

Soft Particle Production, Flow and Correlations in Heavy Ion Collisions at the LHC

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Abstract. In this paper we discuss recent results on soft particle production, correlations and flow in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

1 Introduction

The main goal of heavy ion collision studies at the LHC is the characterization of the Quark Gluon Plasma (QGP), the deconfined matter state created in such collisions.

Heavy ion collisions create a system which undergoes several phases during its evolution [1]. The Lorentz-contracted nuclei in the initial state collide, leading to the initial energy deposition. In our current understanding, after reaching an approximate local thermalization, the system expands under the effect of pressure gradients. This evolution can be described using (nearly) ideal hydrodynamics. As a consequence of the expansion the system cools down and undergoes a phase transition back to the hadron phase, providing a unique opportunity to study the hadronization process.

The “hydrodynamic flow” can be divided into radial (the azimuthally averaged expansion) and anisotropic flow (the φ -differential flow) [2]. The effect of radial flow is imprinted in the transverse momentum p_T distribution of particles, while the anisotropic case can be studied with a Fourier expansion of the $dN/d\varphi$ distributions [3]. The Fourier harmonic coefficients v_n of this expansion (also called flow coefficients) are one of the main observables discussed in this paper. The initial energy deposition from the incoming nuclei fluctuates event-by-event [1], generating a characteristic power spectrum for the v_n coefficients. This poses stringent constraints on the nuclear wave function. The understanding of initial conditions is a fundamental QCD problem, which is connected to saturation phenomena [4]. The final state v_n are determined both by the initial state anisotropy and the viscosity of the QGP. Viscosity dampens the v_n coefficients, affecting in a different way different order harmonics.

The initial hard scattering produces high p_T partons which lose energy while traversing the deconfined medium. Studying this energy-loss provides information about the properties of the QGP and is expected to lead to

a broadening or deformation of the jet peak in rapidity y or in azimuth φ [5].

The study of the QGP entered a new phase of precision measurements at the LHC. As it will be discussed in the following, measurements on production and correlations of soft particles provide a way to study the dynamical evolution of the system, to measure its transport properties and to understand the interplay between high- p_T partons and the medium. Most of the results discussed in this paper have been obtained in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, by the ALICE, ATLAS and CMS collaborations at the CERN LHC.

2 Initial Conditions

As mentioned in the introduction, the azimuthal anisotropy is dampened by shear viscosity: the deformations in the initial state are reduced by the dissipative effects, leading to smaller final state flow coefficients [2]. Higher order (short-distance) harmonics are easier to suppress than the lower order ones. Measurements of harmonics of different order can thus help to disentangle the role of initial conditions and viscosity in the development of anisotropic flow, to distinguish between different models of initial conditions and to constrain the value of the viscosity-over-entropy ratio η/s (one of the main transport properties of the QGP). Studies of harmonics up to the sixth order have been reported by the ALICE, ATLAS and CMS collaborations [8–10]. The results show that v_2 dominates in non-central collisions, consistent with an elliptical deformation of the interaction region. For central collisions v_2 , v_3 and v_4 are all of similar magnitude, indicating the importance of fluctuations in the initial state. Non-null values of v_n coefficients are measured up to relatively high $p_T \simeq 15$ GeV/ c . While the dominant effect is expected to be hydrodynamics at low p_T , at high p_T the likely origin of the finite v_n coefficients is the difference in path length as a function of φ seen by hard partons, which would lead to a different energy loss in different directions.

