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Letter

# Investigating the composition of the $K_0^*(700)$ state with $\pi^{\pm}K_S^0$ correlations at the LHC

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ABSTRACT

The first measurements of femtoscopic correlations with the particle pair combinations $\pi^{\pm}K_S^0$ in pp collisions at $\sqrt{s} = 13$ TeV at the Large Hadron Collider (LHC) are reported by the ALICE experiment. Using the femtoscopic approach, it is shown that it is possible to study the elusive $K_0^*(700)$ particle that has been considered a tetraquark candidate for over forty years. Source and final-state interaction parameters are extracted by fitting a model assuming a Gaussian source to the experimentally measured two-particle correlation functions. The final-state interaction in the $\pi^{\pm}K_S^0$ system is modeled through a resonant scattering amplitude, defined in terms of a mass and a coupling parameter, The extracted mass and Breit–Wigner width, derived from the coupling parameter, of the final-state interaction are found to be consistent with previous measurements of the $K_0^*(700)$. The small value and increase of the correlation strength with increasing source size support the hypothesis that the $K_0^*(700)$ is a four-quark state, i.e. a tetraquark state of the form $(q_1, \overline{q_2}, q_3, \overline{q_3})$ in which $q_1$, $q_2$ and $q_3$ indicate the flavor of the valence quarks of the $\pi$ and $K_S^0$. This latter trend is also confirmed via a simple geometric model that assumes a tetraquark structure of the $K_0^*(700)$ resonance.

## 1. Introduction

Femtoscopy with identical charged pions has been a useful tool for many years to experimentally probe the geometry of the space-time structure of the freeze-out probability distribution in high-energy pp and heavy-ion collisions [1]. Identical-kaon femtoscopic measurements have also been carried out to complement the identical pion studies, examples of which are measurements in Au–Au collisions at center-of-mass energy per nucleon pair $\sqrt{s_{\rm NN}} = 200$ GeV at the Relativistic Heavy-Ion Collider by the STAR Collaboration [2] ($K_S^0K_S^0$) and PHENIX Collaboration [3] ($K^{\pm}K^{\pm}$), and for pp collisions at $\sqrt{s} = 5.02$, 7, and 13 TeV and Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV at the CERN LHC by the ALICE Collaboration [4–7] ($K_S^0K_S^0$ and $K^{\pm}K^{\pm}$).

In the femtoscopic method, the momentum correlations of pairs of particles when interactions with the other particles in the collision system cease, i.e. during "freeze out" [8], can be utilized to get insight into the strength of the pair interaction, i.e. the final-state interaction (FSI), at low relative momentum. The homogeneity region size, the strength, and even the nature of the FSI at freeze out can be determined by fitting the experimental two-particle correlation function to a model based on the FSI. Results on non-identical kaon femtoscopy with $K_S^0K^{\pm}$ pairs were published by ALICE in pp collisions at $\sqrt{s} = 5.02$, 7, and 13 TeV and Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV [7,9,10]. Although the general goals of non-identical kaon femtoscopy studies overlap with those for identical kaon femtoscopy, e.g. to extract information about the space–time geometry of the collision region and determine the pair-wise interaction strength, the latter is different in each case. For the identical kaon cases, in which pair-wise quantum statistical correlations are present, the interactions are the following: $K^{\pm}K^{\pm}$ – Coulomb interaction, and $K_S^0K_S^0$ – strong FSI through the $f_0(980)/a_0(980)$ resonances. For the $K_S^0K^{\pm}$ pairs, there are no quantum statistical correlations and the only interaction present is the strong FSI through the $a_0(980)$ resonance.

$K_S^0K^{\pm}$ femtoscopy should thus be sensitive to the properties of the $a_0(980)$ resonance. It has been suggested in many papers in the literature that the $a_0(980)$ could be a four-quark or tetraquark state [11]. It was first proposed in 1977 that experimentally-observed low-lying mesons, such as the $a_0(980)$ and $K_0^*(700)$, are part of a SU(3) tetraquark nonet using the MIT Bag model [12], which was later followed up with lattice QCD calculations [13]. There have been a number of QCD studies of these mesons that can be categorized as QCD-inspired models, see for example Refs. [11,14–16], and lattice QCD calculations, see for example Refs. [17–19].

Indeed, the results of the ALICE $K_S^0K^{\pm}$ studies mentioned above suggested that the $a_0(980)$ is a tetraquark state. This suggestion is based on comparing the extracted pair-wise interaction strength of $K_S^0K^{\pm}$ between pp and Pb–Pb collisions as well as with the $K_S^0K_S^0$ studies [4,6,7,9,10].

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From a geometric picture, since a tetraquark version of the $a_0(980)$ contains a strange – anti-strange quark pair, a FSI through it should be suppressed for a small system as in pp collisions due to an increased annihilation probability, whereas for a large Pb–Pb collision this suppression should not be present. Thus, a strong FSI would be expected from Pb–Pb collisions and weak FSI from pp collisions, and this is what was observed in experiments. It would also be expected that a strong pair-wise correlation would be seen for $K^0_S K^0_S$ studies since quantum statistics is dominant over FSI effects. This exception is corroborated by experimental findings [4,6,7].

The success of the ALICE $K^0_S K^{\pm}$ studies on the nature of the $a_0(980)$ resonance motivated the first femtoscopic study ever of $\pi^{\pm}K^0_S$ correlations in $\sqrt{s} = 13$ TeV pp collisions. Another resonance that is a tetraquark candidate is the $K^*_0(700)$ that decays with a branching ratio of $\sim 100\%$ into $\pi$K pairs [12]. The $K^*_0(700)$ is listed in the Review of Particle Physics [20] as a strange meson with spin 0 and isospin $\frac{1}{2}$, the quark content of the $K^*_0(700)^+$ state being $u\bar{s}$. Its mass is listed as $845 \pm 17$ MeV/$c^2$ and it is a very broad resonance with Breit–Wigner width of $468 \pm 30$ MeV/$c^2$. The mass of the $K^*_0(700)$ is above the $\pi^{\pm}K^0_S$ threshold, that is of about 637.18 MeV/$c^2$, and its width is seen to encompass this threshold and below. The tetraquark version of the $K^*_0(700)^+$ would have quark content $u\bar{s}d\bar{d}$ and would decay by direct quark transfer into a $\pi^+K^0$ pair [12]. Thus by measuring $\pi^{\pm}K^0_S$ correlations it should be possible to study the quark nature of the $K^*_0(700)$ using similar methods as mentioned above for the $a_0(980)$ studies, i.e. measuring the strength of the FSI, assuming that the $\pi^{\pm}K^0_S$ FSI goes solely through the $K^*_0(700)$. This scenario will be studied by extracting the mass and width parameters of the FSI and comparing them with previous measurements of the $K^*_0(700)$ [21]. In the present Letter, a study of femtoscopic correlations with the non-identical pair combination $\pi^{\pm}K^0_S$ in pp collisions at $\sqrt{s} = 13$ TeV is presented for the first time to study the nature of the $K^*_0(700)$ resonance. The choice of using pp collisions for this work responds to the necessity of studying the FSI in a small system in which the strength of the FSI is expected to be more sensitive to the system size and thus to the quark nature of the resonance [7]. Due to the short-range nature of the strong interaction which might produce the resonant state, measurements in pp collisions are more suited since interparticle distances of a few fm are obtained [8]. Moreover, it has already been observed that the presence of resonances in the correlation function is enhanced for measurements in small colliding systems, since the signal-to-background for the considered state scales as $1/\text{multiplicity}$ [8].

The results presented in this Letter are obtained using data collected by the ALICE Collaboration [22,23] during the 2015–2018 pp LHC run. The Letter is organized into seven sections: Introduction, Data Analysis, Correlation Function, Fitting, Systematic uncertainties, Results and Discussion, and Summary. The Data Analysis section gives details on how the data were taken and how the $\pi^{\pm}$ and $K^0_S$ were reconstructed and identified. The Correlation Function section describes how the $\pi^{\pm}K^0_S$ pairs were used to construct the correlation functions for this analysis. The Fitting section describes the model used to fit the correlation functions in order to extract the source parameters and FSI parameters. The Systematic uncertainties section discusses how the systematic uncertainties were calculated. The Results and Discussion section presents the results for the extracted parameters and discusses their interpretation. The Summary section summarizes the results of the present work.

## 2. Data analysis

The ALICE detector and its performance are described in detail in Refs. [22,24]. Collision events are selected by using the information from the V0 detectors composed of the V0C and V0A scintillator arrays [25,26], located on both sides of the interaction point, covering the pseudorapidity intervals $-3.7 < \eta < -1.6$ and $2.8 < \eta < 5.1$, respectively. In the analysis $5 \times 10^8$ minimum bias triggered pp collisions at $\sqrt{s} = 13$ TeV were used. Charged particle multiplicity classes, given in terms of multiplicity percentile intervals of the visible inelastic pp cross section, were also determined from the V0 detectors [27].

The Time Projection Chamber (TPC) [28] and the Inner Tracking System (ITS) [22] were used for charged particle tracking. These detectors cover the pseudorapidity range of $|\eta| < 0.9$ and are located within a solenoid magnet with a field strength of magnitude $B = 0.5$ T. The momentum ($p$) determination for charged tracks was made using only the TPC space points. The ITS provided excellent spatial resolution in determining the primary collision vertex. This vertex was used to constrain the tracks reconstructed with the TPC, requiring it to be within $\pm 10$ of the center of the ALICE detector. The average momentum resolution typically obtained in this analysis for charged tracks was less than 10 MeV/$c$ [24]. The selections based on the quality of track fitting [24,28,29], in addition to the standard track quality criteria [24], were used to ensure that only well-reconstructed tracks were taken into account in the analysis. The quality of the track was determined by the $\chi^2/N$ value for the Kalman fit to the particle trajectory in the TPC, where N is the number of TPC clusters attached to the track [24]. The track was rejected if the value was larger than 4.0.

