May 1, 2017

CMS Level 1 Trigger Rate Upgrade for Heavy Ion Collisions Supplement to Award DE-SC0011088

Austin Baty[1], Ivan Amos Cali[1], Gian Michele Innocenti[1], Yen-Jie Lee[1], Camelia Mironov[1], Gunther Roland[1], Zhaozhong Shi[1], Jing Wang[1], Ta-wei Wang[1], Boleslaw Wyslouch[1]

[1]Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139

Research in Nuclear Physics: CMS Level 1 Trigger Rate Upgrade for Heavy Ion Collisions

Institution:	Massachusetts Institute of Technology Office of Sponsored Programs
Street Address:	Room NE18-901 77 Massachusetts Avenue Cambridge, MA 02139
Principal Investigator:	Prof. Boleslaw Wyslouch
Phone:	(617) 253-7800
E-mail:	wyslouch@mit.edu
Administrative Contact:	Michele Hudak
Phone:	(617) 324-5382
E-mail:	hudak@mit.edu
Task Supervisor:	Prof. Boleslaw Wyslouch
Proposed Project Period:	June 1, 2017 October 31, 2018
Funding Opportunity Announcement Number:	DE-FOA-0001664
DOE/Office of Science Program Office:	Office of Nuclear Physics
DOE/SC Program Office Technical Contact:	Dr. James Sowinski
DOE Grant Number:	DE-SC0011088
Topic Area:	Heavy Ion Nuclear Physics

Contents

1 Introduction

Relativistic heavy ion collisions allow experimental studies of the quark-gluon plasma (QGP), the equilibrated high-temperature state of deconfined 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 p-p discovery physics in a high luminosity, high pileup environment and for QGP studies in high multiplicity Pb-Pb 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 Pb-Pb collision rate to as high as $\sim 30-50$ 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 $\mathrm{W}^{\pm}$-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 and 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 (HLT), 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 a much lower rate but a much higher multiplicity than those encountered in p-p 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 Physics. As we demonstrated in those proposals, triggering on high p_{T} probes for Pb-Pb collision rates up to several kHz (i.e. the design value for Pb-Pb) is possible using event rejection solely or mostly at the HLT level. In the 2011 Pb-Pb 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 Pb-Pb run, the heavy flavor meson trigger developed by the US CMS HI group from a previous DOE proposal was deployed for the first time. Those triggers increased the high p_{T} D^0 meson statistics for example in p-p (Pb-Pb) collisions by a factor of 600 (20), opening 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 Pb-Pb 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. The CMS during Pb-Pb collisions is being operated close to its hardware limit in terms of readout rate (see Sec. 3 for details). As a consequence, CMS will not be able to benefit from the increased luminosity without a dedicated upgrade. In 2017, a new 4-layer pixel detector will be installed in CMS that will greatly improve the impact parameter resolution of the charged tracks. This is a unique opportunity to combine the capability of CMS for the studies of high p_{T} probes with the heavy flavor program down to $p_{\mathrm{T}} \sim 0$, complementary to the physics goal of the major ALICE upgrade foreseen for Run III.

Moreover, a stage-2 upgrade of the Level-1 trigger system will be commissioned for Pb-Pb data-taking. This requires improvement in the front-end detector readout bandwidth in Pb-Pb collisions, as well as significant development on the trigger strategy for 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 that could be used for studies of low p_{T} heavy flavor mesons. This necessitates the development of underlying event background subtraction for the stage-2 L1 trigger system and improvements in the detector readout to increase the maximum L1 trigger accept rate during the Pb-Pb 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 mesons and jets over a very wide kinematic range at the full delivered rate in high luminosity Pb-Pb runs in 2018 and beyond. This new system will need to be commissioned in 2017-2018 before the next heavy-ion running period at the end of 2018, to make successful Pb-Pb data-taking possible. Section 2 describes the expected performance of the upgraded trigger for several examples of critical measurements, compared to the limitations of the current system. The technical details of the proposed upgrade project are described in Sections 3.2 and 3.3. The support projects needed to guarantee an efficient L1 rate increase are described in Sections 3.4, 3.5 and 3.6. Finally, the proposed schedule, management plan, and the budget are described in Sections 4 and 5.

2 Physics motivation

In this Section we discuss the physics performance of the L1 trigger rate upgraded system for the 2018 high luminosity Pb-Pb run using three examples of measurements with 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 Pb-Pb collisions with L1 trigger rate upgrade.

Below we discuss a selection of measurements that 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 an 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 charged particles, heavy flavor mesons and b-jets.

2. Measurements of the charged particle and heavy flavor meson azimuthal anisotropy (v_2) at very high p_{T} give access to the in-medium path-length dependence of energy loss. The azimuthal anisotropy as a function of particle p_{T} also yields important information about the parton energy dependence of the energy loss. At low p_{T}, hadronization of heavy quarks such as parton-to-jet fragmentation and the recombination of heavy quarks and light flavors has a significant impact on the magnitude of the heavy flavor meson v_2.

3. Studies of jet-heavy flavor meson correlation could give important insights into the parton energy loss mechanism and for the studies of medium induced radiation and medium response to energetic heavy quarks.

These and other measurements rely on a sufficiently selective jet and heavy flavor meson trigger to provide access to the full delivered luminosity. At the same time, a large minimum-bias sample is needed in order to access very low p_{T} heavy flavor mesons and to perform data-driven tracking and jet energy corrections. To illustrate the impact of the L1 rate upgrade, data collected during the 2015 Pb-Pb run were used to estimate physics reach for a future high-luminosity run (assuming L_{int} =3 nb^{-1}) for these three physics cases.

