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

Innovative Triggers for Enhanced Sensitivity at the CMS Experiment

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On behalf of the CMS Collaboration

Doktoratskolleg Particles and Interactions

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Introduction - Long Lived Particles

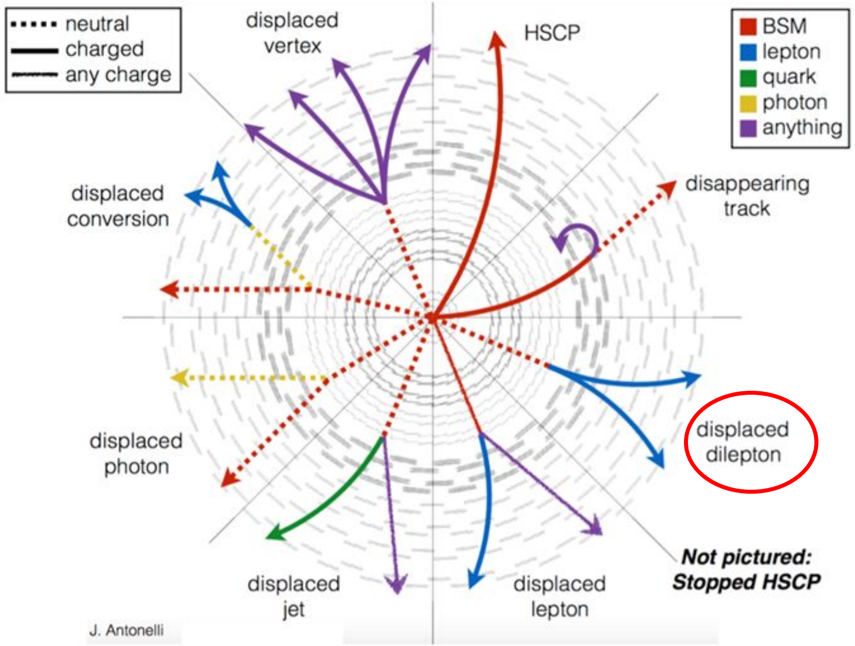
Several theories have been proposed to explain the incompleteness of the SM - Beyond Standard Model **(BSM)** theories

- 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 extensively!

⇒ **Long lived particles!**



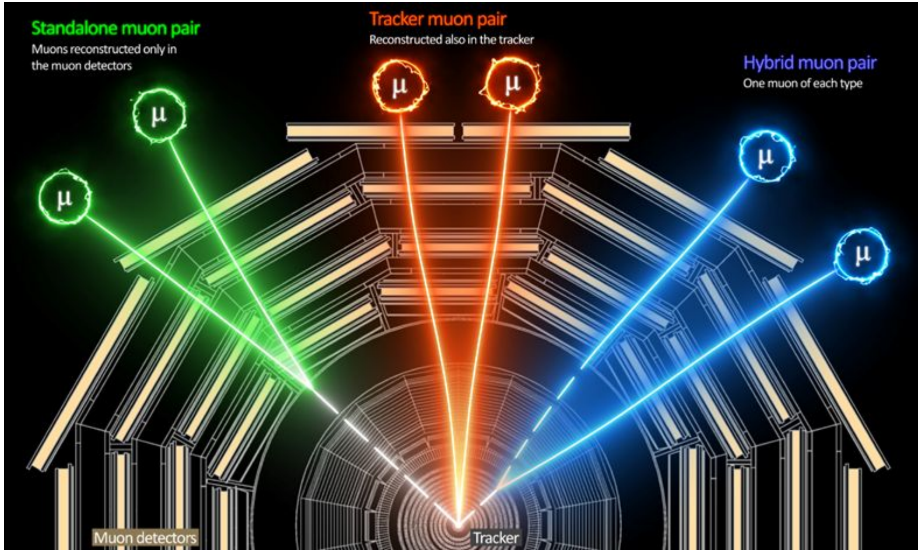
This search :

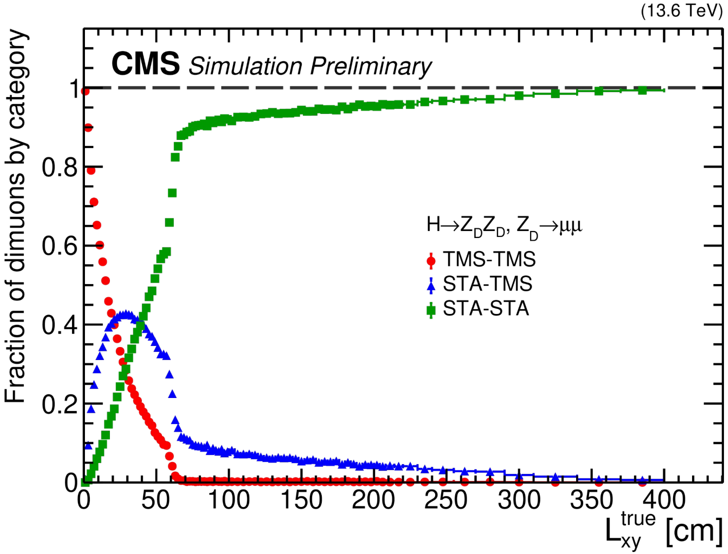
Secondary dimuon vertex displaced from the proton-proton collision point by up to several meters.

