Effect of an Expanding Charged Cloud on two-particle Bose-Einstein Correlations

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Abstract

After rehadronization in heavy-ion collisions, hundreds of charged particles are produced. When measuring the correlation functions, we take into account that the produced hadrons create a strong electromagnetic field around trajectories of the investigated pairs of identical pions. Although this may be seen as an Aharonov-Bohm effect, a more straightforward explanation would be that the phase along the pair's closed path is altered when one of the particles' paths is altered by a phase, as compared to the interaction-free case, when the path is a straight line, and momentum also does not change.This additional phase shift for an infinitesimal path element dx can be expressed as $k \cdot dx$, where $k = p/\hbar$ is the momentum (or wavenumber) of the particle at that point. The alteration of the particles' flight time reaching the detector can be connected to the phase shift of the particles, as we discuss below.

Introduction

- The space-time geometry of the particle emitting source may be explored by measuring BE or HBT correlation functions, which is main source of momentum correlation for identical bosons.
- In quantum mechanics, identical particles are genuinely indistinguishable due to Heisenberg uncertainty principle.

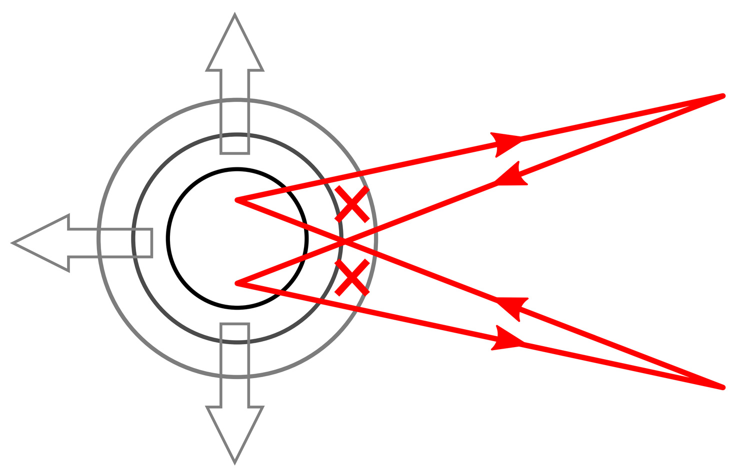

Figure 1: Aharonov–Bohm effect with a Hubble expanding source

Bose-Einstein Correlations

- Momentum correlation function of two identical particles, generally is:

$$C_2(p_1, p_2) \equiv \frac{N_2(p_1, p_2)}{N_1(p_1)N_1(p_2)}, \qquad (1)$$

- Using phase-space density to describe the correlation function of the emitter $S(x,p)$ as:

$$C_2(p_1, p_2) = 1 + Re\frac{\widetilde{S}(q, p_1)\widetilde{S}^*(q, p_2)}{\widetilde{S}(0, p_1)\widetilde{S}^*(0, p_2)} \qquad (2)$$

where $\widetilde{S}(q,p)$ denotes as Fourier transform of the source

- with $q \equiv p_1 - p_2$, the two particle correlation func becomes:

$$C_2(q, K) = 1 + \frac{|\widetilde{S}(q, K)|^2}{|\widetilde{S}(0, K)|^2} \approx 1 + \lambda_2 \frac{|\widetilde{S}(q, K)|^2}{|\widetilde{S}(0, K)|^2} \qquad (3)$$

Two- and Three-particle strengths

- The correlation strength is defined by the fraction of the pions that come from the core to contribute to the visible correlation function:

$$\lambda_2 = f_c^2, \quad f_c = \frac{N_{core}}{N_{core} + N_{halo}} \qquad (4)$$

- The presence of partially coherent pion production distorts $\lambda_2 \& \lambda_3$, however two- and three-particle BEC func. at zero relative momentum are in simple connection to the partially coherent fraction (pc) of the fireball:

$$\lambda_2 = f_c^2((1-p_c)^2 + 2p_c(1-p_c)) \qquad (5)$$

$$\lambda_3 = 2f_c^3((1-p_c)^3 + 3p_c(1-p_c)^2) + 3f_c^2((1-p_c)^2 + 2p_c(1-p_c)) \qquad (6)$$

Model Setup

- The produced hadron gas flow can be described by the dynamical system of equations as:

$$\frac{dp}{dt} = \hbar c \alpha \sum_{j=1}^{N_{ch}} \frac{q(r_j - X)}{r^3} \qquad (7)$$

$$\frac{dX}{dt} = V = \frac{p}{m\gamma} \qquad (8)$$

- Where $r = \sqrt{(r_j - X)^2}$ & $\gamma = \sqrt{1 - \frac{p^2}{m^2}}$
- This model was solved numerically using Euler Method with time iteration for pion mass =139.57, charge $q = \pm 1$,and using the natural units ($\hbar = c = 1$).

