Study of $\gamma$+Jet channel in heavy ion collisions with CMS

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Abstract

We investigate the possibility to measure the energy losses of quark-initiated jet in dense QCD-matter using $\gamma$+jet channel in Pb-Pb collisions with CMS detector. The non-symmetric distribution of differences in transverse energy between the $\gamma$ and jet is shown to be sensitive to the jet quenching effect.

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1 Introduction

One of the most actual goals in high energy physics is reaching the state of deconfinement of hadronic matter and studying the properties of resultant quark-gluon plasma (QGP) [1]. Jet production, as well as other hard processes, is considered to be an efficient probe for formation of QGP in future experiments on heavy ion collisions at LHC [2, 3]. High-p_T parton pair (dijet) from a single hard scattering is produced at the initial stage of the collision process (typically, at ≤ 0.01 fm/c). It then propagates through the QGP formed due to mini-jet production at larger time scales (~ 0.1 fm/c), and interacts strongly with the comoving constituents in the medium.

The actual problem is to study the energy losses of a hard partonic jet evolving through the dense matter. We know two possible mechanisms of energy losses: (1) radiative losses due to gluon “bremsstrahlung” induced by multiple scattering [4, 5, 6, 7] and (2) collisional losses due to the final state interactions (elastic rescatterings) of high-p_T partons off the medium constituents [8, 9, 10]. Since the jet rescattering intensity strongly increases with temperature, formation of a super-dense and hot partonic matter in heavy ion collisions with initial temperature up to T_0 ~ 1 GeV at LHC energies [11] should result in significantly larger jet energy losses as compared with the case of hadronic gas at T_h ≤ 0.2 GeV or ”cold” nuclear matter, the other parameters of the medium being kept the same.

In a search for experimental evidences in favour of the medium-induced energy losses a dijet quenching (a suppression of high-p_T jet pairs) [12] and a monojet/dijet ratio enhancement [13] were proposed as possible signals of dense matter formation in ultrarelativistic nuclei collisions. It has been shown recently, that the significant dijet quenching and monojet/dijet ratio enhancement can be observed in the heavy ion collisions under CMS-detector conditions [14]. Dijet production was shown more sensitive to the multiple scattering of jet partons in dense matter and much less sensitive to the finite resolution and background effects as compared to monojet yield, i.e. it represents a really important process carrying information about the properties of super dense matter, created in ultrarelativistic heavy ion collisions. The monojet/dijet production rate ratio studies can also provide us the additional information about jet energy losses.

The another options is to perform a direct jet energy losses measurement in processes where a hard parton jet is tagged by “unquenched” (i.e. strongly-noninteracting) particle as Z-boson [15] (q + g → q + Z → q + μ^+ + μ^−, q + b → g + Z → g + μ^+ + μ^−) or γ-photon [16] (q + g → q + γ, q + b → g + γ). The advantage of this processes is that one can determine the initial transverse energy of the hard jet, E_T^0 ≈ E_T^0, from momentum conservation. In particular, it gives the possibility to research the dependences jet energy losses dE/dx on the initial jet energy or distance traversed can be studied experimentally by varying the energy of the tagged γ-photon (Z-bosons) in the collisions of different nuclei.

Since the dominant channel for high-p_T γ + jet production is g + g → q + γ, the bulk of detected jets going to be quark-induced in this case (as well as for Z + jet production with the dominant channel q + g → q + Z).

Thus, contrary to the gluon-dominated dijet production where one could investigate jet quenching due to mostly gluon energy losses in dense matter, γ + jet and Z + jet processes give a possibility to study quark energy losses. However it is important to notice that due to the initial state gluon radiation and finite energy resolution of calorimeters, the transverse momenta of γ (Z) and jet are exactly equal and opposite only in average (without jet energy losses), but not for each given event. The relatively broad symmetric distribution of differences in transverse momentum between the γ-photon (Z-boson) and jet emerges already at the parton level, but the average value is zero in the case without jet energy losses (see Figure 1). The non-symmetric shape of the distribution appears if a jet loses energy; the average value of the distribution is equal to the average energy losses of the quark-initiated jet, \( \langle P_T^Z - P_T^{jet} \rangle = \Delta E_T^{jet} \). One has to remember that we are not measuring energy losses of a leading quark by such way, but getting total losses of quark-initiated jet outside the given jet cone.

