

# Exploring long-lived particles decaying into Displaced Dimuons at $\sqrt{s} = 13.6$ TeV : Innovative Triggers for Enhanced Sensitivity at the CMS Experiment

**FAKT Workshop 2024**

**Mangesh Sonawane**



22.02.2024

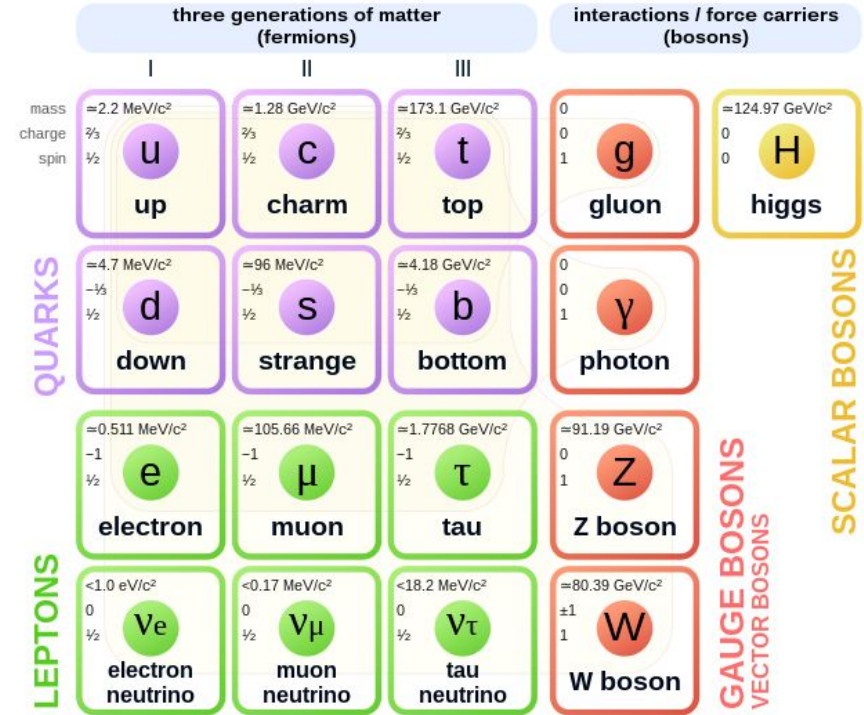
# The Standard Model of Particle Physics

- Comprehensive theory of fundamental particles and their interactions
- Self consistent
- Experimental predictions verified with remarkable precision

## However...

The Standard Model (SM) is not complete. It fails to explain :

- Baryon asymmetry
- Gravity
- Neutrino Oscillations and masses
- Hierarchy problem and fine tuning of masses
- Strong CP problem
- *Dark Matter*



# Introduction - Long Lived Particles

Several theories have been proposed to explain the incompleteness of the SM - Beyond Standard Model (BSM) theories

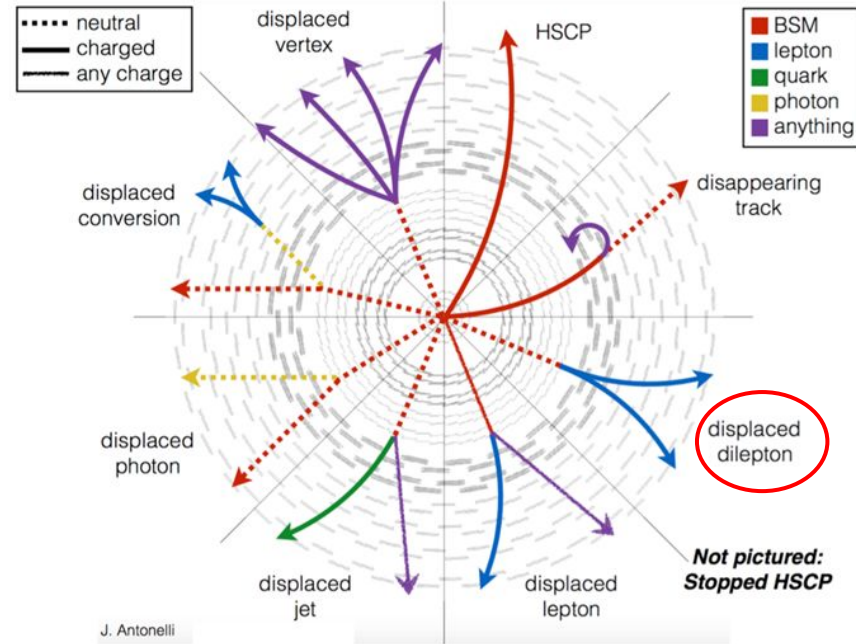
- Examples : Supersymmetry (SUSY), Weakly Interacting Massive Particles (WIMPs)

From searches at colliders and direct detection experiments :

Everything is so far consistent with Standard Model predictions

However there could still be interesting signatures that could be accessible, but we haven't yet probed!

⇒ Long lived particles!

