Description of oscillating HBT radii in Buda-Lund hydrodynamical model

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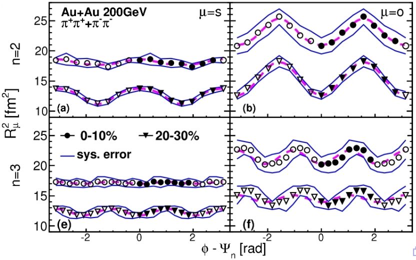
Introduction

- QGP behaves like perfect fluid → hydro description
- Finite number of nucleons → generalized geometry is necessary
- Generalize the space-time and the velocity field distribution
- Higher order flows can be investigated
- HBT radii have cos($n\phi$) dependences in the respective reaction plane
- These can be studied experimentally:

  Nucl.Phys. A904-905 (2013) 439c-442c

  Phys.Rev.Lett. 112 (2014) 22, 222301



The Buda-Lund model

Phys.Rev. C54 (1996) 1390 and Nucl.Phys. A742 (2004) 80-94

- Hydro-model: $S(x,p) = \frac{g}{(2\pi)^3}\frac{p^\nu d^4\Sigma_\nu(x)}{B(x,p)+s_q}$ where $B(x,p) = \exp\left[\frac{p^\nu u_\nu(x)-\mu(x)}{T(x)}\right]$ is the Boltzmann phase-space distribution and the $p^\nu d^4\Sigma_\nu(x) = p^\nu u_\nu H(\tau) d^4x$
- Spatial elliptical asymmetry is ensured by the scaling variable

$$s = \frac{r_x^2}{2X^2} + \frac{r_y^2}{2Y^2} + \frac{r_z^2}{2Z^2} \quad \rightarrow \quad \frac{r^2}{2R^2}(1+\epsilon_2\cos(2\phi)) + \frac{r_z^2}{2Z^2}$$

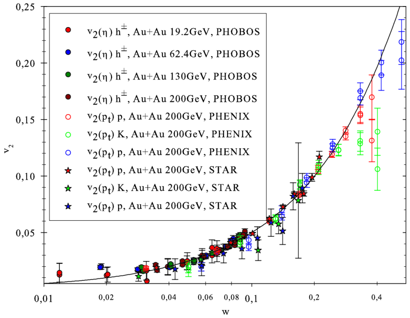
- The asymmetry in the velocity field is also elliptical

$$u_\mu = \left(\gamma, r_x\frac{\dot{X}}{X}, r_y\frac{\dot{Y}}{Y}, r_z\frac{\dot{Z}}{Z}\right) \rightarrow (\gamma, rH(1+\chi_2)\cos\phi, rH(1-\chi_2)\sin\phi, H_z r_z)$$

- The model describes spectra, flows, HBT radii
- Result for elliptic flow: measure of hydrodynamic behavior

$$v_{2n}(p_t) = \frac{I_n(w)}{I_0(w)} \text{ with } w = \frac{\overline{E}_T}{2T_*}\epsilon$$

Universal scaling: Eur.Phys.J.A38:363-368,2008

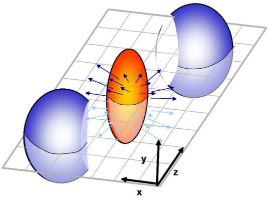


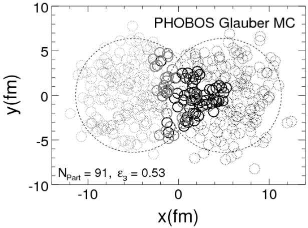
Generalization of the model I.

- The spatial asymmetry is described by the scaling variable
- General n-pole spatial asymmetry (elliptical case: $n = 2$):

$$s = \frac{r^2}{2R^2}\left(1 + \sum_n \epsilon_n \cos(n(\phi - \Psi_n))\right) + \frac{r_z^2}{2Z^2}$$

- Ψ_n is the angle of the n-th order reaction plane



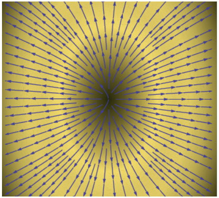


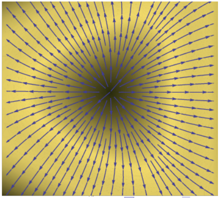
Generalization of the model II.

