HEAVY QUARKS AT THE LHC*

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Ultra-relativistic collisions of heavy ions allow studying strongly interacting matter at extreme energy densities and temperatures. Quantum Chromodynamics predicts that at such conditions normal, hadronic matter turns into a plasma of deconfined quarks and gluons, which are the constituents of atomic nuclei. In cosmology, it is believed that matter in the early universe must have existed in this Quark–Gluon Plasma (QGP) state within the first microseconds after the Big Bang. After the compelling evidence for the existence of the QGP from the previous heavy-ion accelerators SPS and RHIC, the Large Hadron Collider (LHC) at CERN marks the beginning of the exploration of the QGP properties. In this contribution, I will present an overview of the recent heavy-flavour results from the LHC and discuss them in relation to the previous findings.

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1. Introduction

Quantum Chromodynamics (QCD) is well established as the fundamental theory describing the most powerful force in nature, the strong interaction between quarks and gluons. One of the characteristic features of QCD is asymptotic freedom where the interaction becomes weak at large momentum transfer. In contrast, the potential between the quarks rises steeply when they are separated. In fact, the binding force becomes so strong that, in our normal world, quarks and gluons are permanently confined inside hadrons. A fascinating and direct consequence of asymptotic freedom is that under the conditions of sufficiently high temperature or density, the strongly interacting quarks and gluons are liberated from their hadronic confinement.

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This extraordinary new state of matter, where the basic degrees of freedom are released, is called the Quark–Gluon Plasma (QGP). In cosmology, it is believed that the early expanding universe consisted of such plasma approximately 10 microseconds after the Big Bang. This plasma subsequently underwent a phase transition where quarks and gluons became confined to form colourless hadrons, which represent observed particles today. Quark matter may still exist in the core of neutron stars, where the density could exceed the critical value of the phase transition. The properties of such matter are fundamental predictions of QCD and its study is one of the leading and most active fields in contemporary subatomic physics. The aim of high-energy heavy-ion physics is to create the QGP and carefully study its complex nature under controlled laboratory conditions (for recent reviews, see [1, 2]).

At the onset of the collision, the quark and gluon constituents of the incoming nuclei can undergo hard collisions. In elementary proton–proton interactions, these hard-scattered quarks or gluons fragment in the vacuum into jets of collimated, high transverse momentum particles, whose properties can be measured in the detectors (Fig. 1, left panel). In heavy-ion collisions however, these very energetic quarks or gluons traverse through the formed QGP matter and get slowed down or absorbed, much like X-rays traversing a tissue sample (Fig. 1, right panel). The properties of the QGP matter can be studied through the attenuation of these energetic jets [3]. Measurements at the RHIC facility have revealed a softening and broadening of jets inside the QGP matter [1]. The observed jet attenuation is

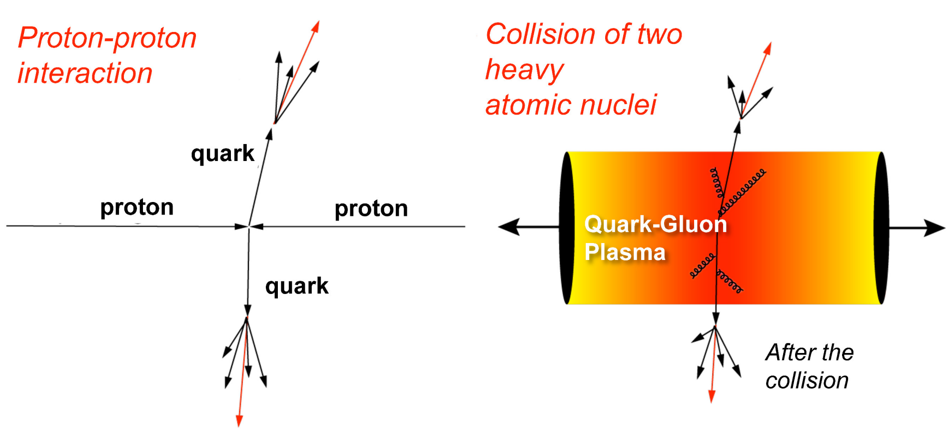

Fig. 1. Sketch of an elementary proton–proton interaction (left panel) and a collision of two heavy atomic nuclei (right panel) where a Quark–Gluon Plasma is formed.

evidence of the extreme energy loss of quarks or gluons traversing a large density of colour charges (so-called jet-quenching) [3] and reflects the extreme opacity of the QGP. First attempts have been made to determine the stopping power of the QGP.

In November 2010, the Large Hadron Collider (LHC) started operation with heavy ion beams, colliding lead nuclei at a centre-of-mass energy of 2.76 TeV per nucleon–nucleon pair. This opened a new era in ultra-relativistic heavy ion physics at energies exceeding previous accelerators by more than an order of magnitude. The initial energy density in the collision zone is about a factor of 3 higher than at the RHIC facility. The higher energy density allows thermal equilibrium to be reached more quickly and to create a relatively long-lived QGP phase. Therefore, most of the in-medium effects should be enhanced, and this has already been observed at the LHC. Precise studies of the jet modification in the QGP matter were performed and important aspects of the jet-quenching theory have been tested over a much broader dynamic range than before [4].

