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Isolation of high $p_\perp$ direct photons and hadrons and correlation with jets in ALICE

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Direct photons will be produced at the LHC and the ALICE experiment will measure and identify them with the help of its calorimeters and tracking system. Their measurement will be challenging since there are different sources of direct photons, like prompt and fragmentation photons, and they are not the main photon source, which is neutral mesons decay. Here, I will discuss the capability of the EMCal calorimeter of detecting prompt photons with the help of the shower shape analysis and the isolation cuts. Also, I will present a study of the production of fragmentation photons and charged hadrons in PYTHIA and the effect on the isolation of such particles and their correlation with other hadrons and jets.

High-pT Physics at LHC - Tokaj'08
March 16 - 19 2008
Tokaj, Hungary

*Speaker.

PoS(HIGH-pTLHC)003

1. Introduction

The study of the properties of the Quark-Gluon Plasma (QGP) is the main objective of the ultrarelativistic heavy-ion collisions programmes at LHC and RHIC. The QGP is a high density colored medium, for this reason hard partons produced in the initial stages of the collision and traversing the plasma will suffer from energy loss as suggested by Bjorken [1]. The energy loss is due to gluon radiation of the parton, and this radiation will be produced almost collinear to the parton. What will be measured in the experiment is a hadron jet containing the fragmenting particles of the parton and of the radiated gluons. Thus, this jet will have different characteristics to those measured in $e^+ - e^-$ and proton-proton (pp) collisions, like a redistribution of the energy inside the jet, effect known as jet-quenching [2]. RHIC experiments have observed the effect in the form of a suppresion of high $p_\perp$ mesons in Au-Au collisions at $\sqrt{s} = 200$ GeV of a factor 5 with respect to pp collisions [3, 4, 5, 6]. Unfortunately, this measurement is not very sensitive to extract quantitative properties of the medium produced in nucleus-nucleus (NN) collisions, specially the transport coefficient, $\hat{q}$, which is the average transverse momentum squared transferred to the projectile [7, 8]. A more precise measurement of the energy redistribution inside the jet is measuring the jet $fragmentation function$, i.e., the jet charged hadrons distribution as a function of $z = p_{\perp hadron}/E_{jet}$. Comparing the fragmentation function in pp collisions and in nucleus-nucleus (NN) collisions, we will observe the jet redistribution and with it we can extract $\hat{q}$.

The measurement of the fragmentation function is difficult since we need to know accurately the energy of the jet, in fact in ultrarelativistic NN collisions, the large underlying event that enters in the jet cone makes impossible the measurement for jet energies smaller than 50 GeV [9]. One way to overcome this difficulty is measuring jets tagged with direct prompt photons, which are produced with an energy similar to the jet energy and back in azimuth and do not interact with the medium [10, 11]. The relevant processes for their production are the Leading Order (LO) $g + q \rightarrow \gamma + q$ (Compton) and $q + \bar{q} \rightarrow \gamma + g$ (annihilation). But their measurement is challenging, there are other sources of direct photons in the event like the Next to Leading Order photons (NLO), which are produced in comparable amounts, even larger for energies smaller than 50 GeV [10]. Besides, LO and NLO direct photons are not the main source of photons in the collisions, which are instead the photons from the decay of neutral mesons. A way to differenciate between LO photons and the other ones is using the isolation cut technique, LO photons are produced in the hard process without other companion particles, which is not the case for NLO and decay photons [12]. A recent study [13, 14] shows the feasibility of the measurement of direct prompt photons with the isolation cut and the tagging of the jet with such photons in the ALICE experiment [6, 7] with the PHOton Spectrometer PHOS as direct prompt photon detector. In ALICE, photons can be measured with PHOS, the ElectroMagnetic Calorimeter EMCal [15] and through conversions in the inner detectors.

The present communication consists of two different parts. First, I will discuss the feasibility of the measurement of prompt photons with the EMCal calorimeter with shower shape analysis and the isolation cuts, and after, I will present a study about the isolation of high $p_\perp$ particles (prompt photons, fragmentation photons and charged pions) and their correlation with jets.

