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Study of event mixing for Bose–Einstein correlations in reactions with $\pi\pi X$ final states around 1 GeV

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We present a new event mixing cut condition, named energy sum (ES) cut, aiming to investigate two-pion Bose–Einstein correlations (BEC) in reaction with only two identical pions among three final state particles. Unlike the previous proposed pion energy cut, which rejects original events with either pion's energy beyond a given level, this cut does not eliminate any original events and hence improves the statistics of both original events and mixed events. It selects mixed events in terms of a weight proportional to the two-pion energy sum distribution of original events. Numerical tests using the $\gamma p \to \pi^0\pi^0 p$ events are carried out to verify the validity of the energy sum cut. Simulation results show this cut is able to reproduce the relative momentum distribution of the original events in the absence of BEC effects. Its ability to observe BEC effects and to extract correct BEC parameters is verified using event sample in the presence of BEC effects. It is found that the BEC effects can be obviously observed as an enhancement in the correlation function and the BEC parameters extracted by this event mixing cut are in good agreement with input values.

Keywords: Bose–Einstein correlations; event mixing; energy sum cut.

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1. Introduction

In particle and nuclear physics, Bose–Einstein correlations (BEC) have important applications to measure the spatial extent of excited region in which identical bosons are produced.[1–3] Around 50 years ago, G. Goldhaber, S. Goldhaber, W. Lee and A. Pais first investigated BEC effects of two identical pions at low relative momenta in terms of the distribution of pion opening angles in a multi-pion system from proton–antiproton annihilation.[4] The correlation method known at present as "correlation femtoscopy" was successfully applied to the measurement of the spacetime characteristics of particle production processes in high-energy collisions, especially in heavy-ion collisions.[5–8]

The modern approach to femtoscopy correlations was developed by Kopylov and Podgoretsky in early '70s of the last century.[9,10] The measurement of correlations involves the construction of a two-particle correlation function from the particles radiated from a source:

$$C_{\mathrm{BEC}}(p_1, p_2) = \frac{P_{\mathrm{BEC}}(p_1, p_2)}{P_0(p_1, p_2)} = 1 + |f(q)|^2 \,, \tag{1}$$

where $P_{\mathrm{BEC}}(p_1, p_2)$ is the joint probability for the emission of two identical bosons with momenta of p_1 and p_2, respectively, subject to Bose–Einstein symmetry (BES), while $P_0(p_1, p_2)$ corresponds to the emission probability in the absence of BES. The quantity $f(q)$ is the Fourier transformation of the relative momentum $q = p_1 - p_2$. If the boson-emission source is assumed to be a sphere with a Gaussian density distribution, Eq. (1) is written as

$$C_{\mathrm{BEC}}(p_1, p_2) = N(1 + \lambda_2 e^{-r_0^2 Q^2}) \,, \tag{2}$$

where $|f(q)|^2 = e^{-r_0^2 Q^2}$ and N is the normalization factor. Q is the relative momentum of two bosons defined by $Q^2 = -(p_1 - p_1)^2 = M^2 - 4\mu^2$, where M is the invariant mass of the two identical bosons of mass μ. r_0 denotes the Gaussian radius of the emitting source. The parameter λ_2 is introduced as a measure of the BEC strength ranging from 0 to 1, where 0 and 1 correspond to completely coherent and totally chaotic emission, respectively.

The measurement of the correlation function involves the construction of $P_0(p_1, p_2)$, namely reference sample, which is obtained in an indirect manner. A highly adopted method to make reference samples is the event mixing technique,[9] which produces "un-correlated" sample from original sample through making artificial events by randomly selecting two bosons' momenta from different original events.

Although BEC has been widely employed in high-energy elementary-particle collisions,[11–21] and relativistic heavy-ion collisions,[22–25] with large multiplicity, its application in exclusive reactions with low multiplicity is relatively rare, which may offer complementary information like duration and size of nucleon resonances excited by hadronic or electromagnetic probes in the non-perturbative QCD energy region and decayed back into the ground states accompanied by emission of identical mesons. The main reason is that the observation is strongly obscured by non-BEC factors such as global conservation laws and decays of resonances.[26,27] Conservation laws induce significant kinematical correlations between final states particles and complicate the BEC analysis.[28,29] An event mixing method suitable for such measurements is highly expected. In the work of Ref. 30, they explored the effects of kinematical correlations on the event mixing for $\gamma p \to \pi^0 \pi^0 p$ reaction at incident photon energies E_γ around 1 GeV (a non-QCD region) and proposed an

Although we here use double neutral pion photo-production $\gamma p \to \pi^0\pi^0 p$ to demonstrate the event mixing method with the ES cut in conjunction with the MMC cut, it can also be applicable for similar reactions with only two identical bosons emission and with very limited number of final state particles down to three.

In reality, the $\gamma p \to \pi^0\pi^0 p$ reaction does not occur in terms of pure phase space distribution. It is actually dominated by delta-resonance process. Further study is required to establish an event mixing method suitable for a more realistic situation, taking into account the impact of resonances and limited transverse momenta of produced particles.

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