

Thermal production of sexaquarks in heavy-ion collisions

David Blaschke

*Institute of Theoretical Physics, University of Wrocław,
Max Born Pl. 1, 50-204 Wrocław, Poland,
Bogoliubov Laboratory of Theoretical Physics,
Joint Institute for Nuclear Research (JINR),
Joliot-Curie Street 6, 141980 Dubna, Russia
National Research Nuclear University (MEPhI),
Kashirskoe Shosse 31, 115409 Moscow, Russia*

Larissa Bravina

*University of Oslo,
P. O. Box 1048, Blindern, N-0316 Oslo, Norway*

Kyrill Bugaev

*Bogolyubov Institute for Theoretical Physics,
Metrologichna Street 14B, Kyiv 03680, Ukraine
Department of Physics, Taras Shevchenko National University of Kyiv,
03022 Kyiv, Ukraine*

Glennys R. Farrar

*Department of Physics, New York University,
New York, NY, USA*

Boris Grinyuk

*Bogolyubov Institute for Theoretical Physics,
Metrologichna Street 14B, Kyiv 03680, Ukraine*

Oleksii Ivanytskyi

*Institute of Theoretical Physics, University of Wrocław,
Max Born Pl. 1, 50-204 Wrocław, Poland
Bogolyubov Institute for Theoretical Physics,
Metrologichna Street 14B, Kyiv 03680, Ukraine*

Sonia Kabana*

*Instituto de Alta Investigación, Universidad de Tarapacá,
Casilla 7D, Arica, Chile
sonja.kabana@cern.ch*

*Corresponding author.

Sergey V. Kuleshov

*Universidad Andrés Bello, Avenida Republica 237,
Santiago, Chile*

*Millennium Institute for SubAtomic Physics
at the High-energy Frontier (SAPHIR) of ANID, Santiago, Chile*

Irina K. Potashnikova

*Departamento de Física, Universidad Técnica Federico Santa María,
Avenida España 1680, Valparaíso, Chile*

Violetta Sagun

*CFisUC, Department of Physics, University of Coimbra,
Coimbra 3004-516, Portugal*

*Bogolyubov Institute for Theoretical Physics,
Metrologichna Street 14B, Kyiv 03680, Ukraine*

Arkadiy Taranenko

*National Research Nuclear University (MEPhI),
Kashirskoe Shosse 31, 115409 Moscow, Russia*

Oleksandr V. Vitiuk

*Department of Physics, Taras Shevchenko National University of Kyiv,
03022 Kyiv, Ukraine*

Evgeny Zabrodin

*University of Oslo, P. O. Box 1048,
Blindern, N-0316 Oslo, Norway*

*Skobeltsyn Institute of Nuclear Physics (SINP),
Moscow State University, RU-119899 Moscow, Russia*

Xiaoming Zhang

*Central China Normal University,
Wuhan, Hubei 430079, P. R. China*

Daicui Zhou

*Central China Normal University, Wuhan,
Hubei 430079, P. R. China*

*Key Laboratory of Quark and Lepton Physics, Ministry of Education,
Wuhan, Hubei 430079, P. R. China*

*Institute of Particle Physics, Central China Normal University,
Wuhan, Hubei 430079, P. R. China*

Received 20 April 2021

Revised 15 July 2021

Accepted 26 July 2021

Published 23 September 2021

We present new results on the thermal production yield of a hypothetical state made of six quarks $uuddss$ assuming its production in heavy-ion collisions at the CERN Large Hadron Collider (LHC). A state with this quark content and mass low enough to be stable against decay in timescales of the order of the age of the Universe has been hypothesized by one of us (G. Farrar) and has been discussed as a possible dark matter candidate. In this work, we address for the first time the thermal production rate that can be expected for this state in heavy-ion collisions at colliders. For this estimate we use a thermal model which has been shown to describe accurately the production of hadrons and nuclei in heavy-ion collisions at LHC energy. This estimate is of great relevance for sexaquark searches at colliders as well as for its consideration as a dark matter candidate and for the composition of neutron stars.

Keywords: Dark matter; particle physics; search for new particles; multiquark states; heavy-ion collisions.

