Particle physics seminar

Three particle Bose-Einstein correlation

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HBT

- 1956. Robert Hanbury Brown and Richard Q. Twiss: A test of a new type of stellar interferometer on Sirius
- Two photomultiplier, different distances $\Rightarrow$ correlation in two measured intensity distributions
- Measured correlation as function of detector distance $\rightarrow$ radius of Sirius

HBT in particle physics

- 1959. G. Goldhaber, S. Goldhaber, W.Y. Lee and A. Pais: proton-antiproton collisions at 1.05 GeV/c:
  - investigating $\rho^0 \rightarrow \pi^+\pi^-$ decay
  - unexpected correlation between π^+ and π^+, π^- and π^-
  - 1960: reason pions are bosons
- Latter was found out correlations contain info about geometry of source

HBT in particle physics

- Amplitude:

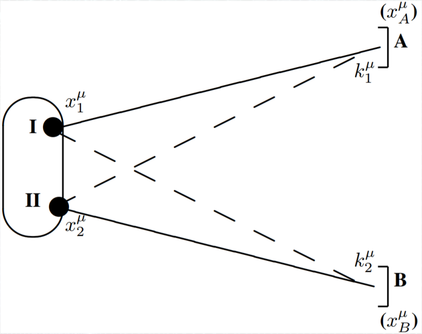
$$A(k_1, k_2) = \frac{1}{\sqrt{2}}\Big(e^{-ik_1(x_A - x_1) + i\Phi_1} e^{-ik_2(x_B - x_2) + i\Phi_2}$$

$$\pm e^{-ik_1(x_A - x_2) + i\phi_2'} e^{-ik_2(x_B - x_1) + i\Phi_1'}\Big)$$

- Probability of joint observation of the two particle with k_1, k_2 momentum:

$$P_2(k_1, k_2) = \langle |A(k_1, k_2)|^2 \rangle$$
$$= 1 \pm \cos{(k_1 - k_2)(x_1 - x_2)}$$

- Chaotic emission: average over random phases $\rightarrow \Phi_i$ not present



HBT in particle physics

- Single particle amplitude:

$$A(k_i) = \frac{1}{\sqrt{2}}\left(e^{-ik_i(x_A - x_1) + i\Phi_1} \pm e^{-ik_i(x_A - x_2) + i\Phi_2}\right)$$

- One particle probability distribution:

$$P_1(k_i) = \langle |A(k_i)|^2 \rangle = 1$$

- Two particle correlation:

$$C_2(k_1, k_2) = \frac{P_2(k_1, k_2)}{P_1(k_1) P_1(k_2)} = 1 \pm \cos\left(k_1 - k_2\right)(x_1 - x_2)$$

HBT in particle physics

- More generally, for extended sources ($\rho(x)$ normalized space-time distribution):

$$P_2(k_1, k_2) = P_1(k_1)P_1(k_2) \int d^4x_1 d^4x_2 |A(k_1, k_2)|^2 \rho(x_1)\rho(x_2)$$
$$= P_1(k_1)P_1(k_2)\left[1 \pm |\tilde{\rho}(q)|^2\right]$$

- $q^\mu = k_1^\mu - k_2^\mu$ and

$$\tilde{\rho}(q) = \int d^4x e^{iq^\mu x_\mu} \rho(x)$$

- Correlation function:

$$C_2(k_1, k_2) = \frac{P_2(k_1, k_2)}{P_1(k_1)P_1(k_2)} = 1 \pm |\tilde{\rho}(q)|^2$$

- Correlation function → Fourier transform → Source function

Three particle HBT

- Invariant momentum distributions: $N_1(p_i), N_2(p_1, p_2), N_3(p_1, p_2, p_3)$
- The definition of the correlation function:

$$C_n(p_1, \dots, p_n) = \frac{N_n(p_1, \dots, p_n)}{N_1(p_1) \cdots N_1(p_n)}$$

for chaotic emission:

$$N_n(p_1, \dots, p_n) = \int \prod_{i=1}^{n} \mathcal{S}(x_i, p_i) |\Psi_n(\{x_i\})|^2 d^4x_1 \dots d^4x_n$$

