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JETS IN HEAVY ION COLLISIONS AT THE LHC*

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We will discuss the new opportunities and experimental challenges of jet physics in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV at the LHC.

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1. Introduction

Hard strongly interacting partons produced at the initial stage of heavy ion collisions have been proposed as a tool to study the properties of the QGP [1, 2]. The partons are expected to undergo multiple interactions inside the collision region prior to hadronisation. Hereby, their energy is reduced through collisional energy loss [3] and medium-induced gluon radiation [2], the latter being the dominant mechanism in a QGP. The BDMPS [4] model describes the parton interaction with the medium as a coherent sum over scatterings with free path length λ and mean transverse momentum transfer μ. The medium is then characterized by the transport coefficient $\hat{q} = \mu^2/\lambda$. The energy loss of the parton is proportional to $\langle\hat{q}\rangle L^2 f(E, m_p)$, where L is the in-medium path length, $\langle\hat{q}\rangle$ the average transport coefficient and m_p the parton mass. The function $f(E)$ varies only slowly with the parton energy E. For cold nuclear matter $\hat{q}_{\mathrm{cold}} \approx 0.05\,\mathrm{GeV}^2/\mathrm{fm}$, whereas for a QGP it is expected to be much higher than $1\,\mathrm{GeV}^2/\mathrm{fm}$. With a $\hat{q}_{\mathrm{QGP}}/\hat{q}_{\mathrm{cold}} > 100$ we expect large effects in ultrarelativistic heavy ion collisions. However a large range of energy is needed to map out these effects as a function of E.

The in-medium energy loss has several consequences for the jet structure. First of all the momentum of the leading particle decreases. This decrease is balanced by an increase of low momentum particles from the gluon radiation [5]. Some of these particles are radiated outside the jet cone

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$R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 1$. In this case a reduction of the jet energy can be observed. At the same time the transverse momentum relative to the jet axis $j_{\rm t}$ increases for high momentum particles (jet heating) [6]. The particles from gluon radiation can be found at low $j_{\rm t}$. The multiple scattering of the partons in the medium will change the dijet co-planarity. Since the energy loss is path length dependent and a statistical process the transverse energy imbalance of di-jets will be increased [7].

2. Jets at the LHC: New opportunities and challenges

From the experimental point of view we have also to consider the underlying event of heavy ion collisions. Whereas it can be almost neglected in *pp* it contributes ≈ 250 GeV (1.9 TeV) to the total energy inside a cone $R = 1$ at RHIC (LHC). Particles from the underlying event are soft and, hence, represent an important background for the measurement of hadrons from gluon radiation. At RHIC where accessible jet energies are limited to $E_{\rm t} \approx 20$ GeV standard jet reconstruction algorithms fail and leading particles are used as a probe. Striking effects have been observed at RHIC in central Au–Au collisions among the most prominent the suppression of high transverse momentum particles [8,9] and the suppression of back-to-back correlations [10]. They show that the jet structure is strongly modified in dense matter consistent with perturbative QCD calculations of partonic energy loss via induced gluon radiation. However, it has also been shown that mainly due to the so called surface bias these measurements alone do not strongly constrain the models of parton interactions with the medium and $\langle \hat{q} \rangle$ [11]. Another problem is the strong bias on the fragmentation. The selected leading particles come all from partons having a harder than average fragmentation; the momentum fraction z being three times higher than the unbiased average (trigger bias). The natural continuation of such studies in a regime where the background conditions allow it is the event-by-event identification and reconstruction of jets. Since almost all the original parton energy is collected this will reduce the surface bias and the bias on the parton fragmentation and, hence, increase the sensitivity to medium parameters. These conditions can be found at the LHC where jets up to $E_{\rm t} \approx 300$ GeV are accessible in heavy ion collisions. In one month of Pb–Pb running ($0.5\,{\rm nb}^{-1}$) we expect 10^6 (5×10^3) jets with $E_{\rm t} > 100$ GeV (> 300 GeV) in the 10% most central collisions and $|\eta| < 2$ [12]. About 10^4 jets are needed to perform a meaningful study of the fragmentation function. The range of measurable jet energies combined with the leading particle correlations that can be performed at lower energies is large enough to map out the energy dependence of in medium partonic energy loss.

