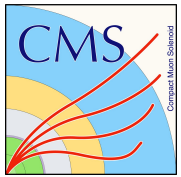
Searches for Long-lived Particles (LLPs) decaying to muons with 2022 data in CMS

Alberto Escalante del Valle on behalf of the CMS collaboration

XV CPAN days at Santander
03.10.2023

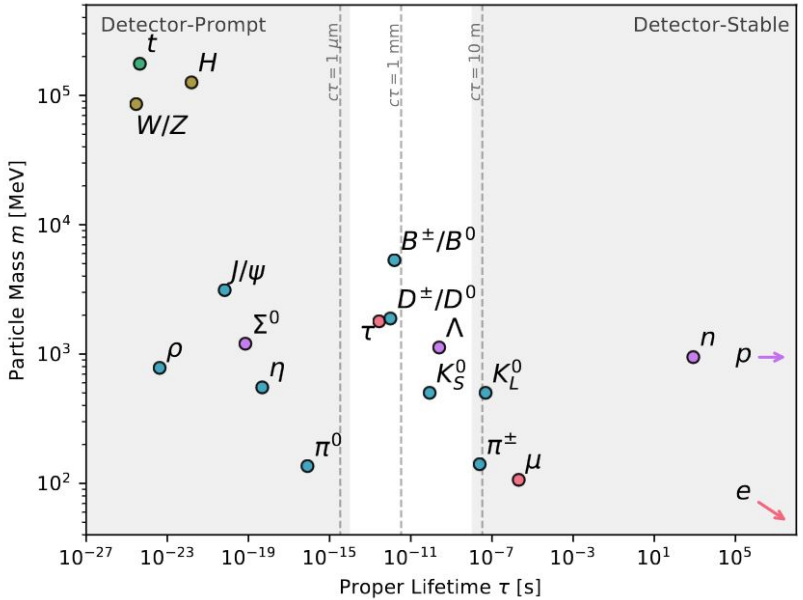


Atracción de Talento 2022-T1/TIC-23778

Plenty of LLPs in the SM

Long-lived particles appear everywhere in SM, e.g τ, π, K, D, B…

- Their $c\tau$ was critical to the design of experiments in HEP



- Kaon physics (e.g NA62)
  - $c\tau(K^{\pm}) = 3.7$ m
- Heavy flavor physics (e.g LHCb)
  - $c\tau(D^{\pm}) = 311.8\ \mu$m
  - $c\tau(B^{\pm}) = 491.1\ \mu$m
- Higgs physics (e.g ATLAS/CMS)
  - $\tau(H) = 1.6 \cdot 10^{-22}$ s
  - $H \rightarrow \tau\tau$, $c\tau(\tau) = 87.0\ \mu$m

arXiv:1810.12602

Why all BSM should be prompt if the SM is not?

LLPs in BSM

LLPs are **predicted in many BSM physics** scenarios in **particular regions of the model phase space…**
For this, the **matrix element and/or phase space must be small**

$$\frac{1}{\tau} = \Gamma = \frac{1}{2m} \int d\Phi_f |M|^2$$

- Decay via heavy virtual mediator (m<<M)
  - e.g Heavy Neutral Leptons
- Small mass splitting
  - e.g Inelastic dark matter, compressed SUSY
- Small couplings:
  - e.g Dark sectors

