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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FWF P 33693

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Introduction - Long Lived Particles

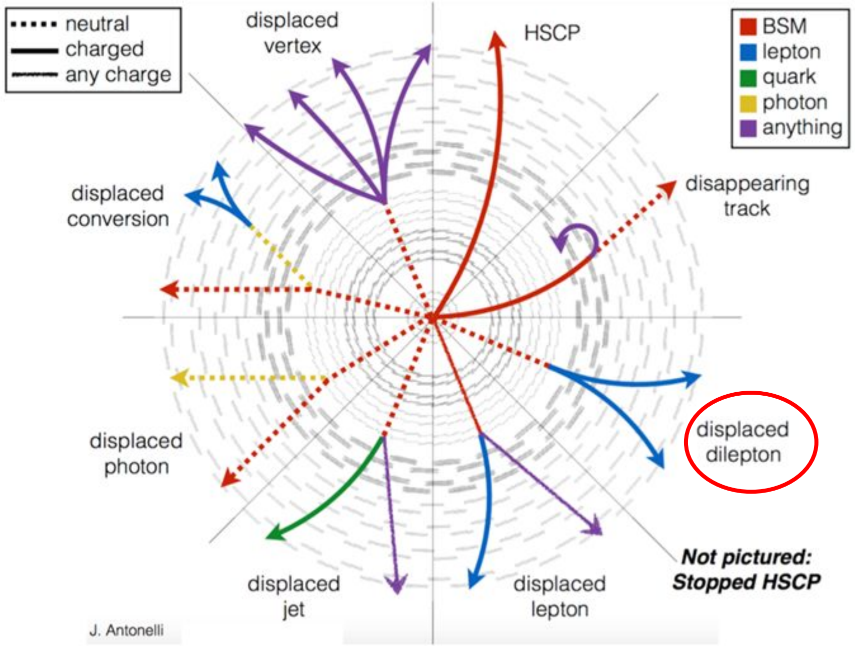
Several theories have been proposed to explain the incompleteness of the SM - Beyond Standard Model **(BSM)** theories

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

From searches at colliders and other 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!**



J. Antonelli, ICHEP 2016

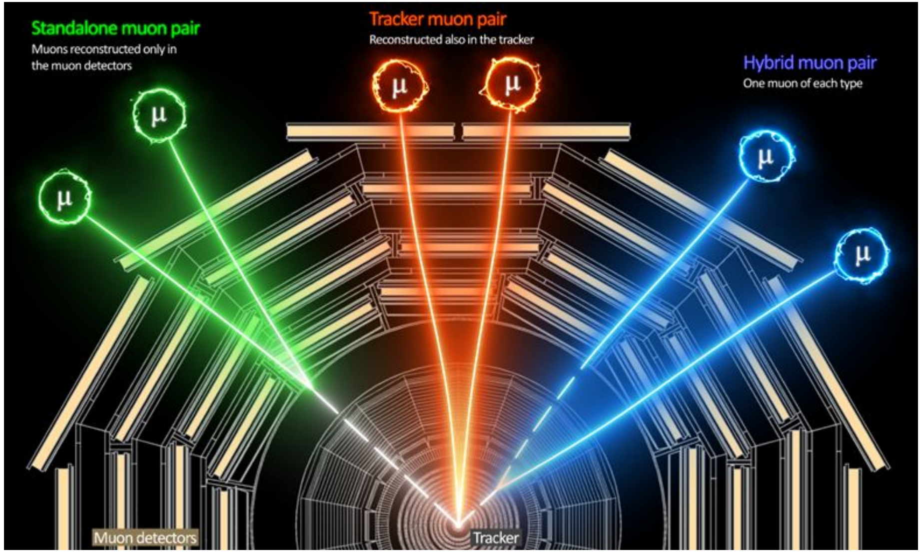
This search :

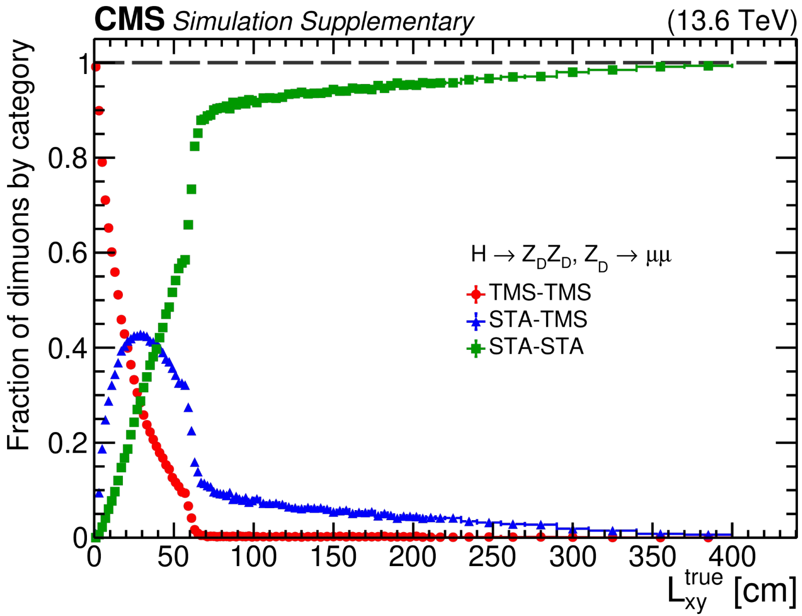
Secondary dimuon vertex displaced from the proton-proton collision point by up to several meters.

i.e. Displaced Dimuons

Search for Displaced Dimuons in Run 3

- 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]**





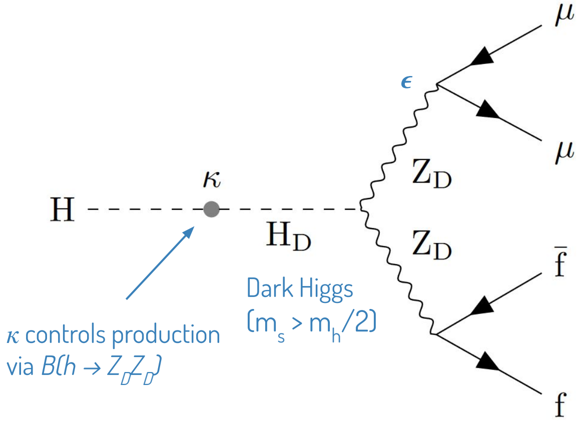
Signal models

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

Two models used as benchmark to interpret results

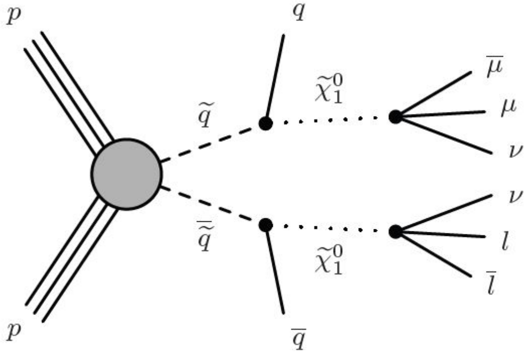
Hidden Abelian Higgs Model [3] : $H \to Z_D Z_D$, $Z_D \to \mu^+\mu^-$

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



RPV SUSY Model [4] :

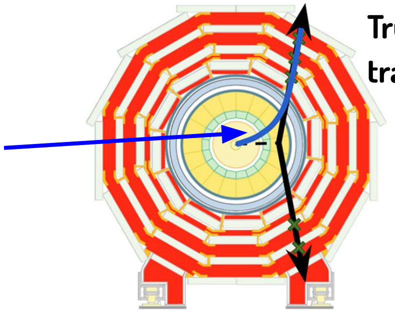
- Non-zero RPV couplings λ_{122} and λ_{122} enable non-resonant long lived neutralino decay. $\tilde{\chi}_1^0 \to \mu\mu\nu$

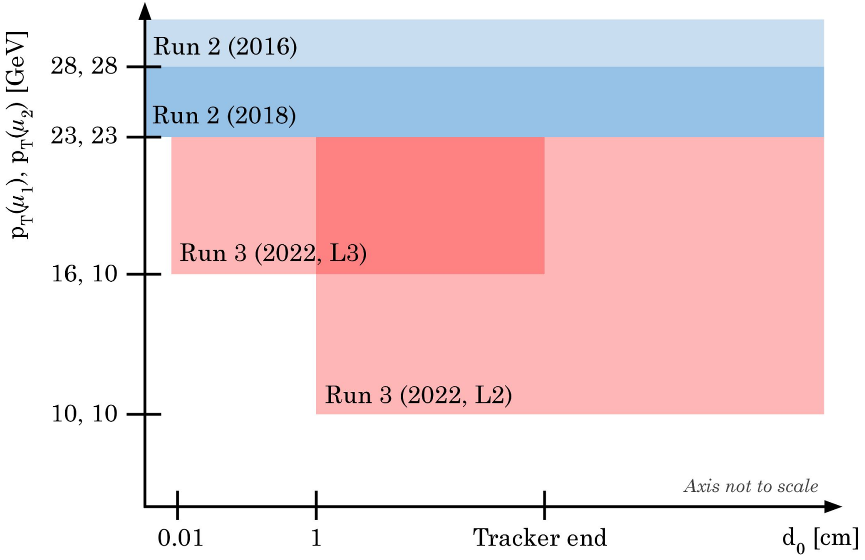


Trigger Strategy

Lessons from the Run 2 analysis :

- ✘ For very displaced muons, beamspot constraint @L1 underestimated pT → **trigger inefficiency.**
- ✘ High p_T thresholds at the HLT
- ✘ HLT use muon system based reconstruction, did not require tracker information



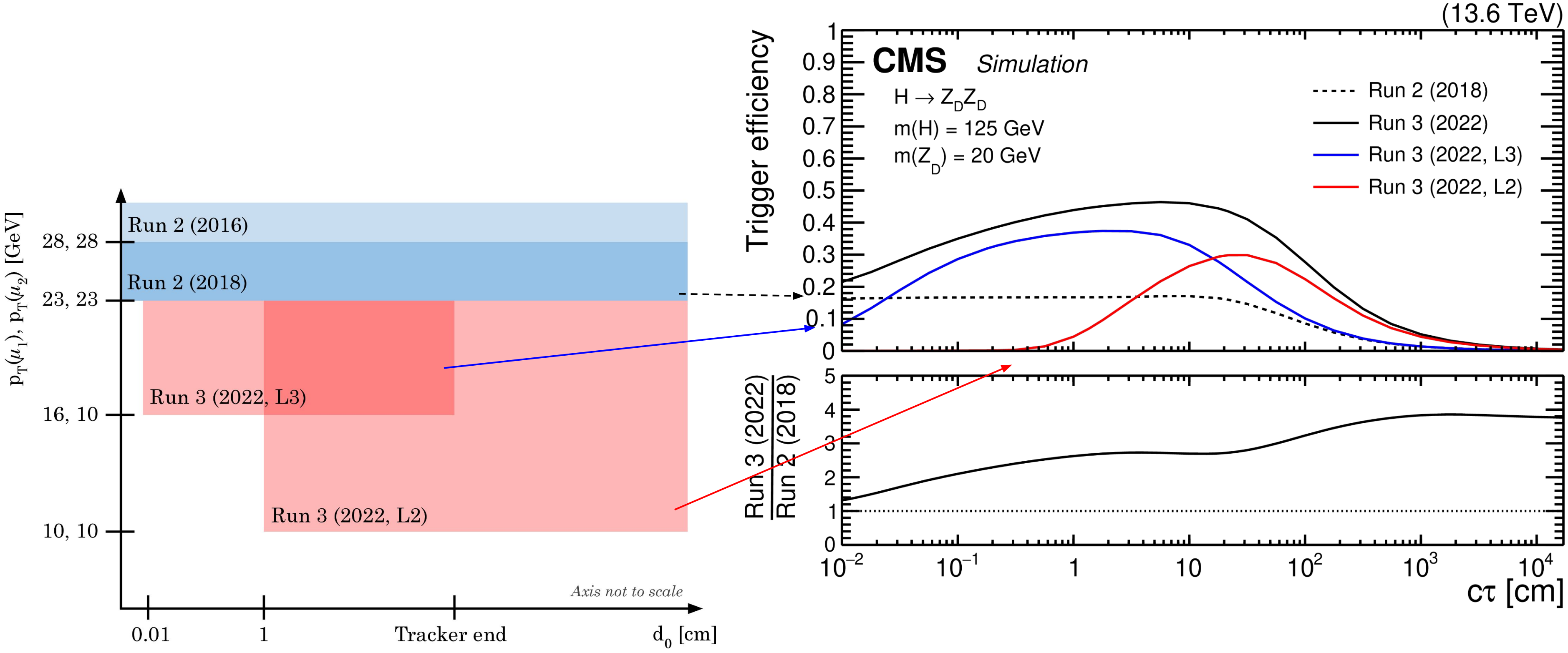


New Triggers developed at L1 and HLT

- ✘ **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, able to reject prompt muons.

Trigger Performance in BSM Signal

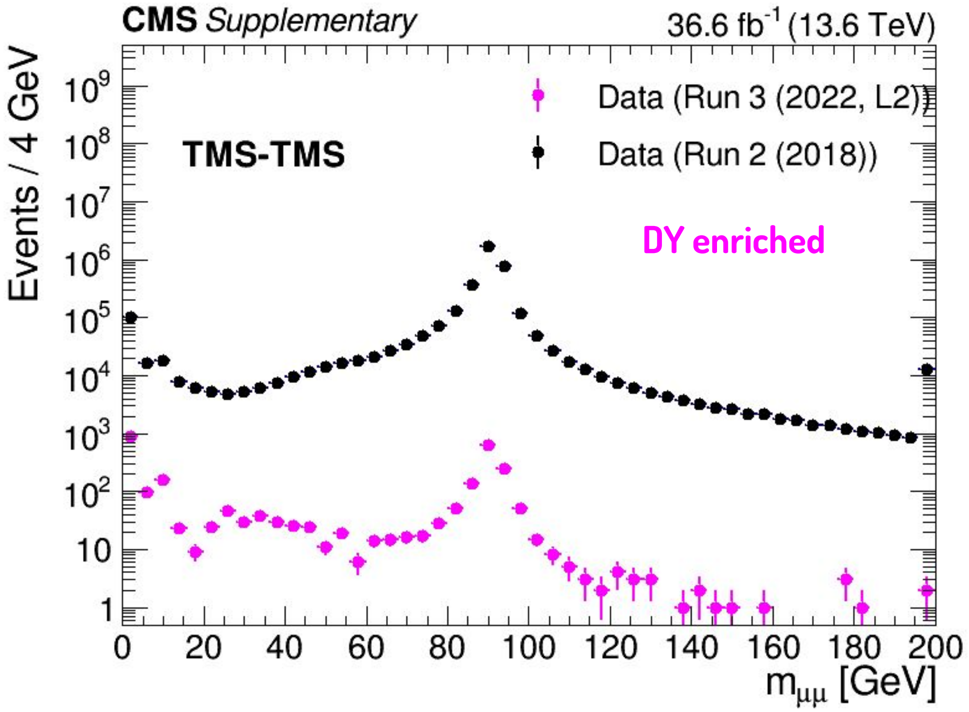
- Efficiency in **signal** increased by a factor **2x to 4x**!