1. Introduction

The papers on quarks by Gell-Mann and Zweig opened the possibility that hadrons with more than the minimal quark content ($q\bar{q}$ or qqq) could exist.^{1,2} In recent years, experiments have discovered some multiquark states, demonstrating that such states do exist in nature and they are currently included in the Review of Particle Properties.³ Among them, we mention as an example the first observation of pentaquark states by the LHCb Collaboration that was not opposed by other experiments via a nonobservation with upper limits conflicting the measured cross-sections.^{4,5} In the analysis of $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays, they observed narrow peaks in the $J/\psi p$ mass spectrum and further analysis led to the discovery of the $P_c(4380)$, $P_c(4440)$, $P_c(4457)$ and $P_c(4312)$ ⁶ pentaquark states with valence quark content $uuds\bar{c}$, which are listed in Ref. 3.

Furthermore, the LHCb Collaboration reported in 2021 a structure seen in the $J/\psi\Lambda$ invariant mass distribution at a mass of $4458.8 \pm 2.9_{-1.1}^{+4.7}$ MeV (with statistical and system errors, respectively) obtained from an amplitude analysis of $\Xi_b^- \rightarrow J/\psi\Lambda K^-$ decays.⁷ To mention a recent result on tetraquarks from another experiment, in 2021, the BESIII Collaboration reported the discovery of an exotic tetra-quark structure, the $Z_{cs}(3985)$, produced in $e^+e^- \rightarrow K^+(D_s - D_0^* + D_s^* - D_0)$ at center-of-mass energy of 4.68 GeV and has a minimal $c\bar{c}s\bar{u}$ four-quark substructure.⁸ Apart from the above given few examples from experimental findings on multiquark states, for a review on discovered multiquark states or multiquark state candidates we refer to the reviews for exotic hadrons in the Particle Data Group³ and to the review in Ref. 9.

Among the multiquark states the neutral flavor singlet multiquark state $uuddss$ has been long discussed as an interesting multiquark candidate, because it is expected to be tightly bound, as first discussed by Jaffe.¹⁰ Using a bag model, Jaffe estimated that the $uuddss$ state is expected to have a mass around 2150 MeV, making it strong interaction stable but allowing first-order weak decay into $\Lambda + p + \pi^-$. Jaffe named the $uuddss$ candidate with such characteristics, the $H0$ dibaryon. A number of experiments have searched for such a state and did not find it. But they have set upper limits to its existence, see, e.g. Refs. 11–16.

It has been recently proposed by one of us (G. Farrar), that a color-flavor-spin-singlet multiquark state made of $uuddss$ quarks may exist, with a hard-core radius of $\sim 0.1\text{--}0.4$ fm and mass lower than 2 GeV, in which case it would be stable or have a lifetime greater than the age of the Universe.^{17–19} In addition, such a $uuddss$ state would couple weakly to hadrons because of its flavor singlet nature that excludes coupling to pions.^{17–19}

In that case, because of its weak coupling matter and its stability, the $uuddss$ state has escaped observation in experiments till now, since experiments in the past searched for the $H0$ dibaryon with the characteristics as discussed by Jaffe. Therefore, the upper limits set by these experiments do not apply to a $uuddss$ state with the above discussed characteristics.^{17–19}

For the above reasons the $uuddss$ state with such characteristics was proposed by one of us (G. Farrar) as a possible dark matter candidate.^{17–19} To distinguish the low mass stable and compact $uuddss$ state from the weakly decaying $uuddss$ state of Jaffe, Farrar proposed the name sexaquark (S).

As discussed by Farrar in Ref. 19, assuming that dark matter is made of equal numbers of u , d and s quarks (in any form, namely it could be a small object as a sexaquark but also a big one like a quark star) leads to an estimated ratio of dark matter to ordinary matter which agrees within a factor of 2 with the measured ratio of dark matter to ordinary matter in the Universe, for the whole range of masses shown in Fig. 2 of Ref. 19; namely 1850–1890 MeV and for quantum chromodynamics (QCD) phase transition temperature of 140–170 MeV. This is a very interesting similarity of predicted and observed values of the dark matter to baryon abundances, suggesting that maybe objects made out of u , d , s quarks can be at the origin of dark matter in the Universe since there is *a priori* no reason why the numbers shown in Fig. 2 of Ref. 19 agree with each other, while they could be different by many orders of magnitude.^a We note that the recent result for T_c of the QCD phase transition, obtained from recent simulations of lattice QCD, is 156.5 ± 1.5 MeV.²⁰ However, the small statistical error of this result cannot be mismatched with the width of the crossover transition region that can be estimated from the full width at half maximum of the chiral susceptibility and which is at least one order of magnitude larger.