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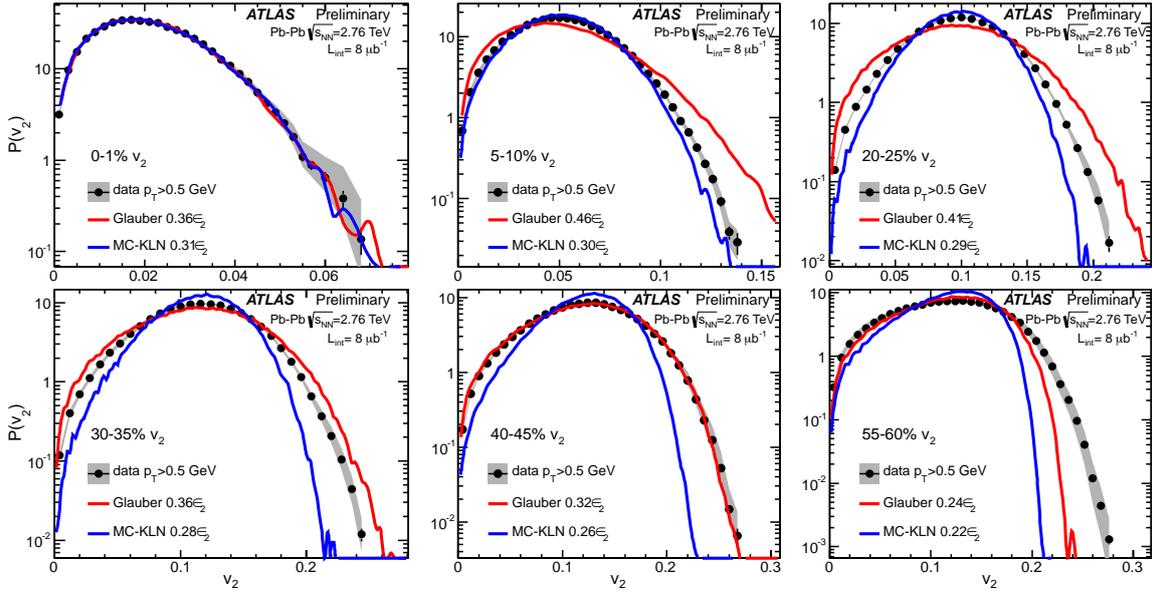


Figure 1. (color online) Event-by-event distributions of the v_2 coefficients for different centrality selections, compared to the Glauber and MC-KLN models of initial conditions [6].

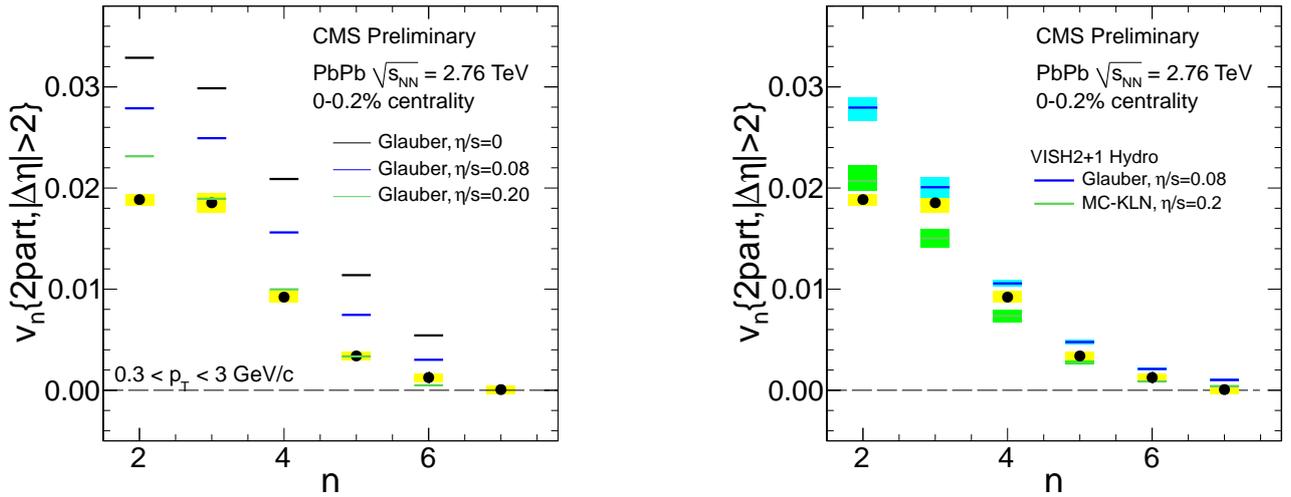


Figure 2. (color online) Power spectrum of the v_n coefficients in ultra-central (0-0.2%) collisions, compared to hydrodynamic models with different initial conditions and η/s values. Left: comparison to the Glauber model for initial conditions, for different η/s values; Right: Comparison to the Glauber and MC-KLN models. Different hydrodynamic models are used for the comparison in the left and right panes, see [7] for the original literature.

