Bilan et perspectives LHCb Ions Lourds

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1 Introduction

Since 2013 and the recording of a pilot pPb run, the LHCb collaboration has developed a fruitful heavy-ion program at CERN. Initially designed for the study of CP violation and rare processes of charm and beauty hadrons produced in the collisions between the LHC proton beams, the detector capabilities are naturally well suited to perform similar measurements in ion collisions. In 2015, the Ion and Fixed Target (IFT) analysis working group has been created within LHCb with a major contribution of IN2P3 physicists.

The c and b hadrons, which LHCb is optimised to detect, are because of their mass, significantly larger than the QCD scale, excellent probes to investigate the properties of the matter formed in the collisions. After their production, early in the collision, c and b quarks form very quickly open heavy flavour D and B hadrons when they associate with light quarks, or quarkonium states when they combine with another c ($c\bar{c}$ charmonium states) or b ($b\bar{b}$ bottomonium states) quark. The elementary production process is studied conveniently in pp collisions. In pA (proton-nucleus) and AB (nucleus-nucleus) collisions, heavy-flavor production is modified by cold nuclear matter (CNM) effects related to the structure of the nuclei and the produced hadronic matter, and, if high enough energy density is reached in the collision, by effects related to the formation of a Quark Gluon Plasma (QGP). Eventually, the particles are detected from their decay products in the detector. Comparing the production rates of charm and beauty particles in the three proposed configurations allows probing the properties of the matter they traverse.

Thanks to its full detection capabilities (vertexing, tracking, calorimetry, particle identification, muons), LHCb offers the unique opportunity to perform precise measurement of hidden and open heavy flavor production in the forward pseudorapidity range $2 < \eta < 5$ down to zero transverse momentum. Moreover, LHCb is the only experiment at the LHC capable of running in a fixed target mode at centre-of-mass energies between $\sqrt{s_{NN}} \sim 70$ GeV and $\sqrt{s_{NN}} \sim 110$ GeV, filling the gap between the CERN/SPS ($\sqrt{s_{NN}} \sim 20 - 30$ GeV) and the BNL/RHIC ($\sqrt{s_{NN}} = 200$ GeV) energies. Thanks to its acceptance coverage and to the boost induced by the incoming beam, LHCb covers, in its fixed-target mode, the almost unexplored large Bjorken-x region.

Since the beginning of the program, IN2P3 teams have been strongly involved in the measurement of heavy flavor production in pPb and Pbp collisions at nominal LHC energies towards the characterisation of CNM effects affecting their production, and in the measurement of charm production in the LHCb fixed-target mode towards the exploration of the color screening mechanism expected to occur when QGP is formed in nucleus-nucleus collisions as well as the characterisation of the CNM effects that may differ with the ones observed in the collider mode because of the different kinematics regimes.

In the following, after a short description of the LHCb detector (section 2), the IN2P3 contributions to the LHCb Ion and Fixed Target program (section 3) and some physics results illustrating the performance of the detector (section 4) will be presented. Finally some perspectives for the early and long future will be drawn (section 5).

2 The LHCb experiment

2.1 The LHCb detector

The LHCb detector is one of the four large experiments installed at the LHC at CERN. It is dedicated and optimised for the study of beauty and charm hadron decays. The detector is shown in Figure 1 and

