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

Poster 140: **Brunella D'Anzi** (University and INFN Bari)
on behalf of the CMS Collaboration
ACAT2022 – 21st International Workshop on Advanced Computing and Analysis Techniques in Physics Research (23 – 28 Oct 2022), Bari, Italy

INTRODUCTION

Accurate reconstruction of **charged particle trajectories (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.

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

mkFit / mkFit / mkFit / mkFit
Tracker-only Seeded Tracks candidates
All tracks candidates

CMS Tracking Iterative process [1,2]

- The iterative tracking approach runs a **standard Kalman Filter algorithm** multiple times. In each iteration, the hits used in previous iterations are removed and the Kalman Filter algorithm is run again with progressively looser settings [1]. The mkFit has been added in some steps [2].

Muon Trajectories candidates used

Tracker-only Seeded Tracks collection: Tracks that make use of CMS tracker-only hits for the seeding.

All-Tracks collection: Tracks which exploit the presence of muon candidates in the muon system to seed the track reconstruction in the inner tracker.

1. An **outside-in track** reconstruction step seeded in the muon system (transverse momentum p_T threshold 2 GeV).
2. An **inside-out iteration** that re-reconstructs muon-tagged tracks (p_T threshold 10 GeV).

- The first set of iterations are seeded by hits in the **inner tracker only**, while the last two steps listed below use **muon candidates** from the muon system to create seeds for the track reconstruction in the inner tracker.

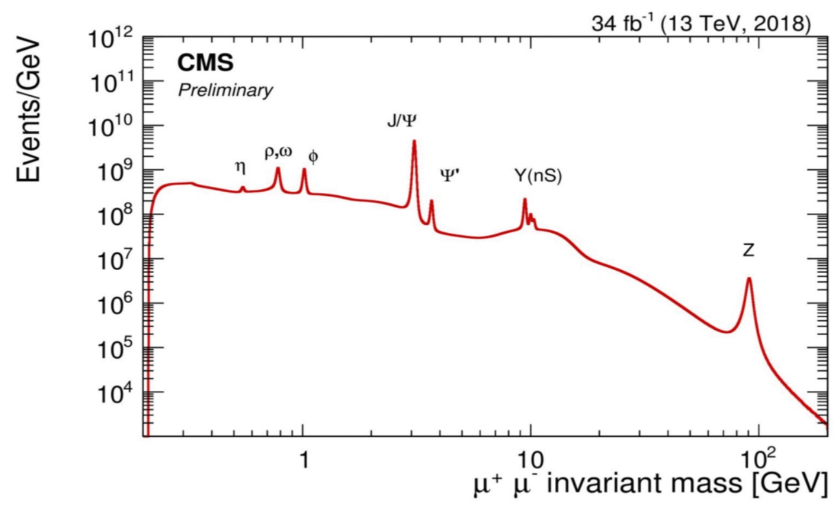
TAG AND PROBE TECHNIQUE

Goal

Identify similar signal in data and in Monte Carlo (MC) and compare the results to validate MC.