$$\Gamma \sim \frac{\epsilon^2}{(8\pi)^{a-1}} \frac{m^n}{M^{n-1}}$$

arXiv:2212.03883

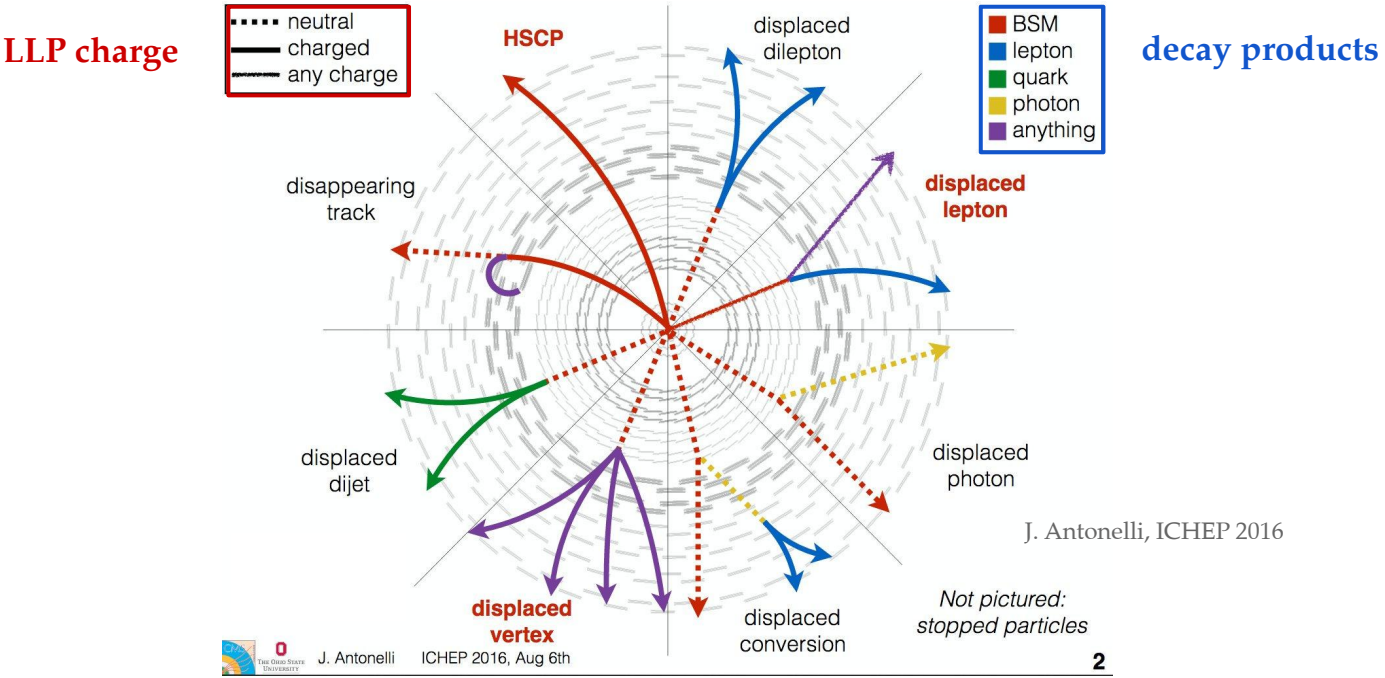
Unclear how BSM looks like

→ **Recently, increase in the number of searches testing $c\tau$(BSM)**

Experimental signatures of LLPs

Depending on LLP properties (e.g **charge**, **cτ**, **decay products**…)

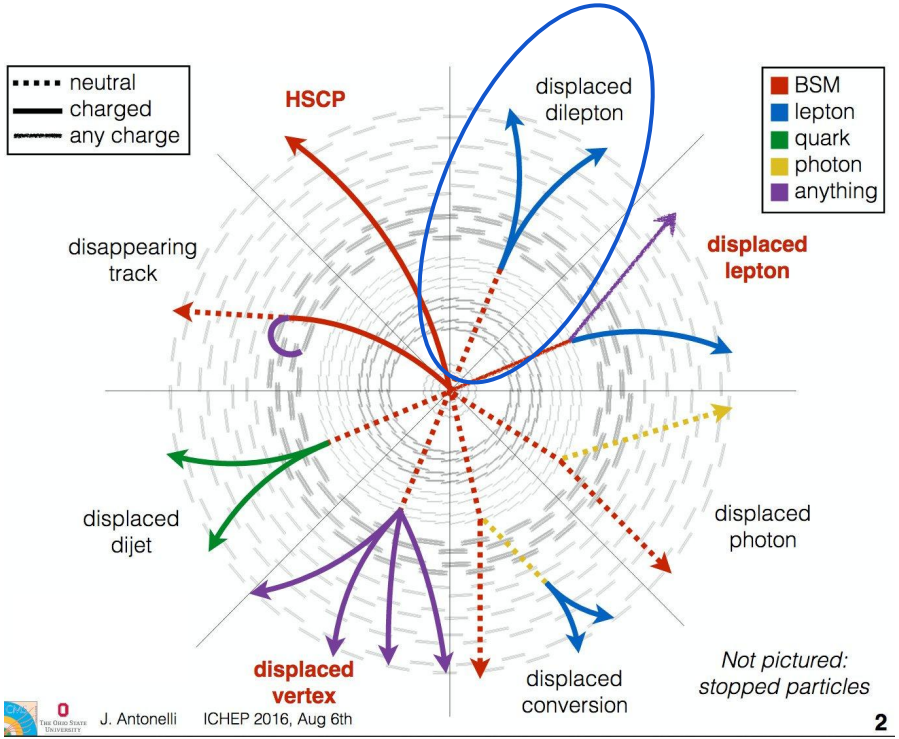
- "zoo" of unconventional **BSM experimental signatures**…