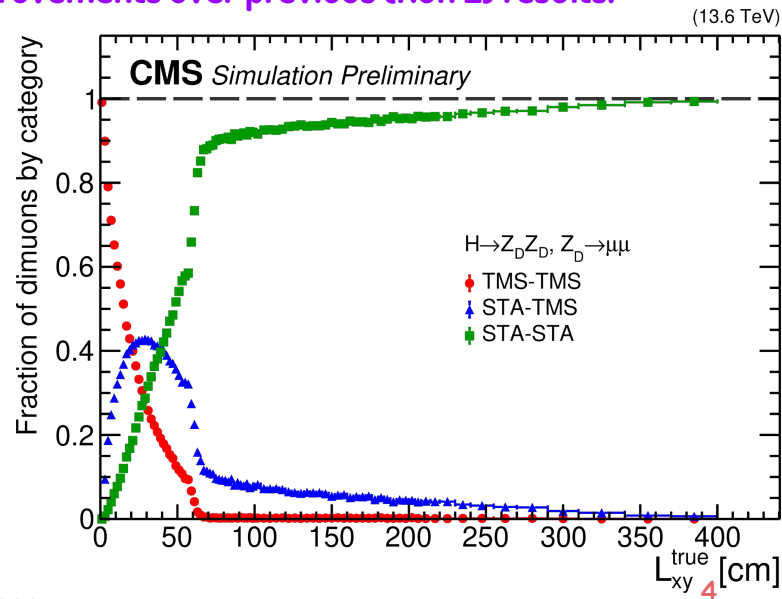
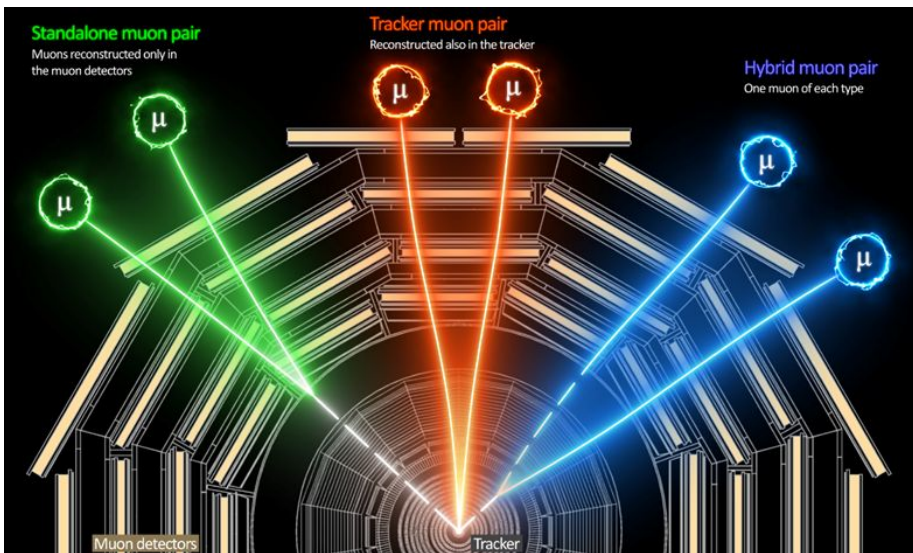


This search :

Secondary dimuon vertex displaced from the proton-proton collision point by up to several meters.

# Search for Displaced Dimuons in Run 3

- ✗ Signature is a pair of muons originating from a secondary vertex macroscopically displaced from the proton-proton collision point.
  - ✗ Muon signatures allow utilization of the largest part of detector volume.
- ✗ Two types of muons based on reconstruction : **STA** (Standalone) and **TMS** (Tracker + Muon System)
  - ✗ Gives three complementary and exclusive categories : **STA-STA**, **TMS-TMS**, **STA-TMS**
- ✗ **First direct search for BSM with LHC Run 3 data<sup>[1]</sup> : significant improvements over previous (Run 2) results!<sup>[2]</sup>**

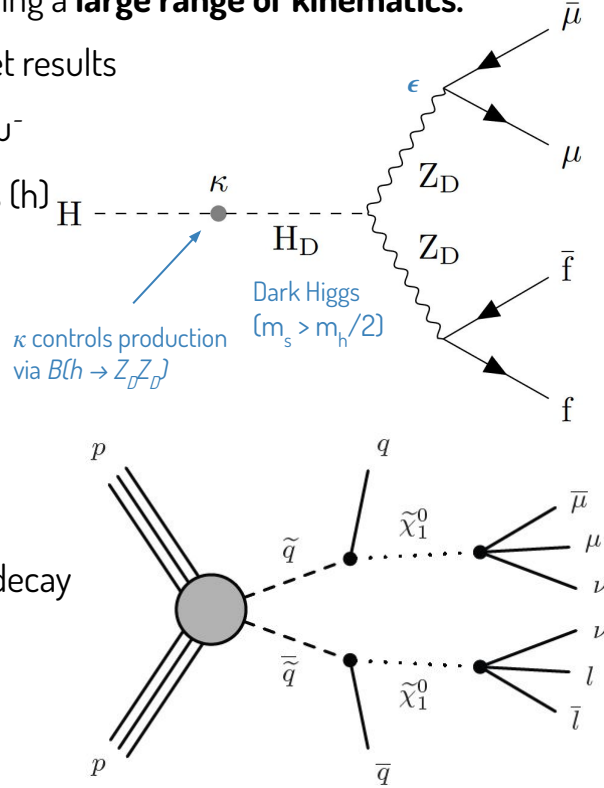


Largely **model-independent** search, covering a **large range of kinematics**.

