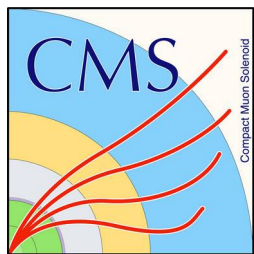


# Search for Displaced Dimuons using Run 3 Data Scouting at CMS

P. Pradeep on behalf of the CMS collaboration



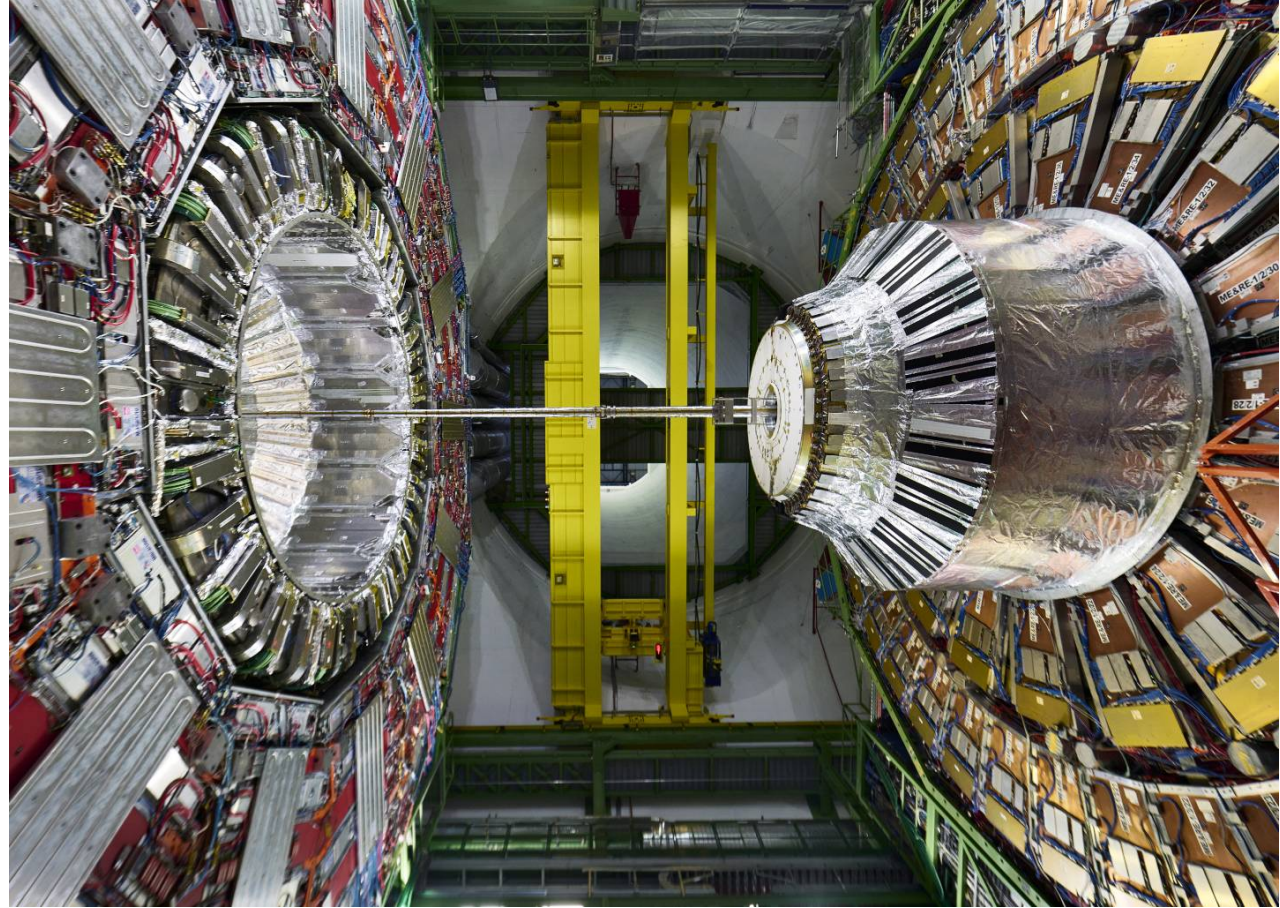
IMPERIAL



UCSB

# Outline

- Motivation
- Data Scouting
- Analysis
  - Selections
  - Categorisation
  - Systematics
- Limits
- Summary

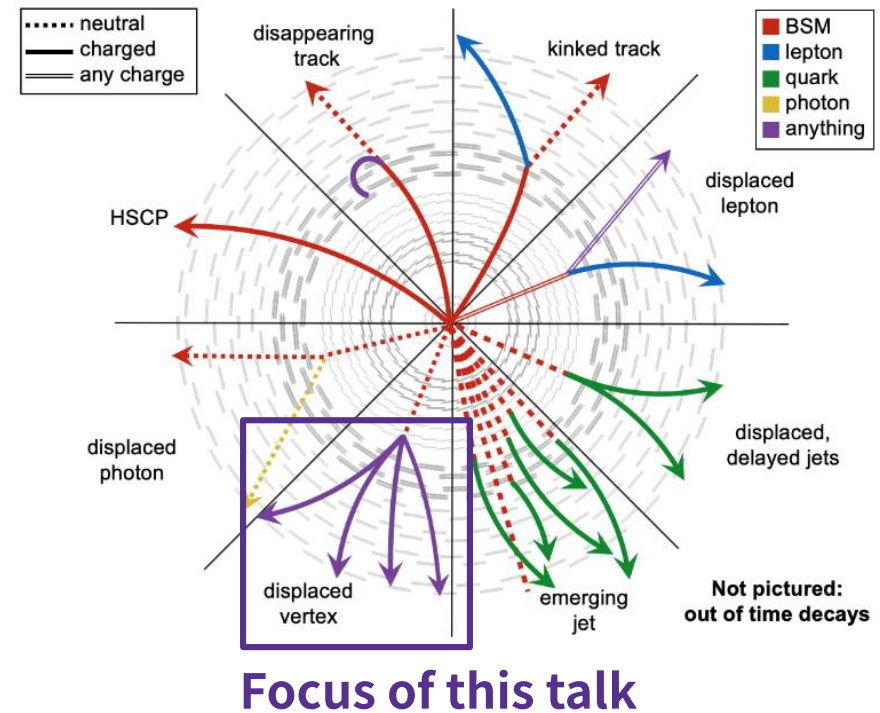


# Motivation

- Standard Model is a very successful description of Particle Physics, but clearly not the full picture
- We need a model beyond the SM to describe dark matter, the scale of the Higgs mass, matter-antimatter asymmetry and more....
- BSM models often predict new particles which are expected to **couple to the SM**
- In 10+ years of the LHC operation, we find no evidence of BSM physics → Need to extend search to more **exotic** signatures

