Flow-background subtraction in charge-separation measurements in heavy-ion collisions

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Recent azimuthal-angle correlation measurements in high-energy heavy-ion collisions have observed charge-separation signals perpendicular to the reaction plane, and the observations have been related to the chiral magnetic effect (CME) [1]. However, the correlation signal is contaminated with the background contributions due to the collective motion (flow) of the collision system, and it remains elusive to effectively remove the background from the correlation. In this poster, we present a method study with a simple Monte Carlo simulation and the AMPT model [2]. We develop a scheme [3] to reveal the true CME signal via the event-shape engineering with the magnitude of the flow vector, Q: the flow-background is removed at $Q^2 = 0$. Artificial signal/background effects will also be discussed.

Introduction

The thermodynamic states of the hot, dense, and de-confined nuclear medium created in high-energy heavy-ion collisions can be specified by the axial chemical potential μ_5, as well as the temperature T and the vector chemical potential μ. The quantity μ_5 characterizes the imbalance of right-handed and left-handed fermions in a system, and a chiral system bears a nonzero μ_5. In a noncentral collision, a strong magnetic field (B ~ 10^{15} T) can be produced (mostly by energetic spectator protons), and will induce an electric current along B in chiral domains, $J_B \propto \mu_5 B$, which is called the chiral magnetic effect (CME).

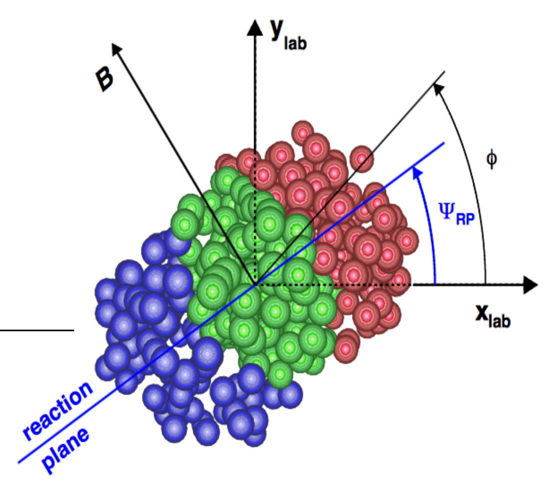
$\frac{dN}{d\phi} \propto 1 + 2v_{1,\alpha}\cos(\Delta\phi) + 2v_{2,\alpha}\cos(2\Delta\phi) + 2a_{1,\alpha}\sin(\Delta\phi) + \ldots$

where $\Delta\phi = \phi - \Psi_{RP}$,

α(+ or -) denotes the charge sign of particle

v_1: directed flow v_2: elliptic flow

a_1: quantifies the charge separation due to CME



$\gamma = \left\langle \left\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \right\rangle_P \right\rangle_E$

$= [\langle v_{1,\alpha} v_{1,\beta}\rangle + B_{in}] - [\langle a_{1,\alpha} a_{1,\beta}\rangle + B_{out}]$

(B_{in}-B_{out}) :flow-related background

$v_2 = \langle\langle \cos(2\phi - 2\Psi_{RP})\rangle_P\rangle_E$ $v_2^{obs} = \langle\langle \cos(2\phi 2\Psi_{EP})\rangle_P\rangle_E$

- Each event is evenly divided into two sub-events, A and B.
- Resolution $R^B \equiv \langle \cos(2\Psi_{EP}^B - 2\Psi_{RP})\rangle_E$, ensemble average $v_2^A = v_2^{obs} / R^B$

Monte Carlo simulation

- There are only input of the charge separation and elliptic flow : $a_{1,+}$=2%, $a_{1,-}$=-2% and v_2=5%.
- Sub-event A provides particles, and sub-event B provides event plane.

AMPT simulation(Au+Au collisions at 200 GeV)

It contains only background contribution, and each event has been divided into 3 sub-events.
A: |η| < 1.5 contains particles of interest.
B_1:1.5 < η < 4, B_2: -4 < η < -1.5 serve as reconstructed sub-event planes.