Two models used as benchmark to interpret results

**Dark Photon Model** [3]:  $H \rightarrow Z_D Z_D$ ,  $Z_D \rightarrow \mu^+ \mu^-$

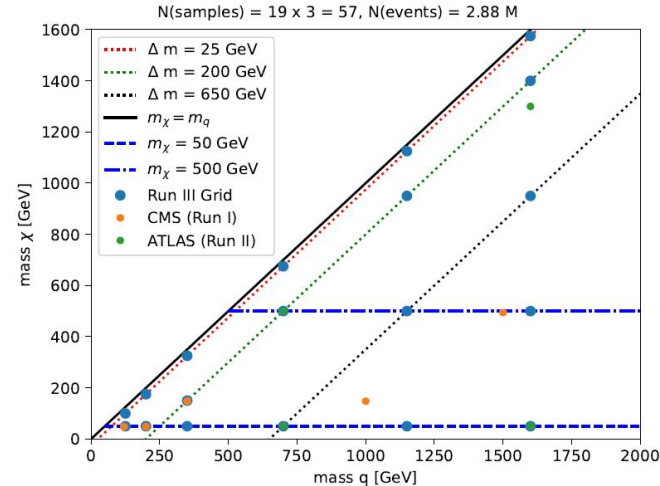
- Dark Higgs ( $H_D$ ) mixes with SM Higgs ( $h$ ) via  $\kappa$
- $\epsilon$  controls dark photon ( $Z_D$ ) lifetime:  $c\tau_{Z_D} \sim \epsilon^{-2}$



$m_h$	$m_{Z_D}$	$B(Z_D \rightarrow \mu\mu)$
125 GeV	10, 20, 30, 40, 50, 60	10-15%

$\times 4 c\tau_{Z_D}$  per mass

$m(\tilde{q}), m(\tilde{\chi}_1^0)$  Sample grid  $\times 3 c\tau_{Z_D}$  per mass



**RPV SUSY Model** [4]:

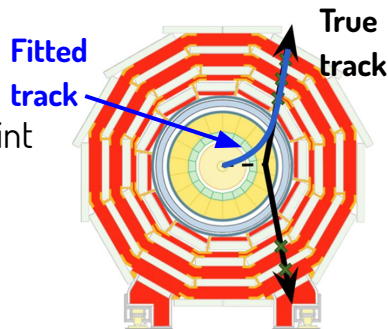
- Non-resonant long lived neutralino decay  $\tilde{\chi}_1^0 \rightarrow \mu\mu\nu$
- $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow \mu\mu\nu) = \mathcal{B}(\tilde{\chi}_1^0 \rightarrow ee\nu)$

CMS uses a **two-tiered trigger** to handle the large volume of collision data produced.

- ✗ **Level 1 (L1)** : Extremely fast hardware trigger - reduces rate from 40 MHz to a few 100 kHz
- ✗ **High Level Trigger (HLT)** : Software trigger - improved reconstruction - reduces rate to ~1kHz

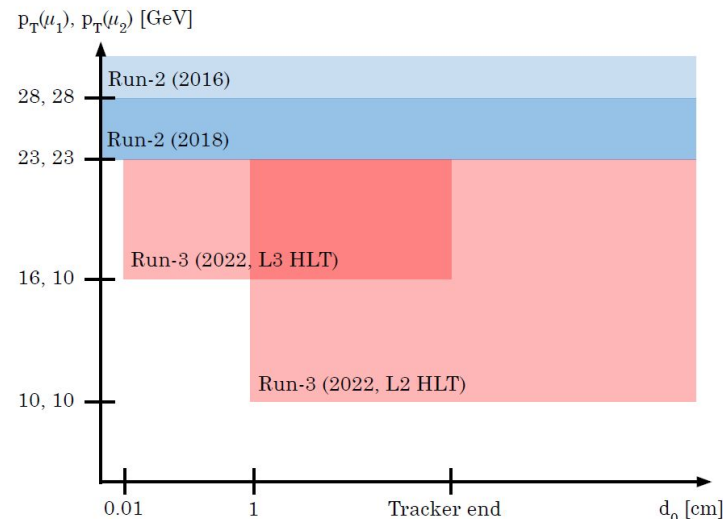
## Lessons from the Run 2 analysis :

- ✗ For very displaced muons, beamspot constraint underestimated  $p_T$  → **trigger inefficiency**.
- ✗ High  $p_T$  thresholds at the HLT



