PROCEEDINGS OF SCIENCE

# Heavy Ion Overview

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A short overview of selected results from heavy ion collisions at RHIC and LHC is presented. The results cover three key areas: collective effects in soft particle production in heavy ion collisions, evidence for similar effects in pp and p-Pb collisions, and hard probes of the Quark Gluon Plasma. The results are compared to theoretical models. The measurements of collective effects constrain both the initial entropy production and the viscosity of the Quark Gluon Plasma. The results from hard probes show that radiative parton energy loss plays an important role in these systems.

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The goal of high-energy collisions of heavy nuclei is to produce a very hot and dense system of strongly interacting matter and study its properties. It is expected that such a system behaves as a liquid-like plasma of quarks and gluons which are effectively deconfined, the so-called Quark Gluon Plasma (QGP). Lattice QCD calculations have shown that the transition from hadronic matter to a QGP is a crossover phase transition in the Standard Model. Recent calculations of the the energy density as a function of temperature for bulk QCD matter put the transition temperature at $T_c \approx 155$ MeV [1, 2].

In these proceedings, I will highlight a few recent results from the heavy ion collision program at the Large Hadron Collider (LHC) at CERN and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. The results can broadly be divided in three categories. Firstly there are results concerning the production of soft particles with transverse momentum $p_{\mathrm{T}}$ of up to a few GeV/$c$, which are mostly produced from the freeze-out of the Quark Gluon Plasma. In particular, results from studies of azimuthal anisotropies expressed as harmonic coefficients $v_n$ of the Fourier-decomposition of the azimuthal distribution, will be shown. These anisotropies have been shown to be a truly collective effect, which is attributed to the transverse expansion of the system after the collision.

Secondly, some recent results from pp and p-Pb collisions are presented, where long-range correlations in pseudo-rapidity are observed in high-multiplicity events, which are qualitatively similar to the azimuthal anisotropy in heavy ion collisions. This has sparked a debate whether these effects in high-multiplicity pp collisions and heavy ion collisions could have the same origin.

Finally, I will review a few new results regarding the use of jets to probe the Quark Gluon Plasma. High-$p_{\mathrm{T}}$ partons are produced in hard scatterings at early times in the collision and encounter low-momentum partons as they propagate through the QGP. The interactions between these partons and the QGP induce additional radiation as the high-energy partons fragment into hadrons, which leads to energy loss effects, often referred to as jet quenching. The effects of jet quenching can be used to study the properties of the plasma.



## 1. Azimuthal anisotropy and the viscosity of the Quark-Gluon Plasma

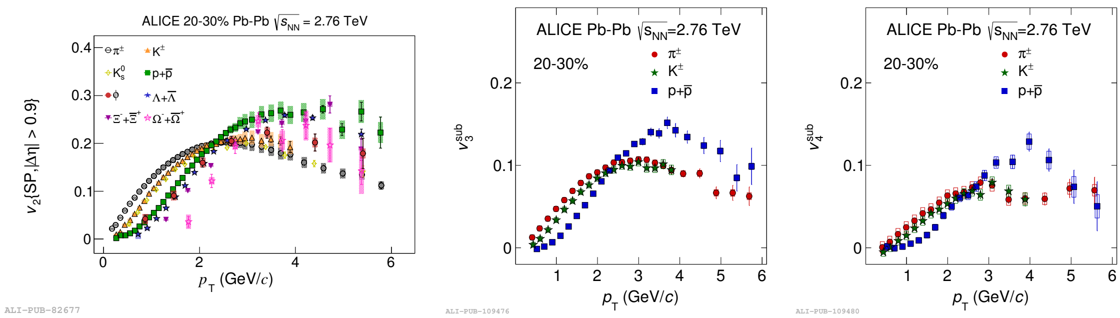


**Figure 1:** Amplitudes $v_n$ of the Fourier decomposition of the azimuthal distributions of particle production with respect to symmetry planes in the event, as a function of $p_{\mathrm{T}}$, for different particle species in $20-30\%$ central Pb-Pb collisions at the LHC [3, 4].