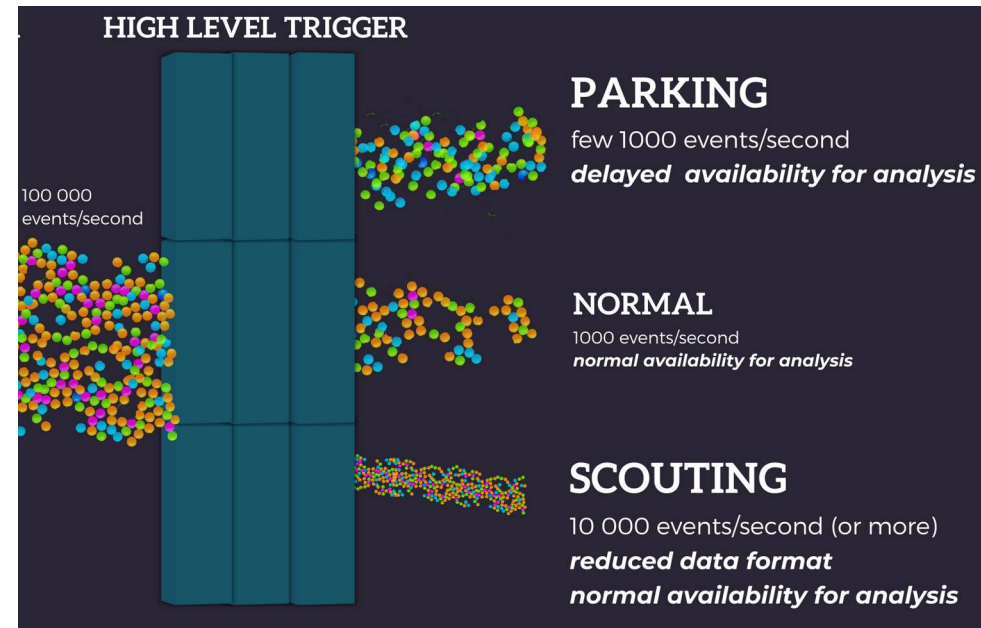
# Long Lived Particles

- If the coupling to SM is weak enough, BSM resonances can have a finite lifetime before decay → **Long Lived Particles** (LLPs)
- LLPs with characteristic travel distances from a few mm can leave distinct signatures in the CMS tracker
- LLP decays to pairs of **muons** especially clean signature → Muons originating from a **displaced vertex**



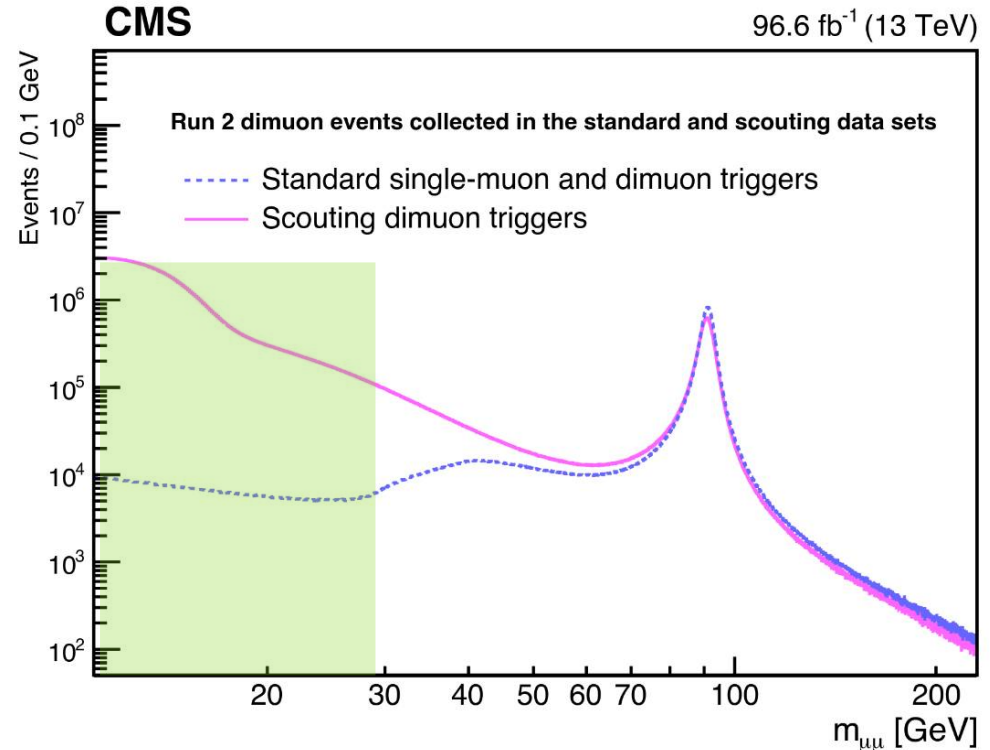
# Data Scouting

- CMS sensitivity to new physics is restricted by the two level trigger system (Level 1 → High Level Trigger → Full reconstruction)
- Most triggers require **high momentum** objects (jets, muons) close to the collision point → Restricts searches for low mass LLPs
- **Data Scouting** bypasses this by storing collision events collected by the HLT
- Events collected at the HLT are much smaller than full reconstruction (~**kB** vs **MB**) → We can store more events



# Data Scouting

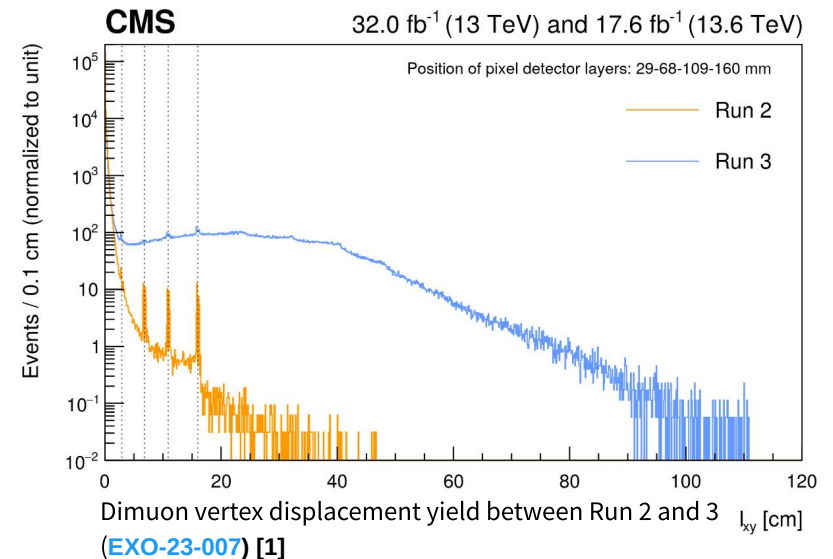
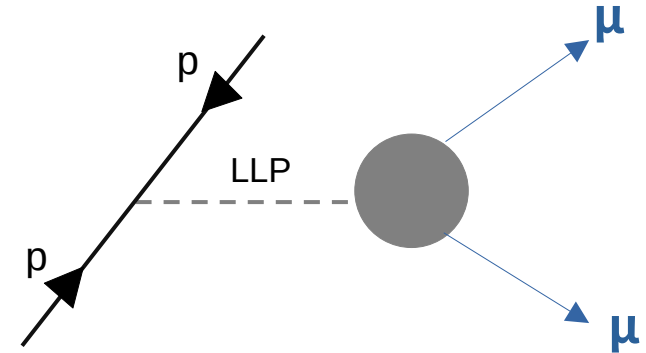
- CMS sensitivity to new physics is restricted by the two level trigger system (Level 1  $\rightarrow$  High Level Trigger  $\rightarrow$  Full reconstruction)
- Most triggers require **high momentum** objects (jets, muons) close to the collision point  $\rightarrow$  Restricts searches for low mass LLPs
- **Data Scouting** bypasses this by storing collision events collected by the HLT
- Events collected at the HLT are much smaller than full reconstruction ( **$\sim$ kB vs MB**)  $\rightarrow$  We can store more events



