ON RESONANCE CONTRIBUTION TO BALANCE FUNCTIONS*

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It is known that resonance decays influence the shape of the charge-balance functions measured in hadronic collisions. That is reflected in their rapidity and azimuthal widths and the integral and, therefore, has consequences for different model interpretations. In this paper, we show that the contribution from neutral resonance decays can be removed from the balance function in an analytical way, and test the performance of the removal procedure with PYTHIA events. Prospects for applications of the procedure to real-data analysis of balance functions are also discussed.

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1. Introduction

Particle production in hadronic collisions is governed by conservation laws such as conservation of the local charge. The charge-balance function (BF) has been proposed as a convenient measure of the resulting correlations between the opposite charges in the momentum space [1]. It is defined as

$$\mathrm{BF}(\Delta y, \Delta\varphi) = \frac{1}{2}\left(\frac{\rho_2^{+-} - \rho_2^{++}}{\rho_1^{+}} + \frac{\rho_2^{-+} - \rho_2^{--}}{\rho_1^{-}}\right), \tag{1}$$

where ρ_1^a is a single-particle density, ρ_2^{ab} represents the density of particle pairs ($a, b = +, -$), and Δy and $\Delta\varphi$ are differences between two particles in rapidity and in azimuthal angle, respectively.

Balance functions are typically characterized by their shape, widths in Δy and $\Delta\varphi$, and by the integral that is the total probability to find the balancing charge within an experimental acceptance. The width of the balance function in rapidity could indicate the time of production of the pair of

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opposite charges and provide information about their subsequent transport in the hadronic medium [1–3], being affected, however, by multiple effects such as radial flow [4], quantum statistics [5], *etc.*

Balance functions for charged particles have been measured in Au–Au collisions at RHIC by STAR [6] and at the LHC energies in Pb–Pb, p–Pb and pp collisions by ALICE [7]. STAR measured balance functions also for the identified particles (charged kaons and pions) [6]. Recently, preliminary results for BF of kaons and pions in different colliding systems were presented by ALICE [8]. The common observation is that the pionic BF becomes narrower in Δy and $\Delta\varphi$ with centrality of A–A collisions, and it is usually advocated to be an indication that hadronization occurs only at the very late stage of the development of the system.

Influence of neutral resonance decays on the shape and the integral of the balance function was discussed, for instance, in [9]. It was found that the decays of the neutral resonances give about a half of the pion pairs in the rapidity window considered. In many papers, however, model interpretations of the balance functions are given without paying enough attention to the role of resonance decays and without quantitative estimation of their impact.

In this article, it is demonstrated how the contribution from neutral resonance decays can be analytically removed from the balance function in order to reveal the underlying BF shape. Prospects of application of the resonance removal procedure in real-data analysis are discussed as well.

2. Balance functions from different particle sources

Let us first consider charged-pion balance functions from different sources in PYTHIA 8 [10] in pp collisions at $\sqrt{s} = 2.76$ TeV. ALICE-like kinematic cuts $|y| < 0.8$ and $0.2 < p_{\mathrm{T}} < 2.0$ GeV$/c$ are adopted for pions. The two-dimensional BF shown in Fig. 1 (a) demonstrates a typical near-side peak as well as a broad ridge-like structure along $\Delta\varphi$, which is visible in pp collisions, but decreases in more central A–A collisions (see experimental 2D-plots for BF measured in ALICE in pp, p–Pb and Pb–Pb collisions [11]). However, there is no characteristic "dip" at $(\Delta y, \Delta\varphi) \approx (0, 0)$ in PYTHIA, since this dip is attributed to Bose–Einstein correlations that are not present in the generator events by default.

