Centrality bin-width independent information entropy in Au + Au collisions at √sNN= 4.7 - 200 GeV from AMPT model

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Abstract

Net-proton multiplicity distributions within finite centrality bins are subject to volume fluctuations, known as the Centrality Bin Width Effect (CBWE). The information entropy of net-proton multiplicity distributions normally serves as an effective observable to reflect the critical fluctuation phenomena, providing a valuable tool for studying the QCD phase transition and the potential existence of the critical point in heavy-ion collisions. However, CBWE may cause inaccuracies in the original information entropy. In this work, the Centrality Bin Width Correction (CBWC) method is applied to correct the original information entropy. A Multi-phase Transport (AMPT) model is used as the event generator to simulate Au+Au collisions across a range of center-of-mass energies √sNN = 4.7 - 200 GeV with impact parameters ranging from 0 to 14 fm. Simulations are conducted with and without mid-rapidity cut ($|y| < 0.5$) and a transverse-momentum cut ($0.4 < PT < 0.8$ GeV/c). By comparing the original and corrected information entropy values, significant differences are observed regardless of whether a mid-rapidity or transverse momentum cut is applied, demonstrating the necessity of applying the CBWC method. The corrected information entropy improves stability and centrality-independence and enhances its effectiveness in probing the QCD critical point.

Full Text

Preamble

Centrality bin-width independent information entropy in Au + Au collisions at GeV from AMPT model sN N = 4.7 - 200

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However, CBWE may cause inaccuracies in the original information entropy. In this work, the Centrality Bin Width Correction (CBWC) method is applied to correct the original information entropy. A Multi-phase Transport (AMPT) model is used as the event generator to simulate Au+Au collisions across a range of center-of-mass energies sN N = 4.7 - 200 GeV with impact parameters ranging from 0 to 14 fm. Simulations are conducted with and without mid-rapidity cut ($|y| < 0.5$) and a transverse-momentum cut ($0.4 < pT < 0.8$ GeV/c). By comparing the original and corrected information entropy values, significant differences are observed regardless of whether a mid-rapidity or transverse momentum cut is applied, demonstrating the necessity of applying the CBWC method. The corrected information entropy improves stability and centrality-independence and enhances its effectiveness in probing the QCD critical point.

Keywords

QCD critical point, Critical fluctuation phenomena, Heavy-ion collisions, Information entropy, CBWE, CBWC method.

INTRODUCTION

(ΔNp−p̄ = Np − Np̄ , where Np and Np̄ represent the numbers of protons and antiprotons, respectively) is conserved in 31 strong interactions within a closed system and its fluctuations 32 can carry essential information about the properties of the cre33 ated medium [23]. In particular, the magnitude and behavior 34 of these fluctuations are expected to differ significantly be35 tween the hadronic and QGP phases [24–26].

High-order fluctuations are widely recognized as sensitive 37 observables for probing the QCD phase transition. In the pre38 vious study [30], the information entropy of net-proton multiplicity distributions simulated by the AMPT model has been demonstrated to be as sensitive to the QCD critical phase transition as higher-order moments through the comparison of the fluctuations of information entropy and kurtosis. Information entropy has been used to study the time evolution process in relativistic heavy-ion collisions [27–29], and these studies have demonstrated that information entropy can be used to assess the fluctuations of conserved quantities and employed to characterize the critical fluctuation phenomena. It is expected to exhibit a nonlinear trend near QCD critical point. A widely adopted method of studying the fluctuations of observables involves dividing the centrality into distinct bins across various energies. However, when focusing on centrality at a single collision energy, it is crucial to take into account the volume fluctuations that stem from the finite width of the centrality bins. The details of the volume fluctuations are presented in Refs. [31, 32]. This study systematically applies the Centrality Bin Width Correction (CBWC) method to the fluctuation analysis of information entropy calculation. The information entropy is derived from the net-proton multiplicity distributions generated by the string melting version of A Multi-phase Transport (AMPT) model [33, 34]. The aim is to suppress the Centrality Bin Width Effect (CBWE) caused by

Searching for critical point (CP) in quantum chromodynamics (QCD) phase diagram is one of the most important questions in particle and nuclear physics [1].

