HF-WINC 2020 - The 8th International Workshop on Heavy Flavour Production in Nuclear Collisions

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Book of Abstracts

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Diffusion of heavy quarks in the early stage of high energy nuclear collisions

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Heavy quarks are considered potential probes of the QCD matter produced in high-energy heavy-ion collisions. In the pre-equilibrium stage of relativistic heavy-ion collisions, strong quasi-classical gluon fields emerge at about $\tau_0 = 0.08$ fm/c which evolves according to the classical Yang-Mills (CYM) equations. These set of classical fields are known as Glasma. We study the diffusion of the heavy quarks, namely, charm and bottom quarks in the early stage of heavy-ion collisions. The diffusion in the evolving Glasma fields is compared with that of the Markovian-Brownian motion in a thermalized medium. The diffusion of HQs in the evolving glasma (EvGlasma) is investigated within the framework of Wong equations while we use famous Langevin equations for the Brownian motion with diffusion coefficients evaluated within the pQCD framework.We observe that for a smaller value of saturation scale, Q_s, the average transverse momentum broadening is approximately the same for the two cases, but for larger Q_s, Langevin dynamics underestimates the σ_p. This difference is related to the fact that heavy quarks in the Glasma fields experience diffusion in strong, coherent gluon fields that lead to a faster momentum broadening due to memory, or equivalently to a strong correlation in the transverse plane. We present another interesting result related to bottom quarks. We have observed that bottom quarks are more affected by the pre-equilibrium phase due to their large masses. Their slow motion makes them spend a longer time within a single filament and experience the coherent gluonic fields for a longer time .

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Analyzing the mass ordering in heavy flavor suppression through theory and data

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One of the intrinsic features of parton's energy loss is the evident flavor dependence. Inspired by the dead-cone effect in radiative energy loss and experimentally detected suppression mass hierarchy, we address the mass ordering in heavy flavor suppression.

While mass hierarchy is analyzed within radiative models, collisional interpretation is still lacking. To this end, we apply recently developed DREENA framework, which is based on our dynamical energy loss formalism. Within this [1] we provide 1) A novel observable, which can disentangle collisional from radiative energy loss, to be rigorously tested by the upcoming high-precision measurements at RHIC and LHC; 2) Analytical derivation of a direct relation between collisional suppression/energy loss and heavy quark mass; 3) Analytical and numerical extraction of the mass ordering in collisional energy loss through this observable.

[1] Bojana Ilic and Magdalena Djordjevic, arXiv:2203.06646 [hep-ph].

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Open HF measurements at RHIC (STAR+PHENIX)

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A kinetic model for J/psi production in heavy ion collisions

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A new Model for J/psi Production in Heavy Ion Collisions
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The experimental observation of J/psi and Bc mesons multiplicities, distributions and azimuthal flows plays a key role in understanding of the properties of the quark gluon plasma (QGP) which is formed in ultrarelativistic heavy ion collisions. This is due to the fact that the heavy quarks can come from different vertices in the initial stage and that the J/psi are not stable when the QGP is produced with a temperature above the J/psi dissociation temperature while resonant states can be achieved before the transition to the hadronic phase, offering the possibility to probe directly these high temperatures.
In our recently developed approach [1], the hidden heavy flavor mesons production rate is described by solving the von Neumann equation of the two body density matrix in the expanding N-body system, following a method introduced by Remler et al. to predict deuteron production in HIC at lower energies [2]. In this formalism, the rate of mesons formation is based on the semi-classical trajectories of c and b quarks, what naturally encodes possible off-equilibrium effects of these quarks. The trajectories are based on the description of the expanding QGP by the EPOS event generator, supplemented by the Nantes energy loss model which have demonstrated successful agreement with the data for open heavy flavor mesons.
This allows for the prediction of the hidden heavy flavor observables (J/psi and Bc) which are confronted with the experimental results on multiplicity, RAA and v2. We discuss what we can learn

from the hidden heavy flavor mesons about the expanding QGP, in particular the time atwhich the mesons appear to be dynamically produced.

[1] Arrebato Villar,D. Thesis, IMT Atlantique, 2021
[2] Gyulassy, M. and Frankel, K. and Remler, E. , Nucl. Phys. A402, 596

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LHCb results on quarkonia

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Bottomonium production from coupled Boltzmann equations

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Quarkonium has been used as an important probe of the quark-gluon plasma in heavy ion collisions. With more precise experimental measurements of quarkonium production conducted at RHIC and LHC, we are able to learn in a more quantitative way how quarkonium interacts with the hot medium. In this talk, I will review the framework of coupled Boltzmann equations to describe quarkonium production in heavy ion collisions. The coupled equations describe both open heavy quark transport and quarkonium dissociation and recombination in a consistent way. I will also show phenomenological results for bottomonium production and compare with recent experimental measurements.

