The effects of pre-hydrodynamic flow in heavy-ion collisions at the RHIC Beam Energy Scan program

Mashhood Munir, Chun Shen

Wayne State University

What are heavy ion collisions and how are they simulated?

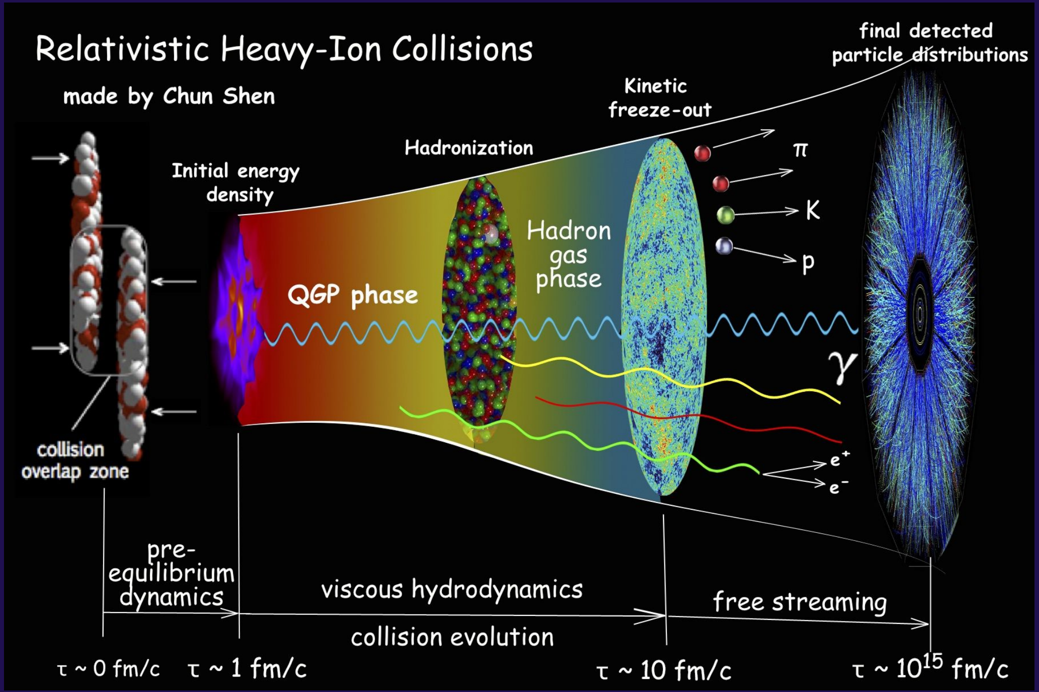
Heavy ion collisions create *extreme* conditions…

Very **quick** (10^{-23}–10^{-24} seconds)

Very **hot** (~2 trillion K)

…and produce rapid exploding matter evolving through multiple stages:

1. **Pre-equilibrium stage** (not extensively studied in 3+1D)
2. **Quark-gluon plasma** creation (hydrodynamics)
3. **Decoupling** (Cooper-Frye freeze-out, hadronic cascade)



How can the pre-equilibrium stage affect observables?

1. Pre-equilibrium stage evolves system's energy-momentum tensor (~1 fm/c)
2. Drives system towards equilibrium, connects into hydrodynamics
3. Affects development of QGP flow (anisotropic flow)
   a. Specifically the **anisotropic flow coefficients**

