A Study of Jet Quenching Near the QCD Phase Transition

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Introduction

Heavy ion collisions at high energies result in a phase transition where quarks and gluons are no longer confined into hadrons. This lasts about 5fm/c long. The quark-gluon plasma (QGP) deconfined state exists above a critical energy density $\varepsilon_c \approx 1$ GeV/fm^3 and critical temperature $T_c \approx 170$ MeV (10^{12} K).

Jet Quenching

If the necessary energy is achieved in a particle physics or heavy ion experiment, quarks and gluons can be kicked out of a hadron. They fragment becoming jets of hadrons before they can be directly detected. These jets can be measure in particle detectors and studied in order to determine the properties of the original particle.

The high-momentum quarks and gluons interact with the hot, dense medium created in a ultra-relativistic heavy-ion collision. As a consequence of this interaction, the jet loses energy, resulting in changes in the jet fragmentation functions. This process is called jet quenching.

High-energy nucleus-nucleus collisions allow us to change the scene of parton fragmentation from vacuum to a QCD medium, e.g. Quark gluon plasma (QGP), and to study the properties of this medium through modifications of the jet structure.

Observables

Nuclear Modification Factor

The nuclear modification factor, R_{AA} , is a useful tool to probe jet suppression, either in the initial or final state. It is a measure of the ratio of number of particles produced in nucleus+nucleus collisions to the number of particle produced in p+p collisions, scaled by the average number of collisions.

$$R_{AA} = \frac{dN^{AA}/dp_T}{N_{coll}dN^{pp}/dp_T} \quad (1)$$

Azimuthal Anisotropy (v_2)

The dense nuclear overlap at the beginning of a heavy ion collision resembles an ellipsoid due to incomplete overlap of the two colliding nuclei, and thus, jets penetrating the fireball in different directions lose different amount of energy according to their varying paths. The azimuthal anisotropy of the spectra in the transverse plane can be characterized in terms of the second Fourier coefficient, $v_2(p_T)$, which dominates over the first and higher order coefficients in non-central collisions. v_2 measures eccentricity in momentum space.

$$v_2(p_T, b) \equiv \frac{\int_0^{2\pi} d\phi \cos(2\phi)\left[\frac{d^2N}{dp_T d\phi}\right]}{\int_0^{2\pi} d\phi\left[d^2N/dp_T d\phi\right]} \quad (2)$$

In our study, v_2 will also depend on impact parameter b for large $p_T > 6$ GeV where hard processes dominate and dependence on p_T is weak. [2]

Density Dependence of Quenching

Previous studies have shown that quenching that grows with the density leads to a upper geometric limit on v_2 that underestimates experimental data [1].

Recently, a Layer-wise geometrical limit was proposed by Shuryak and Liao[2] where quenching peaks for entropy densities close to T_c .

For this model, we use a profile function that depends on a parameter λ. The profile function that gives the suppression of quenching for large s reads [2]:

$$w(s) = [1\theta(s - s_1{}^c)\theta(s_2{}^c - s) + \lambda\theta(s - s_2{}^c)] \quad (3)$$

With $s_1{}^c = 3$/fm^3 and $s_2{}^c = 11$/fm^3 bracketing the near-T_c region. We also introduced a parameter c which measures the quenching strength per entropy density around T_c. We implement this density dependence in an LPM-inspired energy loss formula (sLPM):

$$\Delta E = c \int d\tau(\tau - \tau_0)\, s\, w(s) \quad (4)$$

Parameters c and λ were used to fit the curves of Nuclear Modification Factor and Azimuthal Anisotropy to plotted data from PHENIX[3].