Phase-shift from Time-shift

- The time shift of TOF (Δt) is a result of the phase-shift (σ) after scattering of the test particle during the flight towards the detector due to the final state interactions with the cloud of charged particles.
- Charge cloud has N_{ch} in a 3-D Hubble flow with initial momentum p_{in} in random direction for the test particle.
- From the simulation we measured the Δt according to $\Delta t = t_{\mathrm{TOF}}(d) - t_{\mathrm{TOF}}^{(N_{ch}=0)}$ it is a Gaussian distribution with width σ_t.
- From the fitting of Gassian distribution and determining the width we can get the phase-shift as:

$$\phi = k\Delta x = \frac{p}{\hbar}v\Delta t = \frac{p^2}{\hbar\sqrt{m^2+p^2}}\Delta t \Rightarrow \sigma = \frac{p^2}{\hbar\sqrt{m^2+p^2}}\sigma_t. \qquad (9)$$

Results

From the MC we get the time shift distribution as we can see in figure (2).

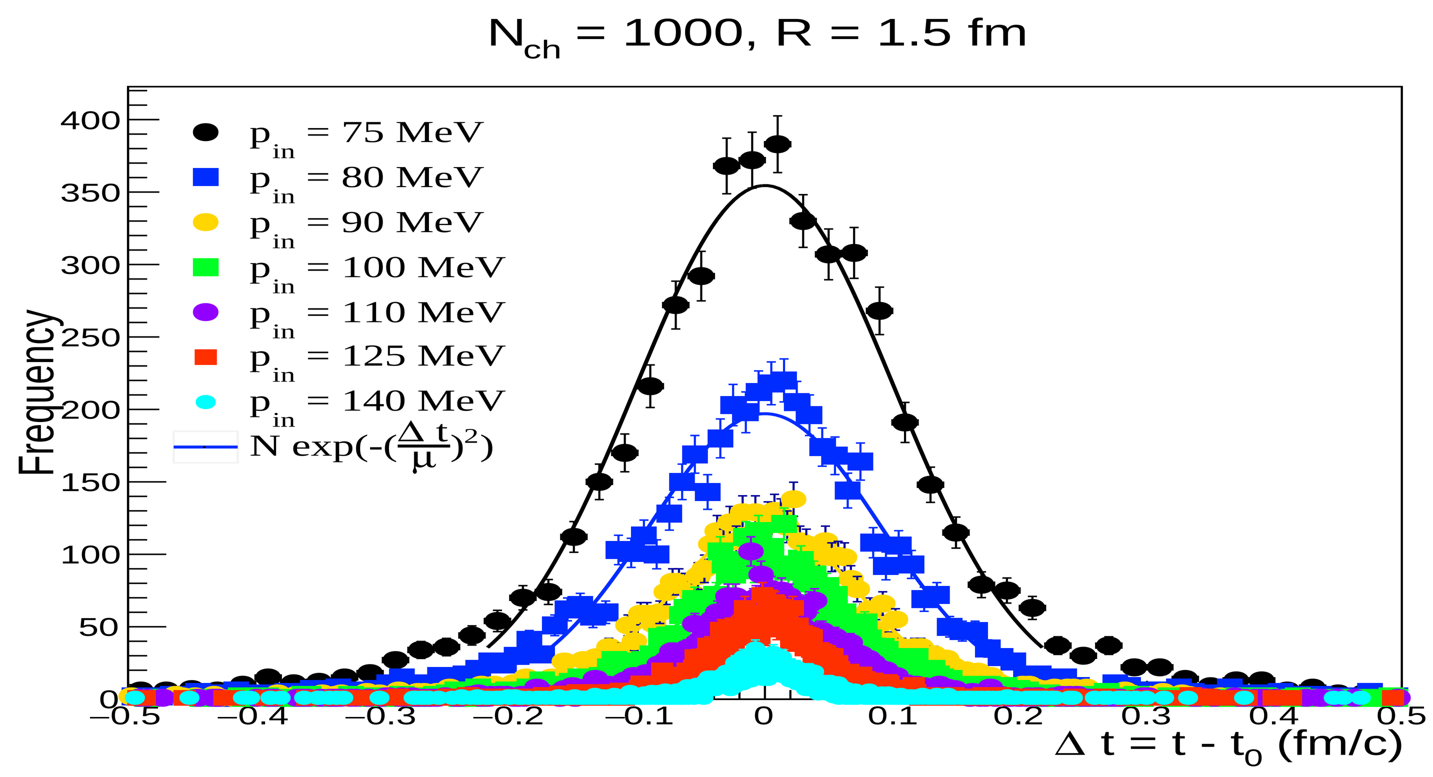

Figure 2: Time shift distributions from the simulation for different initial momentum values.

