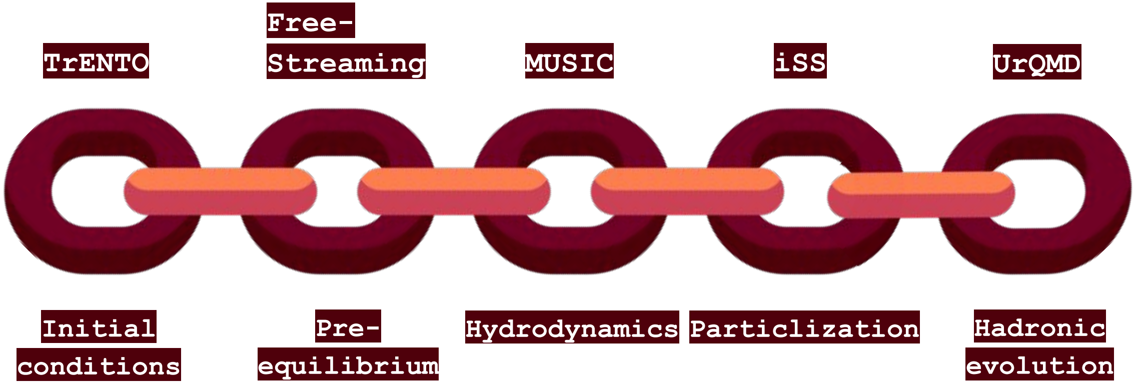
γ = 0, 0.5 and 1

- Particle yields are sample for each hypersurface cell.

- Poisson distribution to decide how many particles in each event.
- Particle momentum is calculated from thermal equilibrium distribution.
- Each sampled momentum is tested with Cooper-Frye formula.

$$f_n = f_{\text{eq},n} + \delta f_n$$ → regulated to prevent negative momentum distribution

Numerical implementation

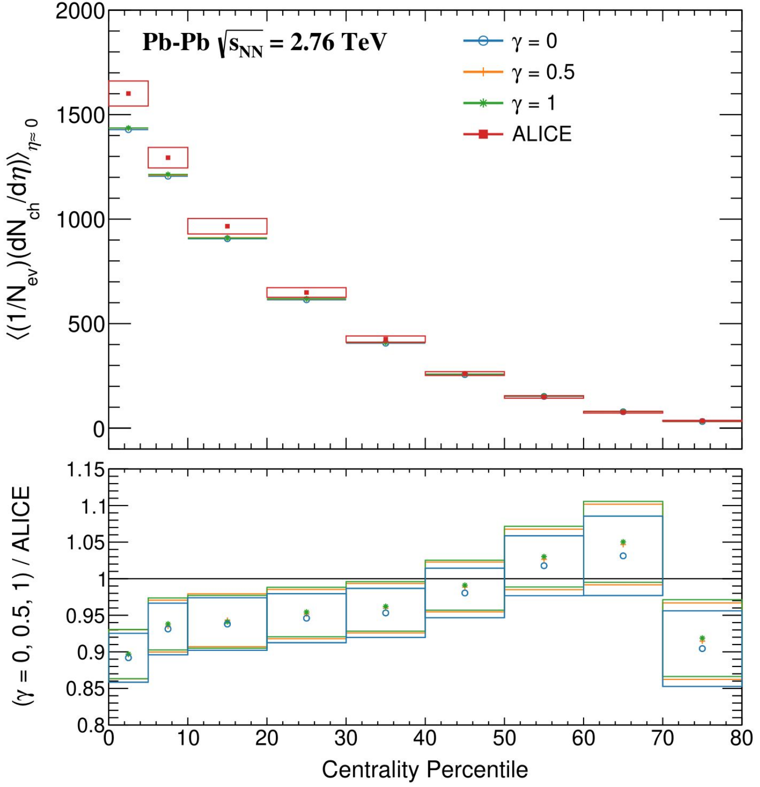


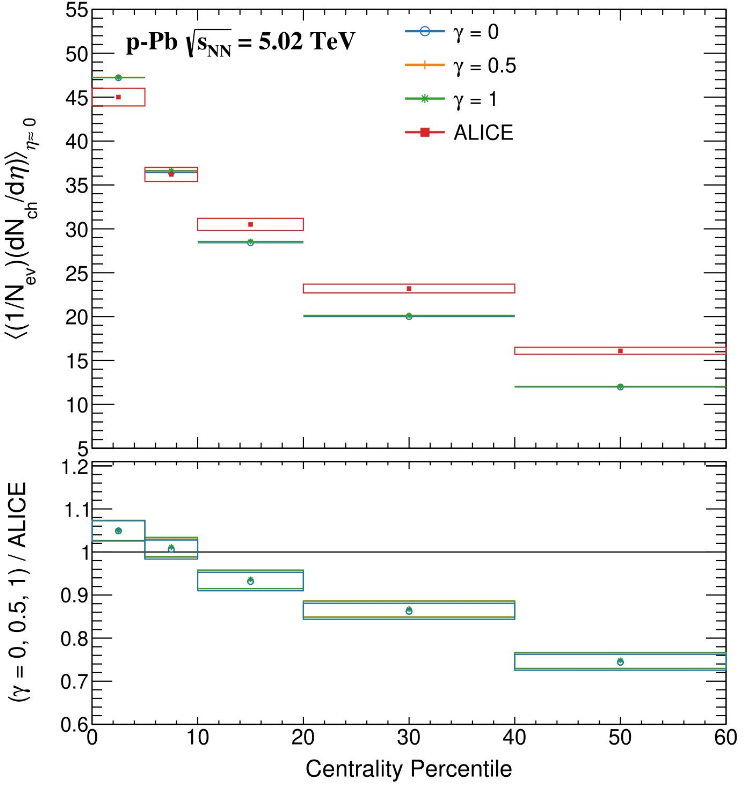
	Pb-Pb			p-Pb		
N° events	1000			1000		
γ	0	0.5	1	0	0.5	1
Free-streaming time	fluctuating			fixed		
Parameters	JETSCAPE			Duke group		

Numerical results

Total Nch:

- No significant dependence on γ.
- Total Nch is insensitive to linear Π corrections.
- ✓ Good cross-check: γ=0 reproduces JETSCAPE and Duke results.

