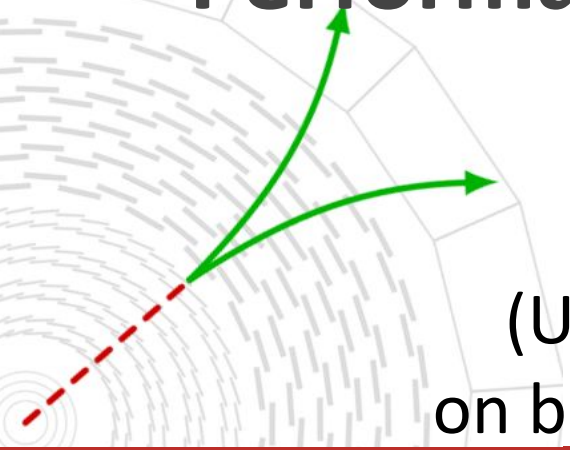
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Istituto Nazionale di Fisica Nucleare

Displaced Muons in CMS:

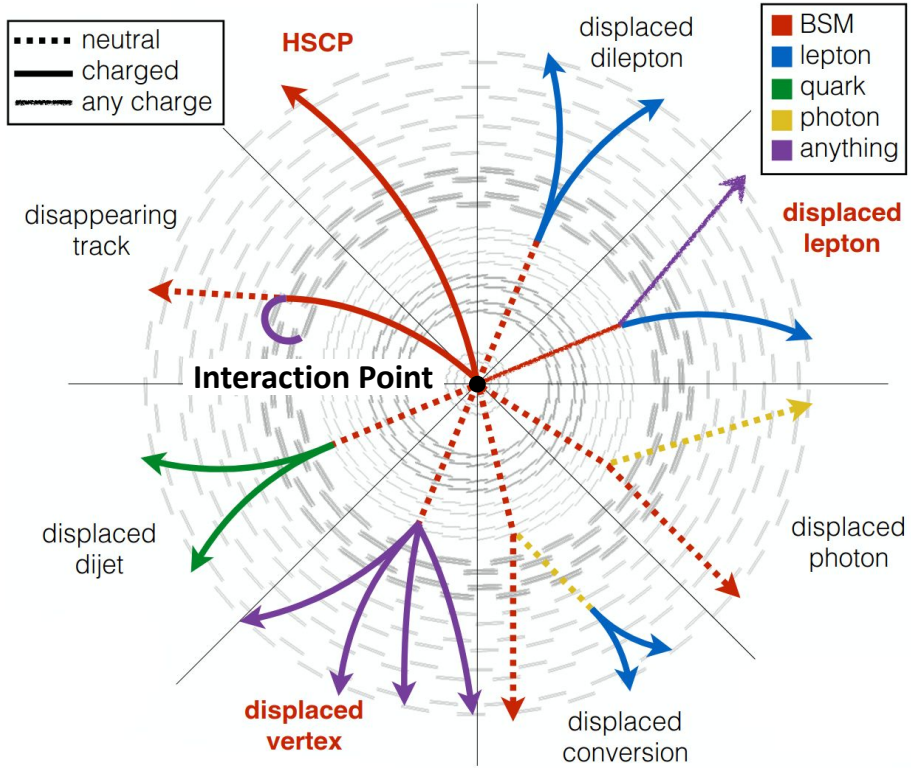
Performance and Applications in LLP Physics



Marco Cruciani
(University and INFN Bologna)
on behalf of the CMS collaboration

Long Lived Particles (LLP)

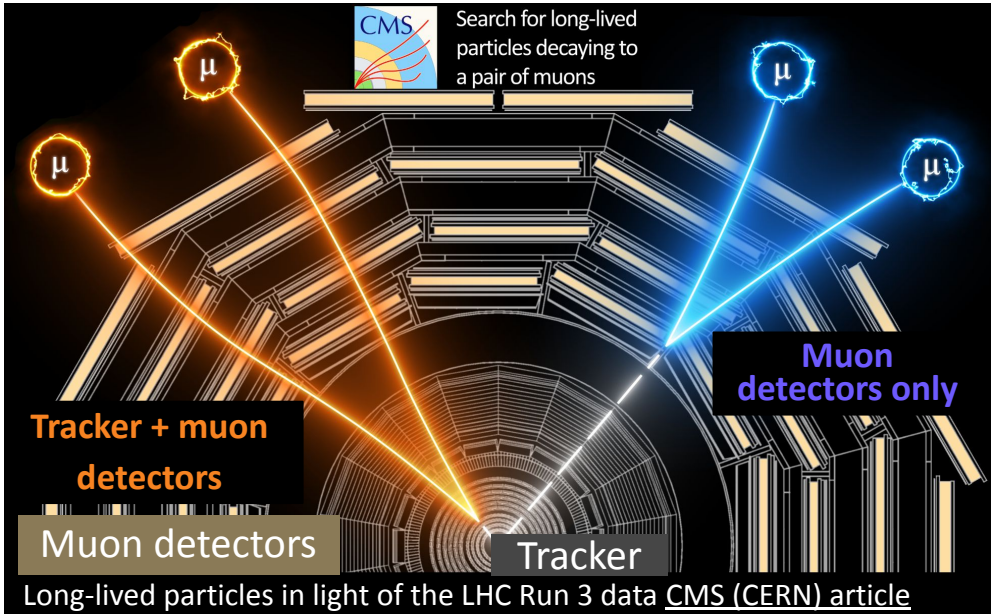
- Some theories **beyond the Standard Model** hypothesize long-lived particles (LLPs)
- Typically have **weak coupling to the Standard Model** particles
- **Variety of signatures** such as: jets, leptons, and photons
- Can produce decay vertices that are **displaced from the interaction point** (IP)



