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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–$\overline{\rm B}$) at low-energy and its strength and range are crucial in the assessment of possible baryon bound states. Experimental data on annihilation cross sections are available for the p–$\overline{\rm p}$ system but not in the low relative momentum region. Data regarding the B–$\overline{\rm B}$ interaction with strange degrees of freedom are extremely scarce or absent, hence the modeling of the annihilation contributions is mainly based on nucleon–antinucleon (N–$\overline{\rm N}$) results, when available. In this letter we present a measurement of the p–$\overline{\rm p}$, p–$\overline{\Lambda}\oplus\overline{\rm p}$–$\Lambda$ and Λ–$\overline{\Lambda}$ 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–$\overline{\rm p}$ system the couplings to the mesonic channels in different partial waves are extracted by adopting a coupled-channel approach with recent χEFT 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–$\overline{\Lambda}\oplus\overline{\rm p}$–$\Lambda$ and Λ–$\overline{\Lambda}$ correlations. The model describes the Λ–$\overline{\Lambda}$ data and underestimates the p–$\overline{\Lambda}\oplus\overline{\rm p}$–$\Lambda$ 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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The baryon–antibaryon interaction (B–$\overline{\mathrm{B}}$) is dominated at low energies by annihilation processes, in which transitions from a state, typically composed of only mesons, to a B–$\overline{\mathrm{B}}$ state and vice versa are occurring, similarly to the dynamics of coupled-channel systems [1].

A rich sample of experimental data is available, mainly in the nucleon–antinucleon (N–$\overline{\mathrm{N}}$) sector. At threshold, measurements of the energy level shifts and widths of antiproton-proton atoms [2] enabled to extract the spin-averaged scattering parameters. The elastic and the charge-exchange ($\mathrm{p\overline{p}} \rightarrow \mathrm{n\overline{n}}$) cross sections were measured down to laboratory momenta $p_{\mathrm{lab}} \approx 200$ MeV/c in low-energy scattering experiments [3–5]. Measurements of the annihilation cross section reach lower momenta but are affected by significant uncertainties and the momentum region close to the p–$\overline{\mathrm{p}}$ threshold is currently lacking any experimental constraint.

Experimental information on B–$\overline{\mathrm{B}}$ interactions with hyperons (Y) and antihyperons ($\overline{\mathrm{Y}}$), e.g. N–$\overline{\mathrm{Y}}$, Y–$\overline{\mathrm{Y}}$, is scarce and concerns only the strangeness exchange process $\mathrm{p\overline{p}} \rightarrow \Lambda\overline{\Lambda}$ [2]. This translates into a modeling of the annihilation part mainly based on N–$\overline{\mathrm{N}}$ [6–9].

A precise understanding of the annihilation dynamics is required to assess the existence of bound states (baryonia) arising from the strong elastic attraction predicted in B–$\overline{\mathrm{B}}$ systems [2, 10]. Moreover, a better understanding of annihilation in the B–$\overline{\mathrm{B}}$ interaction with strangeness can be relevant for a precise modeling of the re-scattering phase in heavy-ion collisions [11, 12]. Precise data in the low-momentum region are hence needed for B–$\overline{\mathrm{B}}$ systems as p–$\overline{\mathrm{p}}$, p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$.

A step in this direction has recently been achieved with the measurements of two-particle correlations in the momentum space for p–$\overline{\mathrm{p}}$, p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$ pairs performed in ultra-relativistic Pb–Pb [13] collisions at LHC. The extracted spin-averaged scattering parameters are similar for all B–$\overline{\mathrm{B}}$ pairs. The same pairs were measured in Au–Au [14] collisions at RHIC, but the results might be biased by neglecting the residual correlations [11]. Similar measurements have been performed in pp and p–Pb collisions and the measured correlation functions delivered the most precise data on baryon–baryon and meson–baryon pairs, enabling access to the short-range strong interaction [15–21]. These kind of measurements in pp collisions are sensitive to the presence of inelastic channels, below and above threshold [17, 22, 23].

In this letter we present the measurements of the correlation functions of p–$\overline{\mathrm{p}}$, p–$\overline{\Lambda} \oplus \overline{\mathrm{p}}$–$\Lambda$ and Λ–$\overline{\Lambda}$ pairs in pp collisions at $\sqrt{s} = 13$ TeV with the ALICE detector [24, 25].

The main observable in this analysis is the two-particle correlation function $C(k^*)$. This quantity depends on the emitting source $S(r^*)$ and on the pair wave function $\Psi(\vec{k^*}, \vec{r^*})$, by means of the relation $C(k^*) = \int S(r^*)|\Psi(\vec{k^*}, \vec{r^*})|^2 d^3r^*$ [26], where the relative distance r^* and relative momentum $k^* = |\vec{p}_1 - \vec{p}_2|/2$ are evaluated in the pair rest frame. If the interaction of the pair in the final state i is affected by inelastic channels j, the formula is modified by the introduction of an additive term related to the processes $j \rightarrow i$ [22, 23, 27]. The experimental correlation is defined as $C(k^*) = \mathscr{N} N_{\mathrm{SE}}(k^*)/N_{\mathrm{ME}}(k^*)$, where $N_{\mathrm{SE}}(k^*)$ is the distribution of pairs measured in the same event, $N_{\mathrm{ME}}(k^*)$ is the reference distribution of uncorrelated pairs sampled from different (mixed) events and $\mathscr{N}$ is a normalization parameter. 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.

The main ALICE subdetectors [24, 25] used in this analysis are: the V0 detectors [28] used as trigger detectors, the Inner Tracking System (ITS) [29], the Time Projection Chamber (TPC) [30] and the Time-of-Flight (TOF) detector [31]. The last three are used to track and identify charged particles. The high-multiplicity (HM) sample employed corresponds to 0.17% of all inelastic pp collisions with at least one measured charged particle within $|\eta| < 1$. A total of 1.0×10^9 HM events are selected by adopting the procedure described in Refs. [19–21].