Fluctuations and event-by-event measurements give a direct handle on the initial state fluctuations, which give rise to a characteristic power spectrum for the harmonic coefficients. The relative flow fluctuations can be obtained combining different methods for the measurement of flow coefficients, as for instance in [8, 11–13]. The relative v_2 fluctuations are seen to have very little dependence over a large range in p_T (up to $p_T \simeq 8$ GeV/c), pointing to a common origin such as fluctuations in the initial state.

The ATLAS collaboration studied the event-by-event v_1, v_2, v_3 coefficients [6]. The results for v_2 in several centrality bins are compared to different models of initial con-

ditions in Fig. 1. In this comparison it is assumed that the v_n coefficients are proportional to the initial eccentricities ϵ_n in the models, i.e. non linear and dissipative hydrodynamic effects are ignored. As can be seen, none of the models tested can reproduce the data. More recently, a new comparison with a more realistic initial conditions model (IP-Glasma), based on Color-Glass-Condensate and saturation ideas, coupled with a full hydro evolution was able to describe all the coefficients satisfactorily [4].

The CMS collaboration studied events in ultra central collisions (0-0.2%). For this event class, the dependence on initial conditions is expected to be reduced [7]. For

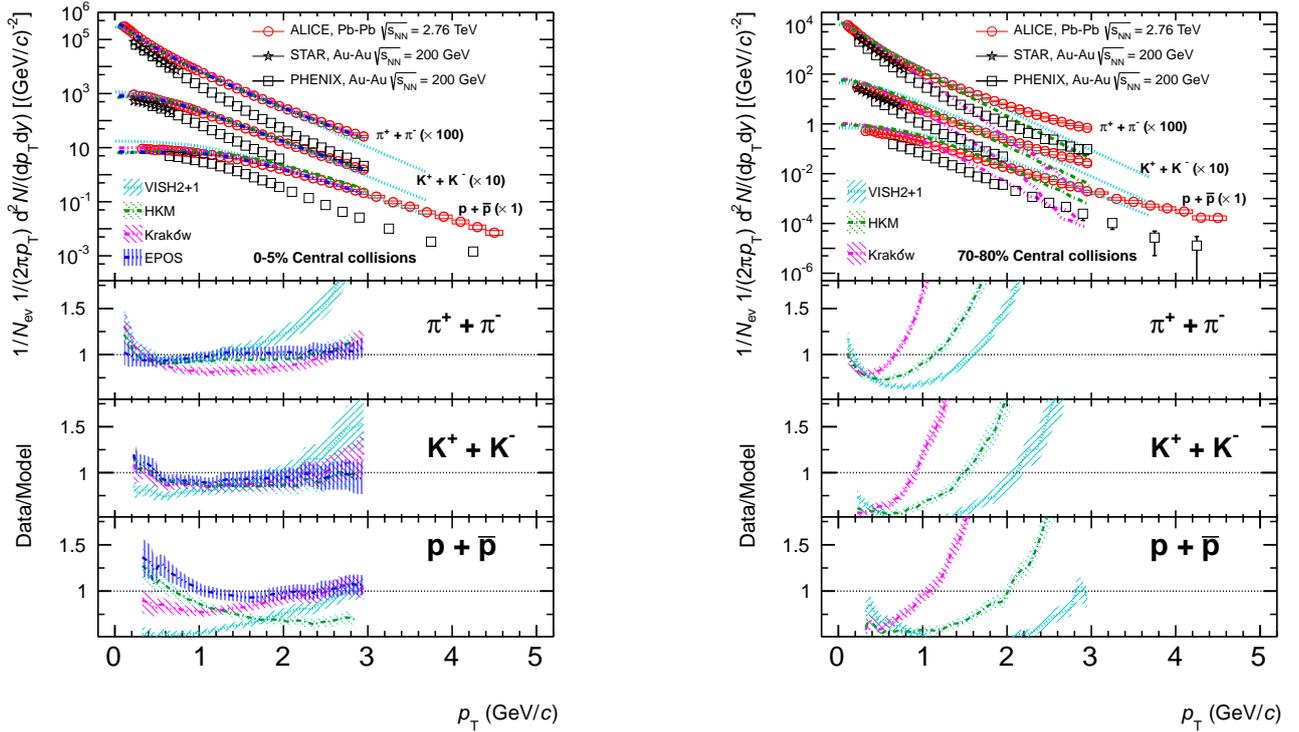


Figure 3. (color online) p_T distributions of pions, kaons, and protons in central (left) and peripheral (right) collisions, compared to RHIC data at $\sqrt{s_{NN}} = 200$ GeV/c and to hydrodynamic model calculations [18].

collisions with vanishing impact parameter, the only origin of the v_n coefficients are the fluctuations in the initial state and thus their relative magnitude should depend mostly on shear viscosity. As shown in Fig. 2, none of the models tested can reproduce the full power spectrum. It will be interesting to see whether these can be reproduced within the IP-Glasma framework mentioned above.

Other approaches, not discussed further in this paper, are sensitive to the interplay between initial conditions and evolution, such as studies as a function of event-by-event flow [14, 15] and event plane correlations [16, 17].

3 Dynamical Evolution

The models that describe the dynamical evolution of the fireball can be constrained by measuring identified particles. In particular, the transverse collective expansion can be studied via transverse momentum distributions.

