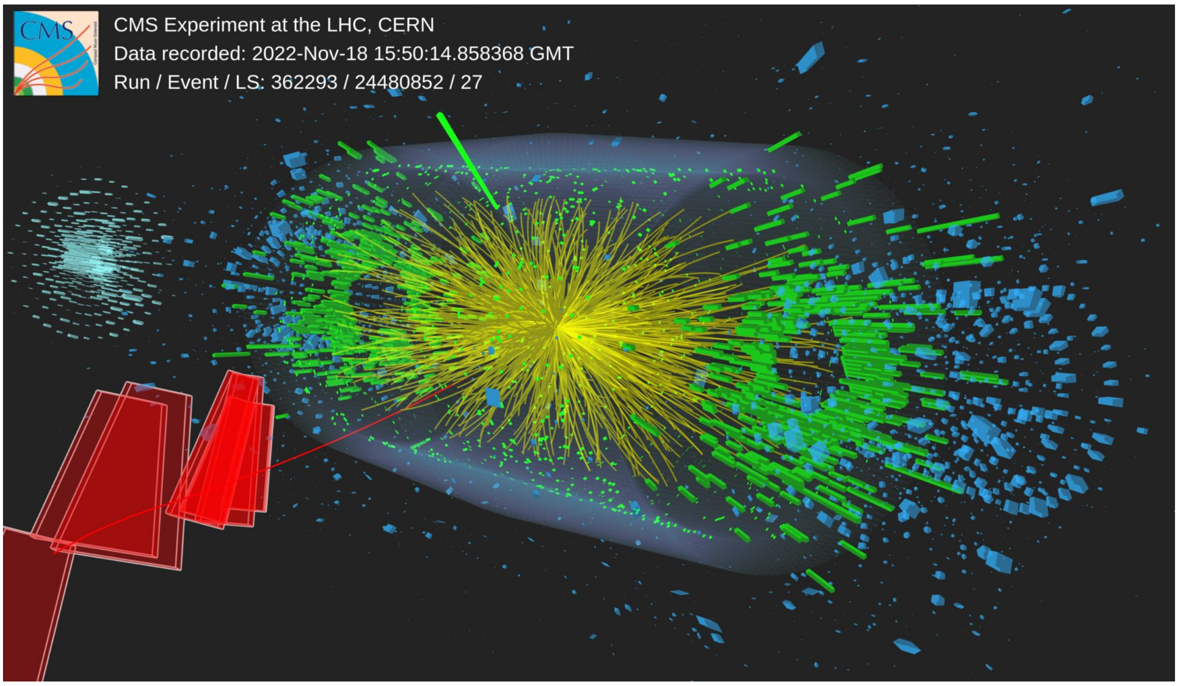
Heavy ions with CMS at the HL-LHC: assessment and prospects

Matthew Nguyen

Laboratoire Leprince-Ringuet, Palaiseau, France



1 Summary

Collisions of heavy ions at relativistic energies are the only experimental means by which we are able to study QCD at high temperature, replicating conditions of the early Universe. Such collisions are an integral part of the program of the Large Hadron Collider. Initially it was foreseen that heavy-ion collisions would be studied exclusively by the ALICE experiment, which was expressly designed for this purpose. As the ALICE experiment took shape, it was realized however, that certain compelling measurements would be best achieved using the other LHC experiments. The first of the other experiments to elaborate a heavy-ion program was CMS, who submitted an addendum to their TDR in 2007 [1].

The primary characteristics of CMS that make it complementary to ALICE are 1) its high rate / fast triggering capabilities, and 2) its large, nearly hermetic acceptance. These characteristics are ideally matched for certain observables that emerged in light of paradigm shifting discoveries at the Relativistic Heavy-Ion Collider in the early 2000's, after the design of ALICE had already been more or less determined. The first was the discovery of jet quenching, first predicted in the early 1980's [2], and finally observed via the suppression of high p_{T} hadrons, and back-to-back azimuthal correlations. The second was the discovery of long-range correlations, the so-called "ridge", that span many unit of rapidity. During the first two Runs of the LHC (2010 – 2018) CMS has produced a plethora of landmark measurements of jets and other "hard probes", e.g., quarkonia and electroweak probes, that were only possible due to its fast triggering, and hermetic coverage. These characteristics also enabled the discovery of the ridge correlations in proton-lead and even in high multiplicity proton-proton collisions, spawning an entire sub-field of investigations into flow effects in such "small systems", and paradigm shift for the field.