Analysis specific event selection criteria were also applied. The event must have one accepted possible $\pi^{\pm}K^0_S$ pair. To reduce the effects of mini-jets which tend to produce non-flat structures in the two-particle correlation functions used in femtoscopy [30], a selection on the event transverse sphericity, calculated from the azimuthal distribution of tracks, was applied by requiring $S_T > 0.7$. $S_T$ is a scalar quantity that takes values in the range $0 - 1$ characterizing the event shape, i.e. $S_T \sim 0$ values represent elongated events that are "jet-like" and result from a single hard-scattering of partons, whereas $S_T \sim 1$ values represent spherical "non-jet-like" events resulting from many soft parton scatterings or several hard parton scatterings. See Ref. [30] for more details. Note that the $S_T > 0.7$ selection is estimated to have $< 10\%$ effect on the multiplicity of tracks entering the femtoscopy analysis since this selection tends to remove single hard-scattering events. Pile-up events were rejected using the timing information from the V0 (for out of bunch pile-up) and multiple reconstructed vertices from tracks (or track segments in the Silicon Pixel Detector layers of the ITS) [29,30]. The possible effect due to remaining pile-up events passing the event selection criteria described above was investigated by performing the analysis using only low interaction-rate data-taking periods. No significant difference was found in the results of the analysis compared with the higher interaction-rate runs used. Both sets of runs were combined for the present analysis.

Charged particles were identified with the central barrel detectors. Particle Identification (PID) for reconstructed tracks was carried out using both the TPC and Time-Of-Flight (TOF) detectors. For the TPC, the specific ionization energy loss $\mathrm{d}E/\mathrm{d}x$ was measured, and for the TOF, the flight time of the particle in the pseudorapidity range $|\eta| < 0.9$ was measured [29,31]. For the PID signal, a value ($N_\sigma$) was assigned to each track denoting the number of standard deviations between the measured PID signal and the expected values, assuming a mass hypothesis, divided by the detector resolution for both detectors [6,24,29,31]. A parametrized Bethe-Bloch formula [24] was used for the TPC PID to calculate the expected energy loss $\langle \mathrm{d}E/\mathrm{d}x \rangle$ in the detector for a particle with a given charge, mass, and momentum. The particle mass was used to calculate the expected time-of-flight as a function of track length and momentum for the TOF PID. The detailed description of the particle identification methods is given in Ref. [32].

For Monte Carlo (MC) calculations, particles from pp collisions simulated by the general-purpose generator PYTHIA8 [33] with the Monash 2013 tune [34] were transported through a GEANT3 [35] model of the ALICE detector. The total number of simulated pp collisions used in this analysis is $5 \times 10^8$.

**Table 1**
$\pi^{\pm}$ and $K^0_S$ selection criteria.

| Neutral kaon selection | Value |
|---|---|
| Daughter $p_T$ | $> 0.15$ GeV/$c$ |
| Daughter $\|\eta\|$ | $< 0.8$ |
| Daughter DCA (3D) to primary vertex | $> 0.4$ cm |
| Daughter TPC PID [$N_\sigma$] | $< 3$ |
| Daughter TOF PID [$N_\sigma$] (for $p > 0.8$ GeV/$c$) | $< 3$ |
| Kalman fit $\chi^2/N$ | $\leq 4$ |
| $\|\eta\|$ | $< 0.8$ |
| DCA (3D) between daughters | $< 0.3$ cm |
| DCA (3D) to primary vertex | $< 0.3$ cm |
| Decay length (3D, lab frame) | $< 30$ cm |
| Decay radius (2D, lab frame) | $> 0.2$ cm |
| Cosine of pointing angle | $> 0.99$ |
| Invariant mass | $0.485 < m < 0.510$ GeV/$c^2$ |
| **Primary pion selection** | **Value** |
| $p_T$ | $0.15 < p_T < 1.2$ GeV/$c$ |
| $\|\eta\|$ | $< 0.8$ |
| Transverse DCA to primary vertex | $< 2.4$ cm |
| Longitudinal DCA to primary vertex | $< 3.0$ cm |
| TOF PID [$N_\sigma$] with valid TOF signal and $p > 0.5$ GeV/$c$ | $< 2$ |
| TPC PID [$N_\sigma$] if no TOF signal for all $p$ | $< 2$ |
| Kalman fit $\chi^2/N$ | $\leq 4$ |

The methods used to select and identify individual $K^0_S$ and $\pi^{\pm}$ particles are similar to those used for the ALICE $K^{\pm}K^0_S$ analysis in pp collisions at $\sqrt{s} = 13$ TeV [7].

$K^0_S$ are reconstructed from their decay into $\pi^+\pi^-$, which has a branching ratio of 69% [20]. The neutral $K^0_S$ decay vertices and parameters are reconstructed and calculated from pairs of detected $\pi^+\pi^-$ tracks, and selected based on their invariant mass and the $K^0_S$ decay topology. The selection criteria for the $K^0_S$ and the daughter pions are shown in Table 1.

The selection criteria are based on decay topology, i.e. distance-of-closest-approach (DCA) between charged pion daughters, DCA of daughter pion to the primary vertex, DCA of reconstructed $K^0_S$ to the primary vertex, cosine of pointing angle, and decay length of $K^0_S$, and were tuned to optimize purity and statistical significance. If two reconstructed $K^0_S$ particles share a daughter track, both are removed from the analysis. The MC samples were used to study any bias that might be induced by this procedure, which resulted in rejecting $< 1\%$ of the $K^0_S$ candidates [6,7]. Reconstructed $K^0_S$ candidates within invariant mass range $0.485 < m(\pi^+\pi^-) < 0.510$ GeV/$c^2$ are used in this analysis which gives $98 \pm 1\%$ purity of $K^0_S$. The purity here is defined as signal/(signal + background). The signal and background counts are calculated by fitting a fourth-order polynomial to the side-bands of the signal region to estimate the background there and subtracting this from the invariant mass histogram. A Gaussian is used to fit the signal peak in the invariant mass distribution (see Fig. 2 of Ref. [6]).

Primary charged pions are selected using the PID information from the TPC and TOF detectors. The TPC is used for PID in the full momentum range, except if a valid TOF signal is available for $p > 0.5$ GeV/$c$ then TOF PID is used. For more details, refer to Refs. [5,6]. Table 1 summarizes the criteria used for the charged pion selection. The average charged pion purity is found using MC simulations to be $98.1 \pm 0.1\%$, in agreement with the charged pion purity reported in Ref. [6].

Two-track effects, such as the merging of two real tracks into one reconstructed track and the splitting of one real track into two reconstructed tracks, are an important challenge for femtoscopic studies. A selection on the minimum separation distance between the primary pion and a daughter pion from the decay of the $K^0_S$ in the $\pi^{\pm}K^0_S$ pair was made from the corresponding TPC tracks using the same method as described in Ref. [7]. The distance between the two tracks was calculated in different positions along their trajectory in the TPC (at radial distances from 85 to 150 cm from the interaction point) and a minimum separation distance of 20 cm was required.

## 3. Measurement of correlation functions

The momentum correlations of $\pi^{\pm}K^0_S$ pairs using the two-particle correlation function are studied in this analysis. The correlation function is defined as $C(k^*) = A(k^*)/B(k^*)$, where $A(k^*)$ is the measured distribution of pairs from the same event and $B(k^*)$ is the reference distribution of pairs from mixed events. The denominator $B(k^*)$ is formed by mixing particles from one event with particles from 10 different events that satisfy the conditions that the primary vertex positions along the beam direction are within 2 cm of each other, and have similar multiplicity, i.e. events within 2% difference in multiplicity percentile are mixed. Other sizes of the mixed events buffer were also investigated with no significant effect on the results of this work. All events used are required to satisfy the $S_T > 0.7$ selection. The $k^*$ is the magnitude of the momentum of each of the particles in the pair rest frame. In the present case of unequal mass particles in the pair, $m_1$ and $m_2$, $k^*$ is given by

$$k^* = \sqrt{\frac{a^2 - m_1^2 m_2^2}{2a + m_1^2 + m_2^2}} \tag{1}$$

where,

$$a \equiv (q_{\text{inv}}^2 + m_1^2 + m_2^2)/2. \tag{2}$$

For convenience, the square of the invariant momentum difference $q_{\text{inv}}^2 = |\vec{p}_1 - \vec{p}_2|^2 - |E_1 - E_2|^2$ is evaluated with the momenta and energies of the two particles measured in the laboratory frame. In the case where $m_1 = m_2$, $k^*$ can be expressed as $k^* = q_{\text{inv}}/2$. A $k^*$ bin size of 20 MeV/$c$ was used in the analyses presented in this Letter.

