# Muon Tracking at the CMS High-Level Trigger for the HL-LHC Upgrade

Luca Ferragina

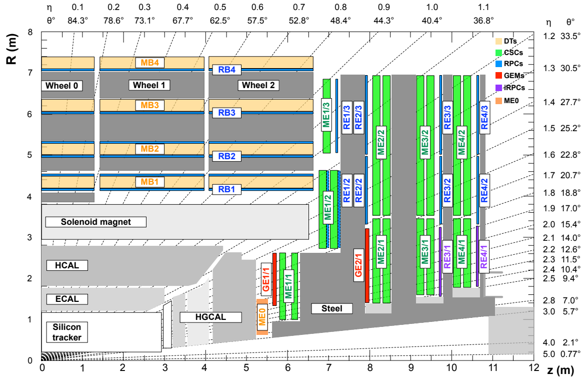
on behalf of the CMS Collaboration

Connecting The Dots
November 11, 2025

# Outline

- **Schematic overview** of the CMS **Muon system** and **reconstruction**
- **Streamlining the reconstruction**
  - Fully adopt upgrades
  - Remove unnecessary redundancies
- **Reworking the tracking**
  - Take full advantage of heterogeneous parts of the reconstruction
- **Outlook**

# CMS Muon system and Trigger



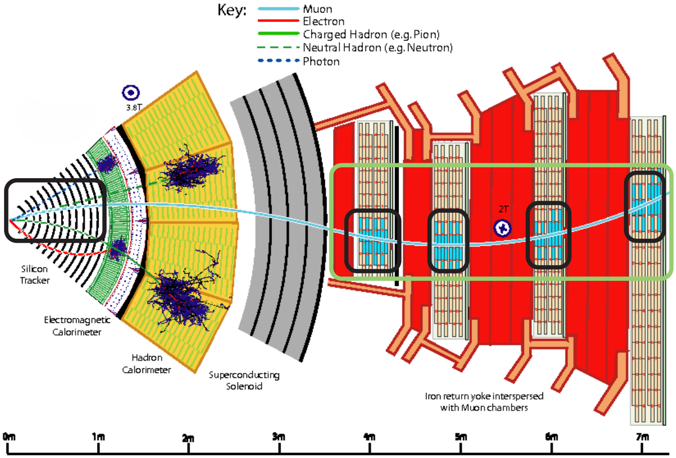

Drift Tubes (DTs): barrel region
Cathode Strip Chambers (CSCs): endcap region

Two-tiered trigger system

- **Level 1 (L1) Trigger** $\rightarrow$ **hardware** trigger with maximum planned rates **up to 750 kHz** in Phase-2
- **High-Level Trigger** (HLT) $\rightarrow$ **software** trigger running a streamlined version of the full Offline reconstruction on a processor farm (**CPUs + GPUs**). **Rates** reduced to **O(10 kHz)** for data acquisition

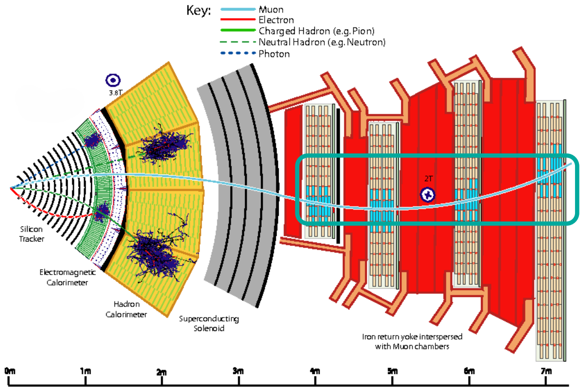
**Phase-2**: the **L1 Trigger** exploits **Inner Tracker** information as well

# L1 Trigger Muon objects




- **L1 Standalone Muon**: built with trigger segments in the muon chambers
- **L1 Tracker Muon (L1Tk Muon)**: built by matching a L1 Tracker track with trigger segments in the muon chambers **(New for Phase-2)**

# HLT Muon objects




- **Standalone Muon**: track built using only information from the muon chambers.
- **L3 IO track**: Tracker track built Inside-Out, from the vertex towards the Tracker (geometrically matched with HLT segments)
- **L3 OI track**: Tracker track built Outside-In from the Tracker towards the pixel (geometrically matched with a Standalone Muon)
- **HLT Muon**: final reconstructed Muon object. Combines all intermediate Muon objects and adds Muon ID variables.