Figure 3 shows the p_T distributions of pions, kaons and protons for central (left) and peripheral (right) collisions, measured by the ALICE collaboration [18]. These are compared to models based on hydrodynamics and to RHIC results at $\sqrt{s_{NN}} = 200$ GeV¹ [19, 20].

When comparing central and peripheral collisions, a clear flattening of the spectra can be seen at low p_T . This effect is more pronounced than at lower energy. It can be interpreted as being due to a strong radial flow. The estimated radial expansion velocity is about 10% higher than at RHIC [18].

¹See also references in [18] for the original literature.

The comparison to hydrodynamic calculations also confirms the collective expansion picture. Models including a description of the late stages of the fireball (either in the form of an explicit hadron phase or introduced via bulk viscosity corrections) give a better description of the data. The models fail in peripheral collisions, as expected since the underlying assumptions are not supposed to hold for such collisions. The mass ordering induced by the collective expansion is also seen in the v_2 of identified particles, as reported e.g. in [21, 22]

Additional information on the expansion dynamics and on the charge formation time can be inferred studying the “Balance Function” [23]. This function gives the conditional probability for a particle with a given momentum to be accompanied (balanced) by a particle of opposite charge (in general with a different momentum). The width of the function is related to the charge formation time: in case of a flowing medium one expects a wide distribution for an early formation time and a narrow distribution for a late formation time. The measurement of the widths made by the ALICE collaboration in $\Delta\eta$ and $\Delta\varphi$ (the difference in pseudorapidity and azimuthal angle of the two particles) are shown in Fig. 4 [23]. The balance function becomes narrower for increasing centrality. This is consistent with the picture of an expanding medium with late hadronization, which is characterized by a stronger radial flow in central collisions. These results are compared to several Monte Carlo calculations based on HIJING and different versions of the AMPT model. Among those, the one which gives the best description of the data includes

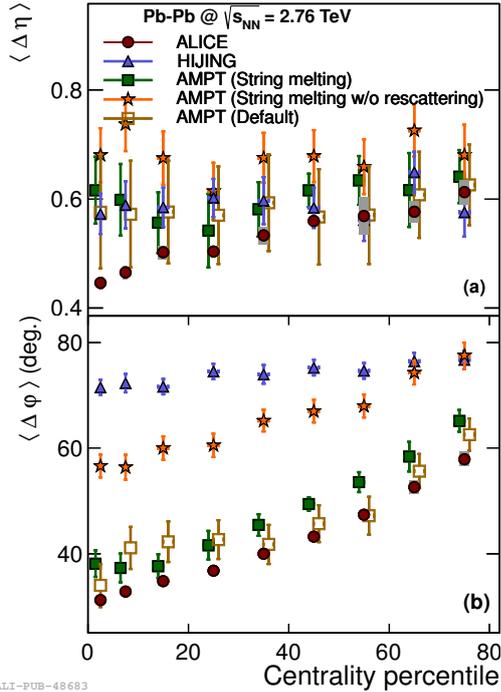


Figure 4. (color online) Width of the balance function in η (top) and ϕ (bottom) as a function of centrality, compared to several Monte Carlo calculations [23].