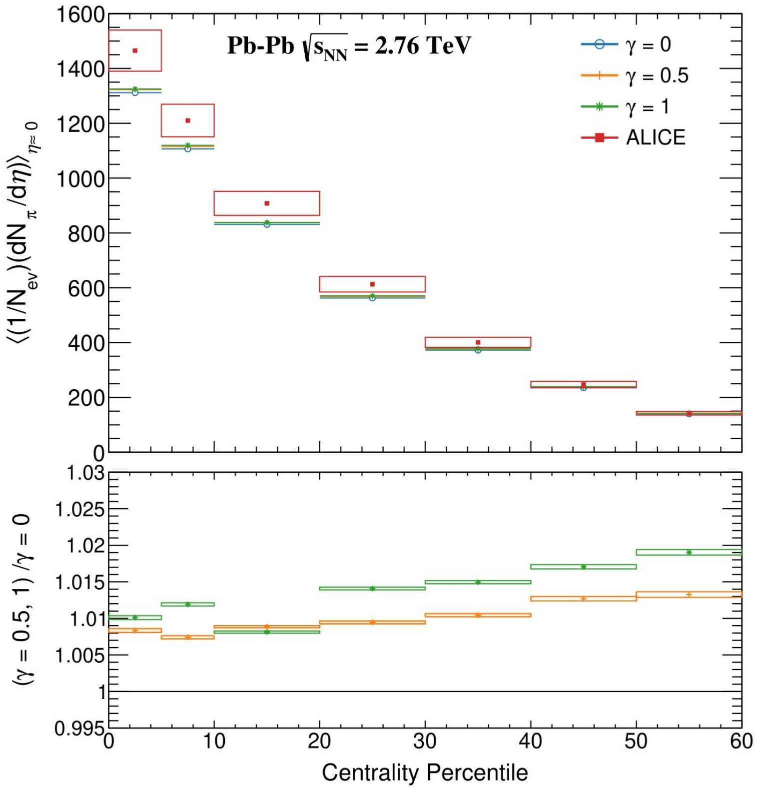


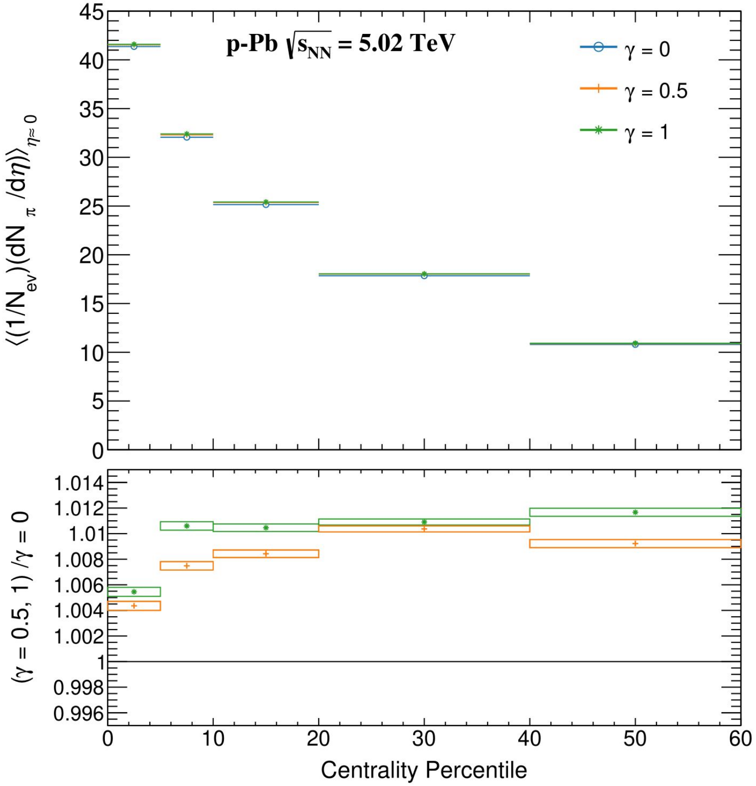


Numerical results

Pions Nch:

- Slight dependence on γ.
- Larger γ produces higher pion yield.
- Agreement with ALICE worsens slightly, suggesting MAP parameters might need retuning.