Relative abundances of charged pions originating from different sources are shown in Fig. 1 (b). Within the chosen acceptance, about 38% of pions originate directly from quarks or gluons (whatever this means in PYTHIA), while the rest of pions come from resonance decays. In particular, $\approx 35\%$ of all charged pions come from decays of *neutral* resonances ρ^0, ω and η. Corresponding balance functions from their decays are shown in Fig. 2. In each case, the shape of the function is determined solely by the decay kinematics, which in most cases corresponds to two-body decays into $\pi^+\pi^-$ (in the case of ω, the main channel is a three-body decay into $\pi^+\pi^-\pi^0$, with π^0 typically being invisible in analysis). Near the $(0,0)$ point, the BF for ρ^0 and ω demonstrate a characteristic volcano-like structure, which in the case of η decays is not visible due to the chosen binning of the histogram.

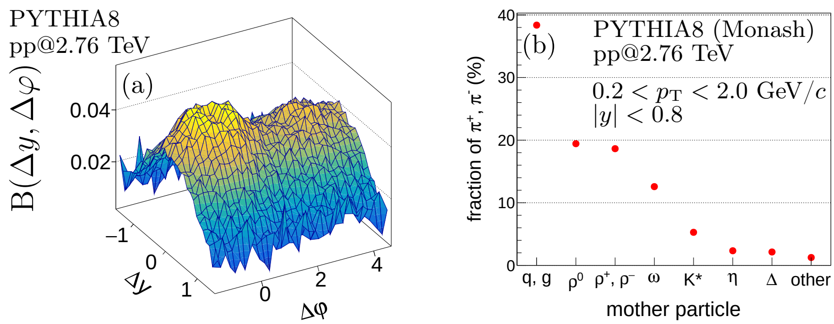

Fig. 1. (a) Two-dimensional balance function in PYTHIA 8 for pions within ALICE-like acceptance. (b) Fractions of charged pions within chosen kinematic cuts coming from different sources in PYTHIA 8.

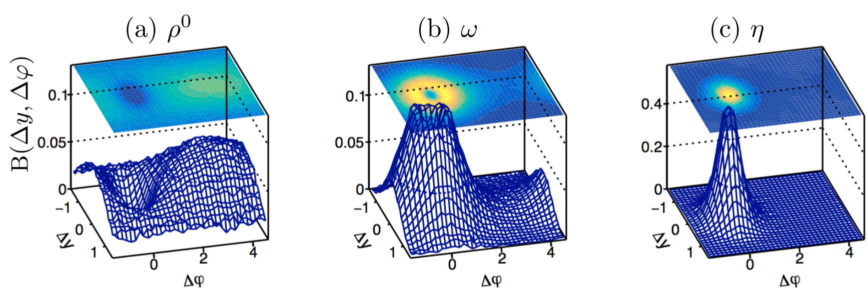

Fig. 2. Balance functions of pions coming solely from (a) ρ^0, (b) ω, and (c) η decays (PYTHIA 8, pions within ALICE-like acceptance).

Balance functions for other sources of pions in PYTHIA are shown in Fig. 3. BF for the case when only "primordial" pions from quarks and gluons are selected for analysis is shown in panel (a). The function demonstrates the absence of the near-side structure. Instead, there is actually a y-broadened structure at $\Delta\varphi = \pi$, which indicates back-to-back correlation between the opposite charges, possibly due to fragmentation of the quark–gluon strings.

Panel (b) of Fig. 3 shows BF for pions which originate exclusively from ρ^+ and ρ^- decays, neglecting other pions in events. In this case, there are no direct decay-induced correlations between charged pions — the correlation is possible only via intrinsic correlations between ρ^+ and ρ^- themselves. As a consequence, the shape of the BF is significantly flatter than for the case of neutral resonance decays, indicating much weaker correlation between π^+ and π^-. Similar conclusion is valid for panel (c), where pionic BF is constructed exclusively from decay products of all types of Δ hyperons.