QGP Fireball

We use a longitudinally expanding fireball with initial entropy density in the center 100(400) fm^{-3} for RHIC (LHC). The spatial distribution is modeled by the participant density ρ_{part}. The distribution of jets is given by the density of binary collisions ρ_{coll}. These densities depend on the geometry of the interaction zone and the impact parameter b:

$$\rho_{coll} = \sigma_{inel} T_A\left(x + \frac{b}{2}, y\right) T_B\left(x - \frac{b}{2}, y\right) \quad (5)$$

$$\rho_{part} = T_A\left(x+\frac{b}{2},y\right)\left[1 - P\left(x - \frac{b}{2},y\right)\right] + T_B\left(x-\frac{b}{2},y\right)\left[1 - P\left(x + \frac{b}{2},y\right)\right] \quad (6)$$

Where, $P(x,y) = \left[1 - \frac{\sigma_{inel} T_A(x,y)}{A}\right]^A \quad (7)$

Where σ_{inel} is the inelastic cross section and $T_A(x, y)$ the thickness function, the integral of the nuclear densities over the longitudinal direction.

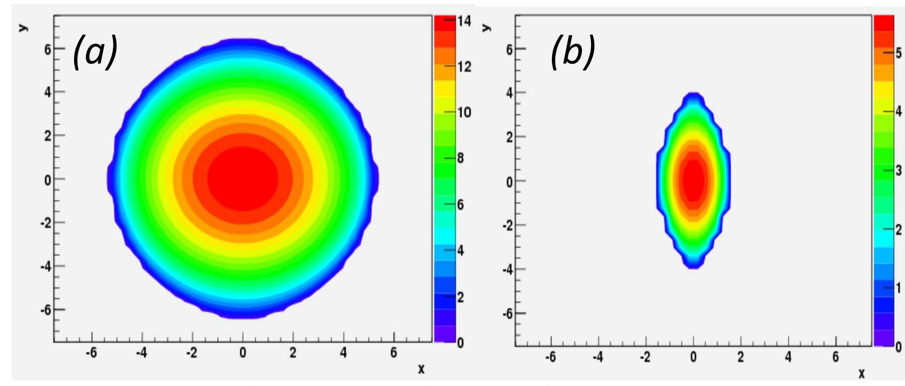

Fig. 1. Density of binary collisions for impact parameter: (a) 3.2 and (b)11.

Results

We systematically study v_2 and R_{AA} for 6 GeV pions as functions of the quenching strength c and the suppression parameter λ. We qualitatively confirm the result by Liao and Shuryak that decreasing λ (increasing shell-like quenching) leads to larger v_2.

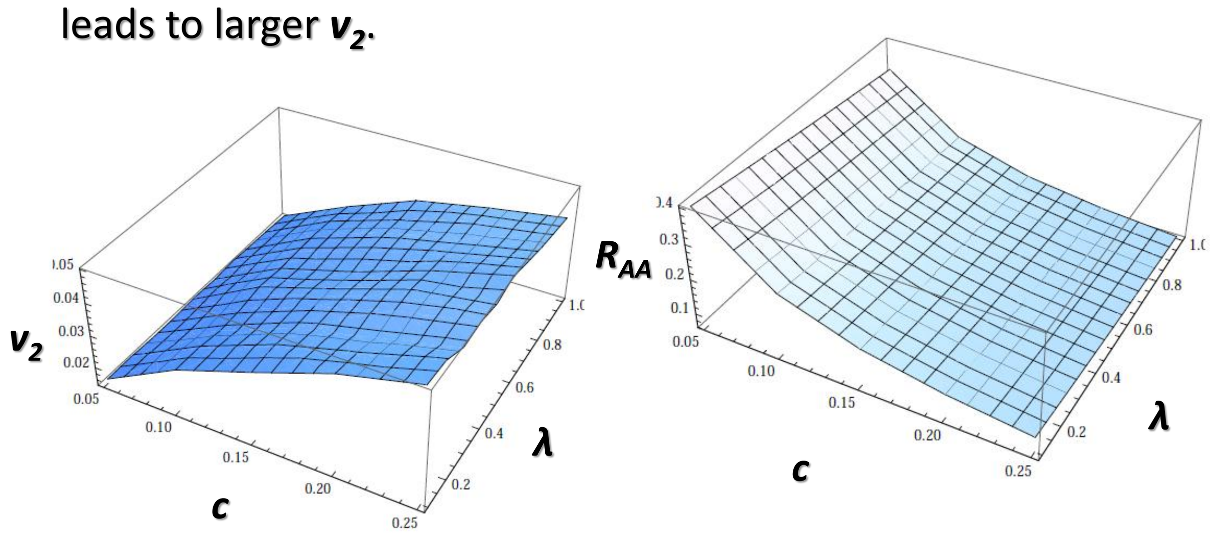

Fig. 2.