Trigger : Prompt Background Rejection

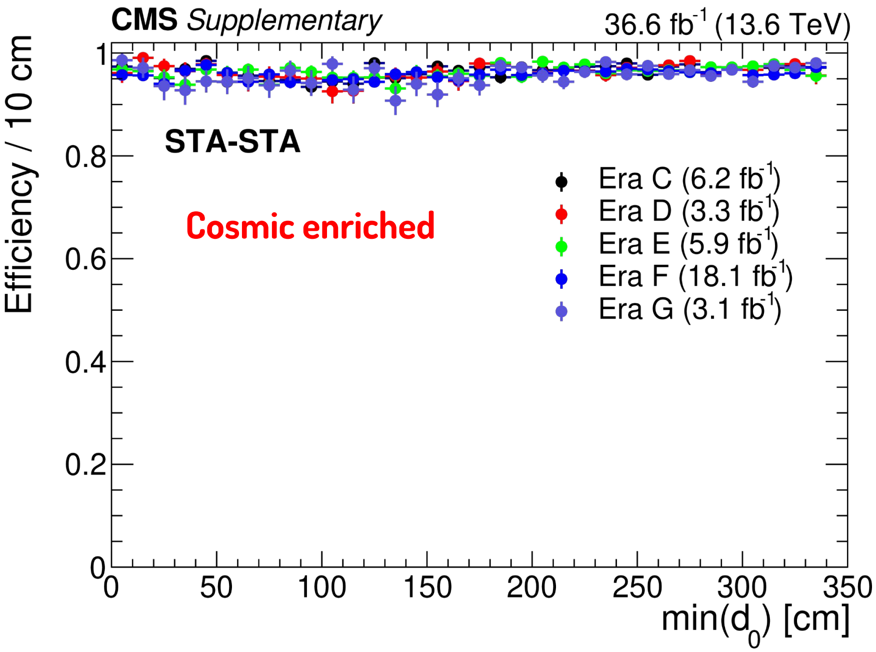
- Efficiency in **signal** increased by a factor **2x to 4x**!
- Performance in data :
  - **Drell-Yan** : prompt dimuons
    - **rejection factor of 2000** :

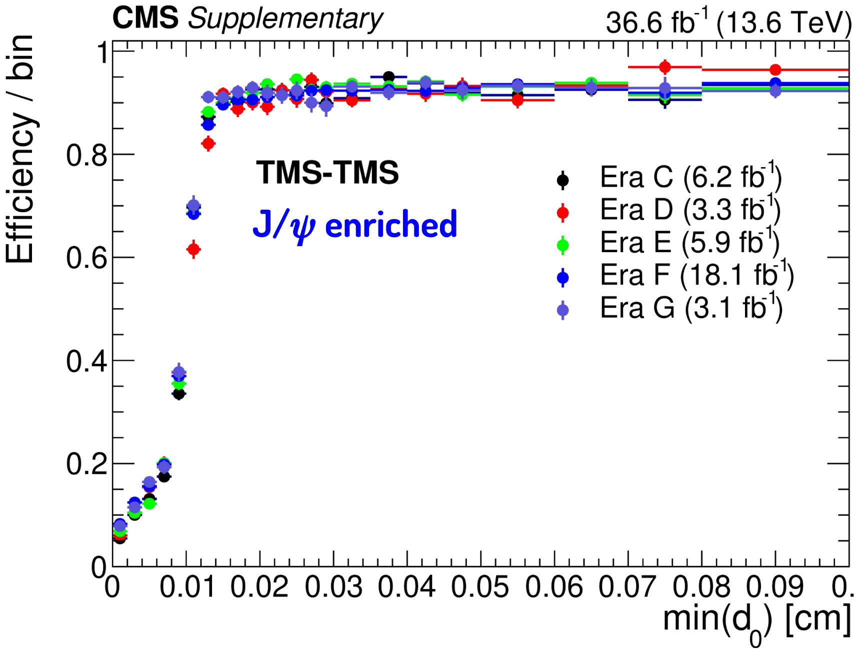
    Makes trigger rate acceptable



Trigger Efficiency in SM displaced dimuons

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





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

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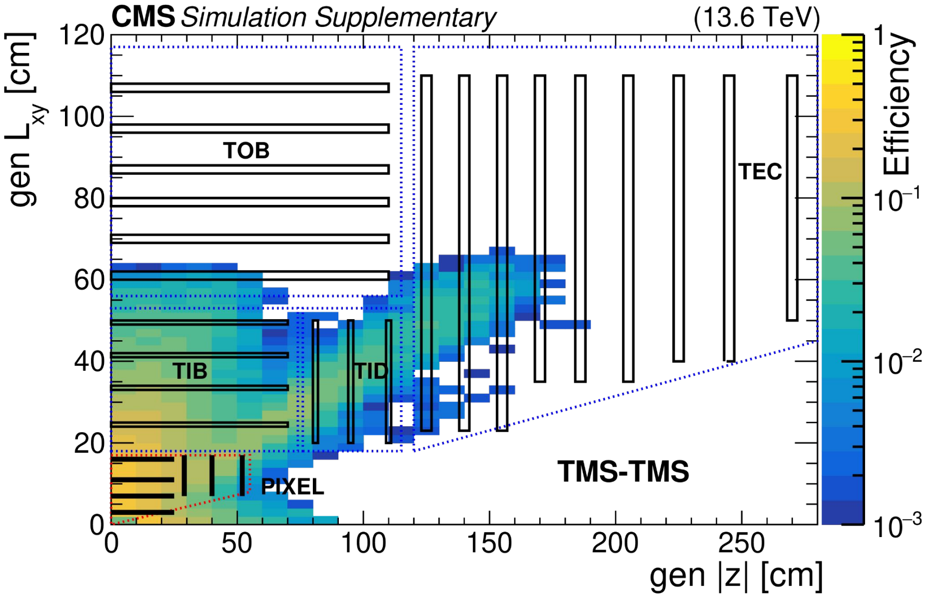
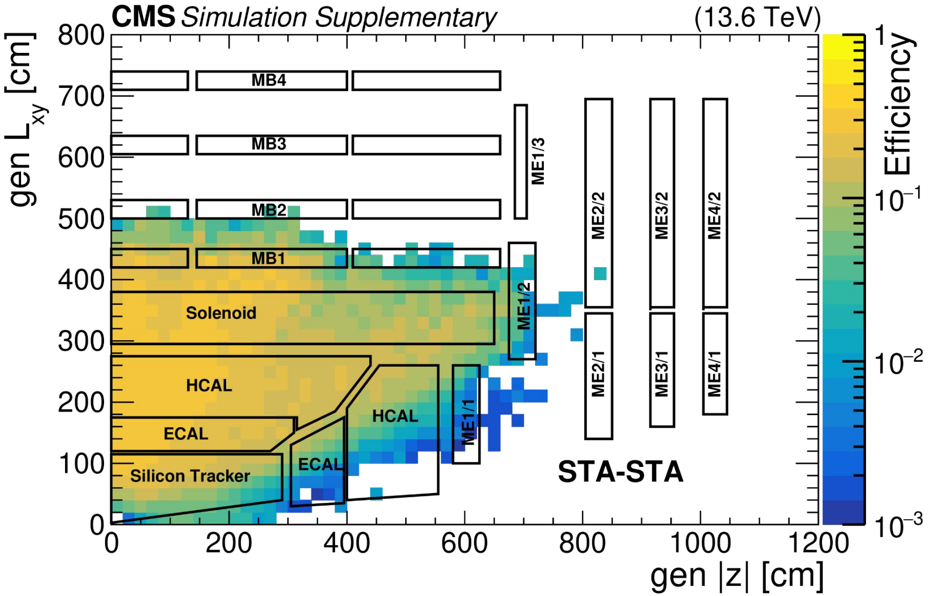
Vertex Efficiency in the CMS Detector

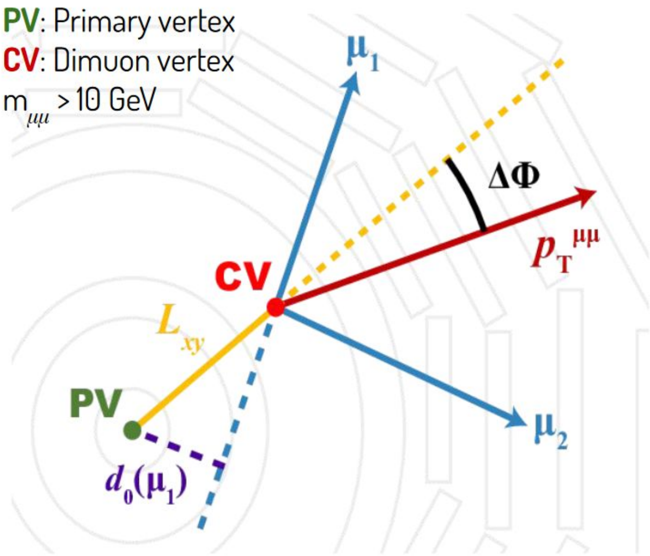
- Typical vertex efficiency in the **TMS-TMS** and **STA-STA** categories, in all HAHM signal samples combined.
  - In **TMS-TMS**, **efficient upto ~60 cm** from tracker muons
  - In **STA-STA**, **efficient up to ~400 cm** in vertex L_{xy} and **~600 cm** in |z| from standalone muons in detector acceptance!





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}, $\alpha_{\mu\mu}$, Collinearity $|\Delta\Phi|$
- Muon direction
- Timing
- Charge (OS/SS)
- Invariant mass : $m_{\mu\mu} > 10$ GeV
- TMS muon isolation



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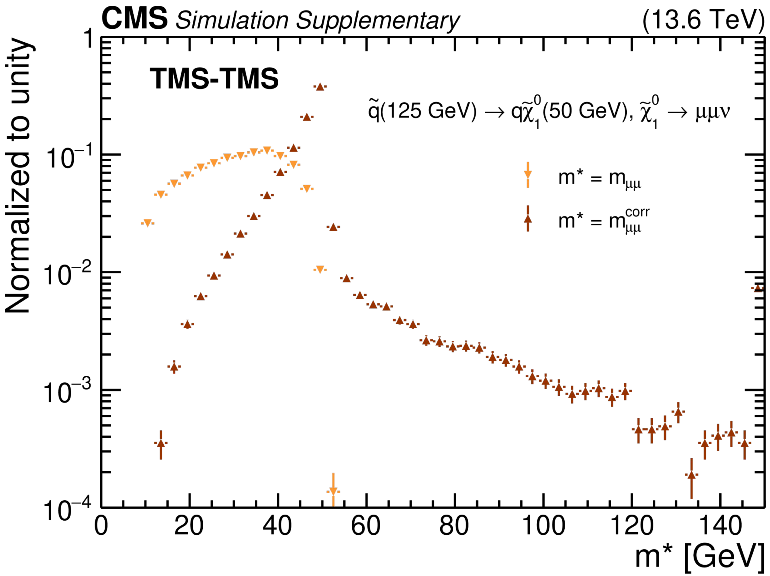


New in Run 3

- Corrected mass for non-resonant dimuon vertices : $m_{\mu\mu}^{\mathrm{corr}} = \sqrt{m_{\mu\mu}^2 + p_{\mu\mu}^2 \sin^2\theta} + p_{\mu\mu}\sin\theta,$
- STA muon isolation

Backgrounds

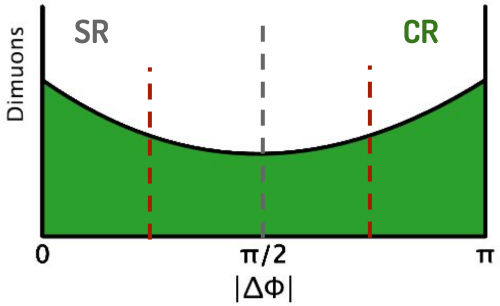
- **Signal region designed to have low to none SM backgrounds** for optimal signal discovery significance
  - Misidentification or mis-reconstruction of muons can cause background events to enter the signal region.
- Backgrounds may be **symmetric** or **asymmetric** in Collinearity ΔΦ.
  - This depends on whether the $p_T^{\mu\mu}$ and L_{xy} vectors point in the same direction (correlated) or not.

