CMS tracking performance in Run 2 and early Run 3 data using the Tag-and-Probe technique

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Abstract. Accurate reconstruction of charged particle trajectories and measurement of their parameters (tracking) is one of the major challenges of the CMS experiment. A precise and efficient tracking is one of the critical components of the CMS physics program as it impacts the ability to reconstruct the physics objects needed to understand proton-proton collisions at the LHC. In this work, we present the tracking performance measured in data where the tag-and-probe technique was applied to $Z \rightarrow \mu^+\mu^-$ resonance for all reconstructed muon trajectories and the subset of trajectories in which the CMS tracker is used to seed the measurement. The performance is assessed using LHC Run 2 at $\sqrt{s} = 13$ TeV and early Run 3 data at $\sqrt{s} = 13.6$ TeV.

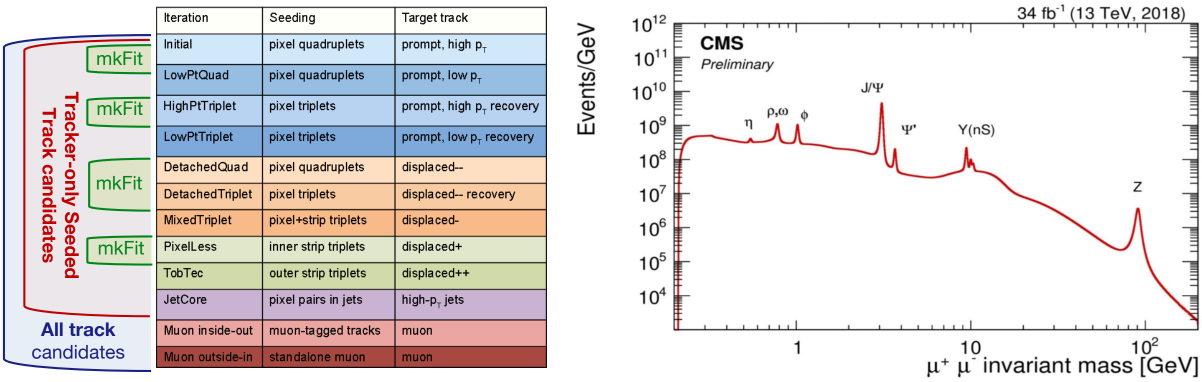
1. Introduction

The Compact Muon Solenoid (CMS) [1] is one of two general-purpose detectors operating at the Large Hadron Collider (LHC) facility at CERN. One of the central features of the CMS detector is a 6-m diameter solenoidal magnet operating at 3.8 T, which enables the measurement of charged particle momenta over more than four orders of magnitude, from less than 100 MeV/c to more than 1 TeV/c, by reconstructing their trajectories as they traverse the CMS inner tracking system consisting of inner silicon pixel and outer strip trackers.

The CMS track reconstruction algorithm [2] (*Iterative Tracking*), is based on the Combinatorial Kalman filter (CKF) [3]. The first set of iterations looks for tracks that are easier to find, like prompt track with relative high p_T. Hits associated with reconstructed tracks are then removed from the set of hits. This procedure reduces the combinatorial complexity so that tracks in the most difficult kinematic regions can be reconstructed. Starting from Run 3, some tracking iterations have been migrated to use a parallelized and vectorized version of the traditional CKF algorithm, called mkFit [4] (see Figure 1a).

As the instantaneous luminosity delivered by the LHC continues to increase, CMS will experience different occupancy environments, with multiple interactions per beam crossing. No single method of measuring track reconstruction efficiency can cover all possible environments, kinematic ranges, and systematic effects.

In this work, we present the procedure used for determining the efficiency of full track reconstruction in CMS during Run 2 and early Run 3 (2016 to 2018, and 4th July – 23rd August 2022) data taking. In particular, tracking efficiency measurements using leptonic decays of Z bosons to muons will be presented in the transverse momentum range from 10 to 120 GeV.



