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Two-particle correlations from RHIC to LHC, a Monte Carlo approach [a]

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Abstract. The aim of this work is to extend to LHC the results observed for two-particle correlations at RHIC, especially in terms of jet quenching effects. In this study a parton quenching model developed in the BDMPS-Z-SW framework is considered and implemented as an afterburner for PYTHIA and HIJING. A simplified parametrization of the quenching mechanism at the parton level is included in one of the most popular Monte Carlo event generators for AA collisions, HIJING. The simulation method, tuned on the RHIC data, is then used to make predictions for the LHC energy regime in order to probe the scenario we will study in the ALICE experiment.

1 Introduction

The well-known results on two-particle correlations from RHIC have generated a substantial interest in jet studies. They provide a way to study the properties of the dense medium produced in heavy ion collisions. This work moves in this direction, first considering some of the jet properties observed at RHIC, and then studying the kinematic region that is more adequate for extending the same analysis to LHC in the parton quenching model scenario [1]. In Fig. 1 the results from the STAR collaboration are reported, showing the back-to-back suppression of the jet correlations in very central Au + Au collisions at intermediate p_T [2]. The absence of this suppression in d + Au collisions strongly suggests that the effect is due to the interaction between the jet and the medium, occurring only in AA collisions.

At RHIC it was observed [3] that the back-to-back correlation shows up again when the p_T value of the trigger particle is increased. Therefore, from RHIC we learn that the strength of the signal effect changes with the p_T of the trigger particle.

In Sect. 2, the quenching model with the Glauber geometry (parton quenching model) is described, together with some relevant results concerning jet physics [1, 4, 5]. The implementation of this model in a Monte Carlo simulation is described in Sect. 3, where the PYTHIA [6] and HIJING [7, 8] generators are considered (see [9]). The results obtained with this Monte Carlo simulation at RHIC energy are then presented. In Sect. 4, the extrapolation at the LHC energy is performed in order to make predictions in the new energy regime. Finally, in Sect. 5 the conclusions are reported.

2 Quenching model description and general results

The quenching model developed in the BDMPS-Z-SW framework [4] is based on the idea that a fast parton interacts strongly with the medium formed in the collision, losing energy via gluonic bremsstrahlung. In particular,

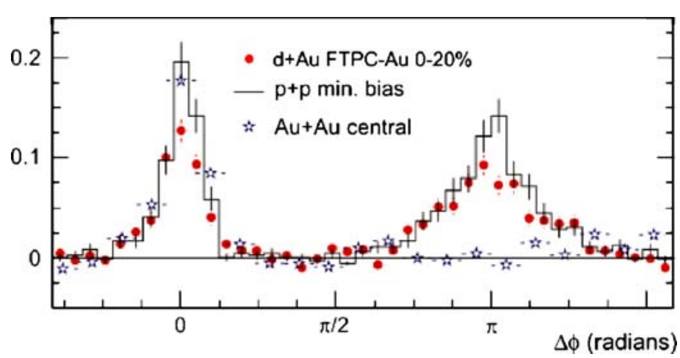

Fig. 1. Two-particle azimuthal distributions for central d + Au collisions compared with those seen in pp and central Au + Au collisions $\left(4 < p_T^{trig} < 6\ \mathrm{GeV}/c, p_T^{assoc} > 2\ \mathrm{GeV}/c\right)$. The corresponding pedestals have been subtracted. Figure taken from [2]

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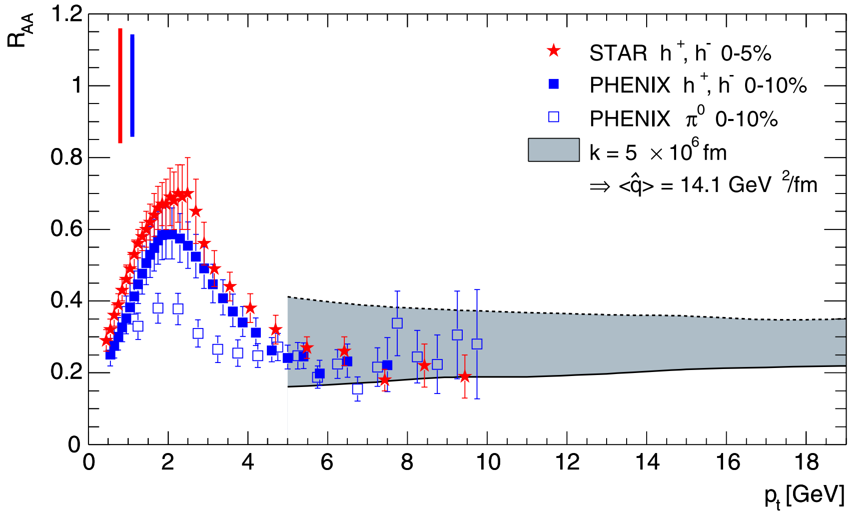

