Study of heavy quark production in heavy ion collisions with the LHCb experiment at the LHC

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1 Summary

The project aims at measuring precisely heavy quark production in heavy ion collisions at the LHC, with the LHCb experiment, exploiting the excellent performances of the detector optimized for the study of heavy quark production and decays. These measurements will improve the understanding of the strong interaction and of the nature of color confinement from the behavior of the heavy quarks in the hot and dense medium formed in the heavy-ion collisions. Two complementary experimental setups can be obtained in LHCb providing unique datasets that are exploited with this project:

- Collisions of protons with Lead ions, where “Cold Nuclear Matter” effects are studied
- Collisions of protons or Lead beams with a gas fixed target at a unique lower energy of about 100 GeV than the one reached in collisions where competing effects seen in high energy collisions can be more easily disentangled

The project uses existing facilities and extends the experiment’s physics program with moderate extra resources. At present, 5 persons at IN2P3 participate, 2 permanent researchers and 3 post-doc, supported by external funding. This team initiated this program within LHCb and obtained first results in the past two years. These results were very well received and attracted new collaborators and ideas to LHCb. The performances expected for the detector after the LS2 Upgrade I (2021-2030) and even more after the hypothetical LS4 Upgrade II (2030-) will reinforce further the attractiveness of the project since even the study of Lead-Lead collisions will become possible. However, the human resources are expected to decrease quickly within the next two years without extra support from IN2P3 and there is a high risk that the leadership of the institute in the project will be strongly reduced within the same timescale.

2 Scientific goals

The scientific goal of the project is to study one essential property of QCD, the color confinement of quarks inside hadrons, which is still poorly known at both theoretical and experimental levels. This is addressed studying hadron collisions at very large energy densities, for example in heavy ion collisions at the LHC, and characterizing precisely the medium formed in the collision using heavy quarks, *ie* charm or beauty quarks, as probes.

2.1 Quark Gluon Plasma

In the late 80's, Matsui and Satz [1] where the firsts to predict theoretically that, in a hot and de-confined medium as produced in heavy-ion collisions and called Quark-Gluon plasma (QGP), color screening would prevent the binding of charm quarks to produce color neutral $c\bar{c}$ bound states. In this scenario, charmonium $c\bar{c}$ suppression should occur and for the same reasons, suppression of bottomonium $b\bar{b}$ states also. Since excited states, such as ψ(2S) or Υ(2S) for example, are less tightly bound than the ground state, *J*/ψ or Υ(1S), they should be suppressed at lower temperature or energy density than the ground state. As a consequence, the in-medium dissociation probability of these states should provide an estimate of the initial temperature reached in the collision and lead to a precise characterization of the phase transition between the normal QCD state of matter and this de-confined state. Moreover, the ground states are partially produced through feeddown from $c\bar{c}$ or $b\bar{b}$ higher excited states [2] such as ψ(2S) or Υ(2S) and χ_c or χ_b which contribute to the inclusive prompt *J*/ψ or Υ(1S) yields at the level of 10% and 30% respectively. Therefore, in a de-confined medium, the *J*/ψ or Υ(1S) production probabilities should exhibit a step-by-step suppression pattern, also called sequential suppression, as illustrated in Figure 1. A first suppression step should occur when the medium temperature or energy density reaches the ψ(2S) dissociation temperature, a second suppression step should occur when the temperature reaches the χ_c dissociation temperature and the last suppression step should occur when the temperature reaches the direct *J*/ψ dissociation temperature.

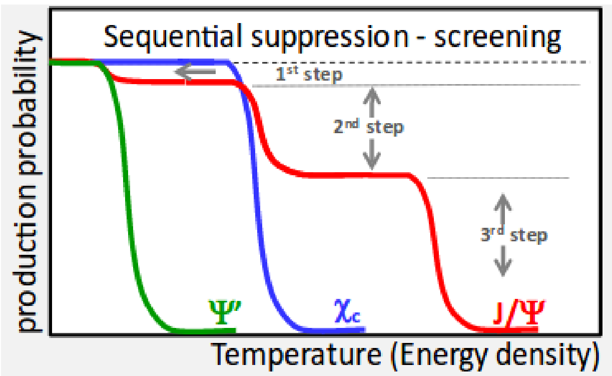

Figure 1: Schematic view of the charmonium sequential suppression pattern

Experimentally, in 1997, the NA50 experiment observed an anomalous suppression of J/ψ production in PbPb collisions at $\sqrt{s}$ = 17.2 GeV [3]. Ten years later, an even larger suppression of ψ(2S) production was observed under the same experimental conditions [4] pointing to the theoretically expected sequential suppression where the ψ(2S) resonance is suppressed at a smaller energy density, or equivalently a lower temperature, than the J/ψ. However, no final conclusion could be made, because of the ψ(2S) very small binding energy of about 50 MeV, which makes it fragile enough to be broken by non QGP mechanisms such as co-moving hadrons [5].

At a collision energy of $\sqrt{s}$ = 200 GeV, more than ten times larger than the one reached at SPS, the PHENIX and STAR experiments in the years 2000 recorded various types of proton and ion collisions at the Relativistic Heavy Ion Collider (RHIC). At these energies, the theory predicts the production of a QGP with a maximal initial temperature well above the QGP critical temperature T_c. Although a larger suppression of the quarkonia was expected at RHIC due to a higher initial temperature and density, the data actually showed a J/ψ suppression surprisingly similar at RHIC and SPS [6, 7]. A usual interpretation of this result is the balance between an initially larger suppression and a final statistical regeneration. The latter is based on the possible secondary production of quarkonia from recombination of uncorrelated c and $\bar{c}$ quarks at the phase boundary [8], as shown in Figure 2. This scenario invokes a new and mostly unknown binding dynamics to form charmonia and is currently determined only by the relative abundance of charm quarks.

