Performance of the CMS muon object in Run3

Federica Primavera (Bologna University and INFN)
on behalf of the CMS Collaboration

Overview

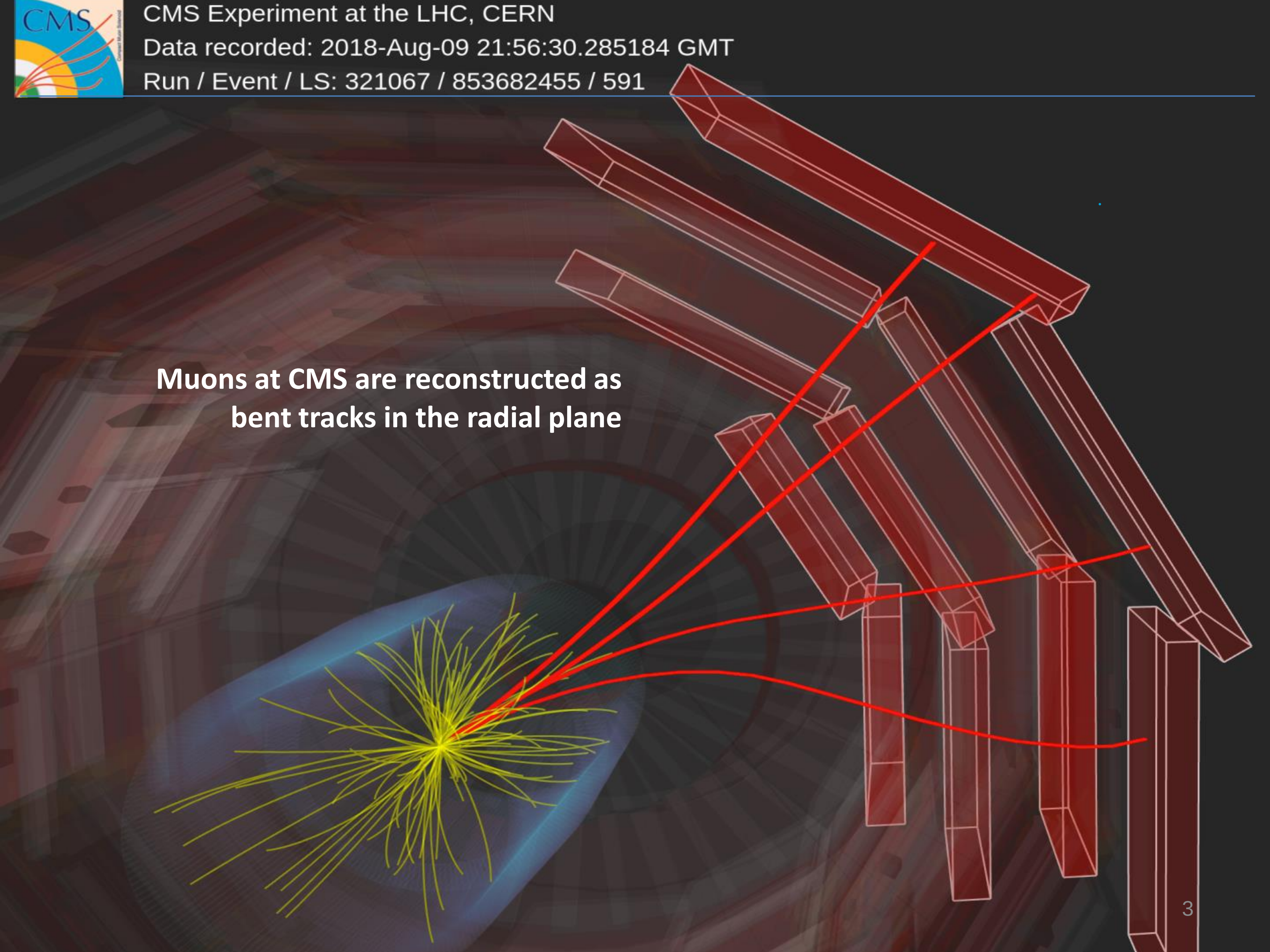
Accurate measurements of processes with muons in the final state are among the main goals of the CMS experiment. Interesting processes cover a **wide range of energy and topologies:**

- prompt muons from decays of the W, Z, or Higgs bosons
- muons from τ lepton decays
- non-prompt muons produced by hadron decays, especially b quark hadrons
- long lived and displaced particles
- new physics at TeV scale

In Run3 the CMS detector recorded about 100 fb^{-1} (more than 1/3 during 2024):

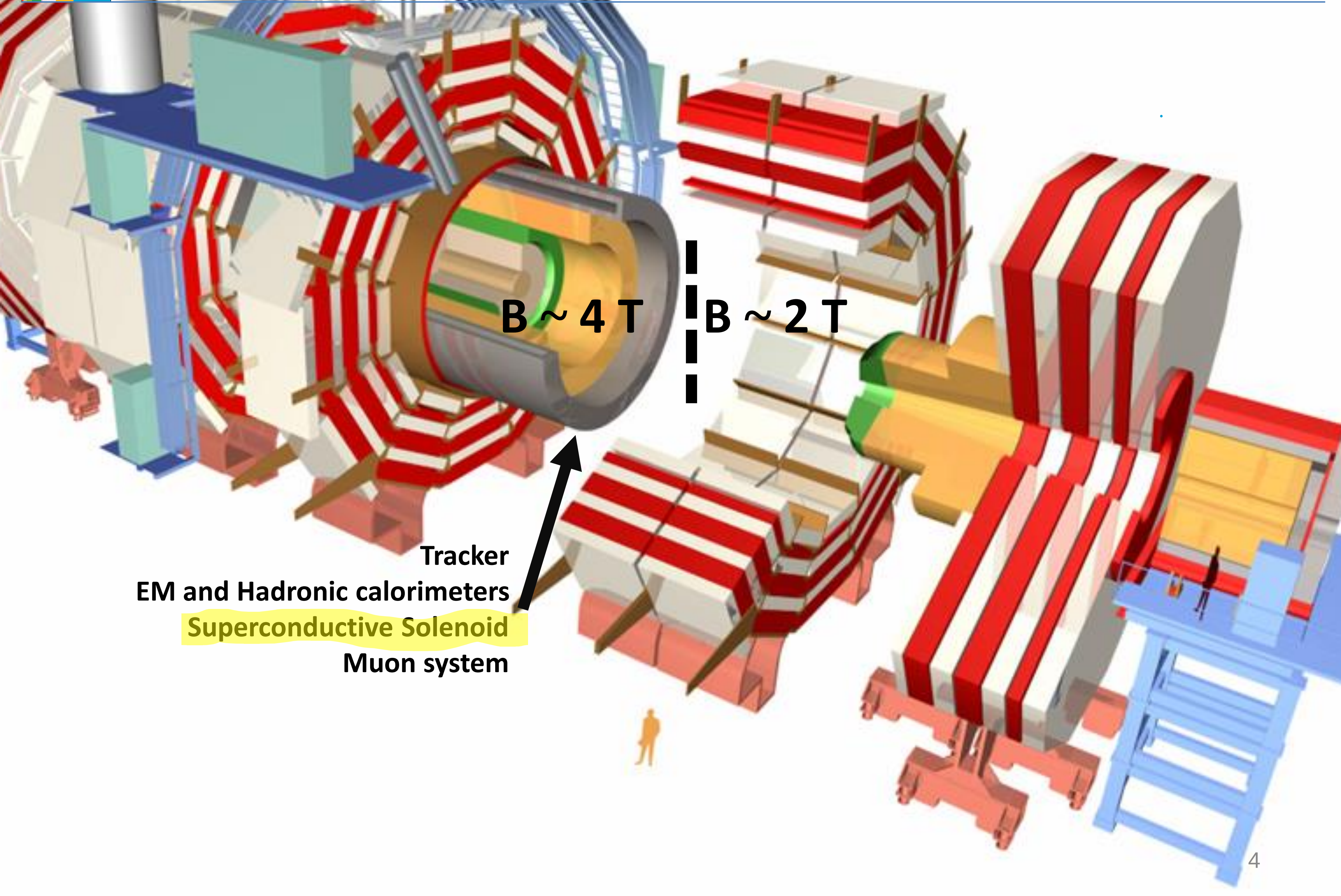
- **muons contribute to about a half of the total trigger rate**
- **even more offline**
    - **analyses relying on the presence of muons as signal or background**

A successful physics program relies on a highly efficient muon reconstruction and identification, further than an accurate measurement of its momentum