Fig. 2. $R_{AA}(p_{\mathrm{T}})$ for central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The model band is obtained with a parton-by-parton calculation of ω_c and R. The average transport coefficient is $14\,\mathrm{GeV}^2/\mathrm{fm}$. The plot is taken from [1]

the formation of a deconfined medium (the so-called quark gluon plasma) would result in a very different kind of interaction compared to the case of purely hadronic matter. The main difference in the type of interaction is due to the fact that, in the former case, the interaction of the radiated gluons with the medium also has to be considered. In particular, the probability for a parton to lose a given amount of energy scales with the square of the path length instead of linearly. A simple explanation for this behaviour is that the amount of the energy lost is proportional to the number of scatterings ($\propto L$) and to the formation probability ($\propto L$), which is approximately an L^2-dependence. The details of the approximation made in this model can be found in [4], where a method to calculate the probabilities for the quenching processes (quenching weights) is also reported. Here, only the main parameters which characterize the model are described in order to help the reader understand the assumptions and the procedure used.

The quenching mechanism states that a parton that has moved in the medium on a path of length L will lose a given amount of energy that is independent of its initial energy. On average, its energy loss is proportional to L^2 (path length squared) [10].

If the two quantities ω_c and R (defined as $\omega_c = \hat{q}L^2/2$ and $R = \hat{q}L^3/2$, where $\hat{q}$ is the mean squared momentum per unit length and L the path length in the medium) are considered, the energy loss is fully determined by these two parameters.

If the Glauber geometry is also considered, the previous quantity can be defined as in the parton quenching model (PQM)[1], as follows:

$$
\begin{aligned}
(\hat{q}L)_{\mathrm{eff}} &= \int_0^\infty k \times T_A(\chi; b) T_B(\chi; b)\,\mathrm{d}\chi\,, \\
I_n &= \int_0^\infty \chi^n \hat{q}(\chi; b)\,\mathrm{d}\chi\,, \\
\omega_c &= I_1\,, \\
R &= I_0^2/(2I_1)\,, \qquad (1)
\end{aligned}
$$

where T_A and T_B are the impact parameter dependent transverse nuclear densities (b being the impact parameter) of nuclei A and B, and k is a parameter linked to the parton density in the nuclei.

It was also proven [4] that in the case of medium expansion the quenching mechanism can be described, as in the static case, over a large parameter range by replacing $\hat{q}$ with

$$\bar{\hat{q}} = \frac{2}{L^2} \int_{\chi_0}^{L+\chi_0} \mathrm{d}\chi (\chi - \chi_0) \hat{q}(\chi)\,,$$

where $\hat{q}(\chi)$ is the time-dependent transport coefficient.

The following figures present some of the results obtained with this model. In particular, Fig. 2 shows how the model describes the R_{AA} ratio suppression in central collisions [1] for a $\langle \hat{q} \rangle \sim 14\,\mathrm{GeV}^2/\mathrm{fm}$. The quantity R_{AA} is defined as

$$R_{AA}(p_{\mathrm{T}}) = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \left[\left(\frac{\mathrm{d}^2 N_{AA}}{\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta} \right) \Big/ \left(\frac{\mathrm{d}^2 N_{pp}}{\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta} \right) \right],$$

which is the ratio of the charged multiplicity per unit rapidity in AA collisions over the pp one normalized with the average number of collisions in a given centrality class, as a function of p_{T}.