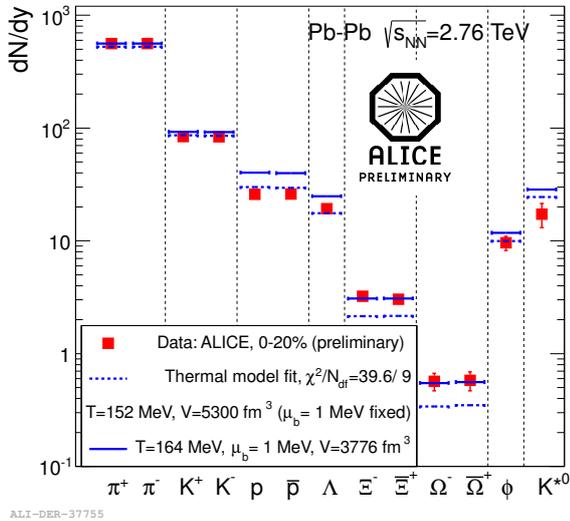


Figure 5. (color online) Mid-rapidity density dN/dy of identified particles in 0-20% central collisions, compared to thermal model calculations [15].

a flowing medium and the explicit effect of the hadronic phase.

4 Hadronization

Heavy ion collisions offer a unique opportunity to study the fundamental mechanisms underlying the hadronization

processes at the phase transition from the Quark Gluon Plasma to the hadron gas phase.

The mid-rapidity densities dN/dy of identified particle species have been studied very successfully in terms of statistical (thermal) hadronization models, where particles are assumed to be produced in thermal equilibrium from a (grand) canonical ensemble. These models gave an accurate description (order 10%) of particle abundances over a large range of energies $2 \text{ GeV} < \sqrt{s_{NN}} < 200 \text{ GeV}$ [24]. The first LHC data revealed a strong deviation of the p/π ratio with respect to these expectations [25]. The comparison of the predictions from the model described in [26] with different particle species is shown in Fig. 5. A fit to these yields based on the same model leads to a lower estimate of the chemical temperature than expected and the quality of the agreement with the data is significantly worse than at lower energies. The origin of these deviations remains open. Possible explanations include non-equilibrium statistical models [27], baryon annihilation in the hadronic phase [28], the existence of flavor-dependent pre-hadronic bound states [29] or missing higher mass resonance states in the thermal models.

A striking feature of the p_T -dependent baryon-over-meson ratios observed in heavy-ion collisions is the development of a pronounced maximum at intermediate $p_T \sim 3 \text{ GeV}/c$, as previously observed at RHIC energies [30, 31], and confirmed at the LHC (Fig. 6, left). This is usually interpreted in terms of radial flow, possibly with an additional contribution from hadronization via parton recombination (or coalescence). In these models, hadrons are formed assuming that the partons from the QGP recombine with each other or with partons from hard processes to form bound states. [32]. This mechanism is expected to dominate at intermediate p_T , and would lead to an enhanced production of baryons due to the steeply falling parton spectrum. A comparison to a recombination model is shown in Fig. 6 (left). The model describes the data above $p_T \approx 3 \text{ GeV}/c$, while overestimating the measurement at lower p_T . Alternative approaches can also give a satisfactory description of the data. For instance, in the EPOS model all p_T regions are described in terms of “flux tubes”, also taking into account interaction between hard particles and bulk matter (“jet-fluid interaction”) [33]. It is also interesting to notice that the low- p_T increase of the ratio finds a natural explanation in the mass-ordering induced by radial flow (see discussion in the previous section). A final understanding of this phenomena may come from the systematic study of different particles with different masses and quark content.