Dimuon yield from Scouting compared to Offline  
[EXO-23-007 \[1\]](#)

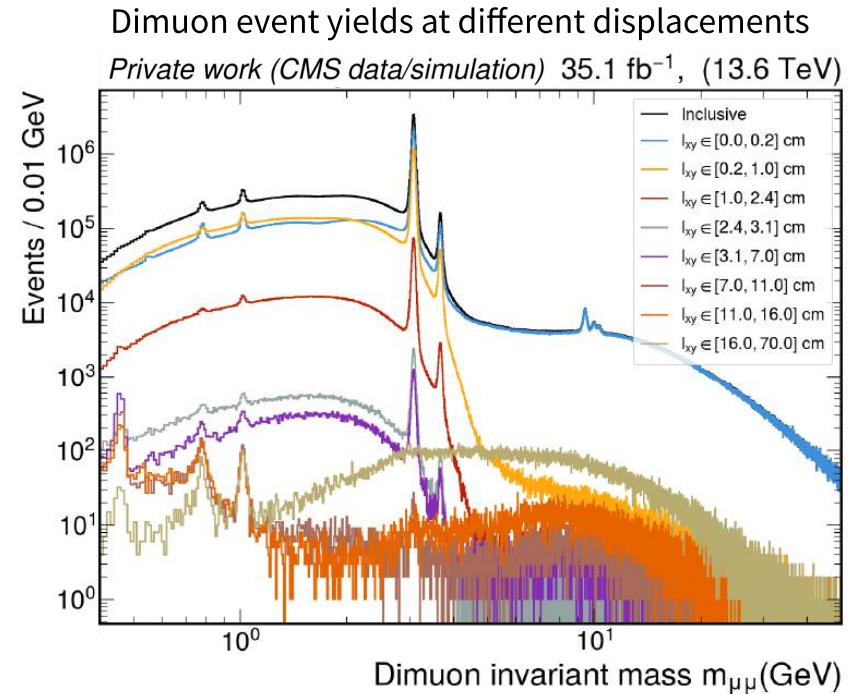
# Scouting for LLPs in Run 3

- Low mass dimuon resonances  $\rightarrow$  Each muon has low transverse momentum  $p_T$
- Data Scouting allows us to probe muons with  $p_T$  as low as **3 GeV** compared to the  $\sim 20$  GeV requirement in standard triggers
- Run 2 Scouting was restricted to LLPs travelling  $\sim 10$  cm due to pixel tracker reconstruction requirements for HLT muons
- **Run 3** relaxes these requirements and stores muon track information  $\rightarrow$  Opportunity to probe longer lifetimes with better background rejection



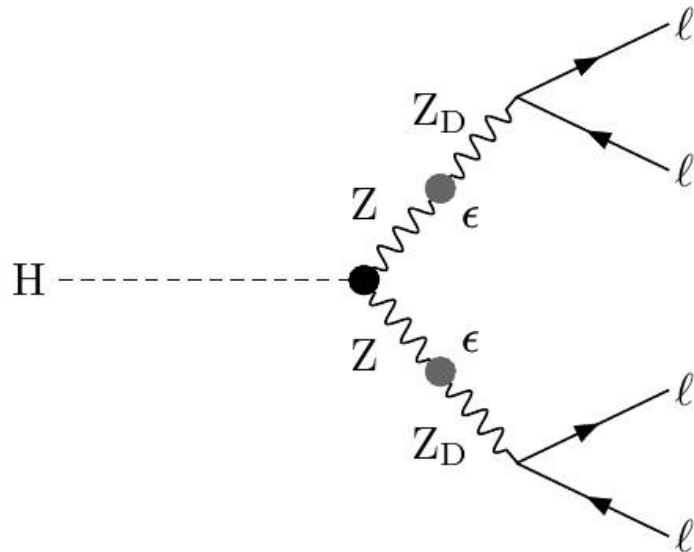
# Analysis

- **Early Run 3** data from 2022 and 2023 ( $\sim 62 \text{ fb}^{-1}$ )
- **Cut-based** selections to preserve model independence and allow easier recasting
- Selections applied to dimuons originating from a **Secondary Vertex (SV)**
- **Improvements** made from Run 2:
  - Access to larger muon displacements
  - More HLT information for better background rejection
  - Reconstruction of overlapping groups of four muons
  - Improved treatment of systematic uncertainties

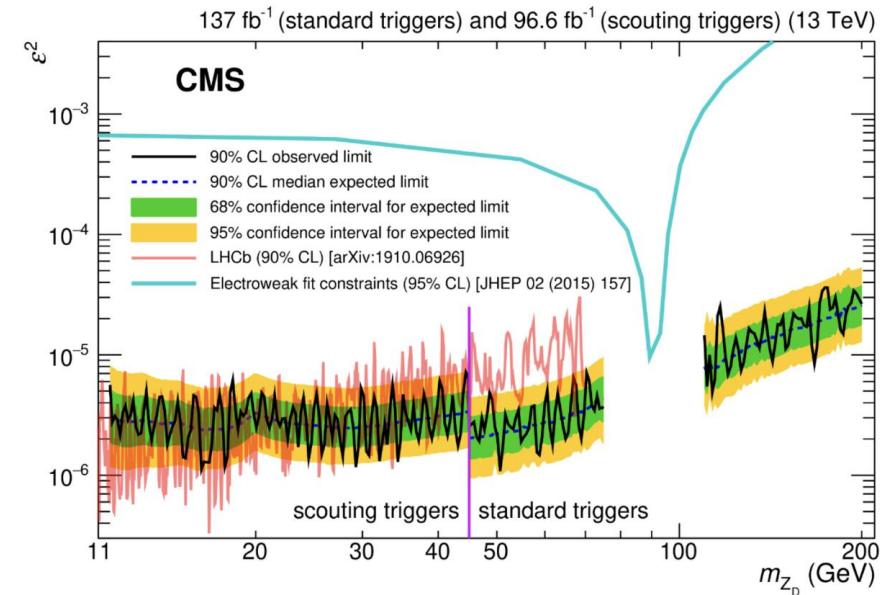


# Analysis: Benchmark model

- **Hidden Abelian Higgs Model (HAHM):** Higgs decays to dark U(1) photon  
→ Kinetic mixing with SM U(1) hypercharge
  - Dark photon ( $Z_D$ ) is the LLP
  - Strong exclusion limits derived from Run 2 Scouting

