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Open heavy-flavour production in nuclear collisions

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Abstract

In these proceedings I will give an overview of the latest experimental results on charm and beauty production at RHIC and the LHC presented at the Quark Matter 2018 conference. The new measurements in p(d)-A collisions have a key impact in the understanding of possible collective effects of heavy quarks in small collision systems. In A-A collisions, new high-precision data and differential observables offer more quantitative ways to investigate different aspects of the interactions of heavy quarks in the Quark Gluon Plasma, like transport properties, energy loss distributions, hadronisation mechanisms, and magnetic effects.

Keywords:
heavy quarks, energy loss, diffusion coefficient, nuclear modification factor, elliptic flow

1. Introduction

Heavy quarks are produced via hard scattering processes in the initial stages of hadronic collisions. In high-energy heavy-ion collisions, they witness the whole evolution of the hot and dense QCD medium, the so called “Quark-Gluon Plasma” (QGP), and they are expected to interact with its constituents and to lose energy via subsequent elastic scatterings and/or gluon radiation.

Many experimental observations from RHIC and the LHC showed evidence that charm and beauty quarks interact strongly with the QGP and that beauty quarks lose less energy compared to charm quarks [1, 2, 3]. As more precise data become available, we can constrain theoretical models that describe the microscopic interactions of heavy quarks with the medium. However, unresolved questions remain: What is the relative contribution of radiative and collisional energy loss? How is the lost energy of heavy quarks redistributed among the jet constituents compared to lighter partons? Are there measurable effects on the heavy-flavour production due to the presence of magnetic fields in early times? How do heavy quarks hadronise? Is the collective behaviour of heavy quarks also detected in smaller systems like p(d)-A collisions?

A selection of the latest results on heavy-flavour production at RHIC and the LHC is presented in these proceedings, with a discussion on their implications in view of addressing the above questions.

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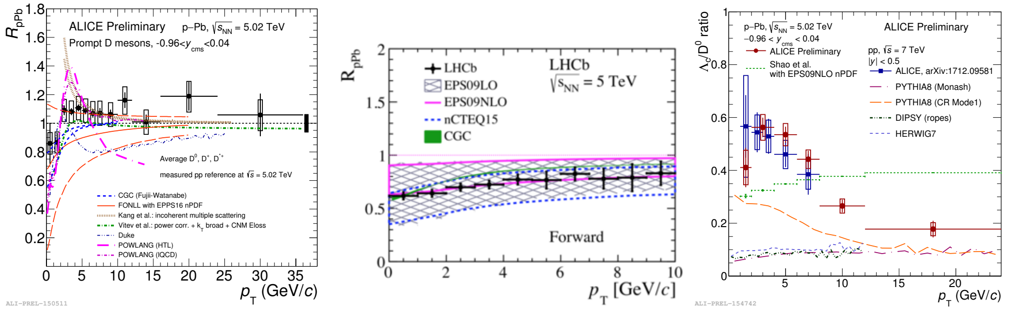

Fig. 1. Left: D-meson nuclear modification factor R_{pPb} as a function of p_T in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV measured with ALICE at mid-rapidity and compared to model calculations [7]. Centre: Forward-rapidity D^0 R_{pPb} as a function of p_T in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV measured with LHCb and compared to theoretical calculations [8]. Right: Λ_c/D^0 ratio as a function of p_T in pp collisions at $\sqrt{s}$ = 7 TeV and in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV [11] measured with ALICE, compared to that obtained using various event generators and a theoretical calculation including PDFs modifications in nuclei.

2. Heavy-flavour production in p(d)-A collisions

Investigation of p(d)-A collisions with heavy-flavour particles is needed to isolate effects due to the cold nuclear matter in a system where an extended and long lived QGP phase is not expected. In addition, precise measurements in small collision systems are crucial to provide experimental constraints to heavy-quark production and hadronization mechanisms, which could improve model calculations. Finally, following the observation of a positive elliptic flow coefficient v_2 for light-flavour hadrons in high-multiplicity p–Pb collisions [4, 5, 6], whose origin is currently debated, efforts started to investigate whether or not heavier quarks like charm and beauty also show collective behaviours in small collision systems with large particle multiplicities.

