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# Design and perspectives of the CMS Level-1 trigger Data Scouting system

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ABSTRACT

The CMS detector will undergo a significant upgrade to cope with the HL-LHC instantaneous luminosity and average number of proton–proton collisions per bunch crossing (BX). The Phase-2 CMS detector will be equipped with a new Level-1 (L1) trigger system that will have access to an unprecedented level of information. Advanced reconstruction algorithms will be deployed directly on the L1 FPGA-based processors, producing reconstructed physics primitives of quasi-offline quality. The latter will be collected and processed by the Level-1 trigger Data Scouting (L1DS) system at the full bunch crossing rate. Besides providing vast amounts of data for L1 and detector monitoring, the L1DS will perform quasi-online analysis in a heterogeneous computing farm. It is expected that the study of signatures too common to fit within the L1 acceptance budget, or orthogonal to the standard physics trigger selection strategies will greatly benefit from this approach. An L1DS prototype system has been set up to operate in the current LHC Run-3, with the main goal of demonstrating the basic principle and shape the development of the Phase-2 system. The Run-3 L1DS receives trigger primitives from the Global Muon and Calorimeter Trigger, the Global Trigger decision bits and the muon segments from the Barrel Muon Track Finder. FPGA boards acquire and aggregate the synchronous trigger data streams and perform basic data reduction, before sending the trigger primitives to a set of computing nodes through 100 Gbps Ethernet connections running a simplified firmware version of the TCP/IP protocol. An Intel TBB-based DAQ software receives the TCP/IP streams and applies further processing before the ingestion of the data into a cluster of servers running the CMS reconstruction framework. The output of the computing farm are data sets in the standard CMS data analysis format. This contribution presents the Run-3 L1DS demonstrator architecture and recent physics results extracted from the collected data.

## 1. Introduction and data scouting

The CMS experiment selects interesting collision events for further analysis using a 2-tier trigger system. It is designed to reduce the event rate from the 40 MHz LHC bunch crossing (BX) rate to around $\mathcal{O}(1)$ kHz, in order to cope with the current storage system capabilities. The Phase-1 CMS Level-1 (L1) trigger discards around 99.75% of the collision events using a coarse reconstruction performed with a subset of the detector information [1,2]. Under these conditions, triggering on specific Standard Model (SM) and exotic signatures might not be fully efficient, or the event accept rate would be too high for a feasible L1 trigger algorithm deployment. These limitations might result in weak or missing constraints in the phase-space regions affected by these limitations.

A solution to address these problems and extend the physics coverage is to analyze the collision data before the trigger decision and with the reconstruction done at the L1 trigger, whenever the L1 objects resolution is sufficient for the task. This Data Scouting approach is being developed inside the L1 trigger system of CMS experiment for its Phase-2 upgrade for High-Luminosity LHC [3,4]. The upgraded L1 trigger system will have access to an unprecedented level of information and approach the offline reconstruction resolution. In particular, the L1 trigger Data Scouting (L1DS) system will have access to the objects reconstructed by a Correlator Trigger running a Particle Flow reconstruction, providing a potential advantage for analyses like $W \rightarrow 3\pi$, $W \rightarrow D_s\gamma$ or $H \rightarrow 2\phi$.

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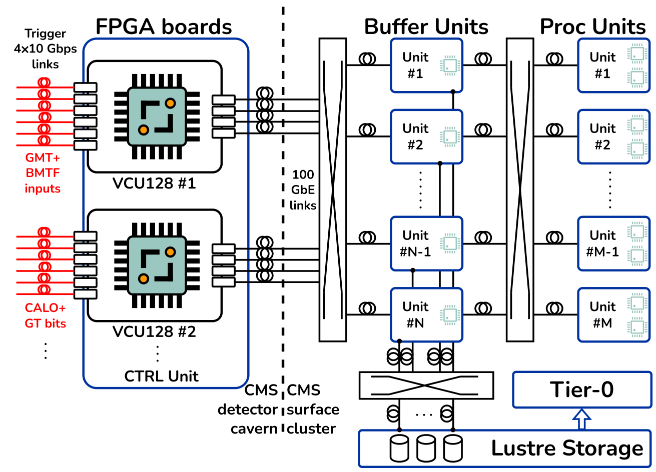


**Fig. 1.** Overview of the CMS L1DS demonstrator for LHC Run-3. The trigger links are concentrated on the scouting FPGA boards, pre-processed and sent via TCP/IP output to a server farm. A first level of Buffer Units acquires the streams and prepares raw data fragments for the second level of Processing Units, which aggregate the events and run the online analysis.