Next we fit c for three different scenarios to RHIC data: (λ = 1 [conventional], λ = 0.4 [Liao/Shuryak], λ = 0.01 [extreme shell scenario]). We find that the best values for c to fit R_{AA} from PHENIX [3] are 0.09 GeVfm, 0.11 GeVfm and 0.135 GeVfm, respectively. The corresponding results for v_2 are shown below. v_2 data from RHIC favors the lowest values of lambda. We then proceed to use the same three sets of parameters to make predictions for Pb-Pb collisions at 5.5 TeV at LHC.

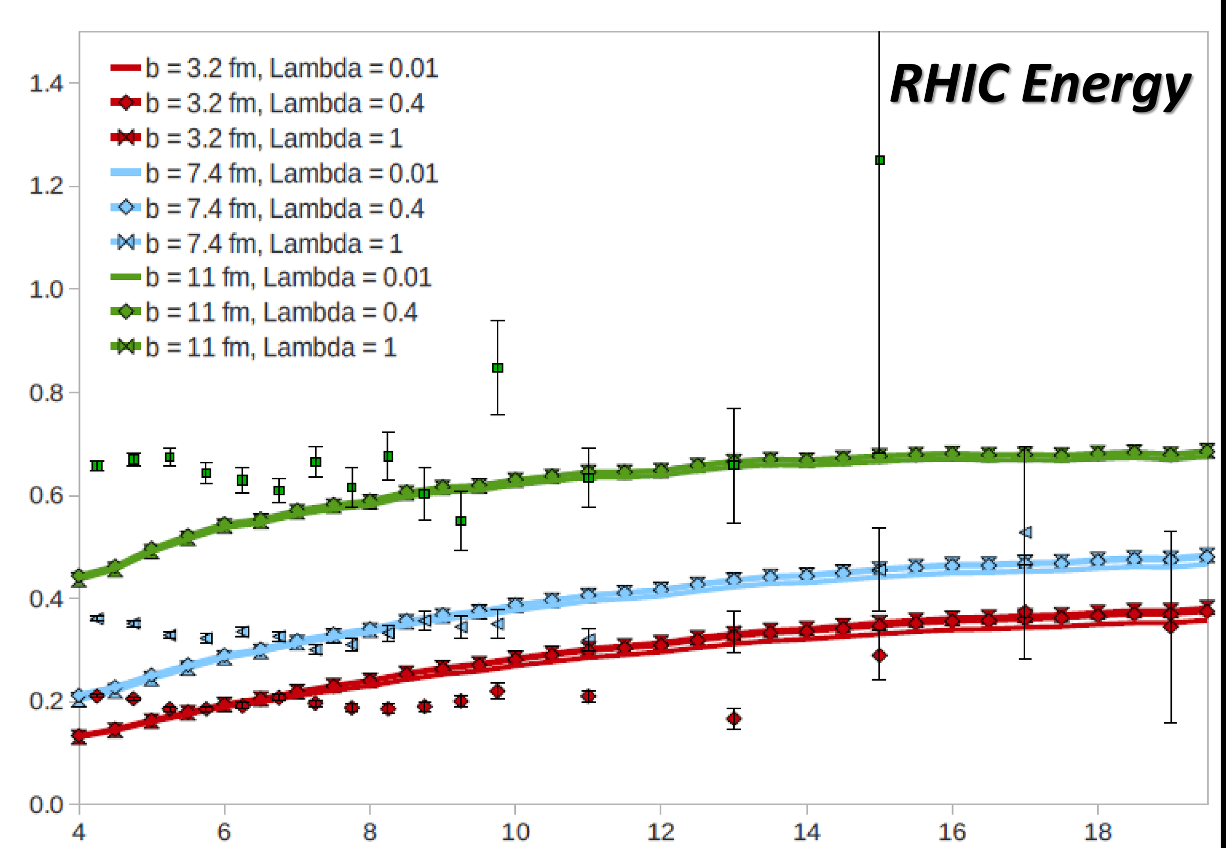

Fig. 3. Fitting of R_{AA} to PHENIX [3] experimental data for Au-Au collisions at RHIC energy.