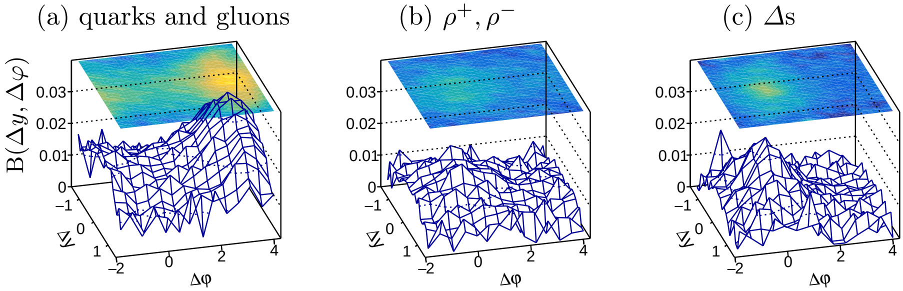

Fig. 3. Pionic balance functions from other sources: (a) quarks and gluons, (b) ρ^+ and ρ^-, (c) Δ hyperons (PYTHIA 8, pions within ALICE-like acceptance).

Figure 4 shows projections on Δy and $\Delta\varphi$ of all-pion BF (solid line) as well as exclusive balance functions for several pion sources. It can be seen that the shapes of the functions are significantly different, especially in the $\Delta\varphi$ projection, where BF from ρ^0 demonstrates a strong depletion at $\Delta\varphi$ around zero, while in the case of ω decays, there is a peak. BF for "primordial" pions from quarks and gluons has a "bump" at $\Delta\varphi \sim \pi$ mentioned above.

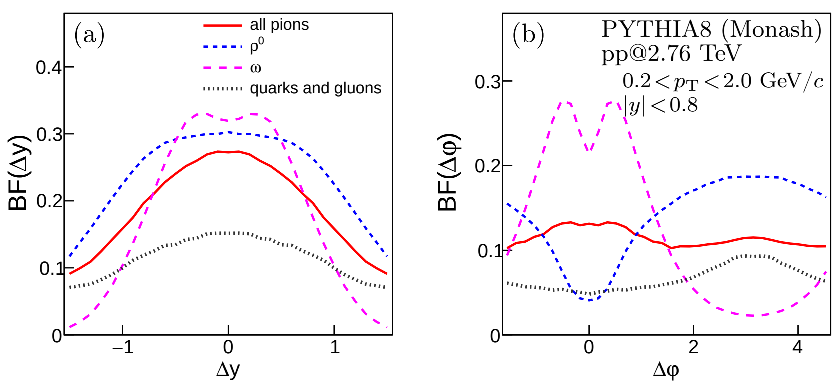

Fig. 4. (Color online) Projections of the balance functions on (a) Δy and (b) $\Delta\varphi$: solid red lines — BF measured for all pions in events, dashed blue lines — for pions from ρ^0 decays, long-dashed magenta lines — for pions from ω decays. Dotted gray lines — BF for pions from quarks and gluons.

3. Removal of the neutral resonance contributions from BF

By measuring the balance functions in the experiment, we would like to get insight into the mechanisms of opposite-charge pair production, their transport and diffusion in quark–gluon medium, time of hadronization and so on. It is also known that decays of resonances in the final state have a strong contribution to the BF and, therefore, in some sense, they distort the signals we desire to measure. It turns out, however, that it is possible, in principle, to "purify" the BF from impact of the *neutral* resonance decays, the corresponding procedure is the subject of this section.

In the paper by Bialas [12], it was noted that in a model, where particles are produced by decays of neutral clusters (these clusters can be correlated), contribution to the balance function from pairs from different clusters cancels in the balance function, and thus only $(+,-)$ pairs from one cluster do contribute. This fact was used, for example, to estimate neutral resonance contribution to the BF in Au–Au collisions with STAR data [9], and it was found that the BF shapes of Δy projections for resonant and non-resonant contributions are nearly the same.

