CMS Muon Object Performance in Run 3

Rencontres de Blois 2024

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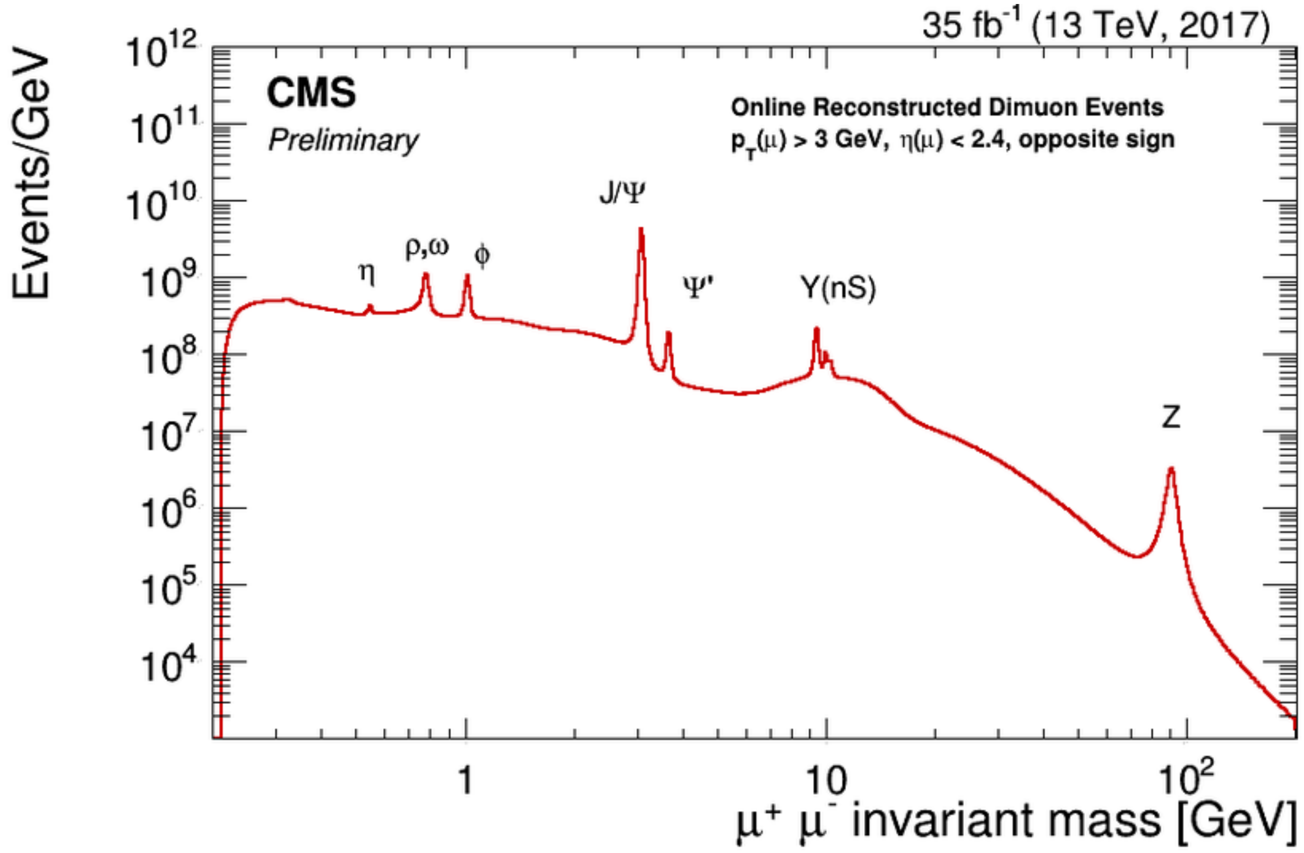
Overview

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

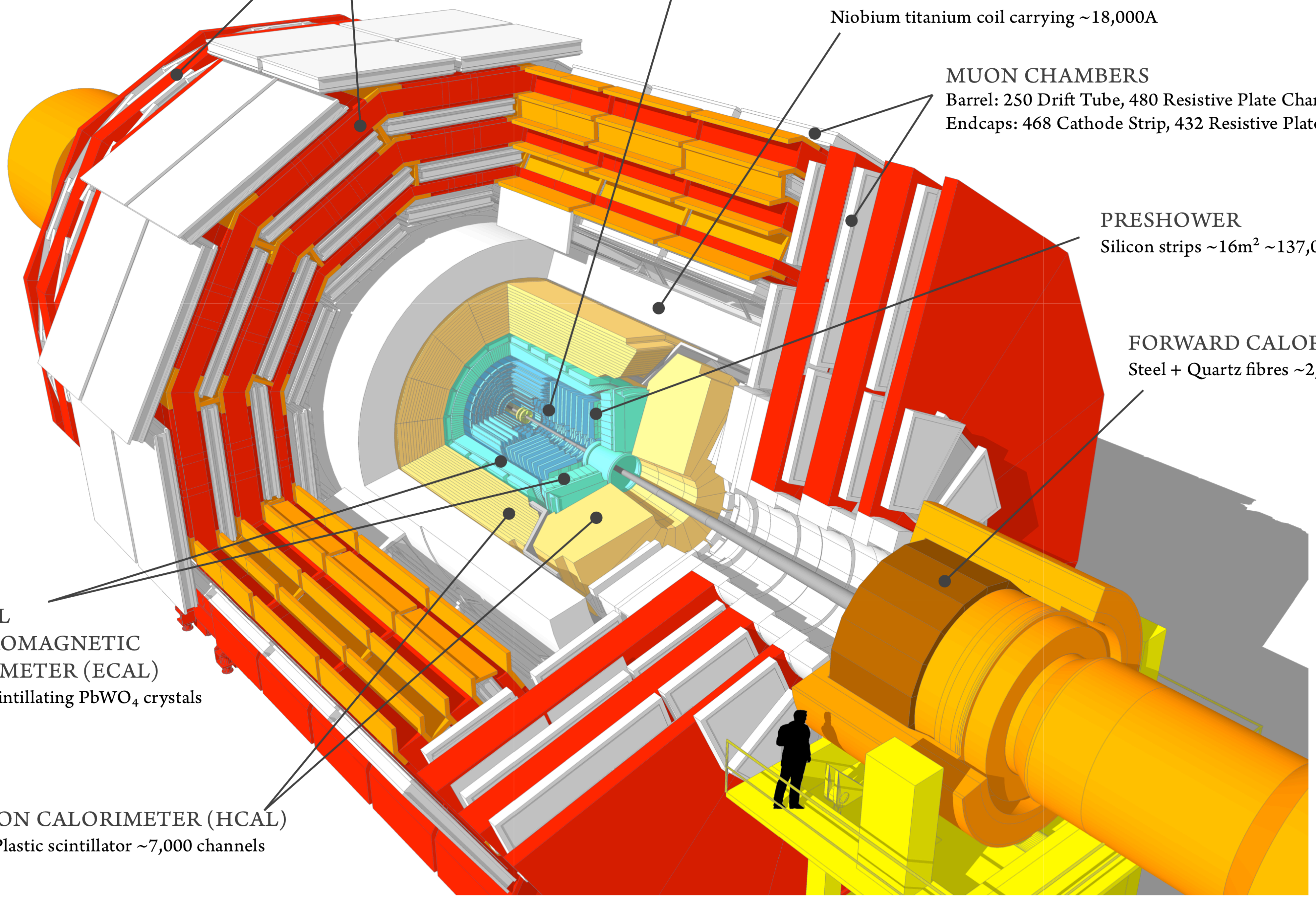


In Run3 the CMS detector recorded about 180 fb^{-1} (about 2/3 during 2024):

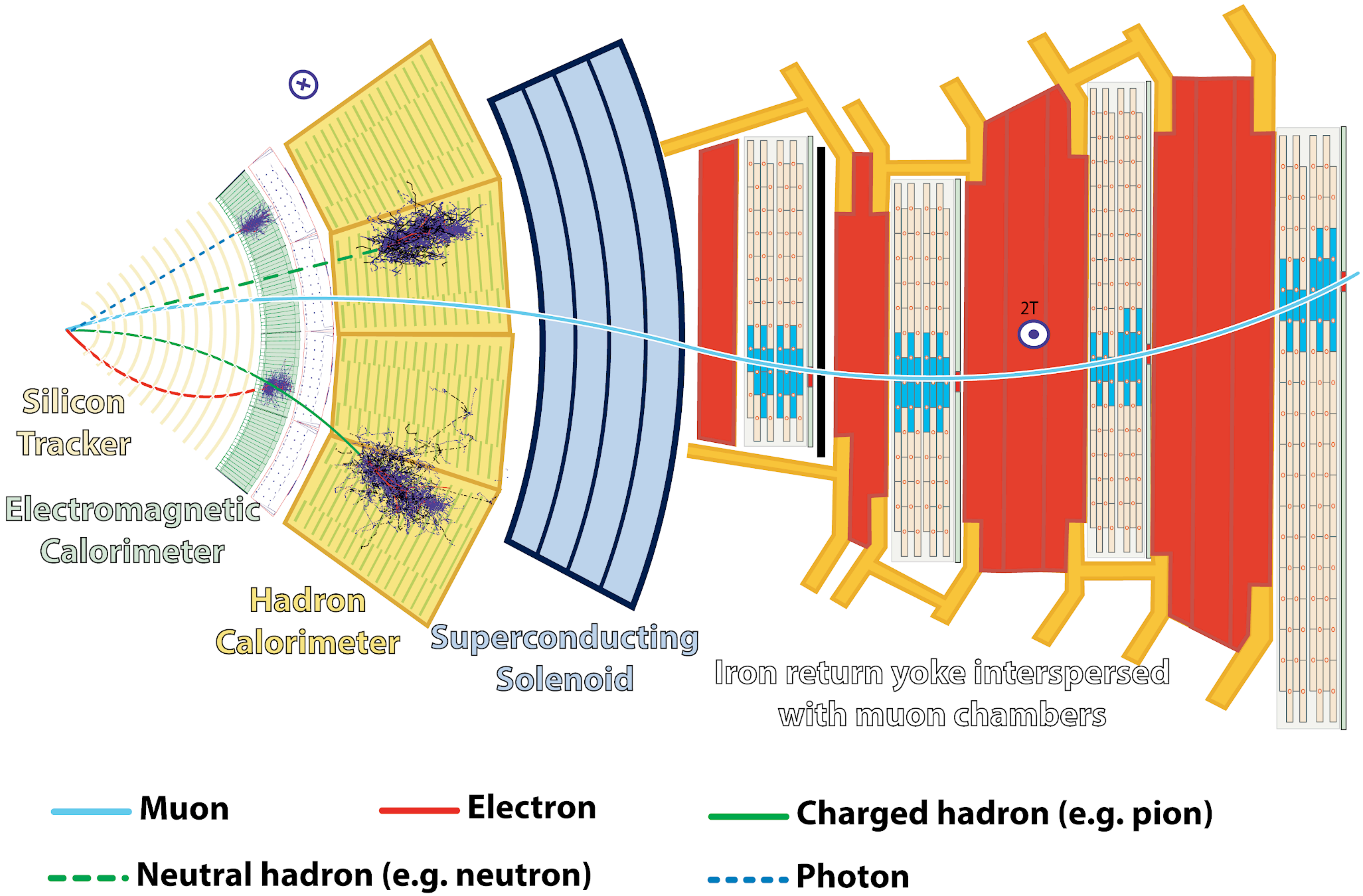
- muons contribute to about a half of the total trigger rate
- offline analyses relying on the presence of muons as signal or background