Correlation functions are analyzed for three cases: 1) $0-100\%$ multiplicity class and $k_T > 0$ GeV/$c$, 2) $0-100\%$ multiplicity class and $k_T < 0.5$ GeV/$c$, and 3) $0-5\%$ multiplicity class and $k_T < 0.5$ GeV/$c$, where $k_T = |\vec{p}_{T1} + \vec{p}_{T2}|/2$, and where $\vec{p}_{T1}$ and $\vec{p}_{T2}$ are the transverse momenta of the particles in the pair. The three cases correspond to the following average $k_T$ and average charged-particle pseudorapidity density ($\langle dN/d\eta \rangle$ in the $|\eta| < 0.8$ range) values [27]: 1) $\langle k_T \rangle = 0.655$ GeV/$c$, $\langle dN/d\eta \rangle = 6.89$, 2) $\langle k_T \rangle = 0.323$ GeV/$c$, $\langle dN/d\eta \rangle = 6.89$, and 3) $\langle k_T \rangle = 0.326$ GeV/$c$, $\langle dN/d\eta \rangle = 21.2$. The purpose of analyzing these

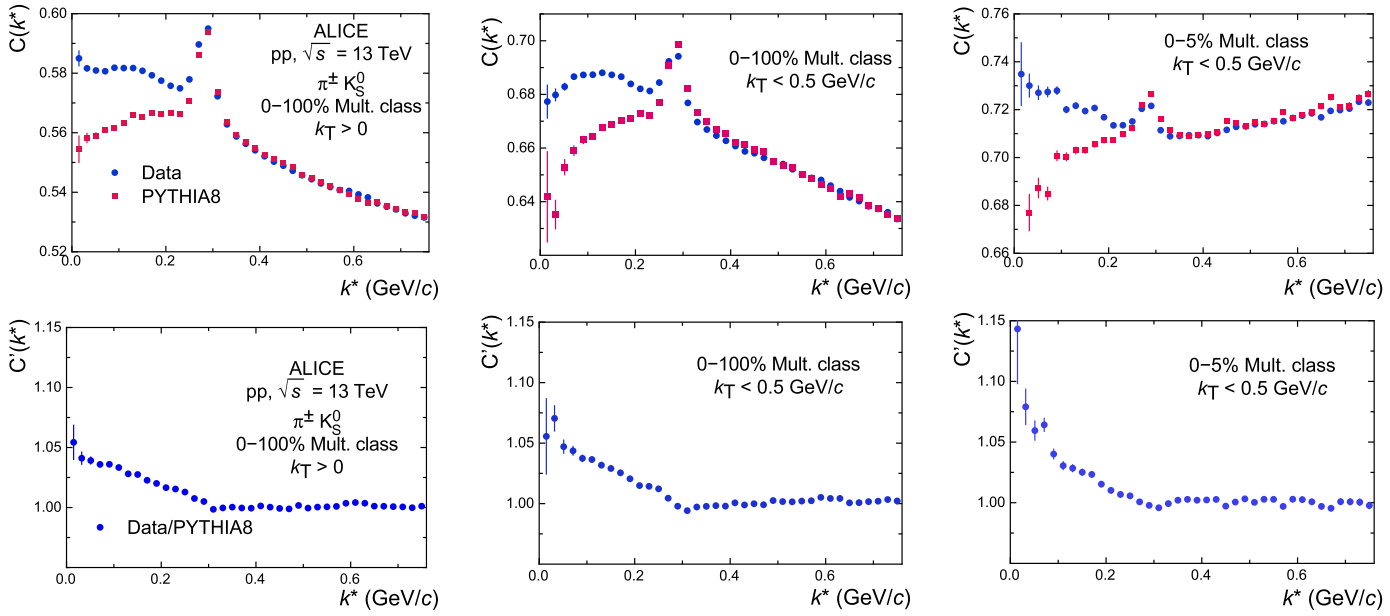


**Fig. 1.** Top row: $\pi^{\pm}K^0_S$ correlation functions experimentally measured (blue dots) compared with PYTHIA8+GEANT3 simulations (red squares) obtained in pp collisions at $\sqrt{s} = 13$ TeV for $0-100\%$ multiplicity class and $k_T > 0$ (left), $0-100\%$ multiplicity class and $k_T < 0.5$ GeV/$c$ (center), and 0–5% multiplicity class and $k_T < 0.5$ GeV/$c$ (right). The PYTHIA8+GEANT3 correlation function is normalized to the data at $k^* = 0.5$ GeV/c. Bottom row: Ratio of Data to PYTHIA8+GEANT3 simulations for the three studied cases. Statistical uncertainties are represented by bars.

cases is to obtain different femtoscopic source sizes and to study the effect of source size on the FSI. It has been found from femtoscopy measurements in pp collisions that the source size depends on both $\langle k_T \rangle$ and $\langle dN/d\eta \rangle$ [4,36]. In addition, case 1) was chosen to maximize the sample size and to provide a selection-free case to compare with the other cases having multiplicity and $k_T$ selections.

Monte Carlo simulations were used to simulate correlation functions which were compared with experimental data. Fig. 1 shows in the top row the correlation functions experimentally measured (blue) along with the simulated ones (red). The MC correlation functions are normalized to the experimental ones at $k^* = 0.5$ GeV/$c$ for the three cases mentioned above. The single-event and mixed-event distributions of the correlation functions are summed over $\pi^+K^0_S$ and $\pi^-K^0_S$ pairs, since it is found that there is no significant difference between the $\pi^+K^0_S$ and $\pi^-K^0_S$ corresponding correlation functions. The decay of the K*(892) meson is clearly seen at $k^* \sim 0.3$ GeV/$c$ for all cases. For $k^* > 0.35$ GeV/$c$ a non-flat baseline is also observed in all cases. This non-flat baseline is associated with soft parton fragmentation, or mini-jets, that are not completely suppressed by the transverse sphericity selection [36–38], as well as the presence of momentum conservation effects. Non-flat baselines in two-particle correlation functions obtained in pp collisions are often observed [9,36,37]. In particular, measured correlation functions show a decreasing dependence of the baseline with increasing $k^*$ for low multiplicity classes, and a reversal of this dependence for higher multiplicity classes, as seen in Fig. 1. This effect in the data is seen to be present as well in the PYTHIA8 simulations. The simulations well reproduce the K*(892) peak and the background visible at larger $k^*$, hence in order to remove these two contributions, the measured correlation function is subsequently divided by the simulated one, defined as $C'(k^*)$, as shown in the bottom panels of Fig. 1. The statistical uncertainty from the MC correlation function is propagated with the uncertainty from the experimental one in the ratio, which becomes the final correlation function.

Finite track momentum resolution can smear the relative momentum correlation functions used in this analysis. This effect is corrected using MC simulations as done in previous works [22,23]. It is found that the effect of the momentum resolution correction is small for the very lowest $k^*$ bin with the largest statistical error bars and negligible for the rest of the bins, resulting in a $< 3\%$ effect on the extracted fit parameters.

## 4. Fitting

The momentum resolution corrected ratio of the experimental $\pi^{\pm}K^0_S$ correlation function to the MC correlation function was fitted by a model in order to extract information on the size of the source, as well as the strength and nature of the FSI between the particles in the pair. The fit function is given by,

$$C'(k^*) = \kappa \left[ C_{\text{Lednicky}}(k^*) + \varepsilon \frac{dN_{BW}}{dm} \frac{dm}{dk^*} \right] \tag{3}$$

where,

$$\frac{dN_{BW}}{dm} \propto \frac{\Gamma_{892}}{(m - m_{892})^2 + \Gamma^2_{892}/4} \tag{4}$$

is the Breit–Wigner resonance distribution. This last term fits out any residual presence of the K*(892) peak (see below).

The quantities $\varepsilon$ and $\kappa$, where $\varepsilon$ is the magnitude of a correction term on the MC modeling of the K*(892) (see below) and $\kappa$ is an overall normalization factor, are fit parameters, and $\Gamma_{892}$ and $m_{892}$ are the full-width at half maximum (FWHM) and mass of the K*(892), respectively, taken from the Review of Particle Physics [20]. The first term in Eq. (3) is a modified version of the Lednicky parametrization [2,39,40] which assumes that the pair interaction is due to strong final-state interaction of a near-threshold resonance. The second term in Eq. (3) is used to fit out the small residual bump in the ratio that results from a slight overcompensation of the MC in modeling the K*(892) peak in the data that can be seen in Fig. 1, located at $k^* \sim 0.3$ GeV/$c$. Fitting out this residual bump results in an improved $\chi^2/\text{ndf}$ for all of the fits.

A Gaussian distribution of the source size in the pair reference frame is assumed in the FSI parameterization. More general forms for this distribution could be used, but using the Gaussian results in the analytic form of the Lednicky equation. Another motivation for staying with the Gaussian is to facilitate comparisons with previous published results that also used the Gaussian distribution.

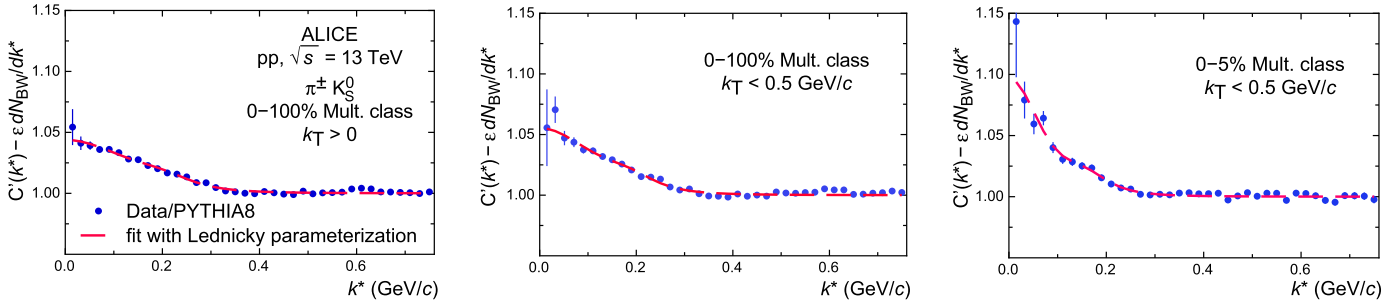


**Fig. 2.** Example fit of Eq. (5) to the corrected correlation functions after Eq. (3) has been used to remove the PYTHIA8+GEANT3 overcompensation of the K*(892), for $\pi^{\pm}\mathrm{K}^0_\mathrm{S}$ from $\sqrt{s} = 13$ TeV pp collisions for 0 – 100% multiplicity class and $k_T > 0$ (left), 0 – 100% multiplicity class and $k_\mathrm{T} < 0.5$ GeV/$c$ (center), and 0–5% multiplicity class and $k_\mathrm{T} < 0.5$ GeV/$c$ (right). Statistical uncertainties are represented as bars.