2.1 Nuclear Modification Factors of Heavy Flavor Mesons

One of the proposed observables that reveal the flavor dependence of in-medium parton energy loss is the reduction of heavy flavor meson yield. This can be studied by measurements of nuclear modification factors (R_{AA}), defined as the ratio of the yield in nucleus-nucleus collisions to that observed in pp collisions, scaled by the number of binary nucleon-nucleon collisions. Theoretical calculations of R_{AA} for fully reconstructed D and B mesons are shown in Figure 1. At low p_{T}, the production rate of heavy flavor mesons in Pb-Pb is sensitive to the elastic energy loss of the heavy quark, the gluon shadowing effect in the nuclear parton distribution function, and the rate of recombination of the heavy quark and light flavors at the hadronization stage. At high p_{T}, the size of the suppression is sensitive to the heavy quark radiative energy loss in the pQCD-based models. Precision measurement of the R_{AA} from intermediate p_{T} ($\sim$ 10 GeV) to very high p_{T} (200-400 GeV) in bins of event centrality could provide insights about the pathlength and momentum dependence of the heavy quark energy loss and potentially distinguish between models based on AdS/CFT and pQCD.

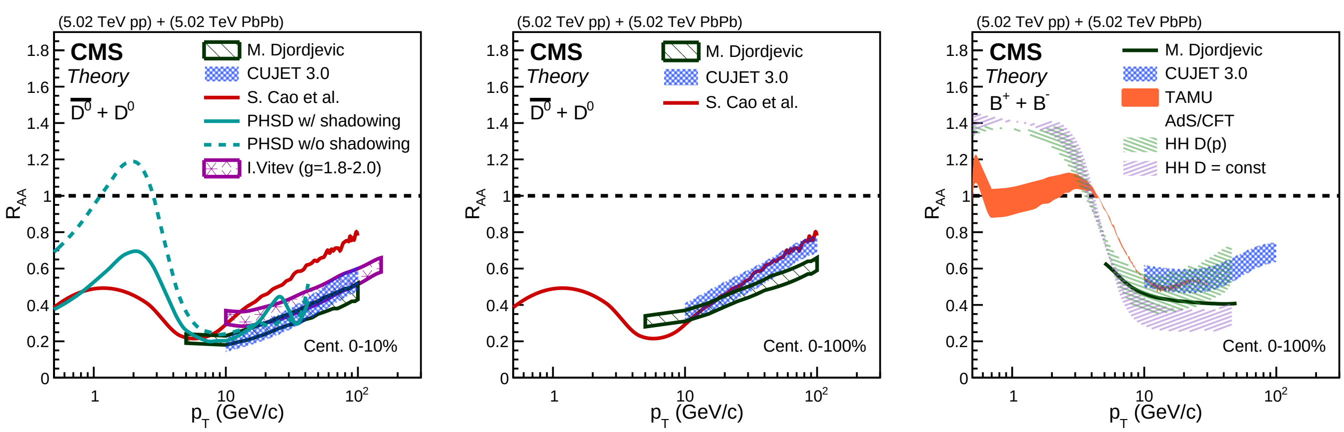

Figure 1: Theoretical calculations of nuclear modification factors of charged particles, D^0 and B^+ mesons.

It is also predicted that a significant fraction of the low p_{T} heavy quarks could hadronize via recombination with other quarks from the medium. This motivates measurements of the R_{AA} from D^0, D^+, (B^+), D_s^+ (B_s) and Λ_c (Λ_b) which could provide crucial information about the interactions of the heavy quarks and the produced medium. The D_s and B_s measurements are especially sensitive to the strangeness content of the produced strongly interacting medium. Figure 2 shows the performance of $D^+ \to \phi\pi^+$, $D_s^+ \to \phi\pi^+$, $\Lambda_c \to pK^-\pi^+$ and $B^+ \to \bar{D}^0\pi^+$ reconstruction in heavy ion collisions with the CMS detector, projected to the expected statistics to be collected with the L1 trigger rate upgrade. Significant signals of D_s^+ and Λ_c could be observed, enabling the measurement of D_s and Λ_c R_{AA} with the CMS detector for the first time.