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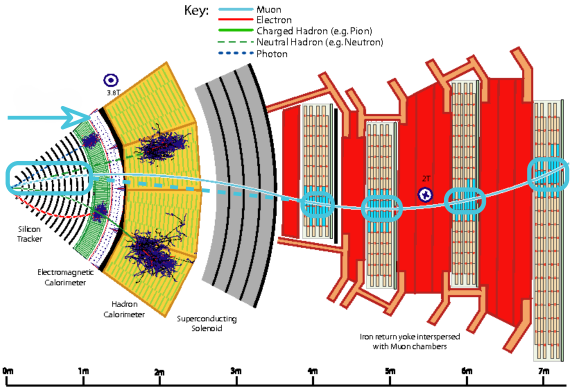


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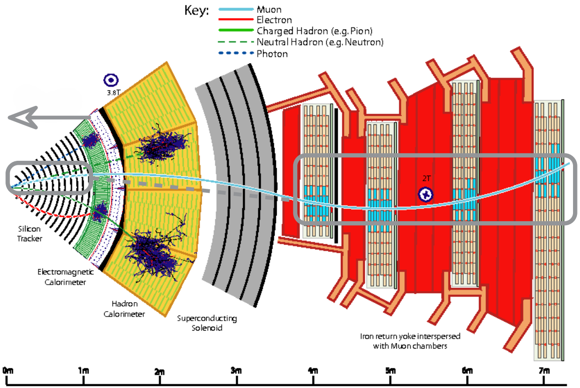


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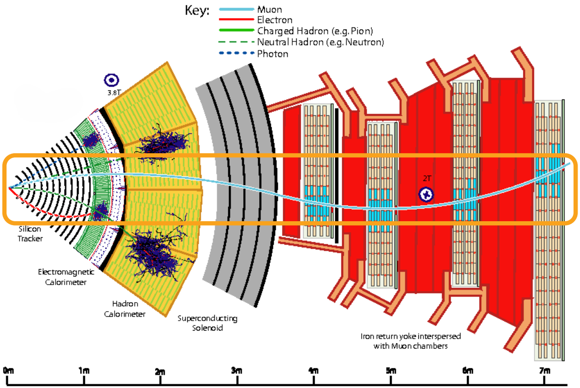


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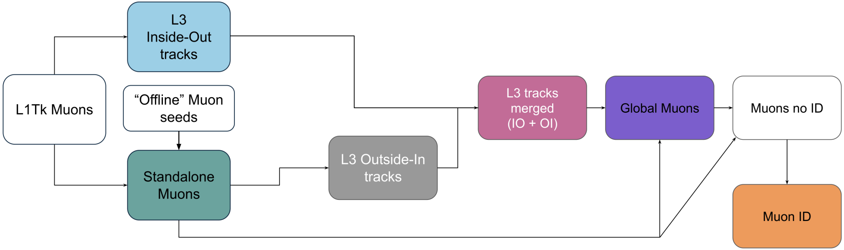
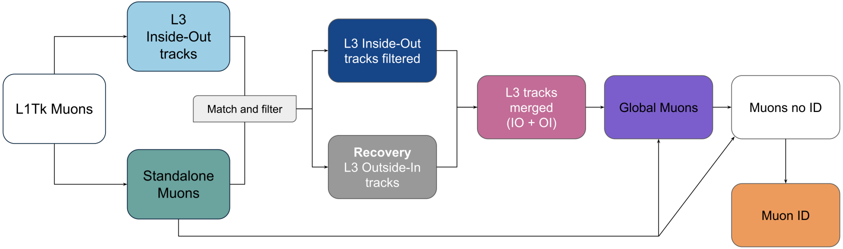
# The starting point