Questions have been raised in the literature as to the possibility that the sexaquark can be a candidate for dark matter (see, e.g. Ref. 22). However, this possibility is not excluded since the authors of Ref. 22 neglected to take into account the robustness of sexaquarks in the hot hadronic phase against breakup to baryons, which follows if the sexaquark is very compact and/or there is a high potential barrier for reconfiguring the quarks.

^aAs shown in subsequent work, within the uncertainties of the calculation and nature of the evolution from the quark–gluon plasma to the hadronic phase as chiral symmetry breaking and confinement turn on, the range of sexaquark masses which can be compatible with the observed dark-matter-to-baryon ratio is larger, possibly from 1700 MeV to 2 GeV. Note a minor plotting error in Ref. 19 which is corrected in Ref. 21.

Experiments aim to explore all possibilities to discover dark matter and started searching for a possible stable sexaquark. In particular, the BABAR Collaboration was the first experimental collaboration that performed a search for sexaquarks and published an upper limit on its production in Upsilon decays.²³ In this search they explored the detection method proposed in Ref. 17, namely to search for the S state via the Upsilon decay in Upsilon factories, as missing mass due to the S or $\bar{S}$ production in association with di-anti-Lambda or di-Lambdas: $\Upsilon \rightarrow S\bar{\Lambda}\bar{\Lambda}$ or $\bar{S}\Lambda\Lambda$ + pions and/or photons. The BABAR Collaboration observed no signal in the exclusive $S\bar{\Lambda}\bar{\Lambda}$ + charge conjugate channel and published the 90% confidence level limits on the branching fraction $\Upsilon(2S, 3S) \rightarrow S\bar{\Lambda}\bar{\Lambda}$ to be $(1.2-1.4) \cdot 10^{-7}$ for a mass of the S below 2.05 GeV.

Comparing this result to expectations, the predicted¹⁷ *inclusive* branching fraction of S in Upsilon decays is of the order $\sim 10^{-7}$. The exclusive to inclusive ratio for Upsilon decay is typically $\lesssim 10^{-4}$, so no exclusive signal would have been expected at the level of sensitivity of BABAR which is 10^{-7} in the exclusive channel as discussed in Ref. 17.

In this paper, we estimate for the first time the production yield of the sexaquark in heavy-ion collisions at the LHC assuming a thermal production of the sexaquark.

We use a model for thermal production of hadrons and nuclei in heavy-ion collisions which has successfully described data at the LHC and other collision energies.²⁴⁻²⁶ In Sec. 2, we describe the model and in Sec. 3 we present the results and their discussion ending in Sec. 4 with conclusions and outlook.

2. The Hadron Resonance Gas Model with Multicomponent Hard-Core Repulsion

The hadron resonance model with induced surface tension which allows us to treat the hard-core repulsion of hadrons and light (anti-)nuclei has been developed by some of us and is discussed in detail in Refs. 24–29. The model was designed for an accurate description of multicomponent hadron mixtures. The effects of hard-core repulsion are known to be important for such systems. Within the present approach their treatment beyond the Van der Waals approximation is provided by attributing a part of the interparticle repulsion to the induced surface tension coefficient Σ . It is remarkable that regardless the number of particle species in the grand canonical ensemble this quantity is defined along with the system pressure p as a solution of the system of two coupled equations (we use the natural units, i.e. speed of light $c = 1$, the Planck constant $\hbar = 1$ and the Boltzmann constant $k_B = 1$ are set to a unity):

$$p = T \sum_{k=1}^N \phi_k \exp \left[\frac{-v_k p - s_k \Sigma}{T} \right], \quad (1)$$

$$\Sigma = T \sum_{k=1}^N R_k \phi_k \exp \left[\frac{-v_k p - s_k \alpha \Sigma}{T} \right]. \quad (2)$$

The summation in this expressions is performed over all particle species labeled by k . Each of them is assigned an own proper volume $v_k = \frac{4}{3}\pi R_k^3$ and surface area $s_k = 4\pi R_k^2$ expressed through the corresponding hard-core radius R_k . The parameter α plays a crucial role within the present approach. It accounts for the higher-order virial coefficient of the equations of state (1) and (2). In Refs. 24 and 25, it was found that in the limit of Boltzmann statistics, $\alpha = 1.25$ reproduces the third and the fourth virial coefficient of the gas of hard spheres, while the widely used Van der Waals prescription is consistent only with the second one. It is important to note, that the description of hadronic mixtures with the Boltzmann statistics is well justified at the LHC energies since the corresponding particle occupation numbers are high. Accounting for this fact, we can write the thermal density of the k th hadron species as

$$\phi_k = \frac{g_k}{N_k(M_k^{\text{Th}})} \int_{M_k^{\text{Th}}}^{\infty} \frac{dm \Gamma_k}{(m - m_k)^2 + \Gamma_k^2/4} \times \int \frac{d^3p}{(2\pi)^3} \exp \left[\frac{\mu_k - \sqrt{p^2 + m^2}}{T} \right]. \quad (3)$$

