Triggering on hard probes in heavy ion collisions with CMS

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Abstract. We present a study of the CMS trigger system in heavy-ion collisions. Concentrating on two physics channels, dimuons from decays of quarkonia and single jets, we evaluate a possible trigger strategy for Pb+Pb running that relies on event selection solely in the High-Level Trigger (HLT). The study is based on measurements of the timing performance of the offline algorithms and event-size distributions using full simulations. Using a trigger simulation chain, we compare the physics reach for the jet and dimuon channels using online selection in the HLT to minimum bias running. The results demonstrate the crucial role the HLT will play for CMS heavy-ion physics.

1. Trigger strategy in CMS Pb+Pb running

The key component in exploiting the CMS capabilities in heavy-ion collisions is the trigger system, which is crucial in accessing rare probes such as high E_T jets and photons, Z^0 bosons, D and B mesons, and high-mass dileptons from the decay of quarkonia. The unique CMS trigger architecture only employs two trigger levels: The Level-1 trigger is implemented using custom electronics and inspects events at the full bunch crossing rate. All further online selection is performed in the High-Level Trigger (HLT) using a large cluster of commodity workstations (the "filter farm") running "offline" reconstruction algorithms on fully assembled event information. The trigger system was designed to deal with the unprecedented luminosities in LHC p+p running, yielding an expected event rate of 40 MHz, with 25 superimposed p+p collisions for each event. Out of the 40 MHz p+p event rate, a 100 kHz data stream will be selected by the Level-1 trigger for further processing in the HLT. The HLT will reduce the 100 kHz input stream to 150 Hz of events written to permanent storage.

The Pb+Pb design luminosity $L = 10^{27}$ cm^{-2}s^{-1} at the beginning of a store is smaller than the p+p design luminosity by 7 orders of magnitude. The corresponding initial Pb+Pb collision rate is $\approx$8 kHz, and the average collision rate over the duration of a store will be $\approx$3 kHz. Therefore, even the maximal event rate for Pb+Pb collisions is much smaller than the 100 kHz input rate for the HLT in p+p collisions after the Level-1 selection. This allows a trigger strategy in Pb+Pb running that can be summarized as follows: Every Pb+Pb collision identified by the Level-1 trigger will be sent to the HLT
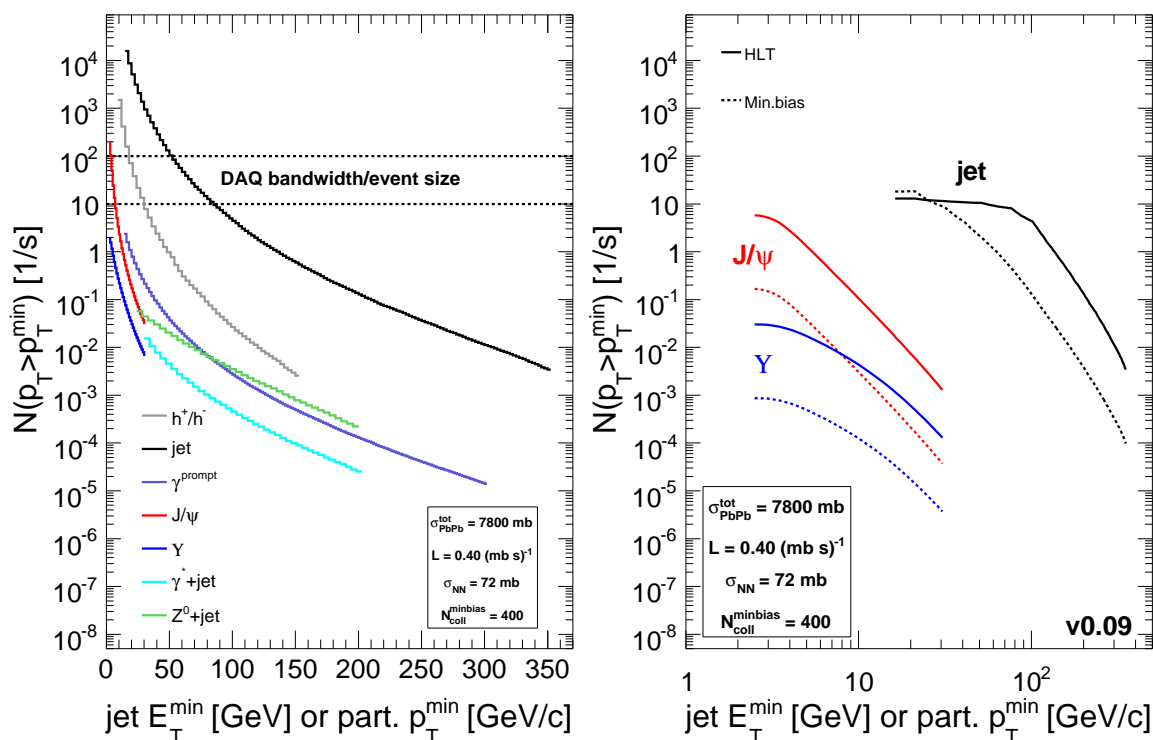
Figure 1. Left: Expected production rates in minimum bias Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV, assuming design luminosity. Right: Expected rates to tape for jets, J/ψ and Υ channels for minimum bias (dashed lines) and HLT triggered data sets (solid lines).