Figure 1 (left) shows the recent measurement from ALICE of D-meson nuclear modification factor in minimum bias p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, obtained with the pp reference data collected in 2017 also at $\sqrt{s}$ = 5.02 TeV [7]. The R_{pPb} is compatible with unity at mid-rapidity within the experimental uncertainties, indicating no significant cold nuclear matter effects in the measured transverse momentum range. Several model calculations including either different initial conditions or energy loss in cold nuclear matter and in a small QGP are also shown. The data exclude a large suppression of the yields at high p_T due to the presence of small QGP-like medium, indicating that the suppression observed in A–A collisions is a consequence of final-state effects (Section 3). The D-meson R_{pPb} measured with LHCb at forward rapidity is reported in the centre panel, at the same collision energy [8, 9]. With these data it is possible to impose constraints to gluon nuclear PDFs in the low-x region dominated by gluon shadowing [10].

Further steps in understanding the hadronisation mechanisms are being made by comparing the productions of baryons and mesons containing charm quarks. Figure 1 (right) shows the ratio Λ_c/D^0 measured with ALICE in pp and p–Pb collisions, together with the results from Monte Carlo event generators and theoretical calculations [11]. The data are compatible in pp and p–Pb collisions within the uncertainties, and the ratio is higher than that obtained with event generators, whose fragmentation parameters are derived from e$^+$e$^-$ collision data. These results, together with those from LHCb [9], provide inputs for theoretical models and event generators which use different hadronisation approaches.

First measurements of positive v_2 for heavy-flavour particles at both RHIC and LHC energies in high-multiplicity d–Au and p–Pb collisions, respectively, were reported at this conference. The analyses utilize two-particle correlation techniques, removing the correlated background from jets by either subtracting low-multiplicity events from those with high multiplicity, or by considering large pseudo-rapidity gaps. Figure 2 shows the v_2 as a function of p_T for D^0 mesons from CMS (left) [12, 13], heavy-flavour decay electrons from ALICE (centre) [14, 7] and heavy-flavour decay muons from PHENIX (right) [15]. The positive heavy-flavour v_2, persisting to high p_T, is lower than that of light-flavour particles. Future comparisons with

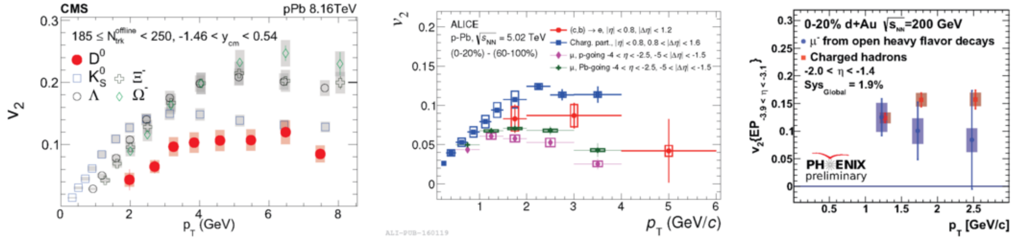

Fig. 2. Left: v_2 for prompt D^0 mesons and strange hadrons as a function of p_T in p–Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV measured with CMS [12]. Centre: heavy-flavour decay electron v_2 as a function of p_T compared to that of unidentified charged particles and inclusive muons, in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV measured with ALICE [14]. Right: v_2 of heavy-flavour decay muons and charged particles as a function of p_T, in d–Au collisions at $\sqrt{s_{NN}}$ = 200 GeV measured with PHENIX [15].

theoretical models will give more information about different scenarios regarding the origin of the observed azimuthal anisotropy.