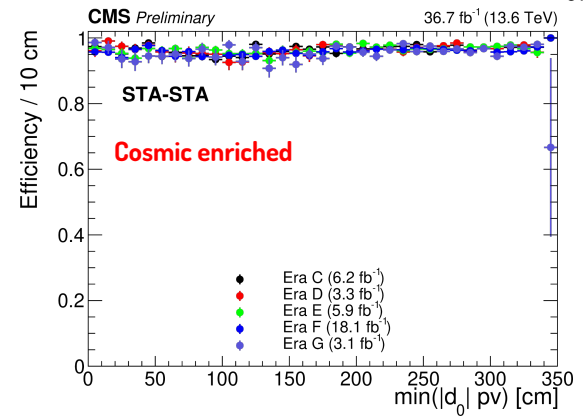
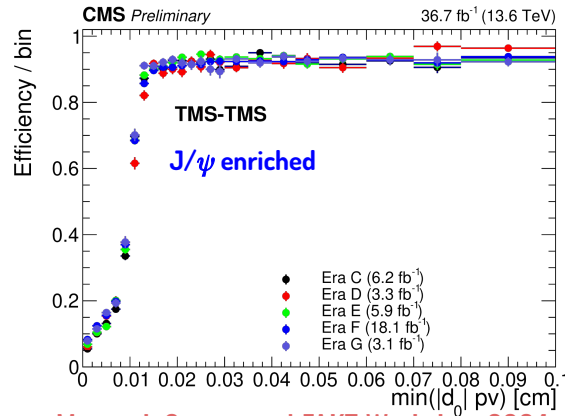
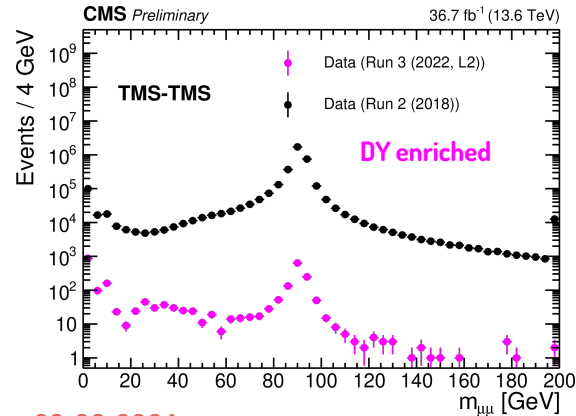
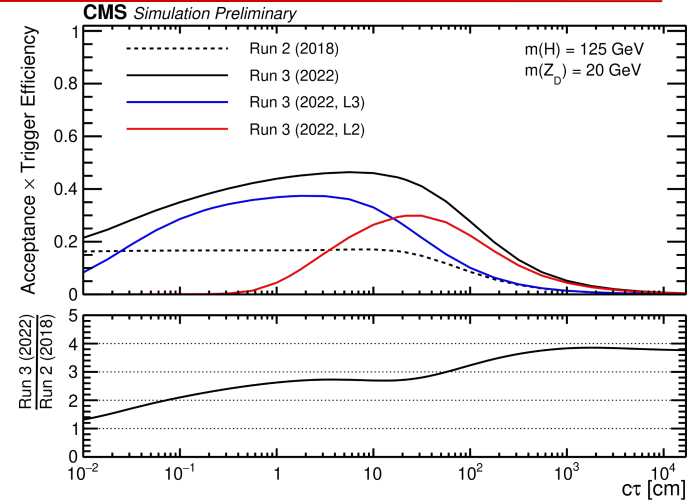
## New Triggers developed at L1 and HLT

- ✗ **L1** : new track finding algorithms for displaced muons
- ✗ **HLT** :
  - ✗ **Lower  $p_T$  thresholds** : 23 GeV → 10 GeV
  - ✗ **Muon  $d_0$  thresholds** : suppress prompt muons
  - ✗ **Utilize tracker information** : higher precision

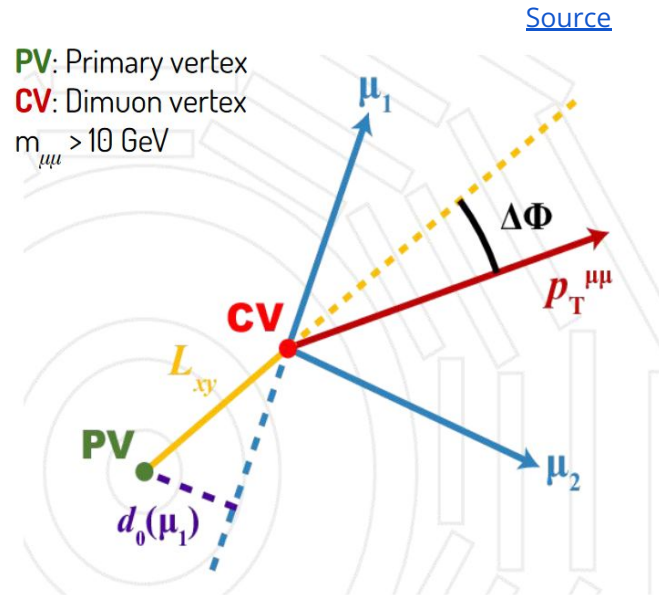


# Trigger Performance

- ✗ Efficiency in **signal** increased by a factor **2x to 4x!**
- ✗ Performance in data :
  - ✗ **Drell-Yan** : prompt dimuons
    - **rejection factor of 2000**
  - ✗  **$J/\psi \rightarrow \mu\mu$ , Cosmic muons** : displaced dimuons, proxy for signal
    - **Selection efficiency > 90%**
    - Prompt dimuons suppressed



- **Signal region designed to be free from SM backgrounds.**
  - Misidentification or mis-reconstruction of muons can cause background events to enter the signal region.
- **Powerful handles to distinguish signal from background**
  - Muon Track/Dimuon Vertex quality (fit  $\chi^2$ )
  - **STA** to **TMS** association.
  - Displacement :  $L_{xy}/\sigma(L_{xy})$ ,  $d_0/\sigma(d_0)$
  - Kinematics :
    - $p_T^\mu$ ,  $\alpha_{\mu\mu}$ ,  $p_T^{\mu\mu}$ , Collinearity  $|\Delta\Phi|$
  - Invariant mass :  $m_{\mu\mu}$
  - Isolation
  - Muon direction
  - Timing
  - Charge (OS/SS)