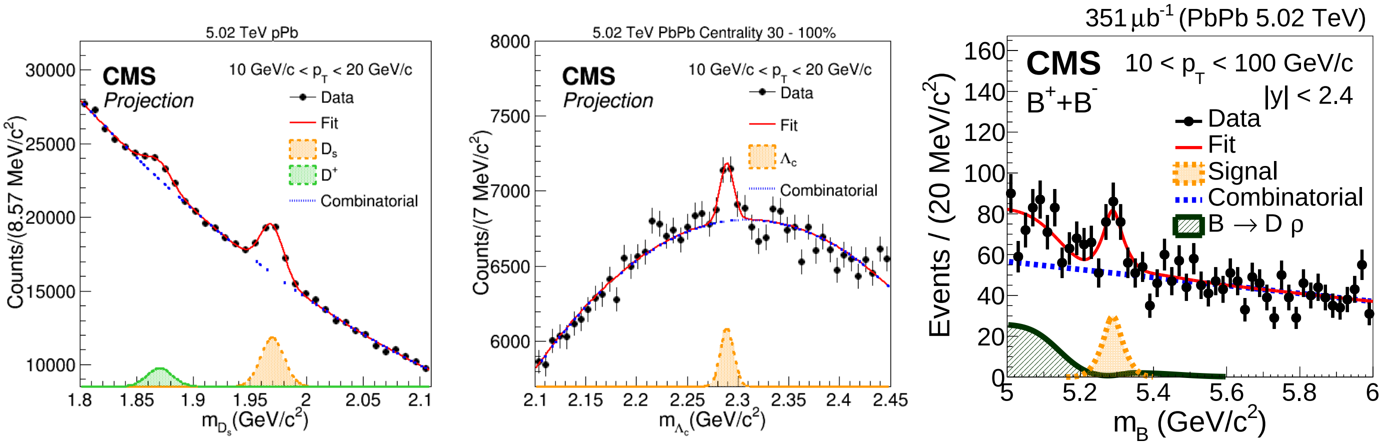

Figure 2: Invariant mass distributions of fully reconstructed heavy flavor mesons

Figure 3 shows the expected performance with the data recorded in 2015 and the projected performance in 2018 and beyond. With the high statistics jet and heavy flavor triggered sample, the precision of the R_{AA} measurements at high p_{T} could be greatly improved. At the same time, with the L1 trigger rate upgrade proposed in this proposal, the much larger minimum-bias sample enables CMS to perform these studies down to the very low p_{T} region. The expected precision of D^0, B^+ and D_s R_{AA} measurements from low p_{T} to high p_{T} could provide a strong constraint on theoretical models, and the difference in the suppression magnitude between those mesons could be observed for the first time.

2.2 Azimuthal anisotropy of Heavy Flavor Mesons

Azimuthal anisotropy of hadrons provides information about their production with respect to the reaction plane (Ψ_n). At high p_{T} , the larger in-medium path-length of the mother partons emitted in the direction of the reaction plane leads to a stronger suppression of the yield due to jet quenching. Therefore, measurements of the v_n coefficients from Fourier expansion of the particle distributions $dN/d\psi$ are sensitive to path length dependence of the parton energy loss. At low p_{T} , a large v_2 (elliptic flow) signal is considered as evidence for collective hydrodynamical expansion of the medium. Measurements of heavy flavor meson v_n could provide important information about the thermalization of the heavy quarks in the medium. Precision measurements of v_n as a function of heavy flavor meson p_{T} could teach us how the azimuthal anisotropy of the light flavor partons contribute to the observed anisotropy through the recombination of heavy quarks and light quarks. As shown in Figure 4, the predicted elliptic flow (v_2) signal covers a large range of values due to the difference in the treatments of in-medium parton transport and parton energy loss. Figure 5 shows the expected performance of elliptic flow (v_2) measurements with the data recorded in 2015 and the projected performance in 2018 and beyond. The new precise data will be able to constrain various components of the theoretical models to determine the heavy quark diffusion coefficient in QGP, and to reveal flavor dependence of the parton energy loss.

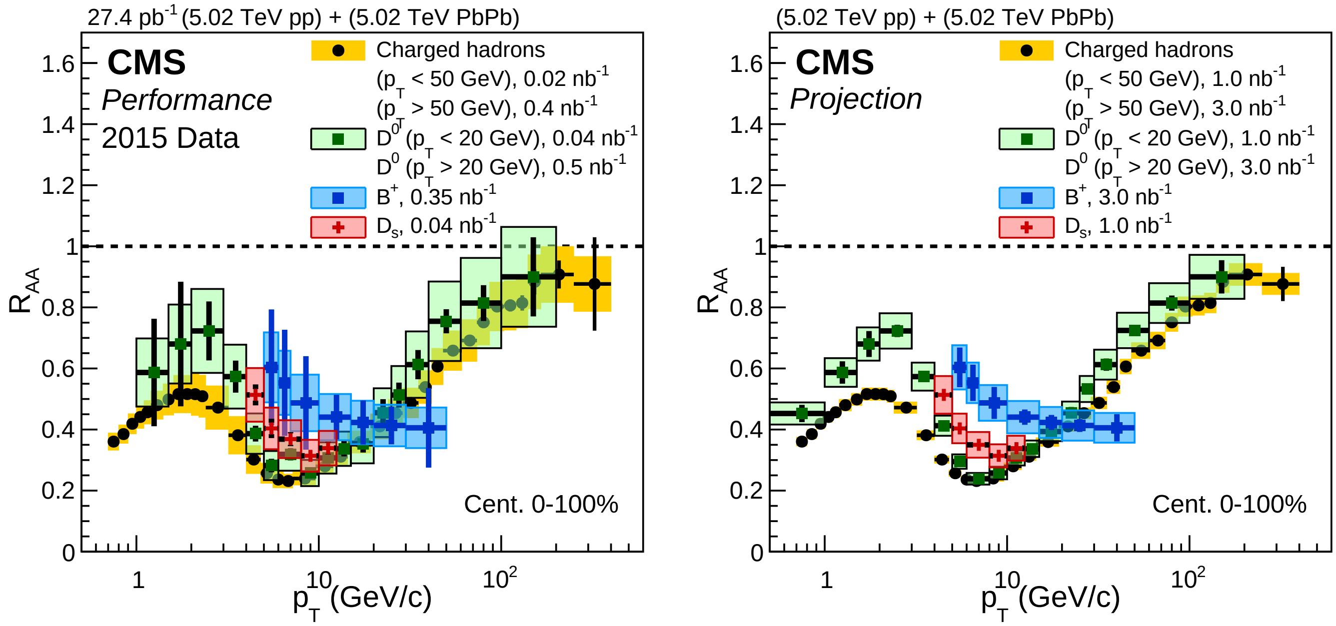

Figure 3: Nuclear modification factors of charged particles, D^0, D_s and B^+ mesons with 2015 data (left panel) and the statistics expected with L1 trigger rate upgrade (right panel).

