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Hypertriton production in p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV

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Abstract

The study of nuclei and antinuclei production has proven to be a powerful tool to investigate the formation mechanism of loosely bound states in high-energy hadronic collisions. The first measurement of the production of $^{3}_{\Lambda}$H in p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV is presented in this Letter. Its production yield measured in the rapidity interval $-1 < y < 0$ for the 40% highest multiplicity p–Pb collisions is $\mathrm{d}N/\mathrm{d}y = [6.3 \pm 1.8(\mathrm{stat.}) \pm 1.2(\mathrm{syst.})] \times 10^{-7}$. The measurement is compared with the expectations of statistical hadronisation and coalescence models, which describe the nucleosynthesis in hadronic collisions. These two models predict very different yields of the hypertriton in charged particle multiplicity environments relevant to small collision systems such as p–Pb and therefore the measurement of $\mathrm{d}N/\mathrm{d}y$ is crucial to distinguish between them. The precision of this measurement leads to the exclusion with a significance larger than 6.9σ of some configurations of the statistical hadronization model, thus constraining the theory behind the production of loosely bound states at hadron colliders.

*See Appendix A for the list of collaboration members

In the last few decades, the production of deuterons, ^{3}H, ^{3}He, ^{4}He and their charge conjugates was measured in many different colliding systems and energies. The results of the measurements in hadronic and heavy-ion collisions at the LHC [1–7], in $e^{+}e^{-}$ collisions at LEP [8], at lower-energy collider [9–16] and fixed target experiments [17–20] significantly constrained the parameter space for production models like coalescence [21–23] and statistical hadronisation [24, 25], yet they were unable to decisively discriminate between these two models. The interest in the phenomenon of nucleosynthesis in the final state of hadronic collisions has risen again in recent years owing to its relevance in dark matter searches in space [26, 27]. A precise modelling of the production of nuclei and antinuclei is required for the interpretation of the expected fluxes of antinuclei originating from dark matter annihilation, and for the relevant Standard Model background channels.

For large colliding systems, such as Pb–Pb collisions at the LHC, the predictions of statistical hadronisation and coalescence models are very similar and they are both able to describe the measured production of nuclei [28]. The statistical hadronisation model (SHM) describes the system as a hadron-resonance gas (HRG) in thermal equilibrium at hadron emission, hence it predicts particle yields starting from the volume and the temperature of the system at chemical freeze-out ($T_{\rm chem}$). The Grand Canonical formulation of the SHM describes the measured production yields of light hadrons and nuclei in Pb–Pb collisions at 2.76 TeV with $T_{\rm chem}$ = 155 MeV [5]. This temperature, which successfully describes the yield of light hadrons in central Pb–Pb collisions, is one to two orders of magnitude larger than the typical binding energies of light nuclei (a few MeVs), and nuclei are likely to interact with the other hadrons in the dense HRG after chemical freeze-out due to the large cross sections [29], thus further modifying the yield. How these loosely bound objects can be formed and survive in such a hostile environment is still an unsolved question [30]. The coalescence model uses a different approach to explain the production of nuclei: the size of the nucleon-emitting source, accessible through the analysis of femtoscopic correlations [31], and the nuclear wave function are the two inputs that determine the formation probability of bound states [23, 26]. While the SHM can compute directly the absolute yields of particles, in the hadron coalescence model the yield of bound states can be computed only relative to the yields of other particles.

The measurement of the production of large bound states in small collision systems, such as pp and p–Pb, is considered to allow for conclusive tests [28, 32] of nucleosynthesis in hadronic collisions. An extreme example is the hypertriton $^{3}_{\Lambda}$H, the bound state of a proton, a neutron, and a Λ baryon. This state is characterised by a very small Λ separation energy, of the order of a few hundreds of keV [33, 34], and consequently it has a wide wave function that can extend up to a radius of $\approx$ 10 fm [35, 36]. The size of the $^{3}_{\Lambda}$H wave function is therefore much larger than the hadron emission radius estimated with a femtoscopic technique in p–Pb collisions (1–2 fm, [37, 38]). For this reason, the $^{3}_{\Lambda}$H yield in p–Pb collisions predicted by the coalescence model, where the ratio of nucleus size to source size directly influences its yield, is suppressed with respect to the statistical hadronisation model expectations, where the nuclear size does not enter explicitly [23, 25, 28].