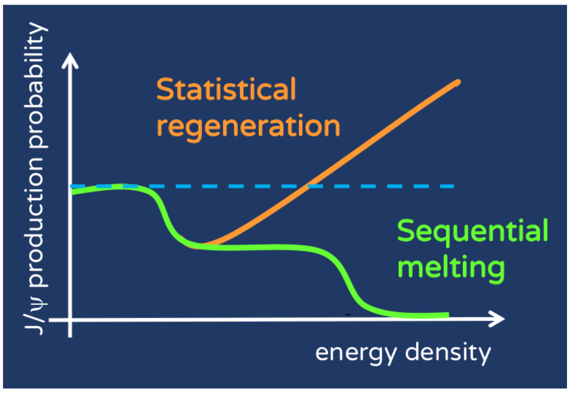

Figure 2: Schematic view of the interplay between sequential suppression and statistical regeneration mechanism.

Statistical regeneration can occur only when charm quarks are abundant enough with respect to light quarks. Since the $c\bar{c}$ pair production cross-section rapidly increases with collision energy, only sufficiently high energy collisions can lead to statistical regeneration. At RHIC, around ten $c\bar{c}$ pairs are produced in central AuAu collisions [9] while, according to the $c\bar{c}$ pair cross-section dependence with energy, only 0.1 $c\bar{c}$ pairs are on average produced at SPS energies where regeneration is thus negligible.

More recently, at LHC, with a collision energy $\sqrt{s_{NN}}$ = 2.76 TeV more than 10 times larger than at RHIC, the ALICE experiment observed a smaller J/ψ suppression than at RHIC [10], which is expected when considering an initial suppression which is partly balanced by statistical regeneration. Since the number of $c\bar{c}$ pairs produced at these energies is of the order of one hundred per central PbPb collision and since recombination increases quadratically with the number of c quarks in the medium, one expects a smaller overall suppression at LHC than at RHIC. Nevertheless, the quantitative description of the statistical regeneration mechanism is currently not accessible, since it requires a full control of the suppression mechanism which is currently lacking and must be studied in dedicated experimental conditions, which can be reached at the LHCb experiment.

2.2 Cold Nuclear Matter effects

The limited understanding of nuclear phenomena, unrelated to de-confinement, and commonly called cold nuclear matter (CNM) effects, restricts the ability of phenomenological models to describe the experimental data on *J*/ψ production in PbPb collisions. Their size can be quantified by measurements in *p*-Nucleus or deuteron-Nucleus collisions, which have been pursued at the SPS, RHIC, HERA and LHC [11]. The feature of CNM drawing the highest attention for *p*Pb collisions at the LHC is the modifications of the gluon-flux coupling to the charm quark pair. This modification is often treated within a collinear parton distribution framework employing nuclear parton distribution functions (nPDFs) [12–15]. For the low-*x* part, calculations within the color glass condensate (CGC) effective field theory, describing the saturation regime of QCD [16, 17], are frequently employed. Several calculations have been pursued to quantify nuclear modifications of *J*/ψ production in the collinear framework [18–21] or in the CGC framework [22–24]. It has to be noted that the low-*x* gluon content of the nucleus is largely unconstrained by any clean experimental data at perturbative scales. In addition, small-angle gluon radiation taking into account interference between initial and final state radiation, called coherent energy loss, was proposed as the dominant nuclear modification of quarkonium production in *p*Pb collisions [25]. The discrimination between these phenomena are a strong motivation for the study of the production of quarkonium as a hard-scale probe of dense QCD.

The measurement of the non-prompt *J*/ψ, coming from *B*-hadron decays, production provides access to the production of beauty hadrons. The modification of their kinematic distributions in nucleus-nucleus collisions carries valuable information about the created matter [3]. In a manner similar to direct charmonium production, the production of beauty-hadrons can be subject to CNM effects altering the interpretation of nucleus-nucleus collision data, which can be precisely measured in *p*Pb collisions.

3 The project

To reach full control of the suppression mechanism, one must:

- Operate heavy ion collisions at an energy small enough to avoid any possible recombination effects, namely at about 70 GeV in the center-of-mass system, where only one $c\bar{c}$ pair is produced in the most violent heavy ion collisions.

- Study several different charmonium states, including 1P states such as χ_c for the charmonium family and precisely measure open-charm production, *ie* of hadrons with only one *c* quark, as a reference to calibrate the charmonium suppression, and also measure the equivalent states for the bottom quark.

- Use collisions of protons on different target nuclei, from small to high atomic number *A*, and also collisions of proton and nuclei in collider mode in order to measure and take into account cold nuclear matter effects on heavy quark production in normal nuclear matter conditions: with protons the energy reached in the collisions is too small to produce a QGP. These effects can have the same suppression signature than that seen in the QGP, so will be a background for the QGP study.

The project consists in measuring precisely the production of heavy quarks with the LHCb detector in different collision environments available at the LHC, mainly in proton-Lead collisions and fixed target collisions.

3.1 The LHCb experiment

The LHCb detector is one of the four large experiments installed at the LHC at CERN. It is dedicated and optimized for the study of beauty and charm hadron decays produced in the pp collisions of the LHC, thus an ideal facility to measure heavy quark productions. The detector has been designed to operate in a low particle multiplicity environment. However, it is running since the beginning of the data taking run in 2010 at a larger instantaneous luminosity, *ie* larger pile-up, than initially foreseen, without any loss of performance, and recorded in these conditions pp collisions at center-of-mass energies of 7 TeV (2010 and 2011), 8 TeV (2012) and 13 TeV (since 2015).

