A Unified 3D Kinetic Framework for Heavy-Ion Collisions

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Simulating the full dynamical evolution of the Quark-Gluon Plasma (QGP) in heavy-ion collisions is a persistent theoretical challenge. Traditionally, the field relies on multi-stage hybrid models that stitch independent computational frameworks together across artificial switching surfaces. Within this composite approach, accurately describing hydrodynamization and freeze-out is notoriously difficult; a fixed handoff forces the dense, rapidly interacting core and the dilute expanding edge to transition into and out of the fluid regime simultaneously.

To overcome this, we utilize a fully three-dimensional Monte Carlo kinetic solver for the relativistic Boltzmann equation that evolves the entire collision within a single, continuous framework, requiring no artificial switching surfaces.

Applying this model to central and peripheral Pb-Pb collisions, we demonstrate that the boundary between the pre-equilibrium, hydrodynamic, and free-streaming regimes is a dynamically evolving volume - not a static surface. We investigate how macroscopic system size and initial spatial eccentricity cooperatively govern this process. By contrasting the evolution of a massive, symmetric central collision with a compact, highly eccentric peripheral collision, we show the dependence of the spatial structure and temporal hydrodynamization of the medium on the initial collision geometry.