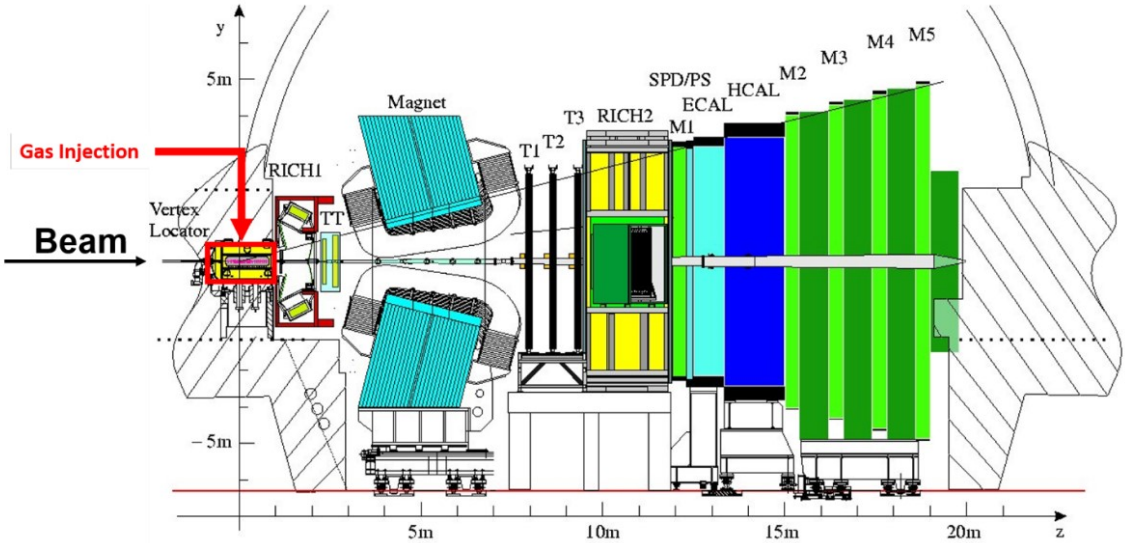

Figure 1: LHCb layout

described in details in Ref. [1]. The most interesting features of the apparatus related to the heavy ion program are listed below:

- A system (SMOG) has been developed to inject gas at the interaction point, inside the Vertex Locator and directly in the LHC beam pipe. This system was originally designed to measure the luminosity at LHCb by measuring the beam-gas overlap region thanks to the reconstruction of beam gas vertices [2]. Since 2015, the original use of the system has been diverted to take physics data of collisions of the LHC proton and lead beams with this gas acting as a fixed target. The centre-of-mass energies reached in the fixed target configuration are of the order of 70 to 110 GeV (depending on the incoming beam energy), unique at the LHC.
- The LHCb detector instruments fully the forward region of the collision, in a pseudo-rapidity range $2 < \eta < 5$. 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 collisions centre-of-mass frame is shifted by about -4.5 rapidity units, that is to say, corresponds to the backward rapidity hemisphere, reaching the Bjorken-x valence quark regime.
- 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^0_s mesons, with a decay time resolution of 45 fs. They are thus 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 Heavy Ion physics program.
- The tracking detectors provide a reconstruction of charged tracks down to very low momentum with good precision; the relative resolution on momentum measurement is about 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 the bunch crossing 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.

2.2 Operation modes

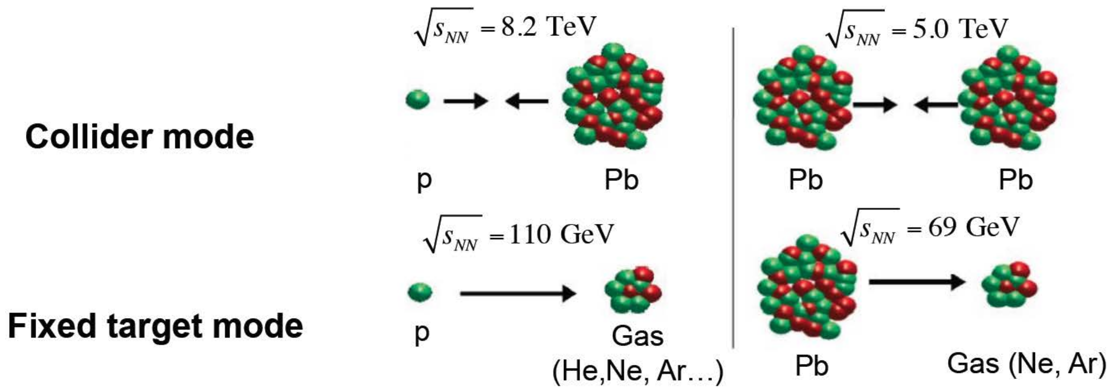

Figure 2: LHCb operation modes. Top line: Regular collider configuration; Bottom line: Fixed-Target configuration.