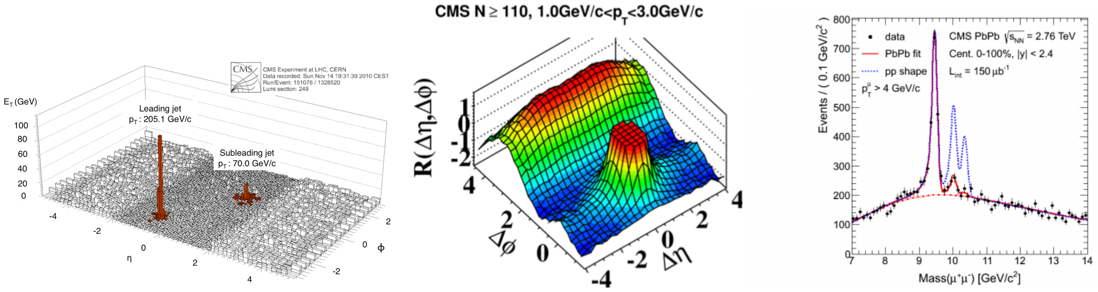


Figure 1: Some iconic results from the CMS heavy-ion program, Left: Distribution of calorimeter tower energies for an imbalanced dijet event in PbPb collisions at 2.76 TeV [3], Middle: Dihadron angular correlations showing the long-range ridge structure in pp collisions at 7 TeV [4], and Right: Invariant mass distribution of dimuon pairs showing the yields of the Υ states in PbPb collisions at 2.76 TeV, compared to the line-shape in pp collisions [5].

The French participation in the CMS heavy-ion program was spearheaded by Raphaël Granier de Cassagnac, with the help of an ERC grant (2010 – 2015). The group was reinforced by the arrival of myself in 2011. We have been joined by a fair number of students and postdocs over the years via diverse funding sources, both national and European. The group has produced a wide array of high impact results on jets, quarkonia and electroweak bosons. Since taking over as group leader in 2020, I have also taken an indefinite role as co-manager of the CMS heavy-ion project (joining Ivan Cali from MIT).

Over the next few years, Run 3 of the LHC will serve to consolidate the achievements of the CMS heavy-ion program, augmenting our statistics by a factor of 2-3, with a detector that is largely unmodified with respect to the Run 2 configuration. During the following shutdown the CMS detector will be nearly entirely replaced. This Phase II upgrade program of CMS is primarily intended to increase the rate and radiation hardness, in order to cope with 200 simultaneous proton interactions (pile-up), compared to around 60 during Run 3. As with its original design, the Phase II upgrades are not specifically designed with heavy-ion collisions in mind – with the notable exception of the MIP Timing Detectors, for which heavy ions feature prominently in its physics case. Nevertheless, with occupancies in pp collisions approaching those of central PbPb interactions, one naturally expects an augmentation in the capabilities for the latter. As it turns out, Phase II will once again enable compelling measurements that are highly complementary to what can be achieved with the other detectors. The goal of this document is to summarize the prospects for heavy-ion measurements with the upgraded detector.

2 Scientific challenges

Over the course of the LHC program thus far, substantial progress has been made in the characterization of the QGP, and towards understanding QCD phenomenology at high temperature. We can now earnestly consider precision measurements in heavy ions. In this section, I outline challenges for achieving that precision, using as examples the classes of observables that are of primary interest to the LLR group.

Jet quenching: Prior to the LHC, jet quenching had only been demonstrated via single hadron spectra or hadron pair correlations, which leads to a convolution of parton energy loss effects with a bias on the selection of jets with a particular fragmentation pattern. With early LHC data detailed measurements were made of basic observables, such as jet yields. In recent years, emerging jet substructure tools have begun to be applied to heavy-ion data, allowing us to start to understand coherence effects for partons showering in the QGP, which turn out to be crucial in the description of parton-medium interactions. There remains, however, a fundamental limitation to (inclusive) jet measurements. QGP effects are necessarily benchmarked by comparing heavy-ion data to a reference constructed from proton-proton data, i.e., the nuclear modification factor (R_{AA}). Reconstructed jets in heavy ions sample parton showers that have lost energy outside the jet. At fixed p_{T}, jets in proton and ion collisions therefore sample a different set of partons, complicating interpretation. The solution is to look at jets recoiling from direct photons, or better yet, Z bosons, whose momenta are measured with very high precision. A selection on the boson p_{T} fixes the hard scale. High statistical precision for photon+jet, and even moreso Z+jet will only be achievable with the larger datasets to be achieved during the HL-LHC. Moreover, systematic uncertainty on the jet energy scale and resolution will start to become the limiting factor. A detector that can pin these uncertainties down to the perfect level will be essential. *Boson+jet measurements can only be achieved with a large acceptance detector, otherwise the leading recoil jet can easily escape the acceptance. Full calorimetry (EM+Hadronic) is also essential to measure the boson-jet balance.*