The results presented in this Letter are based on data collected during the 2013 and 2016 p–Pb LHC runs at $\sqrt{s_{\rm NN}}$ = 5.02 TeV. With this beam configuration, the nucleon–nucleon centre-of-mass system moves in rapidity by $\Delta y_{\rm cms}$ = 0.465 in the direction of the proton beam. The ALICE detector and its performance are described in detail in [39, 40]. Collision events are selected by using the information from the V0A and V0C scintillator arrays [41], located on both sides of the interaction point, covering the pseudorapidity intervals $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$. A coincident signal in both arrays is used as a minimum-bias (MB) trigger. In addition, only events with the primary vertex position within 10 cm along the beam axis to the nominal centre of the experiment are selected to benefit from the full acceptance of the detector. Furthermore, to ensure the best possible performance of the detector and the proper normalisation of the results, events with more than one reconstructed primary interaction vertex (pile-up events) are rejected. In total, about 750 million MB events are selected for analysis, corresponding to an integrated luminosity of $\mathscr{L}_{\rm int}^{\rm MB} = 359\ \mu{\rm b}^{-1}$, with a relative uncertainty determined by the van der Meer scan to be 3.7% [42]. For this analysis, the 40% of events with the highest multiplicity measured by the V0A detector are used.

The $^3_\Lambda$H candidates are reconstructed via the charged two-body decay channel $^3_\Lambda{\rm H} \rightarrow {}^3{\rm He} + \pi^-$ (and the related charge conjugated particles for $^3_\Lambda\overline{\rm H}$). In this work, $^3_\Lambda$H and $^3_\Lambda\overline{\rm H}$ are combined to reduce the statistical uncertainty.

In the following, we use the notation $^3_\Lambda$H and ^{3}He for both the particle and the antiparticle, as well as for their average. The charged-particle tracks are reconstructed in the ALICE central barrel with the Inner Tracking System (ITS) [43] and the Time Projection Chamber (TPC) [44], which are located within a solenoid that provides a homogeneous magnetic field of 0.5 T in the direction of the beam axis. These two subsystems provide full azimuthal coverage for charged-particle trajectories in the pseudorapidity interval $|\eta| < 0.8$. The TPC is also used for the particle identification (PID) of the ^{3}He and the π^- via their specific energy loss d$E/$dx in the gas volume, with a d$E/$dx resolution of about 5% [44]. The $n(\sigma_i^{\rm TPC})$ variable represents the PID response in the TPC expressed in terms of the deviation between the measured and the expected d$E/$dx for a particle species i, normalized by the detector resolution σ. The expected d$E/$dx is computed with a parameterised Bethe-Bloch function [40]. Pion and ^{3}He tracks within $5\sigma^{\rm TPC}$ are selected. The identified ^{3}He and π tracks are then used to reconstruct the $^3_\Lambda$H weak decay topology with an algorithm similar to that used in previous analyses [45, 46]. By combining the information on the decay kinematics and decay vertex, several selection variables are defined. Those used in the analysis are: the radial distance of the decay vertex from the beam line, the distance of each daughter track from both the primary and the decay vertex, the proper decay length of the candidate (ct) and cos($\theta_{\rm P}$), where $\theta_{\rm P}$ is the angle between the total momentum vector of the decay daughters and the straight line connecting the primary and secondary vertices. The final candidate selection based on these variables is performed with a gradient boosted decision tree classifier (BDT) implemented by the XGBoost library [47–49] and trained on a dedicated Monte Carlo (MC) simulated event sample. The MC sample is created using the HIJING event generator [50] for simulating the underlying p–Pb collisions, while $^3_\Lambda$H were injected with a $p_{\rm T}$ distribution represented by a $m_{\rm T}$ exponential function that describes the $p_{\rm T}$ distribution of ^{3}He as measured in p–Pb collisions [5]. The particles are transported through the detector geometry using GEANT4 [51], which simulates the interaction with the material and the weak decay of the $^3_\Lambda$H. The BDT is a supervised learning algorithm that determines how to discriminate between two or more classes, signal and background in this case, by examining sets of examples called the training sets. In this analysis, the training sets are composed of $^3_\Lambda$H signal candidates extracted from the MC sample and background candidates from paired like-sign ^{3}He and π tracks from the data. For each $^3_\Lambda$H candidate, the BDT combines topological and single track variables to return a score, which is proportional to the candidate probability of being signal or background. The selection is based on the BDT score, defining a threshold that maximises the expected signal significance assuming thermal production. In this analysis the default BDT score selection corresponds to a 72% signal efficiency and a 3x10^{-5} background rejection factor. The candidates that pass the BDT selection are used to populate the invariant mass distribution in the transverse momentum interval $0 < p_{\rm T} < 9$ GeV/c. An excess of entries is observed at a mass near 2.99 GeV/c^2, as shown in Fig. 1. The unbinned distribution is fitted with a Kernel Density Estimator (KDE) [52, 53] function tuned on the MC sample to describe the signal and a linear function to describe the background component. The KDE is chosen for smoothing the template extracted from the MC. The invariant mass distribution with the superimposed fit is shown in Fig. 1.