As previously mentionned, LHCb can operate in two different modes, as illustrated in Figure 2:

- Collider mode: This is the regular LHC colliding mode, also performed by the other LHC experiments. About one month every year, the LHC accelerates a (lead) ion beam and collides it either with a proton beam or with another (lead) ion beam. Because of the different Z/A ratio between the proton and the ion, the centre-of-mass energy is different between proton-Pb and PbPb at the nominal energy. Moreover, 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 ion beams are inverted in the LHC. This feature allows the experiment to collect data in two independent and complementary configurations: "proton-ion collisions" where the detector covers (at $\sqrt{s_{NN}} = 8.16$ TeV) a forward centre-of-mass rapidity range $1.5 < y^* < 4.0$, and "ion-proton collisions" where the coverage is $-5.0 < y^* < -2.5$.
- Fixed-target mode: Thanks to the SMOG system, one can study different proton-nucleus and nucleus-nucleus collisions at centre-of-mass energies between 70 and 110 GeV depending of the energy of the incoming beam. Because of the large boost induced by the incoming beam, the centre-of-mass rapidity is shifted by about 4.5 units, providing a rapidity in the centre-of-mass frame $-2.5 < y^* < 0.5$, which for hard (heavy) probes covers almost the entire backward hemisphere. In the SMOG configuration, the gas is injected directly in the VELO vacuum chamber

and can flow into the LHC beam pipe until it is pumped out at ± 20m. Because of this, only noble gases can be injected (so far, He, Ne, Ar have been injected) at a local pressure not higher than 10^{-7} mbar, limiting the density of the target exposed to the beam, hence the sample size collected, especially for small production cross-section processes such as hard probes. So far, the largest sample recorded was obtained in 2017 in pNe collisions, where around five thousands J/ψ where recorded in about 10 days of data taking.

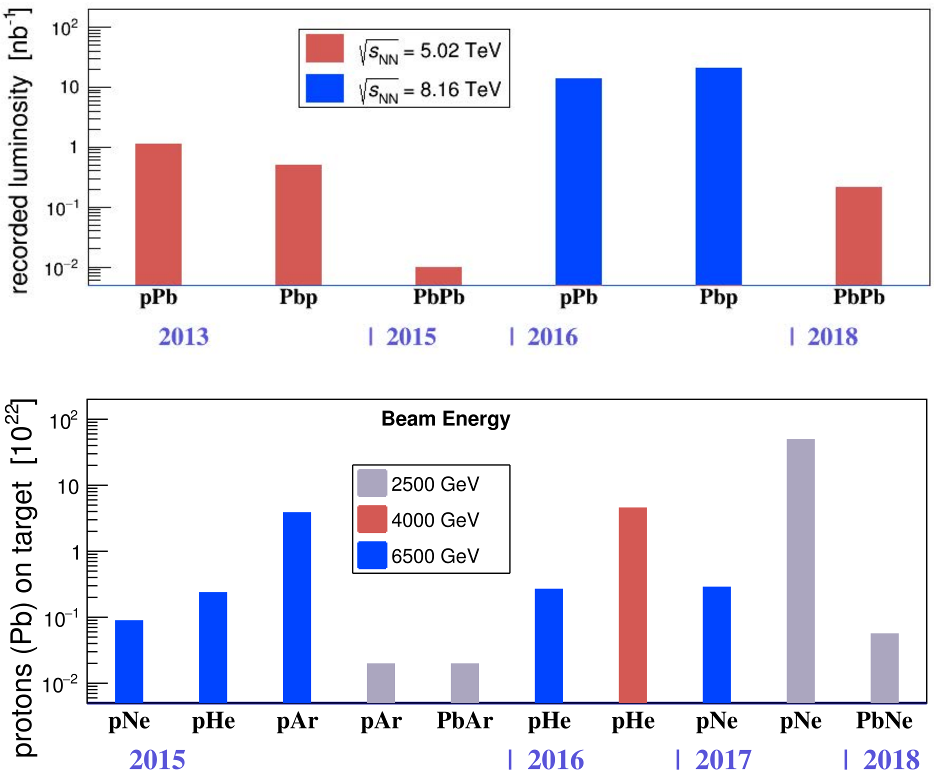

Figure 3: Data recorded by LHCb in collider (top) and fixed-target (bottom) modes.