This includes the spin-isospin degeneracy factor of the k th particle species g_k as well as its chemical potential μ_k . The Breit-Wigner attenuation in Eq. (3) accounts for a finite width Γ_k of hadron resonances with mass m_k . The lower limit M_k^{Th} of the mass integration in Eq. (3) stands for the decay threshold mass of the corresponding hadrons in the dominant channel. The factor

$$N_k(M_k^{\text{Th}}) \equiv \int_{M_k^{\text{Th}}}^{\infty} \frac{dm \Gamma_k}{(m - m_k)^2 + \Gamma_k^2/4} \quad (4)$$

provides a proper normalization of the mass distribution function. A special comment should be made with respect to the chemical potential μ_k of the k th particle species. Hadronic systems produced in the collisions at such high energies as under LHC conditions are characterized by the almost perfect symmetry between particles and antiparticles. This leads to a vanishing of the corresponding chemical potentials.^{24,25} In Eq. (3) they, however, are kept for the convenience of the calculations, while in our analysis we set $\mu_k = 0$.

Having Eqs. (1) and (2) solved for a given value of temperature T , the particle number density of the k th hadron species can be found with the help of the thermodynamic identity $\rho_k = \frac{\partial p}{\partial \mu_k}$. This number density gives a direct access to the thermal yields of particles $N_k^{\text{th}} = V \rho_k$, defined through the effective volume of the system at chemical freeze out (CFO) V . Since inelastic reactions cease to occur after CFO, the particle decays are no longer compensated by their inverse processes. As a result the total yields of particles N_k^{tot} differ from the thermal ones. The corresponding modification can be done using the branching ratios $\text{Br}_{l \rightarrow k}$, i.e. the probability of a particle l to decay strongly into a particle k . The total particle

multiplicities allow us to define the particle yield ratios, which are independent on the CFO volume, i.e.

$$\frac{N_k^{\text{tot}}}{N_j^{\text{tot}}} = \frac{\rho_k + \sum_{l \neq k} \rho_l \text{Br}_{l \rightarrow k}}{\rho_j + \sum_{l \neq j} \rho_l \text{Br}_{l \rightarrow j}}. \quad (5)$$

These ratios can be compared to the experimental data, while the temperature should be adjusted in order to provide the best agreement. In our analysis we used the values of hadronic hard-core radii found in previous works, while the hard-core radius of the sexaquark was analyzed independently. More details on the fitting procedure of experimental data with the hadron resonance gas model (HRGM) can be found in Refs. 24–26.

3. Results

In this paper, we show results on the ratio of thermal sexaquark yields to thermal deuteron (d) yields and to thermal Omega (Ω) hyperon yields. This comparison aims to address two distinct cases, in particular in order to study two different expected times of freeze out, for each of the Ω hyperon and the deuteron, which is related to their internal structure.

Namely, we consider the case of the nuclei, like the deuteron which are expected in principle to build at a late stage of the collision through coalescence of nucleons and second, the case of the Ω hyperon which is expected to have a CFO at an earlier stage of the evolution of the hadronization.³⁰ We consider these two cases as kind of two distinct freeze out assumptions in which the sexaquark production can be assumed.

In Fig. 1, we show the result of the thermal model calculation for the production of sexaquarks in Pb + Pb collisions at the LHC at CERN for a center-of-mass energy of $\sqrt{s_{\text{NN}}} = 2.76$ TeV. The y -axis shows the ratio of the thermal production yield of sexaquarks to the thermal production yield of selected hadrons and nuclei, as a function of the temperature of the thermal particle source, assuming the mass of the sexaquark to be 1700 and 1950 MeV. We will explore a larger range of masses in future work.