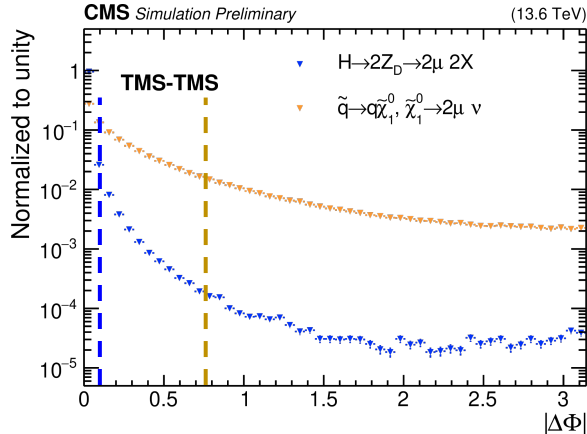


Backgrounds estimated using the **ABCD method**, validated in CRs adjacent to SR :

$$N_{SR}^A = (N_B * N_C) / N_D$$

- ✗ For  $\Delta\Phi$  **asymmetric** backgrounds (e.g. QCD) :
  - Signal expected to have **Opposite Sign** and **isolated muons**
- ✗ For  $\Delta\Phi$  **symmetric** backgrounds (e.g. DY) :
  - Signal expected to have **small  $\Delta\Phi$**

	OS	SS
Isolation	A = QCD background in SR	B
Fail Isolation	C	D



For the **dark photon** model :

- **TMS-TMS** :  $C = 30$
- **STA-STA** :  $C = 10$

For the **RPV SUSY** model :

- $C = 4$

$ \Delta\Phi  < \pi/C$	$ \Delta\Phi  > \pi - \pi/C$
A - DY background in SR	B
C	D

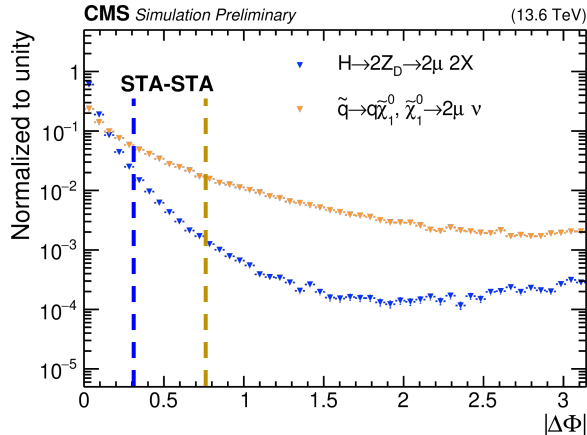
Inverted STA-TMS association

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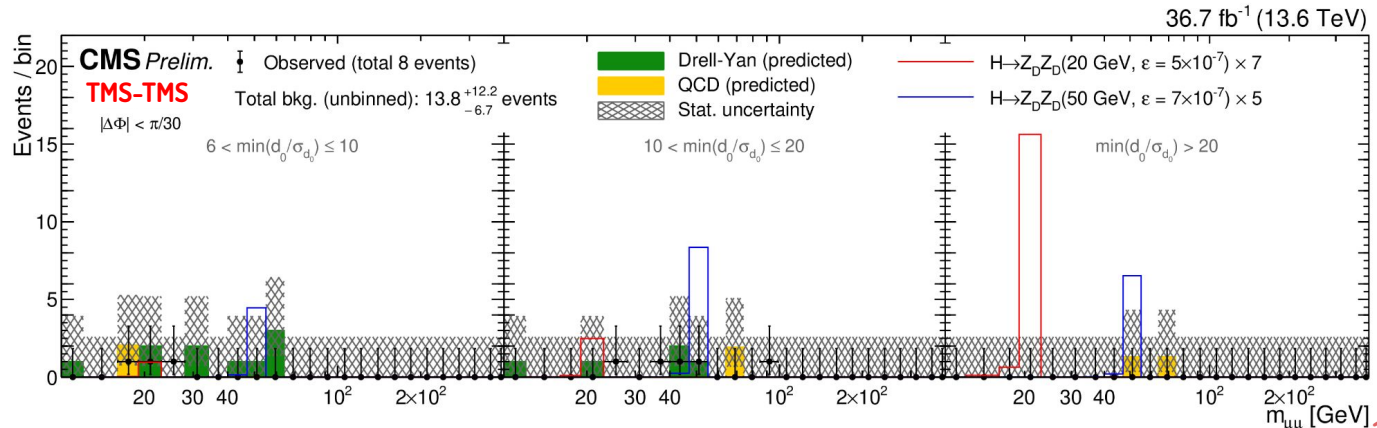
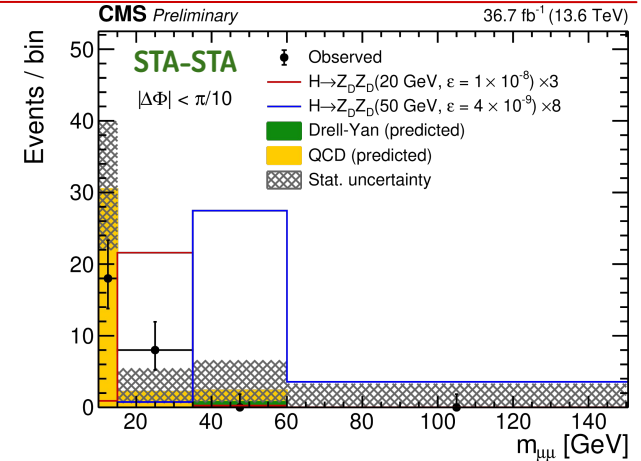
- $C = 4$

$ \Delta\Phi  < \pi/C$	$ \Delta\Phi  > \pi - \pi/C$
A - DY background in SR	B
C	D

Inverted STA-TMS association

# Results - Dark Photon model

- ✗ Background contamination generally very small in both **TMS-TMS** and **STA-STA** categories
  - Most background events in **STA-STA** have low mass.
  
