

Measurement of the energy-energy correlator in the back-to-back limit using the archived ALEPH e^+e^- data at 91.2 GeV

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Recently, energy-energy correlators (EECs) have garnered renewed interest for studying hadronic collisions at the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC). EEC measurements within jets provide a clear scale separation, facilitating the study of both perturbative and non-perturbative Quantum Chromodynamics (QCD) in the collinear limit. These proceedings present recent EEC results from the archived ALEPH e^+e^- data taken at LEP at $\sqrt{s} = 91.2$ GeV. In e^+e^- collisions, perturbative and non-perturbative QCD can be studied with EECs in both the collinear limit using jets and the back-to-back limit using all particles as well as the transition between these two regimes. Comparisons of these results to generators and future extensions of this work will also be discussed.

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1. Introduction

The e^+e^- , collision environment provides the cleanest setting for studying QCD, as the colliding objects are fundamental particles. Unlike hadronic collisions, e^+e^- collisions avoid complications such as beam remnants, gluonic initial-state radiation, and parton distribution functions. In recent years, re-analysis of the archived data from the Apparatus for LEP PHysics (ALEPH) experiment at the Large Electron Positron Collider (LEP) has offered a pathway to investigate current open questions in a well-understood system. For example, two particle correlations reanalyzed with LEP 1 [1] and LEP 2 [2] data reveal an excess in the highest multiplicity interval of LEP 2 data not seen in simulation, providing new insights into the presence of flow signatures in small systems. The archived data enables the application of modern experimental techniques developed in recent years. One recent example of this uses jet reconstruction algorithms developed in the early 2000s [3] to look at jets and their substructure in ALEPH data [4] serving as a precision tests of analytical calculations and phenomenological models in the collinear limit of QCD.

In recent years the N-point energy correlation functions, a class of observables originally developed for the study of e^+e^- collisions [5–8], has been re-imagined in hadronic collision environments [9–11]. The N-point energy correlation functions are defined as the correlation of the energy flow operator

$$\langle \Psi | \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) \cdots \mathcal{E}(\vec{n}_k) | \Psi \rangle \quad (1)$$

where $\mathcal{E}(\vec{n}_1) = \lim_{r \rightarrow \infty} \int dt r^2 n_1^i T_{0i}(t, r\vec{n}_1)$. ENC's characterize the energy flow in the direction of the vector \hat{n} , which is commonly replaced by a distance variable such as $\Delta R = \sqrt{\Delta y^2 + \Delta \phi^2}$ or θ_L (the opening angle in radians) in collider environments. In experimental contexts it is also common to measure the *projected* correlators that integrate out all shape information keeping the longest side (herein referred to as R_L or θ_L) fixed. The projected correlators are useful to isolate the scaling behavior, offering a clean separation between the free hadron region, the quark/gluon region, and the transition between these two regimes. The full energy correlators are useful for studying the *shape* of the energy flow, which has recently been studied in simulated heavy-ion collisions [12].

This paper presents the first fully corrected measurement of the projected two-point energy correlators (E2C). The clean environment of e^+e^- collisions enables the use of all particles in the event, not only those within a jet, allowing the measurement to probe the collinear limit of QCD where $\theta_L \sim 0$ all the way to the back-to-back (or Sudakov) limit where $\theta_L \sim \pi$. Here the E2C is measured as a function of z , where $z = \frac{1 - \cos(\theta_L)}{2}$, in order to compare the free hadron region in the collinear and back to back limits. In this definition the E2C can be written as

$$\text{E2C}(z) = \sum_{i,j}^n d\sigma \frac{E_i E_j}{E^2} \delta(z - z_{ij}). \quad (2)$$

In order to perform a fully-corrected measurement, the E2C must be corrected for detector effects and energy smearing in z and $E_i E_j$ using a two-dimensional Bayesian unfolding procedure [13]. Here, the energy scale E is fixed at the collision energy of $\sqrt{s} = 91.2$ GeV, eliminating the need to explicitly correct for the energy scale and significantly simplifying the unfolding procedure. The remainder of these proceedings is outlined as follows. The details of the dataset utilized for this measurement will be discussed in Section 2. The results will be presented in Section 3. Finally, some conclusions and future research directions will be presented in Section 4.

2. ALEPH Archived Dataset

This measurement uses data collected during the LEP 1 period with ALEPH¹, later archived in the MIT open data format [14]². ALEPH was located at IP4 of the LEP ring and features a complex detector design useful for particle identification and a measurements of particle properties. This was done using precision tracking via its time projection chamber (TPC) and inner tracking chamber and calorimetry via its hadronic and electromagnetic calorimeters. The tracking detectors of ALEPH are located inside of a superconducting magnet with a field strength of 1.5 T. The LEP 1 dataset was taken at the Z-pole with a center of mass energy of $\sqrt{s} = 91.2$ GeV, where the dominant process in hadronic data is $e^+e^- \rightarrow q\bar{q}$. The event selection for this analysis requires at least five high-quality tracks and a total reconstructed charged-particle energy of at least 15 GeV. In addition events must also have a sphericity axis with a polar angle that falls into the acceptance window of $7\pi/36 \leq \theta_{\text{sphericity}} \leq 29\pi/36$. For the E2C measurement, only charged particles were included, with tracks required to have at least 4 TPC hits and a transverse momentum above 0.2 GeV. These tracks must also fall in an acceptance of $|\cos(\theta)| < 0.94$ and have an impact parameter within a radial distance of $d_0 < 2$ cm and a longitudinal distance $z_0 < 10$ cm from the interaction point.

