Measurement of Two-Particle Correlations and Flow Coefficients in High Multiplicity e^+e^- Collisions using Archived ALEPH Data at 91-209 GeV

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Abstract. We present measurements of two-particle angular correlations of charged particles emitted in high-energy collisions using data collected by the ALEPH detector at LEP between 1992 to 2000. The correlation functions are measured over a wide range of pseudorapidity and azimuthal angle as a function of charged particle multiplicity. Previous measurement with LEP1 data at $\sqrt{s}$ = 91 GeV shows no significant long-range correlations in either lab coordinate or thrust coordinate analyses, with associated yield distributions in agreement with predictions from the PYTHIA v6.1 event generator. The use of higher collision energy LEP2 data allows access to not only higher event multiplicity but also additional production channels beyond the $e^+e^- \rightarrow \gamma^*/Z \rightarrow q\bar{q}$ process. Notably, the highest multiplicity bin ($N_{trk} \geq 50$) suggests a tantalizing disagreement with MC and implies the potential to search for collective phenomena in small systems. This measurement is pushing the studies of long-range correlation to the smallest collision system limit and includes the first flow coefficient (v_n) measurement in e^+e^- collisions, which uses a Fourier decomposition analysis to quantify the anisotropy in the azimuthal two-particle correlation as a function of charged particles' transverse momentum. This work supplements our understanding of small-system references to long-range correlations observed in proton-proton, proton-nucleus, and nucleus-nucleus collisions.

1 Introduction

In heavy-ion collision experiments, two-particle correlations [1–6] are extracted for studying the Quark-Gluon Plasma (QGP) [7]. In nucleus-nucleus collisions, a long-range angular correlation, known as the ridge-like structure [2, 3], has been observed in different collision systems and energies. Unexpectedly, similar ridge structure has also been observed in smaller systems, such as proton-proton collisions [8, 9]. The physical origin of the ridge structure in small systems remains under debate [10–14]. Searching for the ridge signal in collisions with elementary particles helps to identify the minimal conditions for collective behavior [15]. The use of electron beams eliminates complications such as multiple parton interactions and initial state correlations. So far, no significant ridge-like signal has been observed in the most elementary electron-positron annihilations [16–21]. In this study, we search for collectivity signals in high multiplicity e^+e^- collisions at $\sqrt{s}$ = 91–209 GeV using archived ALEPH data from LEP-II. Thanks to the high collision energies above the Z^0 pole, this dataset allows

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for studies of higher multiplicity events compared to those from LEP-I. Additionally, the analyzed dataset encompasses various underlying physics processes.

2 Data sample and Methodology

This study utilizes archived data collected by the ALEPH detector at LEP [22] between 1992 and 2000. We apply the requirements on the effective center-of-mass energy ($\sqrt{s'}$), and the visible two-jet invariant mass (M_{vis}) for minimizing the QED radiation background. Hadronic events are selected with the event sphericity axis's polar angle, and by requiring on the minimum number of tracks and the total reconstructed charged-particle energy. For the calculation of the two-particle correlation, we use high-quality tracks, with transverse momenta ($p_{\mathrm{T}}^{\mathrm{lab}}$) above 0.2 GeV/$c$ and $|\cos\theta_{\mathrm{lab}}| < 0.94$ in the lab frame. Details of event and track selections are documented in the analysis note [23] and the paper [24].

We calculate the two-particle correlation function by constructing the efficiency-corrected differential yield of charged-particle pairs per event, denoted as $S(\Delta\eta, \Delta\phi) = \frac{1}{\mathrm{N}_{\mathrm{trk}}^{\mathrm{corr}}} \frac{\mathrm{d}^2\mathrm{N}^{\mathrm{same}}}{\mathrm{d}\Delta\eta \mathrm{d}\Delta\phi}$. To disassociate the random two-particle correlation, a mixed-event background correlation, which pairs charged particles from one event with those from 48 random events of the same multiplicity, is also constructed, giving $B(\Delta\eta, \Delta\phi) = \frac{1}{\mathrm{N}_{\mathrm{trk}}^{\mathrm{corr}}} \frac{\mathrm{d}^2\mathrm{N}^{\mathrm{mix}}}{\mathrm{d}\Delta\eta \mathrm{d}\Delta\phi}$. The final two-particle correlation function is obtained as

$$\frac{1}{\mathrm{N}_{\mathrm{trk}}^{\mathrm{corr}}} \frac{\mathrm{d}^2\mathrm{N}^{\mathrm{pair}}}{d\Delta\eta \mathrm{d}\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}, \tag{1}$$

where the factor $B(0,0)$ is the correlation of pairs with $|\Delta\eta| < 0.32$ and $|\Delta\phi| < \pi/20$, accounting for the detector's pair acceptance for uncorrelated particles. The coordinate representation (η, ϕ) is with respect to the thrust axis [25], which closely related to the outgoing $q\bar{q}$ direction in the e^+e^- collisions.

