



# Investigating the role of strangeness in baryon–antibaryon annihilation at the LHC



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## ABSTRACT

Annihilation dynamics plays a fundamental role in the baryon–antibaryon interaction ( $B\text{--}\bar{B}$ ) at low-energy and its strength and range are crucial in the assessment of possible baryonic bound states. Experimental data on annihilation cross sections are available for the  $p\text{--}\bar{p}$  system but not in the low relative momentum region. Data regarding the  $B\text{--}\bar{B}$  interaction with strange degrees of freedom are extremely scarce, hence the modeling of the annihilation contributions is mainly based on nucleon–antinucleon ( $N\text{--}\bar{N}$ ) results, when available. In this letter we present a measurement of the  $p\text{--}\bar{p}$ ,  $p\text{--}\bar{\Lambda}\oplus\bar{p}\text{--}\Lambda$  and  $\Lambda\text{--}\bar{\Lambda}$  interaction using correlation functions in the relative momentum space in high-multiplicity triggered  $pp$  collisions at  $\sqrt{s} = 13$  TeV recorded by ALICE at the LHC. In the  $p\text{--}\bar{p}$  system the couplings to the mesonic channels in different partial waves are extracted by adopting a coupled-channel approach with recent  $\chi$ EFT potentials. The inclusion of these inelastic channels provides good agreement with the data, showing a significant presence of the annihilation term down to zero momentum. Predictions obtained using the Lednický–Lyuboshits formula and scattering parameters obtained from heavy-ion collisions, hence mainly sensitive to elastic processes, are compared with the experimental  $p\text{--}\bar{\Lambda}\oplus\bar{p}\text{--}\Lambda$  and  $\Lambda\text{--}\bar{\Lambda}$  correlations. The model describes the  $\Lambda\text{--}\bar{\Lambda}$  data and underestimates the  $p\text{--}\bar{\Lambda}\oplus\bar{p}\text{--}\Lambda$  data in the region of momenta below 200 MeV/c. The observed deviation indicates a different contribution of annihilation channels to the two systems containing strange hadrons.

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## 1. Introduction and physics motivation

The baryon–antibaryon interaction ( $B\text{--}\bar{B}$ ) is dominated at low energies by annihilation processes, in which transitions from a state, typically composed of only mesons, to a  $B\text{--}\bar{B}$  state and vice versa are occurring. Since the first measurement of the proton–antiproton ( $p\text{--}\bar{p}$ ) cross section [1], a rich sample of experimental data has become available, mainly in the nucleon–antinucleon ( $N\text{--}\bar{N}$ ) sector. Low-energy scattering experiments [2–4] delivered data on the total cross section, on the elastic ( $p\bar{p} \rightarrow p\bar{p}$ ) and charge-exchange ( $p\bar{p} \rightarrow n\bar{n}$ ) cross sections, down to laboratory momenta  $p_{\text{lab}} \approx 200$  MeV/c. Measurements of the annihilation cross section reach even lower momenta but are affected by significant uncertainties and in particular the momentum region close to the  $p\text{--}\bar{p}$  threshold is currently lacking any experimental constraint. This region is however of particular interest for the theoretical modeling of  $p\text{--}\bar{p}$  interaction since the interplay between the Coulomb and the annihilation dynamics is dominant.

At threshold, measurements of the energy level shifts and widths of  $p\text{--}\bar{p}$  atoms [5] enabled the extraction of the spin-averaged scattering parameters, confirming a non-zero imaginary part of the

scattering length related to the presence of inelastic channels due to the annihilation processes.

Great effort was made in the theoretical description of the short-range interaction (below 1 fm) of  $p\text{--}\bar{p}$  systems since a stronger elastic attraction, with respect to the  $p\text{--}p$  case, is expected to occur in some spin-isospin channels, leading to predictions of the existence of bound states (baryonia) [5,6]. Findings of broad resonances and enhancements in the  $p\text{--}\bar{p}$  invariant mass [7–10] measured in the decays of charmed and bottom mesons were reported but no clear evidence of such bound states has been found yet. A precise understanding of the annihilation dynamics is required to assess the existence of such states since the bound spectrum could be washed out by the  $B\text{--}\bar{B}$  annihilation part of the interaction. The annihilation term in the  $N\text{--}\bar{N}$  sector is typically described in chiral-effective potentials [11], meson-exchange [12–14] and quark models [15] by means of phenomenological optical potentials and contact interactions with parameters to be fixed from the available data. The search for baryonia states for  $B\text{--}\bar{B}$  systems in the strangeness sector with hyperons ( $Y$ ) and antihyperons ( $\bar{Y}$ ), e.g.  $N\text{--}\bar{Y}$ ,  $Y\text{--}\bar{Y}$  is even more challenging since the experimental informations are very scarce, with  $p\bar{p} \rightarrow \Lambda\bar{\Lambda}$  being the only measured strangeness exchange process [5]. Consequently, the modeling of the annihilation for systems as  $Y\text{--}\bar{Y}$  (e.g.  $\Lambda\text{--}\bar{\Lambda}$ ) is mainly based on the  $N\text{--}\bar{N}$  interaction [16–19]. Measurements of the  $p\text{--}\bar{\Lambda}$  invari-

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ant mass spectra in photoproduction processes  $\gamma p \rightarrow \Lambda \bar{\Lambda} p$  will become available in the next years [20], but currently no experimental informations neither theoretical predictions are present for B- $\bar{B}$  interactions involving a nucleon (antinucleon) and an antihyperon (hyperon) such as p- $\bar{\Lambda}$ .

The study of annihilation in B- $\bar{B}$  systems with strangeness is also of great interest for the modeling of the re-scattering phase in heavy-ion collisions (HIC). Several observables as particle spectra and yields strongly depend on the processes occurring at this stage of the HIC evolution, the B- $\bar{B}$  annihilation processes above all. Currently in HIC, the annihilation interaction for pairs containing strangeness is either modeled assuming scattering parameters similar to p- $\bar{p}$  or with an ad-hoc suppression of the cross section with respect to the p- $\bar{p}$  counterpart [21,22].

The present theoretical understanding of the B- $\bar{B}$  interaction requires additional precise data particularly in the low-momentum region, where the inelastic contributions from annihilation are relevant. This would shed light on the presence of baryonia bound states and on how the annihilation dynamics changes for systems with strangeness.

A step in this direction has recently been achieved with the measurements of two-particle correlations in the momentum space for p- $\bar{p}$ , p- $\bar{\Lambda}$  and  $\Lambda$ - $\bar{\Lambda}$  pairs performed in ultra-relativistic Pb-Pb collisions at LHC [23]. The extracted spin-averaged scattering parameters are in agreement for all B- $\bar{B}$  pairs indicating that the annihilation part for all B- $\bar{B}$  pairs is similar at the same relative momentum. The p- $\bar{\Lambda}$  pairs were also measured in Au-Au collisions at RHIC [24], but these results might be biased by the neglected residual correlations [21]. Measurements of hadron-hadron correlations have been performed in small colliding systems such as pp and p-Pb, and they delivered the most precise data on baryon-baryon and meson-baryon pairs, enabling access to the short-range strong interaction [25–31]. This kind of measurements in pp collisions can probe inter-particle distances of around 1 fm and are sensitive to the presence of inelastic channels, below and above threshold [27,32,33].

