

Elliptic Flow from Color Glass Condensate

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Abstract

We show that an observable fraction of the measured elliptic flow may originate in classical gluon fields at the initial stage of a peripheral high-energy nuclear collision. This mechanism complements the contribution of late stage mechanisms, such as those described by hydrodynamics, to the observed elliptic flow.

The elliptic flow v_2 , both integral and differential, is a sensitive measure of collectivity of the excited and dense matter produced in ultra-relativistic heavy ion collisions [1]. The first measurements of v_2 from RHIC, at center of mass energies of 130 and 200 GeV, have been reported recently [3]. Hydrodynamic (HD) analysis, based on the assumption of local thermal equilibrium, matches the data for the integral v_2 at large centralities, but the agreement gets worse for peripheral events [5,6]. HD models also reproduce the differential v_2 up to momenta of 1.5 GeV/c at mid-rapidity. However, above 1.5 GeV, the experimental v_2 appears to saturate, while the HD model v_2 still grows [5].

It is natural to expect v_2 to be sensitive to the early evolution of the system [2], when the energy density of the produced matter is at its highest, and before the system has equilibrated. Here we compute the contribution to v_2 at mid-rapidity from the strong fields generated shortly after the collision. These fields originate in a Color Glass Condensate (CGC) [8], formed in a nucleus by low- x partons as their distributions saturate [7]. The CGC is characterized by the color charge per unit area Λ_s , which grows with energy, centrality and the size of the nuclei. Estimates for RHIC give $\Lambda_s \sim 1.4 - 2$ GeV. Since the gluon multiplicities in CGC are large, $\sim 1/\alpha_s(\Lambda_s^2) > 1$, CGC admits a classical description. In a collision, gluon production results from overlapping CGCs of the incident nuclei [9]. Our numerical work [10,11] confirmed that strong color fields of order $1/\alpha_s$ emerge in a proper time $\tau \sim 1/\Lambda_s$ after the collision.

As before, we assume strict boost invariance, *i.e.*, the dimensionality of the problem is 2+1. For a numerical solution we use lattice discretization. Our original setup, suitable for central collisions of very large nuclei, must be adapted for the task at hand. To study effects of anisotropy and inhomogeneity, we consider finite nuclei. We also impose suitable neutrality conditions on the color sources [13] to prevent gluon production far outside the nucleus.

We model a nucleus as a sphere of radius R , filled with randomly distributed nucleons. Within each nucleon we first generate, throughout the transverse plane, a spatially uncorrelated Gaussian color charge distribution of the width Λ_n . Next, we remove the monopole and dipole components of the distribution by subtracting the appropriate uniform densities. Since the color charges of the nucleons are uncorrelated, Λ_s becomes position-dependent, peaking at the center and vanishing at the periphery of a nucleus. We adjust Λ_n to ensure a desired value of Λ_{s0} , *i.e.*, Λ_s at the center. Next, we use our standard methods [10] and determine the classical fields as a function of τ .

The calculation of v_2 involves determining the gluon number N , a quantity whose meaning is ambiguous outside a free theory. We resolve this ambiguity by computing the number in two different ways; directly in Coulomb Gauge (CG) and by solving a system of relaxation (cooling) equations for the fields [11]. Both definitions give the usual particle number in a free theory. We expect the two to be in good agreement for a weakly coupled theory. If the two disagree strongly, we should not trust either. Details of the cooling method, as applied to v_2 , are presented in our recent paper [12].

The cooling and the CG results should converge at late times, when the system is weakly coupled. The two methods agree for N at fairly early times. For v_2 , this convergence occurs at much later τ , because, as explained below, v_2 is dominated by soft modes with momenta $p_T < \Lambda_{s0}$. Following the evolution of the system to very late τ is computationally taxing. We therefore only compute v_2 at late τ for a selected value of $\Lambda_{s0}R$ and centrality and extrapolate v_2 from the early to the late τ for the remaining values. The results, for different values of $\Lambda_{s0}R$, are shown in Fig. 1 as a function of n_{ch}/n_{tot} . Clearly, our asymptotic values of v_2 undershoot the data. Nevertheless, we see that an observable amount of v_2 is produced classically in the pre-equilibrium stage of a collision.

Our differential v_2 , shown in Fig. 2 for $b/2R = 0.75$ and $\Lambda_{s0}R = 74$, grows rapidly and is peaked for $p_T \sim \Lambda_{s0}/4$. A related analytical result [14] is that for $p_T \gg \Lambda_{s0}$, $v_2(p_T) \sim \Lambda_{s0}^2/p_T^2$, consistent with our numerical data. The dominance of v_2 by very soft modes helps explain the persistent difference between the cooling and the CG values: these modes remain strongly coupled and cannot be described within a free theory until very late τ . Concomitantly, the soft modes contain many gluons and may be described classically even at the late τ considered. Our $v_2(p_T)$ clearly disagrees with experiment [3].

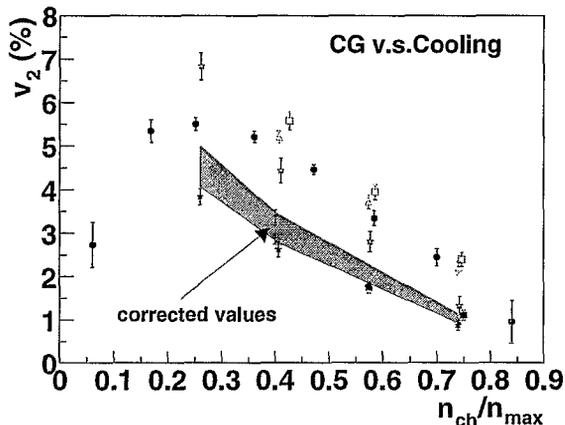


Fig. 1. The centrality dependence of v_2 at early times from cooling (open symbols) and CG (filled symbols). The values of $\Lambda_{s0}R$ span the RHIC-LHC range: 18.5 (squares), 37 (triangles), and 74 (stars). Full circles are *preliminary* STAR data [4]. The band shows the range of v_2 extrapolated to late times. “Corrected values” denote the late time cooling and CG result for $\Lambda_{s0}R = 18.5$ at one centrality value.

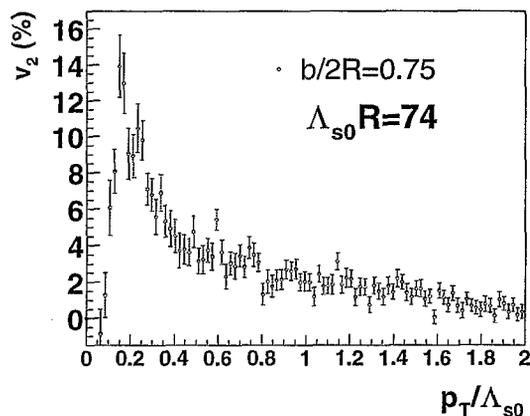


Fig. 2. Differential v_2 as a function of p_T in units of Λ_{s0} for $\Lambda_{s0}R = 74$.

Note that experimental v_2 is found indirectly, in particular, from multiparticle cumulants [15]. It has been argued recently that non-flow correlations explain much of the measured v_2 [16]. We plan a numerical study of non-flow effects.

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