3 Quenching in the Monte Carlo

In the work presented in this paper, the quenching weight probabilities (see Sect. 2) have been implemented and tested in the PYTHIA and HIJING Monte Carlos. This choice has been driven by the fact that other existing quenching models do not provide a satisfactory description of AA collisions. Moreover, the quenching mechanism provided by the HIJING Monte Carlo generator used in this work is not compatible with our aims, since it simulates quenching effects in hadronic matter, where the energy loss is proportional to L and not L^2 (as predicted in the BDMPS-Z-SW framework).

It must be specified that the quenching procedure used here is not a Monte Carlo simulation, but a simplified parametrization which describes the model in a way that accounts for the nuclear geometry.

The possibility to test the same method in the two different generators has the advantage of making it possible to separate the effects due to the single jet modification from the background effects.

The following simulated results were obtained with the modified versions of PYTHIA and HIJING integrated into the ROOT and ALIROOT framework [11, 12].

3.1 PYTHIA

In this subsection the effect of jet quenching in single NN collisions that assume the Glauber geometry of AA collisions is taken into account. This makes it possible to probe jet modification in a way that excludes the background of the rest of the AA collision.

The method used here is based on the parton quenching model [1] and the radiation products are also taken into account.

The simulation is implemented in two steps [5].

1. High-p_T parton production was simulated using the PYTHIA event generator in pp mode with CTEQ5L [13] parton distribution functions.
2. Depending on whether the jet quenching effect is simulated or not, after the final state gluon radiation, the partonic system is either subsequently hadronised or first passed through an afterburner, as described in the previous section.

The probabilities coming from the quenching weights define the fraction z of total energy lost by the initial parton. The number of radiated gluons is given by the expression

$$1/(1-z)\,, \qquad (2)$$

in order to limit their energy to be less than that of the outgoing leading parton. Moreover, the leading parton gets an additional transverse momentum (with respect to its initial direction) given by the expression $\sqrt{\hat{q}L}$.

Figure 3 reports the integrated number of correlated charged particles per trigger particle in the near and opposite side as a function of the centrality of the event. The dashed lines represent the PYTHIA prediction for pp events without quenching effects. It can be observed that the near side correlation (squares) is almost constant when varying the centrality, while the opposite side correlation (triangles) goes down with decreasing impact parameter. Although a residual correlation in the opposite side survives also in central collisions, it is a very small effect. In fact, the suppression factor for $\langle\hat{q}\rangle = 15\ \mathrm{GeV}^2/\mathrm{fm}$ is about 10.

3.2 HIJING

While the PYTHIA generator is a good tool to test the jet quenching model in the absence of background, the HIJING Monte Carlo provides a more realistic description

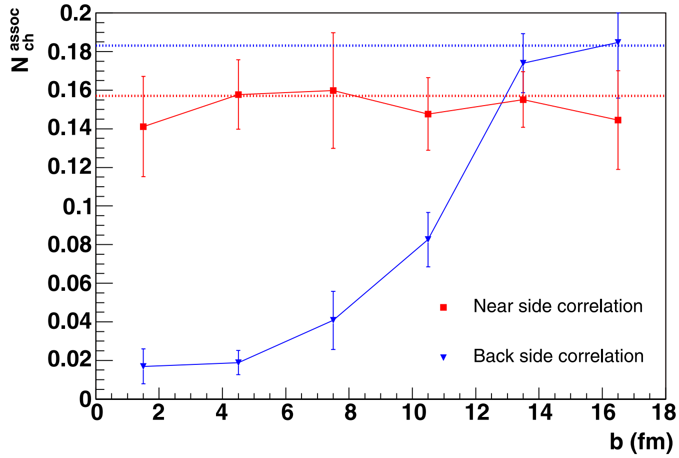

Fig. 3. Behaviour of near and away side correlation as a function of the centrality of the collisions, as explained in the text, when quenching is switched on (modified PYTHIA simulation)