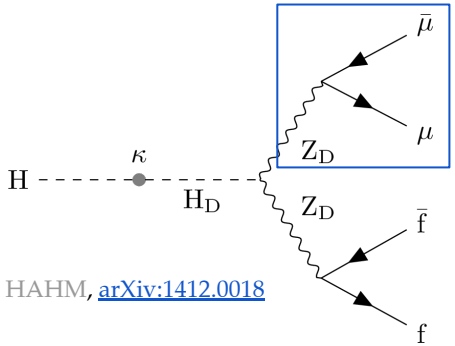
J. Antonelli, ICHEP 2016

Displaced dimuons from common vertex

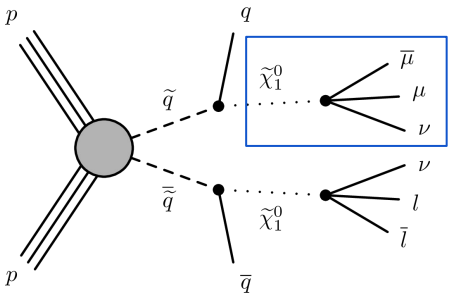
Focus of this talk



Benchmark models:



HAHM, arXiv:1412.0018



RPV SUSY, arXiv:0406039

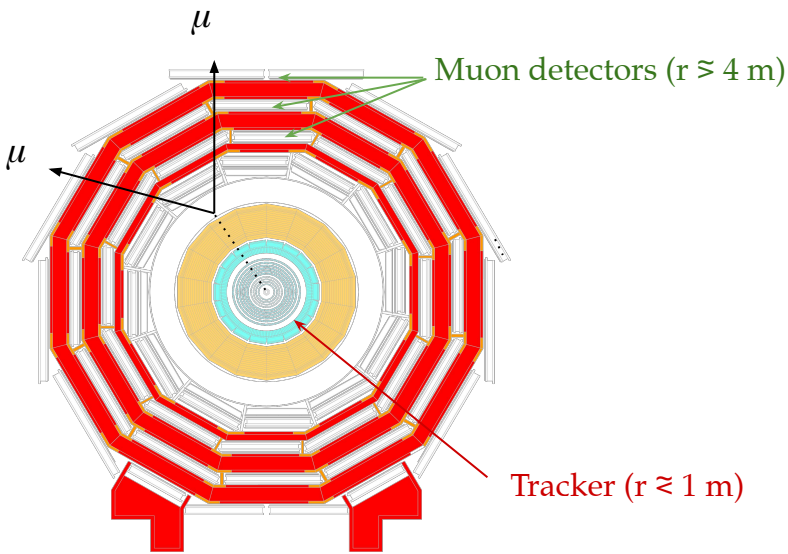
Displaced dimuons in Run 2 (96.7 fb^{-1} at 13 TeV)

[JHEP 05 (2023) 228]

Generic search for LLPs decaying into **displaced dimuons within and beyond the silicon tracker**

Dedicated triggers requiring two muons reconstructed in the muon system alone

- **p_T > 28 GeV**, deployed in 2016
- Dropped in 2017
- **p_T > 23 GeV,** re-deployed and further-optimized in 2018

