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Event plane resolution correction for azimuthal anisotropy in wide centrality bins

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ABSTRACT

We provide a method to correct the observed azimuthal anisotropy in heavy-ion collisions for the event plane resolution in a wide centrality bin. This new procedure is especially useful for rare particles, such as Ω baryons and J/ψ mesons, which are difficult to measure in small intervals of centrality. Based on a Monte Carlo calculation with simulated v_2 and multiplicity, we show that some of the commonly used methods have a bias of up to 15%.

1. Introduction

Azimuthal anisotropy is one of the key observables to study the properties of matter created in high energy heavy-ion collisions (see e.g. [1]). It is characterized by the Fourier decomposition of the azimuthal particle distribution with respect to the participant plane [2].

$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_{\mathrm{PP}_n})]\right), \tag{1}$$

where N_0 is the number of particles in the event, v_n is the n-th harmonic coefficient, ϕ is the azimuthal angle of particles and Ψ_{PP_n} is the azimuthal angle of the nth harmonic participant plane. The participant plane is the symmary plane of the participants.

One of the standard methods is to extract v_n by using the reconstructed event plane from the detected participant particles [3]. The most important task in this method is to estimate the participant plane from the measured particles for each harmonic n. The estimated participant plane is defined as the *event plane* Ψ_n $(-\pi/n \le \Psi_n < \pi/n)$, but due to the finite multiplicity in nuclear collisions and fluctuations, the event plane can be different from the participant plane. The observed $v_n^{\mathrm{obs}}(M)$ for a given, small, centrality range M must be corrected by the *event plane resolution* $\mathcal{R}_n(M)$ in order to take into account the difference between true participant plane and event plane

$$v_n(M) = \frac{\langle\langle \cos[n(\phi - \Psi_m)]\rangle\rangle_M}{\left\langle \cos[n(\Psi_m - \Psi_{\mathrm{PP}_n})]\right\rangle_M} \equiv \frac{v_n^{\mathrm{obs}}(M)}{\mathcal{R}_n(M)}, \tag{2}$$

where m is the harmonic of the event plane and $n{=}km$ is the harmonic of interest. The integer k is taken as unity in this paper. Brackets denote the average over events, while double brackets denote the average over particles in all events. Subscript M on the bracket emphasizes that the average is taken for a given centrality M. For simplicity, we will omit M from the observables, for example, we will write N_0 instead of $N_0(M)$. In experiments the participant plane angle Ψ_{PP_n} in Eq. (1) is not known. Therefore at least two subevent planes are necessary in order to calculate the event plane resolution [3]. An average v_n over a wider centrality range R can be calculated once v_n^{obs} and $\mathcal{R}_n$ are determined within the range R

$$\frac{\int_R dMN_0 \dfrac{v_n^{\mathrm{obs}}}{\mathcal{R}_n}}{\int_R dMN_0} \equiv \left\langle \frac{v_n^{\mathrm{obs}}}{\mathcal{R}_n}\right\rangle = \langle v_n\rangle. \tag{3}$$

We introduced brackets $\langle \ldots \rangle$ for simplicity, which denote the average over a wide centrality range weighted by particle multiplicity N_0 for a given phase space (e.g. for a given transverse momentum range).

$\mathcal{R}_n$ depends on multiplicity and v_n itself, therefore Eq. (3) requires that v_n^{obs} and $\mathcal{R}_n$ are measured in sufficiently small centrality intervals. However, for rare particles (e.g. Ω, J/ψ) it is not always possible to do so. One of the conventional approaches (e.g. see Ref. [4]) is to average v_n^{obs} as well as $\mathcal{R}_n$ separately in a wide centrality range, weighted by the corresponding particle yields, and then divide $\left\langle v_n^{\mathrm{obs}}\right\rangle$ by $\langle \mathcal{R}_n\rangle$. However, this approach systematically

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overestimates v_n as we will discuss in Section 3. The main point of this paper is the following inequality

$$\left\langle \frac{v_n^{\rm obs}}{\mathcal{R}_n} \right\rangle \neq \frac{\left\langle v_n^{\rm obs} \right\rangle}{\langle \mathcal{R}_n \rangle} \neq \left\langle v_n^{\rm obs} \right\rangle \left\langle \frac{1}{\mathcal{R}_n} \right\rangle \tag{4}$$

where the left hand side is the correct average over a wide centrality bin, while the right hand side shows commonly used approximations. However, it is easy to avoid these approximations.

We will show the proper way to correct for the finite event plane resolution in wide centrality bins. Eventhough the resolution is an event-by-event quantity, the calculation of the sum over individual particles for the flow coefficients must be done with the inverse of the reolution for the proper centrality. In Section 2, we derive the equations used to calculate $\langle v_n \rangle$ in our approach. We also show that the derived equations are equivalent to the average calculated from narrow centrality bins (see Eq. (3)). In Section 3, we show a simple Monte Carlo simulation to demonstrate the validity of the method, for the case of v_2. Based on a preliminary version of this paper [5], the method has been applied already in several publications [6–8].