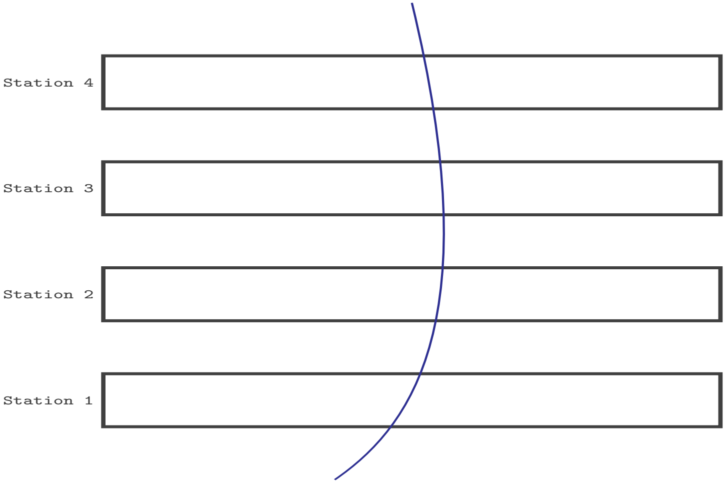

- **L1 Tracker Muons not fully exploited** to seed Standalone Muons
  - **Two-step seeding** approach builds two collections of seeds and matches them
- **Redundant** execution of **Inside-Out and Outside-In** tracking steps
- **Excellent efficiency**, but **cannot scale up to Phase 2** conditions (due to timing, fake rate, ...)
- After ID, some triggers **distinguish prompt muons** (from the Primary Vertex) and muons originating from weak decays within jets.
  - Separate **tracker** and **calorimeters** based **isolations**
  - Tracker isolation sums **reconstructed tracks** found in the cone **around the muon candidate** → currently **requires a separate full tracking step**

# Streamlined workflow



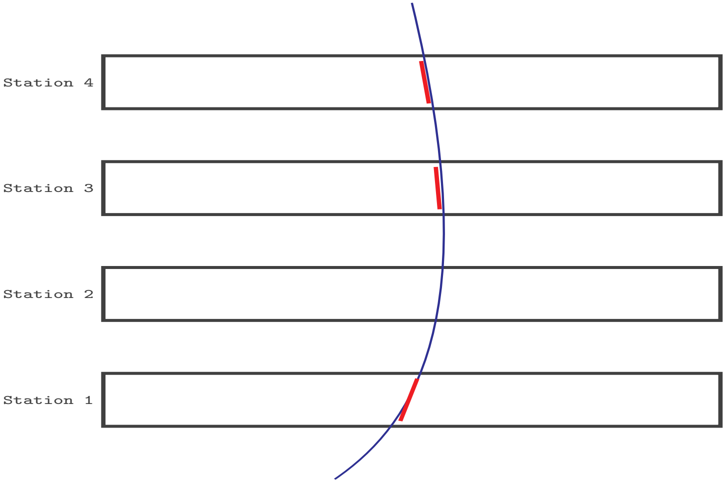

- **Single seed collection** for Standalone reconstruction
- Tracking step can now **chain Inside-Out and Outside-In** reconstruction
  - By default, **Inside-Out** reconstruction is used for **all candidates**
  - Tracks are **geometrically matched with Standalone Muons** and a **quality filter** is applied
  - **Standalone Muons not matched** to tracks passing the quality filter are used to **seed** the **Outside-In** tracking step $\rightarrow$ recovery