J. Antonelli ICHEP 2016

LLPs at CMS

- Sensitive to muons generated at large distances from the interaction point (**displaced muons**)
  ⇒ great potential for **LLPs decaying into muons**

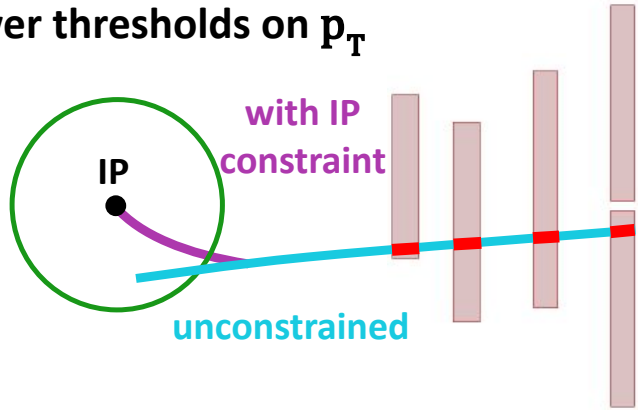


- At CMS a muon can be reconstructed:
  - with muon detectors only
  - using a combination of muon detectors and tracker

- Standard algorithms **assume that tracks are close to the interaction point**
  ⇒ displaced muons require **specific algorithms**

Run 3 triggers for displaced dimuons

- Run 2 triggers for displaced dimuons:
  L1 trigger applies constraint to interaction point
  - **inefficient and underestimate p_T** of track at high displacements
- Run 3 triggers for displaced dimuons:
  - L1 trigger reconstruction **without IP constraint**
  - **lower thresholds on p_T**



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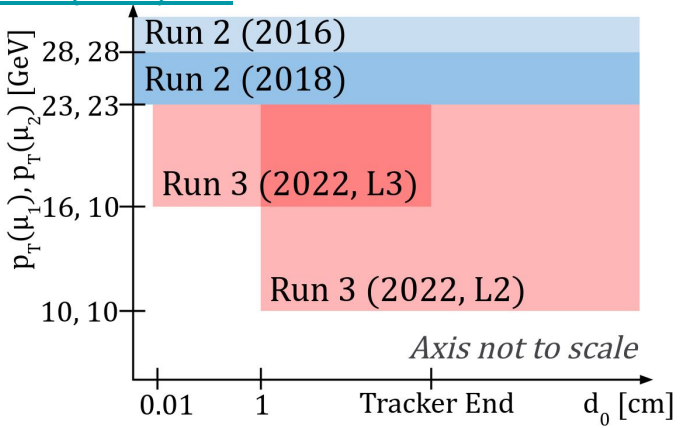