Quarkonium dissociation: Since the prediction of quarkonium “melting”, which is a probe of the QGP temperature, there is along history of charmonium measurements at the SPS and RHIC. While the observation of this effect at the SPS was among the strongest pieces of evidence of QGP formation, there were later understood to be other mechanisms at play that complicate the interpretation, in particular recombination effects that emerge at larger collision energies. Fortunately, measurements of bottomonium states have become possible at the LHC, for which competing effects such as recombination are vastly reduced. With its large magnetic field and precision silicon tracking, CMS is the only experiment that can separate the three lowest lying Υ states in central heavy-ion collisions. Although yield measurements of all three states have now been performed, the excited states remain statistically limited. Moreover, the importance of various types of differential measurements is increasingly recognized. The elliptic flow (v_2) of the fundamental state, which is highly sensitive to final state effects, has now been measured with decent statistical precision, but that is not the case for the excited states. Polarization measurements are event more statistically demanding. First polarization measurements in heavy ions in the charmonium sector suggest that that some polarization may be induced by the QGP [6], but an Υ measurement, which would be much cleaner, has not yet been possible. Finally, hadron production nearby charmonium has recently emerged as an important measurement of the timescale of quarkonium formation, and underscored the importance of late formation in a parton shower, in which case jet quenching effects should be relevant. Extending these measurements to the bottomonium sector, as well as measuring the substructure of quarkonium-jets should clarify not only the interaction of quarkonium with the QGP, but also address long standing puzzles in quarkonium formation in vacuum. *For quarkonium measurements, momentum resolution is tantamount, to cleanly separate resonances from background, but also to separate* *nearby states, such as the $\Upsilon(1s, 2s, 3s)$ states in heavy ions and the p-wave χ_b states in pp, the latter being important to constrain feed-down effects to the Υ states.*

Open heavy flavor & flavor-tagged jets:

Clean identification of b-hadron decays is essential throughout high-energy physics, and motivated the precision silicon tracking system in CMS. In heavy ions b-hadrons are also of great interest, as the quark mass dependence of energy loss is the key to disentangling radiative processes, dominant for light/massless partons, from collisional ones. CMS was the first to measure b-hadrons in heavy-ion collisions, first via nonprompt J/Ψ, and more recently via nonprompt D^0. In heavy ions CMS also produced the first measurement of b-tagged jets [7] and b-jet pairs, as well as the first measurement of the top quark, for which b-tagging is a key ingredient. The open charm sector, where π/K/p identification is an asset, was initially considered primarily the domain of ALICE, however, at large p_{T}, momentum resolution becomes more important, and the most precise data are from CMS. Many measurements in the heavy flavor sector remain statistically limited, for the b-jet p_{T} pair correlation measurement at large p_{T}, which will constrain quark vs gluon energy loss, as well as the lower p_{T} correlation of D meson pairs. *For measurements in the bottom sector large acceptance tracking with excellent impact parameter resolution and a low material budget drive the performance. Measurements in the charm sector require additional timing-based particle identification capabilities for π/K/p separation.*

3 Project

The Phase II upgrades of CMS are thoroughly described in their respective TDR's, and are presumably well-known to this Scientific Council. Here, I only briefly remind the basic features of the upgrades that are relevant to the heavy-ion program, and which are summarized in Table. 1

Subdetector	CMS present	CMS Phase II
L1 bandwidth	30 kHz for PbPb	750 kHz (all PbPb events)
DAQ throughput	6 GB/s	60 GB/s
Inner tracker	$\lvert\eta\rvert < 2.4$ 100×150 μm^2 pixels	$\lvert\eta\rvert < 4$ 50×50 μm^2 pixels
Endcap calorimeter	Low granularity	High granularity
Muon system	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.8$
Time-of-flight	N/A	PID for $\eta\rvert < 3$

Table 1: Summary of salient features of the CMS Phase II upgrades

The **detector readout and throughput** of CMS will be upgraded dramatically to confront the high-luminosity of pp collisions in Run 4. The hardware (L1) level triggers currently allow us to sample around 60% of PbPb interactions. In Phase II, we expect no constraint at this level. CMS has always been able to sample the full luminosity of PbPb collisions delivered by the LHC for events that can be selected with the software-based High-Level Trigger. However, there are important signals that cannot selected rapidly enough to be processed at HLT, in particular those requiring substantial tracking and vertexing, especially low p_{T} heavy flavor. To address such physics topics, we have been recording increasingly larger samples of minimum bias (MB) triggers. In 2018 we were able to record a third of all hadronic PbPb interactions. In Run 3 we are aiming to record one half, by reducing the raw events size using compressed data products, and by reducing noise in the MB sample using the zero-degree calorimeters. In Phase II the DAQ throughput will increase by an order of magnitude. It should be possible to record a larger fraction of PbPb interactions, but this may require additional R&D to further compress the raw event size, as data produced by the Phase II detector will also be significantly larger.