Protons (p), antiprotons ($\overline{\mathrm{p}}$), Λ and $\overline{\Lambda}$ are reconstructed using the procedure described in Refs. [19, 21]. The kinematic and topological criteria related to the reconstruction, as well as the associated systematic uncertainties, are the same as in Refs. [19, 21]. Contributions of secondary (anti)protons stemming from weak decays and misidentified candidates are extracted using Monte Carlo (MC) template fits to the measured distributions of the distance of closest approach to the primary vertex [15]. The resulting p ($\overline{\mathrm{p}}$)

purity is 99.4% (98.9%). The corresponding fraction of primary particles is 82.2% (82.3%).
Rejection of pile-up events and the reconstruction of the Λ ($\overline{\Lambda}$) candidates, via their weak decay $\Lambda \rightarrow \mathrm{p}\pi^-$ ($\overline{\Lambda} \rightarrow \overline{\mathrm{p}}\pi^+$) [32], are performed following the procedures described in Refs. [19,21]. A final selection is applied based on the reconstructed invariant mass [19,21]. The obtained Λ ($\overline{\Lambda}$) purity is 95.2% (96.1%). Primary and secondary contributions for Λ and $\overline{\Lambda}$ are extracted in the same way as for protons, via fits to the cosine of the pointing angle distributions using MC templates. The fraction of primary Λ ($\overline{\Lambda}$) hyperons is about 57%. Secondary contributions from weak decays of neutral and charged Ξ baryons amount to 22%. The remaining fractions are attributed to Σ^0 ($\overline{\Sigma^0}$) particles. The correlation functions of baryon–antibaryon and antibaryon–baryon pairs are combined to enhance the statistical significance for the p–$\overline{\Lambda}$ pairs, hence in the following p–$\overline{\Lambda}$ denotes the sum p–$\overline{\Lambda} \oplus \overline{\mathrm{p}}$–$\Lambda$. The p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$ correlation functions are obtained separately in 6 and 3 pair-transverse-mass (m_T) intervals, respectively.

The p–$\overline{\mathrm{p}}$, p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$ data are fitted with a total correlation function $C_\mathrm{tot}(k^*) = N_D \times C_\mathrm{model}(k^*) \times C_\mathrm{background}(k^*)$, where N_D is a normalization constant fitted to data, $C_\mathrm{model}(k^*)$ is the modeled correlation function and $C_\mathrm{background}(k^*)$ accounts for the non-femtoscopic background. The default fit range is $0 < k^* < 500$ MeV/c, with a variation of ±10% applied for evaluating the systematic uncertainties. The modeled $C_\mathrm{model}(k^*) = 1 + \sum_i \lambda_i \times (C_i(k^*) - 1)$ includes the genuine ($i = \mathrm{p}$–$\overline{\mathrm{p}}, \mathrm{p}$–$\overline{\Lambda}, \Lambda$–$\overline{\Lambda}$) and the residual secondary contributions weighted by the λ_i parameters [15]. The genuine contributions for p–$\overline{\mathrm{p}}$, p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$ amount to 66.5%, 45.8% and 30.9%, respectively. Residual contributions involving pairs measured in this work are modeled assuming the corresponding theoretical predictions. Contributions involving $\Sigma^{\pm,0}$ ($\overline{\Sigma}^{\pm,0}$) and $\Xi^{-,0}$ ($\overline{\Xi}^{+,0}$) are considered to be flat due to the limited theoretical knowledge, and amount to 10.1%, 44.6% and 65.7% for p–$\overline{\mathrm{p}}$, p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$, respectively. The systematic uncertainties of the λ_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 $\Sigma^0{:}\Lambda$ ratio of 0.33 ± 0.07 [21,33–36]. A correction for finite experimental momentum resolution is applied onto the theoretical predictions [15].
The size of the emitting source employed in the calculation of $C_\mathrm{model}(k^*)$ is fixed from the data-driven analysis of p–p pairs [21] which demonstrates a common Gaussian core for baryon–baryon pairs as a function of m_T when contributions from short-lived strongly decaying resonances are included. For the p–$\overline{\mathrm{p}}$ pairs, the core source size is $r_\mathrm{core} = 1.06 \pm 0.04$ fm, corresponding to an effective Gaussian source size $r_0 = 1.22$ fm. The core radii for the p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$ m_T bins presented in this letter are $r_\mathrm{core}(\langle m_\mathrm{T}\rangle = 1.75\,\mathrm{GeV}/c^2) = 0.95 \pm 0.04$ fm ($r_0 = 1.15$ fm) and $r_\mathrm{core}(\langle m_\mathrm{T}\rangle = 2.12\,\mathrm{GeV}/c^2) = 0.87 \pm 0.04$ fm ($r_0 = 1.11$ fm), respectively.

Non-femtoscopic effects stemming from minijet phenomena arising from hard processes at the parton level are present in the measurement of B–$\overline{\mathrm{B}}$ correlations. A data-driven approach is employed using PYTHIA 8.2 [37] to model the term $C_\mathrm{background}(k^*)$. 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 $C_\mathrm{background}(k^*)$ is given by a linear combination of the common and non-common 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 $C_\mathrm{tot}(k^*)$ to the data. A linear baseline $(a + bk^*)$ is added to the ancestors term in $C_\mathrm{background}(k^*)$ to describe non-femtoscopic effects at large k^* [15]. The coefficients a and b are fixed by fitting $C_\mathrm{background}(k^*)$ to the data in the region of $400 < k^* < 2500$ MeV/c. The results for p–$\overline{\mathrm{p}}$ pairs are shown in Fig. 1. Similar results are obtained for the p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$ systems. A change of ±10% in this range and a quadratic polynomial are included to estimate a systematic uncertainty. The band represents the 1σ uncertainty associated to the template fitting. The shape of $C_\mathrm{background}(k^*)$ agrees with the data in the region above $k^* \approx 200$ MeV/c, where the non-flat behavior of minijet contributions is visible.

