Charm quenching in heavy-ion collisions at the LHC

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Abstract
D-meson suppression in Pb–Pb collisions at the LHC due to charm quark in-medium energy loss is estimated within a model that describes the available quenching measurements at RHIC. The result is compared to that previously published by the author. The expected sensitivity of the ALICE experiment for studying charm energy loss via fully reconstructed D^0-meson decays is also presented.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

High-p_t particle suppression in nucleus–nucleus (AA) with respect to pp collisions is regarded as one of the major discoveries at RHIC. The effect can be quantified with the nuclear modification factor:

$$R_{AA}(p_t) \equiv \frac{1}{\langle N_{coll}\rangle_{\text{centrality class}}} \times \frac{d^2 N_{AA}/dp_t d\eta}{d^2 N_{pp}/dp_t d\eta},\tag{1}$$

which, at high p_t, would be equal to unity if the AA collision was a mere superposition of N_{coll} independent NN collisions. In central Au–Au collisions at centre-of-mass energy $\sqrt{s_{NN}} = 200\,\text{GeV}$ per nucleon–nucleon (NN) pair the PHENIX and STAR experiments have measured $R_{AA} \simeq 0.2$ at high p_t ($\gtrsim 4\,\text{GeV}$) and central pseudorapidity ($|\eta| \lesssim 1$) [1]. The observed suppression is explained in terms of hard-parton energy loss (quenching) due to gluon radiation induced by the dense QCD medium expected to be formed in high-energy heavy-ion collisions (see [2–4] and references therein). As the effect depends on the medium properties, and on its density in particular, hard partons can be used as probes to perform tomographic studies of the medium itself.

Charm and beauty quarks are qualitatively different probes with respect to light partons, since the 'dead-cone effect' is expected to reduce the in-medium gluon radiation off massive partons [5]. At the LHC, more than 100 $c\bar{c}$ pairs are expected to be produced per central Pb–Pb collision at $\sqrt{s_{NN}} = 5.5\,\text{TeV}$ and the detectors will be equipped with high position-resolution tracking systems, specifically designed for heavy-flavour detection. Therefore, it will be

important to carry out a comparative study of the quenching of massless and massive probes in order to (a) test the consistency of the interpretation of the effect as due to energy loss in a deconfined medium and (b) further investigate the properties (density) of such a medium.

2. Energy loss for massive partons in the BDMPS formalism

We calculate in-medium parton energy loss in the framework of the 'BDMPS' (Baier–Dokshitzer–Mueller–Peigné–Schiff) formalism, reviewed in [3].

In a simplified picture, a parton produced in a hard collision undergoes, along its path in the medium, multiple scatterings in a Brownian-like motion with mean free path λ. Consequently, the gluons in the parton wavefunction pick up transverse momentum k_t with respect to its direction and they may eventually decohere and be radiated.

The scale of the energy loss is set by the characteristic energy of the radiated gluons, $\omega_c = \hat{q} L^2 / 2$, which depends on the in-medium path-length L of the parton and on the BDMPS transport coefficient of the medium, $\hat{q}$. The transport coefficient is defined as the average medium-induced transverse momentum squared transferred to the parton per unit path length, $\hat{q} = \langle k_t^2 \rangle_{\text{medium}} / \lambda$ [3].

In the case of a static medium, the distribution of the energy ω of the radiated gluons (for $\omega \ll \omega_c$) is of the form:

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \simeq \frac{2\alpha_s C_R}{\pi} \sqrt{\frac{\omega_c}{2\omega}}, \tag{2}$$

where C_R is the QCD coupling factor (Casimir factor), equal to 4/3 for quark–gluon coupling and to 3 for gluon–gluon coupling. In the case of infinite parton energy, $E \to \infty$, the integral of the radiated-gluon energy distribution up to ω_c estimates the average energy loss of the parton:

$$\langle \Delta E \rangle = \int_0^{\omega_c} \omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \mathrm{d}\omega \propto \alpha_s C_R \omega_c \propto \alpha_s C_R \hat{q} L^2. \tag{3}$$

The average energy loss is proportional to C_R and, thus, larger by a factor 9/4 for gluons than for quarks, proportional to the transport coefficient of the medium, proportional to L^2, independent of the parton initial energy E. However, when the realistic case of finite parton energies is considered, the energy loss ΔE has to be constrained to be smaller than E. As discussed in [6, 17], this effectively results in reducing the difference between quark and gluon average energy losses and in changing the L dependence from quadratic to approximately linear. Moreover, since a consistent theoretical treatment of the finite-energy constraint is at present lacking in the BDMPS framework, approximations have to be adopted, thus introducing uncertainties in the results [6].