i.e. **Displaced Dimuons**

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[1] : significant improvements over previous (Run 2) results![2]**





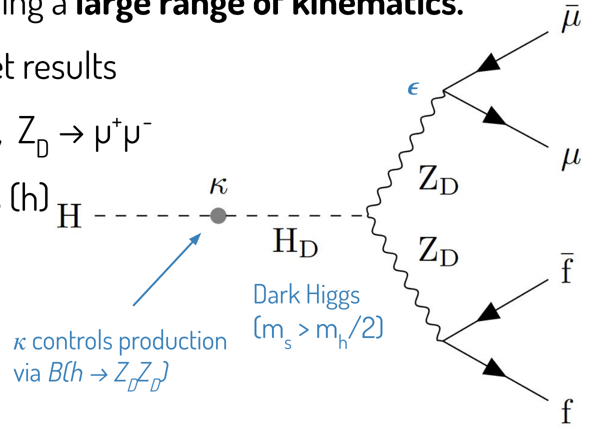
Signal models

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

Two models used as benchmark to interpret results

Hidden Abelian Higgs Model [3] : $H \to Z_D Z_D$, $Z_D \to \mu^+\mu^-$

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

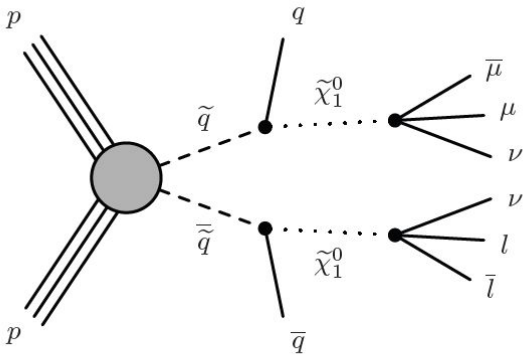


m_h	m_{ZD}	$B(Z_D\text{->}\mu\mu)$
125 GeV	10, 20, 30, 40, 50, 60	10-15%

x 4 $c\tau_{ZD}$ per mass

RPV SUSY Model [4] :

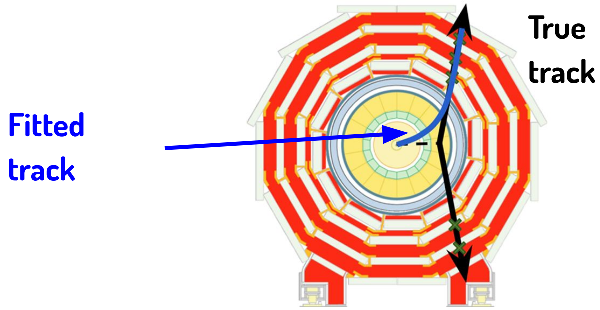
- Non-resonant long lived neutralino decay $\tilde{\chi}_1^0 \to \mu\mu\nu$
- $\mathcal{B}(\tilde{\chi}_1^0 \to \mu\mu\nu) = \mathcal{B}(\tilde{\chi}_1^0 \to ee\nu)$



Trigger Strategy

Lessons from the Run 2 analysis :

- ✘ For very displaced muons, beamspot constraint @L1 underestimated pT → **trigger inefficiency.**
- ✘ High pT thresholds at the HLT