The correlation functions for p–$\overline{\mathrm{p}}$ and for two representative m_T bins of p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$ are shown in Fig. 2 and in Fig. 3, respectively. The lower panels show the statistical deviation between data and model

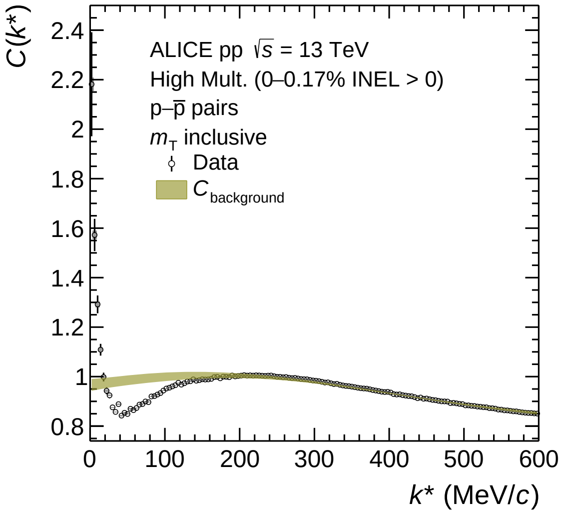

Figure 1: (Color online) Measured p–p̄ correlation function with statistical and systematic uncertainties (grey boxes) and the total $C_{\mathrm{background}}(k^*)$ fit.

expressed in terms of numbers of standard deviation n_σ. The width of the band represents the total uncertainty of the fit. The theoretical correlation functions for all three pairs are evaluated using the CATS framework [38]. The genuine $C_{\mathrm{p-\bar{p}}}(k^*)$ correlation is modeled by assuming a Coulomb-only interaction and by including also a strong interaction from N–N̄ χEFT potentials ($^1S_0$,$^3S_1$ and $^1P_1$,$^3P_0$,$^3P_1$,$^3P_2$ partial-waves) at next-to-next-to-next-to-leading order (N^{3}LO) with a cutoff parameter $R = 0.9$ fm and the n–n̄ → p–p̄ process explicitly included in a coupled-channel approach [39]. The results are shown in blue in Fig. 2. The opening of the n–n̄ channel, expected as a cusp structure in the $C(k^*)$ at $k^* \approx 50$ MeV/c, is not visible confirming the weak coupling measured in scattering experiments [5]. 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 still present close to threshold due to the large presence of multi-meson annihilation channels produced as initial states, feeding into the measured p–p̄ system, and not explicitly accounted for in the chiral potential. An effective way to include these contributions in the correlation function is the Migdal-Watson approximation [40], which relies on the fact that these X mesonic channels open below threshold, hence the momentum dependence of the annihilation potential $V_{X\to p\bar{p}}$ around the p–p̄ threshold can be neglected. The wave functions of $\psi^{PW}_{X\to p\bar{p}}$ for each partial wave (PW) are rewritten in terms of the elastic component as $\omega_{PW}\,\psi^{PW}_{p\bar{p}\to p\bar{p}}$, with the weights ω_{PW} unknown. The modeled correlation function reads [23]:

$$C_{\mathrm{p-\bar{p}}}(k^*) = \int S(r)|\psi_{p\bar{p}\to p\bar{p}}|^2 d^3r + \int S(r)|\psi_{n\bar{n}\to p\bar{p}}|^2 d^3r + \sum_{PW} \rho_{PW}\,\omega_{PW} \int S(r)|\psi^{PW}_{p\bar{p}\to p\bar{p}}|^2 d^3r. \qquad (1)$$

The first and second terms describe the elastic and n–n̄ contributions while the last term accounts for the annihilation channels. The degeneracy in spin and angular momentum is embedded in the statistical factors ρ_{PW}. The coupling weights ω_{PW} contain informations not only on the coupling strength of the mesonic channels to p–p̄, but also on the abundances of the contributing multi-meson channels produced in the initial state. A study on the shape of the inelastic correlation terms in each PW allowed to select three representative contributions: the $^1S_0$ for S states, the $^1P_1$ and $^3P_0$ for P states. The femtoscopic fit yields $\omega_{^1S_0} = 1.19 \pm 0.10\,(\mathrm{stat}) \pm 0.19\,(\mathrm{syst})$ and $\omega_{^3P_0} = 40.04 \pm 4.06\,(\mathrm{stat}) \pm 4.24\,(\mathrm{syst})$, while $\omega_{^1P_1}$ is compatible with zero. The corresponding fit results in Fig. 2 (red band) provide a better description of the data in the low k^* region. The hierarchy of the coupling weights in the different PW agrees with the inelasticity parameters η obtained in the recent partial-wave analysis [5].

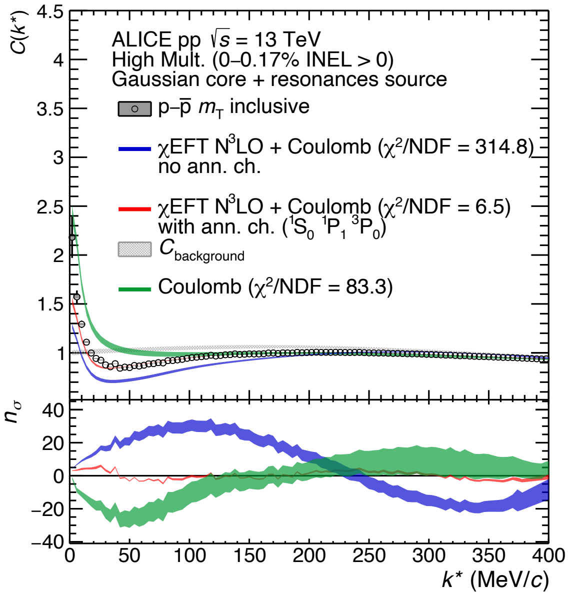

Figure 2: (Color online) Measured correlation function of p–p̄ pairs. Statistical (bars) and systematic (boxes) uncertainties are shown separately. The Coulomb only interaction is shown by the green band. The blue band represents the fit performed using N^{3}LO χEFT potentials [39] with elastic and n–n̄ 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. Lower panel: n_σ deviation between data and model in terms of numbers of statistical standard deviations.