Starting with the detector closest to the interaction point, the **silicon tracking system** will be completely replaced with a lighter and more granular one [8]. Like the current detector, the inner detector will consist of four layers of pixels. In the endcap region, the pixel detector will consist of 12 disks that will extend the pseudorapidity coverage from $|\eta| < 2.4$ to $|\eta| < 4.0$. The outer detector will contain 3 layers of strip-pixel sensors, with 1.5 mm segmentation in z (r) in the barrel (endcap) region, followed by 3 strip layers. Compared to the current detector, the pixel area will be reduced by a factor of 6. For the strip layers the pitch is only slightly reduced, but the number of layers with 2D readout is increased. The thickness of both the pixel and strip layers will be reduced by roughly a factor of 2. The overall material budget will be reduced by a modest amount in the barrel, but by as much as a factor of 2 in the endcap, owing to reduced inactive material from services. The p_{T} resolution of charged particles will range from better than 1% at mid-rapidity to about 10% at $\eta = 4$, with only a modest dependence on p_{T} from 1 to 100 GeV. This constitutes an improvement of about 25% with respect to the current tracker. The transverse impact parameter will be around 10 – 20 μm for 10 GeV particles, an improvement of about 50% compared to the current tracker.

The **MIP timing detector (MTD)** will provide timing information for charged particles with a resolution of 30 – 40 ps, with a coverage of $|\eta| < 3$ [9]. In addition to its role as in pile-up rejection, the MTD will enable separation of π/K/p, as well as light nuclei, in both pp and heavy ions. Protons will be identifiable for $p < 5$ GeV, while charged pions and kaons will be separable for $p < 3$ GeV.

The endcap portion of the calorimeter system ($1.6 < |\eta| < 3$) will be replaced a **high-granularity calorimeter (HGCAL)**, featuring unprecedented transverse and longitudinal segmentation [10]. The HGCAL consists of an electromagnetic part with 28 longitudinal sampling layers, followed by a hadronic part with 24 layers. The active material in the electromagnetic section and part of the hadronic section is composed of silicon cells with an area of less than 1 cm. The rest of the hadronic section is composed of scintillator cells with areas of 4 – 30 cm^2. The granular design is optimal for particle flow calorimetry, wherein calorimeter clusters can be linked to objects from the other subsystems, particularly the tracker. At a pile-up of 200, isolated electrons will be identified with an efficiency of 95% for a background rejection of a factor of 100. Isolated photons can be identified with an efficiency of 85% for a background rejection factor of 100 (10) at 60 (20) GeV. The HGCAL also performs well for jets, with a pile-up subtraction and jet energy resolution that is comparable to the barrel, whereas the endcap performance is considerably worse than the barrel with the current detector. For measurements of jet substructure, the soft-drop mass resolution only degrades from 7.5% to 10%, going from 0 to 200 pileup.

The existing muon system consists of drift tubes in the central region ($|\eta| < 1.2$), partially overlapping with cathode strip chambers at forward rapidity ($0.9 < |\eta| < 2.4$). These are complemented by resistive plate chambers ($|\eta| < 1.9$) that are mainly used for timing information. The **upgrade of the muon system** will add additional chambers in the forward region, where the occupancy is largest, to provide further redundancy for the matching of muon tracks to inner tracks from the silicon tracker [11]. The muon acceptance will be extended from $|\eta| < 2.4$ to $|\eta| < 2.8$ by adding six layers of triple-GEM chambers.

The LHC experiments have requested integrated luminosities of 10 nb^{-1} of PbPb and 2 pb^{-1} of pPb collisions at top beam energy, which corresponds to a factor of 5 and 10 increase with respect to existing data sets, respectively. Some projections have been carried out, focusing primarily on the impact of the improved statistical reach [12–15]. Here instead we emphasize the impact of the detector upgrades. Detailed heavy-ion simulations are only starting to be become available, however, additional qualitative conclusions may also be drawn from high pileup pp simulations, which reach a multiplicity comparable to central heavy-ion collisions.

Precision measurements of jet quenching are a top priority for the high luminosity era. This goal can only be achieved via high statistics boson (Z and photon) + jet measurements. Large acceptance electromagnetic and hadronic calorimetors are essential to capture the full energy of recoiling jets. The Phase II CMS detector is optimized for particle flow reconstruction, enabling precision measurements of jets, leptons and isolated photons over six units of η. The large acceptance is also crucial to constrain the flavor dependence of jet quenching, via the η dependence of inclusive jet quenching, as the quark-gluon fraction varies strongly with rapidity, as well as via the flavor tagging of charm and beauty jets that is made possible by the precision micro-vertexing and large magnetic field of CMS. Precision jet quenching studies also require further constraints on the nuclear parton distributions from measurements of jet and electroweak bosons in pPb collisions. Here again, the large acceptance is key, as nuclear effects become more pronounced at forward rapidity. New processes will also become accessible, such as W boson + charm quark production, which will access the currently unconstrained strange quark distribution, as well as low mass Drell-Yan production, which opens up the phase space for nuclear effects.

The collective properties of the QGP are measured via the "bulk" particle production. The increased tracker acceptance enables the measurement of long-range correlations (i.e., the "ridge") over 8 units of η. The CMS program focuses on the emergence of such effects in small systems (pp and pPb), which has so far been limited by the inability to cleanly trigger on very high multiplicity collisions. With the MTD, true high multiplicity collisions can be differentiated from those due to pileup at trigger level, extending the reach of such measurements. The particle identification provided by the MTD will allow CMS to characterize the hadrochemisty of the bulk via measurements of yields, azimuthal anisotropies, HBT correlations, balance functions, etc.