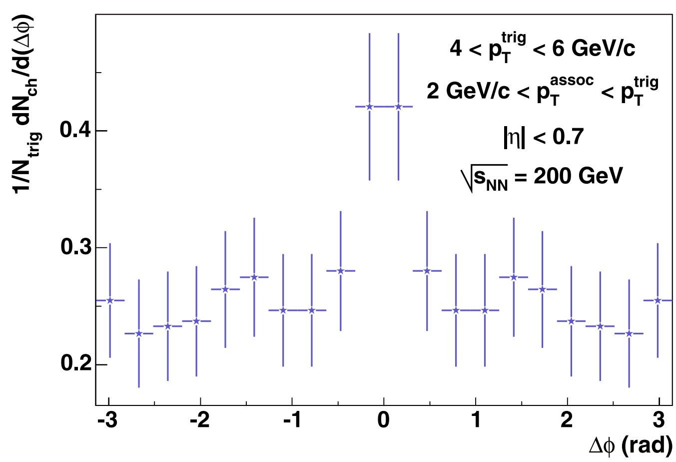

Fig. 4. HIJING simulation in the parton quenching model. The choice of p_T-cuts used here is reported as well

of the environment of AA collisions. For this reason the same jet quenching mechanism has been introduced also in the HIJING code.

Although the code structure is slightly different when the generation of hard processes is performed, the implementation of the jet quenching mechanism is organized in the same two steps as before. The results for central simulated Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV are shown in Fig. 4.

It is necessary to note that in the current version of HIJING the simulation of the elliptic flow contribution, as it was observed at RHIC, is not included.

The preliminary results obtained with the HIJING generator are consistent with the PYTHIA ones. Even if the statistics are still low, because of the background fluctuations and the small number of events ($N_{trig} = 1500$), the back-to-back total suppression for this choice of p_T-cuts (Fig. 4) agrees with what is seen in the RHIC data [2].

The modified version of HIJING used in this work also allows for the simulation of single NN collisions, as in

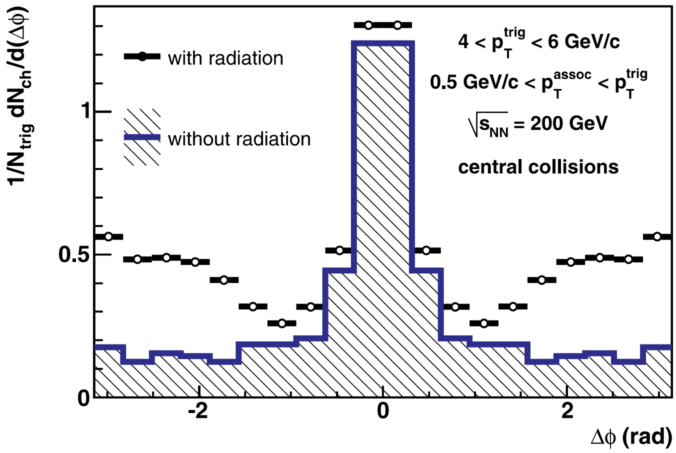

Fig. 5. HIJING simulations (without background) focused on the contribution of radiated gluons at low p_T for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The *open* and *dashed histograms* refer to simulations with and without radiative contribution. The comparison shows that the contribution of radiated gluons is important and dominant at low p_T if formula (2) is assumed

PYTHIA, with jet quenching effects and with the Glauber geometry relative to Au + Au collisions taken into account. This capability was used to check directly the effect of the inclusion of the radiation used in the model presented here (see Sect. 3.1). Figure 5 shows the two-particle correlation for low p_T in the cases of radiation and no-radiation. This plot indicates that the radiation introduced in the generator gives a non-negligible contribution at low p_T. It must be noted that the comparison with data is not straightforward, so that the above should be regarded only as a checking of the procedure.

4 Predictions for LHC

As already mentioned, the main aim of this work is to make predictions for LHC. In this new regime, the range of p_T that can be investigated with the ALICE experiment extends to higher values than those at RHIC. Therefore, the PYTHIA and HIJING generators, which have been used to study the results obtained at RHIC, were used to predict two-particle correlations at the LHC energy.

Figure 6 shows PYTHIA simulations, with the quenching effects described in Sect. 3, at $\sqrt{s_{NN}} = 5.5$ TeV with the same choice of p_T for trigger particles used before ($4 < p_T^{trig} < 6$ GeV/c). The behaviours of the near side and away side correlation as a function of the p_T of the associated particles are considered, assuming central collisions.