For the systems containing strangeness, the Migdal-Watson approach cannot be employed since only scattering parameters for the Λ–$\overline{\Lambda}$ interaction are available [6], predicting values compatible with ALICE measurements in Pb–Pb collisions [13]. The latter are employed in the Lednický–Lyuboshits analytical formula [13, 27] to model the p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$ genuine correlation functions. The results are shown in Fig. 3 (light green). This first approach reproduces the measured Λ–$\overline{\Lambda}$ correlation function, with an average $\chi^2/\text{NDF} = 2.8$ evaluated in the k^* interval $[0,400]$ MeV/c. The model clearly underestimates the p–$\overline{\Lambda}$ correlation data in the k^* region below 200 MeV/c. Similarly to the p–p̄ case, the discrepancy has to be attributed to a larger amount of annihilation channels feeding into the p–$\overline{\Lambda}$ system with respect to the Λ–$\overline{\Lambda}$ 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 $\mathscr{I}f_0$, accounting for inelastic channels, and the effective range d_0. The negative real part of the scattering length $\mathscr{R}f_0$, indicating either a repulsive elastic interaction or a possible bound state, is kept fixed to the Pb–Pb results [13]. To reach an agreement of the model with p–$\overline{\Lambda}$ data, $\mathscr{I}f_0$ has to be increased by approximately a factor 5.3, while the change in the extracted d_0 is negligible. A similar fit is applied to the Λ–$\overline{\Lambda}$ system and values of $\mathscr{I}f_0$ and d_0 compatible with the Pb–Pb measurements are found. The corresponding results are shown in Fig 3 (orange band), for p–$\overline{\Lambda}$ (left panel) and Λ–$\overline{\Lambda}$ (right panel). To substantiate this scenario, a study of the two-meson channel contributions ($\pi\bar{\pi}$, $\pi\overline{K}$) is performed. The EPOS transport model [41] is used to estimate the fractions of two–meson contributions $f_{2M\to B\overline{B}}$ kinematically available to produce B–$\overline{\text{B}}$ pairs with low k^*. A similar amount ($\approx 6.4\%$) is found for p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$ pairs. To quantify the final relative amount of annihilation channels feeding to the p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$ systems, the fractions have to be multiplied by the corresponding coupling constant, obtained within an $SU(3)$ Lagrangian by evaluating the trace of the meson–baryon interaction term [42]. The largest coupling strength occurs for the p–$\overline{\Lambda}$ system. The estimated contribution, although limited to only two-meson channels, for p–$\overline{\Lambda}$ pairs is found to be about 6 times larger than for Λ–$\overline{\Lambda}$ pairs, showing a different annihilation contributions occurring in p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$ interaction which is confirmed by the measured correlation functions in Fig. 3.

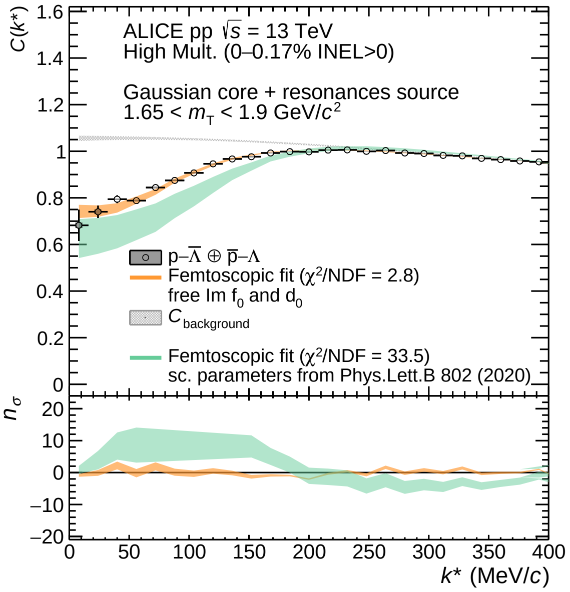

Figure 3: (Color online) Measured correlation function of p–$\overline{\Lambda}$ (left) and Λ–$\overline{\Lambda}$ (right) pairs for two representative m_{T} bins. Statistical (bars) and systematic (boxes) uncertainties are shown separately. Results using the Lednický–Lyuboshits formula with Pb–Pb scattering parameters [13] are shown in light green. Orange bands are the results with d_0 and $\mathscr{I} f_0$ as free parameters. In grey the corresponding $C_{\mathrm{background}}(k^*)$, multiplied by the normalization constant N_D, is shown. Lower panel: same as in Fig. 2.

In conclusion, femtoscopic techniques have been adopted to study the annihilation dynamics in p–$\overline{\mathrm{p}}$, p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$ systems. A quantitative determination of the effective coupling weights, connected to the annihilation channels present in p–$\overline{\mathrm{p}}$, has been obtained adopting a coupled-channel approach with N^{3}LO χEFT potentials [39]. The largest couplings have been obtained in the 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 [13] have been used to model the p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$ data using the Lednický–Lyuboshits formula. A consistent description of the Λ–$\overline{\Lambda}$ correlation is achieved while an increase of the $\mathscr{I} f_0$ in the p–$\overline{\Lambda}$ interaction is needed to improve the agreement with the p–$\overline{\Lambda}$ data. These results, confirmed by kinematics and $SU(3)$ flavor symmetry considerations, indicate a larger contribution in p–$\overline{\Lambda}$ from annihilation channels in comparison to Λ–$\overline{\Lambda}$. The ALICE data shown in this work delivered the most precise measurements on p–$\overline{\mathrm{p}}$, p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$ systems at low momenta and suggest that baryonia are unlikely to occur in p–$\overline{\mathrm{p}}$ and p–$\overline{\Lambda}$ systems due to the large annihilation contributions present for these pairs. A modeling of the B–$\overline{\mathrm{B}}$ interaction for systems as p–$\overline{\Lambda}$, 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.