3 IN2P3 contribution to the LHCb Ion and Fixed Target program

The IN2P3 contribution to the LHCb Ion and Fixed Target (IFT) activities was initially proposed by P. Robbe (IJClab-Orsay) and F. Fleuret (LLR-Palaiseau).

The LHCb IJClab group (LAL group at that time) 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-sections in pp collisions. 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 de-

person	lab/support	current status	convenership in LHCb
L. Massacrier	IJClab/P2IO	perm.@IJClab (CNRS/ALICE)	IFT (2015-16)
F. Bossu	IJClab/ERC	perm.@Irfu (DPhN/Jlab)	IFT (2016-18)
E. Maurice	LLR/P2IO+X	perm.@LLR (polytech./LHCb)	lumi/SMOG (2017-19)
M. Winn	IJClab/ERC	perm.@Irfu (DPhN/Alice)	IFT (2018-19)
Y. Zhang	IJClab/ERC	perm.@Tsinghua (LHCb)	IFT (2019-21)
B. Audurier	LLR/P2IO+X+CNRS	perm.@Irfu (DPhN/LHCb)	IFT (2019-21)
M. Guittière	IJClab/P2IO	postdoc LHCb@IJClab	
O. Boente	LLR/X	postdoc LHCb@LLR	
K. Mattioli	LLR/ANR	postdoc LHCb@LLR	

Table 1: Postdocs who were (are) working with IN2P3 teams on IFT related topics.

veloped a program to study the feasibility and impact of a fixed target program at the LHC, namely the AFTER program [3] led 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. In 2015, a proposal was submitted to the LHCb collaboration [4] to record data in heavy-ion and fixed target collisions, and was accepted. At the same time, 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 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 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 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. Figure 3 shows the list of data recorded in heavy-ion collisions by LHCb during LHC Run 1 and Run 2.

In terms of person-power, Table 1 gives the list of postdocs working with the team on IFT related physics topics. In addition two PhD students defended their PhD theses in 2021: E. Niel (IJClab, under supervision of P. Robbe) who is now postdoc in LHCb at EPFL and F. Garcia (LLR, under supervision of F. Fleuret) who is now working in a private company. Nowadays, the team is made of three permanent physicists (F. Fleuret/*CNRS*, E. Maurice/*École polytechnique*, P. Robbe/*CNRS*) and three postdocs (M. Guittière, O. Boente, K. Mattioli).

4 Physics results

Since 2015, the IN2P3 teams have actively participated to 12 publications within the IFT analysis group [5–16]. Most of those analyses focus on the study of heavy flavor production in $\sqrt{s_{NN}} = 5$ and 8.16 TeV pPb collisions, in particular charmonium and open charm production, and on heavy flavor (charm) production in pA and PbNe collisions in fixed-target configuration. More recently IN2P3 teams also contributed to the study of heavy flavor production in peripheral PbPb collisions. These analyses benefited from the excellent performances of the LHCb detector, in particular vertexing and particle identification capabilities, and the special fixed target mode, as illustrated below:

– Thanks to the **very good vertex resolution** provided by the VELO the prompt (direct) and non-prompt (from B-decays) contributions of J/ψ production can be separated. Figure 4 shows the