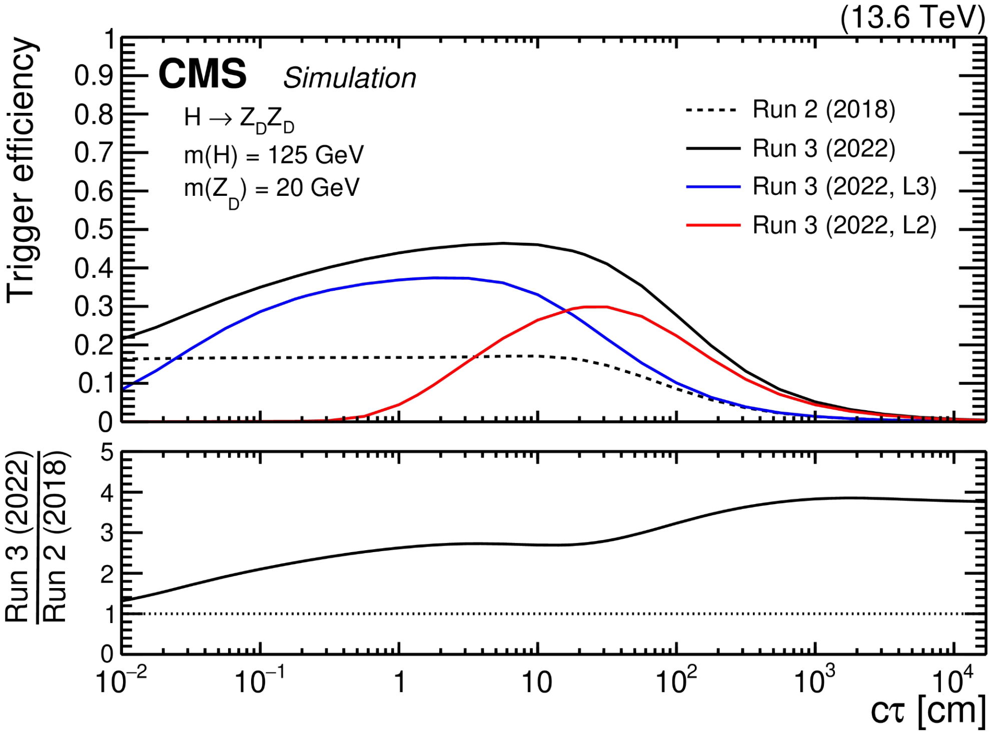


New Triggers developed at L1 and HLT

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

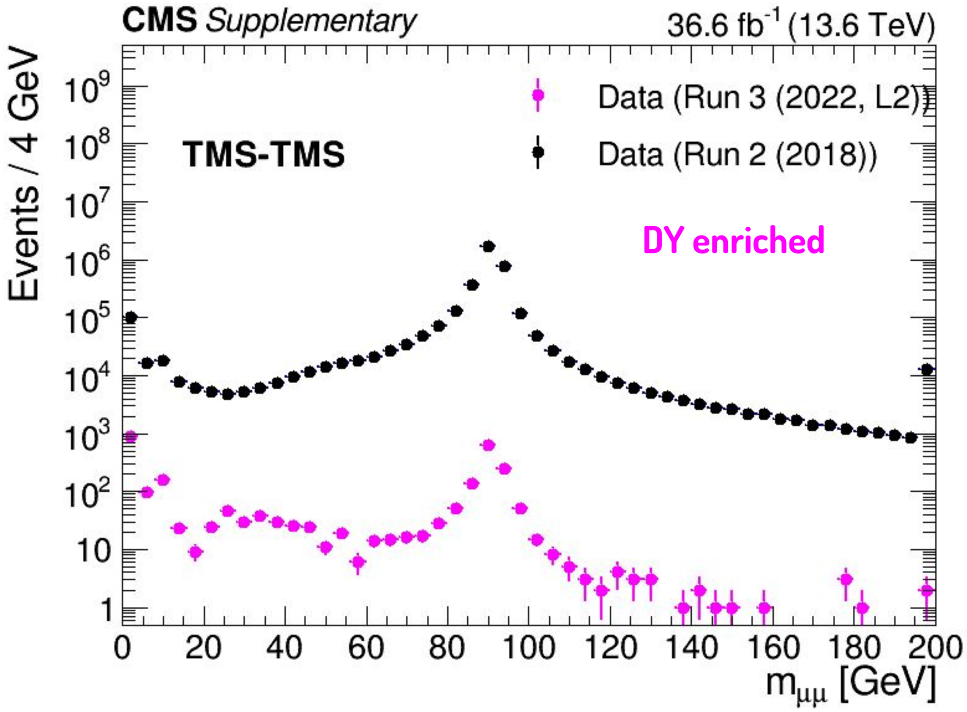
Trigger Performance

✘ Efficiency in **signal** increased by a factor **2x to 4x**!