5 Jet/Bulk interaction

The interactions between bulk and jet particles can be effectively investigated with two-particle correlation measurements. This approach is complementary to fully-reconstructed jet studies at low and intermediate p_T , where jet reconstruction algorithm fail due to the large fluctuations in the underlying event background. In these measurements, a trigger particle in a given p_T interval is associated with all other particles in the event, in general in a

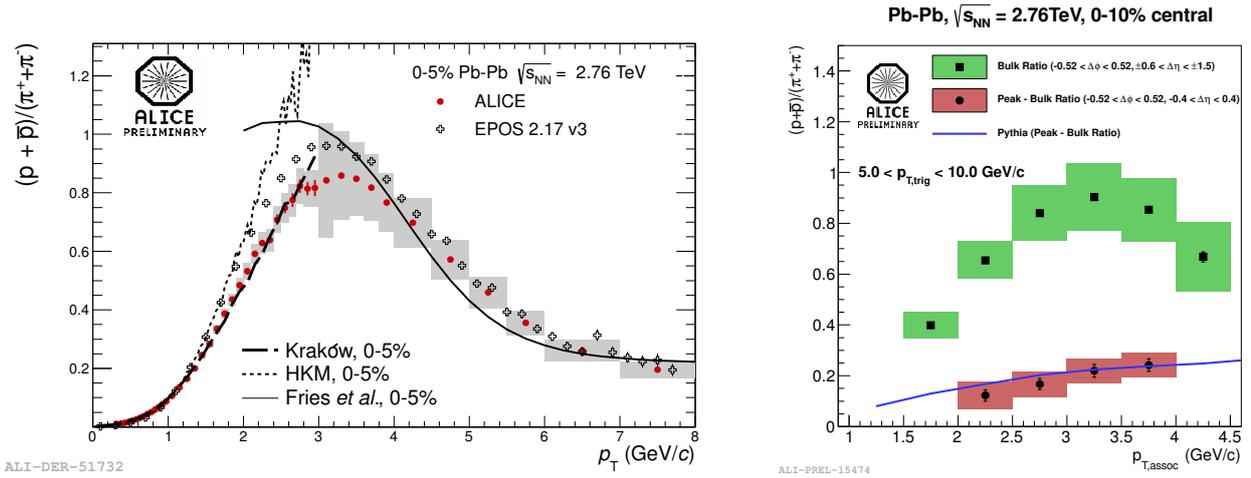


Figure 6. (color online) Proton-over-pion ratio as a function of p_T ; Left: inclusive ratio, compared to Monte Carlo, hydrodynamic and recombination models [35]; Right: ratio measured in the “jet” and in the “bulk” region with a two-particle correlation technique [34].

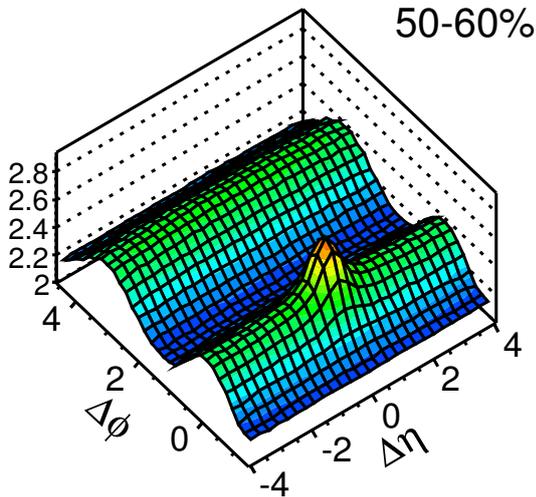


Figure 7. (color online) Correlation function in 50-60% central collisions measured by the CMS collaboration [36].

different p_T bin. The resulting $\Delta\eta$, $\Delta\phi$ “correlation function” shows (after subtraction of the combinatorial background) some pronounced features, as depicted in Fig. 7. On the near side ($\Delta\phi \sim 0$) a peak originating mostly from jet fragmentation is visible. The recoil jet appears as a long-range structure in $\Delta\eta$ (“ridge”), at $\Delta\phi \sim \pi$. The azimuthally anisotropic expansion introduces a modulation in $\Delta\phi$ which is also visible in the correlation function. Measuring this modulation provides an alternative method for measuring the actual v_n coefficients. Studying particle production in different regions of the $\Delta\eta$, $\Delta\phi$ plane allows one to extract information on the interactions between particles originating from jet fragmentation and bulk matter.