The Distance effect and Intial Momentum

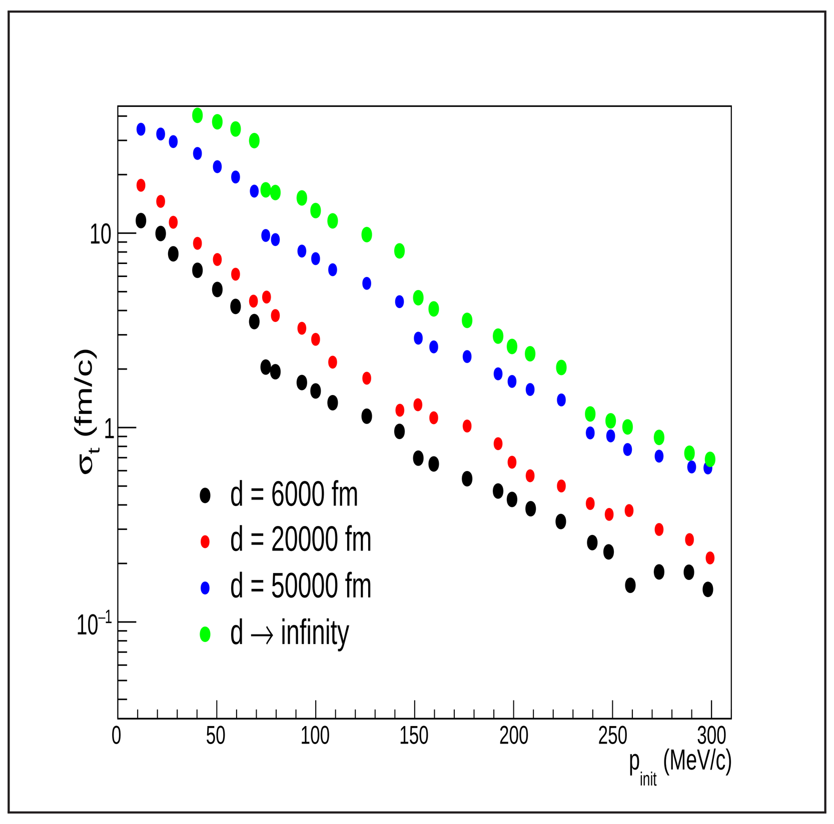

Figure 3: The dependency of the gaussian width and then the phase shift on the initial momentum of the correlated particles

