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CMS Upgradefor Heavy Ion Collisions

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Contents

1 Introduction

Relativistic heavy ion collisions allow experimental studies of quark-gluon plasma (QGP), the equilibrated high temperature state of de-confined quarks and gluons. At the Large Hadron Collider (LHC), the abundant production of hard probes such as vector bosons, heavy quarks, jets and quarkonia produced in the highest energy heavy ion collisions has opened a new era in the characterization of QGP, providing new information on initial state properties, parton energy loss and color screening. The capabilities of the Compact Muon Solenoid (CMS) detector in the detection of high momentum photons, electrons, muons, charged particles and jets have proven to be a unique match for the opportunities at the LHC. A key aspect of this success has been the convergence of detector needs for precision measurements in pp discovery physics in a high luminosity, high pileup environment and for QGP studies in the high multiplicity PbPb collisions. This convergence has allowed CMS to adapt a large number of new analysis techniques to studies of heavy ion collisions, such as particle-flow jet reconstruction, studies of jet substructures, lifetime fits for secondary J/ψ studies, b- and c-tagging of jets, missing p_T measurements of W production and energy flow in dijet events.

The full power of these and other techniques will be exploited in future heavy ion studies beginning in 2018 and Run III, when an increase in the collision energy to $\sqrt{s_{NN}} = 5.02$ TeV and an eventual increase in PbPb collision rate to as high as $3 \sim 30 - 50$ kHz will enhance the production rate of hard probes by more than an order of magnitude. In this high energy and high luminosity era, CMS will undertake precision studies of complex observables such as γ-, Z^0- and $W^{\pm}$-jet correlations, heavy flavor jet quenching, multi-jet correlations and the azimuthal anisotropy of high p_{T} jets and quarkonia. Recently, extensive studies of fully reconstructed heavy flavor mesons such as D^0, B^+ in heavy ion collisions also show that CMS is ideally suited for the studies of heavy flavor production and heavy quark energy loss in the quark-gluon plasma.

The CMS trigger and data acquisition system is the key to achieving the ultimate high p_{T} physics reach in heavy ion collisions. Uniquely, the CMS trigger system only has two main components, the hardware based Level-1 (L1) trigger and the High-Level Trigger, which is implemented as ”offline” algorithms running on a large computer farm with access to the full event information. The conceptual aspects of applying this system to heavy ion collisions, which are characterized by much lower rate, but much higher multiplicity than those encountered in pp collisions, were first developed by the US CMS HI group (see, e.g. [1]). The HLT trigger work formed the basis for our previous proposals to the DOE Office of Nuclear Science. As we demonstrated in that proposal, triggering on high p_{T} probes for PbPb collision rates up to several kHz (i.e. the design value for PbPb) is possible using event rejection solely or mostly at the HLT level. In the 2011 PbPb run, this allowed a reduction of the event rate to storage by more than an order of magnitude compared to the collision rate, without prescaling the most interesting high p_{T} observables. In the 2015 PbPb run, the heavy flavor meson triggers developed by the US CMS HI group from a previous DoE proposal was deployed for the first time. For instance, those triggers increased the high p_{T} D^0 meson statistics in pp (PbPb) collisions by a factor of 600 (20) which opened a new era for the precision heavy flavor physics in heavy ion collisions.

It has now become clear that the LHC will be able to significantly exceed the PbPb design luminosity in future runs, possibly reaching up to 50 kHz already in Run III. This will place an even greater emphasis on the CMS trigger and DAQ system. In 2017, a new 4-layer pixel detector will be installed in CMS which will greatly improve the impact parameter resolution of the charged tracks. This is an uniquie opportunity to combine the capability of CMS for the studies of high p_{T} probes with heavy flavor program down to $p_{\mathrm{T}} \sim 0$, complementary to the physics goal of the O(100M) ALICE upgrade. Moreover, a stage-2 upgrade of the Level 1 trigger system will be commissioned. This requires improvement in the front end detector readout bandwidth in PbPb ccollisions, as well as significant development on the trigger strategy for the data-taking in 2018 and beyond such that CMS could provide unbiased single track, heavy flavor meson, jet triggers, that are critical for the CMS physics program, and at the same time record a large statistics Minimum-Bias triggered sample which could be used to for the studies of low p_{T} heavy flavor mesons. This necessates the development of underlying event background subtraction for the stage 2 L1 system and improvements in the detector readout to increase the maximum L1 accept rate during the PbPb data-taking period.