- $\mathcal{S}(x, p)$ source function (usually assumed to be Gaussian - Levy is more general)

Core-Halo

- Not all particles comes from QGP freeze out
- they also can come from decays
- Both part contribute to source function:

$$\mathcal{S} = \mathcal{S}_{\text{core}} + \mathcal{S}_{\text{halo}}$$

- Particle distribution:

$$N_n(p_1, \ldots, p_n) = N_n^c(p_1, \ldots, p_n) + N_n^h(p_1, \ldots, p_n)$$

- Two particle correlation:

$$C_2(k_1, k_2) = 1 + \lambda_2 |\mathcal{S}(q)|^2$$

where

$$\sqrt{\lambda_2} = f_C \equiv \frac{N^c}{N^c + N^h}$$

Coherence

- If the core partially emits particles in coherent manner:

$$\mathcal{S}_{\mathrm{core}} = \mathcal{S}_{\mathrm{core}}^{\mathrm{pc}} + \mathcal{S}_{\mathrm{core}}^{i}$$

  where pc refers to partially coherent, i to incoherent

- Particle distribution:

$$N_n^c(p_1, \ldots, p_n) = N_n^{c,\mathrm{pc}}(p_1, \ldots, p_n) + N_n^{c,\mathrm{i}}(p_1, \ldots, p_n)$$

- Two particle correlation: $C_2(k_1, k_2) = 1 + \lambda_2 |\mathcal{S}(q)|^2$, but $\lambda_2 \neq f_C^2$
- Fraction of coherently produced pions:

$$p_C \equiv \frac{N_{\mathrm{coherent}}}{N^{\mathrm{coherent}} + N^{\mathrm{incoherent}}} \to \lambda_2(f_C, p_C)$$

- Can this happen? Yes, e.g. due to formation of pion laser or Bose-Einstein condensate of pions

Motivation behind three particle HBT analysis

- Reminder: $C_2(k) = 1 + \lambda_2 |\mathcal{S}(q)|^2$
- Two particle correlation strength: $\lambda_2 \equiv C_2(q=0) - 1$
- Similar definition of three particle correlation strength: $\lambda_3 \equiv C_3(0) - 1$
- Core-Halo:

$$\lambda_2 = f_C^2, \quad \lambda_3 = 2f_C^3 + 3f_C^2$$

$$\kappa_3 = (\lambda_3 - 3\lambda_2)/(2\sqrt{\lambda_2^3}) = 1$$

- Partial coherence (p_C fraction of coherently produced π):

$$\lambda_2 = f_C^2\left[(1-p_C)^2 + 2p_C(1-p_C)\right]$$

$$\lambda_3 = 2f_C^3\left[(1-p_C)^3 + 3p_C(1-p_C)^2\right] + 3f_C^2\left[(1-p_C)^2 + 2p_C(1-p_C)\right]$$

$$\kappa_3 = \kappa_3(p_C)$$

- From λ_2, λ_3 we can investigate the deviation from simple Core-Halo

Dimension

- Definition of correlation function:

$$C_3(\boldsymbol{k_1}, \boldsymbol{k_2}, \boldsymbol{k_3}) = \frac{N_3(\boldsymbol{k_1}, \boldsymbol{k_2}, \boldsymbol{k_3})}{N_1(\boldsymbol{k_1})N_1(\boldsymbol{k_2})N_1(\boldsymbol{k_3})} \qquad \text{(9D)} \tag{1}$$

- Transverse momentum:

$$p_T = \left|\boldsymbol{p}_{T1} + \boldsymbol{p}_{T2} + \boldsymbol{p}_{T3}\right|/3 \tag{2}$$

- Momentum differences: $\boldsymbol{k_{ij}} = \boldsymbol{k_i} - \boldsymbol{k_j}$
- So we want to measure $C_3(\boldsymbol{k_{12}}, \boldsymbol{k_{13}}, \boldsymbol{k_{23}})$ for different p_T bins (6D)