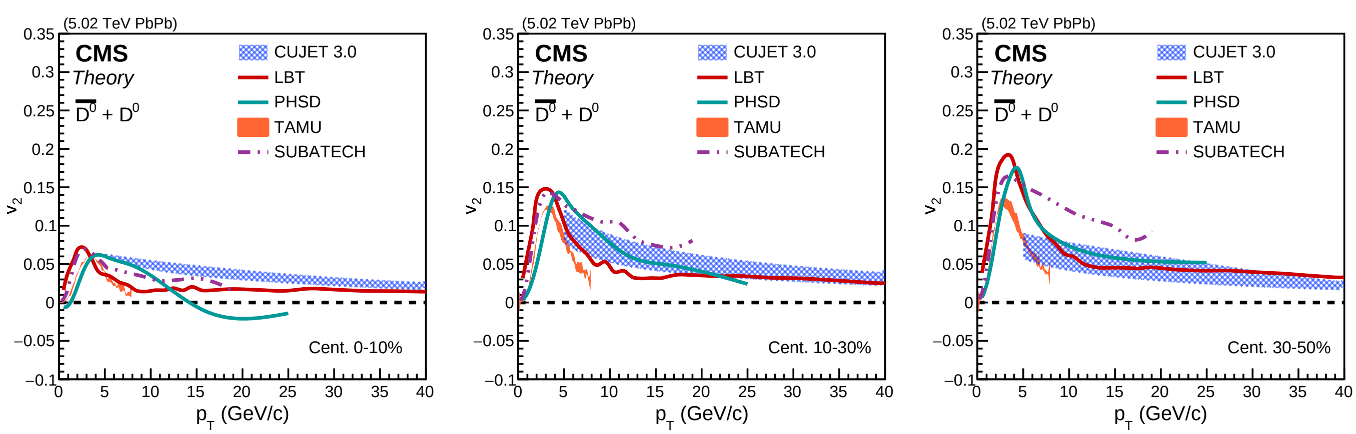

Figure 4: Theoretical calculations of heavy flavor meson v_2 in 0-10% (left) 10-30% (middle) and 30-50% (right) PbPb collisions at 5.02 TeV.

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

CMS has published jet-hadron and jet shape and dijet missing transverse momentum measurements which showed a significant modification of the angular structure of the jets. A significant amount of energy is trans-

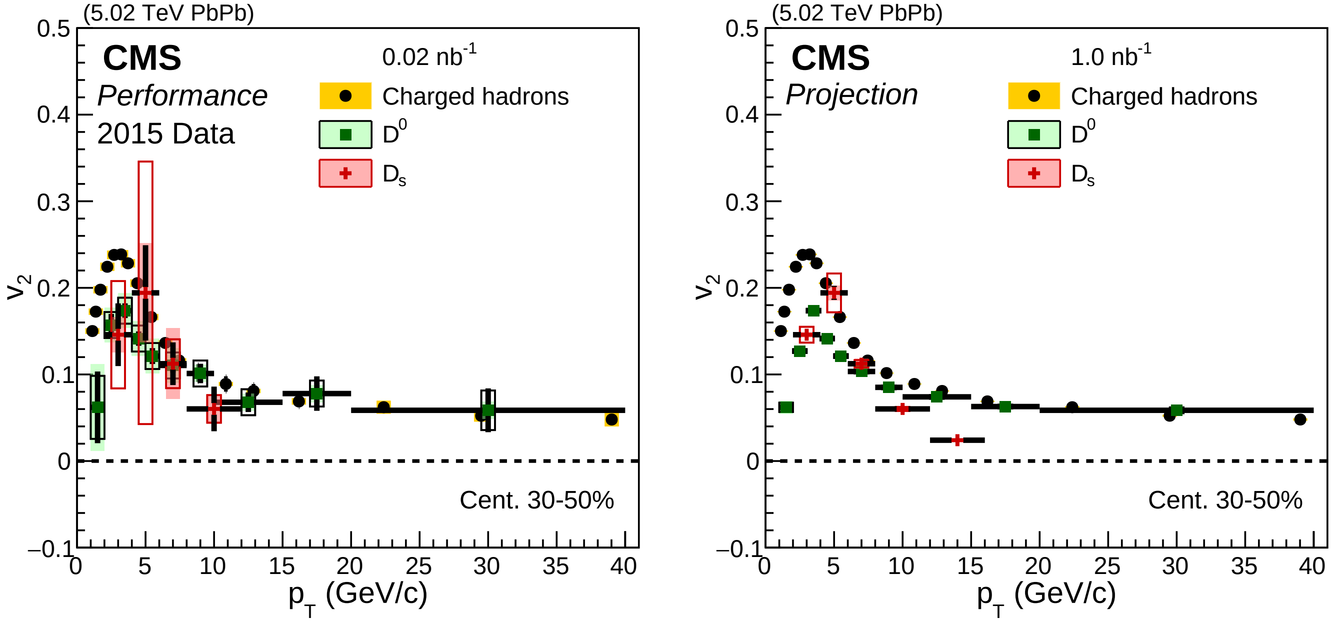

Figure 5: v_2 of charged particles, D^0 and D_s with 2015 data (left panel) and the statistics expected with L1 trigger rate upgrade (right panel).