In this letter we present the measurements of the correlation functions of p- $\bar{p}$ , p- $\bar{\Lambda} \oplus \bar{p} - \Lambda$  and  $\Lambda$ - $\bar{\Lambda}$  pairs in pp collisions at  $\sqrt{s} = 13$  TeV with the ALICE detector [34,35]. To better constrain the interaction, a differential analysis in pair-transverse-mass ( $m_T$ ) intervals has been performed for the p- $\bar{\Lambda} \oplus \bar{p} - \Lambda$  and  $\Lambda$ - $\bar{\Lambda}$  pairs. The work presented in this Letter delivers the most precise data at low momenta for p- $\bar{p}$ , p- $\bar{\Lambda}$  and  $\Lambda$ - $\bar{\Lambda}$  systems and provides additional experimental constraints for the modeling of the B- $\bar{B}$  interaction.

## 2. Data analysis

The main ALICE subdetectors [34,35] used in this analysis are: the V0 detectors [36] used as trigger detectors, the Inner Tracking System (ITS) [37], the Time Projection Chamber (TPC) [38] and the Time-of-Flight (TOF) detector [39]. The last three are used to track and identify charged particles. The high-multiplicity (HM) sample used in this analysis corresponds to 0.17% of all inelastic pp collisions with at least one measured charged particle within  $|\eta| < 1$  (referred to as INEL>0) [29,30]. The corresponding HM trigger is defined by coincident hits in both V0 detectors synchronous with the collider bunch crossing and by requiring as well that the sum of the measured signal amplitudes in the V0 exceeds a multiple of the average value in minimum bias collisions. The rejection of pile-up events have been applied by evaluating the presence of additional event vertices as done in [29,31] and a total of  $1.0 \times 10^9$  HM events are selected.

Protons and antiprotons are reconstructed using the procedure described in Refs. [29,31]. Primary protons and antiprotons are selected in the transverse momentum range  $0.5 < p_T < 4.05$  GeV/c

and pseudorapidity  $|\eta| < 0.8$ . A minimum of 80 out of the 159 available spatial points (hits) inside the TPC are required to obtain high-quality tracks. The TPC and TOF detectors select p ( $\bar{p}$ ) candidates by the deviation  $n_\sigma$  between the signal hypothesis for the considered particle and the experimental measurement, normalized by the detector resolution  $\sigma$  [29,31]. For candidates with  $p < 0.75$  GeV/c, the particle identification (PID) is performed with the TPC only. For larger momenta, the PID information of TPC and TOF are combined. The candidates are accepted if their  $|n_\sigma| < 3$ . To reject non-primary protons (antiprotons), the distance of closest approach (DCA) of the candidates tracks to the primary vertex is required to be less than 0.1 cm in the  $xy$ -plane and less than 0.2 cm along the beam axis. Contributions of secondary (anti)protons stemming from weak decays and misidentified candidates are extracted using Monte Carlo (MC) template fits to the measured distance of closest approach (DCA) distributions of the to the primary vertex [25]. The resulting p ( $\bar{p}$ ) purity is 99.4% (98.9%). The corresponding fraction of primary particles is 82.2% (82.3%). The reconstruction of the  $\Lambda$  ( $\bar{\Lambda}$ ) candidates, via their weak decay  $\Lambda \rightarrow p\pi^-$  ( $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ ) [40], is performed following the procedures described in Refs. [29,31]. A final selection is applied based on the reconstructed invariant mass [29,31]. The obtained  $\Lambda$  ( $\bar{\Lambda}$ ) purity is 95.2% (96.1%). Primary and secondary contributions for  $\Lambda$  and  $\bar{\Lambda}$  are extracted in a similar way as for protons, via fits to the cosine of the pointing angle distributions using MC templates. The fraction of primary  $\Lambda$  ( $\bar{\Lambda}$ ) hyperons is about 57%. Secondary contributions from weak decays of neutral and charged  $\Xi$  baryons amount to 22%. The remaining fractions are attributed to  $\Sigma^0$  ( $\bar{\Sigma}^0$ ) particles. Systematic uncertainties on the data are evaluated by varying the kinematic and topological selection criteria following [29,31].

## 3. Analysis of the correlation function

The main observable in the analysis presented here is the two-particle correlation function  $C(k^*)$ , which depends on the relative momentum  $k^*$  evaluated in the pair rest frame [25]. In femtoscopy measurements, the final state is fixed to the measured particle pair and the corresponding correlation function is sensitive to all the available initial, elastic and inelastic, channels produced in the collision [32,33]. For the study of the B- $\bar{B}$  interaction, the single-channel Koonin-Pratt equation [41] has to be modified in order to accommodate the inelastic contributions stemming from the annihilation channels [32,33].

Assuming that the interaction of the pair in the final state  $i$  is affected by the inelastic channels  $j$ , the Koonin-Pratt formula is modified by the introduction of an additive term related to the processes  $j \rightarrow i$  [32,33,42]:

$$C_i(k^*) = \int d^3r^* S(r^*) |\psi_i(k^*, r^*)|^2 + \sum_{j \neq i}^N \omega_j \int d^3r^* S(r^*) |\psi_j(k^*, r^*)|^2. \quad (1)$$

The first integral on the right-hand side describes the elastic contribution where initial and final state coincide, while the second integral is responsible for the remaining inelastic processes  $j \rightarrow i$ . This last integral depends on two main ingredients: the wave function  $\psi_j(k^*, r^*)$  for channel  $j$  going to the final state  $i$  and the conversion weights  $\omega_j$ . These latter quantities can be written as  $\omega_j = \omega_j^s \times \omega_j^{\text{prod}}$ , in which  $\omega_j^{\text{prod}}$  is related to the amount of  $j$  pairs produced in the initial collision and kinematically available to be converted to the final measured state. Quantitative estimates on these production weights can be obtained combining thermal model calculations of particle yields [43] with kinematics constraints from transport models [44]. If the assumed inelastic

wave function  $\psi_j(k^*, r^*)$  is properly accounting for the coupling strength, the corresponding  $\omega_j^s$  weight is equal to unity.

