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Performance of track reconstruction at the CMS high-level trigger in 2022 data

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The CMS detector has undergone extensive improvements in preparation for Run 3 of the LHC to operate efficiently at the increased luminosity and pileup. This includes the installation of a refurbished innermost pixel detector layer, as well as the development of HLT software to make use of heterogeneous computing architectures. In Run 3, track reconstruction at the HLT is based on a single iteration seeded by pixel tracks reconstructed by the Patatrack algorithm, which can be offloaded to GPUs. The HLT track reconstruction performance has been measured in pp collision data recorded at a center-of-mass energy of $\sqrt{s} = 13.6\,\mathrm{TeV}$ in 2022, in particular during periods with detector condition changes expected to have a significant impact on HLT track reconstruction. The HLT tracking efficiency and fake rate with respect to offline track reconstruction, as well as the impact parameters of tracks reconstructed in the HLT, are presented.

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1. Introduction

The CMS detector is a multi-purpose apparatus operating at the Large Hadron Collider (LHC) at CERN [1]. The CMS inner tracking system, responsible for measuring the trajectories of charged particles, consists of a silicon pixel detector and a silicon strip detector. In preparation for Run 3 of the LHC, a refurbished barrel pixel layer 1 (BPix L1) was installed. The CMS high-level trigger (HLT) runs a version of the full event reconstruction optimized for fast processing. Since the start of Run 3, the HLT makes use of a heterogeneous computing farm [2].

Track reconstruction at the HLT in Run 3 is based on a single iteration of the combinatorial Kalman filter [3], using hits recorded by the pixel and strip detectors. The single iteration is seeded by pixel tracks reconstructed by the *Patatrack* algorithm, which can be offloaded to GPUs [4–6]. To be used as seeds, *Patatrack* pixel tracks are required to be built with at least three pixel hits, have a transverse momentum of $p_{\mathrm{T}} > 0.3\,\mathrm{GeV}$, and be consistent with a leading pixel vertex.

Pixel vertices from primary interactions are reconstructed at the HLT from *Patatrack* pixel tracks with at least four pixel hits and $p_{\mathrm{T}} > 0.5\,\mathrm{GeV}$, by clustering selected pixel tracks on the basis of their z-coordinates at their point of closest approach to the center of the beam spot. Pixel vertices are sorted in descending order by the summed p_{T}^2 of the associated pixel tracks, and the vertex with the largest summed p_{T}^2 is labelled as the primary vertex (PV).

The HLT track reconstruction performance is measured in pp collision data collected at a center-of-mass energy of $\sqrt{s} = 13.6\,\mathrm{TeV}$ in 2022, using runs recorded shortly before or after the first technical stop (TS1) of the LHC, during which several updates in detector conditions took place. These include an increase in the BPix L1 bias high voltage (HV) from 150 V to 300 V, to recover charge collection efficiency and cope with radiation damage in the pixel sensors; as well as an update of the pixel cluster position estimator (CPE), a new pixel detector gain calibration, and a new tracker alignment. Additional comparisons showing the performance before and after increases in the BPix L1 HV from 300 V to 350 V, and from 350 V to 400 V can be found in [4].

2. Efficiency and fake rate with respect to offline tracks

The HLT tracking efficiency and fake rate measured in data are defined with respect to offline tracks, produced by the full offline event reconstruction, which satisfy high-purity track quality criteria [3, 7]. Both HLT and offline tracks are required to have a transverse momentum of $p_{\mathrm{T}} > 0.9\,\mathrm{GeV}$ (except for the efficiency and fake rate as a function of p_{T}), a transverse impact parameter with respect to the primary vertex of $|d_{xy}| < 2.5\,\mathrm{cm}$, and a longitudinal impact parameter with respect to the primary vertex of $|d_z| < 0.1\,\mathrm{cm}$. Matching between HLT and offline tracks is performed by requiring an angular distance between them of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.002$.