2 Signal and background cross-sections in Pb-Pb collisions

The background for γ-jet channel is hard dijet production when one of the jet in an event is misidentified as a photon. The leading n^0 in the jet is a main source of the misidentification. Cross-section for jet-jet and γ-jet production in Pb-Pb collisions were obtained from those in pp interaction given by PYTHIA5.7 [17] at \( \sqrt{S} = 5.5 \) TeV using the parameterization

\[ \sigma_{AA} = A^2 \sigma_{pp}, \quad \alpha = 1 \]  

(1)

Cross-sections for the signal and background are plotted in Figure 2 as a function of the low limit on transverse
momentum $p_T$ defined in the rest frame of the hard interaction (CKIN(3) in PYTHIA). Pseudorapidity is taken as $|\eta| < 2.6$.

In the previous studies it was concluded that jets in Pb-Pb collisions can be effectively reconstructed with transverse energy above 100 - 120 GeV GeV [14, 18]. Figure 3 shows the spectra of transverse energy of the photon from the signal and the leading pion from the jet-jet events for events generated with $p_T > 100$ GeV and $|\eta| < 2.6$. Histograms are normalized on the expected number of events produced in Pb-Pb collisions for two weeks running at $L = 10^{32} cm^{-2} sec^{-1}$ and assuming one experiment: 7800 signal events and 1.1 $\times$ 10$^7$ background events. One can see that for events with $E_T > 100$ GeV the background is still dominant.

One of the variable has to be seen for indication of jet energy losses in the dense QCD-matter created in heavy ion collisions is the difference between transverse energy of the photon and recoiling jet in the event

$$\Delta E_{\gamma-Jet} = E_T^\gamma - E_T^{Jet}.$$  \hspace{1cm} (2)

At the level of partons and without jet quenching the distribution of this variable $\Delta E_{\gamma/p_{\text{parton}}}$ is shown in Figure 4 for the signal and background and for $E_T^{\text{parton}} > 120$ GeV and $|\eta^{\text{parton}}| < 1.5$ ($p$ means recoiling parton; $\pi^0$ - leading pion). Histograms are normalized on the expected number of events: 1854 signal and 5927 background events. We consider only barrel part of the calorimetry $|\eta^{\text{parton}}| < 1.5$ since results on the jet identification and measurement used in this paper were obtained for this part (see chapter 4).

One can see on Figure 4 that the signal is clearly seen at the level of the background. However the identification of the influence of the dense matter formation on signal shape requires the reduction of the background. The detector response has also be taken into account.

In the next chapters we discuss the detector aspects such as a jet and photon identification and measurement in the Pb-Pb collisions and criteria of the background suppression.

### 3 Photon triggering, identification and measurement

The results presented in this chapter were obtain with full GEANT simulation of the CMS calorimetry using cms114 package [19]. The case of Pb-Pb collisions with $dN_{ch}/dY=8000$ is considered.

CMS electron/photon Trigger Algorithm ([20] and Figure 5) is suitable for the triggering of a high energetic photons produced in the Heavy Ion Collisions. Programmable thresholds on a cluster variables used in the Algorithm have to be tuned to make it efficient even for the case of 100% occupancy of the trigger cells expected in the central Pb-Pb collisions. We have estimated the thresholds of the two Algorithm Vetoes: Hadronic Veto and Neighbour $E_T$ Veto (see Figure 5). Figure 6a-b shows the distribution of variables $\sum_0^3$ Neighbours $E_T$ (a) and $H/E$ (b) used in these Vetoes. One can see that thresholds optimized for the $pp$ collisions 1-2 GeV on $\sum_0^3$ Neighbours $E_T$ and 5% on $H/E$ have to be increased up to 22-25 GeV and 40-50% correspondently to keep a high efficiency of the Algorithm. Background rate of $e/\gamma$-Jet trigger is under study.