The significance associated with the signal is evaluated following the procedure described in [54]: the probability for a background fluctuation to be at least as large as the observed maximum excess (local p-value) is computed by employing the asymptotic formulae for likelihood-based tests. The local p-value is expressed as a corresponding number of standard deviations using the one-sided Gaussian tail convention. The excess of entries observed above the expected background has a local significance of

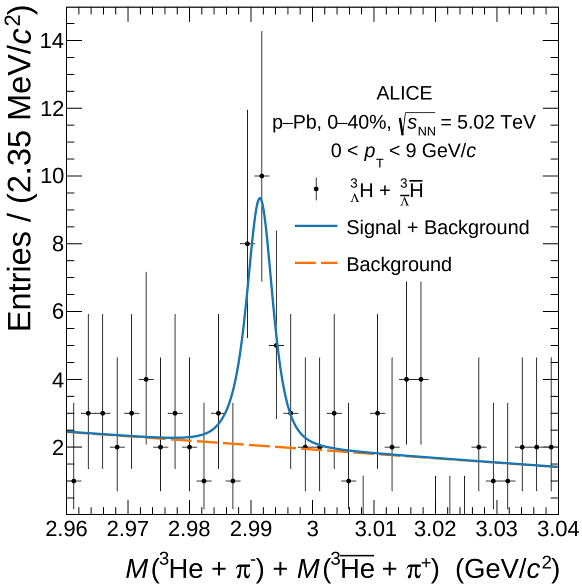

Figure 1: Invariant mass distribution of the $^3\mathrm{He}+\pi^-$ and charge conjugate pairs passing the analysis selections. Vertical lines represent the statistical Poissonian uncertainties. The invariant mass spectrum is fitted with a two-component model: the blue line represents the total fit while the orange dashed line shows the background component only.

4.6 standard deviations at the nominal $^3_\Lambda$H mass. The production yield is obtained starting from the signal extracted from the fit to the invariant mass spectrum. Then the fitted signal is corrected for the reconstruction and the selection efficiency, including reconstruction efficiencies for the daughter particles and the topology, the acceptance of the ALICE detector, the number of analysed events, the branching ratio (B.R.) of the $^3_\Lambda$H in the two-body decay channel and the fraction of $^3_\Lambda$H that are absorbed in the ALICE detector ($f_{\rm abs}$). The simulation of inelastic interactions of the daughter particles is done with GEANT4 and is taken into account in the reconstruction efficiency computation. The B.R. value is assumed to be 0.25 according to the calculation published in [55].