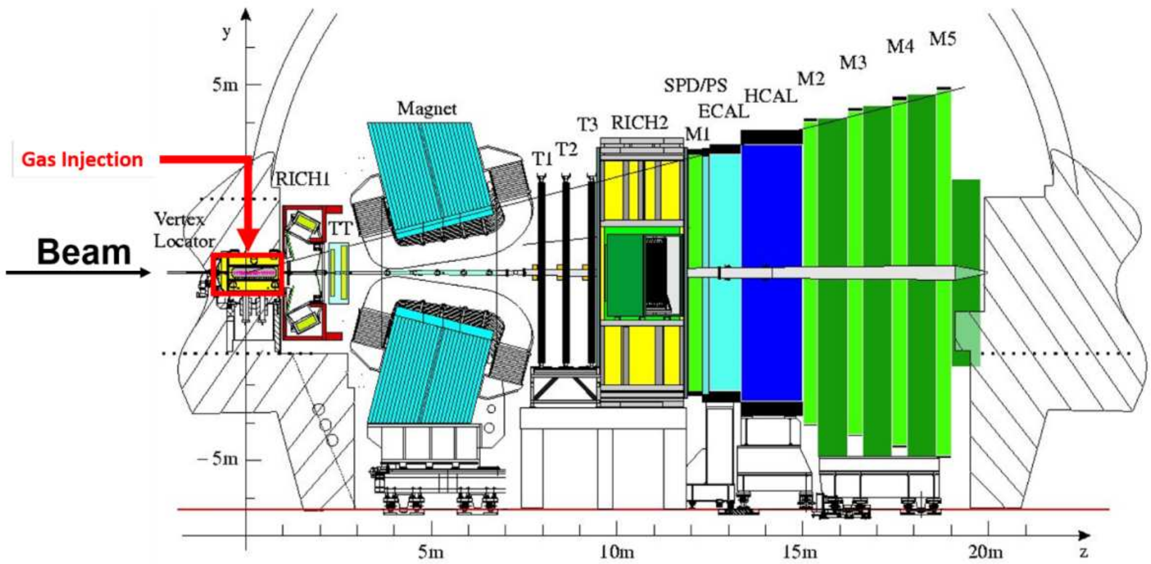

Figure 3: Layout of the LHCb detector

The detector is shown in Figure 3 and described in details in Ref. [26, 27]. The most interesting features of the apparatus related to the project are listed below:

- A system (SMOG) has been developed to inject gas at the interaction point, inside the VELO detector and directly in the LHC beam pipe. This system was originally designed to measure the luminosity at LHCb by measuring the beam overlap thanks to the reconstruction of beam gas vertices providing an image of this overlap region [28]. One of the main idea of the project is to divert the original use of the system to take physics data of collisions of the LHC proton or Lead beams with this gas acting as a fixed target. The center-of-mass energies reached in the fixed target configuration is of the order of 100 GeV, unique at the LHC, compared to energies of the order of 1 to 10 TeV in the collider mode operation.
- The LHCb detector instruments fully the forward region of the pp collision, in a pseudo-rapidity (η) range between 2 and 5. It is the only detector at the LHC containing a complete set of sub-detectors for vertexing, tracking, particle identification and energy reconstruction in this phase space region. The forward geometry is also an asset for the fixed-target configuration since the acceptance covered in the collision centre-of-mass frame is between -2.8 and -0.1 in rapidity (y^*), that is to say the backward region close to mid-rapidity.
- The separation of "prompt" charm hadrons, coming from the collision, from those coming from *b* decays is possible and efficient, thanks to the VELO detector, a silicon strip detector placed very close to the interaction point. The performances of the detector have been optimized to be able to perform time-dependent CP violation analyses with B^0 and B_s^0 mesons, with a decay time resolution of 45 fs. They are thus, by far, ideal to achieve the separation of the prompt and non-prompt components which is crucial to isolate direct charm production, a mandatory point for the scientific program of the project.
- The tracking detectors provide reconstruction of charged tracks down to very low momentum with good precision; the relative resolution on momentum measurement is of 0.5% at low momentum. This means that the production of beauty and charm hadrons can be measured also down to 0 transverse momentum, covering thus a large fraction of the phase space and a region where CNM effects are expected to be large and easier to characterize.
- Performant particle identification is achieved thanks to two Cherenkov detectors, muon stations and a calorimeter system. Beauty and charm decays can then be reconstructed also in purely hadronic final states, and not only using muons. This increases the statistics for the measurements, and in the case of open charm or beauty production, constrains fully the kinematics of the final state in contrast to measurements performed with muons from semi-leptonic decays where the momentum of the particles cannot be measured fully.
- The data acquisition runs with a large bandwidth and at high frequency. The trigger system is a flexible software system using ample computing resources. This allows to record data with full data taking efficiencies and to apply only very loose trigger thresholds, maximizing the trigger efficiencies.

However, as said above, the detector is designed to operate in a low multiplicity environment. The multiplicities reached in proton-Lead collisions, because of the low pile-up in these conditions, and in the fixed target configuration, because of lower center-of-mass energies, are still optimal for the detector, but the ones obtained in Lead-Lead collisions are not. This is why the project is limited currently to the study of heavy quark production in proton-Lead and fixed-target collisions.

3.2 Heavy flavor measurements at top LHC energies in proton-nucleus collisions

Important measurements can be obtained in this configuration, using collisions of protons with Lead at the LHC, at a center-of-mass energy of 8 TeV, and are or will be published. About once per year, the LHC accelerates a Lead ion beam and collides it either with a proton beam or with another Lead beam. The first configuration is the one mentioned in this section. Due to the geometry of the detector, a forward spectrometer geometry, the acceptance covered by the detector is not the same when the proton and Lead beams are inverted in the LHC. This feature allows to collect effectively data in two independent and complementary configurations: "proton-Lead collisions" where the detector covers a forward y* range between 1.5 and 4.0, and "Lead-proton collisions" where the coverage is $-5.0 < y* < -2.0$

The usual and easiest one is the measurement of J/ψ production. This measurement gives both access to the measurement of $c\bar{c}$ bound states but also to the measurement of b quark production since the two production types can be separated by the detector. The main outcome of this analysis is to understand the Cold Nuclear Matter effects, *ie* the suppression of production of these states in nuclear collisions at low energy densities. These effects are expected from the modification of the parton density functions (PDF) in nuclei compared to the ones in free partons, called shadowing, but could also be due to other phenomena such as the presence of co-moving partons or the loss of energy of the heavy quarks in the medium of the collision. Comparison of the experimental data with the various theory predictions can then help disentangling the various contributions. This will in turn be an essential input to understand what happens in collisions with heavier systems, such as PbPb collisions.

