Outer tracker and muon L1 trigger stubs for precision Luminosity measurement in Run 3 and Phase 2

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Precise measurement of instantaneous and integrated luminosity is essential for the physics program of CMS at the LHC. It is needed for accurate cross-section measurements, for testing the Standard Model, and for searches for rare processes and signs of new physics. In Run 3 and especially in Phase 2, the challenge becomes more difficult: instantaneous luminosity will increase nearly tenfold, with up to 200 simultaneous interactions per bunch crossing (pileup), while the target precision is 2% for online monitoring and below 1% for offline analyses. Reaching this goal requires several independent luminometers for redundancy and cross-checks.

One of the key developments is the integration of tracker stub data into online luminosity measurements, a capability not present in previous Runs. The Outer Tracker (OT) Layer 6 will provide Level-1 trigger stubs at the full 40 MHz rate, and the barrel muon track finder (BMTF) will deliver Level-1 primitives with the same granularity. In Run 3, muon primitives from the BMTF are already used for stability checks, but only as orbit-integrated data at the lumisection level (about 23 seconds). This makes them useful for cross-calibration but not for independent absolute measurements. In Phase 2, per-bunch-crossing data will make these primitives powerful online luminometers. Simulation studies show that the OT is the most statistically powerful option, with excellent linearity in the full range of pileup conditions and deviations below 0.01% per unit of pileup for both OT and BMTF stubs.

A central component enabling this approach is the BRIL common Histogrammer. This firmware module, implemented in the back-end FPGAs and integrated into detector-specific firmware, allows fully synchronous or asynchronous processing of trigger primitives. It aggregates counts per bunch crossing at 40 MHz, decodes signals from the Timing and Control Distribution System (TCDS), and streams data over Ethernet to the online software. Crucially, the Histogrammer is designed to be stable against central DAQ state changes or short-term desynchronization: it can continue independent clocked operation to ensure continuous monitoring. The Histogrammer is implemented and validated for OT stubs and muon primitives. Current validation includes a complete Vivado simulation environment, deployment on Serenity boards with OT DAQ, trigger and control (DTC) firmware based on the EMP framework, and ongoing tests with a 2S module using cosmic data at the TIF stand. Dedicated studies on the CHARM test beam are in progress, with offline reinjection of test beam data planned to refine error handling.

Alongside hardware and firmware developments, physics-based reference processes remain essential for cross-checking and ensuring long-term stability. The Z$\rightarrow \mu^+\mu^-$ method, or "Z Counting“, has been a reliable tool since Run 2. It provides a clean signature and a relatively high rate (about 10 000 reconstructed Z bosons per $20\,\mathrm{pb}^{-1}$), enabling monitoring of luminometer stability and aging. In Run 3, the framework has been extended to monitor Z rates relative to all luminometers and to process archived datasets for validation. The integration of HLT scouting streams now provides faster feedback with minimal loss of transverse momentum resolution, and efforts are underway to incorporate Level-1 scouting data for near-real-time Z Counting during Phase 2. These developments promise to reduce the delay between data-taking and feedback from weeks to near-online, enhancing the reliability of online luminosity estimates.

Taken together, these advances in simulation, firmware and analysis form a comprehensive strategy to deliver sub-percent luminosity precision in the challenging conditions of Phase 2. This will improve cross-section measurements in the high-luminosity LHC era.