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Effects of the Hadronic Potentials on Particle Correlation Effects in Heavy Ion Collisions at Intermediate and High Energies

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Outline

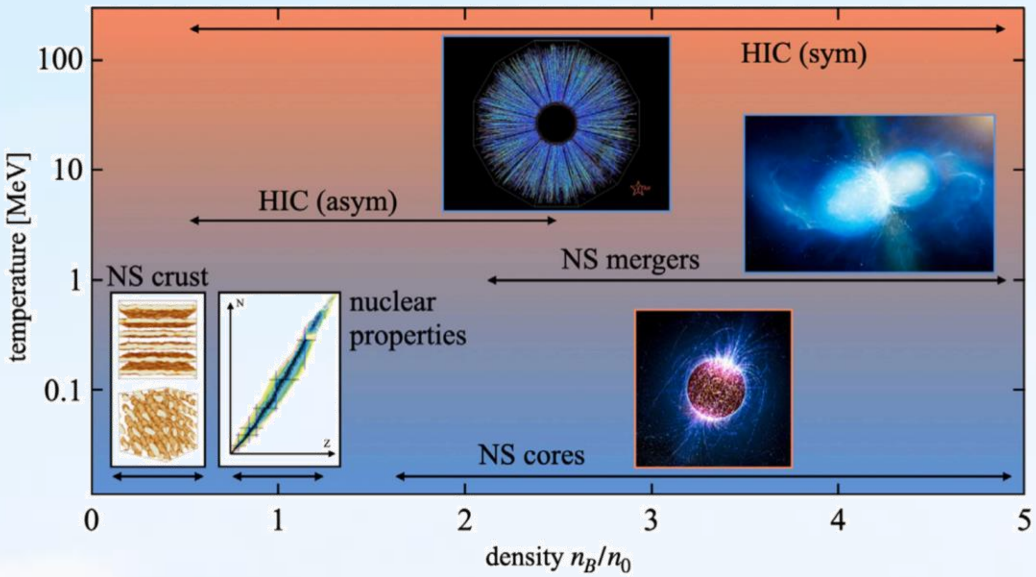
1. Introduction

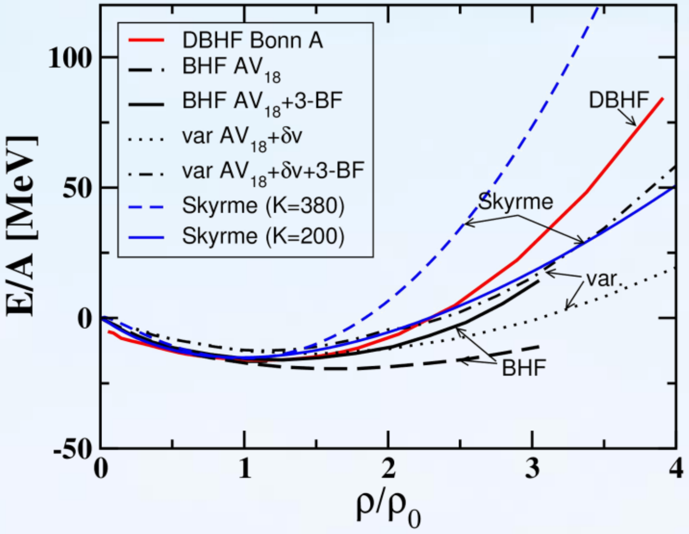
2. Model and two-pion HBT correlation

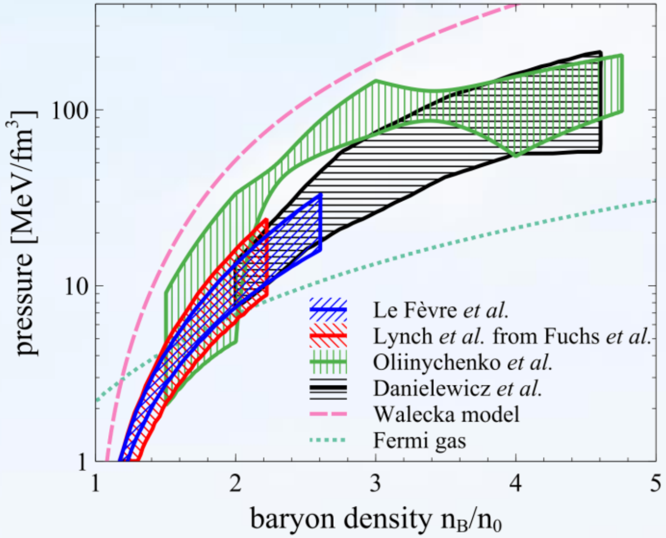
3. Results and discussions

4. Summary and outlook

Introduction







- The nuclear equation of state (nEOS) is at the center of numerous theoretical and experimental efforts in nuclear physics.
- HICs probe the widest range of baryon densities and represent the only means to address the EoS away from ρ_0 in controlled terrestrial experiments.
- Quantitative constraints on the EOS, requires comparisons of experimentally measured observables to results obtained in dynamic simulations, howerver, there do exist deviations on the predications and conclusions from different transport models and observables.

A. Sorensen *et al.*, Prog. Part. Nucl. Phys. 134, 104080(2024).

Introduction

BUU Type	Code Correspondents	Energy Range [A GeV]	Relativity
BLOB	P. Napolitani, M. Colonna	0.01–0.5	non-rel
BUU-VM	S. Mallik	0.02–1	rel
DJBUU	Y. Kim, S. Jeon, M. Kim, C.-H. Lee, K. Kim	0.05–2	cov
GiBUU	J. Weil, T. Gaitanos, K. Gallmeister, U. Mosel	0.05–40	rel/cov
IBL	W.J. Xie, F.S. Zhang	0.05–2	rel
IBUU	J. Xu, L.W. Chen, B.A. Li	0.05–2	rel
LBUU(LHV)	R. Wang, Z. Zhang, L.-W. Chen	0.01–1.5	rel
pBUU	P. Danielewicz	0.01–12	rel
PHSD	E. Bratkovskaya, W. Cassing	0.1–200	rel/cov
RBUU	T. Gaitanos	0.05–2	cov
RVUU	Z. Zhang, C.M. Ko, T. Song	0.05–2	cov
SMASH	D. Oliinychenko, H. Elfner, A. Sorensen	0.5–200	cov
SMF	M. Colonna, P. Napolitani	0.01–0.5	non-rel
χBUU	Z. Zhang, C.M. Ko	0.01–0.5	non-rel
QMD Type	**Code Corespondents**	**Energy Range [AGeV]**	**Relativity**
AMD	A. Ono	0.01–0.3	non-rel
AMD+JAM	N. Ikeno, A. Ono	0.01–0.3	non-rel+r
BQMD/IQMD	A. Le Fèvre, J. Aichelin, C. Hartnack, R. Kumar	0.05–2	rel
CoMD	M. Papa	0.01–0.3	non-rel
ImQMD	Y.X. Zhang, N. Wang, Z.X. Li	0.02–0.4	rel
IQMD-BNU	J. Su, F.S. Zhang	0.05–2	rel
IQMD-SINAP	G.Q. Zhang	0.05–2	rel
JAM	A. Ono, N. Ikeno, Y. Nara, A. Ohnishi	1–158	rel
JQMD 2.0	T. Ogawa, K. Niita, S. Hashimoto, T. Sato	0.01–3	rel
LQMD(IQMD-IMP)	Z.Q. Feng, H.G. Cheng	0.01–10	rel
TuQMD/dcQMD	D. Cozma	0.1–2	rel
UrQMD	Y. J. Wang, Q. F. Li, Y. X. Zhang	0.05–200	rel

To understand the model dependence of transport simulations:

- The Transport Model Evaluation Project (TMEP).
- Investigate the effects of different treatments of the main ingredients in transport model, such as nEoS and cross sections, on the observables.
- Develope sophisticated and reliable transport model.