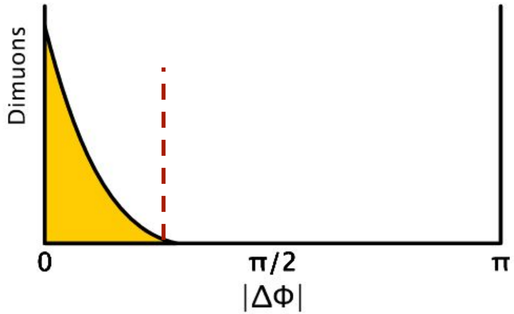
Symmetric

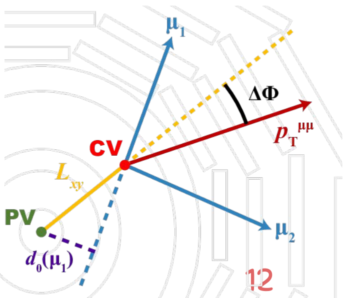
- Symmetrically distributed around $\pi/2$
- Occurs when $p_T^{\mu\mu}$ and Lxy vectors are uncorrelated
  - Mismeasured (prompt) Drell-Yan (DY), dibosons,
  - Cosmic ray muons
  - Unrelated jets, W+jets

Asymmetric

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







Backgrounds : ΔΦ symmetric

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**

|ΔΦ|<π/*C*	|ΔΦ|>π-π/*C*
A = DY background in SR	B
C Inverted STA-TMS association (STA-STA)	D

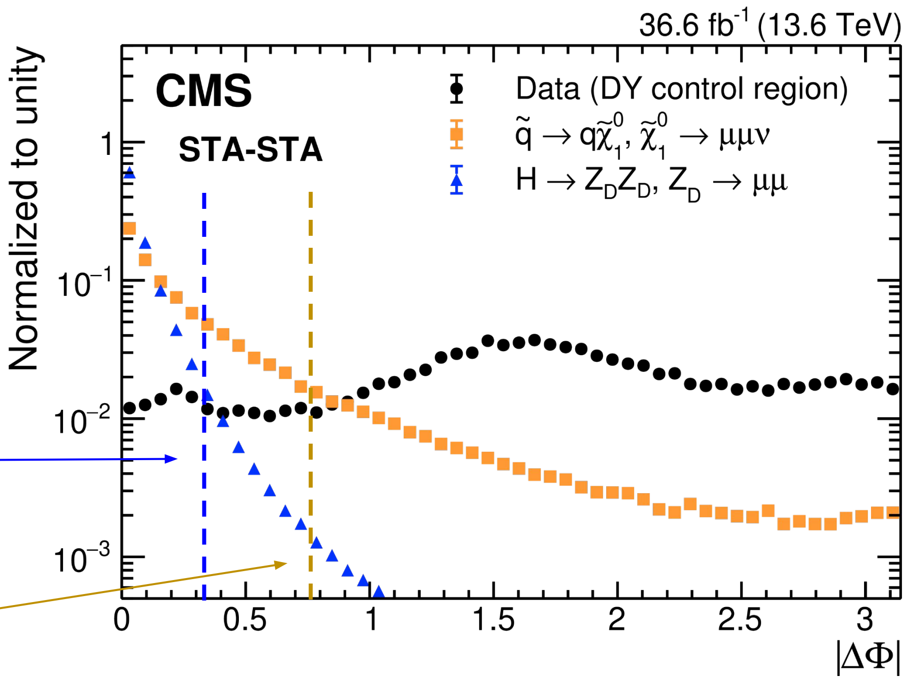
For the **dark photon** model :

➢ **TMS-TMS** : *C* = 30

➢ **STA-STA** : *C* = 10

For the **RPV SUSY** model :

➢ *C* = 4



Backgrounds : ΔΦ asymmetric

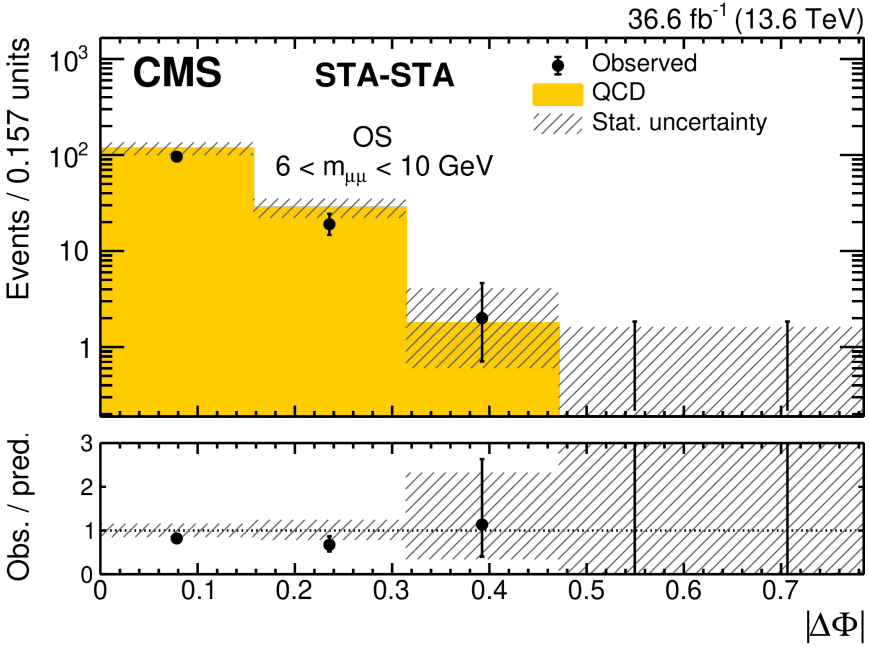
Backgrounds estimated using the **ABCD method,** measured in CRs adjacent to SR :

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

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

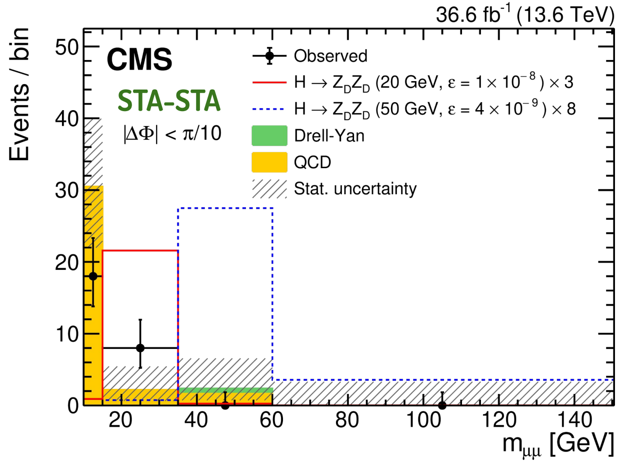
- Signal expected to have **Opposite Sign** and **isolated muons**

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



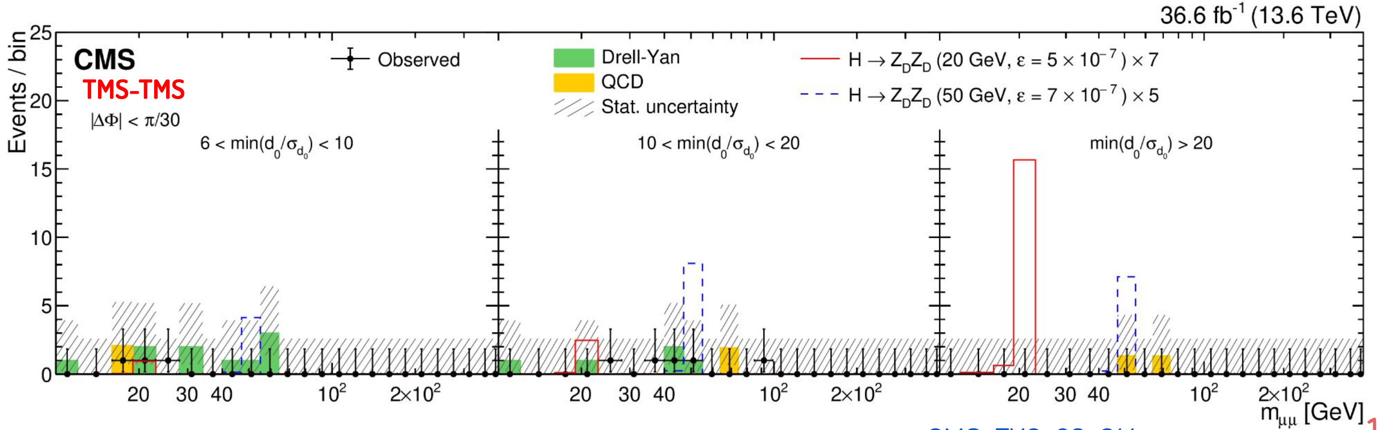
Results - Dark Photon model

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



- ✘ TMS-TMS further divided into SRs based on muon d_0 **Best sensitivity in most displaced SR**
- ✘ Observed number of events consistent with predictions.

No excesses observed.



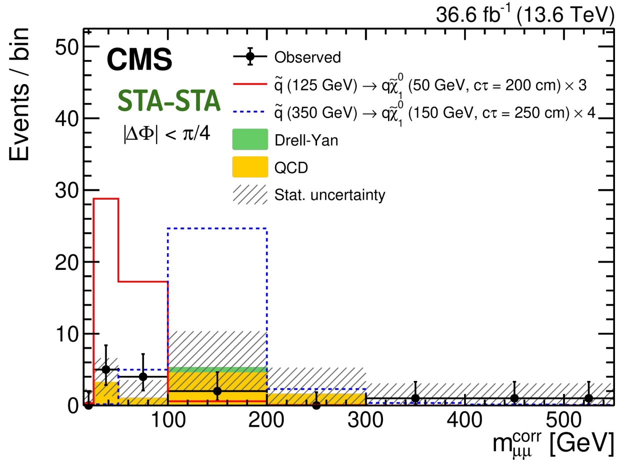
[CMS-EXO-23-014]

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

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

- ✘ TMS-TMS further divided into SRs based on muon d_0
  Best sensitivity in most displaced SR
- ✘ Observed number of events consistent with predictions.



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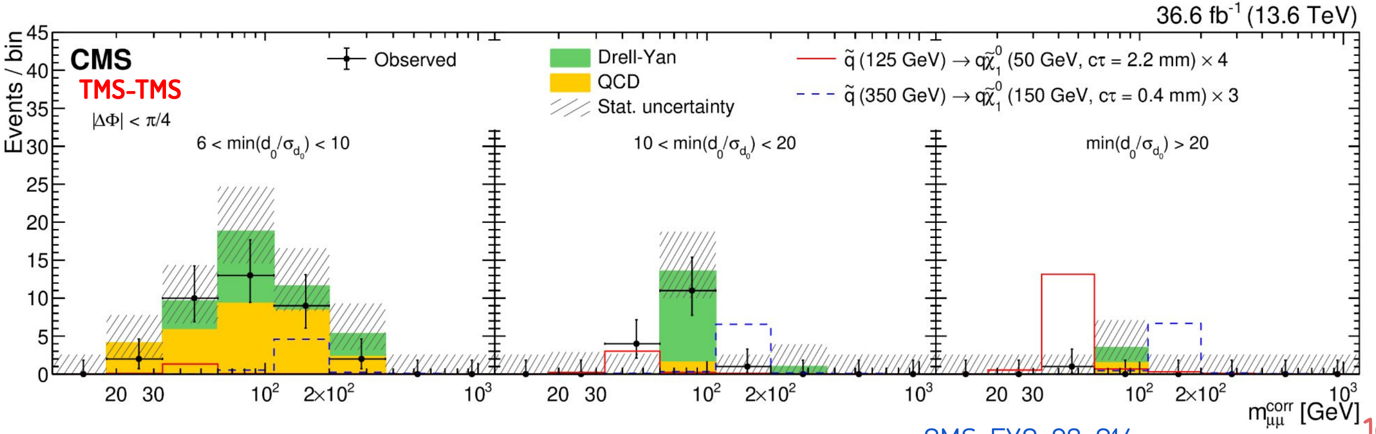
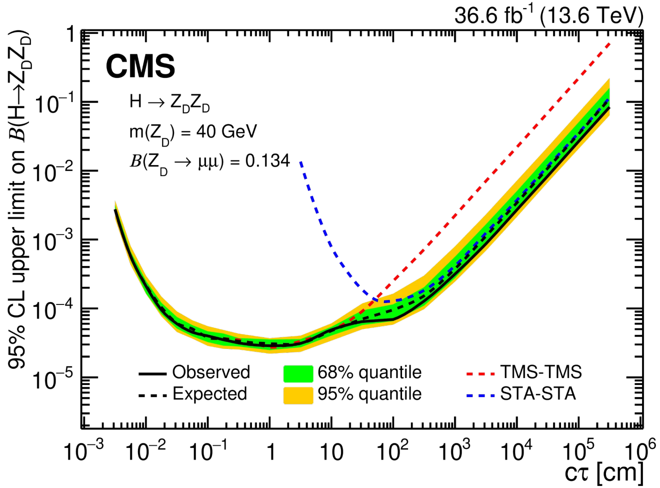


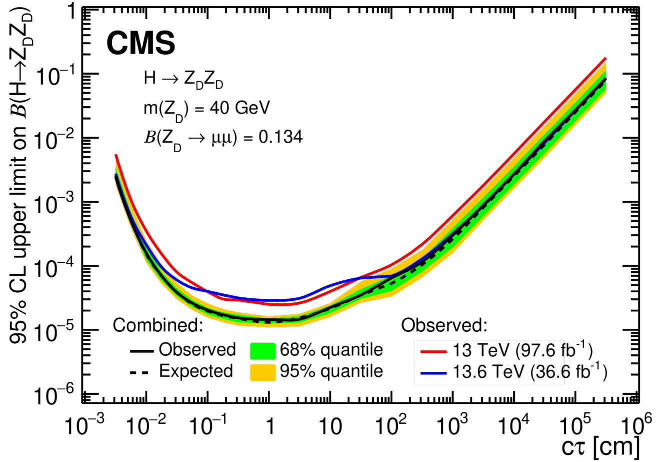
Results - Limits

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





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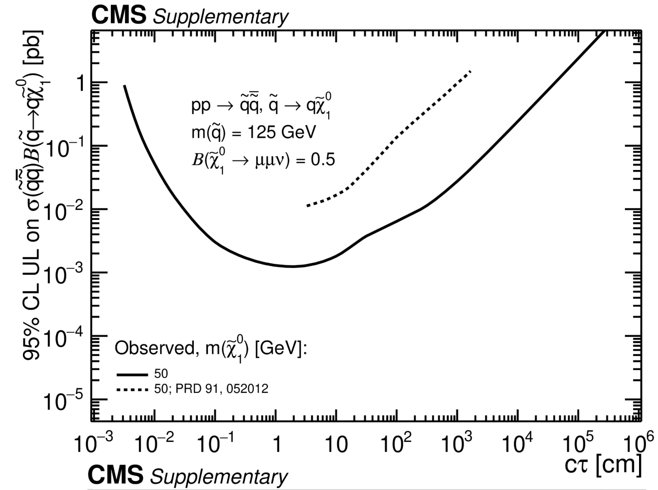
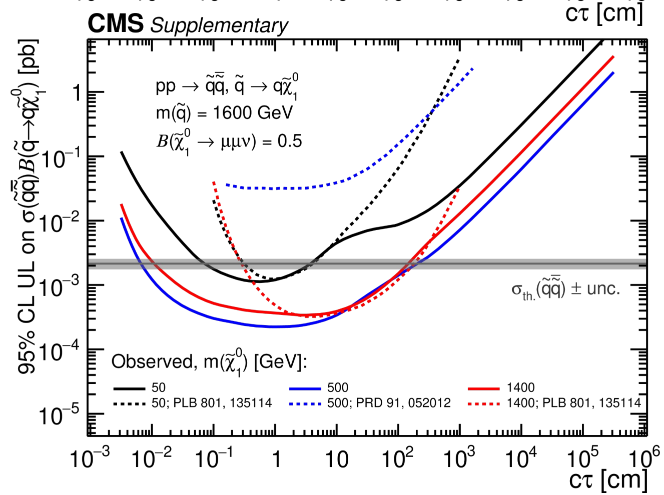
Results - Limits

