Bose-Einstein correlations in random field

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ACHT 2016, Čakovec

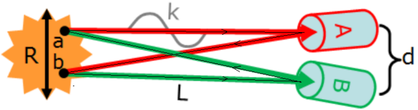
Introduction and motivation

- Hot and dense matter is formed in heavy-ion collisions: sQGP
- An expanding hydrodynamical system
- The particles after the freeze-out can be detected
- HBT interferometry: the measurement of identical particle correlations
- The width of the corr.function can be related to the size of the source
- The strength of the correlation function is the intercept parameter λ
- The λ can be affected by
  - $U_A(1)$ symmetry restoration, the core-halo picture
  - partial coherence
  - Aharonov-Bohm effect
- The separate investigation of the 2- and 3-particle correlation can provide information about the source

The HBT-effect

- The HBT-effect was discovered by R. H. Brown and R. Q. Twiss
- Independently, pion correlation observed in $p + \overline{p}$
- Explained by Bose-Einstein symmetrization by Goldhaber et al.
- Let's have a thermalized source and two detectors
- From the source two (a and b) wave $\frac{1}{|r - r_a|}\alpha e^{ik|r-r_a|+i\varphi_a}$ and $\frac{1}{|r - r_b|}\beta e^{ik|r-r_b|+i\varphi_b}$ travel to the detectors
- The total amplitude is a+b in the detector A and B
- The intensities in the detectors $I_A = |A_A|^2$ and $I_B = |A_B|^2$ and from this the time average of the intensities and the $\langle I_A I_B \rangle$ if $\alpha = \beta$, $d, R \ll L$:

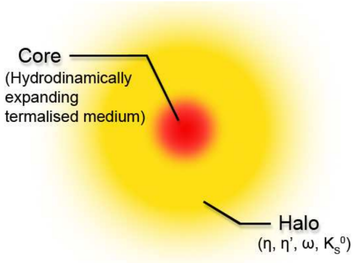
$$\frac{\langle I_A I_B \rangle}{\langle I_A \rangle \langle I_B \rangle} - 1 = \frac{1}{2} \cos \frac{kRd}{L}$$



Core-halo model (Heavy Ion Phys.15:1-80,2002)

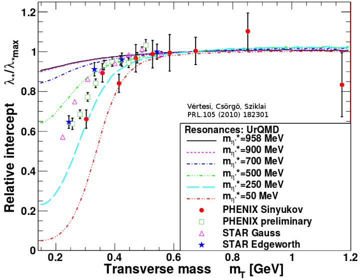
- Definition: $C_2(p_1,p_2) = \frac{N_2(p_1,p_2)}{N_1(p_1)N_1(p_2)}$ where $N_1(p_1) = \int S(x_1,p_1)|\Psi_1(x_1)|^2$ and $N_2(p_1,p_2) = \int S(x_1,p_1)S(x_2,p_2)|\Psi_1(x_1)|^2|\Psi_2(x_2)|^2$
- Introduce $q = p_1 - p_2$, and $K = (p_1+p_2)/2$ and assume $p_1 \approx p_2$
- Source function can be written in two part: $S(x,p) = S_c(x,p) + S_h(x,p)$

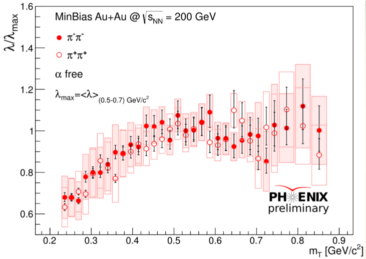
$$C_2(q,K) = 1 + \frac{|\tilde{S}(q,K)|^2}{|\tilde{S}(q=0,K)|^2} \approx 1 + \lambda \frac{|\tilde{S}_c(q,K)|^2}{|\tilde{S}_c(q=0,K)|^2} \text{ where } \lambda = \left(\frac{N_c}{N_c+N_h}\right)^2$$



$U_A(1)$ symmetry restoration (Heavy Ion Phys.15:1-80,2002)