One of the most important observables that probe the soft physics of particle production from the Quark Gluon Plasma directly are the azimuthal anisotropies $v_n$ which are the Fourier coefficients of the azimuthal distributions of particle production with respect to the measured symmetry plane orientations. Figure 1 shows results for the three main harmonic coefficients $v_2$, $v_3$, and $v_4$ as a function of transverse momentum $p_T$ for non-central Pb-Pb collisions at the LHC [3, 4]. The most striking feature in the figures is the fact that the coefficients sharply increase with $p_T$, and that the point at which this increase sets in depends on the mass of the particle. The most natural explanation for this observation is that the particles are produced from a fluid that exhibits a common flow field and then freezes out. A given flow velocity produces a larger momentum boost to heavier particles.

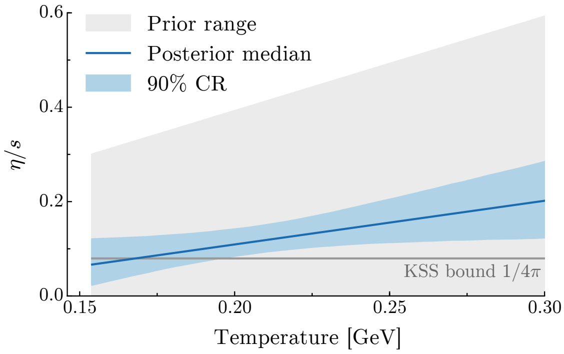


**Figure 2:** Temperature dependence of the viscosity to entropy ratio $\eta/s$ of the Quark Gluon Plasma, as determined using Bayesian inference techniques for a heavy collision model with 9 free parameters [5]. The grey band shows the prior range that was explored, while the blue area shows the 90% CL range that is inferred by comparing the model to experimental data on particle yields, mean $p_T$, and the flow harmonics $v_2$, $v_3$, and $v_4$.

In a heavy ion collisions, we normally distinguish three stages in the evolution: the initial stage where the two nuclei meet and scatterings take place, followed by an expansion phase in which the matter can be described as a fluid. The final phase is the freeze-out and hadron formation followed by rescattering of hadrons. The sensitivity of measured anisotropy coefficients $v_n$ to the stages of the evolution of the collision system has been explored in detail in a recent paper [5] in which 9 free parameters were introduced for the total model, of which 4 concern the initial state, 3 concern properties of the QGP, 1 concerns the hadron gas properties and 1 parameter is of a more model-technical nature. The parameter space was scanned and the model outcome was compared to the particle yields, mean $p_T$ and the $v_2$, $v_3$, and $v_4$ for a range of centrality selections. Bayesian inference was used to quantify the constraints that the measurements impose on the model parameters.

An important conclusion of the study is that the data allow to simultaneously constrain aspects of the initial entropy generation and important properties of the Quark Gluon Plasma, in particular the viscosity $\eta$ and its temperature dependence. Figure 2 show the temperature dependence of the dimensionless ratio of viscosity to entropy $\eta/s$. The value of $\eta/s$ is seen to be very close to the fundamental lower bound of $1/4\pi$ [6] and have only a modest temperature dependence. Or, in short, the Quark Gluon Plasma is seen to behave like a liquid with the lowest possible viscocity $\eta$.

