Physics with the ALICE Electromagnetic Calorimeter

Rene Bellwied¹ for the ALICE Collaboration

¹ Physics Department, Wayne State University,
666 West Hancock, Detroit, MI 48201, USA
e-mail: bellwied@physics.wayne.edu

Abstract. I will present physics measurements which are achievable in the ALICE experiment at the LHC through the inclusion of a new electromagnetic calorimeter. I will focus on jet measurements in proton-proton and heavy ion collisions. Detailed simulations have been performed on jet reconstruction, jet triggering, heavy flavor jet reconstruction through electron identification, gamma-jet reconstruction and the measurements of identified hadrons and resonances in jets. I will show the physics capabilities which are made possible through the combination of calorimeter information with the other detector components in ALICE.

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1. Introduction

The addition of an electromagnetic calorimeter to the RHIC experiments (STAR and PHENIX) has proven to be invaluable for the analysis of neutral pions, photons, electrons, and jets in proton-proton and heavy ion collisions. Both experiments have recently embarked on full jet reconstruction in CuCu and AuAu collisions [1, 2, 3] by combining the charged track information from their main tracking detectors with the neutral energy information from the calorimeters. Past analyses of the interactions of a fast parton with the partonic medium were based on either single particle or two-particle correlation measurements which unavoidably carried a strong geometric bias. Models that had very different initial conditions and dynamic evolution patterns could describe the data, which led to large ambiguities on the deduced medium properties and the partonic energy loss mechanisms. Only full jet reconstruction in the heavy ion environment will enable us to fully understand and quantitatively describe the underlying mechanisms of the interactions between partons and the hot dense medium. In the following I will first show which physics
questions can be addressed using the ALICE calorimeter information. Then I will describe recent developments in modeling and analyzing the parton-medium interaction, which are used to simulate the anticipated physics performance of ALICE as shown in the concluding chapter. I will close with a brief outlook on the future of in-medium jet physics at the LHC.

2. Calorimeter driven physics goals

The inclusion of a high resolution energy measurement in ALICE enables us to determine jet energies in the range shown in Figure 1. Together with the excellent charged particle reconstruction efficiency in the ALICE tracking system (TPC plus Inner Tracking System (ITS)) the jet energy measurement accuracy exceeds 80%. This makes full jet reconstruction possible. Thus the calorimeter driven physics goals focus largely on jet related measurements.

Fig. 1. Estimate for triggered jet yields per year in the ALICE EMCal.

Besides the standard hadronic jets the EMCal also adds substantial capability to the reconstruction of high momentum electrons (from semi-leptonic decay of heavy flavor jets) and photons from photon jets. Both, electron and photon jets, are an excellent probe for quark jets, in an energy domain where the hadronic jets are predominantly formed by gluon fragmentation. I will discuss the background issues
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for electron and photon jets in chapter 4. Photon jets are considered 'the golden channel' of jet reconstruction simply because the photon is not likely to interact and thus carries the full jet energy. The actual jet measurements (energy loss, medium modification of the fragmentation) are then performed on the hadronic away-side jet and scaled to the jet energy information from the reconstructed same side photon. The main measurements that have been proposed in order to quantify the hot medium effect on the hadronization are the measurements of the jet yield, the jet suppression factor, the modified fragmentation function, the modified jet shapes, and the sub-jet distributions [4, 5, 6]. The inclusion of the excellent particle identification capabilities of ALICE even at very high momentum through the relativistic dE/dx measurements in the TPC allow us to measure the hadro-chemistry of the jets, which has also been proposed as a sensitive measure to distinguish different parton energy loss models [7]. In addition the high momentum hadrons might be sensitive to flavor conversion mechanisms in the hot, dense medium [8]. Finally, the modification of high momentum hadronic resonances in jets has been proposed as a possible signature for chiral symmetry restoration [9].

3. New tools for jet physics analysis

Recent developments in the modeling and reconstruction of jets in high multiplicity environments, in pp (pile-up) or heavy ion collisions, have enabled a much more targeted approach to the measurements proposed in the preceding paragraph. Recently both STAR and PHENIX at RHIC have presented early results of full jet reconstruction in heavy ion collisions based on these new methods [1, 2, 3].