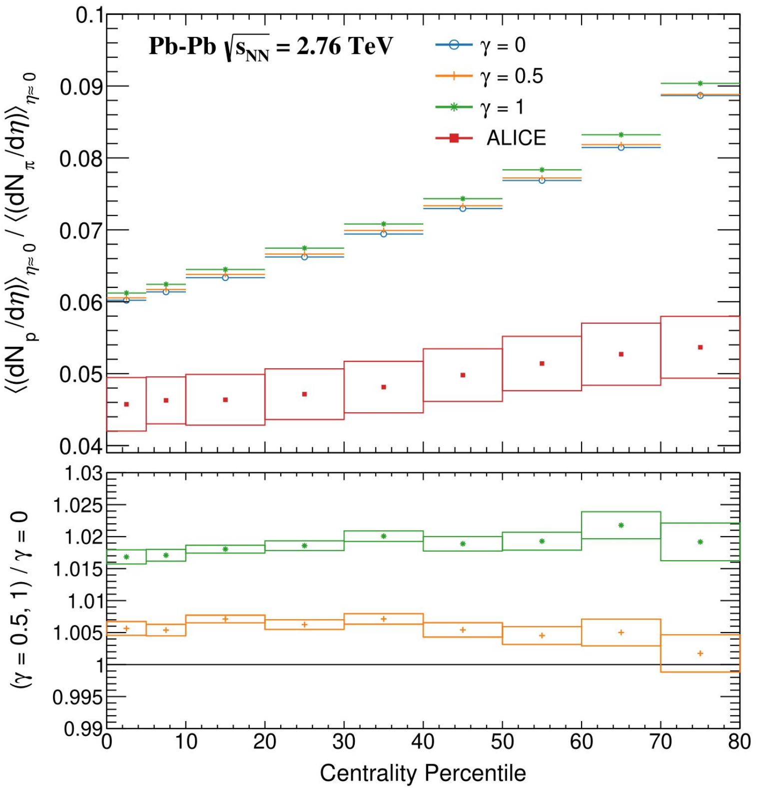


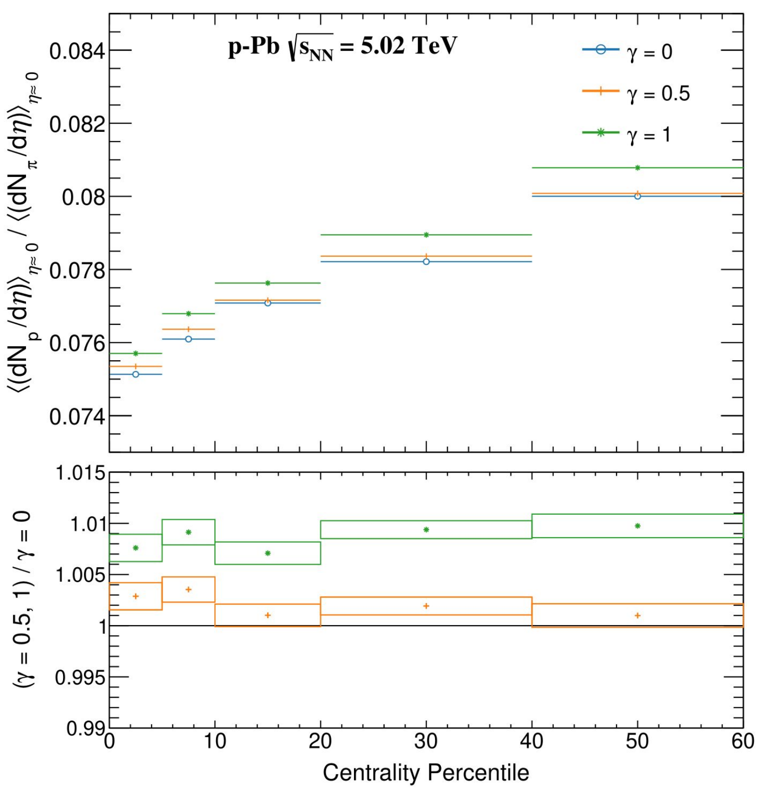


Numerical results

Protons/pions Nch:

- Increases with γ.

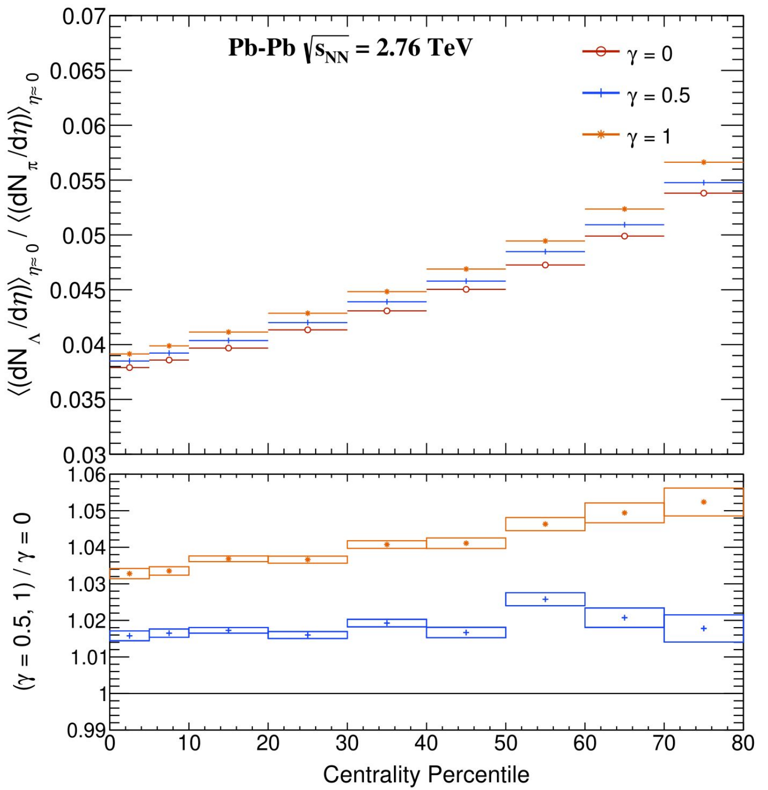


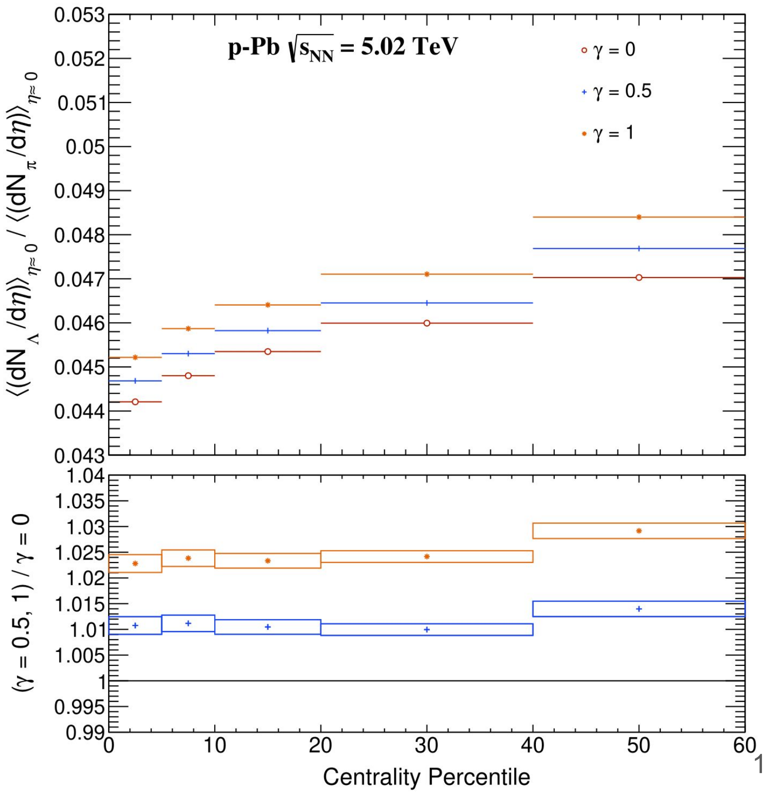


Numerical results

Lambdas/pions Nch:

- Increases with γ.