3. Heavy-flavour production in A–A collisions

3.1. Charm and beauty nuclear modification factor and elliptic flow

The STAR collaboration reported at this conference new results for the nuclear modification factor of D^0 mesons (Fig. 3, left) [16] obtained from the 2014 data and a re-analysis of 2010-2011 data. Differing from the previous results, the R_{AA} is below unity for the entire momentum range, down to p_T = 0. At intermediate p_T a similar D-meson suppression in central collisions is observed at RHIC and the LHC, as reported by ALICE and CMS in Fig. 3 (right) [11, 13, 17, 18], suggesting that a combination of various effects, i.e. greater energy loss and harder spectra at the LHC compared to RHIC, might occur. It will be interesting to compare RHIC data to future measurements at the LHC at very low p_T, where the interplay of contributions from radial flow, p_T shapes, nuclear PDF, and hadronisation via recombination could play a different role at the two collision energies.

Further investigation concerning the dynamic interactions of charm quarks with the medium comes from the study of the elliptic flow coefficient v_2. Final results on v_2 of D mesons in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV were shown at this conference by ALICE and CMS [11, 19, 20]. High-precision measurements of D^0 v_2 (Fig.4, left) confirm that charm quarks suffer subsequent interactions in the medium and develop an elliptic flow, which is lower than that of charged particles at low p_T in semi-central collisions, consistent with the mass ordering predicted by hydrodynamic calculations.

Measurements of particles containing beauty quarks in heavy-ion collisions offer access to the parton mass dependence of energy loss and collectivity in the QGP. First results on v_2 of electrons from beauty hadron decays at RHIC were reported by PHENIX (Fig.4, right) [15], however the uncertainties are still large to conclude on possible collective effects on beauty quarks at these energies. These results are expected to improve with the statistics from RHIC run 2016. Recent results at the LHC from ALICE and CMS indicate that the suppression of high-p_T particles originating from B-meson decays is smaller than that observed for prompt D mesons in central Pb–Pb collisions [2, 3]. This finding was described by models including mass-dependent parton energy loss [21]. New results on non-prompt D^0 R_{AA} from CMS (Fig. 5, left) [22] and final results on non-prompt J/ψ R_{AA} from ATLAS (Fig. 5, right) [23, 24] were presented at this conference. As seen in Fig. 5 (left), the results confirm lower suppression for particles from B-hadron decays compared to prompt D mesons. The suppression persists to very high p_T, increasing for more central events (Fig. 5, right), and it exhibits a constant trend as a function of p_T, within the high precision level of the measurements. With their increasing precision and kinematic coverage, measurements of charm and beauty R_{AA} and v_2 at RHIC and the LHC have started to provide constraints to the model implementation of the interaction of charm quarks with the QGP [25]. This is necessary to obtain a better understanding of charm and beauty degree of thermalization and of the collisional and radiative energy loss mechanisms, which are expected to dominate

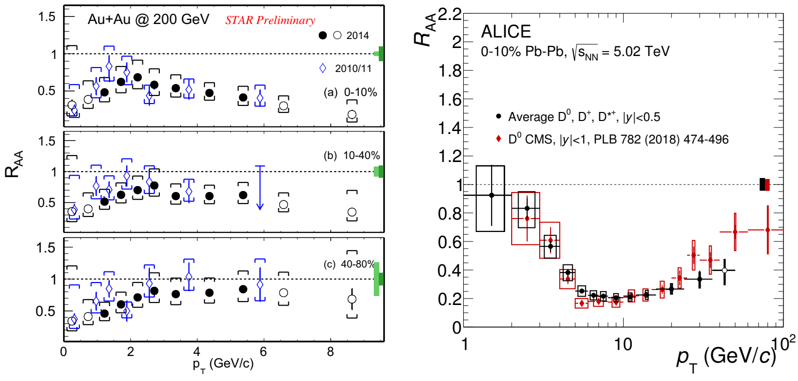

Fig. 3. Left: D^0 R_{AA} as a function of p_T in Au–Au collisions at $\sqrt{s_{NN}}$ = 200 GeV measured with STAR in different collision centralities [16]. Right: prompt D-meson R_{AA} as a function of p_T in central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV measured with ALICE (average of D^0, D^+, D^{*+}) [19] and CMS (D^0) [20].

