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Femtoscopic measurement of proton source in pp collisions at $\sqrt{s}$ = 900 GeV with ALICE

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The study of momentum correlations between nucleon pairs can provide input for describing the formation of light nuclei, such as deuterons, through the coalescence of protons and neutrons into bound states. The femtoscopy technique is applied to measure the correlation in momentum between protons emitted after the hadronization phase of a hadronic collision. The spatial properties of the proton-emitting source are extracted, and the measured source size can be used as an input parameter for the coalescence modelling. This contribution shows new results of proton–proton correlations measured in pp collisions at $\sqrt{s}$ = 900 GeV, using data collected by the upgraded ALICE detector during the Run 3 of the LHC. These measurements contribute to the characterization of the proton-emitting source size in small collision systems for different collision energies, providing an insight into the microscopic description of the strong nuclear force and of the physical processes occurring in hadronic collisions.

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1. The Femtoscopic Technique

Femtoscopy is a technique used to measure momentum correlations between nucleon pairs, providing spatial information about the particle-emitting region, also referred to as the source [1]. The primary observable in femtoscopy is the correlation function, which is theoretically defined as

$$C^{th}(\boldsymbol{k}^*) = \int d^3r^* S(r^*, R_{inv}) |\Psi(r^*, \boldsymbol{k}^*)|^2. \tag{1}$$

In Eq. 1, $S(r^*, R_{inv})$ is the source function, which represents the probability density of finding two nucleons at a relative distance r^*, and it is assumed to be Gaussian with a standard deviation R_{inv}, which is called the source size. The term $\Psi(r^*, \boldsymbol{k}^*)$ denotes the wave function of a particle pair with relative distance r^* and relative momentum $\boldsymbol{k}^*$; it can be derived as a solution to the Schrödinger equation given a specific interaction potential. The superscript * indicates that the physical quantities are evaluated in the pair rest frame (PRF).
The shape of the correlation function is linked to the interaction potential: if there is no interaction, such as when $\boldsymbol{k}^* \longrightarrow +\infty$, the pairs are uncorrelated, and the correlation function equals one. When interactions are present, $C(\boldsymbol{k}^*) > 1$ indicates an attractive potential, while $C(\boldsymbol{k}^*) < 1$ reflects a repulsive potential.
Experimentally, the correlation function is measured as a function of $\boldsymbol{k}^*$, and is defined as the ratio of the distribution of correlated pairs from the same event, $SE(\boldsymbol{k}^*)$, to that of uncorrelated pairs from different events, $ME(\boldsymbol{k}^*)$. The theoretical and experimental correlation functions are connected by the following relation

$$C^{exp}(\boldsymbol{k}^*) = N \frac{SE(\boldsymbol{k}^*)}{ME(\boldsymbol{k}^*)} = 1 + \lambda \left(C^{th}(\boldsymbol{k}^*) - 1 \right), \tag{2}$$

where λ is the correlation strength, accounting for correlations arising from misidentified or non-primary proton pairs (referred to as non-genuine correlations), as well as for possible deviations from the Gaussian shape of the source. The normalization factor N is determined outside the femtoscopic signal region.

2. Measurement of proton source

The proton source size is measured using data from pp collisions at $\sqrt{s}$ = 900 GeV, collected by the ALICE detector at the LHC during Run 3 in 2022 [2]. Using ALICE's high-precision tracking and particle identification, protons and antiprotons are selected and paired to compute the experimental correlation function. Since proton–proton and antiproton–antiproton interaction is the same, the total correlation function (p–$p \oplus \bar{p}$–$\bar{p}$) is taken as the average of the positive (p–p) and negative ($\bar{p}$–$\bar{p}$) correlations. The pair wave function is computed using the Lednicky-Lyuboshitz model [3] with a box potential approach. This model uses the Lednicky-Lyuboshitz wave function only valid in the asymptotic regime, while at short distances, where strong interaction dominates, a square-well potential is used to obtain the solution. By fitting the total experimental correlation using Eq. 2, the proton source size is extracted as $R_{inv} = 1.01 \pm 0.09$ (stat.) $\pm$ 0.04 (syst.) fm and the correlation strength is determined as $\lambda = 0.78 \pm 0.11$ (stat.) $\pm$ 0.05 (syst.). The total experimental correlation function and the fit results are shown in the left panel of Fig. 1. The λ parameter is also

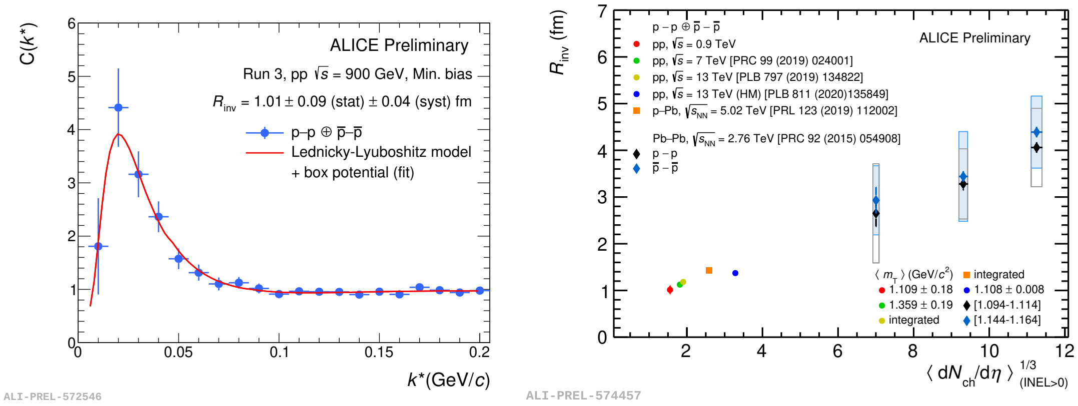

Figure 1: (Left) The total experimental p–$p \oplus \bar{p}$–$\bar{p}$ correlation function with statistical error bands (blue points) measured in pp collisions at $\sqrt{s}$ = 900 GeV. It is fitted with the theoretical model (red line). (Right) The dependence of the proton source size on charged-particle pseudorapidity density $\langle dN_{ch}/d\eta \rangle$, measured for different collision systems and energies with similar pair transverse mass m_T.

computed estimating the fraction of primary protons and sample purity in Monte Carlo simulations, and the calculated value of $\lambda = 0.7$ is consistent with the fit result, validating the procedure. The measured source radius R_{inv} at $\sqrt{s}$ = 900 GeV is compared with other results from proton femtoscopy in pp collisions at higher energies, as well as from p–Pb and Pb–Pb collisions at the LHC. These comparisons are made for similar pair transverse masses $\langle m_T \rangle = \sqrt{k_T^2 + m^2}$, where k_T is the pair transverse momentum and m is the proton mass. The right panel of Fig. 1 shows a clear dependence of the proton source size on charged-particle pseudorapidity density, indicating that the source size increases as the system size grows.

3. Conclusions

The proton source is measured for the first time in pp collisions at $\sqrt{s}$ = 900 GeV. This result is the smallest proton source ever measured at LHC. The proton source size is a key ingredient in coalescence models to estimate deuteron coalescence probability [4], and to constrain the production mechanism of light nuclei in high–energy hadronic collisions.

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