- ✗ Observed number of events consistent with predictions.
  - **No excesses observed.**



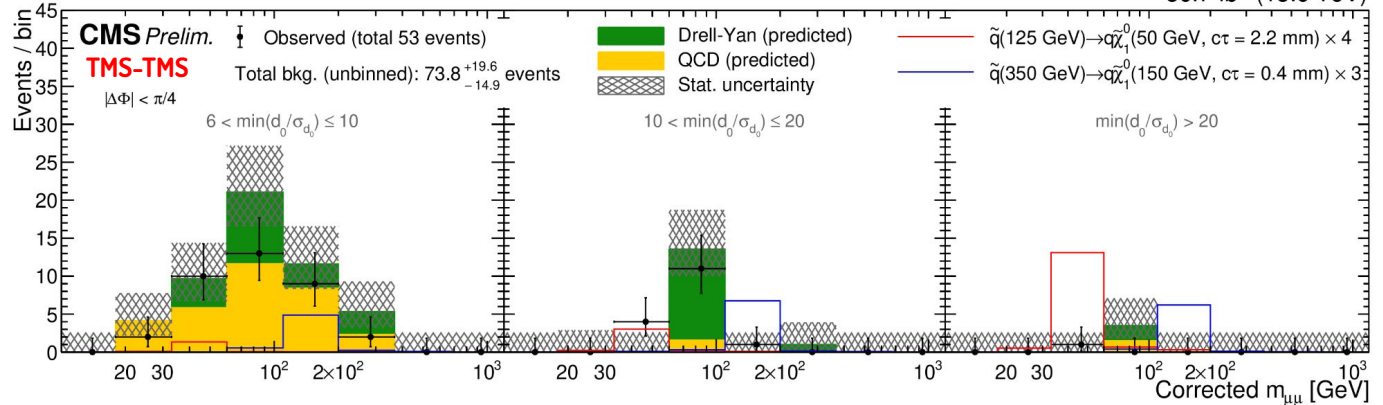
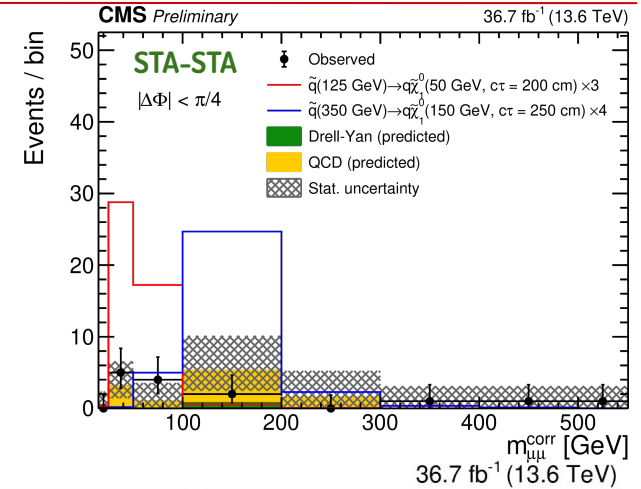
✗ Features **non-resonant dimuon production**

- **Corrected mass** to account for neutrino: minimum mass of secondary vertex consistent with direction of the LLP

$$m_{\mu\mu}^{\text{corr}} = \sqrt{m_{\mu\mu}^2 + p_{\mu\mu}^2 \sin^2 \theta} + p_{\mu\mu} \sin \theta,$$

✗ Observed number of events consistent with predictions.