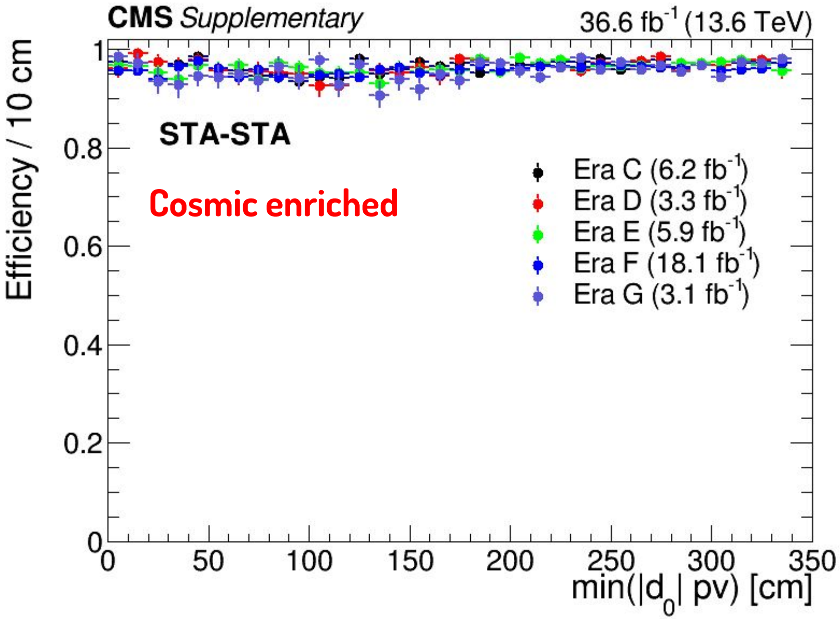
Trigger Performance

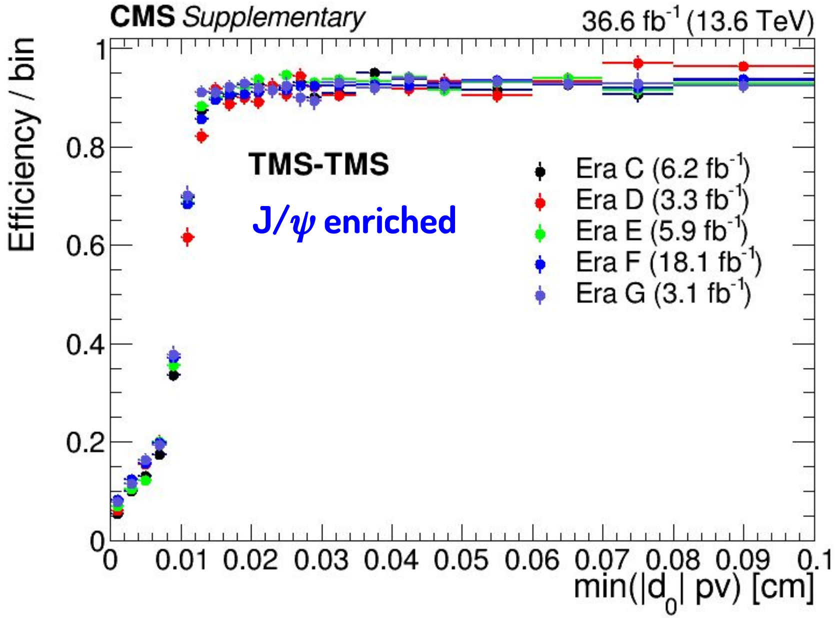
- ✘ Efficiency in **signal** increased by a factor **2x to 4x**!
- ✘ Performance in data :
  - ✗ **Drell-Yan** : prompt dimuons
    - ■ **rejection factor of 2000**



Trigger Performance

- Efficiency in **signal** increased by a factor **2x to 4x**!
- Performance in data :
  - **Cosmic muons**, **$J/\psi \to \mu\mu$** :
    displaced dimuons, proxy for signal

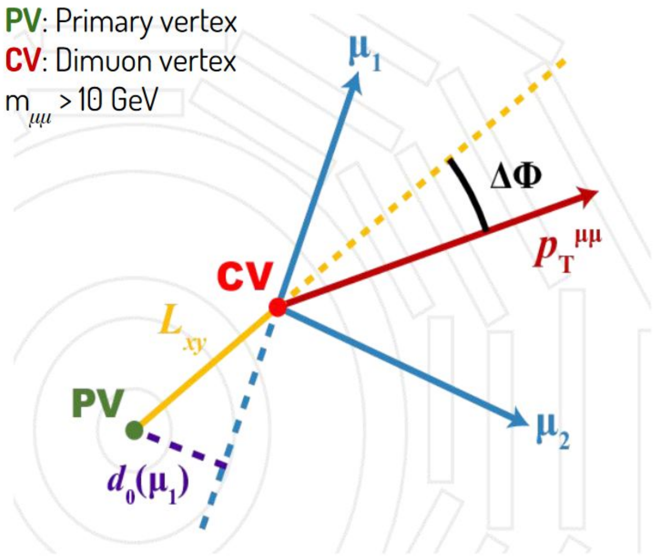




- **Selection efficiency > 90%**
- Prompt dimuons suppressed

Offline analysis : Key Observables

- **Powerful handles to distinguish signal from background**
  - Muon Track/Dimuon Vertex quality (fit χ^2)
  - STA to TMS association.
  - Displacement : $L_{xy}/\sigma(L_{xy})$, $d_0/\sigma(d_0)$
  - Kinematics :
    - p_T^{μ}, $\alpha_{\mu,\mu}$, $p_T^{\mu\mu}$, Collinearity $|\Delta\Phi|$
  - Invariant mass : $m_{\mu\mu} > 10$ GeV
  - Isolation
  - Muon direction
  - Timing
  - Charge (OS/SS)