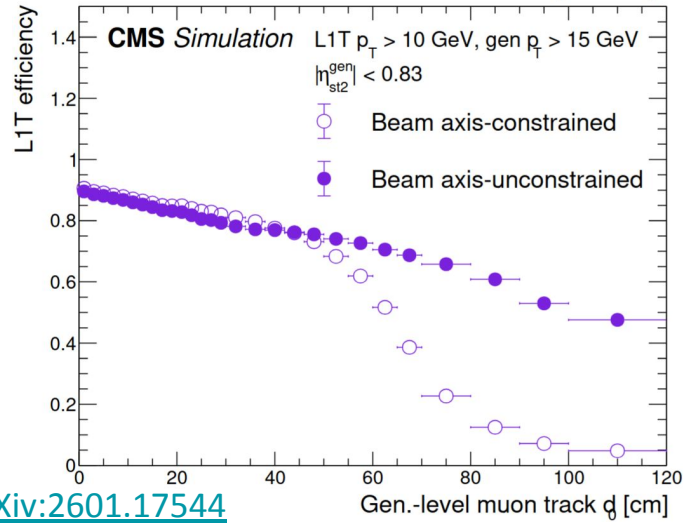

arXiv:2601.17544

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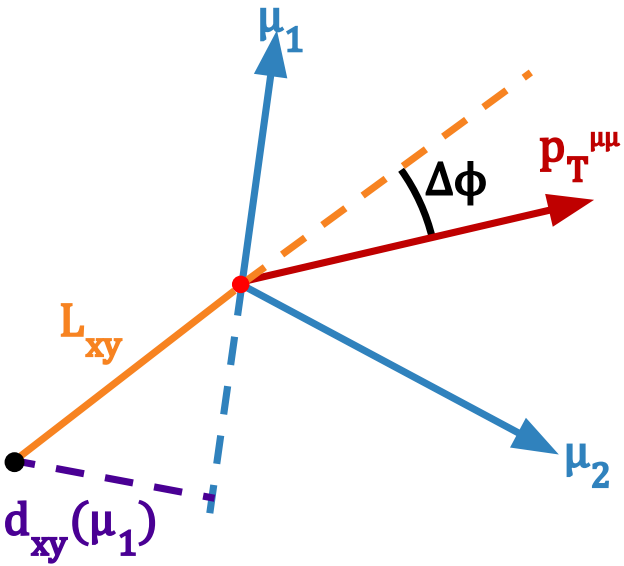
Search for displaced dimuon pairs

- Early Run 3 search for neutral **LLP decaying into displaced dimuon pairs** with opposite sign
- Model independent **bump hunt** in invariant mass spectrum

- Requirements on $L_{xy}/\sigma(L_{xy})$ of pair removes bulk of prompt background

- Complex sources of background, involve **instrumental errors and misreconstructions** e.g:
  - QCD events with genuine or fake muons fitted into a pair
  - Drell-Yan events misreconstructed as displaced



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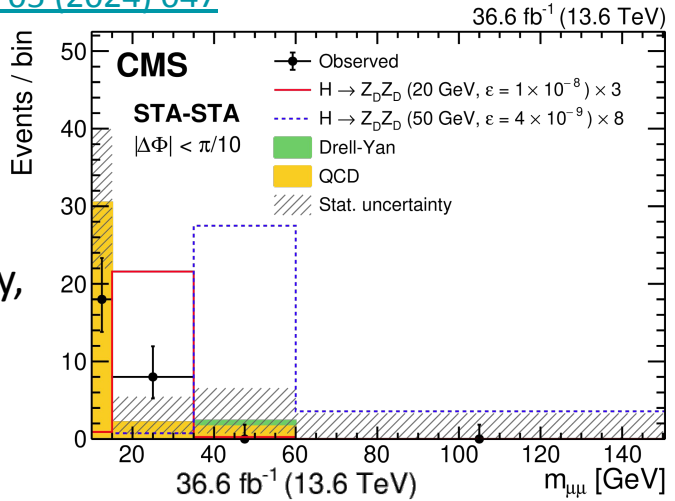
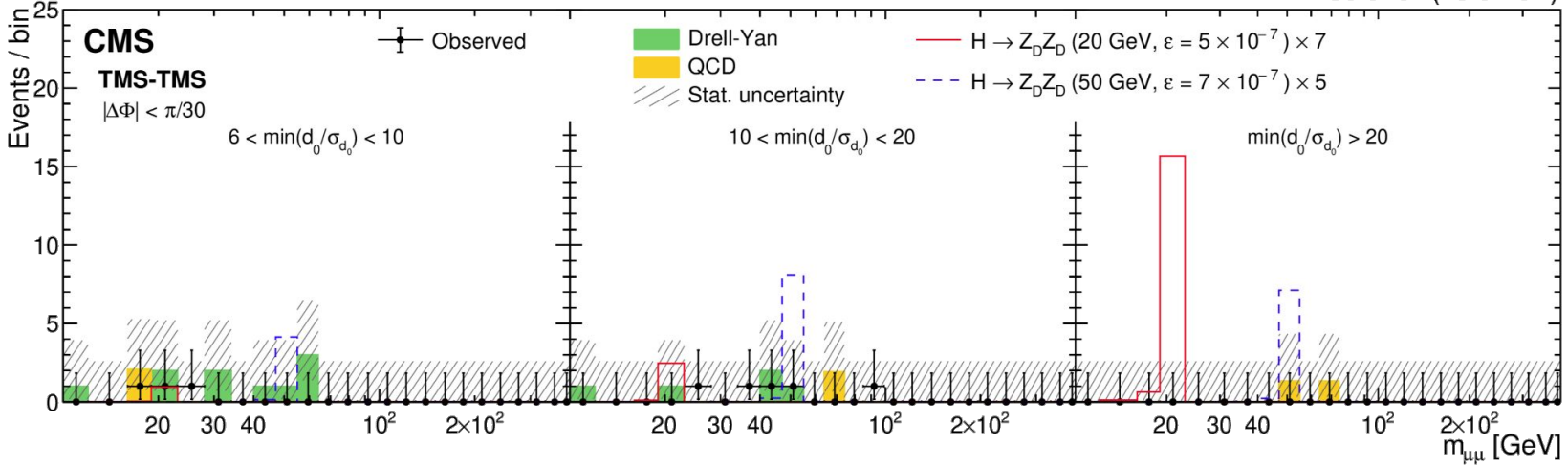
Search for displaced dimuon pairs

