Friction terms in the multi-fluid description of heavy-ion collisions

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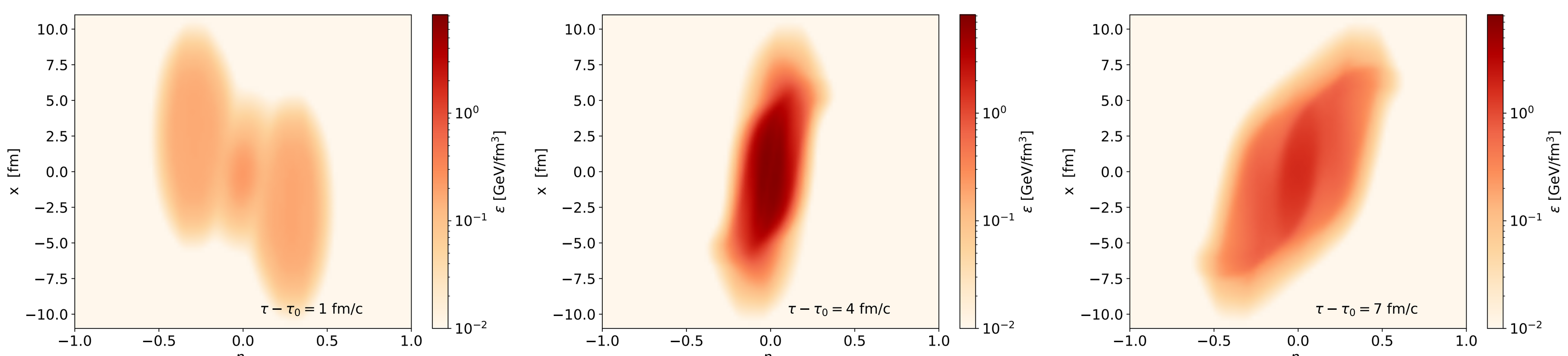
Motivation

- Heavy-ion collisions at $\sqrt{s_{\rm NN}} \sim 7$–62 GeV probe the QCD phase diagram including the area where the QCD critical endpoint can be located (RHIC BES, NA61/SHINE, future FAIR).
- At these energies, the interpenetration time of the nuclei is comparable to the system lifetime ⇒ standard one-fluid hydro with boost-invariance is **not applicable**.
- The **multi-fluid** (three-fluid) approach describes the incoming nuclei as two baryon-rich fluids (projectile & target) interacting via **friction**, producing a third **fireball** fluid.
- Friction terms can be derived from kinetic theory — but they are **not unique**.
- We introduce a new charge transfer (CT) friction model and present the first viscous multi-fluid calculations, reported in .

The MUFFIN model

MUFFIN (MUlti Fluid simulation for Fast IoN collisions), using modified vHLLE code [Karpenko et al., CPC 185 (2014)]:

- Event-by-event fluctuating initial conditions via nucleon sampling (Woods–Saxon).
- Hyperbolic (τ–η_s) coordinate system.
- Equation of State: effective chiral hadron-quark model; easily exchangeable.
- Particlization via Cooper–Frye: SMASH-hadron-sampler.
- Final-state hadronic cascade: SMASH hadronic cascade.



Combined energy density of fluids in x–η_s plane at three evolution stages for Au+Au at $\sqrt{s_{\rm NN}} = 7.7$ GeV

Friction models for projectile–target interaction

Total energy-momentum of the three fluids is conserved:

$$\partial_\mu \left(T_p^{\mu\nu} + T_t^{\mu\nu} + T_f^{\mu\nu} \right) = 0$$

Each fluid evolves with source (friction) terms: $\partial_\mu T_I^{\mu\nu} = F_I^\nu$, and charge: $\partial_\mu N_I^\mu = R_I$.

1. Csernai friction — all scattered particles → fireball:

$$F^\nu_{pt,\rm Cs} = -\xi_{pt}^2 \, m_N \, n_p \, n_t \, u_p^\nu \, V_{\rm rel}^{pt} \, \sigma_{NN\to X}(s_{pt})$$

⇒ Cannot describe baryon transparency (charge transport = energy transport).