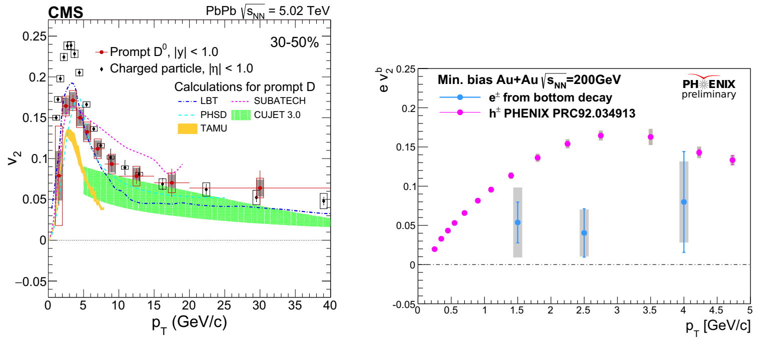

Fig. 4. Left: D^0 v_2 as a function of p_T in semi-central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV measured with CMS and compared to model calculations [20]. Right: v_2 of electrons from beauty-hadron decays as a function of p_T in Au–Au collisions at $\sqrt{s_{NN}}$ = 200 GeV measured with PHENIX [15] and compared to charged hadrons.

at low and high p_T, respectively. The high-precision data that the LHC will collect during Run 3 and Run 4 will allow for accurate determination of the heavy-quark transport coefficients.

3.2. Strange D-, B-meson and charm-baryon production

A key aspect in the study of the interactions of heavy quarks with the evolving medium is the investigation of their hadronisation mechanism, and in particular of the contribution of recombination of heavy quarks with the light quarks in the medium as opposed to the vacuum-like fragmentation [26]. Recent measurements of D_s^+ in Pb–Pb collisions from ALICE show a hint of a reduced suppression for D_s^+ compared to non-strange D mesons [17], in qualitative agreement with models including recombination of charm quarks in the QGP that has a significant strangeness content. The production of J/ψ in A–A collisions, less suppressed at low p_T at the LHC compared to RHIC, also supports a picture of recombination between the charm and anti-charm quarks at low p_T at the LHC energies [27].

The first measurement of the B_s^0 meson in Pb–Pb collisions with CMS is reported in Fig. 6 (left) [22]. While the uncertainties are too large to draw firm conclusions, the measurement represents a first hint of less suppression of B_s^0 compared non-strange B mesons, opening the way to investigate the recombination mechanism in the beauty sector as well.

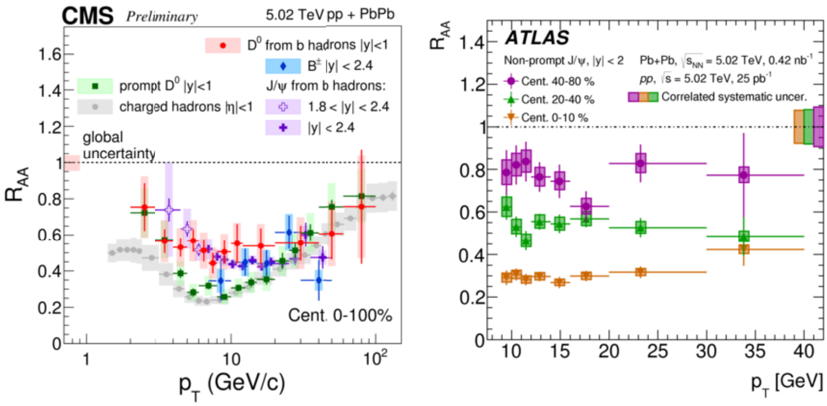

Fig. 5. Left: non-prompt D^0 R_{AA} as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV measured with CMS, compared to charged hadrons, prompt D^0, and non-prompt J/ψ [22]. Right: non-prompt J/ψ R_{AA} as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV measured with ATLAS in different collision centralities [23].