Handle on event-shape

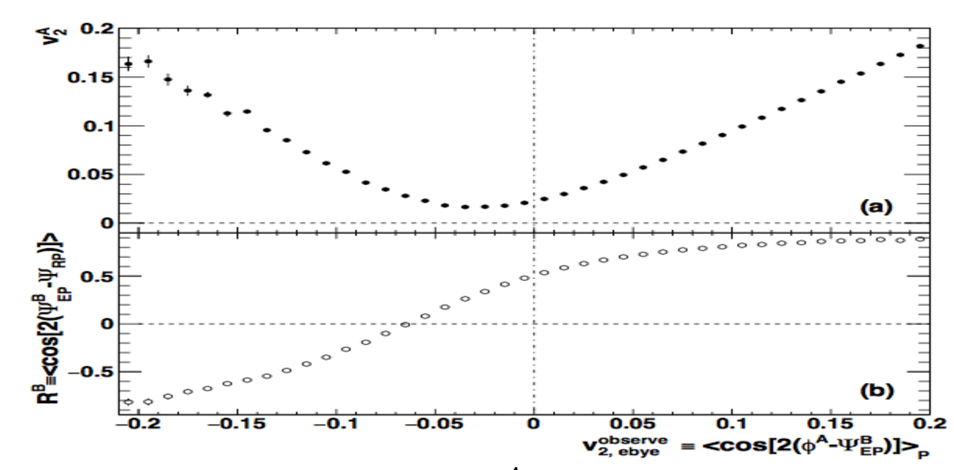


FIG.1: The true elliptic flow v_2^A (upper) and the true event plane resolution R^B (lower) as functions of $v_{2,ebye}^{obs}$, from Monte Carlo simulation.

- v_2^{obs} is not a valid approach since it fails to select sub-event with zero v_2^A. (spherical sub-event), and sphericity depends on beholder. Moreover, true event plane resolution becomes negative, so $v_2^A \neq v_2^{obs}/R^B$ on the $v_{2,ebye}^{obs}$ basis.

Good handle on event shape: $\vec{q} = \left(\frac{1}{\sqrt{N}}\sum_i^N \cos(2\phi_i^A), \frac{1}{\sqrt{N}}\sum_i^N \sin(2\phi_i^A)\right)$

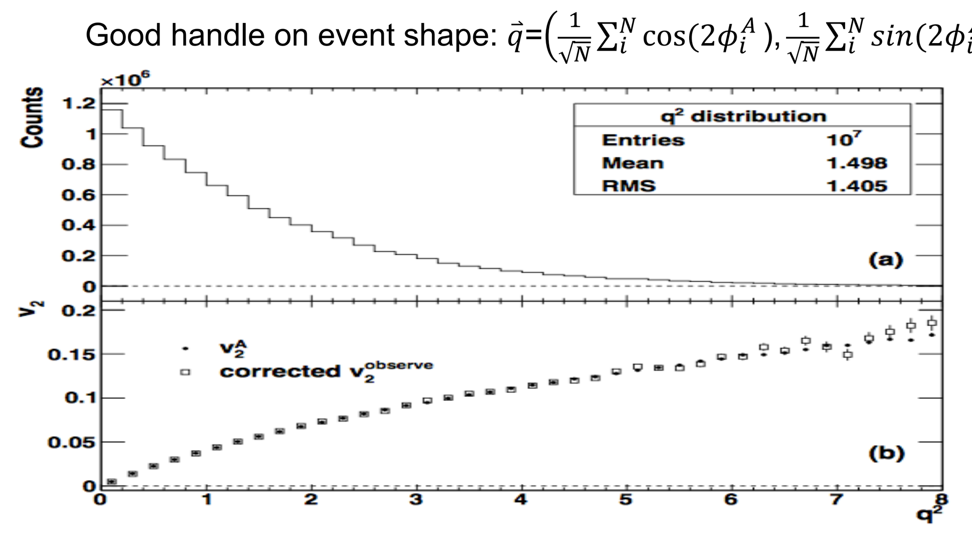


FIG.2: The distribution of q^2 (upper), and the true elliptic flow v_2^A and the corrected v_2^A as functions of q^2 (lower), from Monte Carlo simulation.