Apart of the trigger selections we have considered a possible photon identification based on the calorimeter isolation or zero suppression criteria. An energy of the photon may be measured in a cell of 5x5 crystals (size of the trigger cell) centered on the highest response [21]. Such cell contained about of 97% of the photon energy [23]. Identification may be based on the cut on transverse energy $E_T^{\text{iso}}$ deposited in a bigger area of 3x3 or 5x5 such cells not including the central one. Distribution of $E_T^{\text{iso}}(5 \times 5)$ and $E_T^{\text{iso}}(3 \times 3)$ are shown in Figure 7a-b. The distributions are shown for the energy deposited in the e.m. calorimeter only and in the total ECAL+HCAL system. One can see that only about 6% of transverse energy in the isolation area is measured by the hadron calorimeter that reflects the softness of the charged particles spectrum.

The zero suppression criteria is another method of the photon identification which we have applied for this study. It requires no energy above a given threshold deposited in the every cell of the area around the central cell containing the photon. Transverse energy distribution in the cell is shown in Figure 7c. According to this distribution the threshold $E_T=6.5$ GeV has been taken. With the such threshold the zero suppression criteria has been applied in the area 7x7 cells not including the central 3x3 trigger matrix, since trigger criteria still have to be optimized and applied separately. The $E_T$ of the hottest cell in the such area is shown for the signal and background on Figure 8. Zero suppression gives us rejection factor 2.66 against the background by the price of 14 % of the signal reduction.

Photon energy resolution is degraded due to large “pile up” noise contribution in the heavy ion collisions. In 5x5 crystal matrix we have about 1 GeV “pile up” noise as it is seen in Figure 7d. This means that for examples for
the photons of 120 GeV energy the resolution 0.64% measured in the test beam [21] will be degraded up to 0.80% due to “pile up” noise contribution. Nevertheless such photon resolution is much more better than the jet energy resolution (see next chapter).

4 Jet finding and Jet energy resolution

Utilization of hard jet characteristics to investigate QGP in heavy ion collisions may be difficult because of “false” jet background – fluctuations of the transverse energy flux arising from a huge multiplicity of “thermal” secondary particles in the event. Various estimations give from 3000 to 8000 charged particles per rapidity unit in a central \( Pb - Pb \) collision at LHC energies. In such events the cells of the calorimeter are typically filled completely, and the response of the calorimeter to the transverse energy flux of many “thermal” particles hitting the cell can imitate a signal from a single high-\( p_T \) particle. Under this condition the reconstruction of “true” QCD jets resulting from hard parton-parton scattering is a vital question for the CMS heavy ion physics programme [2].

A number of attempts were dedicated to jet finding algorithm optimization in heavy ion collisions under CMS conditions [18, 14].

We have simulated the pure “thermal” central \( Pb - Pb \) events at LHC energy using simple hydrodynamical model [14] with maximum particles density \( dN^+/dy(y = 0) = 8000 \) in mid-rapidity region; the average hadron transverse momentum being \( < p_T^H > = 0.5 \) GeV for pions and \( < p_T^K > = 0.7 \) GeV for kaons in this case (kaons are supposed to be thermally suppressed because of their heavier mass, \( K/\pi \approx 0.2 \)). The ”hard” central \( Pb - Pb \) event is generated as the superposition of ”thermal” event and hard PYTHIA pp-event.

In order to investigate here the hadronic jet resolution under CMS conditions, CMS calorimeter response was modeled using the CMSIM-008 version adopted for heavy ions collisions and shower parameterization for hadron calorimeter in the barrel part of calorimeters \(| \eta | < 1.5 \).

The modified window-type jet finding algorithm was applied to search ”jet-like” clusters above the average energy. On the first step all possible rectangular windows with given radius \( R = \sqrt{(\Delta \eta^2 + \Delta \phi^2)} \) (window size = \( 2R \)) in calorimeter map in \( \eta - \phi \) space are constructed and sorted over window energy, the average transverse energy in cell \( \bar{E}_c(\eta) \) and the dispersion \( D(\eta) = \sqrt{(\bar{E}_c^2(\eta) - \bar{E}_c(\eta)^2)} \) as function \( \eta \) being calculated. The window energy was calculated as sum over all \( n_c \) cells included into this window, \( E_{wc} = \sum (E_c - \bar{E}_c(\eta)) \). Then the loop on windows starts from the window with maximum transverse energy. The non-overlapping windows with the energy greater than value \( E_{min} = 3\sqrt{\sum D(\eta)^2} \) are considered as candidates for the jets and cells within radius \( R \) from the center of the window are collected. The values of \( \bar{E}_c(\eta) \) and \( D(\eta) \) are recalculated using cells which are not covered by jets. The jet energy is calculated as of energies of collected cells minus background: \( E_{jet} = \sum (E_c - \bar{E}_c) \)

The have found two criteria, which allow the further optimization of jet finding algorithms to be made using a different intrinsic structure of “false” and “true” hard QCD-jets.