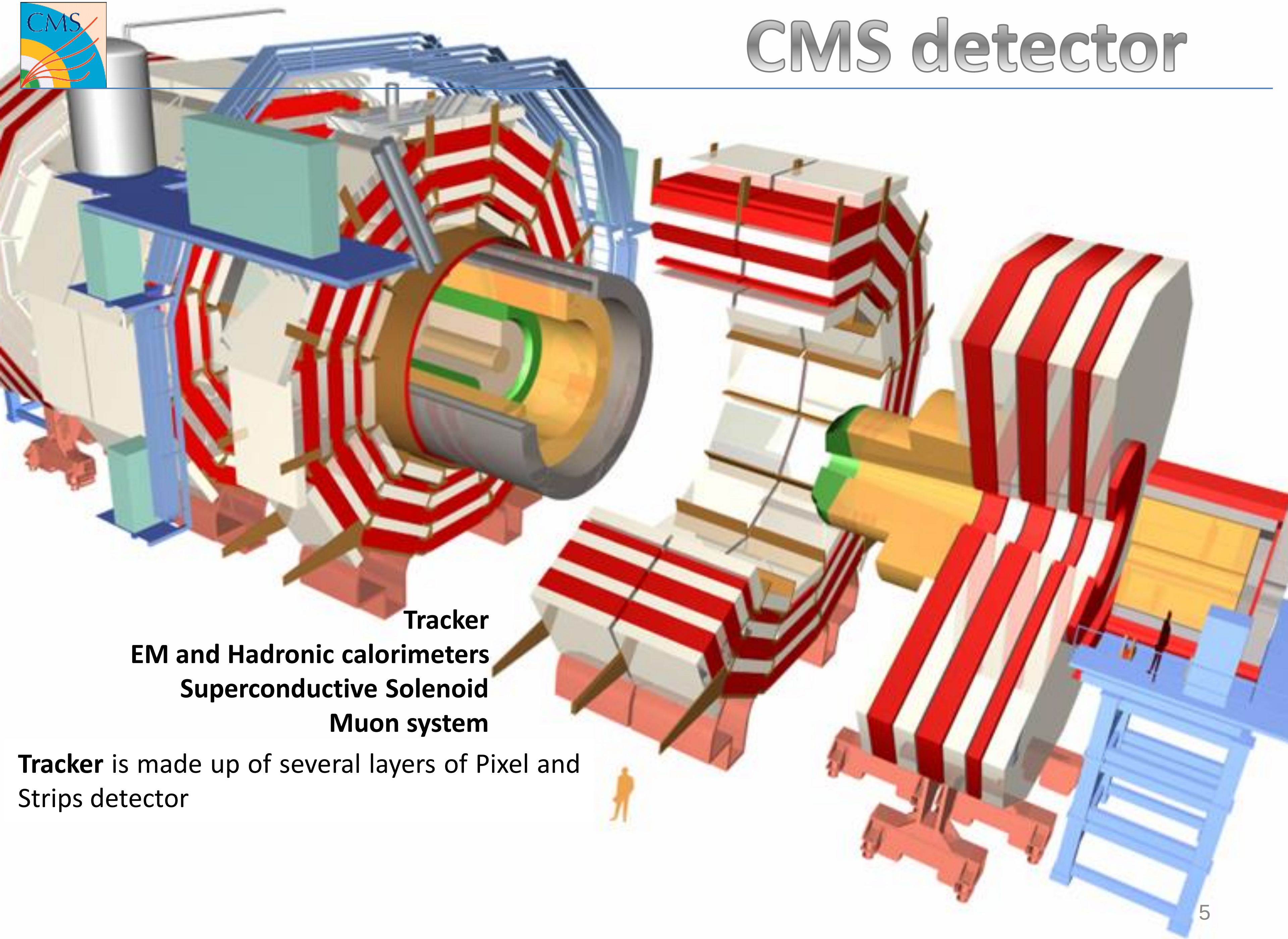


Muons at CMS are reconstructed as bent tracks in the radial plane

CMS detector



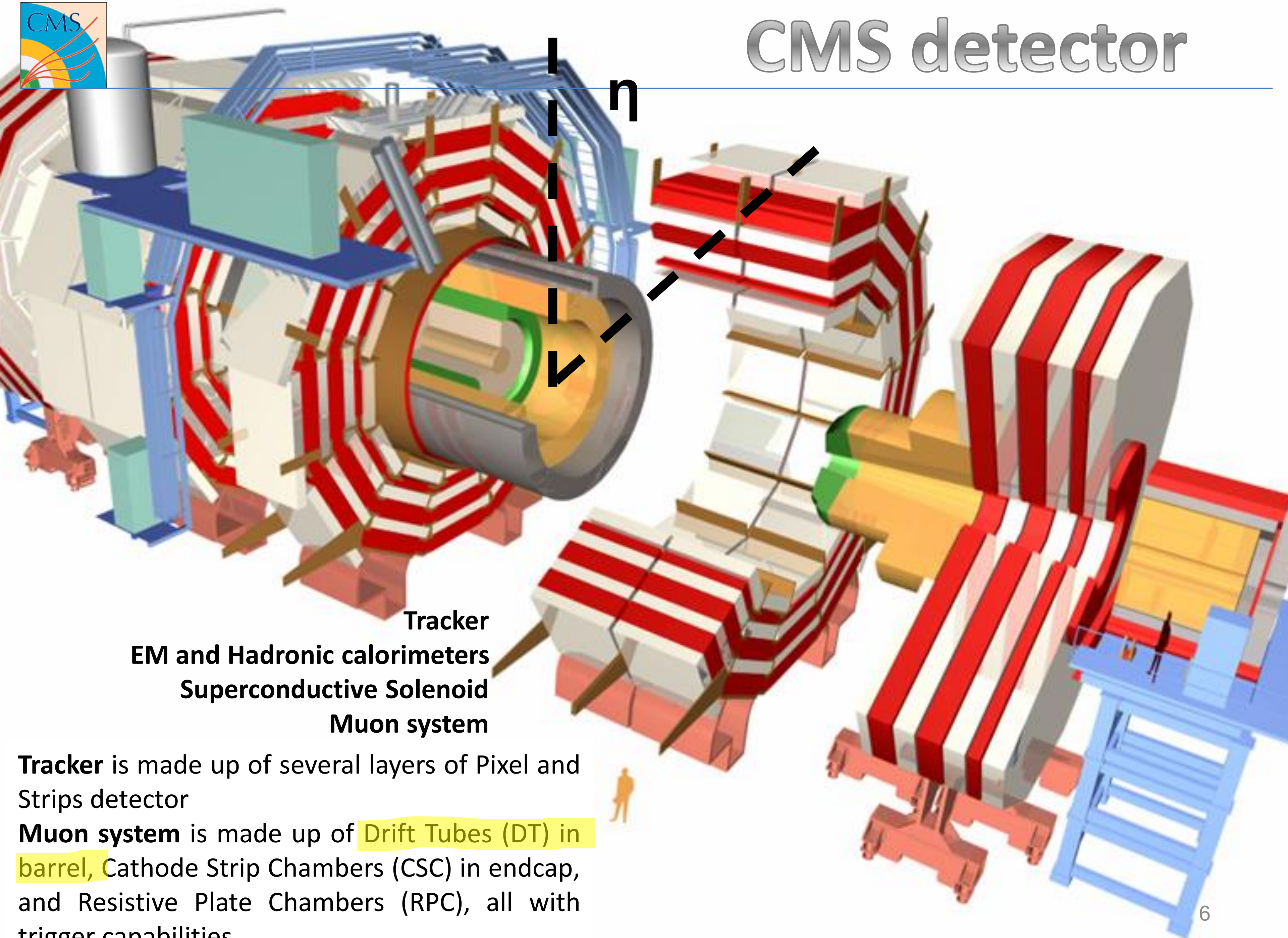
CMS detector



Tracker
EM and Hadronic calorimeters
Superconductive Solenoid
Muon system

Tracker is made up of several layers of Pixel and Strips detector

CMS detector



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Muon system is made up of Drift Tubes (DT) in barrel, Cathode Strip Chambers (CSC) in endcap, and Resistive Plate Chambers (RPC), all with trigger capabilities

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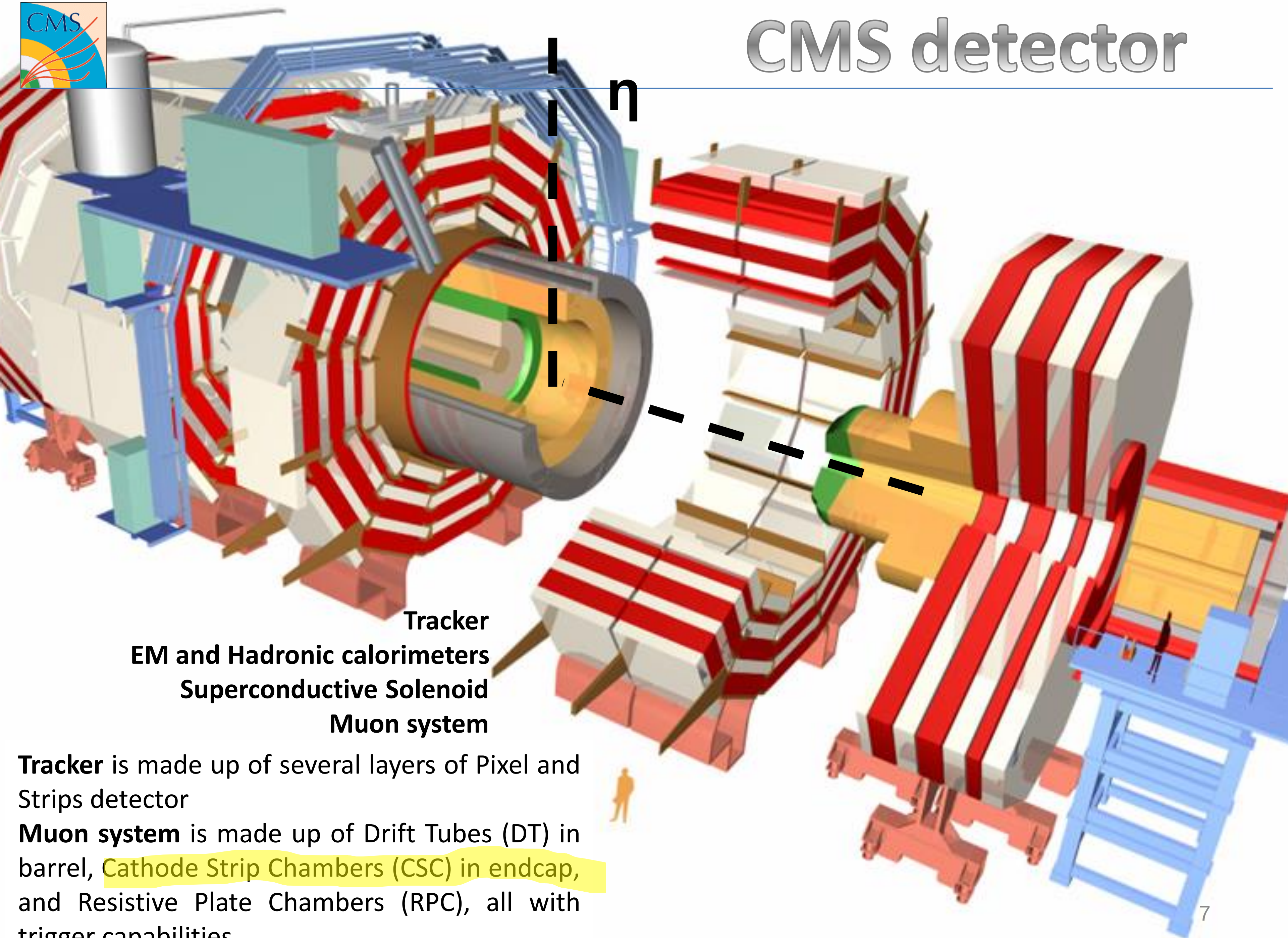

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Muon reconstruction

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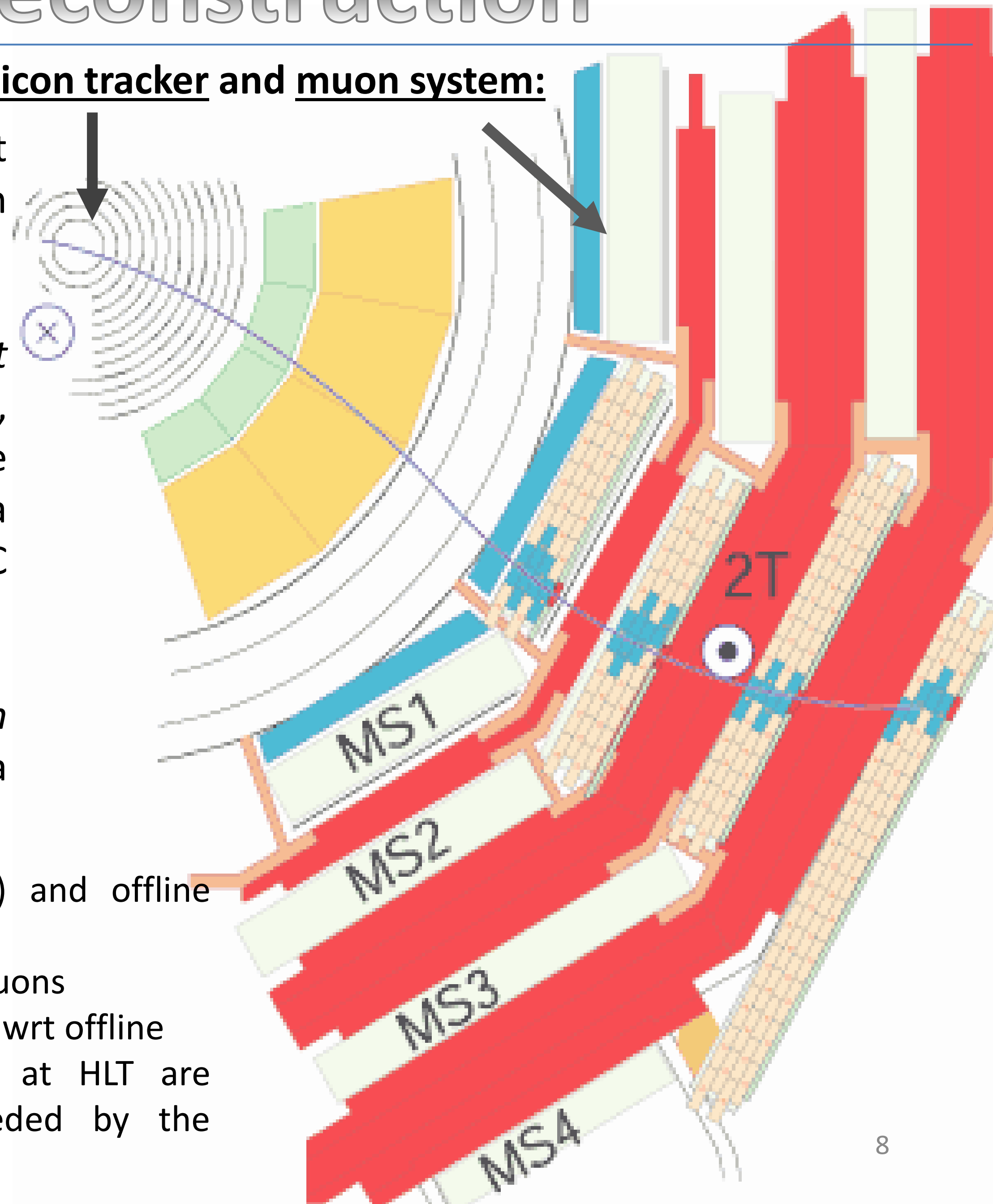

Standalone muon tracks are built *inside-out* using the Kalman filtering in the muon system only

Tracker muon tracks are built *inside-out* by propagating tracker tracks, reconstructed with the iterative tracking, to the muon system, where a loose matching to a DT or a CSC segment track is required

Global muon tracks are built *outside-in* by matching a standalone muon with a tracker track. Global track refit is done

Algorithms for on-line (High Level Trigger) and offline reconstruction are almost the same:

- higher resolution for offline standalone muons
- tracker tracks at HLT exploit less iterations wrt offline
- tracker tracks used for global muons at HLT are reconstructed only in the region seeded by the standalone track