Correlation function

- We use side-out-longitudinal decomposition:
  - long direction: beam direction
  - out direction: direction of average transverse momentum
  - side: orthogonal to long and out
- Coordinate system: LCMS (longitudinal co-moving system) of the triplet: Lorentz boost in long direction
- Instead of $\boldsymbol{k}_{ij}^{\mathrm{LCMS}}$ we measure correlation as function of

$$k_{ij} = |\boldsymbol{k}_{ij}^{\mathrm{LCMS3}}| \qquad (3D)$$

- Reason: not enough statistics

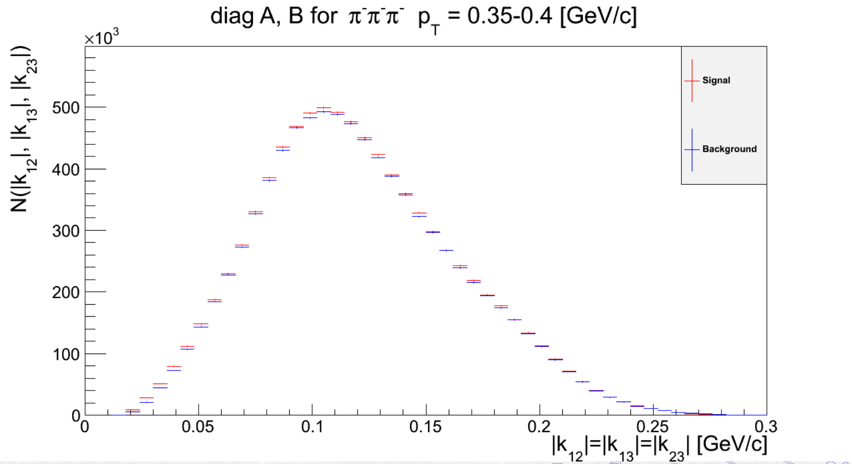
Details of measurement

- BNL RHIC, PHENIX experiment, 200GeV Au+Au collision
- Event-mixing method to measure correlation
- Momentum difference distributions of pion pairs within the triplet from same event: $A(k_{12}, k_{13}, k_{23})$
- Background distribution (triplets from different events): $B(k_{12}, k_{13}, k_{23})$
- MinBias: no centrality filtering
- Lot of cuts (single track, matching cuts, pair cuts)

Details of measurement

- Low bin behavior:

$$k_{ij} \to 0 \quad \overset{?}{\Longrightarrow} \quad A, B \to 0 \tag{3}$$

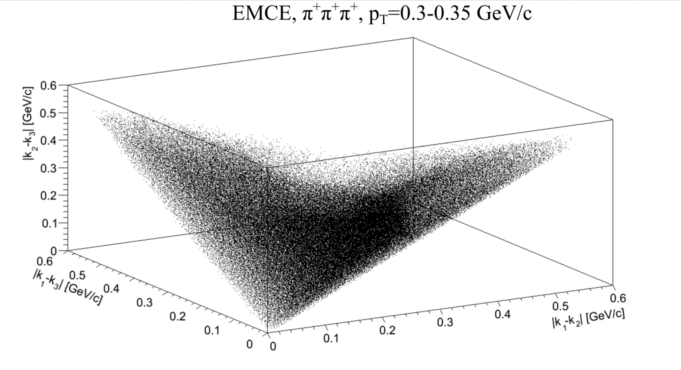


Details of measurement

- The correlation:

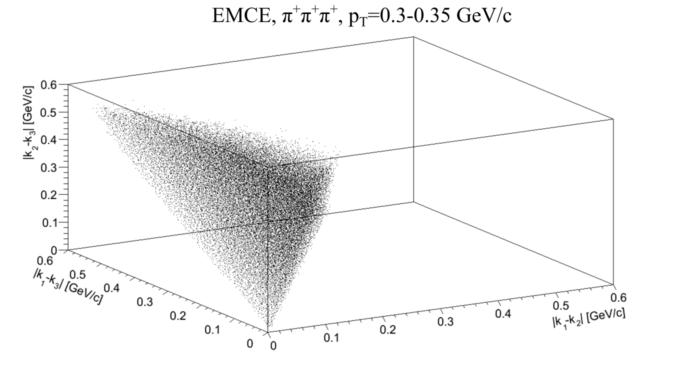
$$C_3(k_{12}, k_{13}, k_{23}) = \frac{A(k_{12}, k_{13}, k_{23})}{B(k_{12}, k_{13}, k_{23})} \frac{\int B}{\int A} \tag{4}$$

