The antiproton puzzle, QCD critical point, and fireball properties in heavy-ion collisions

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Abstract. We discuss factorial cumulants of protons and antiprotons as a tool to probe the properties of the fireball created in heavy-ion collisions. First, we discuss the new RHIC BES-II data on factorial cumulants of protons and their deviation from the non-critical baseline at $\sqrt{s_{NN}} \lesssim 10$–20 GeV in the context of the critical point search. We then show that the acceptance dependence of the appropriately scaled factorial cumulants is flat if correlations are driven solely by long-range effects, such as global baryon conservation and volume fluctuations. The analysis of RHIC BES-I data reveals an *antiproton puzzle*: sizable differences between p and $\bar{p}$ second-order fluctuations at RHIC energies that are not reproduced by a single-fluid picture. We argue that such a splitting indicates incomplete equilibration between stopped and produced matter, which can be further probed with upcoming high-statistics data from RHIC BES-II.

1 Introduction

The QCD critical point (CP) search in heavy-ion collisions primarily relies on a beam energy scan of event-by-event fluctuations of the net-proton number [1, 2]. The corresponding measurements have been presented by the STAR Collaboration, including first results from the precision measurements within phase II from RHIC Beam Energy Scan (BES-II) [3]. By now it is well understood that the interpretation of the measurements is subtle and must rely on quantitative dynamical model theoretical predictions.

2 BES-II data and non-critical baseline

Quantitative predictions for the BES-II measurements have been presented in Ref. [4] in the non-critical scenario. The analysis incorporates hydrodynamic evolution, global baryon conservation, lattice-QCD motivated excluded-volume repulsion, and appropriate experimental momentum cuts. These predictions are in excellent agreement with the BES-II data for proton cumulants at $\sqrt{s_{NN}} \gtrsim 20$ GeV. At lower energies, deviations from the data are evident. These are especially pronounced in factorial cumulants of protons, which show enhanced two-proton correlations and reduced three-proton correlations relative to the non-critical baseline. The deviations may be indicative of approaching the CP in baryon-rich matter [5, 6], however they can also be caused by unrelated effects such as volume fluctuations, centrality selection, and fluctuations in baryon stopping. This may be particularly relevant in light of the preliminary results from RHIC-FXT [7], which show a similar (and even stronger) pattern of deviations from the non-critical baseline at $\sqrt{s_{NN}} \lesssim 4$ GeV.

3 Acceptance dependence of scaled factorial cumulants

Acceptance dependence of fluctuations provides additional leverage to probe the physics mechanisms at play inside the fireball. Let $\hat{C}_n^p$ ($\hat{C}_n^{\bar{p}}$) denote the *factorial* cumulants for protons (antiprotons) in a given acceptance, and let $\hat{C}_{mn}^{p\bar{p}}$ denote the joint factorial cumulants. Following Refs. [8, 9], define the reduced correlation functions ("couplings").

$$\hat{c}_n^p \equiv \frac{\hat{C}_n^p}{\left\langle N_p \right\rangle^n}, \qquad \hat{c}_n^{\bar{p}} \equiv \frac{\hat{C}_n^{\bar{p}}}{\left\langle N_{\bar{p}} \right\rangle^n}, \qquad \hat{c}_{mn}^{p\bar{p}} \equiv \frac{\hat{C}_{mn}^{p\bar{p}}}{\left\langle N_p \right\rangle^m \left\langle N_{\bar{p}} \right\rangle^n}, \tag{1}$$

If all correlations are long-range (which includes any combination of global baryon conservation, volume fluctuations, or uniform efficiency losses), $\hat{c}_n$ is acceptance independent at a fixed $\sqrt{s_{NN}}$ [10].

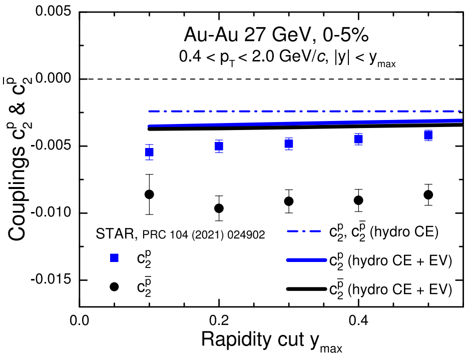

Figure 1. From Ref. [10]. Rapidity acceptance dependence of proton and antiproton couplings $\hat{c}_2^p$ and $\hat{c}_2^{\bar{p}}$ from RHIC-BES-I (symbols) [16] and non-critical hydro baseline with and without the excluded volume correction (solid and dashed lines) [4] in Au-Au collisions at $\sqrt{s_{\rm NN}} = 27$ GeV.