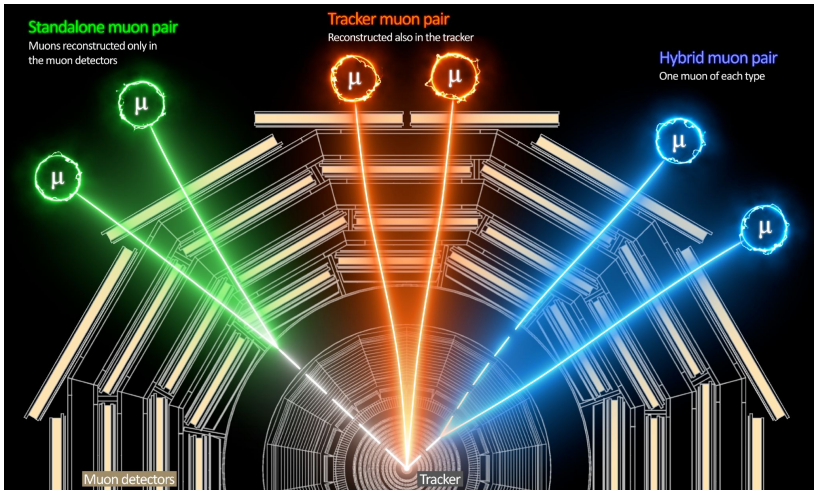


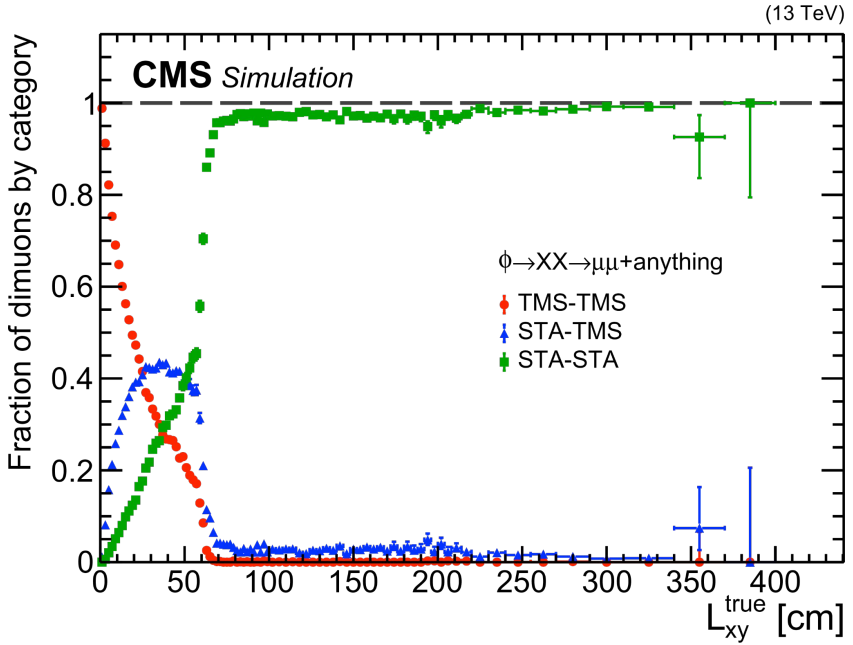
Displaced dimuons in Run 2 (96.7 fb^{-1} at 13 TeV)

Generic search for LLPs decaying into **displaced dimuons within and beyond the silicon tracker**

Use dimuons built from

- STA (muon system)
- TMS (tracker+muon system) muons

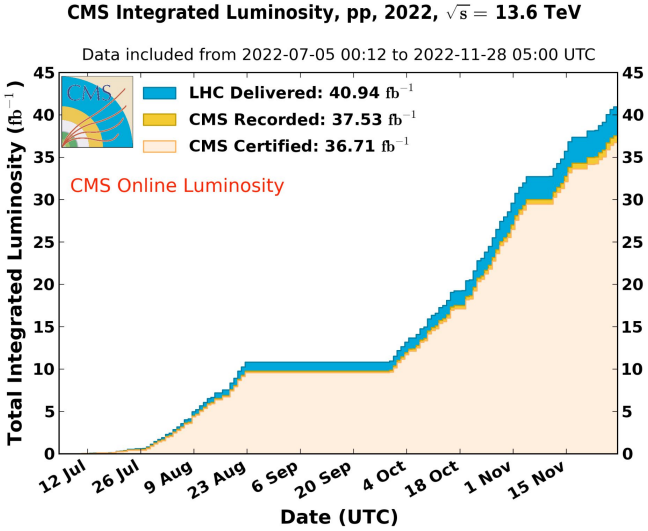


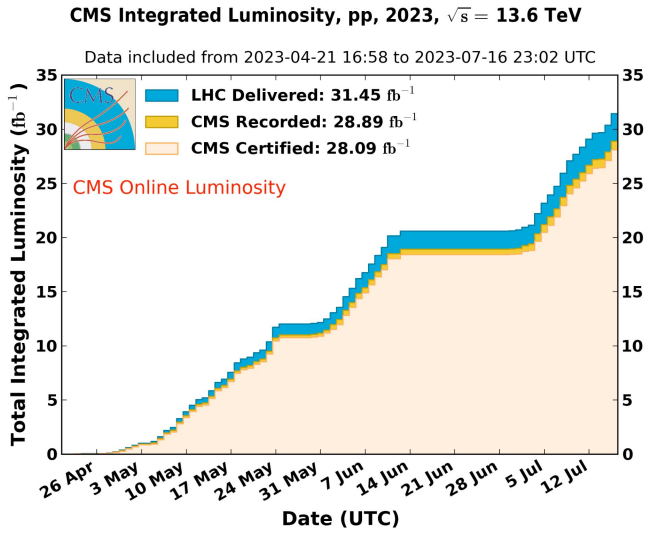


Published in [JHEP 05 (2023) 228]

Run 3 data taking

Extensive LLP trigger development during LS2, building on experience from the Run 2 analysis





66.4 fb^{-1} recorded in CMS in 2022+2023 [ref]

