**Template NA**

|  |  |  |  |
| --- | --- | --- | --- |
| **Work package number** | WP18 | **Start date** | 01/06/2019 |
| **Activity Type** | Networking activity | | |
| **Work package acronym** | NA7-Hf-QGP | | |
| **Work package title** | Quark-Gluon Plasma characterization with heavy flavor probes | | |

1. Work carried out and overview of progress
   1. **Project objectives**

*[Please give an overview of the project objectives for the third reporting period (June 2022 – July 2024), with regard to the overall objectives as described in the Annex 1 of the Grant Agreement and summarized below.]*

Heavy flavor (HF) quarks (charm and beauty) have been identified in the last years as a reliable mean to study the properties of the Quark Gluon Plasma (QGP), which is created in ultra-relativistic heavy ion collisions at the LHC. The reasons are the following: heavy quarks are produced in hard processes with very short formation time. They hence experience the early phase of the QGP and the full evolution of the system. Heavy quarks with large transverse momentum, which do not come to equilibrium, are unique probes to study the parton energy loss mechanism in the QGP, and its dependence on the parton type (gluon vs. quark and light vs. heavy quarks, respectively).

On the theoretical side, several approaches have been proposed which describe the few presently available open HF data within the still large experimental uncertainties.

Objective of the present WP is a systematic comparison of these different approaches in order to discriminate between them and to eliminate uncertainties like details of the expansion of the QGP, initial state fluctuations or the influence of nuclear shadowing. The second main objective is to advance the understanding of hidden charm and bottom mesons in ultra-relativistic heavy ion reactions. The description of hidden HF production is even more challenging. One of the main difficulties in this sector is the multi-disciplinary aspect of the problems.

* 1. **Progress made during the reporting period towards the objectives**

*[Please describe the progress made during the third reporting period in line with your Gantt chart and the project overall tasks as described in the Annex 1 of the Grant Agreement and summarized below.]*