# Standalone Muon seeding



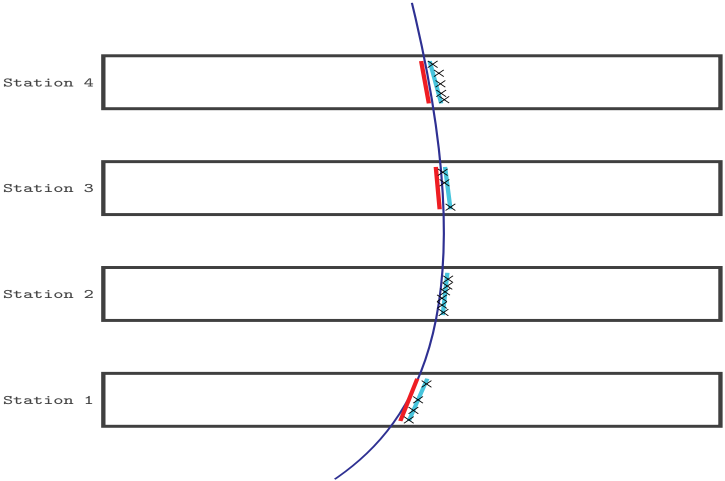

- L1 Tracker Muon

# Standalone Muon seeding



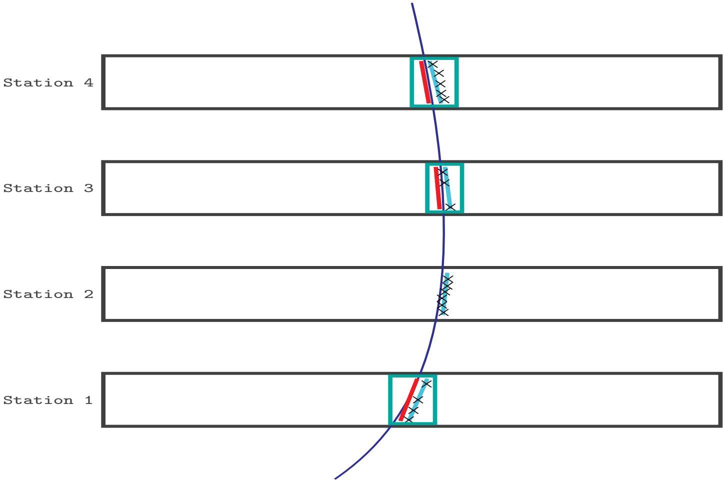

- L1 Tracker Muon
- L1 Trigger segment

# Standalone Muon seeding



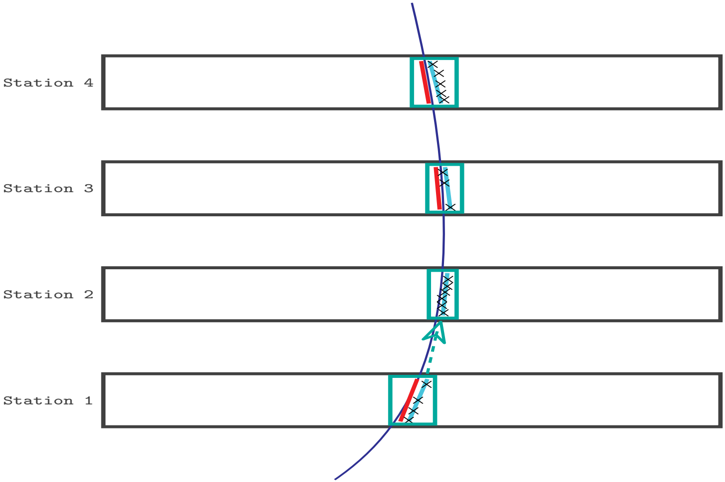

- L1 Tracker Muon
- L1 Trigger segment
- HLT segment

# Standalone Muon seeding



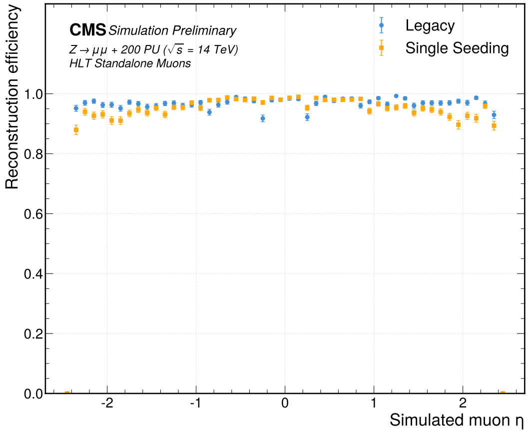

- L1 Tracker Muon
- L1 Trigger segment
- HLT segment
- L1-HLT segment match

# Standalone Muon seeding



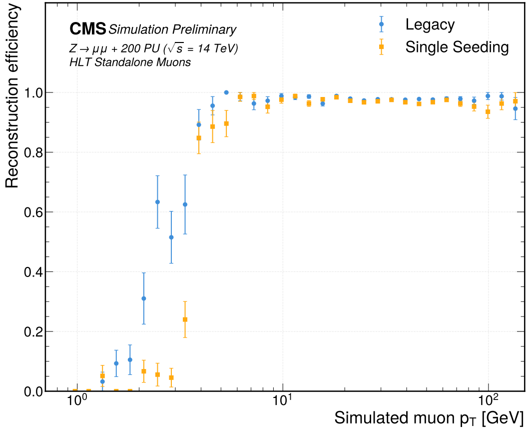

- L1 Tracker Muon
- L1 Trigger segment
- HLT segment
- L1-HLT segment match

# Similar Standalone Muons performance



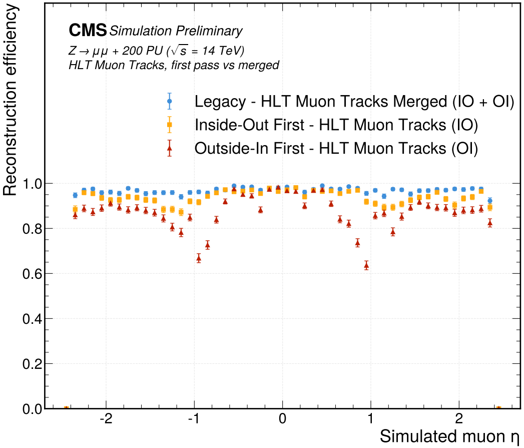

- **Similar or better** performance in the **barrel** region ($|\eta| \lesssim 0.9$)
  - Better $p_T$ assignment using L1Tk Muon information $\rightarrow$ pick up more hits or segments in the muon chambers, especially for regions with difficult-to-model $B$ field
- **Slightly worse** efficiency in the **endcap**
  - Due to geometry-dependent mismatches between L1 trigger primitives and HLT muon segments
  - Still being optimised and validated