Finite temperature Lattice QCD (LQCD) simulations indicate that at zero baryon chemical potential ($\mu B = 0$) the transition from the hadronic phase to the quark-gluon plasma (QGP) phase is a smooth crossover [2]. Conversely, according to the predictions of QCD model, the transition is expected to be of the first order at large μB [3, 4]. The endpoint of this phase transition line is hypothesized to be the QCD critical point [5, 6]. Experimentally, the Beam Energy Scan (BES) program [7, 8] at the Relativistic Heavy Ion Collider (RHIC), which is located at Brookhaven National Laboratory (BNL) [1, 9–11] aims to investigate the structure of QCD phase and determine the location of critical point via heavy-ion collisions [12–14].

In heavy-ion collisions, event-by-event fluctuations of conserved quantities act as sensitive probes for the correlation length of hot dense matter created in the collisions [15] and are connected to the thermodynamic susceptibilities computed in LQCD [6, 16, 17]. Near the QCD critical point, the correlation length ξ theoretically diverges ($\xi \to \infty$) [18, 19]. The well-known phenomenon of critical opalescence arises from enhanced fluctuations at all length scales near a second order phase transition [20, 21]. These long-range correlations allow even minor perturbations to have an impact on spatially extended regions, resulting in substantial fluctuations of conserved quantities [15, 18, 19, 22]. Net-proton number

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volume fluctuations and enhance the reliability of information 113 N and the fluctuation structure of the Pi distribution are of entropy as a probe for exploring the QCD critical point. The 114 critical importance in determining the values of information 64 CBWC method is based on the work of Ref. [31], where this 115 entropy.

Volume fluctuations occur within a finite centrality bin be65 method was first introduced to calculate the high moments of 116 66 net-proton multiplicity distributions to suppress the centrality 117 cause experimental measurements cannot directly obtain the Instead, cen67 bin width effect. The previous study [30] has demonstrated 118 number of participant nucleons (Npart) [36]. 68 the necessity of applying the weighting factor (WF) method to 119 trality is typically defined using charged-particle multiplicity 69 correct information entropy values at different collision ener- 120 (Nch) and smallest centrality bin is determined by a single 70 gies to ensure their comparability, and the CBWC correction 121 value of Nch . However, Npart follows a broad distribution, 71 in this work is applied based on the correction of informa- 122 and each Nch does not correspond to Npart on a one-by-one 72 tion entropy values by WF method. The details of the WF 123 basis. Thus, volume fluctuations are introduced within cen73 method can be found in Ref. [30]. In this work, the CBWC 124 trality bins, as demonstrated in numerous studies [32, 36]. 74 corrected information entropy will be calculated and the in- 125 The CBWE is caused by the volume fluctuations within a 75 fluence of rapidity and transverse momentum selections will 126 finite centrality bin. This effect is especially prominent in 127 heavy-ion collisions and can significantly distort information 76 also be systematically investigated. 128 entropy measurements, potentially obscuring genuine physi129 cal signals. [31, 32, 37].

II. METHOD AND MODEL Centrality is expressed as a percentage of the total cross131 section (e.g., 0 -5 % or 30 -40 %) and is determined via 132 Nch . The smallest centrality bin is a single multiplicity value, A. Information entropy and centrality bin width effect 133 but the results are simulated for a wider centrality bin for bet79 Information entropy, originally introduced in information 134 ter statistical accuracy. Finite centrality bins correspond to a 135 range of multiplicity numbers. Inevitably, in an extreme case 80 theory by C. E. Shannon [35] to quantify the degree of disor136 where the smallest centrality bin corresponds to a single mul81 der within a system, has been widely applied in various sci137 tiplicity value, the finite bin widths introduce volume fluctu82 entific fields, including physics [29]. It serves as a measure 138 ations. Clearly, CBWE can cause a significant difference be83 for assessing the disorderliness of a system. In heavy-ion col139 tween the originally calculated and the genuine information 84 lision, for a probability distribution, information entropy is 140 entropy values. This effect may mask the critical fluctuation 85 defined as 141 signals which heavy-ion collision experiments aim to detect 142 when exploring the QCD critical point [31, 38]. Therefore, it Pi ln Pi , (1) 143 is essential to correct the original information entropy values 144 to

