

Jets structure in Pb–Pb collisions at LHC energies

E. Cuautle, I. Domínguez and G. Paic

Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Apartado Postal 70-543, México Distrito Federal 04510, México

E-mail: isabel@nucleares.unam.mx

Abstract.

Modifications of the structure of jets produced in ion-ion collisions represent a very sensitive tool to study the interactions of partons with the medium. Partonic energy loss manifests itself as a decrease of the number of particles carrying a high fraction of the jet energy and, the additional radiated energy, increases the number of low-energy particles. We present and analysis of jets produced in ion-ion collisions at LHC energies. Predictions with two different Monte Carlo simulation models (PYQUEN and Q-PYTHIA) for the parton energy loss, are analyzed together with modification of the jet structure.

1. Introduction

Jets are produced in hard scattering of partons from nucleons within the incoming particles or ions. The outgoing partons transverse the medium formed in the collision¹ interacting with it and losing energy before fragmenting into jets of hadrons. Evidence for jet energy loss has been reported by *RHIC* experiment. Two evidences to support this are the disappearance of away-side correlations in central $Au + Au$ compare to $p + p$ collisions and the high- p_T hadrons suppression in the nuclear modification factor R_{AB} .

In the disappearance of away-side correlations in central $Au + Au$ compare to $p + p$ collisions (left panel of figure 1), a hadron pair drawn from a single jet will generate an enhanced correlation at $\Delta\phi \approx 0$, as observed for $p + p$, $d + Au$ and $Au + Au$. A hadron pair drawn from back-to-back dijets will generate an enhanced correlation at $\Delta\phi \approx \pi$, as observed for $p + p$ and for $d + Au$ with somewhat broader width than the near-side correlation peak. However, the back-to-back dihadron correlation is absent in central $Au + Au$ collisions. If the correlation is indeed the result of jet fragmentation, the suppression is due to the final state interaction of hard-scattered partons or their fragmentation products in the dense medium generated in $Au + Au$ collisions.

The nuclear modification factor R_{AB} (right panel of figure 1) is defined as the ration of the inclusive momentum spectra of charged hadrons from $Au + Au$ events to $p + p$ reference spectrum, scaled to account for nuclear geometry. It is expected that the number of hard processes in an event scales $\langle N_{bin} \rangle$, in absence of nuclear effect $R_{AB} = 1$. Conventional nuclear effects, such as nuclear shadowing of the parton distribution functions and initial state multiple scattering,

¹ QCD predicts that a high temperature or density ($\epsilon_c \sim 1\text{GeV}/fm^3$), matter should be close to ideal gas called quark-gluon-plasma (QGP)

cannot account for the suppression. Furthermore, the suppression is not seen in $d + Au$ but is unique to $Au + Au$ collisions, proving experimentally that it results not from nuclear effects in the initial state, but rather from the final state interaction of hard scattered partons or their fragmentation products in the dense medium generated in $Au + Au$ collisions.