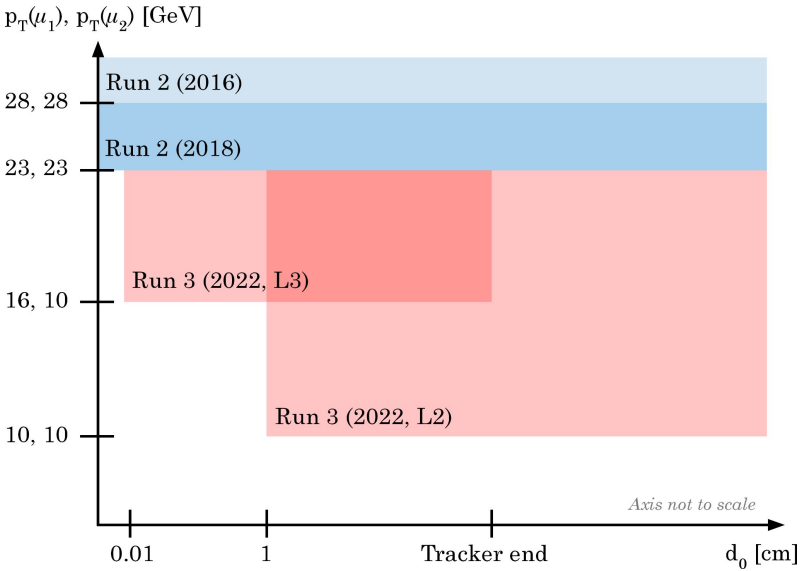
- **36.7 fb^{-1} in 2022 is certified** (= data recorded with muon and tracking detectors showing good performance)

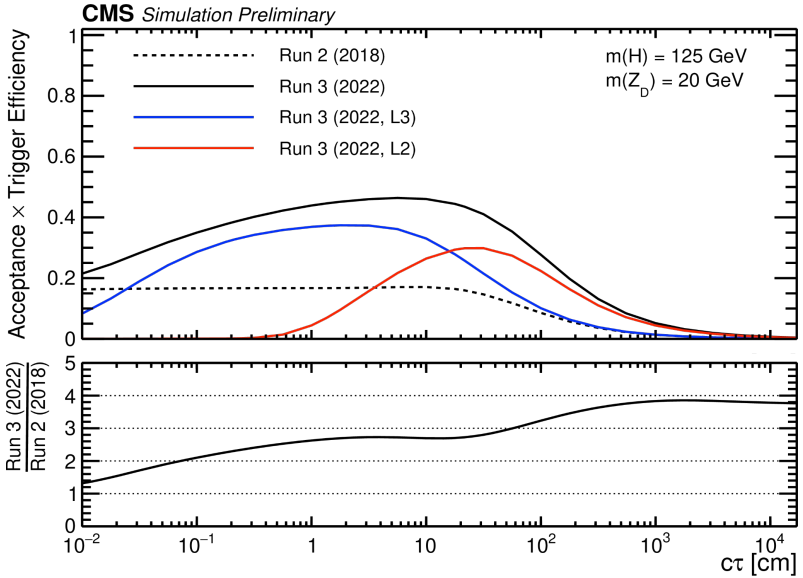
Displaced dimuons in Run 3 (36.7 fb^{-1} at 13.6 TeV)

EXO-23-014 (new)

Use a dataset (**36.7 fb^{-1}**) recorded with **new LLP triggers with thresholds down to p_T> 10 GeV**

- Use d_{xy} information at trigger level to control the background rate
- Re-optimized L1 triggers, including p_T without beam spot constraint in central $|\eta|$ region (barrel)



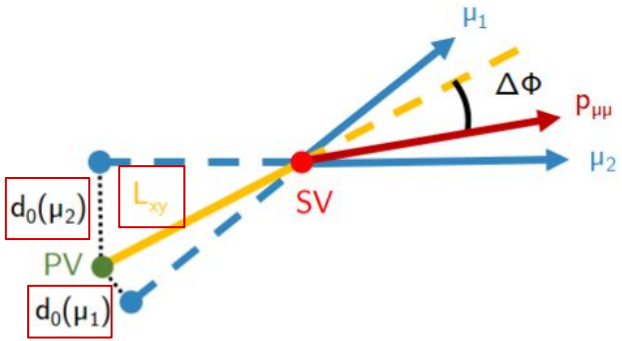


2-4x increase in efficiency, depending on $m(Z_D)$ and $c\tau(Z_D)$, **thanks to new triggers**

Key variables (I)

EXO-23-014 (new)