Heavy quarks with moderate energy, i.e. $m/E > 0$, propagate with a velocity $\beta = \sqrt{1 - (m/E)^2}$ significantly smaller than the velocity of light, $\beta = 1$. As a consequence, in vacuum, gluon radiation at angles Θ smaller than the ratio of their mass to their energy $\Theta_0 = m/E$ is suppressed by destructive interference [7]. The relatively depopulated cone around the heavy-quark direction with $\Theta < \Theta_0$ is called 'dead cone'. In [5] it is argued that the dead-cone effect should characterize also in-medium gluon radiation and it is approximated by means of a suppression factor that multiplies the energy distribution of the radiated gluons (2):

$$\frac{\mathrm{d}I}{\mathrm{d}\omega}\bigg|_{\text{Heavy}} \bigg/ \frac{\mathrm{d}I}{\mathrm{d}\omega}\bigg|_{\text{Light}} = \left[1 + \frac{\Theta_0^2}{\Theta^2}\right]^{-2} = \left[1 + \left(\frac{m}{E}\right)^2 \sqrt{\frac{\omega^3}{\hat{q}}}\right]^{-2} \equiv F_{\text{H/L}}, \tag{4}$$

where the expression for the characteristic gluon emission angle [5] $\Theta \simeq (\hat{q}/\omega^3)^{1/4}$ has been used. The heavy-to-light suppression factor $F_{\mathrm{H/L}}$ in (4) increases (less suppression) as the heavy-quark energy E increases (the mass becomes negligible) and it decreases at large ω, indicating that the high-energy part of the gluon radiation spectrum is drastically suppressed by the dead-cone effect.

A recent detailed calculation of the radiated-gluon energy distribution $\omega \mathrm{d}I/\mathrm{d}\omega$ in the case of massive partons [8] confirms the qualitative feature of lower energy loss for heavy quarks, although the effect is found to be quantitatively smaller than that derived with the dead-cone approximation of [5]. A comparison of the results obtained in the two cases for the D-meson suppression in central Pb–Pb collisions at the LHC will be presented at the end of section 3.3.

3. Calculating nuclear modification factors

3.1. The model

The nuclear modification factor R_{AA} for D mesons is calculated in a Monte Carlo approach developed in [6] for light-flavour hadrons. In this approach partons are produced and hadronized with the PYTHIA event generator [9] and energy loss is sampled combining the 'BDMPS quenching weights' and a realistic description of the nucleus–nucleus collision geometry.

The quenching weight is the parton-energy-loss probability distribution, $P(\Delta E)$, and it is calculated from the radiated-gluon energy spectrum $\omega \mathrm{d}I/\mathrm{d}\omega$ [4]. Input parameters are α_{s}, which we fix to $1/3$; C_{R}; $\hat{q}$ and L, which are different for every parton and depend on the medium geometry and density profile. The distribution of parton production points in the plane transverse to the beam direction and the density profile of the medium are both parametrized with the product of the Glauber-model thickness functions of the two colliding nuclei. We do not consider the medium expansion, since it was shown [4] that this effect can be accounted for by using an equivalent static medium with a time-averaged transport coefficient $\hat{q}$. The procedure to compute, parton-by-parton, $\hat{q}$ and L as integrals along the parton propagation direction in the transverse plane is described in [6]. The absolute magnitude of $\hat{q}$ is set by a $\sqrt{s_{\mathrm{NN}}}$-dependent scale parameter, k, and the decrease of the medium density (and, hence, of $\hat{q}$) when going from central to peripheral collisions is automatically given by the decrease of the product of the thickness functions.

