Open and hidden heavy-flavor production and flow in Heavy Ion Collisions.

Cesar Luiz da Silva  ‘Los Alamos National Lab
LHCb Collaboration
E-mail: cesar_luiz@lanl.gov

Their fast formation and microscopic scale of heavy flavor (HF) probes are ideal for a Quark-Gluon Plasma (QGP) tomography. Besides, the large fraction of energy carried by the measured heavy flavor hadron from the hard process fragmentation also favors a precise study of the partonic density and initial state effects in nucleus. LHC experiments are exploring heavy flavor probes in different manners such as the study of partonic energy loss in cold and QGP medium, diffusion properties, hadron coalescence and local free energy quantification using bound state quarkonia. This manuscript summarizes the most recent experimental developments in the field coming from all LHC experiments using data taken in $\rho$Pb and PbPb collisions in collision energies ranging from 86.6 GeV to 8.16 TeV.
1. Introduction

Passed the phase of discovery in SPS and RHIC, heavy ion physicists are in the era of characterization of the Quark-Gluon plasma. Some of the requirements needed for its study are: i) the medium needs to have a relatively large volume; ii) the probe needs to be formed and not shower in the vacuum before the QGP formation; and have different mass and momentum scales. Relativistic heavy ion collisions produce QGP with volumes on the order of the size of the colliding nucleus. Heavy quarks (charm and bottom) have a formation time \( < 0.07 \text{ fm/c} \), way before the formation of a thermalized QGP which is supposed to take between 0.3 and 1.5 fm/c [1]. The energy that a quark lose when crossing the QGP medium depends on its mass \( m_q \). The gluon radiation formed when an incident quark cross the QGP medium has a cone with minimum angle \( \theta = m_q/E_q \), meaning that the dead radiation cone is larger for heavy quarks [2] producing a mass hierarchy on the amount of energy \( dE/dx \) that quarks lose in the QGP as

\[
\frac{dE_{u,d}}{dx} > \frac{dE_c}{dx} > \frac{dE_b}{dx} \tag{1.1}
\]

Figure 1 illustrate the experimental procedure to scan QGP with heavy flavor probes. It starts from the measurement of heavy flavor yields in \( p+p \) collisions. Heavy flavor yields can be modified by initial effects in the nucleus such as nuclear shadowing, initial state energy loss and gluon saturation effects. A recent overview of initial-state effects can be found in [3]. These effects can be measured in \( p+A \) collisions, where the HF production occurs in a nucleus environment. The initial consensus in the field is that \( p+A \) collisions is a control experiment where no QGP is supposed to be formed. Recent observations of particle flow consistent with QGP hydrodynamics in very central \( p+A \) collisions observed at RHIC [4] and LHC [5] raised the question of a possible hot-dense medium affecting heavy flavor production. Finally, a calibrated heavy flavor probe can scan a large volume QGP in \( A+A \) by looking at the modification of the transverse momentum distribution of heavy flavor hadrons relative to \( p+p \) collisions.

In addition to the open heavy flavor probes, quarkonia have binding energies comparable with the free energy of the QGP as seen in Figure 2. It has been long suggested that the observation of
suppression of quarkonia states can reveal the temperature and Debye color screening of the QGP [6]. There is also a chance for charmonia state yields to be enhanced by coalescence of the large number of $c\bar{c}$ pairs produced in A+A collisions at LHC [7].

This manuscript will summarize the most recent experimental developments in probing nuclear matter and QGP with heavy quarks at LHC.