The systematic uncertainties originate from (1) the $^3_\Lambda$H selection and the signal extraction, (2) the choice of the $^3_\Lambda$H input $p_{\rm T}$ distribution in the Monte Carlo sample, and (3) the $^3_\Lambda$H absorption in the detector. In addition (4), a 9% systematic uncertainty is added due to the uncertainty of the B.R. as explained later in the text. The total uncertainty is obtained as the quadratic sum of the individual contributions. The first contribution, which is the dominant one, is computed by varying simultaneously the BDT threshold ($\pm$5%) and the background fit function (constant, linear, exponential). The standard deviation (RMS) of the different yields represents our systematic error associated with the BDT selection and the signal extraction, and it amounts to 14%. The second contribution is evaluated by using different input $p_{\rm T}$ distributions for the Monte Carlo sample and evaluating the effects on the efficiency. Four different $p_{\rm T}$ models ($m_{\rm T}$ exponential, $p_{\rm T}$ exponential, Boltzmann and Blast Wave [56]) are fitted to the ^{3}He $p_{\rm T}$ distribution [5]. For each of them the efficiency and the yield are computed assuming that the ^{3}He and the $^3_\Lambda$H have the same $p_{\rm T}$ distributions as already seen for light flavour hadrons with similar masses in all collision systems [1, 45, 57]. The RMS among the trials is calculated, yielding a systematic uncertainty of 7%. Finally, the uncertainty of $f_{\rm abs}$ is considered. According to [58], the expected absorption cross section of $^3_\Lambda$H due to the inelastic interactions in the ALICE detector material is $\approx$ 1.5 times that of $^3\overline{\rm He}$ ($\sigma^{^3\overline{\rm He}}_{\rm inel}$). The value of $f_{\rm abs}$ is computed by simulating the passage of hypertritons through the ALICE detector using this cross section and gives a result of $\approx$ 3%. The systematic uncertainty of $f_{\rm abs}$ is evaluated by employing different cross sections for the $^3_\Lambda$H from zero (no interactions) to $2\sigma^{^3\rm He}_{\rm inel}$. For each variation $f_{\rm abs}$ is recalculated. This results in a systematic uncertainty on the yield of about 4%. Larger variations of the inelastic cross section are here not considered as they spoil the exponential trend of the proper

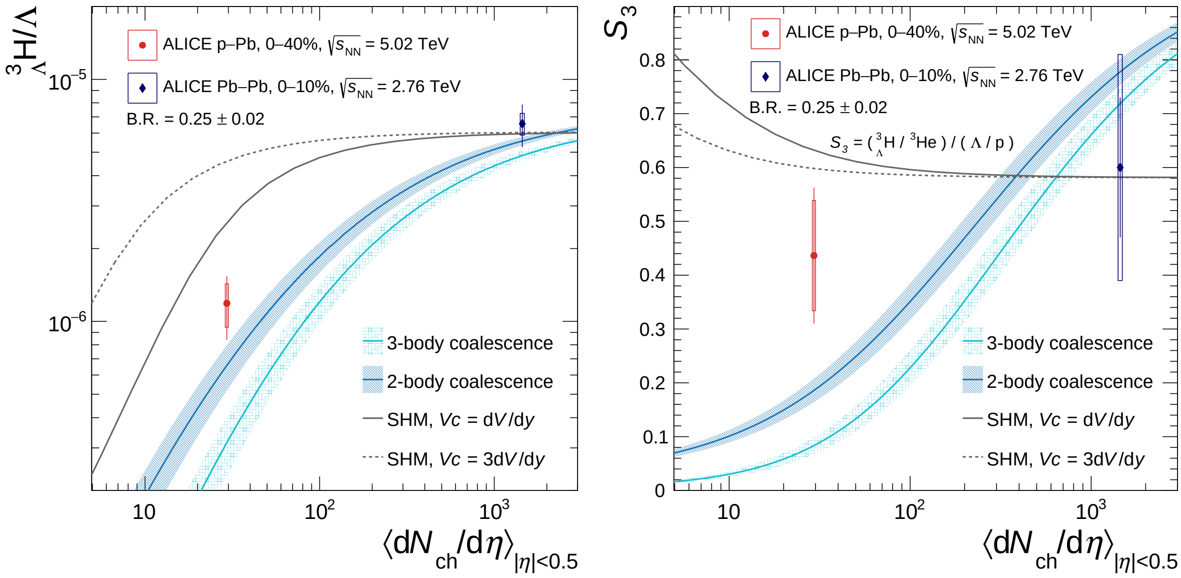

Figure 2: $^3_\Lambda$H/Λ (on the left) and S_3 (on the right) measurements in p–Pb (in red) and Pb–Pb collisions [45] (in blue) as a function of mean charged-particle multiplicity. The vertical lines and boxes are the statistical and systematic uncertainties (including the uncertainty on the B.R.), respectively. The expectations for the canonical statistical hadronization [25] and coalescence models are shown [23].

decay length spectrum measured in Pb–Pb collisions.