Heavy quarks provide a unique handle on the dynamical evolution of the QGP, as they are not created thermally, but rather exclusively in hard scatterings. With the PID provided by the MTD, the nuclear modification and flow of D mesons at low p_{T} will benefit from a reduction of combinatorial background, lowering systematic uncertainties, and will be measurable down to $p_{\mathrm{T}} = 0$, compared to the current limit of 2 GeV. We will be able to precisely measure the Λ_c baryon down to $p_{\mathrm{T}} = 2$ GeV, constraining models of hadronization via color reconnection and coalescence. The coverage out to $|\eta| = 3$ will be unique among the LHC experiments, and should allow us to extrapolate the total charm cross section, which is important input into charmonium dissociation studies.

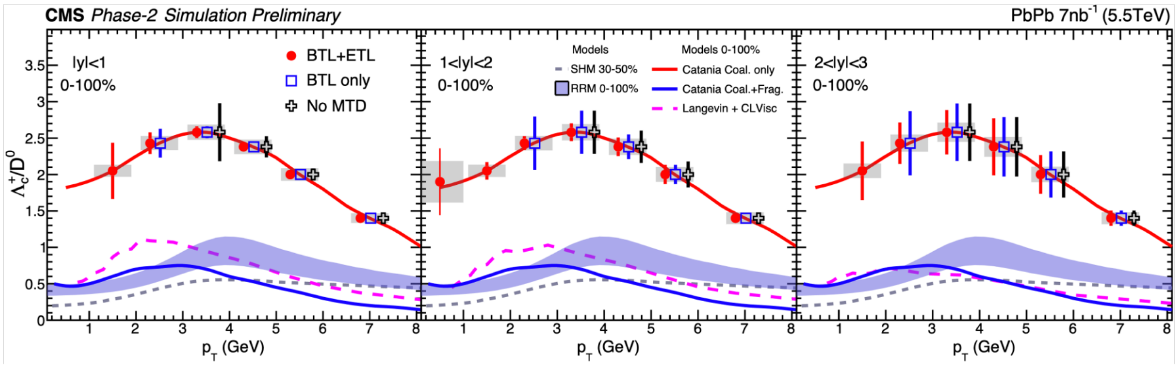


Figure 2: Projection for a measurement of charm hadronization effects, via the yield ratio of Λ_c over D^0, as a function of p_{T}, in several bins of η, with and without the MTD upgrade [16].

Measurements of light nuclei and even hypernuclei are of great interest in both pp and heavy ion collisions, not only for understanding their production in the nuclear fireball, but as inputs for dark matter searches [17] and models of neutron star evolution [18]. With the timing capabilities of the MTD CMS will be able to measure light nuclei for the first time. Additional dE/dx information from the pixel detector will allow us to separate helium-4 from the deuteron, which has the same charge-to-mass ratio. Figure 3 shows projections for light nuclei measurements in pp collisions in Phase II. Triggering on light nuclei can be avoided by measuring them parasitically in pile-up interactions.

The dissociation of quarkonium states in the QGP is firmly established. Precise measurements of all available quarkonium states will help to pin down the spatio-temporal evolution of the QGP. The improved p_{T} resolution of the Phase II tracker will improve the dimuon mass resolution by around 50% [19]. This will drive down uncertainties for all the states, crucially for the highly suppressed $\Upsilon(3S)$,