The quantity $C_{\mathrm{Lednicky}}(k^*)$ has the form

$$C_{\mathrm{Lednicky}}(k^*) = 1 + \left(\frac{\lambda\alpha}{2}\right)\left[\left|\frac{f(k^*)}{R}\right|^2 + \frac{4\mathcal{R}f(k^*)}{\sqrt{\pi}R}F_1(2k^*R) - \frac{2\mathcal{I}f(k^*)}{R}F_2(2k^*R) + \Delta C\right] \quad (5)$$

and

$$F_1(z) = \int_0^z dx\,\frac{e^{x^2-z^2}}{z}; \quad F_2(z) = \frac{1-e^{-z^2}}{z}. \quad (6)$$

$\alpha$ is the symmetry parameter and is set to 0.5 assuming symmetry in $\mathrm{K}^0$ and $\overline{\mathrm{K}^0}$ production since the $\mathrm{K}^0_\mathrm{S}$ is a linear combination of these; $R$ is the radius parameter of the source; and $\lambda$ is the correlation strength. The term $f(k^*)$ is the s-wave $\pi^{\pm}\mathrm{K}^0_\mathrm{S}$ scattering amplitude whose FSI contribution is the near-threshold resonance. A relativistic Breit–Wigner amplitude is assumed,

$$f(k^*) = \frac{\gamma}{M_R^2 - s - i\gamma k^*}. \quad (7)$$

In Eq. (7), $M_R$ is the mass of the resonance, and $\gamma$ is the coupling of the resonance to its decay channel, i.e. $\pi^{\pm}\mathrm{K}^0_\mathrm{S}$. Also, $s = (\sqrt{m_\mathrm{K}^2 + k^{*2}} + \sqrt{m_\pi^2 + k^{*2}})^2$ is the square of the energy of the pair in its rest frame. A Breit–Wigner form was chosen for $f(k^*)$ since the fitted $M_R$ and $\gamma$ to the FSI resonance from the present work will be compared with other measurements that used the Breit–Wigner form in order to identify the resonance [41,42].

The quantity $\Delta C$ is a correction to the derivation of Eq. (5), that assumes spherical outgoing waves, to account for the true scattered waves in the inner region of the short-range potential [2,7], and is given by,

$$\Delta C = \frac{(2 + m_\pi/m_\mathrm{K} + m_\mathrm{K}/m_\pi)}{2\sqrt{\pi}R^3\gamma}|f(k^*)|^2. \quad (8)$$

As a test, a p-wave term was added to the s-wave term in the scattering amplitude in deriving the Lednicky equation to study whether there was interference of the K*(892) with the s-wave FSI. It was found that the p-wave term had a negligible effect on the fits, and was thus ignored.

The fitting strategy was to make a six-parameter fit of Eq. (3) to the corrected ratio of the experimental $\pi^{\pm}\mathrm{K}^0_\mathrm{S}$ correlation function to the corresponding MC correlation function to extract $R$, $\lambda$, $M_R$, $\gamma$, $\varepsilon$, and $\kappa$. The nominal fit range is $0 < k^* < 0.76$ GeV/$c$ in all cases. The nominal maximum of 0.76 GeV/$c$ of the fit range was set to give the optimal overlap between the experimental and MC correlation functions in the baseline region.

Fig. 2 shows the correlation functions and fits. The MC overcompensation of the K*(892) has been removed from the "Data/MC" points by subtracting out the second term in Eq. (3) in order to show how well $C_{\mathrm{Lednicky}}(k^*)$ fits the ratio, and the ratio has been divided by $\kappa$. The $\chi^2$/ndf for the fits shown in Fig. 2 are 1.6, 1.8, and 0.92, with p-values of 1.7% and 0.36% and 60%, respectively.

## 5. Systematic uncertainties

Table 2 shows the total systematic uncertainties on the $R$, $\lambda$ $M_R$, and $\gamma$ parameters extracted from the $\pi^{\pm}\mathrm{K}^0_\mathrm{S}$ correlation function in pp collisions at $\sqrt{s} = 13$ TeV.

The "fit systematic uncertainty" column reports the systematic uncertainty due to varying the $k^*$ fit range. Varying the fit range by 20% resulted in < 3% effect on the fit parameters. Fitting uncertainties were calculated including correlations among the fit parameters as done using a MINOS algorithm in order to obtain conservative estimates of the uncertainties [43].

The "selection systematic uncertainty" column reports the systematic uncertainty related to the variation of track and PID selection criteria used in the data analysis. To determine this, the single particle selection criteria shown in Table 1 were varied by ±10%, and the value chosen for the minimum separation distance of same-sign tracks was varied by ±20% [7]. The systematic uncertainty related to the sphericity selection of $S_\mathrm{T} > 0.7$ is also included in this source of systematic uncertainty, where $S_\mathrm{T}$ was varied by ±10% from its nominal selection value. The uncertainty was estimated from the variation of the results with respect to those obtained with the nominal selections. The resulting relative systematic uncertainties are of about 10% for $\lambda$, about 5% for $R$, and about 2% for the other parameters.

The "total systematic uncertainty" column is obtained as the sum in quadrature of the contribution of the two sources described above. The "total uncertainty" column is the sum in quadrature of the statistical uncertainty and the total systematic uncertainty. As seen, the total systematic uncertainties tend to be greater than or comparable to the statistical uncertainties. Table 3 shows an approximate breakdown of the relative systematic uncertainties (in percentage) from the different variations considered. See Table 1 in Section 2 for the nominal values of the selection criteria. Note that "min. sep. var." refers to the variation of the selection for minimum separation between $\mathrm{K}^0_\mathrm{S}$ daughter and primary pions in the TPC, mentioned earlier, and "$m(\pi^+\pi^-)$ and primary vertex variations" refer to the combined effect of varying the invariant mass selection for $\mathrm{K}^0_\mathrm{S}$ and varying the selection for the primary vertex of the event. As seen, in general the variations have the largest effect on $\lambda$ and the smallest effect on $M_R$ and $\gamma$, with the $S_\mathrm{T}$ variation having the largest single-variation effect on all of the parameters.

## 6. Results and discussion

The $R$, $\lambda$, $M_R$, and $\gamma$ parameters extracted from the present analysis of $\pi^{\pm}\mathrm{K}^0_\mathrm{S}$ correlation functions in pp collisions at $\sqrt{s} = 13$ TeV are reported in Table 2 for the three cases mentioned above. The $\lambda$ parame-

**Table 2**
Fit results for R, $\lambda$, $M_R$, and $\gamma$ showing statistical and systematic uncertainties from the present analysis. Uncertainties are symmetric unless specified otherwise. See the text for the description of the various sources of uncertainties.

| $R$, $\lambda$, $M_R$, or $\gamma$ | fit value | statistical uncertainty | fit systematic uncertainty | selection systematic uncertainty | total systematic uncertainty | total uncertainty |
|---|---|---|---|---|---|---|
| 0 – 100% multiplicity class $k_T > 0$ | | | | | | |
| $R$ (fm) | 0.912 | 0.037 | 0.011 | 0.053 | 0.054 | 0.065 |
| $\lambda$ | 0.0783 | +0.0096 -0.0086 | 0.0032 | 0.0078 | 0.0084 | +0.0127 -0.0121 |
| $M_R$ (GeV/$c^2$) | 0.833 | 0.002 | 0.006 | 0.013 | 0.015 | 0.015 |
| $\gamma$ (GeV) | 0.890 | 0.015 | 0.012 | 0.016 | 0.020 | 0.025 |
| 0 – 100% multiplicity class $k_T < 0.5$ GeV/$c$ | | | | | | |
| $R$ (fm) | 1.063 | 0.058 | 0.015 | 0.064 | 0.066 | 0.088 |
| $\lambda$ | 0.111 | 0.017 | 0.004 | 0.013 | 0.014 | 0.022 |
| $M_R$ (GeV/$c^2$) | 0.804 | 0.003 | 0.005 | 0.013 | 0.014 | 0.014 |
| $\gamma$ (GeV) | 0.801 | 0.023 | 0.020 | 0.014 | 0.024 | 0.033 |
| 0 – 5% multiplicity class $k_T < 0.5$ GeV/$c$ | | | | | | |
| $R$ (fm) | 1.618 | +0.136 -0.109 | 0.015 | 0.089 | 0.090 | +0.163 -0.142 |
| $\lambda$ | 0.274 | +0.077 -0.053 | 0.001 | 0.026 | 0.026 | +0.081 -0.059 |
| $M_R$ (GeV/$c^2$) | 0.765 | 0.004 | 0.002 | 0.012 | 0.013 | 0.013 |
| $\gamma$ (GeV) | 0.714 | +0.042 -0.037 | 0.005 | 0.013 | 0.014 | +0.044 -0.039 |

**Table 3**
Breakdown of the relative systematic uncertainties for R, $\lambda$, $M_R$, and $\gamma$ from the variation of track, PID and mixed-event selection criteria. The %Δ row is the percentage that the quantity was changed. See the text for the description of the various uncertainties.

| Quantity changed | Fit range | Min. sep. var. | TOF, TPC $N_\sigma$ | DCA var. | $m(\pi^+\pi^-)$ and primary vertex var. | Multiplicity difference for event mixing | Decay length | $S_T$ var. |
|---|---|---|---|---|---|---|---|---|
| %Δ | 20 | 20 | 10 | 10 | 10 | 10 | 10 | 10 |
| %$R$ | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 3 |
| %$\lambda$ | 3 | 5 | 3 | 3 | 3 | 2 | 2 | 5 |
| %$M_R$ | 1 | < 1 | < 1 | < 1 | < 1 | < 1 | < 1 | 2 |
| %$\gamma$ | 2 | 1 | < 1 | < 1 | < 1 | < 1 | < 1 | 2 |

ters are corrected for purity by dividing the extracted $\lambda$ values with the product of the $\pi^\pm$ and $K^0_S$ purities (see Section 2).