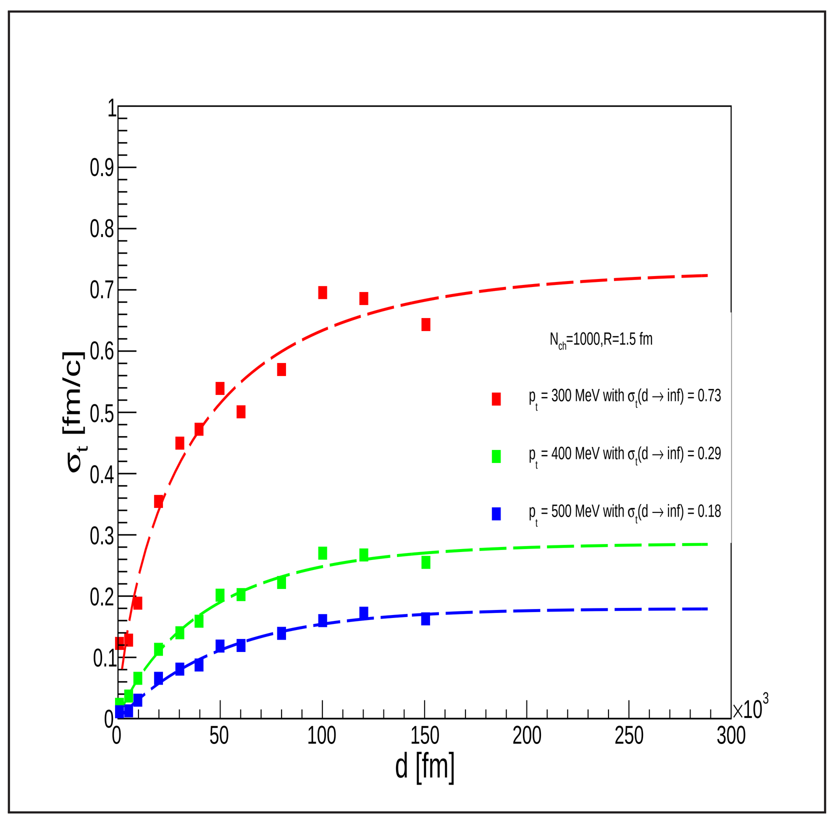

Figure 4: The traveled distance by the investigated correlated particles with the phase-shift distribution σ_0, for $N_{\rm ch} = 1000$, $R = 1.5$ fm.

Corrlation strength

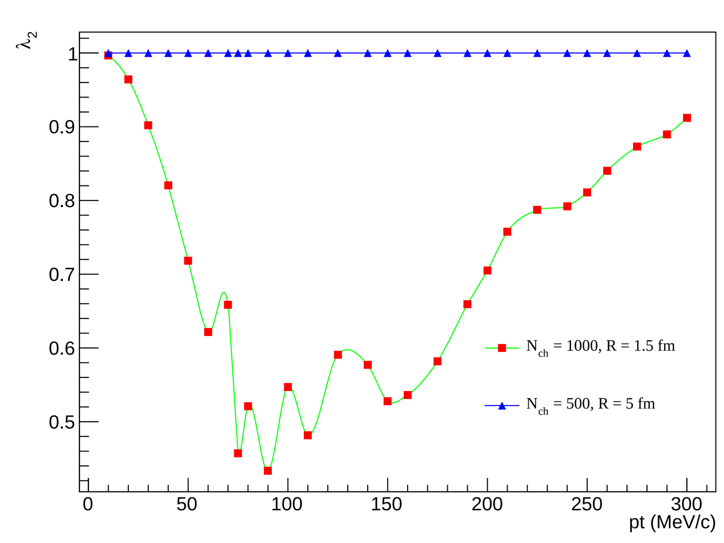

Figure 5: The intercept parameter λ_2 as a function of the initial transverse momentum of the probe particle, for the two scenarios: $N_{\rm ch} = 500$, $R = 5$ fm and $N_{\rm ch} = 1000$, $R = 1.5$ fm.

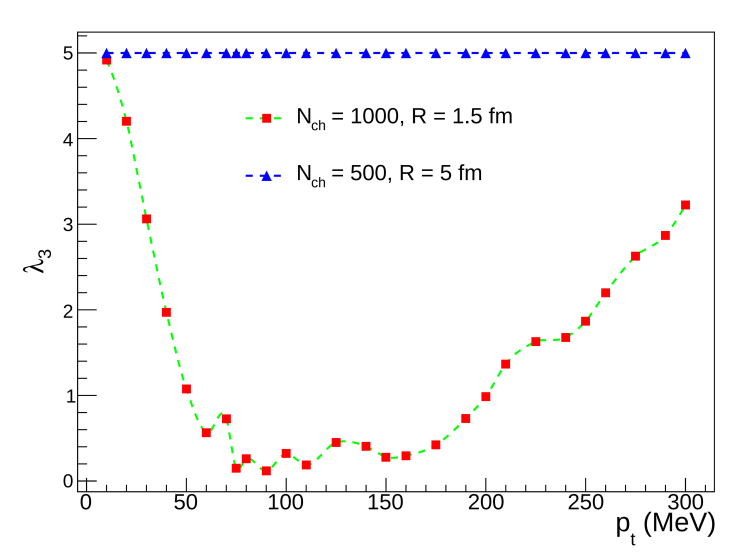

Figure 6: The intercept parameter λ_3 as a function of the initial transverse momentum of the probe particle, for the two scenarios: $N_{\rm ch} = 500$, $R = 5$ fm and $N_{\rm ch} = 1000$, $R = 1.5$ fm.

Conclusion

- Changes in phases due to the Aharonov-Bohm effect, effectuated via the Coulomb interaction, may cause distortion in quantum-statistical correlations.
- Phase changes are prominent at low particle momenta but diminish at higher momenta and also at hight particle densities.
- Incorporating this effect in Monte Carlo simulations is resource-intensive due to the Coulomb interaction's range and the long timescales required. However, it can be accounted for in momentum correlation calculations via an afterburner as proposed.