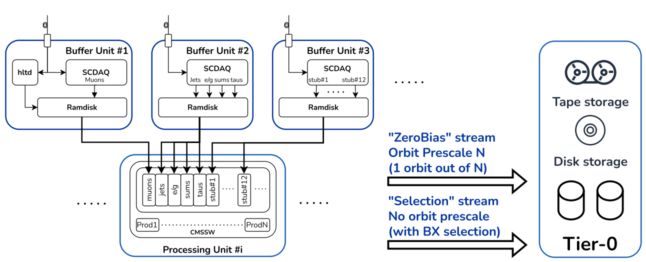


**Fig. 2.** The SCDAQ software on the Buffer Units receives and unpacks the TCP/IP streams sent by the scouting boards. The output fragments are aggregated in the Processing Units, running the online processing and selection. The resulting data set streams are sent to the Tier-0 storage for repacking.

## 2. Overview of L1DS demonstrator for LHC run-3

An L1DS demonstrator has been built for the LHC Run-3 to allow the development of the system while collecting real collision data [2,5,6]. The developed architecture is shown in Fig. 1 and it is fully operational starting from 2024. The L1DS demonstrator collects the L1 trigger objects from the Global Muon Trigger ($\mu$GMT) and Calorimeter Trigger (DeMux), the Global Trigger ($\mu$GT) decision output and the input muon stubs from the Barrel Muon Track Finder (BMTF).

### 2.1. Firmware, control and monitoring of the scouting boards

A set of AMD Xilinx VCU128 development boards are used to receive the 10 Gbps trigger links, align the decoded streams, perform basic pre-processing as zero suppression, buffer the result in the integrated High-Bandwidth Memory of the FPGA chip, and concentrate the pre-processed data into TCP/IP output streams via 100 Gb Ethernet. More details on the firmware implementation and resource usage are provided in [6].

The scouting boards are housed in a PCIe crate, connected to a Control Unit. The Scouting Configuration Endpoint (SCONE) application runs on this server to provide a high-level REST interface for configuration, control and monitoring of the boards via web requests.

### 2.2. Data acquisition and online processing software

The TCP/IP streams are received by an Intel TBB-based data acquisition software (SCDAQ), running on the scouting Buffer Units. The raw data fragments from every TCP/IP stream are prepared by SCDAQ for the next step, running on the scouting Processing Units. Here, the data fragments are injected in the CMS reconstruction framework (CMSSW) for aggregation of the fragments from the same event and for their online processing. The raw trigger primitives are packed in an Analysis Object Data format using as event unit the LHC orbit, namely 3564 bunch crossings (BXs), allowing the possibility to explore inter-BX correlations. The CMSSW framework produces two types of data set streams going to the CMS Tier-0 storage (see Fig. 2): a "Scouting Zero Bias" data set with all the BXs in the orbit and saving 1 orbit every $N$ (prescale factor); a "Scouting Selection" data set with all the orbits but keeping only the BXs satisfying generic signatures as dijet, dimuon, etc. The need to prescale or select is due to a final data set bandwidth constraint of 200 MB/s imposed for storage reasons for Run-3.

## 3. Run-3 demonstrator results

Preliminary results are available and being extended [7], as for instance BX occupancy plots and observed SM candles ($Z \rightarrow \mu\mu$, $Z \rightarrow ee$) as shown in Fig. 3. The goal of the L1DS is to perform physics measurements already with the Run-3 demonstrator, such as dijet searches at low invariant mass.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.


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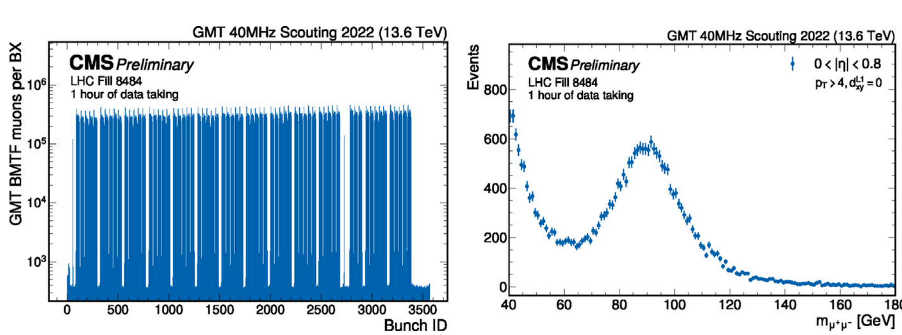


**Fig. 3.** (Left) GMT muons occupancy per BX. (Right) Invariant mass distribution of opposite sign GMT muon pairs in barrel region, featuring a resonance from $Z \rightarrow \mu\mu$ decays. The data for the plots have been collected by a legacy version of L1DS Run-3 demonstrator in 2022.

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