# Sharp L1-driven turn-on




- **Compatible performance** in the relevant $p_T$ range
- Very **sharp turn-on** at $p_T \simeq 4$ GeV $\rightarrow$ **mimicking L1Tk Muons** behaviour

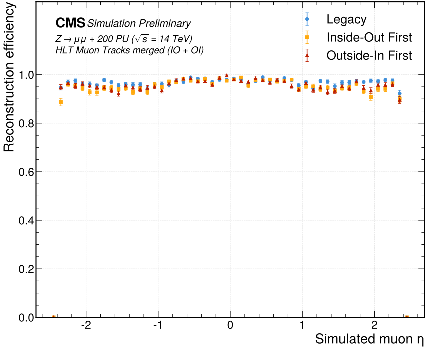
# How much do we need to recover?

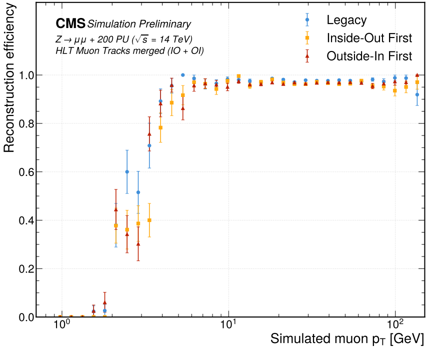



- **Redundant IO + OI** reconstruction for all candidates **compared** with **just Inside-Out (Outside-In)**
- The **IO first** approach manages **similar efficiency to both passes** combined
  - Up to **80% of the events** in this sample **do not require a second tracking step**
  - **Reduce timing and complexity** for downstream modules

# Recovery iteration at work

Comparing the **Legacy merged** collection with **first pass + recovery** (Inside-Out / Outside-In first)

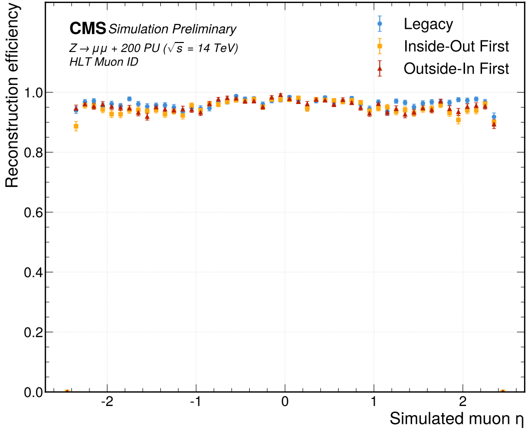



Overall **compatible performance**, slight drop in the endcaps due to Standalone Muons

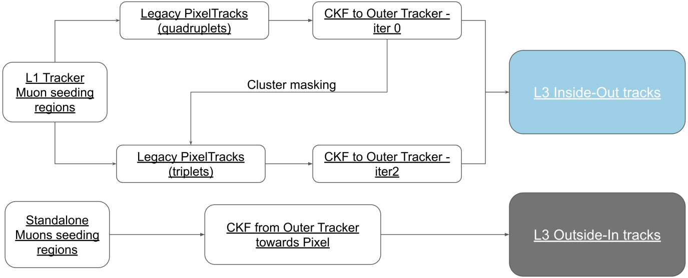
Slightly **different turn-on**, **compatible performance** from $p_T \simeq 5$ GeV

# Overall compatible HLT Muon performance



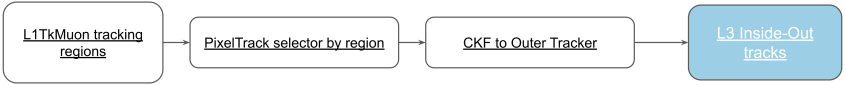

- **Compatible HLT Muon reconstruction** performance for all approaches
- Maintain **flexibility** to swap between **IO/OI first**
  - Resilient against changes in the reconstruction, detector ageing, ...
- Slight drops in the endcaps ($\sim$3%) still due to Standalone Muons