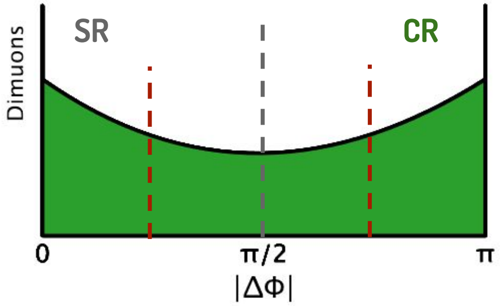
- **Signal region designed to be free from SM backgrounds**
  - Misidentification or mis-reconstruction of muons can cause background events to enter the signal region.

Backgrounds

- Backgrounds may be **symmetric** or **asymmetric** in Collinearity ΔΦ.
  - This depends on whether the p_T and L_{xy} vectors point in the same direction (correlated) or not.

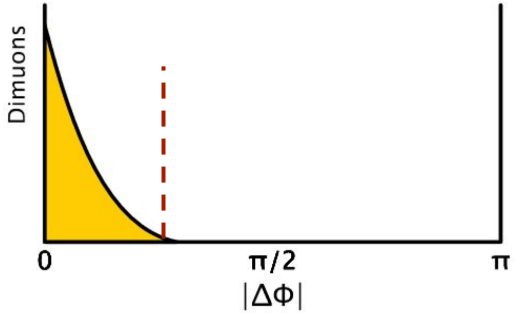
Symmetric

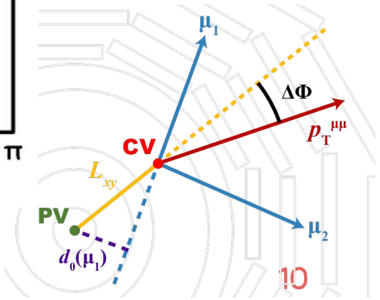
- Symmetrically distributed around $\pi/2$
- Occurs when p_T and Lxy vectors are uncorrelated
  - Mismeasured (prompt) Drell-Yan (DY), dibosons,
  - Cosmic ray muons
  - Unrelated jets, W+jets



Asymmetric

- Signal like peak at zero
- Occurs for non-prompt QCD resonances
  - Mismeasured low-mass non-prompt resonances (e.g. J/ψ)
  - Cascade decays resulting in 2+ muons (e.g. from B mesons)





Backgrounds

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

$$N^A_{SR} = (N_B * N_C)/N_D$$

✘ For ΔΦ **symmetric** backgrounds (e.g. DY) :

- Signal expected to have **small ΔΦ**

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

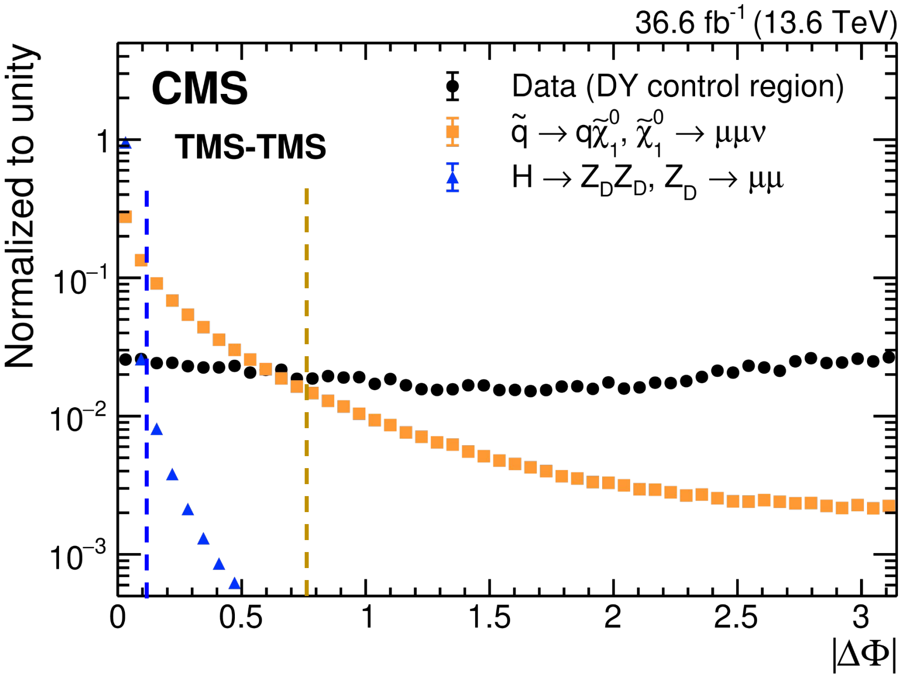
Inverted STA-TMS association

For the **dark photon** model :