- Two separate categories **STA-STA** and **TMS-TMS**
- STA-STA: two muons reconstructed in muon detectors only, **without IP constraint**
- TMS-TMS: two muons reconstructed in both muon detectors and tracker, **with IP constraint**





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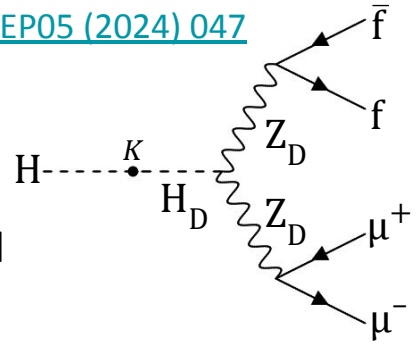
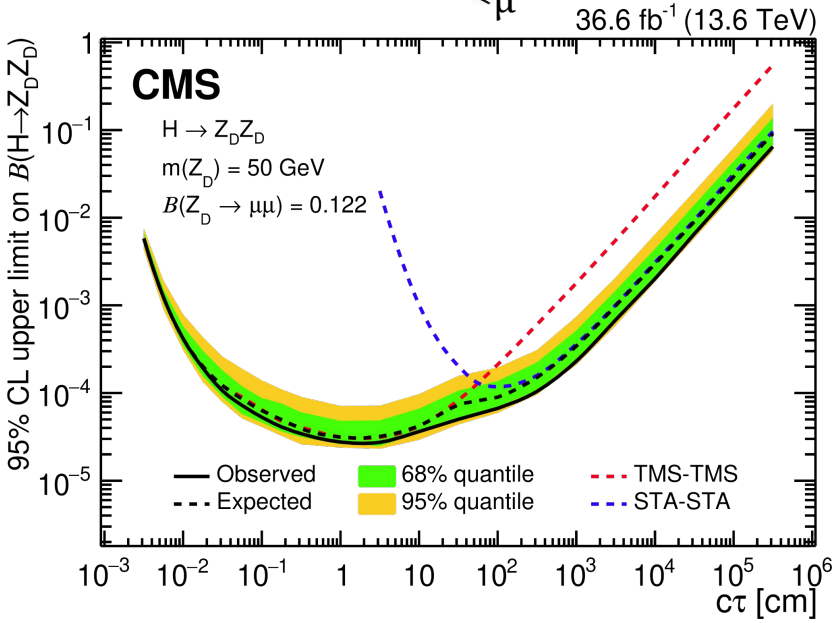
Search for displaced dimuon pairs



- No significant excesses found over expected background
- **Results interpreted as limits** on the parameters of Hidden Abelian Higgs Model (HAHM) where we can have a long lived dark photon Z_D
- **Limits comparable to analogous Run 2** analysis but **with only ⅓ of integrated luminosity** thanks to improvements in trigger efficiency
- **Ongoing refinements** of the selection procedure and extension to all Run 3 data



Offline displaced muon reconstruction

- **Displaced Standalone Muons** (DSA):
  - Built from **muon system segments** without constraining to the IP

Already in use in previously mentioned early Run 3 search

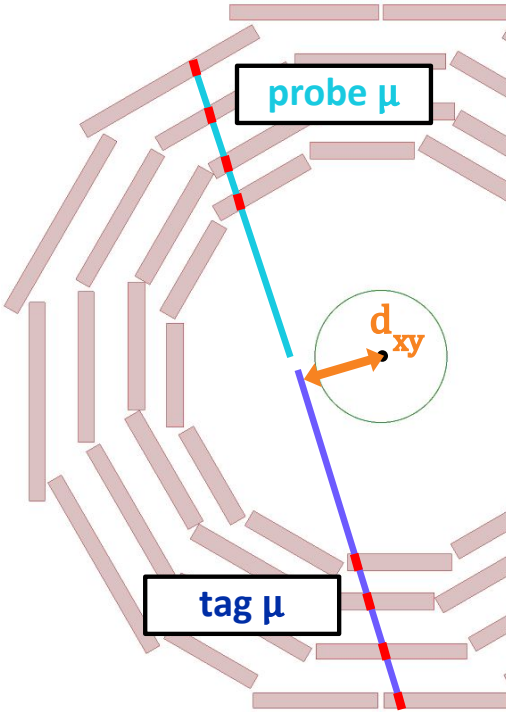
- **Displaced Global Muon** (DGL):
  - Extrapolate DSA tracks to the tracker
  - Refit hits into a **single track exploiting both tracker hits and muon chamber hits**
  - improves sensitivity to muons at **large displacement but still within the tracker**

Not yet available in previously mentioned early Run 3 search!