Since the main goal of this measurement is to study the $K^*_0(700)$ resonance, one must first establish that the FSI of the $\pi^\pm K^0_S$ pair occurs indeed through this resonance. This can be done by comparing the measured $M_R$ and $\gamma$ parameters extracted from this analysis with previously measured values of $M_R$ and $\Gamma_R$ for the $K^*_0(700)$ [41,42], where $\Gamma_R$ is the FWHM of the relativistic Breit–Wigner resonance distribution, whose amplitude is expressed as [44],

$$f(s) \sim \frac{1}{M_R^2 - s - iM_R\Gamma_R}. \tag{9}$$

Comparing this denominator with the denominator of Eq. (7), one can obtain an estimate for $\Gamma_R$ from the present results,

$$\Gamma_R = \frac{\langle k^* \rangle \gamma}{M_R}, \tag{10}$$

where $\langle k^* \rangle$ is the average of $k^*$ determined by weighting $k^*$ by the experimental $dN/dk^*$ distribution over the fit range used in fitting Eq. (3) to the correlation function. Table 4 lists the values of $\Gamma_R$ extracted from the present work using Eq. (10) for the three cases studied. The uncertainties shown for $\langle k^* \rangle$ are estimated by considering different $k^*$ ranges for calculating the average, namely $0 < k^* < 0.6$ GeV/$c$ and $0 < k^* < 2$ GeV/$c$, and taking the differences from the nominal $\langle k^* \rangle$ to obtain conservative estimates of the uncertainties.

**Table 4**
The $\langle k^* \rangle$ and corresponding $\Gamma_R$ extracted from the three cases measured in the present work using Eq. (10).

| Case | $\langle k^* \rangle$ (GeV/$c$) | $\Gamma_R$ (GeV/$c^2$) |
|---|---|---|
| 0 – 100% multiplicity class, $k_T > 0$ | $0.403^{+0.093}_{-0.056}$ | $0.430^{+0.088}_{-0.053}$ |
| 0 – 100% multiplicity class, $k_T < 0.5$ GeV/$c$ | $0.408^{+0.060}_{-0.050}$ | $0.406^{+0.050}_{-0.042}$ |
| 0 – 5% multiplicity class, $k_T < 0.5$ GeV/$c$ | $0.418^{+0.072}_{-0.053}$ | $0.390^{+0.068}_{-0.051}$ |

Fig. 3 compares the values of $M_R$ and $\Gamma_R$ extracted in the present work with measurements of these quantities for the $K^*_0(700)$ from the BES [41] and E791 Collaborations [42]. The BES Collaboration measured the relativistic Breit–Wigner parameters of the $K^*_0(700)$ through the decay of the $J/\psi$ meson, whereas the E791 Collaboration measured them through the decay of the $D^+$ meson. The total uncertainties defined as the quadratic sum of the statistical and systematic uncertainties are shown on the points for all cases. As seen, the values reported in this work agree within uncertainties with the $K^*_0(700)$ Breit–Wigner param-

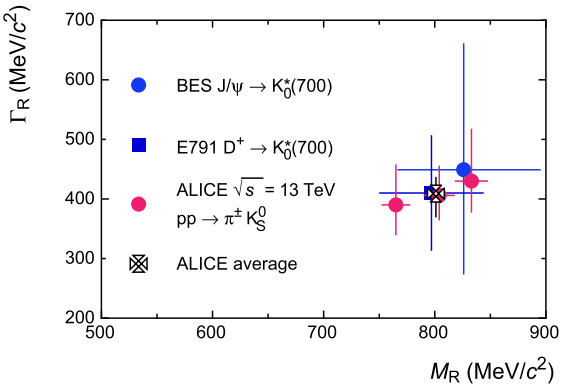


**Fig. 3.** The extracted Breit–Wigner parameters from the $\pi^{\pm}K^0_S$ femtoscopic correlation in pp collisions at $\sqrt{s} = 13$ TeV compared with those for $K^*_0(700)$ from the BES [41] and the E791 [42] experiments. The horizontal and vertical bars represent the total uncertainties. The "ALICE average" value is the weighted average of the three ALICE points.

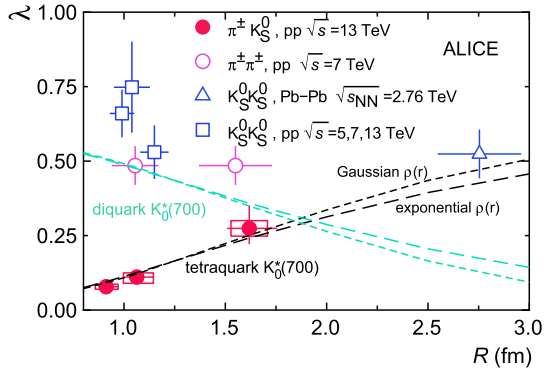


**Fig. 4.** The $\lambda$ parameter as a function of source size $R$ extracted from the $\pi^{\pm}K^0_S$ femtoscopy measurement in pp collisions at $\sqrt{s} = 13$ TeV. Results are compared with the previous ALICE measurements, obtained from $K^0_S K^0_S$ [6,7] and $\pi\pi$ [36] femtoscopy studies in pp and Pb–Pb collisions and the calculations from a toy geometric model (see text). The model calculations for the tetraquark and diquark hypotheses for the $K^*_0(700)$ are shown as black and light green dashed lines, respectively, the short dashed lines representing the Gaussian $\rho(r)$ and the long dashed lines representing the exponential $\rho(r)$.

eters measured in the other two experiments. It is seen that the present results have smaller uncertainties than the previous measurements. It is also seen that although the three $\Gamma_R$ values from the present work agree within uncertainties, the differences among the three $M_R$ values are outside of their uncertainties. This could be a consequence of using the Breit–Wigner function to fit a resonance where the condition $\Gamma_R \ll M_R$ is not fulfilled, which can lead to kinematic dependences on the extracted $M_R$ and $\Gamma_R$ [20,44]. However, these differences in $M_R$ are small compared with the extracted $M_R$ values, and thus it is judged that these results strongly support the assumption that the resonance responsible for the FSI of the $\pi^{\pm}K^0_S$ pairs studied in the present work is the $K^*_0(700)$ resonance.

The extracted $R$ and $\lambda$ parameters shown in Table 2 can be used to obtain information about the quark configuration of the $K^*_0(700)$. Fig. 4 compares the values of $R$ and $\lambda$ extracted in the present work with published results for these parameters from ALICE measurements in pp and Pb–Pb collisions in which $\pi\pi$ and $K^0_S K^0_S$ pairs were analyzed [4,6,7,36]. The $\pi^{\pm}K^0_S$ results are shown with separate statistical (error bars) and systematic (boxes) uncertainties, whereas for the previous results, the error bars represent the combination of the statistical and systematic uncertainties. For the $\pi\pi$ femtoscopic measurements in pp collisions at $\sqrt{s} = 7$ TeV reported in [36] with average $k_T$ values of $\sim 0.15$ and $\sim 0.35$ GeV/$c$, the $\lambda$ values are given as varying in the range $0.42 - 0.55$, so $\lambda$ is plotted as the center of this range with uncertainties extending to the upper and lower limits of the range.

For the $R$ parameter, the values from the present $\pi^{\pm}K^0_S$ analysis are comparable with the published $\pi\pi$ and $K^0_S K^0_S$ measurements in pp collisions, i.e. in the range 1–2 fm, as would be expected from pp collisions where the source size is $\sim 1$ fm. For the $\lambda$ parameter, whereas the results from $\pi\pi$ and $K^0_S K^0_S$ are compatible with values of about 0.5 or greater, for the present $\pi^{\pm}K^0_S$ analysis significantly lower values are obtained, ranging from about 0.05 to about 0.25 depending on $R$. The expectation is that $\lambda$ would be the same for $\pi^{\pm}K^0_S$ as for the identical-meson measurements. The $\lambda$ value of $\sim 0.5$ has been shown to be due to the presence of long-lived resonances whose decay into the detected mesons impacts the measurement of the "direct" mesons coming from the source of interest [7,45]. Another significant difference between the present $\pi^{\pm}K^0_S$ results and the $\pi\pi$ and $K^0_S K^0_S$ results is that $\lambda$ has a strong $R$ dependence for the former, whereas there is no significant dependence of $\lambda$ on $R$ for the latter, i.e. even extending $R$ to the value from Pb–Pb collisions shows no significant effect on $\lambda$.

As discussed in Refs. [7] and [9], a physics effect that could cause this difference in $\lambda$ values for $\pi^{\pm}K^0_S$ pairs is related to the possibility that the $K^*_0(700)$ resonance, that is assumed to be solely responsible for the FSI in the $\pi^{\pm}K^0_S$ pair, is actually a tetraquark state of the form $(q_1, \bar{q_2}, q_3, \bar{q_3})$, in which $q_1$, $q_2$ and $q_3$ indicate the flavor of the valence quarks of the $\pi$ and $K^0_S$. In particular, $q_1$ and $q_2$ can be a u or s quark, while $q_3$ is a d quark. For example, the quark content of a tetraquark $K^*_0(700)^+$ would be $u\bar{s}d\bar{d}$, whereas the diquark version would be $u\bar{s}$. The strength of the FSI through a tetraquark $K^*_0(700)^+$ could be decreased by the small source size of the $\pi^{\pm}K^0_S$ source, i.e. at $R \sim 1$ fm as is measured in these collisions. This could occur since $d-\bar{d}$ annihilation would be enhanced due to the proximity of the $\pi^{\pm}$ and $K^0_S$ at their creation, which would open up a non-resonant channel in the scattering process that would be reflected by reducing $\lambda$. For a FSI through a diquark $K^*_0(700)^+$, with the form $u\bar{s}$, the small source geometry should not reduce its strength. For the $K^0_S K^0_S$ and $\pi\pi$ cases, $\lambda$ should not be affected by the source size since the pair correlation is dominated by the effect of quantum statistics, for which in the ideal case $\lambda$ does not depend on $R$, and which is found to be much stronger than the strong FSI present for these identical particle pairs [2].