H. Wolter et al. [TMEP Collaboration], Prog. Part. Nucl. Phys. 125, 103962 (2022).

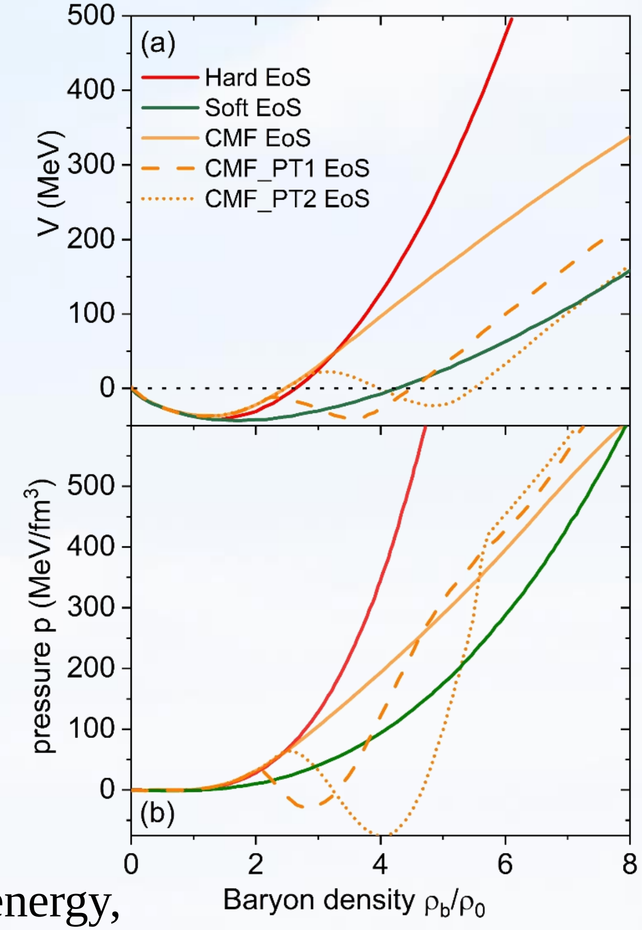
UrQMD model

➢ UrQMD model

(current public version 3.5, https://urqmd.org/)

In UrQMD the real part of the interaction is implemented by a density dependent potential energy $V(n_B)$. Once the potential energy is known, the change of momentum of each baryon in accord with Hamiltons equations of motion can be calculated as

$$\dot{\mathbf{p}}_i = -\frac{\partial \mathbf{H}}{\partial \mathbf{r}_i} = -\frac{\partial \mathbf{V}}{\partial \mathbf{r}_i} = -\left(\frac{\partial V_i}{\partial n_i} \cdot \frac{\partial n_i}{\partial \mathbf{r}_i}\right) - \left(\sum_{j \neq i} \frac{\partial V_j}{\partial n_j} \cdot \frac{\partial n_j}{\partial \mathbf{r}_i}\right),$$



☐ The Skyrme model

The density dependence of the single particle potential for all baryons is given by a simple form:

$$U_{\text{Skyrme}}(n_B) = \alpha(n_B/n_0) + \beta(n_B/n_0)^\gamma \, .$$

$$U(n_B) = \frac{\partial\left(n_B \cdot V(n_B)\right)}{\partial n_B} \, .$$

Parameters	Hard EoS	Soft EoS
α [MeV]	−124	−356
β [MeV]	71	303
γ	2.00	1.17

☐ The CMF model

The single nucleon potential is given by the interactions with the chiral and repulsive mean fields. At $T = 0$, it can be calculated from the self energy of the nucleons as:

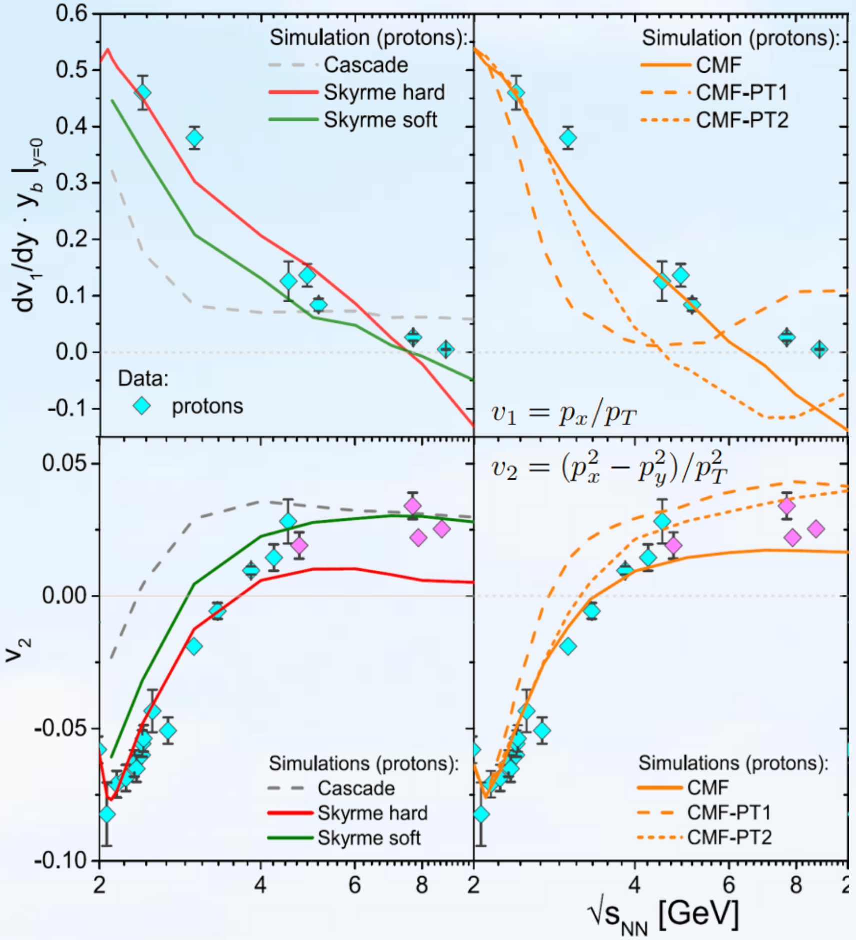
$$U_{\text{CMF}} = m_N^* - m_N^{\text{vac}} - \mu_N^* + \mu_N$$

$$V_{CMF} = E_{\text{field}}/A = E_{\text{CMF}}/A - E_{\text{FFG}}/A$$

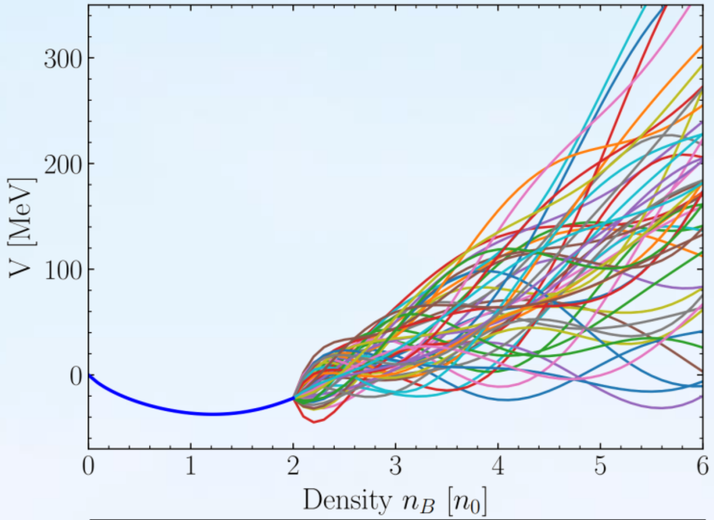
A phase transition can be simply included by adding another minimum in the potential energy, to provide for another metastable state in the mean-field energy per baryon at high densities.

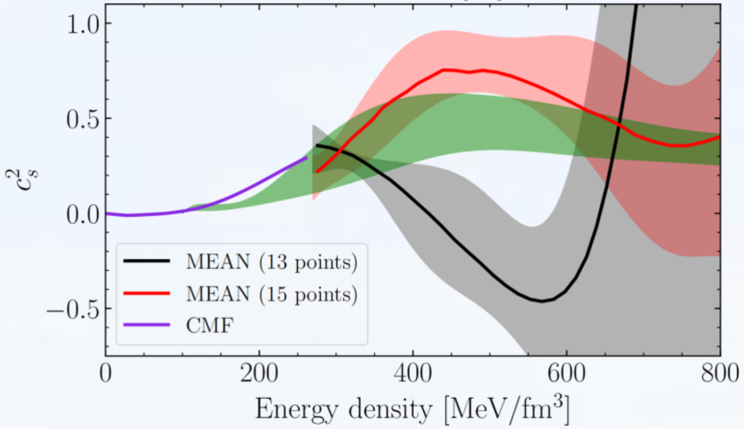
Eur. Phys. J. C 82, 427(2022), Eur. Phys. J. C 82, 911(2022); Sci. China-Phys. Mech. Astron. 66, 232011 (2023); Phys. Rev. Lett 131, 202303 (2023); Phys. Rev. C 107, 024913(2023).