filter farm. At the HLT, the full event information will be available for each event. All rejection of Pb+Pb collisions will be based on the outcome of HLT trigger algorithms that are identical to the corresponding offline algorithms or optimized versions of the offline algorithms. Therefore, algorithms like the offline jet finder will be run on each Pb+Pb event in the CMS interaction region, optimizing the CMS physics reach. This strategy relies on the fact that the HLT in its final configuration will provide sufficient input bandwidth to accept all collision events and sufficient computing power to run full offline algorithms on all events.

The event size and computing time constraints were evaluated using full GEANT 4 based simulations of Pb+Pb events. For events with a charged hadron multiplicity of $dN/d\eta \approx 3000$ for central events, the event size was found to be approximately linear in the charged hadron multiplicity, ranging from 330 kByte/event for a $b = 12$ fm sample to 8.5 MByte/event for a $b = 0$ fm sample. Averaging over impact parameter and adjusting for additional noise, backgrounds and diagnostic information, we obtain an event size of 2.5 MByte per minimum bias event for running at design luminosity. Including all uncertainties, we expect that the bandwidth of 225 MByte/sec will allow a rate of Pb+Pb events to mass storage between 10 and 100 Hz. A large part of this uncertainty will only be resolved once the first LHC data are taken, underscoring the need for a flexible high-level trigger scheme.

The HLT online computing farm is expected to consist of about 1500 servers. The projected CPU budget per event, in units of todays 1.8 GHz Opteron CPUs on which our timing measurements were performed, will be ≈ 1.5 s at the beginning of each store (8 kHz collision rate), and ≈ 4 s averaged over the duration of the store (3 kHz collision rate).

We measured the timing of three key algorithms in the CMS ORCA framework: the jet finding algorithm, the stand-alone muon finder using muon chamber information and the full muon finder including the silicon tracker information. Averaging over the Glauber impact parameter distribution, the execution time of the modified iterative cone jet finding algorithm, including background subtraction, is $\langle t \rangle = 250$ ms. More than 50% of the execution time was spent in unpacking the calorimeter data. The stand-alone muon algorithm has an average execution time of $\langle t \rangle = 80 \pm 20$ ms, using muon candidates from the Level-1 trigger. Both algorithms therefore fit comfortably into the CPU budget per event discussed above.