- Source can be split up into a hydro expanding core and a halo
- The $U_A(1)$ symmetry might be partially restored
- Hot dense matter: $m_{\eta'}$ drops $\rightarrow$ more η' is produced
- From $\eta' \rightarrow \pi^+ + \pi^+ + \pi^- + \pi^- + \pi^0$ more π are produced
- The πs have $p_t \approx 150 - 200$ MeV and contribute to the halo
- πs from the halo do not correlated with the core's πs
- Value of the λ drops





Partial coherence (Heavy Ion Phys.15:1-80,2002)

- In the core-halo model the core is thermalized and fully incoherent
- One can assume that the core may emit bosons coherently: $S(x,p) = S_c^p(x,p) + S_c^i(x,p) + S_h(x,p)$
- Momentum dependent core and partially coherent fraction can be introduced

$$f_c(k) = \frac{\int S_c(x,k) d^4x}{\int S(x,k) d^4x} \qquad p_c(k) = \frac{\int S_c^p(x,k) d^4x}{\int S_c(x,k) d^4x}$$

- λs can be expressed with these

$$C_2(0) - 1 = \lambda_2 = f_c^2[(1-p_c)^2 + 2p_c(1-p_c)]$$
$$C_3(0) - 1 = \lambda_3 = 3f_c^2[(1-p_c)^2 + 2p_c(1-p_c)] + 2f_c^3[(1-p_c)^3 + 3p_c(1-p_c)^2]$$

- The combination: $\frac{\lambda_3 - 3\lambda_2}{\lambda_2^{3/2}}$ does not depend on the core-halo fraction

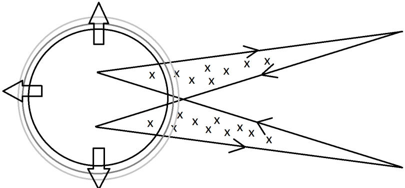
Aharonov-Bohm effect in particle correlations

Aharonov-Bohm effect:

- Early observation: electrically charged particle is affected by an EM potential in a region where the E and B are zero.
- Experimental verification by e.g. Chambers (1960 PRL.5), Tonomura et al. (1986 PRL.56)
- If a particle moves on a closed path in a field it picks up path dependent phase factor

Aharonov-Bohm effect in our case:

- The correlation can be obtained from a closed-path
- The result is sensitive to the fluxes going through the closed path
- Phenomenologically the propagating pion waves pick up phases



Two pion correlation in random field

Aharonov-Bohm effect in our case:

- Random phase have to be applied to the wave-functions $\Phi_a(r)$, $\Phi_b(r)$
- Have to be calculated: $\frac{\langle|\Phi_2(r_A,r_B)|^2\rangle}{\langle|\Phi_a(r)|^2\rangle\langle|\Phi_b(r)|^2\rangle} - 1$
- The time average of the two-particle wave function gets a phase
- ϕ: the total phase picked up. Let introduce $\Delta k = kd/L$!

$$\frac{\langle|\Phi_2(r_A, r_B)|^2\rangle}{\langle|\Phi_a(r)|^2\rangle\langle|\Phi_b(r)|^2\rangle} - 1 = \cos\left(R\Delta k + \phi\right)$$

- Can be regarded as a 0-centered Gaussian: $e^{-\frac{\phi}{2\sigma^2}}$
- Average on ϕ

$$\frac{\langle|\Phi_2(r_A, r_B)|^2\rangle}{\langle|\Phi_a(r)|^2\rangle\langle|\Phi_b(r)|^2\rangle} - 1 = \cos\left(R\Delta k\right) e^{-\frac{\sigma^2}{2}}$$

Three pion correlation in random field

$\langle|\Phi_2(r_A, r_B, r_C)|^2\rangle$ are calculated there will be:

