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Hard probes at RHIC

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At the Relativistic Heavy Ion Collider (RHIC), hard scattering processes become accessible at high transverse momentum, opening up a new set of experimental tools with which to study the properties of hot QCD matter. This paper reviews the status of hard probes at RHIC, with particular emphasis on results from the STAR experiment.

1. Introduction

Relativistic heavy-ion collisions provide a means of studying the many-body, or *bulk*, properties of Quantum Chromodynamics (QCD). In the limit of high temperature and zero net-baryon density, lattice QCD calculations suggest that quarks may become deconfined over an extended volume. Following earlier fixed-target experiments at the Brookhaven National Laboratory and CERN, the Relativistic Heavy Ion Collider (RHIC) has become the focus of efforts to study this high temperature phase of QCD matter.

RHIC is capable of colliding ions ranging from protons to gold at centre-of-mass energies up to 200 GeV per nucleon pair, more than ten times higher than previously possible. At this energy, hard processes, such as jets and the production of heavy quarks (charm and bottom), become accessible for the first time in heavy-ion collisions. Hard scattering occurs early in the evolution of the system and dominates particle production at high transverse momentum, p_T. Final state interactions between hard scattered partons and the underlying event may modify high-p_T hadron production, thereby probing the properties of the medium produced in central (head-on) nucleus-nucleus collisions.

This paper reviews the status of measurements of high-p_T particle production, jet-like correlations and heavy flavour production, with particular emphasis on results from the STAR experiment.

2. High-p_T particle production

In factorised form, the production cross-section of high-p_T hadrons involves a convolution of two parton distribution functions, describing the initial-state parton densities in the colliding ions, a perturbative QCD cross-section and a fragmentation function, describing the hadronisation of the scattered partons. Within this framework, next-to-leading order (NLO) QCD calculations have been shown to provide a good description of hadron production at $p_T > 2$ GeV/c in proton-proton collisions at RHIC, dependent on the choice of fragmentation functions [1]. In Au+Au collisions, high-p_T hadron production may be modified by differences in the parton distributions of nuclei, as well as by final-state interactions with the surrounding medium. In order to disentangle these two effects, control measurements involving d+Au collisions have been performed, which retain sensitivity to the nuclear parton densities while in-medium effects are greatly reduced.

The idea that jets could be modified by final-state interactions was first mooted by Bjorken [2], who considered elastic collisions between the hard scattered partons and partons from the surrounding medium. However, medium-induced energy loss in the form of radiated gluons was found to be much more important for light quarks. There are several theoretical approaches to calculating

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radiative energy loss, which are reviewed elsewhere [3]. Although the various models differ in their approach, they access the properties of the medium through the density of colour charges.

Experimentally, the modification of high-p_T hadron production is determined by comparing hadron p_T distributions in Au+Au collision and p+p collisions. This is accomplished by the nuclear modification factor, R_{AA}, which is given by

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{N_{bin} dN_{pp}/dp_T}, \quad (1)$$

where N_{bin} is the average number of binary nucleon-nucleon collisions occurring in Au+Au collisions, estimated using a Glauber model. A value of $R_{AA} < 1$ would indicate a suppression in Au+Au collisions relative to a superposition of N_{bin} p+p collisions.

STAR measures charged hadrons in a pseudorapidity interval of $|\eta| < 1.8$ and full azimuth using a Time Projection Chamber. The STAR detector is reviewed in detail elsewhere [4]. The nuclear modification of charged hadrons is shown as a function of p_T in figure 1. For $p_T > 6$ GeV/c, R_{AA} is below unity in all but the most peripheral collisions. The suppression increases as a function of centrality and is a factor of 4-5 for the 5% most central Au+Au collisions [5]. By comparison, a Cronin-like enhancement is found in d+Au collisions [6], which strongly suggests that the suppression observed in Au+Au collisions is a final-state effect. Importantly, no such suppression is observed for direct photons [7], which do not suffer any strong final-state interactions.

3. Two- and three-particle correlations

As full jet reconstruction is not yet possible in the high multiplicity environment of central Au+Au collisions at this energy, dijet events are inferred from a two-particle angular correlation analysis. Given its complete azimuthal coverage, STAR is particularly suited to this type of analysis. Figure 2 shows the angular correlation between trigger hadrons with $8 < p_T^{trig} < 15$ GeV/c and associated hadrons in three ranges of p_T^{assoc}, in d+Au, mid-central Au+Au and central Au+Au collisions. For $p_T^{assoc} > 6$ GeV/c, the

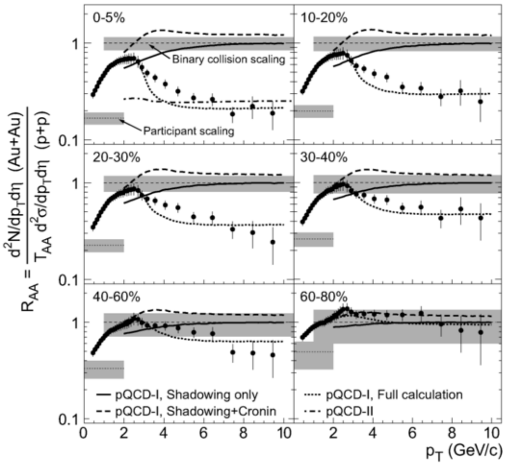

Figure 1. Nuclear modification factor, R_{AA}, of charged hadrons in $|\eta| < 0.5$, for Au+Au spectra measured in six different centrality selections relative to the same p+p spectrum. Details of the calculations can be found in [5].

largely uncorrelated background, is almost entirely eliminated. However, there is also a small correlated background from elliptic flow, which is measured independently. In central Au+Au collisions, the away side correlation peak, located at $\Delta\phi \sim \pi$ radians from the trigger hadron, is clearly suppressed, although the width of the peak is unmodified [8]. Thus, the suppression of high-p_T hadrons appears to be related to jet-quenching.

The fragmentation of the near- and away-side jet can be examined by studying the associated yield as a function of $z_T = p_T^{assoc}/p_T^{trig}$ [8]. Figure 3 (upper panel) shows the near- and away-side z_T distribution, normalised to the number of trigger hadrons. The away-side distributions are clearly suppressed in Au+Au collisions relative to d+Au. The suppression is roughly independent of z_T, as shown in the lower panel. By contrast, the near-side fragmentation distributions show no evidence of suppression, possibly reflecting that the production of high-p_T hadrons is biased toward the surface of the medium. For $p_T^{assoc} > 3$