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

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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 *p*Pb and PbPb collisions in collision energies ranging from 86.6 GeV to 8.16 TeV.

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1. Introduction

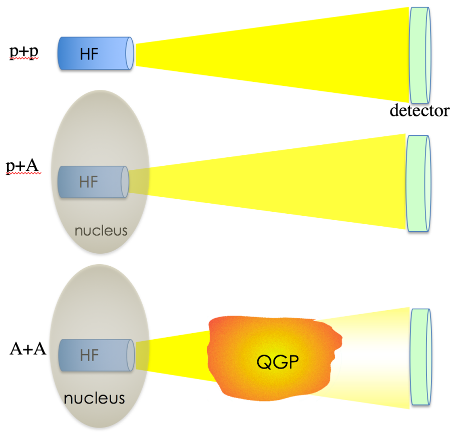

Figure 1: Illustration of the experimental procedure to scan Quark-Gluon plasma using heavy flavor probes.

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 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

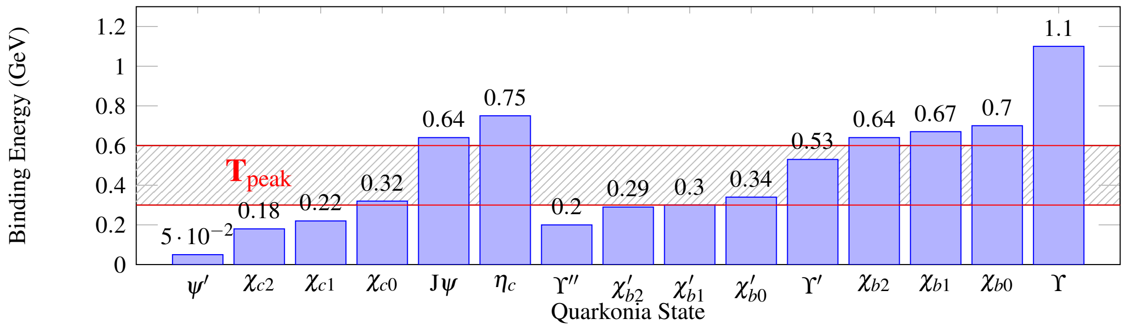

Figure 2: Binding energy of several quarkonia states compared to a peak QGP temperature.

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/ψ since the first pPb 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 pPb 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 pPb 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/ψ 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 pHe and pAr 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

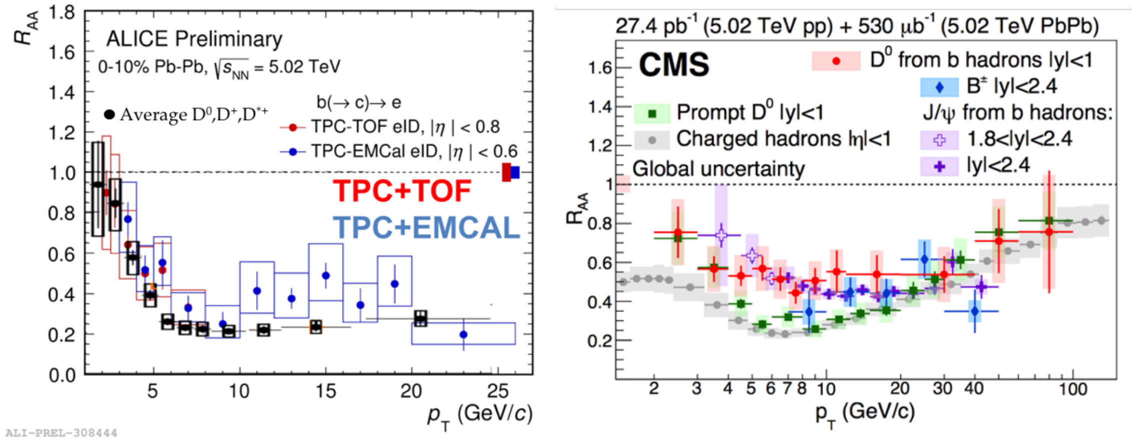

Figure 3: Nuclear modification factor of several decay channels for charm, bottom mesons and light quarks: average D-mesons from ALICE [13], preliminary ALICE result of electrons from beauty, CMS nonprompt D-mesons [14], CMS prompt D-mesons [15], CMS charged particles [16], CMS nonprompt J/ψ [17] and CMS B-mesons [18].