## 2. Long-range correlations in small systems

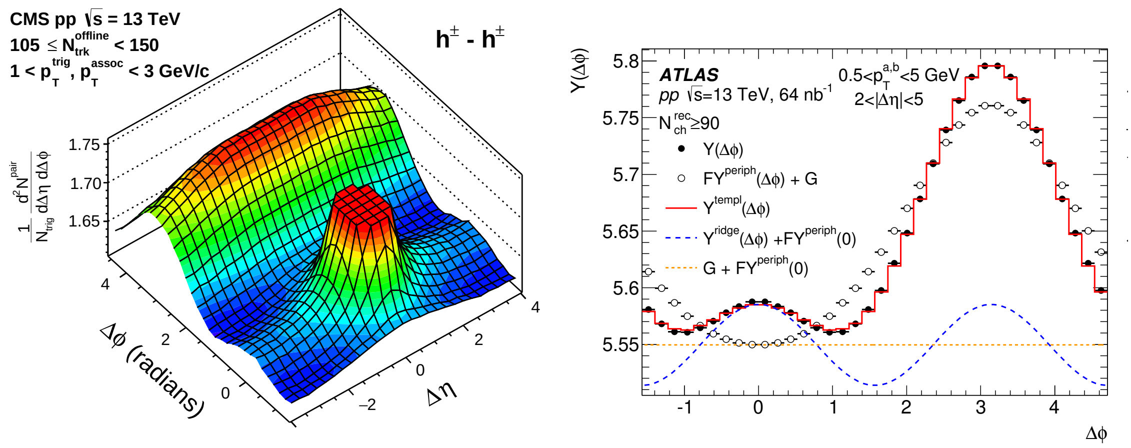


**Figure 3:** Left panel: Distribution of the azimuthal-angle difference $\Delta\phi$ and pseudo-rapidity difference $\Delta\eta$ for pairs of particles with $1 < p_T < 3$ GeV/$c$ in $\sqrt{s} = 13$ TeV pp collisions with large multiplicity [7]. Right panel: Azimuthal angle difference $\Delta\phi$ for pairs of particles with $0.4 < p_T < 5$ GeV/$c$ which are separated by more than 2 units of pseudo-rapidity ($2 < |\Delta\eta| < 5$) [8]. The distribution from high-multiplicity events (solid symbols) is compared to the scaled and shifted distribution in low-multiplicity events (open symbols). The red line shows the sum of the low-multiplicity distribution and a $\cos(2\Delta\phi)$ distribution (blue dashed line).

An important aspect of the azimuthal anisotropies that are measured in Pb-Pb collisions is that they also represent correlations over a long range in $\eta$, which indicates that the correlations are formed at early times. This aspect is naturally explained by the model described in the previous section where the asymmetries originate from the geometry of the incoming nuclei which is imprinted on the initial density distribution when the two nuclei collide.

At LHC, similar long-range correlations have been observed in proton-proton collisions and more recently also in p-Pb collisions. Two recent results are illustrated in Fig. 3. The left panel shows two-particle distributions in azimuthal angle difference $\Delta\phi$ and pseudo-rapidity difference $\Delta\eta$ for particles with $1 < p_T < 3$ GeV/$c$ and $|\eta| < 2.4$ for proton collisions with a collision energy $\sqrt{s} = 13$ TeV and selected high multiplicity of more than 105 reconstructed tracks from CMS [7]. A small but significant correlated particle yield is visible on the near side $\Delta\phi = 0$ at large $\Delta\eta$, apart from the jet peak around $\Delta\eta = 0$. Such a correlated yield is not seen in low-multiplicity pp collisions. A more detailed analysis of the correlation structure at large $\Delta\eta > 2$ is shown in the right panel, which compares the azimuthal distributions of low and high-multiplicity proton-proton collisions [8] (this time from ATLAS). In this projection, we can see not only the near-side correlation structure, but also a modification of the away-side peak (around $\Delta\phi = \pi$). The difference between the two distributions can be described by the second harmonic $\cos(2\Delta\phi)$ distribution, exactly like the second harmonic flow that is measured in Pb-Pb collisions. The result in Fig. 3 represents only the main result, but many more detailed results are available, such as the $p_T$ and particle species dependence [7, 8], multi-particle analysis results that probe whether the observed correlations are collective or not, and a large number of similar results in p-Pb collisions [9, 10].

These results raise a number of interesting questions about particle production and collectivity in all collision systems. The collective azimuthal anisotropy in heavy ion collisions is thought to be an effect of the expansion of the fluid-like medium in the collision. A collective fluid-like behavior is natural for a dense system with a size that is at least several times larger than the mean free path of a soft parton in the system. Estimates of the energy density in heavy ion collisions are in the range where such behavior is expected. A very interesting question is now whether a large enough density and system size is already reached in high-multiplicity pp collisions, or whether an alternative physical picture is needed. For example, it could be that the fluid-like behavior is generated very early in the collision, a behaviour which is being explored using strong-coupling techniques based on AdS-CFT correspondence as well as well as weak-coupling methods that make use of the high energy limit of QCD in the Color Glass Condensate regime [11]. Alternatively one could imagine that overlapping QCD strings have an effective repulsion and/or have a larger string tension generating large transverse momenta, such as in the color reconnection model in Pythia [12] or the color ropes of DIPSY [13, 14]. Active discussion of these phenomena is ongoing in the field, and we expect many developments in the near future. The LHC will be colliding protons with lead nuclei in 2016 to further experimentally investigate these effects in small systems.

