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Importance of non-flow in mixed-harmonic multi-particle correlations in small collision systems

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1. Introduction

Measurements of two-particle angular correlation in small collision systems, such as pp or p+A, have revealed the ridge phenomena [1–5]: enhanced production of pairs at small azimuthal angle separation, Δφ, extended over wide range of pseudorapidity separation Δη. The azimuthal structure of the ridge is often characterized by a Fourier series dN_{pair}/dΔφ ≈ 1 + 2Σν_{n}^{2} cos(nΔφ), and studied as a function of charged particle multiplicity N_{ch}. The ν_{n} denotes the anisotropy coefficients for single particle distribution, with ν_{2} being the largest followed by ν_{3}. The ridge reflects multi-parton dynamics at early time of the collision and has generated significant interests in high-energy physics community. One key question concerning the ridge is the timescale for the emergence of the long-range multi-particle collectivity, whether it reflects initial momentum correlation from gluon saturation effects [6] or it reflects a final-state hydrodynamic response to the initial transverse collision geometry [7].

More insights about the ridge is obtained via multi-particle correlation technique, known as cumulants, involving four or more particles [8–11]. The multi-particle cumulants probe the event-by-event fluctuation of ν_{n}, p(v_{n}), as well as the correlation between ν_{n} of different order, p(v_{n}, v_{m}). For example, four-particle cumulant c_{4}[4] = ⟨v_{4}^{4}⟩ − 2⟨v_{2}^{3}⟩ constrains the width of p(v_{n}) [8], while four-particle symmetric cumulants SC(n, m) = ⟨v_{n}^{2} v_{m}^{2}⟩ − ⟨v_{n}^{2}⟩⟨v_{m}^{2}⟩ quantifies the lowest-order correlation between v_{n} and v_{m} [10].

The main challenge in the study of azimuthal correlations in small systems is how to distinguish long-range ridge correlations from “non-flow” correlations such as resonance decays, jets, or di-jet production. In A+A collisions, non-flow is naturally suppressed due to large particle multiplicity, i.e. non-flow contribution scales as 1/N_{ch} and 1/N_{ch}^{2} for the two- and four-particle cumulants, respectively [12]. In small systems, however, non-flow can be large due to their much smaller N_{ch} values, and one has to employ new methods that explicitly exploit the long-range nature of the collective in η: For two-particle correlations, the non-flow is suppressed by requiring a large Δη gap and a peripheral subtraction procedure [2–4,13–15]. For multi-particle cumulants, the non-flow can be suppressed by requiring correlation between particles from different subevents separated in η, while keeping the genuine long-range multi-particle correlations associated with the ridge. This so-called subevent method [11] has been shown to be necessary to obtain a reliable c_{4}[4] [16], while the C_{2}[4] based on the standard cumulant method [15,17] are contaminated by non-flow correlations over the full N_{ch} range in pp collisions and the low N_{ch} region in p+A collisions.

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Recently CMS Collaboration also released measurements of SC(2, 3) and SC(2, 4) in pp and p+Pb collisions, based on the standard cumulant method [18]. However, since these observables have much smaller signal than $c_s(4)$, they are expected to be even more susceptible to non-flow effects. Therefore, more precise study of the influence of non-flow effects to these observables is required before any interpretation of the experimental measurements. Event generators such as PYTHIA8 [19] and HIJING [20], which contain only non-flow correlations, are perfect test-ground for estimating the influence of non-flow to symmetric cumulants in small systems, which is the focus of this paper. Using a PYTHIA8 simulation of pp collisions and HIJING simulation of p+Pb collisions, we demonstrate that SC(n, m) based on the standard method is dominated by non-flow in pp collisions, and is contaminated by non-flow in p+Pb collisions. We show that reliable SC(n, m) measurements can be obtained using three-subevent or four-subevent methods, which therefore should be the preferred methods for analyzing multi-particle correlations in small systems.

2. Symmetric cumulants

The framework for the standard cumulant is described in Refs. [9, 10], which was recently extended to the case of subevent cumulants in Ref. [11, 21]. The four-particle symmetric cumulants SC(n, m) are related to two- and four-particle azimuthal correlations for flow harmonics of order n and m as (n ≠ m).

\[
\langle \{4\}_{n,m} \rangle = e^{i m (\phi_1 - \phi_2) + i m (\phi_3 - \phi_4)},
\]

\[
\langle \{2\}_{n} \rangle = e^{i m (\phi_1 - \phi_2)}, \quad \langle \{2\}_{m} \rangle = e^{i m (\phi_3 - \phi_4)}.
\]

(1)

SC(n, m) = \langle \{4\}_{n,m} \rangle - \langle \{2\}_{n} \rangle \langle \{2\}_{m} \rangle = e^{i m (\phi_1 - \phi_2) + i m (\phi_3 - \phi_4)} - e^{i m (\phi_1 - \phi_2)} e^{i m (\phi_3 - \phi_4)}.