2. Recent Results with Open Heavy Flavor

Heavy flavor nuclear modification factor has been measured with $D$-mesons and $J/\psi$ since the first $p$Pb data run in 2013 showing general agreement with the nuclear parton density functions (nPDF) such as EPPS16 [8] and nCTEQ15 [9], though with large uncertainties in the nPDFs. A recent effort to use the LHC data taken in $p$Pb collisions to reduce the nPDF uncertainties was carried in [10] producing a new set of nPDFS (EPPS16*). Recent results from LHCb with $B$-mesons measured in $p$Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [11] were a first test for EPPS16*. The results from reconstructed $B$-mesons agree with previous non-prompt $J/\psi$ decays showing no nuclear modification at backward rapidity and around 20% suppression at forward rapidity. The suppression observed at the forward rapidity, corresponding to small Bjorken-$x$, is attributed to nuclear shadowing and partonic energy loss [3]. The rapidity and $p_T$ dependencies of the measured nuclear modification agree with the re-weighted EPP16* despite its smaller uncertainties compared to EPPS16.

One of the first results from LHCb’s fixed target program (SMOG) shows its potential to extend the LHC program. The supposed intrinsic charm quarks belonging to the proton wave function was not seen in the last $D^0$ cross-section measurements covering large-$x$ in $p$He and $p$Ar collisions at $\sqrt{s_{NN}} = 86.6$ GeV and 110.4 GeV respectively [12]. More data probing a larger $x$ range is needed for the intrinsic charm search.

More evidences for the mass hierarchy on the quark energy loss in QGP shown in Eq. (1.1) have been released from ALICE and CMS (Fig. 3-left). The new nuclear modification of electrons from bottom decays was obtained with two samples using different particle identifications. The results are consistent in the $p_T$ region where they overlap. The suppression tends to be weaker than the one observed from fully-reconstructed $D$-mesons. The same conclusion can be made with the new CMS nuclear modification of $b$ hadrons using nonprompt $D$-mesons sources [14] shown

Figure 2: Binding energy of several quarkonia states compared to a peak QGP temperature.
in Figure 3-right. The $R_{AA}$ results shown in the figure are plotted versus the $p_T$ of the observable, that is mixing the $p_T$ of source mesons, decayed mesons and lepton. A consistent picture on the actual quark energy loss $dE/dx$ would require unfolding of the source meson $p_T$.

First results on D-meson tagged jets are now available from ALICE and CMS. The nuclear modification of D-meson tagged jets, relative to pPb measurements used as reference, is consistent with the suppression observed for standalone D-mesons [19]. CMS studied the radial profile of the D-meson relative to the jet axis [20] in pp and PbPb collisions. D-mesons with $p_T < 20$ GeV/c tend to move away from the jet axis whereas high $p_T$ D-mesons have no modification in the radial profile. This measurement is consistent with the picture of D-mesons scattering in the QGP.

Figure 4: $\sigma(\Lambda_c^+)/\sigma(D^0)$ ratio measured by LHCb and CMS in pp and pPb and PbPb collisions [21, 22, 23].

ALICE, CMS and LHCb measured $\Lambda_c^+$ in pp and pPb collisions covering distinct rapidity
regions [24, 23, 21, 22]. The cross-section ratio $\sigma(\Lambda_c^+)/\sigma(D^0)$ obtained by all experiments (Fig. 4) are larger than all previous results obtained in $e^+e^-$ and $ep$ collisions (see Table 5 in [24]). One possible reason is color recombination present in $pp$ collisions [25] which can describe the larger fraction of $\Lambda_c^+$ in LHC data as seen as PYTHIA+CR in Fig.4. Mid-rapidity measurements obtained by ALICE and CMS in $pp$ collisions show a larger ratio compared to the forward measurements in LHCb. ALICE data also show no changes in the ratio between 5 TeV and 7 TeV $pp$ data. No significant $\Lambda_c^+$ enhancement relative to $D^0$ cross-section is observed in $pPb$ and Pb+Pb collisions posing a challenge to hadron coalescence scenarios in QGP. A similar conclusion is taken from the $\Lambda_0$ measurement in $pPb$ collisions done by LHCb in forward and backward rapidities [11], though with large uncertainties. Preliminary $\sigma(\Lambda_c^+)/\sigma(D^0)$ results from ALICE released after LHCP 2019 confirms color recombination in $pp$ collisions and indicates that the ratio tend to grow with particle multiplicity reaching values similar to the ones observed in PbPb collisions [26].