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.

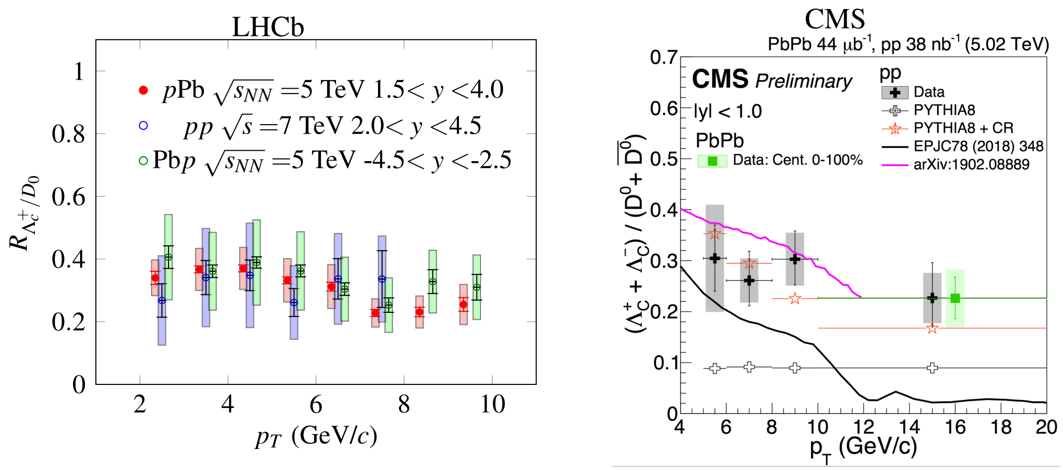

Figure 4: $\sigma\left(\Lambda_c^+\right)/\sigma\left(D^0\right)$ ratio measured by LHCb and CMS in pp and pPb and PbPb collisions [21, 22, 23].

ALICE, CMS and LHCb measured Λ_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 Λ_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 Λ_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 Λ_b^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_s^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

$$v_n = \langle cos(n(\phi - \Psi_n)) \rangle \tag{2.1}$$

relative to a event plane Ψ. 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.

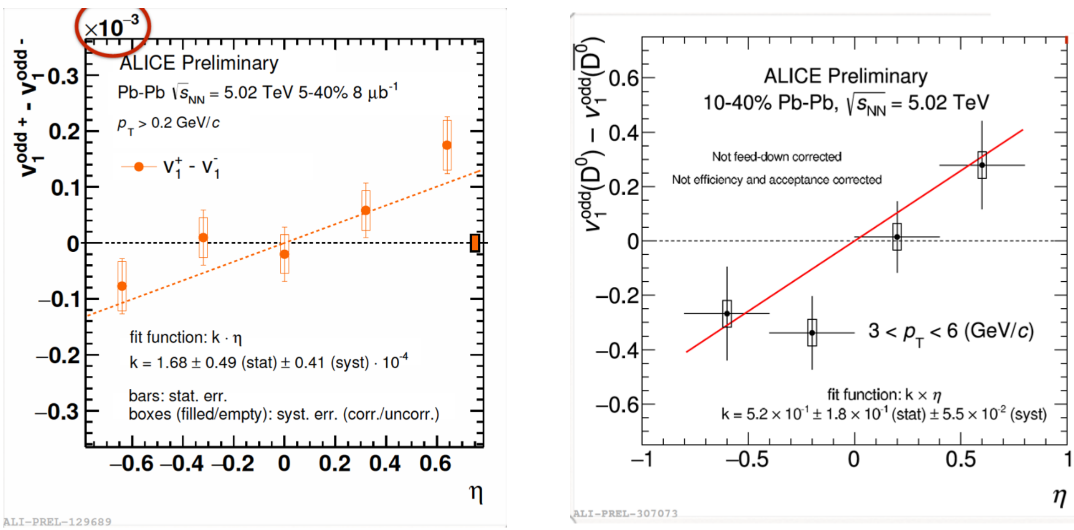

Figure 5: Direct flow charge asymmetry in charged particles and D-mesons in PbPb collisions.