2. Ivanov-Mishustin-Satarov (IMS) friction — pions → fireball fluid; all nucleons stay in projectile/target fluids:

$$F^\nu_{pt,\rm IMS} \propto \tfrac{1}{2}\left[(u_p^\nu - u_t^\nu)\,\sigma_P(s_{pt}) + (u_p^\nu + u_t^\nu)\,\sigma_E(s_{pt}) \right]$$

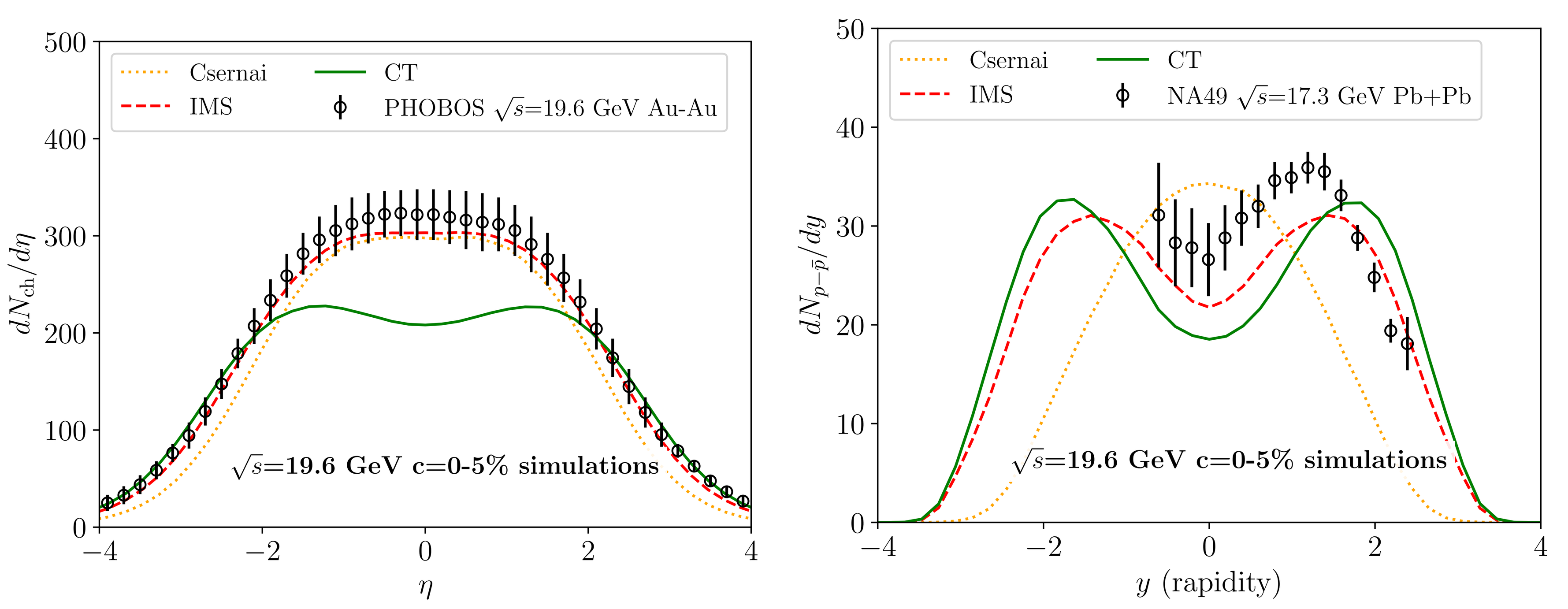
⇒ Enables double-peak in $dN_{p-\bar p}/dy$; no baryon charge in fireball.

3. Charge Transfer (CT) friction (this work) — outgoing nucleons with $|y| < \beta\, y_{\rm in}$ assigned to fireball:

$$F^\nu_{pt,\rm CT} \propto \tfrac{1}{2}\left[(u_p^\nu - u_t^\nu)\,\bar\sigma_P + (u_p^\nu + u_t^\nu)\,\bar\sigma_E \right] + u_p^\nu\,\bar\sigma_R$$

- Interpolates: $\beta = 0$ ⇔ IMS, $\beta = 1$ ⇔ Csernai.
- New parameter α: fraction of energy from rapidity loss → fireball.
- Allows finite baryon density in the fireball ⇒ more realistic.