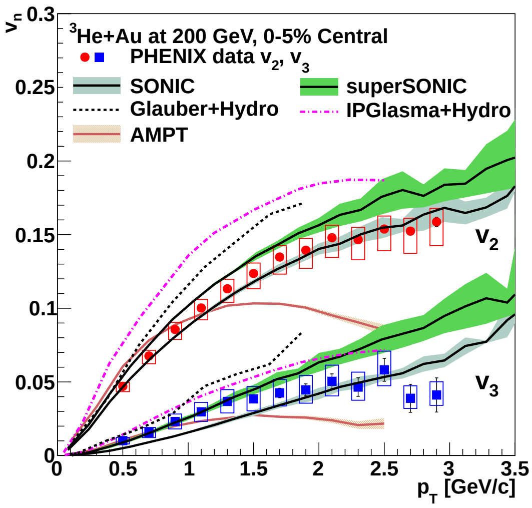


**Figure 4:** Second and third harmonic coefficients of the azimuthal distribution in $^3$He+Au collisions from RHIC as measured by PHENIX (points) compared to model calculations (lines) that include a fluid expansion stage in the system evolution [15].

RHIC has the ability to collide different nuclei at a center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 200$ GeV. In 2014, RHIC collided $^3$He nuclei with gold nuclei to shed further light on the mechanism behind the azimuthal anisotropy observed in small collision system. The $^3$He projectiles are of particular interest since they give rise to triangular configurations in the initial stage of the collision [16]. Figure 4 shows the measured second and third order harmonics of the azimuthal distributions [15]. A sizeable $v_3$ is found, which can be connected to the initial triangular asymmetries. The curves in the figure show several model calculations that include a fluid-expansion stage in to model the collision and produce the anisotropy in the final state [11, 16, 17, 18, 19]. The model curves are in good qualitative agreement with the measurements.

## 3. Jets and parton energy loss

Another way to probe the Quark Gluon Plasma in heavy ion collisions is by studying jet-quenching phenomena, which arise when high-momentum partons that are produced in hard scatterings in the early stages of the collision interact with the color charges in the QGP as they propagate through the collision zone. The interactions of the hard parton with the QGP constituents induces extra gluon radiations, which reduce the momentum of the leading particle in the jet and increase soft radiation at large angle.

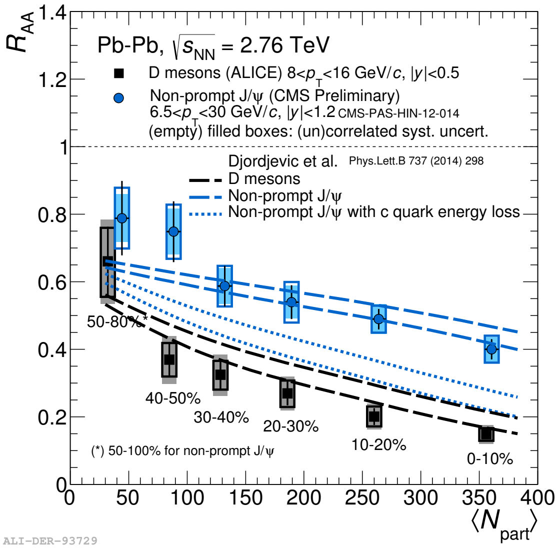


**Figure 5:** Nuclear modification factor $R_{AA}$ for heavy flavour mesons: $D$ mesons [20] and non-prompt $J/\psi$ from $B$ meson decays [21], as a function of centrality in Pb-Pb collisions with $\sqrt{s_{NN}} = 2.76$ TeV.

The effects of jet quenching have been seen in many single-particle and jet-related observables, such as the jet energy asymmetry, suppression of particle and jet yields at high $p_T$. Figure 5 shows the nuclear modification factor $R_{AA}$ for heavy flavour mesons: $D$ mesons [20] and non-prompt $J/\psi$ from $B$ meson decays [21], as a function of centrality. The nuclear modification factor is the ratio of particle production in Pb-Pbcollisions and pp collisions scaled by the number of binary nucleon-nucleon collisions. The observed suppression $R_{AA} < 1$ is due to energy loss of the high-momentum heavy quarks in the QGP. The lines show model calculations that include collisional and radiative energy loss [22]. The difference between the values for $D$ mesons and non-prompt $J\psi$ are due to the 'dead-cone effect', i.e. a reduced radiative energy loss for heavy quarks that have a velocity below the speed of light. The dashed line shows the expectetation for non-promp $J/\psi$ without the dead-cone effect. The observation of this effect implies that radiative energy loss plays an important role in the QGP. New results for these observables from run 2 can be found in [23].