Recent femtoscopic measurements by the ALICE Collaboration performed on  $K^-$ - $p$  pairs in pp [27] and in Pb-Pb collisions [45] showed that by changing the colliding system, and hence the size of the emitting source  $S(r^*)$ , the effects on the  $C(k^*)$  due to the inelastic contributions given by the last term in Eq. (1) are enhanced or suppressed. The wave functions  $\psi_j(k^*, r^*)$  related to the inelastic channels are localized at distances  $r^*$  approximately below 1.5-2 fm and equal to zero above. Hence, performing femtoscopic measurements with a large emitting source, as it occurs in central heavy-ion collisions ( $r^*$  above 5 fm), results in a correlation function mainly dominated by the elastic contribution, given by the first term of Eq. (1). For this reason, the  $C(k^*)$  measured in Pb-Pb can be modeled with the single-channel Lednický-Lyuboshits formula [42] assuming a complex scattering length  $f_0$ , in which the imaginary part  $\mathcal{I}f_0$  accounts for an average inelastic contribution from all  $j$  channels.

These inelastic contributions become more relevant when performing the same measurement in small colliding systems as pp, where the emitting source size is of the order of 1 fm [46] and the modeling of the  $C(k^*)$  requires the knowledge of the exact elastic  $\psi_i(k^*, r^*)$  and inelastic  $\psi_j(k^*, r^*)$  wave functions obtained from the solution of a coupled-channel approach [46]. If the theoretical modeling of the interaction properly accounts for the inelastic channels ( $\omega_j^s = 1$ ), the use of the modified Koonin-Pratt formula in Eq. (1) with a proper estimate of the production weights  $\omega_j^{\text{prod}}$  will describe the data in both small and large colliding systems as shown in [45] for the  $K^-$ - $p$  system. The use of the single-channel Lednický-Lyuboshits model will only be applicable if the wave functions  $\psi_j(k^*, r^*)$  would be strongly suppressed, corresponding to a very weak coupling to the inelastic channels.

The  $B$ - $\bar{B}$  interaction investigated in this work is less known with respect to the  $K^-$ - $p$  case in [27,45], hence two different approaches have been used to calculate the theoretical correlation for the  $p$ - $\bar{p}$  and the  $\Lambda$ - $\bar{\Lambda}$ ,  $p$ - $\bar{\Lambda}$  pairs, respectively. For both approaches the CATS framework is used [47].

The genuine  $p$ - $\bar{p}$  correlation is modeled either by assuming a Coulomb-only interaction or by also including a strong interaction from  $N$ - $\bar{N}$  chiral effective ( $\chi$ EFT) potentials at next-to-next-to-next-to-leading order ( $N^3$ LO) [11]. The  $p$ - $\bar{p}$  wave functions, available for  $S$  ( $^1S_0, ^3S_1$ ) and  $P$  ( $^1P_1, ^3P_0, ^3P_1, ^3P_2$ ) partial-waves (PW), have been evaluated within a coupled-channel formalism in which only the coupling to the charge-exchange  $n$ - $\bar{n}$  channel is explicitly included. The formula in Eq. (1) is used for the genuine  $p$ - $\bar{p}$  correlation function with the chiral wave functions for the elastic  $i = p$ - $\bar{p}$  and the charge-exchange channel  $j = n$ - $\bar{n}$  [11]. The wave functions  $\psi_{X \rightarrow p\bar{p}}^{\text{PW}}$ , accounting for the multi-meson annihilation channels  $j = X$ , are not currently available. The annihilation contribution is implicitly present in the  $\chi$ EFT potentials in [11] since the parameters of the model are constrained to the most-recent partial-wave analysis on the available  $p$ - $\bar{p}$  and  $N$ - $\bar{N}$  cross sections [4].

The Migdal-Watson approximation [48] is used as an approximate way to explicitly include the additional  $j = X$  annihilation channels. This approximation relies on the fact that these  $X$  multi-meson channels open below the  $p$ - $\bar{p}$  threshold and hence the momentum dependence of the annihilation potential  $V_{X \rightarrow p\bar{p}}$  around the  $p$ - $\bar{p}$  threshold can be neglected. The wave functions  $\psi_{X \rightarrow p\bar{p}}^{\text{PW}}$  for each PW can be rewritten in terms of the elastic component as  $\omega_{\text{PW}} \psi_{p\bar{p} \rightarrow p\bar{p}}^{\text{PW}}$ , with the weights  $\omega_{\text{PW}}$  to be determined from data. These latter weights are directly connected to the conversion weights  $\omega_j$  in Eq. (1) with the strong coupling term  $\omega_j^s$  extended to the different PW states. A detailed estimate of the yields and kinematics of the annihilation channels ( $\omega_j^{\text{prod}}$ ), necessary to iso-

late the strong coupling term in each PW, is not trivial since it involves contributions stemming from multi-pions channels and it should include also intermediate states of resonances strongly decaying into pions. For this reason, the extracted weights  $\omega_{\text{PW}}$  in this work contain informations not only on the coupling strength of the mesonic channels to  $p$ - $\bar{p}$ , but also on the abundances of the contributing multi-meson channels produced in the initial state. The modeled correlation function reads [33]:

$$\begin{aligned} C_{p\bar{p}}(k^*) &= \int S(r^*) |\psi_{p\bar{p} \rightarrow p\bar{p}}|^2 d^3 r^* + \int S(r^*) |\psi_{n\bar{n} \rightarrow p\bar{p}}|^2 d^3 r^* \\ &+ \sum_{\text{PW}} \rho_{\text{PW}} \omega_{\text{PW}} \int S(r^*) |\psi_{p\bar{p} \rightarrow p\bar{p}}^{\text{PW}}|^2 d^3 r^* \\ &= C_{p\bar{p} \rightarrow p\bar{p}}(k^*) + C_{n\bar{n} \rightarrow p\bar{p}}(k^*) + \sum_{\text{PW}} C_{X \rightarrow p\bar{p}}^{\text{PW}}(k^*). \end{aligned} \quad (2)$$

The first and second terms describe the elastic and  $n$ - $\bar{n}$  contributions, while the last term accounts for the annihilation channels. The degeneracy in spin and angular momentum is embedded in the statistical factors  $\rho_{\text{PW}}$ . To reduce the number of  $\omega_{\text{PW}}$  weights to be fitted, a study on the shape of the single inelastic correlation terms  $C_{X \rightarrow p\bar{p}}^{\text{PW}}(k^*)$  is performed in each partial wave. The correlations with a different profile in  $k^*$  are selected, allowing to determine three representative contributions: the  $^1S_0$  for  $S$  states, the  $^1P_1$  and  $^3P_0$  for  $P$  states.

For the two systems containing strangeness,  $p$ - $\bar{\Lambda}$  and  $\Lambda$ - $\bar{\Lambda}$ , no theoretical wave functions are currently available, hence the single-channel Lednický-Lyuboshits analytical formula with a complex scattering length  $f_0$  is used to evaluate the theoretical correlations [23,42]. As mentioned above, in this single-channel approach, only the elastic contributions are explicitly accounted for in the  $\mathcal{R}f_0$ , corresponding to the first term in Eq. (1). The imaginary part  $\mathcal{I}f_0$  accounts for an average over all the inelastic contributions of the  $B$ - $\bar{B}$  interaction, mainly dominated by annihilation. The same approach has been used in the ALICE femtoscopic measurements in Pb-Pb collisions [23], which delivered the only available scattering parameters on both the  $p$ - $\bar{\Lambda}$  and  $\Lambda$ - $\bar{\Lambda}$  interaction. For the latter, theoretical predictions are available [16], providing values for the scattering parameters compatible with the ALICE Pb-Pb results [23].