2. Prompt photon identification with EMCal

The EMCal calorimeter is devoted to the jet and photon physics [15, 16]. EMCal is adequate for the high $p_\perp$ photon physics because of its geometrical acceptance, $\Delta\phi = 110$ degrees and $|\eta| < 0.7$, and of its energy resolution, $\sigma_E/E \sim 4-2\%$ for $p_\perp > 10$ GeV/c. The identification capability of prompt photons in pp collisions at $\sqrt{s} = 14$ TeV and Pb-Pb central collisions at $\sqrt{s} = 5.5A$ TeV with the EMCal calorimeter is presented in this section. Prompt photons can be identified combining the two techniques explained in the next subsections: shower shape analysis and isolation cut.

PYTHIA 6.203 event generator [17] was used in this study to generate pp collisions at $\sqrt{s} =$ 14 TeV. Photon tagged jet (γ-jet) events (MSEL=10) which contain prompt photons in the acceptance of EMCal were generated and also di-jet (jet-jet) events (MSEL=1) that contain the main sources of contamination for prompt photons: decay and fragmentation photons. Jet-jet events were selected so that one of the jets had always at least one π^0 with $p_\perp > 5$ GeV/c in the EMCal acceptance, in this way we increase the number of events with some signal in EMCal. I generated events for different hard parton $p_\perp$ bins, 10 bins from from 5 to 100 GeV/c for γ-jet events and 16 bins from 12 to 258 GeV/c for jet-jet events, around 10^4 events in each bin. Pb-Pb central ($b = 0-3$ fm) collisions at $\sqrt{s} = 5.5A$ TeV were generated taking PYTHIA hard processes γ-jet and jet-jet, with the same hard parton $p_\perp$ bins and number of events, and mixing them with a NN underlying event generated with HIJING generator [18]. PYTHIA jets were quenched in the Pb-Pb collisions with a coefficient transport $\hat{q}$ = 50, using the quenching weights model [19]. A full simulation, including particle transport through the ALICE detectors and materials, was done with GEANT3 [20] in both types of collisions.

Figure 1 shows the reconstructed spectrum of prompt photons from γ-jet events and other detected particles coming from jet-jet events (decay photons, hadrons) after one year of data taking[1]. We can observe that if we are able to reject the large amount of jet particles, we can measure the prompt photons with the calorimeter at least up to 100 GeV with good statistics, in pp and Pb-Pb collisions.

2.1 Photon identification with shower shape analysis

The calorimeter consists of a grid of cells. A particle interacting with the calorimeter material will produce a shower that will illuminate different cells. The cluster of cells fired by the particle has different shape, typically ellipsoidal, for different particle types. One of the most discriminating shower parameters is the length of the principal axis of the elipse. Details on how is calculated and which is the best parameter for EMCal can be found in Ref. [15]. Figure 2 shows the ratio of the predicted yields of prompt photons to jet clusters (any cluster from the jet, being decay or fragmentation photons or hadrons) with and without shower shape analysis, both for pp collisions and quenched Pb-Pb collisions. The use of the shower shape reduces the contribution from jet clusters but the ratio is always smaller or close to one. We need another selection criteria in order to remove the remaining jet clusters, which are mainly decay and fragmentation photons.

[1]For pp collisions, luminosity $L = 10^{30}$ cm^2 s^{-1} and running time $T = 10^7$ s, for Pb-Pb collisions $L =$ 0.5 10^{27} cm^2 s^{-1} and $T = 10^6$ s.

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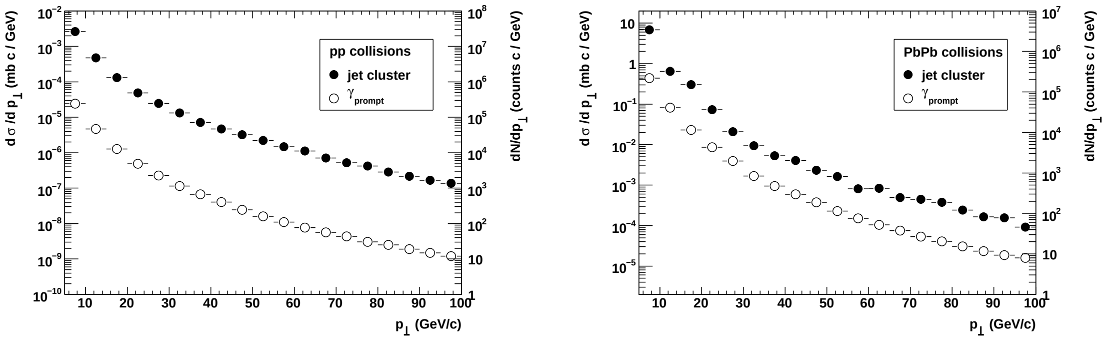