Results used to set upper limits on model parameters :

- For the RPV SUSY model
  - Limits set on $\sigma(\tilde{q}\bar{\tilde{q}})B(\tilde{q}\rightarrow q\tilde{\chi}_1^0)$
  - Limits on $\sigma(\tilde{q}\bar{\tilde{q}})$ significantly stronger than previous CMS (Run 1) limits
  - Stronger limits than ATLAS for $c\tau \lesssim 1$ cm and $c\tau \gtrsim 1$ m





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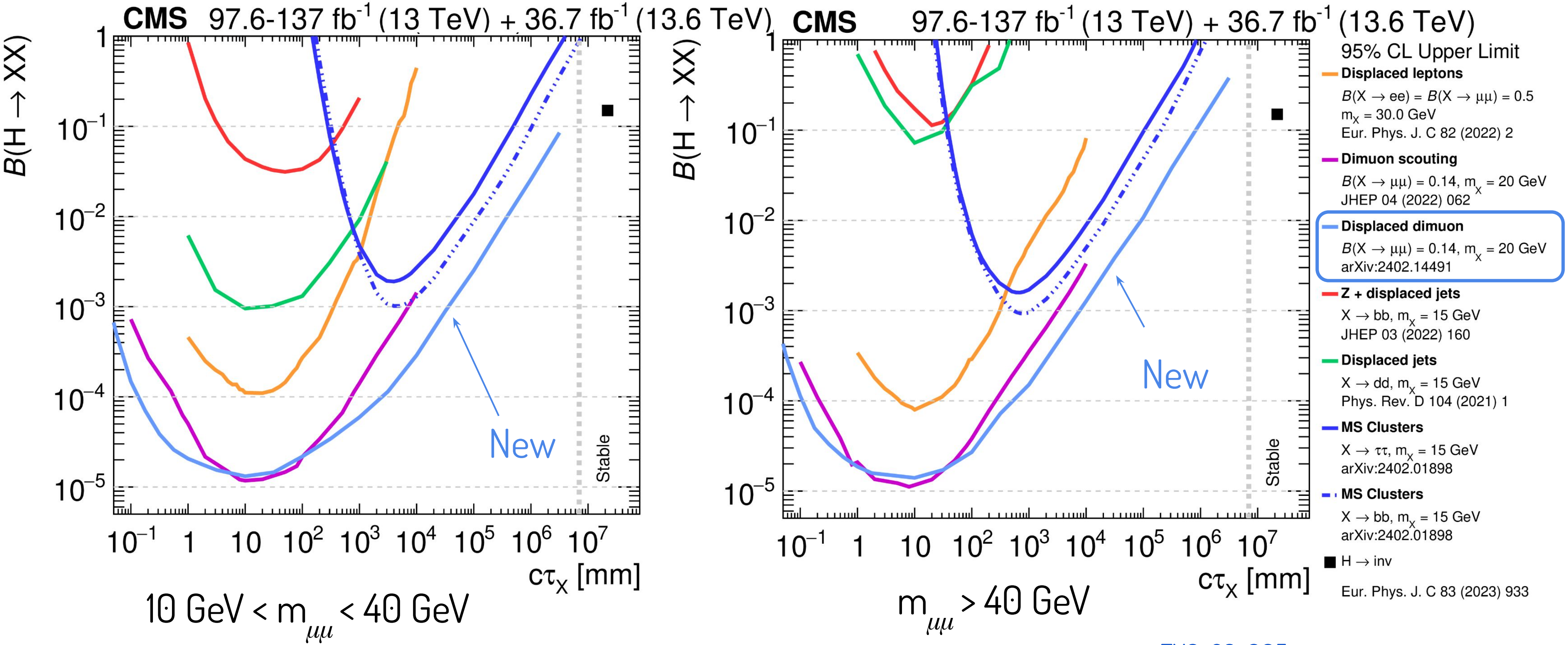
Best constraints to date in B(H→XX) in broad range of cτ(X) for m(X) > 10 GeV



EXO-23-005

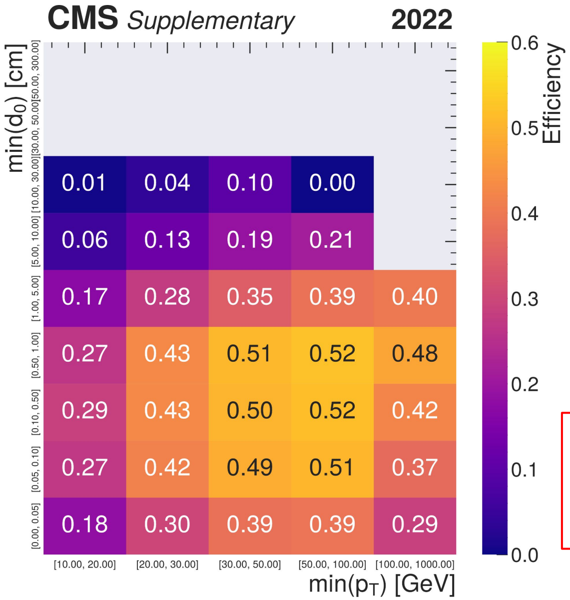
Reinterpretation material in HEPData

- We provide signal efficiencies as a function of the minimum p_T and d_0 of the two muons to aid reinterpretation efforts.
  - Efficiencies provided separately for HAHM and RPV SUSY, in each category, and for different L_{xy} ranges.

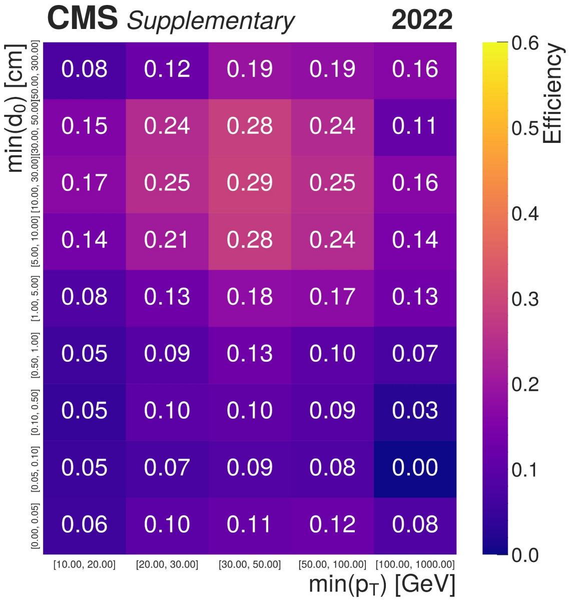
Inviting feedback from our colleagues!

HAHM signal

TMS-TMS $L_{xy}^{gen} < 20$ cm



STA-STA 70 cm < L_{xy}^{gen} < 500 cm



All maps available on the HEPData page here

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 36.6 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.
- ✘ **Limits comparable or better than Run 2** with despite only modest integrated luminosity.
- ✘ 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**
- ✘ Significant improvements in constraints to $\sigma(\tilde{q}\bar{\tilde{q}})$ in RPV SUSY

Published in JHEP, also available on arXiv : 2402.14491

Reinterpretation material provided on HEPData : https://www.hepdata.net/record/ins2760892

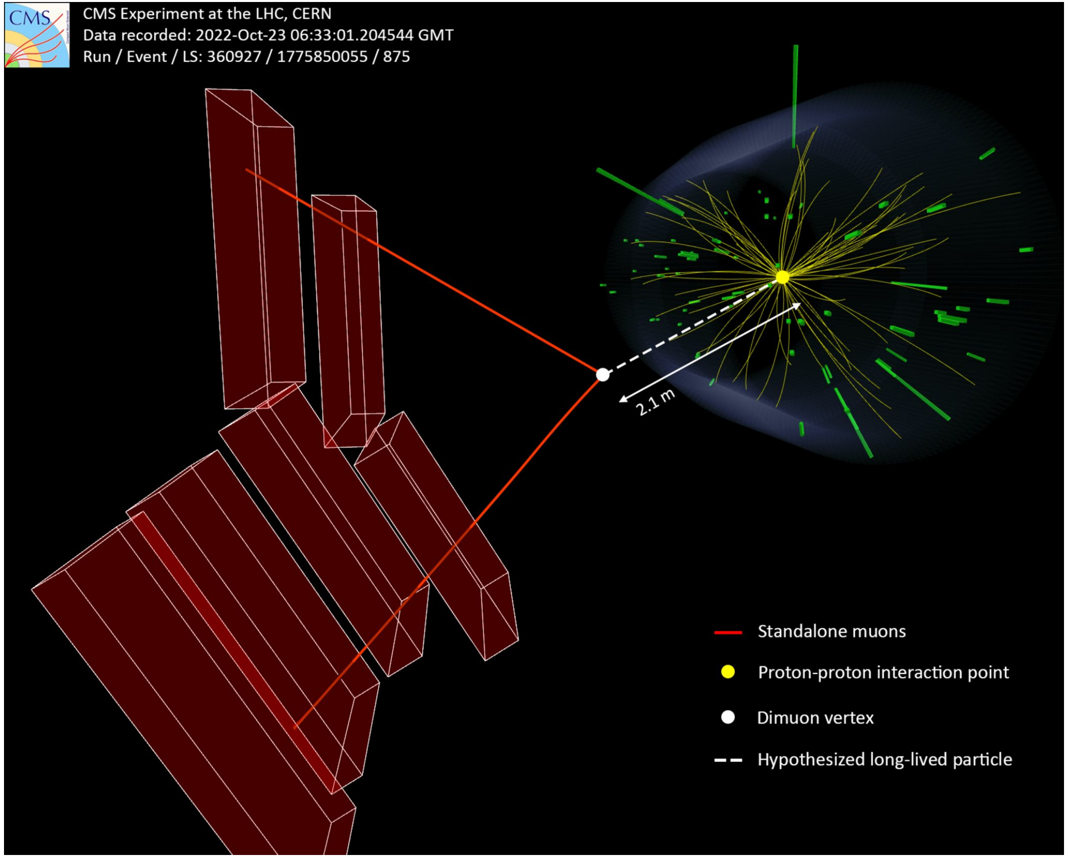
We welcome your feedback! mangesh.sonawane@cern.ch

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. R. Barbier et al., “R-parity-violating supersymmetry”, http://dx.doi.org/10.1016/j.physrep.2005.08.006

Backup

Event Display



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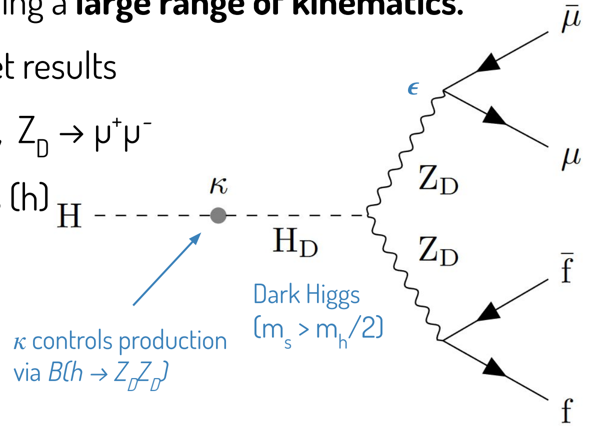
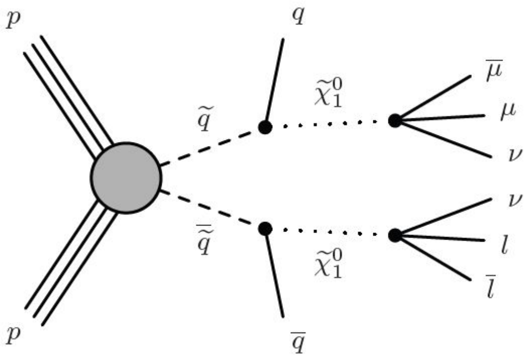


m_h	m_{ZD}	$B(Z_D\text{->}\mu\mu)$
125 GeV	10, 20, 30, 40, 50, 60	10-15%

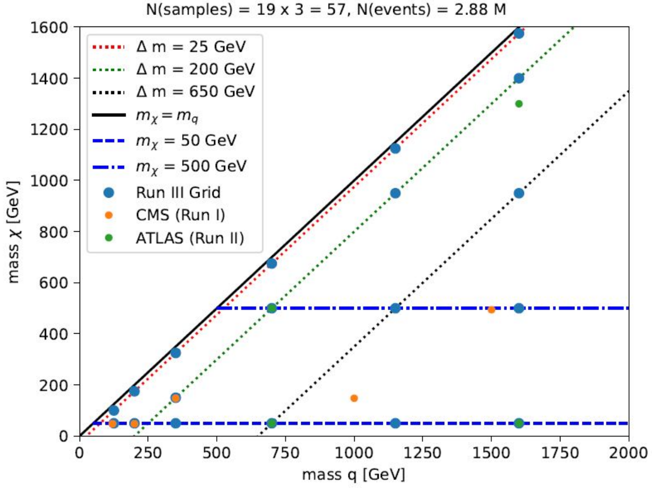
x 4 $c\tau_{ZD}$ per mass

RPV SUSY Model [4] :