3.1. Realistic modeling of parton energy loss in the medium

The first major advance is based on a series of new Monte Carlo event generators which try to quantitatively incorporate an in-medium quenching mechanism on the partonic level. The most advanced are qPYTHIA [10], JEWEL [11], and YaJem [12]. Broadly speaking these models apply an enhanced gluon splitting probability in the dense partonic medium, which leads to the anticipated changes in the fragmentation function, i.e. a quenching of the high z (fractional momentum) component and an increase in multiplicity of low z particles. The main effect, as suggested by Borghini and Wiedemann [13], is a modification of the so-called hump-back plateau in the vacuum fragmentation function measured e^+e^- collisions. All these models, which differ considerably in the actual implementation of the quenching effect, are now available from the authors.

3.2. Novel approaches to jet reconstruction

It was recently realized that the existing cone based jet algorithms, which require a high momentum particle as a seed, are by definition not infrared and collinear safe
and thus not suitable for quenching studies [14, 15]. In response, the group of Cacciari, Salam, and Soyez has put together the FastJet suite which combines different new algorithms that have been tested for IR and collinear safety [16, 17, 18]. In general, the codes can be divided into so-called cone algorithms (seedless cone, SIS) and recombination algorithms (kT, anti-kT, Cambridge/Aachen cluster). Recombination algorithms combine (cluster) particles in a "distant of closest" approach method and start either with the lowest momentum particles (kT) or the highest momentum particles (anti-kT). Thus the resulting shape is not necessarily symmetric in $\Delta \phi$ and $\Delta \eta$. The cone radius parameter has been replaced by a so-called resolution parameter which limits the extent of clustering based on kinematic variables. One of the key investigations at this point, which is shared by all three major LHC experiments, is the relative performance of these jet reconstruction algorithms for varying multiplicities in pp and heavy ion collisions.

3.3. Lessons from RHIC analyses

The RHIC analyses shown at QM09 have revealed a wealth of information in particular regarding the problems in background subtraction for jet analyses in heavy ion collisions. The main conclusion was that a data driven approach, i.e. using the detector response outside of the jet area in order to correct for the background level inside the cone, proved to be most successful. An additional complication is the occurrence of fake jets in the sample and alternate solutions to this problem have been proposed [1, 19, 20]. The jet reconstruction efficiency in heavy ion collisions is presently deteriorating for jet areas exceeding $R=0.4$ and jet energies below 20 GeV. Efforts are underway to further optimize the reconstruction.

4. Anticipated Physics Performance of the ALICE EMCal

4.1. Jet energies and fragmentation functions

Based on our RHIC studies and LHC simulations we expect more than 80% of the jet energy to be contained in a $R=0.4$ area for jet energies higher than 25 GeV. The EMCal provides a 15-20% resolution for these rather low energy jets. In order to conservatively assess our reconstruction capabilities in the heavy ion background, though, we presently limit our fragmentation and jet yield studies to jet energies of 100 GeV and higher, see Figure 2a. Through usage of the new jet reconstruction algorithms we hope to push this threshold down to 50 GeV in the future. Figure 2b shows the simulated ratio of the quenched fragmentation function in PbPb collisions to the unquenched function from pp. This is for a 175 GeV jet assuming a jet modification based on a transport coefficient of $q_{\text{hat}} = 50 \text{ GeV}^2/\text{fm}$, which was suggested in the ASW quenching framework [21]. More realistic simulations based on the new quenching generators are under way. As can be seen in the figure we expect to reliably determine the humpback plateau out to an inverse fractional momentum of about 4.4, which corresponds to a single track.
transverse momentum of about 1.5 GeV/c. Ongoing improvements on the hadron and electron corrections to the jet energy as well as subtracting the effects of elliptic and radial flow will further reduce the errors on the fractional momentum and thus push the measurement to higher $\xi$.