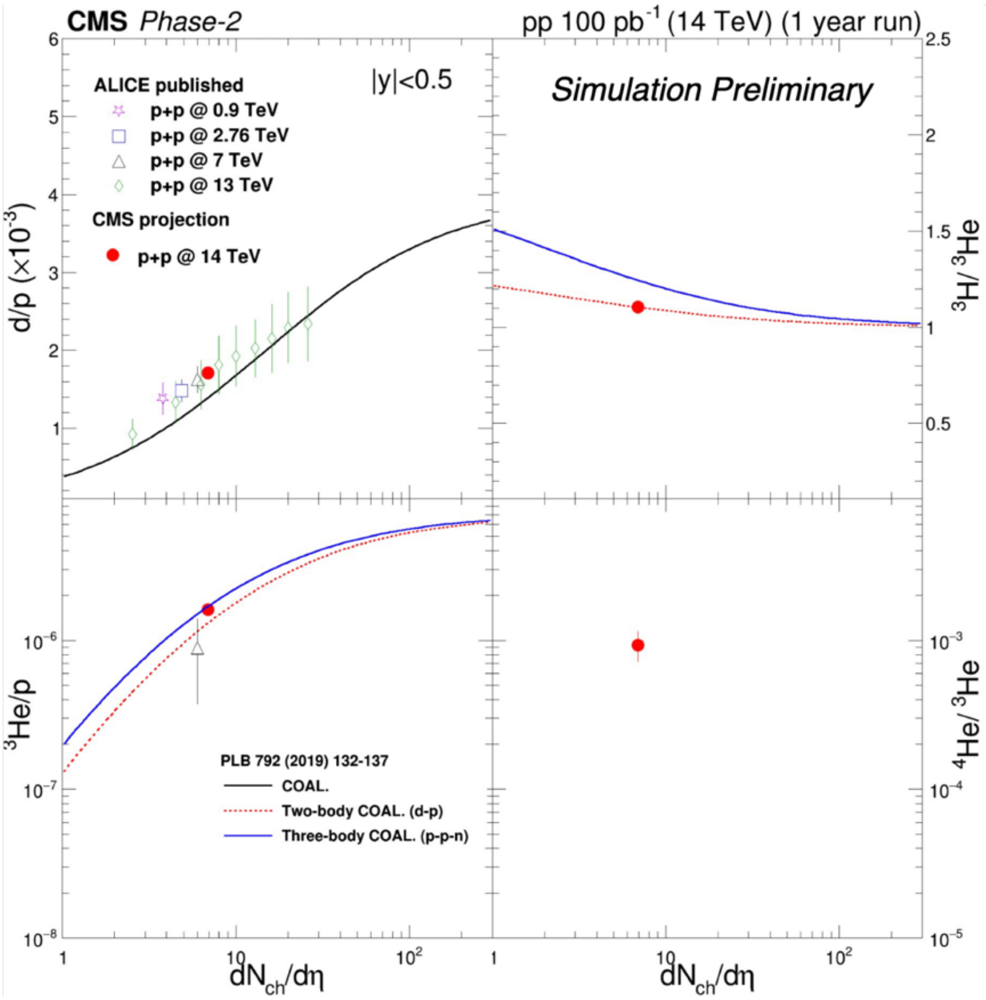


Figure 3: Projections of yield ratios of various species of light nuclei in pp collisions, as a function of charged particle density [16]. Clockwise from upper left: deuteron/proton, tritium/helium-3, helium-4/helium-3, and helium-3/proton.

which was only recently observed in central PbPb collisions, but for which improved statistical precision is needed.

In this brief summary of prospects for CMS in the HL-LHC era, we have focused on the characterization of the QGP in hadronic interactions. Ultra-peripheral collisions are a topic of increasing interest for the community. For example a recent measurement of J/Ψ production in coherent photon-nucleus interactions via shows tantalizing hints of gluon saturation. Beyond Standard Model signatures such as axion-like particles and magnetic monopoles are also being sought in UPCs. Collisions of lighter ion species, such as argon or oxygen, appear particularly promising in this regard. The prospects for such searches are detailed in a contribution to the European Physics Strategy Update [20].

Recently discussions have begun about "Phase III upgrades" to be installed for Run 5. One proposal, still highly speculative, is to install additional timing layers inside the tracker, in order to extend high quality particle identification to low momentum tracks. Another possibility would be to replace the forward hadron calorimeters with a high granularity device, extending jet measurements to at least $|\eta| < 4$. Finally, there is a proposal to lower the magnetic field in a dedicated heavy-ion run, in order to pursue low p_{T} measurements. There is no technical impediment to such a run, but the impact on reconstruction and detector calibration would need to be benchmarked thoroughly in simulation.

4 Genesis and timetable

Preparation of the Phase II upgrades is already well underway, and is proceeding according to the latest LHC schedule. In that schedule, Run 4 will span 2029 – 2032 with an ion run each year. A first round of heavy-ion simulations has mainly focused on the MTD, as the PID capabilities figure strongly in the physics case. Now that simulations of the Phase II detectors have become more mature, at LLR we are planning studies focusing on the other subsystems, focusing this year on muon reconstruction for quarkonium measurements. Extension of these studies to a potential low B-field run could be foreseen, person-power permitting. Planning for Run 5 (2035 – 2038) is more speculative. Possible further "Phase III" upgrades have only been discussed informally, inside CMS.

5 The state of the art

In this section we comment briefly on how the capabilities of the Phase II upgrades of CMS will compare to the other detectors, after their respective upgrades in Run 4 (ATLAS) and Run 5 (LHCb and ALICE).