> suppress centrality-dependent volume fluctuations. This 87 where Pi is a normalized number of net-proton and 145 work calculated the original information entropy values and 146 applied the CBWC method as described in Ref. [32] to cor88 i=1 Pi = 1, the upper limit of the summation N represents 147 rect the volume fluctuations resulting from CBWE. The goal 89 the total number of event types that produce different quan148 is to isolate changes in information entropy that solely stem 90 tities of net-proton in the entire event space. In the context 149 from net-proton multiplicity fluctuations. 91 of this work, Pi represents the proportion of events with mul150 To attain this objective, the CBWC method conducts a 92 tiplicity i within the detector acceptance range, contributed 151 weighted average of information entropy over a finite bin, 93 by events within a given centrality interval. Both the shape 152 which is defined as follows 94 of {Pi } distribution and the number of N exert a substanN 95 tial influence on the values of information entropy, as dePu ni Hni 96 tailed in Ref. [30].

For example, when the distribution is 97 highly skewed, saying P = {0.99, 0.01}, information en- 153 ωi Hni , Hn = N 98 tropy value is low. This implies a high level of predictability 99 for this system. Conversely, when all Pi values are equal, i.e., 100 Pi = 1/N , the distribution is uniform, and the information 154 where ni represents the number of events within the i-th 101 entropy reaches its maximum under such circumstances. To 155 charge-particle multiplicity bin for one centrality interval, 102 further illustrate the impact of N on the information entropy 156 Hn represents the original information entropy for the i-th 103 value, consider two systems A and B with uniform distribuN 104 tions. If NA is larger than NB , the information entropy of sys157 charge-particle multiplicity bin and ωi = ni / ni is the 105 tem A is larger than that of system B, correspondingly. This 106 clearly shows that the value of information entropy is also af- 158 corresponding weight. Nl and Nu denote the lower and up107 fected by N [30]. An extreme scenario is that a non-uniform 159 per limits of charge-particle multiplicity values within a given 108 distribution with a large N may result in a lower information 160 centrality interval (e.g., 0 -5 %, 5 -10 %). Equation (2) is 109 entropy value compared to a more uniform distribution with 161 applied to each centrality bin to obtain the corrected informa110 a smaller N .

This emphasizes that information entropy is 162 tion entropy, which is expected to better reflect the intrinsic 111 determined not only by N but also by the shape of the Pi dis- 163 fluctuations of net-proton multiplicity distributions and to be 112 tribution. In conclusion, both the number of multiplicity bins 164 independent of centrality.

ward and backward rapidities are more likely to be the products of peripheral collisions. In these collisions, only a small 221 fraction of the nuclear matter is involved. Such particles are The AMPT model is used in this work to generate the 222 more likely to reflect the non-equilibrium effects of the ini167 full phase-space density of net protons in Au+Au colli223 tial state or the nucleon fragmentation processes, rather than 168 sions [33, 34, 39]. It is available in two versions: the de224 the actual evolution of the QGP itself [31, 47, 48]. There169 fault version (AMPT-DEF) and the string-melting version 225 fore, the implementation of mid-rapidity and transverse mo170 (AMPT-SM). In high-energy heavy-ion collisions, the forma226 mentum cuts plays a crucial role in suppressing the non-QGP 171 tion of QGP leads to a system evolution dominated by par227 backgrounds and enhancing the sensitivity to information en172 tonic interactions. Consequently, the AMPT-SM model pro228 tropy of the net-proton multiplicity distributions originating 173 vides a more accurate description of the experimentally ob229 from the QGP-dominated region. 174 served collective flow and particle correlations in pp, pA or In theoretical simulations, directly selecting parameters of 175 AA system collisions at RHIC and LHC energies. There231 mid-rapidity (|y| $<$ 0.5) and transverse momentum range 176 fore, this work utilizes the AMPT-SM model to generate the 177 full phase-space information of Au+Au collisions.