The effect of the background is visible in Fig. 7, where HIJING simulations for Pb + Pb central collisions, at $\sqrt{s_{NN}} = 5.5$ TeV, are considered. In this case the increase of the charged particle multiplicity at intermediate p_T is clearly visible (both for the background and the signal). Moreover, it has been found that the rate of particles with $p_T > 4$ GeV/c changes from 1 every 40 events (at the RHIC energy) to two particles per event (at the LHC energy). However the definition of "high" p_T for this regime is not clear because the signal is not well separated from the background sources.

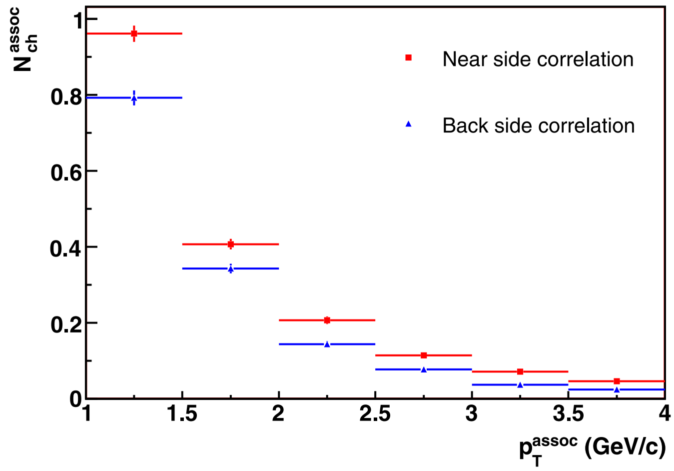

Fig. 6. The behaviour of the near side and away side correlation as a function of the p_T of the associated particles with $4 < p_T^{trig} < 6$ GeV/c, assuming central collisions

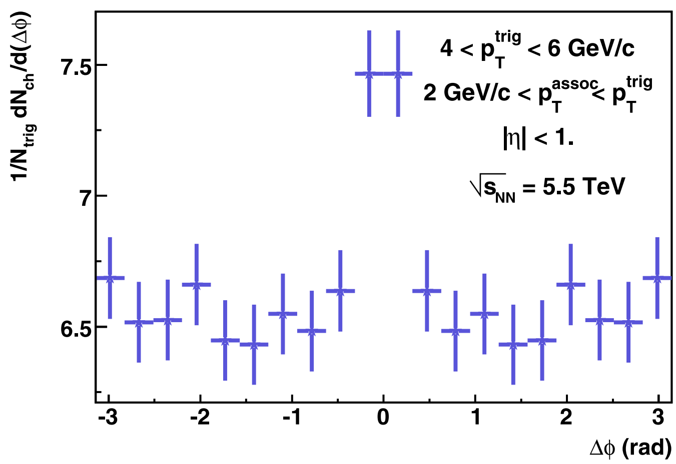

Fig. 7. Two-particle correlation at the LHC energy predicted from the HIJING generator when parton quenching effects are considered (5% most central collisions). The p_T-cut values are reported

The recent results from RHIC [3] have shown that a higher p_T choice provides a signal that is background free. The background reduction with increasing p_T-cuts is expected to be stronger at LHC. To check this, an analysis at higher p_T was performed, and the results are shown in Fig. 8. Also in this case, the HIJING generator with parton quenching model has been used to simulate Pb + Pb collisions. As one can see, the background is reduced by a factor of 13 with respect to the previous case, and the jet-correlations dominate.

The behaviour of the near and away side correlation for $8 < p_T^{trig} < 15$ GeV/c, as a function of p_T^{assoc}, is shown in Fig. 9.

With this choice of cuts, the simulations at the LHC energy with the same quenching strength used for $\sqrt{s_{NN}} = 200$ GeV show a very evident signal, demonstrating that

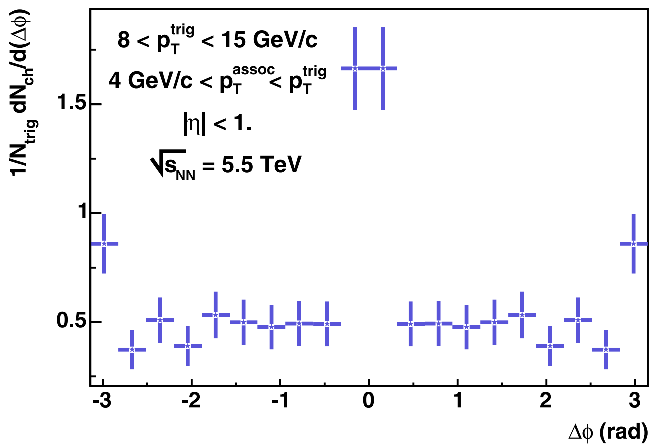

Fig. 8. Two-particle correlation at the LHC energy predicted from the HIJING generator when parton quenching effects are considered (5% most central collisions) for a different choice of p_{T}-cuts. The p_{T}-cut values are reported