The emitting source in Eq. (1) can be determined as a function of the pair-transverse-mass  $m_T$  with a data-driven model based on proton-proton correlations [31]. This allows us to investigate the interaction for different particle pairs. The properties of the underlying interaction in  $p$ - $\bar{\Lambda}$  and  $\Lambda$ - $\bar{\Lambda}$  systems do not depend on  $m_T$  and can hence be better constrained using a  $m_T$  differential analysis. Considering the available sample, 6 and 3  $m_T$  intervals are used for the  $p$ - $\bar{\Lambda}$  and  $\Lambda$ - $\bar{\Lambda}$  measured correlations, respectively. These experimental correlations are compared, in each  $m_T$  interval, to the Lednický-Lyuboshits model by assuming at first the scattering parameters obtained in the Pb-Pb analysis [23]. Secondly, a simultaneous fit for each pair in all the available  $m_T$  bins is performed leaving the  $\mathcal{I}f_0$  to vary in order to test if a better agreement with the data is achieved. Further discussions on the two different fitting procedures can be found in the next section.

Experimentally, the correlation function is defined as

$$C(k^*) = \mathcal{N} \frac{N_{\text{SE}}(k^*)}{N_{\text{ME}}(k^*)} \xrightarrow{k^* \rightarrow \infty} 1. \quad (3)$$

Here  $N_{\text{SE}}(k^*)$  is the distribution of pairs measured in the same event,  $N_{\text{ME}}(k^*)$  is the reference distribution of uncorrelated pairs sampled from different (mixed) events and  $\mathcal{N}$  is a normalization parameter determined by requiring that particle pairs with large  $k^*$  are not correlated. The mixed-event sample is obtained by pairing

particles stemming from events with a similar number of charged particles at midrapidity and a close-by primary vertex position along the beam direction as done in [27,29,30]. The correlation functions of baryon–antibaryon and antibaryon–baryon pairs are combined to enhance the statistical significance for the  $p-\bar{\Lambda}$  pairs, hence in the following  $p-\bar{\Lambda}$  denotes the sum  $p-\bar{\Lambda} \oplus \bar{p}-\Lambda$ . The  $p-\bar{p}$ ,  $p-\bar{\Lambda}$  and  $\Lambda-\bar{\Lambda}$  data are fitted with a total correlation function

$$C_{\text{tot}}(k^*) = N_D \times C_{\text{model}}(k^*) \times C_{\text{background}}(k^*), \quad (4)$$

where  $N_D$  is a normalization constant fitted to data. The default fit range is  $0 < k^* < 500$  MeV/c. The modeled  $C_{\text{model}}(k^*) = 1 + \sum_i \lambda_i \times (C_i(k^*) - 1)$  includes the genuine ( $i = p-\bar{p}, p-\bar{\Lambda}, \Lambda-\bar{\Lambda}$ ) correlation, estimated from Eq. (2) and using the Lednický–Lyuboshits model, and the residual secondary contributions weighted by the  $\lambda_i$  parameters [25]. The genuine contributions for  $p-\bar{p}$ ,  $p-\bar{\Lambda}$  and  $\Lambda-\bar{\Lambda}$  amount to  $\lambda_{p-\bar{p}} = 66.5\%$ ,  $\lambda_{p-\bar{\Lambda}} = 45.8\%$  and  $\lambda_{\Lambda-\bar{\Lambda}} = 30.9\%$ , respectively. Residual contributions involving pairs measured in this work are modeled assuming the corresponding theoretical predictions mentioned above. Contributions involving  $\Sigma^{\pm,0}$  ( $\bar{\Sigma}^{\pm,0}$ ) and  $\Xi^{-,0}$  ( $\bar{\Xi}^{-,0}$ ) are considered to be constant in  $k^*$  due to the limited theoretical knowledge, and amount to 10.1%, 44.6% and 65.7% for  $p-\bar{p}$ ,  $p-\bar{\Lambda}$  and  $\Lambda-\bar{\Lambda}$ , respectively. A crosscheck on these residuals by assuming a strong interaction based on the scattering parameters extracted in Pb–Pb measurements [23] was performed and differences in the extracted results with respect to the constant assumption are found to be negligible.

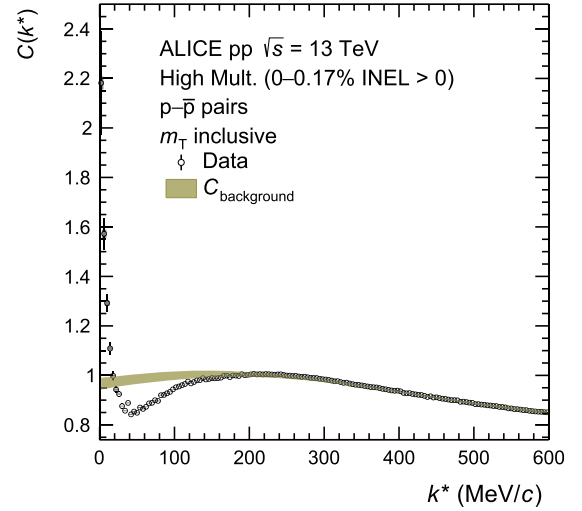
A variation of  $\pm 10\%$  to the upper limit of the default fit range is applied for evaluating the systematic uncertainties. Additionally, the systematic uncertainties related to the  $\lambda_i$  parameters are evaluated based on variations of the amount of secondary contributions to each measured particle species, where the largest source of uncertainty stems from the ratio  $\Sigma^0 : \Lambda = 0.33 \pm 0.07$  [31,43,49–51]. In addition to the feed-down contributions, a correction for finite experimental momentum resolution has to be taken into account for a direct comparison with data [25].

The size of the emitting source employed in the calculation of  $C_{\text{model}}(k^*)$  for the three B– $\bar{B}$  pairs is fixed from the data-driven analysis of p–p pairs, which demonstrates the existence of a common Gaussian core as a function of  $m_T$  for all baryon–baryon pairs when contributions from short-lived strongly decaying resonances are properly included [31]. For the  $p-\bar{p}$  pairs, the core source size at the corresponding  $\langle m_T \rangle = 1.45$  GeV/c<sup>2</sup> is  $r_{\text{core}} = 1.06 \pm 0.04$  fm and the associated effective Gaussian source size is  $r_0 = 1.22$  fm. The core radii for the  $p-\bar{\Lambda}$  and  $\Lambda-\bar{\Lambda}$   $m_T$  bins presented in this letter are  $r_{\text{core}}(\langle m_T \rangle = 1.75$  GeV/c<sup>2</sup>) =  $0.95 \pm 0.04$  fm ( $r_0 = 1.15$  fm) and  $r_{\text{core}}(\langle m_T \rangle = 2.12$  GeV/c<sup>2</sup>) =  $0.87 \pm 0.04$  fm ( $r_0 = 1.11$  fm), respectively.