Other similar measurements are foreseen in the project since they can provide additional constraints: measurements of other $c\bar{c}$ states such as ψ(2S) or χ_c will give information about the effect of the feed-down from excited states in the J/ψ measurement and about the importance of the bound state binding energy and size in the suppression mechanisms. Measurements of $b\bar{b}$ bound states (Upsilons, χ_b, …) will give information about the influence of the energy scale on the theoretical computations. Study of the production of open charm or beauty mesons (D^0, D^+, B^0, B_s^0, …) or baryons (Λ_c, Λ_b, …) will give the overall normalization for the charm and beauty production. They will also provide very important constraints for the determination of the nuclear PDFs, which are for the moment very poorly known especially in the acceptance region covered by LHCb. These PDFs are particularly important for the characterization of charmonium suppression in the QGP.

With the data set acquired by the experiment, other measurements can be envisaged. One example is the measurement of the correlations between the two charm quarks when produced, looking at multiple D^0 production for example. This is also interesting in order to understand better the QCD processes at play in hadronic collisions, in this example in particular, the role of multiple parton interactions that can also occur in pp collisions but which is boosted here by the fact that the Pb nuclei contains a large number of nucleons. In the future, many other measurements will be studied and will emerge.

3.3 Heavy flavor measurements at O(100 GeV) energies in nucleus-nucleus collisions

Thanks to the SMOG subsystem, one can study different proton-nucleus and nucleus-nucleus collisions at energies of 70 to 110 GeV, small enough so that the statistical regeneration mechanism can be neglected[1]. Studies based on the EPOS generator [29] show that operating PbAr collisions at 71 GeV with 2.75 TeV incoming Pb beams will reach energy densities equivalent to the ones reached by the NA50 experiment with 17 GeV PbPb collisions. As shown in Table 1, in the most central collisions (0-10%), the particle multiplicity, which is a good characterization of the energy density, is similar in PbAr collisions at 71 GeV and in PbPb collisions at 17 GeV. With PbKr and PbXe collisions, energy densities larger than reached at the SPS can be explored.

System\centrality	**100-60%**	**60-50%**	**50-40%**	**40-30%**	**30-20%**	**20-10 %**	**10-0%**
Pb-Ne 71 GeV	108.6	254.4	392.5	588.0	814.5	1086.0	1494.9
Pb-Ar 71 GeV	**123,6**	**308,8**	**496,5**	**806,6**	**1228,3**	**1711,9**	**2372,7**
Pb-Kr 71 GeV	196,9	533,6	919,1	1451,2	2205,5	**2986,6**	**4084,3**
Pb-Xe 71 GeV	201,4	581,7	1031,0	1587,3	2400,2	**3541,7**	**5065,7**
Pb-Pb 17 GeV	**124,2**	**331,6**	**605,9**	**919,6**	**1338,7**	**2035,8**	**2980,5**

Table 1: Particle multiplicities as function of centrality for various colliding systems and energies. 100-60% correspond to the most peripheral collisions, 10-0% to the most central collisions.

4 History and Calendar

The project is proposed by physicists from the Laboratoire Leprince Ringuet (LLR, Palaiseau) and Laboratoire Linéaire d'Orsay (LAL, Orsay), Frédéric Fleuret and Patrick Robbe. The LHCb LAL group is deeply involved in the measurement of heavy flavor production since the beginning of the experiment, even before the start of data taking. It was leading the measurements performed during the Run 1 of the LHC (2010-2012) of the J/ψ, B^+ and B_c^+ production cross-section. This activity was supported by an ANR "Jeunes Chercheurs" grant and is also supported since 2006 by the France-China FCPPL LIA. Two PhD theses were prepared, supervised jointly at LAL and at the Tsinghua University in

[1] At 70 GeV, one expects on average no more than one $c\bar{c}$ pair in central PbPb collisions

Beijing and several publications were obtained [30–32]. The quality and precision of the LHCb measurements concerning heavy flavor production were favorably received by the particle physics community and it was clearly established that LHCb is a major contributor in this scientific domain. The measurement of the production of heavy quarks in other environments than *pp* collisions was the natural extension of this early physics program and an excellent way to benefit from the methods developed during these first measurements. A first short pilot run in 2013, where LHCb collected a very small amount of collisions in proton-Lead and proton-Ne, Ne being the gas injected by the SMOG system at that time, proved the feasibility from the operational point of view of taking these data.

In parallel, theorists and experimental physicists including Frédéric Fleuret from the IN2P3 developed a program to study the feasibility and impact of a fixed target program at the LHC, namely the AFTER program [53] lead by Jean-Philippe Lansberg from the Institute of Nuclear Physics in Orsay. Rapidly the connection was made with the LHCb SMOG system and Frédéric Fleuret joined LHCb to explore further this area. His participation was examined by the LLR scientific council which brought strong support to the project [33]. In 2015, a proposal was submitted to the LHCb collaboration to record data in heavy-ion and fixed target collisions, and was accepted. Soon after, a consolidator ERC project was accepted and funded by the European Commission which allowed to form a small group at LAL to implement the proposal, hiring several post-docs. The project was also examined by the LAL scientific council at that time [34] which showed strong support.

The next steps were to acquire these data. Both for the collider mode and the fixed target mode, data taking conditions are not usual for the LHCb detector and a lot of preparation had to be made to ensure the success of these data taking campaigns. These are dedicated short runs of maximum one month, in special LHC planned slots during which the standard pp data taking stops. The LAL and LLR teams were heavily involved in the preparation of these special runs, both for the justifications with the LHC committees [35] and the operation of the detector. The LAL group has been heavily involved in the building and the commissioning of the experiment in particular for the calorimeter, the L0 trigger and the experimental control system. The involvement of the group continued during the operation of the detectors, ensuring a large number of shifts and Patrick Robbe was run coordinator of the experiment in 2015 and 2016, so the team of the project also took part fully to the data taking activities related to heavy-ions in LHCb. In 2015, for the first time, LHCb recorded PbPb collisions at a centre of mass energy of 5 TeV. While we are not participating to the analysis of this data which is limited by the degraded performances of the detector in this high multiplicity environment, we provided strong support for the data taking and the offline reconstruction of the data.