The LHC measurements are currently focusing on jet observables which allow to study the the redistribution of energy by interactions with the QGP. A number of recent jet shape measurements are even sensitive to event-by-event differences in the energy loss, due to differences in path length and density from event to event.

Figure 6 shows preliminary results on two different jet shape measurements from ALICE, the girth $g$ ($p_T$-weighted mean $r$) and $p_{T,D}$, the normalized $p_T$-dispersion in central Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV [24]. Both results are fully corrected for detector effects and background fluctuations and compared to particle-level PYTHIA results. In this measurement, the jet resolution

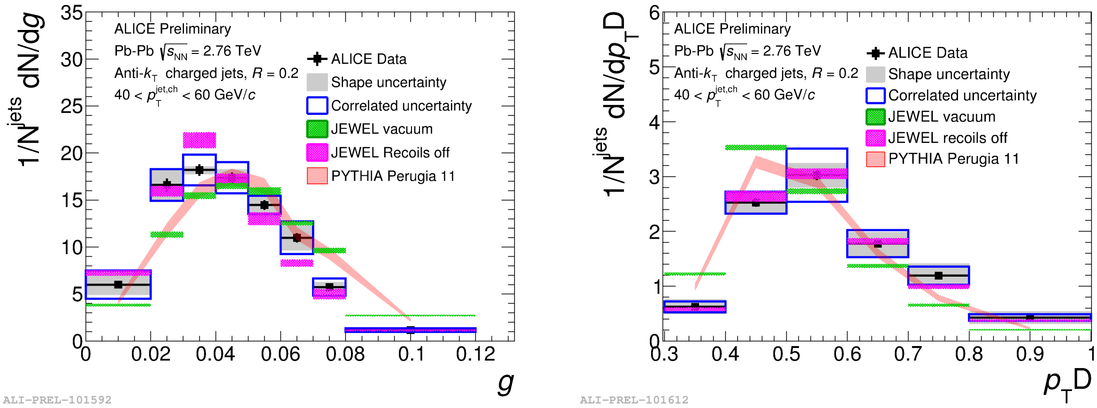


**Figure 6:** Jet shape variables girth $g$ (left panel) and $p_T$-dispersion $p_{T,D}$ (right panel) for charged particle jets with $40 < p_T < 60$ GeV/$c$ in central Pb-Pb collisions [24]. The measurement is compared to expectations from PYTHIA for pp and JEWEL for pp (vacuum) and Pb-Pb collisions (labeled: recoils off).

parameter is relatively small, $R = 0.2$, so the results characterize the changes in the jet core. Both girth and $p_{T,D}$ are slightly smaller in Pb-Pb collisions than in PYTHIA pp simulations, indicating that the fragments in the jet are closer to the jet axis (narrowing), and a softening of the dsitribution possibly combined with a decrease of multiplicity of the jet core.

The results are also compared to the JEWEL jet quenching Monte Carlo, which models radiative and collisional energy loss, including formation time effects associated with the Landau-Pomeranchunk-Migdal effect [25]. The JEWEL generator is known to describe the existing single particle and jet suppression measurements fairly well. It can be seen in the figure that JEWEL also agrees well with the new jet shape measurements.