- Non-resonant long lived neutralino decay $\tilde{\chi}_1^0 \to \mu\mu\nu$

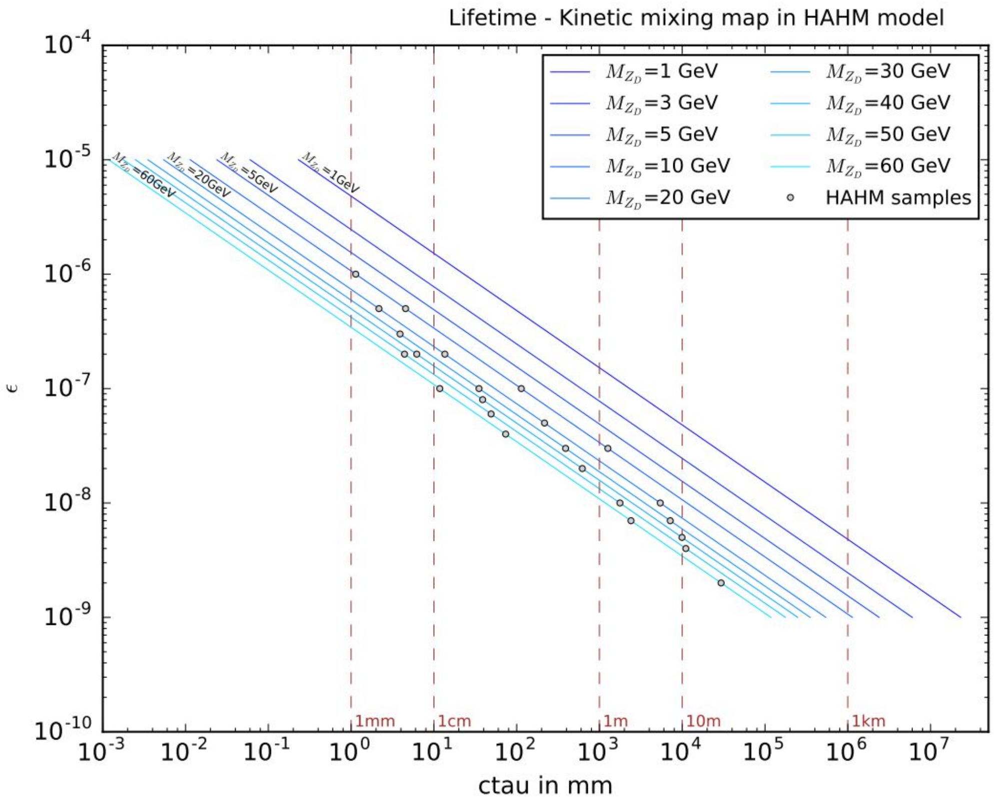


$m(\tilde{q})$, $m(\tilde{\chi}_1^0)$ Sample grid   x 3 $c\tau_{ZD}$ per mass



$$\mathcal{B}(\tilde{\chi}_1^0 \to \mu\mu\nu) = \mathcal{B}(\tilde{\chi}_1^0 \to ee\nu)$$

Signal samples – grid



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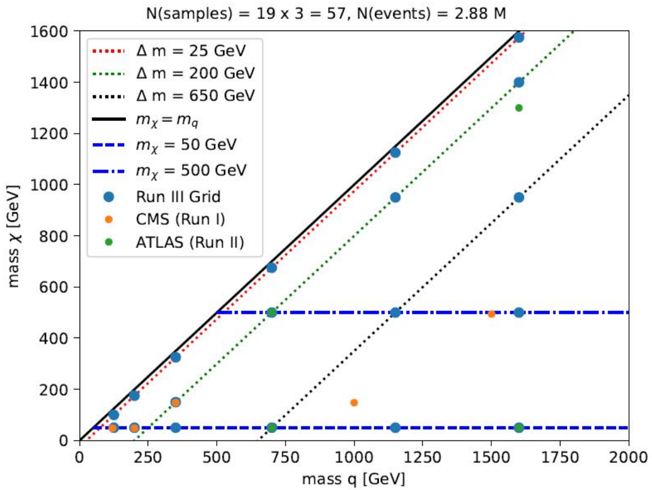


$$\mathcal{B}(\tilde{\chi}_1^0 \to \mu\mu\nu) = \mathcal{B}(\tilde{\chi}_1^0 \to ee\nu)$$

Full Run 2 event selection

Event selection			
N(PV)	≥1		
HLT-STA muon matching	yes		
N(nearly parallel STA muons)	<4		

Muon selection	*Muon type*	
	STA	TMS
STA-to-TMS muon association	not matched to TMS μ	matched to STA μ
N(CSC+DT hits)	>12	—
- associated STA muon	—	>12
N(DT hits) for muons in barrel	>18	—
tracker muon	—	yes
N(matched muon segments)	—	>1
p_T	>10 GeV	>10 GeV
σ_{p_T}/p_T	<1.0	<1.0
χ^2_{trk}/dof	<2.5	—
I^{rel}_{trk}	—	<0.075
$\|\Delta t\|$	<12 ns	—
muon direction	inside-out	—
d_0/σ_{d_0}	—	>6

Dimuon selection	*Dimuon category*		
	STA-STA	STA-TMS	TMS-TMS
DCA	<15 cm	<15 cm	<15 cm
pairing criteria	best 1–2 ranked dimuons selected		
χ^2_{vtx}	<10	<20	<10
ΔN(pixel hits)	—	—	<3
N(hits before vertex)	—	<6	<3
N(tracker layers) + floor(L_{xy} [cm]/15)	—	>5	>5
$\|\phi_\mu^{TMS}\|$	—	<2.9	—
$\cos\alpha$			
- 2016 data analysis	>−0.8	>−0.8	>−0.8
- 2018 data analysis	>−0.9	>−0.9	>−0.99
N(dimuon segments)	>4	—	—
if $\|\Delta\eta_{\mu\mu}\| < 0.1$			
- N(dimuon segments)	>5	—	—
- N(DT hits) for muons in barrel	>24	—	—
no back-to-back muon			
with $\|\Delta t_{b2b}\| > 20$ ns	yes	—	—
$m_{\mu\mu}$	>10 GeV	>10 GeV	>10 GeV
p_T of the leading muon	—	—	>25 GeV
$L_{xy}/\sigma_{L_{xy}}$	>6	>3	>6
$\|\Delta\Phi\|$	<π/4	<π/4	<π/4
opposite-sign muons	yes	yes	yes

Run 3 event selection

Event Selection

Requirement	Dimuon Category	
	STA-STA	TMS-TMS
Good primary vertex	yes	yes
HLT-RECO matching	yes	yes
N(parallel pairs)	< 6	< 6

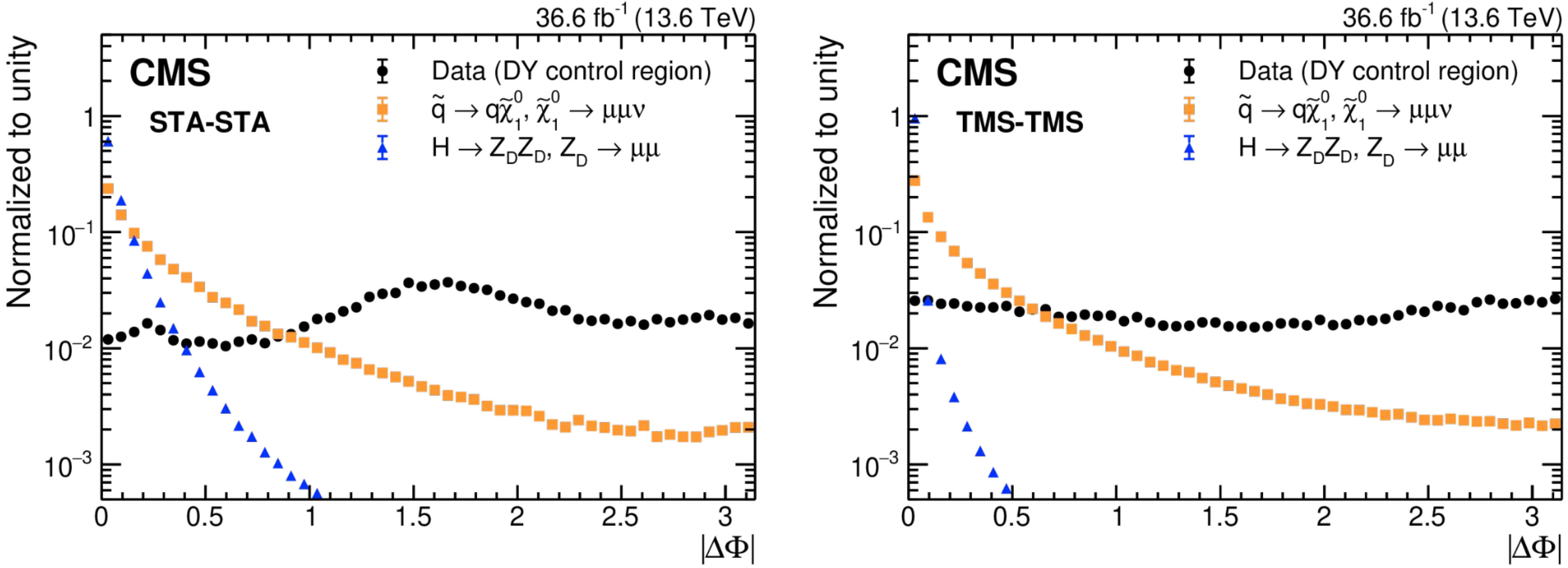
Muon Selection

Requirement	Muon Type	
	STA	TMS
STA to TMS muon association	not matched to TMS μ	matched to STA μ
N(CSC + DT hits)	> 12	> 12 (assoc. STA muon)
N(DT hits) for muon in barrel	> 18	-
Tracker muon	-	yes
N(matched muon segments)	-	> 1
p_T	> 10 GeV	> 10 GeV
$\sigma(p_T)/p_T$	< 1.0	< 1.0
χ^2_{track}/dof	< 2.5	-
I^{rel}	< 0.15*	< 0.075
$\lvert t_{\text{in-out}} \rvert$	< 12 ns	-
Muon direction	+1 ('inside-out')	-
$d_0/\sigma(d_0)$	-	> 6

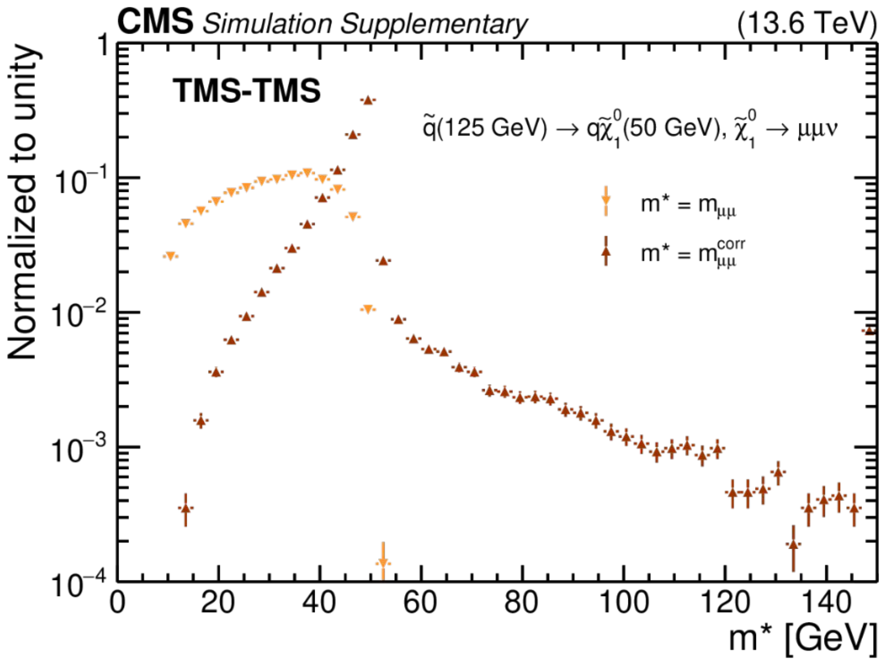
Dimuon Selection

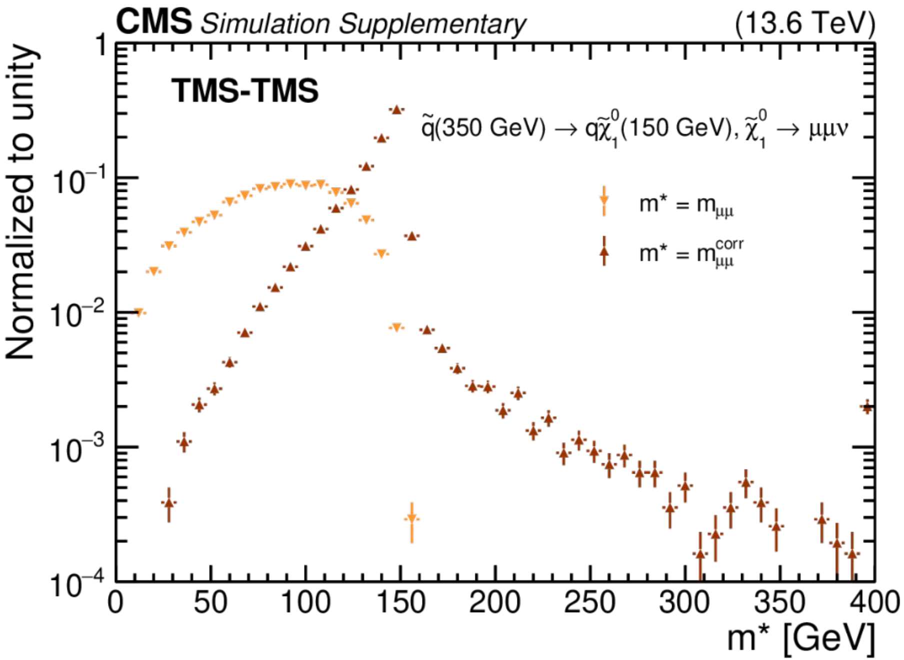
Requirement	Dimuon Category	
	STA-STA	TMS-TMS
DCA	< 15 cm	< 15 cm
Convergent common vertex fix	yes	yes
Pairing criteria	Select best 1-2 dimuons ranked by $\min(\Sigma\chi^2_{\text{vertex}}/\text{dof})$	
χ^2_{vertex}	< 10	< 10
ΔN(pixel hits)	-	< 3
N(hits before vertex)	-	Not applied*
$\sigma(L_{xy})$	< 20 cm*	-
$\cos\alpha$	$>$ -0.9	- 0.99
Back-to-back muon timing, $\lvert\Delta t_{\text{b2b}}\rvert$	> 20 ns	-
N(dimuon segments)	> 4	-
If $\lvert\Delta\eta_{\mu\mu}\rvert < 0.1$		
·N(dimuon segments)	> 5	-
·N(DT hits) for muons in barrel	> 24	-
$m_{\mu\mu}$	> 10 GeV	> 10 GeV
Leading muon p_T	-	> 25 GeV
$L_{xy}/\sigma(L_{xy})$	> 6	> 6
Muon sign correlation	opposite-sign (OS)	
$\lvert\Delta\Phi\rvert$ for $H \to Z_D Z_D$ (HAHM)*	$< \pi/10$*	$< \pi/30$*
$\lvert\Delta\Phi\rvert$ for $\tilde{q} \to q\tilde{\chi}^0_1$ (RPV SUSY)*	$< \pi/4$*	$< \pi/4$*
$m_{\mu\mu}, m^{\text{corr}}_{\mu\mu}$ intervals*	See Section 6.6*	

