ALICE tracks charm energy loss in the QGP

The first direct observation of the suppression of charmed mesons at high transverse-momentum in head-on nucleus–nucleus collisions indicates that charm quarks suffer a strong loss of energy in hot quark–gluon plasma.

When heavy nuclei collide at high energies, a high-density colour-deconfined state of strongly interacting matter is expected to form. According to lattice QCD calculations, the confinement of coloured quarks and gluons into colourless hadrons vanishes under the conditions of high energy-density and temperature that are reached in these collisions and a phase transition to a quark–gluon plasma (QGP) occurs.

The LHC, operating with heavy ions, is nowadays the frontier machine for exploring the QGP experimentally, but such studies began 25 years ago with fixed-target experiments at the Alternating Gradient Synchrotron at Brookhaven and the Super Proton Synchrotron at CERN. The field entered the collider era in 2000 with Brookhaven's Relativistic Heavy-Ion Collider (RHIC). Experiments there showed that initial hard partonic collisions produce energetic quarks and gluons that interact with the hot and dense QGP, probing its properties and, more generally, those of the strong interaction in an extended many-body system. The abundant production of these "hard probes" constitutes one of the leading opportunities that have opened up at the LHC – where collisions of heavy ions have nearly a 14-fold increase in centre-of-mass energy with respect to RHIC – and their extensive study is a leading feature of the heavy-ion programmes of the ALICE, ATLAS and CMS experiments.

Heavy quark probes

High-momentum partons are created in hard-scattering processes that occur in the early stage of the nuclear collision. They subsequently traverse the hot QGP, losing energy as they interact with its constituents. This energy loss is expected to occur via inelastic processes (gluon radiation induced in the medium, or radiative energy loss, analogous to bremsstrahlung in QED) and via elastic processes (collisional energy loss).

The massive c and b quarks ($m_c \sim 1.5\,\text{GeV}/c^2$, $m_b \sim 5\,\text{GeV}/c^2$) are useful probes of these energy-loss mechanisms. In QCD, quarks have a lower colour coupling-strength than gluons, thus the energy loss should be smaller for quarks than for gluons. At LHC energies, hadrons containing light flavours originate mainly from gluons. Therefore, charmed mesons provide an experimental tag for a low colour-charge, quark parent. In addition, the "dead-cone effect" should reduce small-angle gluon radiation for heavy quarks that have moderate energy-over-mass values, i.e. for c and b quarks with momenta up to about 10 GeV/*c*.

The nuclear modification factor, R_{AA}, is one of the observables that are sensitive to the interaction of hard partons with the medium. This quantity is defined as the ratio of particle production measured in nucleus–nucleus (AA) interactions to that expected on the basis of the proton–proton (pp) spectrum, scaled by the average number of binary nucleon–nucleon collisions occurring in the collisions of the nuclei. Loss of energy in the medium leads to a suppression of hadrons at moderate-to-high transverse momentum ($p_t > 2\,\text{GeV}/c$), so $R_{AA} < 1$. In the range $p_t < 10\,\text{GeV}/c$, where the masses of the heavy c and b quarks are not negligible with respect to their momenta, the properties of parton energy-loss described above mean that an increase in R_{AA} (i.e. a smaller suppression) is expected when going from the mostly gluon-originated light-flavour hadrons (such as pions) to D and B mesons with c quarks and b quarks, respectively: $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$.

The measurement and comparison of these different probes provides a unique test of how the energy loss of the partons depends on their colour charge and mass. Because these dependences are predicted by QCD, their experimental verification is a crucial step for the understanding of the properties of the strongly interacting medium.

Experiments at RHIC reported a strong suppression, by a factor of 4–5 at $p_t > 5\,\text{GeV}/c$, for light-flavour hadrons in central collisions of gold nuclei at a centre-of-mass energy $\sqrt{s_{NN}} = 200\,\text{GeV}$. The suppression of heavy-flavour hadrons, measured inclusively from their decay electrons by the PHENIX and STAR experiments, turned out to be similar to that of pions and generally stronger than most expectations based on radiative energy loss. This striking ▷

Left: An event display of a lead–lead collision in ALICE, with the layers of the inner tracking system highlighted. These play an important role in identifying charmed mesons among the thousands of particles that are produced.

observation raised high expectations for the separate measurements of charm and beauty hadrons in the collisions of lead ions at $\sqrt{s_{NN}}$ = 2.76 TeV at the LHC. Such a study is favoured by the abundant production yields (e.g. about 50 $c\bar{c}$ pairs per central collision, according to perturbative QCD calculations) and by the design of the LHC experiments, all of which have excellent capabilities for the detection of heavy flavour.