- No collision data at large displacements to measure reconstruction performance:
  ⇒ use **cosmic ray muons** that populate the detector at **any position**

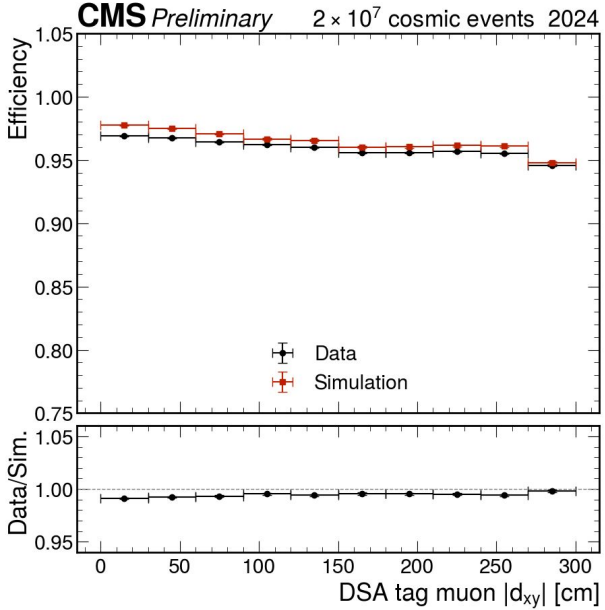
Cosmic muons to study displaced muons

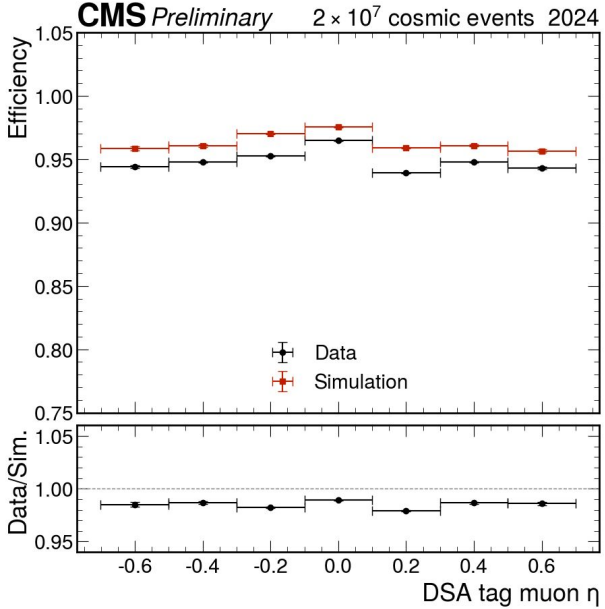
- Single physical muon **reconstructed as two muon objects**, one in upper hemisphere one in lower
- **Tag-and-probe method**: select down-going muon with tight criteria and look for back-to-back probe muon
- Compute **efficiency** as: $\frac{\text{events with reconstructed tag and probe}}{\text{events with reconstructed tag}}$
- **Additional acceptance selections** to exclude peculiar cosmic muon topologies where muon crosses areas that are not instrumented
- Measure the efficiency for **DSA muons and DGL muons**

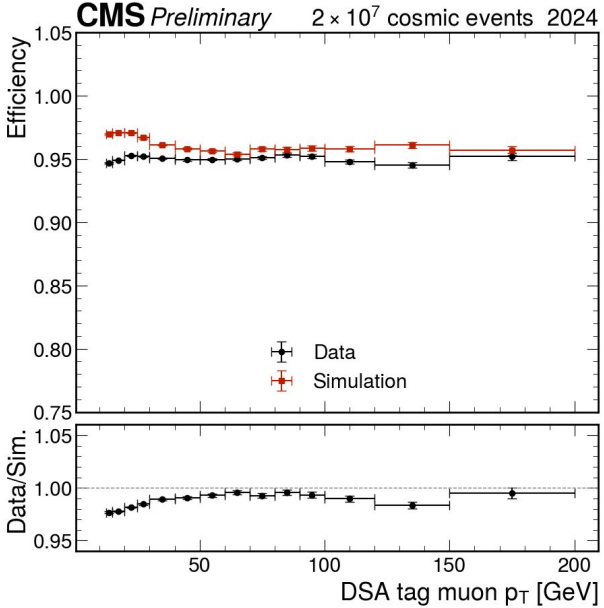


Reconstruction efficiency for DSA

- Data recorded during **regular cosmic data-taking campaigns** with active magnet at 3.8 T, **from 2022 to 2025**
- Simulation of cosmic muons mimics the trigger configuration of cosmic data-taking
- **Efficiency > 94 %** across all displacements, **few % difference** between Data and Simulation