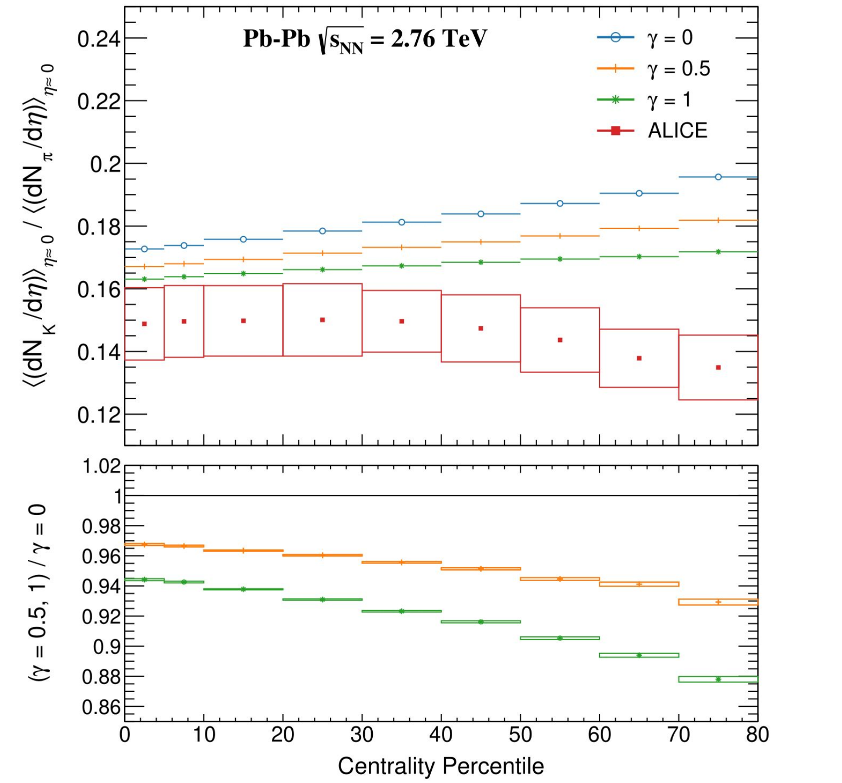


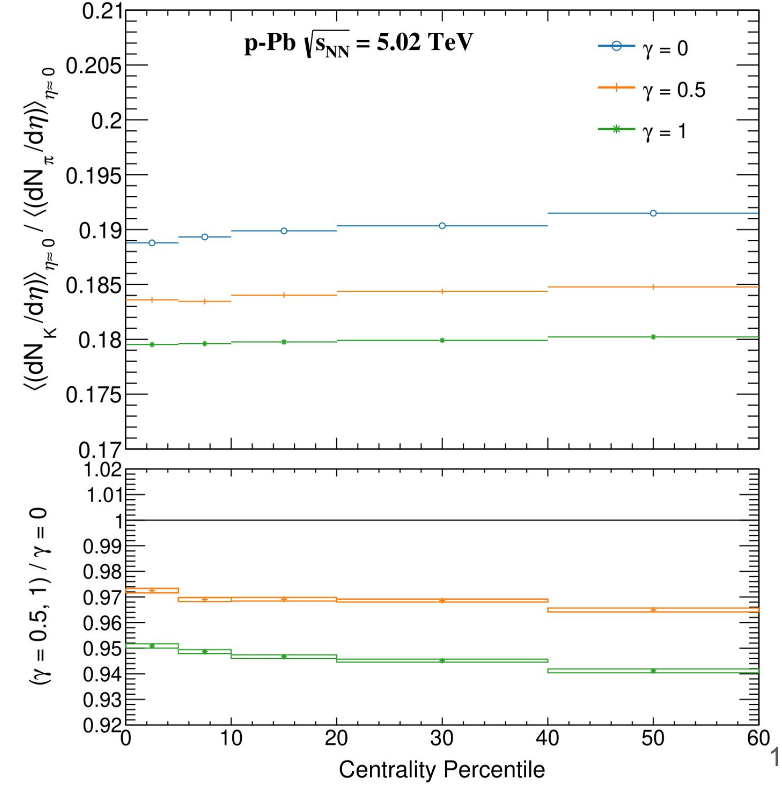


Numerical results

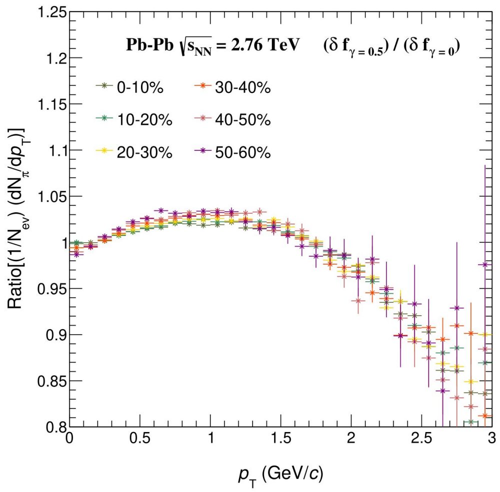
Kaons/pions Nch:

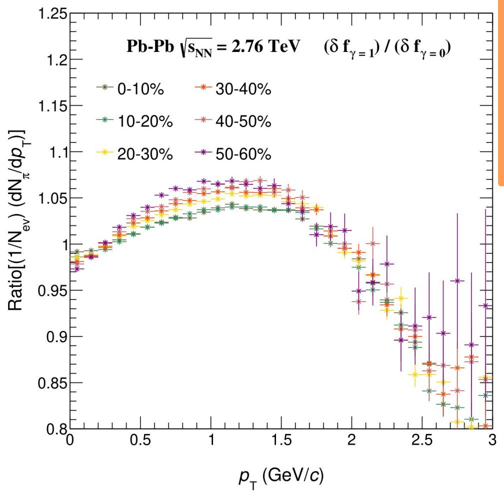
- Decreases with γ.