Below, we show how to get rid of the resonance contribution in BF analytically. Let us write a master equation that allows to construct the BF for a system of neutral sources. Denote number of source types as M_s, average number of sources of i^th type per event as $\langle k^i \rangle$, single- and two-particle densities of source decay products as ρ_1^i and ρ_2^i, then the balance function can be expressed as

$$\mathrm{BF} = \frac{1}{2} \frac{\sum_{i=1}^{M_\mathrm{s}} \langle k^i \rangle \left({\rho_2^i}^{(+,-)} + {\rho_2^i}^{(-,+)} - {\rho_2^i}^{(+,+)} - {\rho_2^i}^{(-,-)} \right)}{\sum_{i=1}^{M_\mathrm{s}} \langle k^i \rangle \, {\rho_1^i}^{(+)}} \,. \tag{2}$$

With (2), we can explicitly remove resonance contributions from the BF measured in an experiment, by subtracting unwanted neutral-source contributions from numerator and denominator. For that, we need to know single- and two-particle densities for products of a resonance decay, and single-particle distributions of resonances themselves. This information is usually available, since experiments do measure resonance yields and spectra, while the ρ_1 and ρ_2 of the decay products are determined by the decay kinematics.

In order to test the resonance removal procedure, PYTHIA events are utilized. In each event, we define the four types of neutral sources of charged pions: three neutral resonances ρ^0, ω and η (contribution to the BF from them we would like to eliminate), and the fourth source is the rest of charged pions — let us call it a "bulk"[1]. Note that the procedure of resonance removal can be applied directly to the two-dimensional $\mathrm{BF}(\Delta y, \Delta\varphi)$. Below, for clarity of representation, only projections of the BF are discussed.

[1] The "bulk" can be considered as a neutral object, since at the LHC energies $\langle N^+ \rangle \approx \langle N^- \rangle$ at mid-rapidity. The bulk consists of pions from other resonances as well as those from quark–gluon strings, minijets, *etc.* (see the right panel of Fig. 1).

Figure 5 demonstrates projections on Δy and $\Delta\varphi$ of the initial BF for all pions (closed circles), BF of the "true" bulk (stars) and BF of the bulk extracted from the initial BF with the resonance removal procedure (open circles). It can be seen that the points of the extracted bulk are on top of the "true" points. We may note also that without the ρ^0, ω and η resonances, the balance function in a region of $|\Delta y| \lesssim 1$ and $|\Delta\varphi| \lesssim 2$ significantly deviates from the initial BF, which affects the BF widths in Δy and $\Delta\varphi$ as well as the BF integral (from 0.361 for the all-pion BF to 0.330 for the "bulk" BF).

In the same plots, the dashed lines show the BF for the case when electric charges of pions in each event are shuffled within $|y| < 2$, "washing out" the angular correlations in this range. Balance functions for shuffled events can be considered as baselines, with which the measured BF should be compared.

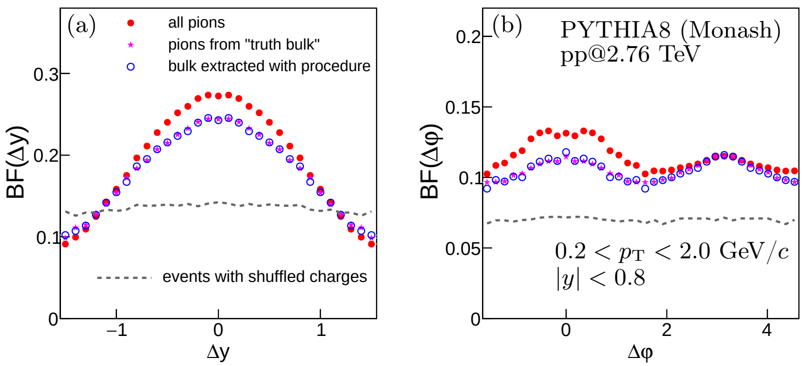

Fig. 5. Projections of the balance functions on (a) Δy and (b) $\Delta\varphi$: closed circles — BF measured for all pions in events, star markers — for pions from the "bulk" (see definition in the text), open circles — BF of the "bulk" extracted with the resonance removal procedure. Dashed curves — BF for events with shuffled charges within $|y| < 2$.