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CMS results on quarkonia in A-A collisions

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Medium effects on Υ yields in p-Pb and Pb-Pb collisions

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The respective contributions of cold-matter and hot-medium effects to the suppression of $\Upsilon(1S)$ and $\Upsilon(2S)$ mesons in p-Pb collisions at energies reached at the Large Hadron Collider (LHC) are investigated [1]. Whereas known alterations of the parton density functions in the lead nucleus and

coherent parton energy loss [2] account for the leading fraction of the modifications in cold nuclear matter (CNM), the hot-medium (quark-gluon plasma, QGP) effects turn out to be relevant in spite of the small initial spatial extent of the fireball.

We compare our transverse-momentum-, rapidity-, and centrality-dependent theoretical results for the $\Upsilon(1S)$ suppression in p-Pb collisions at a center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV with recent LHCb [3] and ALICE [4] data from the Large Hadron Collider (LHC). Both cold-matter and hot-medium effects are needed to account for the data, lending support to a transient QGP formation in small systems. The initial central temperature of the fireball in p-Pb at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV is found to be $T_0 \simeq 460$ MeV.

The results for the asymmetric p-Pb system are compared to the hot-medium effects on Υ-suppression in symmetric Pb-Pb-collisions at LHC energies, where the spatially extended fireball is mostly responsible for the dissociation of quarkonia, and cold-matter effects are less relevant. Here the hot-medium model [5] yields excellent agreement with CMS data at 2.76 and 5.02 TeV.

[1] V. H. Dinh, J. Hoelck and G. Wolschin, Hot-medium effects on Υ yields in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV, Phys. Rev. C 100, 024906 (2019).

[2] J. L. Albacete et al., Predictions for cold nuclear matter effects in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV, Nucl. Phys. A 972, 18 (2018).

[3] R. Aaij et al., LHCb Collaboration, Study of Υ production in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV, JHEP 11, 194 (2018).

[4] S. Acharya et al., ALICE Collaboration, Υ production in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV, Phys. Lett. B 806, 135486 (2020).

[5] J. Hoelck, F. Nendzig and G. Wolschin, In-medium Υ suppression and feed-down in UU and PbPb collisions, Phys. Rev. C 95, 024905 (2017).

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ALICE results on quarkonia in A-A collisions

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Exotica / **14**

Heavy flavor transport and exotic hadron production in heavy ion collisions

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For heavy ion collisions in the TeV beam energy region, the large number of initial hard scatterings create a richly "doped"hot quark-gluon plasma embedding an unparalleled abundance of charm quarks/anti-quarks. This provides a uniquely "charming"environment for the massive production of exotic hadrons in nuclear collisions and possibly helps solve puzzles about their intrinsic structures, as demonstrated by the latest theoretical studies and experimental measurements. A notable example concerns the nature of the well-known X(3872) particle. Despite significant efforts, consensus on their internal structures is still lacking and it remains a pressing open question to decipher the X(3872) state between two popular exotic configurations: a loose hadronic molecule or a compact tetraquark. It turns out the two different structures have rather different sensitivity to size of the production source and thus the the fireball volume in heavy ion collisions could play a crucial role. By scanning centrality and thus systematically tuning the fireball volume, recent dynamical simulations based on a multiphase transport model (AMPT) have indeed found about 2-order-of-magnitude difference in the X(3872) yield and a markedly different centrality dependence between hadronic molecules and compact tetraquarks, offering a novel approach for distinguishing the two scenarios. More recently such study has been further extended to the newly observed doubly-charmed exotic states, finding about three-order-of-magnitude enhancement in the production of the Tcc states in Pb-Pb collisions as compared with the yield in proton-proton collisions. Compared with X(3872), the Tcc yield shows an even stronger decrease from central toward peripheral collisions, due to a "threshold"effect of the required double charm quarks for its formation. This talk will report such exciting theoretical progress and discuss relevant experimental results. The talk will end with an outlook on interesting issues to be addressed and opportunities in the future. [Refs: PRL126,012301(2021);PRD104,L111502(2021); Eur.Phys.J.C80(2020)7,671; Chin.Phys.C43(2019)4,044101]

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In-Medium Transport of charmonia, X(3872) and B_c at the LHC