Search for dimuon vertices displaced wrt primary vertex

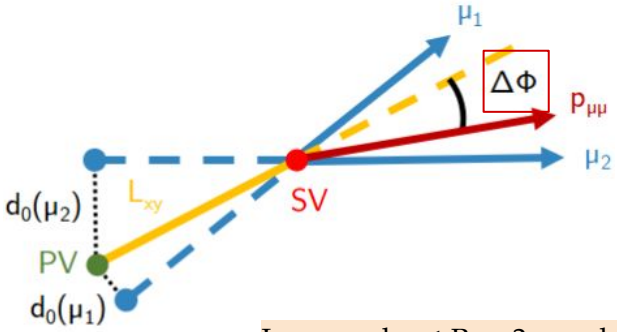


	TMS-TMS	STA-STA
$\min(d_0/\sigma_{d_0})$	[6, 10], [10, 20], > 20	-
$L_{xy}/\sigma_{L_{xy}}$	> 6	> 6

Key variables (II)

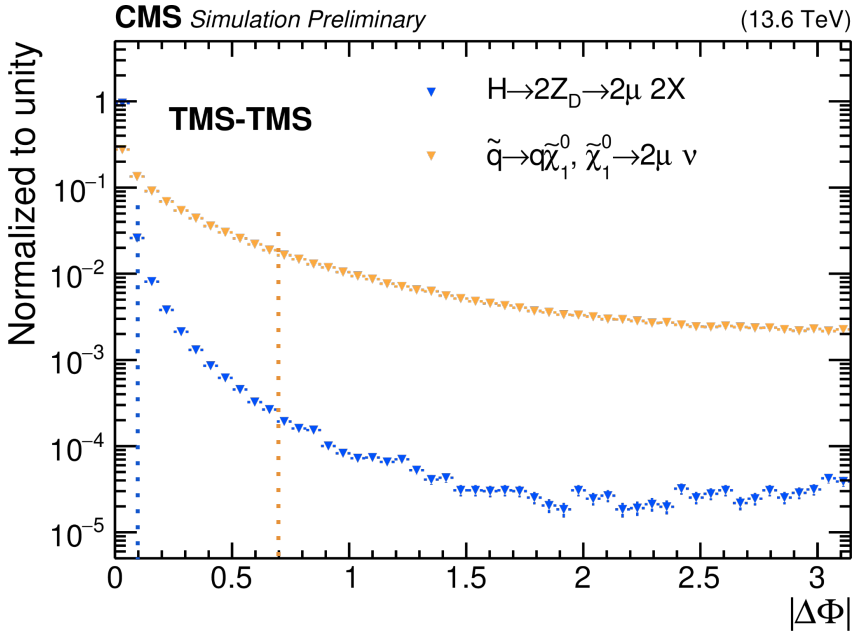
EXO-23-014 (new)

Search for dimuon vertices displaced wrt primary vertex, with collinearity ($\Delta\phi$) compatible with LLP decay



Improved wrt Run 2 search

$\lvert\Delta\phi\rvert$	TMS-TMS	STA-STA
$Z_D \to \mu\mu$	$<\pi/30$	$<\pi/10$
$\tilde{\chi}_1^0 \to \mu\mu\nu$	$<\pi/4$	$<\pi/4$



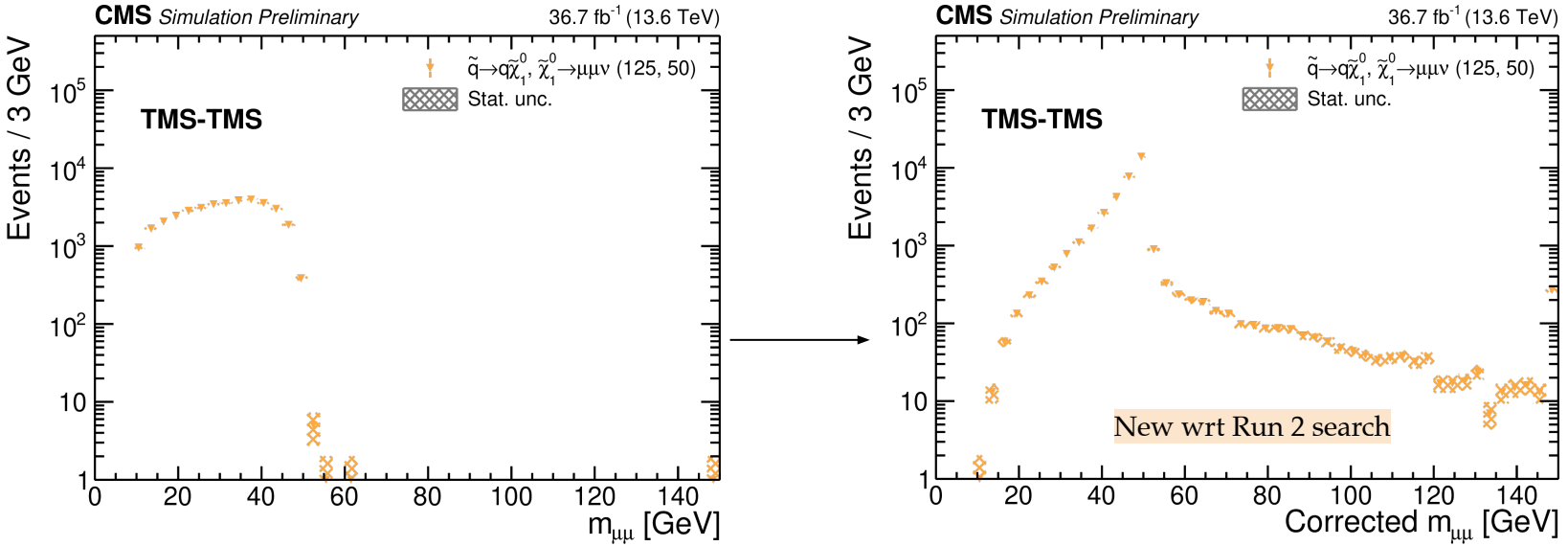
Signal regions with different $\lvert\Delta\phi\rvert$ requirements **to maximize sensitivity to $\mu\mu$ and $\mu\mu\nu$ vertices**