AMPT 232 (0.4 $<$ pT $<$ 0.8 GeV/c) brings about direct alterations to the 233 net-proton multiplicity distributions. These changes have a 178 model is composed of four main components: initial con234 significant influence on the sensitivity of information entropy 179 ditions, partonic interactions, the hadronization of partonic 235 to volume fluctuations, especially to the centrality bin width 180 matter, and hadronic interactions. The initial conditions are 236 effect. To conduct a systematic exploration of the impact of 181 provided by the Heavy Ion Jet INteraction Generator (HI237 the CBWC on information entropy, this work employs the 182 JING) model [40, 41], which gives the spatial and momen238 AMPT model to simulate net-proton multiplicity distributions 183 tum distributions of minijet partons and soft strings. In the 239 under four kinematic cuts scenarios: (1) no cut, (2) with only 184 string melting mechanism, both excited strings and minijet 240 mid-rapidity cut, (3) with only the transverse momentum cut, 185 partons are transformed into partons. Zhang' s Parton Cas241 and (4) with both cuts applied concurrently. For each of these 186 cade (ZPC) model [42] is used to simulate the strong interac187 tions among partons. Regarding hadronization, AMPT-DEF 188 employs Lund string fragmentation, whereas AMPT-SM em189 ploys a quark coalescence model [33] to describe the conver190 sion of these partons into hadrons. A Relativistic Transport 191 (ART) model [43] is used to simulate the interactions among 192 the hadrons, their corresponding inverse reactions and reso193 nance decays. Further details of the AMPT model are pro194 vided in Refs. [33, 34].

This work chooses AMPT-SM to 195 simulate Au+Au collisions at center-of-mass energies 196 = 4.7, 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV, with the 197 impact parameter b spanning from 0 to 14 fm.

A Multi-phase Transport model

Normalized distribution

4.7GeV

7.7GeV

11.5GeV

19.6GeV

27GeV

39GeV

62.4GeV

200GeV

AMPT, Au+Au Collision Width_0-5%

No kinematic cuts

|y|<0.5

RESULT AND DISCUSSION

p <0.8(GeV/c)

|y|<0.5, 0.4<

p <0.8(GeV/c)

Net-proton

In the experimental analysis of nuclear collisions, it is a common approach to implement both a mid-rapidity cut AMPT-SM model at 4.7 - 200 GeV. The centrality bin width is cho201 ($|y| < 0.5$) and a transverse momentum cut (0.4 < pT < 0.8 sen as 5 %, the kinematic cuts are chosen as (1) no cut represented 202 GeV/c). This combined kinematic selection strategy effecby blue symbols, (2) with only mid-rapidity cut represented by red symbols, (3) with only the transverse momentum cut represented 203 tively enhances the sensitivity of fluctuation observables to by pink symbols, and (4) with both cuts applied concurrently repre204 the potential critical phenomena.

In the central collisions, 205 which are characterized by small impact parameters, nu- 242 sented by green symbols. 206 clear matter exhibits greater overlap, leading to a significantly 243 207 higher energy density. The concurrent application of mid- 244 scenarios, this work calculates net-proton multiplicity distri208 rapidity cut and transverse momentum cut is crucial to isolat- 245 butions within the width of 0-5 % at 4.7 - 200 GeV, shown in 209 ing the particles emerging from the hottest and densest region 246 Fig. 1 [Figure 1: see original paper]. Under different kinematic cut windows, the net-proton 210 of the collision [23]. This region reaches extreme conditions, 247 multiplicity distributions are significantly different. The hor211 including high temperature and energy density, which are 248 izontal axis represents the particle number corresponding to i 212 closely associated with the formation of the QGP [1, 44, 45]. 249 in Equation (1), while the vertical axis denotes the normalized 213 The mid-rapidity cut serves to suppress the excessive contri- 250 number of net-proton Pi associated with having i particles in 214 butions to the net-proton yields that stem from longitudinal 251 Equation (1). Then, the information entropy of the net-proton 215 fragmentation and pre-equilibrium effects. Meanwhile, the 252 multiplicity distributions both prior to and subsequent to the 216 transverse momentum cut mitigates contamination from net- 253 applying CBWC can be calculated using Equation (1) and (2) 217 protons carried by high-pT particles generated in the initial 254 as shown in Fig. 2 [Figure 2: see original paper], 3, 4 and 5. These calculations are carried 218 hard scatterings [23, 46]. In contrast, particles emitted at for- 255 out across five different types of centrality bin widths, namely