- Derive the velocity field from a potential: $u_\mu = \gamma(1, \partial_x\Phi, \partial_y\Phi, \partial_z\Phi)$
- General n-pole asymmetrical potential (elliptical case: $n = 2$):

$$\Phi = r^2 \frac{H}{2}\left(1 + \sum_n \chi_n \cos(n(\phi - \Psi_n))\right) + \frac{H_z}{2} r_z^2$$

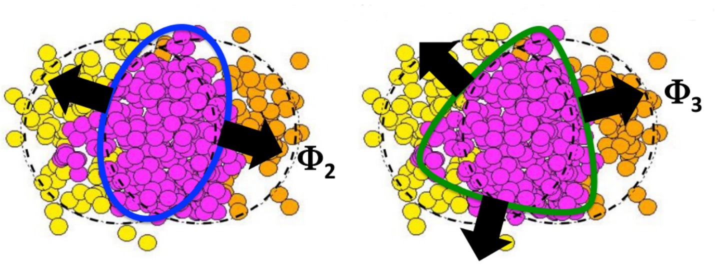
- $u^\mu \partial_\mu s = 0$ can be held if $\dot{\epsilon}_n = -2H\chi_n$ in $\mathcal{O}(\epsilon_n), \mathcal{O}(\chi_n)$
- There is multipole solution: Phys.Rev.C90,054911 (2014) based on HeavyIonPhys.A21:73-84,2004
- There is no solution with generalized velocity field





Observables at freeze-out

- Invariant transverse momentum distribution, flows, azimuthally sensitive HBT radii
- All asymmetries are investigated in their respective reaction plane
- Rotate the system to the second / third order plane and average on the angle of the third / second order plane



Averaging on event planes

- The spatial asymmetry:
  $s = \frac{r^2}{R^2}(1 + \epsilon_2 \cos(2\phi - \Psi_2) + \epsilon_3 \cos(3\phi - \Psi_3)) + \frac{r_z^2}{Z^2}$
- If we rotate the system to the second order event plane:

$$s = \frac{r^2}{R^2}(1 + \epsilon_2 \cos(2\phi) + \epsilon_3 \cos(3\phi - \Delta\Psi_{2,3})) + \frac{r_z^2}{Z^2}$$

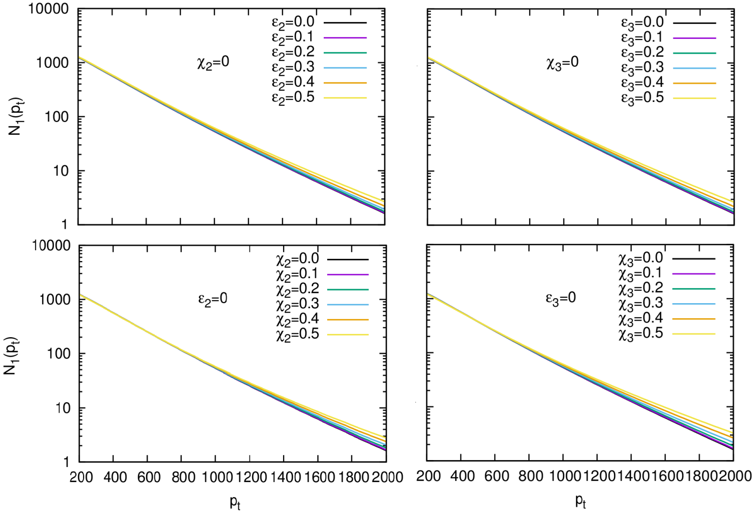
- If we rotate the system to the third order event plane:

$$s = \frac{r^2}{R^2}(1 + \epsilon_2 \cos(2\phi + \Delta\Psi_{2,3}) + \epsilon_3 \cos(3\phi)) + \frac{r_z^2}{Z^2}$$

  where $\Delta\Psi_{2,3} = \Psi_3 - \Psi_2$.
- The method is the same in the case of the velocity field.
- Averaging on $\Delta\Psi_{2,3}$ is necessary.