Comparison of friction models



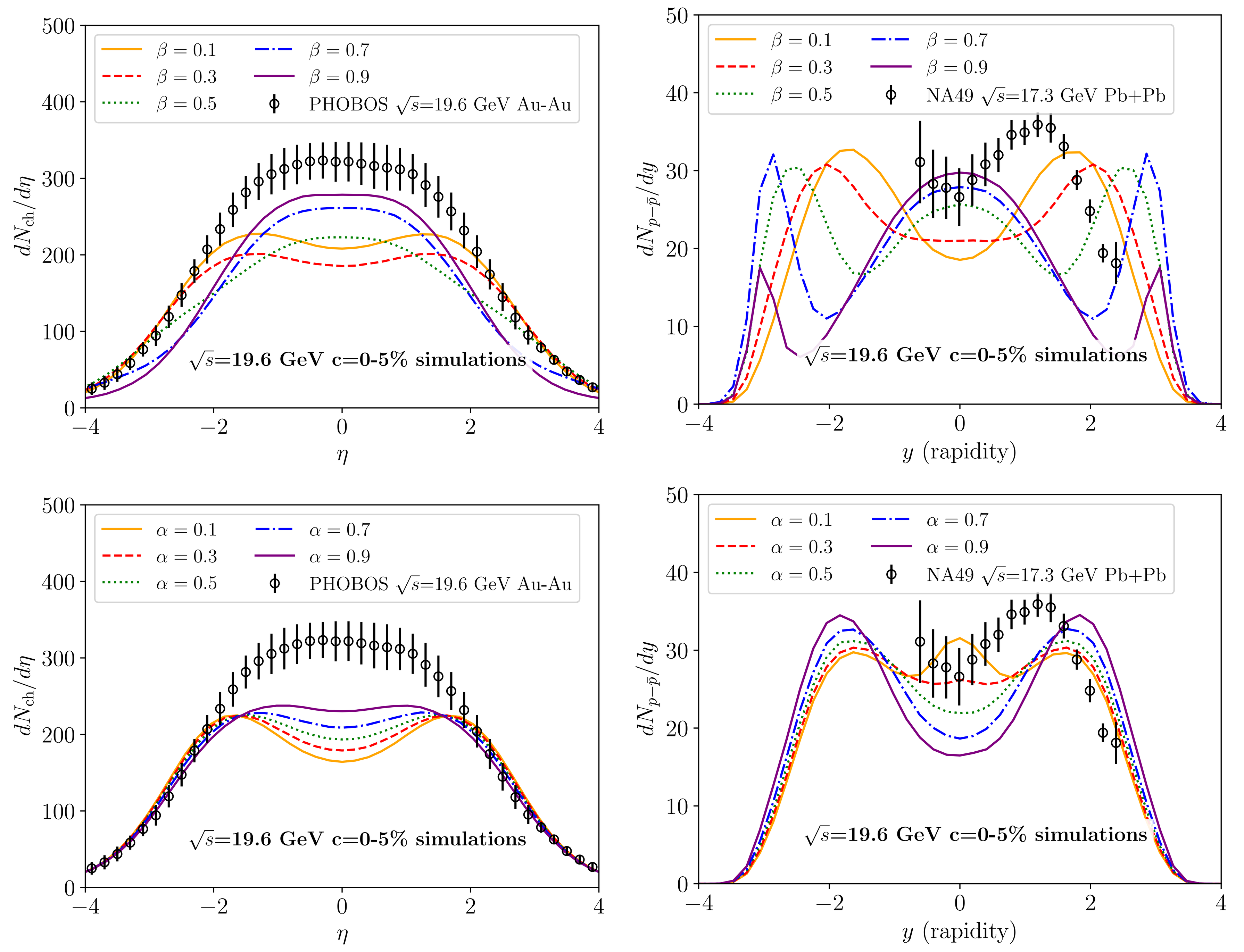
Au+Au at $\sqrt{s_{\rm NN}} = 19.6$ GeV, 0–5%. Parameters: $\xi_{pt} = 1.0$, $\xi_f = 0.1$, $\alpha = 0.7$, $\beta = 0.1$ for CT.

- Csernai: reasonable $dN_{\rm ch}/d\eta$, but over-stops baryons.
- IMS: correct double-peak structure in net protons.
- CT: less entropy production ⇒ lower midrapidity $dN_{\rm ch}/d\eta$, but leaves room for viscous entropy generation.

Conclusions

- Introduced charge transfer (CT) friction: allows baryon charge transfer to fireball, more consistent with momentum-space separation of fluids.
- CT friction with ideal hydro underestimates $dN_{\rm ch}/d\eta$ ⇒ leaves room for **dissipative entropy production**.
- First viscous multi-fluid calculations: shear viscosity resolves the tension between $dN_{\rm ch}/d\eta$ and $dN_{p-\bar p}/dy$, and brings v_2 into agreement with data.
- Predictions for p_T spectra and $v_2(p_T)$ reasonable across $\sqrt{s_{\rm NN}} = 7.7$–39 GeV.