Iteration	Seeding	Target track
Initial	pixel quadruplets	prompt, high p_T
LowPtQuad	pixel quadruplets	prompt, low p_T
HighPtTriplet	pixel triplets	prompt, high p_T recovery
LowPtTriplet	pixel triplets	prompt, low p_T recovery
DetachedQuad	pixel quadruplets	displaced--
DetachedTriplet	pixel triplets	displaced-- recovery
MixedTriplet	pixel+strip triplets	displaced-
PixelLess	inner strip triplets	displaced+
TobTec	outer strip triplets	displaced++
JetCore	pixel pairs in jets	high-p_T jets
Muon inside-out	muon-tagged tracks	muon
Muon outside-in	standalone muon	muon

(a)

(b)

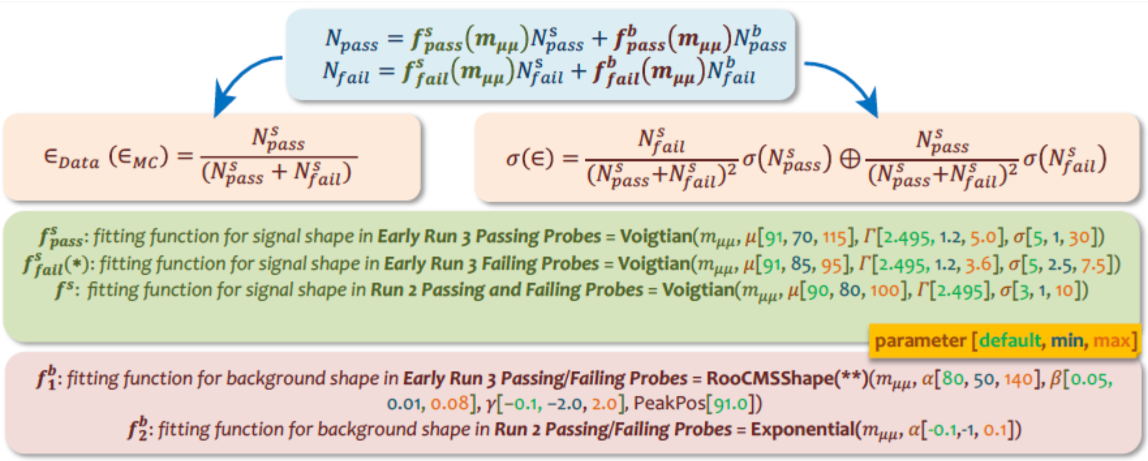
Figure 1: (1a) Scheme of CMS tracking iterative process: the first set of iterations are seeded by hits in the inner tracker only, while the last two steps use muon candidates from the muon system to create seeds for the track reconstruction in the inner tracker. *Tracker-only seeded tracks* collection makes use of CMS tracker-only hits for the seeding, while the *All Track* candidates exploit the presence of muons in the muon system to seed the track reconstruction in the inner tracker via an outside-in-track step having a transverse momentum threshold of 2 GeV and an inside-out iteration reconstructing muon-tagged tracks with a $p_T > 10$ GeV [5]. (1b): Di-muon invariant mass spectrum reconstructed in the High Level Trigger system of the CMS detector for data collected in 2018. Well known di-muon resonances from meson or Z boson decays are indicated. A small excess of events around 330 MeV corresponds to $\phi \rightarrow K^+K^-$ decays where Kaons are misidentified as prompt muons [7].

2. The Tag-and-Probe method and its application

The Tag-and-Probe technique [6] is a generic tool developed to measure any user-defined object efficiency from data by exploiting resonances which are produced copiously and whose attributes are measured with high precision, as the ones shown in Figure 1b. The goal of this technique is identifying similar signal in data and in Monte Carlo simulation (MC) and compare the results to validate MC. A di-lepton resonance (such as J/ψ, and Z boson) is reconstructed requiring stringent quality requirements on one lepton, referred to as the tag, and then comparing the relative efficiency of two different selection criteria on the second one, referred to as the probe. Probes are separated into two categories depending on whether they pass or fail the less restrictive selection. For example, to measure trigger efficiency, probes would be separated into those that pass or fail the given trigger requirements. In this work, the efficiency is estimated using events with Z boson decays into a pair of muons. The tag muon is reconstructed using signals from both the muon chambers and the inner silicon tracker, while probe muons, instead, are reconstructed using only hits from the muon system and identified by looser requirements. Probe muons, combined with tag muons, should define a good Z candidate passing cuts that clean the sample from random dimuon combinations. Probes are then sorted into two categories, passing and failing, considering whether or not they can be matched to at least one tracker track having p_T larger than 10 GeV in a cone ($\Delta R < 0.3$, $\Delta\eta < 0.3$) around the probe muon. Finally, tracking efficiency is calculated as the ratio between number of passing probes and their total.