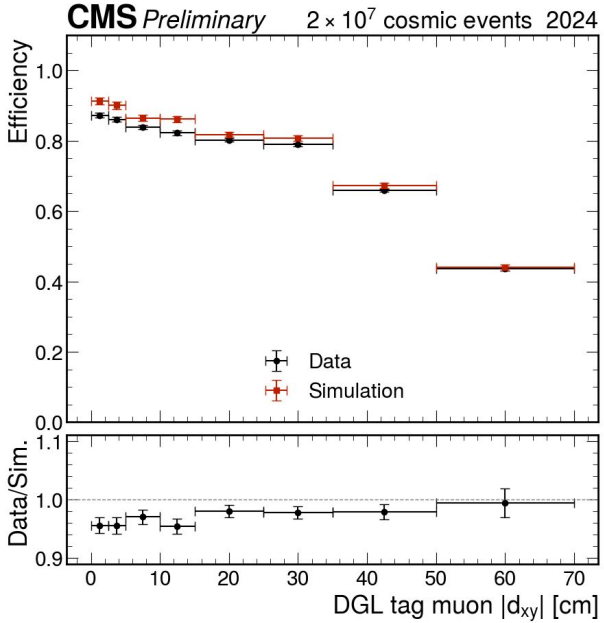


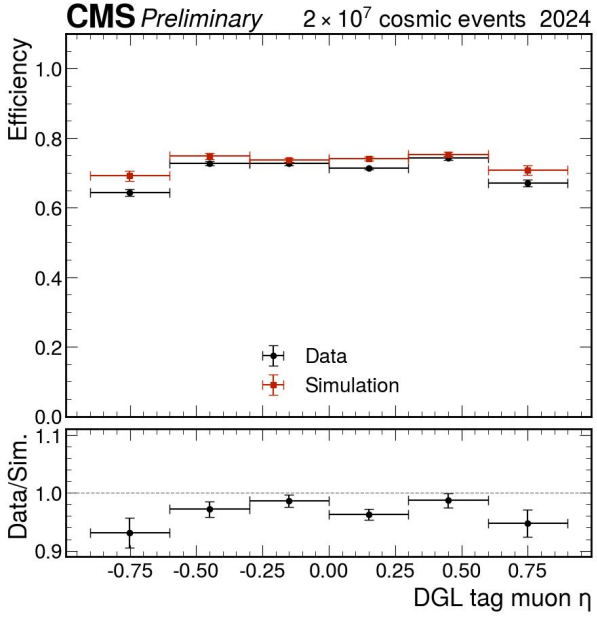


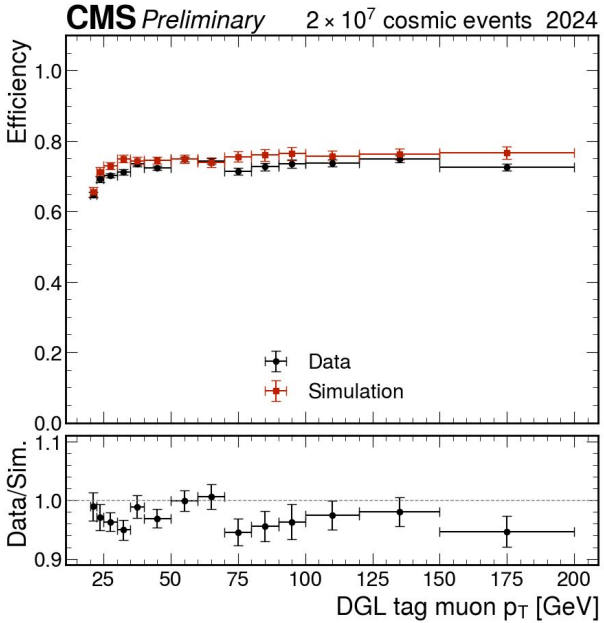


Reconstruction efficiency for DGL

- Data recorded during **regular cosmic data-taking campaigns** with active magnet at 3.8 T, **from 2022 to 2025**
- Simulation of cosmic muons mimics the trigger configuration of cosmic data-taking
- **Strong dependance on displacement** due to missing tracker layers, **agreement within 10 %**