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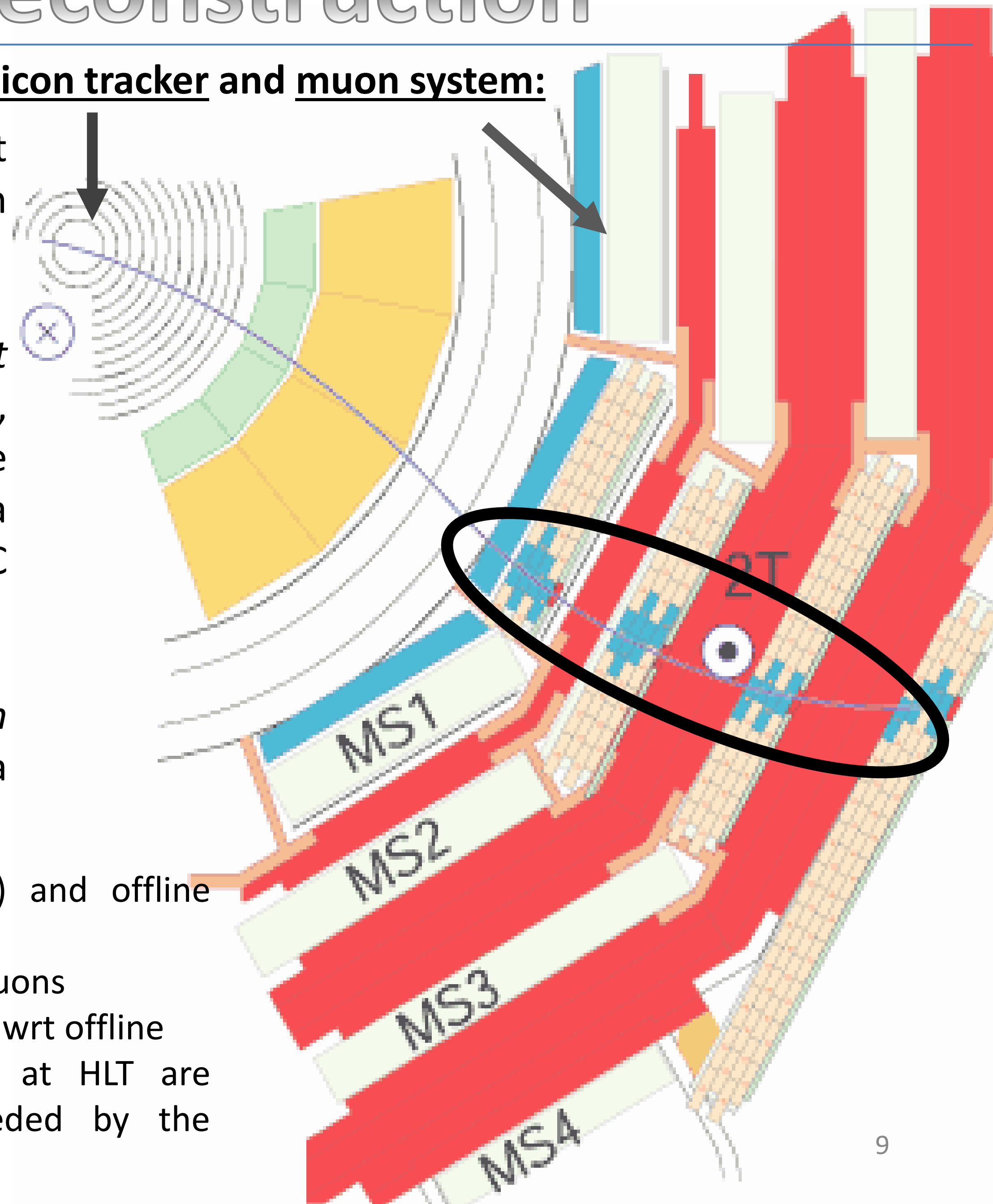

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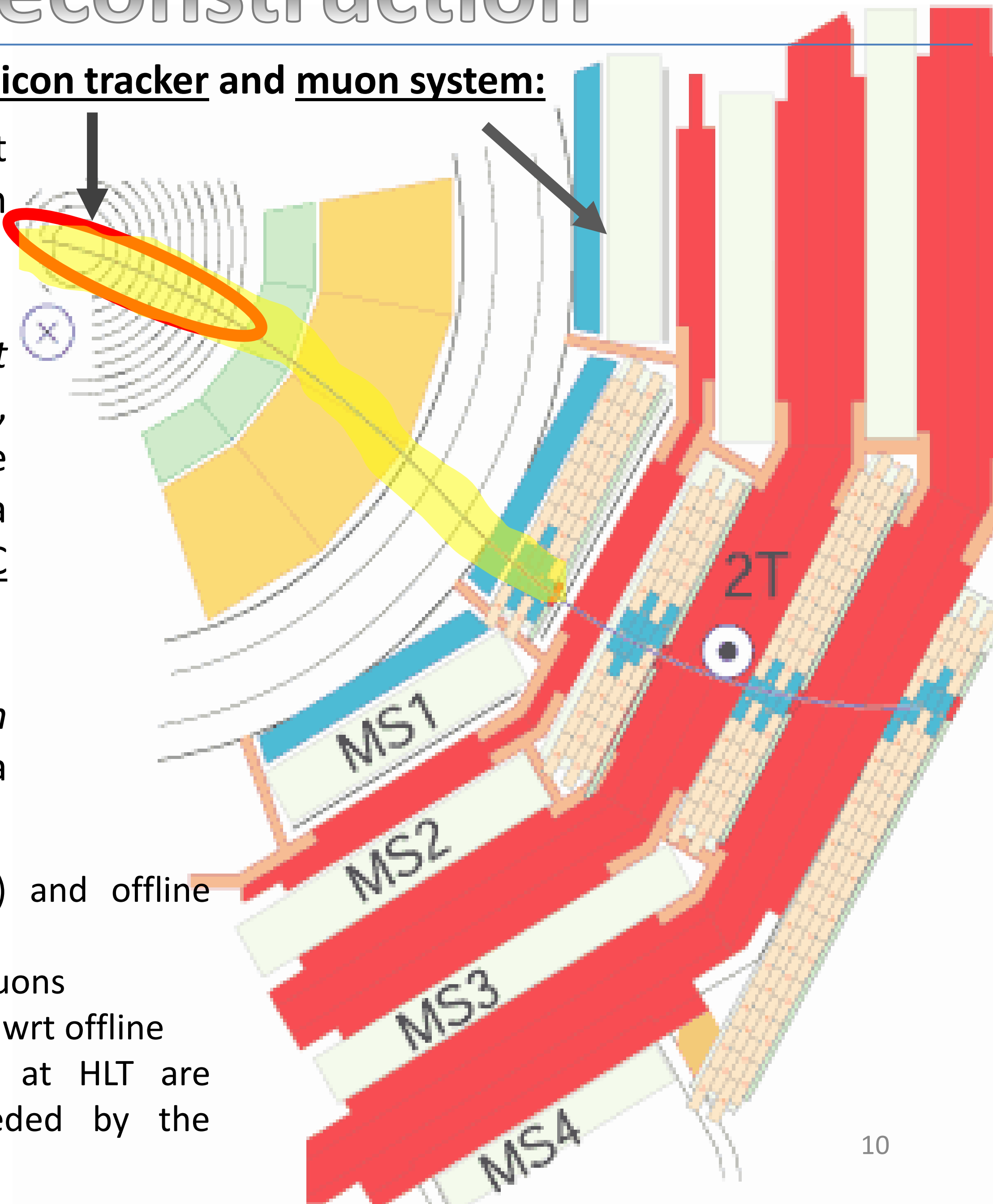

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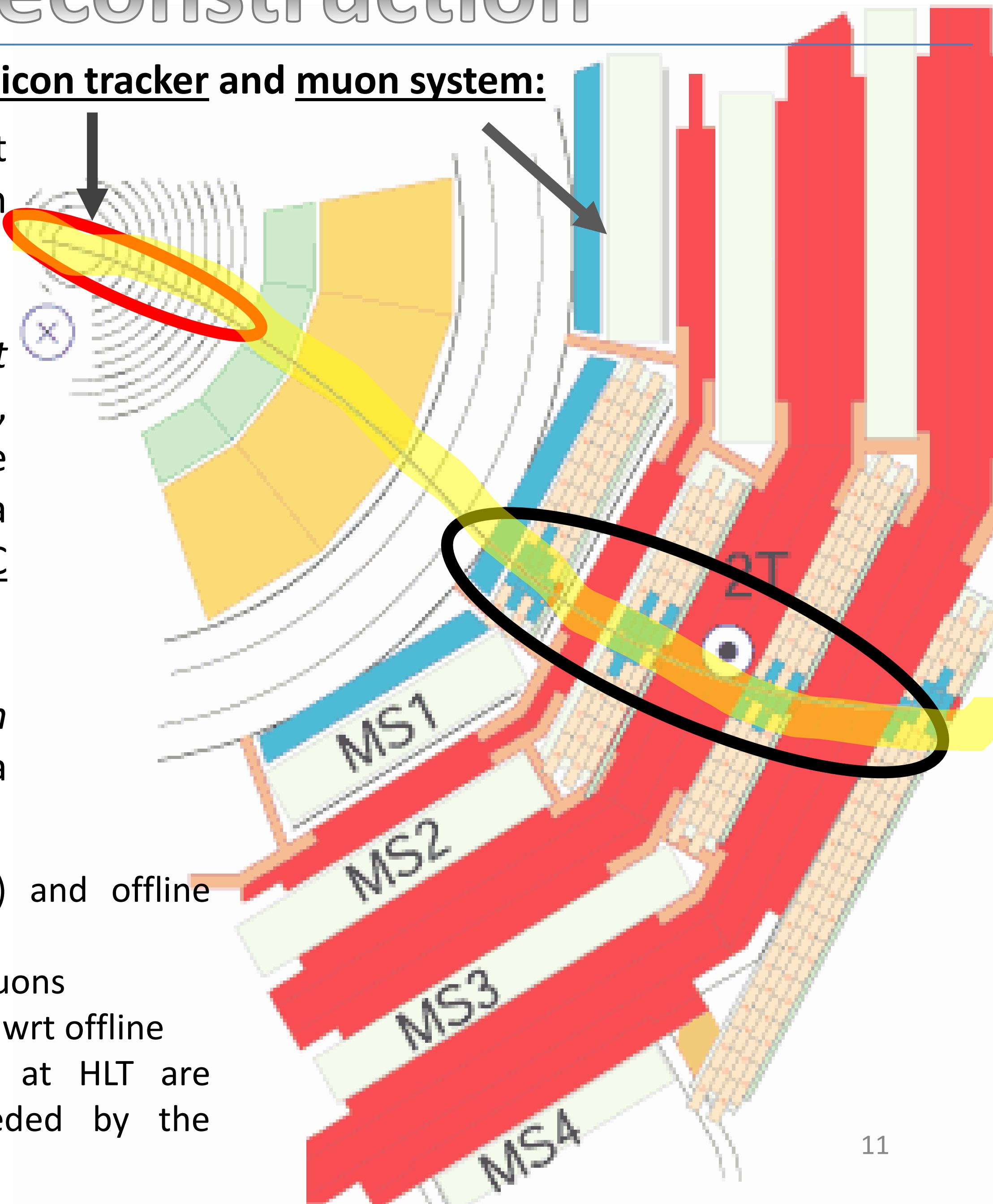