3. Selection strategy and Tag-and-Probe Fit procedure

Concerning the tag muon, a Tight muon ID [8] with transverse momentum p_T larger than 27 GeV is required, the relative combined isolation with $\Delta\beta$ correction [8] in $\Delta R = 0.4$ is applied



$$N_{pass} = f^{s}_{pass}(m_{\mu\mu})N^{s}_{pass} + f^{b}_{pass}(m_{\mu\mu})N^{b}_{pass}$$

$$N_{fail} = f^{s}_{fail}(m_{\mu\mu})N^{s}_{fail} + f^{b}_{fail}(m_{\mu\mu})N^{b}_{fail}$$

$$\epsilon_{Data}\ (\epsilon_{MC}) = \frac{N^{s}_{pass}}{(N^{s}_{pass} + N^{s}_{fail})}$$

$$\sigma(\epsilon) = \frac{N^{s}_{fail}}{(N^{s}_{pass}+N^{s}_{fail})^2}\sigma(N^{s}_{pass}) \oplus \frac{N^{s}_{pass}}{(N^{s}_{pass}+N^{s}_{fail})^2}\sigma(N^{s}_{fail})$$

f^{s}_{pass}: *fitting function for signal shape in* **Early Run 3 Passing Probes = Voigtian(**$m_{\mu\mu}$, μ[91, 70, 115], Γ[2.495, 1.2, 5.0], σ[5, 1, 30])

f^{s}_{fail}(*): *fitting function for signal shape in* **Early Run 3 Failing Probes = Voigtian(**$m_{\mu\mu}$, μ[91, 85, 95], Γ[2.495, 1.2, 3.6], σ[5, 2.5, 7.5])

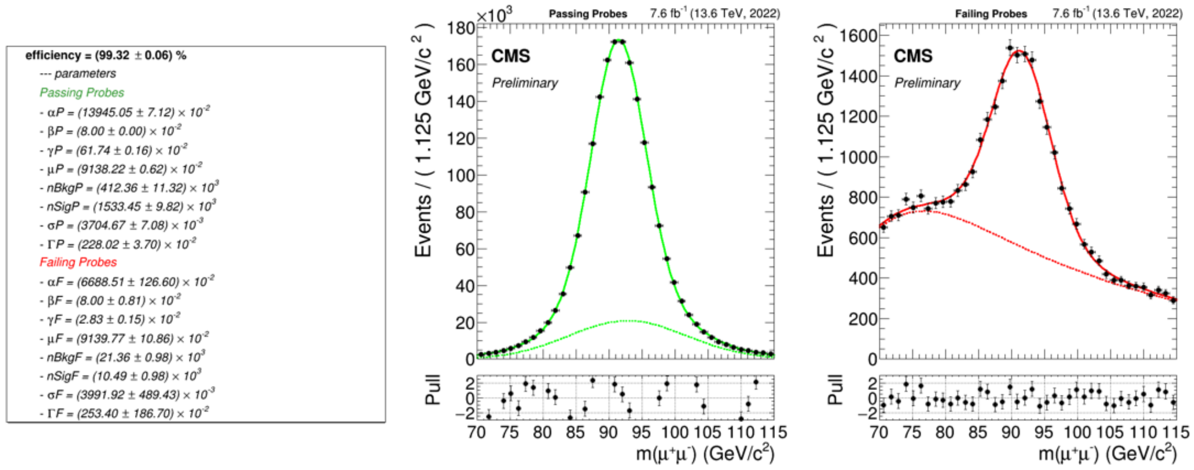
f^{s}: *fitting function for signal shape in* **Run 2 Passing and Failing Probes = Voigtian(**$m_{\mu\mu}$, μ[90, 80, 100], Γ[2.495], σ[3, 1, 10])

parameter [default, min, max]

f^{b}_{1}: *fitting function for background shape in* **Early Run 3 Passing/Failing Probes = RooCMSShape(**)(**$m_{\mu\mu}$, α[80, 50, 140], β[0.05, 0.01, 0.08], γ[−0.1, −2.0, 2.0], PeakPos[91.0])

f^{b}_{2}: *fitting function for background shape in* **Run 2 Passing/Failing Probes = Exponential(**$m_{\mu\mu}$, α[-0.1,-1, 0.1])