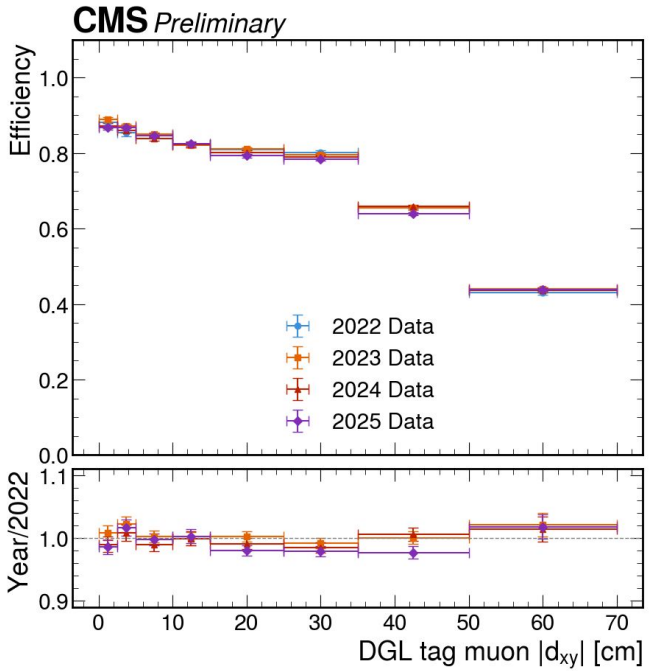


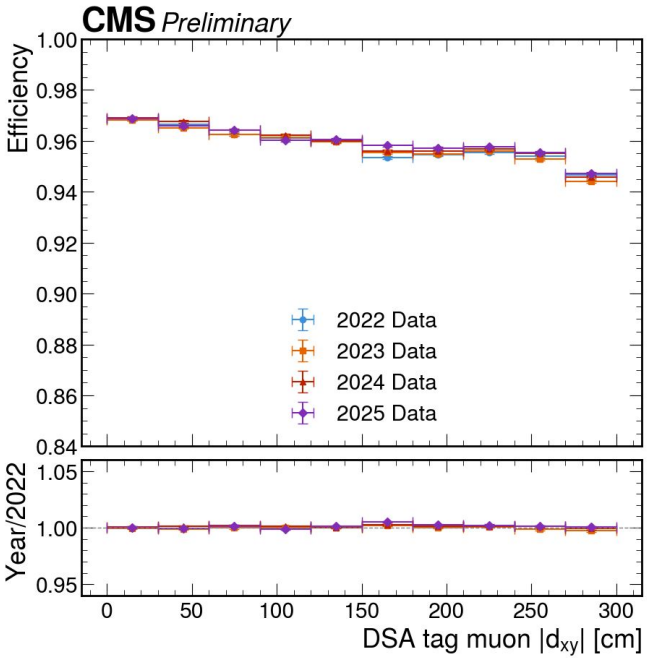




Reconstruction efficiency across years

- Steady performance for efficiency across all years



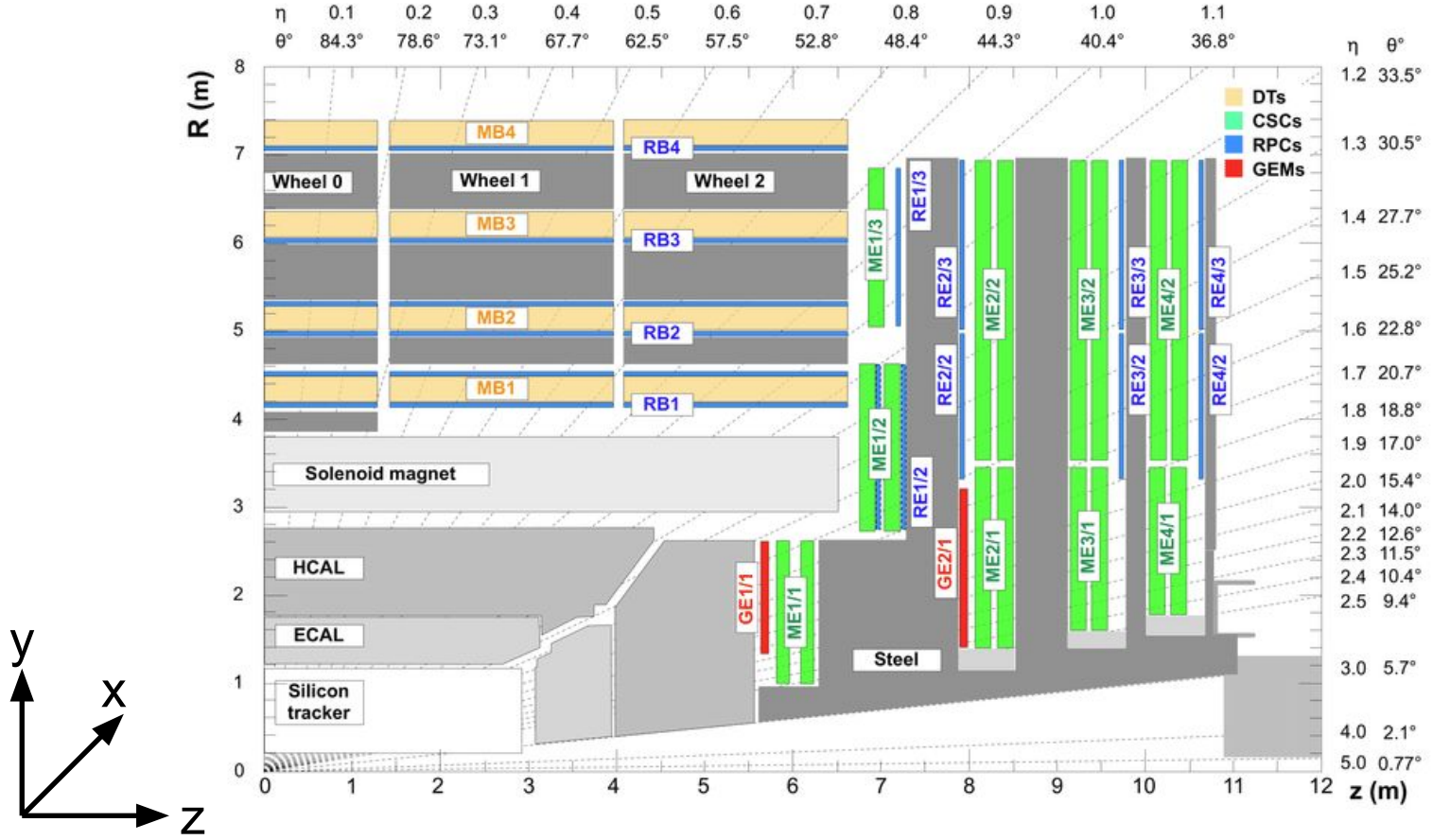


Conclusions

- During Run 3 CMS improved its **triggers for LLPs** decaying to muons
- Early Run 3 analysis searching for LLPs decaying to pairs of muons shows **promising results while using a fraction of total integrated luminosity**
- Offline reconstruction available in Run 3 producing **Displaced Standalone (DSA)** and **Displaced Global** (DGL) muons
- Studies on reconstruction efficiency of displaced muons were performed exploiting cosmic ray muons ⇒ fundamental step to **study efficiency of reconstruction at large displacements** and constraint systematic uncertainties in searches using these objects