The resulting corrected $^3_\Lambda$H yield in the rapidity interval $-1 < y < 0$ together with its statistical and systematic uncertainties is

$$\frac{{\rm d}N}{{\rm d}y} = [6.3 \pm 1.8({\rm stat.}) \pm 1.2({\rm syst.})]{\rm x}10^{-7}.$$

The result is compared with the expectations from the canonical SHM [25], which assumes exact conservation of baryon number, strangeness, and electric charge across a correlation volume V_c. The SHM predictions are computed using a fixed chemical freeze-out temperature of $T_{\rm chem}$ = 155 MeV and two correlation volumes extending across one unit ($V_c = {\rm d}V/{\rm d}y$), and three units ($V_c = 3{\rm d}V/{\rm d}y$) of rapidity [25]. The size of the correlation volume governs the influence of exact quantum number conservation, with smaller values leading to a stronger suppression of conserved charges and $V_c \to \infty$ leading to the grand canonical ensemble. The $^3_\Lambda$H $p_{\rm T}$ integrated yield is 1.1x10^{-6} and 2.0x10^{-6} with $V_c = {\rm d}V/{\rm d}y$ and $V_c = 3{\rm d}V/{\rm d}y$, respectively. The ${\rm d}N/{\rm d}y$ predictions by the model were obtained using the code released together with the publication [59].

As explained above, in the case of the coalescence model it is not possible to compare directly the measured absolute yield to the model prediction. Hence, this comparison is attained by computing the $^3_\Lambda$H /Λ ratio and the strangeness population factor $S_3 = (^3_\Lambda{\rm H}/^3{\rm He})/(\Lambda/{\rm p})$ [60] using previous ALICE measurements of p, Λ, and ^{3}He yields [5, 57], as shown in Fig. 2. The yield of the Λ baryon, measured in $-0.5 < y < 0$, has been extrapolated to the $^3_\Lambda$H rapidity region using MC generators [61–63] that are known to reproduce the pseudorapidity density distribution of charged hadrons [64]. The corresponding correction is approximately 2%. In central Pb–Pb collisions the data are consistent with both coalescence and SHM predictions, which are similar, as shown in Fig. 2. The situation is different for p–Pb collisions where the two models are well separated. Taking into account the uncertainties of the measurement as well as the model uncertainty, the measured S_3 ratio is compatible with the two-body (deuteron-Λ) and three-body (proton-neutron-Λ) coalescence within 1.2σ and 2σ, respectively. With its large uncertainties, also due to the large uncertainty on the ^{3}He yield, the S_3 is compatible within 2σ with the SHM calculations too. Hence, the $^3_\Lambda$H /Λ ratio is used as a test for coalescence and SHM predictions in the following. In this case, the measurement is deviating by 3.2σ and 7.9σ from the SHM with $V_c = 1\mathrm{d}V/\mathrm{d}y$ and $V_c = 3\mathrm{d}V/\mathrm{d}y$, respectively. On the other hand, both the coalescence calculations are within 2σ of the measured ${}^{3}_{\Lambda}$H /Λ. It has to be noted that recent measurements of the ${}^{3}_{\Lambda}$H mass [34] suggest a larger binding energy, and hence a smaller wave function, of the ${}^{3}_{\Lambda}$H. This would further shift upward the coalescence predictions.

