Particle spectra and HBT radii for simulated, central nuclear collisions of C+C, Al+Al, Cu+Cu, Au+Au, and Pb+Pb from $\sqrt{s} = 62.4 - 2760$ GeV

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Abstract

We study the temperature profile, pion spectra, and HBT radii in central, symmetric, and boost-invariant nuclear collisions, using a **super hybrid model for heavy-ion collisions (SONIC), combining pre-equilibrium flow with viscous hydrodynamics and late-stage hadronic rescatterings**. In particular, we simulate Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV, Au+Au, Cu+Cu, Al+Al, and C+C collisions at $\sqrt{s} = 200$ GeV, and Au+Au and Cu+Cu collisions at $\sqrt{s} = 62.4$ GeV. We find that SONIC provides a **good match to the pion spectra and HBT radii for all collision systems and energies**, confirming earlier work that a combination of pre-equilibrium flow, viscosity, and QCD equation of state can **resolve the so-called HBT puzzle**. For reference, we also show p+p collisions at $\sqrt{s} = 7$ TeV.

Methodology

The **employed code package SONIC** solves the system evolution via

- Overlap function of nuclei $\quad T_A(r) = \epsilon_0 \int_{-\infty}^{\infty} dz \left[1 + e^{-(r^2+z^2-R)/a}\right]$ (1)
- Charge radius R, skin depth a, renormalization constant ϵ_0, and $r = \sqrt{x^2+y^2}$
- Initial energy density: $\quad \epsilon(\tau, r) = T_A^2(r)\,,$ (2)
- **The pre-equilibrium flow** has been calculated numerically assuming an infinite number of colors and infinite coupling for central (and smooth) Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV in Ref. [1]. This is consistent with the early-time, analytic result derived in Ref. [2] up to an overall factor of '2'.
- Pre-equilibrium, radial flow profile: $\quad v^r(\tau, r) = -\frac{\tau}{3}\partial_r \ln T_A^2(r)\,,$ (3)
- Parameters:

$$\eta/s = 0.08\,,\quad \zeta/s = 0.01\,,\quad T_S = 170\,\text{MeV}\,,\quad \tau_{sw} \in [0.35\,\text{fm/c}, 0.6\,\text{fm/c}]\,, \tag{4}$$

- Equation of state from Ref. [3] which is consistent with Ref. [4, 5] at vanishing baryon density and matches a hadron resonance gas at low temperatures.
- Hadron cascade B3D for rescattering dynamics [6] with 5000 B3D events for each hydrodynamic event; hadron resonances are computed for $m_{\text{hadron}} \leq 2.2$ GeV.
- SONIC collects information on **particle spectra, total charged multiplicity** $\frac{dN_{\text{ch}}}{dy}$**, mean pion transverse momentum** $\langle p_T \rangle$ **and the pion HBT radii** R_{out}, R_{side}, and R_{long}.

Total of 6 free parameters:

- 3 numbers: R, a, and T_S;
- 3 functions: $\eta/s(T)$, $\zeta/s(T)$, and equation of state;
- τ_{SW} does not play a significant role because varying it leaves final particle $\langle p_T \rangle$ and HBT radii unchanged. Thus, it is not a relevant, free parameter (see eq. (4))
- $\epsilon_0 = const.$ is constrained by experimental data on the final, charged multiplicity (if available, see eq. (1)). For C+C and Al+Al collisions at $\sqrt{s} = 200$ GeV, we employ the formula

$$\frac{dN_{\text{ch}}}{dy} = \left[\alpha(\sqrt{s})N_{\text{coll}} + \frac{1-\alpha(\sqrt{s})}{2}N_{\text{part}}\right]\frac{dN_{pp}}{dy}\,,\quad \alpha(\sqrt{s} = 200\text{ GeV}) = 0.13\,. \tag{5}$$

SONIC Results

- **Pion** $\langle p_T \rangle$ **spectra match experimental data** very well for all collision systems; see Fig. 1.
- Larger systems obviously generate smaller, radial flow; thus, they tend to live longer than smaller systems
- In detail, Au+Au collisions at $\sqrt{s} = 62.4$ GeV start out close to the Cu+Cu $\sqrt{s} = 200$ GeV results, but then eventually approach the Au+Au $\sqrt{s} = 200$ GeV curve.
- The full, two-dimensional space–time evolution profiles could be used in jet energy loss, direct photon emission, or heavy-quark diffusion [7].
- **SONIC calculates HBT radii quite well for different collision energies via pre-equilibrium flow, viscosities, and a QCD-like equation of state.**
- Granular initial conditions could produce higher, transverse flow velocities, probably improving the agreement between experimental data at $p_T > 1.5$ GeV and SONIC.