Charmed meson suppression

In the ALICE experiment, the charmed mesons D^0, D^+ and D^{*+} are reconstructed in the central barrel through their decays to charged hadrons, namely $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^{*+} \rightarrow D^0\pi^+$, followed by $D^0 \rightarrow K^-\pi^+$. The signal is extracted from the invariant-mass distributions of the combinations of charged tracks reconstructed in the inner tracking system (ITS) and the time-projection chamber (TPC). The high-multiplicity environment of lead–lead (PbPb) interactions, where about 1600 primary charged particles per unit of rapidity are produced for head-on collisions, is particularly challenging for the exclusive reconstruction of D-meson decays because of the large combinatorial background. However, the signal-to-background ratio can be enhanced by requiring the separation of the D^0 and D^+ decay vertices from the interaction vertex. This separation, typically of a few hundred microns, is resolved thanks to the high-spatial-precision hits measured by the six-layer silicon ITS. Background is reduced further using the excellent particle-identification capabilities provided by the measurement of the specific energy deposit in the TPC and of the particle time-of-flight (TOF) from the interaction vertex to the TOF detector. The D-meson yields are corrected for detector effects and for the contribution from B-meson decays. The nuclear modification factor R_{AA} is then computed using as the pp reference the cross-section measured at 7 TeV centre-of-mass energy and scaled – via perturbative QCD calculations – to the PbPb energy of 2.76 TeV (ALICE collaboration 2012a).

Figure 1 shows the nuclear modification factor measured by ALICE in the transverse momentum interval $6 < p_t < 12$ GeV/*c*, as a function of the collision centrality for the three species of D meson (ALICE collaboration 2012b). The centrality of the collision is determined from the measured particle multiplicity and it is quantified by the average number of participant nucleons, $\langle N_{part} \rangle$, i.e. nucleons that suffered at least one inelastic scattering with a nucleon of the other nucleus. The more central the collision, the larger the number of participant nucleons. The observed suppression increases (R_{AA} decreases) with increasing centrality – as expected because of the larger, hotter and denser medium created in more central collisions – reaching a factor of about four for head-on collisions.

Figure 2 shows the average R_{AA} of the three D-meson species as a function of the transverse momentum for the most central collisions (ALICE collaboration 2012b). To study the expected dependences of the energy loss on colour charge and parton mass, the nuclear modification factor is compared with those of charged hadrons measured by ALICE and those of non-prompt J/ψ mesons (from B decays) measured by the CMS experiment for $p_t > 6.5$ GeV/*c* (CMS collaboration 2012). The charged-hadron nuclear modification factor is dominated by light flavours and coincides with that of charged pions above $p_t \approx 5$ GeV/*c*. This comparison between the values of R_{AA} for D mesons and charged hadrons shows that the average nuclear modification factor for the D mesons is close to that of charged hadrons. However, considering that the systematic uncertainties of D mesons are not fully correlated with p_t, there is an indication for $R_{AA}(D) > R_{AA}(\text{charged})$. The suppression of J/ψ from B decays is clearly weaker than that of charged hadrons, while the comparison with D mesons is not conclusive and requires more differential and precise measurements of the transverse momentum dependence.