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos(\phi - \Psi_n)\right)$$

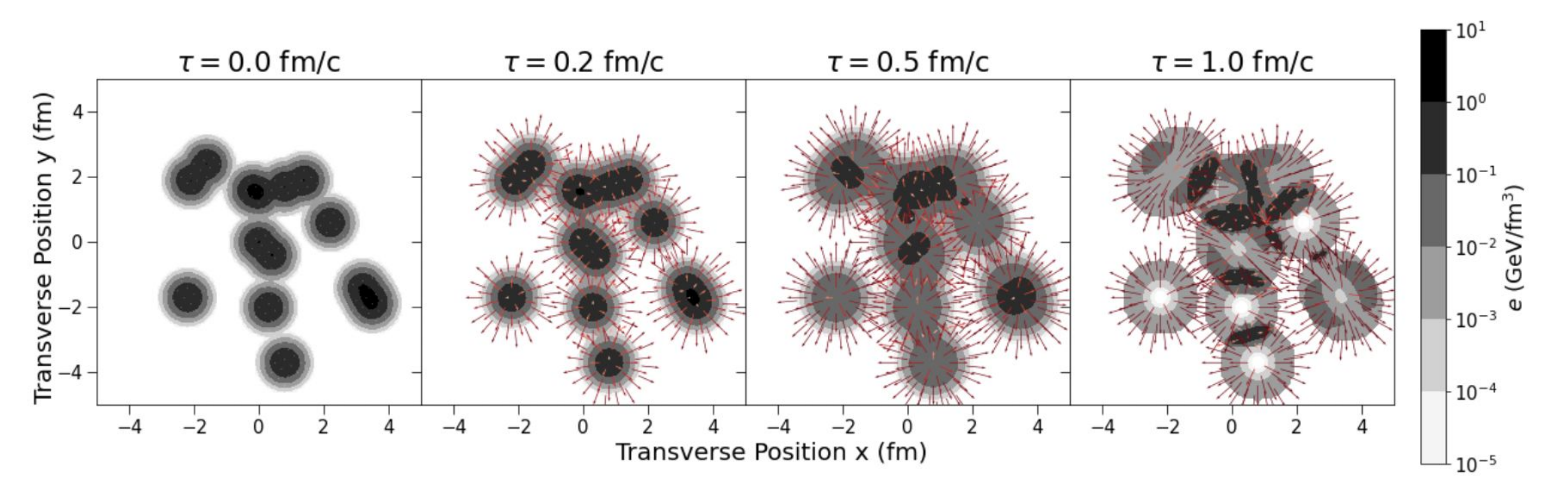
- Compare simulated anisotropic flow coefficients with experimental measurements to constrain pre-equilibrium stage
- Requires parameterization of pre-equilibrium stage

Modeling the pre-equilibrium stage with free-streaming

Pre-equilibrium dynamics **evolve energy-momentum tensor** $T^{\mu\nu}$ in spacetime.

- Free-streaming evolves $T^{\mu\nu}$ as follows:

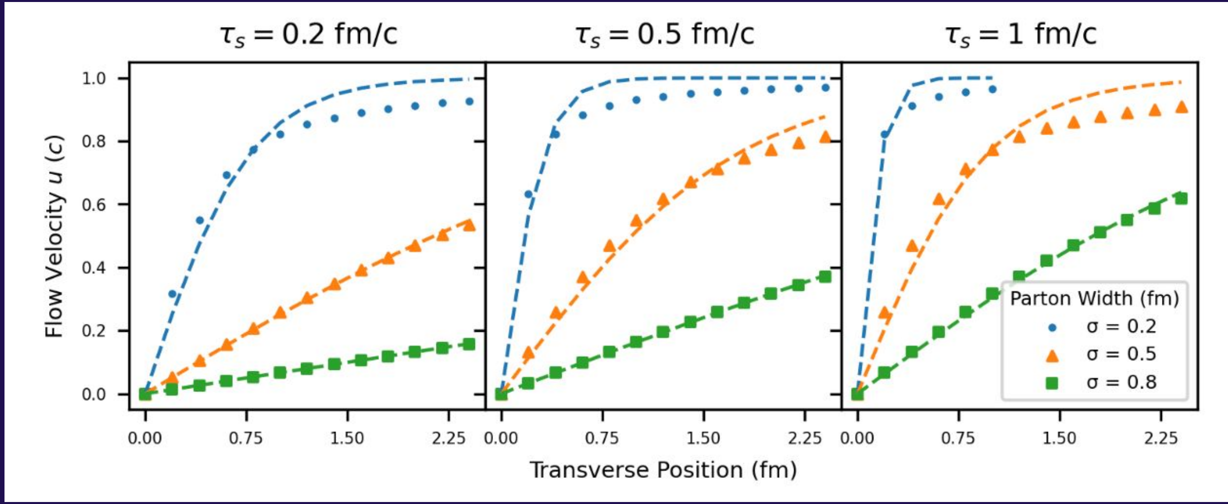
$$T^{\mu\nu}(\tau, \boldsymbol{x}_\perp, \eta_s) = \frac{1}{2\pi}\int_0^{2\pi} d\varphi_p \hat{\boldsymbol{p}}^\mu \hat{\boldsymbol{p}}^\nu T^{\tau\tau}(\tau_0, \boldsymbol{x}_\perp - (\tau_s - \tau_0)\hat{\boldsymbol{p}}, \eta_s)$$