4.1 Current fixed-target program

Concerning the fixed-target program, in 2015, a first short physics run with 18h of data taking was performed with a 6.5 TeV proton beam hitting argon atoms. The LLR and LAL teams were in charge of the analysis of these data. Figure 4 shows (*left*) the invariant mass of two opposite charge muons from J/ψ decays and (*right*) the invariant mass of $K^-\pi^+$ mesons from D^0 decays. These preliminary results, shown for the first time at the Quark Matter 2017 conference in Chicago (USA) [36], clearly prove the feasibility of the heavy flavour fixed-target program. Another short physics run was performed in 2016, with a 4 TeV proton beam hitting helium gas. These collisions are currently analyzed to compare with the proton-argon results. These two first SMOG runs are statistically limited, with no significant number of 2S and 1P charmonium states in the recorded data.

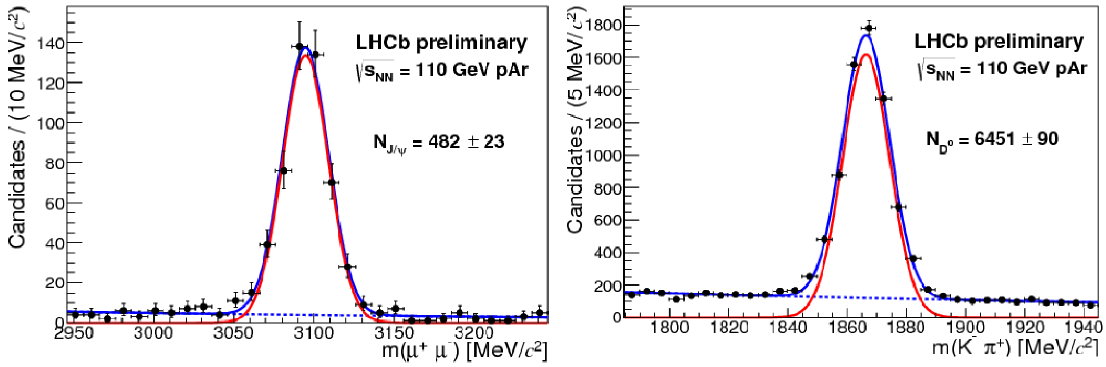

Figure 4: J/ψ (left) and D^0 (right) invariant mass distributions

Following this first study, the LHCb collaboration has decided to dedicate to the fixed-target setup a much longer run in November 2017. We collected collisions of 2.5 TeV protons on Neon, during 120h. With this longer run and for the very first time, we will collect enough SMOG data to observe and study the $c\bar{c}$ 2S and P states.

4.2 Current collider program

Concerning proton-Lead collisions, a large data set corresponding to an integrated luminosity of 35 nb^{-1} (14 nb^{-1} of pPb collisions and 21 nb^{-1} of Pbp collisions) was recorded in 2016. This is the main sample for the measurements planned in proton-Lead collisions for the project, the next proton-Lead at the LHC being planned for in about 10 years. The first measurement that we performed is the one of the cross-section of the J/ψ, reconstructed in the $\mu^+\mu^-$ channel. Thanks to the very good quality of the data, precise measurements of the cross-section and of the suppression were obtained and are shown in Figure 5. This analysis was published in Ref. [37] and this measurement is the first one made between all experiments with the 2016 proton-Lead sample. Other measurements are ongoing which will be published during the year 2018: the cross-section of open beauty hadron production (B^0, B^+, B_s^0 and Λ_b), the cross-section of χ_c which would be a pioneering analysis in heavy-ion collisions and the study of D^0-$\overline{D}^0$ correlations.