2.5 %, 5 %, 10 %, 15 % and 20 %.

energies, the correction effect remains obvious at high energies overall.

Information entropy with centrality bin width correction

4.7GeV

7.7GeV

11.5GeV

19.6GeV

27GeV

39GeV

62.4GeV

200GeV

11.5GeV

7.7GeV

4.7GeV

Information entropy

Net-proton Au+Au Collision

19.6GeV

39GeV

27GeV

Information entropy

Net-proton Au+Au Collision

|y|<0.5

Width_2.5%

Width_5%

Width_{10}%

Width_{15}%

62.4GeV

200GeV

Width_{20}%

Width_2.5%

Centrality(%)

Width_5%

Width_{10}%

Width_{15}%

Width_{20}%

Centrality(%)

net-proton multiplicity distributions from Au+Au collisions with the kinematic cuts of |y| < 0.5 and impact parameter b = 0 - 14 fm at sN N = 4.7, 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV by AMPT simulation. The solid and open symbols represent the results calculated with and without CBWC method. The centrality bin width selections are 2.5 %, 5 %, 10 %, 15 % and 20 %, respectively.

kinematic cuts and impact parameter b = 0 - 14 fm at sN N = 4.7, 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV by AMPT simulation. 287 The solid and open symbols represent the results calculated with and 288 cut (|y| < 0.5) additionally. Under this condition, the inwithout CBWC method. The centrality bin width selections are 2.5 289 formation entropy both before and after CBWC correction %, 5 %, 10 %, 15 % and 20 %, respectively. 290 was calculated. In high-energy heavy-ion collisions, the mid-

291 rapidity region is characterized by a high particle density, These characteristics make the mid-rapidity cut 260 pletely removed. By computing the information entropy of 294 an ideal window for investigating the properties of hot and 261 the net-proton yields in this simulation scenario, the differ- 295 dense matter. However, this kinematic constraint eliminates 262 ences between the originally calculated information entropy 296 the contributions from protons transported to the forward and 263 and the corrected one are relatively minor at lower collision 297 backward rapidity regions. This exclusion introduces non264 energies. In contrast, as the collision energy increases, these 298 critical fluctuations in the information entropy of the net265 discrepancies gradually become more significant. This phe- 299 proton multiplicity distributions. In the case of small wide 266 nomena can be explained as follows: At low energies, the 300 centrality bins, the large-scale fluctuations of net-proton mul267 range of net-proton number multiplicity distributions is rela- 301 tiplicity distributions tend to obscure the fluctuations solely 268 tively narrow. Moreover, when no

cuts are applied, the simu- 302 attributable to the CBWE.As a result, across all energy re269 lation results also incorporate a large number of background 303 gions, the difference in information entropy before and after 270 events. As a result, the information of the fireball carried by 304 the correction appears relatively insignificant for small cen271 these events tends to be integrated into the general events dis- 305 trality bins. Conversely, larger centrality bins encompass a 272 tribution. This causes the distribution within the system to 306 greater quantity and a more diverse range of net-protons. In 273 approach uniformity, thereby increasing the true information 307 such cases, the CBWC continues to exert a discernible influ274 entropy values. At high energies, the range of the net-proton 308 ence. 275 number multiplicity distributions expands. Even in the pres- 309 In Fig. 4 [Figure 4: see original paper], a transverse momentum cut ($0.4 < pT < 0.8$ 276 ence of a high level of background events, the net-proton 310 GeV/c) is implemented, and the information entropy be277 number multiplicity distribution can still stand out. As ex- 311 fore and after CBWC is calculated under this condition. In 278 pressed in Eq. (1), the true information entropy decreases. 312 heavy-ion collisions, both high-pT protons generated from 279 Therefore, the net-proton number multiplicity distributions 313 hard-processes and low-pT thermalized protons can be pro280 obtained at low energies without any cuts show an extremely 314 duced [49]. Applying pT cut excludes these high-pT com281 minor centrality dependence, and have little difference in the 315 ponents, isolates low-pT thermalized protons that reflect the 282 information entropy values before and after corrections. Al- 316 thermodynamic properties of the system, and modifies the 283 though the corrected information entropy shows some simi- 317 overall normalization of the net-proton distribution. Similarly 284 larities to the originally calculated information entropy at low 318 to mid-rapidity cuts, across all energy regions, the informa258