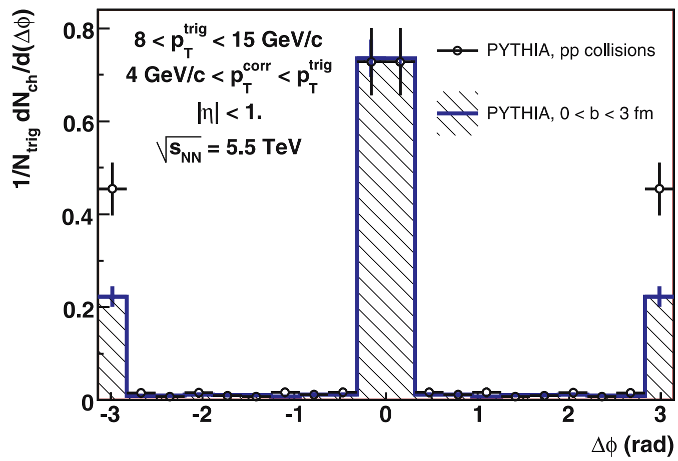

Fig. 10. A comparison between *pp* collisions at LHC energy performed using the PYTHIA generator with and without quenching effects (quenched events are for central collisions with $0 < b < 3$ fm)

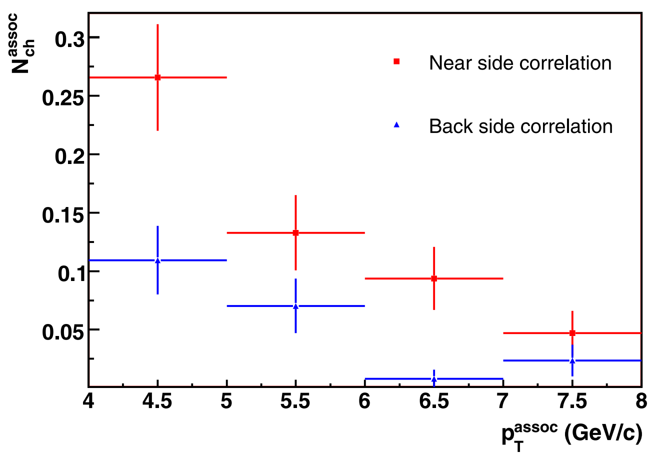

Fig. 9. The behaviour of the near side and away side correlation as a function of the p_{T} of the associated particles with $8 < p_{\mathrm{T}}^{\mathrm{trig}} < 15$ GeV$/c$

this kind of selection may be better suited for extending the study to the jet-medium interaction at high-p_{T}. This is also suggested by the comparison of *pp* collisions obtained with the PYTHIA generator with and without quenching, as shown in Fig. 10. Here it can be noted that the back-to-back correlation is meaningfully suppressed when quenching effects are taken into account.

The results presented for the last choice of p_{T}-cuts reveal that two-particle correlations at LHC will be particularly sensitive to quenching effects, provided that the model employed and the values used here for the quenching strength are still valid.

5 Conclusions

A parton quenching model was implemented in Monte Carlo generators. This approach described the two-particle correlations observed in the RHIC data in a satisfactory way. The same model was used to determine the sensitivity of this kind of analysis at the LHC. In particular, it was shown that an increase of the p_{T}-cuts is necessary to separate the signal from the background and that in this case, quenching effects, when occurring, could be identified through this analysis.

One characteristic feature of the model is the inclusion of gluon radiation in the jet quenching mechanism, to which the analysis has shown itself to be sensitive.

The Monte Carlo approach appears to be a very useful tool for probing and predicting the behaviour of jet observables. In order to have a more realistic description of nuclear collisions, in the future we plan to add the elliptic flow contribution into this study.

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