Key variables (III)

EXO-23-014 (new)

Search for dimuon vertices displaced wrt primary vertex, with collinearity ($\Delta\phi$) compatible with LLP decay, and $m_{\mu\mu}$ or $m^{corr}_{\mu\mu}$ compatible with LLP mass

$$m^{corr}_{\mu\mu} = \sqrt{m^2_{\mu\mu} + p^2_{\mu\mu}\sin^2\theta} + p_{\mu\mu}\sin\theta,$$



Require **$m_{\mu\mu}$ > 10 GeV to suppress QCD background** and use **$m^{corr}_{\mu\mu}$ to improve resolution for $\mu\mu\nu$ vertices**

Expected backgrounds

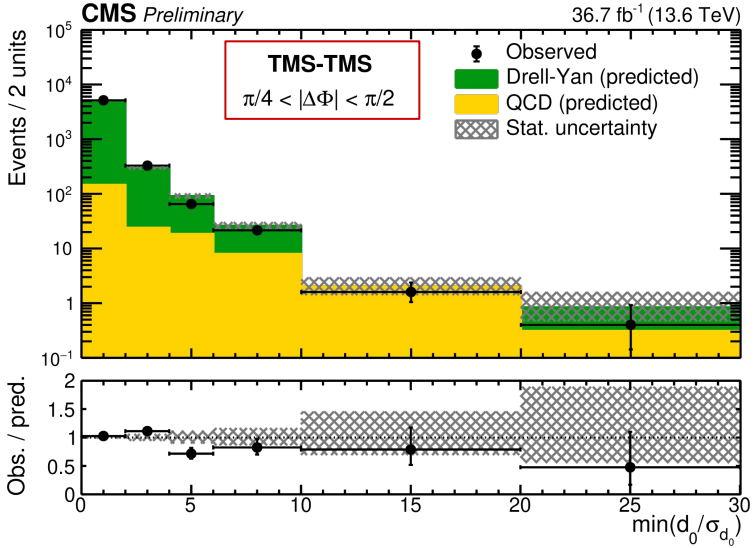
EXO-23-014 (new)

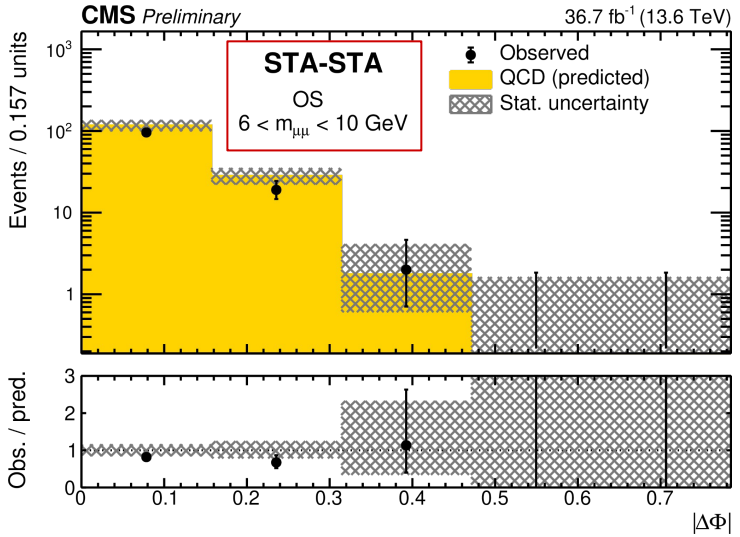
There are **no SM LLP with m> 10 GeV**

- Residual background is instrumental or from reconstruction mistakes → **Backgrounds estimated from data**
  - Control regions obtained inverting $|\Delta\phi|$, dimuon charge, and muon isolation requirements

