Jet Physics at the Large Hadron Collider

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For jets, collimated showers of energetic particles, with great power comes great opportunity. The unprecedented center of mass energies available at the Large Hadron Collider (LHC), the most complex scientific machine ever built, opens new windows on the studies of the quark-gluon plasma (QGP), a new state of matter created in the ultra-relativistic collisions of heavy nuclei [1]. We demonstrate that jet shape and jet cross-section measurements become feasible as a new, differential, and accurate test of the underlying theory of Quantum Chromo-Dynamics (QCD). We present a first step in understanding these shapes and cross sections in heavy ion reactions [2]. Our approach allows for detailed simulations of the experimental acceptance/cuts that help isolate jets in such high-multiplicity environments. It is demonstrated for the first time that the pattern of stimulated gluon emission can be correlated with a variable quenching of the jet rates, providing an approximately model-independent approach to determining the characteristics of the medium-induced bremsstrahlung spectrum. Surprisingly, in realistic simulations of parton propagation through the QGP we find a minimal increase in the mean jet radius even for large jet attenuation. Jet broadening is manifest in the tails of the energy distribution away from the jet axis, and its quantification requires high statistics measurements that will be possible at the LHC. In summary, we expect that the theoretical developments reported here will allow us to pinpoint the correct mechanisms of quark and gluon interaction with the hot nuclear medium and thereby eliminate the order-of-magnitude of uncertainty in the determination of the QGP properties, such as temperature, density, and equation-of-state (EOS) [3].

We first refine an analytic calculation of jet shapes, a measure of the intrajet energy flow in a cone of radius R around the center of the jet [4], to include experimental acceptance cuts ω^{min}. Our numerical results include all contributions from leading order processes, resummation, and power corrections with infrared scale $Q_0 = 2$ GeV. Variation in the jet-finding algorithm is simulated with a transverse energy-dependent parameter R_{sep}. We employ this theoretical model to obtain predictions for the LHC at $\sqrt{s} = 5.5$ TeV. The emphasis is to produce a baseline in proton-proton $(p+p)$ reactions for comparison with the full in-medium jet shapes

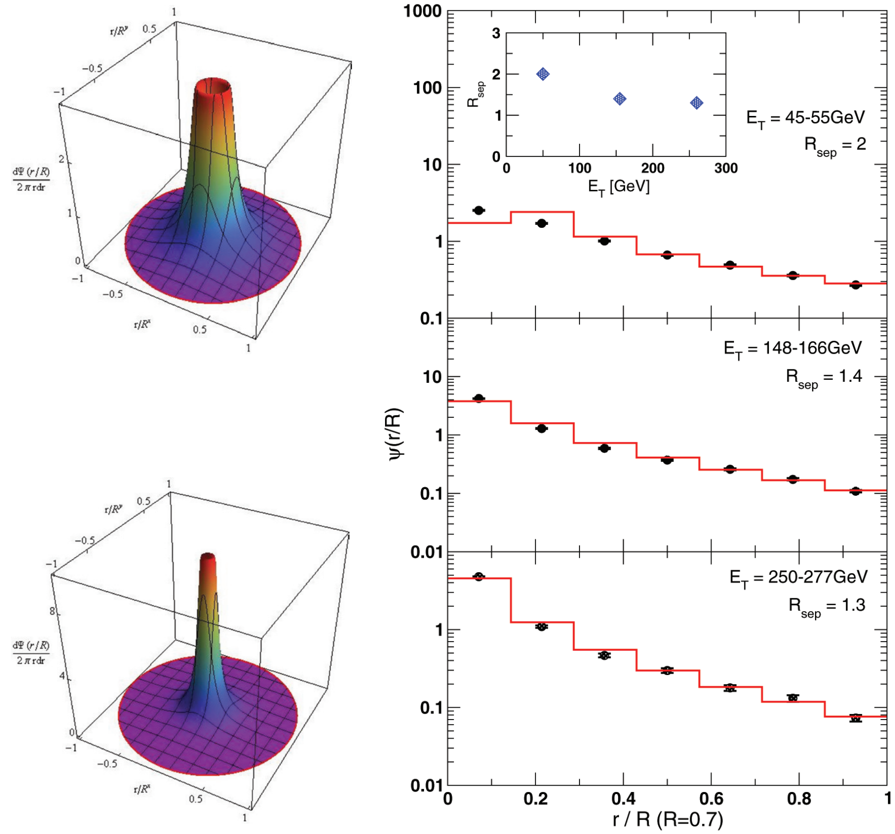

Fig. 1. Left panel: 3D plot of the differential jet shapes at two different jet energies $E_T = 20$, 100 GeV with a radius $R = 0.7$ in $p+p$ collisions at $\sqrt{s} = 5.5$ TeV at the LHC. Right panel: Comparison of numerical results from our theoretical calculation to experimental data on the differential jet shapes at $\sqrt{s} = 1960$ GeV by CDF II. Insert shows the E_T dependence of R_{sep}.