Definition

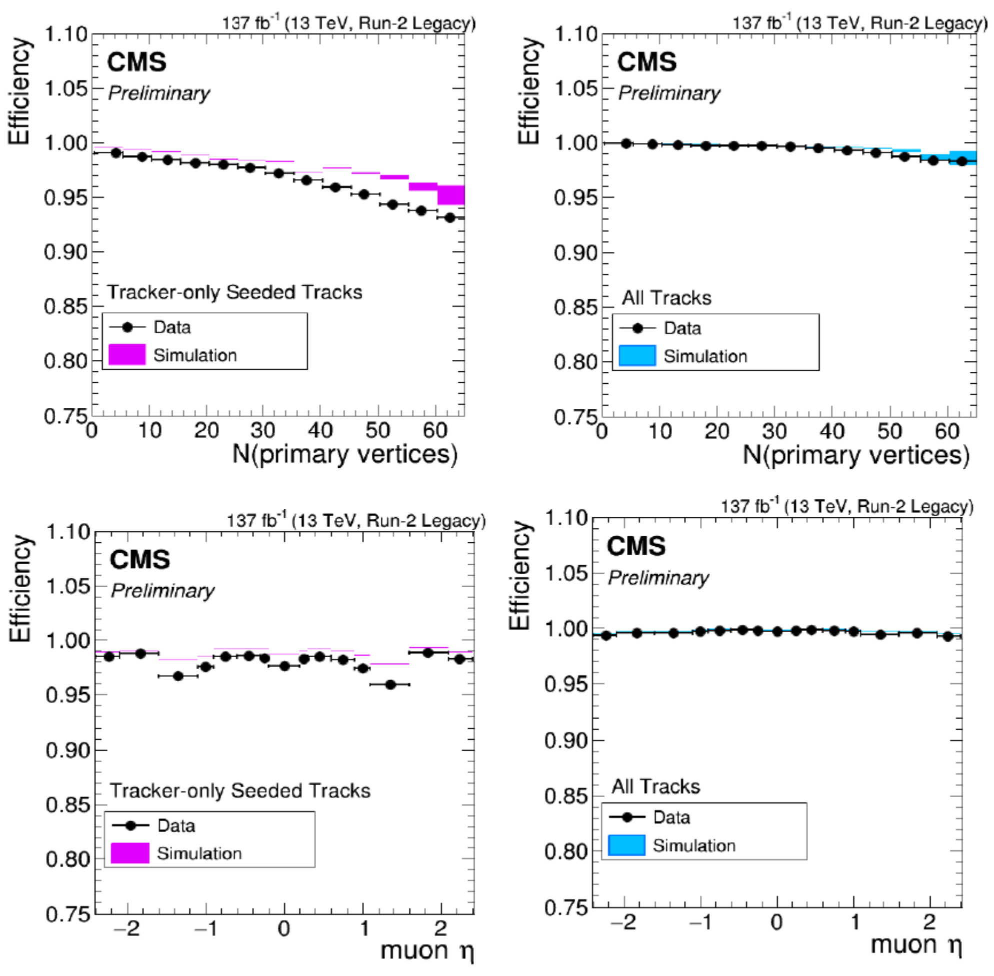
A generic tool developed to measure any user- defined object efficiency from data by exploiting resonances.



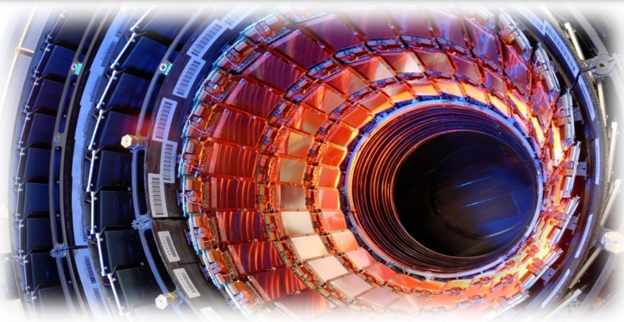
1. Use **known resonances** decaying to two muons, produced copiously, attributes measured with high precision.
2. Require a muon identified by stringent requirements and reconstructed using both the **muon chambers** and the **tracker** (**Tag**).
3. Take all muons reconstructed using **only signals from the muon system** and identified by looser requirements that, combined with Tag, defines a good candidate passing cuts that clean the sample from random combinations (**Probes**).
4. Check if probe muons can be **matched** to at least **one Tracker track** in a cone around the probe muon (**Passing Probes**).

RUN-2 TRACKING PERFORMANCE

Full CMS Run-2 data have been used to retrieve the **tracking efficiency** vs the main event **kinematic variables** [3].



The uncertainties shown are **statistical**. The biggest difference between data and MC ~ 2 % is observed in the transition between the barrel and end-cap regions in the probe muon η spectra.