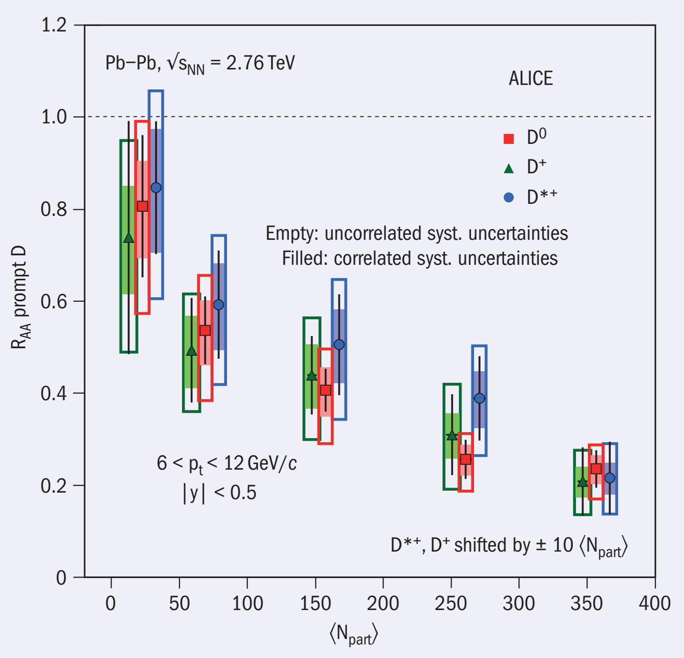
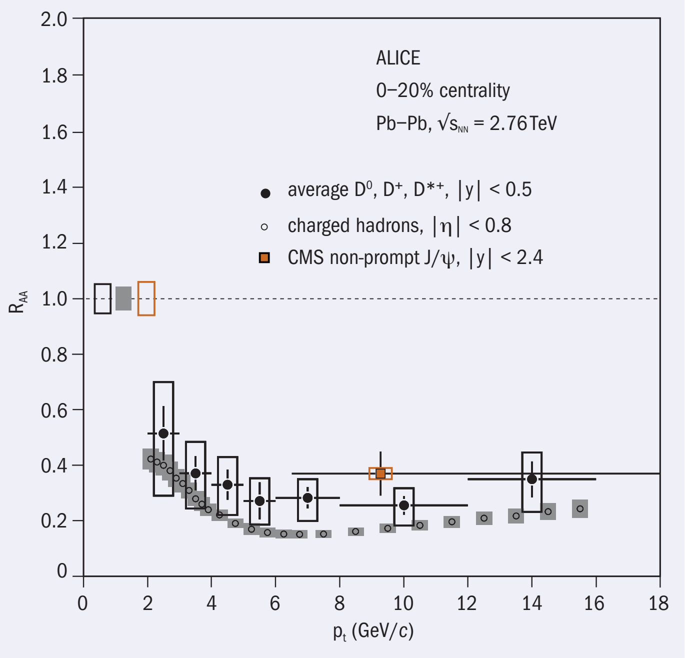


Fig. 1. Centrality dependence of R_{AA} for prompt D mesons with $6 < p_t < 12$ GeV/c.

Apart from final-state effects, which are related to the formation of a hot and deconfined medium, initial-state effects are also expected to influence the nuclear modification factor, because it is nuclei rather than nucleons that collide. In particular, the modification of the parton distribution functions (PDFs) of the nucleons in the nuclei affects the initial hard-scattering probability and, thus, the yields of energetic partons, including heavy quarks. In the kinematic range relevant for charm production at LHC energies, the main effect is nuclear shadowing, which induces a reduction in the yields of D mesons at low momentum. As shown in figure 3, a perturbative QCD calculation supplemented with a phenomenological parameterization of the nuclear modification of the PDFs indicates that the shadowing-induced effect on R_{AA} is limited to ±15% for $p_t > 6$ GeV/*c*. This suggests that the strong suppression observed in the high-p_t data is a final-state effect, arising predominantly from energy loss of c quarks in the medium.

Models based on parton energy loss describe well the measured suppression of high-momentum charmed mesons.



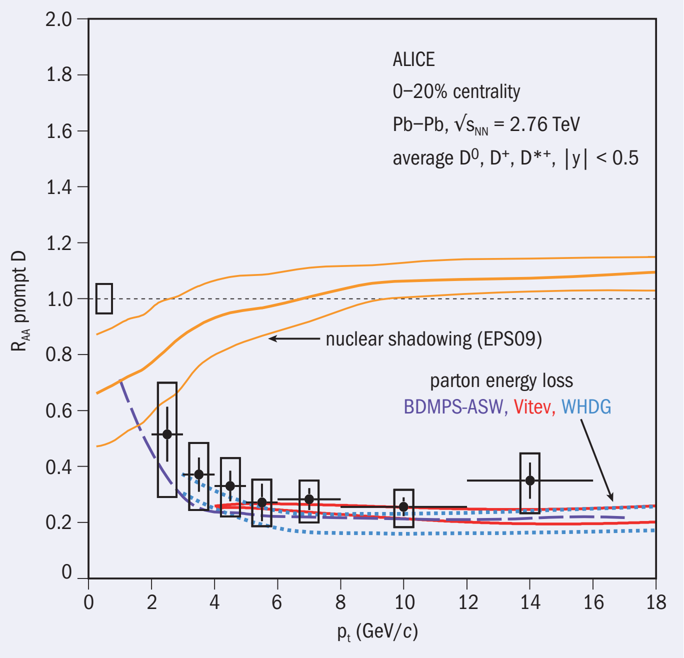


Fig. 2. Average R_{AA} of D mesons in the 0–20% centrality class compared with the nuclear modification factors of charged hadrons and non-prompt J/ψ from B decays in the same centrality class. The boxes at R_{AA}=1 represent the relative normalization uncertainties.