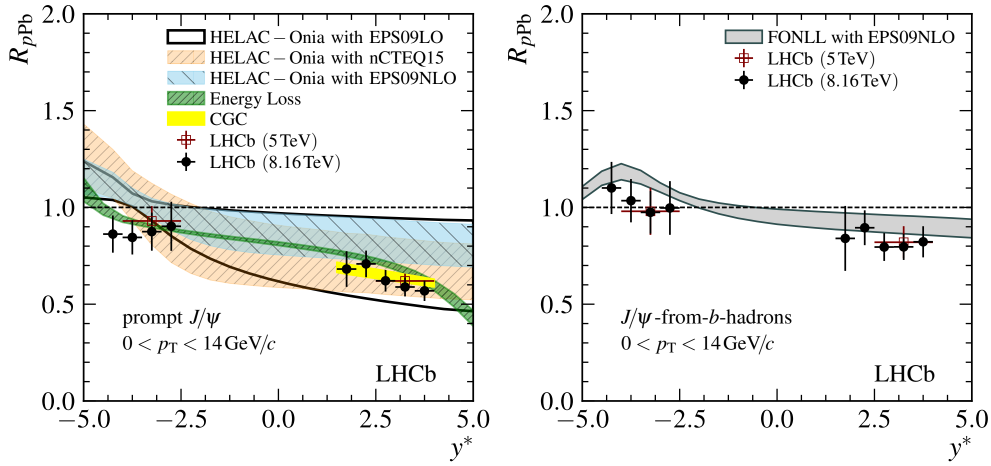

Figure 4: Nuclear modification factor $R_{p\mathrm{Pb}}$ as a function of the rapidity in the centre-of-mass frame, y^*, for the prompt (left) and non-prompt (right) contributions to J/ψ production in $\sqrt{s_{NN}} = 8.16$ TeV pPb collisions.

differential production cross-section of prompt and non-prompt J/ψ mesons in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [5]. The nuclear modification factor $R_{p\mathrm{Pb}} = \sigma_{p\mathrm{Pb}}/(A.\sigma_{pp})$ is reported as a function of the rapidity in the centre-of-mass frame y^*. The J/ψ candidates are reconstructed via their decay into two muons, and the prompt and non-prompt contributions are distinguished with a simultaneous fit of the dimuon invariant mass and the pseudo-proper time $t_z = (z_{J/\psi} - z_{PV}) \times (M/p_z)_{J/\psi}$ of the J/ψ. The $R_{p\mathrm{Pb}}$ ratio is presented along with comparisons with different predictions. A clear suppression is observed in the forward region for the prompt J/ψ, while almost no effect is observed for the non-prompt contribution. Ths pattern is reasonably described with recent theory predictions of several CNM effects using state of the art nuclear PDF (nPDF).

– The powerful **particle identification** system gives the opportunity to reconstruct beauty and charm particle decays in purely hadronic states, such as $D^0 \to K^{\mp}\pi^{\pm}$. Figure 5 shows the nuclear

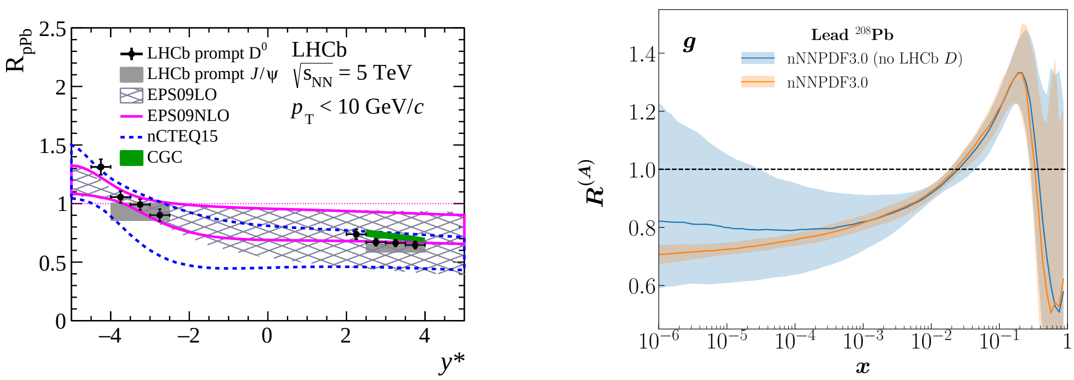

Figure 5: Left: D^0 Nuclear modification factor $R_{p\mathrm{Pb}}$ as a function of the rapidity in the centre-of-mass frame, y^*, measured by LHCb at $\sqrt{s_{NN}} = 5$ TeV [6]; Right: Comparison of the nPDFs of lead nuclei between nNNPDF3.0 with (brown band) and with no (blue band) LHCb D data included in the fit [17].

modification factor $R_{p\mathrm{Pb}}$ obtained for D^0 production in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV [6]. The observed pattern is similar to the J/ψ one, as expected by nPDF predictions. Those results have been used to constraint the nPDF by the nNNPDF collaboration [17]. The results of this new fit is presented in Figure 5, showing a strong reduction of the nPDF uncertainties, in particular at very low Bjorken-x, corresponding experimentally to the forward rapidity region.