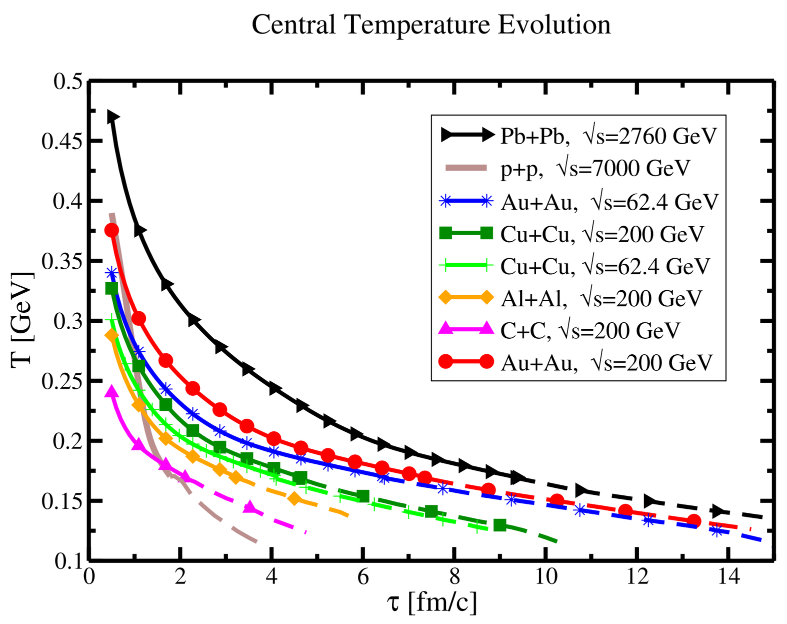

Figure 1: **Central temperature** as a function of proper time for different collision systems and energies. Solid lines denote evolution within hydrodynamics ($T > T_S$), dashed lines denote hadron gas regime ($T < T_S$).

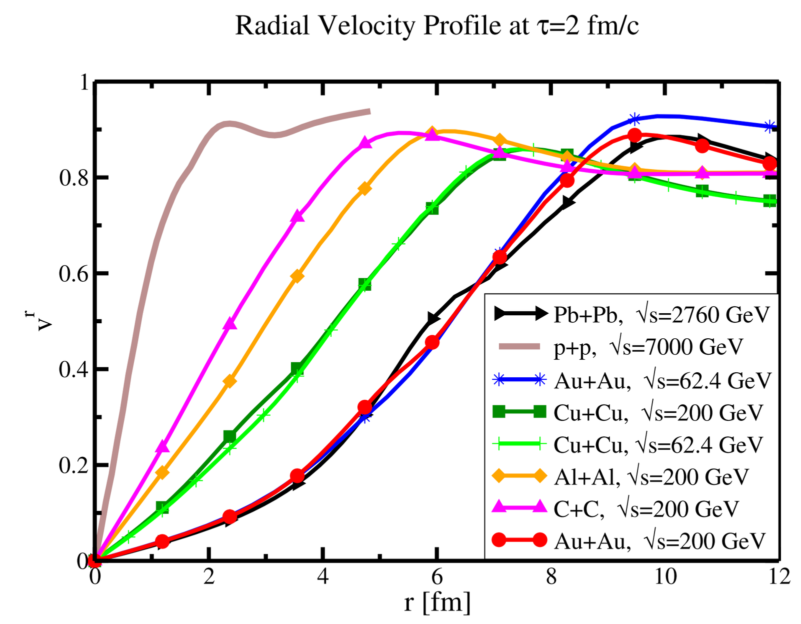

Figure 2: **Velocity profile** at $\tau = 2$ fm/c for the different collision systems ($\tau = 1.9$ fm/c for p+p). The final-observed larger radial flow at higher $\sqrt{s}$ is simply due to the longer lifetime of the Pb+Pb system.