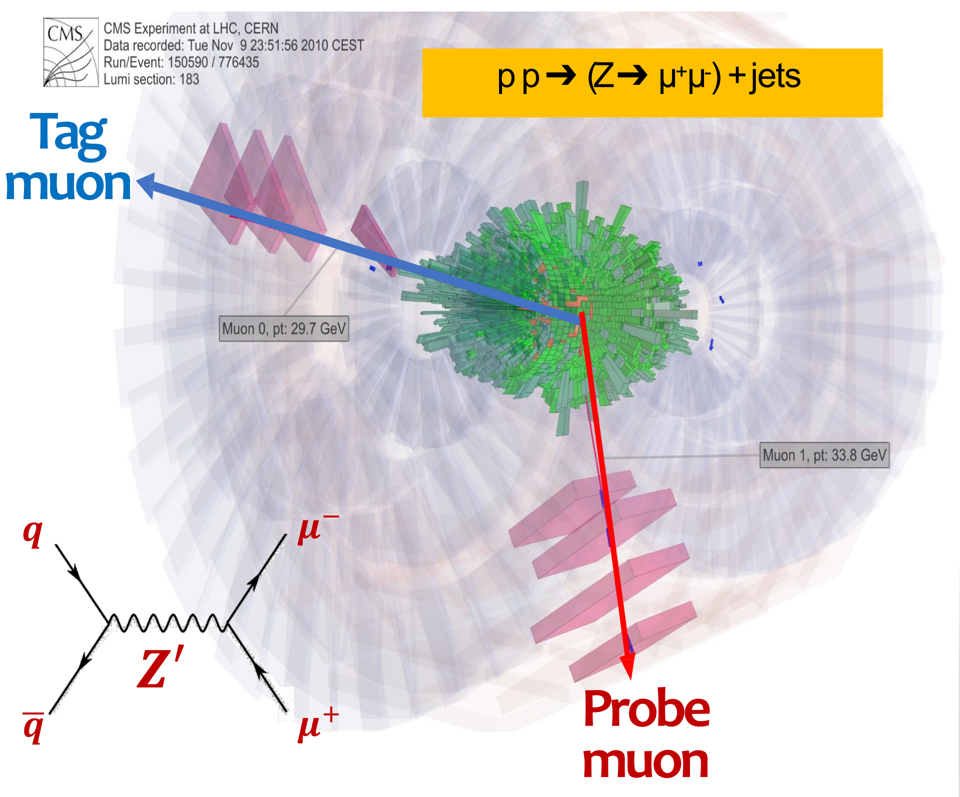


Credits: CMS Collaboration

DATA, MC SAMPLES AND SOFTWARE

- Tracking efficiencies are computed using the tag-and-probe method exploiting the $Z \to \mu^+\mu^-$ resonance.
- Proton-proton collision early **Run-3 data (Run-2)** collected until the 23rd August (2016 to 2018) at $\sqrt{s}$ = **13.6 TeV (13 TeV)**, corresponding to an integrated luminosity of **7.6 fb^{-1} (137 fb^{-1})**.
- **Drell-Yan + jets** Leading Order (LO) sample (Madgraph). Events are weighted to match the pile-up distribution in the data.

Old software written in **C++** and running using Run-2 **ROOT files** ➔ Procedure completed in ≥ 48 hours.



APACHE Spark — **New software** written in **Python** and running on **Apache Spark** for processing acceleration of Run-3 data ➔ Procedure completed in ~1 hour using Spark with converted **Parquet files**.

SELECTION STRATEGY

The tag muon:

- **Tight muon ID** [4] with transverse momentum p_T larger than 27 GeV.
- **Relative combined isolation** with Δβ correction [4] in ΔR = 0.4 is applied to be less than 0.15.
- 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 muon:

- Any **standalone muon** with at least one valid hit in the muon system (i.e. good track-hit χ^2).

Cuts for Tag and Probe pairs:

- Select a **pair of opposite-sign** tag-and-probe objects.
- Z mass window: [70-115 GeV].

