Hadrons inclusively produced with large $p_T$ in high-energy collisions originate from the jets, whose initial virtuality and energy are of the same order, what leads to an extremely intensive gluon radiation and dissipation of energy at the early stage of hadronization. Besides, these jets have a peculiar structure: the main fraction of the jet energy is carried by a single leading hadron, so such jets are very rare. The constraints imposed by energy conservation enforce an early color neutralization and a cease of gluon radiation. The produced colorless dipole does not dissipate energy anymore and is evolving to form the hadron wave function. The small and medium $p_T$ region is dominated by the hydrodynamic mechanisms of hadron production from the created hot medium. The abrupt transition between the hydrodynamic and perturbative QCD mechanisms causes distinct minima in the $p_T$ dependence of the suppression factor $R_{AA}$ and of the azimuthal asymmetry $v_2$. Combination of these mechanisms allows to describe the data through the full range of $p_T$ at different collision energies and centralities.

1 Introduction

In-medium hadronization can serve as a way to study the jet space-time development if the medium properties are well known, like in semi-inclusive deep inelastic scattering \cite{1,2}, or as a probe for the medium properties, like jet quenching effect observed in heavy ion collisions \cite{3,4}. We concentrate here on a rare type of jets in which the main fraction $z_h$ of the jet momentum is carried by a single (leading) hadron. The weight of such jets is strongly enhanced by selection of events with inclusive production of high-$p_T$ hadrons, due to the convolution with the steeply falling transverse-momentum distribution of the partons initiating the jet. The peculiar feature of such jets is the extremely high initial virtuality, which is of the order of the jet energy. This leads to an intensive gluon radiation and energy dissipation at the early stage of hadronization. In order to respect energy conservation in the production of a high-$z_h$ hadron, the radiative dissipation of energy must stop by the production of a colorless hadronic state (a QCD dipole usually called pre-hadron) on a short distance from the jet origin \cite{4}. This distance, called production length $l_p$, was evaluated in a model of perturbative hadronization, including energy conservation and Sudakov suppression, and found rather short \cite{6} and nearly independent of jet
energy. Although the Lorentz factor makes $l_p$ longer at higher $p_T$, the rate of vacuum energy loss increases as well trying to shorten $l_p$.

Short length scale $l_p$ implies that a created colorless dipole has to survive through the medium in order to be detected (any inelastic interaction in the medium results in continuation of energy loss conflicting with energy conservation). The evolution of the dipole in the medium and its attenuation was calculated in [5] using path integral technique [7]. Here the key phenomenon controlling attenuation of the dipole, is color transparency, which corresponds to the increased transparency of the medium for small-size dipoles [8].

We employ the relation between the dipole cross section and transport coefficient (broadening rate) found in [9] [10]. Then the observed magnitude of hadron attenuation can be used as a probe for the transport coefficient, which characterizes the medium density. Adjusting only a single parameter, the transport coefficient, we can describe well data for inclusive production of large-$p_T$ hadrons in heavy ion collisions with different centralities at LHC and RHIC [5] (see also the left panel of Figs. 1 and 2).

As a complementary test of the pQCD mechanism we also calculated the azimuthal anisotropy of produced hadrons in good agreement with the measured asymmetry parameter $v_2(p_T)$, with no further adjustments [5] (see the right panel of Figs. 1 and 2).

Within the pQCD mechanism we also included an additional effect related to the initial state interactions of the colliding nuclei. Excitation of higher Fock components in the colliding nucleons by multiple interactions leads to the energy-sharing conflict between different partons upon approaching to the kinematic limit of either large Feynman $x_F$, or/and transverse $x_T = 2p_T/\sqrt{s}$ [11]. This effect can be seen in the $p_T$ dependence of the suppression factor $R_{AA}$ at the RHIC energies $\sqrt{s} = 200$ GeV and 62 GeV. Even the LHC data at $\sqrt{s} = 2.76$ TeV indicate that $R_{AA}$ is leveling off at the high end of the measured $p_T$ interval. Moreover, we expect a fall of $R_{AA}$ at higher $p_T \gtrsim 100$ GeV [5] (see the left panel of Figs. 1 and 2).