Parameter scans of CT friction



Top row: Increasing β pushes more baryons into fireball → third peak in $dN_{p-\bar p}/dy$.
Bottom row: Increasing α increases midrapidity multiplicity, deepens dip in net protons.

Key tension: parameter changes improving $dN_{\rm ch}/d\eta$ tend to worsen $dN_{p-\bar p}/dy$ ⇒ points to the need for **dissipation**.

First viscous multi-fluid calculation

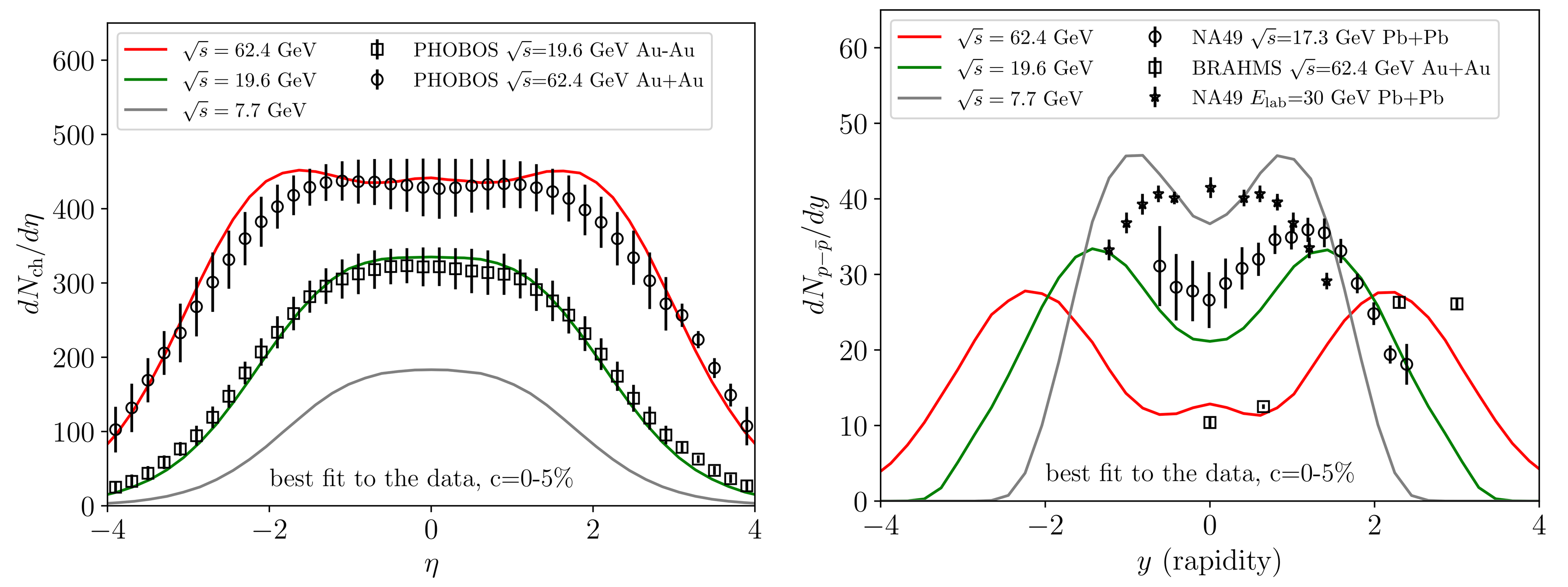
Shear viscosity with μ_B-dependent parametrisation [Jahan, Roch & Shen, PRC 110 (2024)]:

$$\tilde\eta(\mu_B) = \frac{\eta\, T}{\varepsilon + p} = \begin{cases} \eta_0 + (\eta_2 - \eta_0)\dfrac{\mu_B[\text{GeV}]}{0.2}, & \mu_B \le 0.2\ \text{GeV} \\ \eta_2 + (\eta_4 - \eta_2)\dfrac{\mu_B[\text{GeV}] - 0.2}{0.2}, & 0.2 < \mu_B < 0.4\ \text{GeV} \\ \eta_4 = 0.287, & \mu_B \ge 0.4\ \text{GeV} \end{cases}$$