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We investigate the in-medium kinetics of heavy quarkonia focusing on recent developments and results for the $\psi(2S)$, X(3872), and B_c particles in ultra-relativistic heavy-ion collisions (URHICs). Based on our previous calculations, our approach is governed by two transport parameters for each quarkonium state: the equilibrium limit and inelastic reaction rate. The equilibrium limits are entirely determined by the particles' masses and the charm-quark and bottom-quark fugacities. The reaction rate for the $\psi(2S)$ was previously constrained by analysis of d-Au and p-Pb collisions at RHIC and the LHC. The rate for the X(3872) is evaluated depending on its structure, being "large" for a DD^* molecule and "small" for a tetraquark (diquark-antidiquark). The reaction rate of the B_c is calculated in the quasi-free approximation based on binding energies extracted from in-medium T-matrix calculations. We assess the sensitivity of the final X(3872) yields and p_T spectra on different scenarios for its width and initial conditions. We find that the final yields of the molecule structure are generally smaller than for the tetraquark, by around a factor of two, which is qualitatively different from calculations using instantaneous coalescence models. We also present our predictions for the centrality and transverse-momentum dependence of the R_{AA} for $\psi(2S)$ and B_c and discuss it in the context of recent experimental data.
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Exotic charmed hadrons production in relativistic heavy-ion collisions

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The deconfined quark-gluon plasma (QGP) created in relativistic heavy-ion collisions is not only a perfect fluid with very small η/s but also a most "charming" system with hundreds of charm quarks. Meanwhile, it is widely accepted that the quark hadronization mechanism changes with the appearance of QGP. The production of charmed hadrons differs significantly in A-A collisions from that of p-p and e^+-e^- collisions.
The yield of hadrons(including exotic hadrons like tetraquarks, pentaquarks, etc.) with multiple charm quarks would be enhanced through the charm coalescence process in the "charming" QGP medium.
In this talk, we will present our recent studies on the generation of rare charmed hadrons, such as B_c, $X(3872)$, and $X_{cc\bar{c}\bar{c}}(6900)$ in relativistic heavy-ion collisions at LHC. We study the static properties of those charmed hadrons in vacuum and finite temperature by solving the two/four-body Schr\"odinger equations. Their yields in heavy ion collisions are investigated dynamically through the transport and coalescence hadronization model. The results show the yield of B_c, $X(3872)$, and $X_{cc\bar{c}\bar{c}}(6900)$ are order of 1-3 magnitude increased in heavy-ion collisions. This provides a new avenue for scientists to observe/discover those charmed hadrons in the experiment.

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System size dependence of tetraquark production in heavy ion collisions

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Using the coalescence model, we calculate the multiplicities of X(3872) and T_{cc}^+ at the end of the quark gluon plasma phase in nucleus-nucleus collisions at the LHC. Then, using effective lagrangians and a rate equation, we calculate the changes in these multiplicities during the hadron gas phase. Finally, we present the multiplicities at the end of the collisions and also plot them as a function of $dN/d\eta(\eta = 0)$, which gives a measure of the system size. We discuss the possibility of discriminating compact tetraquark from extended molecular configurations. This talk is based on arXiv:2202.10882 and on arXiv:2110.11145 .

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Quarkonium measurements at RHIC (STAR+PHENIX)

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LHCb results on open heavy flavour and quarkonia in small systems

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ATLAS and CMS results on open heavy flavour and quarkonia in small systems

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Open heavy flavour and quarkonia in small systems (theory)

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ALICE results on open heavy flavour and quarkonia in small systems

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Missing beauty of proton-proton interactions

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Multiparton interactions in proton-proton collisions have long been a topic of great interest. A new look at them has begun to emerge from work being done to understand the dynamics of 'small systems', a topic that is taking center stage in the physics of relativistic heavy-ion interactions. Numerous studies conducted at the LHC and lower energies reveal that proton-proton collisions at high energy form a system in which final state interactions substantially impact experimentally observable quantities in the soft sector. However, until recently, no evidence was shown that final state interactions could also affect observables produced in the hard scattering processes. Studies performed by the LHC experiments present strong evidence that the final state interactions in proton-proton collisions have a drastic impact on the b-quark bound states production, whose yields may be reduced by more than a factor of two.

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Overview on transport models for open and hidden charm production in nuclear collisions

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Application of Open Quantum systems framework to quarkonium production

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Overview on statistical models

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Quarkonia and heavy flavours at EIC

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Quarkonia and heavy flavours at EIC (theory)

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Quarkonia and heavy flavours in NA60+

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Cold Nuclear Matter Effects on J/ψ and D Meson Production at High Baryon Densities

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Open heavy flavors and quarkonium have played important roles in the understanding of the QCD matter produced at high temperatures and low baryon densities. However, they could also provide crucial information about QCD at the lowe center of mass energies employed to probe high baryon density matter at existing or planned facilities.