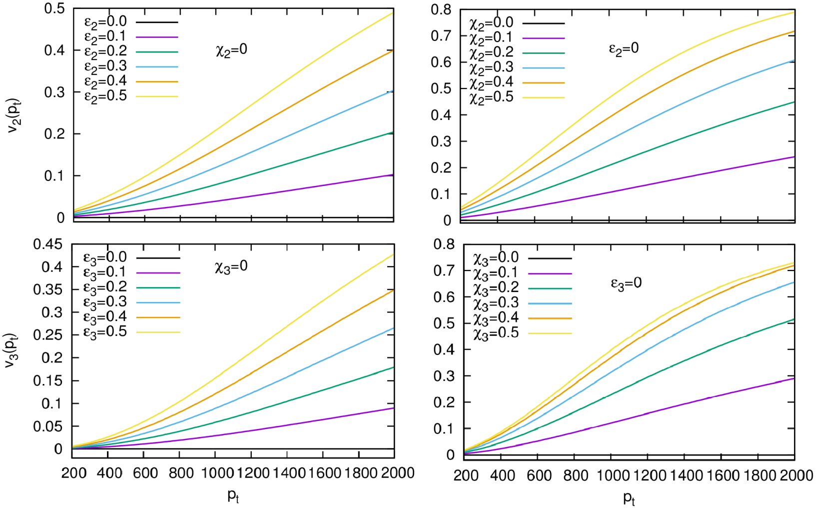
Invariant momentum distribution

Significant change could be at high p_t, the log slope is not affected strongly



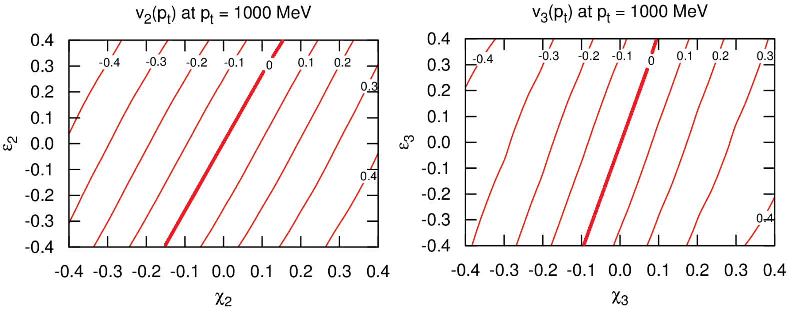
Flows

Elliptic and triangular flows are affected by their own asymmetry parameters



Mixing of parameters

- The parameters affect the flows together
- The generalization of velocity field is necessary



HBT radii

- Calculate in the *out* − *side* − *long* system

$$R_{\text{out}}^2 = \langle r_{\text{out}}^2 \rangle - \langle r_{\text{out}} \rangle^2 \text{ and } R_{\text{side}}^2 = \langle r_{\text{side}}^2 \rangle - \langle r_{\text{side}} \rangle^2$$

  where $r_{\text{out}} = r\cos(\phi - \alpha) - \beta_t t$ and $r_{\text{side}} = r\sin(\phi - \alpha)$

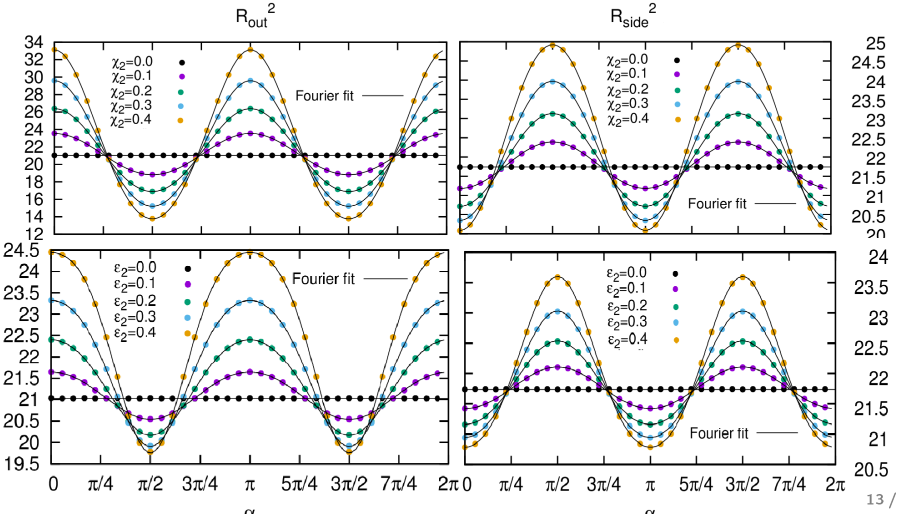
  → C. J. Plumberg, C. Shen, U. W. Heinz Phys.Rev. C88 (2013) 044914
- There can be higher order parts

  → B. Tomášik and U. A. Wiedemann, in *QGP3*, pp. 715–777.
- We use the following parameterization in
  - elliptical case:
    $R_{\text{out}}^2 = R_{\text{out},0}^2 + R_{\text{out},2}^2\cos(2\alpha) + +R_{\text{out},4}^2\cos(4\alpha) + R_{\text{out},6}^2\cos(6\alpha)$
  - triangular case:
    $R_{\text{out}}^2 = R_{\text{out},0}^2 + R_{\text{out},3}^2\cos(3\alpha) + R_{\text{out},6}^2\cos(6\alpha) + R_{\text{out},9}^2\cos(9\alpha)$
- Similar to the R_{side}^2