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References

[1] A. M. Badalian, L. P. Kok, M. I. Polikarpov, and Y. A. Simonov, "Resonances in Coupled Channels in Nuclear and Particle Physics", *Phys. Rept.* **82** (1982) 31–177.

[2] E. Klempt, F. Bradamante, A. Martin, and J. M. Richard, “Antinucleon–nucleon interaction at low energy: Scattering and protonium”, *Phys. Rept.* **368** (2002) 119–316.

[3] C. Amsler and F. Myhrer, “Low-energy anti-proton physics”, *Ann. Rev. Nucl. Part. Sci.* **41** (1991) 219–267.

[4] C. B. Dover, T. Gutsche, M. Maruyama, and A. Faessler, “The Physics of nucleon - anti-nucleon annihilation”, *Prog. Part. Nucl. Phys.* **29** (1992) 87–174.

[5] D. Zhou and R. G. E. Timmermans, “Energy-dependent partial-wave analysis of all antiproton-proton scattering data below 925 MeV/c”, *Phys. Rev.* **C86** (2012) 044003, `arXiv:1210.7074 [hep-ph]`.

[6] J. Haidenbauer, K. Holinde, V. Mull, and J. Speth, “Meson exchange and quark - gluon transitions in the $\bar{p}p \to \bar{\Lambda}\Lambda$ process”, *Phys. Rev.* **C46** (1992) 2158–2171.

[7] R. G. E. Timmermans, T. A. Rijken, and J. J. de Swart, “Strangeness exchange in anti-proton proton scattering”, *Phys. Rev.* **D45** (1992) 2288–2307.

[8] J. Haidenbauer, T. Hippchen, K. Holinde, B. Holzenkamp, V. Mull, and J. Speth, “The Reaction $\bar{p}p \to \bar{\Lambda}\Lambda$ in the meson exchange picture”, *Phys. Rev.* **C45** (1992) 931–946.

[9] J. Haidenbauer, K. Holinde, and J. Speth, “The $\bar{p}p \to \bar{\Xi}\Xi$ reaction in the meson exchange picture”, *Phys. Rev.* **C47** (1993) 2982–2985.

[10] B. Loiseau and S. Wycech, “Extraction of baryonia from the lightest antiprotonic atoms”, *Phys. Rev.* **C102** no. 3, (2020) 034006, `arXiv:2007.01775 [nucl-th]`.

[11] A. Kisiel, H. Zbroszczyk, and M. Szymański, “Extracting baryon-antibaryon strong interaction potentials from p$\bar{\Lambda}$ femtoscopic correlation functions”, *Phys. Rev.* **C89** no. 5, (2014) 054916, `arXiv:1403.0433 [nucl-th]`.

[12] E. Seifert and W. Cassing, “Baryon-antibaryon annihilation and reproduction in relativistic heavy-ion collisions”, *Phys. Rev.* **C97** no. 2, (2018) 024913, `arXiv:1710.00665 [hep-ph]`.

[13] **ALICE** Collaboration, S. Acharya *et al.*, “Measurement of strange baryon–antibaryon interactions with femtoscopic correlations”, *Phys. Lett.* **B802** (2020) 135223, `arXiv:1903.06149 [nucl-ex]`.

[14] **STAR** Collaboration, J. Adams *et al.*, “p–Λ correlations in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV”, *Phys. Rev.* **C74** (2006) 064906, `arXiv:nucl-ex/0511003`.

[15] **ALICE** Collaboration, S. Acharya *et al.*, “p-p, p-Λ and Λ-Λ correlations studied via femtoscopy in pp reactions at $\sqrt{s}$ = 7 TeV”, *Phys. Rev.* **C99** (2019) 024001, `arXiv:1805.12455 [nucl-ex]`.

[16] **ALICE** Collaboration, S. Acharya *et al.*, “Study of the Λ-Λ interaction with femtoscopy correlations in pp and p-Pb collisions at the LHC”, *Phys. Lett. B* **797** (2019) 134822, `arXiv:1905.07209 [nucl-ex]`.

[17] **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]`.

[18] **ALICE** Collaboration, S. Acharya *et al.*, “First Observation of an Attractive Interaction between a Proton and a Cascade Baryon”, *Phys. Rev. Lett.* **123** (2019) 112002, `arXiv:1904.12198 [nucl-ex]`.

[19] **ALICE** Collaboration, S. Acharya *et al.*, “Investigation of the p-Σ^0 interaction via femtoscopy in pp collisions”, *Phys. Lett. B* **805** (2020) 135419, `arXiv:1910.14407 [nucl-ex]`.

[20] **ALICE** Collaboration, S. Acharya *et al.*, “Unveiling the strong interaction among hadrons at the LHC”, *Nature* **588** no. 7837, (2020) 232–238.

[21] **ALICE** Collaboration, S. Acharya *et al.*, “Search for a common baryon source in high-multiplicity pp collisions at the LHC”, *Phys. Lett. B* **811** (2020) 135849, `arXiv:2004.08018 [nucl-ex]`.

[22] Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, and W. Weise, “$K^- p$ Correlation Function from

High-Energy Nuclear Collisions and Chiral SU(3) Dynamics", *Phys. Rev. Lett.* **124** no. 13, (2020) 132501, `arXiv:1911.01041 [nucl-th]`.

[23] J. Haidenbauer, "Coupled-channel effects in hadron-hadron correlation functions", *Nucl. Phys.* **A981** (2019) 1–16, `arXiv:1808.05049 [hep-ph]`.

[24] **ALICE** Collaboration, K. Aamodt *et al.*, "The ALICE experiment at the CERN LHC", *J. Instr.* **3** (2008) S08002.

[25] **ALICE** Collaboration, B. Abelev *et al.*, "Performance of the ALICE experiment at the CERN LHC", *Int. J. Mod. Phys.* **A29** (2014) 1430044.

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

[27] R. Lednický and V. Lyuboshits, "Final State Interaction Effect on Pairing Correlations Between Particles with Small Relative Momenta", *Sov. J. Nucl. Phys.* **35** (1982) 770.