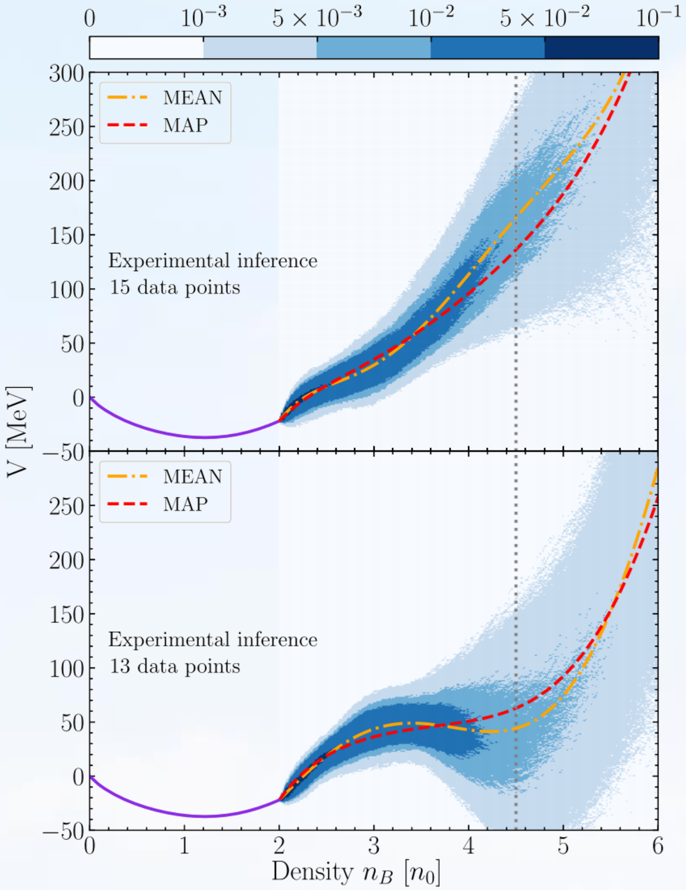
UrQMD model



The CMF EoS gives good results on collective flows. Sensitivity up to $\approx 4n_0$.







Results depend strongly on the data used. If all data on the mean m_T and v_2 are used, constraints are similar to those from astrophysics (NS and BNSM).

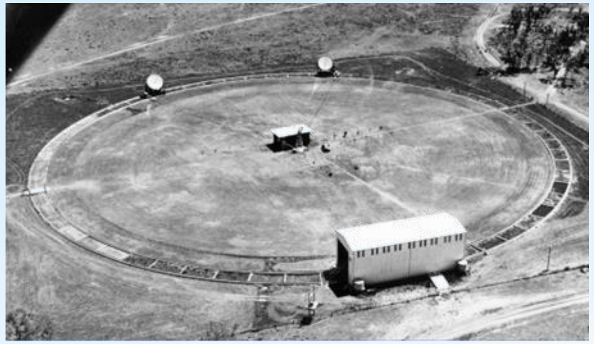
- The phase transitions with a low coexistence density ($\sim 4\rho_0$), shows a distinct minimum in the slope of the directed flow as a function of the beam energy.
- For densities from $2\rho_0$to $4\rho_0$, the EoS is well constrained, and excluding any strong phase transition at densities below$\sim 4\rho_0$.

J. Steinheimer, A. Motornenko, A. Sorensen, Y. Nara, V. Koch and M. Bleicher, Eur. Phys. J. C 82, 911(2022).

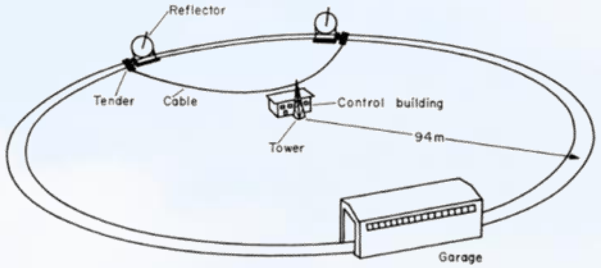
M. Omana Kuttan, J. Steinheimer, K. Zhou and H. Stoecker, Phys. Rev. Lett. 131, 202303 (2023).

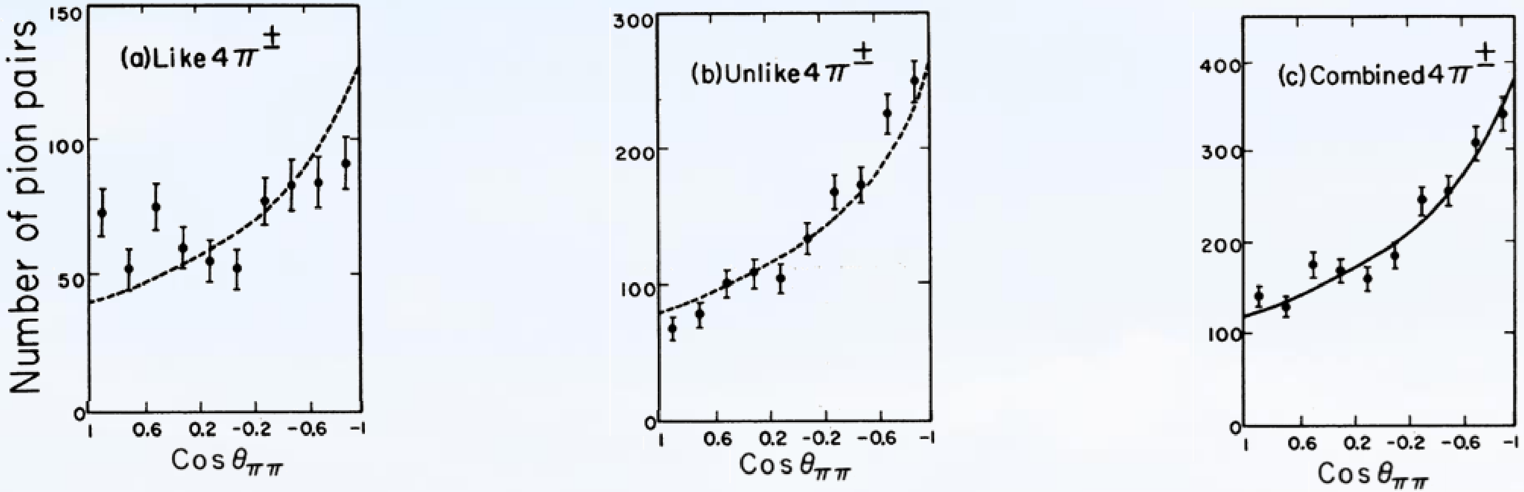
Two-pion HBT correlation

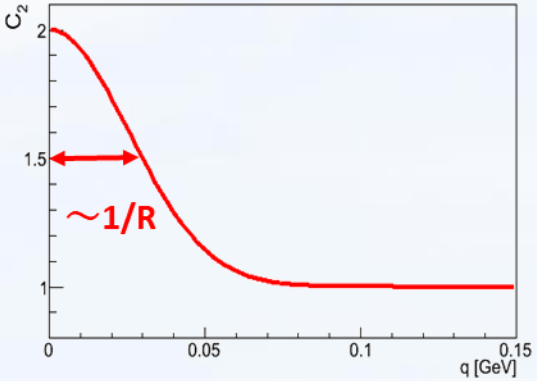
Robert Hanbury-Brown and Richard Q. Twiss (HBT) interferometry
(also known as two-identical particle correlation, femtoscopy)



In 1959, Goldhaber, Goldhaber, Lee and Pais performed $p+\bar{p}$@1.05 GeV/c at the Bevalac/LBL, aiming at the discovery of the ρ_0 resonance ($\rho_0 \rightarrow \pi^+\pi^-$). They observed an unexpected angular correlation among identical pions (GGLP effect)!







This effect was a consequence of the Bose-Einstein nature of $\pi^+\pi^+$ and $\pi^-\pi^-$, and parameterized the observed correlation as