In this proposal, we will present the CMS L1 rate upgrade design and demonstrate that the planned upgrade delivers the needed capability to record heavy flavor meson and jets over a very wide kinematics range at the full delivered rate in high luminosity PbPb runs in 2018 and beyond. This new system will need to be commissioned by 2017-2018, before the next heavy ion running period at the end of 2018, to make successful PbPb data taking possible. Section 2 describes the expected performance of the upgraded trigger for several examples of critical measurements, compared to the the limitations of the current system. The CMS trigger system and the technical details of the proposed upgrade project are described in Section **??**. In Section **??** the trigger performance based on simulation and extrapolation are illustrated. Finally, the proposed schedule, management plan and the budget are described in Sections 9 and 10.

2 Physics motivation

[Yen-Jie working on this section]

In this Section we discuss the physics performance of the upgraded L1 trigger system for the 2018 high luminosity PbPb run using three examples of measurements using rare probes. The performance of the upgraded system, which uses background subtraction for L1 event rejection and provides access to the full expected luminosity of 3 nb^{-1} is compared to that of the current system. These examples illustrate the large improvements in statistical precision afforded by the improved ability to select jet events and high p_{T} particles during high luminosity PbPb collisions.

Below we discuss a selection of measurements which exploit the future high luminosity data sets to provide important insights into the parton energy loss mechanism and heavy flavor particle production:

1. The flavor dependence of jet quenching is a crucial important test ground for various parton energy loss models. Compared to light quarks, heavy quarks are expected to suffer from smaller radiative energy loss when passing through the medium because gluon radiation is suppressed at angles smaller than the ratio of the quark mass M to its energy E [2]. This effect (and its disappearance at high p_{T}) can be studied using tagging of b-decays and b-jets.

2. Compared to quarks, gluons are expected to suffer a larger energy loss because of the larger color factors. This effect can be studied using three-jet events.

3. Measurements of the single particle azimuthal anisotropy at very high p_{T} give access to the in-medium path-length dependence of energy loss. The azimuthal anisotropy as a function of charged particle p_{T} also yields important information about the parton energy dependence of the energy loss.

These and other measurements rely on a sufficiently selective jet and heavy flavor meson trigger to provide access to the full delivered luminosity and a large minimum-bias sample. Data collected during the 2015 PbPb run were used to estimate physics reach for a future high-luminosity run (assuming L_{int} =3 nb^{-1}) for these three physics cases.

Figure 1: The jet finder is applied to minimum bias data from 2011 without event selection using the L1 primitives present in the RAW data. The fraction of events which have a jet above a given E_t threshold is plotted as a function of that threshold. Note that the threshold is applied to the L1 jet energy and does not correspond to the HLT or offline jet energy scales.

2.1 Nuclear Modification Factors of Heavy Flavor Mesons

[To be updated]

A proof of principle measurement of b-jet production in PbPb collisions has been performed with the 2011 data. This measurement of the b-jet to inclusive jet ratio, however, suffers from large statistical and consequently also systematic uncertainties. The golden measurement in the b-jet channel would be a measurement of the dijet asymmetry for doubly-tagged b-jets, where we expect systematic uncertainties to be small, and to mostly cancel with respect to the corresponding light-quark jet measurements. The rate of doubly-tagged b-jets has been estimated based on the number of inclusive dijets in the 2011 sample. The b-jet to inclusive jet ratio was measured to be approximately 0.03 in pp collisions at 7 TeV, as well as in 2.76 TeV PbPb collisions, with significantly larger uncertainties in the latter case. Of these b-jets only about 20% will be produced back-to-back with another b-jet, in the so-called flavor creation mode. Using a simple secondary vertex tagger, one can achieve about 50% tagging efficiency in PbPb. For doubly-tagged jets, then, one only obtains a tagging efficiency of 25%, but with a purity close to unity. Assuming x_T scaling with an exponent of $n = 4.5$, the yield of jets at fixed p_{T} increases by a factor of 5 for the increased collision energy expected in 2015.