Of particular interest is the dependence of the parton energy loss on colour charge and quark mass [5], which gives access to the dynamical properties of the QGP. For this purpose, heavy quarks (charm and beauty) are the ideal probes. Charm quarks are about 250 times heavier than the light up and down quarks that dominate the QGP phase, and their mass is not affected by chiral symmetry breaking [6]. Beauty quarks are even 3–4 heavier than charm quarks. These large masses mean that charm and beauty quarks have much higher penetrating power than light quarks. Due to their large mass, heavy quarks are produced predominantly in the (hottest) initial phase of the collision via gluon fusion processes [7] and, therefore, probe the complete space-time evolution of the QGP. As RHIC measurements have shown [8, 9], heavy-quark production by initial state gluon fusion dominates in heavy-ion collisions where many (in part overlapping) nucleon–nucleon collisions occur. Thermal processes later in the collision might contribute to heavy-quark production at low transverse momentum [10].

The data reported in this contribution are obtained from the ATLAS, ALICE, CMS and LHCb experiment at the CERN-LHC [11]. The measurement and analysis techniques are detailed elsewhere [12].

2. Baseline measurements: Open heavy-flavour production in elementary proton–proton interactions

Open charm production in inelastic pp collisions at $\sqrt{s} = 2.76$ and 7 TeV has been studied by the ALICE, ATLAS and LHCb experiment [13–15]. It is determined through the measurement of the direct reconstruction of D mesons in the hadronic decay channel. In Fig. 2 (left panel), the total nucleon–nucleon charm cross sections are compared to results at lower collision energies and to next-to-leading-order (NLO) perturbative QCD calculations [16]. A very good agreement between the LHC experiments is observed. The data are systematically higher than the central value of the NLO pQCD calculations, but consistent within theoretical uncertainties. The measured beauty production cross section [17] agree with the FONLL calculation in the studied $\sqrt{s}$ range.

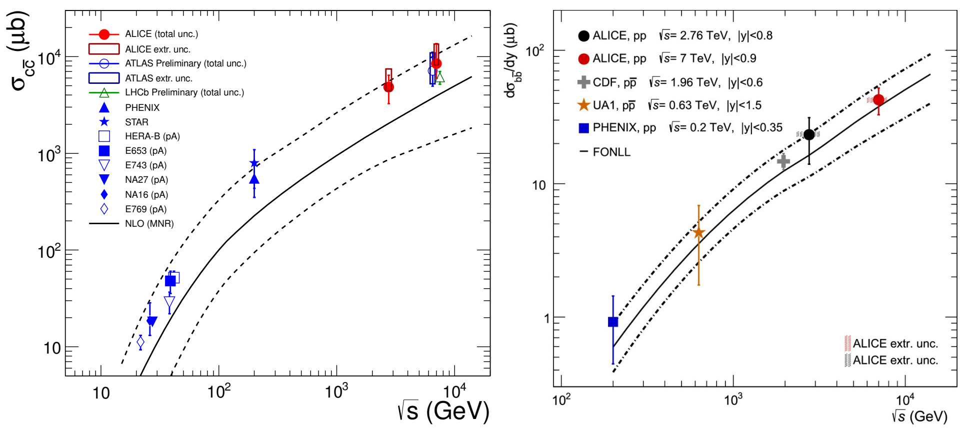

Fig. 2. Total nucleon–nucleon charm (left panel) and beauty production cross section (right panel) *versus* centre-of-mass energy [13, 17]. The NLO MNR calculation [16] (and its uncertainties) is shown by solid (dashed) lines.

ATLAS has measured the D^{*+} meson production in jets in pp collisions at $\sqrt{s} = 7$ TeV for jets with a transverse momentum between 25 and 70 GeV [18]. Figure 3 depicts the 'D^{*+} in jet' production rate (R) at mid-rapidity for two different jet energies. The data are compared to state-of-the-art NLO pQCD calculations using the Monte Carlo event generators Pythia and HERWIG for parton showering. Since R is defined as the ratio between the number of D^{*+} jets and inclusive jets, the changes of total jet cross sections and p_{T} distributions between LO and NLO QCD calculations largely cancel. However, the Monte Carlo calculations fail to describe the data at small fractional momentum of the D^{*+} mesons (z). This discrepancy is strongest at low jet transverse momentum and cannot be explained by varying the mixture of charm and beauty jets in the Monte Carlo calculations. Rather this is an indication that jet fragmentation into D^{*+} mesons is not well modelled in current Monte Carlo generators.