Results of the parametrization – Second order case

This case already have been investigated: Eur.Phys.J.A37:111-119,2008

Mainly $\cos(2\phi)$ behavior but higher order oscillations are also present



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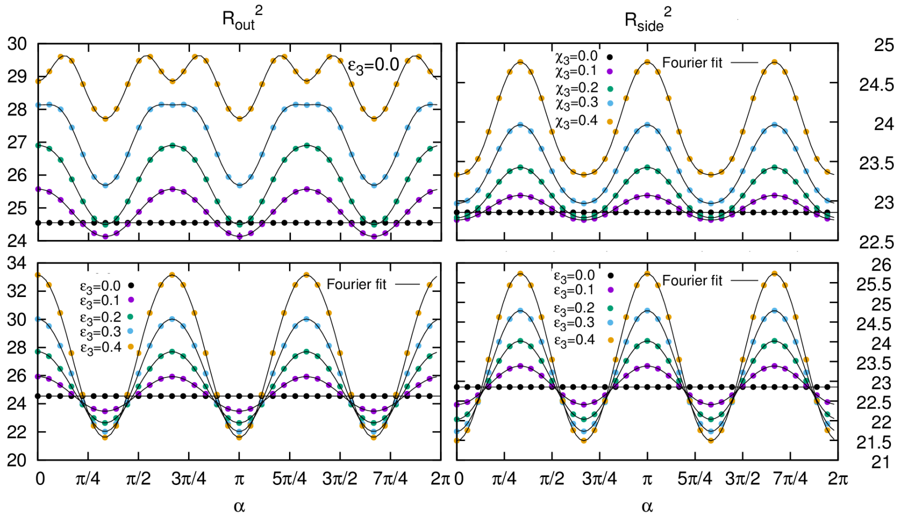
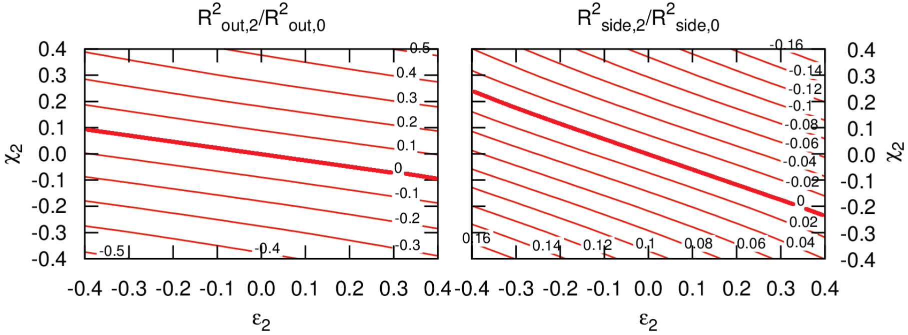


Mixing of the parameters

The dependence of the amplitudes of the R^2_{out} and R^2_{side} in the second order case



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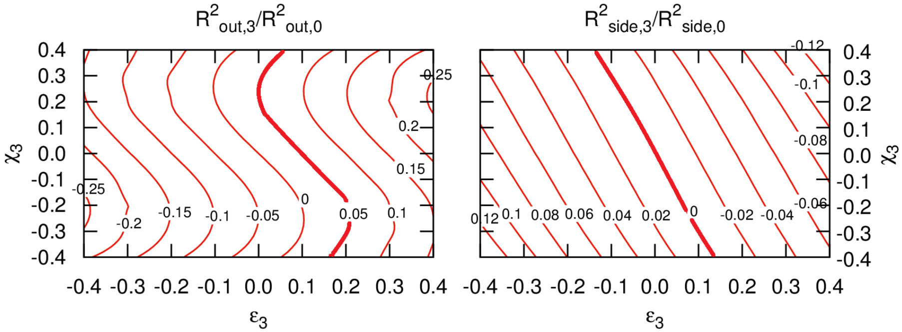

Conclusions

- Generalization of the spatial and the velocity field distribution is done
- The averaging between the different event plane is necessary
- Higher order oscillation can be observed in HBT radii
- Absolute value of the azimuthal HBT radii depend on asymmetries
- The spatial and velocity field anisotropies both influence the v_n coefficient and the HBT radii
- The asymmetry parameters can be disentangled from the flows and the amplitudes

Thank you for your attention!

Value of the parameters

Meaning	Sign	Value
Mass of the particle	m	140 MeV
Freeze-out time	τ_0	7 fm/c
Freeze-out temperature	T_0	170 MeV
Temperature-asymmetry parameter	a^2	0.3
Spatial slope parameter	b	-0.1
Transverse size of the source	R	10 fm
Longitudinal size of the source	Z	15 fm
Velocity-space transverse size	H	10 c/fm
Velocity-space longitudinal size	H_z	16 c/fm
Elliptical spatial asymmetry parameter	ϵ_2	0.0
Triangular spatial asymmetry parameter	ϵ_3	0.0
Elliptical velocity-field asymmetry parameter	χ_2	0.0
Triangular velocity-field asymmetry parameter	χ_3	0.0

Usually one anisotropy parameter is varied, and the others are kept zero

About the spectra

Plot the N_1 with non zero coefficient divide by N_1 with zero coefficient