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Measurement of the charge separation along the magnetic field with Signed Balance Function in 200 GeV Au + Au collisions at STAR

Yufu Lin (for the STAR Collaboration)

Key Laboratory of Quark & Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China

Brookhaven National Laboratory, Upton, New York 11973, USA

Abstract

Experimental searches for Chiral Magnetic Effect (CME) in heavy-ion collisions have been going on for a decade, and so far there is no conclusive evidence for its existence. Recently, the Signed Balance Function (SBF), based on the idea of examining the momentum ordering of charged pairs along the in- and out-of-plane directions, has been proposed as a probe of CME. In this approach, a pair of observables is invoked: one is r_{rest}, the out-of-plane to in-plane ratio of ΔB measured in pair's rest frame, where ΔB is the difference between signed balance functions; The other is a double ratio, $R_{\text{B}} = r_{\text{rest}}/r_{\text{lab}}$, where r_{lab} is a measurement similar to r_{rest} but measured in the laboratory frame. These two observables give opposite responses to the CME-driven charge separation compared to the background correlations arising from resonance flow and global spin alignment. Both r_{rest} and R_{B} being larger than unity can be regarded as a case in favor of the existence of CME. It is found experimentally that r_{rest}, r_{lab} and R_{B} are larger than unity in Au+Au collisions at 200 GeV, and larger than realistic model calculations with no CME implemented. These findings are difficult to be explained by a background-only scenario.

Keywords: Heavy-ion collisions, chiral magnetic effect, signed balance function, reaction plane

1. Introduction

It has been pointed out that the hot and dense matter created in relativistic heavy-ion collisions may form metastable domains where the parity and time-reversal symmetries are locally violated, creating fluctuating, finite topological charges [1]. In non-central collisions, when such domains are immersed in the ultra-strong magnetic fields produced by spectator protons, they can induce electric charge separation parallel to the system's orbital angular momentum — the chiral magnetic effect (CME) [2]. To study the CME experimentally one has to look for the enhanced fluctuation of charge separation in the direction perpendicular to the reaction plane, relative to the fluctuation in the direction of reaction plane itself. This is the basis of all CME searches in heavy-ion collisions. Recently, a new method, namely the Signed Balance Function (SBF) method, is proposed as an alternative way to study the charge separation induced by CME in relativistic heavy-ion collisions [3]. The SBF method is based on the idea of examining the fluctuation of net momentum ordering of charged pairs along the in- and out-of-plane directions. In this approach, a pair of

26   observables were proposed, one is r_{rest}, the out-of-plane to in-plane ratio of ΔB measured in pair's rest frame,
27   where ΔB is the difference between signed balance functions; the other is a double ratio $R_B = r_{rest}/r_{lab}$, where
28   r_{lab} is a measurement similar to r_{rest} but performed in the laboratory frame. These two observables have pos-
29   itive responses to signal, but opposite, limited responses to known backgrounds arising from resonance flow
30   and global spin alignment. In this proceedings, we review tests made for the SBF with toy models, and give
31   an update on tests made with realistic models. Latter ones include combinations of background and signal
32   with various strengths. After that we will show SBF results from Au + Au collisions at 200 GeV measured
33   by the STAR experiment at RHIC.

2. Results and discussion

2.1. Review on toy model studies and update on realistic model studies

36   The major challenge in CME searches is that backgrounds, in particular those related to resonance
37   elliptic flow and global spin alignment, can produce similar enhancement of fluctuations with the CME
38   signal in the direction perpendicular to the reaction plane [3, 4]. The effects of both signal and backgrounds
39   have been implemented in toy model simulations [3], and for the configuration details of toy model please
40   see Ref [5]. With the toy model, the responses of SBF observables can be studied using various signal and
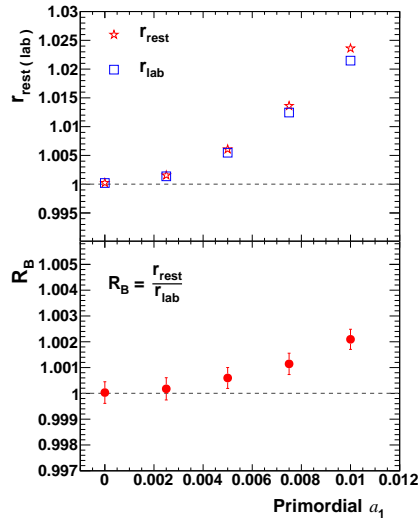41   background combinations, in a controlled and systematic way.