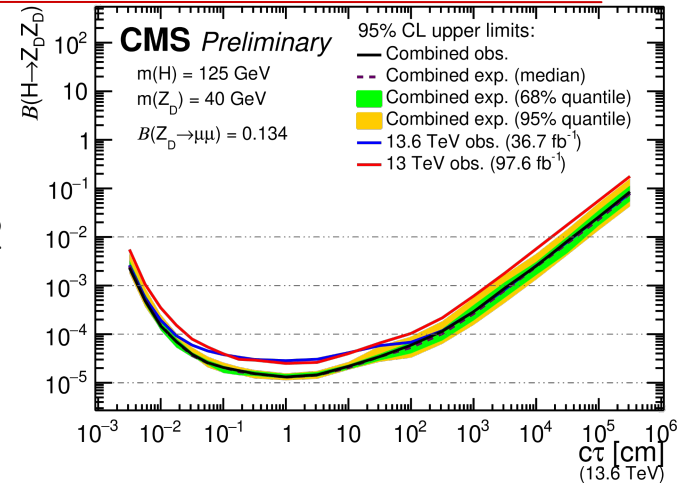
- **No excesses observed.**



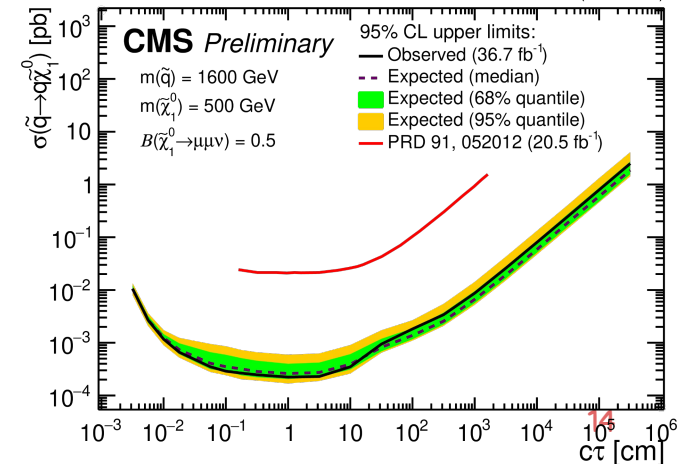
# Results - Limits

Results used to set upper limits on model parameters :

- ✗ For the Dark Photon model :
  - Limits set on  $B(H \rightarrow Z_D Z_D)$
  - Run 3 (2022 only) limits **comparable or better** than full Run 2 with **only 40% of the luminosity!**
  - **Combined** Run 2 + Run 3 limits **stronger by factor 2**

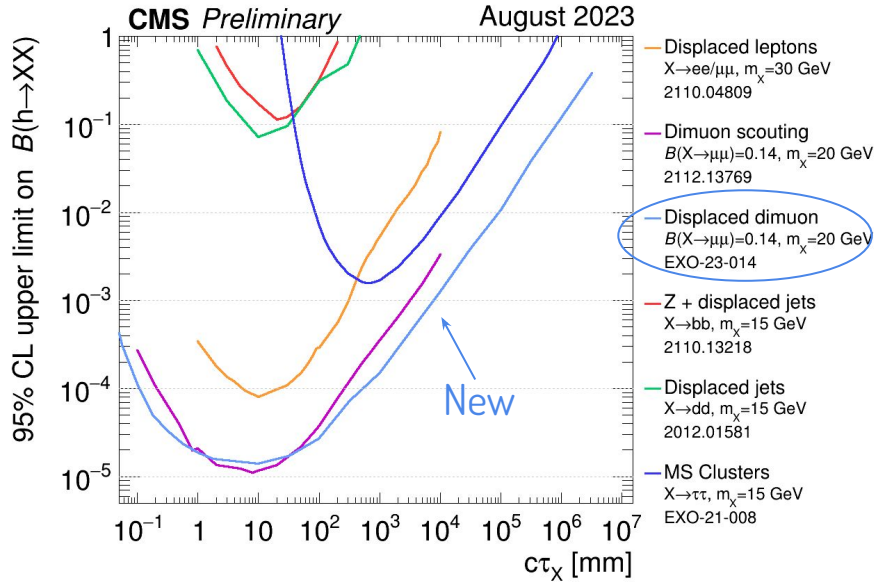


- ✗ For the RPV SUSY model
  - Limits set on  $\sigma(\tilde{q}\tilde{q}^*)B(\tilde{q} \rightarrow q\tilde{\chi}_1^0)$
  - Limits on  $\sigma(\tilde{q}\tilde{q}^*)$  significantly stronger than previous CMS (Run 1) limits

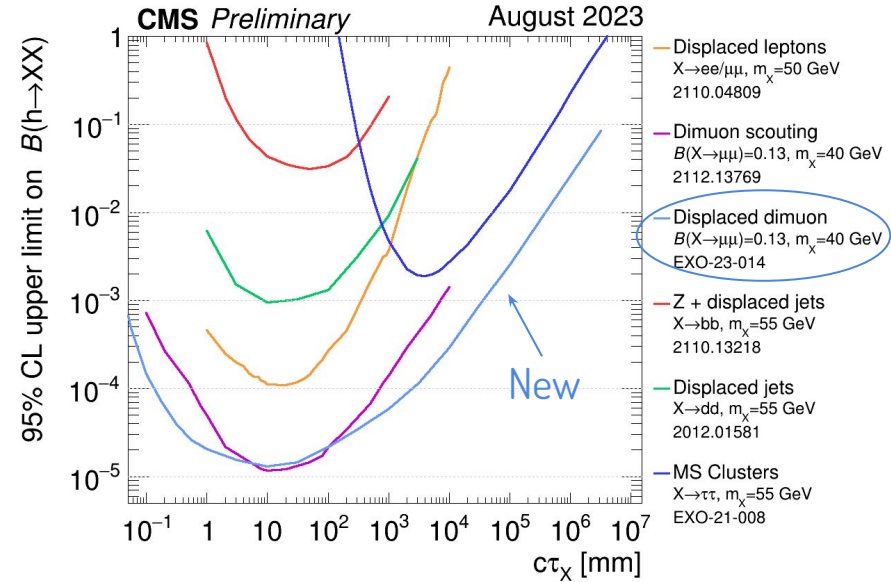


# Comparison to other LLP searches : $H \rightarrow XX$

Best constraints to date in  $B(H \rightarrow XX)$  in broad range of  $c\tau(X)$  for  $m(X) > 10$  GeV



$10 \text{ GeV} < m_{\mu\mu} < 40 \text{ GeV}$



$m_{\mu\mu} > 40 \text{ GeV}$

Innovation in trigger strategy allowed CMS to explore new BSM territory already with data from the first year of LHC Run 3 : **First search for new physics at 13.6 TeV**, with  $36.7 \text{ fb}^{-1}$  of data collected in 2022.