The Monte Carlo chain used to obtain the quenched hadron p_{t} distribution is:

(i) Generation of a parton with PYTHIA (pp collisions).
(ii) Sampling of a production point and azimuthal propagation direction.
(iii) Determination of $\hat{q}$ and L and, from these, of the $P(\Delta E)$ distribution.
(iv) Sampling of a ΔE to be subtracted from the initial parton energy E. As aforementioned, the BDMPS calculations are done in the limit $E \to \infty$; therefore, for small E part of the $P(\Delta E)$ distribution lies above E. Since there is no unique way to implement the finite-energy constraint $\Delta E \leqslant E$, we use two approaches [6] and use the band between the two results to visualize the theoretical uncertainty.
(v) Hadronization of the parton to a hadron according to a fragmentation function.

The nuclear modification factor is calculated as the ratio of the quenched to unquenched (only steps (i) and (v)) p_{t} distributions.
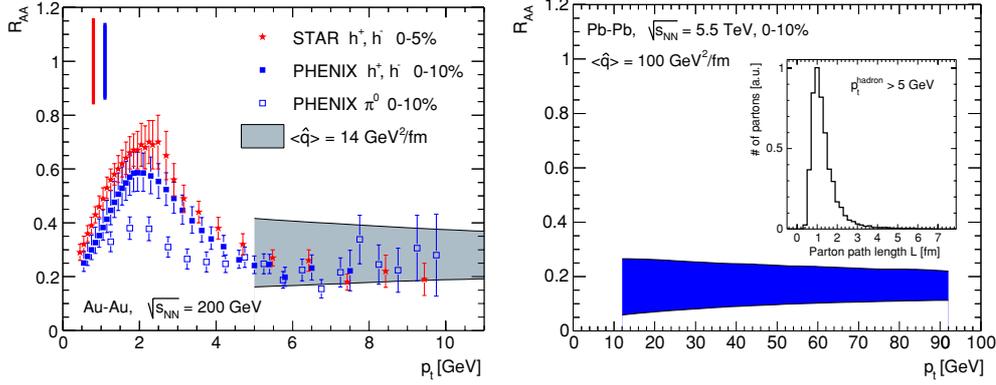
Figure 1. Charged hadrons ($h^{\pm}$) and $\pi^0 R_{AA}(p_t)$ in central collisions at RHIC (left) and LHC (right). PHENIX and STAR data [1] are reported with combined statistical and p_t-dependent systematic errors (bars on the data points) and p_t-independent systematic errors (bars at $R_{AA} = 1$). The model bands correspond to $\langle \hat{q} \rangle \approx 14\,\mathrm{GeV}^2\,\mathrm{fm}^{-1}$ (RHIC) and $\langle \hat{q} \rangle \approx 100\,\mathrm{GeV}^2\,\mathrm{fm}^{-1}$ (LHC) [6]. For the LHC case, the inset shows the L distribution for partons that escape the medium and fragment into hadrons with $p_t > 5\,\mathrm{GeV}$.

### 3.2. Light-flavour hadrons suppression from RHIC to LHC

The model was tuned for light-flavour hadrons in central Au–Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ [6]. In this case PYTHIA was used with CTEQ4L parton distribution functions [10] to generate light quarks (u, d) and gluons and hadronization was done with KKP fragmentation functions [11]. The scale parameter k was chosen in order to reproduce the R_{AA} suppression measured by PHENIX and STAR for charged hadrons ($h^{\pm}$) and π^0. The result is shown in the left-hand panel of figure 1: the p_t independence of the suppression for $p_t \gtrsim 5\,\mathrm{GeV}$ [1] is well reproduced and the ensuing parton-averaged $\langle \hat{q} \rangle$ is $\approx 14\,\mathrm{GeV}^2\,\mathrm{fm}^{-1}$. The measured centrality dependence of the R_{AA} suppression, as well as that of the back-to-back jet-like di-hadron correlations disappearance, is correctly reproduced by the model without changing the value of k [6].