Figure 2: Scheme of the fit procedure strategy for both passing (pass) and failing (fail) probes in signal (s) and background (b) in Run 2 and early Run 3 data taking campaigns. (*) The parameters (μ , Γ, σ) range for the signal failing probes is restricted w.r.t. range of the passing probes to improve fit stability. (**) `RooCMSShape` is a probability density function which has exponential decay distribution at high mass beyond the pole position (say, Z peak) but turns over (i.e., error function) at low mass due to threshold effect. This is used to model the background shape in $Z \to \mu\mu$ invariant mass [5].



```
efficiency = (99.32 ± 0.06) %
  --- parameters
  Passing Probes
  - αP = (13945.05 ± 7.12) × 10^-2
  - βP = (8.00 ± 0.00) × 10^-2
  - γP = (61.74 ± 0.16) × 10^-2
  - μP = (9138.22 ± 0.62) × 10^-2
  - nBkgP = (412.36 ± 11.32) × 10^3
  - nSigP = (1533.45 ± 9.82) × 10^3
  - σP = (3704.67 ± 7.08) × 10^-3
  - ΓP = (228.02 ± 3.70) × 10^-2
  Failing Probes
  - αF = (6688.51 ± 126.60) × 10^-2
  - βF = (8.00 ± 0.81) × 10^-2
  - γF = (2.83 ± 0.15) × 10^-2
  - μF = (9139.77 ± 10.86) × 10^-2
  - nBkgF = (21.36 ± 0.98) × 10^3
  - nSigF = (10.49 ± 0.98) × 10^3
  - σF = (3991.92 ± 489.43) × 10^-3
  - ΓF = (253.40 ± 186.70) × 10^-2
```

Figure 3: The fit in passing and failing probes plots for the probe muon transverse momentum bin (40,50) GeV as a function of the invariant mass of the tag and probe muons in the *Tracker-only Seeded Tracks* collection in early Run 3 data. Data are shown in black dots [5].

to be less than 0.15 and the tag object is geometrically matched to a trigger object that fired the single muon trigger for isolated muons with a nominal p_T threshold of 24 GeV. The probe corresponds to any muon with at least one valid hit in the muon system. In the early Run 3 data, since the calibration of the momentum scale in data is not yet at the level of the simulation due to misalignment effects, we restrict the measurement to the kinematical region in which both muons have $|\eta| < 1.6$. Finally, the tag and probe pairs which have opposite-sign objects and are included in the Z mass window (70,115) GeV are considered. As the selected events may not come from the resonance, there could be a bias in the efficiency measurement. To avoid this, a simultaneous fit to the signal (Z peak) and the background is performed (for both passing and