3. Results

The results are presented using a unique double-log format to emphasize angular limits, with the collinear region spanning $z \sim 0$ to $z \sim 1/2$ and the Sudakov region spanning $z \sim 1$ to $z \sim 1-1/2$. The E2C in the collinear limit is similar to the analogous quantity constructed from particles inside jets with clear free hadron, transition, and quark/gluon regions. However, in this case there is no cutoff in the distribution due to the jet radius. Then the Sudakov region demonstrates a reflected version of these regions with the free hadron region appearing at large values of z and then the transition and quark/gluon region emerge as z decreases.

This initial result iteration provides conservative systematic uncertainty estimates, with expectations for further refinement. The dominant systematic uncertainties are those associated with the unfolding procedure, including the choice of binning, the number of iterations, as well as the impact of the choice of prior. An uncertainty for the TPC hit requirement for good tracks (taking a nominal value of 4 and increased to 7 for the systematic uncertainty) as well as for the matching method are also included.

In the left panel of Figure 1 the fully-corrected E2C is shown as a function of z compared to the archived PYTHIA 6 MC, with the ratio of the two distributions shown in the bottom panel. The data demonstrates excellent agreement with the MC simulation, although significant differences exist between generators for jet substructure observables [4]. Additionally, with the unprecedented binning and kinematic reach, one can see that the collinear and Sudakov free hadron regions are roughly compatible with one another.³ In the right panel of Figure 1, this distribution is compared

¹Currently only data taken during 1994 is analyzed due to the availability of simulation.

²The authors would like to specifically thank Roberto Tenchini and Guenther Dissertori for their help in making this archival effort possible through their advice and expertise with ALEPH data.

³Quantitative comparisons between the two are left for future work.

to a theoretical calculation⁴. In the collinear region this calculation is performed as a Next-to-Next-To-Leading-Log (NNLL) collinear resummation. In the Sudakov region this is implemented as a Next-to-Next-To-Next-To-Leading-Log (NNLL) Sudakov resummation where the Collins-Soper Kernel is extracted from lattice QCD. In both predictions the non-perturbative parameter Ω is extracted from the thrust distribution. The theoretical calculation exhibits excellent agreement with the data over all regions of phase space. This measurement represents the first of its kind and will be useful to further constrain the theory in the relatively unexplored Sudakov limit.

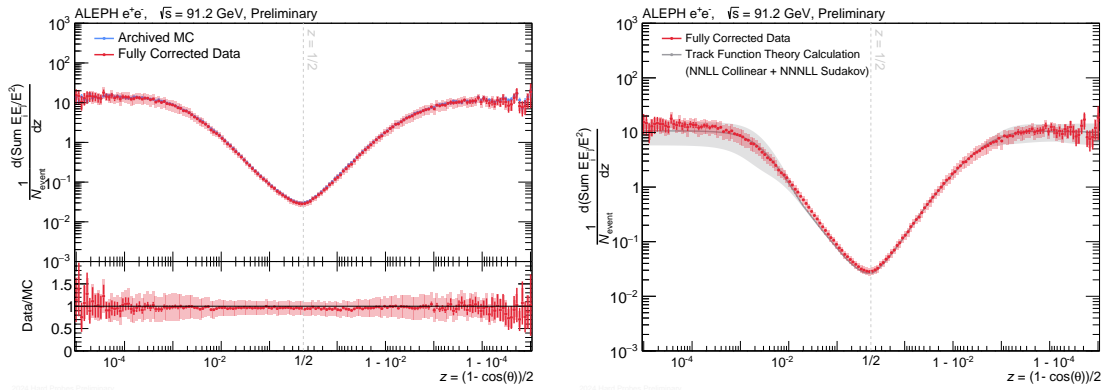


Figure 1: Left: E2C distribution as a function of z for the archived PYTHIA 6 MC distribution (blue) and the fully corrected ALEPH data with the corresponding systematic uncertainties (red). The ratio of the data to MC is shown in the bottom panel. Right: E2C distributions as a function of z for the fully corrected data compared to a track function theory calculation with NNLL Collinear and NNNLL Sudakov regions.

4. Conclusions

These proceedings present the first fully-corrected measurement spanning from the collinear to the back-to-back limit of QCD using ALEPH archived data. These studies show excellent agreement with the archived PYTHIA 6 MC and theoretical calculations, providing crucial tests for QCD calculations and phenomenological models. This is especially true in the relatively-unexplored Sudakov limit where this measurement provides one of the first experimental constraints.

The ALEPH archived dataset is full of nearly-limitless opportunities. For example, a value for α_s can be extracted from the ratio of higher point correlators to the E2C. The α_s fits from e^+e^- event shapes and analytical hadronization were recently removed from the world average [15], making such a measurement timely. This measurement marks the beginning of a new investigative direction in e^+e^- collisions, revisiting concepts from the 1970s to address contemporary physics questions. This work also has the potential to shape the future, serving as a catalyst to inspire and inform studies at the proposed FCC-ee [16].

⁴"A Precision Calculation of the Energy-Energy Correlator on Tracks", Max Jaarsma, Yibei Li, Ian Moult, Wouter Waalewijn, HuaXing Zhu, in preparation

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