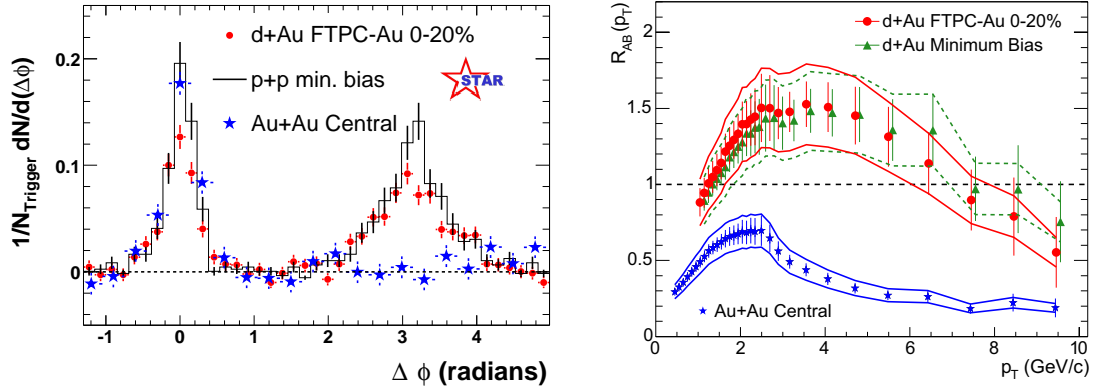


Figure 1. Dihadron azimuthal correlations at high p_T for $p + p$, central $d + Au$ and central $Au + Au$ collisions (background subtracted) from *STAR* [1] (left). Binary-scaled ratio R_{AB} of charged hadron and π_0 inclusive yields from $\sqrt{s_{NN}} = 200$ GeV $Au + Au$ and $d + Au$ relative to that from $p + p$ collisions, from *STAR* [2] (right).

In this work, we studied the effects of parton energy loss in a medium under extreme conditions of temperature and density. To achieve that, we simulate high- p_T events in $p + p$ collision with PYTHIA [3], as a baseline, and events passed through two afterburner model of energy loss PYQUEN [4] and Q-PYTHIA [5]. After events simulation, jets were reconstructed with a cone jet finding algorithm and event shape analysis was done. Finally modifications in jet structure, due to energy loss, were studied.

2. Energy loss Monte-Carlo simulation

PYQUEN (PYthia QUENched) is a Monte Carlo event generator routine implemented to simulate re-scattering, radiative and collisional energy loss of hard partons in expanding quark-gluon plasma created in ultra-relativistic heavy ion-ion collisions. The internal model parameters are the initial conditions for the QGP formation expected for central ion-ion collisions (table 1).

Q-PYTHIA is a Monte Carlo implementation of medium-induced gluon radiation in the final-state branching process. Medium effects are introduced through an additive term in the vacuum splitting functions. A realistic Glauber-like collision geometry is defined, the production points of the hard scatterings are distributed in the nuclear overlapping area according to the probability of central nucleon-nucleon collisions. In this model the only free parameter is the scale of the transport coefficient $k = 6 \cdot 10^6$ fm, which corresponds to an average $\langle \hat{q} \rangle = 14$ GeV²/fm in a 0-10% central collision.

Once particles production simulation was made, with and without energy loss, we proceed to reconstruct jets using a cone jet algorithm [6] and event shape analysis (ESA) [7].

Table 1. PYQUEN internal model parameters.

Description	Parameter	Value
Medium-induced partonic energy loss	ienglu	0 - radiative and collisional 1 - radiative 2 - collisional
Initial temperature of quark-gluon plasma	T_0	$0.2 \text{ GeV} < T_0 < 2 \text{ GeV}$
Proper time of quark-gluon plasma formation	τ_0	$0.01 \text{ fm/c} < \tau_0 < 10 \text{ fm/c}$
Number of active quark flavors in quark-gluon plasma	n_f	0, 1, 2 or 3
Angular distribution of emitted gluons	ianglu	0 - small - angular 1 - wide - angular 2 - collinear

3. Cone jet algorithm

Cone jet algorithms associated particles whose trajectories lie within a circle of specific radius R in $\eta \times \phi$ space. Starting with a trial geometric center (or axis) for a cone in $\eta \times \phi$ space, the energy-weighted centroid is calculated including contributions from all particles within the cone. This new point in $\eta \times \phi$ is then used as the center for a new trial cone.

As this calculation is iterated the cone center “flows” until a “stable” solution is found, *i.e.*, until the centroid of the energy depositions within the cone is aligned with the geometric axis of the cone. The cone variables are:

$$E_T^J = \Sigma E_T^i \quad \eta^J = \frac{1}{E_T^J} \Sigma E_T^i \eta^i \quad \phi^J = \frac{1}{E_T^J} \Sigma E_T^i \phi^i$$

where E_T^i is the transverse energy, η^i is the rapidity and ϕ^i is the azimuthal angle for the particle i and E_T^J is the transverse energy, η^J is the rapidity and ϕ^J is the azimuthal angle for the jet J .