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

For the **RPV SUSY** model :

- ➢ C = 4



Backgrounds

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

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

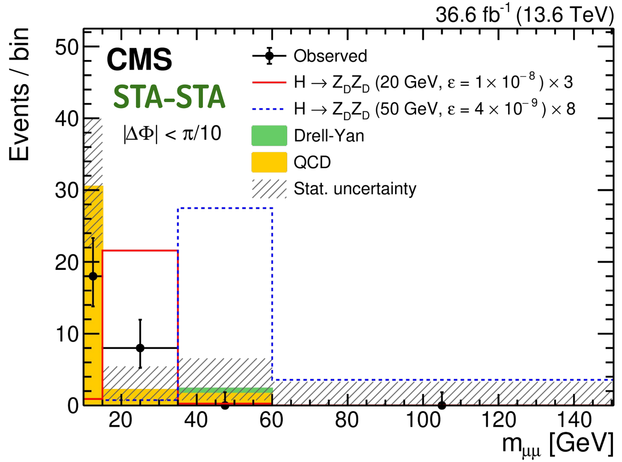
✘ For ΔΦ **asymmetric** backgrounds (e.g. QCD) :

- Signal expected to have **Opposite Sign** and **isolated muons**

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

Results - Dark Photon model

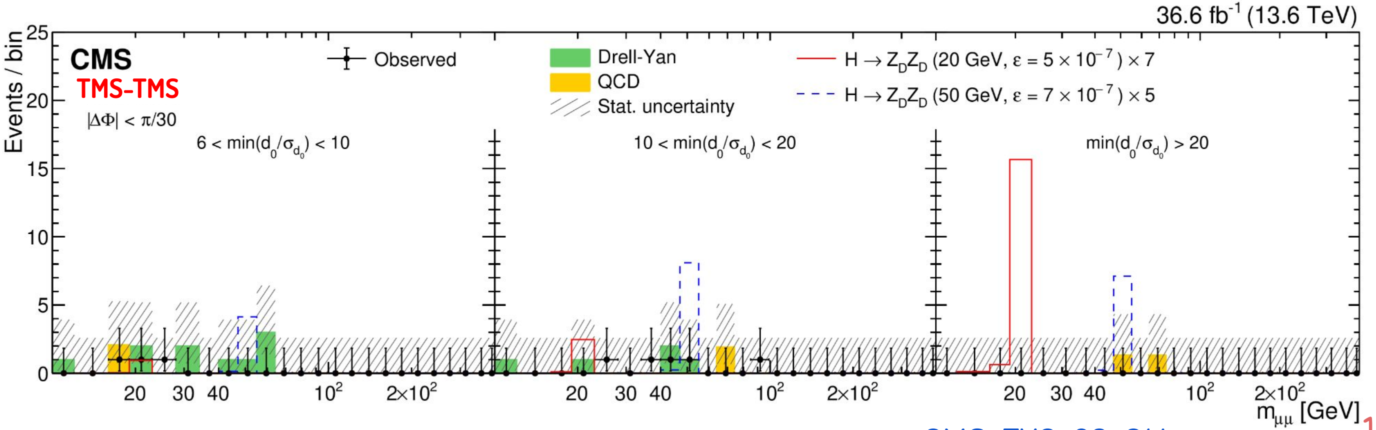
- Background contamination generally very small in both **TMS-TMS** and **STA-STA** categories
  - Most background events in **STA-STA** have low mass.



- Observed number of events consistent with predictions.
  - **No excesses observed**.

- TMS-TMS further divided into SRs based on muon d_0

Best sensitivity in most displaced SR

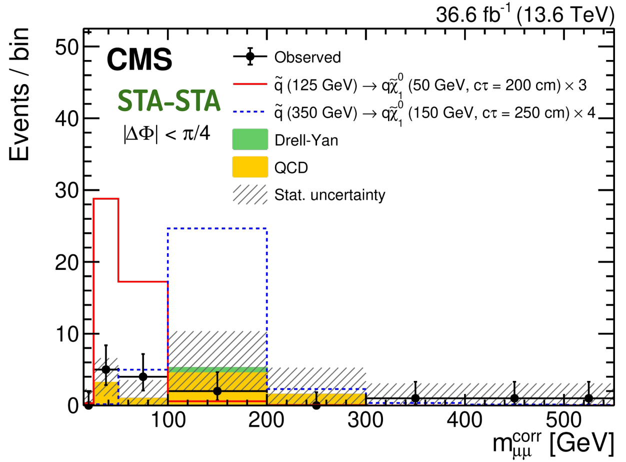


Results – RPV SUSY model

- ✘ Features **non-resonant dimuon production**
  - **Corrected mass** to account for neutrino: minimum mass of secondary vertex consistent with direction of the LLP