***Table 1.2: Progress made during the reporting period towards objectives***

|  |
| --- |
| ***The NA7 will start by assigning tasks to working groups in view of the review paper. Both theoreticians and experimentalists of different experiments will be nominated to coordinate each working group. Two working groups “Open HF” and “Quarkonia” will be formed.***  ***Task 1: Open heavy flavor. The work will start with an assessment of the numerical models (Catania, Frankfurt, GSI and Nantes)that describe the dynamical variables of open heavy flavor hadrons***  ***Please note that Task 1 in the Gantt Chart reads:***  *1. Interpretation of LHC results development of the necessary theory and preparation of next run*  *1.1 Interpretation of LHC results*  *1.2 Preparation for HI-IL LHC runs*  *1.3 Theory developments*  ***We refer to these tasks 1.1, 1.2. and 1.3 in the following*** |
| Tasks 1.1 and 1.3 were well advanced already, and their finalization progressed smoothly over the period covered by this report.  A very intense work was done in this period for task 1.2. The original deliverables (and associated milestone) related to this activity was a paper with recommendation for the dedicated heavy-ion periods of LHC. It was agreed in the amendment of the grant to post-pone the due date for this deliverable (from month 26 to the end of the project) and the study had it focus on LHC Run 5 and beyond. The opportunity to have LHC periods with lighter collision systems than Pb-Pb was investigated in detail. In particular, two benchmark observables were selected: multi-charmed baryon production and azimuthal angular correlation of D and Dbar mesons.  On the one hand new theoretical studies have been conducted to provide predictions in different collision systems (O-O, Ar-Ar, Ca-Ca, In-In, Xe-Xe, etc…) for these two observables by two different groups. On the other hand, the expected performance for an experimental apparatus analogue to the new proposed ALICE 3, which is supposed to replace ALICE in the LHC Long Shutdown 4. was studied considering the previously mentioned colliding systems. The study demonstrated the impressive potentiality of lighter colliding systems as tool to understand the mechanism by which heavy quarks tend to reach equilibrium with the lighter (and equilibrated) partons of the QGP. This in turn has the potential to further elucidate the properties of the expanding QGP, the key objective of the experimental study of ultra-relativistic heavy-ion collisions. Therefore, also the remaining task 1.2 was fully completed at the end of the project. |
| ***Task 2: Hidden heavy flavor. The theory for hidden heavy flavour production in heavy ion collisions is even more complex and therefore less developed. It needs a multidisciplinary approach of different subfields to solve the questions at hand, which include the stability of quarkonia at high density and temperature, the recombination of c and cbars from different primary vertices, their hadronization and their final interaction with hadronic matter***  ***Again, please note that Task 2 in the Gantt Chart reads:***  *2. Interactive Framework for Theory-Data comparison*  *2.1 Theory data-base development*  *2.2 Retrieving of and matching to Experimental Data*  *We refer to Tasks 2.1 and Task 2.2 in the following* |
| Both sub-tasks were completed already before the start of the period covered by this report.  In the period from 1 June 2022 to 31 July 2024, there has been some remaining work to include a few further analysis (published results from the ALICE Collaboration ) in the Rivet DB, previously developed for proper treatment of Heavy Ion physics. In particular, the analyses and results documented in these papers:   * **Prompt and non-prompt J/y production at midrapidity in Pb–Pb collisions at = 5.02 TeV** DOI/journal: [10.1007/JHEP02(2024)066](http://dx.doi.org/10.1007/JHEP02(2024)066) * **Measurement of non-prompt D-meson elliptic flow in Pb–Pb collisions at  TeV** DOI/journal: [10.1140/epjc/s10052-023-12259-3](http://dx.doi.org/10.1140/epjc/s10052-023-12259-3) * **Measurement of the J/ψ Polarization with Respect to the Event Plane in Pb-Pb Collisions at the LHC** DOI/journal: [10.1103/PhysRevLett.131.042303](http://dx.doi.org/10.1103/PhysRevLett.131.042303) |
| ***Task 3: Workshops. Significant progress can only be expected from a common effort. The three network workshops will bring the driving forces of the different subfields together. The objective is that these workshops are seeds for future collaborations***  ***In this case, in the Gantt Chart this task reads properly, i.e.:***  *3. Meeting & workshop*  *3.1 Network meetings*  *3.2 Ordinary workshop at ECT\** |
| (in red the events in the period from 1 June 2022 to 31 July 2024)  The second network workshop was held from 28 September to 4 October 2023 in Giardini Naxos, Sicily, Italy. It included two series of lectures about "Exploring the phase diagram of strong-interaction matter with QCD inspired models" by M. Buballa, and "Jets in strongly interacting matter" by K. Tywoniuk. The workshop was attended by 54 participants. Every participant gave a talk.  <http://theory.gsi.de/~ebratkov/Conferences/HFHF-STRONG-2023/index.html>  Overall, in the full period, two theory workshops were held, plus the main workshop held at ECT\* in Trento. Other standard, online or hybrid workshops were organized and/or supported. This is the full list:   * First theory workshop: 4.10 – 8.10 2021 Crete (Greece)[*http://theory.gsi.de/~ebratkov/Conferences/STRONG2021/index.html*](http://theory.gsi.de/~ebratkov/Conferences/STRONG2021/index.html) * *Second theory workshop:* 28.9 – 4.10 2023 Giardini di Naxos (Italy) <http://theory.gsi.de/~ebratkov/Conferences/HFHF-STRONG-2023/index.html> * Main workshop: 15-19 November 2021 ECT\* Trento (Italy) [*https://www.ectstar.eu/workshops/quark-gluon-plasmacharacterisation-with-heavy-flavour-probes/*](https://www.ectstar.eu/workshops/quark-gluon-plasmacharacterisation-with-heavy-flavour-probes/) * Hybrid workshop “Heavy-flavour hadronization in pp and heavy ion collisions at the LHC” 2–3 Mar 2020 (CERN) <https://indico.cern.ch/event/866418/overview> * Online workshop “HF-QGP: theory meets experiments for the usage of RIVET”: 8.4.2021   <https://indico.cern.ch/event/1022351/>   * Support for the participations of students at the “11th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions” 26–31 March 2023, one of the major conference of the field, was given by this Network activity.   See <https://indico.uni-muenster.de/event/1409/page/48-supported-by> |