It is worth emphasizing that our approach, based on perturbative QCD, is irrelevant to data at $p_T \lesssim 6$ GeV apparently dominated by the statistical mechanisms. Here the observed $R_{AA}(p_T)$ and $v_2(p_T)$ expose quite a different behavior towards smaller $p_T$, steeply rising and shaping a bump (see Figs. 1 and 2). We attribute this behavior to the contribution of the hydrodynamic mechanism responsible for the evaporation of hadrons from the created hot medium. In this paper we combine the hydrodynamic mechanism from [12] with the pQCD calculations attempting at a description of data on $R_{AA}$ and $v_2$ in the full measured range of $p_T$ at different energies and centralities [13].

2 Comparison with data

Combination of hydrodynamic [12] and pQCD [5] calculations for the suppression factor $R_{AA}$ represented by the solid lines is compared with ALICE [14] and CMS [15] [16] data at different centralities in the left panel of Fig. 1. Our results are in a good accord with in the full range of $p_T$. The dashed and dotted curves represent calculations performed either within only pQCD or hydrodynamical mechanism, respectively.

The right panel of Fig. 1 shows the corresponding calculations for azimuthal anisotropy, $v_2$, demonstrating again a successful description of ALICE [17] and CMS [18] data in the full range of $p_T$ at different centralities.

Fig. 2 presents the results of calculations based on combination of hydrodynamic and pQCD mechanisms in the full measured range of $p_T$ vs PHENIX data for the suppression factor.
Figure 1: (Left) Centrality dependence of the suppression factor $R_{AA}(p_T)$ for lead-lead collisions at $\sqrt{s} = 2.76$ TeV. The intervals of centrality are indicated in the plot. The dashed and dotted line is calculated within the pQCD [5] and hydrodynamic [12] mechanism, respectively. The solid lines represent a combination of the both mechanisms. Data for $R_{AA}$ are from the ALICE [14] and CMS [15, 16] experiments. (Right) ALICE [17] and CMS data [18] for azimuthal anisotropy, $v_2$, vs $p_T$ for charge hadron production in lead-lead collisions at mid rapidity, at $\sqrt{s} = 2.76$ TeV and at different centralities indicated in the figure. The meaning of the curves is the same as in the left panel.

$R_{AA}(p_T, b)$ [19, 20] (the left panel) and for the azimuthal anisotropy [21] (the right panel) at different centralities.

It worth emphasizing that calculations for different observables employ the same value of the transport coefficient $q_0$, which however, varies with collision energy. We found $q_0 = 2$ GeV$^2$/fm and 1.6 GeV$^2$/fm at the energies $\sqrt{s} = 2.76$ GeV and 200 GeV respectively. Important is also that the hydrodynamic calculations were done with the same value of $q_0$.

### 3 Summary

In this paper we developed a quantitative understanding of experimentally observed strong attenuation of hadrons inclusively produced with large $p_T$ in heavy ion collisions. For the first time we describe data for the suppression factor $R_{AA}$ and azimuthal anisotropy $v_2(p_T)$ in the full measured range of $p_T$ at different energies and centralities. The peculiar behavior of these observables is explained [13] by the interplay of two mechanisms: (i) evaporation of hadrons from
Figure 2: (Left) Centrality dependence of the suppression factor $R_{AA}(p_T, b)$ measured in the PHENIX experiment $[19, 20]$ in gold-gold collisions at $\sqrt{s} = 200$ GeV. The intervals of centrality are indicated in the plot. The meaning of the curves is the same as in Fig. 1. (Right) PHENIX data $[21]$ for azimuthal anisotropy, $v_2$, vs $p_T$ for neutral pion production in gold-gold collisions at mid rapidity, at $\sqrt{s} = 200$ GeV and at different centralities indicated in the figure. The meaning of the curves is the same as in Fig. 1.

the created hot medium controlled by hydrodynamics $[12]$; (ii) perturbative QCD mechanism $[5]$ for high-$p_T$ hadron production based on a non-energy-loss scenario. The observed suppression is attributed to the survival probability of the colorless dipoles, which are produced on a short length scale and propagate through the dense medium. The abrupt transition between the two mechanisms causes distinct minima in $R_{AA}(p_T)$ and in $v_2(p_T)$ at the same values of $p_T$, while the hydrodynamic mechanism alone would lead to a monotonically rising $v_2(p_T)$. The detailed calculation and results will be published elsewhere $[13]$.

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