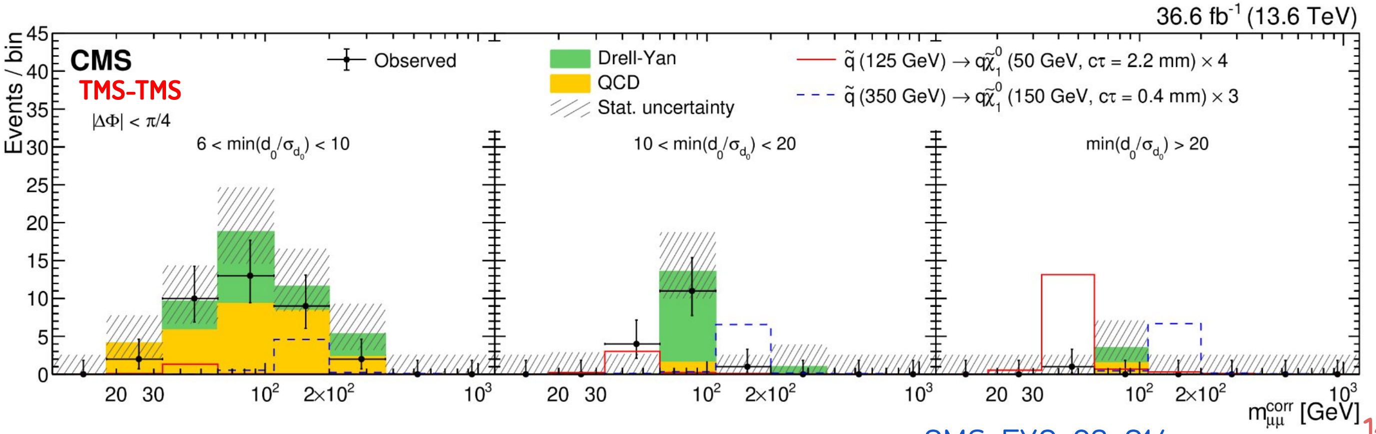
$$m_{\mu\mu}^{\text{corr}} = \sqrt{m_{\mu\mu}^2 + p_{\mu\mu}^2 \sin^2\theta} + p_{\mu\mu}\sin\theta,$$

- ✘ Observed number of events consistent with predictions.
  - **No excesses observed**.



- ✘ TMS-TMS further divided into SRs based on muon d_0

Best sensitivity in most displaced SR



Results – Limits

Results used to set upper limits on model parameters :

✘ For the Dark Photon model :

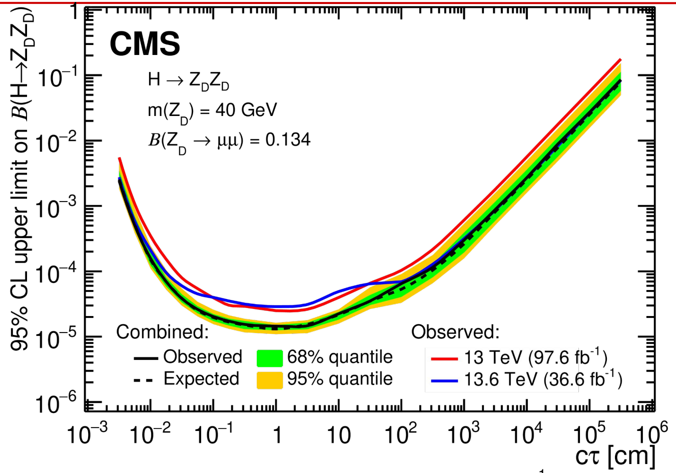
- Limits set on $B(H \to Z_D Z_D)$
- Run 3 (2022 only) limits **comparable or better** than full Run 2 with **only 40% of the luminosity**!

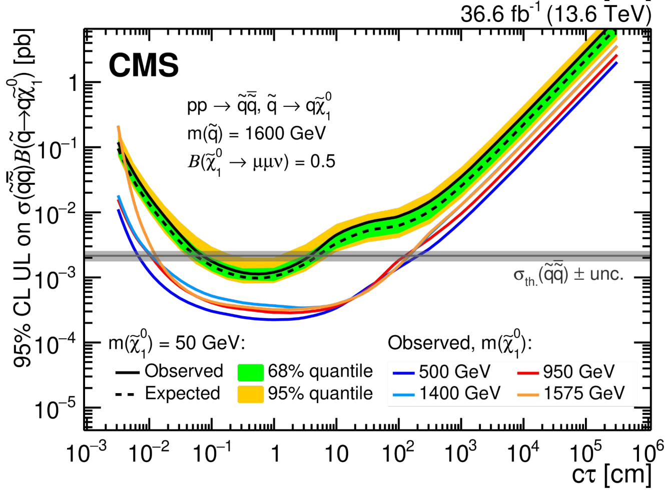
  ($36.6\ fb^{-1}$ vs $97.6\ fb^{-1}$)
- **Combined** Run 2 + Run 3 limits **stronger by factor 2**