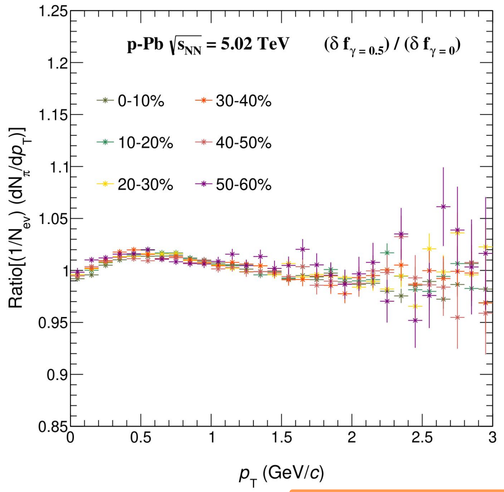


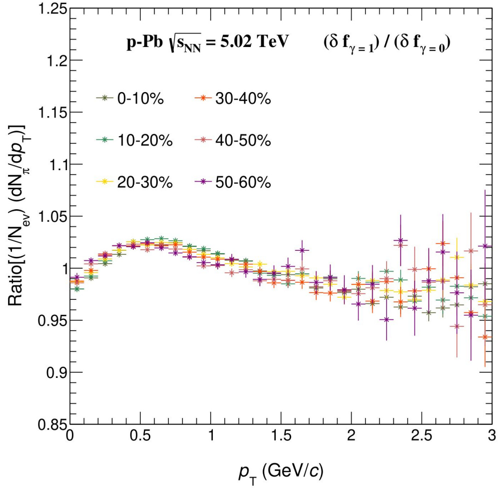


Numerical results





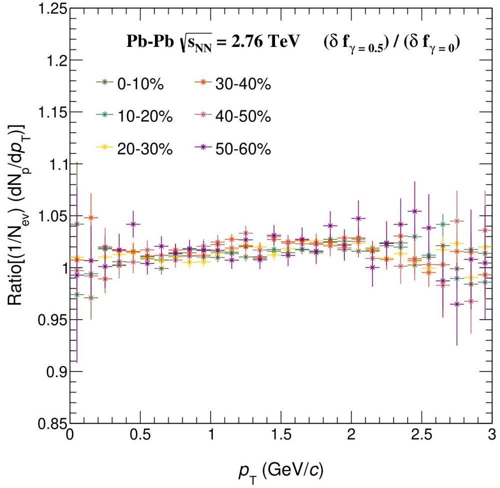


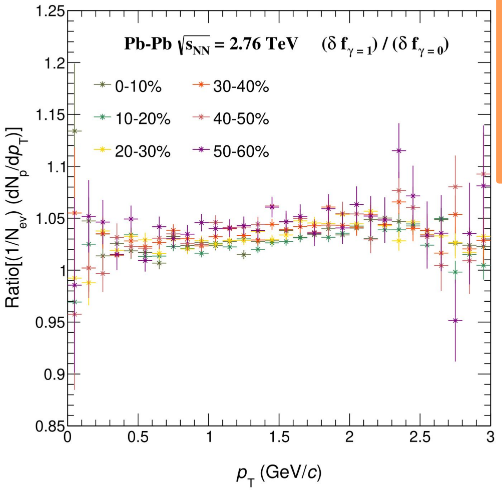


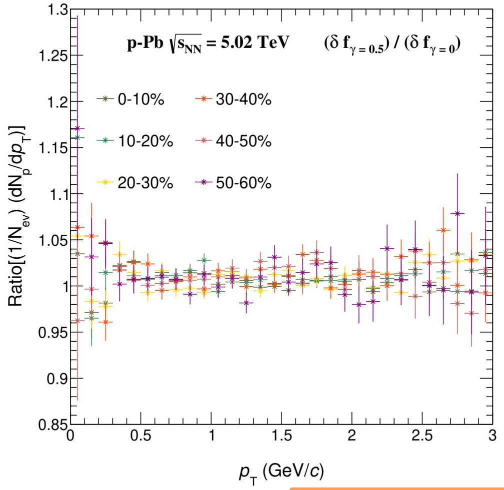
Pion $p_\perp$-spectra ratio:

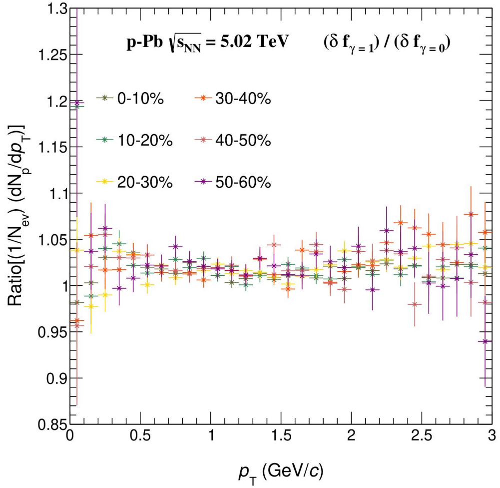
- Mid-$p_\perp$ peak grows with γ.