Strange D-meson yield $D_s^+$ is enhanced in PbPb collisions when compared to other D-mesons as reported by ALICE [13]. A new result from CMS shows a similar tendency for $B_0^0$ in PbPb collisions [27]. The results support the scenario of hadron recombination in the medium created in these collisions.

Particle collectivity is probed using the Fourier components of azimuthal anisotropy

$$v_n = \langle \cos(n(\phi - \Psi_n)) \rangle$$

relative to a event plane $\Psi$. Hydrodynamics and transport models can be tested using nuclear modification factors and $v_n$. Transport models applied to heavy flavor were recently tested using ATLAS $R_{AA}$, elliptic $v_2$ and triangular $v_3$ flow [28]. The conclusion is that no model can simultaneously reproduce the transverse momentum dependency of the heavy flavor suppression and the flow patterns. ALICE recently presented an original study on D-meson in two event shape eccentricity categories [29]. The results indicate a positive correlation between the D-meson elliptic flow and the bulk medium shape but no differences in the yields between the two event categories within the $\sim 10\%$ overall uncertainties.

Figure 5: Direct flow charge asymmetry in charged particles and D-mesons in PbPb collisions.
Relativistic heavy ion collisions are expected to produce magnet fields up to \( eB \sim (m_\pi)^2 \approx 10^{14} \) T at its first instants, probably the largest magnet fields in nature [30]. This field can alter the direct flow \( v_1 \) in Eq. 2.1 of positive and negative charged particles around the reaction plane. ALICE reported charge asymmetry in \( v_1 \) of charged particles and D-mesons versus pseudorapidity as shown in Figure 5. The asymmetry shows a linear dependence with pseudorapidity which can be attributed to the magnetic field effect. The news is that the linear slope is around three orders of magnitude larger for D-mesons, where the quark mass amplify the magnetic field effect. The slope has significance of 2.7 standard deviations.

### 3. Recent Quarkonia Results.

The most recent quarkonia results are based on measuring the yield of some excited state \( O_{ns} \), with weaker binding, relative to the one from a ground state quarkonia \( O_{1S} \) in \( pp \) collisions as reference and in any collision species with a higher particle density \( AB \)

\[
\rho_{AB}^{O_{ns}/O_{1S}} = \frac{\sigma(O_{ns}^{AB}) / \sigma(1S)}{\sigma(O_{1S}^{pp}) / \sigma(1S)} \tag{3.1}
\]