The second term in Eq. (4),  $C_{\text{background}}(k^*)$ , accounts for non-femtoscopic effects due to energy-momentum conservation at large  $k^*$  [25] and to minijet phenomena arising from hard processes at the parton level, largely present in the measurement of B– $\bar{B}$  correlations:

$$\begin{aligned} C_{\text{background}}(k^*) &= C_{\text{minijet}}(k^*) + C_{\text{baseline}}(k^*) \\ &= [w_C C_C(k^*) + (1 - w_C) C_{NC}(k^*)] + (a + bk^*). \end{aligned} \quad (5)$$

A data-driven approach is employed using PYTHIA 8.2 [52] to model the mini-jet part contained in  $C_{\text{background}}(k^*)$ . The particle production in such simulations is associated to two processes: particles stemming from a common parton (common ancestors), leading to the minijet component, and particles coming from different partons (non-common ancestors), responsible for the non-jet part. The  $C_{\text{minijet}}(k^*)$  in Eq. (5) is given by a linear combination

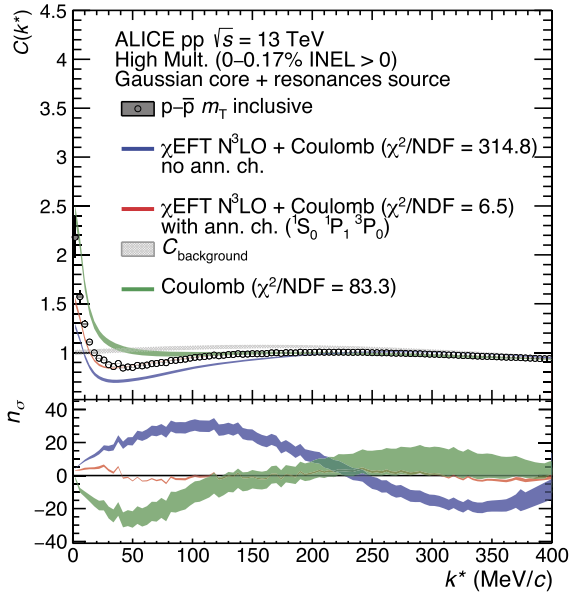


**Fig. 1.** Measured  $p-\bar{p}$  correlation function (empty points) with statistical (line) and systematic (grey boxes) uncertainties. The band represents the  $C_{\text{background}}(k^*)$  fit as described in the text.

of the common ( $C_C(k^*)$ ) and non-common ( $C_{NC}(k^*)$ ) contributions weighted by a factor  $w_C$  and  $(1 - w_C)$ , respectively. The ancestor weight  $w_C$  is a free parameter in the fit of  $C_{\text{tot}}(k^*)$  to the data. The common and non-common correlations obtained from PYTHIA 8.2 are fitted with a product of three Gaussian functions up to  $k^* = 2500$  MeV/c, providing good agreement with the simulated data. To account for remaining non-femtoscopic effects at large  $k^*$  [25], a linear baseline  $C_{\text{baseline}}(k^*) = a + bk^*$  is added to the ancestors term in Eq. (5). The coefficients  $a$  and  $b$  are fixed by fitting  $C_{\text{background}}(k^*)$  to the data in the region of  $400 < k^* < 2500$  MeV/c. The results for  $p-\bar{p}$  pairs are shown in Fig. 1. The band represents the  $1\sigma$  uncertainty associated to the template fitting. The shape of  $C_{\text{background}}(k^*)$  agrees within uncertainties with the data in the region above  $k^* \approx 200$  MeV/c, where the non-flat behavior of minijet contributions is visible. A change of  $\pm 10\%$  in this range and a quadratic polynomial are included to estimate the systematic uncertainty related to the total background. Similar results and conclusions are obtained for the  $p-\bar{\Lambda}$  and  $\Lambda-\bar{\Lambda}$  systems.

#### 4. Results

The correlation functions for  $p-\bar{p}$  and for two representative  $m_T$  bins of  $p-\bar{\Lambda}$  and  $\Lambda-\bar{\Lambda}$  are shown in Fig. 2 and in Fig. 3, respectively. The results for the remaining  $m_T$  bins are presented in Figs. A.1, A.2 of Appendix A.1. The lower panels show the statistical deviation between data and model expressed in terms of numbers of standard deviation  $n_\sigma$ . The width of the band represents the total uncertainty of the fit. The grey boxes correspond to the systematic uncertainties of the data. They are maximal at the lowest  $k^*$  bin and amount to 1%, 4% and 10% for  $p-\bar{p}$ ,  $p-\bar{\Lambda}$  and  $\Lambda-\bar{\Lambda}$  pairs, respectively. The  $C_{p-\bar{p}}(k^*)$  correlation is compared first to a Coulomb-only interaction and secondly to a Coulomb + strong interaction from N– $\bar{N}$   $\chi$ EFT potentials with wave functions for the  $n-\bar{n} \rightarrow p-\bar{p}$  process explicitly included [11]. Results for this latter scenario are obtained by evaluating the genuine  $p-\bar{p}$  correlation in Eq. (2) with only the first two terms and shown in blue in Fig. 2. The opening of the  $n-\bar{n}$  channel above threshold, expected as a cusp structure in the  $C(k^*)$  at  $k^* \approx 50$  MeV/c, is not visible in agreement with the weak coupling already measured in scattering experiments [4]. The chiral model underestimates the data in the region below 200 MeV/c and it cannot reproduce the enhancement above unity of the  $C(k^*)$  as  $k^*$  approaches zero. This increase is not described either by assuming only the Coulomb attraction (green band), showing that annihilation is largely present



**Fig. 2.** Measured correlation function of  $p\bar{p}$  pairs. Statistical (bars) and systematic (boxes) uncertainties are shown separately. The Coulomb only interaction is shown by the green band. The blue band represents the fit performed using  $N^3\text{LO}$   $\chi\text{EFT}$  potentials [11] with elastic and  $n\bar{n}$  coupled-channel. The inclusion of annihilation channels is shown by the red band, along with the  $C_{\text{background}}(k^*)$ , multiplied by the normalization constant  $N_D$  obtained in the fit. The reported average  $\chi^2/\text{NDF}$  is evaluated in the  $k^*$  interval [0, 400] MeV/c and it includes correlations between the data points. Lower panel:  $n_\sigma$  deviation between data and model in terms of numbers of statistical standard deviations.

close to threshold as  $k^* \rightarrow 0$  MeV/c. The contributions to the  $p\bar{p}$  correlation from the multi-meson annihilation channels, produced as initial states which feed into the measured  $p\bar{p}$  system, are not explicitly accounted for in the chiral potential and hence the last term  $\sum_{PW} C_{\chi \rightarrow p\bar{p}}^{PW}(k^*)$  in Eq. (2) is currently missing in the fit shown by the blue band.