Parameterization of the pre-equilibrium stage with flow velocity

We parameterize the free-streaming flow velocity as $u(r_\perp) = tanh(\alpha r_\perp)$.

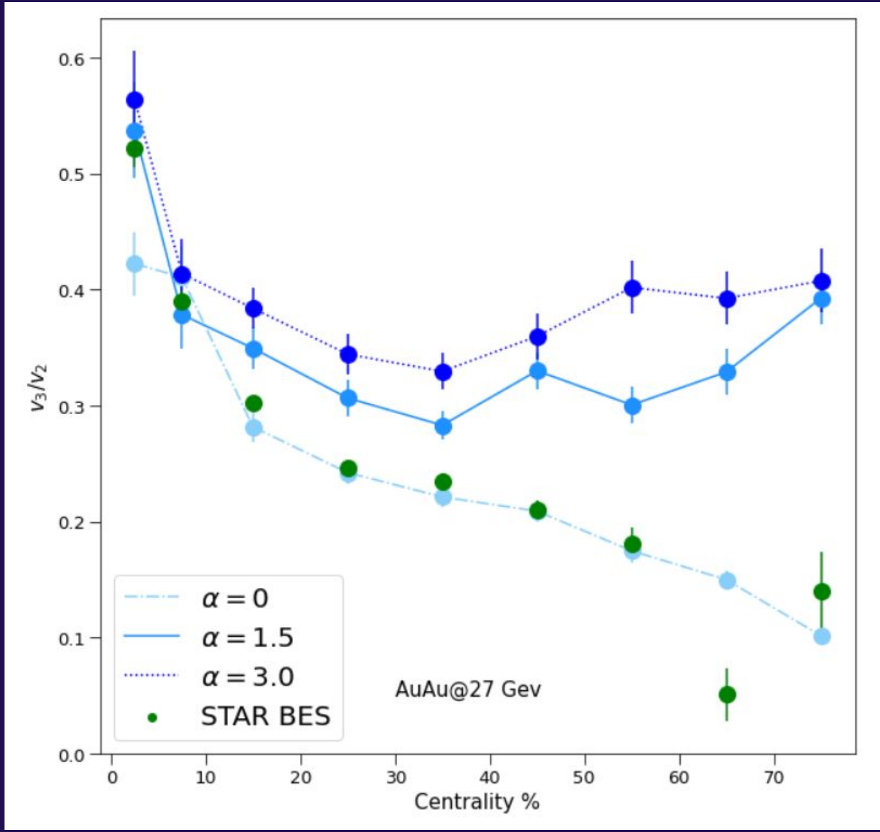
- The flow factor $\boldsymbol{\alpha}$ **is large** if the hot spot width $\boldsymbol{\sigma}$ **is small**
- The flow factor $\boldsymbol{\alpha}$ **increases** with the **free-streaming time** $\boldsymbol{\tau_s}$



		Parton Width σ (fm)		
		0.2	0.5	0.8
τ_s (fm/c)	0.2	1.28	0.26	0.07
	0.5	3.19	0.57	0.16
	1	5.52	1.04	0.31