As mentioned earlier, even at LHC the background conditions will be severe. One has to find means to reduce the background inside the jet cone in order to be able to identify the jet event-by-event and to reduce the background fluctuations in order to obtain a reasonable jet energy resolution. Using a cone jet finder this can be achieved by reducing the cone size. The background energy varies like R^2 and its rms is proportional to R. Studies using the HIJING [13] generator to simulate central Pb–Pb collisions ($dN_{\rm ch}/d\eta \approx 5000$) the optimal cone size is around $R = 0.4$. This reduces the background by a factor of 0.16 but preserves 88% of the jet energy. Additional cuts on the particle $p_{\rm t}$ or calorimeter cell energy can be applied to further reduce the background. The LHC experiments planning to take Pb–Pb data (ALICE, ATLAS, CMS) [14–16] have developed iterative cone algorithms modified to subtract the soft background event-by-event and for each iteration. Also modified $k_{\rm t}$-algorithms and a reconstruction based on deterministic annealing has been successfully applied. For jets with $E_{\rm t} > 100\,{\rm GeV}$ the angular resolution is typically $\delta\eta = \delta\eta = 0.03$ and energy resolution $\Delta E_{\rm t}/E_{\rm t} \approx 14\%$ (ATLAS, CMS). ALICE bases its jet reconstruction on information from charged particle tracking and neutral energy measured with an electromagnetic colorimeter (EMCal). The energy resolution is including signal fluctuation due to the reduced cone size is $\approx 20\%$. ALICE usually quotes 30% including out-of-cone fluctuations.

We discuss now the modification of the longitudinal fragmentation function $1/N_{\rm jet} dN/d\xi$ ($\xi = \ln(1/z)$). From medium induced gluon radiation we expect a depletion of the low-ξ region and an increase in multiplicity in the high ξ region. To quantify the effect of jet quenching one has to determine the nuclear modification factor by calculating the ratio between distributions obtained in central Pb–Pb collisions and pp, pA or peripheral Pb–Pb collisions ($R_{AA}(\xi)$). Fig. 1 shows the expected ratios measured by ALICE (central Pb–Pb over pp) in one year of LHC running for 5.5 TeV central Pb–Pb collisions (transport coefficient $\hat{q} = 50\,{\rm GeV}^2/{\rm fm}$) [17]. Error bars are

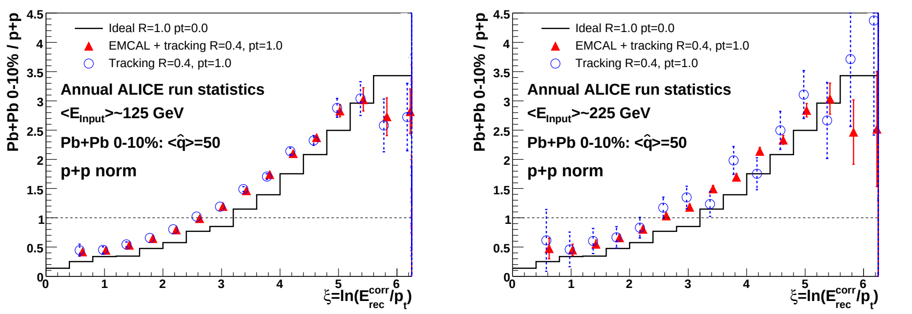

Fig. 1. Ratio of fragmentation functions for cent. Pb–Pb compared to 14 TeV pp.

due to statistical errors and the systematic uncertainty of the background subtraction. The EMCal jet triggering and reconstruction based on EMCal and tracking is compared to minimum bias triggering and jet reconstruction based solely on charged particle tracking. Results for jet samples with two different energies 125 and 225 GeV are shown. At both energies one observes a shift of the expected measured curve with respect to the ideal one toward smaller ξ values. It is caused by a systematic underestimation of the jet energy due to out-of-cone radiation. The average amount of out-of-cone radiation can be determined by measuring the transverse jet shapes. This will help to improve the ξ measurement. In the high-ξ region where $S/B \approx 0.01$ the systematic error from the background subtraction is important. The error bars shown correspond to $0.2\% B$, where B is the number of entries per bin from the background. Recent studies on the background subtraction have confirmed effects close to this magnitude [18]. Incomplete background subtraction can result from the migration of low energetic jets into the bin of reconstructed energy due to upward fluctuations of the background. These upward migrations are more likely than the corresponing downward migrations due to the steeply falling jet production spectrum.

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