In order to demonstrate the $R$ dependence of $\lambda$ for a tetraquark or a diquark $K^*_0(700)$ based on the geometric considerations discussed above, a simple toy model is constructed, taking the form of the $\lambda$ factor for a tetraquark state,

$$\lambda = \lambda_0(1 - aP) \tag{11}$$

and for a diquark,

$$\lambda = \lambda_0 aP \tag{12}$$

where,

$$P \equiv \frac{\int \rho(r)\rho(|\vec{r} - \vec{R}|)dV}{\int |\rho(r)|^2 dV} \tag{13}$$

can be considered the "overlap probability" between the $\pi$ and $K^0_S$ in the pair as they are emitted from the pp collision. The quantity $\rho(r)$ is the meson volume distribution, assumed to be the same for the $\pi$ and $K^0_S$, $\lambda_0$ is the maximum value for $\lambda$, and $a$ is essentially the "$d-\bar{d}$ annihilation efficiency" that in principle could take any value in the range $0 - 1$. Assuming $\rho(r) \sim e^{-r^2/(2\sigma^2)}$ or $\sim e^{-r/r_0}$, $\lambda_0 = 0.6$, the average value for $\pi\pi$ and $K^0_S K^0_S$ measurements from Refs. [36] and [6,7], and assuming 100% $d-\bar{d}$ annihilation efficiency for any non-zero overlap, $a = 1$, the free parameters of the model, i.e. $\sigma$ and $r_0$, are adjusted to give a good fit to the $\pi^{\pm}K^0_S$ measurements. The results from Eqs. (11) and (12) are shown in Fig. 4, along with the results from $\pi^{\pm}K^0_S$ measurements of this work and

published ALICE measurements for $K^0_S K^0_S$ [6,7] and $\pi\pi$ pairs [36] from pp and Pb–Pb collisions. The free model parameters are set to $\sigma = 1.1$ fm and $r_0 = 0.85$ fm for the Gaussian (short dashed lines) and exponential (long dashed lines) distributions, respectively, which are considered reasonable values since hadronic sizes are expected to be $\sim 1$ fm. As seen, using reasonable model parameter values, the tetraquark case, Eq. (11), describes the $R$ dependence of $\lambda$ from the present measurements well for both the Gaussian and exponential meson shapes as being a geometric effect. The diquark case is seen to predict an $R$ dependence that is incompatible with the measured one.

Therefore, the present results of $\pi^{\pm}K^0_S$ femtoscopy in pp collisions at $\sqrt{s} = 13$ TeV suggest that the $K^*_0(700)$ is a tetraquark state.

## 7. Summary

Femtoscopic correlations with the particle pair combination $\pi^{\pm}K^0_S$ are studied in pp collisions at $\sqrt{s} = 13$ TeV for the first time by the ALICE experiment at the LHC. Source parameters and final-state interaction parameters are extracted by fitting a model based on a Gaussian distribution of the source to the experimental two-particle correlation functions. The model used assumes that solely the final-state interaction through a resonance determines the correlations, and is defined in terms of a mass and the coupling parameter to the decay into a $\pi^{\pm}K^0_S$ pair. The extracted mass and width parameters of the FSI are consistent with previous measurements of the $K^*_0(700)$ resonance, and the smaller value and increasing behavior of the $\lambda$ parameter with $R$ compared with identical boson measurements give support that the $K^*_0(700)$ is a four-quark state, i.e. a tetraquark state [19]. A simple geometric model that assumes a tetraquark FSI describes well the $R$ dependence of $\lambda$ extracted from the measured correlation functions.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

This manuscript has associated data in a HEPData repository at: https://www.hepdata.net/record/ins2739149.

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## References

[1] M.A. Lisa, S. Pratt, R. Soltz, U. Wiedemann, Femtoscopy in relativistic heavy ion collisions, Annu. Rev. Nucl. Part. Sci. 55 (2005) 357–402, arXiv:nucl-ex/0505014 [nucl-ex].

[2] STAR Collaboration, B.I. Abelev, et al., Neutral kaon interferometry in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, Phys. Rev. C 74 (2006) 054902, arXiv:nucl-ex/0608012 [nucl-ex].

[3] PHENIX Collaboration, A. Adare, et al., Systematic study of charged-pion and kaon femtoscopy in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, Phys. Rev. C 92 (2015) 034914, arXiv:1504.05168 [nucl-ex].

[4] ALICE Collaboration, B. Abelev, et al., $K^0_s - K^0_s$ correlations in pp collisions at $\sqrt{s} = 7$ TeV from the LHC ALICE experiment, Phys. Lett. B 717 (2012) 151–161, arXiv:1206.2056 [hep-ex].

[5] ALICE Collaboration, B. Abelev, et al., Charged kaon femtoscopic correlations in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Rev. D 87 (2013) 052016, arXiv:1212.5958 [hep-ex].

[6] ALICE Collaboration, J. Adam, et al., One-dimensional pion, kaon, and proton femtoscopy in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV, Phys. Rev. C 92 (2015) 054908, arXiv:1506.07884 [nucl-ex].

[7] ALICE Collaboration, S. Acharya, et al., $\rm K^0_s K^0_s$ and $\rm K^0_s K^\pm$ femtoscopy in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV, Phys. Lett. B 833 (2022) 137335, arXiv:2111.06611 [nucl-ex].

[8] L. Fabbietti, V. Mantovani Sarti, O. Vazquez Doce, Study of the strong interaction among hadrons with correlations at the LHC, Annu. Rev. Nucl. Part. Sci. 71 (2021) 377–402, arXiv:2012.09806 [nucl-ex].

[9] ALICE Collaboration, S. Acharya, et al., Measuring $\rm K^0_S K^\pm$ interactions using pp collisions at $\sqrt{s} = 7$ TeV, Phys. Lett. B 790 (2019) 22–34, arXiv:1809.07899 [nucl-ex].

[10] ALICE Collaboration, S. Acharya, et al., Measuring $\rm K^0_S K^\pm$ interactions using Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV, Phys. Lett. B 774 (2017) 64–77, arXiv:1705.04929 [nucl-ex].

[11] E. Santopinto, G. Galata, Spectroscopy of tetraquark states, Phys. Rev. C 75 (2007) 045206, arXiv:hep-ph/0605333 [hep-ph].

[12] R.L. Jaffe, Multi-quark hadrons. 1. The phenomenology of $\rm qq\overline{qq}$ mesons, Phys. Rev. D 15 (1977) 267.

[13] M.G. Alford, R.L. Jaffe, Insight into the scalar mesons from a lattice calculation, Nucl. Phys. B 578 (2000) 367–382, arXiv:hep-lat/0001023 [hep-lat].

[14] S. Narison, Light scalar mesons in QCD, Nucl. Phys. B, Proc. Suppl. 186 (2009) 306–311, arXiv:0811.0563 [hep-ph].

[15] N. Achasov, A. Kiselev, Light scalar mesons and two-kaon correlation functions, Phys. Rev. D 97 (2018) 036015, arXiv:1711.08777 [hep-ph].

[16] K. Azizi, B. Barsbay, H. Sundu, Light scalar $K_0^*(700)$ meson in vacuum and a hot medium, Phys. Rev. D 100 (2019) 094041, arXiv:1909.00716 [hep-ph].

[17] Hadron Spectrum Collaboration, J.J. Dudek, R.G. Edwards, D.J. Wilson, An $a_0$ resonance in strongly coupled $\pi\eta$, $K\overline{K}$ scattering from lattice QCD, Phys. Rev. D 93 (2016) 094506, arXiv:1602.05122 [hep-ph].

[18] R.A. Briceno, J.J. Dudek, R.G. Edwards, D.J. Wilson, Isoscalar $\pi\pi$ scattering and the $\sigma$ meson resonance from QCD, Phys. Rev. Lett. 118 (2017) 022002, arXiv:1607.05900 [hep-ph].

[19] F.-K. Guo, L. Liu, U.-G. Meissner, P. Wang, Tetraquarks, hadronic molecules, meson-meson scattering and disconnected contributions in lattice QCD, Phys. Rev. D 88 (2013) 074506, arXiv:1308.2545 [hep-lat].

[20] Particle Data Group Collaboration, R.L. Workman, et al., Review of particle physics, PTEP 2022 (2022), 083C01.

[21] T.J. Humanic, Feasibility of studying the $\rm K_0^*(700)$ resonance using $\rm \pi^\pm K^0_S$ femtoscopy, J. Phys. G 46 (2019) 055001, arXiv:1810.10959 [hep-ph].

[22] ALICE Collaboration, K. Aamodt, et al., The ALICE experiment at the CERN LHC, J. Instrum. 3 (2008) S08002.

[23] ALICE Collaboration, The ALICE experiment – a journey through QCD, arXiv e-prints, arXiv:2211.04384 [nucl-ex], Nov. 2022.

[24] ALICE Collaboration, B. Alessandro, et al., ALICE: physics performance report, volume II, J. Phys. G 32 (2006) 1295–2040.