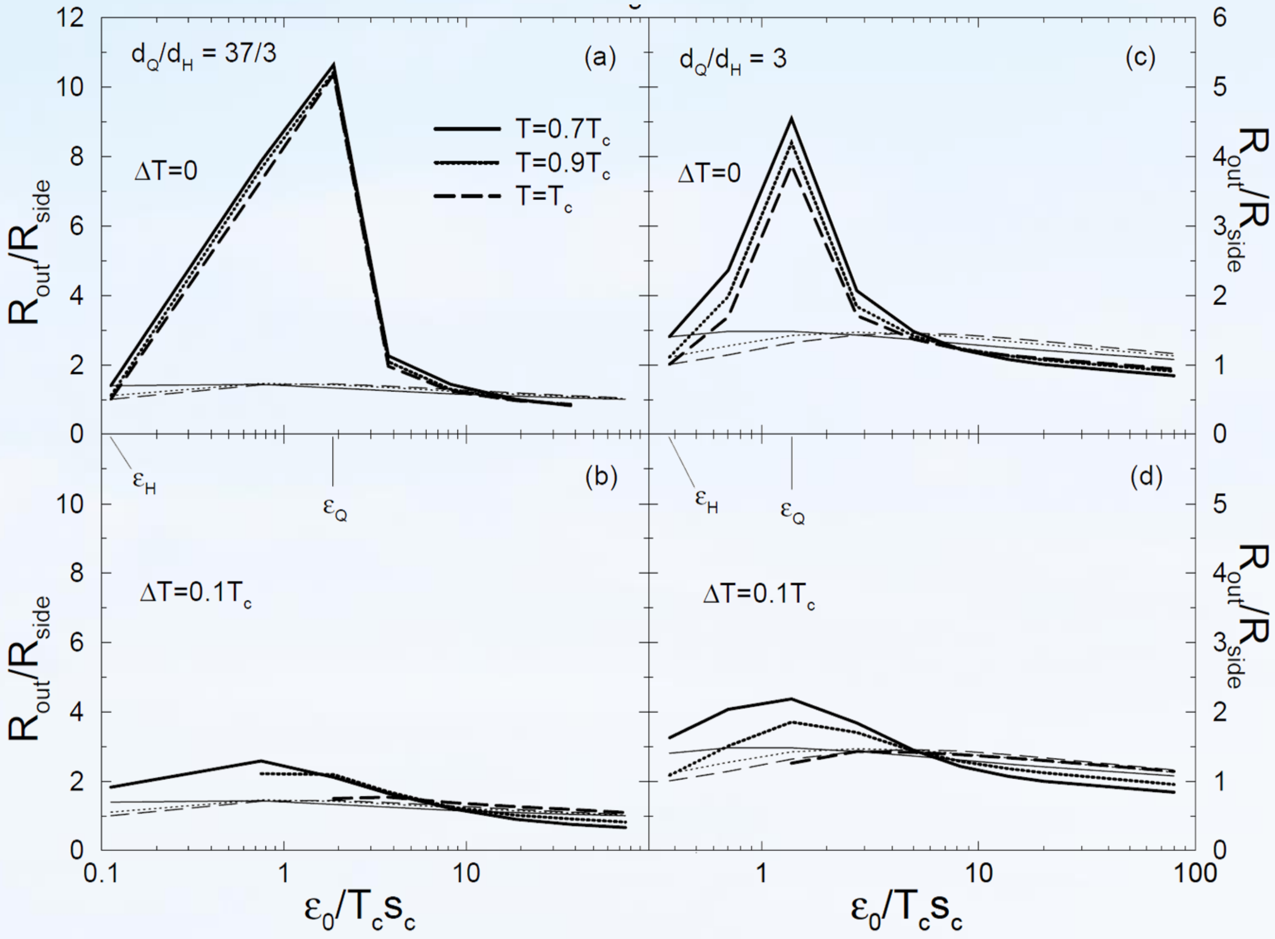
$$C(Q^2)=1+e^{-Q^2R^2}=1+e^{(q_0-\mathbf{q}^2)R^2}.$$

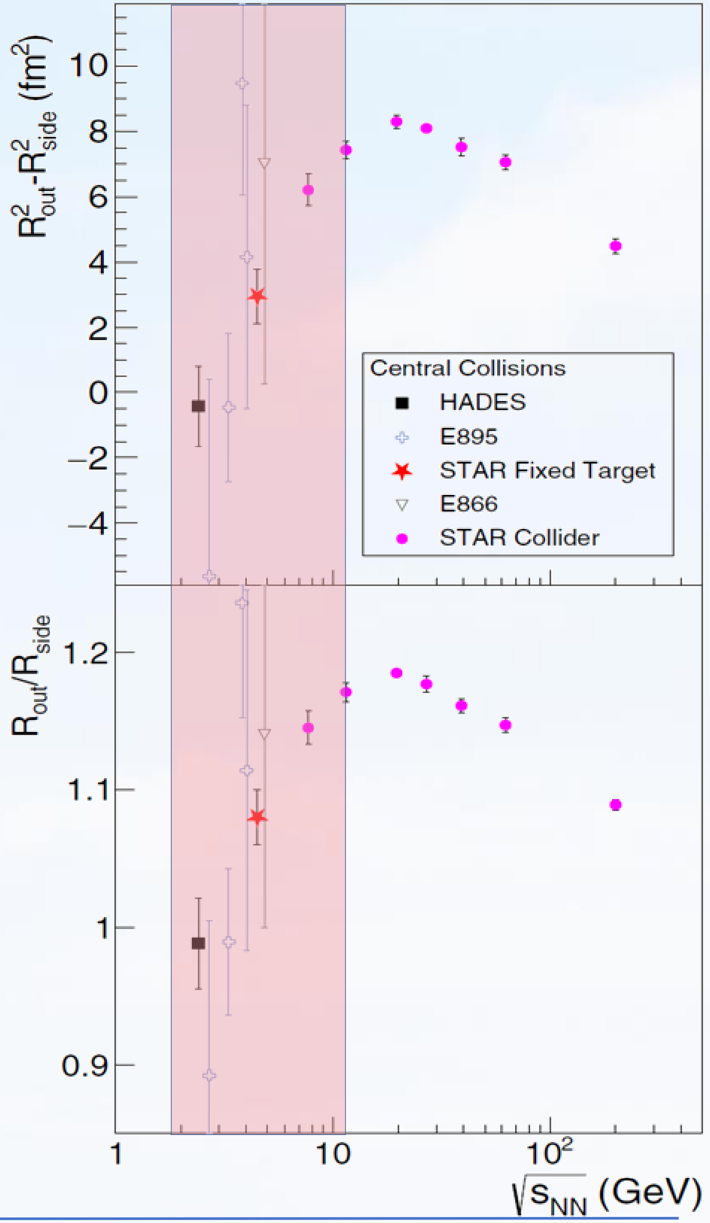
"…the dependence of angular correlation effects on the value of the radius is rather sensitive…"

Phys. Rev. Lett. 3, 181-183 (1959). Phys. Rev. 120, 300 (1960). Braz. J. Phys.35, 70-99 (2005). Ann. Rev. Nucl. Part. Sci. 55, 357-402(2005).

Two-pion HBT correlation

- The EoS remains sufficiently soft in the transition region to delay the propagation of ordinary rarefaction waves for a considerable time. The signature of time delay, proposed by Pratt and Bertsch, is an enhancement of the ratio of the inverse width of the pion correlation function in out-direction to that in side-direction.



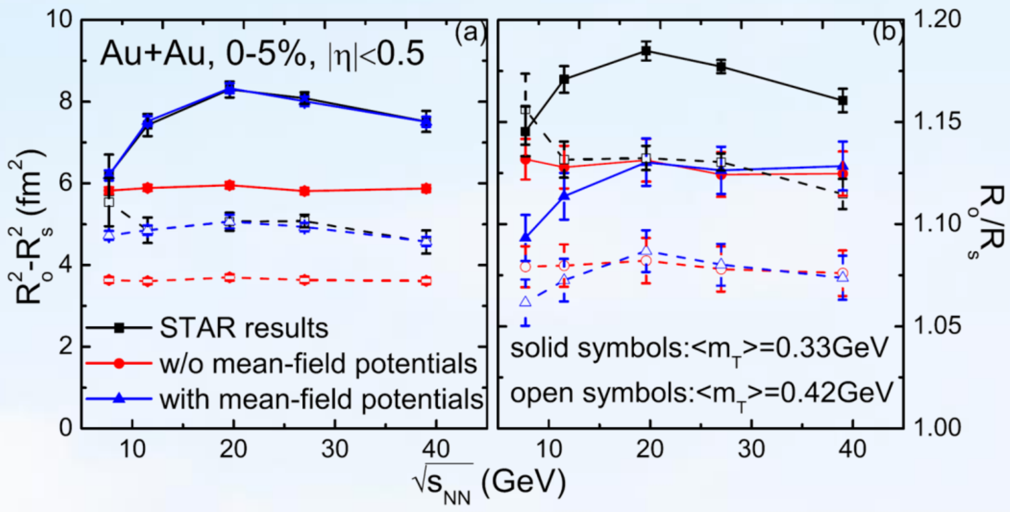


Phys. Rev. D 33, 1314 (1986). Phys. Rev. C.37.1896 (1988). Nucl. Phys. A 608, 479 (1996). arXiv:nucl-th/9606039 New J. Phys. 13, 065006 (2011).

Two-pion HBT correlation

- **AMPT**: The effects of the hadronic mean-field potentials on the HBT correlation in relativistic HICs were studied.

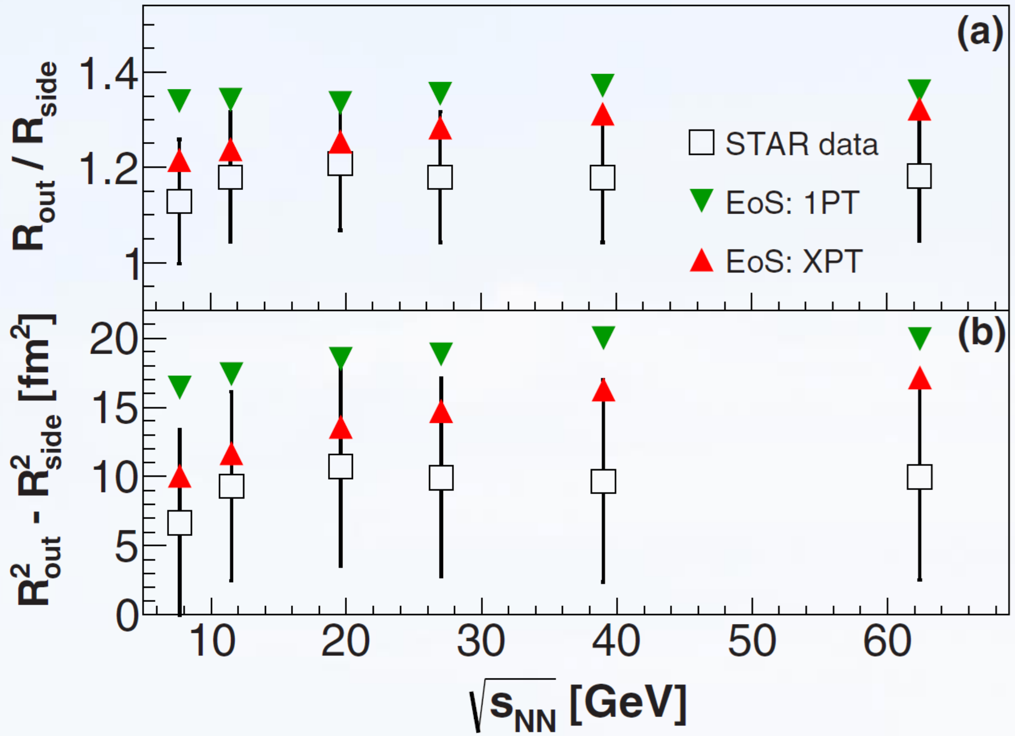
The hadronic mean-field potentials are found to delay the emission time of the system and lead to large HBT radii extracted from the correlation function. (Soft attractive mean-field potentials at lower densities delay the emission of pions and baryons).