Fig. 3. Average R_{AA} of D mesons in the 0–20% centrality class compared with a perturbative QCD calculation that is supplemented with nuclear shadowing and to models that implement parton energy loss.

Theoretical models based on parton energy loss describe well the measured suppression of high-momentum charmed mesons. Figure 3 displays the comparison with the data of some selected models that within the same framework compute the suppression of particles with heavy and light flavour. A thorough validation of the ingredients of the models, which differ from one another, requires a systematic comparison, extended to higher momentum, over a range in collision centrality for a variety particle species, in particular beauty hadrons. This will eventually provide important constraints on the energy density of the hot QGP formed at the LHC.

In conclusion, the first ALICE results on the nuclear modification factor R_{AA} for charm hadrons in PbPb collisions at a centre-of-mass energy $\sqrt{s_{NN}}$ = 2.76 TeV indicate strong in-medium energy loss for charm quarks. There is a possible indication, which is not fully significant with the current level of experimental uncertainties, that $R_{AA}(D) > R_{AA}(\text{charged})$. The precision of the measurements will be improved in the future, using the large sample of PbPb collisions recorded in 2011. In addition, proton–lead collisions will provide insight into possible initial-state effects, which may play an important role, mainly in the low-momentum region.

● Further reading

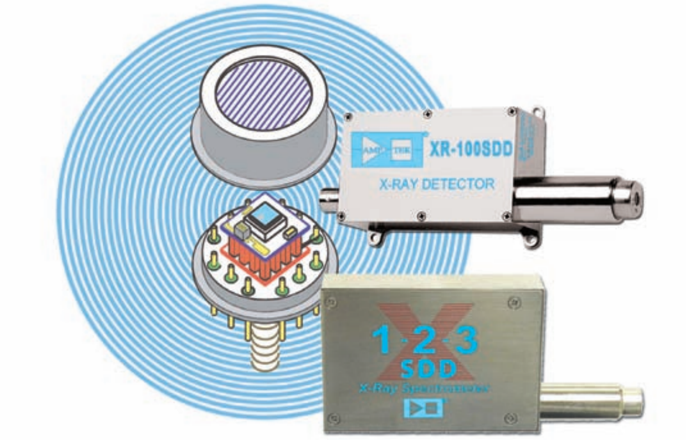
ALICE collaboration 2012a *JHEP* **1201** 128, arXiv:1111.1553.
ALICE collaboration 2012b arXiv:1203.2160.
CMS collaboration 2012 arXiv:1201.5069.

Résumé

ALICE cherche la perte d'énergie du charme dans le plasma

La collaboration ALICE a publié de premiers résultats concernant la production de mésons charmés (D^0, D^+ et D^{*+}) dans les collisions plomb–plomb au LHC. Dans les collisions centrales, où l'on s'attend à voir se former un plasma quarks–gluons chaud et dense, la production à une impulsion transversale élevée est largement réduite par rapport aux attentes fondées sur les mesures relatives aux collisions proton–proton. Ce déficit indique que les quarks charmés connaissent une forte perte d'énergie dans l'état chaud et dense de la matière formé dans ces collisions.

Andrea Dainese, INFN Padova, and **Francesco Prino**, INFN Torino, on behalf of the ALICE collaboration.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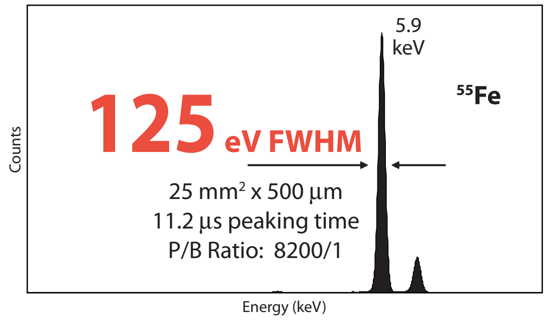
X-RAY DETECTOR
AMP TEK
1 2 3
SDD
X-Ray Spectrometer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^{55}Fe
125 eV FWHM
25 mm^2 x 500 µm
11.2 µs peaking time
P/B Ratio: 8200/1
Counts
Energy (keV)


1 2 3
X-Ray Spectrometer
XR-100CR
Si X-RAY DETECTOR
AMP TEK