– Figure 6 shows the main results obtained in **fixed-target mode** with pHe, pNe and PbNe data. Top left plot of Figure 6 shows the total J/ψ cross-section production obtained in pNe and pHe

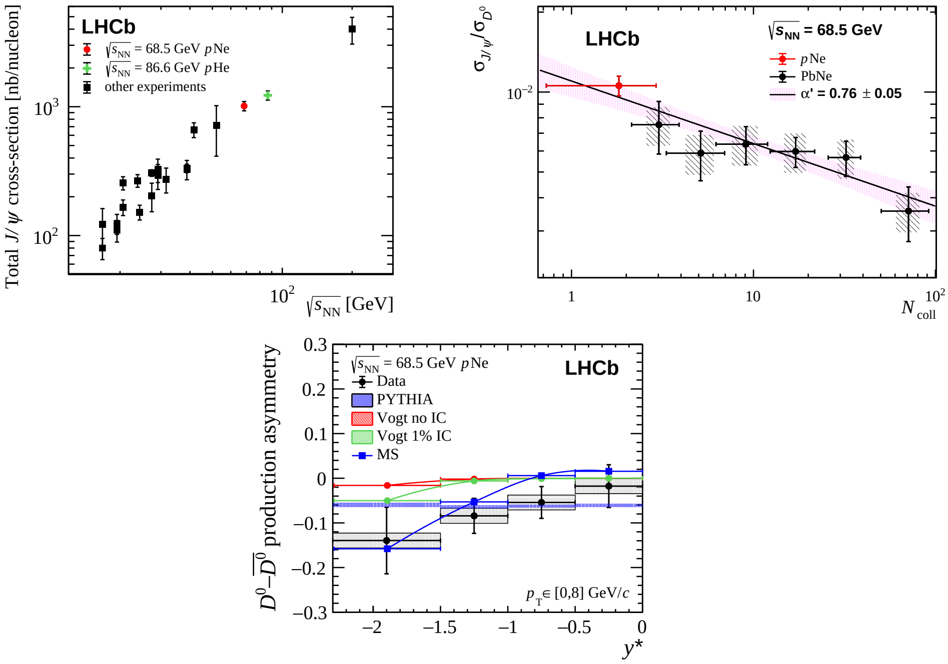

Figure 6: Top left: Total $J\psi$ production cross-section as a function of centre-of-mass energy [13]; Top right: $J/\psi/D^0$ cross-section ratio in $\sqrt{s_{NN}} = 68.5$ GeV PbNe collisions as a function of the number of binary nucleon-nucleon collisions [14]; Bottom plot: $D^0 - \bar{D}^0$ production asymmetry as a function of the centre-of-mass rapidity, y^*, in $\sqrt{s_{NN}} = 68.5$ Gev pNe collisions [15].

at $\sqrt{s_{NN}} = 68.5$ and 86.6 GeV respectively, compared to experimental results obtained from other experiment [13]. Overall, the J/ψ production cross-section exhibits a power-law dependence on the centre-of-mass energy. Top right plot of Figure 6 shows the $J/\psi/D^0$ cross-section ratio obtained with the $\sqrt{s_{NN}} = 68.5$ GeV PbNe data as a function of the number of binary nucleon-nucleon collisions, N_{coll} [14]. The PbNe data sample is divided into intervals of N_{coll} corresponding to different centrality intervals related to the overlap region between the two colliding nuclei. The larger the N_{coll} the larger is the overlap region. Those results are compared with the results obtained with the $\sqrt{s_{NN}} = 68.5$ Gev pNe data, showing a smooth exponential decrease. This indicates that J/ψ meson production is affected by additional nuclear effects with respect to D^0 production. However, within uncertainties, no additional suppression with respect to the smooth exponential pattern is observed, that could indicate the formation of a deconfined medium, contrary to the NA50 results in the most central PbPb collisions obtained at $\sqrt{s_{NN}} \sim 17$ GeV at CERN/SPS. Last, bottom plot of Figure 6 shows the $D^0 - \bar{D}^0$ production asymmetry obtained with the $\sqrt{s_{NN}} = 68.5$ Gev pNe data [15]. The results indicate a negative asymmetry from ~ 0 down to $\sim -15\%$ from $y* = 0$ to $y^* = -2.29$. The largest asymmetry is obtained at $y^* = -2.29$, where the valence quark contribution of the neon target is more significant than at $y* \sim 0$. When compared to theoretical predictions, data are reasonably described by a model (MS) including a 10% recombination contribution and 1% Intrinsic Charm (IC) content.