# A deeper look at HLT Muon tracking



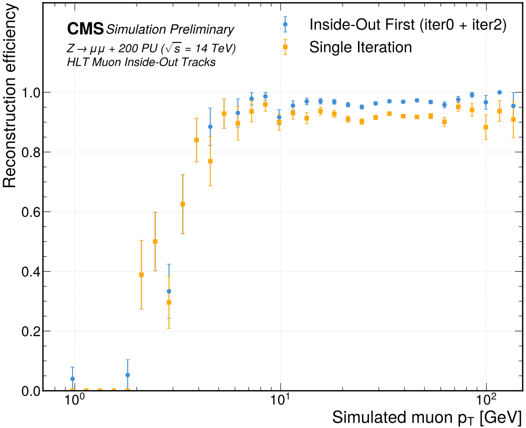

- **Inside-Out Muon tracking** (default first pass)
  - **iter0**: produce **quadruplets** in the **Inner Tracker** (IT), propagate them to the Outer Tracker (OT) via Combinatorial Kalman Filter (CKF)
  - **iter2**: recover missed **IT** tracks with **triplets**, CKF to propagate to OT
- **Outside-In Muon tracking**
  - **Single** CKF-based **tracking** starting from Standalone-Muon-defined regions of interest
- **Another** full **Inside-Out-like tracking step** performed to compute **tracker isolation**

# Moving to a (faster) single-iteration approach



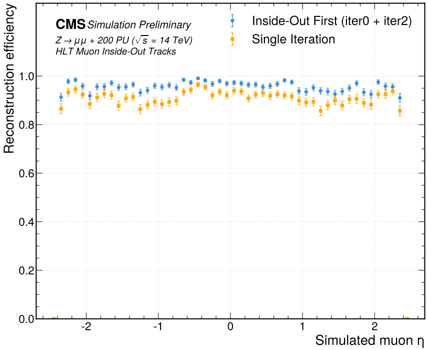

- **Simplify Inside-Out** step to take advantage of recent **PixelTracking improvements**
  - Use **already-made extended PixelTracks** (see talk by Jan) in **regions** defined around **L1Tk Muons**
    - Extended PixelTracks start from IT hits and can go up to the third (out of six) layer of the OT in the barrel region
    - Improved efficiency and better overall track quality with respect to legacy quadruplets
  - **No dedicated IT tracking** performed specifically **for muons**
  - Single CKF iteration to fully propagate the extended PixelTracks to the last OT layer
- **IT muon reconstruction** moves **from legacy** (CPU based) code **to** the same **heterogeneous PixelTracking** algorithm currently used in Run 3, improved and extended for HL-LHC

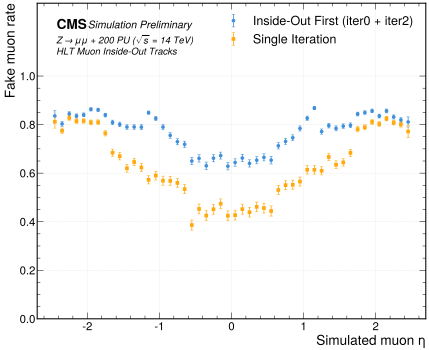
# Can we skip the dedicated muon tracking step?




- Tracks produced by the single iteration approach are **slightly less efficient** ($\sim$5%)
- **Drop small enough** to be **recovered** by the **Outside-In** step
- Overall single iteration **performance strongly depends** on the **L1Tk Muon based track selection**
  - Still under **active development** to maximise efficiency and reduce fake muon rate

# Slightly lower efficiency with reduced fake muon rate

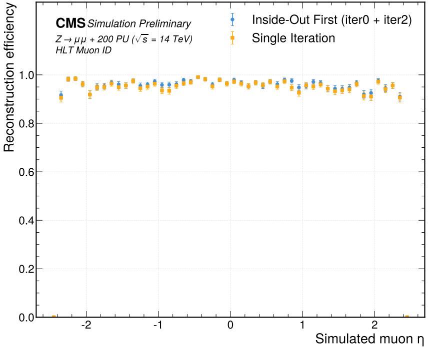


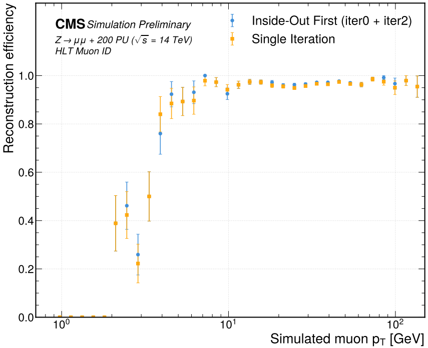




**Small drop in efficiency** visible over the entire $\eta$ acceptance

**Significant reduction in fake muon rate** from the preliminary parameters used by the track selector from L1Tk Muons

# Recovered HLT Muon efficiency

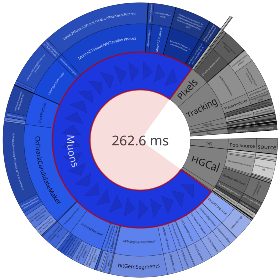


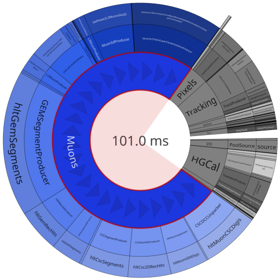

Adding the **Outside-In recovery** step **brings up** the **single iteration efficiency** in the entire $\eta$ and $p_T$ ranges