The HLT tracking efficiency with respect to offline tracks is defined as the fraction of selected offline tracks that are matched to a selected HLT track. The tracking efficiency with respect to offline tracks measured in data collected shortly before and after the LHC TS1 is shown as a function of the offline track pseudorapidity η, transverse momentum p_{T}, and azimuthal angle ϕ in Figure 1. Differences in efficiency over the full η range are due to differences in efficiency in BPix L1, which has acceptance also at high $|\eta|$ [8]. Inefficiencies at $\phi = 0.6$ and $\phi = -1.5$ are due to bad pixel detector components, and worsened by single-event upsets in the BPix L1 readout electronics.

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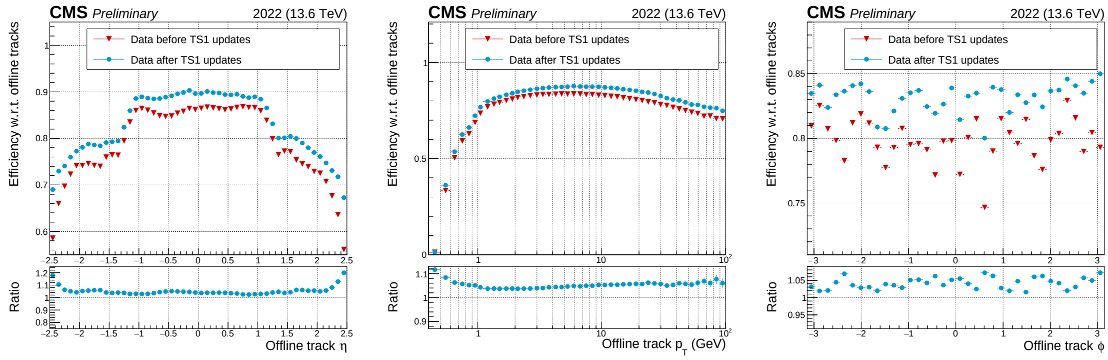

Figure 1: The tracking efficiency with respect to offline tracks measured in data collected shortly before (red) and after (blue) the LHC TS1 is shown as a function of the offline track pseudorapidity η on the left, transverse momentum p_T in the middle, and azimuthal angle ϕ on the right. The ratio between the distributions in data collected after and before TS1 is shown at the bottom [4].

The HLT tracking fake rate with respect to offline tracks is defined as the fraction of selected HLT tracks that could not be matched to a selected offline track. The tracking fake rate with respect to offline tracks measured in data collected shortly before and after the LHC TS1 is shown as a function of the offline track pseudorapidity η, transverse momentum p_T, and azimuthal angle ϕ in Figure 2.

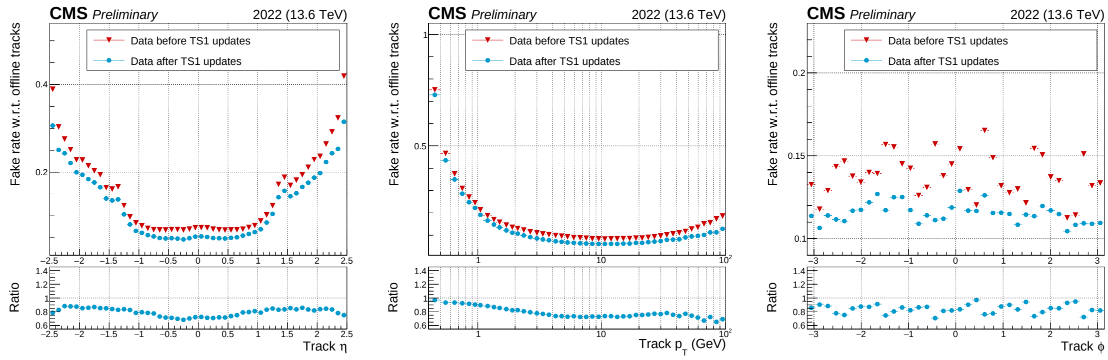

Figure 2: The tracking fake rate with respect to offline tracks measured in data collected shortly before (red) and after (blue) the LHC TS1 is shown as a function of the offline track pseudorapidity η on the left, transverse momentum p_T in the middle, and azimuthal angle ϕ on the right. The ratio between the distributions in data collected after and before TS1 is shown at the bottom [4].