Figure 1: Spectra of particles found in the EMCal calorimeter coming from γ-jet events (prompt photons, ○) and jet particles spectra coming from jet-jet events (decay photons, fragmentation photons and hadrons, •). Raw reconstructed spectra in the calorimeter, no identification used. Left axis is the production cross section and right axis is the expected number of counts after a standard LHC year of data taking. Left frame represents pp collisions at $\sqrt{s} = 14$ TeV and right frame Pb-Pb quenched central collisions at $\sqrt{s} = 5.5A$ TeV.

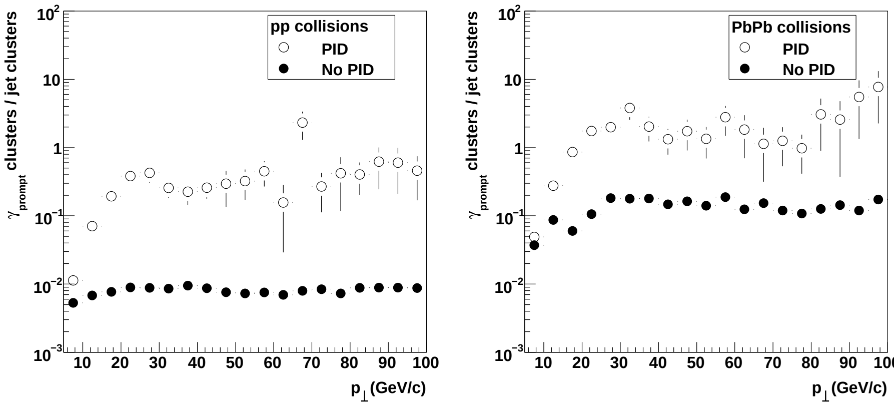

Figure 2: Ratio of photon clusters spectra coming from γ-jet events and jet clusters spectra coming from jet-jet events in EMCal acceptance, without (•) and with (○) photon identification with shower shape analysis. Left frame represents pp collisions at $\sqrt{s} = 14$ TeV and right frame Pb-Pb quenched central collisions at $\sqrt{s} = 5.5A$ TeV.

2.2 Prompt photon identification with isolation cut

Prompt photons are produced isolated since they are back to the hard parton to which they are associated. Looking in a cone around the direct prompt photon we should find small hadronic activity, only due to the underlying event of the collision. As discussed in detail in Ref. [13], we can find a prompt photon measured in the calorimeter just looking if there is no particle above a given $p_\perp{}^{threshold}$ in a cone of size $R = \sqrt{(\phi_0 - \phi)^2 + (\eta_0 - \eta)^2}$. For this measurement we need to get the information of the charged tracks measured in the ALICE central tracking system that may fall in the cone and other clusters in the calorimeter. I found that in pp collisions for EMCal, the appropriate parameters are $p_\perp{}^{threshold} = 0.5 - 1$ GeV/c and $R = 0.4 - 0.5$, and in Pb-Pb collisions $p_\perp{}^{threshold} = 2$ GeV/c and $R = 0.4 - 0.5$. Figure 3 shows the ratio direct prompt photon to jet clusters (any cluster from the jet, being decay or fragmentation photons or hadrons), with $p_\perp{}^{threshold} = 0.5$ GeV/c and two cone sizes $R = 0.2$ and $R = 0.5$, for pp collisions and quenched Pb-Pb collisions. The isolation cut increases the ratio to values much larger than 1 for $p_\perp$ of the candidates larger than $15 - 20$ GeV/c, thus, the identification of direct prompt photons is feasible only above this $p_\perp$.