ferred to very large angle with respect to the jet axis. Studies of D^0-jet and D^0-hadron angular correlation are sensitive to the energy loss mechanism. Due to the large mass of the c-quark, the proposed measurement could also potentially distinguish models that explain the out-of-cone radiation as signals of medium response from the ones that describe the data with medium-induced semi-hard gluon radiations. Figure 6 shows the performance of D^0 meson reconstruction as a function of the distance with respect to the jet axis ΔR. With the high statistics data taken in 2018 with jet trigger, high precision D^0-Jet correlation and D^0-hadron correlation could be performed for the first time (Figure 7).

2.4 Summary

The current and projected physics performance of various measurements are shown in Table 1. With the proposed work on the L1 trigger rate upgrade project, the kinematic range covered by CMS could be greatly increased and many more observables that are not yet accessible with 2015 data will become feasible for the first time with the data taken in 2018 and beyond.

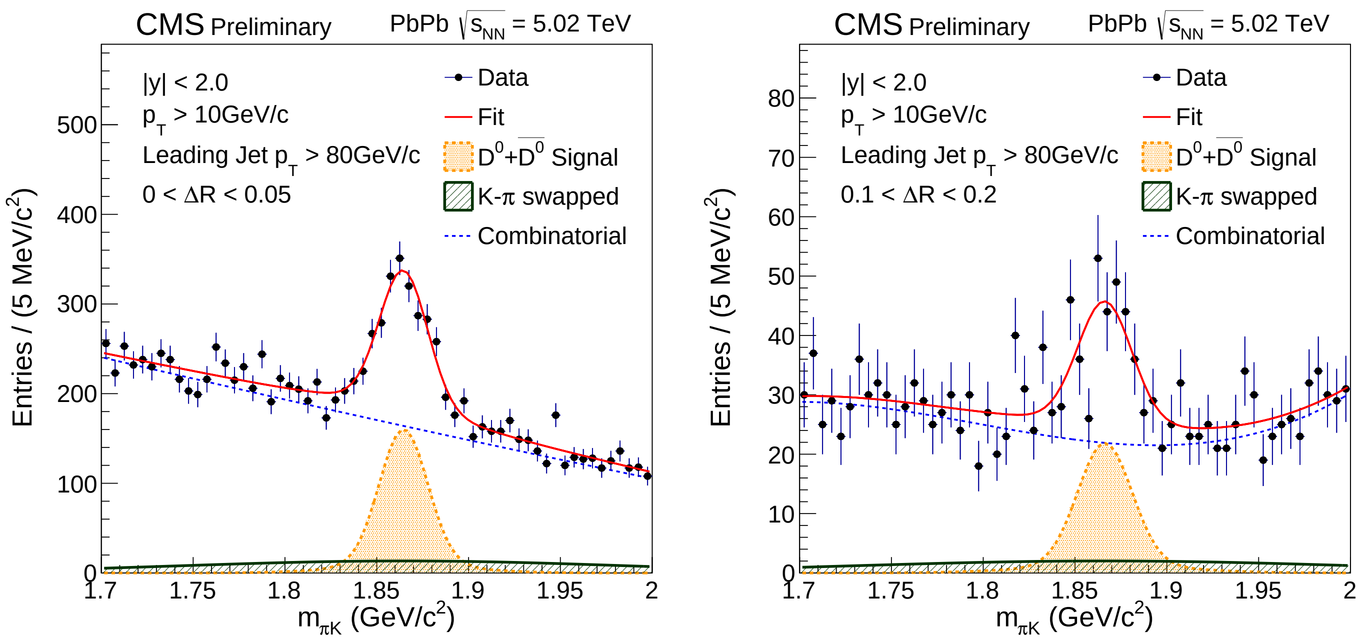

Figure 6: D^0 signal extracted in bins of distance with respect to the jet axis ΔR.

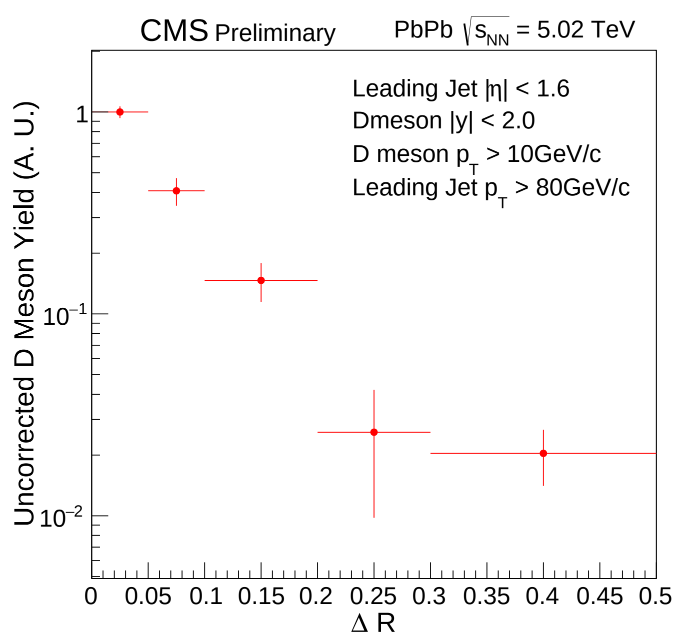

Figure 7: Extracted D^0 yield as a function of ΔR.