The red band in Fig. 2 represents the results obtained from the explicit inclusion of the annihilation channels in the third term of Eq. (2) via the Migdal-Watson approximation. The corresponding fit provides a better description of the data in the low  $k^*$  region where annihilation is dominant. The extracted coupling weights  $\omega_{PW}$  from this femtoscopic fit are  $\omega_{1S_0} = 1.19 \pm 0.10$  (stat)  $\pm 0.19$  (syst) and  $\omega_{3P_0} = 40.04 \pm 4.06$  (stat)  $\pm 4.24$  (syst), while  $\omega_{1P_1}$  is compatible with zero. The hierarchy of the coupling weights in the different PW agrees with the inelasticity parameters  $\eta$  obtained in the recent partial-wave analysis [4].

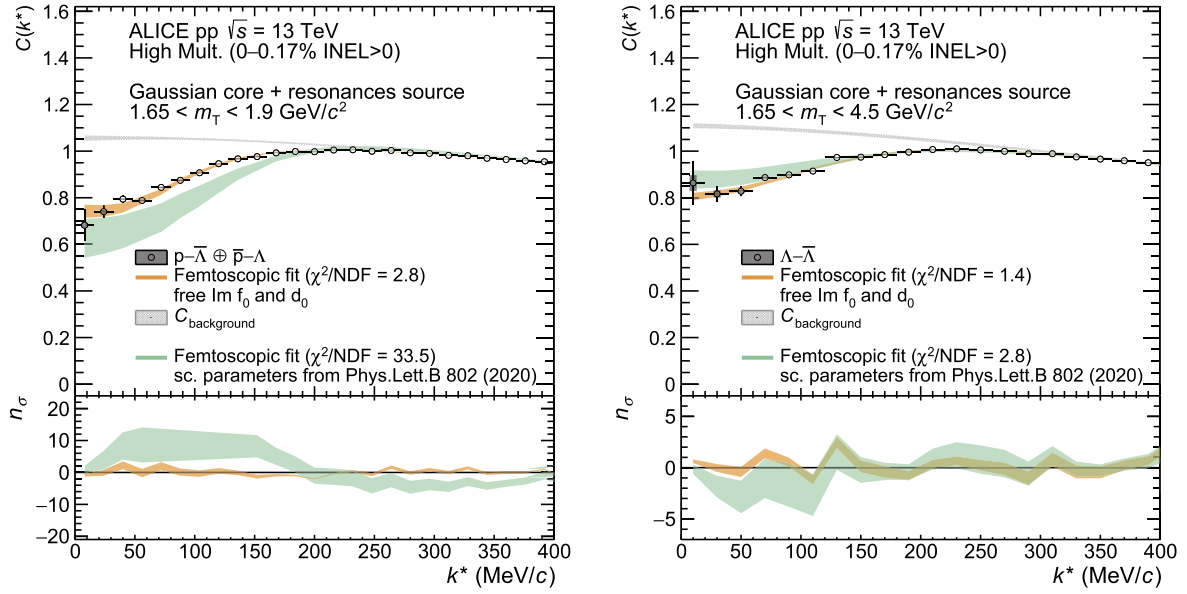
For the systems containing strangeness, the Migdal-Watson approach cannot be employed since only scattering parameters for the  $p\bar{\Lambda}$  and  $\Lambda\bar{\Lambda}$  interaction are available [23]. The values of  $\mathcal{R}f_0$  and  $\mathcal{I}f_0$  obtained in Pb-Pb measurements are employed in the Lednický-Lyuboshits analytical formula [23,42] to model the  $p\bar{\Lambda}$  and  $\Lambda\bar{\Lambda}$  genuine correlation functions. In Fig. 3, the results obtained modeling the  $p\bar{\Lambda}$  and  $\Lambda\bar{\Lambda}$  theoretical correlations with the Lednický-Lyuboshits model described in Sec. 3 are shown. The first tested scenario assumes the scattering parameters extracted from Pb-Pb results [23] and the results are denoted by light green bands. It can be expected that if the direct contributions of the annihilation channels are negligible, the values extracted in Pb-Pb will reproduce well also the pp data in this analysis. As can be seen from the right panel in Fig. 3, this first approach reproduces the measured  $\Lambda\bar{\Lambda}$  correlation function, with an average  $\chi^2/\text{NDF} = 2.8$  evaluated in the  $k^*$  interval [0, 400] MeV/c but it clearly underestimates the  $p\bar{\Lambda}$  correlation data in the  $k^*$  region below 200 MeV/c. A similar trend is observed when performing the fit to the  $p\bar{p}$  measured correlation with the Lednický-Lyuboshits

approach used in the Pb-Pb results [23] as shown in Fig. A.3 in the Appendix A.2. The discrepancy hence, as in the  $p\bar{p}$  case, has to be attributed to a larger amount of annihilation channels feeding into the  $p\bar{\Lambda}$  system with respect to the  $\Lambda\bar{\Lambda}$  pairs. To validate this interpretation, a simultaneous fit in all the  $m_T$  bins is performed leaving free to vary the imaginary part of the scattering length  $\mathcal{I}f_0$ , accounting for inelastic channels, and the effective range  $d_0$ . The negative real part of the scattering length  $\mathcal{R}f_0$ , indicating either a repulsive elastic interaction or a possible bound state, is kept fixed to the Pb-Pb results [23]. To reach a reasonable agreement of the model with  $p\bar{\Lambda}$  data,  $\mathcal{I}f_0$  has to be increased by approximately a factor 5.3, while the change in the extracted  $d_0$  is negligible. Such a discrepancy can be attributed to the failure of the single-channel Lednický-Lyuboshits model to properly accommodate the direct contribution of inelastic channels (last term in Eq. (1)). A similar fit is applied to the  $\Lambda\bar{\Lambda}$  system and values of  $\mathcal{I}f_0$  and  $d_0$  compatible with the Pb-Pb measurements are found, implying a negligible effect of the direct contribution of annihilation channels. The corresponding results are shown in Fig. 3 (orange band), for  $p\bar{\Lambda}$  (left panel) and  $\Lambda\bar{\Lambda}$  (right panel). A similar trend is obtained in the remaining  $m_T$  intervals and shown in Appendix A.1.