|ΔΦ| distributions

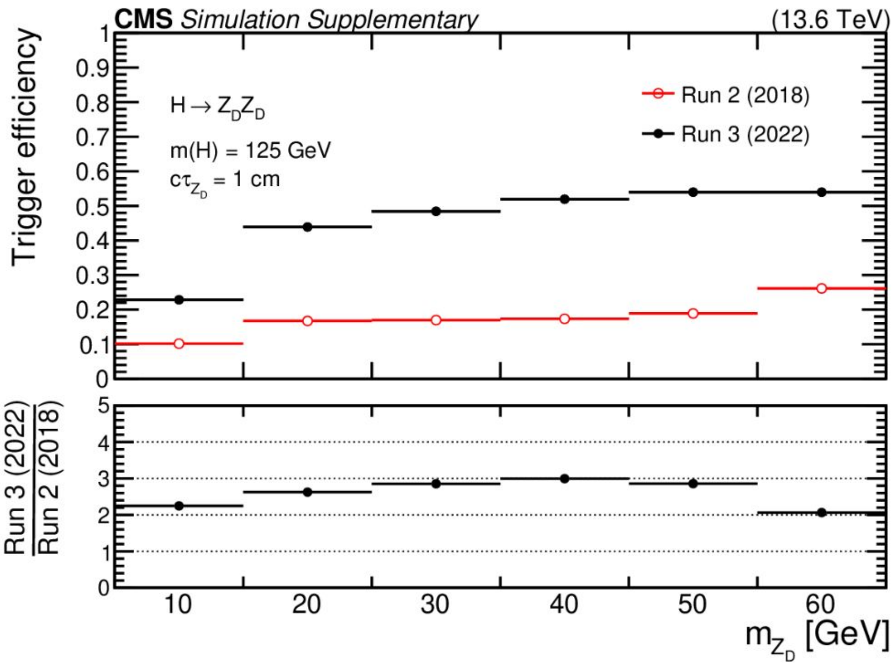


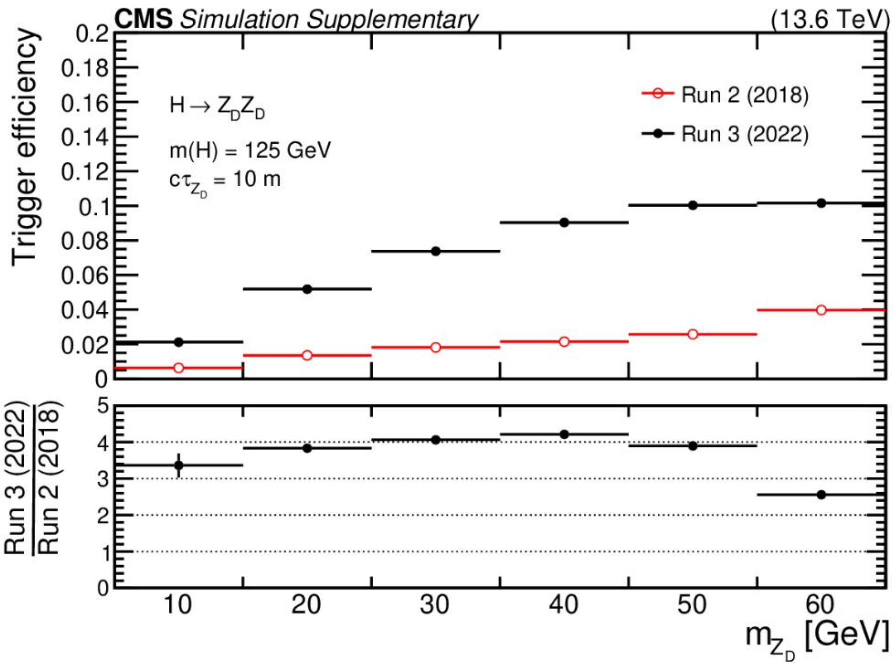
Corrected mass



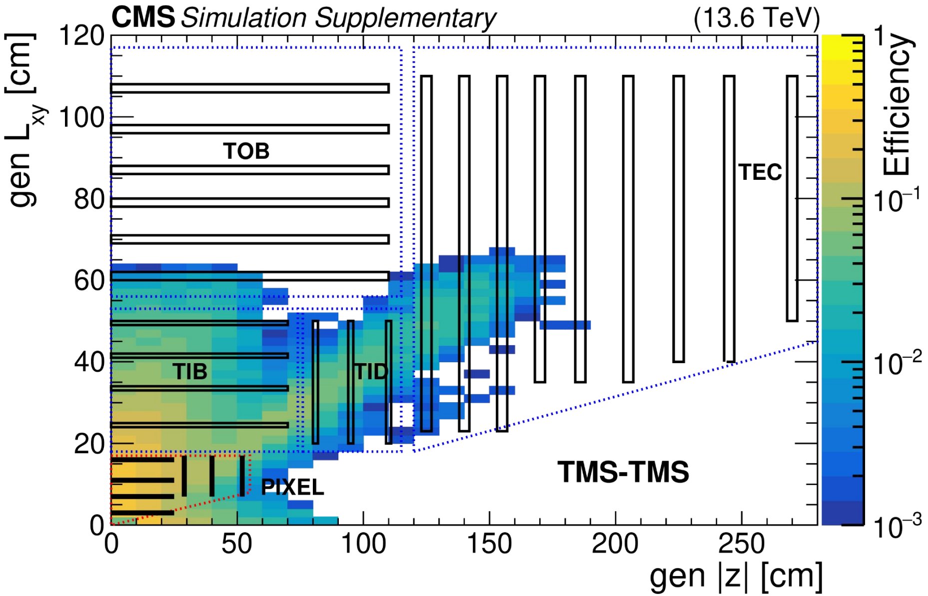


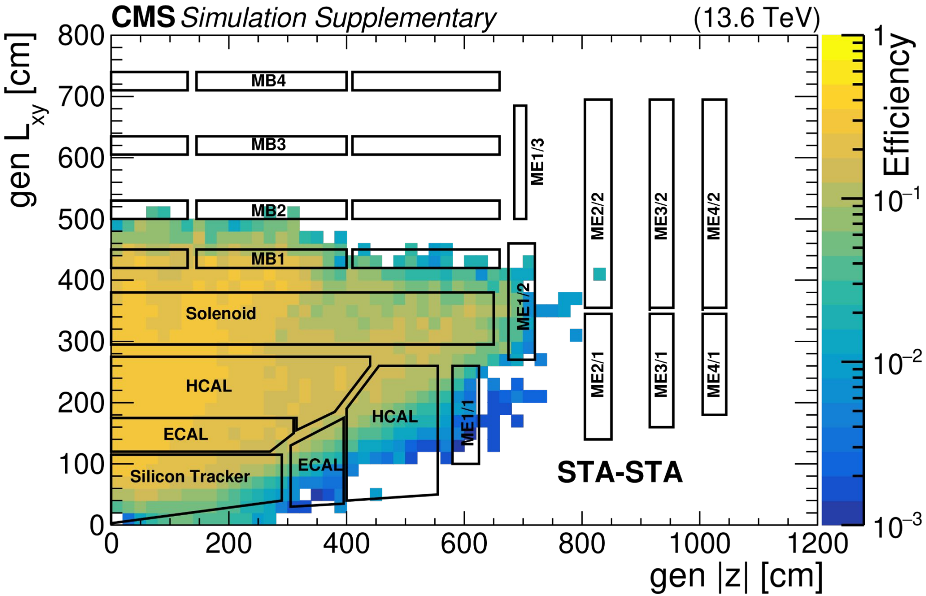
Signal Efficiency vs Z_D mass



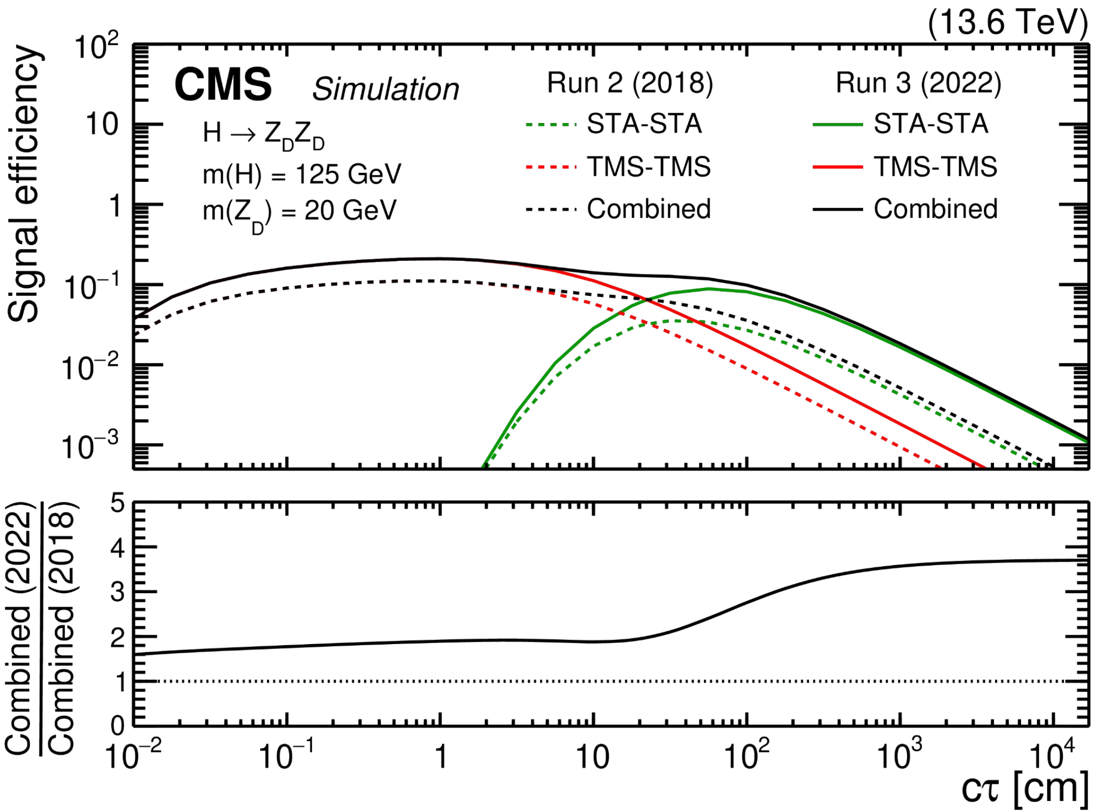


Signal Efficiency in detector

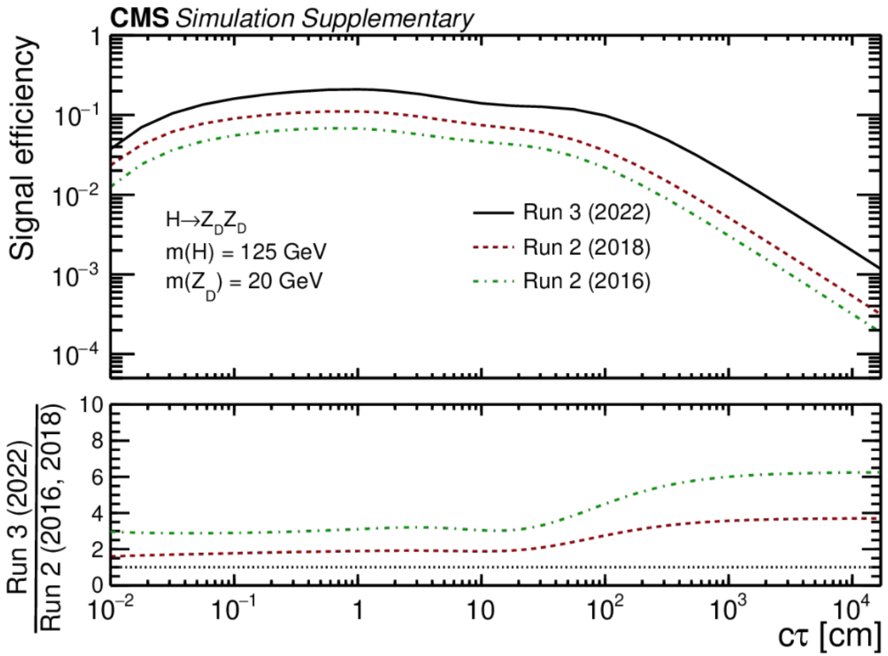


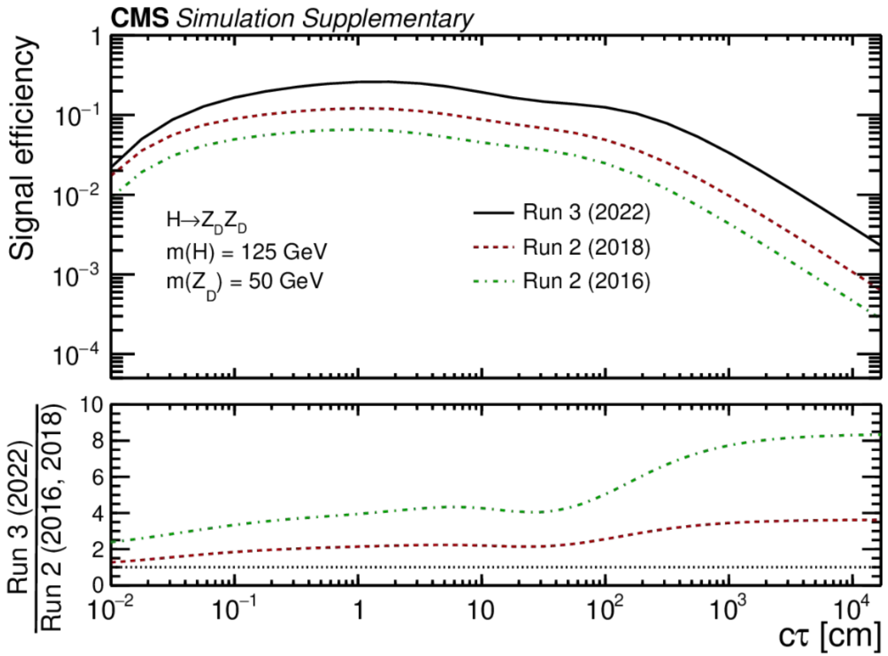


Signal Efficiency vs cτ

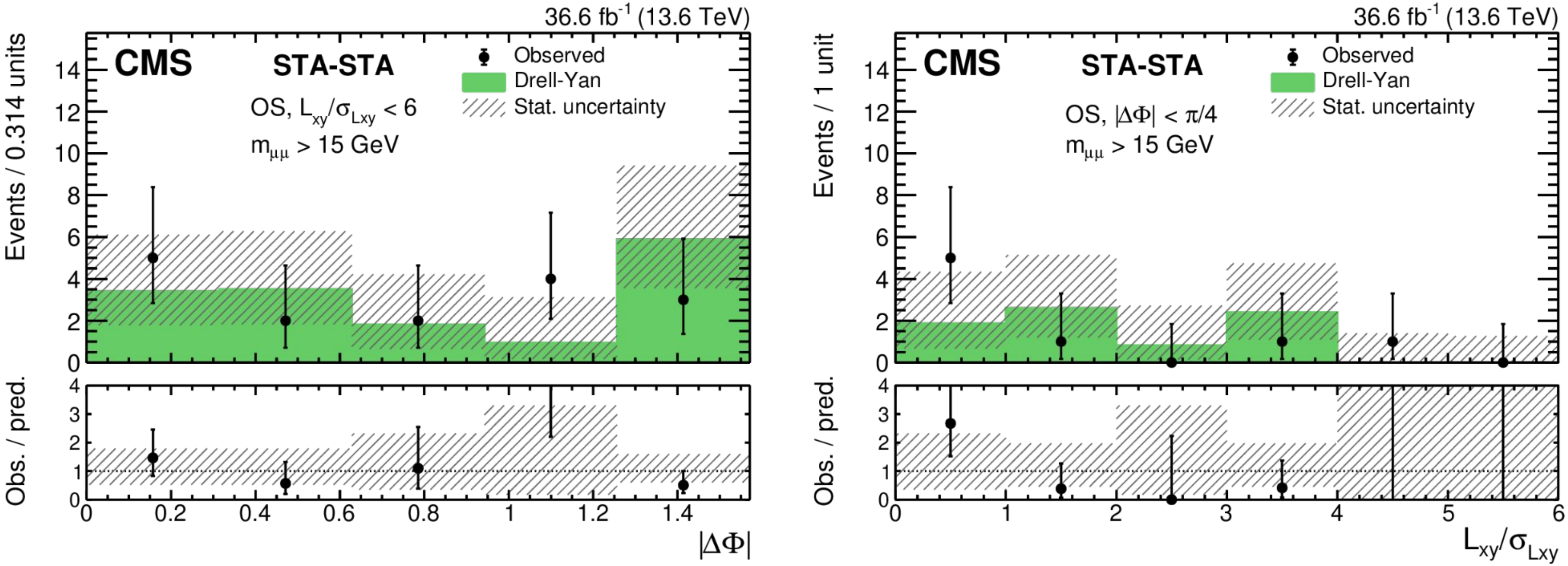