1. The average radius of a jet can be introduced as:

\[
< R > = \sum_i R_{i0} \cdot |E_i - \bar{E}_i|/E_{jet}, \quad E_{jet} = \sum_i (E_i - \bar{E}_i),
\]

where \( R_{i0} \) is the distance between cell \( i \) covered by the jet and the center of the jet in the \( \eta - \phi \) space, \( E_i \) and \( E_{jet} \) are the transverse energy of the cell and the jet respectively, \( \bar{E}_i \) is the average transverse energy in the cell. The selection criterion \( < R > / R_{jet} \leq 0.5 \) allows most of the “false” jets to be removed.

2. The energy density in center region of a jet can be introduced as a ratio of the sum of transverse energy of cells covered by the jet within radius \( r = 0.7 R_{jet} \) to the total jet energy. The selection criterion \( E (r < 0.7 R_{jet}) / E_{jet} \geq 0.7 \) allows most of the “false” jets to be removed in this case.

In the present work jets with the energy density in center region \( r < 0.7 R_{jet} \) grater 0.7 and transverse energy grater 30 GeV (which being the average transverse energy of “false” jets in \( Pb - Pb \) collisions) has been only accepted. For such jets the average background transverse energy in cell \( E_r(\eta) \), dispersion \( D(\eta) \), energy and center of the jet have been finally determined.

Figure 9 shows the jet energy resolution at mid-rapidity \( \eta = 0 \) as a function of jet energy for \( p - p \) and \( Pb - Pb \) collisions with \( dN^+/dy(y = 0) = 8000 \) in mid-rapidity region. We used rather narrow jet radius \( R = 0.3 \), because the resolution of the \( \eta \) and \( \phi \) position of jets getting worse with jet radius increasing.
5 Results and conclusion

We have used the jet energy resolution at the mid-rapidity obtained for Pb−Pb collisions (Figure 9) to smear the energy of the recoiling parton (the slight improvement of the resolution with increasing $|\eta|$ [24] is not taken into account). Distribution of the variable $\Delta E_{\gamma-jet}$ (see chapter 2) shown in the Figure 10 for the signal and background takes into account such smearing as well as the jet rejection factor and signal efficiency obtained in chapter 3. No energy losses of parton-initiated jet are taken into account in this figure. We expect about 1600 signal and 2200 background events (using formula (1)) after two weeks running at $L = 10^{27} cm^{-2} sec^{-1}$ and assuming one experiment.

In order to test the possibility to measure the energy losses of quark-initiated jet in dense QCD-matter in Pb−Pb collisions with CMS detector, we consider three different scenarios for jet quenching due to collisional energy losses of jets [14]: (i) no jet quenching, (ii) jet quenching in a perfect quark-gluon plasma (the average collisional losses of a hard quark $<\Delta E_q>\simeq 4$ GeV, $<\Delta E_q> = 9/4 \cdot <\Delta E_q>$), (iii) jet quenching in a maximally viscous quark-gluon fluid, resulting in $<\Delta E_q>\simeq 8$ GeV.

In this model for different values of jet energy losses we have calculated the the distributions of differences in transverse energy between the $\gamma$ and jet with $E_{\gamma-jet}^{T} > 120$ GeV for two weeks LHC running (Figure 11a) – without ($\pi^0$ + jet) background counting; Figure 11b) – with ($\pi^0$ + jet) background counting) in the rapidity region $|\eta_{\gamma,jet}| < 1.5$ for different values of jet energy losses. Note that the shape of the background distribution very slightly sensitive to the jet energy losses, because the leading $\pi^0$ carries only part of whole hadronic jet energy, and only small fraction of jet energy losses influence on final energy of the isolated pion.