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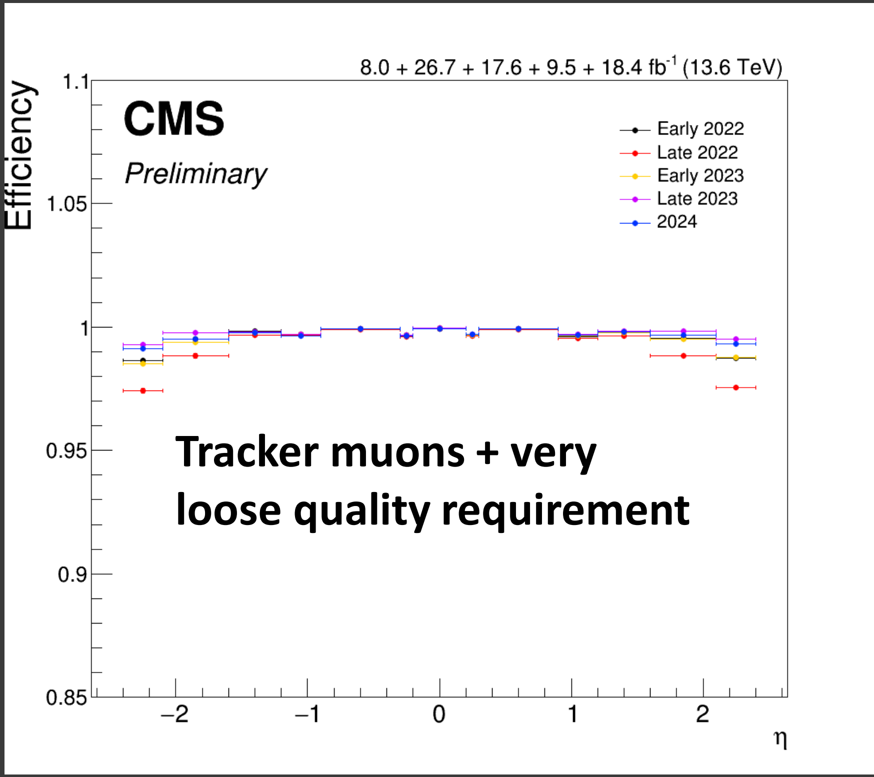
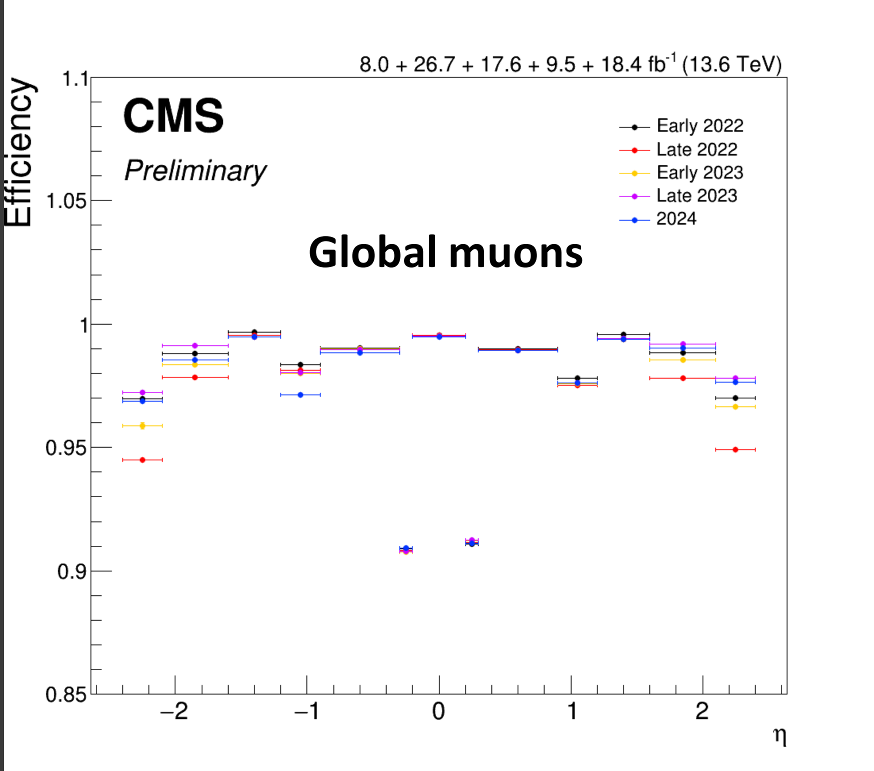
Muon reconstruction performance

CMS DP-2024/067

Reconstruction efficiency is studied using *the fitting tag-and-probe method at the Z mass peak:*





Tracker muons are meant to be highly efficient in regions of the CMS detector with less instrumentation (for routing of detector services) and for muons with low p_T:

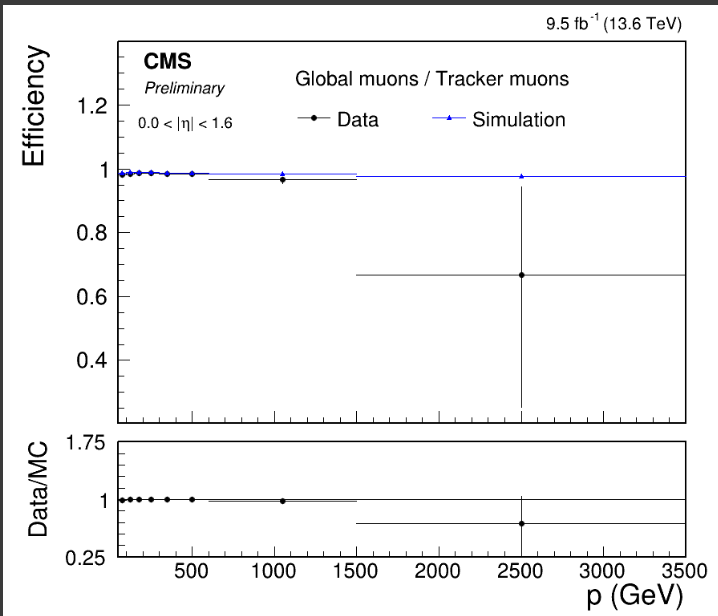
- typically matched to segments in the innermost muon station
- higher probability of muon misidentification from hadronic showers

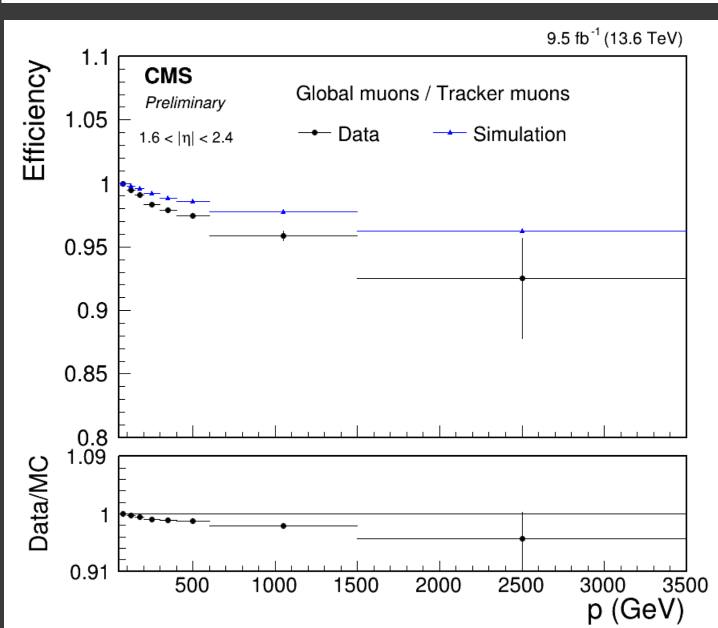
Global muons are meant to have high efficiency for muons penetrating through more than one muon station:

- reduced muon misidentification rate
- but more sensitive to the conditions of muon system

Global reco for high-p_T muons

CMS DP-2024/023





For high-p_T muons curvature and multiple scattering along trajectory are reduced: **muon system contributes to the p_T measurement** but in some cases (e.g. in presence of showers) out-of-the-box p_T from global muons may be suboptimal:

- accurate knowledge of tracker and muon system alignment becomes critical
- radiative contributions to muon energy loss (EM showers) becomes sizable (critical energy of muons in iron ~350 GeV)

- **dedicated high- p_T track refits have been developed**

- **dedicated studies of global reconstruction efficiency at high P are performed with a *cut and count extended tag-and-probe technique:***

TAG: muon satisfying high-pT ID criteria and very tight isolation cut, matched with single muon trigger
PROBE: tracker muon, with very tight isolation cut (+ potentially cuts on the inner track, e.g. # of layers, vertex proximity)
PAIR: no upper cut on on invariant mass, plus add cuts (e.g. pT balance) to select non resonant DY events

- P-dependent inefficiency for $|\eta| > 1.6$ with data/MC < 5%
- rather flat efficiency in barrel with data/MC SF ~99%

Reconstruction of displaced muons

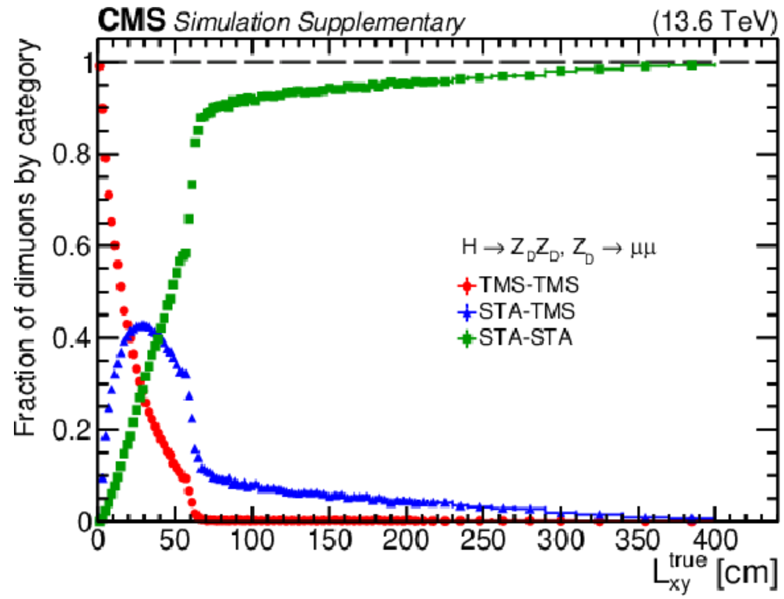
EXO-23-014

Displaced muons are, by definition, not produced in the primary interaction, therefore, dedicated algorithms have been developed to efficiently and accurately reconstruct them:

Displaced Standalone muon tracks (DSA) are initiated by cosmic-like seeds, which allows to accept all the possible bending directions for the initial state of the track. Constraint at the primary vertex of interaction is removed to improve the momentum measurement

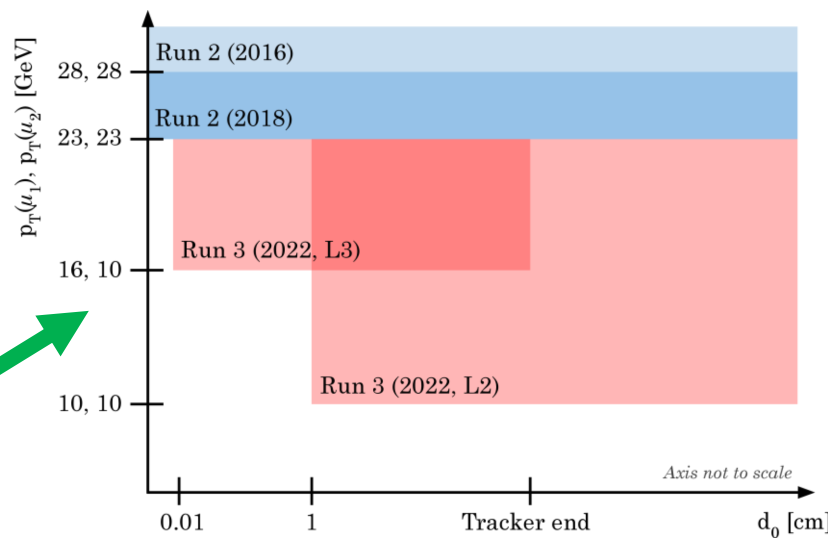
Displaced (tracker) tracks are reconstructed in the tracker with dedicated tracking iterations seeded by DSA.

Displaced Global muon tracks are built *outside-in* by matching a DSA with a displaced track. Global track refit is done with no vertex constraints



DSA muons strongly efficient for very large displacements (transverse decay length)

Similar approach at HLT allowed to strongly reduce the p_T thresholds in Run3, and increase the sensitivity at large displacement



Muon identification

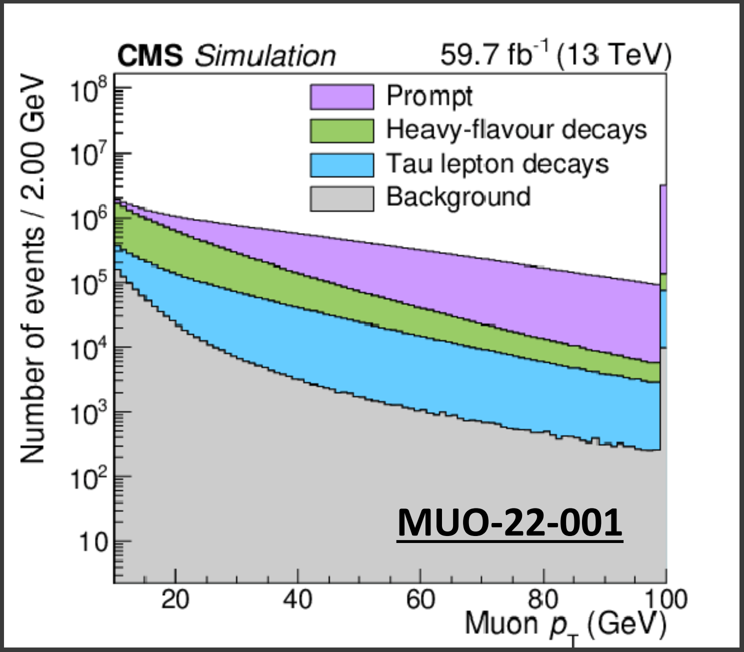
Since the wide muon p_T range and topologies in physics searches, some commonly valid sets of identification (ID) criteria have been developed to discriminate genuine muons from background.