and cross sections in nucleus-nucleus (A + A) collisions. A 3D representation of the jet shapes in p + p at the LHC for transverse energy $E_T = 20$, 100 GeV and jet radius R = 0.7 is shown in the left panel of Fig. 1. Our predictions for the still unexplored center of mass energies build upon the successful comparison of this theory with the experimental measurements in proton-antiproton collisions at $\sqrt{s} = 1960$ GeV at Fermilab from Run II (CDF II) (shown in the right panel of Fig. 1). At high jet ET our theoretical model gives very good descriptions of the large r/R experimental data with R_{sep} = 1.3-1.4. For $E_T = 45$-55 GeV, the largest meaningful value $R_{sep} = 2$ can describe the data fairly well, except at very small r/R regions.

The main idea behind the proposed improvement in the determination of the QGP properties with jets is that their shapes in p + p and A + A collisions are expected to be different. The energy of a fast quark or gluon is redistributed as it loses energy in the plasma via gluon bremsstrahlung and the energy flow pattern in hot nuclear matter is much broader than in the vacuum [5]. Consequently, selecting different jet cone radii R^{max} will affect the amount of energy recovered inside the cone and the experimentally measured cross section. Radiative energy loss in QCD generally proceeds through soft gluon radiation. Another handle for studying the radiation intensity spectrum is the minimum energy cut for the particles accepted in the jet, ω^{min}, which also controls the amount of energy recovered in the cone, $r < R^{max}$, $\omega > \omega^{min}$.

Figure 2 demonstrates the sensitivity of the relative suppression of the jet cross section $R_{AA}{}^{jet}(R^{max},\omega^{min})$ to the properties of the medium-induced gluon radiation through the independent variation of R^{max} and ω^{min}, advocated in our paper [2]. Note that for perfect acceptance $R^{max} \rightarrow \infty$, $\omega^{min} = 0$, there should not be any difference between the jet cross section per elementary nucleon-nucleon collision in the vacuum and in the QGP, $R_{AA}{}^{jet} = 1$. The top panel shows a smooth evolution of the nuclear suppression factor with the jet cone radius Rmax, a signature of the large-angle bremsstrahlung [5]. The bottom panel presents the corresponding change in $R_{AA}{}^{jet}$ with the acceptance cut ω^{min}. Our results on the *variable* quenching rate of jets are quite striking when compared with the known single-suppression value for leading particles at any given E_T/p_T and centrality from the currently operating Relativistic Heavy Ion Collider [6]. In summary, the continuous variation of quenching values may help differentiate between competing models of parton energy loss, thereby eliminating the order of magnitude of uncertainty in the extraction of the QGP properties.

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[1] M. Gyulassy et al., *Quark-Gluon Plasma III,* **123,** Eds. R.C. Hwa and X.-N. Wang, World Scientific (2004).
[2] I. Vitev et al., *J. High Energ. Phys.* **0811,** 093 (2008).
[3] G.J. Kunde et al., LA-UR-08-06010 (2008).
[4] M.H. Seymour, *Nucl. Phys. B* **513,** 269 (1998).
[5] I. Vitev, *Phys. Lett. B* **630,** 78 (2005).
[6] I. Vitev, M. Gyulassy, *Phys. Rev. Lett.* **89,** 252301 (2002).

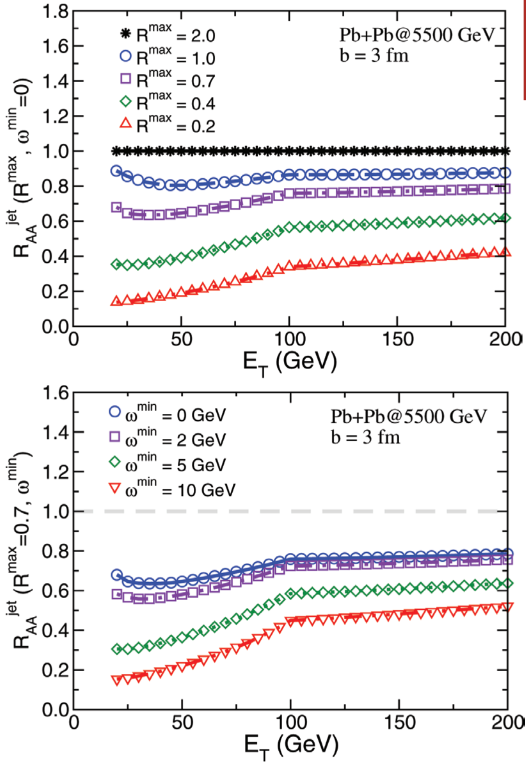

Fig. 2. Transverse jet energy-dependent nuclear modification factor $R_{AA}{}^{jet}(R^{max},\omega^{min})$ for different jet cone radii R^{max} (top panel) and at different acceptance cuts ω^{min} (bottom panel) in central Pb + Pb collisions at $\sqrt{s} = 5.5$ TeV.

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