Fig. 1. The r_{rest}, r_{lab} and R_B as a function of a_1 obtained for the toy model (signal only, no backgrounds) [3].
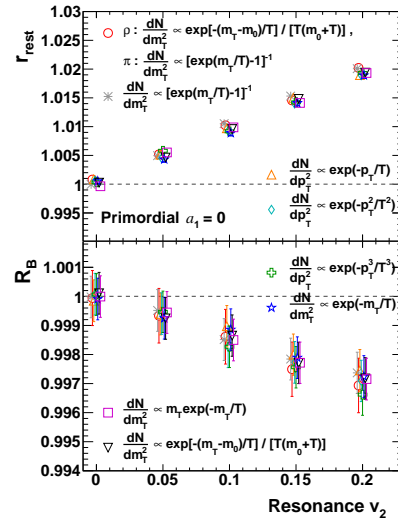
Fig. 2. The r_{rest} and R_B as a function of resonance v_2 for various transverse momentum/mass spectra obtained for the toy model [3].

42   In Fig. 1 SBF observables are shown as a function of primordial a_1, which a_1 refers to the signal of
43   CME, without any backgrounds. Here a_1 represents the strength of CME signal [3]. The r_{rest}, r_{lab} and R_B are
44   consistent with unity when $a_1 = 0$, and increase with increasing a_1. The r_{rest} and r_{lab} follow each other to
45   the first order but r_{rest} responds to signal more than r_{lab} does, which is the information shown in the bottom
46   panel. The results indicate that SBF observables are sensitive to the CME signal. The influence of elliptic
47   flow of resonances are shown in Fig. 2. The R_B is found to decrease with the increasing of resonance v_2,
48   while the r_{rest} increases with it. The two observables show opposite dependence on resonance v_2 assuming
49   various transverse momentum (p_T) spectra shape. More cases with additional background configurations
50   can be found in Ref [3]. Figure 3 shows toy model results with CME signal and two major backgrounds
51   (resonance flow and global spin alignment) considered, which are closer to the realistic scenario. One can
52   see that similar to the case of resonance flow only, r_{rest} and R_B respond in opposite directions to the change
53   of global spin alignment (ρ_{00}). On top of that, both increase with increasing signal (a_1). It will be a case

54 supporting CME if both r_{rest} and R_B are larger than unity, barring additional background from Local Charge
55 Conservation (LCC) and Transverse Momentum Conservation (TMC). Both LCC and TMC have to be
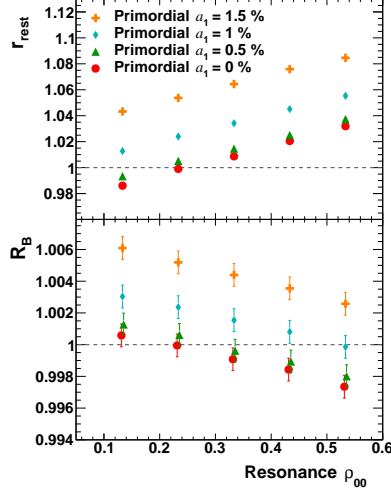56 studied with realistic models, which will be presented below.

Fig. 3. The r_{rest} and R_B as a function of reso-
nance ρ_{00} for various a_1 values obtained for the
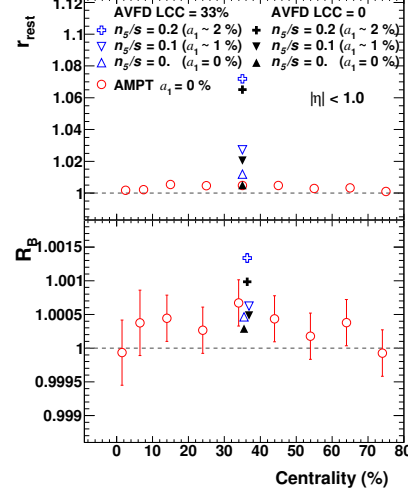toymodel [3]).

Fig. 4. The r_{rest} and R_B as a function of centrality,
calculated for events from AMPT and AVFD.