(2)

One firstly averages all distinct quadruplets or pairs in one event to obtain \langle \{4\}_{n,m} \rangle, \langle \{2\}_{n} \rangle and \langle \{2\}_{m} \rangle, then average over an event ensemble to obtain \langle \{4\}_{n,m} \rangle, \langle \{2\}_{n} \rangle, \langle \{2\}_{m} \rangle and SC(n, m). In the absence of non-flow correlations, SC(n, m) measures the correlation between event-by-event fluctuations of $v_n$ and $v_m$:

SC(n, m)_{flow} = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle.

(3)

In the standard cumulant method, all quadruplets and pairs are selected using the entire detector acceptance. To suppress the non-flow correlations that typically involve particles emitted within a localized region in $\eta$, the particles can be grouped into several subevents, each covering a non-overlapping $\eta$ interval. The multi-particle correlations are then constructed by correlating particles between different subevents, further reducing non-flow correlations.

Specifically, in the two-subevent cumulant method, the entire event is divided into two subevents, labeled as a and b, for example according to $-\eta_{max} < \eta_a < 0$ and $0 < \eta_b < \eta_{max}$. The symmetric cumulant is defined by considering all quadruplets comprised of two particles from each subevent, or pairs comprised of one particle from each subevent:

\[
SC(n, m)_{n,b} = e^{i m (\phi_1 - \phi_2) + i m (\phi_3 - \phi_4)} - e^{i m (\phi_1 - \phi_2)} e^{i m (\phi_3 - \phi_4)}.
\]

(4)

where the superscript or subscript a (b) indicates particles chosen from the subevent a (b). The two-subevent method suppresses correlations within a single jet (intra-jet correlations), since each jet usually emits particles to one subevent.

Similarly for the three-subevent and four-subevent methods, the $|\eta| < \eta_{max}$ range is divided into three or four equal ranges, and are labelled as a, b and c or a, b, c and d, respectively. The corresponding symmetric cumulants are defined as:

\[
SC(n, m)_{3-sub} = \langle e^{i m (\phi_1 - \phi_2) + i m (\phi_3 - \phi_4)} \rangle - \langle e^{i m (\phi_1 - \phi_2)} \rangle \langle e^{i m (\phi_3 - \phi_4)} \rangle.
\]

(5)

\[
SC(n, m)_{4-sub} = \langle e^{i m (\phi_1 - \phi_2) + i m (\phi_3 - \phi_4)} \rangle - \langle e^{i m (\phi_1 - \phi_2)} \rangle \langle e^{i m (\phi_3 - \phi_4)} \rangle.
\]

(6)

Since the two jets in a dijet event usually produce particles in at most two subevents, the three-subevent and four-subevent method further suppresses inter-jet correlations associated with dijets. Furthermore, four-subevent suppresses possible three-jet correlations, although such contributions are expected to be small. To enhance the statistical precision, the $\eta$ range for subevent a is also interchanged with that for subevent b, c or d, which results in three independent SC(n, m)_{3-sub} and three independent SC(n, m)_{4-sub}. They are averaged to obtain the final result.

3. Model setup

To evaluate the influence of non-flow to SC(n, m) in the standard and subevent method, the PYTHIA8 and HIJING models are used to generate pp events at $\sqrt{s} = 13$ GeV and p+Pb events at $\sqrt{s_{NN}} = 5.02$ TeV, respectively. These models contain significant non-flow correlations from jets, dijets, and resonance decays, which are reasonably tuned to describe the data, such as $p_T$ spectra, $N_{ch}$ distributions. Multi-particle cumulants based on the standard method as well as subevent methods are calculated as a function of charged particle multiplicity $N_{ch}$. To make the results directly comparable to the CMS measurement [18], the cumulant analysis is carried out using charged particles in $|\eta| < \eta_{max} = 2.5$ and several $p_T$ ranges, and the $N_{ch}$ is defined as the number of charged particles in $|\eta| < 2.5$ and $p_T > 0.4$ GeV.