- Both v_2 values approach to zero at vanishing q^2 on the q^2 basis.
- The correction for the event plane resolution is valid.
- Advantages of q^2 :
  1. v_2 is linearly related to q^2 at small v_2.
  2. q^2 distribution is "squeezed" in phase space towards zero.

Disappearance of background

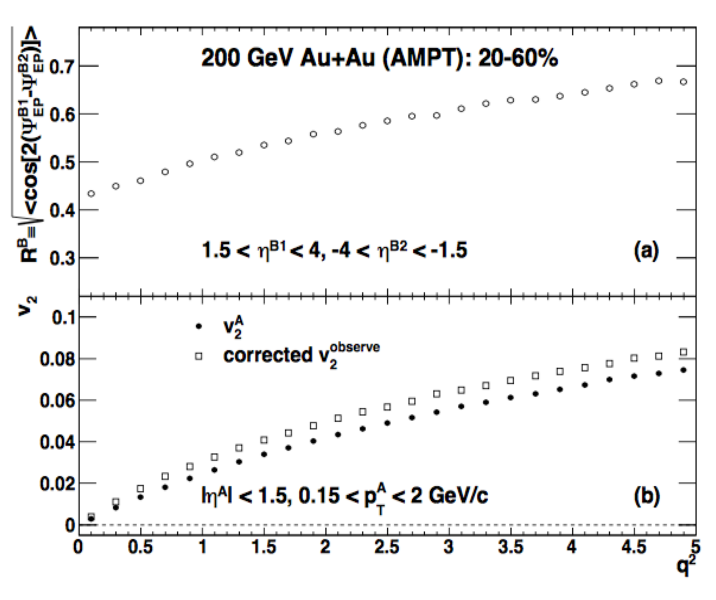


FIG.3:The sub-event plane resolution (upper), and the true elliptic flow v_2^A and the corrected v_2^{obs} as functions of q^2(lower), from AMPT simulation.

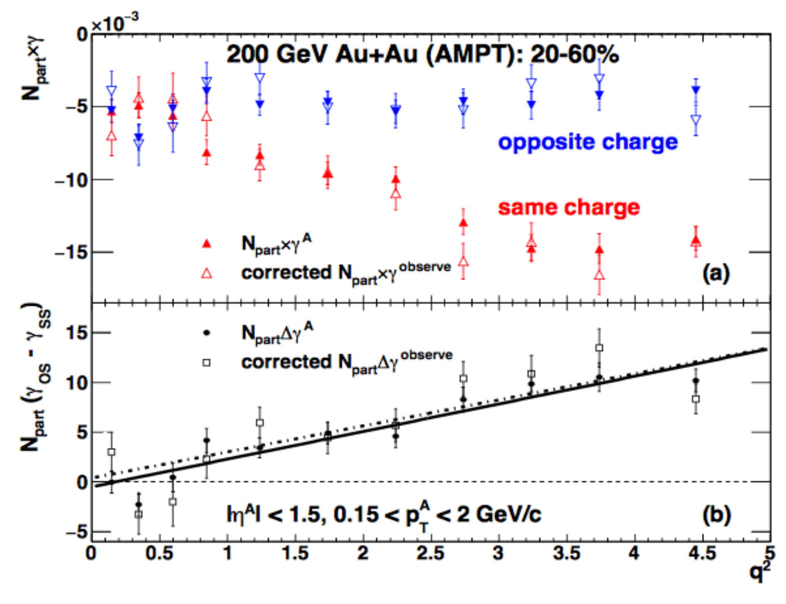


FIG.4:(Color online) $N_{part}\times\gamma$(upper) and $N_{part}\Delta\gamma$(lower) as functions of q^2, from AMPT simulation.The solid (dashed) line in the lower panel is a linear fit of the full (open) data points.