The extrapolation of $\hat{q}$ from RHIC to LHC energy was done by assuming the scaling $\hat{q} \propto n^{\mathrm{gluons}}$, where n^{gluons} is the initial volume density of gluons, which, according to the saturation model [12], increases by a factor ≈ 7 when $\sqrt{s_{NN}}$ increases from 200 GeV to 5.5 TeV. The simulation for charged hadrons at the LHC was performed by running PYTHIA at $\sqrt{s_{NN}} = 5.5\,\mathrm{TeV}$ and computing energy loss with $k_{\mathrm{LHC}} = 7k_{\mathrm{RHIC}}$ (i.e. $\langle \hat{q} \rangle_{\mathrm{LHC}} \approx 100\,\mathrm{GeV}^2\,\mathrm{fm}^{-1}$) [6]. The resulting nuclear modification factor in central Pb–Pb collisions, shown in the right-hand panel of figure 1, is of 0.1–0.2 and rather independent of p_t up to 100 GeV. The path-length distribution for partons that escape the medium with large enough energy to fragment into hadrons with $p_t > 5\,\mathrm{GeV}$, shown in the inset, reveals that, within this model extrapolation, only partons produced close to the surface ($L \lesssim 2\,\mathrm{fm}$) can escape the medium, while all other partons are absorbed.

3.3. Estimate of D-meson suppression at the LHC

In order to study the nuclear modification of the D mesons in central Pb–Pb collisions at the LHC, we generate c quarks with PYTHIA using a set of parameters that allows us to

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[1] Since, for light-flavour hadrons, we did not include the nuclear modification of the parton distribution functions, we show the model results for $p_t > 5\,\mathrm{GeV}$ at RHIC energy and for $p_t > 10\,\mathrm{GeV}$ at LHC energy, where this effect is expected to be small.
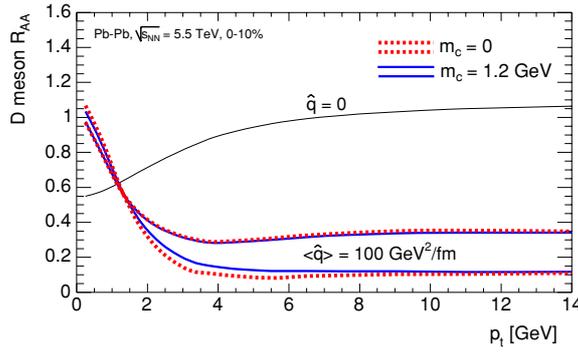
Figure 2. D-meson nuclear modification factor in central (0–10%) Pb–Pb collisions at the LHC [16]. The curve labelled '$\hat{q} = 0$' includes only nuclear shadowing. The two bands include *also* energy loss for massless (dashed) or massive (solid) c quarks, with a quark-averaged $\langle \hat{q} \rangle \approx 100 \, \text{GeV}^2 \, \text{fm}^{-1}$.

reproduce the p_t distribution given by next-to-leading order (NLO) perturbative QCD (pQCD) calculations [13] with charm mass $m_c = 1.2 \, \text{GeV}$ and factorization and renormalization scales $\mu_F = \mu_R = 2m_t$, where $m_t = \sqrt{p_t^2 + m_c^2}$ is the c-quark transverse mass, (see [14]). We use CTEQ4L parton distribution functions (PDFs) and include, for Pb–Pb, their nuclear modification (shadowing) in the EKS98 parametrization [15]. For the hadronization to D mesons, we use a fragmentation function parametrized from PYTHIA pp simulations done with the standard Lund string model.

The energy loss is sampled from the quenching weights for massive partons calculated [16] with the full massive formalism developed in [8]. The sampling procedure is the same as for charged hadrons (section 3.2) and the same scale parameter $k_{\text{LHC}} = 7k_{\text{RHIC}}$ is used. Differently from the case of charged hadrons, c quarks that lose all their energy, $\Delta E = E$, are 'thermalized' and assigned a transverse momentum according to the transverse mass distribution $dN/dm_t \propto m_t \exp[-m_t/(300 \, \text{MeV})]$; thus, the total c-quark production cross section is conserved.