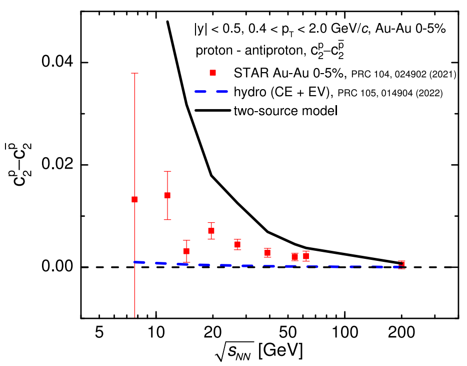

Figure 2. From Ref. [10]. The difference between proton and antiproton couplings as a function of collision energy. The symbols depict RHIC-BES-I data [16], while the blue and black lines correspond to the hydrodynamics baseline [4] and two-source model [10], respectively.

Global baryon conservation: Global baryon conservation is a source of long-range correlations among (anti)baryons, which yields an acceptance independent $\hat{c}_n$ when no other correlations are present. Considering an ideal gas of baryons and antibaryons in the canonical ensemble [11], one can derive the expressions for $\hat{c}_n$ in terms of the total number of baryons and antibaryons $\langle N \rangle = \langle N_B \rangle + \langle N_{\bar{B}} \rangle$ and the number of baryons $\langle N_B \rangle$. One can show that all second-order couplings of protons and antiprotons are equal in magnitude, namely

$$\hat{c}_2^p = -\hat{c}_{1,1}^{p,\bar{p}} = \hat{c}_2^{\bar{p}} = -\frac{1}{\langle N \rangle}. \tag{2}$$

Therefore, observing a splitting between $\hat{c}_2^p$ and $\hat{c}_2^{\bar{p}}$ would indicate that additional physics mechanisms are at play.

Volume fluctuations: Volume fluctuations are known to distort the interpretation of measurements of the ordinary cumulants [12, 13]. However, since volume fluctuations are a source of long-range correlations, they keep the couplings $\hat{c}_{nm}^{p\bar{p}}$ flat. In other words, if the couplings exhibit flat acceptance dependence at a fixed volume, they will remain flat also in the presence of volume fluctuations. Therefore, we advocate for the analysis of couplings $\hat{c}_{nm}^{p\bar{p}}$ in experiment without any corrections for volume fluctuations [such as the centrality-bin-width-correction (CBWC)], which can be complex to implement and interpret.

Couplings and the CP: Deviations from the acceptance-independence of $\hat{c}_n^p$ at a fixed $\sqrt{s_{NN}}$ can be a clear signature of short-range correlations, as discussed above. One particular example of short-range correlations (as compared to the total fireball volume), is critical fluctuations [14]. In particular, critical fluctuations can be expected to induce a pronounced acceptance dependence of $\hat{c}_n^p$ at a fixed $\sqrt{s_{NN}}$ [14, 15] in high-order cumulants especially. High-statistics data are required to probe this effect, however, which should be accessible with RHIC BES-II.

Second-order couplings from RHIC-BES-I: The couplings $\hat{c}_2^p$ of protons have been analyzed in Ref. [10] using RHIC-BES-I data [16]. The data reveal that the scaling $\hat{c}_2^p = \text{const}$ approximately holds (blue symbols in Fig. 1), at least within the experimental uncertainties, with the possible exception of the 54.4 GeV energy. The non-critical baseline from hydrodynamics also predicts $\hat{c}_2^p \approx \text{const}$ (solid blue line), with a weak acceptance dependence due to short-range excluded volume repulsion. It describes the shape of the data well.

The antiproton puzzle: RHIC-BES-I measurements are also available for the couplings $\hat{c}_2^{\bar{p}}$ of antiprotons. Like protons, these show approximately flat acceptance dependence (black symbols in Fig. 1) within the experimental uncertainties. However, there is a clear and significant splitting in the magnitude between the couplings of protons and antiprotons, which gets larger at lower energies (Fig. 2). The non-critical hydrodynamics baseline, on the other hand, predicts $|\hat{c}_2^{\bar{p}}| \approx |\hat{c}_2^p|$ to high precision (the tiny splitting visible in Figs. 1 and 2 is due to excluded volume repulsion). We refer to this splitting, and the failure of the current baseline to describe it, as the "antiproton puzzle" [10].