[28] **ALICE** Collaboration, E. Abbas *et al.*, "Performance of the ALICE VZERO system", *J. Instr.* (2013) P10016.

[29] **ALICE** Collaboration, K. Aamodt *et al.*, "Alignment of the ALICE Inner Tracking System with cosmic-ray tracks", *JINST* **5** (2010) P03003, `arXiv:1001.0502 [physics.ins-det]`.

[30] J. Alme, Y. Andres, H. Appelshäuser, S. Bablok, N. Bialas, *et al.*, "The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events", *Nucl.Instrum.Meth.* **A622** (2010) 316–367, `arXiv:1001.1950 [physics.ins-det]`.

[31] A. Akindinov *et al.*, "Performance of the ALICE Time-Of-Flight detector at the LHC", *Eur. Phys. J. Plus* **128** (2013) 44.

[32] **Particle Data Group** Collaboration, M. Tanabashi *et al.*, "Review of Particle Physics", *Phys. Rev.* **D98** (2018) 030001.

[33] V. Vovchenko and H. Stoecker, "Thermal-FIST: A package for heavy-ion collisions and hadronic equation of state", *Comput. Phys. Commun.* **244** (2019) 295–310, `arXiv:1901.05249 [nucl-th]`.

[34] **ARGUS** Collaboration, H. Albrecht *et al.*, "Observation of Octet and Decuplet Hyperons in e^+e^- Annihilation at 10-GeV Center-of-mass Energy", *Phys. Lett. B* **183** (1987) 419–424.

[35] M. W. Sullivan *et al.*, "Measurement of the Ratio of Σ^0 to Λ^0 Inclusive Production From 28.5-GeV/*c* Protons on Beryllium", *Phys. Rev.* **D36** (1987) 674.

[36] B. S. Yuldashev *et al.*, "Neutral strange particle production in p Ne-20 and p N interactions at 300-GeV/c", *Phys. Rev.* **D43** (1991) 2792–2802.

[37] T. Sjöstrand *et al.*, "An Introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159–177.

[38] D. Mihaylov, V. Mantovani Sarti, O. Arnold, L. Fabbietti, B. Hohlweger, and A. Mathis, "A femtoscopic Correlation Analysis Tool using the Schrödinger equation (CATS)", *Eur. Phys. J. C* **78** (2018) 394, `arXiv:1802.08481 [hep-ph]`.

[39] L.-Y. Dai, J. Haidenbauer, and U.-G. Meißner, "Antinucleon-nucleon interaction at next-to-next-to-next-to-leading order in chiral effective field theory", *JHEP* **07** (2017) 078, `arXiv:1702.02065 [nucl-th]`.

[40] J. Haidenbauer, C. Hanhart, X.-W. Kang, and U.-G. Meißner, "Origin of the structures observed in e^+e^- annihilation into multipion states around the $\bar{p}p$ threshold", *Phys. Rev.* **D92** no. 5, (2015) 054032, `arXiv:1506.08120 [nucl-th]`.

[41] T. Pierog, I. Karpenko, J. Katzy, E. Yatsenko, and K. Werner, "EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider", *Phys. Rev.* **C92** no. 3, (2015) 034906, `arXiv:1306.0121 [hep-ph]`.

[42] L. Olbrich, M. Zétényi, F. Giacosa, and D. H. Rischke, "Three-flavor chiral effective model with

four baryonic multiplets within the mirror assignment”, *Phys. Rev.* **D93** no. 3, (2016) 034021, `arXiv:1511.05035 [hep-ph]`.