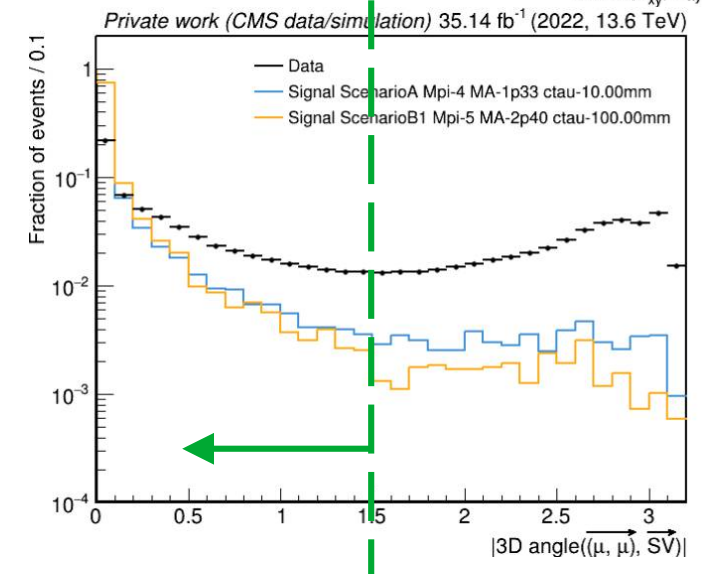
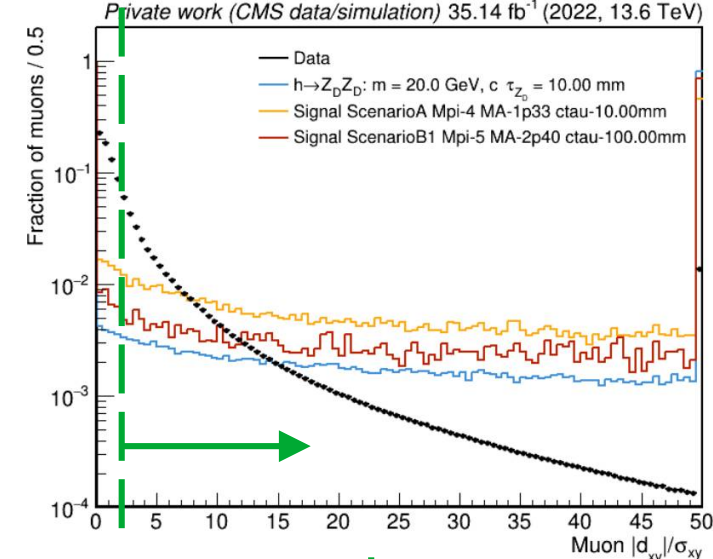


Limits on the dark photon kinetic mixing from Run 2 analyses [2]



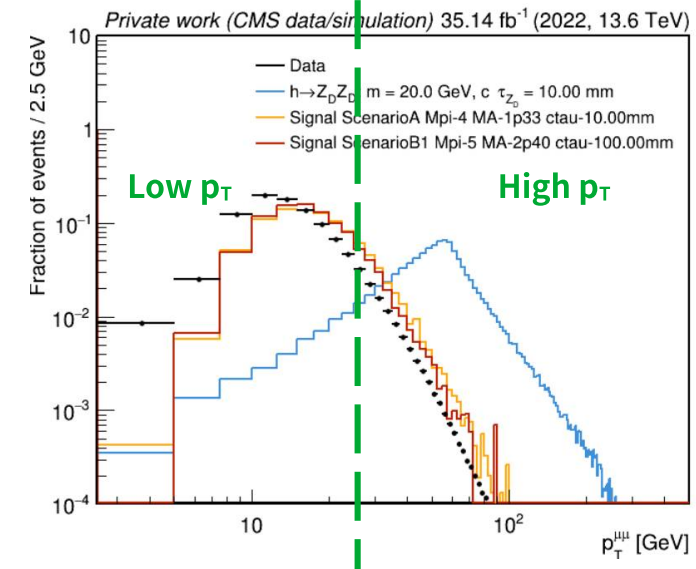
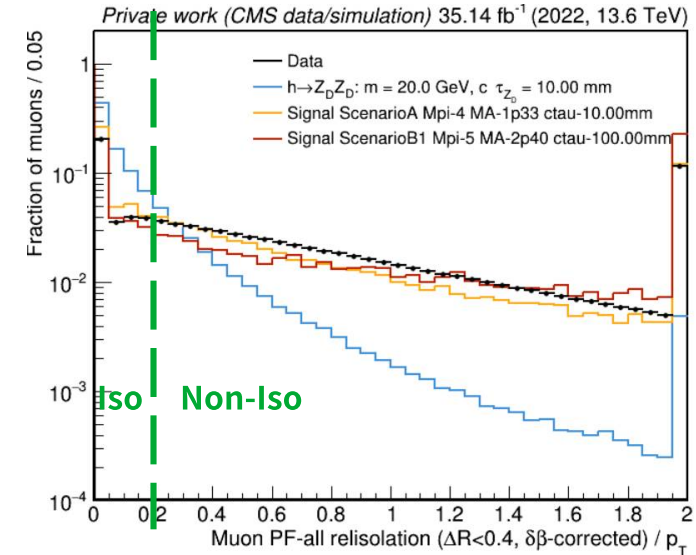
# Analysis: Selections

- Cuts applied on the muons and associated SVs
- Selections applied on muon transverse displacement  $d_{xy}$  and significance  $d_{xy}/\sigma_{xy}$
- Additional selections applied on dimuon angular variables (3D angle,  $\Delta\phi$ ) to remove SVs from accidental muon crossings
- Material veto applied to remove SVs associated with tracker material interactions



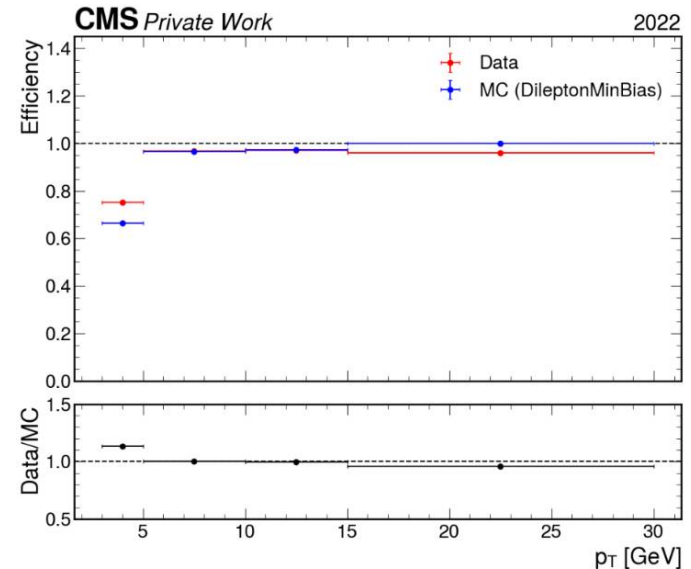
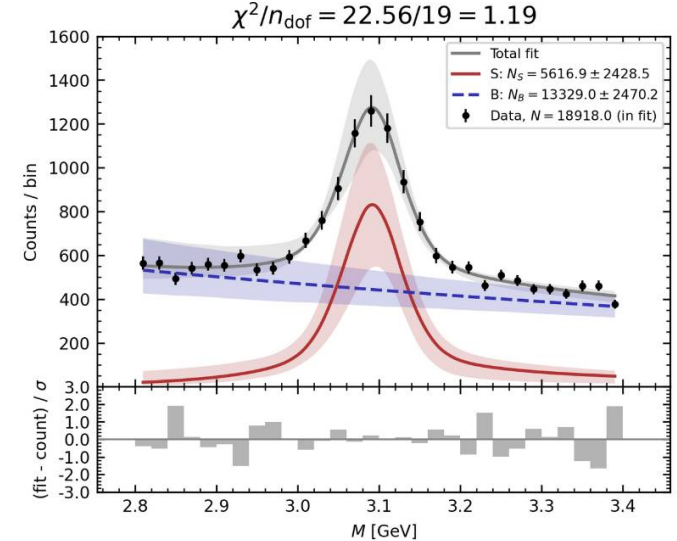
# Analysis: Categorisation