ATLAS: Despite rather different technology choices, the two "general-purpose" detectors have managed to perform rather similarly, both in proton collisions and heavy ions. As a stand-alone detector, the ATLAS calorimeter system performs better for jets, but CMS has been able to compensate with excellent charged particle tracking, relying on particle flow reconstruction. In heavy ions, ATLAS currently has superior $|\eta|$ coverage for jets and photons, as radiation damage to the CMS endcaps has limited their utility. The Phase II upgrade programs of the two experiments are conceptually similar. ATLAS will also undergo a full replacement of the tracker, similarly extending their tracking coverage to $|\eta| < 4$. On the other hand, their calorimeter system will not undergo a major revision, whereas the CMS endcap will be vastly improved by the HGCAL upgrade. In conjunction with forward tracking, the photon, jet and electron performance of CMS should be at least as good as ATLAS, if not better. Both experiments will also benefit from the addition of a timing layer. Whereas the one of CMS will have both a barrel and endcap component ($|\eta| < 3$), the ATLAS HGTD will be limited to the endcap, which in this case covers ($2.4 < |\eta| < 4$) [21]. As far as I'm aware there are no publicly available studies of particle identification in heavy ions with the HGTD. Although the timing resolution will be similar to the CMS MTD, the range of PID in p_T is more limited as one goes forward, simply due to the boost of particles (PID quality scales with momentum, not p_T). On the other hand, the ATLAS upgrade is further from the interaction point, which will improve the quality of the PID. In any case, it will be interesting to see the ATLAS performance, as the $|\eta|$ coverage is complementary.

LHCb: LHCb was the last of the four experiments to develop their heavy-ion program. The detector is undergoing progressive upgrades of their tracking capabilities such that they expect to finally measure central PbPb collisions from Run 5. LHCb is a forward detector designed for heavy flavor measurements, featuring excellent tracking, PID, and EM calorimetry. Their heavy flavor capabilities at forward rapidity will be unmatched. In terms of jets, the capabilities of LHCb are rather limited, due to the lack of hadron calorimetry and the modest acceptance, which is ill-suited for p_T balance measurements. Their ability to measure jets in central heavy-ion events remains to be demonstrated. The acceptance will be similarly challenging for pair measurements in the heavy flavor sector, such as $D - \bar{D}$ correlations, which is a key observable for constraining charm quark diffusion. The acceptance of LHCb ($2 < |\eta| < 5$) is highly complementary to that of CMS, which will be fully optimized for particle flow out to $|\eta| < 3$.

ALICE: The ALICE program continues to undergo a steady series of upgrades, notably the adoption of a continuous readout scheme for Run 3 that will allow them to record the full PbPb luminosity delivered by the LHC. By contrast, in Run 3 CMS will sample the full luminosity only for triggerable signals, while the minimum bias rate will sample from 1/3 to 1/2 of the integrated luminosity, depending the success of raw event size compression efforts. It should be noted that the acceptance of CMS is substantially larger than the current ALICE detector. Recently, ALICE has submitted a letter of intent to completely replace their current detector from Run 5 [22]. Although the design has been evolving, the main target of the this upgrade is low p_{T} physics. This will be achieved by using low material budget MAPS silicon technology. The acceptance of the tracker will match that of CMS $|\eta| < 4$. Excellent PID will be achieved with TOF and RICH detectors. Electromagnetic calorimetry and muon systems at central rapidity are also foreseen, although, as more recent additions, they are somewhat more briefly described in the LOI than the tracker. As its raison d'être, the low p_{T} capabilities of the ALICE should be unparalleled. Notable physics targets include charmonium at rest, including the p-wave states, as well as thermal photons. The limitations of CMS in this regime have not yet been fully explored. For example, at forward rapidity, the combination of the extended muon acceptance, with a veto on showering particles in the HGCAL, might be sufficient to measure charmonium at rest. Low energy photon reconstruction with the HGCAL has similarly not yet been explored. The high p_{T} sector, especially jets, is not emphasized in the ALICE3 LOI. Here the lack of hadronic calorimeter will be a disadvantage. It should be also noted as well that ALICE will taken limited high luminosity pp data. Precision pp data are of great interest for CMS heavy-ions, e.g., as shown in the light nuclei projections (Fig. 3.

6 Technical realizations

The Phase II upgrade program is already well-documented elsewhere. French participation is strong, and benefits from several TGIR's. Possible further upgrade plans include the insertion of additional timing layers into the inner tracker, based on the same LGAD technology as the endcap portion of the MTD.

7 SWOT

Strengths: The CMS detector is a world-class instrument, which is the best suited for many of the hard probes observables that have been at the forefront of heavy-ion research in recent years. The Phase II upgrades strengthen the capabilities further, but also expands them into other sectors, such as low p_{T} charm production and light nuclei. These upgrades are already financed, and the planning for construction and integration is mature. In this environment it is relatively easy for even a small group to have a large impact.

Weaknesses: Although our group takes a leadership role in the CMS heavy-ion program, we have not made any major contributions to detector or hardware development. Although alongside our HEP colleagues at LLR, we have begun to contribute the HGCAL effort, there have been and will continue to be dedicated detector developments for CMS heavy ions such as the Phase L1 calorimeter upgrade, the zero degree calorimeters, and many aspects of endcap portion of the MTD.

Opportunities: The CMS heavy ion program continues to be an ample opportunity to benefit from the massive French investment in the Phase II upgrades, while diversifying the both the physics output of the CMS community, and the heavy-ion community in France. Although I have committed to CMS through Run 4, ongoing discussion on further upgrades may create opportunities for Run 5 as well.