The different results for the  $p\bar{\Lambda}$  and  $\Lambda\bar{\Lambda}$  systems may also be related to a different amount of initially produced multi-meson states feeding into the two  $B\bar{B}$  pairs. To substantiate this scenario, a study of the two-meson channel contributions ( $\pi\bar{\pi}$ ,  $\pi\bar{K}$ ) is performed using the EPOS transport model [44]. The fraction of two-mesons pairs  $f_{2M \rightarrow B\bar{B}}$  produced in the initial collision and kinematically available to produce  $B\bar{B}$  pairs with low  $k^*$  is estimated. The latter is obtained by dividing the amount of meson-meson pairs initially produced, having a center-of-mass energy above the  $B\bar{B}$  threshold and leading to  $B\bar{B}$  pairs at low  $k^*$ , by the total number of produced two-meson pairs kinematically allowed to create the  $B\bar{B}$  pairs. Based on this study and considering these kinematics considerations, a similar amount ( $\approx 6.4\%$ ) is found for  $p\bar{\Lambda}$  and  $\Lambda\bar{\Lambda}$  pairs, indicating that the above effect is related to the properties of the  $p\bar{\Lambda}$  and  $\Lambda\bar{\Lambda}$  interaction. To quantify the final relative amount of annihilation channels feeding to the  $p\bar{\Lambda}$  and  $\Lambda\bar{\Lambda}$  systems, the fractions have to be multiplied by the corresponding coupling constant  $g$ , obtained within an SU(3) Lagrangian by evaluating the trace of the meson-baryon interaction term [53]. Within this simplified calculations, the coupling strength for the  $p\bar{\Lambda}$  system is found to be approximately 3.3 times larger than for the  $\Lambda\bar{\Lambda}$  pairs.

The estimated contribution  $g \times f_{2M \rightarrow B\bar{B}}$ , although limited to only two-meson channels, for  $p\bar{\Lambda}$  pairs is found to be about 6 times larger than for  $\Lambda\bar{\Lambda}$  pairs, indicating a different annihilation contributions occurring in  $p\bar{\Lambda}$  and  $\Lambda\bar{\Lambda}$  interaction which is confirmed by the measured correlation functions in Fig. 3. These estimations, even though based on a qualitative approach, clearly indicates that the annihilation for the  $\Lambda\bar{\Lambda}$  interaction is present but it should not be largely dominant over the elastic part. More input from theory is needed in order to claim if such a condition is ideal for the formation of bound-states in the  $\Lambda\bar{\Lambda}$  system. The results for the  $p\bar{\Lambda}$  system, however, clearly point to a much larger presence of the annihilation channels, which might reduce the possibility to create baryonia. The data presented in Fig. 3 represent the most precise data currently available on  $p\bar{\Lambda}$  and  $\Lambda\bar{\Lambda}$  pairs and can provide constraints for theoretical models on these interactions.

In conclusion, femtoscopic techniques have been adopted to study the annihilation dynamics in  $p\bar{p}$ ,  $p\bar{\Lambda}$  and  $\Lambda\bar{\Lambda}$  systems. A quantitative determination of the effective coupling weights, connected to the annihilation channels present in  $p\bar{p}$ , has been obtained adopting a coupled-channel approach with  $N^3\text{LO}$   $\chi\text{EFT}$  potentials [11]. The largest couplings have been obtained in the



**Fig. 3.** Measured correlation function of  $p-\bar{\Lambda}$  (left) and  $\Lambda-\bar{\Lambda}$  (right) pairs for two representative  $m_T$  bins. Statistical (bars) and systematic (boxes) uncertainties are shown separately. Results using the Lednický-Lyuboshits formula with Pb-Pb scattering parameters [23] are shown in light green. Orange bands are the results with  $d_0$  and  $\mathcal{I}f_0$  as free parameters. In grey the corresponding  $C_{\text{background}}(k^*)$ , multiplied by the normalization constant  $N_D$ , is shown. The reported average  $\chi^2/\text{NDF}$  is evaluated in the  $k^*$  interval [0, 400] MeV/c and it includes correlations between the data points. Lower panel: same as in Fig. 2.

spin triplet  $P(^3P_0)$  and singlet  $S(^1S_0)$  state. The inclusion of these inelastic channels leads to a better agreement between data and model in the region of  $k^*$  below 50 MeV/c, indicating a wide presence of annihilation channels close to threshold. The scattering parameters obtained in Pb-Pb collisions [23] have been used to model the  $p-\bar{\Lambda}$  and  $\Lambda-\bar{\Lambda}$  data using the Lednický-Lyuboshits formula. A consistent description of the  $\Lambda-\bar{\Lambda}$  correlation is achieved while an increase of the  $\mathcal{I}f_0$  in the  $p-\bar{\Lambda}$  interaction is needed to improve the agreement with the  $p-\bar{\Lambda}$  data. These results, confirmed by kinematics and SU(3) flavor symmetry considerations, indicate a larger contribution in  $p-\bar{\Lambda}$  from annihilation channels in comparison to  $\Lambda-\bar{\Lambda}$ . The ALICE data shown in this work delivered the most precise measurements on  $p-\bar{p}$ ,  $p-\bar{\Lambda}$  and  $\Lambda-\bar{\Lambda}$  systems at low momenta and suggest that baryonia are unlikely to occur in  $p-\bar{p}$  and  $p-\bar{\Lambda}$  systems due to the large annihilation contributions present for these pairs. A modeling of the  $B-\bar{B}$  interaction for systems as  $p-\bar{\Lambda}$ , based on optical potentials, and a quantitative estimate of production of the multi-meson annihilation channels in the collisions, can provide a better understanding of the elastic and the annihilation term which can help to strengthen final conclusions on possible bound states.