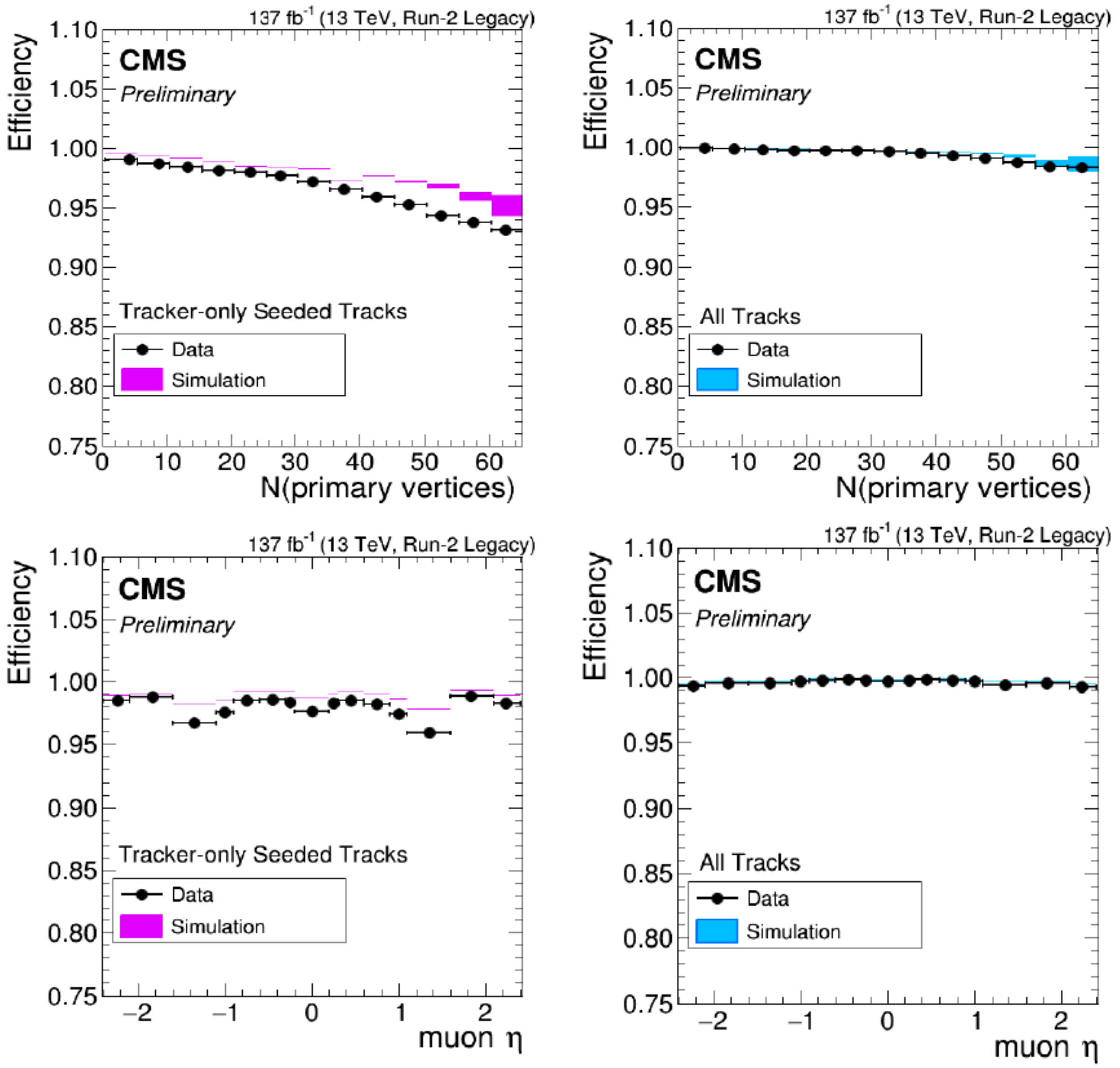


Figure 4: The tracking efficiency in Run 2 Legacy final data reprocessing as a function of the number of primary vertices (top) and of probe muon pseudo-rapidity η (bottom) using the tag and probe technique [10].

failing probes, data and MC, see the strategy summary in Figure 2 as shown in Figure 3. For early Run 3 data, a large mass resolution for $|\eta| > 1.1$ have been noticed due to the large probe transverse momentum resolution: a fit mass range extension to (40, 150) GeV has been used allowing more events off the peak for the background component fit. Moreover, the usage of an Apache Spark-based framework [9] saved 50% of CPU time processing to run the whole analysis process for early Run 3 data.

4. Run 2 and early Run 3 Tracking performance

The whole Run 2 data have been used to retrieve the tracking efficiency vs the main event kinematic variables. A tracking efficiency of about 99.9% for tracks associated with muons has been measured in the whole muon pseudo-rapidity acceptance through the whole Run 2 data