Mean values of the distributions without background (in Figure 11a) are:

$$<E_{\gamma-jet}^{T} - E_{jet}^{T}> \simeq 0.0 \pm 0.7, 2.9 \pm 0.7 and 6.6 \pm 0.7 \text{ GeV};$$

for the input values of average jet energy losses $<\Delta E_q> = 0, 4 \text{ and } 8 \text{ GeV}$ respectively. The jet energy resolution leads to difference between input values $<\Delta E_q>$ and ones obtained from the spectra. The background of $\pi^0$-contamination results in non-zero negative values of the final distributions (Figure 11b) already in the case without jet energy losses. In the real experiment however it would be possible to estimate the number of background events using the region without the signal $(E_{\gamma-jet}^{T} - E_{jet}^{T}) < -100 \text{ GeV}$ (see Figure 10) and background shape from Monte-Carlo simulation and (or) from pp data. Thus it may be possible to substract the background events from the experimental spectra.

One can see on Figure 11a-b that shape of the distribution is well distinguish for the scenarios considered. For the region $(E_{\gamma-jet}^{T} - E_{jet}^{T}) > 0$ there is a difference for almost every bin grater than $1 \sigma$ for the rather small jet energy losses 8 GeV and even for the losses 4 GeV. The predicted number of events in this region is 830 for the case (i), 920 for the case (ii) and 1200 for the case (iii). Thus all 3 scenarios are well distinguished from each other:

$$N_{(ii)} - N_{(i)} / \sqrt{N_{(ii)}} = 3, \quad N_{(iii)} - N_{(i)} / \sqrt{N_{(ii)}} = 10, \quad \text{and} \quad N_{(iii)} - N_{(ii)} / \sqrt{N_{(ii)}} = 8. \quad (4)$$

in the region $(E_{\gamma-jet}^{T} - E_{jet}^{T}) > 0$.

The previous data were obtained assuming two weeks running time at luminosity $L = 10^{27} cm^{-2} sec^{-1}$ for one Pb-Pb experiment. If we assume more realistic case of the two experiments running each at luminosity $L = 6 \times 10^{26} cm^{-2} sec^{-1}$ the scenarios considered can be still distinguished by the number of events expected in the region $(E_{\gamma-jet}^{T} - E_{jet}^{T}) > 0$ :

$$N_{(ii)} - N_{(i)} / \sqrt{N_{(ii)}} = 2.3, \quad N_{(iii)} - N_{(i)} / \sqrt{N_{(ii)}} = 8.3, \quad \text{and} \quad N_{(iii)} - N_{(ii)} / \sqrt{N_{(ii)}} = 6.3 \quad (5)$$

Figure 12a shows the distribution of $\Delta E_{\gamma-jet}$ for the scenarios (ii-i) and (ii) normalized on expected number of events for two weeks running at luminosity $L = 6 \times 10^{26} cm^{-2} sec^{-1}$.

We conclude that $\gamma$-jet channel will give us the possibility to determine the energy losses of quark-initiated jet in dense QCD-matter in Pb-Pb collisions with CMS detector.

6 Acknowledgments

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References

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Figure 1: The distribution of differences in transverse momentum between the $\gamma$-photon and jet with $P_T^{\gamma, jet} > 100$ GeV in the rapidity region $|y_{\gamma, jet}| < 1.5$ for different values of jet energy losses (initial state gluon radiation is taken into account with PYTHIA model)
Figure 2: Cross-sections for $\gamma$-Jet (circles) and Jet-Jet (squares) production in Pb-Pb collisions as a function of the low limit on transverse momentum $p_T$ defined in the rest frame of the hard interaction. $|\eta| < 2.6$. Calculated with formula (1) (see text).
Figure 3: Transverse energy of the photon from the $\gamma$-Jet events (shaded histogram) and the leading pion from the Jet-Jet events (solid line) for events generated with $p_T > 100$ GeV and $|\eta| < 2.6$. Histograms are normalized on the expected number of events produced in Pb-Pb collisions for two weeks running at $L = 10^7$ cm$^{-2}$sec$^{-1}$ and assuming one experiment: 7800 signal events and $1.1 \times 10^7$ background events.
Figure 4: Distribution of the variable $\Delta E_{\gamma/p}$ (see text) for the signal (shaded histogram) and background (solid line) for the pseudorapidity region $\mid \eta^{\text{parton}} \mid < 1.5$ and $E^{\text{parton}} > 120$ GeV. Histograms are normalized on the expected number of events produced in Pb-Pb collisions for two weeks running at $L = 10^{27} \text{cm}^{-2}\text{sec}^{-1}$ and assuming one experiment: 1854 signal events and 5927 background events.
**Shower Profile Cuts:**
Fine-grain feature
- Compare max $E_i$ $\eta$-strip pair out of 4 pairs versus total $E_i$ in trigger tower, e.g., require 80% energy in a pair.