2. Implementation

We now show two practical implementations to correct v_n for the event plane resolution in wide centrality bins. There are two or three steps to calculate v_n in wide centrality bins

1. Determine the event plane resolution $\mathcal{R}_n$ as a function of M in narrow centrality ranges.
2. Analyse v_n with the weights $1/\mathcal{R}_n$ for any, wide, centrality range of interest.
3. In addition for the event-plane method, one must multiply the result by the average weight.

In the following subsections, we discuss detailed implementations of how to apply corrections for different types of particle identification. For the sake of simplicity, we assume that non-flow effects are negligible, and all correlations between particles are induced by flow. A systematic study of other effects can be found in Ref. [8].

The azimuthal particle distribution with respect to the event plane can be written as

$$\frac{dN}{d(\phi - \Psi_m)} = \frac{N_0}{2\pi}\left(1 + 2\sum_n^{\infty} v_n^{\rm obs}\cos[n(\phi - \Psi_m)]\right). \tag{5}$$

2.1. Event-by-event particle identification

If the particle of interest can be identified on an event-by-event basis, one can directly calculate $\cos[n(\phi - \Psi_m)]$ for every particle, corrected with the event plane resolution for the corresponding centrality M

$$\frac{\cos[n(\phi - \Psi_m)]}{\mathcal{R}_n}, \tag{6}$$

where $\mathcal{R}_n(M)$ is supposed to be averaged over many events in advance. The event and centrality average in the range of multiplicities R of term (6) over $\phi - \Psi_m$ reduces in this case to Eq. (3):

$$\frac{\int_R dM \int_0^{2\pi} d(\phi - \Psi_m)\frac{dN}{d(\phi - \Psi_m)}\frac{\cos[n(\phi - \Psi_m)]}{\mathcal{R}_n}}{\int_R dM \int_0^{2\pi} d(\phi - \Psi_m)\frac{dN}{d(\phi - \Psi_m)}} = \frac{\int_R dM N_0 \frac{v_n^{\rm obs}}{\mathcal{R}_n}}{\int_R dM N_0} = \langle v_n \rangle \tag{7}$$

The main difference of our implementation to the conventional approach is the event-by-event resolution correction in Eq. (7). As we have mentioned earlier, event-by-event $\mathcal{R}_n$ correction does not mean that the $\mathcal{R}_n$ should be calculated event-by-event, but rather that $\mathcal{R}_n(M)$ is calculated for many events and then the resolution correction is made event-by-event as a function of centrality, M.

2.2. Statistical particle identification

There are two approaches in case the particle yield of interest can only be extracted statistically: the invariant mass fit method and the event plane method. The invariant mass fit method is almost equivalent to the one introduced in Section 2.1, while the event plane method needs one additional step to obtain the final v_n.

2.2.1. Invariant mass fit method

The invariant mass method [9] is quite useful to analyse particles that are detected through their decay products, such as $K_s^0 \to \pi^+\pi^-$, $\Lambda \to p\pi^-$ and so on. The point of this method is to calculate the mean azimuthal angle relative to the event plane, $\cos[n(\phi - \Psi_m)]$, as a function of invariant mass $M_{\rm inv}$

$$v_n^{S+B}(M_{\rm inv}) = \left\langle \cos\left[n(\phi - \Psi_m)\right]_{\rm inv} \right\rangle, \\ = v_n^S \frac{S}{S+B}(M_{\rm inv}) + v_n^B(M_{\rm inv})\frac{B}{S+B}(M_{\rm inv}). \tag{8}$$

where S is the signal yield peaked at the mass of the particle, B is the smooth background yield, ${v_n}^S$, ${v_n}^B$ and v_n^{S+B} are the v_n for signal, background and total particles, respectively. Signal and background contributions are decomposed by taking into account the measured signal-to-background ratio and using a parametrization of the background ${v_n}^B$ shape by assuming that $B(M_{\rm inv})$, and $v_n^B(M_{\rm inv})B(M_{\rm inv})$ are smooth functions of $M_{\rm inv}$ [9], while $v_n^S S(M_{\rm inv})$ is peaked at $M_{\rm inv}$. Since the average cosine is calculated in this approach, one can directly extract the ${v_n}^S$ by subtracting the background contribution. The only modification is to add a weight $1/\mathcal{R}_n$ on an event-by-event basis when one fills the histograms for $\cos[n(\phi - \Psi_m)]$ versus invariant mass similar to Eq. (7).

2.2.2. Event plane method

The event plane method [3] with $\phi - \Psi_m$ binning is an alternative approach to a v_n analysis when particle yields can be determined only statistically after a background is subtracted. This method requires the decomposition of signal and background in several $\phi - \Psi_m$ bins (typically 10–20), while the invariant mass fit method only requires the decomposition once. The event plane method does not need the assumption of a background v_n shape. Therefore this method has some advantage, especially when the signal to background ratio is poor.

The first step in the event plane method is the signal extraction for a given $\phi - \Psi_m$ bin

$$N^{\mathcal{R}}(\phi - \Psi_m) = \int_R dM \frac{1}{\mathcal{R}_n}\frac{dN}{d(\phi - \Psi_m)}, \tag{9}$$

where $N^{\mathcal{R}}(\phi - \Psi_m)$ is the number of particles for a given $\phi - \Psi_m$