✘ For the RPV SUSY model

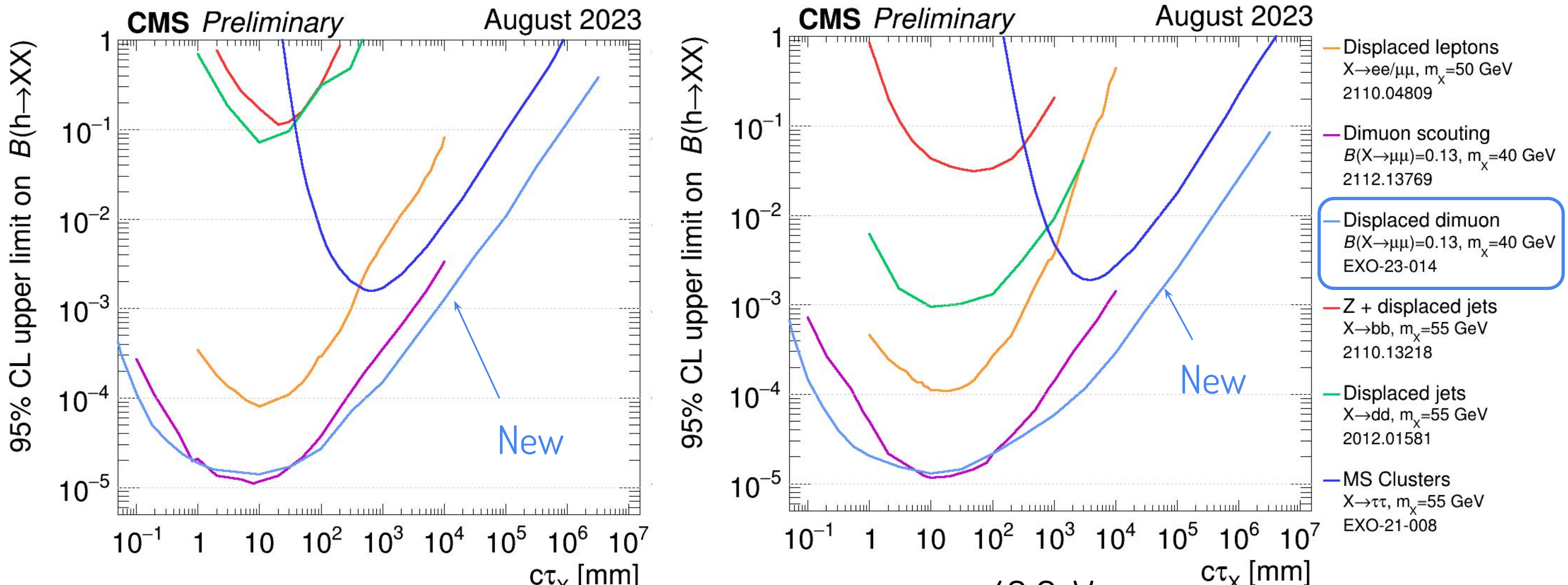
- Limits set on $\sigma(\tilde{q}\bar{\tilde{q}})B(\tilde{q} \to q\tilde{\chi}_1^0)$
- Limits on $\sigma(\tilde{q}\bar{\tilde{q}})$ significantly stronger than previous CMS (Run 1) limits

CMS-EXO-23-014





Best constraints to date in B(H→XX) in broad range of cτ(X) for m(X) > 10 GeV



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

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

Summary

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 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 pT, 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 $\mathbf{m(Z_D) > 10}$ **GeV**
  - ✗ **Comparable or better than Run 2** with despite only modest integrated luminosity.
- ✘ Significant improvements in constraints to $\sigma(\tilde{q}\bar{\tilde{q}})$ in RPV SUSY

Submitted to JHEP, available on arXiv : 2402.14491

HEPData : https://www.hepdata.net/record/ins2760892

References

1. CMS Collaboration, “Search for long-lived particles decaying to a pair of muons in pp collisions at √s=13.6 TeV with 2022 data”, https://cds.cern.ch/record/2889915
2. CMS Collaboration, “Search for long-lived particles decaying to a pair of muons in proton-proton collisions at √s = 13 TeV”, 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
4. Strassler and Zurek, “Discovering the Higgs through highly-displaced vertices”, https://doi.org/10.1016/j.physletb.2008.02.008

Backup