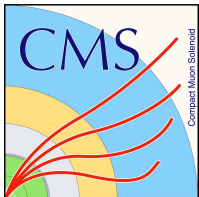
- ✗ Improves upon previous Run 2 search by a **factor 2x to 4x** – **sensitivity gain driven by new triggers**
  - ✗ At L1 Trigger : new algorithms implemented for displaced dimuons
  - ✗ At HLT : new dimuon paths with lower  $p_T$ , and displacement thresholds to reject prompt muons
- ✗ No excesses observed.
- ✗ Results combined with Run 2 data for Dark Photon model
  - ✗ Best constraints to date to  $B(H \rightarrow Z_D Z_D)$  in broad range of  $c\tau(Z_D)$  for  $m(Z_D) > 10 \text{ GeV}$
  - ✗ **Comparable or better than Run 2** with despite only modest integrated luminosity.
- ✗ Significant improvements in constraints to  $\sigma(\tilde{q}\tilde{q})$  in RPV SUSY

Physics Analysis Summary already available<sup>[1]</sup>, paper in final stages of collaboration review.

1. CMS Collaboration, “Search for long-lived particles decaying to a pair of muons in pp collisions at  $\sqrt{s}=13.6$  TeV with 2022 data”, <https://cds.cern.ch/record/2868338>
2. CMS Collaboration, “Search for long-lived particles decaying to a pair of muons in proton-proton collisions at  $\sqrt{s} = 13$  TeV”, [http://dx.doi.org/10.1007/JHEP05\(2023\)228](http://dx.doi.org/10.1007/JHEP05(2023)228)
3. Curtin et al., “Illuminating dark photons with high-energy colliders”, [https://doi.org/10.1007/JHEP02\(2015\)157](https://doi.org/10.1007/JHEP02(2015)157)
4. Strassler and Zurek, “Discovering the Higgs through highly-displaced vertices”, <https://doi.org/10.1016/j.physletb.2008.02.008>

# Backup

<i>Event selection</i>			
$N(\text{PV})$	$\geq 1$		
HLT-STA muon matching	yes		
$N(\text{nearly parallel STA muons})$	$< 4$		
<i>Muon selection</i>			
	<i>Muon type</i>		
	STA	TMS	
STA-to-TMS muon association	not matched to TMS $\mu$	matched to STA $\mu$	
$N(\text{CSC+DT hits})$	$> 12$	—	
- associated STA muon	—	$> 12$	
$N(\text{DT hits})$ for muons in barrel tracker muon	$> 18$	—	
$N(\text{matched muon segments})$	—	yes	
$p_T$	—	$> 1$	
$\sigma_{p_T}^r / p_T$	$> 10 \text{ GeV}$	$> 10 \text{ GeV}$	
$\chi_{\text{trk}}^2 / \text{dof}$	$< 1.0$	$< 1.0$	
$I_{\text{trk}}^{\text{rel}}$	$< 2.5$	—	
$ \Delta t $	—	$< 0.075$	
muon direction	$< 12 \text{ ns}$	—	
$d_0 / \sigma_{d_0}$	inside-out	—	
	—	$> 6$	
<i>Dimuon selection</i>			
	<i>Dimuon category</i>		
	STA-STA	STA-TMS	TMS-TMS
DCA	$< 15 \text{ cm}$	$< 15 \text{ cm}$	$< 15 \text{ cm}$
pairing criteria	best 1–2 ranked dimuons selected		
$\chi_{\text{vtx}}^2$	$< 10$	$< 20$	$< 10$
$\Delta N(\text{pixel hits})$	—	—	$< 3$
$N(\text{hits before vertex})$	—	$< 6$	$< 3$
$N(\text{tracker layers}) + \text{floor}(L_{xy} [\text{cm}] / 15)$	—	$> 5$	$> 5$
$ \phi_{\mu}^{\text{TMS}} $	—	$< 2.9$	—
$\cos \alpha$			
- 2016 data analysis	$> -0.8$	$> -0.8$	$> -0.8$
- 2018 data analysis	$> -0.9$	$> -0.9$	$> -0.99$
$N(\text{dimuon segments})$	$> 4$	—	—
if $ \Delta \eta_{\mu\mu}  < 0.1$			
- $N(\text{dimuon segments})$	$> 5$	—	—
- $N(\text{DT hits})$ for muons in barrel	$> 24$	—	—
no back-to-back muon			
with $ \Delta t_{\text{b2b}}  > 20 \text{ ns}$	yes	—	—
$m_{\mu\mu}$	$> 10 \text{ GeV}$	$> 10 \text{ GeV}$	$> 10 \text{ GeV}$
$p_T$ of the leading muon	—	—	$> 25 \text{ GeV}$
$L_{xy} / \sigma_{L_{xy}}$	$> 6$	$> 3$	$> 6$
$ \Delta \Phi $	$< \pi / 4$	$< \pi / 4$	$< \pi / 4$
opposite-sign muons	yes	yes	yes



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Particles and Interactions

# Exploring long-lived particles decaying into Displaced Dimuons at $\sqrt{s} = 13.6$ TeV :

## Innovative Triggers for Enhanced Sensitivity at the CMS Experiment



FWF

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