- Triangle inequality for $\vec{k}_{12}$, $\vec{k}_{13}$, $\vec{k}_{23}$



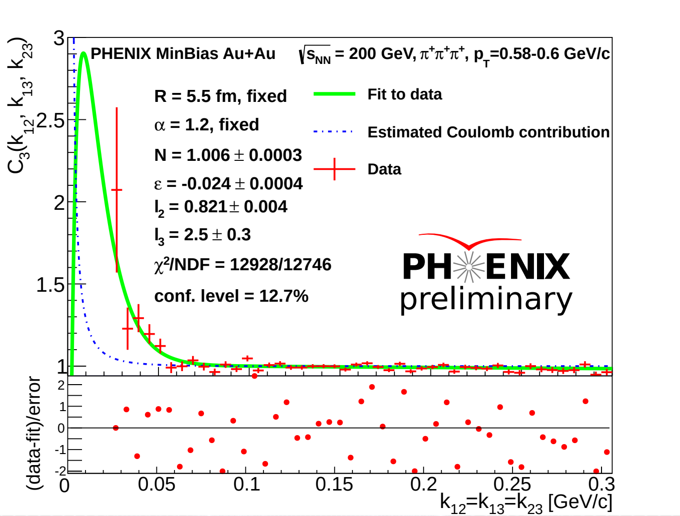
Details of measurement

- Order within triplet doesn't matter
- But when we measure do matter $\Rightarrow$ we have to fold the histogram
  $A(5,6,7) += \ A(6,7,5) \ + \ A(7,5,6) \ + \ A(5,7,6)$
  $+ \ A(7,6,5) \ + \ A(6,5,7)$



Details of measurement

- Diagonal correlation function



Model without Coulomb correction

- Assumption for source: Levy-distribution

$$\mathcal{L}(\alpha, R, r) = (2\pi)^{-3} \int d^3 q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$$

- Approximation for C_3 can be derived ($\mathcal{L}_3 = 2f_C^3$):

$$C_3^{(0)}(k_{12}, k_{13}, k_{23}) = 1 + \ell_3 e^{-0.5(|2k_{12}R_C|^\alpha + |2k_{13}R_C|^\alpha + |2k_{23}R_C|^\alpha)}$$
$$+\ell_2\left(e^{|2k_{12}R_C|^\alpha} + e^{|2k_{13}R_C|^\alpha} + e^{|2k_{23}R_C|^\alpha}\right)$$

- Background: $N(1+\epsilon k_{12})(1+\epsilon k_{13})(1+\epsilon k_{23})$
- Fit parameters: ℓ_3, ℓ_2, R_C, α, N, ϵ
- We are looking for: $\lambda_3 \equiv C_3(k_{12} = k_{13} = k_{23} = 0) - 1 = \ell_3 + 3\ell_2$
- In an other analysis λ_2 was measured

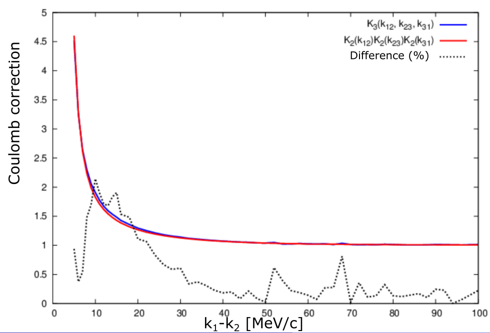
Coulomb correction

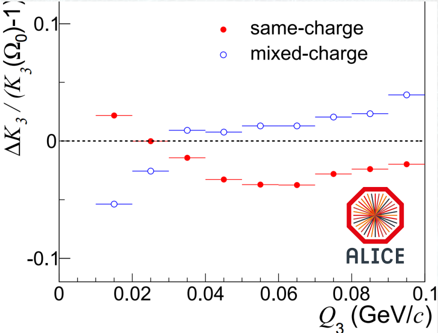
- Corrected model:

$$C_3(k_{12}, k_{13}, k_{23}) = C_3^{(0)}(k_{12}, k_{13}, k_{23}) \cdot K_3(k_{12}, k_{13}, k_{23})$$