4. Event Shape Analysis (ESA)

The event shape analysis measures the geometrical properties of the energy flow in QCD states, its leads us a method to determine areas where one does encounter special topologies of jets in an event, allow an easy selection of events. In hadron-hadron collisions, three shapes variables are used: thrust (T), recoil (R) and thrust-minor (T_{min}).

The thrust variable (T) is defined using only transverse variables:

$$T \equiv \underbrace{\max}_{\vec{n}_T} \frac{\sum_i |\vec{q}_{\perp,i} \cdot \vec{n}_T|}{\sum_i |\vec{q}_{\perp,i}|}$$

$\vec{q}_{\perp,i}$ represent the momentum components transverse to the beam and \vec{n}_T is the transverse vector that maximizes the ratio. The sphericity of the event is defined as $\tau \sim 1 - T$. For events with narrow back-to-back jets, τ is close to 0 and for events with a uniform distribution of

momenta τ is close to 0.3

The recoil variable R is defined as the vector sum of the transverse momentum:

$$R \equiv \frac{|\sum_i \vec{q}_{\perp i}|}{\sum_i |\vec{q}_{\perp i}|}$$

This quantity measures the balance of momenta of the event. For example for monojets events, *i.e.*, two jets in a event but only one of them inside detector acceptance, R tends to 1, because there are no vectorial transverse momentum cancellations between particles. Otherwise, in the case of narrow back-to-back jet inside the acceptance, R tends to 0 because the vectorial transverse momentum sum is 0.

T_{min} is a measure of the momentum out of the plane formed by the transverse momentum and the beam. Given the thrust axis (\vec{n}_t), we can define it as:

$$T_{min} \equiv \frac{\sum_i |\vec{p}_{t,i} \times \vec{n}_t|}{\sum_i |\vec{p}_{t,i}|}$$

5. Cone jet algorithm results

In table 2 are shown the parameters used in this analysis, both for particle production and for the jets reconstruction using a cone jet algorithm.

Table 2. Parameters used.

Particle production	Cone jet algorithm
100 000 events	Charged particles with
PYTHIA,	$p_T > 0.3 \text{ GeV}/c$
PYQUEN and Q-PYTHIA	$R = 0.7$
$\sqrt{s_{NN}} = 5.5 \text{ TeV}$	$E_T^J > 5 \text{ GeV}$
$p_T^{hard} = 50 \text{ GeV}/c$	$ \eta^J < 0.5$

Taking the ration (R_{AA}) between the particles produced with PYTHIA and the both models of energy loss as a function of p_T and the transverse momentum $j_T = p_T \sin \Delta\phi$, changes in the structure of jets can be observed due to the parton energy loss.

Partonic energy loss manifests itself as a decrease of the number of particles carrying a high fraction of the jet energy and additional radiated energy increases the number of low-energy particles (left panel of figure 2). In addition, broadening of the distribution of jet-particle momenta perpendicular to the jet axis, j_T distribution was observed and clear differences between the two Monte Carlo models in the pattern of increase of low-momentum particles and depletion of high-momentum particles can be observed (right panel of figure 2).

5.1. Acoplanarity between dijets

Instead of being back-to-back in the transverse plane the partons are affected by additional transverse momentum contributions from the intrinsic k_T of the scattering partons and from NLO processes. In nucleus-nucleus collisions the interaction with the medium further increases