The distribution of the dijet asymmetry variable A_J is defined as the difference between the leading and subleading jet transverse momenta, divided by their sum. The A_J distribution for doubly tagged b-jets is estimated from the inclusive jet A_J distribution, scaling the uncertainties to those expected from 1.5 nb^{-1} of data at 5.5 TeV, with a tagging efficiency of 25%. This distribution is shown in Figure 2 for the 10% most central PbPb events. The kinematic cuts on the leading and sub-leading jets are $p_{\mathrm{T}} > 100$ GeV/c and $p_{\mathrm{T}} > 30$ GeV/c, respectively, for jets in $|\eta| < 2$.

2.2 Ellipic Flow of Heavy Flavor Mesons

Events with three or more jets in the final state originate from hard gluon radiation and other higher-order QCD processes. A measurement of the inclusive 3-jet to 2-jet cross section ratio (R_{32}) is an interesting testing ground of pQCD, with possible modification of parton shower and gluon jet-quenching in QGP, because major systematic uncertainties such as jet energy scale, reconstruction efficiency and integrated luminosity measurement largely cancel. The expected number of 3-jet events at 5.5 TeV is estimated based on the observed statistics in the 2011 data sample, in which we recorded about 106 3-jet events and 8225 dijet events, with all jets having $p_{\mathrm{T}} > 100$ GeV/c. The ratio from PYTHIA events, with uncertainties scaled to the expected 2015 statistics, is shown in Figure 3. With the upgrade L1 system, R_{32} measurements as a function of the average p_{T} of the two leading jets are made possible.

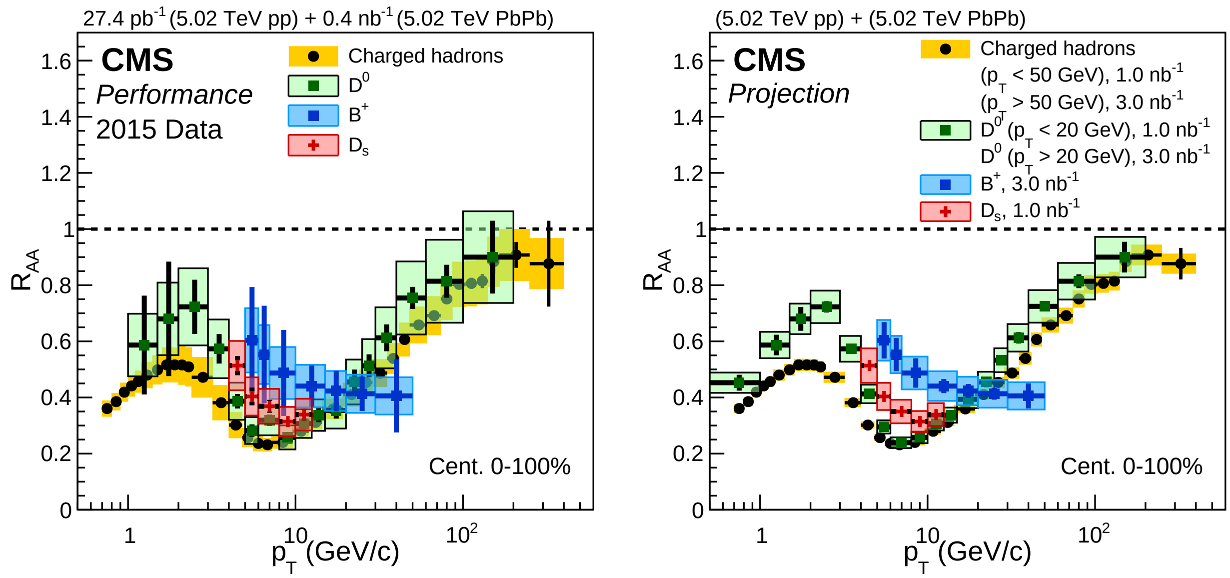

Figure 2: Nuclear modification factors of charged particles, D^0, D_s and B^+ mesons with 2015 data (left panel) and the statistics expected with L1 trigger rate upgrade.