A The ALICE Collaboration

S. Acharya[143], D. Adamová[98], A. Adler[76], J. Adolfsson[83], G. Aglieri Rinella[35], M. Agnello[31], N. Agrawal[55], Z. Ahammed[143], S. Ahmad[16], S.U. Ahn[78], I. Ahuja[39], Z. Akbar[52], A. Akindinov[95], M. Al-Turany[110], S.N. Alam[41], D. Aleksandrov[91], B. Alessandro[61], H.M. Alfanda[7], R. Alfaro Molina[73], B. Ali[16], Y. Ali[14], A. Alici[26], N. Alizadehvandchali[127], A. Alkin[35], J. Alme[21], T. Alt[70], L. Altenkamper[21], I. Altsybeev[115], M.N. Anaam[7], C. Andrei[49], D. Andreou[93], A. Andronic[146], M. Angeletti[35], V. Anguelov[107], F. Antinori[58], P. Antonioli[55], C. Anuj[16], N. Apadula[82], L. Aphecetche[117], H. Appelshäuser[70], S. Arcelli[26], R. Arnaldi[61], I.C. Arsene[20], M. Arslandok[148,107], A. Augustinus[35], R. Averbeck[110], S. Aziz[80], M.D. Azmi[16], A. Badalà[57], Y.W. Baek[42], X. Bai[131,110], R. Bailhache[70], Y. Bailung[51], R. Bala[104], A. Balbino[31], A. Baldisseri[140], B. Balis[2], M. Ball[44], D. Banerjee[4], R. Barbera[27], L. Barioglio[108,25], M. Barlou[87], G.G. Barnaföldi[147], L.S. Barnby[97], V. Barret[137], C. Bartels[130], K. Barth[35], E. Bartsch[70], F. Baruffaldi[28], N. Bastid[137], S. Basu[83], G. Batigne[117], B. Batyunya[77], D. Bauri[50], J.L. Bazo Alba[114], I.G. Bearden[92], C. Beattie[148], I. Belikov[139], A.D.C. Bell Hechavarria[146], F. Bellini[26,35], R. Bellwied[127], S. Belokurova[115], V. Belyaev[96], G. Bencedi[71], S. Beole[25], A. Bercuci[49], Y. Berdnikov[101], A. Berdnikova[107], D. Berenyi[147], L. Bergmann[107], M.G. Besoiu[69], L. Betev[35], P.P. Bhaduri[143], A. Bhasin[104], I.R. Bhat[104], M.A. Bhat[4], B. Bhattacharjee[43], P. Bhattacharya[23], L. Bianchi[25], N. Bianchi[53], J. Bielčík[38], J. Bielčíková[98], J. Biernat[120], A. Bilandzic[108], G. Biro[147], S. Biswas[4], J.T. Blair[121], D. Blau[91], M.B. Blidaru[110], C. Blume[70], G. Boca[29,59], F. Bock[99], A. Bogdanov[96], S. Boi[23], J. Bok[63], L. Boldizsár[147], A. Bolozdynya[96], M. Bombara[39], P.M. Bond[35], G. Bonomi[142,59], H. Borel[140], A. Borissov[84], H. Bossi[148], E. Botta[25], L. Bratrud[70], P. Braun-Munzinger[110], M. Bregant[123], M. Broz[38], G.E. Bruno[109,34], M.D. Buckland[130], D. Budnikov[111], H. Buesching[70], S. Bufalino[31], O. Bugnon[117], P. Buhler[116], Z. Buthelezi[74,134], J.B. Butt[14], S.A. Bysiak[120], D. Caffarri[93], M. Cai[28,7], H. Caines[148], A. Caliva[110], E. Calvo Villar[114], J.M.M. Camacho[122], R.S. Camacho[46], P. Camerini[24], F.D.M. Canedo[123], F. Carnesecchi[35,26], R. Caron[140], J. Castillo Castellanos[140], E.A.R. Casula[23], F. Catalano[31], C. Ceballos Sanchez[77], P. Chakraborty[50], S. Chandra[143], S. Chapeland[35], M. Chartier[130], S. Chattopadhyay[143], S. Chattopadhyay[112], A. Chauvin[23], T.G. Chavez[46], C. Cheshkov[138], B. Cheynis[138], V. Chibante Barroso[35], D.D. Chinellato[124], S. Cho[63], P. Chochula[35], P. Christakoglou[93], C.H. Christensen[92], P. Christiansen[83], T. Chujo[136], C. Cicalo[56], L. Cifarelli[26], F. Cindolo[55], M.R. Ciupek[110], G. Clai[II,55], J. Cleymans[I,126], F. Colamaria[54], J.S. Colburn[113], D. Colella[109,54,34,147], A. Collu[82], M. Colocci[35,26], M. Concas[III,61], G. Conesa Balbastre[81], Z. Conesa del Valle[80], G. Contin[24], J.G. Contreras[38], M.L. Coquet[140], T.M. Cormier[99], P. Cortese[32], M.R. Cosentino[125], F. Costa[35], S. Costanza[29,59], P. Crochet[137], E. Cuautle[71], P. Cui[7], L. Cunqueiro[99], A. Dainese[58], F.P.A. Damas[117,140], M.C. Danisch[107], A. Danu[69], I. Das[112], P. Das[89], P. Das[4], S. Das[4], S. Dash[50], S. De[89], A. De Caro[30], G. de Cataldo[54], L. De Cilladi[25], J. de Cuveland[40], A. De Falco[23], D. De Gruttola[30], N. De Marco[61], C. De Martin[24], S. De Pasquale[30], S. Deb[51], H.F. Degenhardt[123], K.R. Deja[144], L. Dello Stritto[30], S. Delsanto[25], W. Deng[7], P. Dhankher[19], D. Di Bari[34], A. Di Mauro[35], R.A. Diaz[8], T. Dietel[126], Y. Ding[138,7], R. Divià[35], D.U. Dixit[19], Ø. Djuvsland[21], U. Dmitrieva[65], J. Do[63], A. Dobrin[69], B. Dönigus[70], O. Dordic[20], A.K. Dubey[143], A. Dubla[110,93], S. Dudi[103], M. Dukhishyam[89], P. Dupieux[137], N. Dzalaiova[13], T.M. Eder[146], R.J. Ehlers[99], V.N. Eikeland[21], D. Elia[54], B. Erazmus[117], F. Ercolessi[26], F. Erhardt[102], A. Erokhin[115], M.R. Ersdal[21], B. Espagnon[80], G. Eulisse[35], D. Evans[113], S. Evdokimov[94], L. Fabbietti[108], M. Faggin[28], J. Faivre[81], F. Fan[7], A. Fantoni[53], M. Fasel[99], P. Fecchio[31], A. Feliciello[61], G. Feofilov[115], A. Fernández Téllez[46], A. Ferrero[140], A. Ferretti[25], V.J.G. Feuillard[107], J. Figiel[120], S. Filchagin[111], D. Finogeev[65], F.M. Fionda[56,21], G. Fiorenza[35,109], F. Flor[127], A.N. Flores[121], S. Foertsch[74], P. Foka[110], S. Fokin[91], E. Fragiacomo[62], E. Frajna[147], U. Fuchs[35], N. Funicello[30], C. Furget[81], A. Furs[65], J.J. Gaardhøje[92], M. Gagliardi[25], A.M. Gago[114], A. Gal[139], C.D. Galvan[122], P. Ganoti[87], C. Garabatos[110], J.R.A. Garcia[46], E. Garcia-Solis[10], K. Garg[117], C. Gargiulo[35], A. Garibli[90], K. Garner[146], P. Gasik[110], E.F. Gauger[121], A. Gautam[129], M.B. Gay Ducati[72], M. Germain[117], J. Ghosh[112], P. Ghosh[143], S.K. Ghosh[4], M. Giacalone[26], P. Gianotti[53], P. Giubellino[110,61], P. Giubilato[28], A.M.C. Glaenzer[140], P. Glässel[107], D.J.Q. Goh[85], V. Gonzalez[145], L.H. González-Trueba[73], S. Gorbunov[40], M. Gorgon[2], L. Görlich[120], S. Gotovac[36], V. Grabski[73], L.K. Graczykowski[144], L. Greiner[82], A. Grelli[64], C. Grigoras[35], V. Grigoriev[96], A. Grigoryan[I,1], S. Grigoryan[77,1], O.S. Groettvik[21], F. Grosa[35,61], J.F. Grosse-Oetringhaus[35], R. Grosso[110], G.G. Guardiano[124], R. Guernane[81], M. Guilbaud[117], K. Gulbrandsen[92], T. Gunji[135], A. Gupta[104], R. Gupta[104], I.B. Guzman[46], S.P. Guzman[46], L. Gyulai[147], M.K. Habib[110], C. Hadjidakis[80], G. Halimoglu[70], H. Hamagaki[85], G. Hamar[147], M. Hamid[7], R. Hannigan[121], M.R. Haque[144,89], A. Harlenderova[110], J.W. Harris[148], A. Harton[10], J.A. Hasenbichler[35], H. Hassan[99], D. Hatzifotiadou[55], P. Hauer[44], L.B. Havener[148], S. Hayashi[135], S.T. Heckel[108], E. Hellbär[70], H. Helstrup[37], T. Herman[38], E.G. Hernandez[46], G. Herrera Corral[9], F. Herrmann[146], K.F. Hetland[37], H. Hillemanns[35], C. Hills[130], B. Hippolyte[139], B. Hofman[64], B. Hohlweger[93,108], J. Honermann[146], G.H. Hong[149], D. Horak[38], S. Hornung[110], A. Horzyk[2], R. Hosokawa[15], P. Hristov[35], C. Huang[80], C. Hughes[133], P. Huhn[70], T.J. Humanic[100], H. Hushnud[112], L.A. Husova[146], A. Hutson[127], D. Hutter[40], J.P. Iddon[35,130],