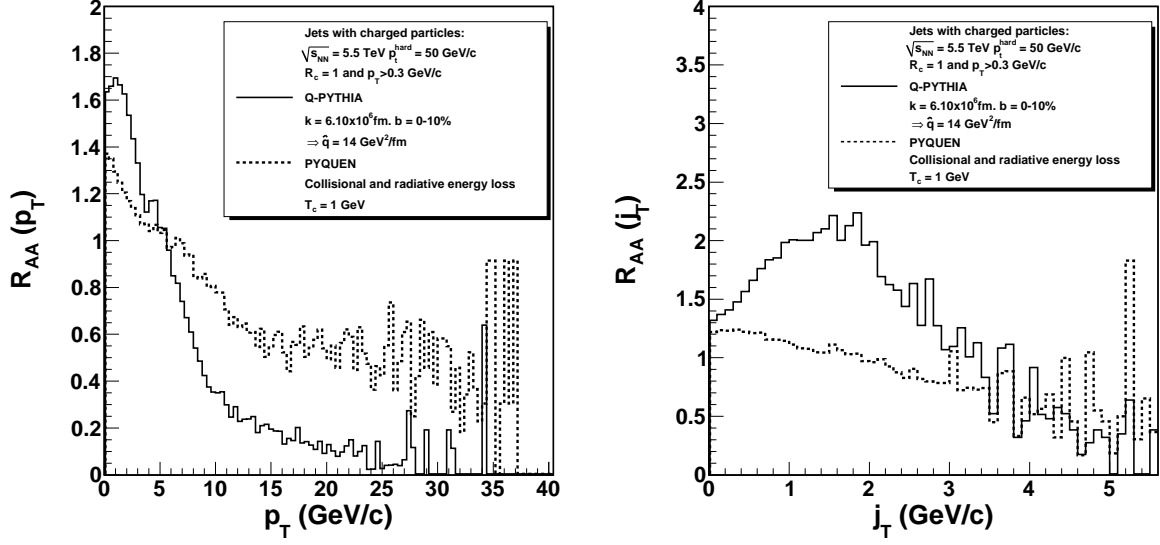


Figure 2. Ratio of particles yield (R_{AA}) between Q-PYTHIA and PYTHIA (solid line) and PYQUEN (with $T_0 = 1$ GeV) and PYTHIA (dashed line) as function of p_T (left) and j_T (right).

the so called acoplanarity of the parton pair.

Acoplanarity is defined as the average transverse momentum component of the away-side jet. $\vec{p}_{T,a}$ perpendicular to the plane formed by the beam and the near side jet with transverse momentum $\vec{p}_{T,t}$.

$$p_{out} = |p_{Ta}| \sin \Delta \phi = \sqrt{2} k_{Ty}$$

and the transverse momentum imbalance is the difference between the trigger jet ($\vec{p}_{T,t}$) and the away-side jet ($\vec{p}_{T,a}$) transverse momentum in the trigger jet-beam plane.

$$p_{T,diff} = p_{max} - p_{proj} = |p_{Tt}| - |p_{Ta}| \text{Proj}(p_{Tt}) = \sqrt{2} k_{Ty}$$

Figure 3 show both distribution, p_{out} and $p_{T,diff}$ comparing PYTHIA with Q-PYTHIA and PYQUEN. The increase in the acoplanarity due to the parton energy loss was calculated as:

$$\sqrt{\langle \mathbf{p}_{out_{col}}^2 \rangle} = \sqrt{\langle \mathbf{p}_{out_{med}}^2 \rangle - \langle \mathbf{p}_{out_{pp}}^2 \rangle}$$

and is observed for both Monte Carlo. For Q-PYTHIA we obtained $\sqrt{(8.44)^2 - (7.80)^2} = 3.2$ GeV/c and for PYQUEN $\sqrt{(9.24)^2 - (7.80)^2} = 4.9$ GeV/c

6. Event Shape Analysis results

The event shape analysis starts by plotting a two dimensional distribution (“thrust map”), with τ ($1 - T$) in the horizontal axis and R in the vertical axis. This plot allows to identify different classes of events according with their location in the thrust map (table 3).

First of all, was observed that at low $p_T^{cut} > 0.3$ GeV/c (left panel of figure 4), isotropics events are presents, even hard processes are simulated. Increasing $p_T^{cut} > 4$ GeV/c (right panel of figure 4)