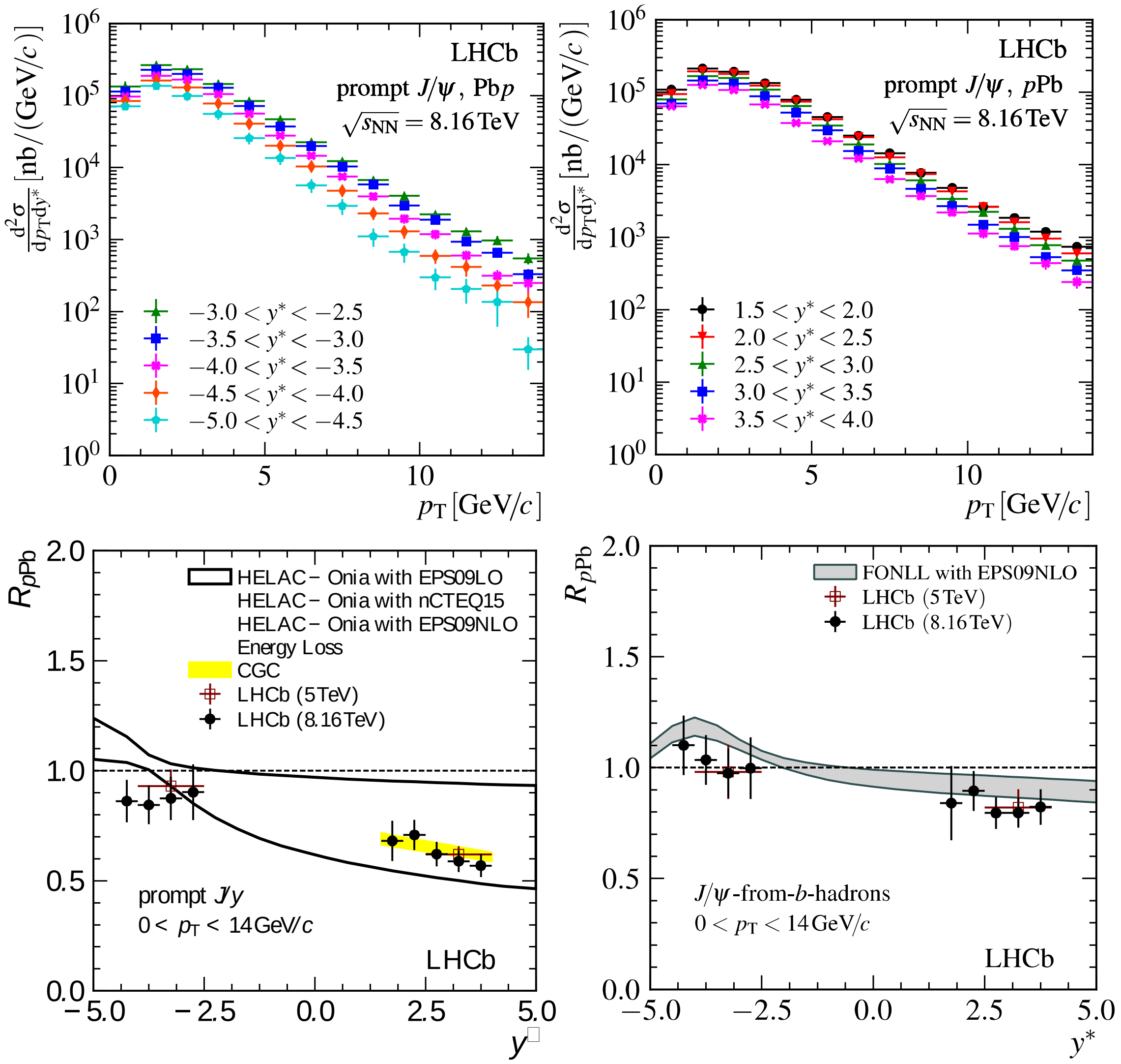

Figure 5: Production cross-section of prompt J/ψ in pPb (top left) and Pbp (top right) collisions, J/ψ suppression in pPb and Pbp collisions: prompt (bottom left) and non-prompt (bottom right)

Both fixed-target and collider results were presented by members of the LLR-LAL team at several important conferences in the field: ICHEP 2016 in Chicago [38], Quark Matter 2017 in Chigaco [39–41], HEP-EPS 2017 in Venice [42, 43]. Contacts were also established with theorists, working in the Orsay area: Jean-Philippe Lansberg at IPN in Orsay, François Arleo at LLR in Palaiseau and Samuel Wallon at LPT in Orsay. The theroretician Elena Gonzales Ferreiro, professor at the University of Santiago, expert in heavy flavor physics with heavy ion collisions, has been granted by the Paris-Saclay d'Alembert program to collaborate with our team. She is currently spending one year, since October 2017, in the Paris-Saclay area working with us on the phenomenological aspects of our analysis.

4.3 Short-term future

Concerning the immediate future, at the end of 2018, the LHC plans to have a long Lead ion run. We will collect Lead-Neon collisions at an energy of 70 GeV in the centre-of-mass, identical to the 2017 *p*Ne energy, which we estimated will reach maximum multiplicities just at the limit of the detector reach. As it will be the first large sample of Pb-induced collisions, we will need few months to fully reconstruct and understand it. These data will be available for physics analyses six months after their collection. We will fully exploit them during the LHC shutdown 2, from 2019 to 2021.

4.4 Middle-term future

For the middle-term future, during the LHC shutdown 2 between 2019 and 2020, many subdetectors of the LHCb experiment will be upgraded, significantly improving its overall performance. This upgrade has been primarily designed to stand higher luminosities in proton-proton runs, but it will also highly improve the detector performance in the fixed-target configuration and for heavy-ion collisions, pushing further the performances of the detector for high multiplicity events.

The track reconstruction and the vertex determination will be upgraded with the replacement of the Vertex Locator by a hybrid pixel detector [44]. The improvement will result both from the pixel geometry (41 million of 55 µm x 55 µm pixels) and from a closest distance to the LHC beams of 5.1 mm. The track reconstruction in dense environments, *ie* for nucleus-nucleus collisions, will be clearly improved thanks to the new high granularity tracker. The Turicensis Tracker, identified as TT in Figure 3, is located upstream from the LHCb magnet and is currently made of 4 planar detection layers of large area silicon sensors. It will be replaced by the Upstream Tracker (UT) [45] made of 4 planes of silicon strips with thinner sensors, finer segmentation and larger coverage. In addition, the three tracking stations, called T1-T3 in Figure 3, located downstream from the LHCb magnet, will be replaced by a scintillating Fibre Tracker, made of 2.5m long fibres read out by silicon photo-multipliers. The new tracking system will improve track reconstruction in very dense environments. Indeed, with the current configuration, the tracking efficiency for events with more than 5 primary vertices drops dramatically. The efficiency is below 80% for 5 primary vertices and around 60 % for 10 primary vertices, while with the upgraded trackers, the efficiency will remain above 80 % for events with 10 primary vertices. The tracking performance for nucleus-nucleus collisions will be highly improved. The current LHCb tracking algorithm cannot reconstruct the most central PbPb collisions, and leads to a large amount of lost data. With the tracking system upgrade, the most central nucleus-nucleus collisions will be measurable.

The last significant upgrade regarding SMOG data taking is related to the trigger and the readout of all the subdetectors [46]. The current LHCb trigger is divided into a hardware and a software part. The hardware trigger identifies basic signatures from few subdetectors with a 40 MHz readout. It reduces the trigger rate to 1 MHz. Data are then transferred to the software level where more elaborated algorithms are applied. The upgrade of the trigger removes this bottleneck namely the hardware level. All the subdetectors readout will thus run at 40 MHz and more efficient algorithms will select interesting events. With this configuration, the full event will be reconstructed with a precision identical to the offline precision. We will thus be able to exploit the full event, without applying tight preselection cuts. The upgrade of the trigger will be particularly useful for hadronic final states such as open charm decays. In conclusion, the upgrade of LHCb will clearly enhance its vertexing and tracking capabilities. The SMOG data taking during Run 3 will thus greatly benefit from all these foreseen upgrades, opening the possibility to take fixed target collisions with heavier gas such as Xenon.