# Significant muon reconstruction speed-up

Average **running time of HLT Muon modules** on a **simplified Run 4 menu**, containing a subset of the most representative paths used in Run 2

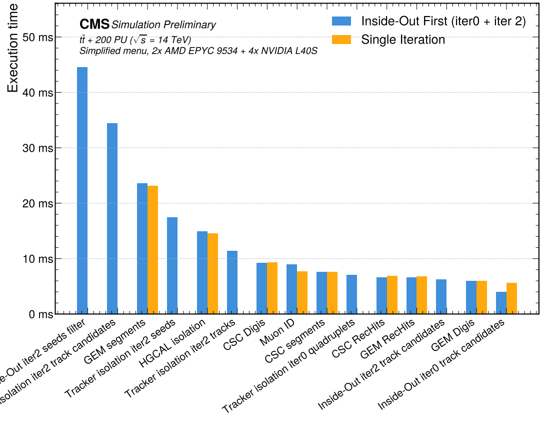



**Two tracking iterations** are used for the **Inside-Out** reconstruction step and for **tracker isolation**




**Single tracking iteration** for Inside-Out tracking (tracker isolation), starting from **already-made Extended PixelTracks** in regions around L1Tk Muons (HLT Muon candidates)

# Comparing per-module time




- **15 most time-consuming modules** in HLT Muon reconstruction (and isolation)
- The **single iteration** approach effectively **removes the largest modules**
- Only marginal increase in the single iteration CKF track producer
- Overall **HLT muon reconstruction time reduced by ∼60%**

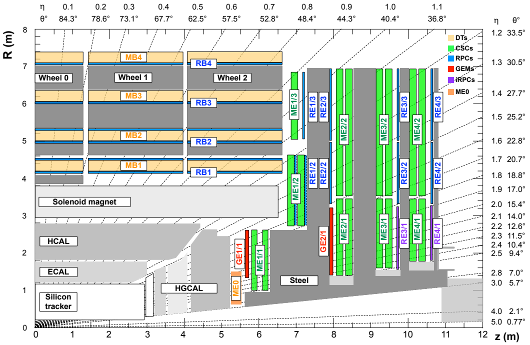
# Outlook

- **Streamlined HLT muon reconstruction achieves compatible performance with legacy approach**
  - Standalone Muons built using Phase-2 L1Tk Muons
  - Tracking steps chained to avoid unnecessary redundancies
- **Single iteration approach takes full advantage of heterogenous developments of tracking at HLT**
  - Recoverable drop in efficiency in IO reconstruction (still subject to tuning)
  - Significant ($\sim$60%) reduction in computing time for muon reconstruction

This work has been funded by the Eric & Wendy Schmidt Fund for Strategic Innovation through the CERN Next Generation Triggers project under grant agreement number SIF-2023-004.

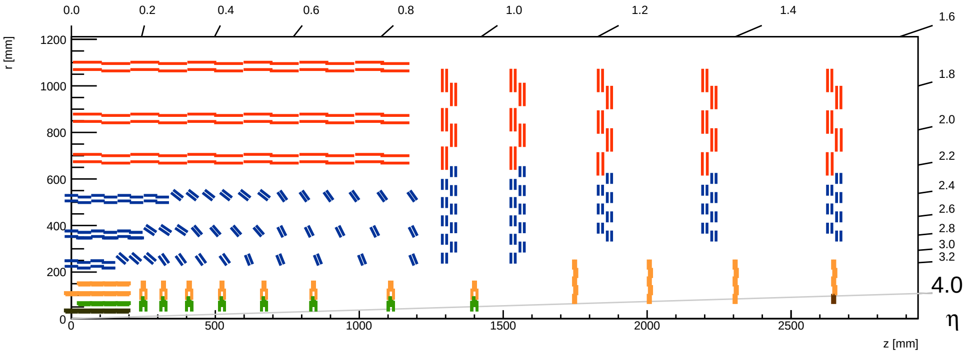
# Backup

# Phase 2 Muon system




R−z quadrant of the CMS Phase 2 muon system [1] with z parallel to the beamline and increasing from left to right, R increasing upwards. The interaction point is in the lower left corner. The Drift Tubes (DTs) are labelled MB (Muon Barrel) and shown in light yellow, the Cathode Strips Chambers (CSCs) are labelled ME (Muon Endcap) and shown in light green, and the iron return yoke is shown in dark grey. Resistive Plate Chambers (RPCs) are mounted both in the barrel and in the endcap where they are labelled RB and RE, respectively. Phase-2 Improvements mainly focus on the high-η region, where GEM stations have been added and are shown in orange and red. The endcap region also benefits from new improved Resistive Plate Chambers (iRPC) shown in purple