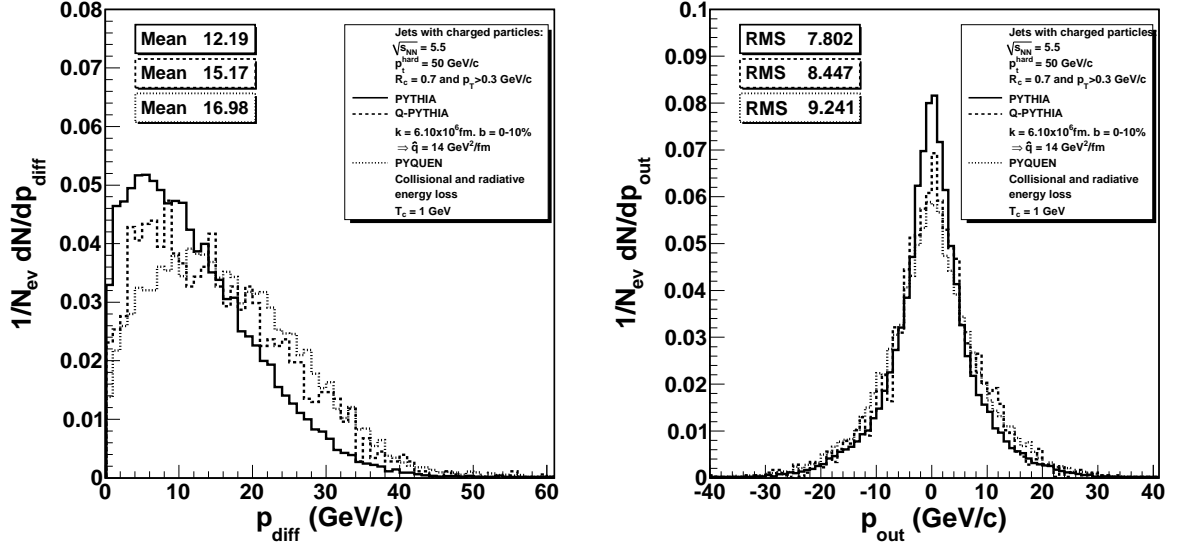


Figure 3. $p_{T,diff}$ (left) and p_{out} (right) for dijets produced with PYTHIA (solid line), Q-PYTHIA (dashed line) and PYQUEN with $T_0 = 1$ GeV (dotted line).

events with monojets and dijets are selected, decreasing background. This behavior is more notorious in the azimuthal correlations between particles (figure 5 for low (left) and high (right) p_T).

Table 3. Parameters used and cuts for events selection

Particle production	ESA	Class of event
100 000 events	Charged particles with	Dijets (A): $1 - T < 0.05$, $R \leq 0.35$
PYTHIA,	$p_T^{leading} > 10$ GeV/c	Mono jet (B): $1 - T \leq 0.05$, $R \geq 0.9$
PYQUEN and Q-PYTHIA	$p_T^{assoc} > 0.3$ GeV/c and	Isotropic (C): $1 - T \geq 0.3$, $R \leq 0.4$
$\sqrt{s_{NN}} = 5.5$ TeV	$p_T^{assoc} > 4$ GeV/c	
$p_T^{hard} = 50$ GeV/c	$ \eta < 0.9$	

Now, taking the ration (R_{AA}) between the particles produced with PYTHIA and the both models of energy loss as a function of event shape analysis variables, $1 - T$ and T_{min} , which provide a measure of the radiation perpendicular to that plane, shows modifications because of the parton energy loss, being higher at low p_T .

7. Summary

Two Monte Carlo models for jet quenching in $Pb + Pb$ collisions at LHC energy were studied. We observed:

- An increase of low-momentum particles and depletion of high-momentum particles.
- In $Pb+Pb$ collisions the acoplanarity between dijets is increased due to partonic interactions with the dense medium can be observed