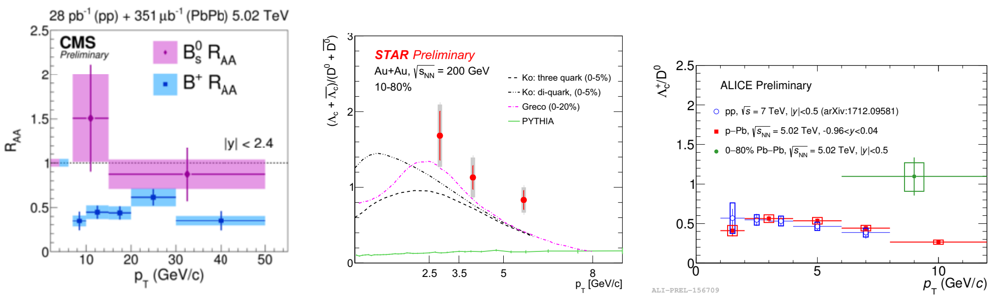

Fig. 6. Left: B^0_s R_{AA} as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV measured with CMS, compared to that of B^+ [22]. Centre: Λ_c/D^0 ratio as a function of p_T in semi-central Au–Au collisions at $\sqrt{s_{NN}}$ = 200 GeV measured with STAR [16], compared to theoretical models. Right: Λ_c/D^0 ratio as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV measured with ALICE, compared to the results in pp and p–Pb collisions [11].

At the previous Quark Matter conference, the STAR collaboration reported for the first time the measurement of the Λ_c baryon yield in heavy-ion collisions, showing that the ratio Λ_c/D^0 is enhanced in Au–Au collisions with respect to PYTHIA [28], suggesting a relevant role of recombination of charm quarks with the light quarks in the medium. New results with higher precision presented at this conference by STAR show a p_T-dependent Λ_c/D^0 ratio, increasing towards lower p_T with a value above unity at low p_T (Fig. 6, centre) [16]. The observed enhancement is larger than that predicted by models based on hadronisation via fragmentation and recombination. Furthermore, ALICE reported the measurement of the Λ_c baryon yield for the first time in Pb–Pb collisions at the LHC (Fig. 6, right) [11], also indicating an enhancement of the Λ_c/D^0 ratio compared to pp and p–Pb collisions, in qualitative agreement with the STAR measurement. These results, along with the higher precision measurements expected from the next heavy-ion runs at the LHC, provide important constraints on the role of hadronisation via recombination in models describing the process of the heavy-quark in-medium interactions. In addition, these measurements are relevant for an accurate determination the total $c\bar{c}$ cross section, needed as reference for quarkonia measurements.

3.3. Heavy-flavour jets

Jet observables complement measurements of single particles by adding dimensionality to the study of jet quenching. Heavy-flavour tagged jets give access to the redistribution of the energy that was lost by

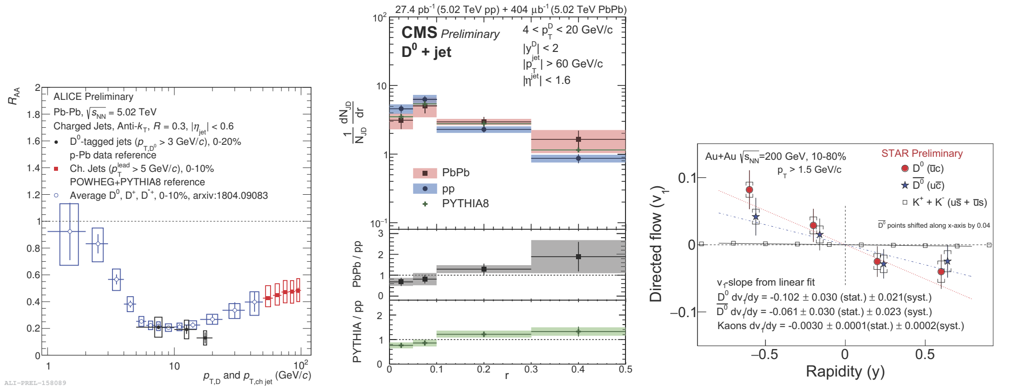

Fig. 7. Left: R_{AA} of D^0-tagged jets as a function on p_T measured in central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE, compared with inclusive jets and D mesons (average of D^0, D^+, D^{*+}) [29]. Centre: Radial correlations between D^0 mesons and jets in pp collisions at $\sqrt{s} = 5.02$ TeV and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, measured with CMS [30]. The ratios of the distributions in Pb–Pb and PYTHIA 8 relative to pp collisions are reported in the lower panels. Right: Directed flow v_1 as a function of rapidity for D^0 and $\overline{D^0}$ mesons compared to that of kaons, measured in semi-central Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV with STAR [31].