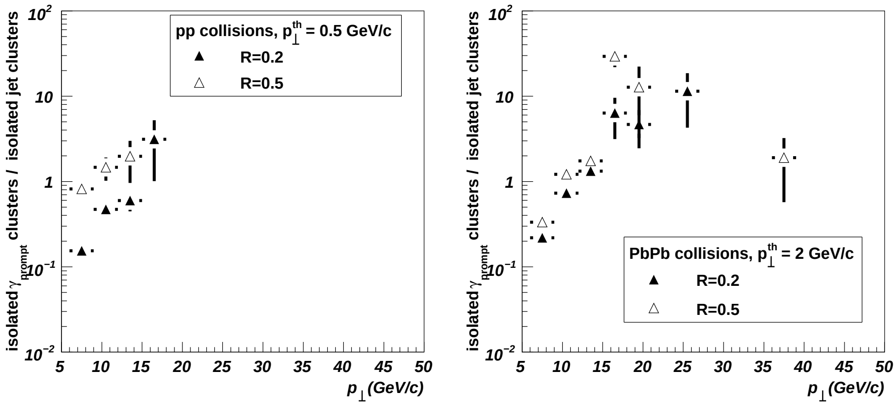

Figure 3: Ratio of isolated photon clusters spectra coming from γ-jet events and isolated jet clusters spectra coming from jet-jet events in EMCal acceptance, with $R = 0.2$ (▲) and with $R = 0.5$ (△). Left frame stands for pp collisions at 14 TeV with $p_\perp{}^{threshold} = 0.5$ GeV/c and right frame for Pb-Pb quenched collisions with $p_\perp{}^{threshold} = 2$ GeV/c.

PYTHIA jets contain fragmentation photons (the parton fragments into a photon and other particles that form the jet, also called final state radiation (FSR) particles) that are background to the measurement of prompt photons. Unfortunately, the probability to produce such photons in jet-jet events is very low and the amount of them in the previous simulation is small. In order to see what is the effect of the isolation cut on such particles I made the study presented in the next section.

3. High $p_\perp$ particle isolation and correlation with jets

As explained before, a much larger sample of events was necessary to study the production of fragmentation photons in PYTHIA. An event production only at the generator level was done since a full detector simulation and reconstruction took an unaffordable computing time with the required amount of events. I generated $2\ 10^7$ events in the same $p_\perp$ bins as in the previous study, but this time no special selection on the jet was used. The only cut was that all particles in the event should be in the region $|\eta| < 1$. Only pp collisions at $\sqrt{s} = 14$ TeV were considered. In this study I concentrated on the isolation in ideal conditions (no detectors acceptance and response) of prompt photons, fragmentation photons and charged pions (denoted in the figures as γ_{prompt}, γ_{FSR} and π_{FSR}, respectively) and their correlation with hadrons and jets.

3.1 High $p_\perp$ particle isolation

High $p_\perp$ particles were isolated with the technique explained in Sect. 2.2, with the isolation parameters $R = 0.4$ and $p_\perp^{threshold} = 1$ GeV/c. In Fig.4-left, the fraction of direct prompt photons, fragmentation photons and charged pions that pass the isolation cut is shown as a funtion of $p_\perp$. It can be observed that the isolation fraction, ratio between the isolated particle spectrum and the initial particle spectrum before isolation, is of the order of 90% for prompt photons, 50-60% for fragmentation photons and from 10% to less than 1% for charged pions in the $p_\perp$ range under study. The result for fragmentation photons was not expected, since fragmentation photons belong to a jet like pions, the isolation fraction of both should be small. A way to understand this result is looking to the isolation fraction as a function of the ratio between the fragmentation photon or charged pion transverse momentum and the transverse momentum of the jet to which they belong, as shown in Fig. 4-right. The jet momentum was reconstructed with the jet finder provided by PYTHIA. We can observe that the isolation rejects jet particles that have small part of their jet energy. The higher the particle-jet $p_\perp$ ratio the more dificult is their rejection with isolation cuts because the jet will contain less high energy particles which are the key to isolate them. This means that PYTHIA produces mainly fragmentation photons which carry most of the jet energy. We can also observe that the higher the $p_\perp$ of the jet particles, the more isolated they are. This result leads to the following question: if any isolated high $p_\perp$ jet particle contains most of the jet energy to which it belongs, this can be considered as a jet composed of a single particle, so is the correlation of these isolated particles with the jets in opposite direction the same as the correlation between prompt photons and their corresponding opposite direction jets?