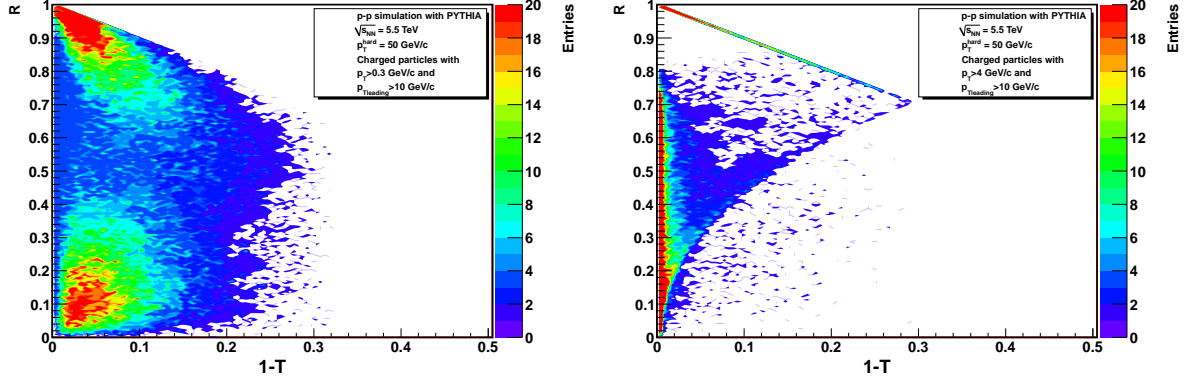


Figure 4. $1 - T$ vs R for particles produced with PYTHIA. The cuts used in ESA are: $|\eta| < 0.9$, $p_{T\text{leading}} > 10$ GeV/c, $p_T^{\text{cut}} > 0.3$ GeV/c (left) and $p_T^{\text{cut}} > 4$ GeV/c (right).

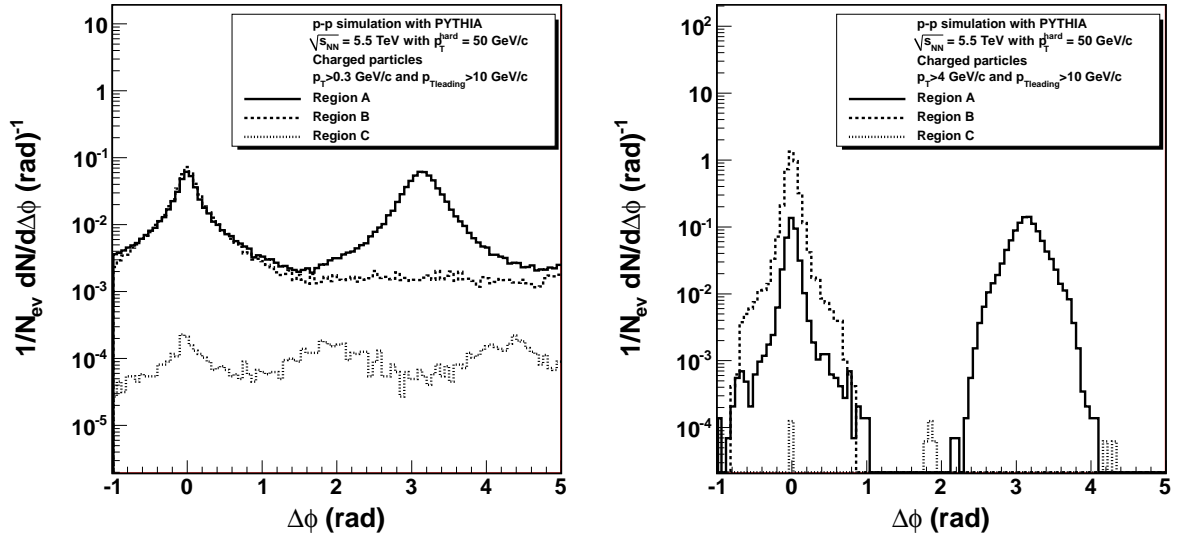


Figure 5. Azimuthal correlations produced with PYTHIA. The cuts used in ESA are: $|\eta| < 0.9$, $p_T^{\text{cut}} > 0.3$ GeV/c (left), $p_T^{\text{cut}} > 4$ GeV/c (right) and $p_{T\text{leading}} > 10$ GeV/c. Events in the different regions of the plot R vs $1 - T$ are shown: events in region (A) (solid line), events in region (B) (dashed line), events of region (C) (dotted line), according to the table 3.

Event Shape Analysis (ESA) is available to describe the topology of events in $Pb + Pb$ collisions.

- Using the variables thrust and recoil and constructing the thrust is possible to study different configurations, like dijets.
- Both, thrust minor and azimuthal correlations can be used to study the acoplanarity of a pair of jets and modifications in their structure.