Backup

CMS Muon Chambers



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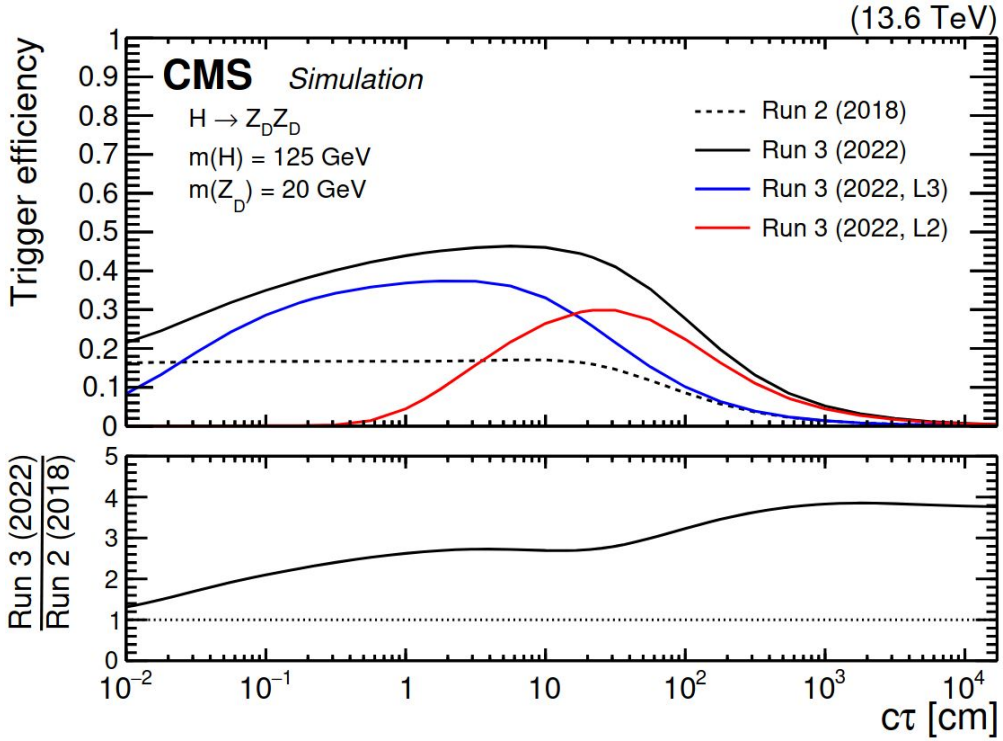
Trigger efficiency improvements early Run 3 analysis



Selection for cosmic study of DSA and DGL muons

DSA tag muon selection

$-4/5\pi < \phi < -\pi/5$

$|\eta| < 0.7$

$p_T > 12.5$ GeV

$\sigma(p_T)/p_T < 0.2$

number of valid DT hits > 30

track χ^2/d.o.f. < 2

DGL tag muon selection

$-4/5\pi < \phi < -\pi/5$

$|\eta| < 0.9$

$p_T > 20$ GeV

$\sigma(p_T)/p_T < 0.3$

number of valid muon hits > 12

number of valid strip hits > 5

time of the muon from muon chambers > 0 ns

DSA probe muon selection

$p_T > 12.5$ GeV

3D angle with respect to tag direction larger than 2.1 rad

DGL probe muon selection

$p_T > 20$ GeV

3D angle with respect to tag direction larger than 2.8 rad