In order to investigate further the origin of the enhanced baryon production described in the previous section, the ALICE collaboration studied the p/π ratio sepa-

rately in the “bulk” region (defined as $|\Delta\phi| < 0.52$ rad. and $0.60 < |\Delta\eta| < 1.10$, or $0.60 < |\Delta\eta| < 1.50$) and in the “jet” (defined as the difference of yields between a peak region $|\Delta\phi| < 0.52$ rad., $|\Delta\eta| < 0.45$, and the bulk) [34]. The result is shown in Fig. 6 (right). The p/π ratio in the bulk shows the same enhancement observed in the inclusive distributions. The ratio in the jet, on the other hand, is much closer to that in pp collisions. This result shows that the enhancement of the baryon-over-meson ratio is a bulk effect, and disfavors coalescence models where the recombination of partons from the jet shower and the QGP plays a dominant role.

As mentioned in the introduction, two-particle correlations allow for the study of modification of the jet peak and of the distribution of the energy lost by high p_T partons in the medium. It is possible to study the energy loss measuring the evolution of the near side jet peak in the correlation function as a function of centrality. For events with increasing centrality, the modulation induced by flow also affects the correlation function in the near side peak region. In order to remove this contribution, the per-trigger yield at large $|\Delta\eta| > 1$ is subtracted from the near side peak at $|\Delta\eta| < 1$. The resulting peak is then fitted with a 2-dimensional Gaussian as a function of centrality. The results reported by the ALICE collaboration in [37] are shown in Fig. 8. The peak broadens in $\Delta\eta$ with increasing centrality, ultimately leading to a skewed distribution in central collisions. This evolution is found to have a p_T dependence, being more pronounced at lower p_T . As suggested in [5] this could be a consequence of the interplay of longitudinal flow and fragmenting high p_T partons.

6 Conclusions

In this paper we presented some recent results on soft particle production, flow and correlations measurements in Pb–Pb collisions at the CERN LHC. These observables provide essential information on the system, in particular on its bulk properties and on the interplay between hard

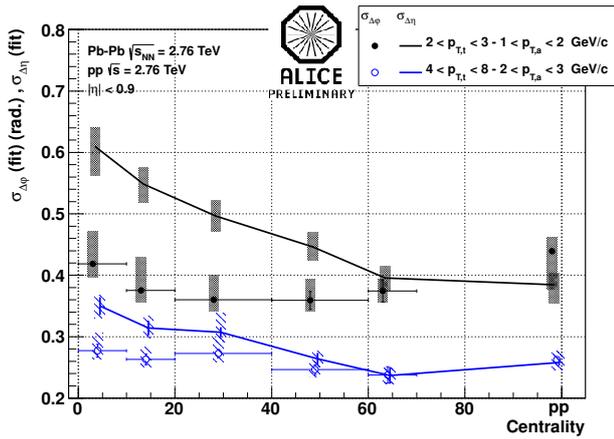


Figure 8. (color online) Gaussian widths of the near side jet peak, after subtraction of the large η component [37].

processes and the medium. Hydrodynamic calculations were found to successfully describe the evolution of the system. Bulk measurements on p_T distributions, particle ratios and balance function suggest that the late hadronic phase of the system could have a non-negligible effect. Fluctuations in the initial conditions play a crucial role, and the recent experimental constraints will allow to distinguish different models of the initial state. Two-particle correlation studies offer the possibility to investigate the suppression of hard partons and the interplay of jet and medium to a lower p_T than accessible with fully reconstructed jet measurements. The many new results from the LHC experiments presented here provide a first step towards precision measurement of the properties of deconfined matter.

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