Two-source model: The antiproton puzzle indicates that physics beyond the hydrodynamics-based non-critical baseline is at play, and perhaps even beyond the standard hydrodynamics description in general. One possibility is an incomplete equilibration between the stopped and produced matter. To model this scenario, we explore a two-source model, where stopped and produced particles are considered as separate sources. Such a scenario naturally introduces different correlations for protons and antiprotons. Whereas the antiprotons are absent in the stopped matter, the protons are present in both the stopped and produced matter, with the former component becoming dominant as the collision energy decreases.

The produced matter in the two-source model is described as a net-baryon-free matter in the canonical ensemble (exactly the same total numbers of produced baryons and antibaryons). Antiprotons come only from the produced matter. The factorial cumulants of protons, on the other hand, contain contributions from both the stopped and produced matter. The stopped protons are modeled by a binomial distribution with Bernoulli probability of $p = \left\langle N_p \right\rangle_{\text{stopped}} / N_{\text{part}}$, where N_{part} is the total number of participants. One can show that the couplings $\hat{c}_2^p$ and $\hat{c}_2^{\bar{p}}$ under these assumptions read

$$\hat{c}_2^p = -\frac{(1-R_{\bar{p}p})^2}{N_{\text{part}}} - \frac{R_{\bar{p}p}^2}{2\left\langle N_{\text{pairs}}^{B\bar{B}} \right\rangle}, \qquad \hat{c}_2^{\bar{p}} = -\frac{1}{2\left\langle N_{\text{pairs}}^{B\bar{B}} \right\rangle}. \tag{3}$$

Here $\left\langle N_{\text{pairs}}^{B\bar{B}} \right\rangle$ is the total number of baryon-antibaryon pairs in the produced matter and $R_{\bar{p}p} = \left\langle N_{\bar{p}} \right\rangle / \left\langle N_p \right\rangle$ is the antiproton-to-proton ratio.

Taking the mean multiplicities of protons and antiprotons from the STAR data, and the total number of participants and produced baryon-antibaryon pairs from MUSIC [17], we calculate the couplings in the two-source model. The results, shown in Fig. 2 by the black line, qualitatively describe the splitting between protons and antiprotons seen in RHIC-BES-I data. One can see, however, that this splitting is overestimated at energies $\sqrt{s_{\rm NN}} \leq 39$ GeV. This may indicate that the two sources are not completely independent. However, they are also not fully thermalized, as the latter scenario would correspond to the one-component model where there is no splitting.

Opportunities at the LHC: As discussed above, acceptance dependence of the couplings $\hat{c}_2^{(p)}$ and $\hat{c}_2^{(\bar{p})}$ can be used to probe short-range correlations. This extends to LHC energies as well. Although the LHC energies are not expected to be sensitive to the CP, one can probe other effects, such as the baryon annihilation in the hadronic phase. The treatment of the baryon correlations is somewhat simpler at the LHC due to the approximate longitudinal boost invariance and the vanishing of the baryon chemical potential. The following combinations of the couplings are particularly instructive

$$r_1 \approx \frac{1}{4}\left(\hat{c}_{2,0}^{p\bar{p}} + \hat{c}_{0,2}^{p\bar{p}} - 2\hat{c}_{1,1}^{p\bar{p}}\right), \qquad \hat{c}_2^{p+\bar{p}} = \hat{c}_2^{p} + \hat{c}_2^{\bar{p}} + 2\hat{c}_2^{p\bar{p}}. \tag{4}$$

By construction, they obey the same flat acceptance dependence in the absence of short-range correlations as the ordinary couplings. In addition, r_1 is insensitive to volume fluctuations, whereas $\hat{c}_2^{p+\bar{p}}$ is insensitive to exact baryon conservation, including the local conservation scenario [18]. On the other hand, $\hat{c}_2^{p+\bar{p}}$ is sensitive to the baryon annihilation in the hadronic phase and can be used to constrain this effect, which can also be relevant for RHIC-BES energies and the antiproton puzzle.

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