The full muon algorithm extends the tracks found in the muon system to the silicon tracker and provides a significant improvement in momentum resolution and background rejection. This is particularly important for low p_T dimuons, which are expected to take up the largest fraction of the output bandwidth to tape. This algorithm is called for less than 2% of all events. The current $L3$ execution time corresponds to about 10 ± 3 s per minimum bias event. Work on porting the the present offline algorithms to a new framework, CMSSW, and optimizing or significantly modifying the present algorithms for use in the HLT event selection is ongoing.
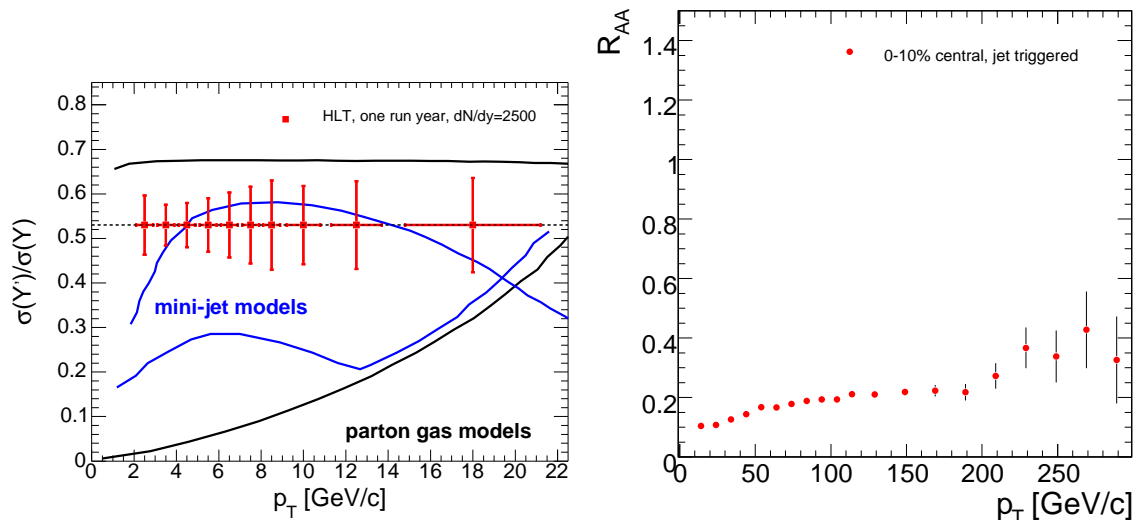

Figure 2. Left: Υ' over Υ ratio vs p_T. Statistics correspond to 10^6 s of data taking (one nominal year of LHC heavy ion running). Shown in comparison to the statistical uncertainty are calculations in different theoretical scenarios. Right: The nuclear modification factor R_{AA} as a function of p_T for charged particles, for minimum bias data (left panel) and for data triggered on high-E_T jets (right panel), for 10^6 s of data taking.

2. HLT simulation results

Using results from event size and timing studies, a simulation chain was set up to translate the production cross-sections into rates to tape. The simulations used parametrizations of the acceptance, efficiency and background rates of the offline jet finding and muon finding algorithms which are expected to form the basis of the HLT algorithms. Details of the model calculations and reconstruction algorithms can be found in [3].

In Figure 1 (right) we show the rates of signal events to tape for minimum bias running (no event selection in HLT) in comparison to those for event selection using the HLT. The rates were calculated for design average luminosity, using a trigger table that devoted about 30% of the output bandwidth to dimuon chanels and about 35% to jet channels.

Using the HLT, a gain in statistics of more than an order of magnitude is achieved for jets at large E_T and for dimuons. Correspondingly, the usable range in E_T (p_T) for the jet and dimuon measurements is extended by more than than factor of 2 and 3, respectively. Note that, for this comparison, the HLT rate for each process was only counted in the corresponding trigger stream.

Two key examples of the physics benefit of the HLT for quarkonium and jet related measurements are shown below. The left plot of Fig. 2 shows the ratio of Υ' to Υ yields as a function of transverse momentum. The projected statistical resolution is compared to four model calculations. This measurement, which relies on the added statistics provided by the HLT selection, allows a clear distinction of the different scenarios, and may therefore serve as a sensitive probe of the initial QCD medium.

In the right plot of Fig. 2 we show the nuclear modification factor R_{AA} for events selected by an HLT trigger on high E_T jets (right). Compared to a minimum bias data set, the triggered sample extends the useful range in p_T by more than a factor of 2.5, to more than 200 GeV/c. Predictions for R_{AA} in Pb+Pb collisions at the LHC have been made for several models of the parton energy loss in the QCD medium. The predictions differ most markedly in the high p_T region, which can only be measured with high precision in the jet-triggered event sample. In summary, the flexibility of the HLT system will allow us to allocate bandwidth to trigger channels differentially as a function of rapidity, y, and p_T of the trigger object and as a function of collision centrality, using full offline algorithms. This sophisticated triggering system will be critical in maximizing the overall physics reach of CMS in heavy ion running.

[1] CMS Collaboration, "The TriDAS Project Technical Design Report, Volume 2: Data Acquisition and High-Level Trigger,", *CERN/LHCC***2002-26** (2002). CMS-TDR-006-add-2.

[2] CMS Collaboration, "CMS physics : Technical Design Report v.2 : Physics performance", *CERN/LHCC***2002-021** (2002). CMS-TDR-008-2.

[3] see Betts R, for the CMS Collaboration, these proceedings, and CMS Collaboration, "Heavy Ion Physics Technical Design Report" , under preperation.