- **Four muon system:**
  - Four muons associated to one merged vertex (Overlapping SV)
  - Four muons from two distinct vertices (Non-overlapping SV)
- **Dimuon system:** Categorised in terms of displacement in bins of [0.0, 0.2, 1.0, 2.4, 3.1, 7.0, 11.0, 16.0, 70.0] cm
  - **Non-pointing:**  $|\Delta\phi(\mu\mu, SV)| > 0.02$
  - **Pointing:**  $|\Delta\phi(\mu\mu, SV)| < 0.02$ 
    - **Dimuon  $p_T$ :** Bins of [0, 25, inf) GeV
    - **Isolation:** Fully or partially isolated SVs
- **42** analysis categories in total → Sensitivity to a wide range of signatures



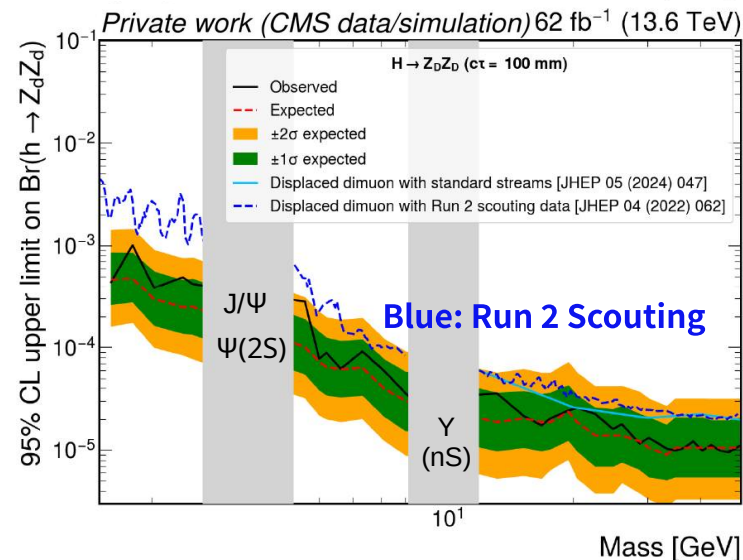
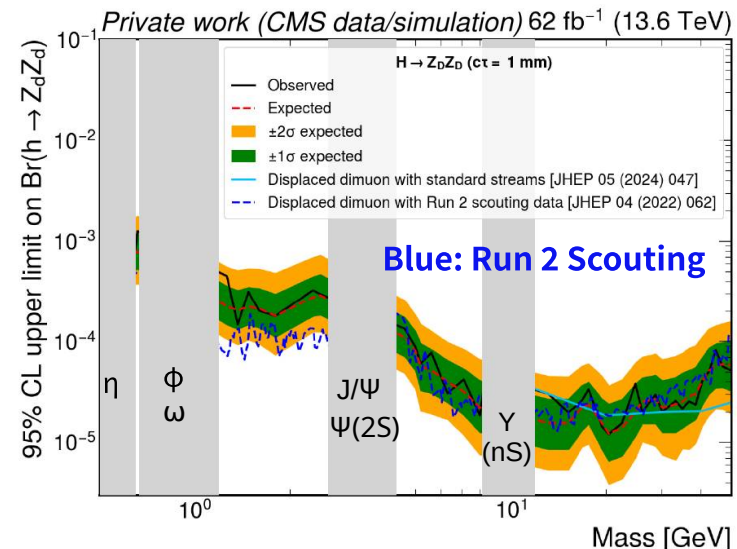
# Analysis: Systematics

- Systematic uncertainties and corrections derived using the  $J/\psi$  as a proxy for signal
- Simulation is an inclusive soft QCD sample
- Primarily focused on muons:
  - **Trigger efficiency:** Data using orthogonal triggers
  - **Selection efficiency:** Applying analysis selections on  $J/\psi$
- Yield extraction performed by fitting to  $J/\psi$  peak
- Compare efficiencies between data and simulation



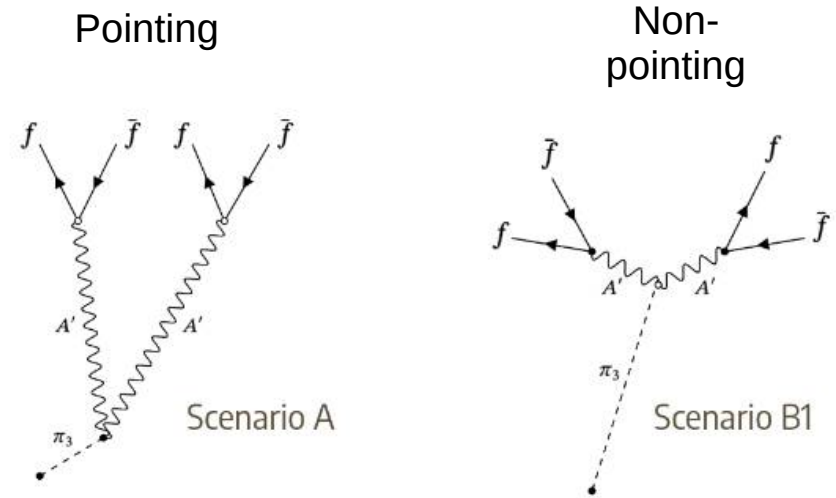
# Limits:

- At **low displacements**, Run 3 results comparable to Run 2 despite lower integrated luminosity (factor 2)
- At **high displacements**, Run 3 improves on Run 2 limits due to higher displacement sensitivity
- Dimuon Scouting probes low mass signatures ( $< 10$  GeV), providing **complementarity** with dedicated displaced dimuon searches in Run 3 (EXO-23-014)