Effects of varying pre-equilibrium flow: anisotropic flow

- Compute charge hadron v_2, v_3 with varying α
  - v_2 elliptic flow, v_3 triangular flow
- Increase in v_3/v_2 towards higher centrality for larger α
- **Stronger initial flow correlates with larger v_3/v_2 ratio**
- **Agreement with experimental implies weakly coupled early stage**



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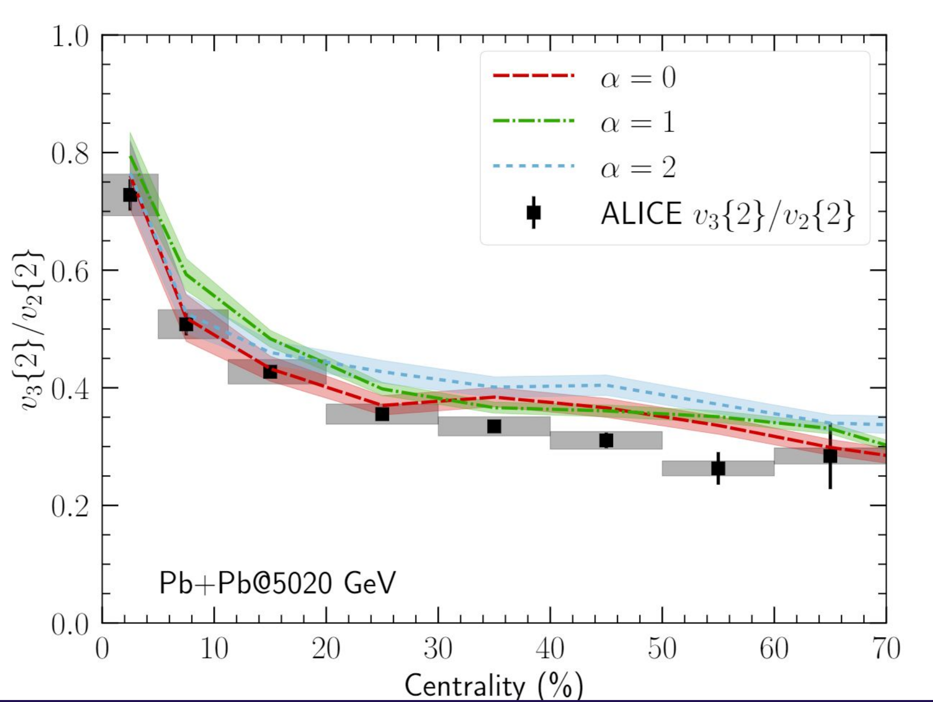
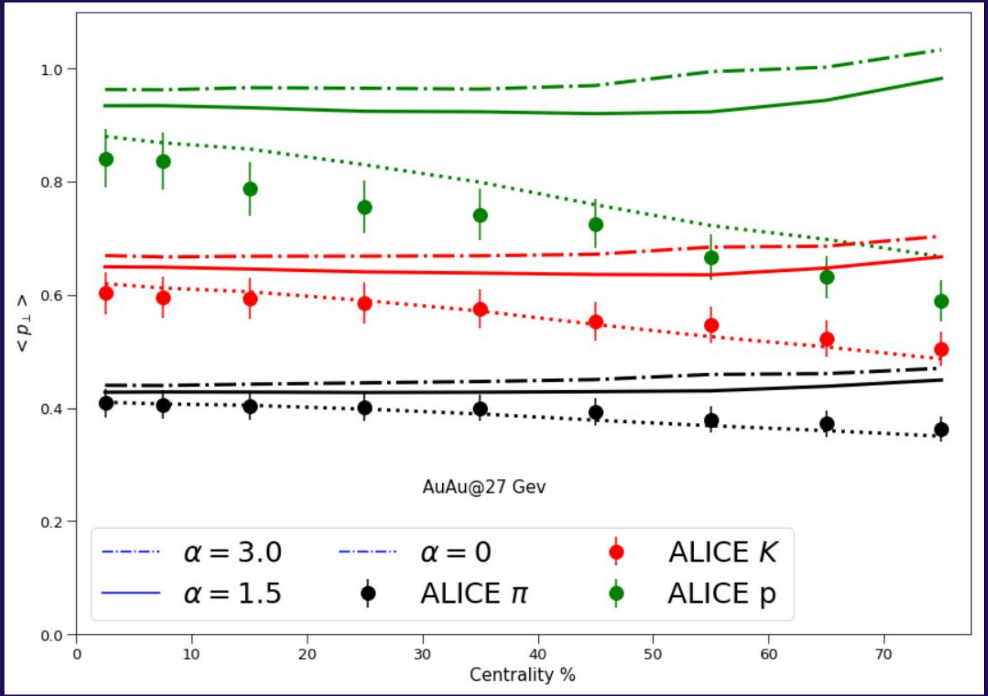
- **Stronger initial flow correlates with larger v_3/v_2 ratio**
  - **Not true at higher energies!**