	Current 0.04 nb^{-1} + Present System		**2018 Pb-Pb 1 nb^{-1} + Upgraded System**	
Observables	p_T min	Statistical Uncertainty	p_T min	Statistical Uncertainty
$D^0 R_{AA}$	2	15%	0.5 - 1	10%
$D_s R_{AA}$	~ 4	20%	< 4	4%
$\Lambda_c R_{AA}$	10	$> 20\%$	< 10	4%
$B \to D R_{AA}$	6	20%	2	10%
$B^+(D^0\pi) R_{AA}$	Not accessible		~ 4	
Low p_T c and b jets	Not accessible		~ 30	
$D^0 v_2$ $(= 0.06)$	1	80%	0.5 - 1	18%
$D_s v_2$	Not accessible		~ 4	
$B \to D v_2$	Not accessible		~ 2	
$\Lambda_c v_2$	Not accessible		~ 6	

Table 1: Summary of the heavy flavor measurements with 2015 data and 2018 data with L1 trigger rate upgrade

3 Hardware Upgrade

3.1 Introduction

The CMS experiment is mainly designed to record high luminosity, high pile-up (PU) proton-proton collisions events. However, with several detector adjustments/configuration changes over the last several years, the CMS experiment has been able to record successfully also the high multiplicity heavy ion collisions delivered by the LHC. As discussed already in previous proposals, the main changes required to allow CMS to operate in the HI environment can be summarized as follows:

- A dedicated silicon pixel Front End Driver (FED) firmware for a high multiplicity environment. The overall FED data flow has been re-designed, changing the readout scheme of the input links and redistributing internal buffers.
- The silicon tracker zero-suppression was bypassed and all channel information was forwarded to the CMS DAQ system. Zero-suppression was then performed in the HLT. A new tracker FED firmware was also designed to reduce the event payload by $\sim 30\%$ without information loss. The reduction was obtained by stripping unused information out from the standard data format.
- DAQ reconfiguration / rebalance to deal with big data volume and high throughput. In standard p-p collision operation, an average event size corresponds to $\sim 1 - 1.5$ MB. During Pb-Pb collision operation, the average event size is around 17 MB.
- 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 other small adjustments not mentioned here, CMS was able to run smoothly during the 2015 Pb-Pb data-taking with an average L1 rate of $\sim$ 10 kHz. A few hours of the Pb-Pb data-taking period were also devoted to exploring the limit of CMS in terms of the maximum L1 rate allowed. With the 2015 CMS configuration for Pb-Pb, the absolute L1 rate limit was observed at 12 kHz. In the next sections, this limit, as well as solutions to increase it, will be discussed.

During the 2015 run, the collision rate was $\sim$ 20 kHz. For the 2018 Pb-Pb run we expect an increase in the collision rate to $\sim$ 30 kHz. Without applying any changes to the L1 trigger mix used in 2015, this extra factor would mean operating CMS above its limit, with a significant impact on the physics program. In addition, as discussed in the previous sections, it would be beneficial to also further increase the number of minimum bias events collected.

The CMS subsystems, as well as their interaction with the DAQ, have been studied and a series of bottleneck areas have been identified. This proposal addresses certain aspects of these limitations. The goal is to increase the CMS readout rate to 30 kHz. There are multiple places to improve the throughput. Some of these are interdependent. Some are in progress, or are planned as part of general CMS Experiment Physics Responsibilities (EPR). These throughput improvements will be discussed below. In particular the Tracker FED FW and ECAL DCC FW updates are the projects that match well with MIT expertise, for which funds are requested in this proposal. It is, however, important to bear in mind that this proposal will focus only on aspects that will require hardware changes. The comprehensive series of tasks needed for overall run preparation are not reported here.

3.2 Silicon Strip Tracker

In standard p-p collision operation, the tracker detector sends the full detector information to 430 Front-End Driver (FEDs). They apply common mode noise subtraction and strip zero-suppression. However, the common noise subtraction algorithm implemented in the Tracker FEDs firmware doesn't allow compensation of the baseline distortion observed in the presence of Highly Ionizing Particles (HIP), with the consequent potential loss of clusters associated with the affected readout chip. Due to the stringent requirements on tracking for high multiplicity HI events, the cluster-finding inefficiency propagates directly to the track-finding inefficiency, depending on the centrality of the collision.

The solution adopted up to now was to bypass the tracker zero-suppression implemented in the tracker FEDs and send the full detector information to the DAQ/HLT. HI-specific common mode noise subtraction and zero-suppression algorithms were implemented as HLT processes. However, this solution results in a heavy load on the links between the FEDs and the DAQ and on the DAQ itself. The links are based on S-Link technology with a maximum speed of 200 MB/s. Some FEDs (connected to sensors in which higher multiplicity is expected) have duplicate links, allowing a maximum of $\sim$ 400 MB/s per FED. Considering that on the average fragment size is 32 kB/event, the readout limit is at around 12 kHz. It has already been demonstrated that the FED itself is designed to sustain up to 520 MB/s of throughput. The limitation is then only coming from the links to the DAQ.