Genuine muons:

- prompt muons from mesons, top and bosons decays
- muons from secondary heavy-flavour decays like b, b→c, and b→τ cascade
- prompt high-p_T (> 200 GeV/c) muons from heavy resonances or boosted topologies

Background:

- muons from light-flavour decays
- hadron punch-through

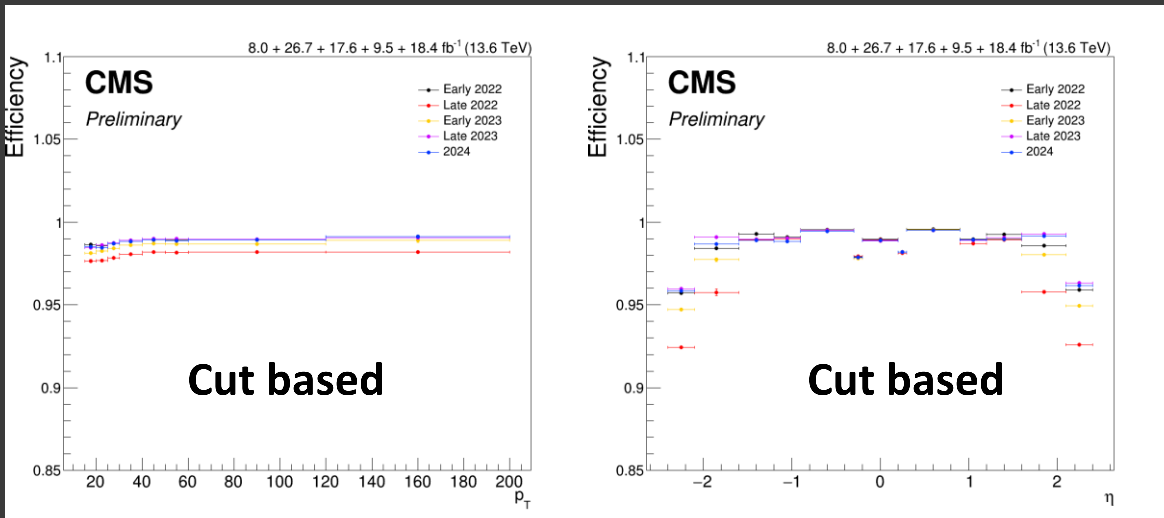


Selection criteria:

- **Loose ID** and **Soft-MVA** (almost ready to be deployed) optimized for low-p_T (< 30 GeV/c)
- **Medium ID**, **Tight ID**, and **Muon-MVA ID**: targeting a wider p_T range (10-200 GeV) and topologies (prompt and heavy-flavour muons)
- **Isolation** (on top of IDs): to select prompt muons
- **Prompt-MVA ID**: optimized for prompt isolated muons
- **High-p_T ID**: applied to the dedicated muon track refits, optimized for high momentum muons

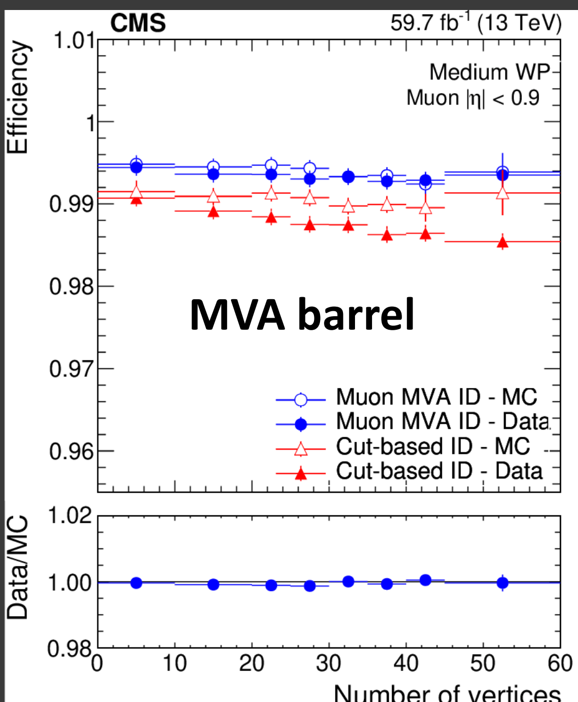
Medium cut based and MVA IDs

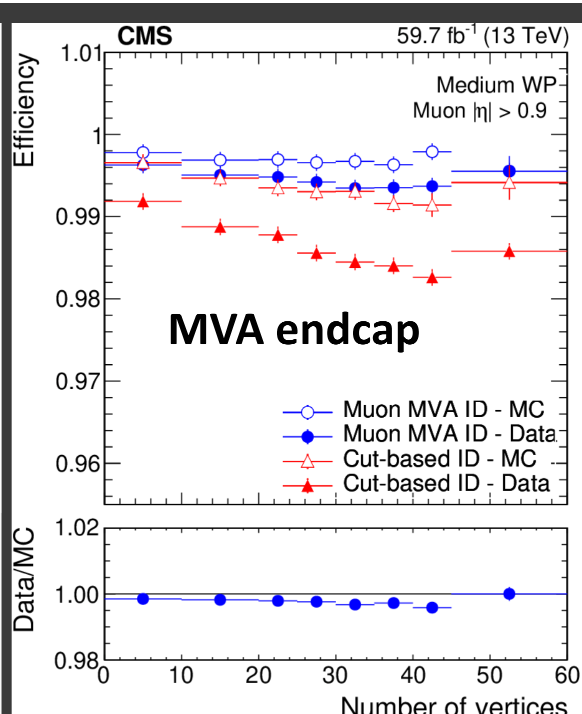
CMS DP-2024/067
MUO-22-001



Medium cut-based ID performance measured in Run3 met the expectations:

- 98-99% efficient rather flat vs p_T
- slightly affected (<5%) by some hardware issues in the forward muon system





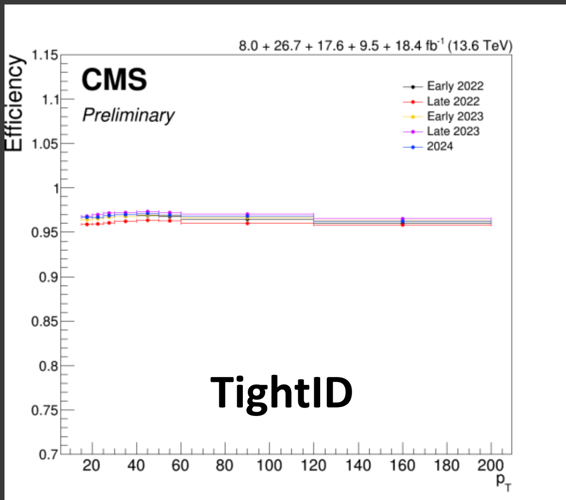
Performance of the **new developed MVA ID** (medium working point) have been measured with Run2 data, but targeting Run3 analyses:

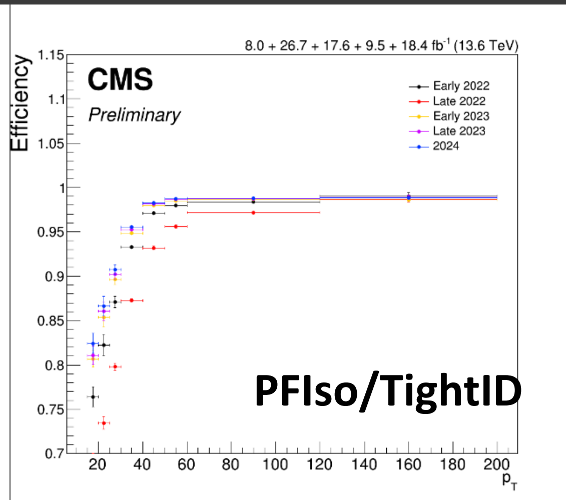
- **recent preliminary Run3 measurements confirmed the expectations**
- no retraining will be done
- **more resilient wrt PU** than the corresponding cut-based
- larger use is expected as new Run3 analyses will start

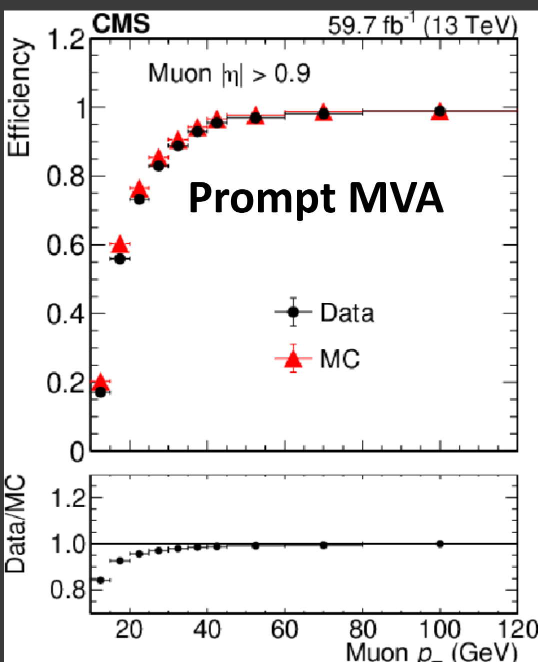
Tight ID + Isolation vs Prompt MVA

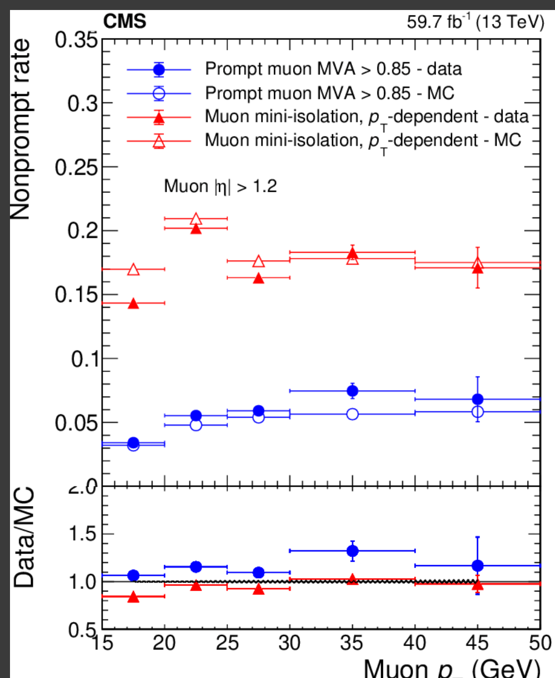
CMS DP-2024/067

MUO-22-001









Tight cut-based ID exploits tighter quality cuts on the muon system leg, that, together with vertexing requirements, aim at returning high efficiency and purity for prompt muons:

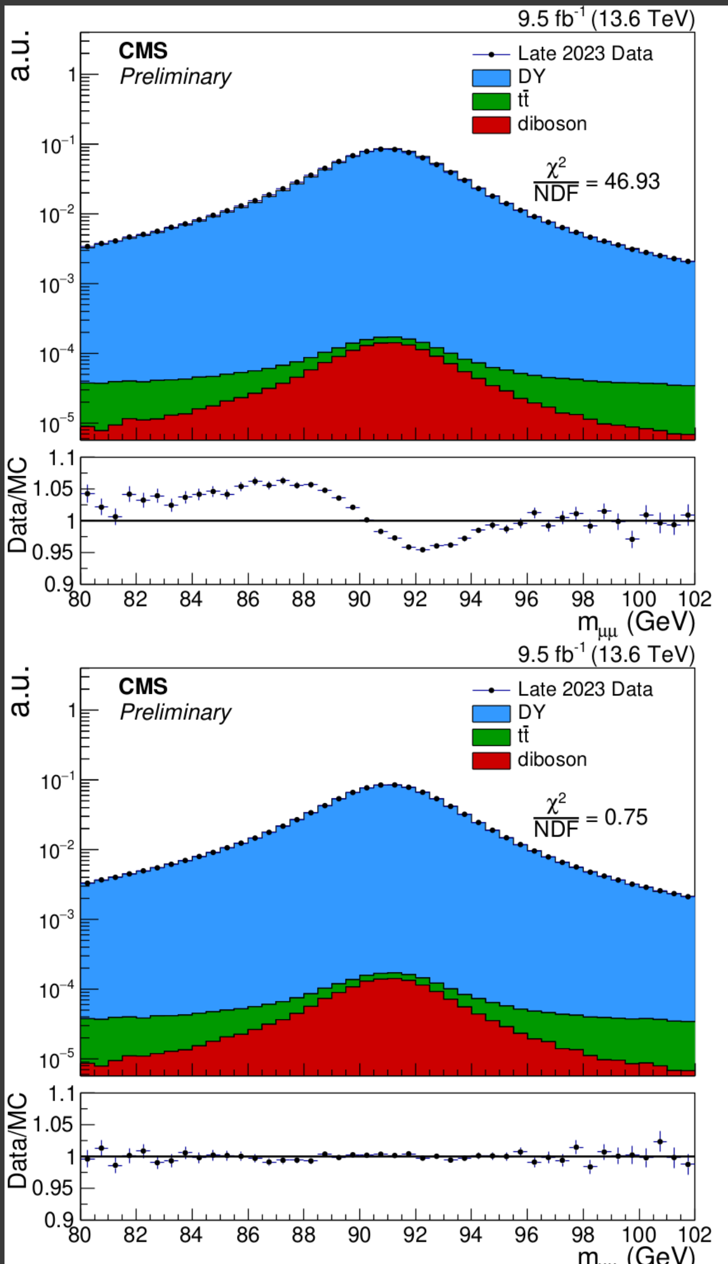
- Run3 measurements within the expectations: 96-97% efficient rather flat vs p_T, slightly more (<8%) affected by some hardware issues in the forward muon system (backup)