3. HLT track impact parameters

Track longitudinal and transverse impact parameters are sensitive to the tracker alignment and calibration [9]. Both impact parameter distributions are expected to be centered at zero for prompt tracks in the case of ideal detector conditions. Random misalignments of detector modules deteriorate the track impact parameter resolution, increasing the width of the distributions, while systematic misalignments and miscalibrations introduce biases, shifting the mean of the distributions away from zero.

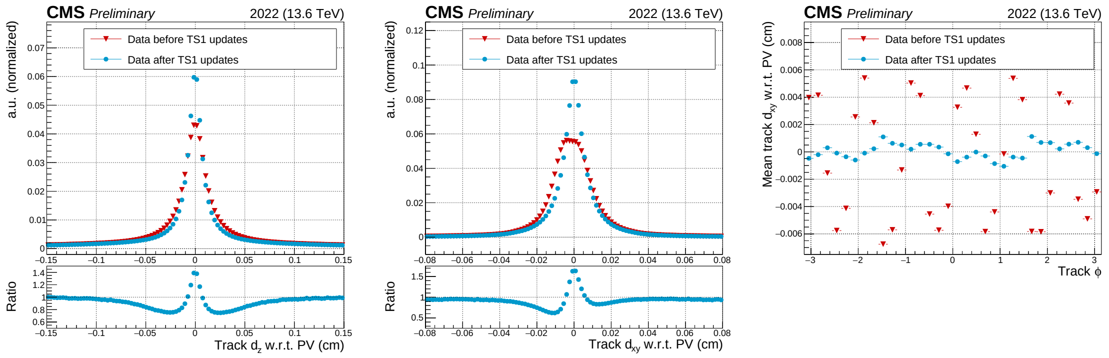

Figure 3: The HLT track impact parameters with respect to the primary vertex measured in data collected shortly before (red) and after (blue) the LHC TS1 are shown, with the longitudinal impact parameter d_z on the left, the transverse impact parameter d_{xy} in the middle, and the mean transverse impact parameter d_{xy} as a function of the HLT track azimuthal angle ϕ on the right. All reconstructed HLT tracks are considered. In the case of a suboptimal Lorentz angle calibration, pixel hits are reconstructed with some displacement from their true position. The direction of the displacement depends on the orientation of the electric field within the silicon modules with respect to the direction of the magnetic field in the CMS solenoid, and an alternating pattern is created due to the opposite orientations in adjacent modules. Performance is recovered by the BPix L1 HV increase and pixel CPE updates, which include an adjusted Lorentz angle calibration [4].

The mean track transverse impact parameter is expected to be flat as a function of the track azimuthal angle in the case of perfect tracker alignment and calibration. Hits reconstructed with an incorrect Lorentz angle calibration due to radiation damage are displaced in a direction dependent on the orientation of the electric field within the module. Due to the opposite orientations of modules adjacent in the azimuthal direction in a given detector layer, an alternating pattern as a function of the track azimuthal angle is created. Deviations are corrected through a dedicated Lorentz angle calibration and residual effects are absorbed in the tracker alignment procedure.

The HLT track impact parameters, together with the mean transverse impact parameter as a function of the HLT track azimuthal angle, measured in data collected shortly before and after the LHC TS1 are shown in Figure 3. Performance is visibly recovered by the BPix L1 HV increase and the corresponding pixel CPE updates, which include an adjusted Lorentz angle calibration, as well as the alignment update that took place during the LHC TS1.

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