In agreement with the Tracker group, the only solution available to significantly increase the overall L1 rate is to modify the FEDs firmware, including a more refined common mode subtraction algorithm accounting for baseline distortion. The output of the FED would again be zero-suppressed, allowing a reduction of the event size to DAQ of a factor of at least 4. The system could then run at an L1 rate greater than 50 kHz.

The tracker FEDs are based on a Xilinx Virtex-2 FPGA that is quite limited in terms of on-chip resources as well as the clock frequency. This limitation implies that only an algorithm designed specifically for HI could be implemented in the FEDs' FPGA. Due to the limited on-chip resources, it would not be possible to have a single FW version allowing both p-p and Pb-Pb operation. Two FW versions would then be used, depending on the type of collision system considered.

In 2013 a specific HI zero-suppression algorithm designed for high multiplicity environments that would satisfy the FPGA constraints was designed offline; it is named a "baseline follower". Preliminary studies performed by the Tracker and MIT HI groups showed promising performance results for the algorithm. The first part of the project proposed here requires the detailed study of the algorithm offline and the associated clustering and tracking performance studies. This will require roughly 3 months of work. We expect that hardware feasibility studies will be performed in parallel by tracker engineers using information provided by the MIT HI group. In late spring/early summer 2017, we anticipate the project will be handed over completely to the MIT HI group, where a developer (an engineer or a postdoctoral associate/scientist with hardware experience) will implement the actual algorithm in firmware. We estimate that the activity of coding will last 9 months. Afterward, three months of commissioning time, including tests on the bench and at P5, should be considered. This schedule should leave some resources available for the actual 2018 HI run preparation. The 12 months of work by 100 % of and engineer are expected to be funded by this proposal. An MIT research scientist should be dedicated to the project for roughly 3 months at 100 % effort; funding is requested for this person. The MIT research scientist will perform and supervise the offline performance studies and will collaborate with the firmware developer for the algorithm implementation and testing.

For completeness, we should also report that other possible strategies were studied/considered to increase the L1 rate without modifying the tracker FED FW. However, they were rejected as being either too complicated to be implemented or as underperforming. The two other solutions envisaged were either to increase the number of links between the tracker FEDs and the DAQ or to reduce the data payload. The first solution appears to be too complicated, adding an extra $\sim$ 400 links. Apart from the technical constraints, there would also not be enough time to install and commission the links during the available shutdown time. The second solution is to reduce the data payload. A FED firmware version implemented already in 2015 allows the reduction from 10 to 8 in the number of bits read out by each strip ADC. However, this strategy would allow only a moderate increase of $\leq 20\%$ of the overall L1 rate at the cost of a reduction of the detector resolution/sensitivity.

3.3 ECAL

The ECAL off-detector electronics (DCC) were designed to cope with an L1 rate of 100 kHz and an average event size of 2 kB/event. During p-p high pile-up collisions the average event size is at around 1.5-1.8 kB. However, during Pb-Pb collisions the average event size is 15-20 kB (depending on the trigger mix) while the average event size for central Pb-Pb collisions is 34 kB. With such large event sizes, the maximum tolerated L1 rate is 12 kHz. In the specific ECAL case, 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 10% in the total L1 rate. Also, the increase of clock frequency on the mezzanine card is being considered. The second limit encountered is the actual DCC internal firmware speed. An increase of 50 % (and perhaps 100 %) in speed can be achieved by modifying the internal DCC firmware structure, allowing the firmware to run at a higher clock frequency.

The ECAL group engineers already expect to participate and supervise the project. However, the concrete implementation should be the responsibility of the CMS Heavy Ion group. An MIT research scientist should be dedicated to the project for roughly 6 months at 100 % effort; funding is requested for this person.

In parallel to the DCC firmware development project, another project adjusting the operational DCC parameters is anticipated. An extra reduction in the event size can be obtained by adjusting the Selective Readout and Zero Suppression threshold. The ECAL group is already studying the performance for p-p collisions and the study should be repeated by the HI group for Pb-Pb collisions. The ECAL event size could also potentially be reduced up to 40 % by reducing the number of samples collected for each event. At present, the ECAL reads out 10 BXs for each event and this number can be programmed down to a minimum of 6 BXs. However, reducing the number of samples could have strong implications for the energy resolution. A complete study should be performed to understand the significance of the effect on the x-fit in Pb-Pb collisions and the impact on the physics program. Any of the two offline solutions mentioned above would require specific performance studies and also the implementation of CMSSW code for the new configuration. The calorimeter calibrations should also be re-derived. The work needed for the project of adjusting the operational DCC parameters could be done by the CMS HI group as part of the CMS EPR that corresponds to the service work that should be provided by each CMS author.

3.4 Silicon Pixel Detector

A new silicon pixel detector with 4 layers is being installed and commissioned for the 2017 p-p run. The detector front end electronics and sensors are equivalent to the ones installed in the legacy detector. The whole off-detector electronics was re-designed and the FEDs are based on the latest Xilinx FPGA technology (Virtex-7). The new firmware designs already take into account high multiplicity events. However, the performance of the FED has not yet been evaluated in the HI multiplicity environment.

An electronics board to emulate the detector response was designed to commission the off-detector electronics. The test board is able to receive input files with hit positions and produces at its output link a response equivalent to one of the actual FE electronics. The Pixel group took the responsibility to use the test board and define as soon as possible the pixel operational parameters for Pb-Pb collisions. However, a person in the CMS HI group will act a liaison person and provide the necessary information required by the Pixel group to perform the emulation. The liaison person should also supervise the test phases to guarantee perfect adherence with the expected conditions during collisions. The results of the emulations should be evaluated carefully and possible solutions identified in case the performance is below expectations.