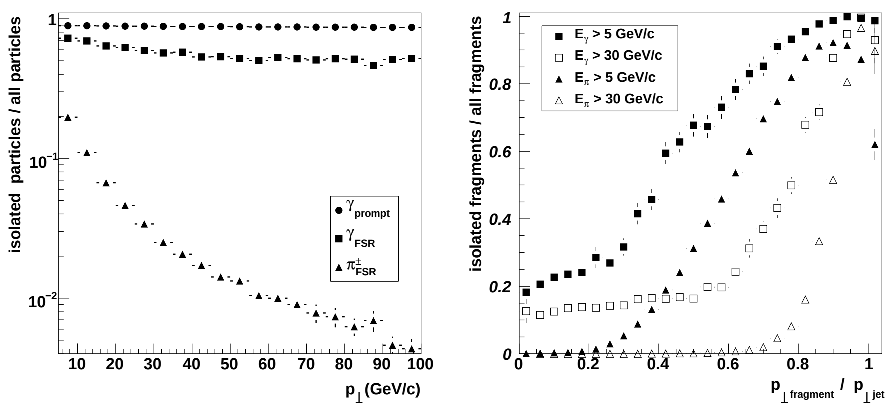

Figure 4: Fraction of particles that pass the isolation cut in pure PYTHIA events, pp collisions at $\sqrt{s} =$ 14 TeV, with isolation parameters $R = 0.4$ and $p_\perp^{threshold} = 1$ GeV/c. Right frame, isolation fraction as a function of the particles $p_\perp$ for direct prompt photons (●), fragmentation photons (□) and charged pions (▲). Left frame, isolation fraction as a function of the $p_\perp$ ratio of the particles and the jet to which they belong for fragmentation photons with $p_\perp$>5 GeV/c (■) or $p_\perp$>30 GeV/c (□) and charged pions with $p_\perp$>5 GeV/c (▲) or $p_\perp$>30 GeV/c (△).

3.2 Correlation of isolated high $p_\perp$ particles and jets

Prompt photons are associated with jets which are opposite in azimuth and which have a similar energy. If we look to the correlation between the prompt photons and all the charged hadrons of the event in the azimuthal plane we should observe that around the photon there are no particles and that at 180 degrees there are, as seen in Fig. 5-left. For high $p_\perp$ photons and pions from jet fragmentation, there should be other jet particles near them and in the opposite direction, as observed. Figure 5-right shows the effect of the isolation cut on the correlation, the isolated particles have no other hadrons in their vicinity but still they have an strong correlation in the opposite side.

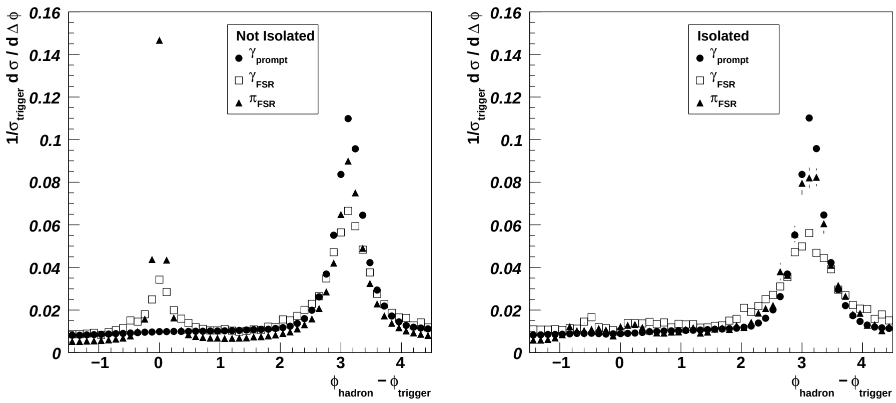

Figure 5: Correlation function: distribution of charged hadrons in the event with $p_\perp > 2$ GeV/c as a function of $\Delta\phi$ calculated as the difference between the azimuthal angle of the hadron and of the trigger particle and normalized to the total number of trigger particles in pp collisions at $\sqrt{s} = 14$ TeV. Trigger particles are direct prompt photons (●), fragmentation photons (□) and charged pions (▲), all with $p_\perp > 20$ GeV/c. Left frame shows the correlation function for all trigger particles and right frame for isolated trigger particles with isolation parameters $R = 0.4$ and $p_\perp{}^{threshold} = 1$ GeV/c.