Signal Efficiency - Gain

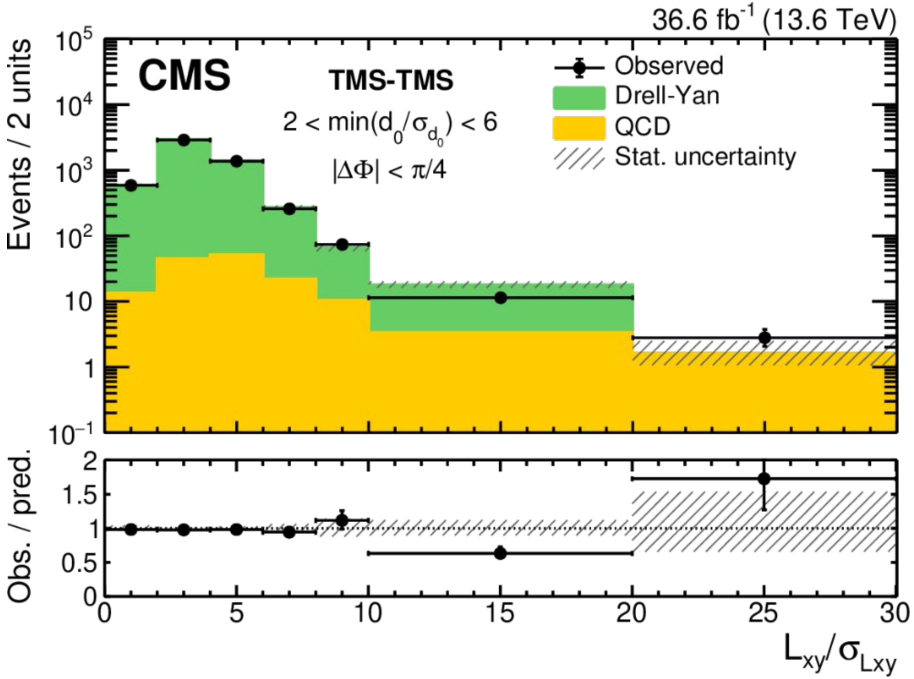


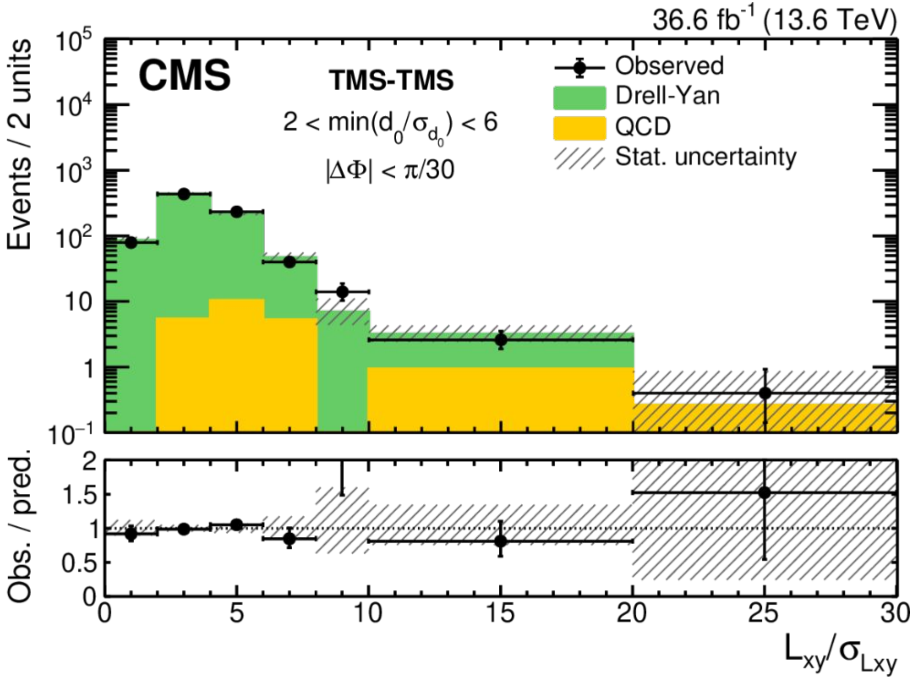


Validation of bg prediction : STA-STA

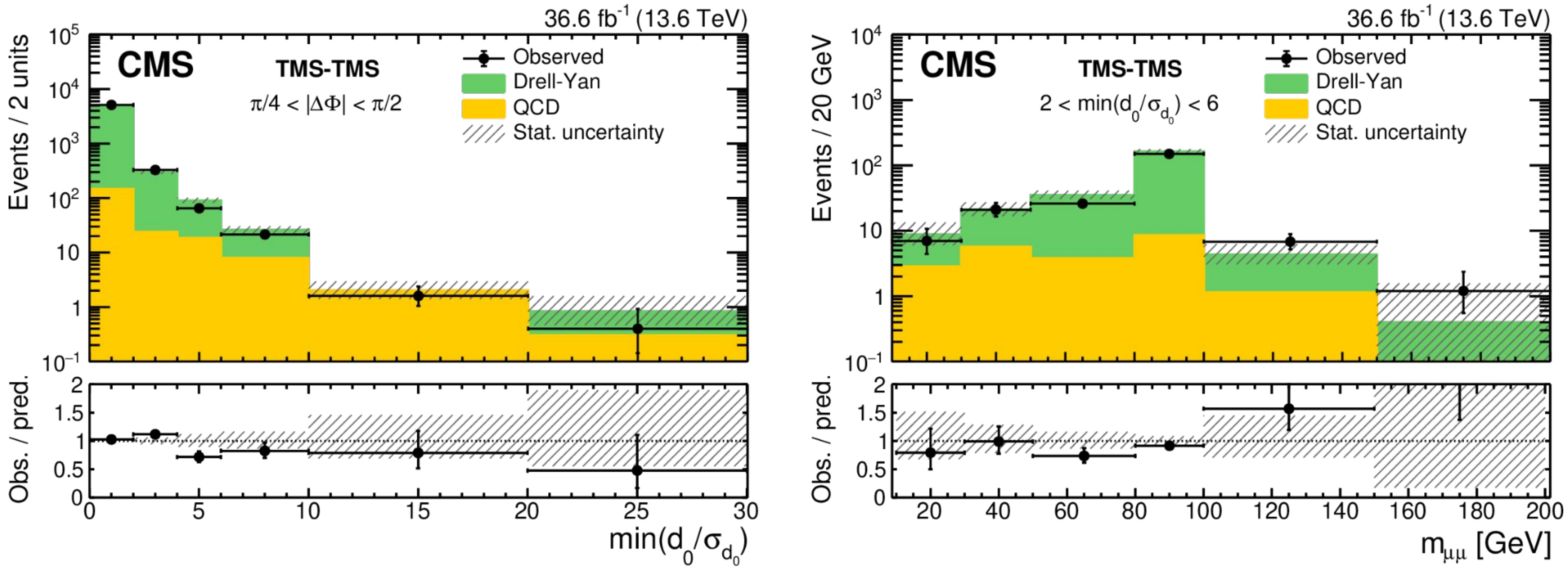


Validation of bg prediction : TMS-TMS

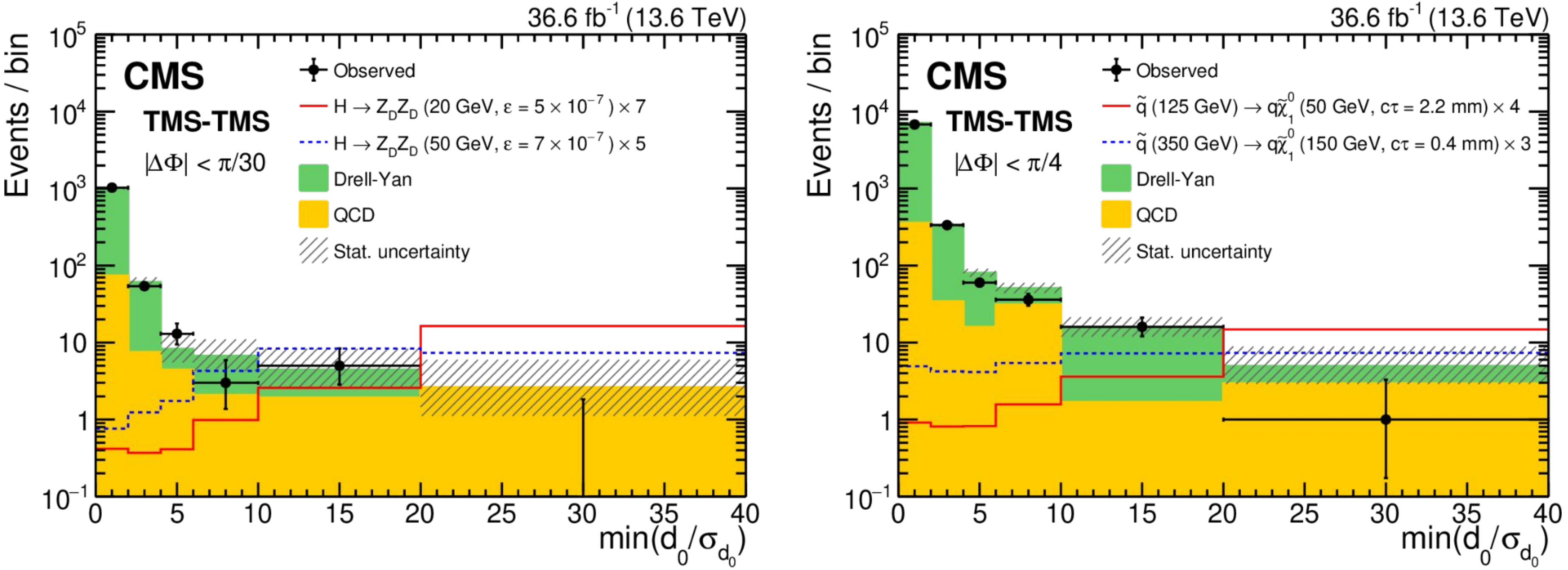




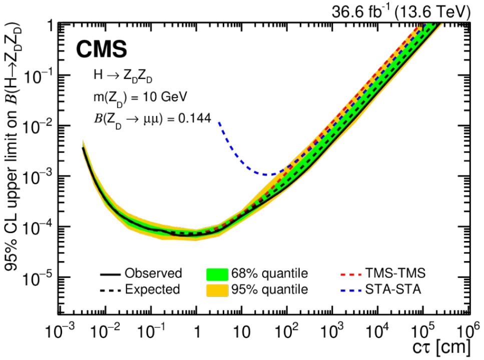
Validation of bg prediction : TMS-TMS

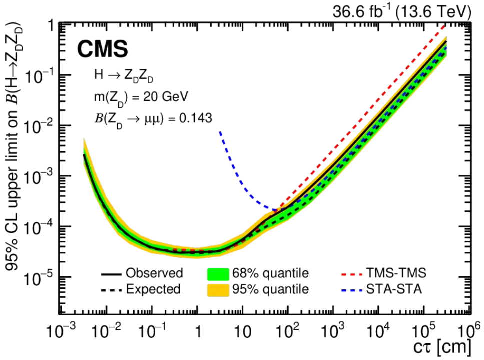


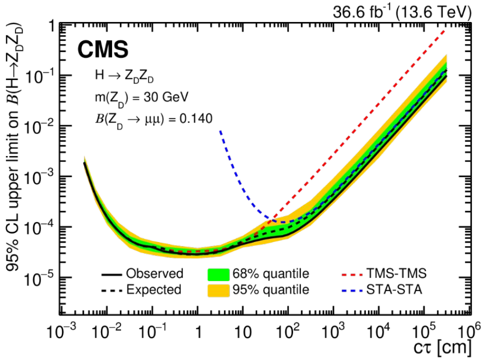