4.7GeV

7.7GeV

11.5GeV

Au+Au Collision

p <0.8(GeV/c)

19.6GeV

27GeV

39GeV

Information entropy

Information entropy

Net-proton

11.5GeV

7.7GeV

4.7GeV

Net-proton

|y|<0.5

Au+Au Collision

p <0.8(GeV/c)

19.6GeV

27GeV

62.4GeV

200GeV

39GeV

Width_2.5%

200GeV

62.4GeV

Width_5% Width_{10}%

Width_{15}%

Width_2.5%

Width_5%

Width_{10}%

Width_{15}%

Width_{20}%

Width_{20}%

Centrality(%)

Centrality(%)

net-proton multiplicity distributions from Au+Au collisions with the only kinematic cut of $0.4 < pT < 0.8$ GeV/c and impact parameter b = 0 - 14 fm at sN N = 4.7, 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV by AMPT simulation. The solid and open symbols represent the results calculated with and without CBWC method. The centrality bin width selections are 2.5 %, 5 %, 10 %, 15 % and 20 %, respectively.

net-proton multiplicity distributions from Au+Au collisions with the kinematic cuts of $|y| < 0.5$, $0.4 < pT < 0.8$ GeV/c and impact pa√ rameter b = 0 - 14 fm at sN N = 4.7, 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV by AMPT simulation.

The solid and open symbols represent the results calculated with and without CBWC method. The red stars represent the results calculated with data from the STAR experiment at RHIC [23, 50]. The centrality bin width selections are 2.5 %, 5 %, 10 %, 15 % and 20 %, respectively.

tion entropy of net-proton multiplicity distributions becomes lisions is more sensitive to the CBWE. However, after applyless sensitive to CBWE in centrality bins with small widths, ing both pT and y cuts, the differences in information entropy and this results in a weaker CBWC effect. In contrast, for before and after CBWC correction at all energies are smaller larger centrality bins, the influence of CBWE remains pro- than those observed under the previous three kinematic cut nounced and the CBWC exhibits a significant disparity. conditions. This is because kinematic cuts not only exclude In the three scenarios above, unlike previous experimental marginal particles which located at the edges outside the ac conditions, the rapidity y cut and the transverse momentum ceptance window, but also filter the particles which inside pT cut were not applied simultaneously in the simulations the acceptance window to the same range for each central of particle collision distributions. These results demonstrate ity class. As a result, centrality width bin distributions tend to that applying CBWC to the information entropy is both fea- cluster around the same condition, thereby reducing the dif sible and effective. The distinct differences observed across ferences among different centrality classes. The information all energies offer a solid basis for further investigation and entropy is significantly sensitive to the shape of the distri validate the reliability of information entropy when used with butions and the volume of data [27, 29, 35]. Although the the CBWC method. Therefore, when calculating the infor- differences in the information entropy values before and after mation entropy of net-proton multiplicity distributions with- correction are reduced when both the transverse momentum out simultaneously applying kinematic cuts, it is essential to cut and the mid-rapidity cut are applied simultaneously, the implement CBWC to ensure the accuracy of the results, par- CBWC method remains an effective approach to improve the ticularly at higher collision energies. accuracy of the fluctuations reflected by information entropy The last kinematic cut scenario simultaneously applies the in probing the critical point in the QCD phase diagram. In mid-rapidity cut and transverse momentum cut, obtains mul- this work, only the final net-proton multiplicity distributions tiplicity distribution of net-proton yields, and verifies the sen- were available when obtaining the corresponding experimen sitivity of the information entropy of the net-proton multiplic- tal data. Therefore, we can only calculate the uncorrected in ity distribution to the CBWE under conditions consistent with formation entropy using publicly available experimental data. the experimental setup. The calculated information entropy This serves to verify the validity of the AMPT model pa both before and after the implementation of the CBWC, as rameters and the event-number cut ranges used in this work. well as that obtained from the experimental data [23, 50], are 376 Therefore, in Fig. 5 [Figure 5: see original paper], only the experimental information en346 shown in Fig. 5 for comparison. Similar to the trends of the 377 tropy values before the correction are presented. It can be 347 information entropy obtained under the previous three kine- 378 seen that the experimental data agree well with the AMPT 348 matic cut conditions, the results show that the CBWC correc- 379 model results in overall trend.