The next step is to check if the fragmentation function constructed correlating the different isolated particles species is similar. For that, we reconstructed the jet in the opposite side with the PYTHIA jet finder and constructed the fragmentation function with all the charged hadrons around the jet axis in a cone of size $R = 1$. Figure 6 shows the fragmentation function as a function of z, where z is the ratio between the transverse momentum of the jet hadron and of the high $p_\perp$ trigger particle (prompt photon, fragmentation photon, charged pion). The right figure was done for all prompt photons, fragmentation photons and charged pions produced by PYTHIA and on the left frame when they are isolated. We can see that after isolation the fragmentation function calculated with fragmentation photons and charged hadrons tends to agree with the one of prompt photons although the match is not perfect due to the fact that their energy is still exactly not equal to the jet to which they belong. We selected events where the opposite jet fragments from a quark jet, for gluon jets the same behaviour is observed.

4. Conclusions

I studied the capability of the ALICE-EMCal calorimeter at LHC to measure direct prompt photons. The combination of shower shape analysis and isolation cuts shows that we will able

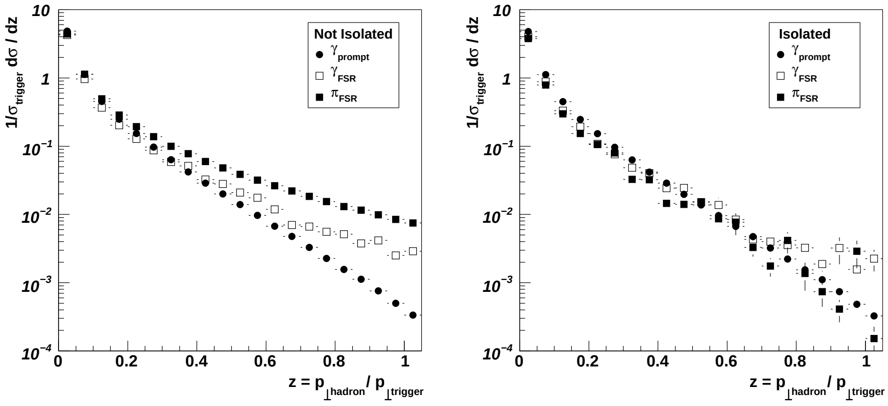

Figure 6: Fragmentation function: distribution of charged hadrons in the jet as a function of the ratio of the transverse momentum of the hadron and the transverse momentum of the trigger particle with $p_\perp > 20$ GeV/c and normalized to the total number of trigger particles in pp collisions at $\sqrt{s} = 14$ TeV. Trigger particles and jets are in opposite azimuth directions. Trigger particles are direct prompt photons (●), fragmentation photons (□) and charged pions (▲). No cut on the $p_\perp$ of the jet hadron. Left frame shows the fragmentation function for all trigger particles and right frame for isolated trigger particles with isolation parameters $R = 0.4$ and $p_\perp{}^{threshold} = 1$ GeV/c. Here we selected only events where jets come from quarks.

to measure the prompt photon spectrum with low contamination level for energies of the prompt photon larger than 15-20 GeV, with good statistics up to 100 GeV in a standard year of data taking, in both pp and Pb-Pb collisions at LHC.
PYTHIA predicts the production of fragmentation photons, a priori background for prompt photon studies. My analysis finds that fragmentation photons are basically isolated like the prompt photons, but they are isolated because when they are produced by PYTHIA, they have most of the jet energy. If this prediction is correct, we could assume such isolated fragmentation photons similar to prompt photons. Moreover, if we isolate charged hadrons like pions, we will select pions which will be a jet themselves. In fact, the correlation of isolated fragmentation photons and charged pions with their opposite jets showed the same behaviour as the correlation for prompt photons. This result leads to think that we have another way to calibrate jets or calculate the jet fragmentation function without having to reconstruct the jet with standard jet algorithms, what right now would be only possible with γ-jet events. More detailed studies are needed with full detector reconstruction or other generators. In Pb-Pb collisions, this exercise might be more difficult or even not possible to do because the parton will be quenched and then the amount of isolated hadrons will be suppressed. Besides, only isolated hadrons from partons produced in the border of the QGP will escape and the associated jet might be too quenched, but this should be investigated also with realistic quenching models.

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