# Phase 2 Tracker




R-z view of the Phase-2 tracker system

# HLT Muon reconstruction

The HLT Muon reconstruction builds separate tracks collections in the tracker [2] (tracker muons tracks) and in the muon chambers (standalone muons), which are then linked together in the global muon reconstruction step [3]. Tracker muon tracks are built in two ways for each candidate:

- Inside-Out (IO): L1 Tracker Muons (L1Tk Muons) [4] define regions of interest in the Inner Tracker (IT), where a Cellular-Automaton-based algorithm iteratively produces tracks by combining hits in adjacent layers [5]. In particular, two iterations are performed: one using tracks with 4 hits (iter0) and another recovery step using tracks built with 3 hits (iter2), considering only hits that were not used in the previous iteration. The IT tracks produced by this approach are then propagated to the Outer Tracker (OT) via Combinatorial Kalman Filter (CKF)
- Outside-In (OI): Standalone muons are used to define regions of interest in the OT, where a CKF approach is used to produce a trajectory connecting hits towards the IT

Standalone muons are built by combining information from all muon chambers (DTs, CSCs, RPCs, GEMs) along a trajectory via CKF. Global muons are produced by matching tracker muon tracks with standalone muons, by comparing parameters after propagating both trajectories to a common surface. Finally, a standard ID procedure is applied to HLT muon candidates aiming to identify prompt muons originating at the primary vertex, and muons from light and heavy flavor decays, as well as maintain a low rate of charged hadrons misidentification. In particular, the HLT Muon ID requires a global muon with at least 6 hits in the tracker (of which at least 1 in the IT). The tracker muon track should also match segments in at least two muon chambers

# HLT Muon isolation

Some trigger paths require to distinguish between prompt muons and muons originating from weak decays within jets. The isolation of a muon is evaluated relative to its pT by summing up the energy in geometrical cones, $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$, surrounding the muon [3]. Two main strategies are used:

- Track based isolation: sums reconstructed tracks found in the cone around the muon candidate. Currently, this requires a separate full tracking step, separate from the ones used during the reconstruction. The isolation tracking step starts from the final HLT Muon objects, defining regions of interest around them. In these regions a full IO-like tracking iteration is performed, with tracks made of 4 hits as a first iteration and a further recovery step with 3-hits tracks considering only hits that were not previously used.
- Particle Flow (PF) based isolation: sums the the pT of all charged hadrons and neutral candidates (hadrons and photons) within the ΔR cone starting from the primary vertex. The neutral component is corrected to account for pileup contributions by summing the charged contributions from pileup vertices, scaling it by a factor 0.5, and subtracting the resulting value from the neutral hadron and photons contributions. The correction factor originates from simulations and roughly corresponds to the neutral particle to charged hadron ratio in inelastic proton-proton collisions.

# Performance metrics

Physics performance metrics, such as efficiency and fake muon rate, are based on the by-hit-matching of simulated muon objects with reconstructed ones. Muons undergo different reconstruction steps, involving different parts of the CMS detector, thus requirements are adjusted according to the type of reconstructed muon object to evaluate. However, some general conditions apply to all reconstructed objects. In particular, a reconstructed muon object is considered matched to a simulated muon if they share more than 75% of their hits: either just in the tracker (tracker muon tracks), just in the muon chambers (standalone muons) or in total (global muons). Note that for the purposes of assessing reconstruction performance, only a subset of the simulated muons is considered (simulated target muons). In particular, the pseudorapidity of the simulated particle needs to be within the geometrical acceptance of the Phase 2 Muon system (not including ME0): $|\eta| \leq 2.4$. Moreover, the simulated muon must have a transverse momentum $p_T$ > 0.9 GeV is required and only simulated muons coming from the signal event are considered. Taking all of this into account, all reconstructed objects not matched to a simulated target muon are considered fake.

- Efficiency is defined as the fraction of simulated target muons that were associated to a reconstructed muon object
- Fake muon rate is defined as the ratio of reconstructed objects not matched to any simulated target muon over the total number of reconstructed objects