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Jet modifications in event-by-event hydrodynamically evolving media

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Abstract

The nearly perfect fluid-like nature of the Quark Gluon Plasma may be understood through two key experimental signatures: collective flow and jet suppression. Event-by-event relativistic viscous hydrodynamics (with an extremely small shear viscosity to entropy density ratio) has been very successful at describing collective flow observables for the last 7 years. More recently, the effects of event-by-event fluctuations have been studied in the context of high p_T particles that lose energy as they pass through the dense Quark Gluon Plasma liquid. In this summary of the corresponding plenary talk at Quark Matter 2017, the recent developments on the effects of event-by-event fluctuations on jet suppression are summarized.

Keywords: jet quenching, collective flow, relativistic hydrodynamics, Quark Gluon Plasma, energy loss

1. Introduction

The triangular flow study made in relativistic heavy-ion collision in 2010 by [1] ignited the event-by-event fluctuating initial conditions "revolution" within relativistic viscous hydrodynamics [2, 3]. Since then significant advances have been made in understanding the nature of collective flow, the connection between the initial state and final flow harmonics [4, 5, 6], the influence of the Equation of State [7], and the temperature dependence of various shear and bulk viscosity profiles [8, 9, 10, 11]. It has been shown that the eccentricity ε_n of the initial state is closely related to the final flow harmonics measured experimentally for elliptical and triangular flow. Thus, if the initial ε_2 is too small, one would expect difficulties in reproducing large enough v_2 or vice versa.

Theory vs. experimental data comparisons are now so fine-tuned that differences in energies on the order of a few percent points can be predicted [12, 13] and later confirmed [14]. In the last couple of years, new observables have been created to explore the effects of event-by-event fluctuations such as event-shape engineering [15] and Soft-Hard Event Engineering (SHEE) to name a few. Finally, the very nature of the definition of collective flow has come into question due to tantalizing signatures of the Quark Gluon Plasma in small systems [16], so multi-particle cumulants have been used extensively to quantify the strength of fluctuations [17, 18].

Within the initial stages after a heavy-ion collision, pQCD predicts hard scattering processes that produce jets. When these jets pass through the Quark Gluon Plasma they are bumped around by the fluctuations in the medium and lose energy [19, 20]. In order to quantify the amount of energy loss transversing the medium

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the nuclear modification factor, $R_{AA} = \frac{dN_{AA}/dy dp_T d\phi}{N_{\text{coll}}\, dN_{pp}/dy dp_T}$, is measured where the ratio of large systems AA to small systems pp is calculated and one expects values less than 1 when jets are suppressed. Reconstructing jets is quite complicated both on the theory and experimental sides but significant advances have been made in Monte Carlo Event Generators [21, 22, 23, 24, 25, 26] as well as jet reconstruction [27] in recent years. Since flow is well-understood in the soft sector, it is natural, as a first step, to extend those same techniques to high p_T using single particles rather than full reconstructed jets, following the original idea from [28, 29]. Thus, the rest of this proceedings will focus only on comparisons to the charged particle azimuthal anisotropy results from experiments from theory calculations.

Below, a discussion follows on how energy loss models have now been combined with event-by-event relativistic hydrodynamic backgrounds to solve the 10 year old $R_{AA} \otimes v_2$ puzzle. Then, theory predictions of high p_T flow harmonics that were confirmed experimentally at LHC run2 are analyzed. Using the knowledge about event-by-event fluctuations Making allows one to think up new experimental observables involving, e.g., Soft-Hard Event Engineering. Finally, I will comment on the possible further implications of initial condition fluctuations on jet observables and the combination of event-by-event hydrodynamics with MC event generators.

2. $R_{AA} \otimes v_2$ puzzle

While a clear suppression has been measured across all energies from RHIC to LHC, R_{AA} is a relatively robust observable that does not provide a significant amount of distinguishing power between theoretical models. Thus, Refs. [28, 29] proposed measuring the azimuthal asymmetry of high p_T particles with the understanding that the path length dependence due to an initial anisotropy would lead to a non-zero elliptical flow, v_2, at high p_T. Indeed, v_2 at high p_T was measured [30] though for $\sim$ 10 years theoretical calculations consistently under-predicted experimental data [31] (for a historical overview see [32]).

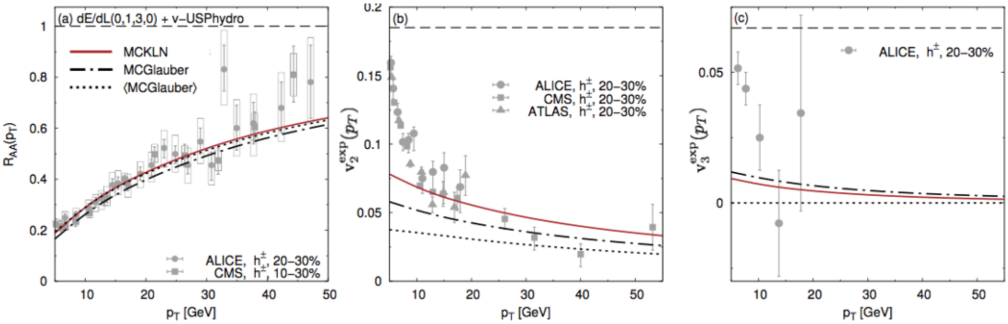

Fig. 1. (Color online) Comparisons of theory calculations (using $dE/dL \sim L$) with various types of initial conditions to data from $20-30\%$ centrality at $\sqrt{s} = 2.76$ TeV Pb+Pb collisions at the LHC [33, 34, 35, 36, 37]. The experimental observables are (a) the nuclear modification factor R_{AA}, (b) elliptical flow v_2, and (c) triangular flow v_3. MCKLN initial conditions are shown in the solid red lines, MCGlauber is black dashed-dotted, and averaged MCGlauber in black dotted neglects initial state fluctuations.

In [38] the first calculations combining event-by-event viscous hydrodynamics with a simplified energy loss model that includes parameterized energy loss fluctuations (v-USPhydro+BBMG [8, 9, 10, 39, 40]) were made where R_{AA}, $v_2\{SP\}(p_T)$, and $v_3\{SP\}(p_T)$ gave a good description of experimental data, as shown in Fig. 1. All previous calculations using averaged initial conditions returned $v_3 = 0$ and only in the case that event-by-event fluctuations are considered can one obtain a non-zero v_3 across all p_T's.

Experimentally, $v_n(p_T)$ is measured using the scalar product [41]

$$v_n\{2\}(p_T) = \frac{\langle v_n\, v_n^{hard}(p_T) \cos\left[n\left(\psi_n - \psi_n^{hard}(p_T)\right)\right]\rangle}{\sqrt{\left\langle (v_n)^2 \right\rangle}}. \tag{1}$$

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