C. J. Zhang, J. Xu, Phys. Rev. C 96, 044907 (2017)

The HBT correlations can also be useful in understanding the mean-field potentials of protons, kaons, and antiprotons as well as baryon-antibaryon annihilations.

- **vHLLE+UrQMD**:
The bag model EoS (1PT EoS, first order phase transition) results in a systematically worse reproduction of the data, the chiral model EoS (XPT EoS, crossover transition) results in a quite reasonable reproduction of the STAR data.



P. Batyuk et.al., Phys. Rev. C 96, 024911 (2017)

Two-pion HBT correlation

1. Performing UrQMD simulations, obtain the particles' freeze-out phase space coordinates.

2. The freeze-out space-time coordinates and 4-momenta serve as input for the "correlation afterburner" program (CRAB v3.0β) to construct the HBT correlator based on:

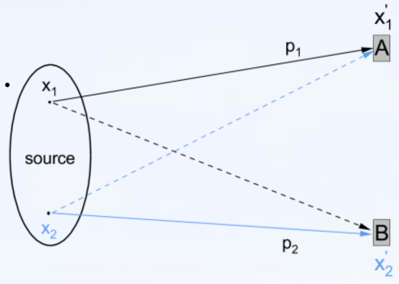
Phys. Rev. Lett. 53 (1984) 1219-1221. https://web.pa.msu.edu/people/pratts/freecodes/crab/home.html

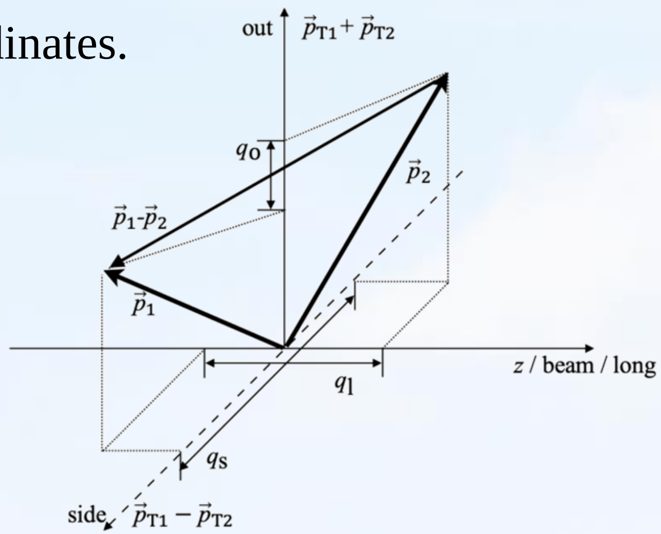
$$C(\mathbf{k},\mathbf{q}) = 1 + \frac{\int d^4x_1 d^4x_2 S_1(x_1,\mathbf{p}_1)S_2(x_2,\mathbf{p}_2)|\phi_{rel}(x_2' - x_1')|^2}{\int d^4x_1 d^4x_2 S_1(x_1,\mathbf{p}_1)S(x_2,\mathbf{p}_2)}$$

$S(x_i, p_i)$ is an effective probability for emitting a particle i with 4-momentum $p_i = (E_i, \mathbf{p}_i)$ from the space-time point $x_i = (\mathbf{r}_i, t_i)$.

ϕ_{rel} is the relative wave function in the pair's rest frame.

$\mathbf{q} = \mathbf{p}_i - \mathbf{p}_j$ and $\mathbf{k} = (\mathbf{p}_i + \mathbf{p}_j)/2$ are the relative momentum and the average momentum of the two particles i and j.

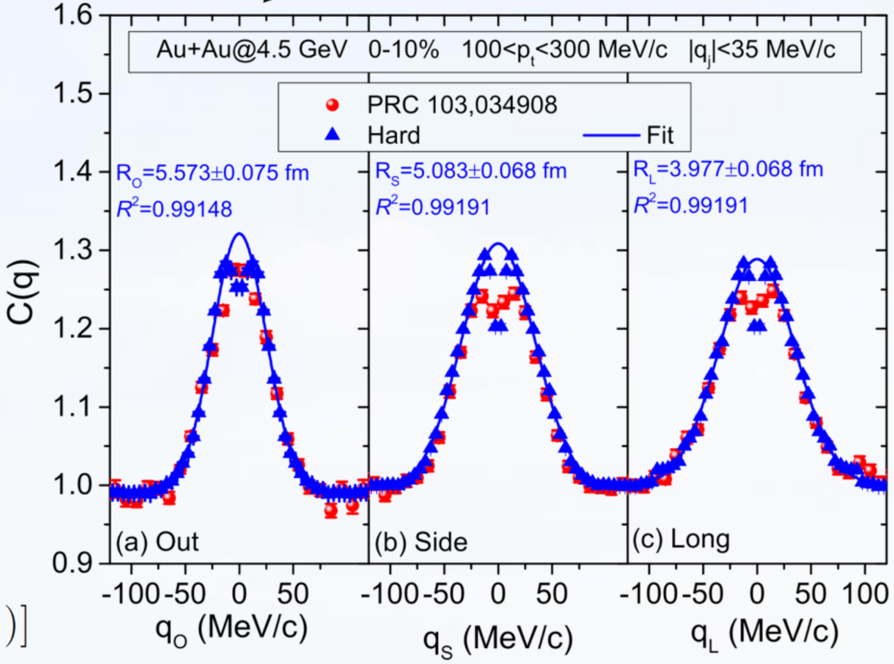




3. Lastly, the correlation function is then fitted assuming a 3D Gaussian form in the longitudinally comoving system.

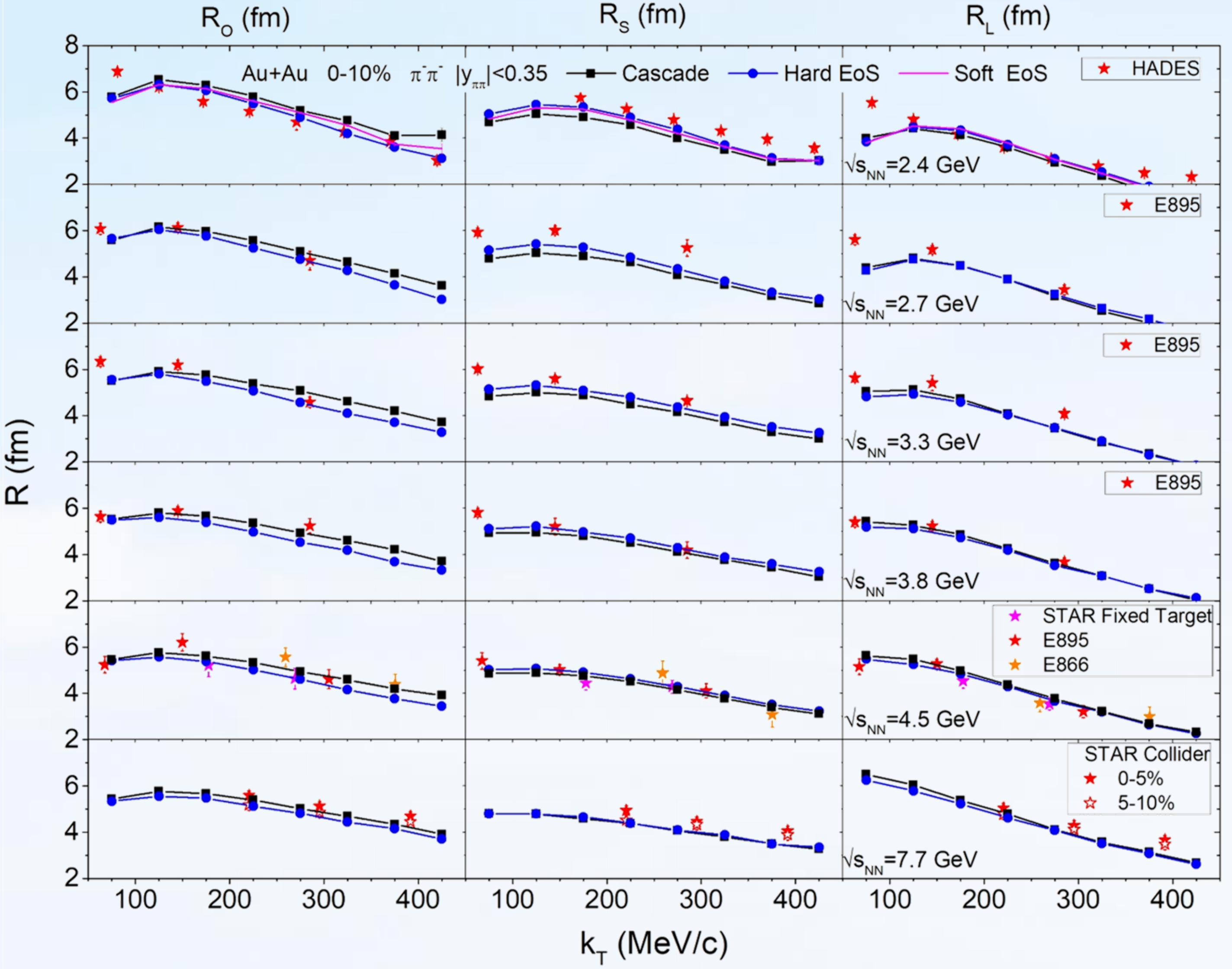
Phys. Lett. B 270, 69 (1991). Phys. Lett. B 432, 248 (1998). Phys. Rev. C 103, 034908 (2021)