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

CMS Experiment

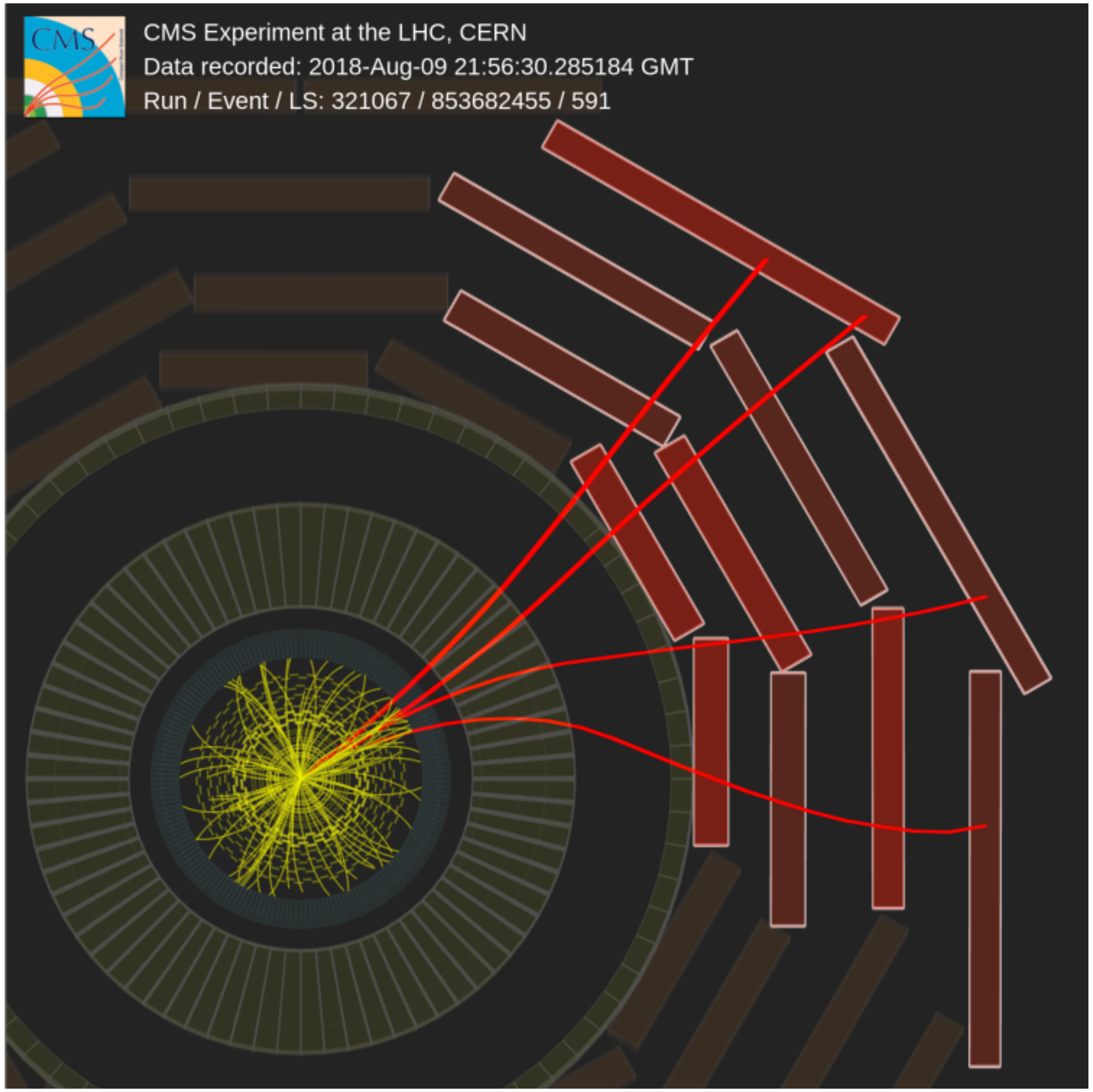


Particle Reconstruction



Muon Reconstruction

Muon trajectory is built using hits in silicon tracker and muon system



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

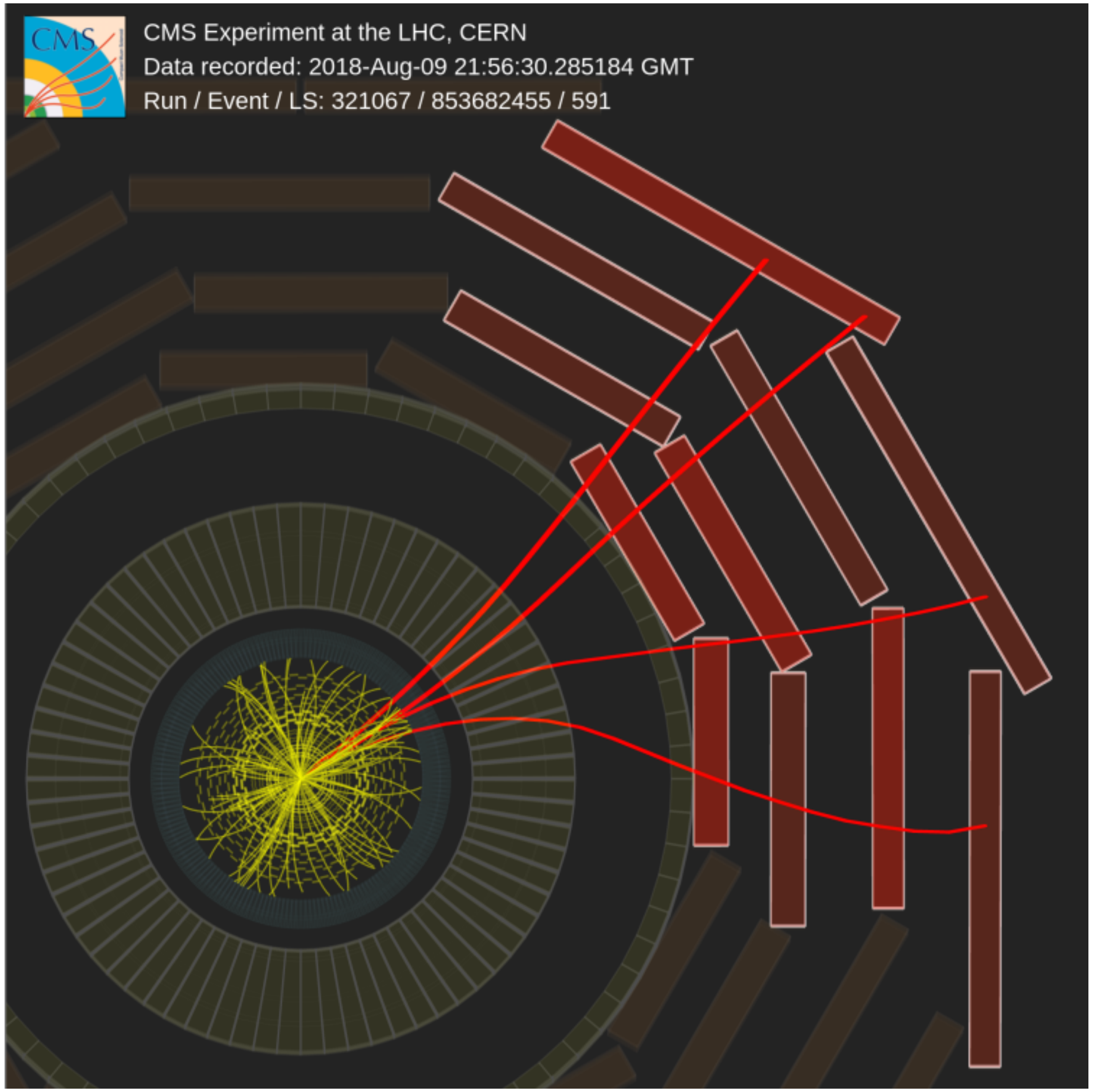
Tracker muon tracks are built *inside-out* by propagating tracker tracks, reconstructed with the iterative tracking, to the muon system, where a loose matching to a DT or a CSC segment track is required

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

High-energy muons have almost straight tracks and could undergo radiative losses and showering. Dedicated track refit strategy have been developed and an accurate knowledge of the detector alignment becomes critical.

Displaced muons are not produced in the primary vertex. Dedicated algorithms have been developed to reconstruct them.