In addition to ID, **isolation is generally recommended for muons:**

- sum of charged hadrons and neutral particles energy (reconstructed using tracker and calorimeter information, **Particle-Flow isolation**) in a cone ΔR < 0.4 around the muon
- sum of charged tracker tracks as alternative, used for high- p_T muons

Competitive results for the **new prompt Muon MVA ID**

Muon momentum scale and resolution



CMS DP-2024/065

Very accurate (10^{-3}) measurement of the muon momentum scale is achieved using $Z \rightarrow \mu^+\mu^-$ events in data and NLO simulations (similarly to Run2 arXiv:1208.3710)

$$1/p_T \rightarrow M*1/p_T + q*A$$

Multiplicative (magnetic field) and additive (alignment) corrections are derived in 2 steps:

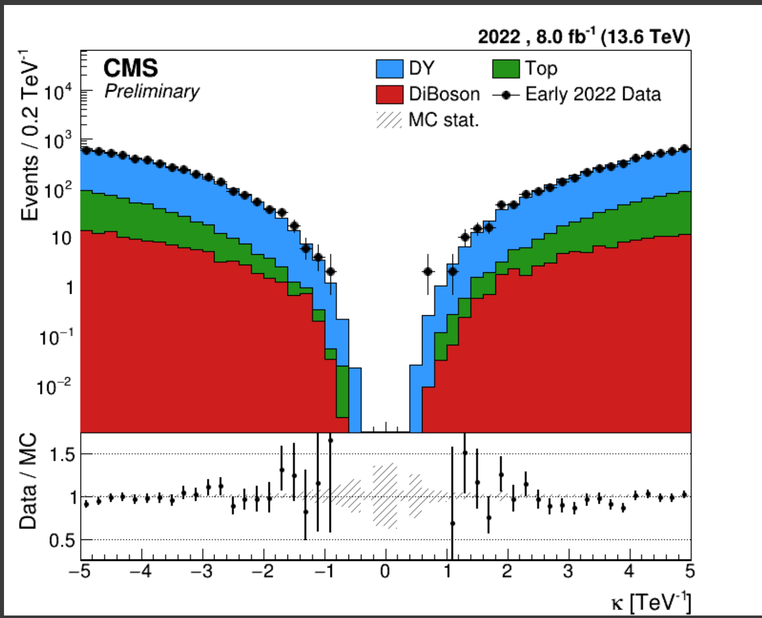
first step:

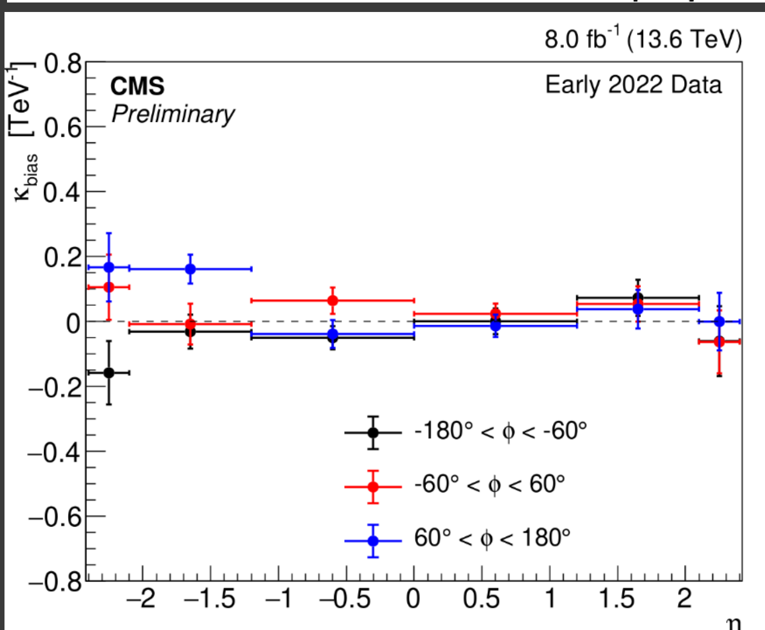
- **scale correction** on the curvature $<1/p_T>$ is obtained in bins of charge (Q), η and ϕ, by keeping μ^+ and μ^- separated (allows to obtain Z mass value free of bias in simulation)
- **resolution correction** based on the difference between generated and reconstructed muon momentum in MC vs p_T in bins of abs(η), and number of tracker layers.

second step: the initial corrections are fine tuned to optimize the data-MC agreement

- final **scale correction** is extracted in bins of η and ϕ.
- final **resolution corrections** for simulated muons are extracted binned abs(η).

Momentum scale for high-p_T muons

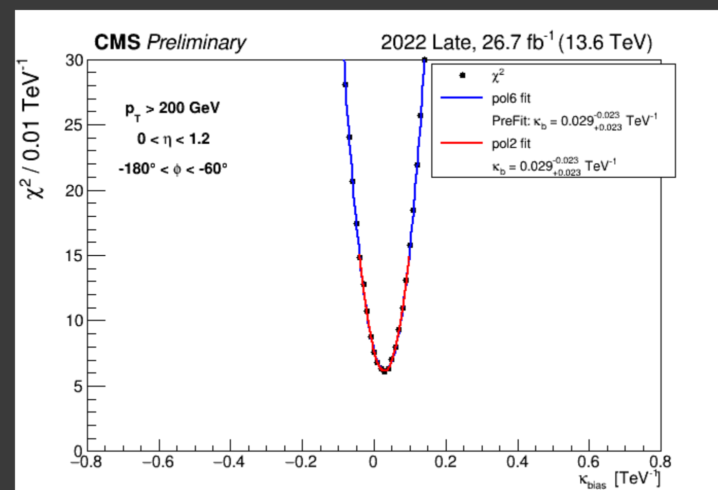




CMS DP-2024/065

Bias in the muon momentum scale for **high-p_T muons** is estimated using the **Generalized Endpoint method**:

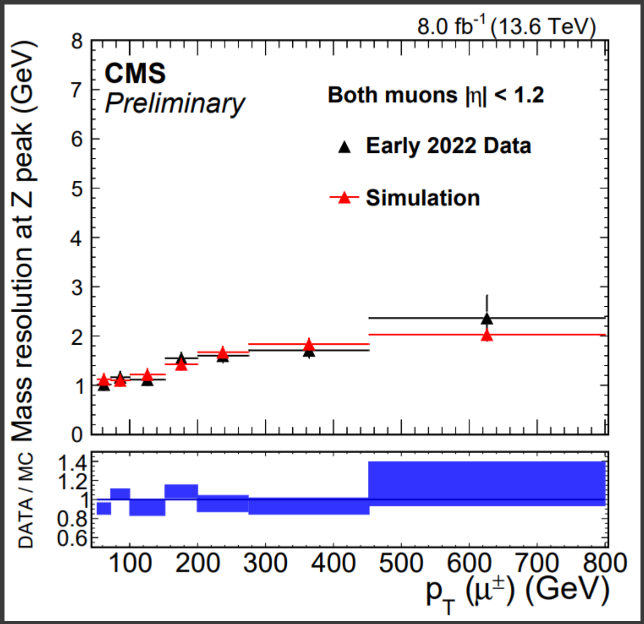
- based on data-MC comparisons after injecting a set of hypothetical values of bias in the simulated **muon curvature ($\kappa = q/p_T$)**
- most reliable additive bias is the one which minimizes the χ^2 of the difference between the curvature measured in data and the one hypothesized in MC

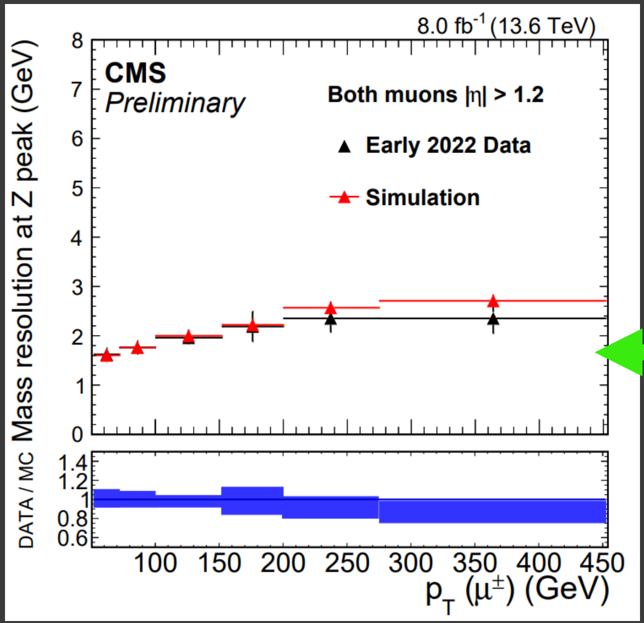


- bias is derived in different bins of η and ϕ for muons with a p_T > 200 (110) GeV and |η| < 2.1 (> 2.1)
- bias in the muon momentum scale measurement is rather compatible with 0 within the statistical uncertainty

Momentum resolution at high-p_T

CMS DP-2024/065





The **muon momentum resolution** for **high-p_T muons** is measured in collision data by exploiting the dimuon mass resolution of events from the Z boson decays:

- dimuon mass resolution ΔM/M, is fitted for different p_T and η ranges relative to the individual muon p_T
- 3 different functions are convoluted with a **Breit-Wigner** to perform the dimuon mass fit:
  - a **Crystal Ball** to extract the nominal value
  - a **Cruijff,** and a **Double-sided Crystal Ball** to extract the systematic variations
- The same procedure is applied to both data and MC:

  barrel: rather good agreement between simulated p_T and the one measured in data

  endcap: an additional 5% of smearing has been applied to the p_T of the simulated muons to correctly match the data

  an additional flat **10% of systematic uncertainty** has been measured on top of the statistical uncertainty shown in the ratio plots

Summary

A successful physics program relies on a highly efficient muon reconstruction and identification, further than an accurate measurement of its momentum

Standard muon objects demonstrated to efficiently work:

- Overall high efficiency among the 3 years of data taking
- Good understanding of the impact of the detector conditions (in particular during 2022)
- Successful recovery/mitigation strategies, returning an excellent performance since Late 2023 data taking
- Excellent measurement of the muon momentum scale

Dedicated studies to “less standard” muon objects (high-pT muons) show very good results

New developments done during and right after (displaced muons and MVA selectors) Run2 are now starting to be applied

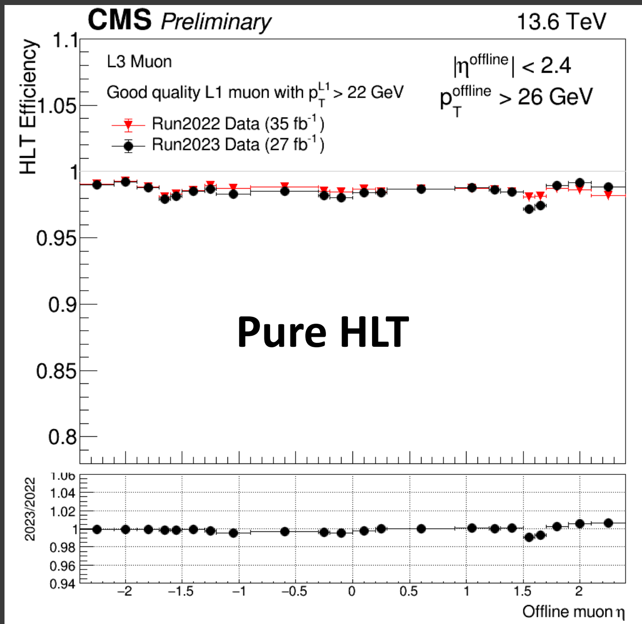
- MVA IDs confirmed the expected performance without any further Run3 retraining
- Promising results for analyses using displaced muons
- Ongoing efforts to keep these studies centralized

We hope to see soon in the coming Run3 analyses the further ongoing developments that are very close to be deployed!