The symmetric cumulants are calculated in several steps using charged particles with $|\eta| < 2.5$, similar to Refs. [11, 16]. Firstly, the multi-particle correlators \langle \{k\} \rangle with $k = 1, 2$ (indexes $n$ and $m$ are dropped for simplicity) in Eq. 1 are calculated for each event from particles in one of the two $p_T$ ranges, 0.3 < $p_T$ < 3 GeV and 0.5 < $p_T$ < 5 GeV, and the number of charged particle in this $p_T$ range, $N_{ch}$, is calculated. Note that $N_{ch}$ is not the same as $N_{ch}$ defined earlier due to different $p_T$ ranges used. Secondly, \langle \{k\} \rangle are averaged over events with the same $N_{ch}$ to obtain \langle \{k\} \rangle and SC(n, m). The SC(n, m) values calculated for unit $N_{ch}$ are then combined over broader $N_{ch}$ ranges of the event ensemble to obtain statistically significant results. Finally, the SC(n, m) obtained for a given $N_{ch}$ are mapped to given ($N_{ch}$) to make the results directly comparable to the CMS measurements [18].

To further study the influence of non-flow fluctuations associated with multiplicity fluctuations, several other $p_T$ ranges, different from those used for \langle \{k\} \rangle, are also used to calculated $N_{ch}$. The results from this study are discussed in Appendix A.

4. Results

First we calculate the SC(2, 4) and SC(2, 3) from PYTHIA and HIJING using the standard cumulant method and compare them with the CMS pp and p+Pb data for charged particles. The same $p_T$ selection, 0.3 < $p_T$ < 3 GeV, is used to calculate the cumulants as well as to select the event class $N_{ch}$. The comparison is shown in Fig. 1. The results from models are non-zero and they decrease as a function of $N_{ch}$, similar to the
Fig. 1. The SC(n,m) calculated for charged particles with $0.3 < p_T < 3$ GeV with the standard cumulant method in 13 TeV pp collisions (left panel) and 5.02 TeV p+Pb collisions (right panel) compared between data (solid symbols) and Monte Carlo models (open symbols).

Fig. 2. The SC(2,3) (left panel) and SC(2,4) (right panel) in $0.3 < p_T < 3$ GeV and $|\eta| < 2.5$ as a function of $N_{ch}$ obtained from 13 TeV pp PYTHIA 8 simulations using the standard cumulant, two-subevent, three-subevent and four-subevent methods.

Fig. 3. The SC(2,3) (left panel) and SC(2,4) (right panel) for charged particles in $0.5 < p_T < 5$ GeV and $|\eta| < 2.5$ as a function of $N_{ch}$ obtained from 13 TeV pp PYTHIA 8 simulations using the standard cumulant, two-subevent, three-subevent and four-subevent methods.
Fig. 4. The SC(2, 3) (left panel) and SC(2, 4) (right panel) in $0.3 < p_T < 3$ GeV and $|\eta| < 2.5$ as a function of $N_{ch}$ obtained from 5.02 TeV $p$+Pb HIJING simulations using the standard cumulant, two-subevent, three-subevent and four-subevent methods.

Fig. 5. The SC(2, 3) (top row) and SC(2, 4) (bottom row) calculated for charged particles in $0.3 < p_T < 3$ GeV and several $N_{ch}$. They are obtained using the standard cumulant method (left column) and four-subevent method (right column) in pp collisions generated with PYTHIA 8 model.

data, indicating that the data may have significant non-flow contributions. In pp collisions as shown in the left panel, both SC(2, 4) and SC(2, 3) from the PYTHIA8 model are larger than the data, suggesting that either PYTHIA8 overestimates the non-flow contribution in SC$(n, m)$ or the flow correlation signals are negative. In $p+$Pb collisions as shown in the right panel, SC$(n, m)$ from the HIJING model are larger than (for SC(2, 3)) or roughly comparable (for SC(2, 4)) with the data for $N_{ch} < 70$, but their magnitudes are much smaller than the data for $N_{ch} > 100$. This implies that the influence of the non-flow is subdominant in $p+$Pb collisions, about 20% or less, at large $N_{ch}$ region, but it still dominates the small $N_{ch}$ region.

The comparison shown in Fig. 1 suggests that the symmetric cumulants measured with the standard method are strongly bi-
used by non-flow correlations in pp collisions over the full $N_{ch}$ range and in p+Pb collisions at low $N_{ch}$ region. On the other hand, the non-flow correlations are expected to be greatly suppressed in the subevent methods. Figs. 2 and 3 show $SC(n, m)$ obtained from various methods in pp collisions for charged particles in $0.3 < p_T < 3$ GeV and $0.5 < p_T < 5$ GeV, respectively. The same $p_T$ selections are used to calculate the cumulants as well as to select the event class.