### 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.

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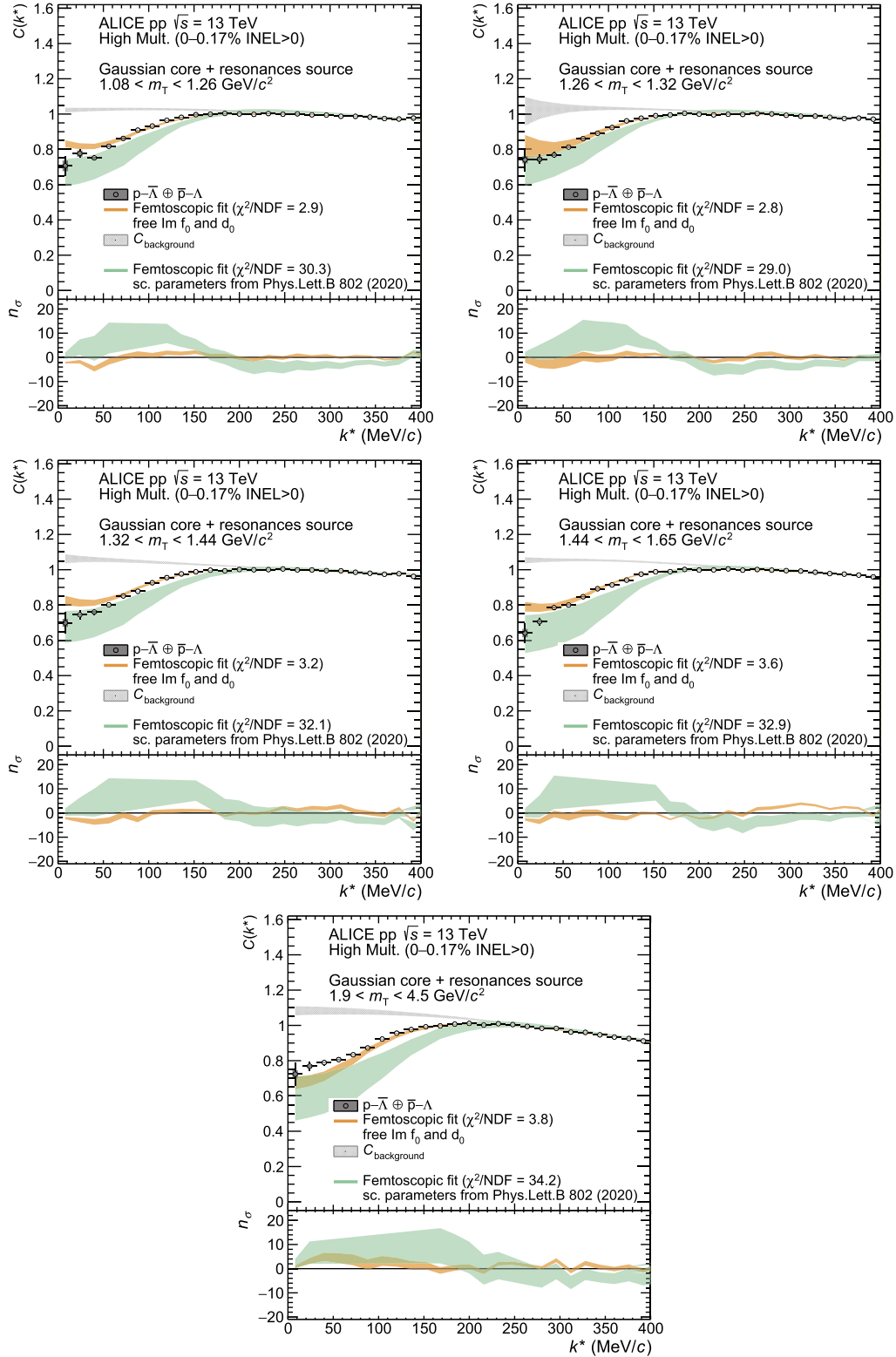
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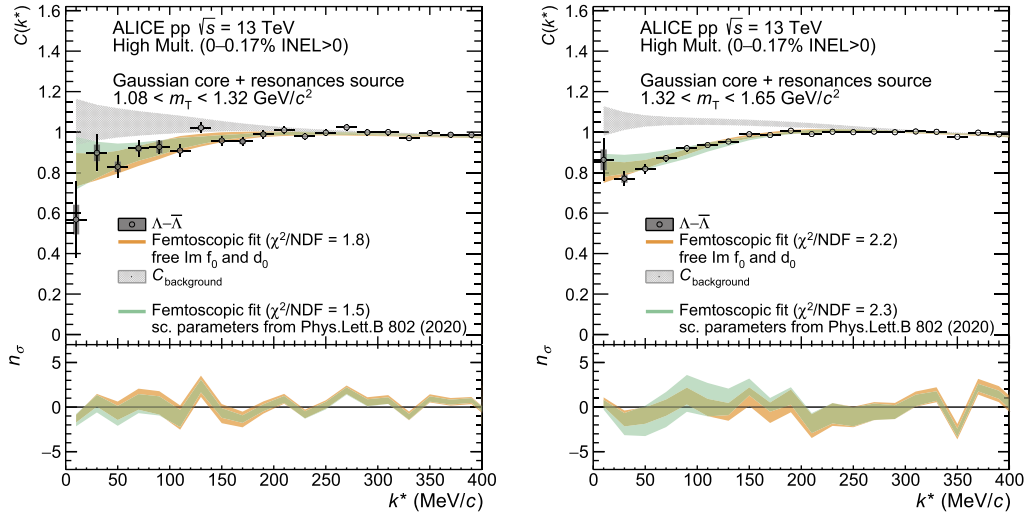
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## Appendix A. Additional material

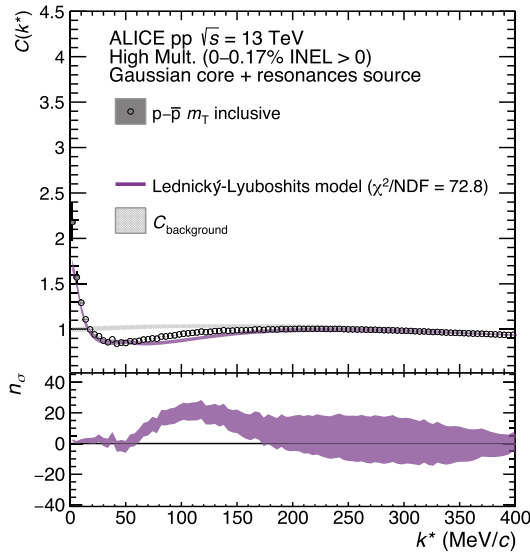
A.1.  $p-\bar{\Lambda}$  and  $\Lambda-\bar{\Lambda}$  results in  $m_T$  intervalsFig. A.1. Measured correlation function of  $p-\bar{\Lambda}$  pairs for remaining  $m_T$  bins. Same description as in Fig. 3.





**Fig. A.2.** Measured correlation function of  $\Lambda$ - $\bar{\Lambda}$  pairs for remaining  $m_T$  bins. Same description as in Fig. 3.

## A.2. Results on $p$ - $\bar{p}$ pairs with the Lednický-Lyuboshits model



**Fig. A.3.** Measured correlation function of  $p$ - $\bar{p}$  pairs. Statistical (bars) and systematic (boxes) uncertainties are shown separately. The results assuming the Lednický-Lyuboshits model with Coulomb included, as in [23], are shown by the violet band. The scattering parameters used as input for the Lednický-Lyuboshits calculations include only the  $n$ - $\bar{n}$  contribution as coupled-channel [54–56]. The model completely underestimates the  $k^*$  region from 50 to 150 MeV/c. As can be seen in Fig. 2, the annihilation channels play a role in this intermediate region and a better description of the data is achieved when using the Migdal-Watson approximation to include them. This is a clear indication that the multi-meson channels are explicitly needed to model the current measured  $p$ - $\bar{p}$  correlation function. The Lednický-Lyuboshits calculation also overestimates the coupling to the  $n$ - $\bar{n}$  channel, as can be seen from the large cusp structure at  $k^* \approx 50$  MeV/c not present in the data. Lower panel:  $n_\sigma$  deviation between data and model in terms of numbers of statistical standard deviations.

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