Figure 2 shows the estimated R_{AA} for D mesons. The effect of shadowing is visible as a suppression at low p_t in the curve without energy loss. The EKS98 parametrization gives a reduction of a factor about 0.65 for the total $c\bar{c}$ cross section and the suppression, at the D-meson level, is limited to the region $p_t \lesssim 7 \, \text{GeV}$, corresponding to partonic momentum fractions (x Bjorken) $x_1 \simeq x_2 \lesssim 3 \times 10^{-3}$. Since there is a significant uncertainty on the magnitude of shadowing in this x region, we studied the effect of such uncertainty on R_{AA} by varying the modification of the PDFs in a Pb nucleus. Even in the case of shadowing 50% stronger than in EKS98, we found $R_{\text{AA}} > 0.93$ for $p_t > 7 \, \text{GeV}$ [18]. We can, thus, conclude that c-quark energy loss can be cleanly studied, being the only expected effect, for $p_t \gtrsim 7 \, \text{GeV}$.

The results that include shadowing *and* energy loss, with $\langle \hat{q} \rangle \approx 100 \, \text{GeV}^2 \, \text{fm}^{-1}$, are presented as two bands, obtained with $m_c = 0$ and $m_c = 1.2 \, \text{GeV}$ [16]. According to this estimate and within the present theoretical uncertainties, the two results, massless and massive, do not differ significantly. The predicted D-meson R_{AA} is in the range 0.1–0.35 and essentially p_t independent for $p_t > 7 \, \text{GeV}$.

In a previous estimate [17, 18], done before the analysis of RHIC data that we have summarized in section 3.2, we had employed a similar Monte Carlo procedure and description of the system geometry but a much smaller value for the transport coefficient,
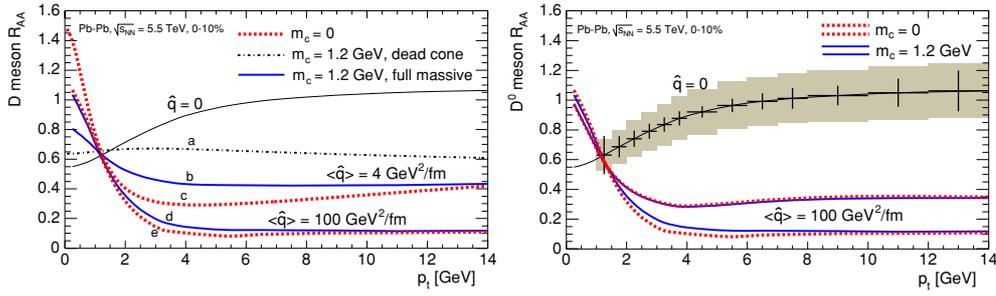
Figure 3. Left: current results on D-meson R_{AA} compared to those previously published in [17] (see text for details). Right: expected sensitivity attained by ALICE with $D^0 \rightarrow K^-\pi^+$ reconstruction; bars = statistical errors, shaded area = combined systematic errors (see text).

$\hat{q} = 4\,\mathrm{GeV^2\,fm^{-1}}$, that was expected to be 'reasonable' for the LHC (see, e.g., [19]). As the full massive calculation of the radiated-gluon energy distribution [8] was not yet available, we had included the effect of the c-quark mass by means of the dead-cone approximation (4) of [5]. In that work we had found a significant difference between the massive and massless results [17, 18]. In figure 3, left-hand panel, we show how the results of [18, 17] with $\hat{q} = 4\,\mathrm{GeV^2\,fm^{-1}}$ and the dead cone evolved into the present ones with $\hat{q} = 100\,\mathrm{GeV^2\,fm^{-1}}$ and the full massive calculation (for simplicity, we plot only the curves corresponding to the lower bound of the uncertainty bands of figure 2). As a first step, keeping $\hat{q} = 4\,\mathrm{GeV^2\,fm^{-1}}$, we remove the dead-cone approximation (curve 'a') and use the full massive calculation (curve 'b'): the difference with respect to the massless result (curve 'c') is already reduced. Then, we increase $\hat{q}$ to $100\,\mathrm{GeV^2\,fm^{-1}}$: the suppression is much stronger and the difference between massive (curve 'd') and massless (curve 'e') is further reduced. We are now in a scenario in which only partons produced nearby the surface escape and the (small) difference induced by the mass of the c quark on the gluon-radiation phase space becomes a minor effect. The effect should be more significant for the heavier b quarks [16].