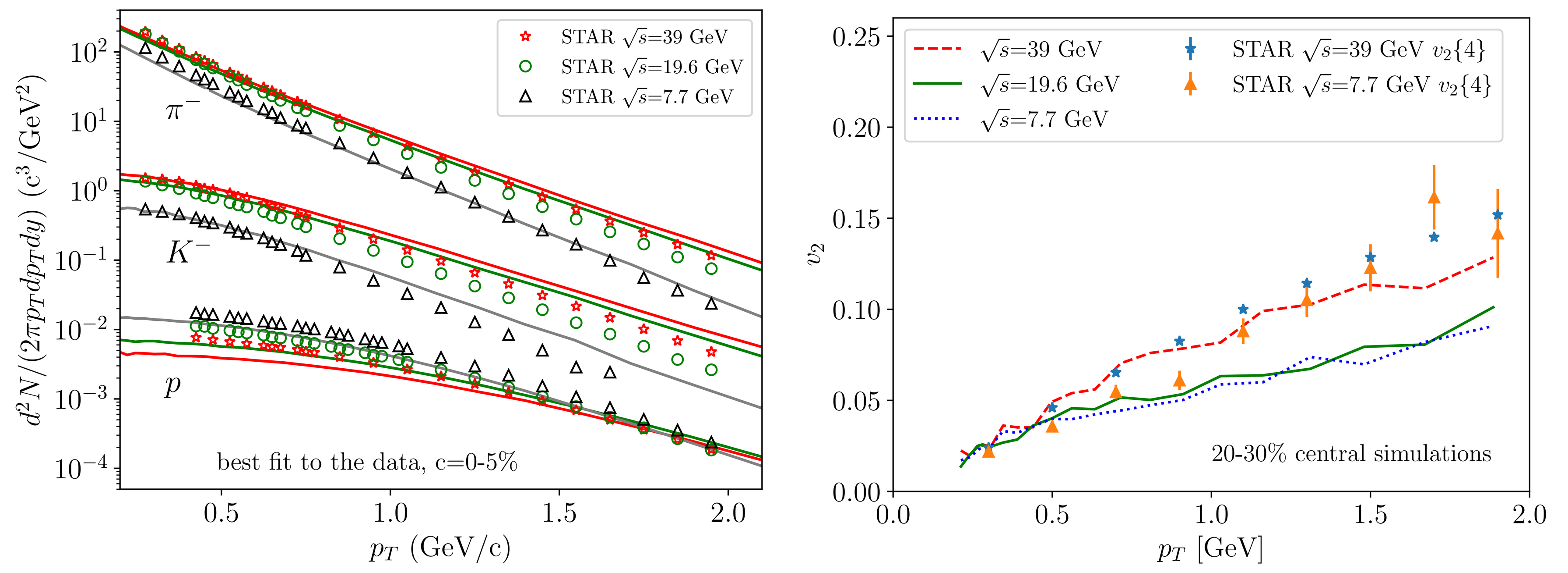
Shear viscosity increases charged hadron multiplicity (entropy production) while leaving net-proton distribution nearly unchanged ⇒ resolves the tension between $dN_{\rm ch}/d\eta$ and $dN_{p-\bar p}/dy$.

Data comparison across BES energies

Best-fit: $\alpha = 0.8$, $\beta = 0.1$, $\xi_{pt} = 1.0$, $\xi_f = 0.1$ (at 62.4 GeV: $\alpha = 0.75$, $\xi_{pt} = 0.8$). Viscous evolution.



Correct transition from single-peak to double-peak net-proton structure. Good agreement with PHOBOS, NA49, BRAHMS data.



Left: p_T spectra agree at low p_T; high-p_T slopes slightly too hard → may need bulk viscosity.
Right: Elliptic flow brought close to STAR data by viscosity; remaining over-suppression at high p_T → room for improved $\eta(T, \mu_B)$.

Note: p_T spectra and v_2 are predictions — model parameters fixed from rapidity distributions only.

Outlook

Include bulk viscosity and baryon diffusion. Consistent treatment of how friction affects dissipative quantities. Event-by-event initial conditions with CT friction. Bayesian analysis of friction + transport parameters.

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References: C. Werthmann, I. Karpenko, P. Huovinen, arXiv:2511.10487; J. Cimerman et al., PRC 107 (2023) 044902 [arXiv:2301.11894]; I. Karpenko et al., CPC 185 (2014) 3016; J. Weil et al. [SMASH], PRC 94 (2016) 054905.