Muon High Level Trigger



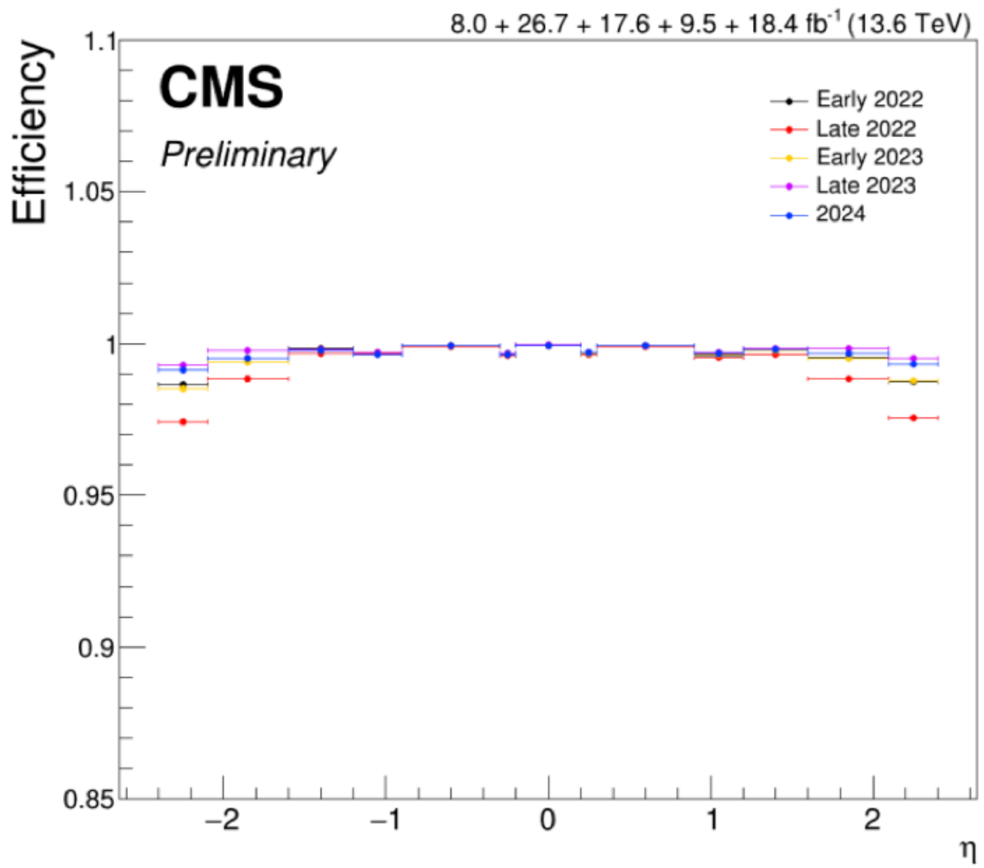
Algorithms for on-line (**High Level Trigger)** and offline reconstruction are almost the same:

- 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

Reconstruction Performance

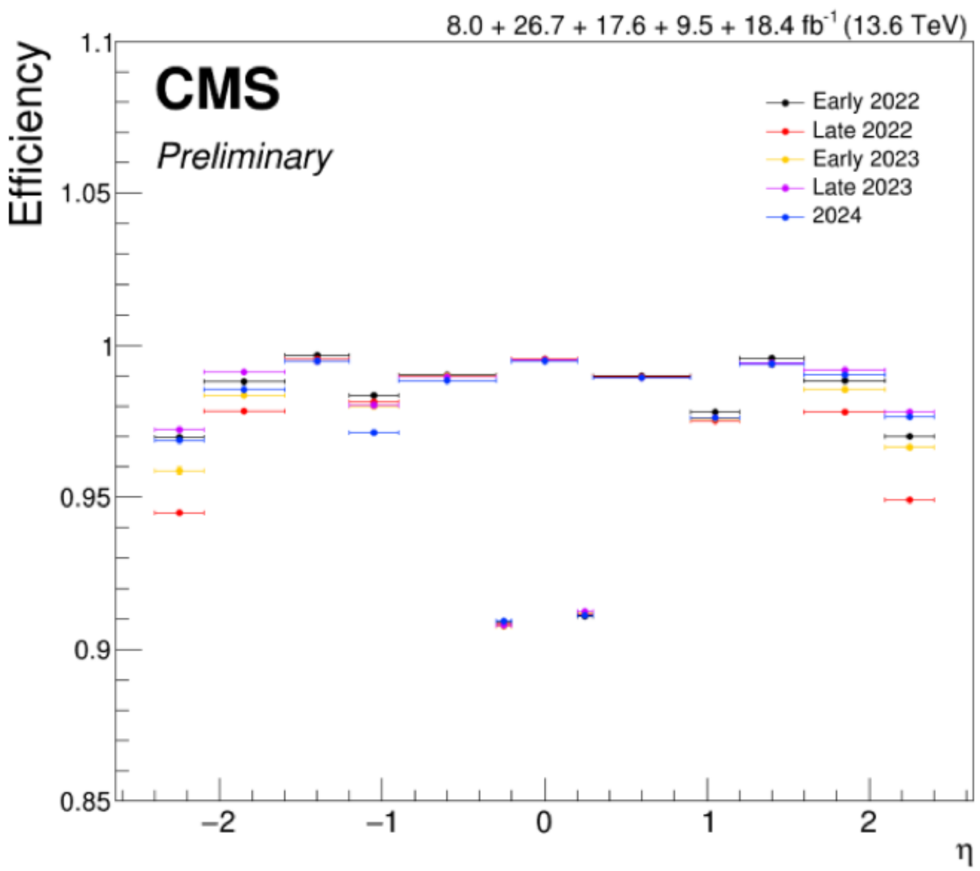
Reconstruction efficiency is studied using the fitting tag-and-probe method at the Z mass peak

Tracker muons (Loose ID)



Tracker muons are highly efficient in regions of the CMS detector and for muons with low momentum

Global muons



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

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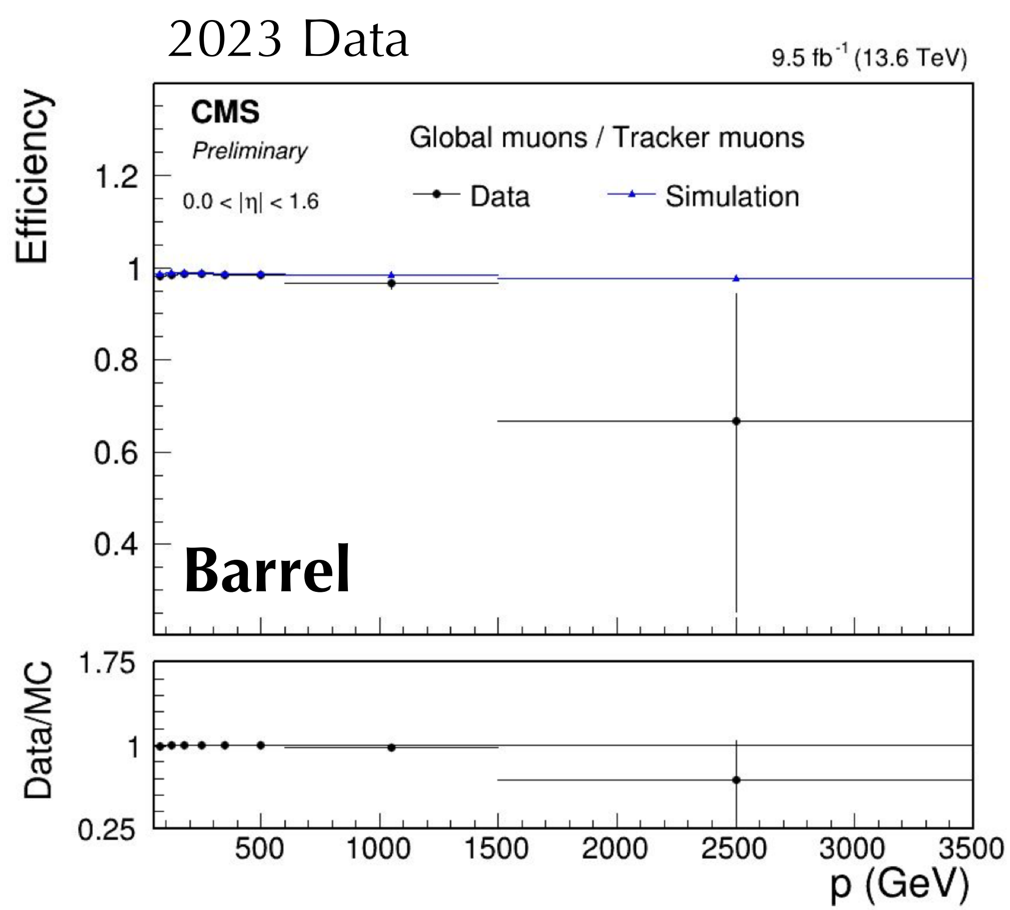
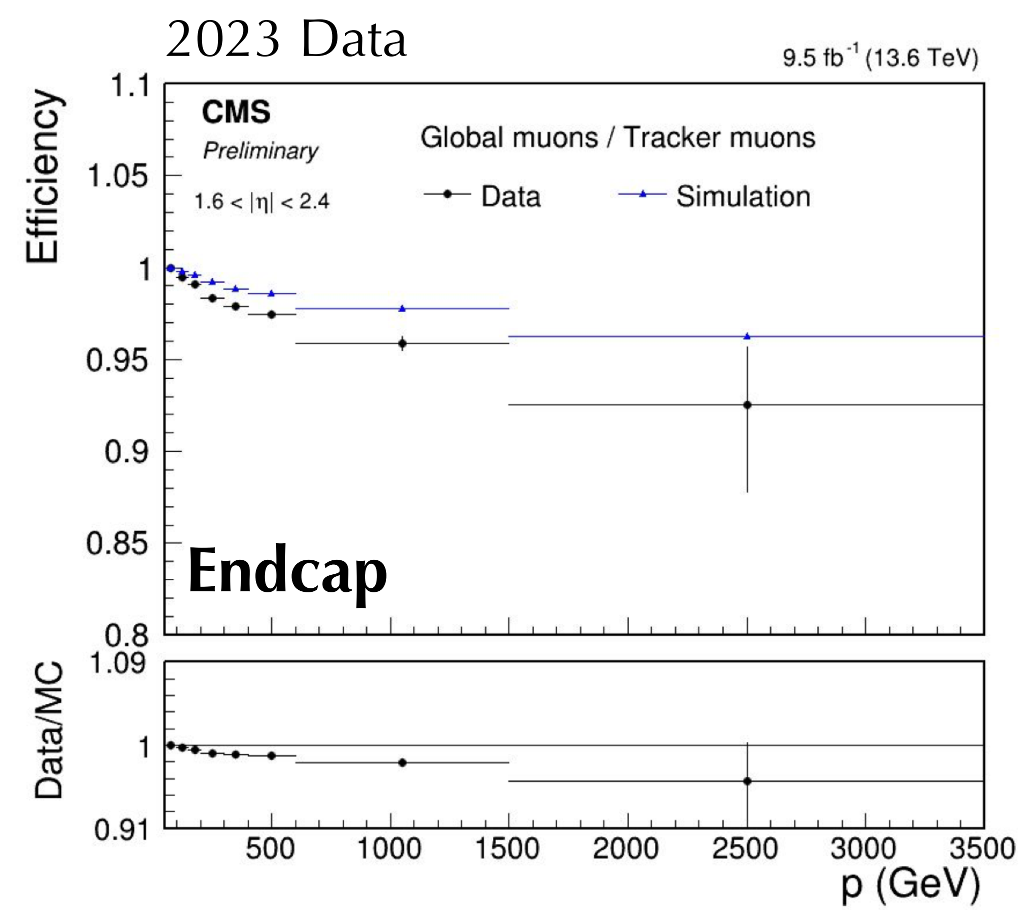
Reconstruction at high-energy

Global reconstruction efficiency **at high-energies** is performed using a cut and count tag-and-probe method using boosted DY events.