2.3 D^0-Jet and D^0-hadron correlations

The expected p_T reach of charged particle spectra is presented in Figure 4. With the upgraded L1 system and improved L1 jet trigger with underlying event subtraction, a large improvement in correlation between the track p_T and L1 jet p_T can be achieved, as shown in Figure 5 (left) for 0–30% centrality and Figure 6 (left) for 40–100% centrality. Therefore, it is feasible to use high p_T L1 jet as a seed to the high p_T track high-level trigger. In this way, one can fully access the total delivered luminosity to significantly extend the track p_T reach in the high luminosity PbPb run (red markers in Figure 4), which is crucial for studying the high p_T charged particle suppression and anisotropic azimuthal distribution. As shown on the right hand sides of Figure 5 and 6, by selecting L1 jet p_T of 40–50 GeV/c, one can maintain 100% efficiency for the high p_T track trigger in both central (p_T > 60 GeV/c) and peripheral (p_T > 40 GeV/c) heavy ion collisions, while the L1 jet rate can be well controlled. Unprescaled access to high p_T single particle production provides the basis for a large number of important energy loss analyses complementary to jet-trigger bases approaches.

Figure 3: The ratio of 3-jet to 2-jet events (R_{32})as a function of the average p_T of the two leading jets for p_T > 100 GeV/c in the ten percent most central collisions expected in the 2015 PbPb Run.

Figure 4: Track p_{T} distribution for 2.76 TeV PbPb in 2011 with a total integrated luminosity of $150\mu\mathrm{b}^{-1}$ (solid black), projection to 5.5 TeV in 2015 based on x_T scaling without upgraded L1 trigger (open red), and with upgraded L1 trigger (solid red).

Figure 5: Leading L1 jet E_T, with upgraded L1 system, vs leading track p_{T} in 0-30% PbPb collisions at 2.76 TeV (left), and efficiency turn-on curve as a function of leading track p_{T} for L1 jet E_T thresholds of 40, 50 and 60 GeV (right).

Figure 6: Leading L1 jet E_T, with upgraded L1 system, vs leading track p_{T} in 40-100% PbPb collisions at 2.76 TeV (left), and efficiency turn-on curve as a function of leading track p_{T} for L1 jet E_T thresholds of 40, 50 and 60 GeV (right).

3 Hardware Introduction

The CMS experiment is mainly designed to record high luminosity, high-PU proton-proton collisions events. However, with several detectors tweaks/configuration changes, over the last several years, the CMS experiment has been able to record successfully also the high multiplicity Heavy-Ions collisions delivered by LHC. As discussed already in previous proposals, the main changes required to allow CMS to operate in HI environments could be summarized as follows:

- Dedicated Silicon Pixel Front End device firmware for high multiplicity environment.
- The Silicon Tracker zero suppression were bypassed and all the channels information were forwarded to the CMS DAQ system. The Zero Suppression was performed in HLT. A new tracker FED firmware was also designed to reduce the event payload of 30
- DAQ reconfiguration / rebalance to deal with big data volumes and high throughput. In standard p-p collisions operation, an average event size correspond to 1- 1.5 MB/even. During Pb-Pb collision operation, the average event size is at around 17 MB/event.
- The Level-1 trigger firmware was redesigned to perform a dedicated underlying event subtraction algorithm and to include specific HI algorithms
- Significant adjustment in the overall CMS dataflow