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

$$\rho_{AB}^{O_{nS}/O_{1S}} = \frac{\sigma\left(O_{nS}^{AB}\right)/\sigma\left(O_{1S}^{AB}\right)}{\sigma\left(O_{nS}^{pp}\right)/\sigma\left(O_{1S}^{pp}\right)}. \tag{3.1}$$

Table 1 summarizes the recent results on the suppression of excited quarkonia states relative to ground states in pPb and PbPb collisions at LHC. In general, the results show a significant yield suppression of ψ(2S) relative to J/ψ, Υ(2S) and Υ(3S) relative to Υ(1S). The relative suppression is seen in pPb, PbPb 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 1: List of relative quarkonia suppression results from LHC.

	Exp.	$\sqrt{s_{NN}}$	p$_T$ range	rapidity range	ref.
$\rho_{p\mathrm{Pb}}^{\psi(2S)/J/\psi}$	ALICE	5.02 TeV	$p_T < 8$ GeV/c	-4.46 $< y <$ -2.96, 2.03 $< y <$3.53	[32]
	ATLAS	5.02 TeV	9$< p_T <$40 GeV/c	-2 $< y <$ 1.5	[33]
	CMS	5.02 TeV	4$< p_T <$30 GeV/c	-2.4 $< y <$1.93	[34]
	LHCb	5.02 TeV	$p_T <$ 14 GeV/c	-5.0 $< y <$ -2.5, 1.5$< y <$4.0	[35]
$\rho_{\mathrm{PbPb}}^{\psi(2S)/J/\psi}$	ALICE	2.76 TeV	$p_T < 8$ GeV/c	2.5 $< y <$ 4.0	[36]
	ATLAS	5.02 TeV	9$< p_T <$40 GeV/c	-2 $< y <$ 2.0	[37]
	CMS	2.76 TeV	3$< p_T <$30 GeV/c	$\|y\|$ <2.4	[38]
$\rho_{p\mathrm{Pb}}^{\Upsilon(nS)/\Upsilon(1S)}$	ALICE	8.16 TeV	$p_T <$ 15 GeV/c	-4.46 $< y <$ -2.96, 2.03 $< y <$3.53	[39]
	LHCb	8.16 TeV	$p_T <$ 25 GeV/c	-5.0 $< y <$ -2.5, 1.5$< y <$4.0	[40]
	ATLAS	5.02 TeV	$p_T <$40 GeV/c	-2 $< y <$ 1.5	[33]
	CMS	5.02 TeV	$p_T <$ 30 GeV/c	$\|y\|$<1.93	[31]
$\rho_{\mathrm{PbPb}}^{\Upsilon(nS)/\Upsilon(1S)}$	ALICE	5.02 TeV	$p_T <$ 15 GeV/c	2.5 $< y <$ 4.0	[41]
	CMS	2.76 TeV	$p_T <$ 30 GeV/c	$\|y\|$<2.4	[42]
	CMS	5.02 TeV	$p_T <$ 30 GeV/c	$\|y\|$<2.4	[43]

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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/ψ 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/ψs are coming from these charms, J/ψs may also have a significant flow. ALICE, ATLAS and CMS have all reported significant J/ψ 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 Υ state yields. ALICE and CMS reported the first preliminary measurements of Υ 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/ψ v_2 as big as D-meson v_2 in pPb 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 estipulate 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 Υ v_2 mentioned in Sec. 3. New results such as J/ψ 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

[1] Fu-Ming Liu and Sheng-Xu Liu. Quark-gluon plasma formation time and direct photons from heavy ion collisions. *Phys. Rev.*, C89(3):034906, 2014.

[2] Yuri L. Dokshitzer and D. E. Kharzeev. Heavy quark colorimetry of QCD matter. *Phys. Lett.*, B519:199–206, 2001.

[3] Javier L. Albacete et al. Predictions for cold nuclear matter effects in p+pb collisions at $\sqrt{s_{NN}}$=8.16 tev. *Nuclear Physics A*, 972:18 – 85, 2018.

[4] C. Aidala et al. Creation of quark–gluon plasma droplets with three distinct geometries. *Nature Phys.*, 15(3):214–220, 2019.

[5] Serguei Chatrchyan et al. Observation of long-range near-side angular correlations in proton-lead collisions at the LHC. *Phys. Lett.*, B718:795–814, 2013.

[6] T. Matsui and H. Satz. J/ψ suppression by quark-gluon plasma formation. *Physics Letters B*, 178(4):416 – 422, 1986.