3.5 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 algorithms specific to p-p collision operation.

For the 2018 HI run, the specific HI algorithms must be ported to the new system, including 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 firmware implementation and commissioning. However, we anticipate the CMS HI group will conduct the performance studies of the algorithms and a specific description of the implementation. Furthermore, several tests on the bench or at P5 would be performed by the CMS HI group. Also, the compilation of the L1 and HLT menus would remain responsibility of the CMS HI group. This work would be done as part of the CMS EPR.

3.6 Dataflow

The previous sections of this proposal have discussed the possibility of increasing the CMS readout L1 rate and the number of events on tape for Pb-Pb collisions. This strategy has a direct impact on several areas associated with data handling, data transfer, data storage and data processing. It is not part of the scope of this proposal to discuss the details associated with the work required in the different areas, but the list of tasks that will be considered before the 2018 HI run is reported below:

- Optimize the DAQ operation for Pb-Pb collisions. This includes also a further increase of the bandwidth between HLT and Storage Manager. Also, the buffering strategy of data at P5 should be studied
- Reduce the average RAW event size and create a new Analysis Object Data (AOD), reducing further the data volume of processed data.
- Adjust the computing model for HI data to maximally benefit from the dedicated HI T2 computing center based at Vanderbilt University.

Although reduction of the size of RAW events is important, few details are given here since it is not within the scope of this proposal. With the actual configuration, it is indeed impossible to reduce the event size without creating a new event data content for RAW data. Only a fraction of the CMS detector would be stored in the event, reducing the overall event size by a factor 2 or 3. This solution is definitely the most promising but it has significant drawbacks. All the information stripped from the event cannot be recovered. The new event content should also be general enough to foresee any future analysis of these data. At present the most promising idea is to have the HLT produce two main data streams. The first data stream would contain events in standard CMS event data format, while the second data stream would contain events where only a subset of the tracker and pixel FEDs information is recorded. This latter data format will be used only for minimum bias events (or a fraction of the minimum bias events recorded), while the first data format will be used for all the other triggered events. The overall trigger mix decided in the future will define the exact average data size, but rough estimation indicates a reduction of ~ 30 % in the event data size. Another solution being investigated is to have a similar approach to the one described above, but to replace the specific minimum bias data format with already processed objects. In this case, the HLT calculates tracks for minimum bias events and instead of outputting the RAW data format, the computed track objects are instead outputted. Preliminary studies demonstrate than this approach could reduce further the event data size. However, the track reconstruction in HLT would be performed using online conditions of detector alignment and calibrations, leading to the possibility of having a lower tracking efficiency as well as a high fake rate.

4 Management Plan, Personnel, Schedule

The overall organization of the upgrade effort 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 corresponding detector groups and follow the established management procedures within CMS. The leader of the project for Heavy Ion physics will be Prof. Yen-Jie Lee of MIT. The project will include the following deliverables:

- 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;
- Participation in the phases of validation, test and commissioning of the HI tracker FED firmware in the CMS experiment;
- Performance studies 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.

The performance physics studies required in the early phases of the project are already being carried out by MIT graduate students under the supervision of Dr. Ivan Cali.

The firmware for the silicon tracker will be developed by a engineer who is part of the HI group, supervised by Dr. Ivan Cali of MIT. The project will be closely coordinated with the experts at the Imperial College, London group.

The firmware for the ECAL DCC change will be developed by Dr. Ivan Cali of MIT. The CMS LIP (Lisbon) group in charge of the ECAL DCC firmare will provide support.

The schedule of the whole project is driven by the need to complete the project by the beginning of Fall 2018. Then a few months are left for online operation and final commissioning phases before the 2018 HI run. We have identified the following milestones in the proposed schedule:

- Silicon Tracker zero suppression algorithm performance studies to be finished by June 2017;
- Silicon Tracker FW implementation to be completed by April 2018;
- Commissioning of the Silicon Tracker FED and corresponding software by September 2018;
- ECAL preliminary performance studies 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, October 2018;

5 Budget

In this proposal the overall budget for the MIT 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 firmware. Manpower for 2018 Pb-Pb run preparations will be a part of the activities covered by the CMS "Experimental Physics Responsibility" system that requires each CMS member to contribute to the service work, and is only mentioned here to provide context for the proposed activities.

The full chain of development, testing and commissioning of Tracker and ECAL FW will happen at CERN. The test facilities in CERN B906 and B186 will be used in the early phases while the production system will be used for the final commissioning. The interaction with the hardware and the experienced developer is vital for the project. 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 a temporary firmware development engineer at CERN and an MIT research scientist. The engineer will devote 12 months at 100 % effort to the project starting June 2017 while the MIT research scientist will devote 50% of his time starting in June 2017 until the end of October 2018.

The cost of an engineer to be hired as temporary help at CERN is estimated at roughly 7000 CHF/month. To compensate for the higher cost of living in Geneva, the budget includes a Cost of Living Allowance (COLA) to the scientist.

References

[1] Roland G (CMS Collaboration) 2007 *J.Phys.* **G34** S733–736 (*Preprint* `nucl-ex/0702041`)

[2] Dokshitzer Y L and Kharzeev D 2001 *Phys.Lett.* **B519** 199–206 (*Preprint* `hep-ph/0106202`)