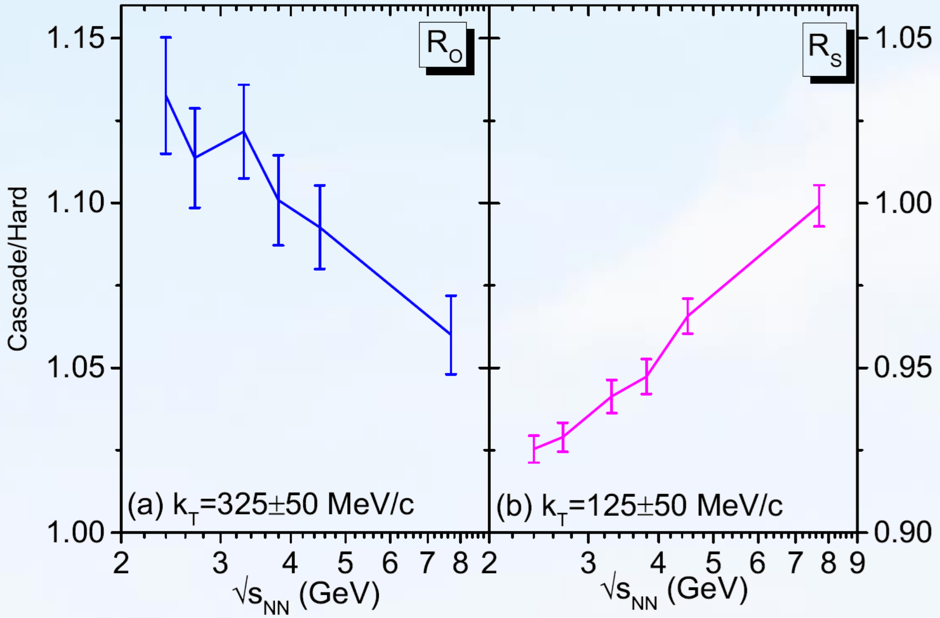
$$C(q_L, q_O, q_S) = N[(1-\lambda) + \lambda K_C(q_{inv}, R_{inv})(1 + e^{-R_L^2 q_L^2 - R_O^2 q_O^2 - R_S^2 q_S^2 - 2R_{OL}^2 q_O q_L})]$$



Results and discussion——$\pi\pi$ HBT correlation

EoS without phase transitions



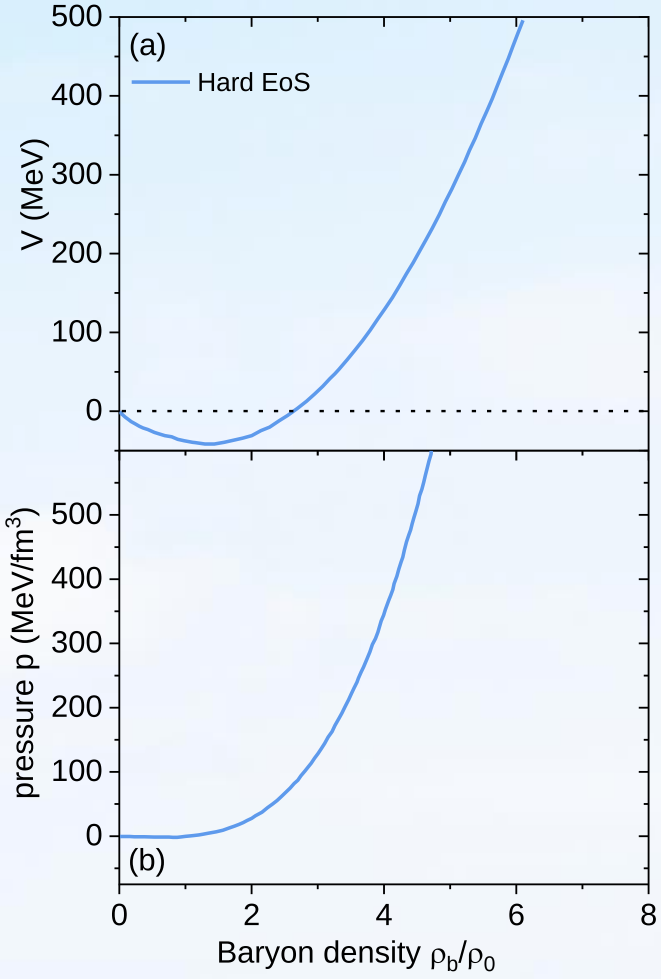


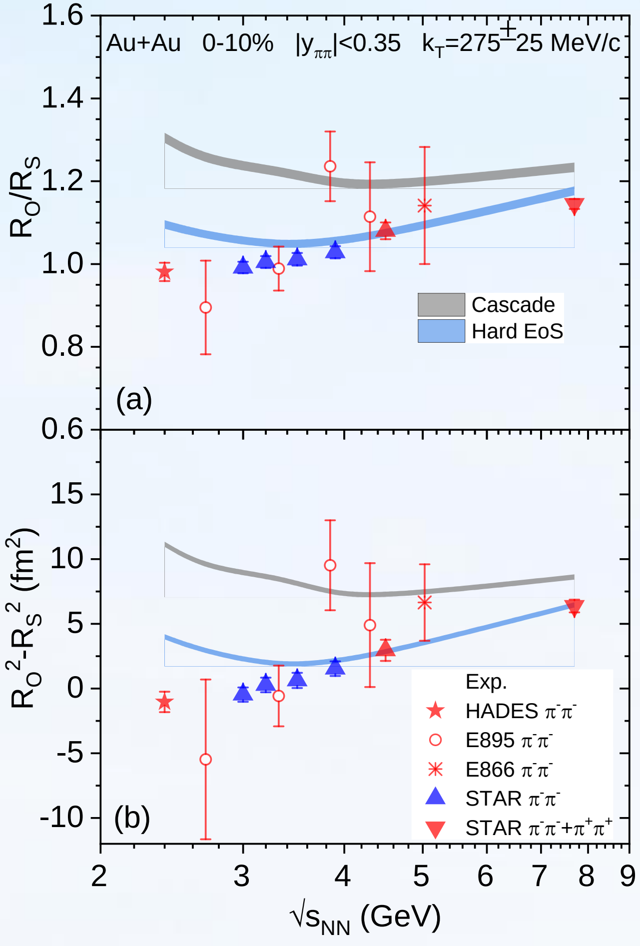
- With increasing stiffness of the potential (stronger repulsion as function of density), the R_O at large k_T is driven down while the R_S at small k_T is pulled up.
- A repulsive density dependent EoS will lead to a stronger phase-space correlation explaining the HBT time-related tensions.

P. C. Li, J. Steinheimer, T. Reichert, A. Kittiratpattana, M. Bleicher and Q. F. Li, Sci. China Phys. Mech. Astron. 66, 232011 (2023).