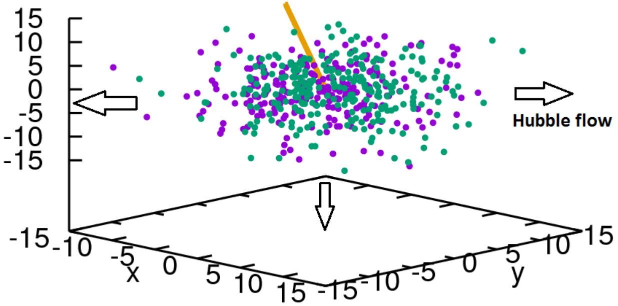
- 6 terms like $\exp[ik(r_{aA} + r_{bB} + r_{cC}) + i(\phi_{aA} + \phi_{bB} + \phi_{cC})] = 1$
- 3x6 terms which belong to the pair-correlation where e.g. $r_{aA} + r_{bB} + r_{cC}$ and $r_{aB} + r_{bA} + r_{cC}$ meet
- 12 "almost" pair-correlation like terms where e.g. $r_{aB} + r_{bC} + r_{cA}$ and $r_{aB} + r_{bA} + r_{cC}$ meet
- 12 terms which contain nine paths: nine $i\phi_{xX}$ like terms
- Previously introduce the ϕ as a sum of four ϕ_{xX} like phases with a Gaussian distribution: $e^{-\phi^2/(2\sigma)^2}$
- Based on the summing of random variable while the nine-path term $e^{-\frac{\phi^2}{(2(2\sigma/3)^2)}}$

The final result from the calculation

$$\frac{\langle|\Phi_3|^2\rangle}{\langle|\Phi_a|^2\rangle\langle|\Phi_b|^2\rangle\langle|\Phi_c|^2\rangle} - 1 = \frac{1}{6}\left(6 + 18e^{-\frac{\sigma^2}{2}} + 12e^{-\frac{(2\sigma/3)^2}{2}}\right) - 1 = 3e^{-\frac{\sigma^2}{2}} + 2e^{-\frac{2\sigma^2}{9}}$$

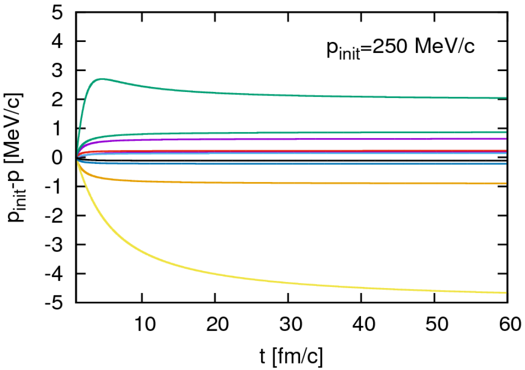
Toy model

- Hubble expanding source made of uniformly distributed charges with a probe charge in the middle of the source
- Probe particle: given momentum with lot of random charge distribution
- Relativistic motion of probe particle through Coulomb field of the expanding charge cloud



Toy model

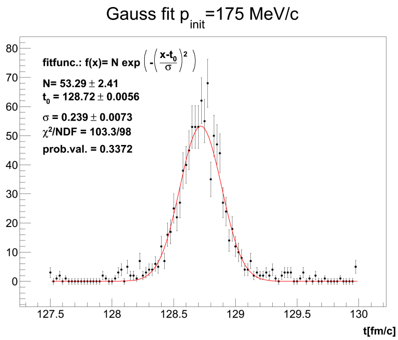
- Charge cloud accelerates or decelerates probe
- Momentum changes in time:

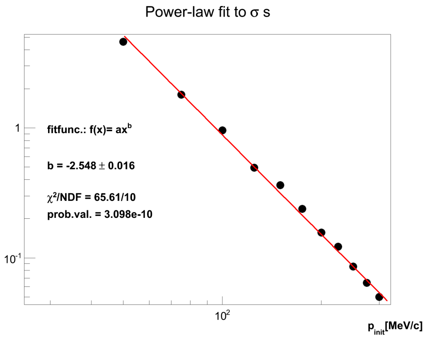


- Time to reach a given location fluctuates
- Random phase shift equivalent to time shift