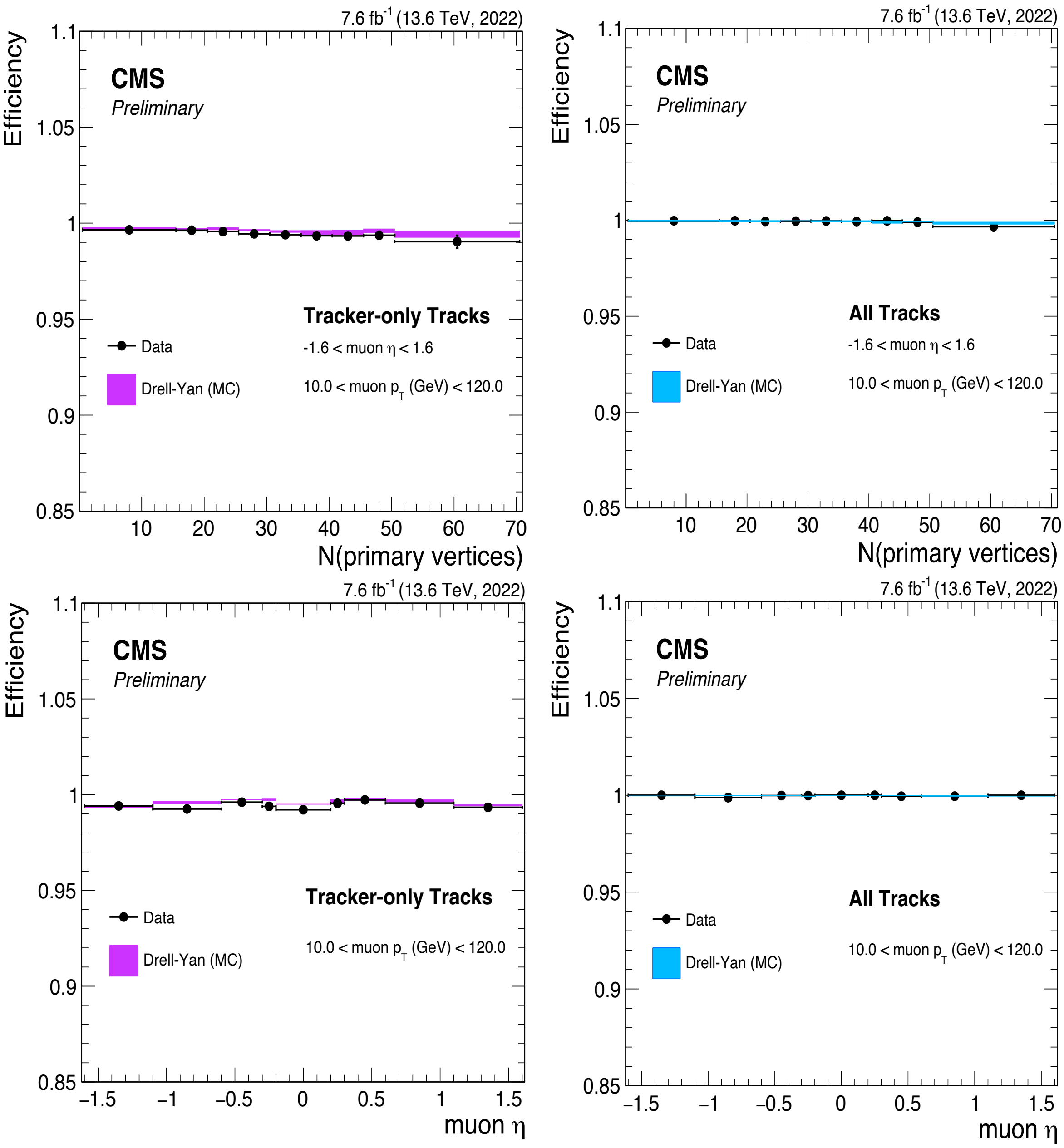


Figure 5: The tracking efficiency in early Run 3 as a function of the number of primary vertices (top) and probe muon pseudo-rapidity η (bottom) using the tag and probe technique [5].

taking, as shown in Figure 4. The tracking efficiency as a function of number of primary vertices, pseudo-rapidity η of probe muons in the *Tracker-only Seeded Tracks* and *All tracks* collections has been computed in Data (black dots) and a Drell-Yan sample simulated at Leading Order in perturbation theory, using the Madgraph generator [11] (violet and blue rectangles) for early Run 3 as well (see Figure 5). In this case, a much higher efficiency has been found due to the replaced innermost pixel layer [12]. In both cases the uncertainties shown are statistical and frequently smaller than the marker size. Systematic uncertainties are not yet evaluated and can be significant due to the fit procedure adopted.

5. Conclusions and Outlook

Despite the challenging environment at the LHC in Run 2 and early Run 3, the CMS tracker features robust performance and efficient tracking capabilities. Calibration and alignment are undergoing for Run 3 data and new software technologies (e.g. automatic fit failing checking or job parallelization via Apache Spark) are under development to produce tracking performance results in the fastest and most efficiency way.

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