Results and discussion——$\pi\pi$ HBT correlation

EoS without phase transitions



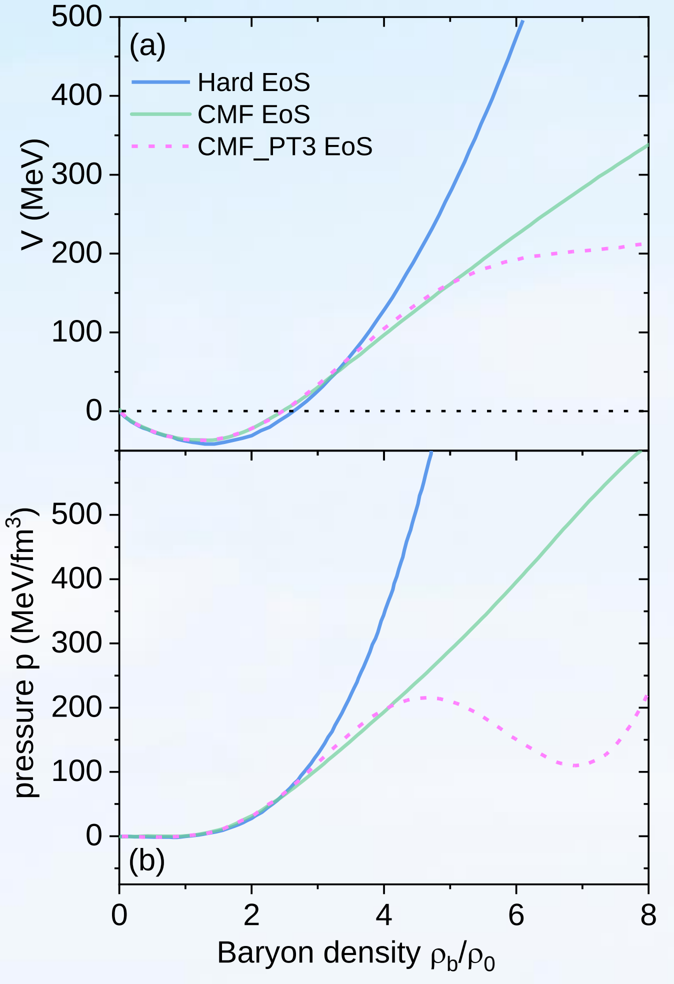


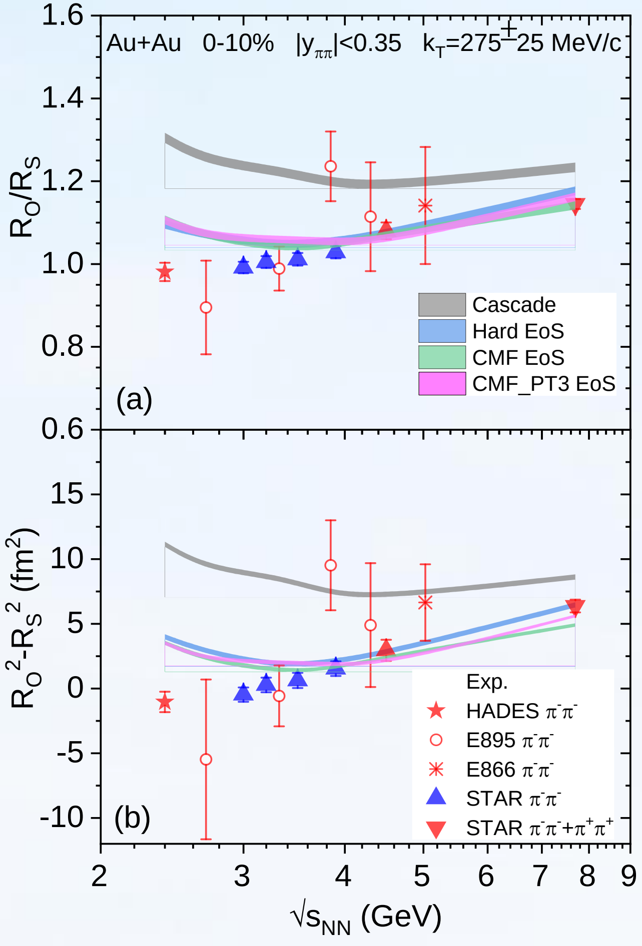
- A repulsive density dependent EoS will lead to a stronger phase-space correlation explaining the HBT time-related tensions.
- The effects of the density dependent equation of state on the HBT radii decreases with increasing energy.

P. C. Li, J. Steinheimer, T. Reichert, A. Kittiratpattana, M. Bleicher and Q. F. Li, Sci. China Phys. Mech. Astron. 66, 232011 (2023).

Results and discussion——$\pi\pi$ HBT correlation

EoS with phase transitions



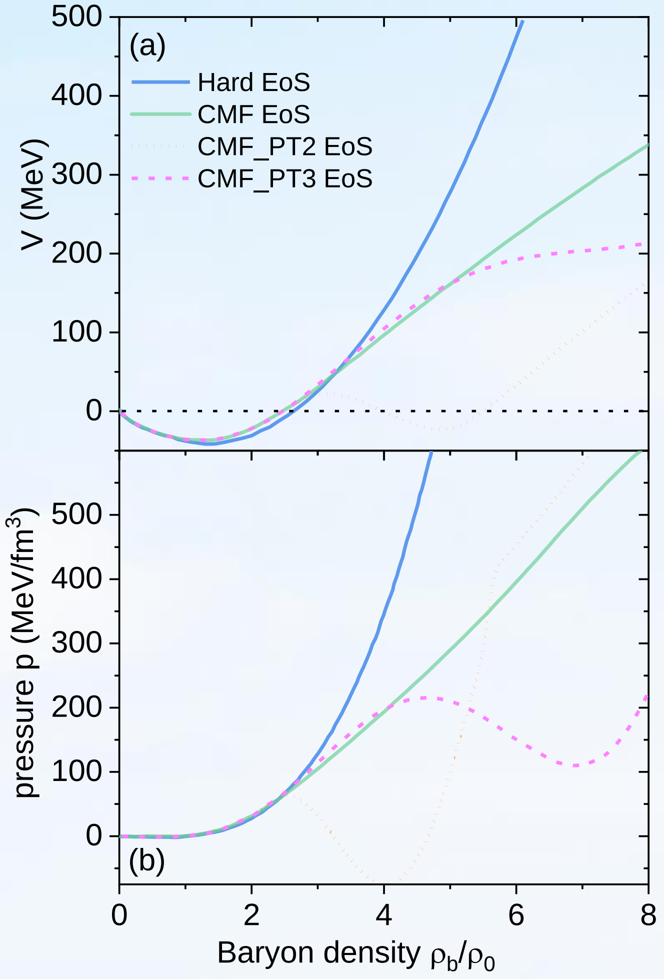


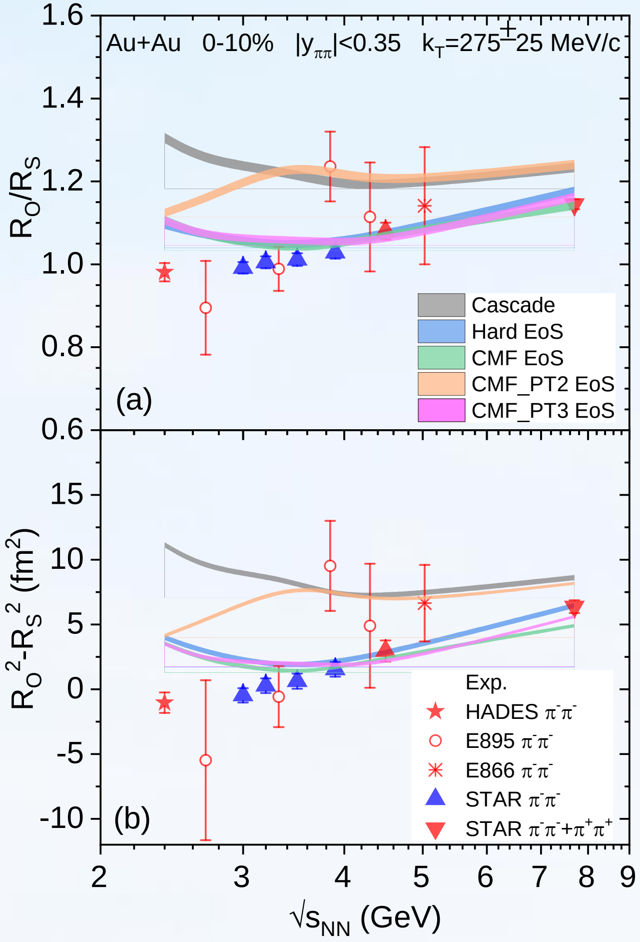
- A repulsive density dependent EoS will lead to a stronger phase-space correlation explaining the HBT time-related tensions.
- The effects of the density dependent equation of state on the HBT radii decreases with increasing energy.
- CMF/PT3 EoSs and hard EoS: a strong repulsion leading to earlier pion emission, and the phase transition in PT3 is never really reached.

P. C. Li, J. Steinheimer, T. Reichert, A. Kittiratpattana, M. Bleicher and Q. F. Li, Sci. China Phys. Mech. Astron. 66, 232011 (2023).