**HAC Veto**
- Compare HCAL versus ECAL $E_i$ in Memory
- Lookup to veto non-EM deposits, e.g., $H/E < 5\%$ when $E$ is significant.

**Max $E_t$ of 4 Neighbors**
- Hit + Max $E_t >$ Threshold

**Hit**
- Candidate Energy:
  - Summary:
    - Regional
      - Pick highest energy candidate in 4x4 trigger tower region.
    - Global
      - Sort to find top-4 isolated and non-isolated candidates separately.
  - Isolation Cuts:
    - Neighbor HAC Veto
      - HAC Veto passes on all eight neighbors also.
    - Neighbor $E_i$ Veto
      - $\Sigma_{S}^{5}$ Neighbors $E_i$
      - At least one of four corners has $\Sigma_{S}^{5} E_i < 1.0 \text{ GeV}$

**Figure 5: The CMS electron/photon trigger algorithm**
Figure 6: Distribution of variables $\sum_N$ Neighbours $E_t$ (a) and $H/E$ (b) used in the Hadronic Veto and Neighbour $E_t$ Veto of the CMS $e\gamma$ algorithm.
Figure 7: Distribution of the measured transverse energy in the area of 5×5 (a) and 3×3 (b) trigger cells not including the central one; (c) - transverse energy measured in one trigger cell. Solid line in (a)-(c) - energy in the electromagnetic calorimeter; dashed line - energy in ECAL+HCAL system. (d) - fit of the distribution of the transverse energy measured in the e.m. part of the one trigger cell.
Figure 8: Transverse energy of the hottest cell in the isolation area where zero suppression is applied (see text)
Figure 9: squares - Jet resolution in pp mode with cone size 0.7 [24]; open circles - Jet resolution in pp mode with window algorithm optimized for HI collisions; full circles - Jet resolution in Pb-Pb collisions with window algorithm for the case of $dN^\pm/dy(y = 0) = 8000$ in mid-rapidity region
Figure 10: Distribution of the variable $\Delta E_{\gamma/jet}$ for the signal (shaded histogram), background (dashed line) and sum of them (solid line) for the pseudorapidity region $|\eta^{\text{parton}}| < 1.5$ and $E_{\gamma/jet} > 120$ GeV. Histograms are normalized on the expected number of events in Pb-Pb collisions for two weeks running at $L = 10^{27}$ cm$^{-2}$ sec$^{-1}$, assuming one experiment and taking into account efficiency of the event selections (see chapter 3): 1600 signal events and 2200 background events.
Figure 11: The distributions of differences in transverse energy between the $\gamma$ and jet with $E_{T}^{\gamma, \text{jet}} > 120$ GeV for two weeks LHC running at $L = 10^{27} \text{cm}^{-2}\text{s}^{-1}$ and assuming one experiment (a) without ($\pi^{0} + \text{jet}$) background counting; b) with ($\pi^{0} + \text{jet}$) background counting) in the rapidity region $|y_{\gamma, \text{jet}}| < 1.5$ for different values of jet energy losses (initial state gluon radiation and finite jet energy resolution are taken into account).
Figure 12: The distributions of differences in transverse energy between the $\gamma$ and jet with $E^{\gamma,\text{jet}}_T > 120$ GeV for two weeks of LHC running at $L = 6 \times 10^{26}$ cm$^{-2}$sec$^{-1}$: (a) without ($\pi^0$ + jet) background counting; (b) with ($\pi^0$ + jet) background counting) in the rapidity region $|y_{\gamma, \text{jet}}| < 1.5$ for different values of jet energy losses (initial state gluon radiation and finite jet energy resolution are taken into account).