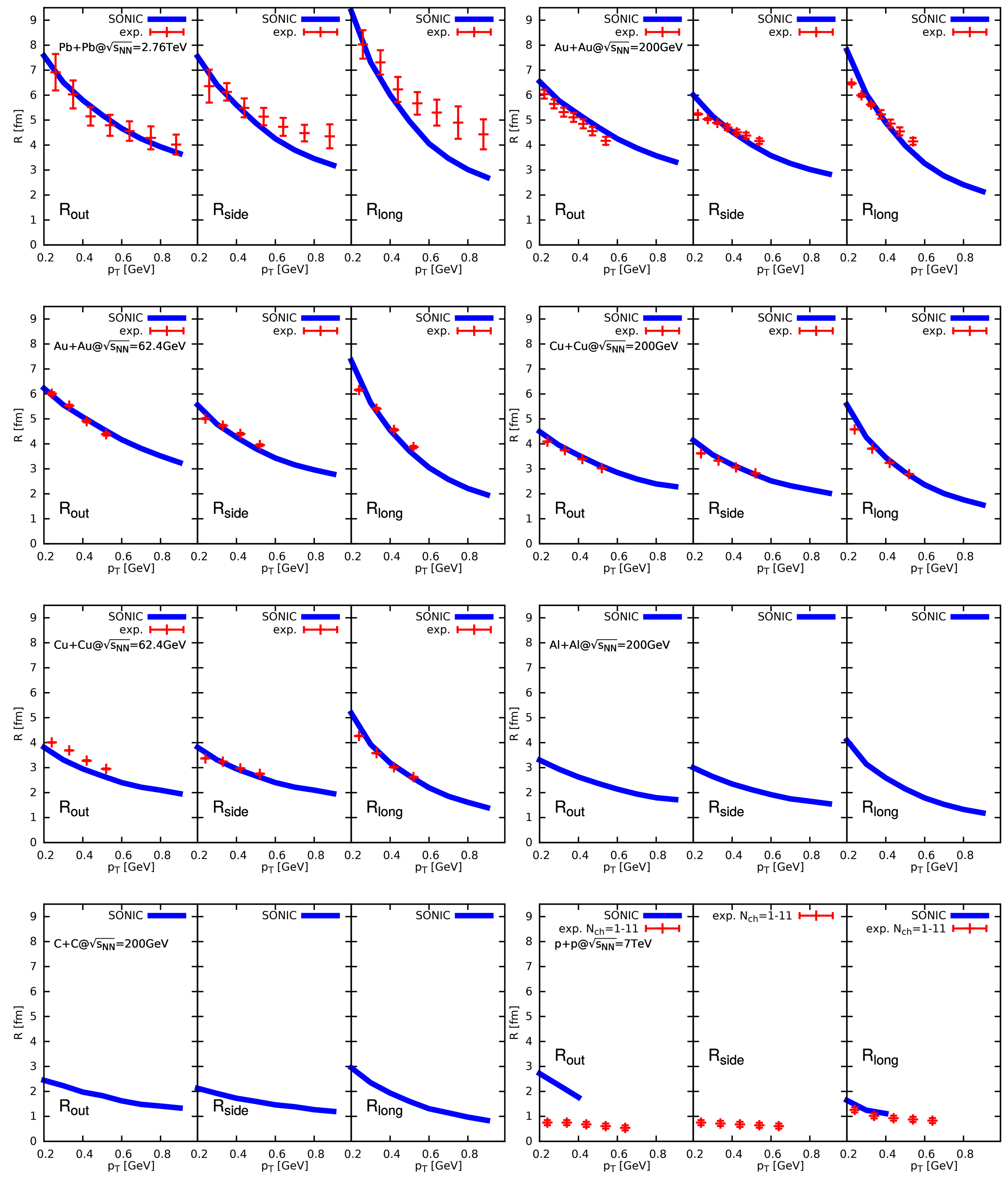

Figure 3: **Pion HBT Radii** for the different collision systems. Shown are model results (SONIC) and experimental results where available [8, 9, 10, 11]. For p+p collisions, our numerical method to calculate HBT radii is breaking down, so we only report partial results. Experimental data is for 0-5% most central events for Pb+Pb and Au+Au collisions, 0-10% most central events for Cu+Cu collisions and minimum-bias events for p+p collisions.