the heavy quark in the medium, to possible modification of their longitudinal and transverse structures, and open the way to investigate the differences between quark and gluon interactions with the medium. The first result on charm jets in Pb–Pb collisions was presented at this conference. The R_{AA} of D^0-tagged jets from ALICE is reported in Fig. 7 (left) [29], compared with that of D mesons and inclusive jets. A strong suppression of D^0-tagged jets is observed, down to charged jet $p_T = 5$ GeV/c, compatible with that of D mesons. CMS reported measurements of radial correlations between D^0 mesons and jets in pp and Pb–Pb collisions (Fig. 7, centre) [30]. The ratio of the distributions in Pb–Pb relative to pp collisions (lower panel) suggests that D^0 at intermediate p_T are more likely to be located at larger angles from the jet axis in Pb–Pb with respect to pp collisions. Comparison to theoretical models will help with the interpretation of this measurement. A hint for a wider radial profile for low-p_T D^0 with PYTHIA 8 with respect to pp data is also seen in the figure.

3.4. *Directed flow*

The presence of magnetic fields in the early phase of heavy-ion collisions is expected to have an impact on the directed flow of charm quarks [32, 33, 34, 35], resulting in a v_1 value which is larger than that of lighter particles. This is a consequence of the relatively short formation time of the charm quark, which makes it particularly sensitive to the maximum magnetic field strength. The effect of the magnetic field is opposite for particles which contain charm compared to anti-charm due the Lorentz force. The initial vorticity of non-central collisions is also expected to influence the directed flow [33, 34, 35]. The STAR collaboration presented at this conference the first measurement of the directed flow coefficient for D^0 and $\overline{D^0}$ mesons (Fig. 7, right) [31]. The observation of non-zero v_1 for charm mesons, larger than that of lighter particles, is in qualitative agreement with theoretical models including both electromagnetic and vorticity effects. The uncertainties on the difference between the v_1 of D^0 and that of $\overline{D^0}$ from STAR are, at the moment, too large to draw conclusions on the charge-dependent effects of the early magnetic fields.

4. Conclusions and outlook

The study of particles with charm and beauty has provided essential elements to quantify our understanding of the QGP transport properties. Several highlights were presented at the Quark Matter 2018 conference, both on small and large collision systems. A positive v_2 of D mesons and heavy-flavour decay leptons was observed in high-multiplicity p(d)-A collisions at RHIC and LHC energies, adding new information that will help to clarify the source of these effects on light and heavy quarks.

Along with experimental efforts for higher precision measurements, steps forward are being made to study new observables and more differential measurements. New measurements of beauty mesons with strangeness and Λ_c baryons are adding new constraints to heavy-quark hadronisation: in particular, the large Λ_c/D^0 ratios at both RHIC and the LHC pose a challenge to models including charm hadronization via recombination which tend to under-predict the data. First measurements of D^0 tagged jets and angular correlations between D^0 and jets in heavy-ion collisions show a strong modification of charm-jet spectra in Pb–Pb collisions relative to reference data, as well as hints of larger angular separation between D mesons and inclusive jets. Further studies with heavy-flavour tagged jets and comparison with model calculations will help to understand how the heavy flavor jet structure is modified by the presence of the medium. Finally, the first measurement of non-zero directed flow of D^0 mesons in heavy-ion collisions, larger than that of lighter particles, suggests that heavy quarks are excellent probes of the initial vorticity and electromagnetic fields.

I expect important steps to be made in this field in the next years: the new detectors at RHIC and the LHC, and the LHC accelerator upgrade, will allow for higher precision and more differential measurements (analyses of heavy-flavour correlations and jets, event-shape engineering techniques) which, together with a close collaboration with the theory community, will provide deeper insights into the properties of the QCD matter at high temperatures and densities.

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