# Upcoming interpretations

- **Dark Showers:** Higgs decaying to dark quarks which hadronise under separate SU(3) gauge group to give dark pseudoscalar and vector mesons
  - Pseudoscalar mesons decay to muons through dark photons
  - Muons decay topologies can be pointing (**Scenario A**) or non-pointing (**Scenario B1**)
- **New interpretation** for Run 3 Scouting in progress
- Complementarity with Run 2 Parking analysis (EXO-24-008)



Benchmark model [paper](#) [3]

# Summary

- Muons reconstructed at the HLT allow us to probe Long Lived Particles at low masses
  - Cut-based selections on vertex and dimuon properties allow us to study a wide range of models
- Improvements in background rejection, muon displacement and systematics
  - Preliminary results demonstrate improvement compared to Run 2 Scouting
- Limits obtained for HAHM models, DQCD model interpretations in progress with the potential for additional interpretations

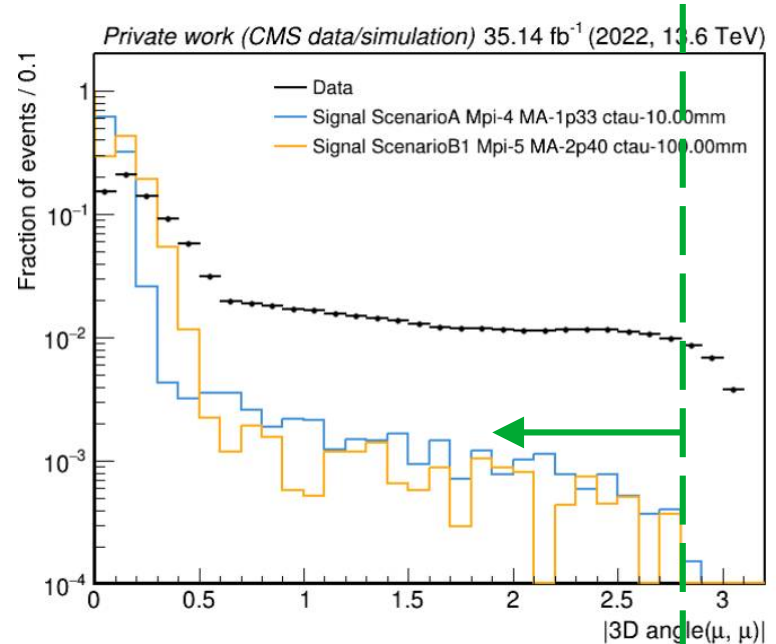
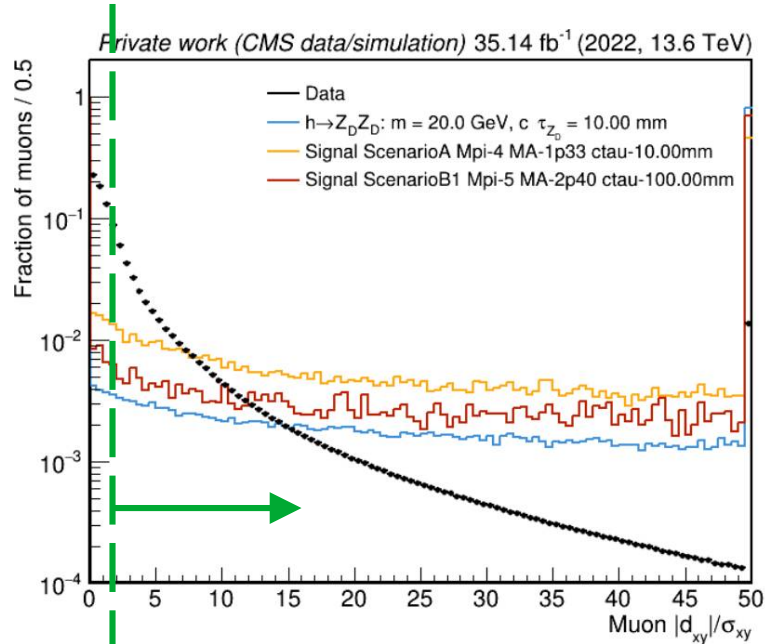
# Bibliography

- [1] CMS Collaboration, “Enriching the Physics Program of the CMS Experiment via Data Scouting and Data Parking”, arXiv:2403.16134
- [2] CMS Collaboration, “Search for a narrow resonance lighter than 200 GeV decaying to a pair of muons in proton-proton collisions at  $\sqrt{s} = 13$  TeV”, Phys. Rev. Lett. 124 (2020) 131802, doi:10.1103/PhysRevLett.124.131802, arXiv:1912.04776
- [3] S. Born, R. Karur, S. Knapen, and J. Shelton, “Scouting for dark showers at CMS and LHCb”, Phys. Rev. D 108 (2023) 035034, doi:10.1103/PhysRevD.108.035034, arXiv:2303.04167

# Backup

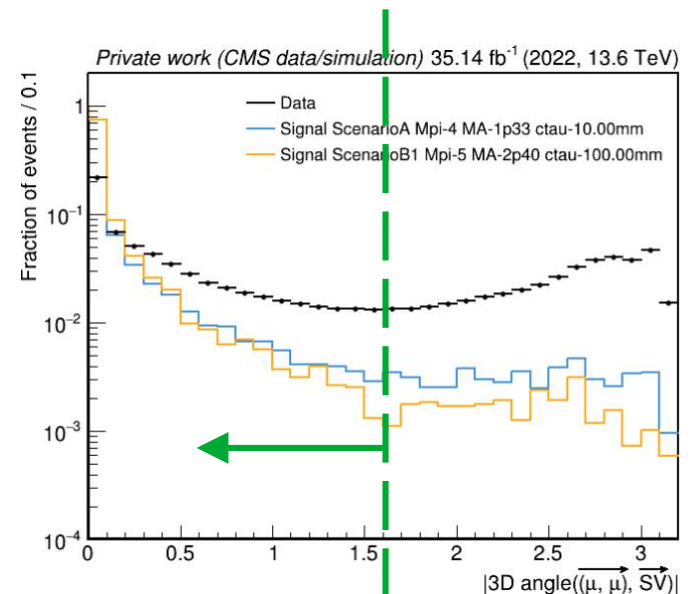
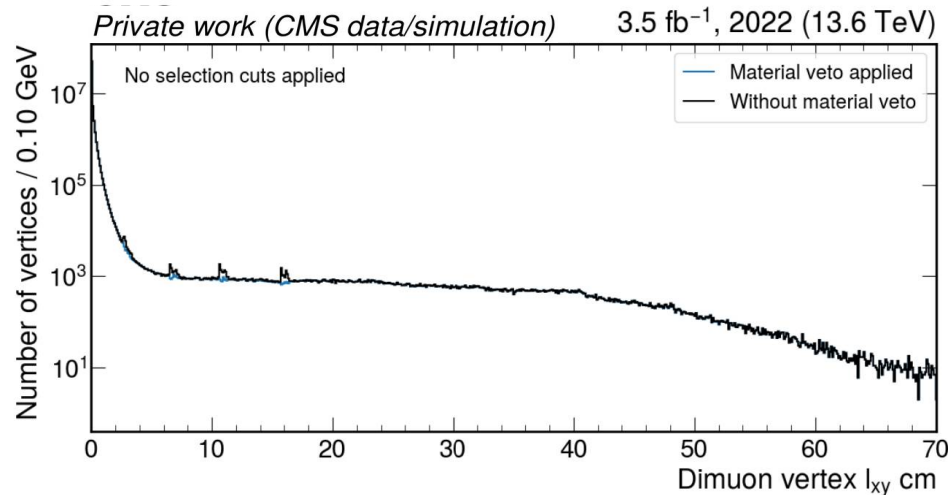
# Analysis: Muon selections