Threats: While we can manage to continue to do interesting physics with only a small group here at LLR, we do require a steady stream of talented students and postdocs to maintain a solid contribution. We have managed so far to obtain financing via numerous sources, but continued success is far from guaranteed. If I fail to secure the reinforcement necessary to maintain a vibrant group, at some point it may be more interesting to look for other scientific opportunities with a more stable support stream.

Bibliography

[1] CMS Collaboration, "CMS physics technical design report: Addendum on high density QCD with heavy ions", J. Phys. G **34** (2007) 2307.

[2] J. D. Bjorken, "Energy loss of energetic partons in quark-gluon plasma: possible extinction of high p_T jets in hadron-hadron collisions", FERMILAB-PUB-82-59-THY, 1982, https://cds.cern.ch/record/141477.

[3] CMS Collaboration, "Observation and studies of jet quenching in PbPb collisions at nucleon-nucleon center-of-mass energy = 2.76 TeV", Phys. Rev. C **84** (2011) 024906, arXiv:1102.1957.

[4] CMS Collaboration, "Observation of long-range near-side angular correlations in proton-proton collisions at the LHC", JHEP **09** (2010) 091, arXiv:1009.4122.

[5] CMS Collaboration, "Observation of sequential Υ suppression in PbPb collisions", Phys. Rev. Lett. **109** (2012) 222301, arXiv:1208.2826, [Erratum: Phys. Rev. Lett.120,199903(2018)].

[6] ALICE Collaboration, "Measurement of the J/ψ polarization with respect to the event plane in Pb-Pb collisions at the LHC", (2022), arXiv:2204.10171.

[7] CMS Collaboration, "Suppression of nonprompt J/ψ, prompt J/ψ, and $\Upsilon(1\mathrm{S})$ in PbPb collisions at $\sqrt{s_\mathrm{NN}} = 2.76$ TeV", JHEP **05** (2012) 063, arXiv:1201.5069.

[8] CMS Collaboration, "The Phase-2 Upgrade of the CMS Tracker", CERN-LHCC-2017-009, 2017, https://cds.cern.ch/record/2272264.

[9] CMS Collaboration, "A MIP Timing Detector for the CMS Phase-2 Upgrade", CERN-LHCC-2019-003, 2019, https://cds.cern.ch/record/2667167.

[10] CMS Collaboration, "The Phase-2 Upgrade of the CMS Endcap Calorimeter", CERN-LHCC-2017-023, 2017, https://cds.cern.ch/record/2293646.

[11] CMS Collaboration, "The Phase-2 Upgrade of the CMS Muon Detectors", CERN-LHCC-2017-012, 2017, https://cds.cern.ch/record/2283189.

[12] CMS Collaboration, "Open heavy flavor and quarkonia in heavy ion collisions at HL-LHC", CMS-PAS-FTR-18-024, 2018, http://cds.cern.ch/record/2650897.

[13] CMS Collaboration, "Performance of jet quenching measurements in pp and PbPb collisions with CMS at the HL-LHC", CMS-PAS-FTR-18-025, 2018, http://cds.cern.ch/record/2651892.

[14] CMS Collaboration, "Predictions on the precision achievable for small system flow observables in the context of HL-LHC", CMS-PAS-FTR-18-026, 2018, http://cds.cern.ch/record/2650773.

[15] CMS Collaboration, "Constraining nuclear parton distributions with heavy ion collisions at the HL-LHC", CMS-PAS-FTR-18-027, 2018, http://cds.cern.ch/record/2652030.

[16] CMS Collaboration, New opportunities of heavy ion physics with CMS-MTD at the HL-LHC, CMS-DP-2021-037, 2021, https://cds.cern.ch/record/2800541.

[17] ALICE Collaboration, S. Acharya *et al.*, "Measurement of anti-^{3}He nuclei absorption in matter and impact on their propagation in the Galaxy", Nature Phys. **19** (2023) 61, 2202.01549.

[18] I. Vidaña, "Hyperons in Neutron Stars", J. Phys. Conf. Ser. **668** (2016) 012031, arXiv:1509.03587.

[19] CMS, Measurement of rare $B \to \mu^+\mu^-$ decays with the Phase-2 upgraded CMS detector at the HL-LHC, CMS-PAS-FTR-18-013, 2018, https://cds.cern.ch/record/2650545.

[20] R. Bruce *et al.*, "New physics searches with heavy-ion collisions at the LHC", 2018, arXiv:1812.07688.

[21] ATLAS Collaboration, "A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade“, CERN-LHCC-2020-007, 2020, https://cds.cern.ch/record/2719855.

[22] ALICE Collaboration, Letter of intent for ALICE 3: A next generation heavy-ion experiment at the LHC, CERN-LHCC-2022-009, 2022, arXiv:2211.02491, https://cds.cern.ch/record/2803563.