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

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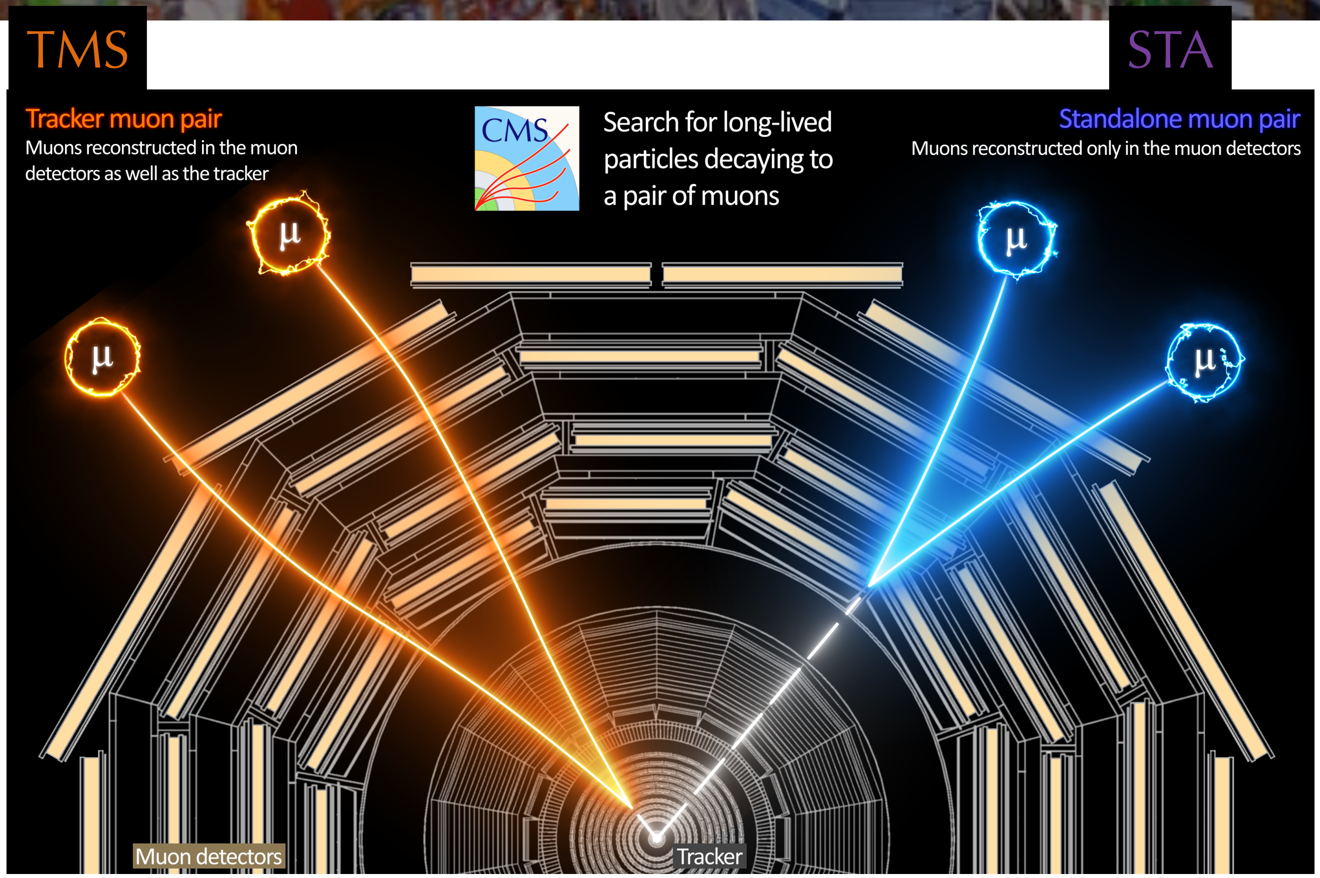
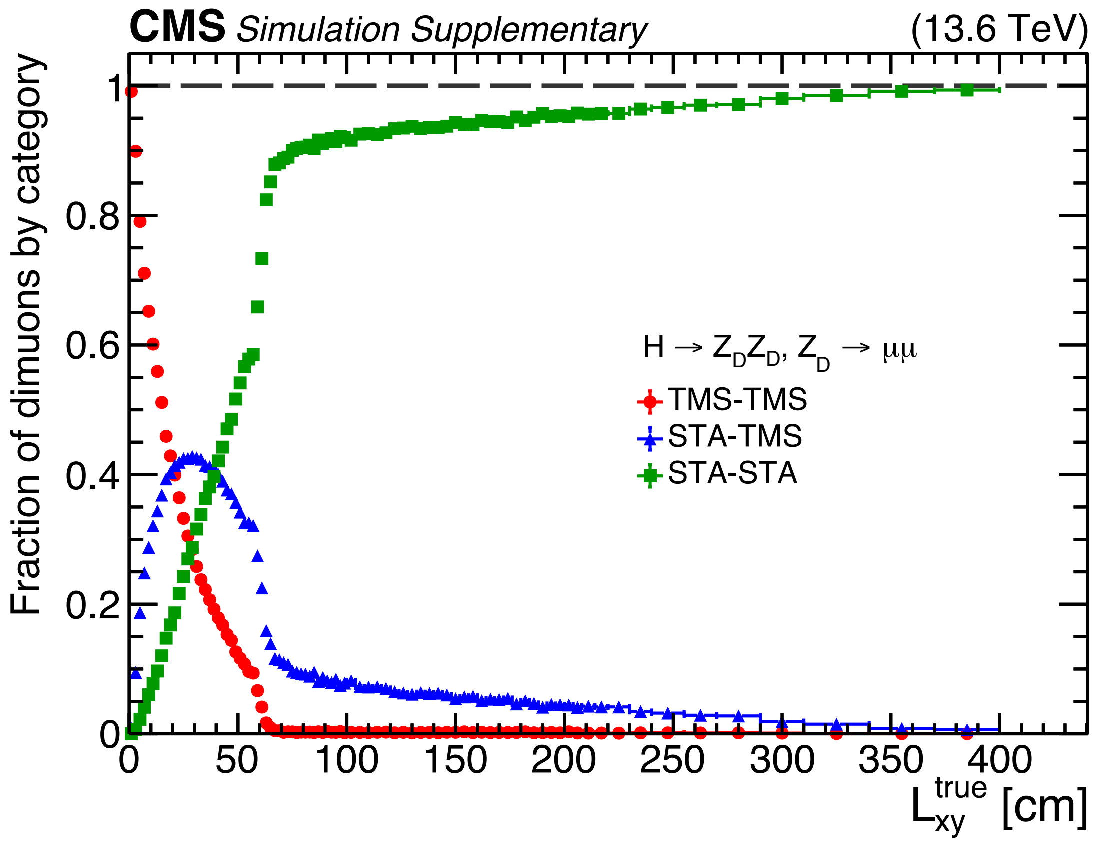
Reconstruction of displaced muons



Displaced standalone muon tracks allows to accept all the possible bending directions for the initial state of the track. No primary vertex constraint is applied to improve the momentum measurement

Displaced tracker tracks are reconstructed also in the tracker with dedicated tracking iterations seeded by displaced standalone tracks.