**1.3 Highlights of significant results**

*[Include an overview of the project results towards the objectives in line with the structure of the Annex 1 to the Grant Agreement*.*]*

Few highlights for this period are the following:

* Paper with title “Hadronization of heavy quarks “, Phys. Rev. C 109, 054912 (2024), where the differences in the hadronization processes due to the assumptions each approach have been studied in detail, which paved the way to unify the hadronization procedures in the different codes. This is the paper of the systematic comparison of transport approaches for heavy quarks/hadrons. The plots below shows the v2 coefficient, which quantifies the elliptic flow of D mesons, as a function of transverse momentum for the different models.

Immagine che contiene testo, linea, Diagramma, diagramma

Descrizione generata automaticamente

* The results of the paper “Phys.Rev.D 109 (2024) 5, 054011 (& arXiv:2401.17096 )” , about the study in small colliding systems with EPOS4HQ approach. The surprising enhancement of HF baryons over mesons and the appearance of an elliptic flow which has been observed in proton-proton data can be understood assuming that also in p-p collisions at the LHC a quark gluon plasma is formed if critical energy density of 0.57 GeV/fm3 is obtained. The plots below show a comparison between the model and the data.

Immagine che contiene testo, linea, diagramma, Carattere

Descrizione generata automaticamenteImmagine che contiene testo, diagramma, linea, Carattere

Descrizione generata automaticamente

* Results of prompt and non-prompt J/y production in Pb-Pb collisions at mid-rapidity down to very low transverse momentum, results presented EPS-HEP 2023, Hamburg. Significantly better precision w.r.t. LHC run 1 data. The plots below show the nuclear modification factor for prompt (left) and non-prompt (right) J/y versus the transverse momentum. Non prompt J/y production originates from beauty hadron decays.

Immagine che contiene testo, diagramma, schermata, linea

Descrizione generata automaticamente Immagine che contiene testo, schermata, linea, diagramma

Descrizione generata automaticamente

* First study ever of azimuthal angular correlation between a Lambda\_c baryon and charged particles. Preliminary results based on ALICE data and a paper ready for publication. The result below show the comparison between D meson and Lambda\_c.

Immagine che contiene testo, schermata, Carattere, numero

Descrizione generata automaticamente

1. Critical Implementation risks and mitigation actions

**2.1 Risk materialization**

*[Provide the information on the project risks described in Annex 1 to the Grant Agreement*.*]*

1. Delay in the LHC operations, e.g. in the hypothesis of a prolongation of the Long Shutdown phase 2. The probability of a cancellation or delay of the approved Pb-Pb ion run, scheduled at the end of 2018 is extremely low. The risk of delay or change in the schedule for the first ion run with High Luminosity (in 2021) is low. The above level of likelihood is assessed from current experience with LHC operations (maximum 2 weeks delay except at the LHC start-up)

Whether the risk has materialized? YES

1. Lack of work force for the development of the theory of the hidden heavy flavor mesons as well as for performing the transport calculations. The network has not the means to fund these activities. The progress will depend on that the funding by other institutions will continue on the present level (low)

Whether the risk has materialized? (Yes/No) NO

**2.2 Risk-mitigation measures applied**

*[Please indicate whether the risk-mitigation plan described in Annex 1 to the Grant Agreement and corresponding to the risk number was applied in the reporting period*.*]*

1. In case of change of schedule (delay) for the first ion run with High Luminosity: - extend the preparation of LHC HI-IL runs - focus on pp collisions at very high multiplicity, to study if and how a small QGP droplet can be formed

Whether the risk-mitigation plan was applied? YES

1. Optimizing the time frame for the deliverables and milestones associated with these activities

Whether the risk-mitigation plan was applied? YES – work has been anticipated significantly on the front of Task 2. Milestone and deliverable associated to Task 1 was moved towards the end of the project and the project itself was extended.