Note that, in principle, with expression (2) we can construct balance functions as combinations of other kinds of charge-neutral sources, in particular, quark–gluon strings can be considered (if they are long enough in rapidity, so that charges at the string ends do not play a role). It would be interesting, for example, to consider centrality dependence of the BF in the models where several kinds of strings with varied particle emission functions (which depend, for instance, on string tension parameter) are packed together [13, 14], or in the model with repulsive interaction between strings, where ρ_2 for each string is modified in a laboratory frame by the flow-like effect due to string repulsions [15, 16]. In such models, shape of the BF is determined by local charge conservation in string fragmentation process, and modified further by the decays of resonances which are produced from strings.

4. Prospects for application of the removal procedure to real-data BF

The resonance removal procedure can be applied to real data, for instance, to BF measured in pp, p–A and A–A collisions. For that, as it was mentioned above, it is necessary to know yields of resonances and single- and two-particle densities for their decay products, which evolve with centrality of the collision.

For example, for analysis of pionic balance functions in the ALICE data, one may use relative fractions of $2\rho^0/(\pi^+ + \pi^-)$ measured by ALICE [17], which are about 0.1, and the yields of ω, that are very similar. However, the measured transverse momentum (p_{T}) spectra for ρ^0 at different centralities are not precise enough to be used for calculation of resonance pair densities ρ_2. Instead, one can make approximations for resonance spectra, for example, take blast wave fit parameters from π, K, p spectra analysis in ALICE [18], construct spectra of resonances of desired types, sample them and apply simple decay kinematics in order to obtain necessary densities of the decay products. For illustration, the balance functions solely from (a) ρ^0, (b) ω, and (c) η decays are plotted in Fig. 6, where in different columns spectra correspond to peripheral, mid-central and central Pb–Pb collisions. We may note how the shape of the BF changes towards central events — while spectra become harder, width of the near-side peak narrows, also, in the case of ρ^0, the ridge-like structure along $\Delta\varphi$ decreases. The centrality evolution of the BF shown in Fig. 6 can be qualitatively compared with two-dimensional preliminary plots presented by ALICE in [7].

The effect of balance function narrowing with hardening of the spectra is a more general phenomenon, valid not only for resonances. For instance, in thermal models, the higher the transverse velocity of particles at the freeze-out surface, the closer the distance between balancing charges in rapidity and azimuth [4]. In the balance function, an interplay between the magnitude of the radial flow of the "bulk" and boosted neutral resonances may, in principle, be resolved with an analytical procedure (2).

Narrowing of the pionic BF widths in Δy and $\Delta\varphi$ projections for ρ^0, ω, and η decays with hardening of the spectra towards central events is demonstrated in Fig. 7 (a) and (b). The preliminary ALICE results [8] are plotted as well for comparison. Of course, the blast-wave approximation for resonance spectra is quite rude[2], especially for ρ^0, which has a broad mass spectrum and a lifetime of about $c\tau \approx 1.3$ fm$/c$, so that daughter pions can rescatter in the surrounding medium, altering the ρ^0 spectrum and the struc-

[2] Note that we can use the same expression (2) in a more "differential" way, namely, to construct BF for any given neutral resonance spectrum by treating resonances within each p_{T} bin as an independent kind of source. Similar trick can be done with bins of the resonance mass peak.