This demonstrates the reli349 tion becomes more pronounced at higher collision energies, 380 ability of the information entropy values obtained from the 350 indicating that the net-proton distribution in high-energy col- 381 AMPT model simulations in this work.

Further investigation of centrality bin width effect

The centrality bin width effect arises because centrality bins are divided by Nch , but the smallest centrality bin is 385 usually a single multiplicity value and it will cause volume 386 variation within centrality bins [32]. To further explore the 387 influence of the centrality bin width effect under different col388 lision conditions, the deviations and ratios of information en389 tropy before and after the CBWC method of the net-proton 390 multiplicity distribution are evaluated. In Fig. 6 [Figure 6: see original paper], the devia-

HCBWC/HW/O

|y|<0.5

Centrality 20-22.5% (Width_2.5%)

Deviation (%)

4.7GeV

p <0.8 (GeV/C)

19.6GeV

27GeV

62.4GeV

200GeV

39GeV

Width_5% Width_{20}% Net-proton

(Width_5%)

20-30%

(Width_{10}%)

15-30%

(Width_{15}%)

(Width_{20}%)

(GeV)

single cut (mid-rapidity or transverse momentum) and all cuts (midrapidity and transverse momentum). (a) and (b) represent net-proton multiplicity distributions generated within |y| < 0.5 and 0.4 < pT < 0.8 GeV/c, respectively; (c) represents net-proton multiplicity distributions generated within both |y| < 0.5 and 0.4 < pT < 0.8 GeV/c. The net-proton multiplicity distributions are generated from Au+Au collisions with impact parameter b = 0 - 14 fm at sN N = 4.7, 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV in the AMPT-SM model.

Au+Au Collision

20-25%

20-40%

11.5GeV

7.7GeV

Au+Au collision, AMPT

|y|<0.5

p <0.8 (GeV/C)

Centrality (%)

The net-proton multiplicity distributions are generated from Au+Au 419 bin widths (15 %, 20 %), the ratio increases with increasing collisions without any kinematic cuts and with impact parameter b 420 energy. This indicates that smaller bin widths require CBWC = 0 - 14 fm at sN N = 4.7, 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 421 corrections in the high-energy region, while larger bin widths GeV in the AMPT-SM model. The solid and open symbols represent 422 require more significant CBWC corrections in the low-energy centrality bin width of 5 % and 20 %. 423 region. Therefore, when using information entropy as a probe

to study critical fluctuation phenomena, the CBWE should be taken into account for different choices of centrality bin 426 widths, and the original results should be corrected using the 394 and without CBWC method are shown under the condition of 427 CBWC. Meanwhile, regardless of whether both small and y 395 none kinematic cuts. In this condition, CBWC exhibit a sig428 cuts are applied in experiments or only one type of cut is cho396 nificant energy-dependence. The deviation increases as the 429 sen in theoretical simulations, the CBWC is also necessary 397 collision energy increases. At higher energies, the deviation 430 when calculating the information entropy of the net-proton 398 can exceed 18 % at sN N = 200 GeV. This trend reveals a 431 multiplicity distribution. 399 significant disparity between the information entropy before