- Discrepancy between v_2^A and corrected v_2^{obs} comes from non-flow and flow fluctuation.
- Both v_2 drop to 0 at vanishing q^2.
- γ is less sensitive to non-flow and flow fluctuation.
- Intercepts are consistent with zero (−4.9 ± 6.1) ×10^{-4} for $N_{part}\Delta\gamma^A$ and (3.9 ± 9.9) ×10^{-4} for $N_{part}\Delta\gamma^{observe}$, so disappearance of background at zero q^2 is demonstrated.

Ensemble average method

When the q reconstruction is not applicable or reliable, we resort to the ensemble average of several observables.

$\gamma \equiv \ll \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \gg = \kappa_B v_2 B - H$

$\delta \equiv \ll \cos(\phi_\alpha - \phi_\beta) \gg = B + H$

H: CME signal contribution.
B: Flow background contributions, include the decays of the clusters, transverse momentum conservation (TMC) and local charge conservation (LCC).
Baseline: $\kappa_B = \Delta\gamma/(v_2\Delta\delta)$

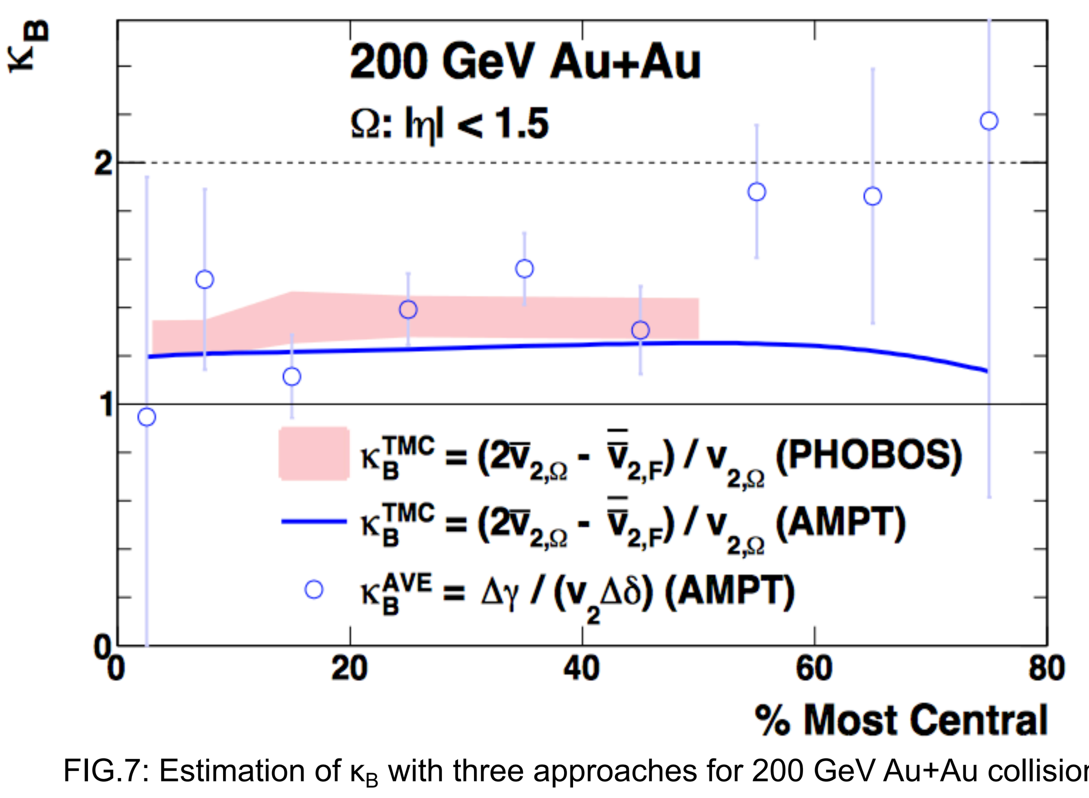


FIG.7: Estimation of κ_B with three approaches for 200 GeV Au+Au collision.