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

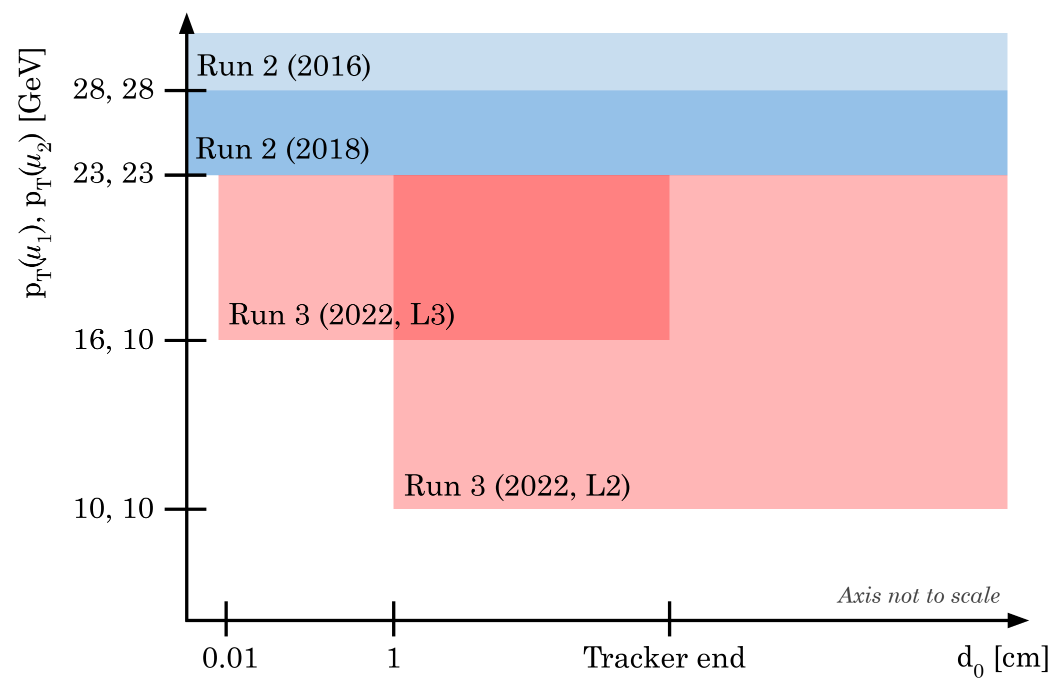


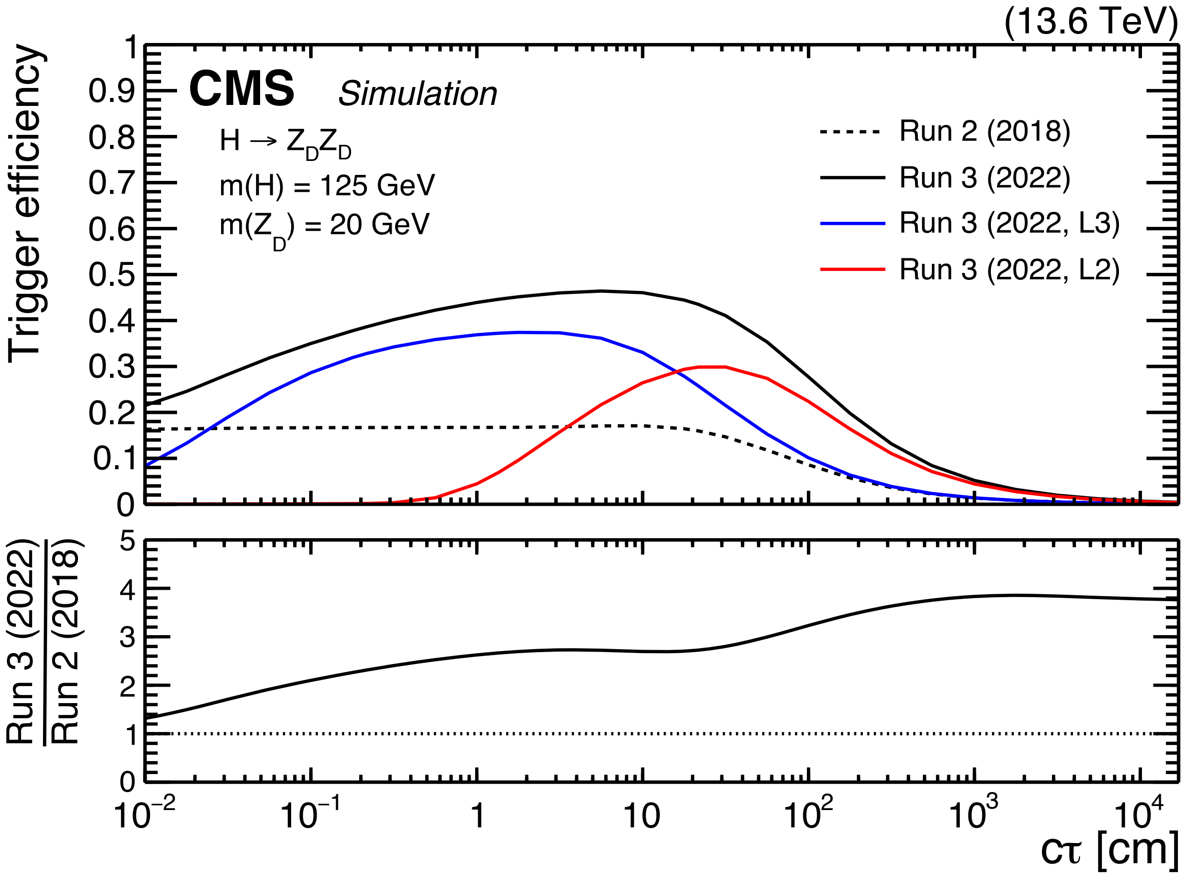
Fractions of signal events with zero, one, and two STA muons matched to TMS muons, as a function of the transverse decay length for generated hidden Abelian Higgs model.

EXO-23-014

Reconstruction of displaced muons

Dedicated triggers aims at recording dimuons produced both within and outside of the tracker.





In Run 2, these triggers required two muons reconstructed in the muon system alone, without using information from the tracker. The trigger optimization for Run 3 allows to increase the signal efficiency by lowering the p_T thresholds and by removing the beam spot constraint at L1.

The Run3 HLT algorithm (2022, L3) introduces new paths relying entirely on the online L3 muon reconstruction.

EXO-23-014

Muon Identification and Isolation

Identification (ID) criteria have been developed to discriminate muons from different physics topology from background:

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

Source of background could be muons from light-flavour decays and hadron punch-through

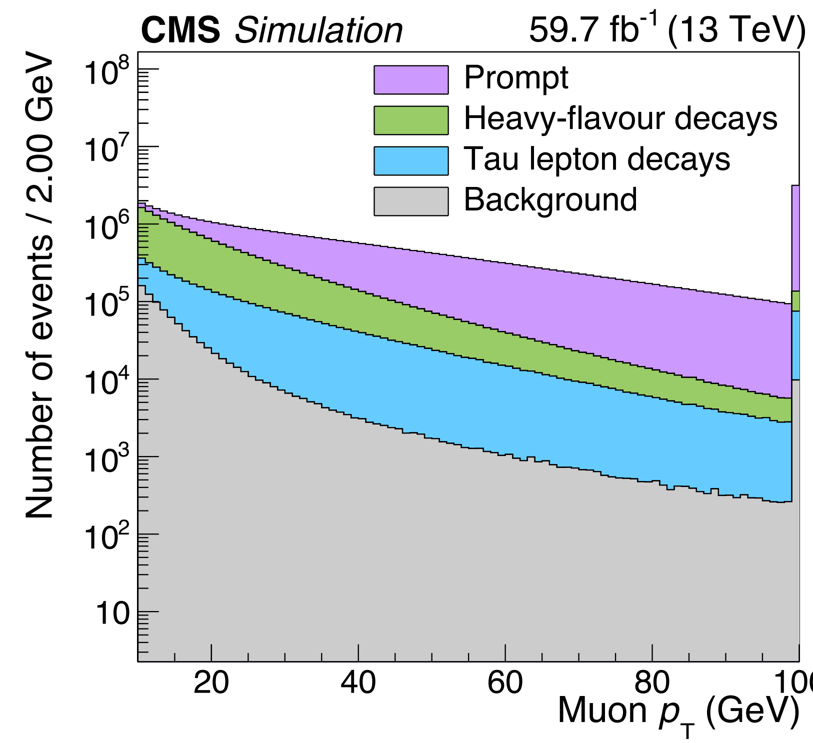
Loose ID and **Soft-MVA** (in publication) for $p_T < 30$ GeV.

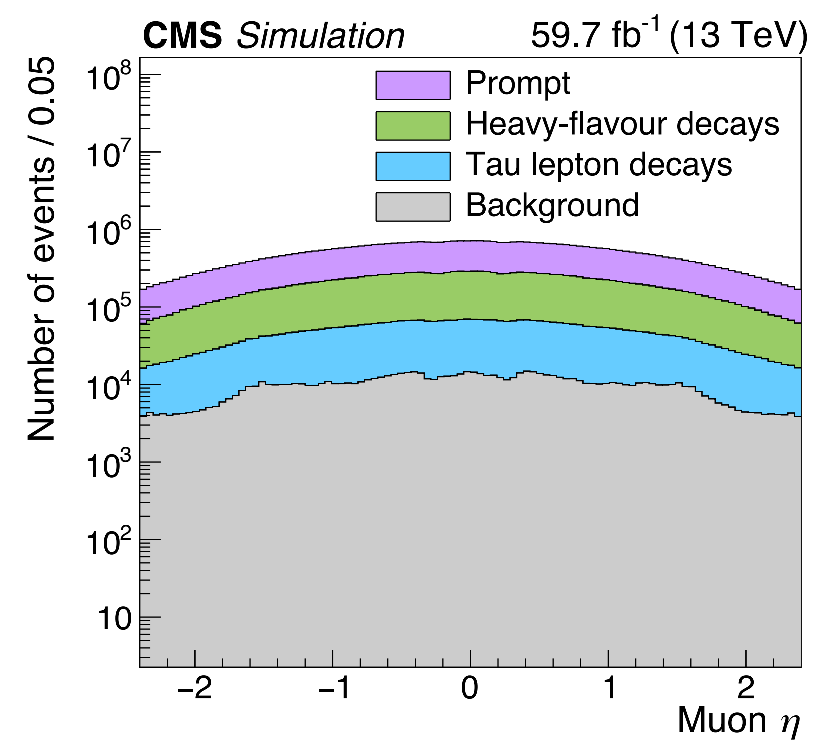
Medium ID, **Tight ID**, and **Muon-MVA ID** targeting a wider range of topologies (prompt and heavy-flavour muons) and $10<p_T<200$ GeV.

Prompt-MVA ID: optimized for prompt isolated muons.

High-p_T ID: applied to the dedicated muon track refits, optimized for high momentum muons.

Isolation (on top of IDs) to select prompt muons estimated as sum of charged hadrons and neutral particles energy in a cone $\Delta R < 0.4$ around the muon..