In both figures, the upper two lines show the ratio of thermal sexaquark yields to thermal deuteron yields, and the two lower lines show the ratio of thermal sexaquark yields to thermal Ω hyperon yields. The variable denoted by R is the assumed hard-core radius of the sexaquark. From top to bottom, each line corresponds to $R = 0, 0.4, 0, 0.4$ fm. The lines corresponding to $R = 0$ fm case show the thermal model result for pointlike particles. We will explore a larger range of R values a sexaquark masses in future work.

The range of temperatures studied here is between 140 and 180 MeV, which is a relevant range for the temperature of the QCD phase transition that is expected to have occurred in the early Universe and can be reproduced in small scale today in the laboratory when colliding high-energy heavy ions in accelerators. The particle

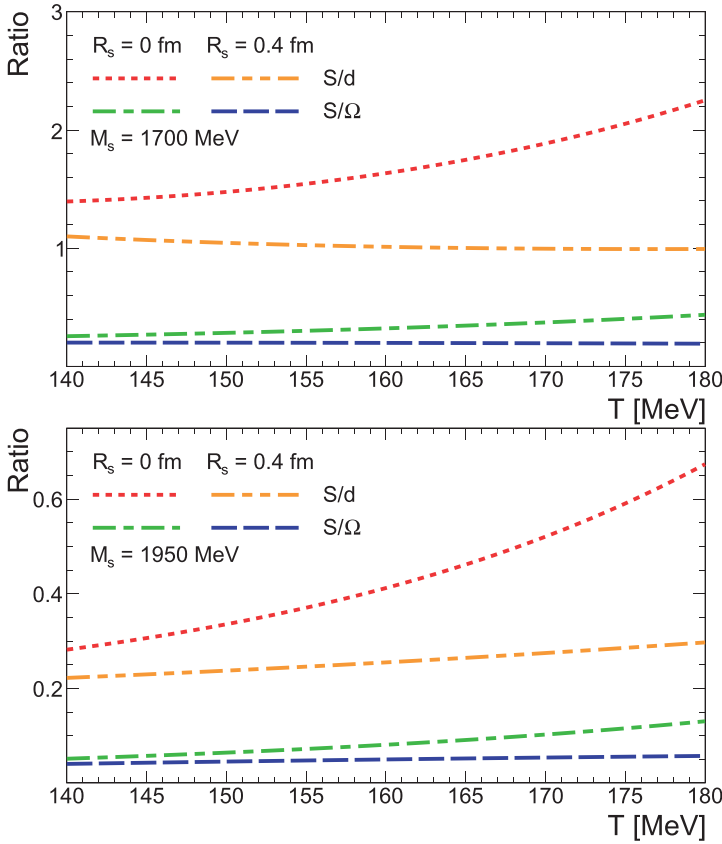


Fig. 1. Ratio of thermally produced sexaquarks to thermally produced hadrons and nuclei, as a function of the temperature of their thermal particle source, assuming the mass of the sexaquarks to be 1700 MeV (upper picture) and 1950 MeV (lower picture). The two upper lines show the ratio of thermal sexaquarks to thermal deuterons, whereas the two lower lines show the ratio of thermal sexaquarks to thermal Ω hyperons. The R parameter shown on the lines is the assumed hard-core radius of the sexaquark.

source in Pb + Pb collisions at the center-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV at LHC was found in previous papers analyzing hadron production in these reactions to be characterized by a temperature of about 150 MeV.

We find that the ratio of the thermal sexaquarks to thermal light nuclei and strange hadrons varies between about 0.2 and 1.4 for the sexaquark mass of 1700 MeV, and between about 0.05 and 0.27 MeV for the sexaquark mass of 1950 MeV. In particular the ratio of the thermal sexaquark yields to thermal deuteron yields is about 1.1 to 1.4 for the sexaquark mass of 1700 MeV, and between 0.22 and 0.27 for for the sexaquark mass of 1950 MeV. The ratio of the thermal sexaquark yields to thermal Ω hyperon yields is about 0.2–0.25 for the sexaquark mass of 1700 MeV, and about 0.05 for the sexaquark mass of 1950 MeV. The ratio to thermal Ω hyperon yields is rather similar for pointlike and nonpointlike

cases as compared to the ratio to the thermal deuteron yields, especially at lower temperatures.