- "Generalized Riverside" method for 3 particle Coulomb problem

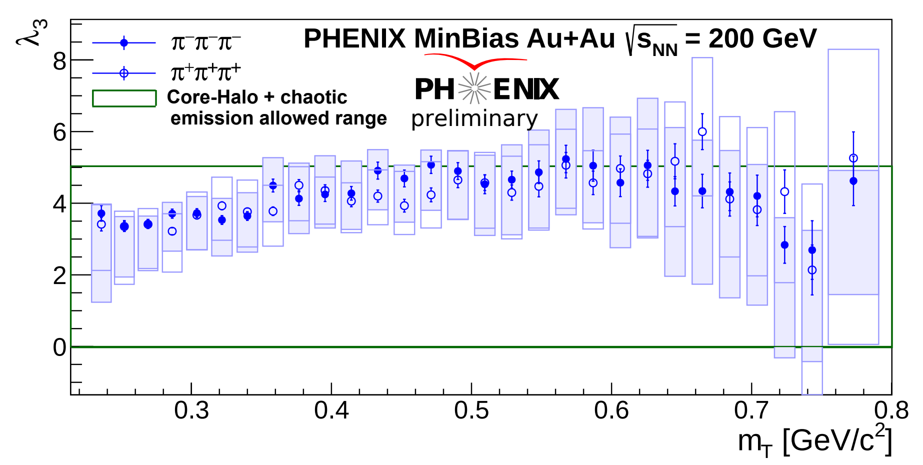
$$K_3(k_{12}, k_{13}, k_{23}) \approx K_1(k_{12})K_1(k_{13})K_1(k_{23})$$





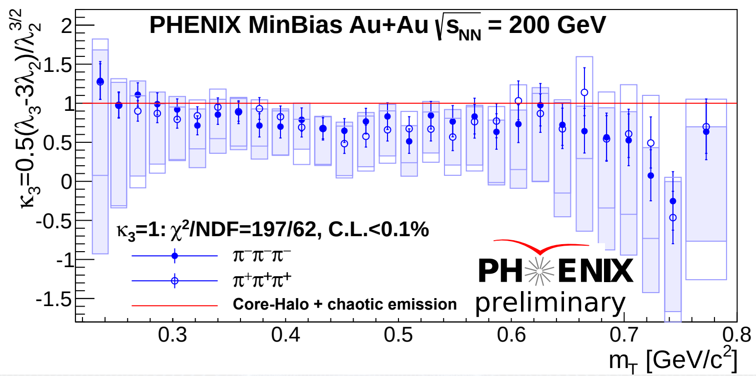
Three particle correlation strength: λ_3

- λ_3 within Core-Halo + chaotic emission range for all m_T



Core-Halo independent parameter

- $\kappa_3 \equiv \frac{\lambda_3 - 3\lambda_2}{2\sqrt{\lambda_2^3}}$ not depend on f_C $(f_C = \text{core}/(\text{core}+\text{halo}))$
- Core-Halo + chaotic emission: $\kappa_3 = 1$
- additional effect (eg. not fully thermal): $\kappa_3 \neq 1$
- Statistically significant deviation from $\kappa_3 = 1$



Partial coherence (p_c) vs fractional core

- Simple theoretical model: $\lambda_2(f_c, p_c)$, $\lambda_3(f_c, p_c)$
- Measured $\lambda_2^{\text{meas.}} \to \lambda_2^{\text{meas.}} = \lambda_2(f_c, p_c) \Longrightarrow f_c(p_c)$ (green lines)
- Measured $\lambda_3^{\text{meas.}} \to \lambda_3^{\text{meas.}} = \lambda_3(f_c, p_c) \Longrightarrow f_c(p_c)$ (blue lines)
- $f_c < 0.82$ and $p_c > 0.5$ can be excluded, $p_C < 0.5$ can't be excluded