Results and discussion——$\pi\pi$ HBT correlation

EoS with phase transitions



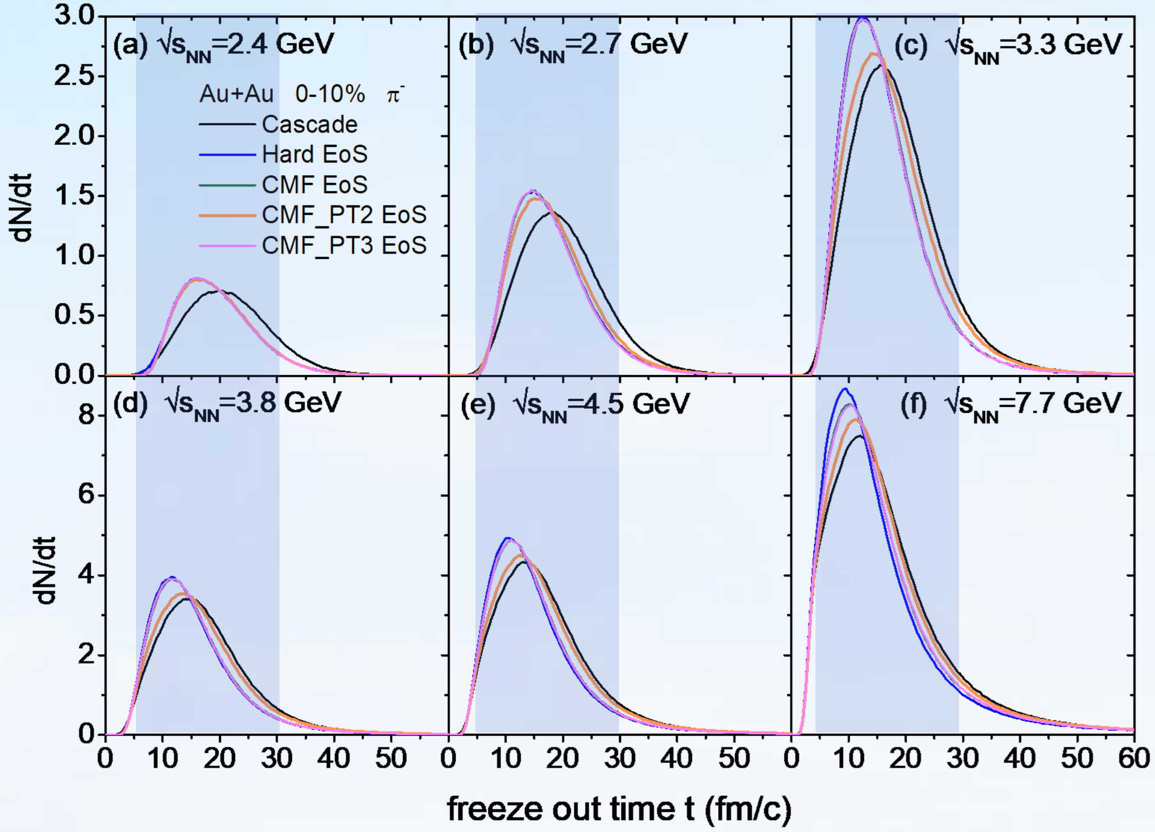


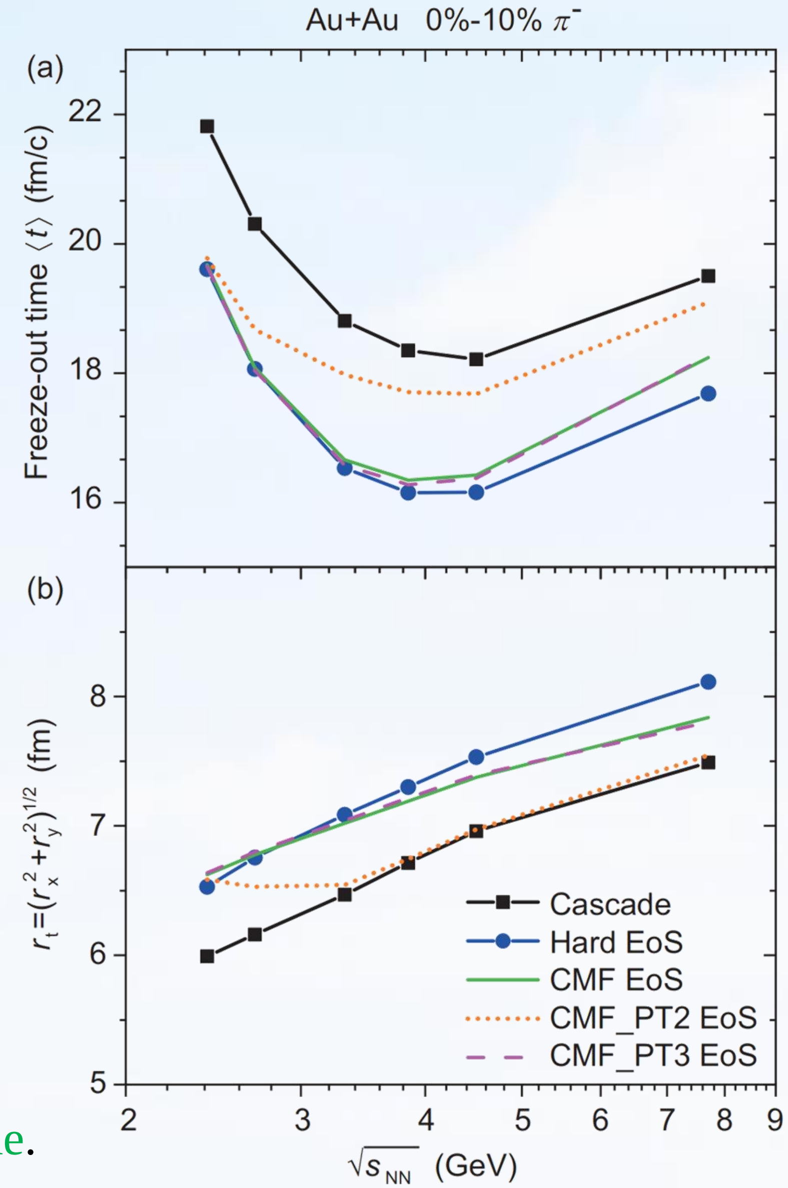
- ➢ A repulsive density dependent EoS will lead to a stronger phase-space correlation explaining the HBT time-related tensions.
- ➢ The effects of the density dependent equation of state on the HBT radii decreases with increasing energy.
- ➢ CMF/PT3 EoSs and hard EoS: a strong repulsion leading to earlier pion emission, and the phase transition in PT3 is never really reached.
- ➢ As the collision energy increases, the calculated results of CMF PT2 EoS gradually increase compared to the standard CMF (or Hard/PT3) EoS as expected for the appearance of a phase transition.

P. C. Li, J. Steinheimer, T. Reichert, A. Kittiratpattana, M. Bleicher and Q. F. Li, Sci. China Phys. Mech. Astron. 66, 232011 (2023).

Results and discussion——$\pi\pi$ HBT correlation

Pion freeze-out time





- The mean values of the freeze-out time (transverse radii) from hard EoS are smaller (larger) than that of the softer ones.
- The larger pressure generated by the potentials, leading to a stronger expansion, consequently larger transverse radii and an earlier freeze-out time.

P. C. Li, J. Steinheimer, T. Reichert, A. Kittiratpattana, M. Bleicher and Q. F. Li, Sci. China Phys. Mech. Astron. 66, 232011 (2023).

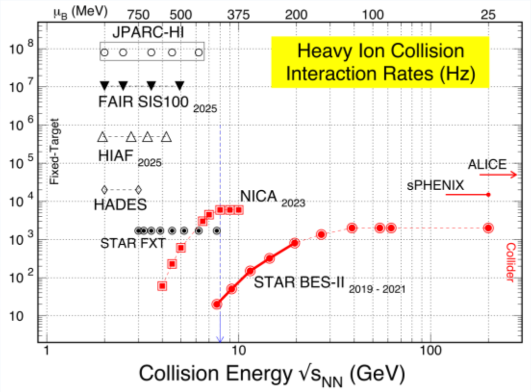
Summary and outlook

- The source radii parameters (R_O/R_S and $R^2_O - R^2_S$) where shown to be sensitive to the EoS at densities up to $4{\sim}5\rho_0$.

- The present data, in the investigated energy region, can be qualitatively and quantitatively reproduced by simulations with an equation of state that shows stiff behavior.

- By comparing to the available HBT data we can exclude the existence of a strong phase transition for densities up to $\sim 4\rho_0$.

- More theoretical works on understanding the uncertainty from the model are needed, such as the in-medium inelastic cross sections, resonance decay width, nuclear structure etc.
- Explaining the splitting in source radii between $\pi^+\pi^+$ and $\pi^-\pi^-$.
- Two-kaon interferometry.



Thank you for your attention!