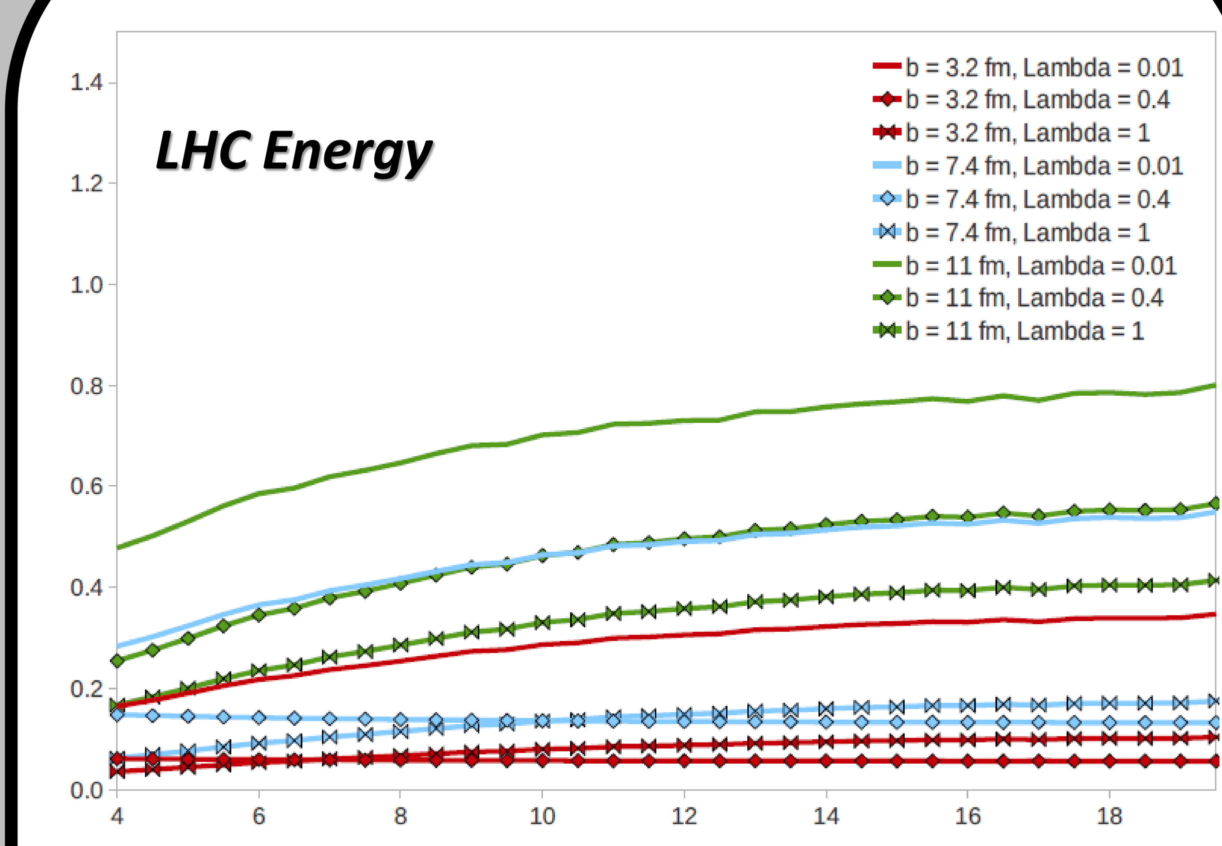

Fig. 4. R_{AA} results for Pb-Pb collisions at LHC energies using the same parameters λ and c as for RHIC.