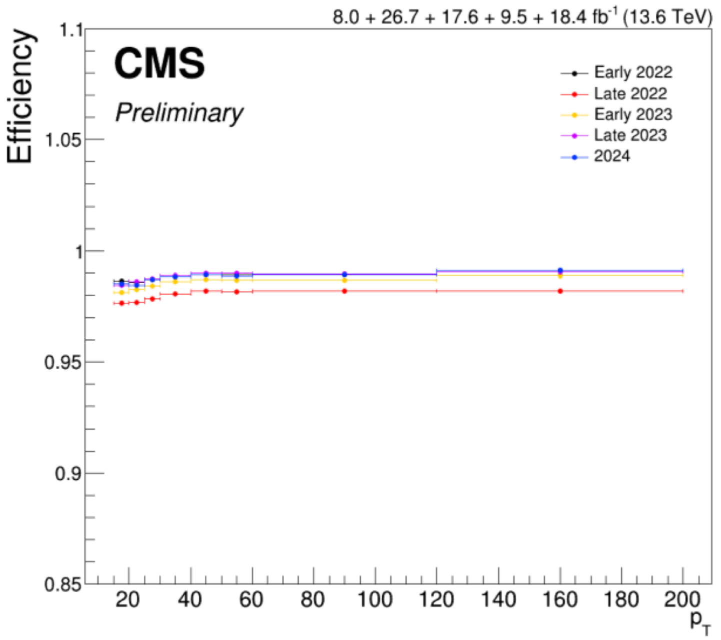


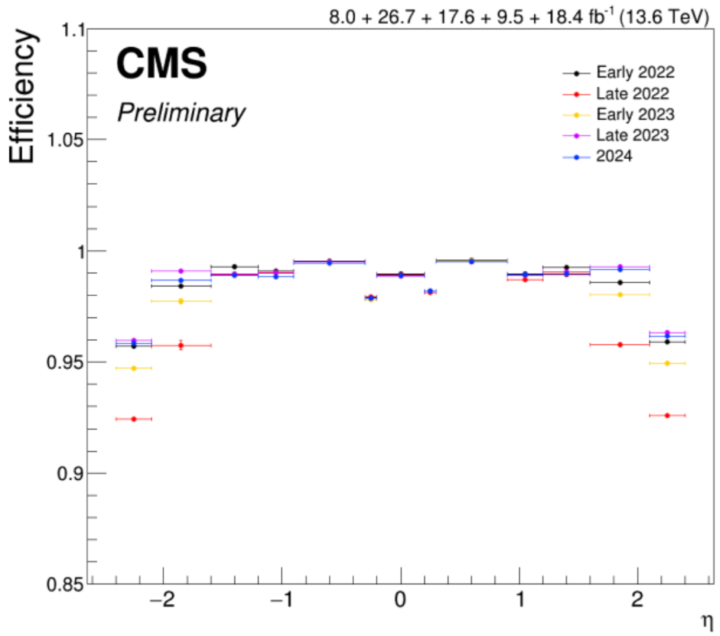


Sources of the muons included in the training of the MVA-ID (MUO-22-001)

Cut-based IDs and Iso

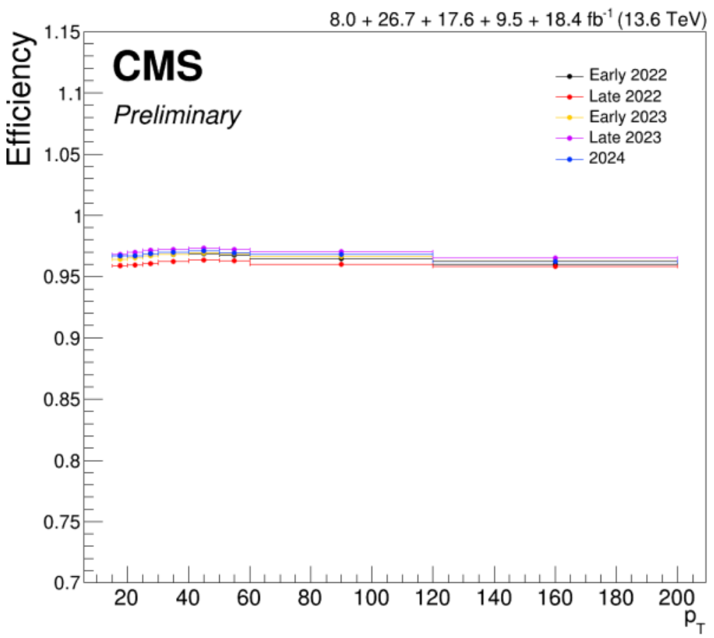
Medium ID efficiencies

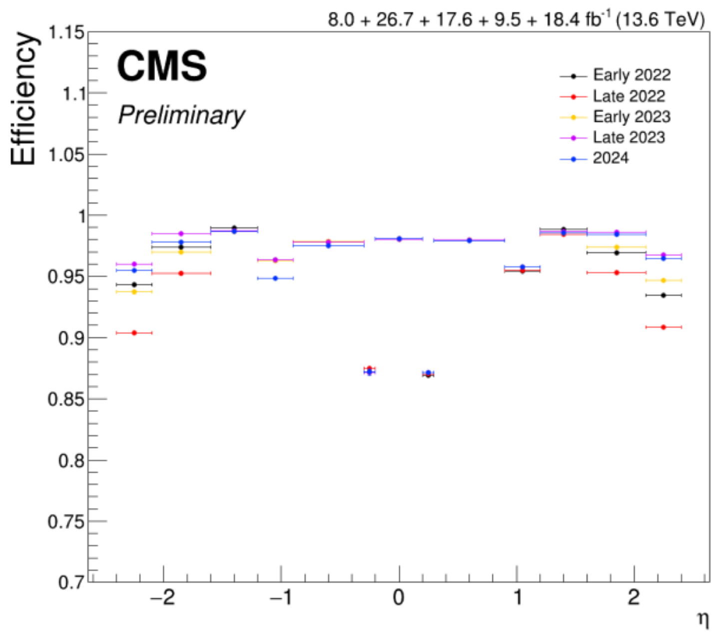




Medium ID performance in Run3 is 98-99% efficient rather flat vs p_T. Slightly affected (<5%) by some hardware issues in the forward muon system

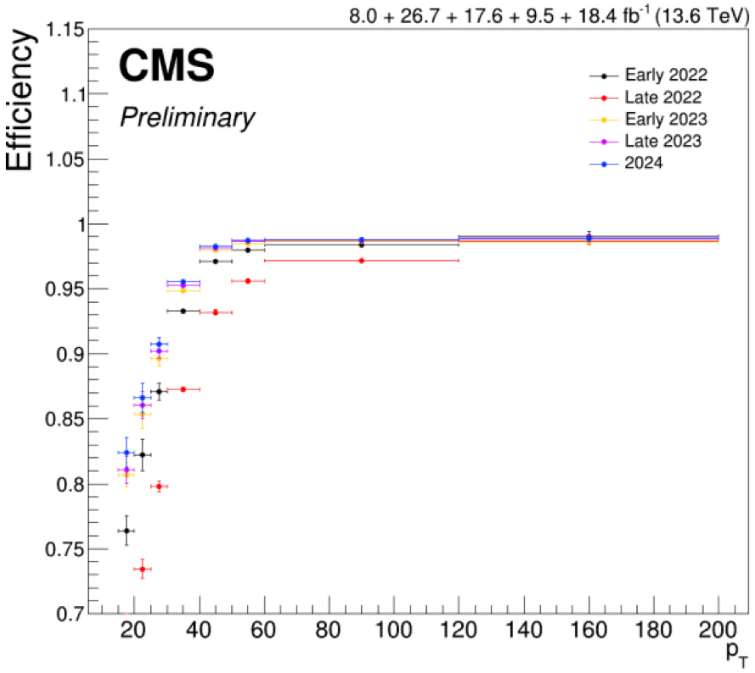
Tight ID efficiencies





Tight ID exploits tighter quality cuts and vertex requirements, returning high purity for prompt muons. Run3 efficiencies are 96-97%, slightly more (<8%) affected in the forward region.

Tight PF Iso efficiencies



Isolation is recommended for muons and the Iso efficiency is measured starting from muons that pass ID criteria