Numerical results





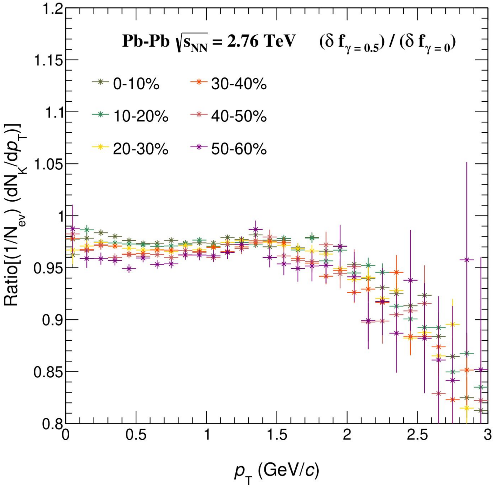


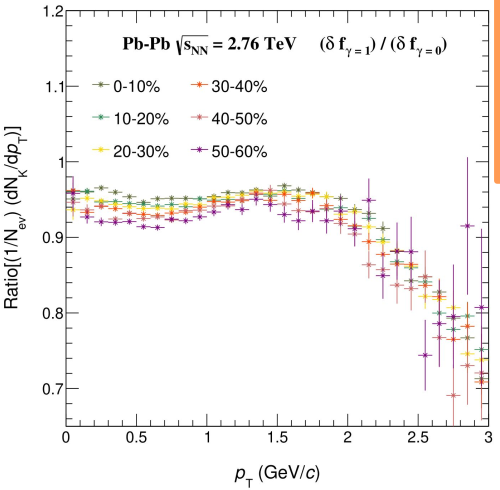


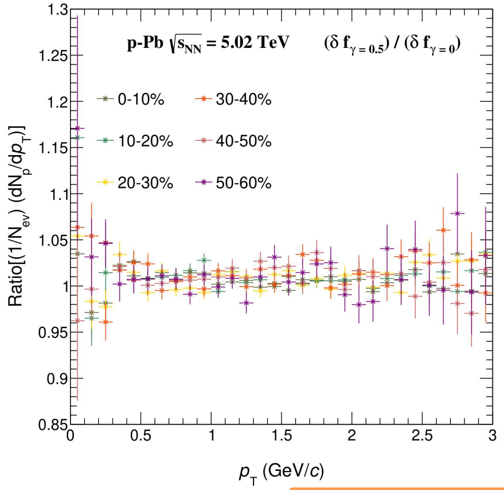
Proton $p_\perp$-spectra ratio:

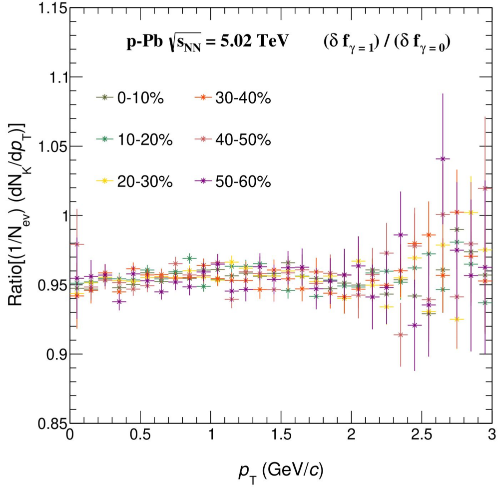
- Similar but weaker effect.

Numerical results









Kaon $p_\perp$-spectra ratio:

- Opposite trend, compensating changes in pions/protons.

Conclusions & outlook

Conclusions:

- Implemented a new RTA-based particlization scheme with mass-dependent viscous corrections, controlled by parameter γ.
- Found that identified particle yields, ratios, and $p_\perp$-spectra depend on γ, with different trends for different species.
- Opens a new avenue to constrain QGP transport coefficients using identified particle observables in hybrid models.

Outlooks:

- Study other observables (e.g. flow coefficients, viscosity - is it big?, centralities without scatterings).
- Include γ and identified species data in Bayesian analyses.

Thank you for your attention!

Obrigada!

What is this particlization stage?