Table 1 summarizes the recent results on the suppression of excited quarkonia states relative to ground states in \( p\bar{p} \) and \( p\bar{p} \) collisions at LHC. In general, the results show a significant yield suppression of \( \psi(2S) \) relative to \( J/\psi \), \( Y(2S) \) and \( Y(3S) \) relative to \( Y(1S) \). The relative suppression is seen in \( p\bar{p} \), \( p\bar{p} \) and even in high multiplicity \( pp \) collisions [31] as expected from a medium breaking quarkonia states. Nuclear modification factor measurements also reveal the possibility that ground states may also be broken in the medium. Further studies on the initial state effects and a careful calculation of the feed-down contributions are needed to confirm ground state breaking in the medium formed in dense collision environments.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>( \sqrt{s_{NN}} )</th>
<th>( p_T ) range</th>
<th>rapidity range</th>
<th>ref.</th>
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<tr>
<td>( \rho_{p\bar{p}^{(2S)/J/\psi}} )</td>
<td>ALICE 5.02 TeV</td>
<td>( p_T &lt; 8 \text{ GeV/c} )</td>
<td>-4.46 &lt; ( y ) &lt; -2.96, 2.03 &lt; ( y ) &lt; 3.53</td>
<td>[32]</td>
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<td>ATLAS 5.02 TeV</td>
<td>9&lt; ( p_T &lt; 40 \text{ GeV/c} )</td>
<td>-2 &lt; ( y ) &lt; 1.5</td>
<td>[33]</td>
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<td></td>
<td>CMS 5.02 TeV</td>
<td>4&lt; ( p_T &lt; 30 \text{ GeV/c} )</td>
<td>-2.4 &lt; ( y ) &lt; 1.93</td>
<td>[34]</td>
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<td></td>
<td>LHCb 5.02 TeV</td>
<td>( p_T &lt; 14 \text{ GeV/c} )</td>
<td>-5.0 &lt; ( y ) &lt; -2.5, 1.5 &lt; ( y ) &lt; 4.0</td>
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<td></td>
<td>ALICE 2.76 TeV</td>
<td>( p_T &lt; 8 \text{ GeV/c} )</td>
<td>2.5 &lt; ( y ) &lt; 4.0</td>
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<td>9&lt; ( p_T &lt; 40 \text{ GeV/c} )</td>
<td>-2 &lt; ( y ) &lt; 2.0</td>
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<td></td>
<td>CMS 2.76 TeV</td>
<td>3&lt; ( p_T &lt; 30 \text{ GeV/c} )</td>
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<td>( \rho_{p\bar{p}^{(3S)/Y(1S)}} )</td>
<td>ALICE 8.16 TeV</td>
<td>( p_T &lt; 15 \text{ GeV/c} )</td>
<td>-4.46 &lt; ( y ) &lt; -2.96, 2.03 &lt; ( y ) &lt; 3.53</td>
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Few hundreds of $c\bar{c}$ pairs are produced in a typical central PbPb collision. These pairs placed in the QGP medium have a good chance to form bound state charmonia in the medium [7]. Charmonium coalescence is the sole explanation to the large $J/\psi$ yield enhancement observed at low $p_T$ [44]. As discussed in Section 2, D-mesons have a significant elliptic flow indicating a significant diffusion of charm quarks with the bulk medium. If a large fraction of $J/\psi$s are coming from these charms, $J/\psi$s may also have a significant flow. ALICE, ATLAS and CMS have all reported significant $J/\psi$ elliptic flow $v_2$ in PbPb collisions, supporting the role of charmonium coalescence in QGP [45, 46, 17]. Bottomonia yields should not be affected by coalescence given the small number of $b\bar{b}$ pair produced in PbPb collisions at LHC. In fact, no enhancements is observed in $\Upsilon$ state yields. ALICE and CMS reported the first preliminary measurements of $\Upsilon$ $v_2$ in PbPb collisions indicating that elliptic flow is consistent with zero [47]. The picture of coalescence as the sole source of quarkonia $v_2$ was recently challenged with the new results from ALICE and CMS of $J/\psi$ $v_2$ as big as D-meson $v_2$ in $p$Pb collisions [48, 49], where the much smaller number of $c\bar{c}$ pairs disfavor coalescence [50]. The interpretation of this result is still under debate but one can stipulate that other sources of $v_2$ may come from jet fragmentation.

4. New developments

Larger luminosities are allowing experiments to reach new levels of precision and introducing new probes. One example is the D-meson tagged jets mentioned in Sec. 2 and $\Upsilon$ $v_2$ mentioned in Sec. 3. New results such as $J/\psi$ polarization recently released by ALICE are also an outcome of the new accumulated luminosities which are going to be even higher after the current LHC shutdown. Other developments are coming from the fixed-target program in LHCb showing open and hidden heavy flavor signal in collisions such as PbNe at $\sqrt{s_{NN}}=69$ GeV.

5. Conclusions

The confirmation of a quark mass ordering for the energy loss in QGP, observation of medium phenomena even in $pp$ collisions such as color regeneration, flow and quarkonia suppression and heavy flavor probing strong magnetic fields created in the first instants of heavy ion collisions are some of the highlights in the field. Further constraints to cold and hot medium properties and new observables are some of the promises from heavy flavor probes with current data on disks and LHC Run 3.

References


6


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