Back-up

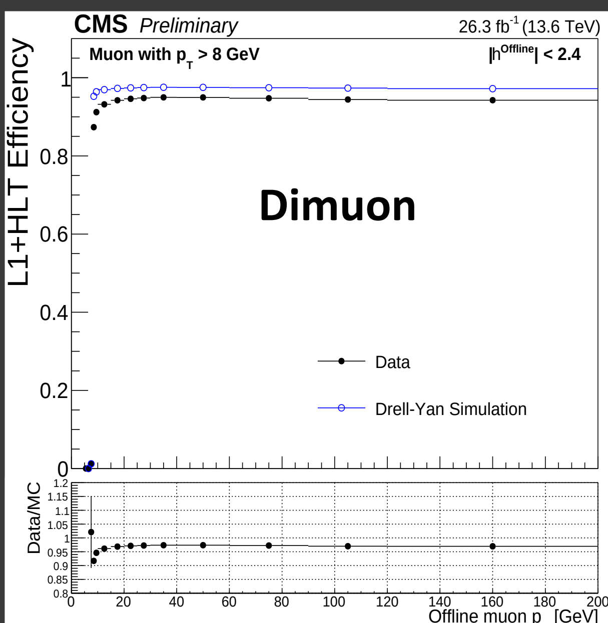
High Level Trigger performance

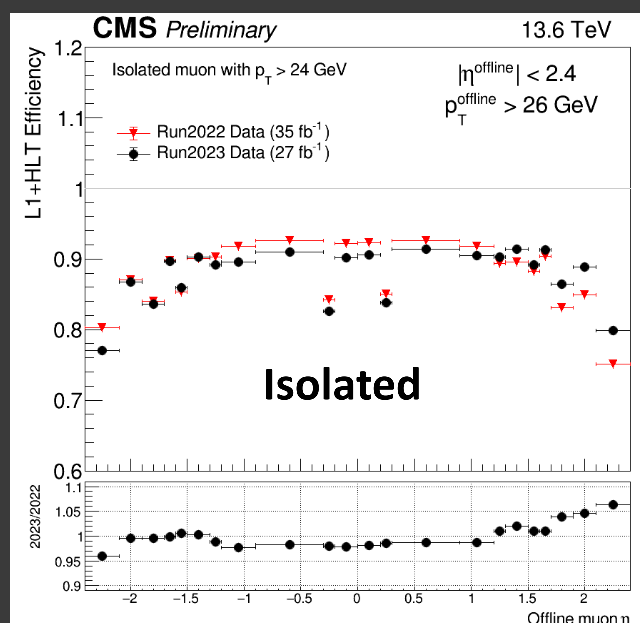
CMS DP-2023/017
CMS DP-2024/005

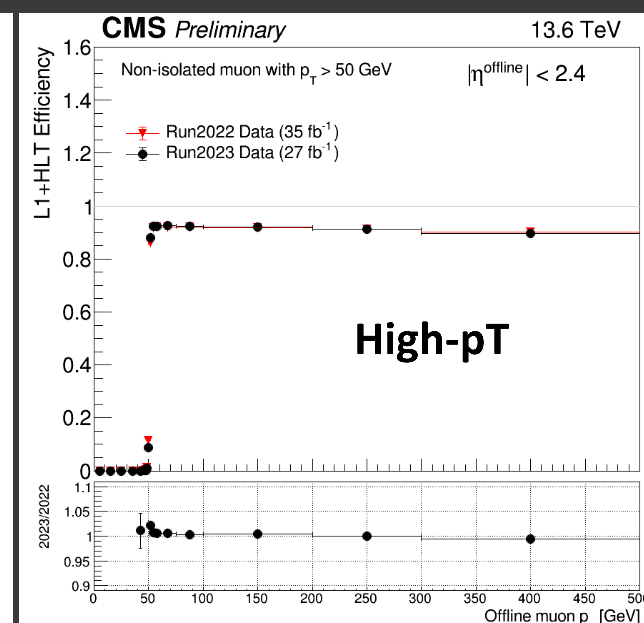


Pure HLT reconstruction efficiency achieves 99%:

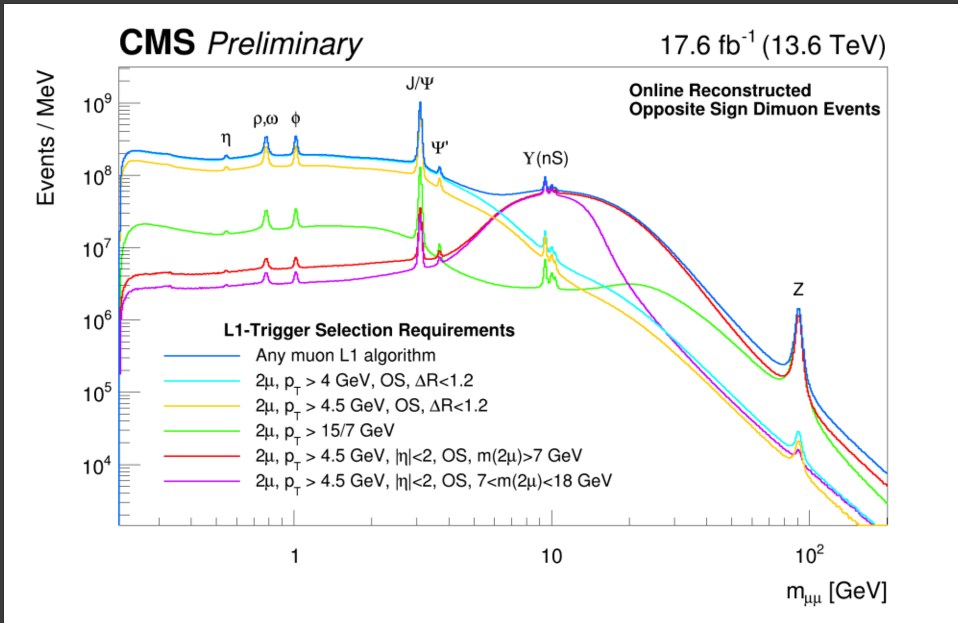
- efficiency is about 95% also considering the effect of the L1 (hardware) trigger based on the muon system only
- HLT paths exploiting muon objects are many (dimuon scouting, dimuon displaced) in addition to the most general three:
    - **Double muon with low p_T** threshold
    - **Single muon** with **isolation** for medium-p_T searches
    - **Single muon** with no isolation **for high-p_T** searches