Toy model – $\sigma(p_{\text{init}})$

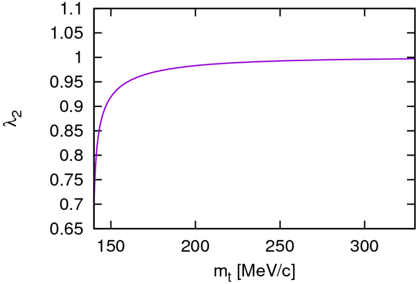
- Time shift distribution $\leftrightarrow$ random phase shift distribution
- An example at $p_{\text{init}} = 175$ MeV/c
- Momentum dependence can be analyzed
- $\sigma_t \frac{p^2}{\hbar\sqrt{m^2+p^2}} = \sigma_\phi$

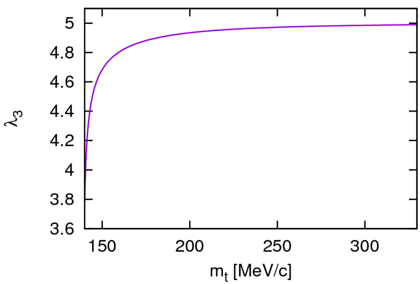




Toy model – λ_2, λ_3

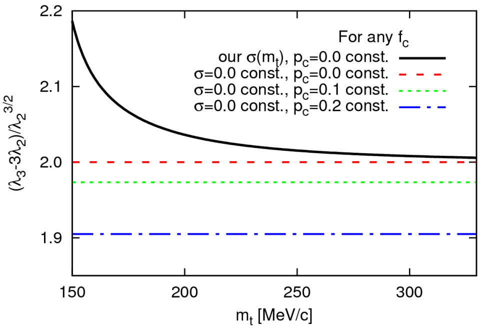
- Midrapidity $p \to p_t$
- The width of the phase $\sim$ the cross section of the outgoing pion
- The σ_t function is known from the fit
- The $\sigma_\phi = \frac{\sigma_t p_t^2}{\hbar\sqrt{m^2+p^2}}$ from the fit $\sigma_\phi \sim \frac{p_t^{-0.55}}{\hbar\sqrt{m^2+p^2}}$
- Plot the derived: $\lambda_2 \to e^{-\frac{\sigma^2}{2}}$ and $\lambda_3 \to 3e^{-\frac{\sigma^2}{2}} + 2e^{-\frac{2\sigma^2}{9}}$
- To be compared to experimental results





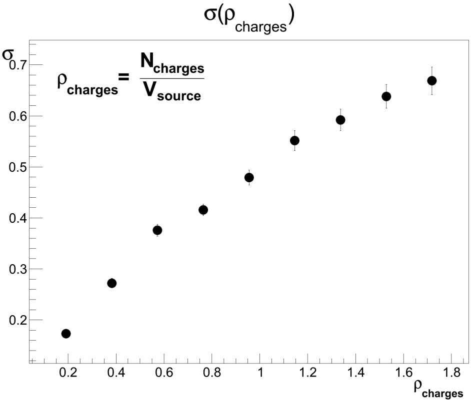
Toy model – a combination of λs

- In our calculation $N_{\mathrm{ch}} = 100$ and $R_{\mathrm{init}} = 5$ fm
- Let us introduce $\kappa_3 = \frac{\lambda_3 - 3\lambda_2}{\lambda_2^{3/2}}$
- Quantifies "pure" three-particle correlations
- Does not depend on core/halo fraction!
- E.g. core/halo + partial coherence case $\kappa_3 = \frac{2((1-p_c)^3 + 3p_c(1-p_c)^2)}{((1-p_c)^2 + 2p_c(1-p_c))^{3/2}}$



Toy model – $\sigma(\rho_{ch})$

- How does the width depend on the ρ_{ch}?
- Distribute different number of charges in the source size $R = 5$ fm
- The width depends more-or-less linearly on the density



Summary

- The Aharonov-Bohm effect can play role in the HBT-interferometry
- Theoretically can be calculated by introducing random phase on the path of the particle
- Phase distribution determined from toy model simulations
- Phase distribution width decreases with increasing momentum
- The effect increases with the N_{ch} more-or-less linearly
- Effect on two-and three-particle correlations different
- Separating the effect: $\kappa_3 = ... = 2$ if only core/halo
- $\kappa_3 < 2$ if nonzero coherent fraction
- Our results: $\kappa_3 > 2$ if $p_c = 0$

Thank you for your attention!