57 The two observables are also tested with two popular realistic models, namely the AMPT [6] and
58 AVFD [7] models. Both models can reasonably describe data's key features (spectra, elliptic flow, etc.).
59 For the AMPT version that is used in the test, no CME signal is implemented and charge-conservation has
60 been assured. It can serve as a good baseline for apparent charge separation arising from pure backgrounds.
61 In the AVFD model [7], the anomalous transport current from CME has been implemented by introducing
62 finite ratio of axial charge over entropy (n_5/s), allowing a quantitatively and systematically study on observ-
63 able's responses to signal embedded an environment of realistic backgrounds. Figure 4 shows the results of
64 r_{rest} and R_B as a function of centrality for AMPT and AVFD events. To match the typical acceptance used
65 by the STAR Collaboration, only particles in $|\eta| < 1$ and $0.2 < p_T < 2$ GeV/c are considered in the analysis.
66 For the two cases without CME (AMPT and AVFD with $n_5/s = 0$), r_{rest} and R_B are consistent with unity
67 within statistical uncertainties. Both r_{rest} and R_B increase with increasing n_5/s in AVFD results, results for
68 the two LCC cases (LCC = 33% and LCC = 0%). The increase of the strength of LCC shifts both r_{rest} and
69 R_B upwards, but only limited response is seen for the SBF observables when LCC changes from 0% to 33%.
70 More detailed investigation on LCC is ongoing.

2.2. STAR's Results from Au + Au collisions at 200 GeV

72 Experimental data used in this analysis are 200 GeV Au + Au collisions taken by the STAR experiment
73 in year 2016. About one billion minimum-bias events were used in the analysis. The transverse momentum
74 range for particles included in the analysis is $0.2 < p_T < 2$ GeV/c. The second order event-plane (EP), ψ_2,
75 is reconstructed with Time Projection Chamber (TPC) withing $0.5 < \eta < 1.0$. Pions are used to calculate
76 SBF, and they are identified with the information from both the TPC and the Time-Of-Flight detector. Pion
77 kinematic region is confined in $|\eta| < 0.5$, a different region than that for ψ_2 to avoid auto-correlation effects.
78 In Fig. 5, r_{rest} , r_{lab} and R_B are shown as a function of centrality for both experimental data and AVFD
79 model events. Results presented in Fig. 5 are not corrected for the EP resolution. Instead, we smeared
80 reaction plane in AVFD events with measured event plane resolution in order to compare with data. The
81 finite efficiency effect is also applied to AVFD events to assure a fair comparison. One can find that both
82 r_{rest}, r_{lab}, and R_B are larger than unity for all centralities for experimental data. As a consistency check,
83 we also randomized each particle's charge while keep the total number of charged particles (positive and

negative) in event unchanged. Such events and they are called shuffled events, and they are analyzed in the
same way as what real events are analyzed. As shown in 5, SBF observables for shuffled events are at unity
as expected. In the centrality of 30-40%, r_{rest} and R_B from data are both larger than the AFVD calculation
without CME (the case of $a_1 = 0$), indicating that there is a room to accommodate the CME explanation.
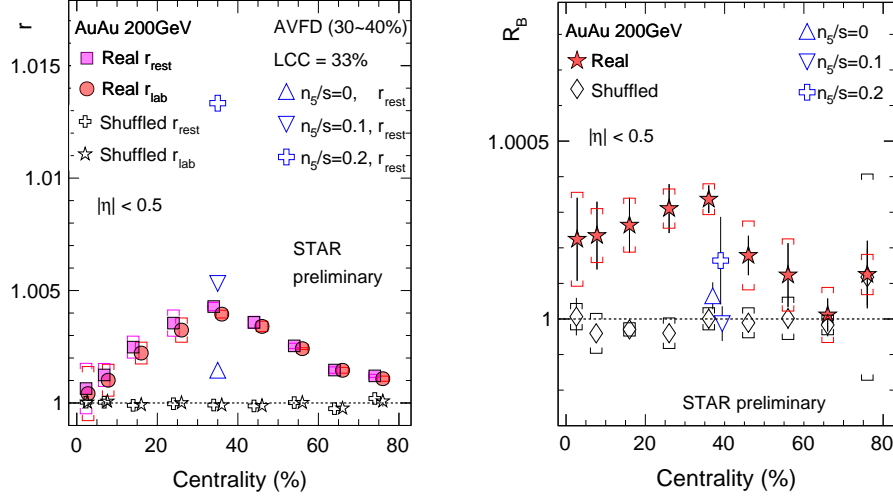Our overall observation is difficult to be explained by background-only model.

Fig. 5. (Color online) r_{rest} , r_{lab} and R_B as a function of centrality from Au + Au 200 GeV at STAR.

3. Summary

We reviewed tests of SBF with toy models, and gave an update on studies made with two realistic
models. Toy model simulation studies show that the two observables, r_{rest} and R_B, respond in opposite
directions to signal and backgrounds arising from resonance v_2 and ρ_{00}. If both r_{rest} and R_B are larger than
unity, then it can be regarded as a case in favor of the existence of CME. In Au+Au collisions at 200 GeV,
r_{rest} , r_{lab} and R_B are found to be larger than unity, and larger than AVFD model calculation with no CME
implemented. Our results are difficult to be explained by a background-only scenario.

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