**2.3 Comments/new risk-mitigation measures proposed**

*[Provide any significant comments on the risks encountered and the mitigation plan applied. Give any unforeseen risks encountered during the reporting period and not mentioned above*.*]*

The schedule of the first Pb-Pb run with LHC run3 was further delayed by one year and data could be collected only in Autumn 2023. With the new LHC schedule the overall delivered integrated luminosities was higher than originally planned with two shorter ion runs in 2022 and 2023. With this new LHC schedule the opportunity to study lighter ion colliding systems than Pb-Pb can concretize realistically after LS4, in LHC Run5 and Run6. We therefore extended even further our studies and we showed how an apparatus like that proposed for the ALICE 3 experiment would offer unique and best opportunity for these studies.

3. Deviations from Annex 1 (Description of Action) and Annex 2 (Estimated budget for Action) (if applicable)

**3.1 Deviations from planned objectives and tasks, and their impact on the progress of the work package**

*[Explain the reasons for deviations, the consequences and the proposed corrective actions.]*

*None*

**3.2 Deviations between actual and planned person months**

*[Explain deviations between actual and planned person-months. If applicable, propose corrective actions.]*

There might have been slight deviations, which depends on the cost of the hired new personnel (less months for more experienced personnel, due to the higher cost of their contracts, or vice versa for young researchers). No real impact on the activity of this WP.

1. Deliverables and milestones tables

**4.1 Deliverables**

*[Please list all the deliverables due in this reporting period, as indicated in Annex I.*

*Deliverables must also be accompanied by a short report (deliverable description and technical documentation, such as photo, list of publications, etc.), so that the European Commission has a record of their existence.]*

***Table 4.1 List of deliverables***

| **Deliverable No.** | **Deliverable name** | **Lead Beneficiary** | **Nature** | **Dissemination level[[1]](#footnote-1)** | **Delivery month from Annex I** | **Delivered**  **(yes/no)** | **Actual delivery month** | **Comments** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| D18.2 | Talks delivered at the workshop/meetings  published at the webpage | 1 - CNRS | Report | PU | 52 | yes | 52 | All talks available on October the 4th 2023 |
| D18.3 | Paper with  recommendation for the dedicated heavy-ion periods of LHC after the 2nd Long Shutdown for the different LHC  experiments | 1 - CNRS | Report | PU | 62 | yes | 62 | Focus moved to LHC runs after LS4 and with a new concept of experimental apparatus (ALICE 3) |

*In case a deliverable has been delivered in the reporting period and a report exists in the Participant Portal, you can indicate “uploaded report” in correspondence of a deliverable*

**4.2 Milestones**

*[Please complete the table if milestones are specified in Annex I.*

*Milestones will be assessed against specific criteria and performance indicators as defined in Annex I.]*

***Table 4.2 List of milestones***

| **Milestone number** | **Milestone name** | **Lead beneficiary** | **Delivery month from Annex I** | **Delivered**  **(yes/no)** | **Actual delivery month** | **Comments** |
| --- | --- | --- | --- | --- | --- | --- |
| MS31 | Draft of strategy paper for next LHC Runs | 30 - INFN | 54 | yes | 61 | Delay for the further extension to Run 5 and beyond |

**4.3 Deliverable Reports**

*[Please provide, per each deliverable listed in Table 4.1, a brief description, including if possible some technical documentation (photos, list of publications, etc.). Use as many pages as needed per each report.]*

The report was provided on the 30th of July 2024, it includes a published papers and another paper submitted as a preprint to arXive. The report without the two papers is 11 pages, the full report with the paper is 38 pages. This is the front page.

Immagine che contiene testo, schermata, Carattere, documento

Descrizione generata automaticamente

1. PU = Public

   PP = Restricted to other programme participants (including the Commission Services).

   RE = Restricted to a group specified by the consortium (including the Commission Services).

   CO = Confidential, only for members of the consortium (including the Commission Services). [↑](#footnote-ref-1)