With the specific configuration described above and with a series of small adjustments not mentioned here, CMS was able to run smoothly during the 2015 Pb-Pb data-taking with and average L1 rate of 10 kHz. Few hours of the Pb-Pb data-taking period were also devoted to explore the limit of the system. With the 2015 CMS configuration for Pb-Pb, the absolute L1 rate limit is of 12 kHz. During the 2015 run, the collision rate was of 20 kHz. For the 2018 Pb-Pb run and beyond the rate limits could significantly impact the expected physics program. On one hand it would be beneficial to increase the number of min bias events collected and on the other hand LHC will deliver a higher luminosity. We are considering a collision rate of 30 kHz already for 2018 Pb-Pb run. The CMS subsystems as well as their interaction with the DAQ have been studied and a series of bottlenecks were identified. In this proposal the main interest area are specified reporting also about the corresponding manpower needs. The preliminary goal is to increase the CMS readout rate to 30 kHz. It is however important to bear in mind that this proposal will focus only on aspects that will potentially require hardware changed. The comprehensive series of tasks needed for the overall run preparation is not reported here.

4 ECAL

The ECAL off detector electronics (DCC) was designed to cope with a L1 rate of 100 kHz and an average event size of 2 kB/event. During p-p high-pu collisions the average event size is at around 1.5 1.8 kB/event. However, during Pb-Pb collisions, the average event size is of 15-20 kB/event (depending by the trigger mix) and it is up to 34 kB/event for central PbPb collisions. With so big event sizes, the L1 rate tolerated is up to 12 kHz. In the specific ECAL case, the hardware limits can be identified in two main areas: the link between ECAL DCC and DAQ, and the internal DCC speed. The links to DAQ are standard S-Link designed for 200 MB/s. For the 2017 run an upgrade of the mezzanine card on the DCC side including a bigger buffer is already planned. This upgrade should allow an increase of 10Also the increase of clock frequency on the mezzanine card could be considered but the benefits are still to be evaluated. The second limit encountered is the actual DCC internal speed firmware speed. An increase of 50 100 clock frequency. The ECAL group engineers gave already their availability to participate and supervise the project. However, the concrete implementation should be responsibility of the HI group. A person should be dedicated to the project for roughly 6 months. Before envisaging the firmware change hypothesis, there are other two configurations that should be evaluated. The ECAL group is already studying the calorimeter performance adjusting the Selective Readout and Zero Suppression threshold. It is not clear yet how much the new settings could influence the event size for Pb-Pb collisions but definitively a benefit could be directly obtained. On the same line, the ECAL event size could be reduced up to 40 and this number can be programmed down to a minimum of 6 BX. However, reducing the number of samples could have strong implication in the energy resolution. A complete study should be performed to understand how significant could be the effect of x-fit in Pb-Pb collisions and the consequently effects on the physics program. Considering the amount of work required for the offline studies mentioned above, we should allocate a person for one year to the project. Any of the two offline solutions mentioned above indeed require specific performance studies and also the implementation of CMSSW code for the eventually new configuration. Also the calorimeter calibrations should be re-derived.

5 Silicon Pixel Detector

A new silicon pixel detector including 4 layers is being installed and commissioned. The detector FE electronics and sensors is equivalent to the legacy detector while the whole off detector electronics was redesigned and based on the latest FPGA technology (Xilinx virtex-7 family). The new firmware designs takes already into account high multiplicity events. However, at present the performance of the latter has not been evaluated in HI multiplicity environment. An electronics board with the scope to emulate the detector response was also designed to perform the commissioning of the off detector electronics. The pixel group toke the responsibility to use this latter and define as soon as possible the pixel operational parameters. A person in the HI group should however act a liaison person and provide the necessary information required by the pixel group to perform the emulation. Accordingly, also the results should be evaluated and possible solutions identified in case the performances are below expectations. As a rough estimation, a couple of months should be enough for this activity.