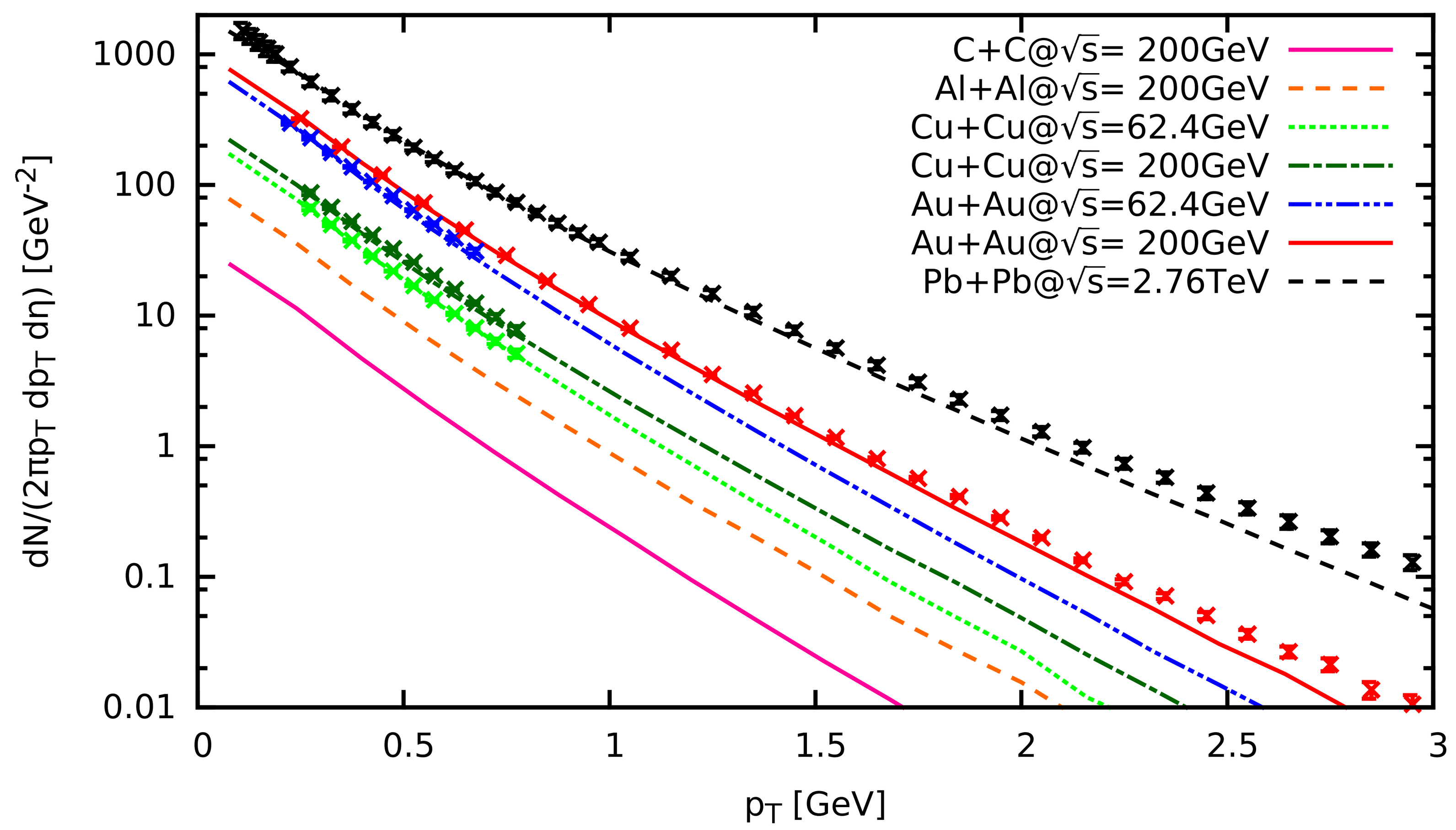

Figure 4: **SONIC Pion spectra** compared to experimental data if available [12, 13, 14, 15]. Centrality 0-5% for Pb+Pb and Au+Au collisions and 0-10% for Cu+Cu collisions.

Conclusion

We have presented SONIC, a new super hybrid model for heavy-ion collisions that combines pre-equilibrium flow, viscous hydrodynamics, and hadronic cascade dynamics into one package. SONIC was used to simulate **boost-invariant, central, symmetric** collisions of smooth nuclei (Pb, Au, Cu, Al, C) at energies ranging from $\sqrt{s} = 62.4$ GeV to $\sqrt{s} = 2.76$ TeV. We found that for a QCD equation of state and a choice of QCD viscosity over entropy ratios of $\eta/s = 0.08$, $\zeta/s = 0.01$, the **particle spectra and pion HBT radii were in reasonable agreement with available experimental data**. We also made predictions for pion mean transverse momentum and HBT radii for C+C and Al+Al collisions at $\sqrt{s} = 200$ GeV. The 2+1 dimensional space–time evolutions of the temperature obtained with SONIC are publicly available [7] in order to be of use in future studies of jet energy loss or photon emission.

Acknowledgments & References

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