- For 200 GeV Au+Au collision, κ_B is estimated to be [1.2, 1.4] from AMPT simulation.
- CME signal can be obtained from κ_B: $\Delta H^\kappa = (\kappa_B v_2 \Delta\delta - \Delta\gamma)/(1+\kappa_B v_2)$
- If $\kappa_B = (\Delta\gamma)/(v_2\Delta\delta)$ obtained from real data is significantly above 2, it evidences a real charge separation due to CME.

Restore ensemble average of signal

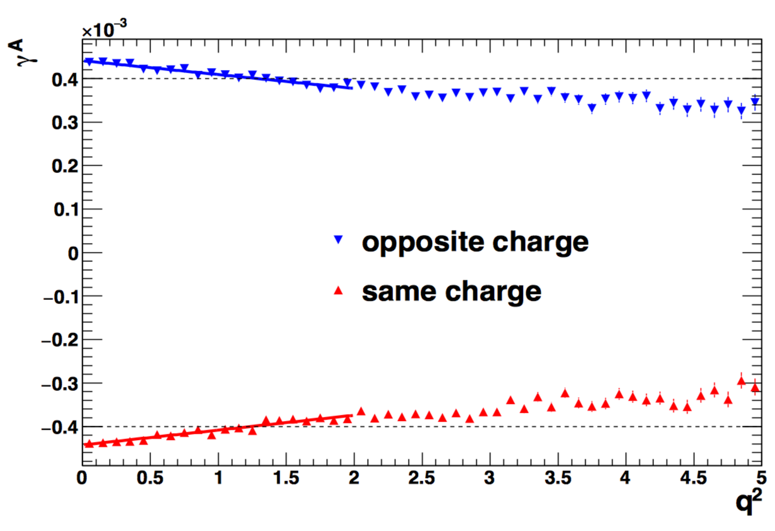


FIG. 5: (Color online) γ obtained with the true reaction plane as a function of q^2, from the Monte Carlo simulation.

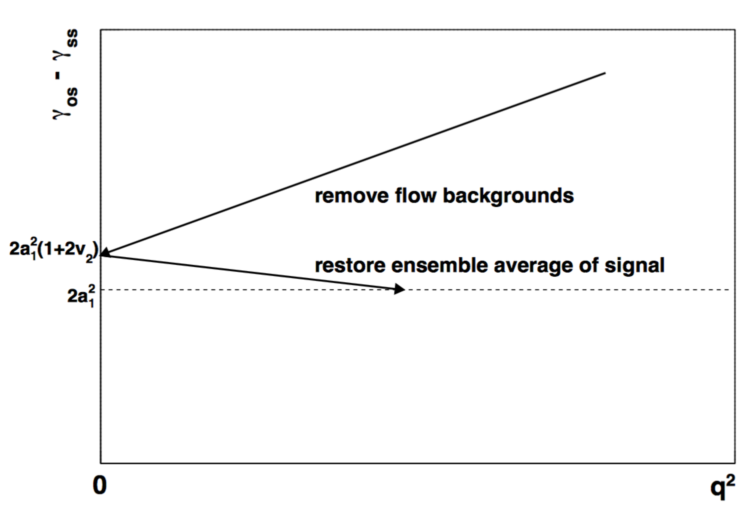


FIG. 6: A schematic diagram of how to reveal the ensemble- averaged CME signal via the ESE.

- $\gamma_{ebye} \equiv \langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle_P \approx 2\delta_{ebye} v_{2,ebye} - a_{1,\alpha} a_{1,\beta} - 2\delta v_2$
- The apparent value at zero q^2 exaggerates the charge separation: $\Delta\gamma = \Delta\gamma(q^2 = 0)/(1 + 2v_2)$.

Summary

- q^2 is a valid basis to select spherical sub-event.
- First projection is applied to remove the flow background, and second projection is applied to remove artificial background.
- Real CME signal can be obtained from $\Delta\gamma = \Delta\gamma(q^2 = 0)/(1 + 2v_2)$.

Reference

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[2] Z.W. Lin and C.M. Ko, Phys. Rev. C 65, 034904 (2002).
[3] F. Wen, L. Wen, and G. Wang, (2016), 1608.03205

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