- Quality:  $p_T$ , reduced  $\chi^2$ ,  $\eta$
- Displacement: Transverse displacement significance (Muon  $d_{xy}/\sigma_{dxy}$ ),
- Angular: 3D angle and  $\phi$  between pairs of muons



# Analysis: SV selections

- Quality: Reduced  $\chi^2$ , position error
- Accidental crossings: Selections on excess tracker hits and crossing angle of muons associated with SV
- Material veto: Remove vertices originating from interactions with tracker material
- Angular: 3D angle and  $\phi$  between SV and dimuon system



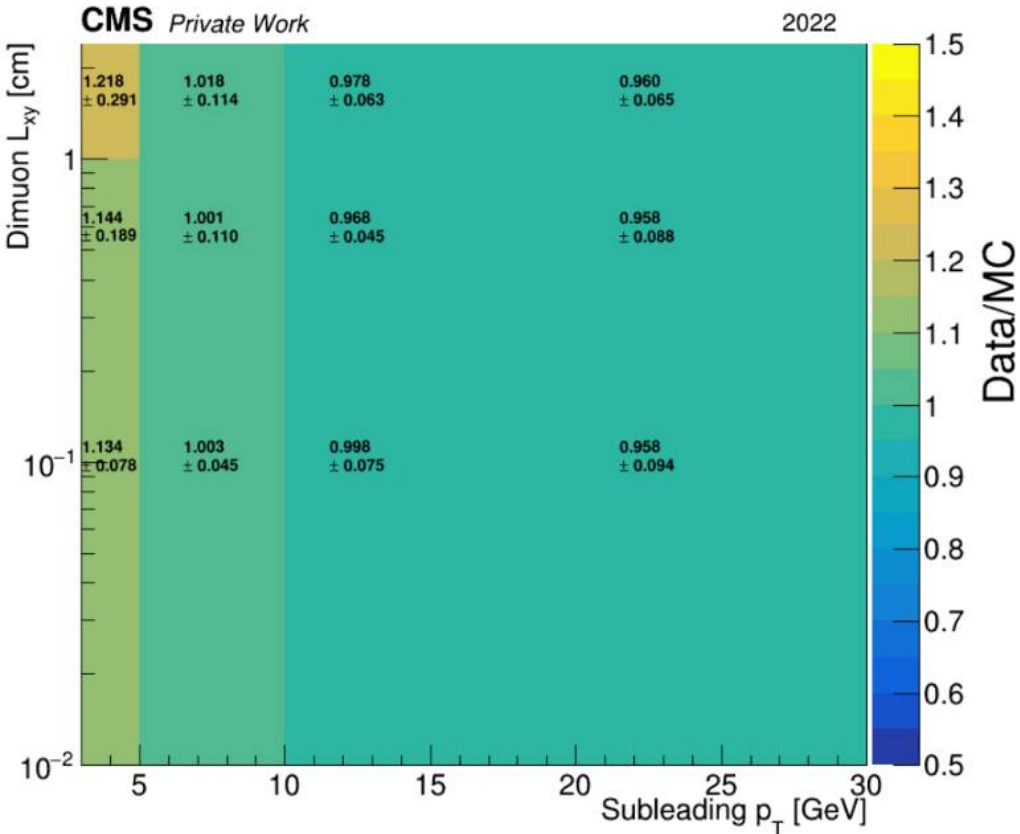
# Analysis: Summary table

Event selection			
Requirement	Dimuon	Four muon (2-SV)	Four muon (OSV)
Muon preselection	$p_T > 3 \text{ GeV},  \eta  < 2.4, \chi^2/\text{ndof} < 3$		
SV preselection	$\delta x < 0.05, \delta y < 0.05, \delta z < 0.1, \chi^2/\text{ndof} < 3$		
Material veto	Yes		
SM resonance veto	Yes		
Dimuon kinematics	$ \Delta\phi(\mu\mu, \text{SV})  < \pi/2$ $ \text{3D angle}(\mu\mu, \text{SV})  < \pi/2$ $ \Delta\phi(\mu, \mu)  < 2.8$ $ \text{3D angle}(\mu, \mu)  < 2.8$	$ \Delta\phi(4\mu, \text{SV})  < \pi/2$ $ \text{3D angle}(4\mu, \text{SV})  < \pi/2$ $ \Delta\phi(\mu, \mu)  < 2.8$ $ \text{3D angle}(\mu, \mu)  < 2.8$	
Pileup veto	Yes	-	-
Prompt muon veto	$ d_{xy} /\sigma_{d_{xy}} > 2$ $ d_{xy} /(l_{xy} m_{\mu\mu}/p_T^{\mu\mu}) > 0.1$	$ d_{xy} /\sigma_{d_{xy}} > 2$	$ d_{xy} /\sigma_{d_{xy}} > 2$
Excess hits	$N_{\text{excess}}^{\mu\mu} = 0 (l_{xy} \in [0, 11] \text{ cm})$ $N_{\text{excess}}^{\mu\mu} \leq 1 (l_{xy} \in [11, 16] \text{ cm})$ $N_{\text{excess}}^{\mu\mu} \leq 2 (l_{xy} \in [16, 70] \text{ cm})$	-	-
Rel. mass difference	-	$\Delta m_{\mu\mu}/\langle m_{\mu\mu} \rangle < 0.05$	-