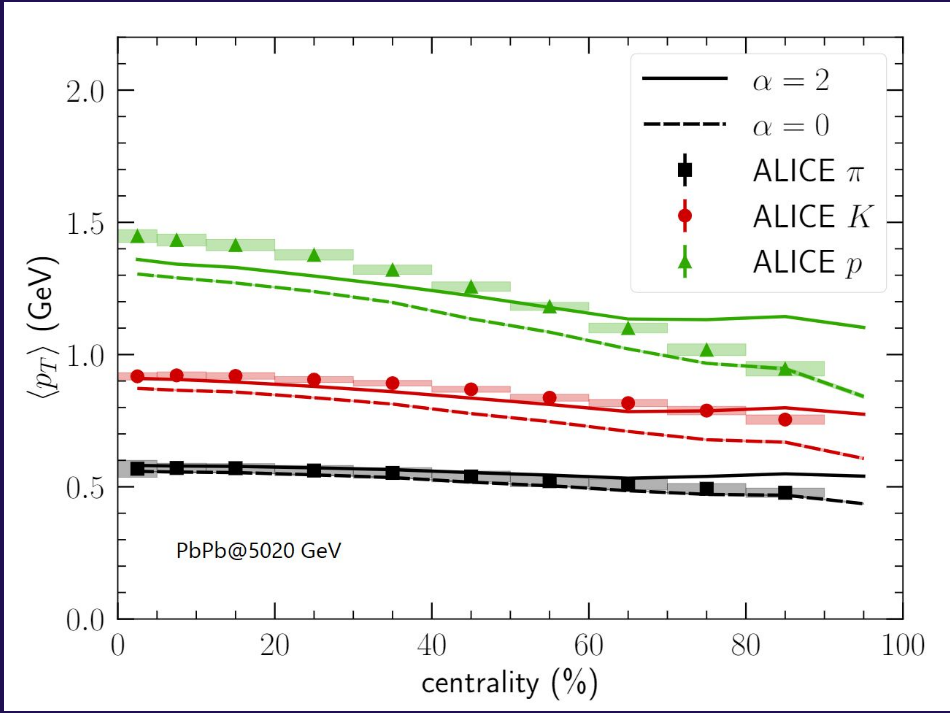
Effects of varying pre-equilibrium flow: transverse momenta

- Pre-equilibrium flow increases transverse momenta towards higher centrality
- Predicts no pre-equilibrium flow (α = 0) at lower energies



Effects of varying pre-equilibrium flow: transverse momenta

- Pre-equilibrium flow increases transverse momenta towards higher centrality
- Predicts no pre-equilibrium flow (α = 0) at lower energies
- Predicts higher pre-equilibrium flow at higher energies
    - Parameterization meaningful in both cases



Conclusions

- We provide a generic parameterization of the transverse velocity field at pre-equilibrium stage of heavy ion collisions
- Full hybrid simulations showed how adjusting the strength of pre-equilibrium flow affects observables

In the future…

- Investigate other observables potentially affected pre-equilibrium flow
  - Further constrain pre-equilibrium flow
- Interpret the phenomenological constraints on α with microscopic models
  - How strongly coupled is the pre-equilibrium stage?