Passing probe criteria:

- The standalone muon is **matched** in (ΔR < 0.3, Δη < 0.3) with tracks having p_T larger than 10 GeV.

$$N_{pass} = f^s_{pass}(m_{\mu\mu})N^s_{pass} + f^b_{pass}(m_{\mu\mu})N^b_{pass}$$
$$N_{fail} = f^s_{fail}(m_{\mu\mu})N^s_{fail} + f^b_{fail}(m_{\mu\mu})N^b_{fail}$$

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

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

- 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])

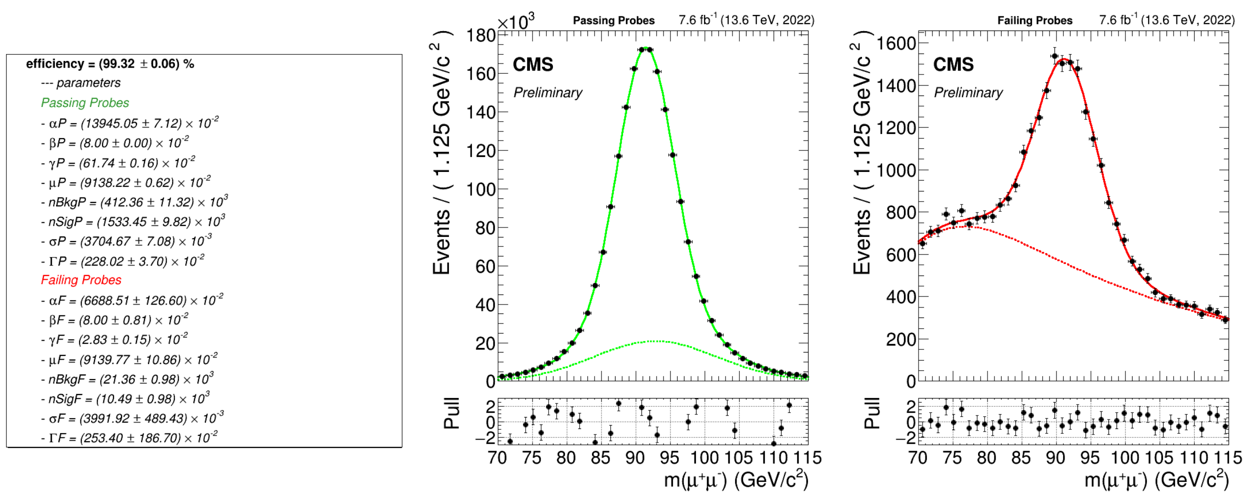
parameter [default, min, max]

- 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])