R. Ilkaev[111], H. Ilyas[14], M. Inaba[136], G.M. Innocenti[35], M. Ippolitov[91], A. Isakov[38,98], M.S. Islam[112], M. Ivanov[110], V. Ivanov[101], V. Izucheev[94], M. Jablonski[2], B. Jacak[82], N. Jacazio[35], P.M. Jacobs[82], S. Jadlovska[119], J. Jadlovsky[119], S. Jaelani[64], C. Jahnke[124,123], M.J. Jakubowska[144], M.A. Janik[144], T. Janson[76], M. Jercic[102], O. Jevons[113], F. Jonas[99,146], P.G. Jones[113], J.M. Jowett [35,110], J. Jung[70], M. Jung[70], A. Junique[35], A. Jusko[113], J. Kaewjai[118], P. Kalinak[66], A. Kalweit[35], V. Kaplin[96], S. Kar[7], A. Karasu Uysal[79], D. Karatovic[102], O. Karavichev[65], T. Karavicheva[65], P. Karczmarczyk[144], E. Karpechev[65], A. Kazantsev[91], U. Kebschull[76], R. Keidel[48], D.L.D. Keijdener[64], M. Keil[35], B. Ketzer[44], Z. Khabanova[93], A.M. Khan[7], S. Khan[16], A. Khanzadeev[101], Y. Kharlov[94], A. Khatun[16], A. Khuntia[120], B. Kileng[37], B. Kim[17,63], D. Kim[149], D.J. Kim[128], E.J. Kim[75], J. Kim[149], J.S. Kim[42], J. Kim[107], J. Kim[149], J. Kim[75], M. Kim[107], S. Kim[18], T. Kim[149], S. Kirsch[70], I. Kisel[40], S. Kiselev[95], A. Kisiel[144], J.P. Kitowski[2], J.L. Klay[6], J. Klein[35], S. Klein[82], C. Klein-Bösing[146], M. Kleiner[70], T. Klemenz[108], A. Kluge[35], A.G. Knospe[127], C. Kobdaj[118], M.K. Köhler[107], T. Kollegger[110], A. Kondratyev[77], N. Kondratyeva[96], E. Kondratyuk[94], J. Konig[70], S.A. Konigstorfer[108], P.J. Konopka[35,2], G. Kornakov[144], S.D. Koryciak[2], L. Koska[119], A. Kotliarov[98], O. Kovalenko[88], V. Kovalenko[115], M. Kowalski[120], I. Králik[66], A. Kravčáková[39], L. Kreis[110], M. Krivda[113,66], F. Krizek[98], K. Krizkova Gajdosova[38], M. Kroesen[107], M. Krüger[70], E. Kryshen[101], M. Krzewicki[40], V. Kučera[35], C. Kuhn[139], P.G. Kuijer[93], T. Kumaoka[136], D. Kumar[143], L. Kumar[103], N. Kumar[103], S. Kundu[35,89], P. Kurashvili[88], A. Kurepin[65], A.B. Kurepin[65], A. Kuryakin[111], S. Kushpil[98], J. Kvapil[113], M.J. Kweon[63], J.Y. Kwon[63], Y. Kwon[149], S.L. La Pointe[40], P. La Rocca[27], Y.S. Lai[82], A. Lakrathok[118], M. Lamanna[35], R. Langoy[132], K. Lapidus[35], P. Larionov[53], E. Laudi[35], L. Lautner[35,108], R. Lavicka[38], T. Lazareva[115], R. Lea[142,24,59], J. Lee[136], J. Lehrbach[40], R.C. Lemmon[97], I. León Monzón[122], E.D. Lesser[19], M. Lettrich[35,108], P. Lévai[147], X. Li[11], X.L. Li[7], J. Lien[132], R. Lietava[113], B. Lim[17], S.H. Lim[17], V. Lindenstruth[40], A. Lindner[49], C. Lippmann[110], A. Liu[19], J. Liu[130], I.M. Lofnes[21], V. Loginov[96], C. Loizides[99], P. Loncar[36], J.A. Lopez[107], X. Lopez[137], E. López Torres[8], J.R. Luhder[146], M. Lunardon[28], G. Luparello[62], Y.G. Ma[41], A. Maevskaya[65], M. Mager[35], T. Mahmoud[44], A. Maire[139], M. Malaev[101], Q.W. Malik[20], L. Malinina[IV,77], D. Mal'Kevich[95], N. Mallick[51], P. Malzacher[110], G. Mandaglio[33,57], V. Manko[91], F. Manso[137], V. Manzari[54], Y. Mao[7], J. 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