hadronization encoded in the equation of state

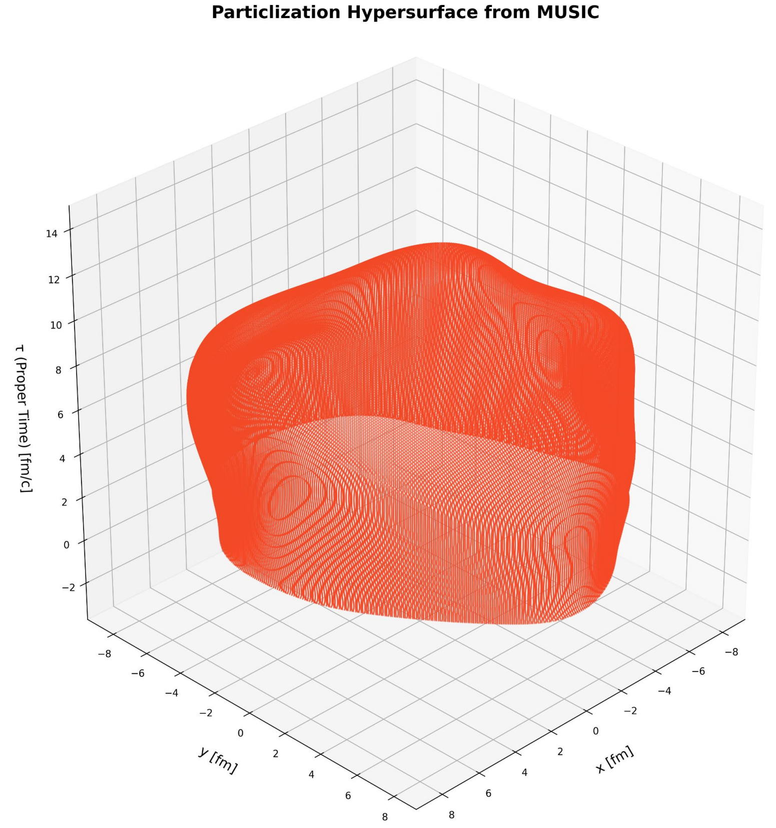
unphysical

⤊

hydrodynamics

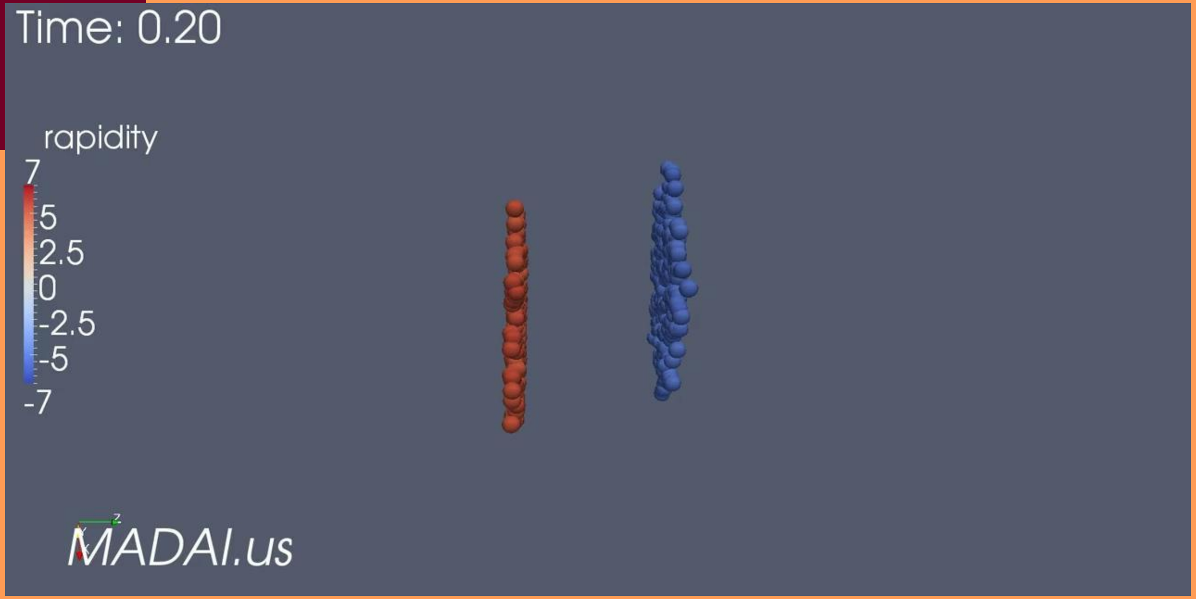
particlization

kinetic theory



What is this particlization stage?

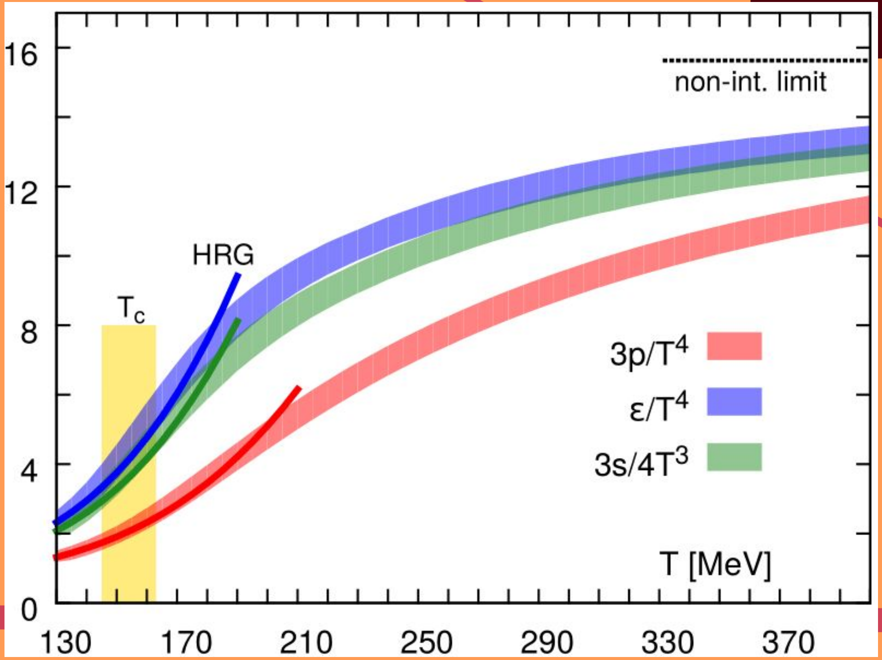
look at what happens after QGP is formed:



Adapted from: MADAI collaboration.

What is this particlization stage?

hadronization encoded in the equation of state



Adapted from: HotQCD collaboration.