5 Perspectives

5.1 LHCb upgrade I

After an upgrade phase started in 2019 [18], the detector is now ready to take new data. The major upgrades include the installation of a new pixel VELO [19], a new tracker upstream of the magnet, the UT, made of silicon-strip sensors [20] and a new tracker downstream of the magnet, the SciFi, made of scintillating fibers [20]. The layout of the upgrade LHCb detector is presented in Figure 7. These new trackers will already impact the ion program. Indeed, the tracking performance in nucleus-nucleus data was limited with the previous detector due to the saturation of the VELO channels in central collisions. Only the 50% most peripheral PbPb collisions were exploitable for physics analysis. This limitation also affected the fixed-target program in Pb-nucleus collisions, where only PbNe collisions were fully reconstructible up to the most central collisions.

The new LHCb detector should be able to cope with higher particle multiplicities, up to semi-central (30 $\%$ centrality) PbPb collisions where most of the QGP effects can be studied. Indeed, based on dedicated simulations of PbPb collisions, it has been shown that tracking limitations will come from the occupancy in the SciFi, while the new VELO, thanks to its pixel-based design, should return a linear response on the number of reconstructed clusters with respect to the event energy measured in the electromagnetic calorimeter. For the fixed-target program, the improvement of the tracking performances should permit to access to the most central PbAr collisions where QGP is expected to be produced. Limitations due to tracking performances are expected to occur with heavier ions such as Kr and Xe.

