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Design and deployment of a fast neural network for measuring the properties of muons originating from displaced vertices in the CMS Endcap Muon Track Finder

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We report on the development, implementation, and performance of a fast neural network used to measure the transverse momentum in the CMS Level-1 Endcap Muon Track Finder. The network aims to improve the triggering efficiency of muons produced in the decays of long-lived particles. We implemented it in firmware for a Xilinx Virtex-7 FPGA and deployed it during the LHC Run 3 data-taking in 2023. The new displaced muon triggers that use this algorithm broaden the phase space accessible to the CMS experiment for searches that look for evidence of LLPs that decay into muons.

Summary (500 words)

The CMS Level-1 trigger comprises custom electronics that select up to 110 kHz of interesting events out of a possible 40 MHz. It is crucial to accurately measure the properties of the particles in the event to decide which events to keep. Many theories beyond the Standard Model introduce long-lived particles (LLP); in some cases, they can decay into muons, producing events with decay vertices displaced from the collision point. These muons are dubbed displaced muons. In the Endcap Muon Track Finder (EMTF), we are interested in triggering on these kinds of events to boost the trigger efficiency of analyses that rely on such signals. This task is particularly challenging in the endcaps of the CMS experiment due to the non-uniform magnetic field, reduced bending of particle trajectories, and the extensive background contributions from the collisions in regions close to the beamline. These challenging conditions are ideal for machine learning (ML) based solutions. We developed a feed-forward neural network (NN) that measures the properties of displaced muons, namely the transverse momentum and the transverse impact parameter, with more parameters under consideration for future upgrades. The chips that host the logic currently used by EMTF are Field Programmable Gate Arrays (FPGAs), namely a Xilinx Virtex-7 690T FPGA. These FPGAs are capable of running small feed-forward NNs, as they contain dedicated digital signal processing resources for performing fixed-point multiplications. However, the FPGAs used in the EMTF already contain extensive logic to build tracks for triggering on prompt muons, leaving few resources and very little latency for new algorithms. Adding the NN logic to the FPGA required optimizing our models to use leftover resources and latency while retaining as much performance as possible. We used several customizations on top of the hls4ml toolkit to optimize our model to use the remaining resources in the FPGA, enabling it to run alongside the current algorithms. In 2023, this EMTF NN was deployed as the first neural network in the CMS Level-1 Trigger during the Run-3 data-taking period. The new displaced muon triggers that use our neural network-based approach for measuring the properties of displaced muons will broaden the phase space accessible to the CMS experiment for searches that look for evidence of LLPs that decay into muons, as predicted by many beyond the Standard Model scenarios.

Authors: MADORSKY, Alexander (Boston University (US)); ACOSTA, Darin (Rice University (US)); YIGITBASI,

Efe (Rice University (US)); LOW, Jia Fu (Rice University (US)); MIGUEL, Osvaldo (Rice University (US)); KELLING, Patrick (Rice University (US)); JINDARIANI, Sergo (Fermi National Accelerator Lab. (US))

Presenter: KELLING, Patrick (Rice University (US))

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