The two-particle correlation functions, and the correlations projected in the long range region $1.6 < |\Delta\eta| < 3.2$ for inclusive and high multiplicity events are shown in Fig. 1. No significant ridge-like structure was observed in the correlation function at low multiplicity ($\mathrm{N}_{\mathrm{Trk}} < 50$). In the highest multiplicity bin ($\mathrm{N}_{\mathrm{Trk}} \geq 50$), an intriguing excess of correlation yields on the small $\Delta\phi$ and the away-side regions over MC was revealed.

We measure the flow coefficient v_n by decomposing the two-particle correlation functions using a Fourier series. The comparison of v_n extraction as a function of track-pairs' p_T between data and MC for the inclusive and high-multiplicity is shown in Fig. 2. A difference is seen for high multiplicity events with $\mathrm{N}_{\mathrm{Trk}} \geq 50$, as shown in the right panel. The simulation generally predicts a smaller magnitude for $|v_n|$, reflecting the more complex event topologies selected by the large particle multiplicity. The data, however, shows an intriguing trend compared to the simulation, especially in v_2 and v_3, where the magnitude is larger.

To further visualize these distinctions, we present the difference in v_2 between data and the MC as a function of associated particle p_T, overlaid with the v_2^{sub} measured in high multiplicity pp collisions in Fig. 3. A remarkably similar trend is observed in the ALEPH data compared to $v_2^{\mathrm{sub}}\{2\}$ in proton-proton collisions.

3 Summary

We report the first measurement of two-particle angular correlations for charged particles resulting from e^+e^- annihilation using ALEPH archived data, with energies up to $\sqrt{s}$ = 209 GeV. In the high-multiplicity events, a long-range near-side excess is seen in the correlation function, and larger magnitudes of v_2 and v_3 compared to MC are seen. These intriguing

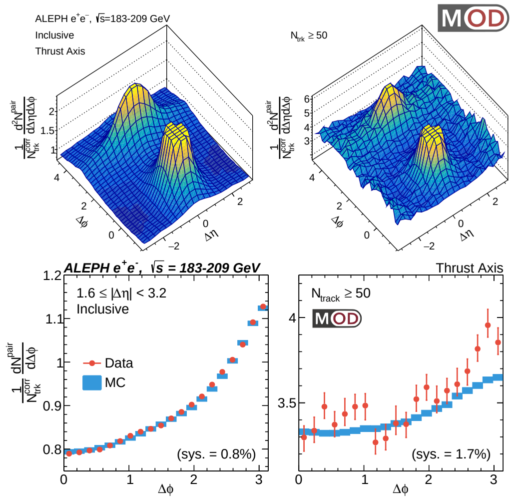

Figure 1. Two-particle correlation functions for events with the number of charged particle tracks in hadronic e^+e^- in the thrust coordinate analysis with $\mathrm{N_{trk}} \geq 5$ (top left) and $\mathrm{N_{trk}} \geq 50$ (top right). For the long-range region $1.6 < |\Delta\eta| < 3.2$, the azimuthal associated yield is presented for $N_{\mathrm{trk}} \geq 5$ (bottom left) and $N_{\mathrm{trk}} \geq 50$ (bottom right). Data is presented in red dots with statistical error bars, while systematic uncertainties are detailed in the text. The PYTHIA 6 model is shown in blue with its statistical error band.

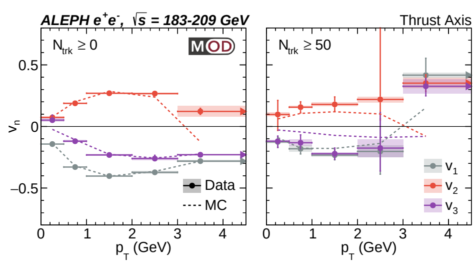

Figure 2. v_n as a function of the track pairs' p_T requirement in different multiplicity intervals for the thrust axis analysis for the LEP-II high-energy sample. Data's v_1, v_2, and v_3 are shown in black, red, and purple error bars. MC results are dashed lines with corresponding colors.

findings fortify our understanding of the underlying mechanisms in particle collisions and shed light on the origins of flow-like signals in smaller collision systems.

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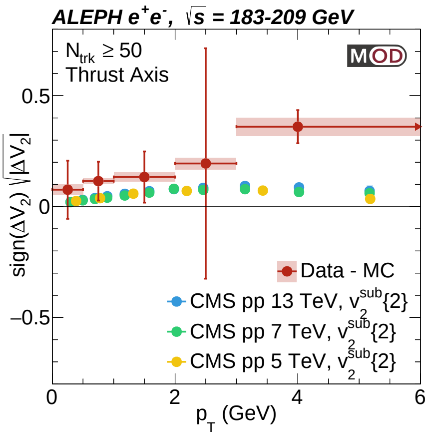

Figure 3. Excess of flow coefficient $\mathrm{sign}(\Delta V_2)\sqrt{\Delta V_2}$, where $\Delta V_2 = V_{2,\mathrm{data}} - V_{2,\mathrm{MC}}$, as a function of the track pairs' p_T requirement for $\mathrm{N}_{\mathrm{trk}} \geq 50$ in the thrust axis analysis for LEP-II high-energy sample. The result is overlaid with CMS subtracted flow coefficient measurements [26].

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