[25] ALICE Collaboration, B. Abelev, et al., Centrality dependence of $\pi$, K, p production in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV, Phys. Rev. C 88 (2013) 044910, arXiv:1303.0737 [hep-ex].

[26] ALICE Collaboration, B. Abelev, et al., Centrality determination of Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV with ALICE, Phys. Rev. C 88 (2013) 044909, arXiv:1301.4361 [nucl-ex].

[27] ALICE Collaboration, S. Acharya, et al., Pseudorapidity distributions of charged particles as a function of mid- and forward rapidity multiplicities in pp collisions at $\sqrt{s} = 5.02$, 7 and 13 TeV, Eur. Phys. J. C 81 (2021) 630, arXiv:2009.09434 [nucl-ex].

[28] J. Alme, et al., The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events, Nucl. Instrum. Methods A 622 (2010) 316–367, arXiv:1001.1950 [physics.ins-det].

[29] ALICE Collaboration, B.B. Abelev, et al., Performance of the ALICE experiment at the CERN LHC, Int. J. Mod. Phys. A 29 (2014) 1430044, arXiv:1402.4476 [nucl-ex].

[30] ALICE Collaboration, S. Acharya, et al., Event-shape and multiplicity dependence of freeze-out radii in pp collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 09 (2019) 108, arXiv:1901.05518 [nucl-ex].

[31] A. Akindinov, et al., Performance of the ALICE time-of-flight detector at the LHC, Eur. Phys. J. Plus 128 (2013) 44.

[32] ALICE Collaboration, K. Aamodt, $\pi^0$ and $\eta$ reconstruction from photon conversions in ALICE for first pp collisions at the LHC, J. Phys. Conf. Ser. 270 (2011) 012035.

[33] T. Sjostrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026, arXiv:hep-ph/0603175.

[34] P. Skands, S. Carrazza, J. Rojo, Tuning PYTHIA 8.1: the Monash 2013 tune, Eur. Phys. J. C 74 (2014) 3024, arXiv:1404.5630 [hep-ph].

[35] R. Brun, F. Bruyant, F. Carminati, S. Giani, M. Maire, A. McPherson, G. Patrick, L. Urban, GEANT detector description and simulation tool, CERN-W5013 1 (1994) 1.

[36] ALICE Collaboration, K. Aamodt, et al., Femtoscopy of pp collisions at $\sqrt{s} = 0.9$ and 7 TeV at the LHC with two-pion Bose-Einstein correlations, Phys. Rev. D 84 (2011) 112004, arXiv:1101.3665 [hep-ex].

[37] ALICE Collaboration, S. Acharya, et al., Scattering studies with low-energy kaon-proton femtoscopy in proton-proton collisions at the LHC, Phys. Rev. Lett. 124 (2020) 092301, arXiv:1905.13470 [nucl-ex].

[38] ALICE Collaboration, S. Acharya, et al., Experimental evidence for an attractive p-$\phi$ interaction, Phys. Rev. Lett. 127 (2021) 172301, arXiv:2105.05578 [nucl-ex].

[39] R. Lednicky, V. Lyuboshits, Final state interaction effect on pairing correlations between particles with small relative momenta, Sov. J. Nucl. Phys. 35 (1982) 770.

[40] R. Lednicky, Correlation femtoscopy, Nucl. Phys. A 774 (2006) 189–198, arXiv:nucl-th/0510020 [nucl-th].

[41] BES Collaboration, M. Ablikim, et al., Observation of charged $\kappa$ in $J/\psi \to K^*(892)^\pm K_s \pi^\pm$, $K^*(892)^\pm \to K_s \pi^\pm$ at BESII, Phys. Lett. B 698 (2011) 183–190, arXiv:1008.4489 [hep-ex].

[42] E791 Collaboration, E.M. Aitala, et al., Dalitz plot analysis of the decay $D^+ \to K^-\pi^+\pi^+$ and the study of the $K\pi$ scalar amplitudes, Phys. Rev. Lett. 89 (2002) 121801, arXiv:hep-ex/0204018.

[43] W.T. Eadie, et al., Statistical Methods in Experimental Physics, North Holland, Amsterdam, 1971.

[44] A.R. Bohm, Y. Sato, Relativistic resonances: their masses, widths, lifetimes, superposition, and causal evolution, Phys. Rev. D 71 (2005) 085018, arXiv:hep-ph/0412106.

[45] T.J. Humanic, Hadronic observables from Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV and Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 5.5$ TeV from a simple kinematic model, Phys. Rev. C 79 (2009) 044902, arXiv:0810.0621 [nucl-th].


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S. Acharya [128], D. Adamová [87], G. Aglieri Rinella [33], L. Aglietta [25], M. Agnello [30], N. Agrawal [26], Z. Ahammed [136], S. Ahmad [16], S.U. Ahn [72], I. Ahuja [38], A. Akindinov [142], M. Al-Turany [98], D. Aleksandrov [142], B. Alessandro [57], H.M. Alfanda [6], R. Alfaro Molina [68], B. Ali [16], A. Alici [26], N. Alizadehvandchali [117], A. Alkin [33], J. Alme [21], G. Alocco [53], T. Alt [65], A.R. Altamura [51], I. Altsybeev [96], J.R. Alvarado [45], M.N. Anaam [6], C. Andrei [46], N. Andreou [116], A. Andronic [127], E. Andronov [142], V. Anguelov [95], F. Antinori [55], P. Antonioli [52], N. Apadula [75], L. Aphecetche [104], H. Appelshäuser [65], C. Arata [74], S. Arcelli [26], M. Aresti [23], R. Arnaldi [57], J.G.M.C.A. Arneiro [111], I.C. Arsene [20], M. Arslandok [139], A. Augustinus [33], R. Averbeck [98], M.D. Azmi [16], H. Baba [125], A. Badalà [54], J. Bae [105], Y.W. Baek [41], X. Bai [121], R. Bailhache [65], Y. Bailung [49], R. Bala [92], A. Balbino [30], A. Baldisseri [131], B. Balis [2], D. Banerjee [4], Z. Banoo [92], F. Barile [32], L. Barioglio [57], M. Barlou [79], B. Barman [42], G.G. Barnaföldi [47], L.S. Barnby [116], E. Barreau [104], V. Barret [128], L. Barreto [111], C. Bartels [120], K. Barth [33], E. Bartsch [65], N. Bastid [128], S. Basu [76], G. Batigne [104], D. Battistini [96], B. Batyunya [143], D. Bauri [48], J.L. Bazo Alba [102], I.G. Bearden [84], C. Beattie [139],

P. Becht [98], D. Behera [49], I. Belikov [130], A.D.C. Bell Hechavarria [127], F. Bellini [26], R. Bellwied [117], S. Belokurova [142], L.G.E. Beltran [110], Y.A.V. Beltran [45], G. Bencedi [47], A. Bensaoula [117], S. Beole [25], Y. Berdnikov [142], A. Berdnikova [95], L. Bergmann [95], M.G. Besoiu [64], L. Betev [33], P.P. Bhaduri [136], A. Bhasin [92], M.A. Bhat [4], B. Bhattacharjee [42], L. Bianchi [25], N. Bianchi [50], J. Bielčík [36], J. Bielčíková [87], A.P. Bigot [130], A. Bilandzic [96], G. Biro [47], S. Biswas [4], N. Bize [104], J.T. Blair [109], D. Blau [142], M.B. Blidaru [98], N. Bluhme [39], C. Blume [65], G. Boca [22,56], F. Bock [88], T. Bodova [21], S. Boi [23], J. Bok [17], L. Boldizsár [47], M. Bombara [38], P.M. Bond [33], G. Bonomi [135,56], H. Borel [131], A. Borissov [142], A.G. Borquez Carcamo [95], H. Bossi [139], E. Botta [25], Y.E.M. Bouziani [65], L. Bratrud [65], P. Braun-Munzinger [98], M. Bregant [111], M. Broz [36], G.E. Bruno [97,32], M.D. Buckland [24], D. Budnikov [142], H. Buesching [65], S. Bufalino [30], P. Buhler [103], N. Burmasov [142], Z. Buthelezi [69,124], A. Bylinkin [21], S.A. Bysiak [108], J.C. Cabanillas Noris [110], M.F.T. Cabrera [117], M. Cai [6], H. Caines [139], A. Caliva [29], E. Calvo Villar [102], J.M.M. Camacho [110], P. Camerini [24], F.D.M. Canedo [111], S.L. Cantway [139], M. Carabas [114], A.A. Carballo [33], F. Carnesecchi [33], R. Caron [129], L.A.D. Carvalho [111], J. Castillo Castellanos [131], F. Catalano [33,25], S. Cattaruzzi [24], C. Ceballos Sanchez [143], R. Cerri [25], I. Chakaberia [75], P. Chakraborty [137,48], S. Chandra [136], S. Chapeland [33], M. Chartier [120], S. Chattopadhyay [136], S. Chattopadhyay [100], T. Cheng [98,6], C. Cheshkov [129], V. Chibante Barroso [33], D.D. Chinellato [112], E.S. Chizzali [96,II], J. Cho [59], S. Cho [59], P. Chochula [33], D. Choudhury [42], P. Christakoglou [85], C.H. Christensen [84], P. Christiansen [76], T. Chujo [126], M. Ciacco [30], C. Cicalo [53], M.R. Ciupek [98], G. Clai [52,III], F. Colamaria [51], J.S. Colburn [101], D. Colella [97,32], M. Colocci [26], M. Concas [33], G. Conesa Balbastre [74], Z. Conesa del Valle [132], G. Contin [24], J.G. Contreras [36], M.L. Coquet [131], P. Cortese [134,57], M.R. Cosentino [113], F. Costa [33], S. Costanza [22,56], C. Cot [132], J. Crkovská [95], P. Crochet [128], R. Cruz-Torres [75], P. Cui [6], A. Dainese [55], M.C. Danisch [95], A. Danu [64], P. Das [81], P. Das [4], S. Das [4], A.R. Dash [127], S. Dash [48], A. De Caro [29], G. de Cataldo [51], J. de Cuveland [39], A. De Falco [23], D. De Gruttola [29], N. De Marco [57], C. De Martin [24], S. De Pasquale [29], R. Deb [135], R. Del Grande [96], L. Dello Stritto [33,29], W. Deng [6], P. Dhankher [19], D. Di Bari [32], A. Di Mauro [33], B. Diab [131], R.A. Diaz [143,7], T. Dietel [115], Y. Ding [6], J. Ditzel [65], R. Divià [33], D.U. Dixit [19], Ø. Djuvsland [21], U. Dmitrieva [142], A. Dobrin [64], B. Dönigus [65], J.M. Dubinski [137], A. Dubla [98], S. Dudi [91], P. Dupieux [128], M. Durkac [107], N. Dzalaiova [13], T.M. Eder [127], R.J. Ehlers [75], F. Eisenhut [65], R. Ejima [93], D. Elia [51], B. Erazmus [104], F. Ercolessi [26], B. Espagnon [132], G. Eulisse [33], D. Evans [101], S. Evdokimov [142], L. Fabbietti [96], M. Faggin [28], J. Faivre [74], F. Fan [6], W. Fan [75], A. Fantoni [50], M. Fasel [88], A. Feliciello [57], G. Feofilov [142], A. Fernández Téllez [45], L. Ferrandi [111], M.B. Ferrer [33], A. Ferrero [131], C. Ferrero [57,IV], A. Ferretti [25], V.J.G. Feuillard [95], V. Filova [36], D. Finogeev [142], F.M. Fionda [53], E. Flatland [33], F. Flor [117], A.N. Flores [109], S. Foertsch [69], I. Fokin [95], S. Fokin [142], E. Fragiacomo [58], E. Frajna [47], U. Fuchs [33], N. Funicello [29], C. Furget [74], A. Furs [142], T. Fusayasu [99], J.J. Gaardhøje [84], M. Gagliardi [25], A.M. Gago [102], T. Gahlaut [48], C.D. Galvan [110], D.R. Gangadharan [117], P. Ganoti [79], C. Garabatos [98], T. García Chávez [45], E. Garcia-Solis [9], C. Gargiulo [33], P. Gasik [98], A. Gautam [119], M.B. Gay Ducati [67], M. Germain [104], A. Ghimouz [126], C. Ghosh [136], M. Giacalone [52], G. Gioachin [30], P. Giubellino [98,57], P. Giubilato [28], A.M.C. Glaenzer [131], P. Glässel [95], E. Glimos [123], D.J.Q. Goh [77], V. Gonzalez [138], P. Gordeev [142], M. Gorgon [2], K. Goswami [49], S. Gotovac [34], V. Grabski [68], L.K. Graczykowski [137], E. Grecka [87], A. Grelli [60], C. Grigoras [33], V. Grigoriev [142], S. Grigoryan [143,1], F. Grosa [33], J.F. Grosse-Oetringhaus [33], R. Grosso [98], D. Grund [36], N.A. Grunwald [95], G.G. Guardiano [112], R. Guernane [74], M. Guilbaud [104],