4. Measurement of the D-meson nuclear modification factor with ALICE

The transverse momentum distribution of D^0 mesons produced at central rapidity, $|y| < 1$, can be directly measured from the exclusive reconstruction of $D^0 \rightarrow K^-\pi^+$ decays (and charge conjugates) in the inner tracking system (ITS), time projection chamber (TPC) and time of flight (TOF) detectors of the ALICE barrel, $|\eta| < 0.9$ [20]. The expected production yields per unit of rapidity at central rapidity for D^0 (and $\overline{D^0}$) mesons decaying in a $K^\mp\pi^\pm$ pair, estimated [14] on the basis of NLO pQCD calculations with $m_c = 1.2\,\mathrm{GeV}$ and $\mu_F = \mu_R = 2m_t$, are $BR \times dN/dy = 5.3 \times 10^{-1}$ in central (0–5%) Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5\,\mathrm{TeV}$ and $BR \times dN/dy = 7.5 \times 10^{-4}$ in pp collisions at $\sqrt{s} = 14\,\mathrm{TeV}$. The main feature of the D^0 decay topology is the presence of two tracks displaced from the interaction point by, on average, 50 μm, for D-meson $p_t \simeq 0.5\,\mathrm{GeV}$, to 120 μm, for $p_t \gtrsim 5\,\mathrm{GeV}$. Such displacement can be resolved with the ALICE tracking detectors and thus a large fraction of the combinatorial background in the $K^\mp\pi^\pm$ invariant mass distribution can be rejected. The low value of the magnetic field, 0.4 T, and the K/π separation in the TOF detector extend the D^0 measurement down to $p_t \approx 1\,\mathrm{GeV}$. The analysis strategy and the pertinent selection cuts were studied with a detailed simulation of the detector geometry and response, including the main background sources [18, 21]. The accessible p_t range is

1–14 GeV for Pb–Pb and 0.5–14 GeV for pp collisions. The statistical error corresponding to 1 month of Pb–Pb data taking ($\sim 10^7$ central events) and 9 months of pp data taking ($\sim 10^9$ events) is better than 15–20% and the systematic error (acceptance and efficiency corrections, subtraction of the feed-down from $B \to D^0 + X$ decays, cross-section normalization, centrality selection for Pb–Pb) is better than 20% [18].

In figure 3 (right-hand panel) we show the expected sensitivity for the measurement of the D^0 meson R_{AA}. The reported errors, associated with the curve with shadowing and *no* energy loss, are obtained combining the previously mentioned errors in Pb–Pb and in pp collisions and considering that several systematic contributions will partially cancel out in the ratio. The uncertainty of about 5% introduced in the extrapolation of the pp results from 14 TeV to 5.5 TeV by means of pQCD, estimated in [18], is also included. In the p_t range 7–14 GeV, where energy loss is the only expected effect, R_{AA} can be measured with systematic errors better than 20% and statistical errors better than 15%.

5. Conclusions

We estimated the nuclear modification factor for open-charm mesons in central Pb–Pb collisions at LHC energy, including PDFs shadowing and parton-energy-loss effects. The latter were simulated using a model that combines the BDMPS quenching weights (specifically calculated for heavy quarks) and a realistic description of the collision geometry. The medium transport coefficient was extrapolated, according to the saturation model, from the value needed to describe $h^{\pm}$ and π^0 data at RHIC.

The D-meson suppression due to energy loss is found to be of approximately a factor of 5 for $p_t \gtrsim 4$ GeV. The comparison of our results with $m_c = 0$ and 1.2 GeV suggests that the c-quark mass may not reduce significantly the suppression, in contrast to what expected from the dead-cone effect. This is due to (a) the fact that the dead-cone effect resulting from the full massive calculation is indeed quite small for charm quarks and (b) the fact that, within this model, the medium is found to be very opaque, already at RHIC energies, and only partons produced nearby the surface can escape. Note, however, that the results have a significant uncertainty, because a rigorous theoretical treatment of the finite parton energies is still lacking in all parton-energy-loss calculations.

The ALICE experiment, whose inner tracker is specifically optimized for heavy-flavour measurements, can address the intriguing phenomenology of charm quenching by reconstructing $D^0 \to K^- \pi^+$ decays and measuring with good sensitivity the D nuclear modification factor up to about 15 GeV in transverse momentum.

Acknowledgment

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