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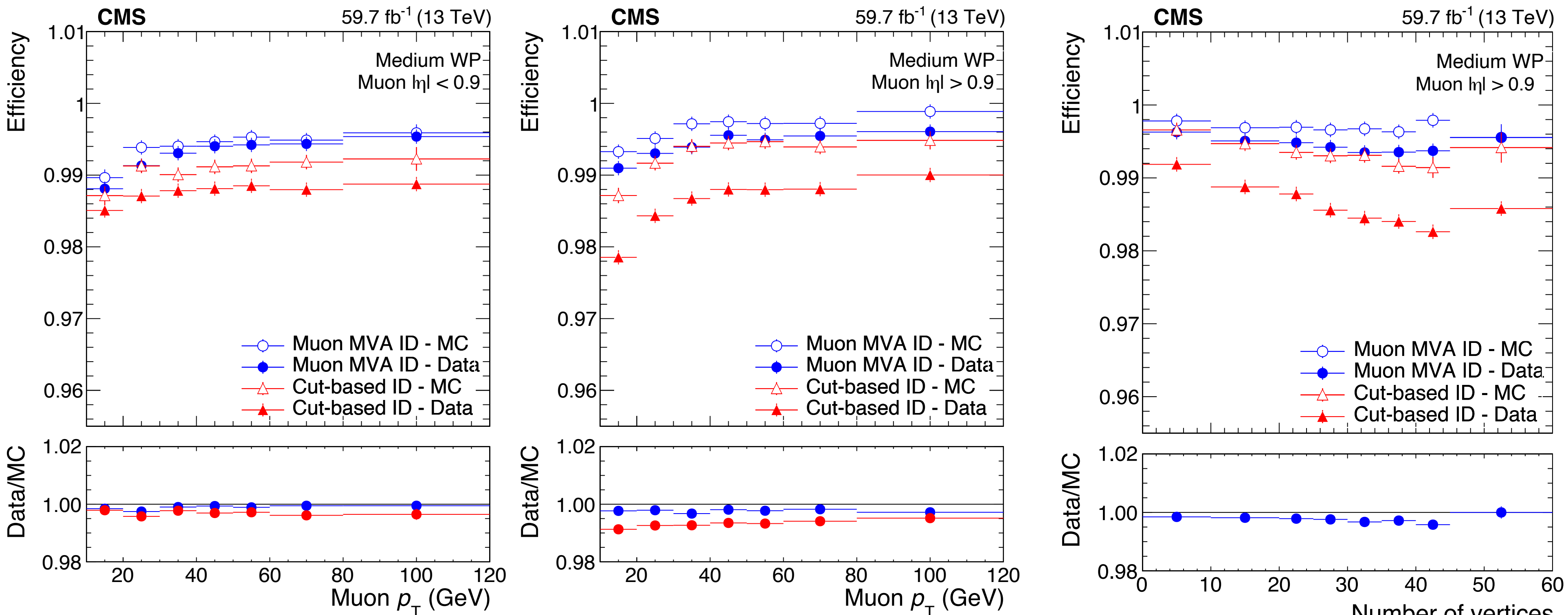
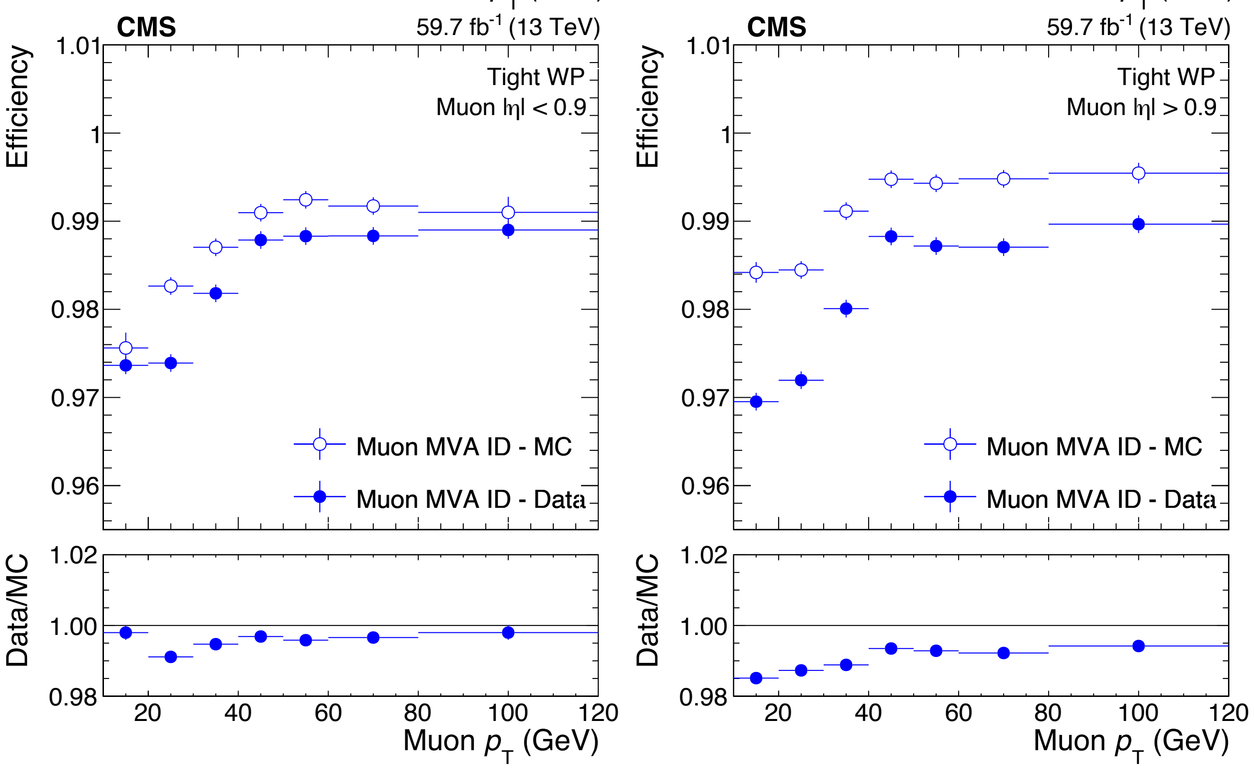
MVA-IDs





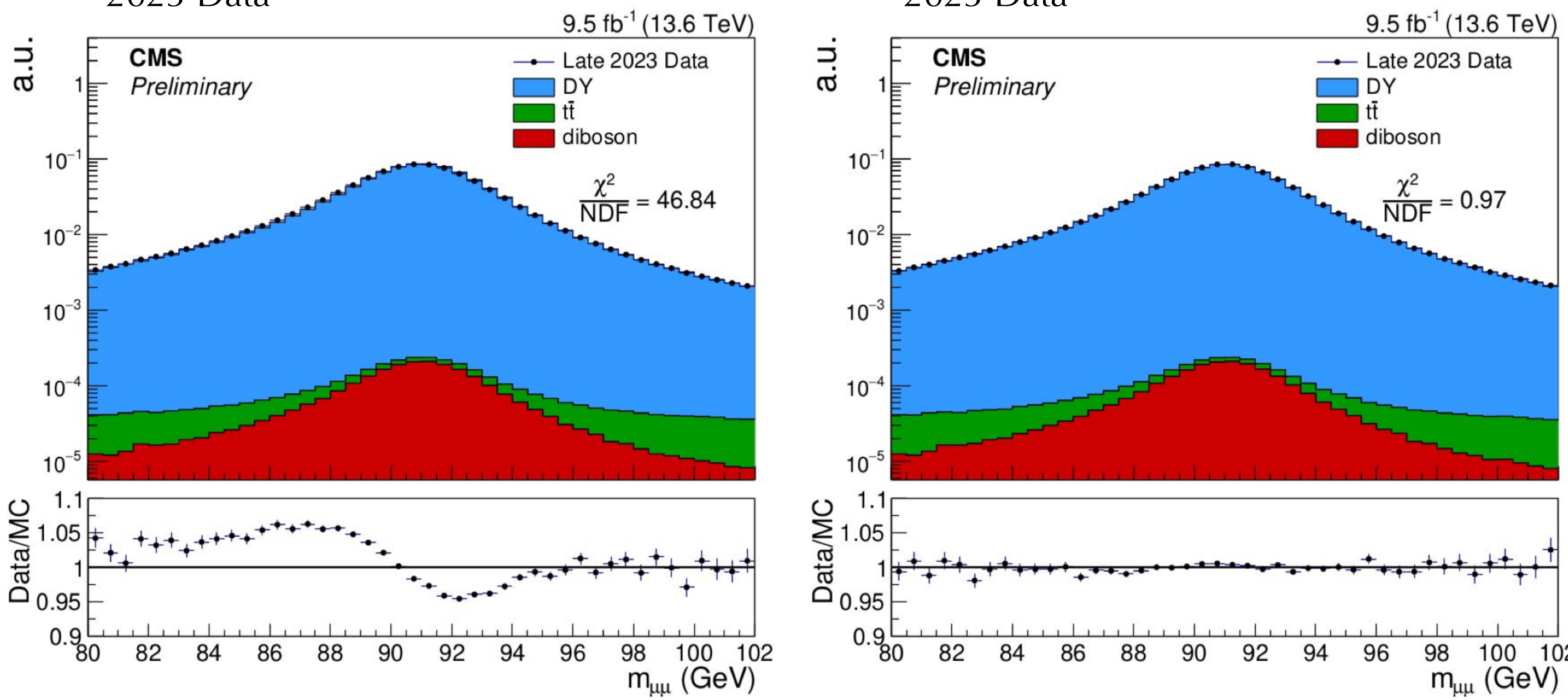
- Performance of the MVA ID have been measured with Run2 data, but targeting Run3 analyses.
- No retraining using Run3 data will be performed.
- Preliminary Run3 measurements confirmed the expected performance.
- Flat performance vs PU than the corresponding cut-based ID.

MUO-22-001

Momentum scale and resolution

Muon momentum scale is achieved using $Z \rightarrow \mu^+\mu^-$ events in data and NLO simulations.

2023 Data　　　　　　　　2023 Data



Mometum scale modelled as multiplicative correction for the magnetic field mismodelling (charge independent) and additive correction for alignment mismodelling (charge dependent) $\frac{1}{p_T} \rightarrow \frac{M}{p_T} + q \times A$

- final scale correction is extracted in bins of η and ϕ.

Momentum resolution correspond to a smear of MC generated quantities so that the resolution of the generated muon momentum matches the reconstructed one.

- final resolution corrections for simulated muons are extracted binned abs(η).