6 Silicon Strip Tracker

In standard p-p collision operation, the tracker detector sends the full detector information to 439 Front End devices (FEDs). They apply the common mode noise subtraction and the strip zero suppression. However the common noise subtraction algorithm implemented in the tracker FEDs firmware doesnt allow compensation of the baseline distortion observed in high multiplicity HI events. The solution adopted up to now was to bypass the tracker zero suppression in the tracker FEDs and implement a specific HI common mode noise subtraction and zero suppression algorithms as a HLT process. However, this solution implies and heavy load on the link between the FEDs and the DAQ. The whole interconnection was indeed designed with a maximum of 400 MB/s per FED (two links of 200 MB/s each for heavy load FEDs). Considering that in average fragment size it is at 32 kB/event. The readout limit is at around 12 kHz. It was also already demonstrated that the FED is designed to sustain up to 520 MB/s. In this optic the only solutions available are either to increase the number of links between the tracker FEDs and the DAQ or to reduce the data payload. The first solution appear to be too complicated adding other 400 links. Apart the technical constraints, there would also not be enough time to install and commission the links during the EYTS. The second option is to reduce the data payload. A FED firmware version implemented already in 2015 allows the reduction from 10 to 8 the number of bits readout by each strip ADC. However, this strategy would allow moderate increase of ¡ 20 the detector resolution/sensitivity. At present there are not conclusive studies on the effects of this change on the overall tracking efficiency. The second strategy considered is to modify the FEDs firmware including a more refined common mode subtraction algorithm accounting for baseline distortion. At present this strategy is considered to be the preferable considering the rate increase obtained. The system could run at ¿ 50 kHz. The tracker FEDs are based on Xilinx Virtex-2 FPGA that is quite limited in term of on chip resources as well as clock frequency. This limitation implies that only algorithm designed with specific attention could be implemented in the FEDs FPGA. It also implies that the FED firmware development should be branched between p-p and Pb-Pb operation not having enough on-chip resources to maintain both features. In 2013 a specific HI zero suppression algorithm designed for high multiplicity environment and that would satisfy the FPGA constraints was designed offline and it is named baseline follower. Preliminary studies performed by the tracker and HI groups showed promising performance results for the algorithm. The first part of the project requires the detailed study of the algorithm offline. It will imply roughly 3 months of work and detailed clustering and tracking studies. Hardware feasibility studies are going to be performed in parallel by tracker engineers. During this phase the HI group should participate in providing the required information but the amount of work could not be quantified yet. In the late spring/early summer 2017 the project will be handed over completely to the HI group where a developer will implement the actual algorithm in firmware. We estimate that the activity of coding will last between 6 and 8 months. Afterwards, three months commissioning time including tests on the bench and test at P5 should be considered. This schedule should leave some resources available for the actual 2018 HI run preparation. At present the tracker group is focusing on the tracker operation during p-p collisions and the tracker upgrade project. In this optic, a significant fraction of the work required for this project will need to fall under the HI group responsibility as mentioned above.

7 L1 trigger

For the 2015 Pb-Pb run an upgraded L1 trigger system was designed. The Stage-1 L1 trigger was operated with specific HI algorithms. However, in the middle of 2016 the full trigger upgrade (referred as Stage-2 in previous proposals) was installed and commissioned. The upgraded trigger system has a new layer-1 and the single MP7 board layer-2 was replaced with 9 MP7 boards operating with a time-multiplexed architecture. Also the firmware was completely redesigned by the L1 team including a series of new algorithm specific to p-p collision operation. In this optics, it is mandatory for the 2018 run to port to the new system the specific HI algorithm. In the list we have a specific background subtraction, centrality triggers, single-track triggers and Q2 triggers. It was agreed with the L1 team that the stage-2 engineers would take care of the actual firmware implementation and commissioning. However, it will be responsibility of the HI group to provide support. It includes the performance studies of the algorithms and a specific description of the implementation. Furthermore some of the several tests on the bench or at P5 will be performed by the HI group. Also the compilation of the L1 and HLT menus will remain responsibility of the HI group. In term of manpower, it should be considered a person for 6 months to follow the implementation process of the layer-2 and uGT firmware as well as performing the performance studies needed for the algorithm implementation. The preparation of the L1 menu could be considered as part of this time. ======= The electron/photon sort operation must determine the four highest transverse energy objects from 72 candidates supplied by the RCT, for both isolated and non-isolated electrons/photons.

To sort the jets the GCT must first perform jet finding and calibrate the clustered jet energies. The jets are created from the 396 regional transverse energy sums supplied by the RCT. These are the sum of contributions from both the hadronic and electromagnetic calorimeters.