In addition to the detector upgrade, the SMOG system will be improved. With the current SMOG system, the gas pressure cannot be higher than 10^{-7} mbar. To compensate this low pressure, we have to take longer data taking periods. In order to increase the interaction rate and, at the same time, minimize the collision vertex location spread, a SMOG upgrade is currently under development. It consists of a gas storage cell located upstream from the vertex detector as shown in Figure 6. The target gas will mostly be contained in this 20 cm long cell, thanks to an appropriate pumping configuration, which will both increase the pressure up to 50 times and lead to a significantly more accurate vertex location spread. The building of the upgraded SMOG system is taken care of by a team of physicists from INFN in Italy, but one of the post-doc of our team (Emilie Maurice) is following closely the developments in this area.

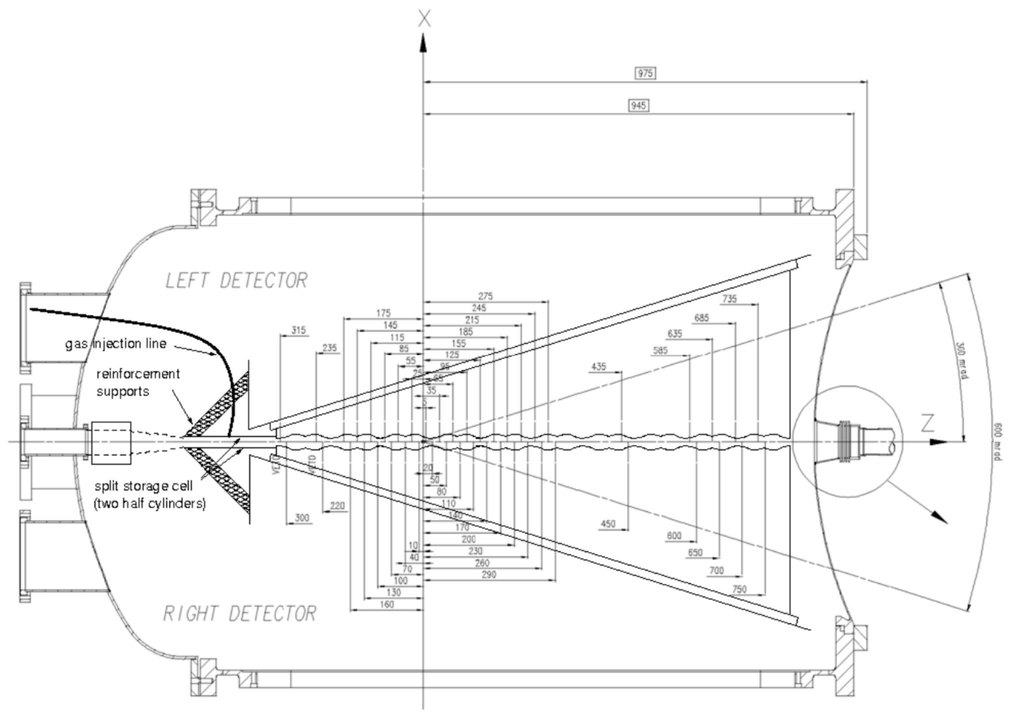

Figure 6: Detailed schematics of the upgrade VELO area with dimensions and structure of the VELO geometry. The elements needed for the upgrade of SMOG are indicated in this figure, on the left part: gas injection line, supports and the storage cell with the gas.

4.5 Long-term future

On the longer term, the first success of the heavy-ion data taking campaigns realized by the team motivated new ideas, in particular for improved fixed target experiments at LHCb in the future. Several ideas are discussed at the moment within the collaboration: the possibility to install a solid wire target, to inject polarized gas or to use bent crystals to deflect the beam halo and send it on a solid target. These projects have been initiated outside IN2P3 except for the last one, with bent crystals which was developed at LAL within the UA9 group by Achille Stocchi. This project aims at measuring the Magnetic Dipole Moment of charm baryons to test various models of physics beyond the standard model [47]. Finally, an expression of interest for a LS4 Upgrade II of the LHCb experiment was recently prepared [48]. This upgrade which would be installed in 2030 aims at running at even much higher luminosities, meaning much higher multiplicity than for the first upgrade. It is clear that heavy ion physics in LHCb would benefit a lot from these developments, but this has not yet been studied in details.

5 State of the art

The first results obtained within this project were extremely well received, because of their precision in the case of proton-Lead collision measurements or because they provide measurements in a different energy than what was available up to now in the fixed-target case [36–43]. They also motivated several new groups to join the collaboration. In 2017, three new groups officially joined out of which two will participate in heavy ion analyses: Michigan and Los Alamos, USA.

Currently the main experimental results in high energy heavy ion collisions are produced at the LHC. All large four experiments have now a program in this area: the other three experiments (ALICE, ATLAS and CMS) study heavy flavor production but have a broader physics program that LHCb which for the moment only measure heavy quark production. Moreover, the LHCb experiment can hardly contribute to measurements in Lead-Lead collisions because of the too large multiplicity and thus cannot compete in this area. However, for measurements in proton-Lead, the large dataset collected in 2016 has a huge potential, currently largely under-exploited due to the lack of persons working in this area in the collaboration. The LHCb acceptance is unique between the large experiments at the LHC, complementary to the acceptance of the other experiment: LHCb covers the forward region and low p_{T} region while the others study the central and high p_{T} regions. The ALICE experiment covers nevertheless also the forward region with a Muon detector and obtains results of similar precision for di-muon final states such as the J/ψ. These results are obtained for inclusive production of such states, without for the moment separation of the non-prompt contribution, which makes the interpretation of the results more difficult.