For example, a nonperturbative contribution to charm production, intrinsic charm, has long been speculated, with much contradictory empirical evidence. LHCb recently reported evidence for intrinsic charm in $Z+\mathrm{jet}$ events at $\sqrt{s}=13$ TeV [1]. While J/ψ production by intrinsic charm would normally only manifest itself outside the range of the LHC detectors, even at forward rapidity, the high Q^2 of these events allowed for their detection.

On the other hand, at low center of mass energies, J/ψ and D meson production by intrinsic charm could manifest itself at midrapidity, as described for the SeaQuest experiment at Fermilab [2]. This talk will explore the rapidity and p_T dependence of an intrinsic charm signature for laboratory beams of 40 GeV and higher, both in $p+p$ and $p+A$ interactions and place the results in context of previous experimental evidence [3].

[1] https://lhcb-public.web.cern.ch/Welcome.html\#IC, 27 July 2021.

[2] R. Vogt, Limits on Intrinsic Charm Production from the SeaQuest Experiment, Phys. Rev. C **103**, 035204 (2021).

[3] R. Vogt, in preparation, to be submitted to Phys. Rev. C.

Future experiments (high-muB, EIC) / 72

Quarkonia and heavy flavours in CBM

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Heavy quark transport and thermalization / 73

Heavy quark thermalisation (theory)

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Soft gluon emission from heavy quark scattering in sQGP

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We apply the Low's theorem to soft gluon emission from the heavy quark scattering in nonperturbative strongly interacting quark-gluon plasma (sQGP). The sQGP is described in terms of the DQPM (dynamical quasiparticle model) based on propagator representation in 2PI representation and adjusted to reproduce the EoS from lQCD at finite temperature and chemical potential. Since emitted gluon is soft and of long wavelength, it does not provide the information on the detailed structure of the scattering, since only the emission from incoming and outgoing partons is accounted. It simplifies the calculations making amplitude factorizable into the leading-order scattering and the emission of soft gluon. Imposing a proper upper limit on the energy of emitted gluon, we obtain the scattering cross sections of charm quark with the off-shell partons of the medium as well as the

transport coefficients (momentum drag and diffusion) of charm quark in QGP and compare with those only from the leading-order calculations, i.e. elastic scattering.

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Heavy-meson transport coefficients in a thermal medium (and in the hadronic phase)

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We have investigated the many-body equations of D and $\overline{B}$ mesons in a thermal medium by applying an effective field theory based on chiral and heavy-quark spin symmetries. Exploiting the same symmetries for the construction of the kinetic theory, we have derived an off-shell Fokker-Planck equation which incorporates information of the full spectral function of these states.

I will present the latest results on heavy-flavor transport coefficients below the chiral restoration temperature. I will also detail the origin of the in-medium reactions which contribute to the heavy-meson thermal width and energy loss, including the soft-pion emission (Bremsstrahlung) process.

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D meson scattering parameters with light-flavor hadrons

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HF and quarkonium polarization (theory)

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Topical heavy-quark studies / 78

Experimental results on heavy flavour and quarkonium polarization

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Experimental results on heavy quark hadronization

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Topical heavy-quark studies / 80

Heavy quark hadronization (theory)

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Inferring QGP parameters with heavy flavor probes

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High-pt theory and data are traditionally used to explore parton interactions with QGP, while QGP parameters are commonly constrained through low-pt data and corresponding models. However, rare high-pt probes can also be a powerful tool for inferring bulk QGP properties, providing a proper description of high-pt parton-medium interactions.

We here advocate a novel QGP tomography approach, which employs our finite-temperature dynamical energy loss framework. The main idea is to constrain QGP parameters by exploiting both low and high-pt data. We can use any set of QGP parameters consistent with low-pt observables and: i) Generate the corresponding temperature profile, ii) Implement this profile in the dynamical energy loss framework and generate corresponding high-pt predictions. iii) Test these predictions against high-pt data to further constrain QGP parameter values. We show that heavy flavor observables are particularly sensitive within this approach and can be used to i) constrain the early evolution of QGP, ii) infer geometrical properties of bulk QCD medium, iii) explore if QGP in small systems is consistent with high-pt data.

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ALICE results on heavy-flavour jets

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Heavy quarks jets (theory)

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ATLAS and CMS results on heavy-flavour jets

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ATLAS, CMS, LHCb: HF and quarkonium plans for Run 4 and beyond

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Plans for heavy flavour and quarkonium studies in ALICE 3

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S-PHENIX heavy flavour and quarkonium studies

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Final remarks and conclusions

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