Fig. 2. a.) comparison of jet energy resolution in EMCal in pp and AA collisions, b.) ratio of quenched to unquenched fragmentation function for a 175 GeV jet in the ALICE EMCal reconstructed in pp and PbPb collisions, respectively. The ratio is shown as a function of the inverse fractional momentum. For the quenched simulation a $q_{hat} = 50$ GeV$^2$/fm was assumed.

4.2. Jet triggering

The trigger hierarchy in ALICE allows us to utilize information from the EMCal at two levels, Level-1 (L1) and the high level trigger (HLT). The L1 trigger is formed after 6.5 $\mu$s and is based on EMCal patch energy information. The resulting jet trigger efficiency and background rejection rate in Pb-Pb collisions are shown in Figure 3.

The HLT will combine information from the calorimeter, the tracking detector and the transition radiation detector in order to cut more specifically on photons, electrons and heavy flavor mesons at high momentum. It will also improve the jet triggering efficiency down to lower jet energies (as low as 50 GeV). Based on the L1 performance we already expect an improvement in the jet rate above 100 GeV of a factor 5 in central PbPb collisions, a factor 50 in peripheral PbPb collisions, and a factor 500 in pp collisions. Annually we will record around 200,000 jets above a jet energy of 100 GeV in minimum bias PbPb collisions. Due to the effective jet triggering the identified particle spectra will reach out to 25 GeV/c for $\pi$, K, p and out to 20 GeV/c for hadronic resonances ($K^*$, $\Delta$, $\phi$, $\Sigma^*$, $\Lambda^*$).
4.3. Photon and electron jets

The limited coverage in the EMCal allows us to reconstruct photon jets with reasonable statistics out to a photon energy of about 50 GeV. The main issue with isolating the golden channel for jet energy measurements is the suppression of background from $\pi^0$ decays and from fragmentation photons. Two methods have been applied successively in the present simulations, a shower shape condition and an isolation cut. The shower shape cut is based on the fact that a $\pi^0$ decay will cause an asymmetric photon shower in the calorimeter whereas the direct photon showers symmetrically. Details about this analysis can be found in [22]. Figure 4a shows the improvement in the $\gamma/\pi^0$ when the shower shape condition is applied. In the key region of the photon energy spectrum (20-30 GeV) the ratio reaches unity with the cut. This sample is then subjected to an isolation cut based on the energy in the surrounding calorimeter towers. Another factor 10 is gained (see Figure 4b) in central PbPb collisions where the pions are assumed to be quenched according to a scaling based on the measurements at RHIC [23].

A preliminary study shows that the fragmentation function in the away-side jet for isolated 30 GeV photon jets can be measured out to an inverse fractional momentum of about 3.2 as shown in Figure 5.
**Fig. 4.** a.) direct gamma to $\pi^0$ rate before (open) and after (solid) shower shape analysis, b.) using the output of the shower shape analysis before (open) and after (solid) additional isolation cut.

**Fig. 5.** Ratio of quenched to unquenched fragmentation function for a 30 GeV photon jet in the ALICE EMCal reconstructed in pp and PbPb collisions, respectively. The ratio is shown as a function of the inverse fractional momentum. For the quenched simulation a $q_{\text{hat}} = 50$ GeV$^2$/fm was assumed. The subtraction curve refers to the result in which the soft bulk matter background, as obtained in Pb-Pb events outside the jet cone, has been subtracted from the Pb-Pb fragmentation function.
Electron jets are used for heavy quark tagging for two specific reasons. First, the heavy quark jet is predominantly formed by a fragmenting quark rather than a gluon which is the dominant process in the untagged jet sample. Second the high momentum heavy quark supposedly undergoes a different jet energy loss mechanism than the light quarks or the gluons. Dead cone effects [24] as well as an enhanced probability for collisional energy loss [25] should affect the amount of energy a heavy quark loses in the partonic medium. This flavor sensitivity of the QCD degrees of freedom in the medium interaction is not represented in the recently applied AdS/CFT approach to energy loss [26]. In a strongly interacting conformal field theory the energy loss becomes independent of the degree of freedom and the collision energy. Thus a detailed measurement of the energy dependence of the energy loss for charm and bottom quarks should enable us to distinguish between pQCD and AdS/CFT [27]. The key issue in reliably identifying electrons in the calorimeter is an effective hadron discrimination. Figure 6 shows preliminary results for pion rejection for different electron efficiencies as a function of charged track momentum.