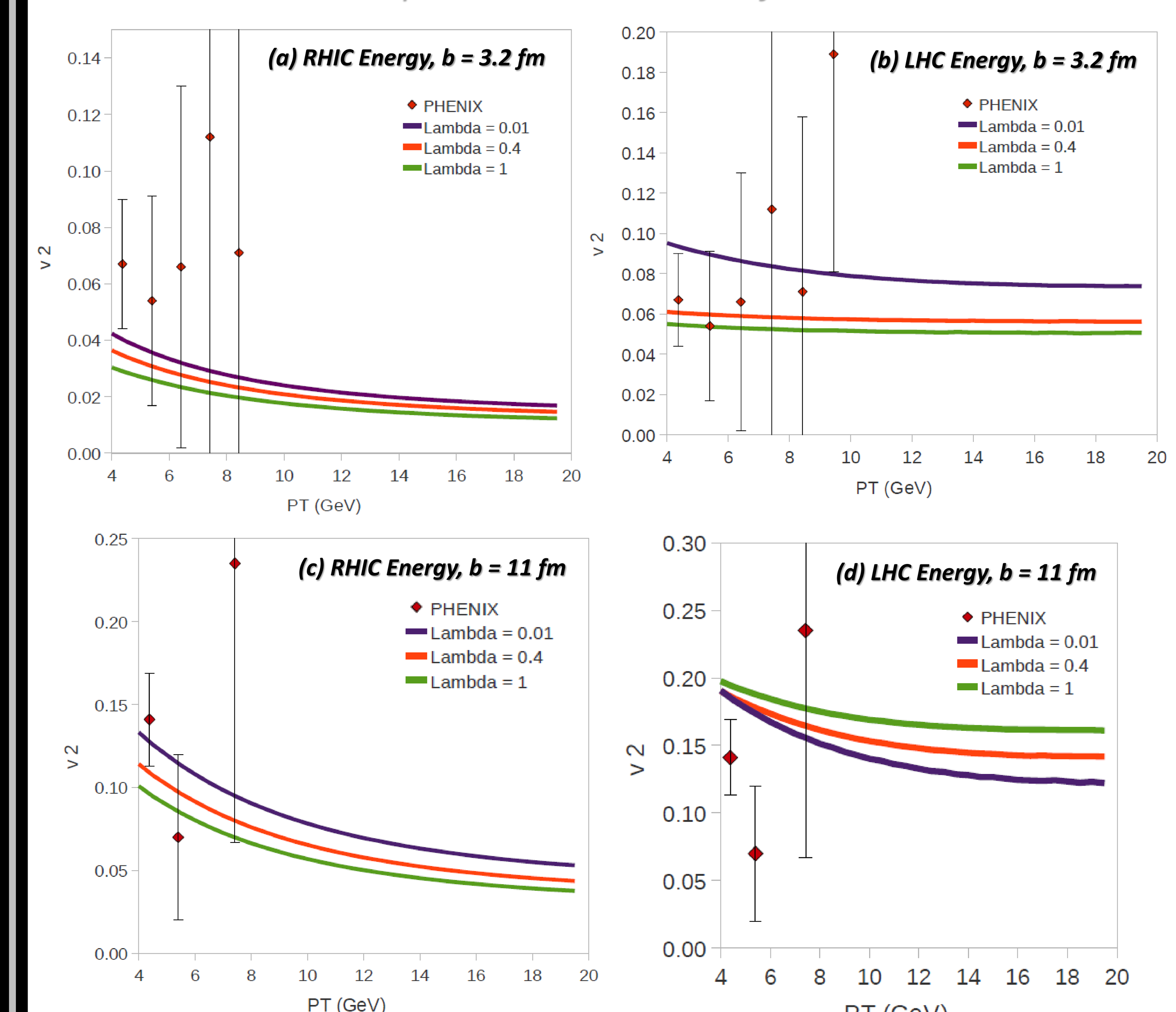

Fig. 5. v_2 results for energies at RHIC and LHC. Impact parameters 3.2 fm and 11 fm are shown.

Summary

If we decrease λ while increasing c to fit RHIC R_{AA} we observe less suppression at LHC. We also observe larger v_2 at LHC for decreasing λ except for the most peripheral bins. This tells us that LHC data will be able to rule on the validity of enhanced quenching around T_c.

References

[1]Phys. Rev. C, 66, 027902 (2002)
[2]Phys. Rev. Lett., 102, 202302 (2009)
[3] Phys. Rev. Lett. 101, 232301 (2008)

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