K. Gulbrandsen [84], T. Gündem [65], T. Gunji [125], W. Guo [6], A. Gupta [92], R. Gupta [92], R. Gupta [49], K. Gwizdziel [137], L. Gyulai [47], C. Hadjidakis [132], F.U. Haider [92], S. Haidlova [36], M. Haldar [4], H. Hamagaki [77], A. Hamdi [75], Y. Han [140], B.G. Hanley [138], R. Hannigan [109], J. Hansen [76], J.W. Harris [139], A. Harton [9], M.V. Hartung [65], H. Hassan [118], D. Hatzifotiadou [52], P. Hauer [43], L.B. Havener [139], E. Hellbär [98], H. Helstrup [35], M. Hemmer [65], T. Herman [36], S.G. Hernandez [117], G. Herrera Corral [8], F. Herrmann [127], S. Herrmann [129], K.F. Hetland [35], B. Heybeck [65], H. Hillemanns [33], B. Hippolyte [130], F.W. Hoffmann [71], B. Hofman [60], G.H. Hong [140], M. Horst [96], A. Horzyk [2], Y. Hou [6], P. Hristov [33], P. Huhn [65], L.M. Huhta [118], T.J. Humanic [89], A. Hutson [117], D. Hutter [39], M.C. Hwang [19], R. Ilkaev [142], H. Ilyas [14], M. Inaba [126], G.M. Innocenti [33], M. Ippolitov [142], A. Isakov [85], T. Isidori [119], M.S. Islam [100], M. Ivanov [98], M. Ivanov [13], V. Ivanov [142], K.E. Iversen [76], M. Jablonski [2], B. Jacak [19,75], N. Jacazio [26], P.M. Jacobs [75], S. Jadlovska [107], J. Jadlovsky [107], S. Jaelani [83], C. Jahnke [111], M.J. Jakubowska [137], M.A. Janik [137], T. Janson [71], S. Ji [17], S. Jia [10], A.A.P. Jimenez [66], F. Jonas [75,88,127], D.M. Jones [120], J.M. Jowett [33,98], J. Jung [65], M. Jung [65], A. Junique [33], A. Jusko [101], J. Kaewjai [106], P. Kalinak [61], A.S. Kalteyer [98], A. Kalweit [33], A. Karasu Uysal [73,V], D. Karatovic [90], O. Karavichev [142], T. Karavicheva [142], P. Karczmarczyk [137], E. Karpechev [142], M.J. Karwowska [33,137], U. Kebschull [71], R. Keidel [141], D.L.D. Keijdener [60], M. Keil [33], B. Ketzer [43], S.S. Khade [49], A.M. Khan [121], S. Khan [16], A. Khanzadeev [142], Y. Kharlov [142], A. Khatun [119], A. Khuntia [36], Z. Khuranova [65], B. Kileng [35], B. Kim [105], C. Kim [17], D.J. Kim [118], E.J. Kim [70], J. Kim [140], J. Kim [59], J. Kim [70], M. Kim [19], S. Kim [18], T. Kim [140], K. Kimura [93], A. Kirkova [37], S. Kirsch [65], I. Kisel [39], S. Kiselev [142], A. Kisiel [137], J.P. Kitowski [2], J.L. Klay [5], J. Klein [33], S. Klein [75], C. Klein-Bösing [127], M. Kleiner [65], T. Klemenz [96], A. Kluge [33], C. Kobdaj [106], T. Kollegger [98], A. Kondratyev [143], N. Kondratyeva [142], J. Konig [65], S.A. Konigstorfer [96], P.J. Konopka [33], G. Kornakov [137], M. Korwieser [96], S.D. Koryciak [2], A. Kotliarov [87], N. Kovacic [90], V. Kovalenko [142], M. Kowalski [108], V. Kozhuharov [37], I. Králik [61], A. Kravčáková [38], L. Krcal [33,39], M. Krivda [101,61], F. Krizek [87], K. Krizkova Gajdosova [33], M. Kroesen [95], M. Krüger [65], D.M. Krupova [36], E. Kryshen [142], V. Kučera [59], C. Kuhn [130], P.G. Kuijer [85], T. Kumaoka [126], D. Kumar [136], L. Kumar [91], N. Kumar [91], S. Kumar [32], S. Kundu [33], P. Kurashvili [80], A. Kurepin [142], A.B. Kurepin [142], A. Kuryakin [142], S. Kushpil [87], V. Kuskov [142], M. Kutyla [137], M.J. Kweon [59], Y. Kwon [140], S.L. La Pointe [39], P. La Rocca [27], A. Lakrathok [106], M. Lamanna [33], A.R. Landou [74], R. Langoy [122], P. Larionov [33], E. Laudi [33], L. Lautner [33,96], R. Lavicka [103], R. Lea [135,56], H. Lee [105], I. Legrand [46], G. Legras [127], J. Lehrbach [39], T.M. Lelek [2], R.C. Lemmon [86], I. León Monzón [110], M.M. Lesch [96], E.D. Lesser [19], P. Lévai [47], X. Li [10], B.E. Liang-gilman [19], J. Lien [122], R. Lietava [101], I. Likmeta [117], B. Lim [25], S.H. Lim [17], V. Lindenstruth [39], A. Lindner [46], C. Lippmann [98], D.H. Liu [6], J. Liu [120], G.S.S. Liveraro [112], I.M. Lofnes [21], C. Loizides [88], S. Lokos [108], J. Lömker [60], P. Loncar [34], X. Lopez [128], E. López Torres [7], P. Lu [98,121], F.V. Lugo [68], J.R. Luhder [127], M. Lunardon [28], G. Luparello [58], Y.G. Ma [40], M. Mager [33], A. Maire [130], E.M. Majerz [2], M.V. Makariev [37], M. Malaev [142], G. Malfattore [26], N.M. Malik [92], Q.W. Malik [20], S.K. Malik [92], L. Malinina [143,I,VIII], D. Mallick [132], N. Mallick [49], G. Mandaglio [31,54], S.K. Mandal [80], V. Manko [142], F. Manso [128], V. Manzari [51], Y. Mao [6], R.W. Marcjan [2], G.V. Margagliotti [24], A. Margotti [52], A. Marín [98], C. Markert [109], P. Martinengo [33], M.I. Martínez [45], G. Martínez García [104], M.P.P. Martins [111], S. Masciocchi [98], M. Masera [25], A. Masoni [53], L. Massacrier [132], O. Massen [60], A. Mastroserio [133,51], O. Matonoha [76], S. Mattiazzo [28], A. Matyja [108], C. Mayer [108],

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