![EMCAL PID efficiency](image)

**Fig. 6.** Hadron (pion) rejection rate in the EMCal as a function of momentum for several electron reconstruction efficiencies.

### 4.4. Hadrons and resonances in jets

Recent interest in the hadro-chemistry of jets in the medium was triggered by several theoretical papers. The gluon splitting mechanism, which is the basis of the energy loss modeling in qPYTHIA and JEWEL, was predicted to also affect the hadro-chemistry of the quenched jet. Sapeta and Wiedemann postulated that the
splitting causes a hadron mass dependent shift in the particle abundance at high momentum \[7\]. The quenching will affect the production of higher mass particles less, i.e. ratios such as \(K/\pi\) or \(p/\pi\) will increase in the medium compared to fragmentation in vacuum. Figure 7 (upper row) shows a prediction by Sapeta and Wiedemann. The goal of our simulation was to show that the in-jet particle identification capabilities are such that this effect could be cleanly measured. Particle identification in ALICE at momenta higher than 6 GeV/c is presently solely possible through relativistic dE/dx measurements in the TPC. This method was successfully applied in STAR \[28\] and has been detailed in two technical publications \[29, 30\]. Early calibration runs indicate that the dE/dx resolution of the ALICE-TPC is slightly better than the STAR-TPC, and based on these cosmic ray results, we have performed a simulation on the expected PID resolution in the high momentum region. Figure 7 (lower row) shows the result, based on scaled PYTHIA yields, which can be compared directly to the predictions in Figure 7 (upper row).

Clearly ALICE will have the capability to distinguish between medium and vacuum jets based on particle ratios out to 25 GeV/c. This PID resolution will also enable us to measure potential flavor conversion effects \[8\] which were proposed as an explanation for the nuclear suppression factor differences for pion, Kaons and protons at high pT as seen in preliminary STAR data \[31\].
Finally we have embarked on a study of high momentum hadronic resonances in jets. Very little is known on resonances formation in jets, but a recent paper [9] claims that hadronic resonances in a particular high momentum window could actually form and decay inside the partonic medium. The argument is based on formation time calculations of pre-hadron (color neutral) states which have been successfully applied to explain hadron attenuation measurements in cold nuclear matter [32, 33]. If the resonances can indeed form and decay off-shell in the medium, then they would be a probe sensitive to chiral symmetry restoration. The proposed signal [9] will require to measure resonances in quadrants relative to a jet axis in order to distinguish between jet and bulk resonances. Figure 8 shows the available statistics for such a measurement. An early feasibility test was performed on STAR data for lower momentum resonances using the highest pT particle in the event rather than the reconstructed jet axis [34]. This analysis will benefit tremendously from the increased statistics and jet reconstruction capability in ALICE. In addition the reconstruction of resonance over non-resonant hadrons (e.g K*/K, Λ*/Λ) ratios has been used previously [35] in conjunction with HBT data to determine the partonic and hadronic lifetimes of the medium formed in heavy ion collisions.

![Graph showing hadronic resonance yields in PbPb collisions.](image)

**Fig. 8.** Estimate for yearly reconstructed hadronic resonance yields in jets triggered with the EMCal in PbPb collisions.
5. Outlook