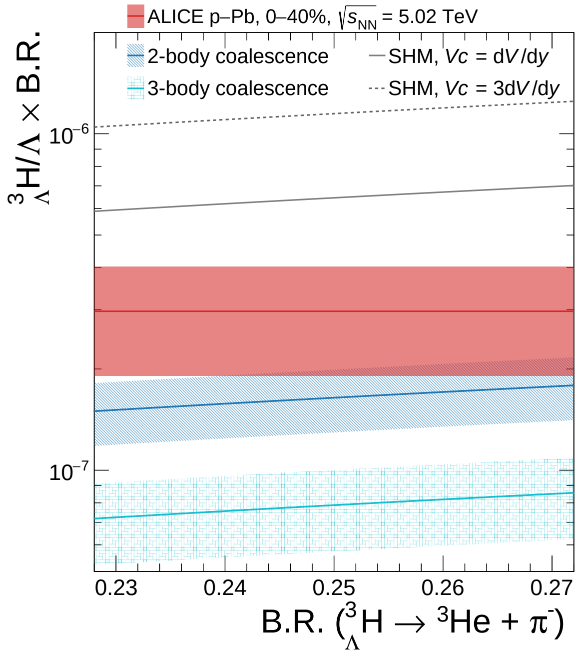

Figure 3: ${}^{3}_{\Lambda}$H/Λ times branching ratio as a function of branching ratio. The horizontal line is the measured value and the band represents statistical and systematic uncertainties added in quadrature. The expectations for the canonical statistical hadronization [25] and coalescence models are shown [23].

The value of B.R. = 0.25 for the ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi$ decay used in this analysis was computed theoretically in Ref. [55]. To investigate the uncertainty resulting from this assumption, Fig. 3 shows the measured ${}^{3}_{\Lambda}$H/Λ $\times$ B.R. for different theoretical model calculations [23, 25] assuming a possible variation of the B.R. value. The variation range is chosen by evaluating the relative deviation between the theoretical R_3 and the world average of all the R_3 measurements including the most recent measurement in heavy-ion collisions [65], where R_3 is defined as:

$$\mathrm{R}_3 = \frac{\Gamma({}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^-)}{\Gamma({}^{3}_{\Lambda}\mathrm{H} \rightarrow \text{all } \pi^- \text{ decay channels})}.$$

This uncertainty on R_3 is propagated to the B.R.$({}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^-)$ and corresponds to a variation range of $\pm 9\%$ around the nominal value. While the two-body coalescence calculation is compatible with the data for the nominal or larger B.R., a discrepancy of 2σ is observed between data and the three-body coalescence prediction. Furthermore, in the whole B.R. variation interval, the SHM is more than 2.7σ and 6.9σ away from the measured ${}^{3}_{\Lambda}$H/Λ $\times$ B.R. for the $V_c = 1\mathrm{d}V/\mathrm{d}y$ and $V_c = 3\mathrm{d}V/\mathrm{d}y$ configurations, respectively.

In summary, the first measurement of the production yield of hypertriton in p–Pb collisions at the LHC is reported. The measurements of yields of ${}^{3}_{\Lambda}$H in p–Pb collisions provide an opportunity to potentially discriminate between nucleosynthesis models. The measured p_{T} integrated yield excludes, with high significance, canonical versions of the SHM with $V_c \geq 3\mathrm{d}V/\mathrm{d}y$ to explain the (hyper)nuclei production in p–Pb collisions. It remains to be seen if advanced versions of the SHM using the S-matrix approach to account for the interactions among hadrons [66] will be able to solve this discrepancy. The ${}^{3}_{\Lambda}$H/Λ ratio is well described by the two-body coalescence prediction, while the three-body formulation is slightly disfavoured by our measurement. While the general conclusions of the comparison with the models are unaltered even when considering large variations of the B.R.($^{3}_{\Lambda}$H $\rightarrow$ ^{3}He + π^{-}) around the value available in literature, the significance of the comparison between data and models is influenced by this uncertainty. Upcoming studies using the LHC Run 2 Pb–Pb data will help to reduce this uncertainty by measuring the $^{3}_{\Lambda}$H $\rightarrow$ d + p + π^{-} decay channel relative branching ratio. Furthermore, with the upgraded ALICE apparatus and the upcoming LHC Run 3, it will be possible to reduce both the statistical and the systematic uncertainties of the $^{3}_{\Lambda}$H yield measurements in pp [67] and p–Pb collisions and to study the $^{3}_{\Lambda}$H production as a function of the size of the nucleon-emitting source measured with femtoscopic correlations. These studies may make it possible to decisively distinguish between the two production models.

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