TMS-TMS signal region

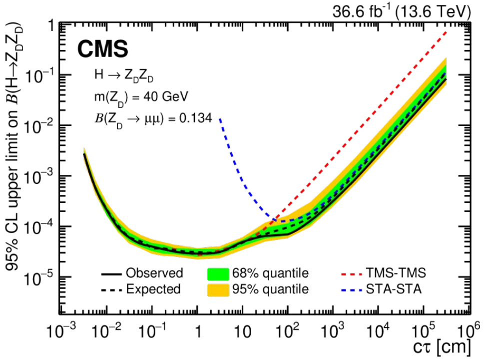


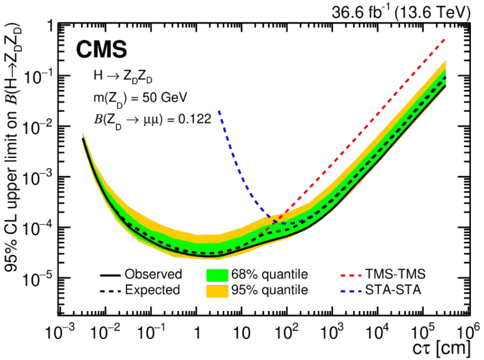
Dark Photon Limits – Categorywise

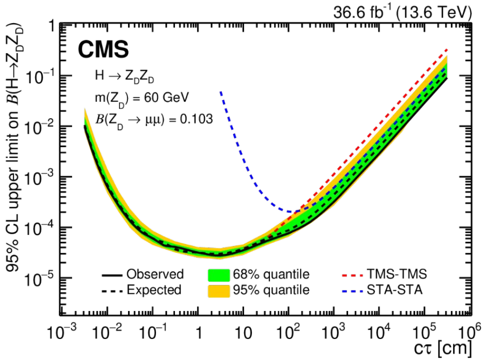




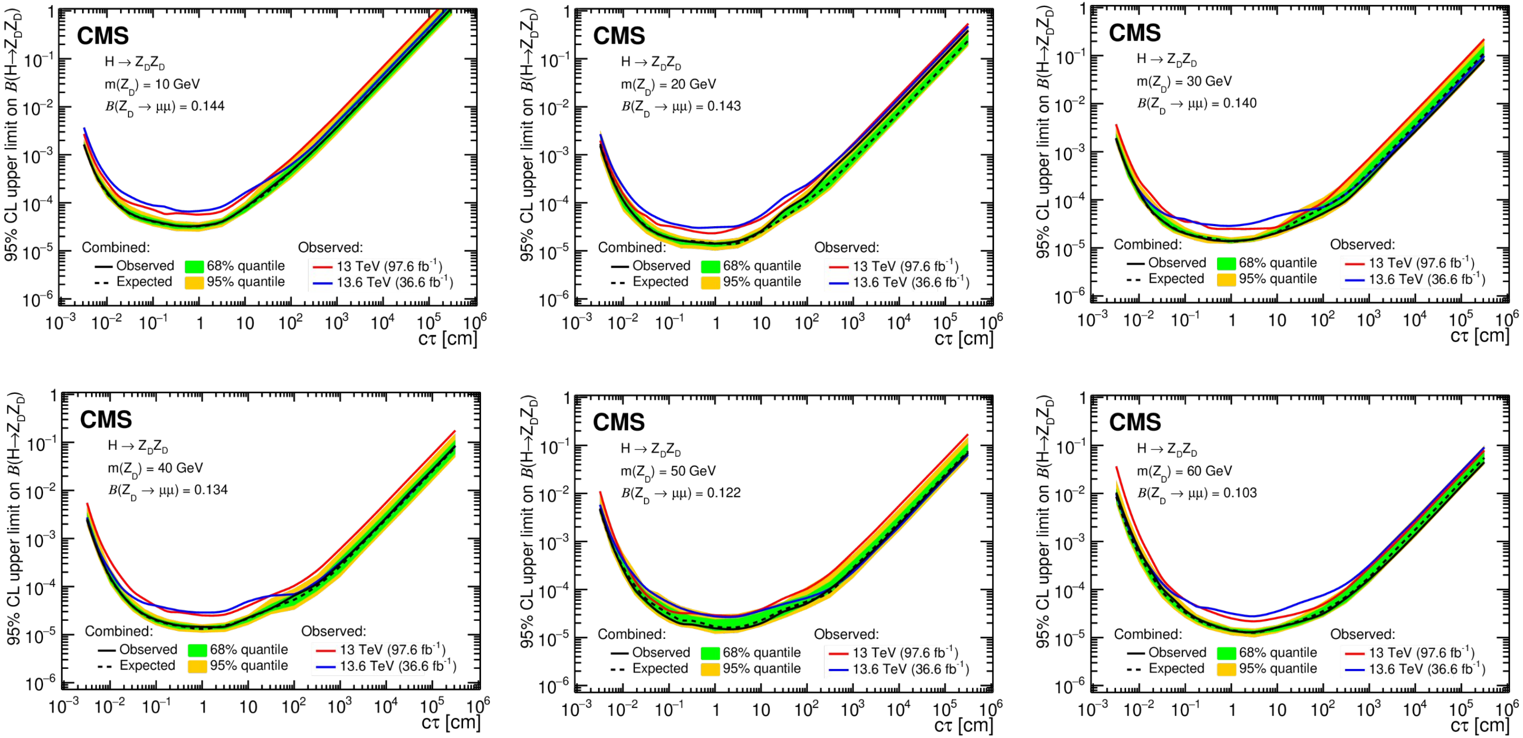




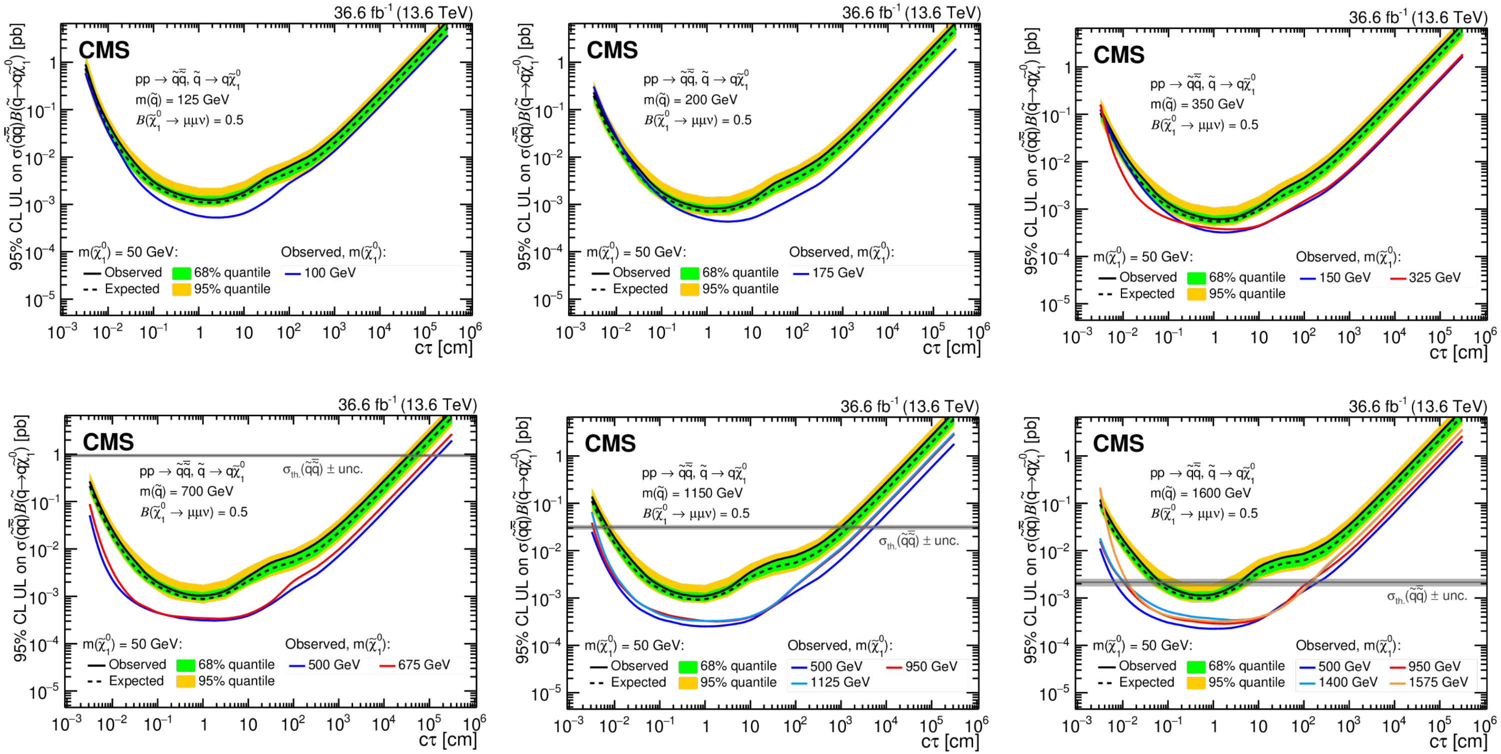




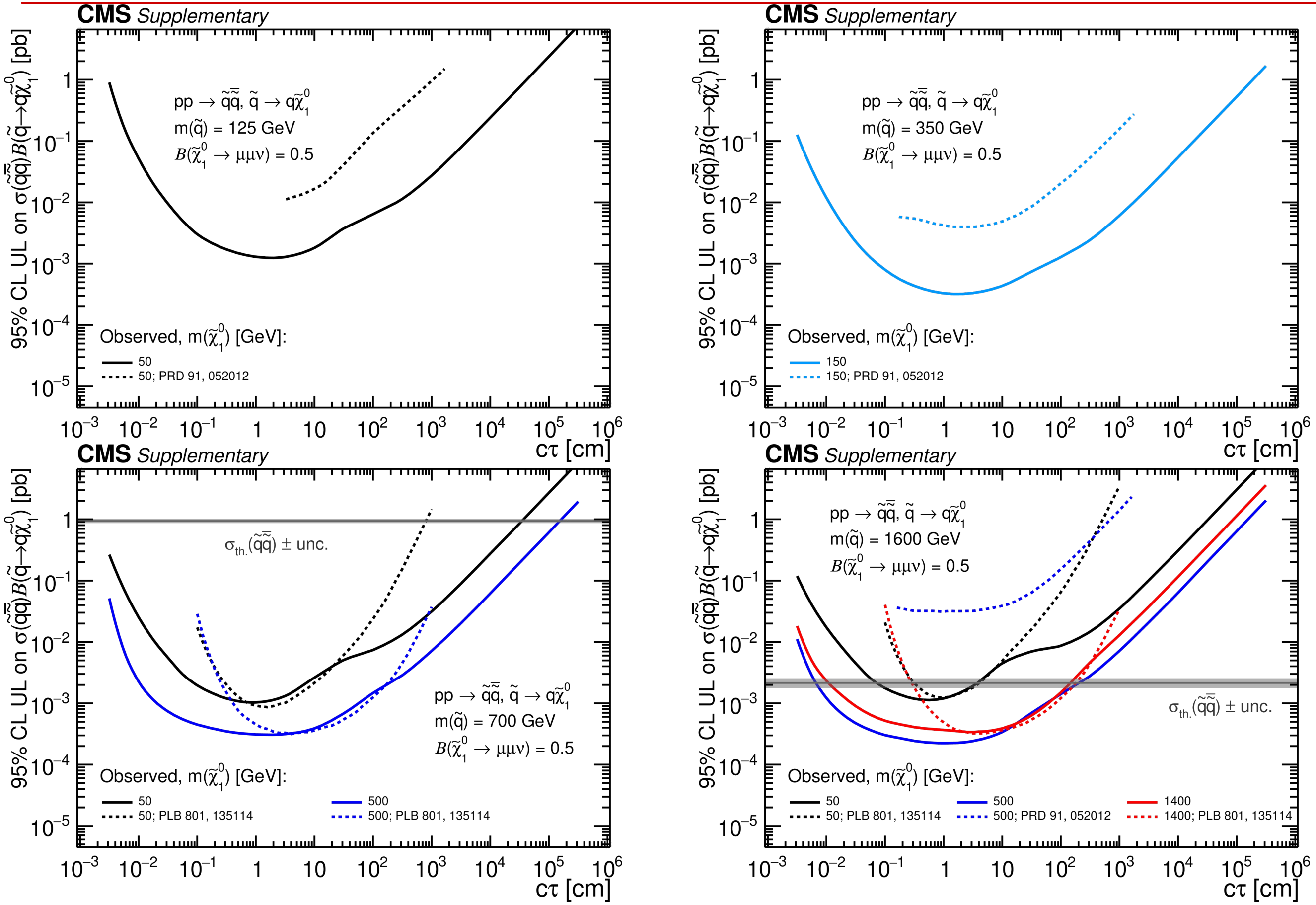
Dark Photon Limits - Run 2 and 3



RPV SUSY Limits



RPV SUSY limits – Comparison



Solid lines :

limits set by this search