Selections on 4mu categories updated after discussion with ARC

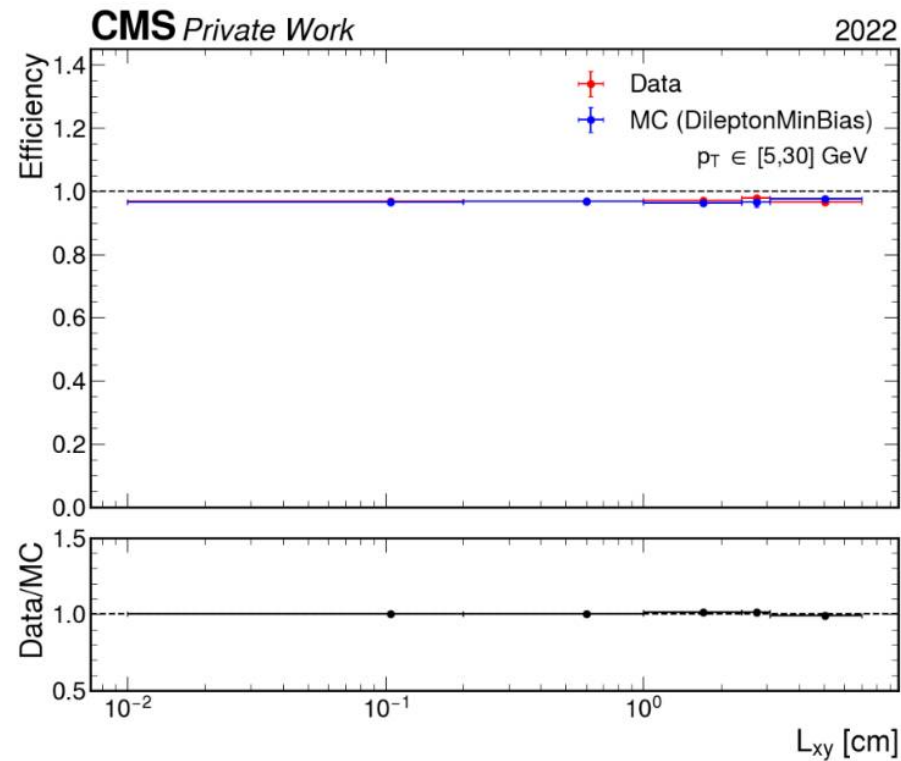
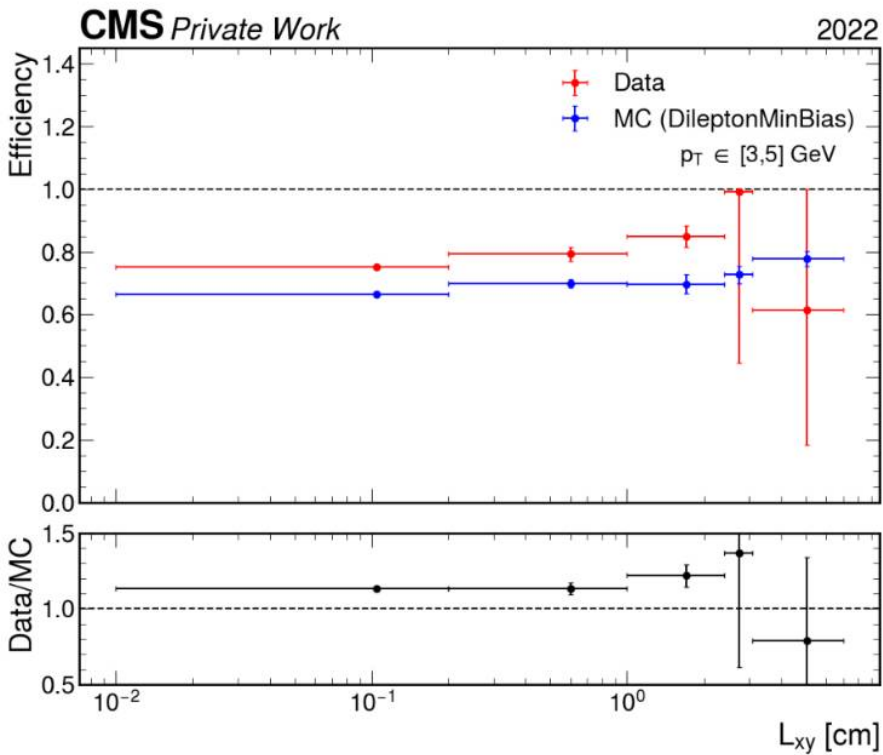
Isolation requirements not used to reject events but applied in categorization

# Trigger efficiency SF: 2D

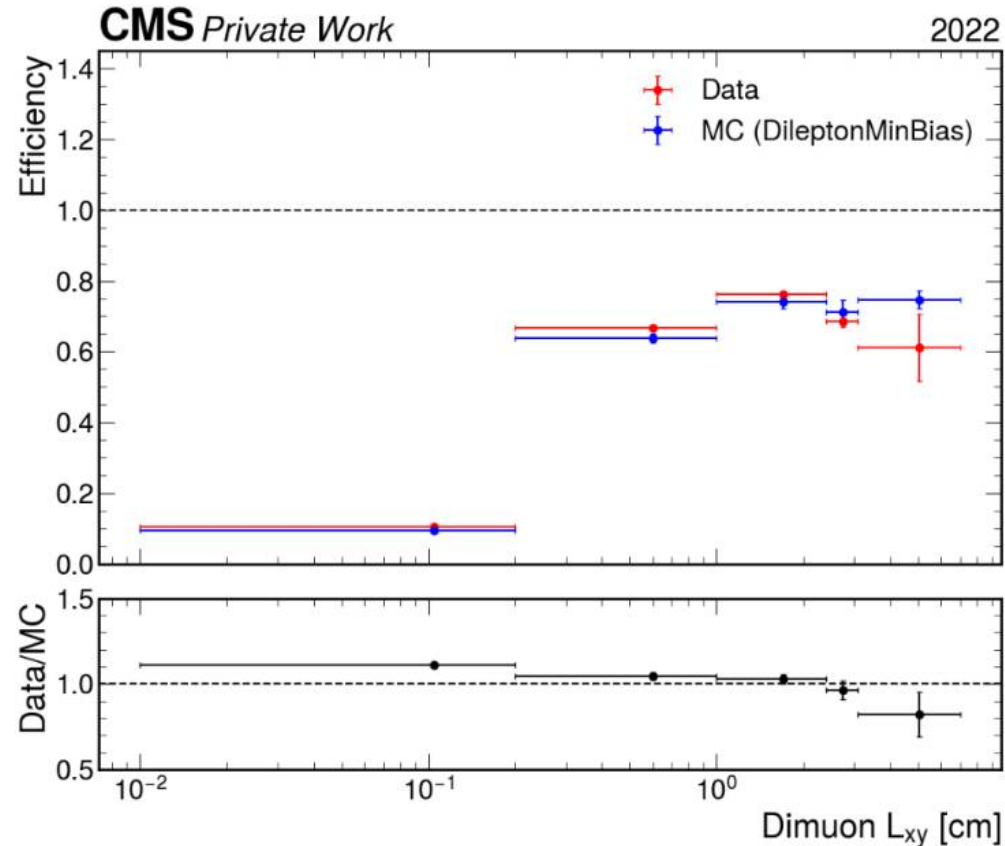


- 2D scale factors obtained for displacements up to 2.4 cm
- 1D scale factors used for higher  $l_{xy}$  categories

# Trigger efficiency SF 1D $l_{xy}$



# Selection efficiency 1D $l_{xy}$



- Limited in  $J/\Psi$  stats at higher  $l_{xy}$  bins ( $> 7.0$  cm) for data

# Pointing categorisation

- Represents collinearity of the dimuon system
- **Pointing:** Small  $\Delta\phi$  between Trajectory of dimuon system ( $p_{\mu\mu}$ ) and position of SV ( $x_{SV}$ )
  - Direct decay of LLP to muons (Scenario A)
- **Non-pointing:** Large  $\Delta\phi$  between Trajectory of dimuon system ( $p_{\mu\mu}$ ) and position of SV ( $x_{SV}$ )
  - Decay of LLP to muons through intermediate (Scenario B1)