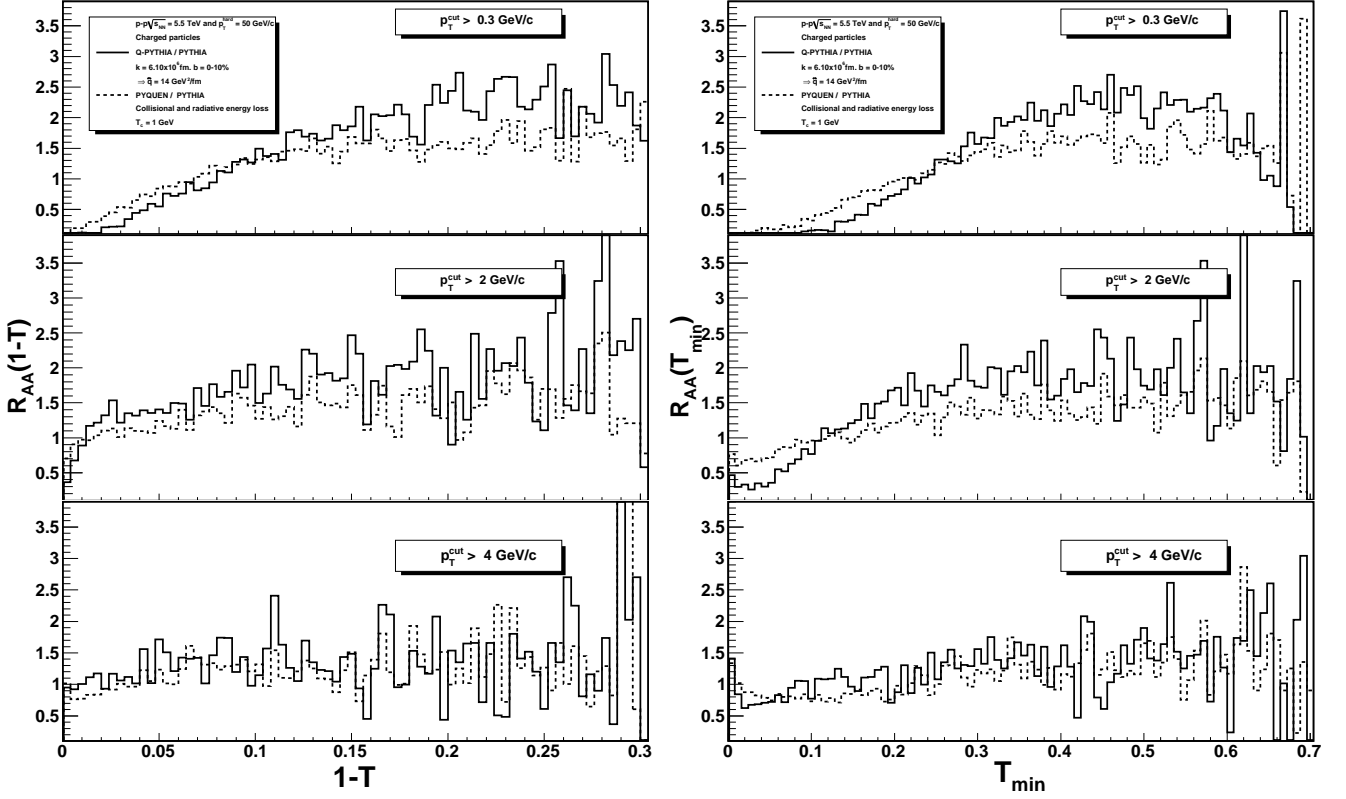


Figure 6. Ratio of particles yield (R_{AA}) between PYQUEN and PYTHIA (solid line) and Q-PYTHIA and PYTHIA (dashed line) as a function of $1 - T$ (left) and R (right) with $p_{T1} = 10 \text{ GeV}/c$ and $p_{Ta} = 0.3 \text{ GeV}/c$ (top), $p_{Ta} = 2 \text{ GeV}/c$ (middle) and $p_{Ta} = 4 \text{ GeV}/c$ (bottom).

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