The heavy ion program at the LHC benefits tremendously from the inclusion of an electromagnetic calorimeter in ALICE. By bringing extended jet reconstruction capabilities to the full suite of ALICE sub-systems, which have been optimized for relativistic heavy ion research, the experiment has extended its portfolio into a regime that proved to be very important in the ongoing RHIC experiments. STAR and PHENIX have been successful in the high pT regime by making first measurement of nuclear suppression factors, direct photons and semi-leptonic decays of heavy mesons, but they lack the statistics to unambiguously reconstruct jets at sufficiently high momentum to embark on a quantitative and systematic exploration of the energy loss and medium effects of partons in the hot dense matter. Although the ALICE EMCal lacks the coverage of the comparable calorimeters in CMS and ATLAS its pairing with the superior tracking and particle identification detectors in ALICE allows for a unique set of pp and heavy ion measurements. In particular the particle identified measurements in jets, as well as the correlation of identified photons and electrons with jets and jet particles down to very low fractional momentum are unique to ALICE. We expect to quantitatively solve the questions of quark and gluon energy loss as well as medium response to the jets. The uncertainties of the degrees of freedom above the critical temperature and chiral symmetry restoration will be addressed as well.

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References

1. M. Ploskon for the STAR collaboration, QM 2009 procs, J.Phys.G (to be published)
2. E. Bruna for the STAR collaboration, QM 2009 procs, J. Phys. G (to be published)
3. Y.S. Lai for the PHENIX collaboration, QM 2009 procs, J.Phys. G (to be published)
4. I. Vitev, S. Wicks, B-W.Zhang, arXiv:0810.2807
5. T. Renk, arXiv:0808.1803
6. K. Zapp et al., Eur.Phys.J. C60 (2008) 617
7. A. Sapeta and U. Wiedemann, Eur. Phys. J. C55 (2008) 293.
8. W. Liu and R.J. Fries, Phys.Rev. C77 (2008) 054902
9. C. Markert, R. Bellwied, I. Vitev, Phys.Lett. B669 (2008) 92
10. N. Armesto, L. Cunqueiro, C.A. Salgado, arXiv:0906.0754
11. K. Zapp, J. Stachel, U.A. Wiedemann, arXiv:0904.4885
12. T. Renk, arXiv:0906.3397
13. N. Borghini and U.A. Wiedemann, arXiv:hep-ph/0506218 and Nucl. Phys. A774 (2006) 549
14. S. Salur, arXiv:0809.1606 (24th WWND proceedings) and contribution to this workshop (arXiv:0905.1917)
15. J. Putschke, arXiv:0809.1419 (Hard Probes 2008 proceedings)
16. G. Soyez, arXiv:0812.2362
17. G. Soyez, contribution to this workshop (arXiv:0905.2851)
18. M. Cacciari and G. Salam, Phys. Lett. B659 (2008) 119
19. Y.-S. Lai and B. Cole, arXiv:0806.1499
20. N. Grau for the ATLAS collaboration, arXiv:0810.1219
21. N. Armesto, C.A. Salgado, U.A. Wiedemann, Phys. Rev. D69 (2004) 114003
22. G. B. Conesa for the ALICE collaboration, Nucl. Instr. and Meth. A580 (2007) 1446
23. S.S. Adler et al. (PHENIX coll.), Phys. Rev. Lett. 96 (2006) 032302
24. Y.L. Dokshitzer and D. Kharzeev, Phys. Lett. B519 (2001) 199
25. M. Djordjevic, Phys. Rev. C74 (2006) 064907
26. S. S. Gubser, Phys. Rev. D74 (2006) 126005
27. W. A. Horowitz and M. Gyulassy, J. Phys. G35 (2008) 104152
28. J. Adams et al. (STAR coll.), Phys. Rev. Lett. 97 (2006) 152301
29. M. Shao et al., Nucl. Instr. and Meth. A558 (2006) 419
30. Y. Xu et al., arXiv:0807.4303
31. A. Timmins for the STAR collaboration, QM09 procs., J. Phys. G (to be published)
32. A. Airapetian et al. (HERMES coll.), Nucl. Phys. B780 (2007) 1 (2007).
33. A. Accardi, Phys. Lett. B649 (2007) 384
34. C. Markert, arXiv:0706.0724 (23rd Winter Workshop proceedings)
35. B.I. Abelev et al., Phys. Rev. Lett. 97 (2006) 132301