Overall, Figs. 6 and 7 demonstrate from two complemen400 and after the application of the CBWC method. It also sug433 tary perspectives that the centrality bin width has different and 401 gests that the centrality bin-width dependence of net-proton 434 non-negligible effect on information entropy under different 402 multiplicity distributions becomes more prominent at higher 435 conditions. Therefore, CBWC is essential when using infor403 energies. For low-energy reactions, the deviations are rela436 mation entropy as a probe for exploring the critical fluctuation 404 tively small indicating that the centrality bin width effect is 437 phenomena in heavy-ion collisions under any circumstances. 405 mitigated to a certain extent. However, even at 4.7 GeV, a

HCBW C −HW/O 393 tions (D = | |) of the information entropy with

non-negligible deviation is still observed. Implying that small bin width alone cannot fully eliminate CBWE and CBWC re438 IV. CONCLUSION 409 mains essential regardless of centrality bin width.

The ratios (R = HCBWC /HW/O) under distinct kinematic 411 cut conditions of a mid-rapidity cut ($|y| < 0.5$) only, a trans- 439 The information entropy of net-proton multiplicity distri412 verse momentum cut ($0.4 < pT < 0.8$ GeV/c) only and the 440 butions is proposed as a probe to search for the QCD critical 413 simultaneous application of both cuts are presented in Fig. 7 [Figure 7: see original paper]. 441 point through the critical fluctuation phenomena. However, 414 The behavior of the ratio R as a function of collision en- 442 such investigations face significant challenges due to volume 415 ergy for five centrality bin widths: 2.5 %, 5 %, 10 %, 15 443 fluctuations induced by finite centrality bin widths, known 416 % and 20 %.

It can be clearly observed that, for smaller 444 as the CBWE. To address this problem, this work imple417 centrality bin widths (2.5 %, 5 %), the ratio decreases with 445 ments the CBWC method to suppress artificial volume fluctu418 increasing collision energy. In contrast, for larger centrality 446 ations that can obscure genuine critical signals. The CBWC

method is applied to information entropy derived from net- 467 width. proton multiplicity distributions generated from the AMPT- 468 Finally, the approach of information entropy—additionally 449 SM model for Au+Au collisions across a range of center-of- 469 advantaged by the reduced statistical volume of the net-proton 450 mass energies from 4.7 to 200 GeV. Various analysis scenar- 470 multiplicity distributions—offers a complementary alterna451 ios are considered, including cases with no kinematic cuts, 471 tive to the traditional high-order cumulant analyses. Mean452 with a mid-rapidity cut ($|y| < 0.5$), with a transverse mo- 472 while, compared with cumulants, the calculation of informa453 mentum cut ($0.4 < pT < 0.8$ GeV/c) and with both cuts 473 tion entropy is relatively simple, and it can serve as an al454 applied simultaneously. The results show that CBWC effec- 474 ternative method as well as a complementary cross-check. 455 tively suppresses CBWE, especially at higher collision en- 475 This method may be further extended in future studies to in456 ergies and for wider centrality bins.

The corrected infor- 476 clude other conserved observables, such as net charge and net 457 mation entropy exhibits improved centrality bin-width in- 477 strangeness, thereby enriching the toolkit for exploring the 458 dependence and demonstrates the necessity of applying the 478 QCD phase structure. 459 CBWC method with information entropy in real experimen460 tal analyzes, thereby reinforcing its credibility as an observACKNOWLEDGMENTS 461 able for probing critical fluctuation phenomena. Furthermore, 479 462 through a quantitative analysis of the deviation (D) and ratio 463 (R) between the corrected and original information entropy 480 This work was supported by the National Natural Sci464 values across different collision energies and centrality bin 481 ence Foundation of China (No. 12105079) and the Nat465 widths, this work confirms the necessity of applying CBWC 482 ural Science Foundation of Henan Province, China (No. 466 regardless of the collision energy or the size of centrality bin 483 262300421851 and No. 242300421048).

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