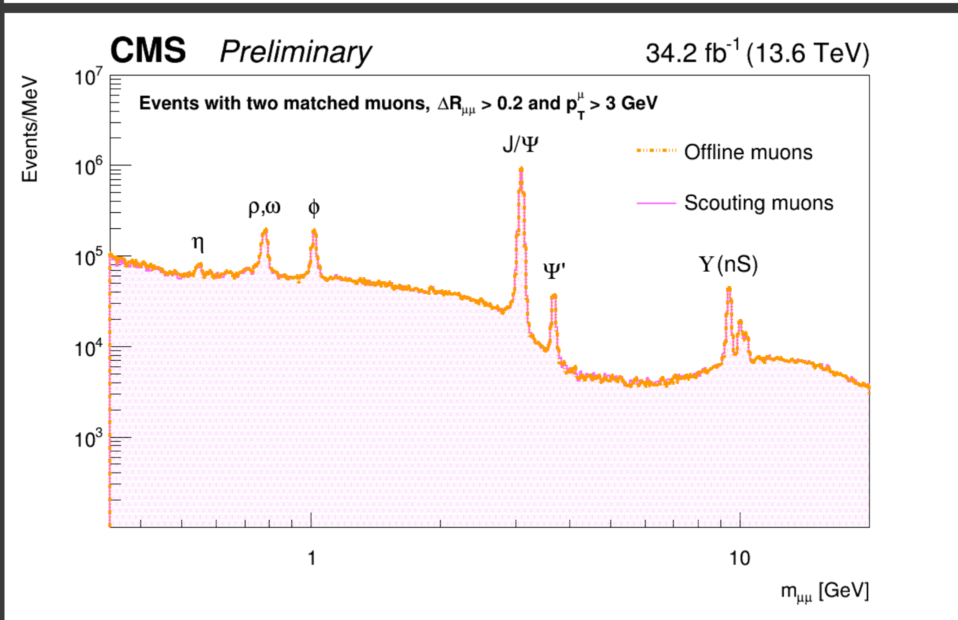




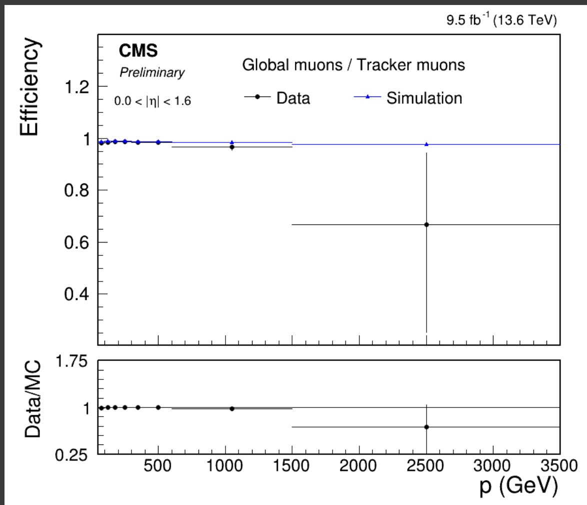


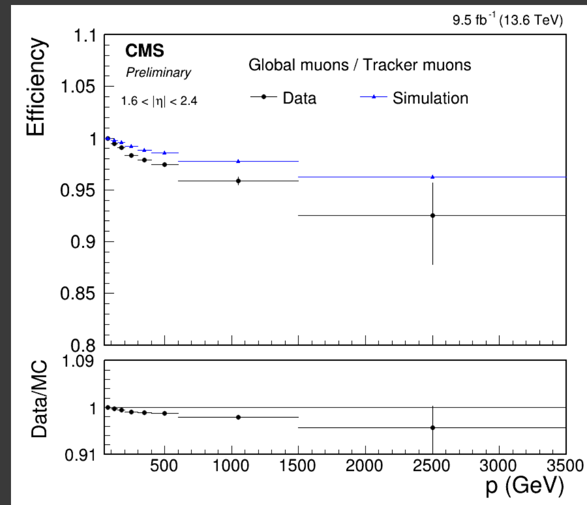
HLT Scouting

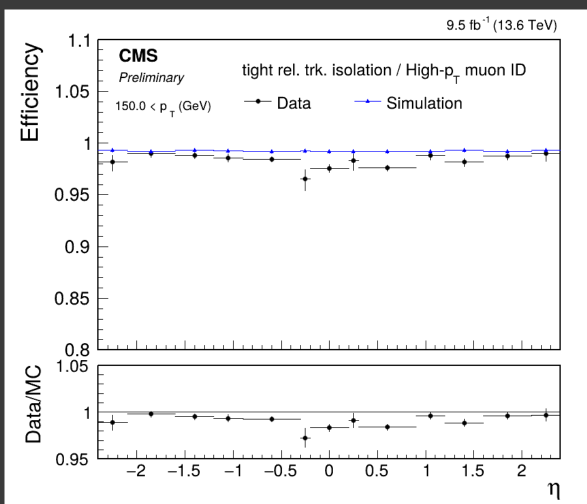


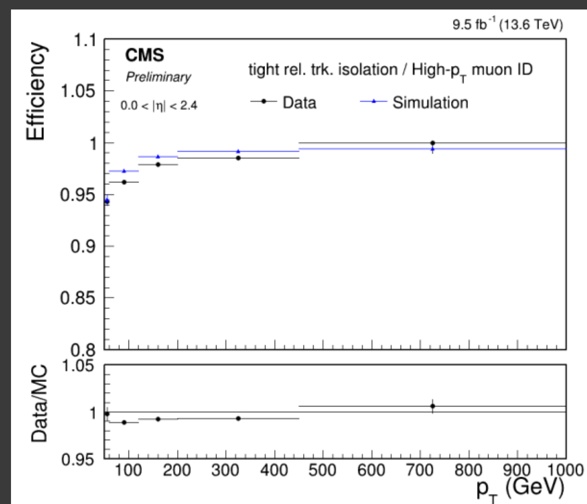


High-p_T muons







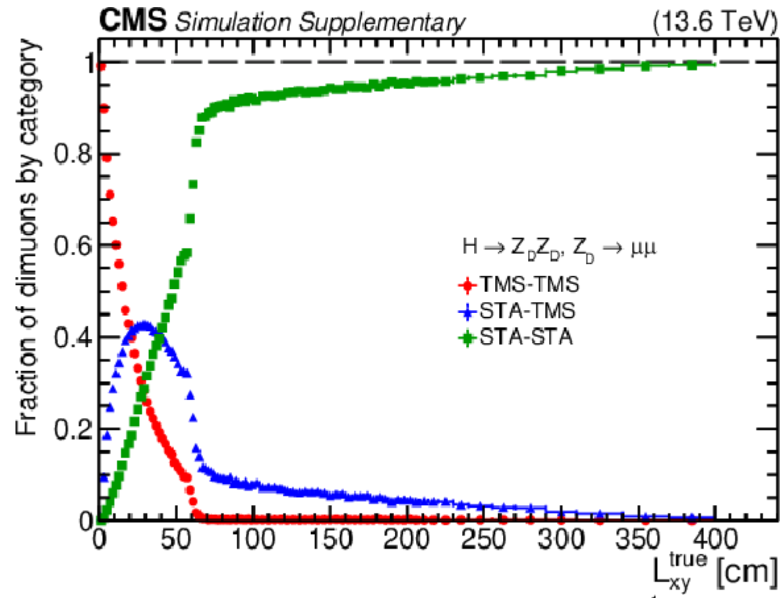


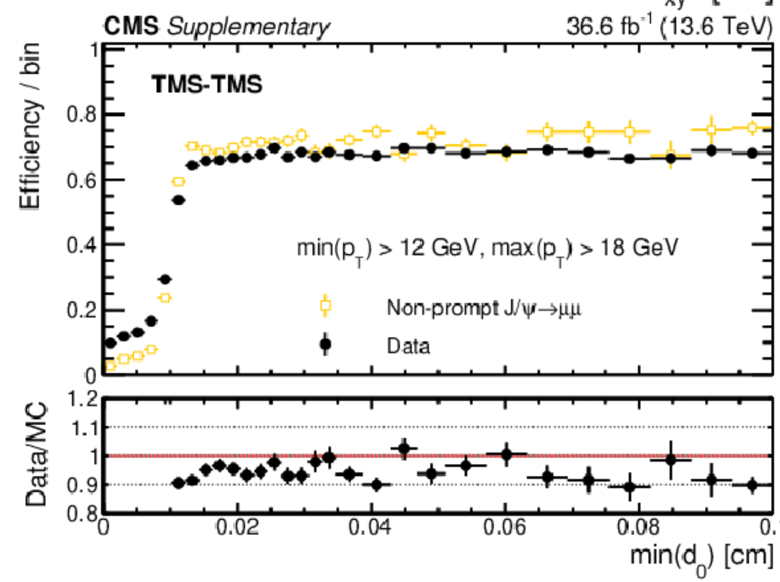
Reconstruction of displaced muons

Displaced muons are, by definition, not produced in the primary interaction, therefore, dedicated algorithms have been developed to efficiently and accurately reconstruct them:

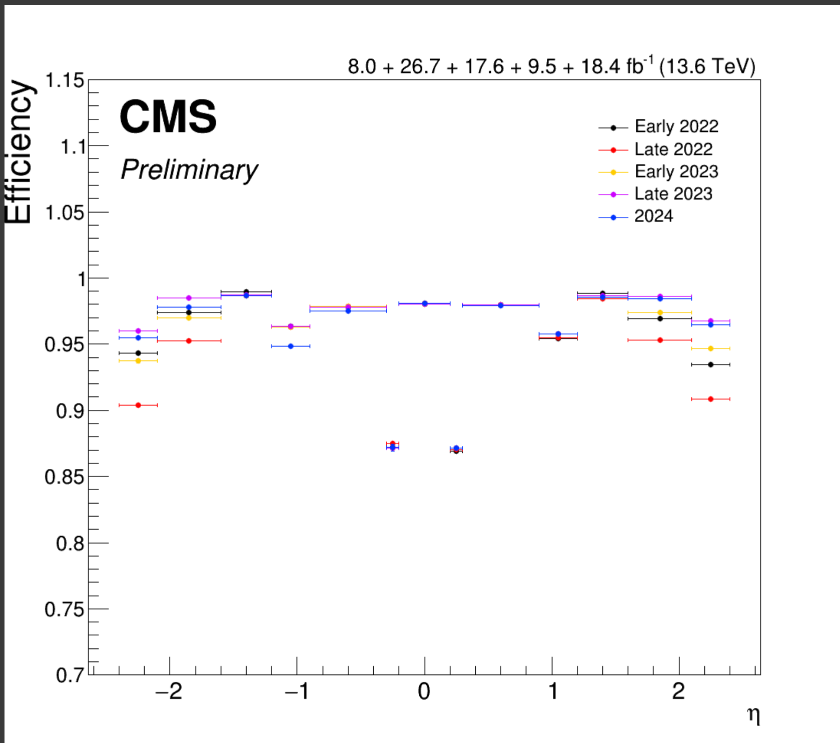
Trajectories of muons produced within the silicon tracker can be reconstructed by both tracker and muon system, while particles produced in the outer tracker layers or beyond can only be reconstructed by the muon system.
Since the dimuon vertex resolution and background composition strongly depends on whether the muon is reconstructed in the tracker or not:

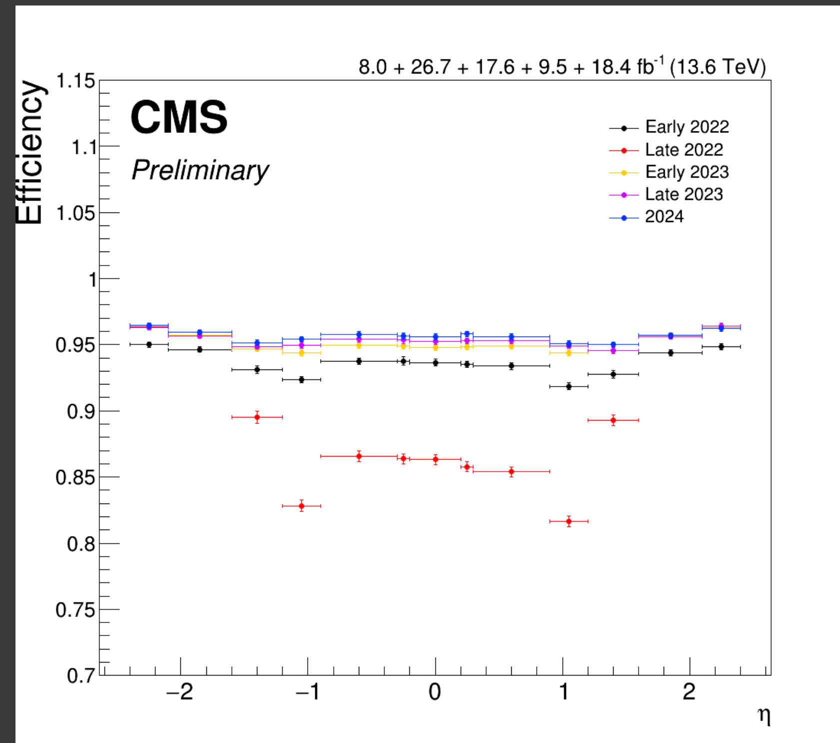
a) both muons are reconstructed using both the tracker and the muon system (TMS-TMS category);
b) both muons are reconstructed using only the muon system (STA-STA category)
c) one muon is reconstructed only in the muon system, the other muon is reconstructed using both the tracker and the muon system (STA-TMS category).





Tight ID and Isolation vs eta



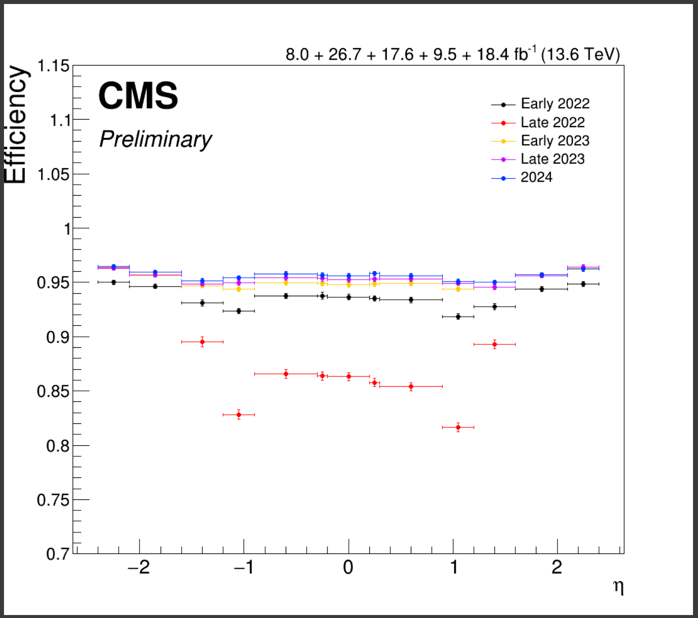


Isolation is fundamental to select prompt muon decays from

evaluated by summing up the energy in a $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ cone around the muon:

- **track-based isolation** in a cone $\Delta R < 0.3$, used for **high-p_T muons**
- charged hadrons + neutral particles in a cone $\Delta R < 0.4$, reconstructed using both tracker and calorimeter information (**Particle-Flow isolation**)

Isolation



Isolation evaluated by summing up the energy in a

$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ cone around the muon:

- **track-based isolation** in a cone $\Delta R < 0.3$, used for **high-p_T muons**
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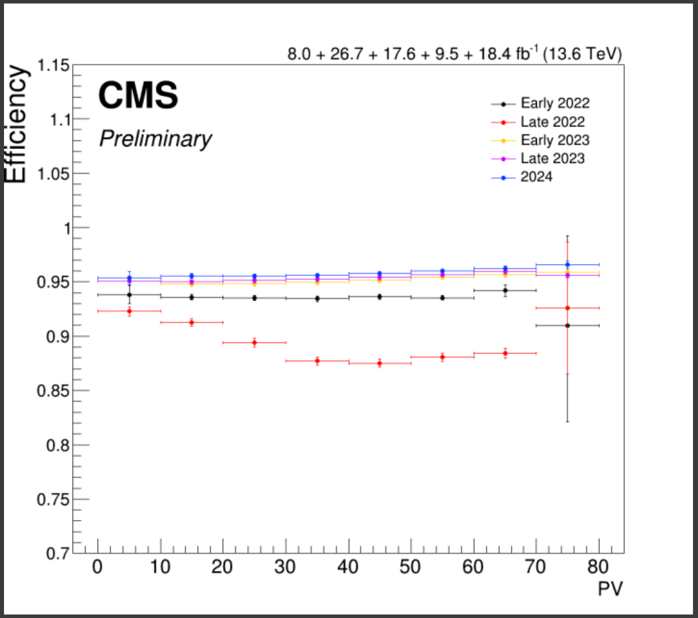

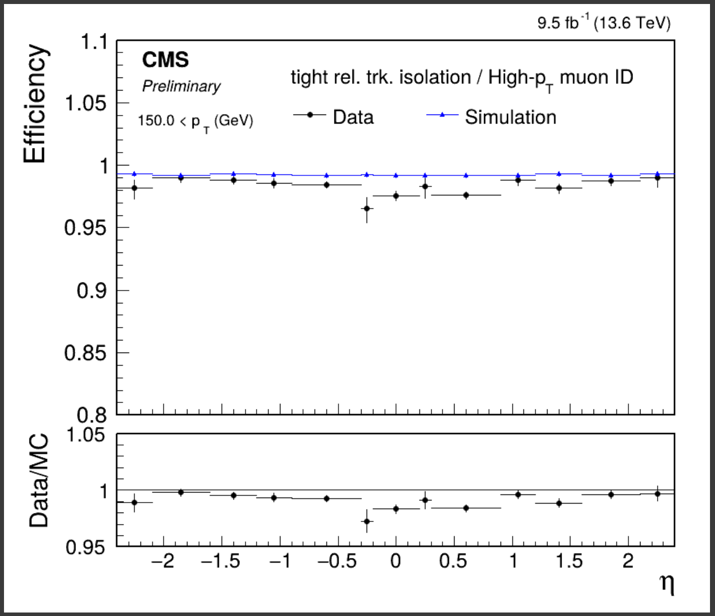

Prompt-Muon MVA performance