8 Dataflow

9 Management Plan, Personnel, Schedule

The overall management of the upgrade of the tracker and ECAL for the 2018 HI run will be conducted within the existing management structure of CMS. MIT personnel supported by this request will be part of the two main groups and following the established management procedures within CMS. The leader of the project related to the trigger functionality for the heavy ion physics will be Dr. Yen-Jie Lee of CERN & MIT, who is presently the upgrade coordinator within the CMS heavy ion group. The responsibilities related of the heavy ion group in the various projects mentioned above will be the following:

- Help and support to the pixel group for the validation and commissioning of the pixel FEDs for HI collisions
- Detailed performance studies of the alternative algorithm for the tracker zero suppression. It includes the commissioning of the offline software dedicated to the local reconstruction code
- Re-design of the tracker FED firmware including the derivative follower algorithm
- Participate in the phases of validation, test and commissioning of the HI tracker FED firmware in the CMS experiment
- Performance sties on ECAL data reduction adjusting ECAL operational conditions. This activity implies also a significant re-design of the offline ECAL local reconstruction
- Adjust/re-design a part of the ECAL DCC firmware to increase overall rate. Also small hardare changes including power distributions/supply should be envisaged.
- Performance studies, test and commissioning of the specific HI L1 algorithms
- Development and commissioning of a dataflow able to reduce the HLT output event size

At present the performance physics studies required in the early phases of the project are carried by MIT graduate students and a CERN porstdoc under the supervision of Ivan Cali.

The pixel FED performance studies are going to be performed by the William Johns and Karl Ecklund. The contact person for the HI group is still Ivan Cali.

The firmware for the silicon tracker will be developed by Ivan Cali of MIT in collaboration with another person in the HI community and the Imperial College group.

The firmware for the ECAL DCC change doesn't have a person associated yet. The LIP group will provide support.

The L1 trigger firmware implementation will be performed by the Imperial College group. At present the L1 contacts are: Maxime Guilbaud and Ivan Cali.

The schedule of the whole project/s is driven by the need to terminate the project/s by the beginning of fall 2018. Few months are left for online operation and final commissioning phases before the 2018 HI run. We identified the following milestones in the proposed schedule:

- Silicon Pixel FED performance to be evaluated by June 2017;

- Silicon Tracker zero suppression algorithm performance studies to be fineshed by May/June 2017;
- Silicon Tracker FW implementation to be completed by April 2018;
- Commissioning of the Silicon Tracker FED and corresponding software, September 2018;
- ECAL preliminare performance studied to be concluded by June 2017;
- ECAL calibration and corresponding offline software by August 2018;
- ECAL firmware implementation by March 2018;
- ECAL DCC commissioning finished by September 2018;
- Commissioning of the system in CERN/P5, September 2018;
- L1 trigger specific algorithms full definition by September 2017;
- L1 trigger algorithm implementation by March 2018;

10 Budget

The overall budget for the heavy-ion group contribution to the projects includes only the costs of manpower for the study, development and commissioning of the tracker and ECAL FEDs. Some hardware can be required to increase the storage manager disk space but it cannot be foreseen at present.

The full chain of development, testing and commissioning will happen at CERN using the test facilities in CERN B906 and B186. In addition, the experience developed during testing will be applicable to the installation and commissioning in the experiment. This is why the group of people involved must be stationed at CERN in Geneva.

The members of the team from the heavy-ion groups will consist of an MIT research scientist, a postdoctoral associate and a graduate student. The fully loaded off-campus base salary of the MIT postdoc is presently 87K$. To compensate for the CHF/$ exchange rate and the higher cost of living in Geneva we will provide Cost of Living Allowance to the postdoc and Per Diem to the graduate students. The exact amount depends on the exchange rate at the time of payment but we estimate it to be about 35K$ for the postdoc and 15K$ per student per year. In addition there is some amount allocated for travel to and from Geneva. The costs is summarized in Table 1 and they all include MIT overhead.

Year	Salary	COLA	Equipment	Travel	Travel	Total
	1 postdoc	1 postdoc		Per diem	Add. Travel	
7/1/13-6/30/14						

Table 1: L1 trigger upgrade funding profile, in K$

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