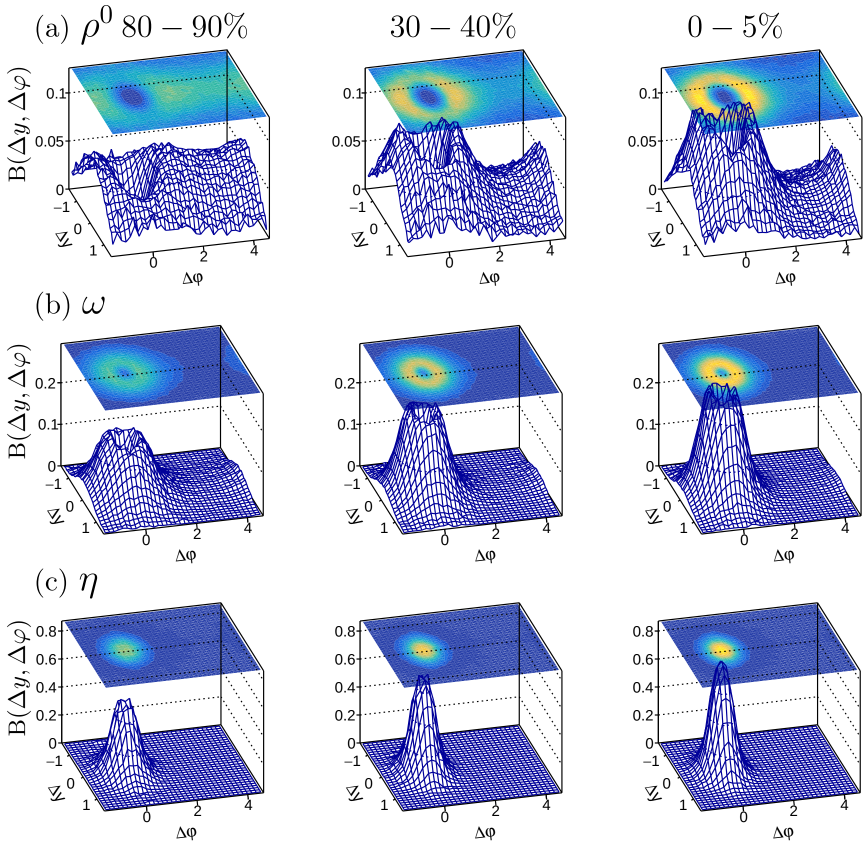

Fig. 6. Evolution of the shape of the pionic 2D balance function from (a) ρ^0, (b) ω and (c) η decays due to hardening of the spectra with centrality of Pb–Pb collisions $\sqrt{s_{NN}} = 2.76$ TeV. Spectra of resonances are obtained by utilizing blast-wave fit parameters from [18]. Acceptance for pions is $0.2 < p_{\mathrm{T}} < 2.0$ GeV/c, $|y| < 0.8$.

ture of the balance function [19]. In addition, relative fractions of resonances change with centrality [17], and an interplay between the resonance yields and abundances of "primordial" pions at different centralities may partially be responsible for the observed centrality dependence of the real-data BF widths.

Panel (c) in Fig. 7 shows BF integrals for resonances at different centralities within the ALICE acceptance. Larger integrals in central events indicate higher probability for each particle to observe an oppositely charged partner within the acceptance, which is just another indication of narrowing of the BF for sources boosted in transverse direction.

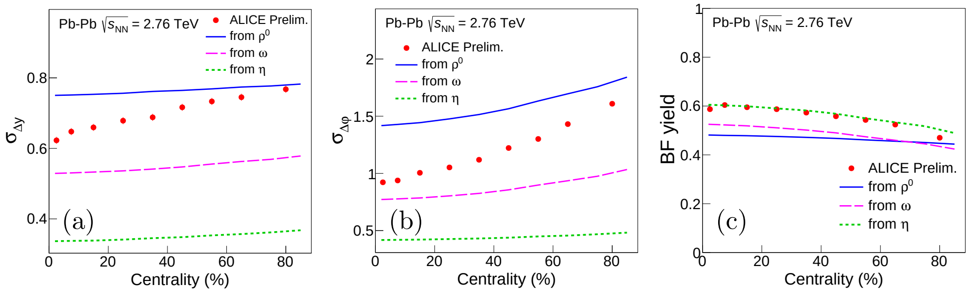

Fig. 7. Widths of the pionic balance functions for ρ^0, ω, and η decays in (a) Δy and (b) $\Delta\varphi$ dimensions as a function of centrality, in comparison to the ALICE preliminary results [8]. Spectra of resonances are obtained by utilizing the blast-wave fit parameters from [18]. Panel (c) shows comparison of the BF integrals over the ALICE-like acceptance.