The fixed target program has for the moment no competition since it is done at energies that are unique to LHCb in this configuration. The performances of the detector and the fixed target capabilities will further improve during the LS2 Upgrade I of the experiment starting from 2021 and will make it competitive even in the area of heavy ion (PbPb) collisions. The design of the detector that will be upgraded in 2030 is only starting now, and there is possibly room to integrate in this design considerations for running also with heavy-ion collisions. This would make LHCb a very attractive facility to do heavy ion physics during the high luminosity phase of the LHC.

5.1 Resources

In January 2018, 5 people work at IN2P3 on the project, 2 physicists with permanent position and 3 post-docs. Since the beginning of the project, 2 post-docs who worked on the project left, Laure Massacrier who got a CNRS permament position in ALICE at IPN Orsay and Francesco Bossu who got a permanent position at CEA-DPHN in Saclay. In the entire collaboration, about 10 persons in total work in the same scientific area, that is to say that IN2P3 represents 50% of the human resources. The scientific work inside LHCb is coordinated by a "physics working group", called IFT – Ion and Fixed target, with 2 convenors. Since the creation of this group, at least one of the two convenor was from IN2P3 and both of them now: Laure Massacrier (LAL) in 2015-2016, Francesco Bossu (LAL) in 2017 and Michael Winn (LAL) and Frederic Fleuret (LLR) for 2018 and 2019.

Human resources:

- Laboratoire Leprince Ringuet (LLR – Palaiseau)
    - Frédéric Fleuret, DR CNRS, 1 FTE
    - Emilie Maurice, Post-doc P2IO, 1 FTE until September 2018
- Laboratoire de l'Accélérateur Linéaire (LAL – Orsay)
    - Patrick Robbe, DR CNRS, 0.3 FTE
    - Yanxi Zhang, Post-doc ERC, 1 FTE until October 2018
    - Michael Winn, Post-doc ERC, 1 FTE until April 2019

In September 2018, Emilie Maurice and Yanxi Zhang postdoctoral positions will end. Michael Winn's postdoctoral position will end in spring 2019. In absence of support, the IN2P3 LHCb heavy ion team will be limited, in a two year time scale, to only two senior physicists.

Financial resources:

This project is using an existing facility, and so far, no contributions, apart from human resources together with the associated costs such as travel money, were necessary. Apart from the salary of Frédéric Fleuret, all these human resource costs were covered by sources external to IN2P3. A consolidator ERC grant with a total budget of 1.1 MEuros until April 2020 is used to fund the salaries of three post-docs: Francesco Bossu, Yanxi Zhang and Michal Winn and for 30% of the salary of Patrick Robbe. This budget includes also about 10000 Euros of travel money per year and per person for all team members. The salaries of two other post-docs were covered by a grant from the P2IO labex of the Paris-Saclay University: Laure Massacrier and Emilie Maurice. In addition a grant of 20000 Euros was received by Emilie Maurice from the *L'Oréal foundation for women in science*. This money should cover the need of the team until mid-2020.

It should be noted that all members of the team also participate to common LHCb activities, for the benefit of the entire collaboration:

- Laure Massacrier, Francesco Bossu, Michael Winn and Frédéric Fleuret participate to physics working group organization
- Emilie Maurice is the current convenor of the LHCb luminosity working group responsible for the provision of the precise luminosity numbers used in all LHCb publications, including the ones for “standard” measurements in *pp* collisions.
- Yanxi Zhang is the current convenor of the LHCb quarkonium physics working group, responsible for many important measurements in pp collisions concerning quarkonium and exotic states such as tetraquark and pentaquark states.
- Michael Winn is one of the 4 LHCb representative in the HL-LHC working group [49], responsible for the heavy-ion part. This LHC wide group is responsible to build the physics case for the High luminosity phase of the LHC.
- Yanxi Zhang participated actively to the discovery of the Ξ_{cc}, a new doubly-charm baryon observed during summer 2017 [50]; Michael Winn is also actively taking parts to efforts to improve the analysis of *B* decays with electrons in the final state, in which intriguing anomalies with respect to standard model expectations were reported in 2017 [51].
- A large part of the travel money was used to ensure shifts for LHCb and piquets for the L0 trigger or the calorimeters which is one of the responsibility of the IN2P3 groups within LHCb.

We strongly wish in the future to keep the interaction of our team members with the rest of the LHCb collaboration and to give them the possibility to contribute to the main stream analyses of the experiment.

6 Technical realization

No large technical involvement is foreseen at mid-term. The upgrade of the SMOG system will be realized and is funded by INFN-Italy. We wish to be involved in this project, helping for the design and simulation of the new setup, but our requests for this would be limited to travel money (20 kEuros).

7 Strength, weakness, opportunities and threat

<u>Strength:</u>

- The success of the first data taking campaigns and the first results obtained for the project brought a large visibility for the IN2P3 persons working on it.
- The project benefits from the excellent performances of a well-controlled and understood detector and these activities are almost “transparent” for the collaboration.
- Several tight collaborations with theory groups in the Orsay area were established.
- Several new groups joined LHCb to participate to the project that we initiated. This will ensure that, within LHCb, these activities will be maintained.

- Several proposals to improve the fixed target setup in the LHCb experiment emerged. They were actively discussed in the Physics Beyond Collider workshops organized in 2016 and 2017 at CERN [52] and very well received there. It is also a guarantee that a fixed target program at LHCb is foreseen in the LHC future plannings.
- The "heavy-ion" IN2P3 team is well integrated within the collaboration and also contributes actively to the standard physics program of the experiment

Weakness:

- The project is entirely based on external fundings which will end in 2020.
- On the long term, only 1.3 FTE of IN2P3 researcher time is available

Opportunities:

- While the detector's design for the LHCb LS2 Upgrade I is frozen, there is plenty of room to contribute to a LS4 Upgrade II upgrade hardware or software development program. The integration of a heavy-ion part in the future LHCb physics case (for 2030) could make LHCb very attractive for new persons or groups at that time.

Threats:

- Because of the attractivity of this physics program, demonstrated by the IN2P3 team, new groups are joining LHCb and the initial large visibility of IN2P3 will be strongly reduced if no additional human resources are brought to the project.

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