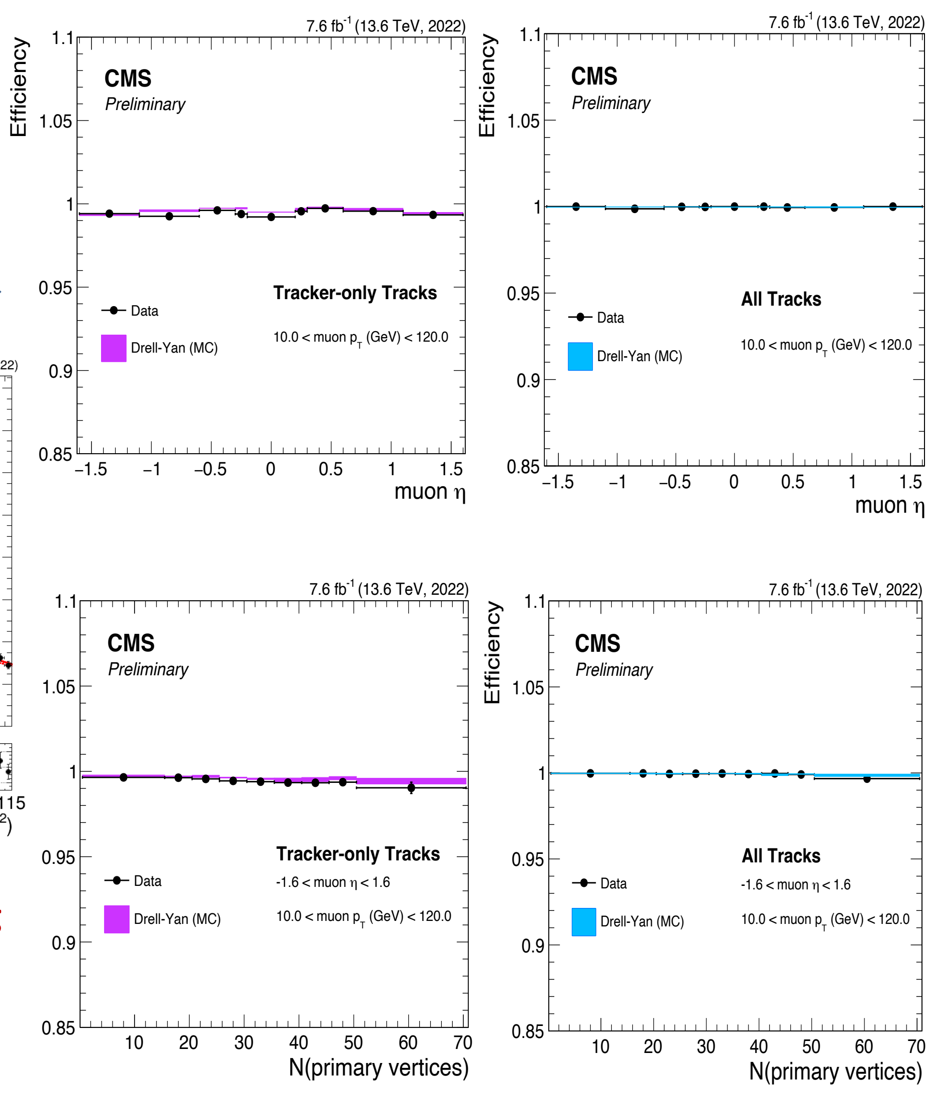
(*) The parameters (μ , Γ, σ) range for the signal Failing Probes is restricted w.r.t. range of the Passing Probes to improve fit stability.
(**) RooCMSShape is a probability density function which has exponential decay distribution at high mass beyond the pole position (say, Z peak) but turns over (i.e., error function) at low mass due to threshold effect. This is used to model the background shape in Z → ll invariant mass.

EARLY RUN-3 DATA PERFORMANCE RESULTS

The tracking efficiency as a function of **number of primary vertices**, **pseudo-rapidity η**, and **transverse momentum** of probe standalone muons in the **"Tracker-only Seeded Tracks"** and **"All Tracks"** collections has been computed [5] in Data (black dots) and Madgraph DY (violet and blue rectangles). The uncertainties shown are statistical and are frequently smaller than the marker size. Systematic uncertainties are not yet evaluated and can be significant.



The simultaneous fit to signal and background in **Passing** and **Failing Probes** plots for the probe standalone 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. Early Run 3 Data are shown in black dots [5].



Challenges

- **Momentum scale** in data is not yet at the level of the simulation due to misalignment and miscalibration effects: the measurement in the barrel (probe muons having $|\eta| < 1.6$), which is better understood, is delivered.
- **Large mass resolution** for $|\eta| > 1.1$: a fit mass range extension to [40, 150] GeV has been used allowing more events off the peak for the background component fit.

References

[1] The CMS Collaboration, *Description and performance of track and primary-vertex reconstruction with the CMS tracker*, JINST 9 (2014) P10009.
[2] The CMS Collaboration, *Performance of Run-3 track reconstruction with the mkFit algorithm*, CMS-DP-2022-018.
[3] The CMS Collaboration, *Muon tracking performance in the CMS Run-2 Legacy data using the tag-and-probe technique*, CMS-DP-2020-035.
[4] The CMS Collaboration, *Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at √s = 13 TeV*, JINST 13 (2018) no.06, P06015.
[5] The CMS Collaboration, *CMS Tracking Efficiency from Tag & Probe in Early Run-3 data*, CERN Twiki Page.