[7] Robert L. Thews, Martin Schroedter, and Johann Rafelski. Enhanced J/ψ production in deconfined quark matter. *Phys. Rev.*, C63:054905, 2001.

[8] Kari J. Eskola, Petja Paakkinen, Hannu Paukkunen, and Carlos A. Salgado. EPPS16: Nuclear parton distributions with LHC data. *Eur. Phys. J.*, C77(3):163, 2017.

[9] A. Kusina et al. nCTEQ15 - Global analysis of nuclear parton distributions with uncertainties. *PoS*, DIS2015:041, 2015.

[10] Aleksander Kusina, Jean-Philippe Lansberg, Ingo Schienbein, and Hua-Sheng Shao. Gluon Shadowing in Heavy-Flavor Production at the LHC. *Phys. Rev. Lett.*, 121:052004, Aug 2018.

[11] Roel Aaij et al. Measurement of B^+, B^0 and Λ_b^0 production in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$. *Phys. Rev.*, D99(5):052011, 2019.

[12] Roel Aaij et al. First Measurement of Charm Production in its Fixed-Target Configuration at the LHC. *Phys. Rev. Lett.*, 122(13):132002, 2019.

[13] S. Acharya et al. Measurement of D^0, D^+, D^{*+} and D_s^+ production in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. *JHEP*, 10:174, 2018.

[14] Albert M Sirunyan et al. Studies of Beauty Suppression via Nonprompt D^0 Mesons in Pb-Pb Collisions at $Q^2 = 4$ GeV^2. *Phys. Rev. Lett.*, 123(2):022001, 2019.

[15] Albert M Sirunyan et al. Nuclear modification factor of D^0 mesons in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. *Phys. Lett.*, B782:474–496, 2018.

[16] Vardan Khachatryan et al. Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{\mathrm{N\,N}}} = 5.02$ TeV. *JHEP*, 04:039, 2017.

[17] Vardan Khachatryan et al. Suppression and azimuthal anisotropy of prompt and nonprompt J/ψ production in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Eur. Phys. J.*, C77(4):252, 2017.

[18] Albert M Sirunyan et al. Measurement of the $B^{\pm}$ Meson Nuclear Modification Factor in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$TeV. *Phys. Rev. Lett.*, 119(15):152301, 2017.

[19] ALICE collaboration. Nuclear Modification Factor of D0-tagged charged jets (Anti-kT, R=0.3) D^0 meson with $p_{T,D}$ >3 GeV/c Pb-Pb at 5.02 TeV (Run 2) - with charged jets and D mesons. ALI-PREL-157488 http://alice-figure.web.cern.ch/node/13858.

[20] CMS Collaboration. Measurement of the radial profile of D^0 mesons in jets produced in pp and PbPb collisions at 5.02 TeV. 2018.

[21] R Aaij et al. Prompt charm production in pp collisions at $\sqrt{s}$=7 TeV. *Nucl. Phys.*, B871:1–20, 2013.

[22] Roel Aaij et al. Prompt Λ_c^+ production in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *JHEP*, 02:102, 2019.

[23] CMS Collaboration. Production of Λ_c in pp and PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. CMS-PAS-HIN-18-009, 2019.

[24] Shreyasi Acharya et al. Λ_c^+ production in pp collisions at $\sqrt{s} = 7$ TeV and in p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. *JHEP*, 04:108, 2018.

[25] Jesper R. Christiansen and Peter Z. Skands. String formation beyond leading colour. *Journal of High Energy Physics*, 2015(8):3, Aug 2015.

[26] G.M. Innocenti. Latest D and Λ_c results in pp and Pb-Pb collisions with ALICE at the LHC. https://indico.cern.ch/event/792436/contributions/3535790/attachments/1939672/3215598/QMInnocenti.pdf, 2019. [Online; accessed 10-No-2019].

[27] Albert M Sirunyan et al. Measurement of B_s^0 meson production in pp and PbPb collisions at $\sqrt{s_{\rm NN}} =$ 5.02 TeV. *Phys. Lett.*, B796:168–190, 2019.

[28] M. Aaboud et al. Measurement of the suppression and azimuthal anisotropy of muons from heavy-flavor decays in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector. *Phys. Rev. C*, 98:044905, Oct 2018.