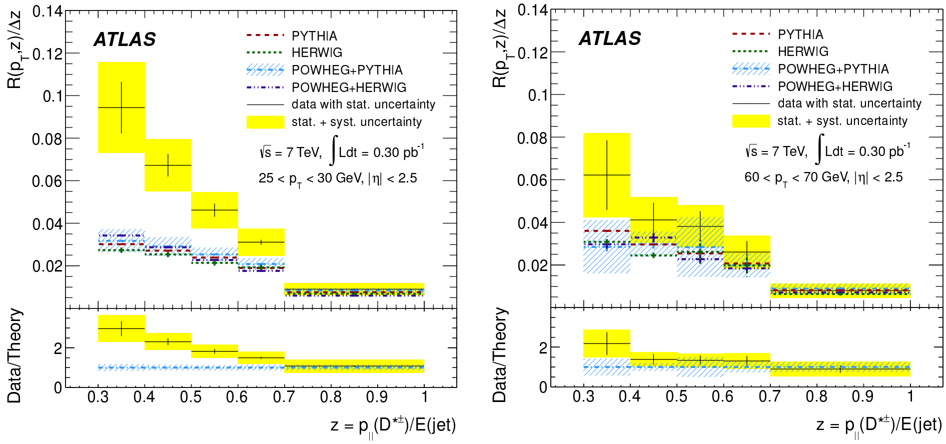

Fig. 3. D production rate $R(p_{\mathrm{T}}, z)/\Delta z$ in the jet p_{T} range of 25–30 GeV (left panel) and 60–70 GeV (right panel) *versus* z, measured in 7 TeV proton–proton interactions [18], compared with predictions from Monte Carlo event generators.

3. Energy loss of heavy quarks

The particle production yield in heavy ion collisions has contributions from both initial- and final-state effects. They are typically quantified using the nuclear modification factor R_{AA}, where the particle yield in nucleus–nucleus collisions is normalised by the yield in proton–proton reactions scaled by the number of binary collisions. Initial-state effects, such as Cronin enhancement, nuclear shadowing and gluon saturation [19–22], result in an R_{AA} different from 1. Final state effects, such as radiative and collisional energy loss in the QGP matter, give an R_{AA} smaller than unity [23]. The so-called "dead cone effect" is expected to reduce the radiative energy loss for heavy quarks compared to light quarks. By comparing the nuclear modification factor of charged pions ($R_{AA}^{\pi^{\pm}}$), mostly originating from gluon fragmentation at this collision energy, with that of hadrons with charm R_{AA}^{D} and beauty R_{AA}^{B} the dependence of the energy loss on the parton nature (quark/gluon) and mass can be investigated.

Figure 4 illustrates the R_{AA} for prompt D mesons at mid-rapidity in lead–lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The D meson yield for the most central events is strongly suppressed (by factor of ≈ 5 at around 10 GeV/c). Energy loss models currently describe the observed suppression at high transverse momentum reasonably well [24] whereas the description at low transverse momentum (≤ 2 GeV/c) is more challenging. The D meson yields are suppressed at the same level as observed for light-quark hadrons, which was not expected due to the dead-cone and colour-charge effects. Measurements based on displaced J/ψ production [25] provide first indications for a smaller energy loss for beauty compared to charm.

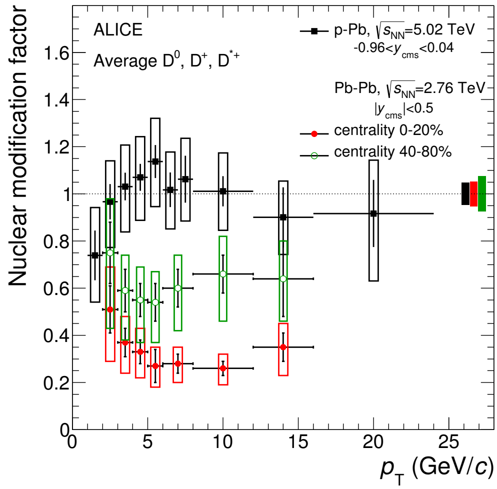

Fig. 4. R_{AA} of the averaged prompt D mesons *versus* p_{T} for two different centralities in Pb–Pb collisions (full light grey and open symbols) at $\sqrt{s_{NN}} = 2.76$ TeV [24] and in minimum bias p–Pb collisions (black symbols) at $\sqrt{s_{NN}} = 5.02$ TeV [26].

To quantitatively understand the heavy-ion data in terms of energy loss, it is important to disentangle the hot nuclear matter from cold nuclear matter. The latter initial-state effects can be investigated in p–Pb collisions. The R_{AA} of prompt D mesons in p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV [26] is shown in Fig. 4 and is compatible with unity within systematic uncertainties over the full p_{T} range. Thus, the strong suppression of the heavy-flavour hadron yield observed in central Pb–Pb collisions is indeed a final-state effect and arising from the QCD matter.

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