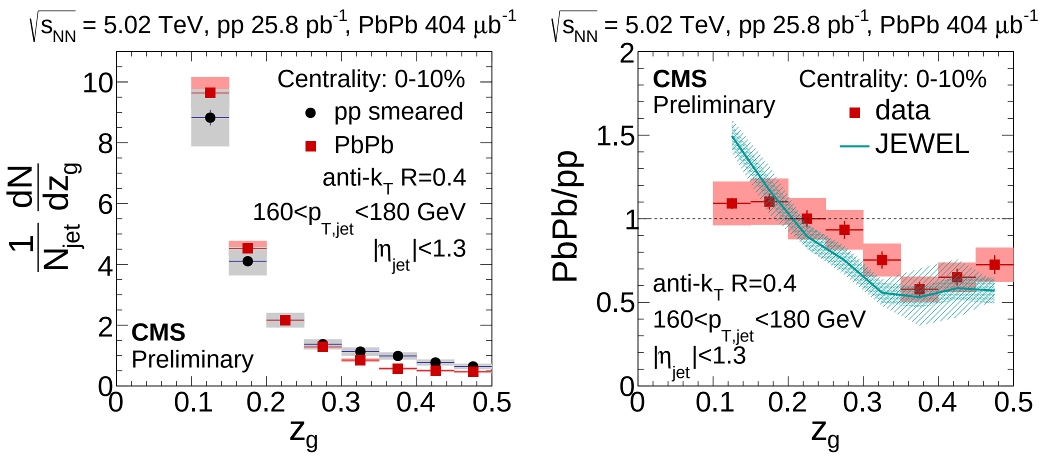


**Figure 7:** Momentum sharing variable $z_g$ for jets with $160 < p_T < 180$ GeV/$c$. Left panel: $z_g$ in central Pb-Pb collisions and a reference based on the measurement in pp collisions, which were then smeared with a response to model the effect of background fluctuations [26]. Right panel: ratio of $z_g$ in Pb-Pb collisions and the reference, compared to a JEWEL calculation.

Figure 7 shows preliminary results on the momentum sharing variable $z_g$ measured by CMS in Pb-Pb collisions with $\sqrt{s_{\rm NN}}$= 5.02 TeV [26]. The momentum sharing variable is calculated using Softdrop declustering until a condition of sufficient resolution is reached and calculating the momentum fraction $z_g$ of the lowest momentum branch. The variable has been shown to follow the expected behavior from the vacuum splitting function in simulated pp events [27]. In the left panel of Fig. 7, the Pb-Pb result is compared to a reference measurement on pp events which were smeared with a response function that was derived by comparing results from PYTHIA events to PYTHIA events superimposed on a HYDJET event to include the effect of the fluctuations of the uncorrelated background in heavy ion collisions. The measurement in Pb-Pb events shows an excess over the reference at low $z_g$ and an decrease at large $z_g$, indicating that more soft fragments are produced already in the first (highest virtuality) splitting. The right panel shows the ratio of the Pb-Pb measurement to the reference and compares it with the JEWEL jet quenching Monte Carlo event generator. The results from JEWEL are in good agreement with the measurement. However, the CMS measurement also explores the jet energy dependence (not shown here), which seems to be stronger in the measurement than in the JEWEL calculation.

The overall agreement of the jet quenching results with the calculations from the JEWEL event generator show that many aspects of the interactions of high-momentum partons with the Quark-Gluon Plasma are understood. One notable effect that is currently being explored in theoretical calculations and that is not fully addressed in the JEWEL Monte Carlo generator, is the impact of the color structure on angular ordering [28]. The impact of this on jet quenching phenomenology will become clearer in the future. A drawback of Monte Carlo models is that there is no standard path for systematic improvements of the calculations. Analytical calculations are being pursued in parallel, using for example the Soft-Collinear Effective Theory framework [29].

## 4. Conclusion

New results have been obtained in key areas of the heavy ion physics programme at the LHC and RHIC, covering both soft particle production and hard probes of the Quark Gluon Plasma. The modeling of the evolution of collision system is becoming increasingly sophisticated and allows to draw conclusions about initial state entropy production as well as the viscosity of the QGP, which is found to be close to the fundamental bound $\eta/s = 1/4\pi$. Long-range correlation structures have been observed in pp and p-Pb collisions. These strcutures are reminiscent of similar observations in Pb-Pb collisions, where the effect is thought to originate from initial state geometry and driven by subsequent expansion of the QGP. These observations raise the question whether similar processes play a role in small systems as well, and how this affects the early stages of heavy ion collisions. The LHC will be colliding protons with lead nuclei in 2016 to further experimentally investigate these effects in small systems. In the area of hard probes, the nuclear modification factors of charm and beauty mesons are found to agree with expectations from theoretical calculations that include the dead cone effect for radiative energy loss. Jet measurements are used to further explore interactions between high-energy partons and the QGP. Parton-shower models with medium-induced radiation such as JEWEL are being developed to understand the mechanisms for jet quenching in more detail and to use hard probes to determine the density of the QGP.

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