[29] Shreyasi Acharya et al. Event-shape engineering for the D-meson elliptic flow in mid-central Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. *JHEP*, 02:150, 2019.

[30] Yang Zhong, Chun-Bin Yang, Xu Cai, and Sheng-Qin Feng. A systematic study of magnetic field in Relativistic Heavy-ion Collisions in the RHIC and LHC energy regions. *Adv. High Energy Phys.*, 2014:193039, 2014.

[31] Serguei Chatrchyan et al. Event activity dependence of Y(nS) production in $\sqrt{s_{NN}}$=5.02 TeV pPb and $\sqrt{s}$=2.76 TeV pp collisions. *JHEP*, 04:103, 2014.

[32] Betty Bezverkhny Abelev et al. Suppression of ψ(2S) production in p-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV. *JHEP*, 12:073, 2014.

[33] Morad Aaboud et al. Measurement of quarkonium production in proton–lead and proton–proton collisions at 5.02 TeV with the ATLAS detector. *Eur. Phys. J.*, C78(3):171, 2018.

[34] Albert M Sirunyan et al. Measurement of prompt ψ(2S) production cross sections in proton-lead and proton-proton collisions at $\sqrt{s_{_{\rm NN}}} = 5.02$ TeV. *Phys. Lett.*, B790:509–532, 2019.

[35] Roel Aaij et al. Study of $\psi(2S)$ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV. *JHEP*, 03:133, 2016.

[36] Jaroslav Adam et al. Differential studies of inclusive J/ψ and ψ(2S) production at forward rapidity in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. *JHEP*, 05:179, 2016.

[37] M. Aaboud et al. Prompt and non-prompt J/ψ and ψ(2S) suppression at high transverse momentum in $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb collisions with the ATLAS experiment. *The European Physical Journal C*, 78(9):762, Sep 2018.

[38] Vardan Khachatryan et al. Measurement of Prompt $\psi(2S) \to J/\psi$ Yield Ratios in Pb-Pb and $p-p$ Collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Rev. Lett.*, 113(26):262301, 2014.

[39] Shreyasi Acharya et al. Inclusive Υ production in p-Pb collisions at $\sqrt{s_{\rm NN}}$ = 8.16 TeV. 2019.

[40] Roel Aaij et al. Study of Υ production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. *JHEP*, 11:194, 2018.

[41] Shreyasi Acharya et al. Υ suppression at forward rapidity in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV. *Phys. Lett.*, B790:89–101, 2019.

[42] Serguei Chatrchyan et al. Observation of Sequential Upsilon Suppression in PbPb Collisions. *Phys. Rev. Lett.*, 109:222301, 2012. [Erratum: Phys. Rev. Lett.120,no.19,199903(2018)].

[43] Albert M Sirunyan et al. Measurement of nuclear modification factors of Υ(1S), Υ(2S), and Υ(3S) mesons in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. *Phys. Lett.*, B790:270–293, 2019.

[44] Betty Bezverkhny Abelev et al. Centrality, rapidity and transverse momentum dependence of J/ψ suppression in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$=2.76 TeV. *Phys. Lett.*, B734:314–327, 2014.

[45] Morad Aaboud et al. Prompt and non-prompt J/ψ elliptic flow in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ Tev with the ATLAS detector. *Eur. Phys. J.*, C78(9):784, 2018.

[46] Shreyasi Acharya et al. J/ψ elliptic flow in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. *Phys. Rev. Lett.*, 119(24):242301, 2017.

[47] Measurement of the elliptic flow of Υ(1S) and Υ(2S) mesons in PbPb collisions at $\sqrt{\mathrm{s_{NN}}} = 5.02$ TeV. Technical Report CMS-PAS-HIN-19-002, CERN, Geneva, 2019.

[48] S. Acharya et al. Search for collectivity with azimuthal J/ψ-hadron correlations in high multiplicity p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 and 8.16 TeV. *Phys. Lett.*, B780:7–20, 2018.

[49] A.M. Sirunyan et al. Observation of prompt J/ψ meson elliptic flow in high-multiplicity pPb collisions at $\sqrt{s_{NN}}$=8.16 TeV. *Physics Letters B*, 791:172 – 194, 2019.

[50] Xiaojian Du and Ralf Rapp. In-Medium Charmonium Production in Proton-Nucleus Collisions. *JHEP*, 03:015, 2019.