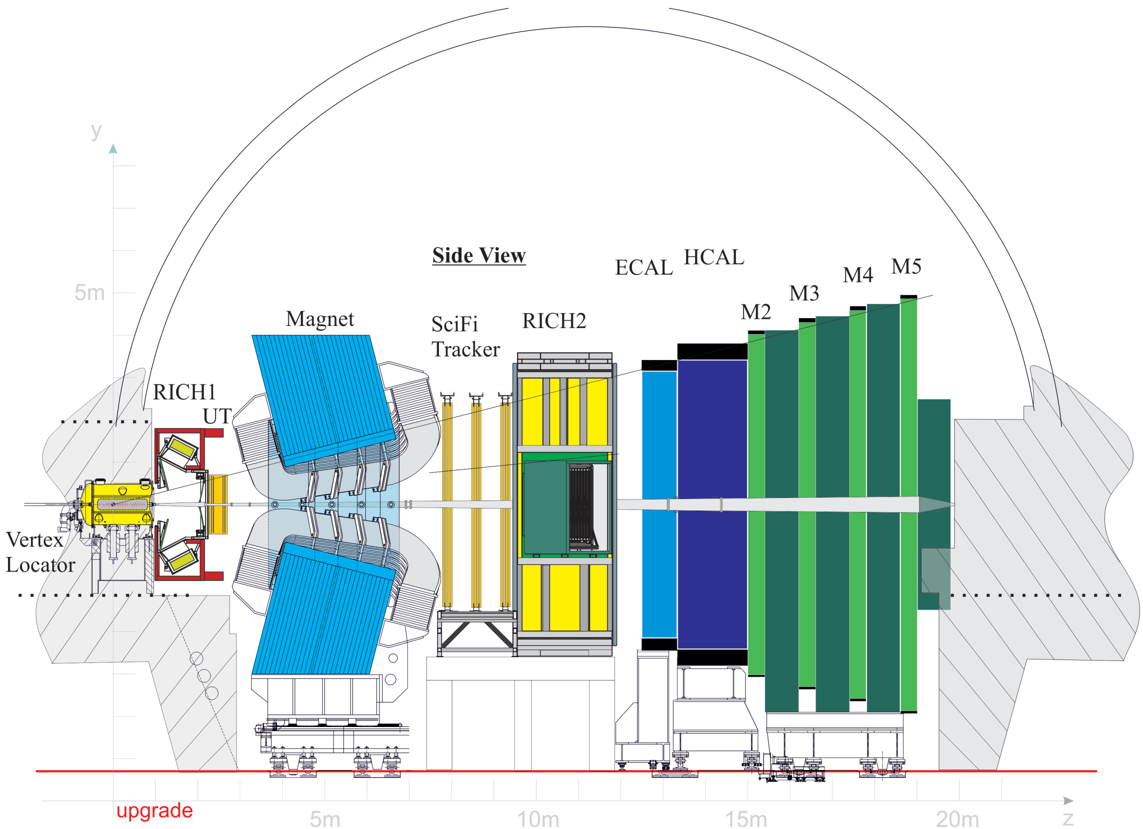

Figure 7: Upgrade LHCb layout

Beside the detector upgrade, the fixed-target program will also be enhanced thanks to the installation of a new gas target, SMOG2 [21], integrated into the VELO vessel. In the SMOG2 design, the gas is contained in a storage cell, consisting of a 20 cm long tube with a diameter of 1 cm, fed by a capillary tube. The target is placed within $Z \in [-50, -30]$ cm upstream of the nominal LHCb Interaction Point (IP), allowing for an effective areal density increase in the target by up to two orders of magnitude compared to SMOG for the same gas flow. In addition, the use of more gas species, notably H_2 and D_2, and heavier noble gases (Kr, Xe) could become possible. Thanks to its displacement with respect to the nominal IP, it is now possible to exploit all circulating bunches for fixed target physics, i.e. to run simultaneously in fixed-target and collider mode.

5.2 LHCb upgrade II

In the far future, during the LHC Long Shutdown 4 (LS4), LHCb will undergo a second major upgrade. The new detector will have to operate in the luminosity conditions of the HL-LHC phase with around forty simultaneous pp interactions per bunch crossing. The aim is to preserve, in Run 5 and Run 6, the same performances as in Run 3 and Run 4 with a much larger charged particle multiplicity and higher detector occupancy.

Preliminary studies show that upgrade I limitations in PbPb collisions and fixed-target PbXe collisions will be fully overcome thanks to new tracking detectors. More specifically, a new Upstream Tracker (upstream of the magnet) will help to reduce the number of fake reconstructed trakcs in high-occupancy collisions thanks to a pixel-based design. Similarly, the Mighty Tracker, that will replace the inner part of the SciFi, downstream of the magnet, will also use pixels in the innermost region of the detector close to the beam pipe. Together with new PID systems, the LHCb upgrade II will grant access to the most central ion-ion collisions at the LHC, both in the collider and fixed-target modes.

Finally the addition of magnet stations inside the magnet will improve the efficiency to detect low momentum charged tracks. Together with the upgrade of the Electromagnetic Calorimeter, where the granularity of the sub-detector will be greatly improved with newly designed modules of smaller cell sizes, this future detector will provide new capabilities to study photon-hadron correlations and perform measurements or put constraints of the gluon saturation scale in the nucleus and on the colour-glass condensate models in heavy ion collisions.

IN2P3 teams are interested in contributing to the upgrade II, in particular to the upstream tracker and calorimeter upgrades.

6 Conclusion

Since 2015 and the creation of the Ion and Fixed-Target analysis working group, LHCb has developed a fruitful heavy-ion program. The excellent performances of the detector have been demonstrated both in collider and in its unique fixed-target modes, especially for the measurement of heavy flavor hadrons. The main limitation of the detector for heavy-ion physics has been observed for central Pb-Pb collisions, where the tracking saturates and reconstruction efficiency drops. This limitation will be partially overcome thanks to the LHCb detector upgrade I, opening the gate for semi-central (up to 30 $\%$ most central) PbPb collisions and central fixed-target PbAr collisions, and fully overcome thanks to the upgrade II, giving access to full central PbPb collisions and central fixed-target PbXe collisions starting from LHC Run 5.

The IN2P3 teams, IJClab and LLR, have been strongly involved in this activity since the beginning, representing at that time about 50 $\%$ of the human resources in this scientific area within the LHCb collaboration (around 15 $\%$ nowadays).

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