Application of the resonance removal procedure to real experimental data is out of scope of the present paper. As a final remark in this section, we note that in analysis of real experimental data there could be other undesired neutral-source contributions to the BF. Namely, weak decays $K^0_{\rm S} \rightarrow \pi^+\pi^-$ may noticeably contribute to the pionic balance function, if track selection cuts are not tight enough to reject secondary particles from weak decays. This problem is relevant also for other types of balance functions, for example, the BF between pions and protons may contain a contribution from $\Lambda^0 \rightarrow \pi p$ decays. Such "parasitic" contributions from weak decays can be eliminated with the neutral source removal procedure (2), provided that the proper simulation of detector response exists and fractions of secondary particles are known.

5. Conclusions

In this article, we discussed how resonance decays influence the shape of the charge-balance function, its rapidity and azimuthal widths, the integral, and indicate that proper treatment of resonance contributions may have important consequences for different model interpretations of the BF. It was shown how the contribution from neutral resonance decays can be analytically removed from the BF measured in an experiment. The procedure was tested with PYTHIA events. As an example, it was demonstrated, that after removal of contributions from ρ^0, ω, and η decays, the shape of the near-side peak of the pionic BF in Δy and $\Delta\varphi$ is visibly modified.

Removal of the neutral resonance contributions from real-data balance functions measured in pp, p–A and A–A collisions is possible in case when the resonance yields and their spectra are known in each centrality (multiplicity) class with enough precision. The procedure may be also of a practical use for purification of balance functions from contamination by products of weak decays of neutral particles (such as $K^0_{\rm S}$ and Λ^0). The described procedure can be applied to two-dimensional balance functions, not only for their 1D projections.

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REFERENCES

[1] S.A. Bass, P. Danielewicz, S. Pratt, *Phys. Rev. Lett.* **85**, 2689 (2000).

[2] J. Kapusta, C. Plumberg, *Phys. Rev. C* **97**, 014906 (2018).

[3] S. Pratt, *Phys. Rev. Lett.* **108**, 212301 (2012).

[4] P. Bożek, *Phys. Lett. B* **609**, 247 (2005).

[5] S. Pratt, S. Cheng, *Phys. Rev. C* **68**, 014907 (2003).

[6] STAR Collaboration, *Phys. Rev. C* **82**, 024905 (2010).

[7] ALICE Collaboration, *Eur. Phys. J. C* **76**, 86 (2016).

[8] J. Pan, *Nucl. Phys. A* **982**, 315 (2019).

[9] P. Bożek, W. Broniowski, W. Florkowski, *Acta Phys. Hung. A* **22**, 149 (2005).

[10] T. Sjöstrand, S. Mrenna, P. Skands, *J. High Energy Phys.* **0605**, 026 (2006); *Comput. Phys. Commun.* **178**, 852 (2008).

[11] J. Pan, "Balance Functions of (un)identified Hadrons in Pb–Pb, p–Pb and pp Collisions from ALICE", report at Quark Matter, 2018.

[12] A. Bialas, *Phys. Lett. B* **579**, 31 (2004).

[13] E. Andronov, V. Vechernin, *Eur. Phys. J. A* **55**, 14 (2019).

[14] V. Kovalenko, *EPJ Web Conf.* **204**, 03006 (2019).

[15] V. Abramosvkii, E. Gedalin, E. Gurvich, O. Kancheli, *Pisma Zh. Eksp. Teor. Fiz.* **47**, 281 (1988).

[16] I. Altsybeev, *AIP Conf. Proc.* **1701**, 100002 (2016).

[17] ALICE Collaboration, CERN-EP-2018-106, `arXiv:1805.04365 [nucl-ex]`.

[18] ALICE Collaboration, *Phys. Rev. C* **88**, 044910 (2013).

[19] S. Pratt, C. Plumberg, *Phys. Rev. C* **99**, 044916 (2019) [`arXiv:1812.05649 [nucl-th]`].