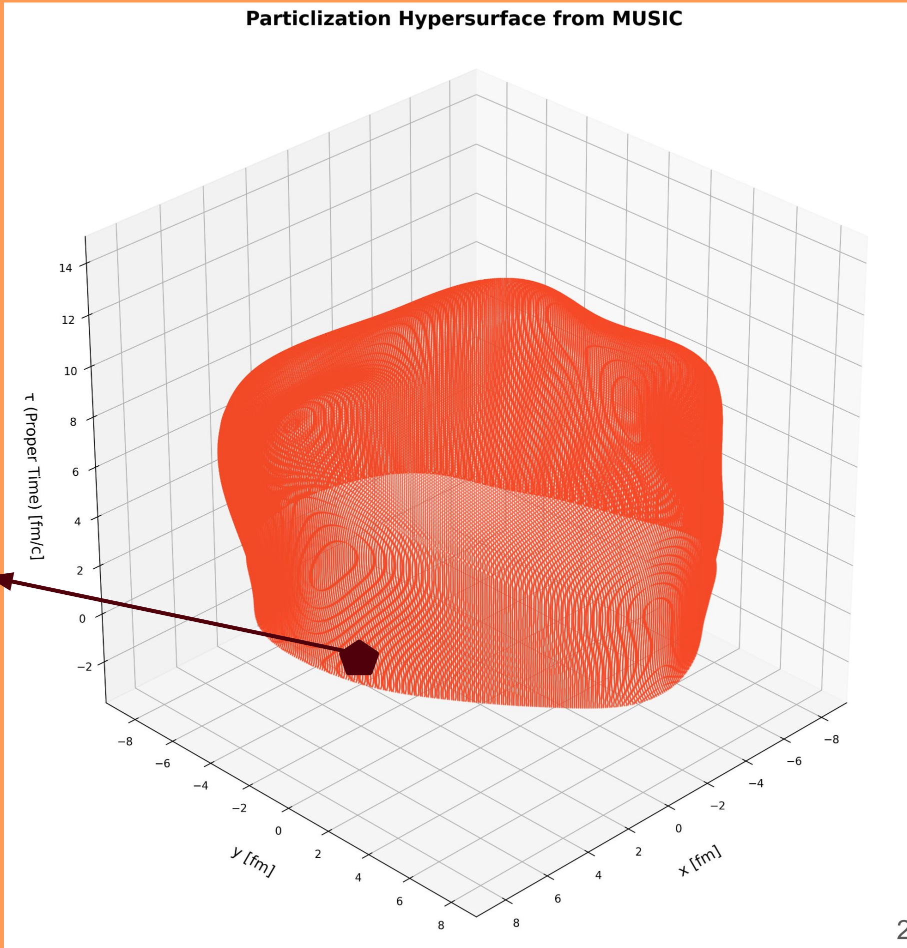
hydrodynamics

kinetic theory

particlization

The particlization scheme

$$E_p \frac{dN_n}{d^3p} = \frac{1}{(2\pi\hbar)^3} \int_\Sigma p \cdot d^3\sigma \, f_n(x,p)$$



probability given by its phase-space distribution

What is this particlization stage?

QGP has viscosity!

$$p_n^\mu \partial_\mu \left[f_{eq,n}(x,p) \; + \; \delta f_n(x,p) \right] = C_n[f]$$

$$f_{eq,n}(x,p) = g_n \left[\exp\left(\frac{p_n^\mu u_\mu}{T} \right) + a_n \right]^{-1}$$

encode the effects of non-equilibrium dynamics

RTA is a approximation to solve Boltzmann equation

Hydro description

Macroscopic currents can be connected with microscopic deviations through Chapman-Enskog expansion

Constitutive relations:

$$\Pi \simeq -\zeta\theta \qquad \pi^{\mu\nu} \simeq 2\eta\sigma^{\mu\nu}$$

Commonly used in particlization models

Anderson-Witting ansatz:

$$f_{eq,n}\hat{L}_n\phi_n \simeq -\frac{E_{p,n}}{\tau_R}\delta f_n = -\frac{E_{p,n}}{\tau_R} f_{eq,n}\bar{f}_{eq,n}\phi_n$$

RTA: works with Landau matching and an independent τ_R on particle parameters

if τ_R depend on the particle species, or the momentum of that given species, and on spacetime:

$$\partial_\mu T^{\mu\nu} = -\sum_n \int dP_n \frac{E_{p,n}}{\tau_{R,n}} p_n^\nu \delta f_n$$

Get to know: new RTA

new RTA ansatz:

$$f_{\mathrm{eq},n}\hat{L}_n\phi_n \simeq -\frac{E_{p,n}}{\tau_{R,n}} f_{\mathrm{eq},n}\bar{f}_{\mathrm{eq},n}\left[\phi_n - \frac{\sum_m \langle \phi_m, E_{p,m}\rangle}{\sum_m \langle E_{p,m}, E_{p,m}\rangle} E_{p,n} - \frac{\sum_m \left\langle \phi_m, p_m^{\langle\mu\rangle}\right\rangle}{\frac{1}{3}\sum_m \left\langle p_m^{\langle\nu\rangle}, p_{m\langle\nu\rangle}\right\rangle} p_{n\langle\mu\rangle}\right]$$

$$\tau_{R,n} = t_R \left(\frac{E_p}{T}\right)^{\gamma}$$

nRTA: counter-terms constructed from the conserved quantities of the system

- Framework that respects fundamental conservation laws
- Flexibility in describing how different hadrons, and different momentum modes, relax towards equilibrium

Get to know: new RTA

new RTA ansatz:

$$f_{\mathrm{eq},n}\hat{L}_n\phi_n \simeq -\frac{E_{p,n}}{\tau_{R,n}} f_{\mathrm{eq},n}\bar{f}_{\mathrm{eq},n}\left[\phi_n - \frac{\sum_m \langle \phi_m, E_{p,m}\rangle}{\sum_m \langle E_{p,m}, E_{p,m}\rangle} E_{p,n} - \frac{\sum_m \left\langle \phi_m, p_m^{\langle\mu\rangle}\right\rangle}{\frac{1}{3}\sum_m \left\langle p_m^{\langle\nu\rangle}, p_{m\langle\nu\rangle}\right\rangle} p_{n\langle\mu\rangle}\right]$$

$$\tau_{R,n} = t_R \left(\frac{E_p}{T}\right)^{\gamma}$$

nRTA: counter-terms constructed from the conserved quantities of the system

- Framework that respects fundamental conservation laws
- Flexibility in describing how different hadrons, and different momentum modes, relax towards equilibrium

Numerical implementation

Precomputed tables			
$\beta_{\square}$	β_{Π}	$c_s^{\,2}$	$\varphi(T)$

- Particle momentum is calculated from thermal equilibrium distribution
- New RTA corrections are calculated using the precomputed tables
- Each sampled momentum is tested with Cooper-Frye formula

$$f_n = f_{\mathrm{eq},n} + \delta f_n \longrightarrow$$

regulated to prevent negative momentum distribution

Numerical implementation

Precomputed tables			
$\beta_{\square}$	β_{Π}	c_s^2	$\varphi(T)$

- Particle yields are sample for each particlization hypersurface cell
- Poisson distribution to decide how many particles in each event

$$N_{\text{spec}} = \max(0,\ N_{\text{total}})$$

Numerical methodology