Furthermore, we observe that the dependence of the ratio of the thermal sexaquark yields to thermal light nuclei and strange hadron yields has a weak dependence on the temperature except for the case of pointlike particles ($R = 0$) in which case the ratio rises with temperature. The expected CFO temperature of the Pb+Pb system at the center-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV is about 150 MeV. For the sexaquark mass of 1700 MeV and at the temperature of 150 MeV, the ratio of the thermal sexaquark yields to the thermal light nuclei yields is around 1.45 for $R = 0$ fm and around 1.00 for $R = 0.4$ fm, while the ratio of the thermal sexaquark yields to thermal Ω hyperon yields is around 0.25 for $R = 0$ fm and around 0.20 for $R = 0.4$ fm. For the sexaquark mass of 1950 MeV and at the temperature of 150 MeV, the ratio of the thermal sexaquark yields to the thermal light nuclei yields is around 0.27 for $R = 0$ fm and around 0.22 for $R = 0.4$ fm, while the ratio of the thermal sexaquark yields to thermal Ω hyperon yields is around 0.05 for both $R = 0$ fm and around 0.04 for $R = 0.4$ fm.

In all cases the ratio of the thermal sexaquark yields to thermal light nuclei and strange hadron yields is quite high and therefore abundant production of thermal sexaquarks may be expected in heavy-ion collisions at LHC energies.

4. Conclusions and Outlook

A stable, compact $uuddss$ state has been proposed as a dark matter candidate by one of us (G. Farrar) and was named sexaquark in order to make clear the difference from previous theoretical works on a $uuddss$ state with different characteristics that was proposed as $H0$ dibaryon by R. Jaffe. If indeed there is a stable sexaquark and the amplitude for its breakup to two baryons is small as argued, then the experimentally measured ratio of Omega (dark matter)/Omega (matter) in the Universe can be very well reproduced, suggesting that (u, d, s) -symmetric matter of any form may be the source of dark matter in the Universe.

In this work, we estimate for the first time the thermal production rates of sexaquarks and in particular the ratios of thermal sexaquark states to thermal hadrons with the particular example of the Ω baryon, as well as to thermal light nuclei with the particular example of the deuteron, in heavy-ion collisions at a center-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV at the LHC. The study has been performed an assumed mass of 1700 and 1950 MeV for the sexaquark and for two cases of radii of the sexaquarks, $R = 0.0$ and 0.4 fm.

It is shown that sexaquarks may be produced at relatively high rates for both cases of the investigated radii of 0.0 and 0.4 fm. At 150 MeV, thermal sexaquarks with a mass of 1700 MeV are found to be produced with similar rate as thermal deuterons, and thermal sexaquarks with a mass of 1950 MeV are found to be produced with a rate of $1/4$ of the thermal deuterons, in Pb+Pb collisions at the center-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV at the LHC.

The estimated production rate of the sexaquark in heavy-ion collisions is of great interest for future searches of this hypothetical particle and may be relevant for other considerations about the role of the sexaquark in cosmological phase transitions and in neutron stars. We will explore a larger range of masses, hard-core radii R , collision systems and center-of-mass collision energies in future work.

Acknowledgments

The work of D.B. and O.I. was supported by the Polish National Science Center under Grant No. 2019/33/B/ST9/03059. D.B. received funding from the Russian Foundation for Basic Research (RFBR) under Grant No. 18-02-40137. K.B., O.I. and V.S. acknowledge partial support by the Section of Physics and Astronomy of the National Academy of Science of Ukraine under Grant No. 0118U003197. V.S. is also thankful for the support by the Fundação para a Ciência e Tecnologia (FCT), Portugal, under the project No. UID/04564/2021. L.B. and E.Z. acknowledge support by the Norwegian Research Council (NFR) under Grant No. 255253/F50, “CERN Heavy Ion Theory”, and by the RFBR under Grant Nos. 18-02-40084 and 18-02-40085. G.R.F. was supported in part by NSF-2013199. I.K.P. was supported in part by grants ANID — Chile FONDECYT 1170319, and ANID PIA/APOYO AFB180002. S. Kabana acknowledges partial support by ANID PIA/APOYO AFB180002 (Chile). S. Kuleshov and S. Kabana acknowledge partial support by the Millennium Institute for SubAtomic Physics at the High-energy Frontier (SAPHIR), ICN2019_044, ANID, Chile. S. Kuleshov acknowledge partial support by the grant FONDECYT 1191103, ANID, Chile. A.T. received funding by Russian Federation for Basic Research (RFBR) under Grant No. 18-02-40086 and was supported by the Ministry of Science and Higher Education of the Russian Federation, Project “Fundamental properties of elementary particles and cosmology”, under Grant No. 0723-2020-0041.

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