Figs. 2 and 3 show that the values of $SC(n, m)$ from subevent methods are much smaller than those from the standard method. In particular, the four-subevent method gives results that are closest to 0, followed by the three-subevent method and then the two-subevent method. Since non-flow contributions are known to increase with $p_T$, such hierarchy between different methods are more clearly revealed in Fig. 3 than in Fig. 2. It is also interesting to note that the values of $SC(2, 3)$ is negative in the subevent methods, and can't be fully suppressed to zero even in the four-subevent method. The sign-change of $SC(2, 3)$ between the standard and two-subevent can be understood as the interplay between the inter-jet and intra-jet correlations: while the inter-jet correlation gives a positive contribution to $SC(2, 3)$, the intra-jet correlation from dijets gives a negative contribution. The $SC(2, 3)$ in standard method is positive because the inter-jet correlation dominates over the intra-jet contribution. However since the dijet contributions are further suppressed in the three-subevent and four-subevent methods, the residual negative $SC(2, 3)$ in these two methods suggest the existence, in PYTHIA8 and HIJING, of a small long-range non-flow source that correlate between the 2nd and 3rd harmonics.

Similar observations are found in p+Pb collisions as shown in Fig. 4, i.e. results from the subevent methods are closer to zero than those from the standard method. However, due to a much smaller non-flow in p+Pb collisions (~ten times smaller than pp at comparable $N_{ch}$ for $N_{ch} > 100$), the precision of the simulation does not allow a clear separation between different subevent methods. This also implies that we can already obtain reliable $SC(n, m)$ as soon as the subevent method is applied.

5. Summary

Multi-particle azimuthal correlation between different flow harmonics $v_n$ and $v_m$, known as symmetric cumulants $SC(n, m)$, has been used to study the nature of the long-range ridge in pp and p+Pb collision. Using the PYTHIA and HIJING models which contain only non-flow correlations, we show that recently measured $SC(2, 4)$ and $SC(2, 3)$, by the CMS Collaboration via the standard cumulant method, are likely contaminated by non-flow associated with jet and dijets. By requiring azimuthal correlation between multiple pseudorapidity $\eta$ ranges, we show that calculations using the recently proposed subevent cumulant methods are much less sensitive to these non-flow sources. Although the subevent methods can suppressed $SC(2, 4)$ to nearly zero in high-multiplicity pp and p+Pb collisions, the $SC(2, 3)$ from subevent methods still shows a small but negative correlation in these collisions. These studies suggest that the measurements of $SC(n, m)$ need to be re-
done with the subevent methods, before any physics conclusion related to long-range collectivity can be drawn.

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Appendix A. Sensitivity to event class definition

Another way to quantify the influence of the non-flow in the cumulant method is to study the sensitivity of $SC(n, m)$ on the choice of $N_{ch}^{sel}$. Previous studies show that different $N_{ch}^{sel}$ leads to drastically change the nature of the non-flow fluctuations, leading to different cumulant results. Following the example of Ref. [11, 16], the impact of non-flow fluctuations to $SC(n, m)$ are probed by varying the $p_T$ requirements used to define $N_{ch}^{sel}$ as follows: When $\langle(2k)\rangle$ is calculated in the range $0.3 < p_T < 3$ GeV, $N_{ch}^{sel}$ is evaluated in four different track $p_T$ ranges: $0.3 < p_T < 3$ GeV, $p_T > 0.2$ GeV, $p_T > 0.4$ GeV and $p_T > 0.6$ GeV. When $\langle(2k)\rangle$ is calculated in $0.5 < p_T < 5$ GeV, $N_{ch}^{sel}$ is evaluated in four different track $p_T$ ranges: $0.5 < p_T < 5$ GeV, $p_T > 0.2$ GeV, $p_T > 0.4$ GeV and $p_T > 0.6$ GeV. The $SC(n, m)$ values obtained for a given $N_{ch}^{sel}$ are mapped to given $N_{ch}$, so that $SC(n, m)$ obtained for different $N_{ch}^{sel}$ can be compared using a common x-axis defined by $N_{ch}$.

The results of this study are shown in Fig. 5 and 6 for pp and p+Pb collisions, respectively. A strong sensitivity of $SC(n, m)$ on $N_{ch}^{sel}$ is observed in the standard method. But such sensitivity is greatly reduced in the subevent method.

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