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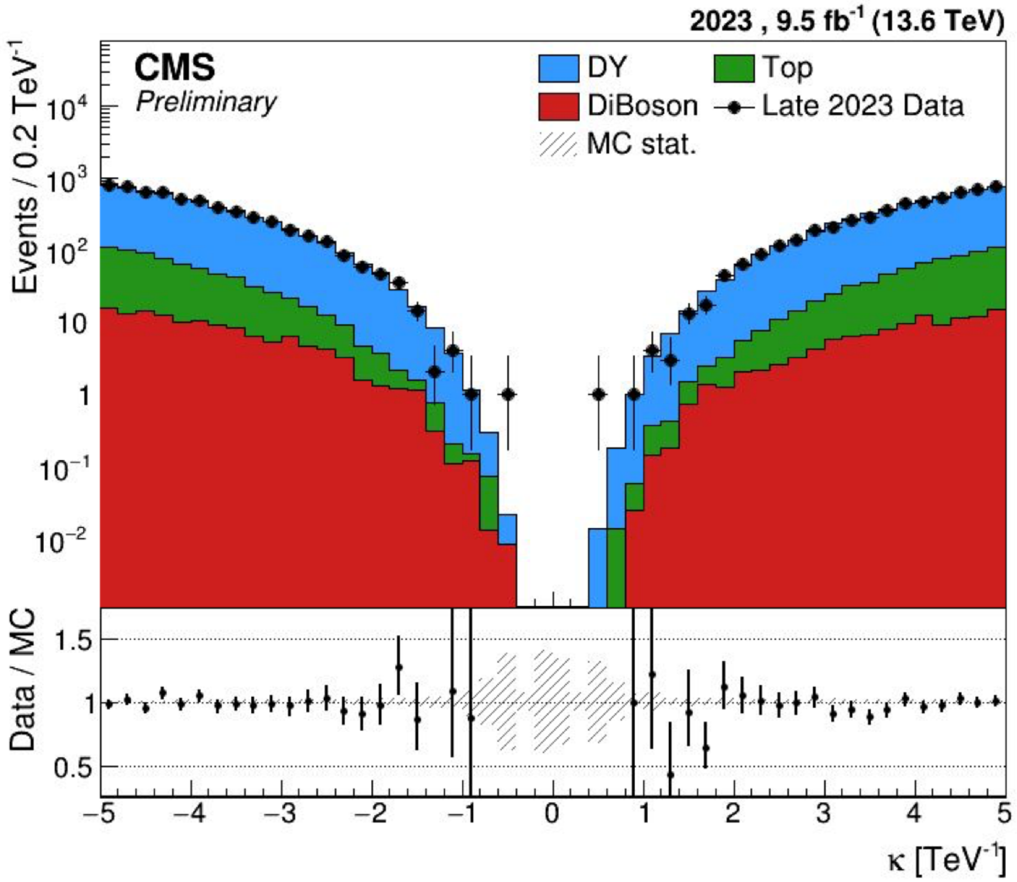
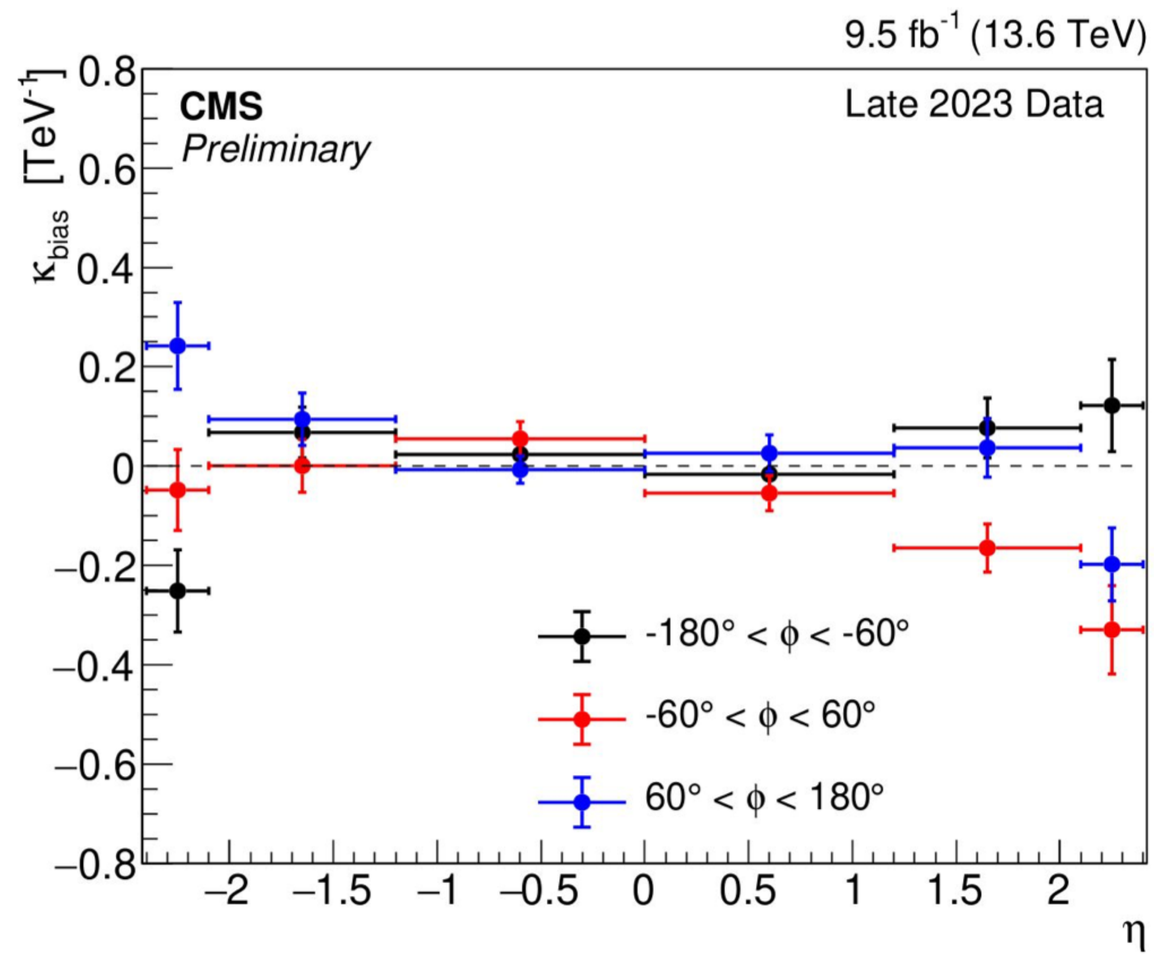
Momentum scale at high-p_T





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

- hypothetical values of bias are injected in the simulated **muon curvature ($\kappa = q/p_T$)** to match data
- 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
- derived in different bins of η and ϕ for muons with a $p_T > 200$ (110) GeV and $|\eta| < 2.1$ (> 2.1)

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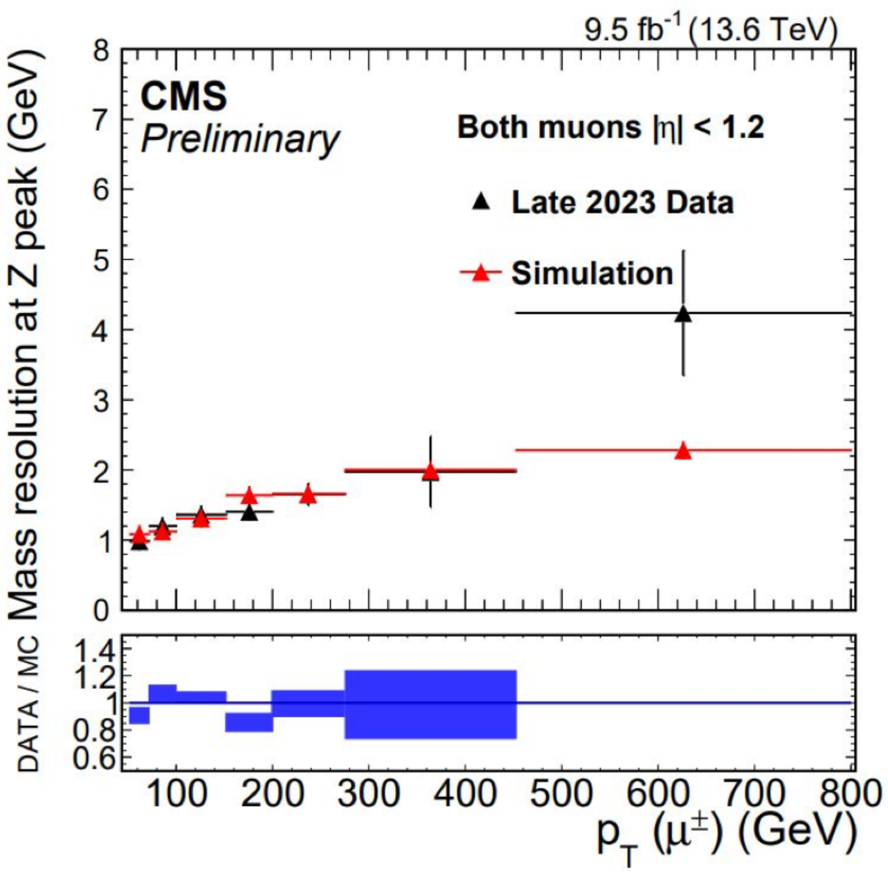
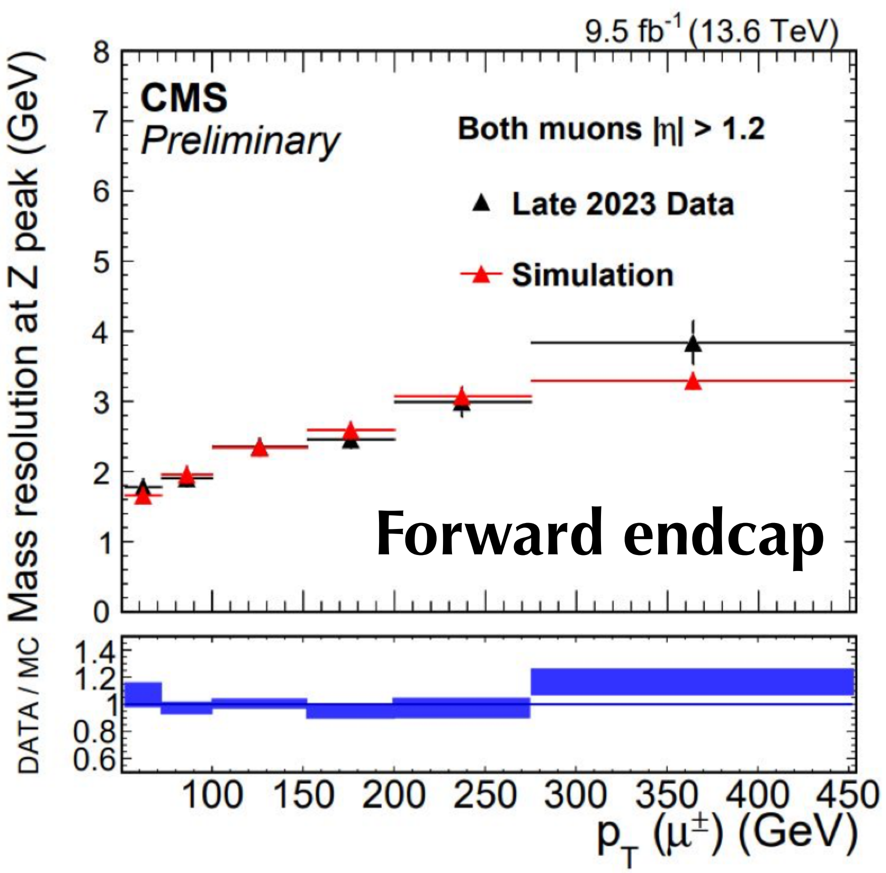
Momentum resolution at high-p_T

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

- a dimuon mass distribution is created and fitted for different p_T and η ranges relative to the individual muon
- muon momentum of simulated events is smeared to correctly describe the dimuon mass resolution obtained with data.





- 15% of smearing applied to the p_T of the simulated muons to correctly match the data
- flat additional 10% of systematic uncertainty

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Summary

- A successful physics program relies on a highly efficient muon reconstruction and identification, further than an accurate measurement of its momentum
- Overall muon object performance in Run3 show:
  - high efficiency among the 3 years of data taking
  - good understanding of the impact of the detector conditions
  - successful recovery/mitigation strategies, returning an excellent performance since Late 2023 data taking
  - excellent measurement of the muon momentum scale
- Promising results for analyses using displaced muons
- Dedicated studies to high-pT muons show very good results
- MVA IDs confirmed the expected performance without any further Run3 retraining
- Further ongoing developments will soon be deployed.