Categorize backgrounds in two classes

- DY from prompt high-mass dimuons misreconstructed as displaced. **Symmetric in $|\Delta\phi|$.**
- QCD from poorly measured low mass dimuons, especially in STA-STA. **Peaks at $|\Delta\phi| \sim 0$.**

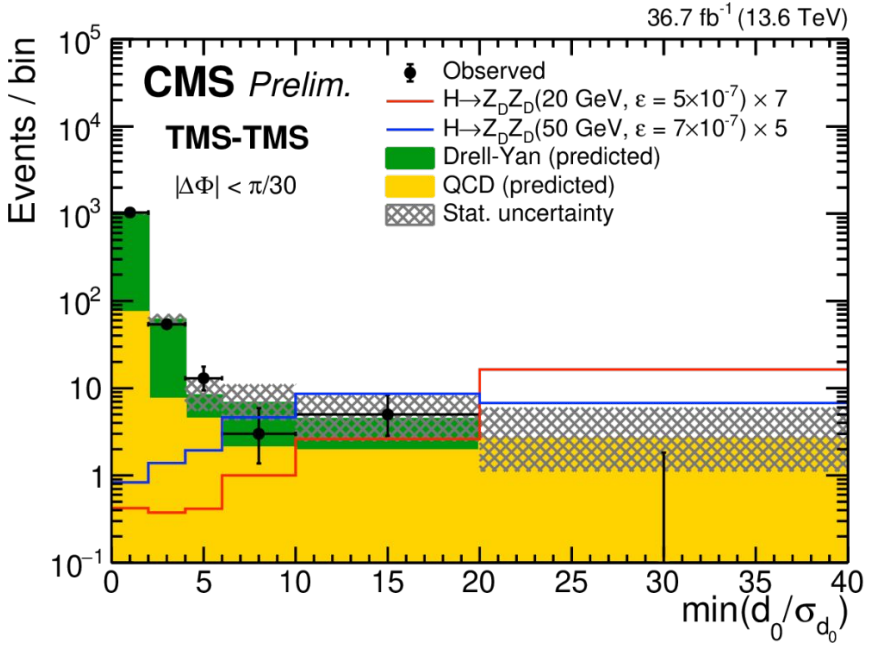


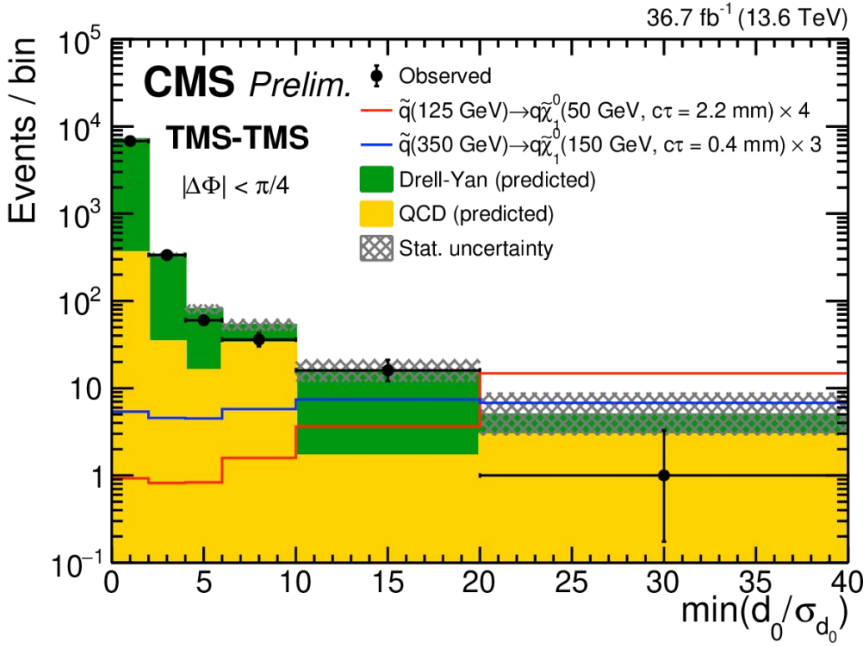


Signal region in **TMS-TMS** (I)

EXO-23-014 (new)

$\min(d_0/\sigma_{d0})$ distribution for **two $|\Delta\phi|$ requirements**

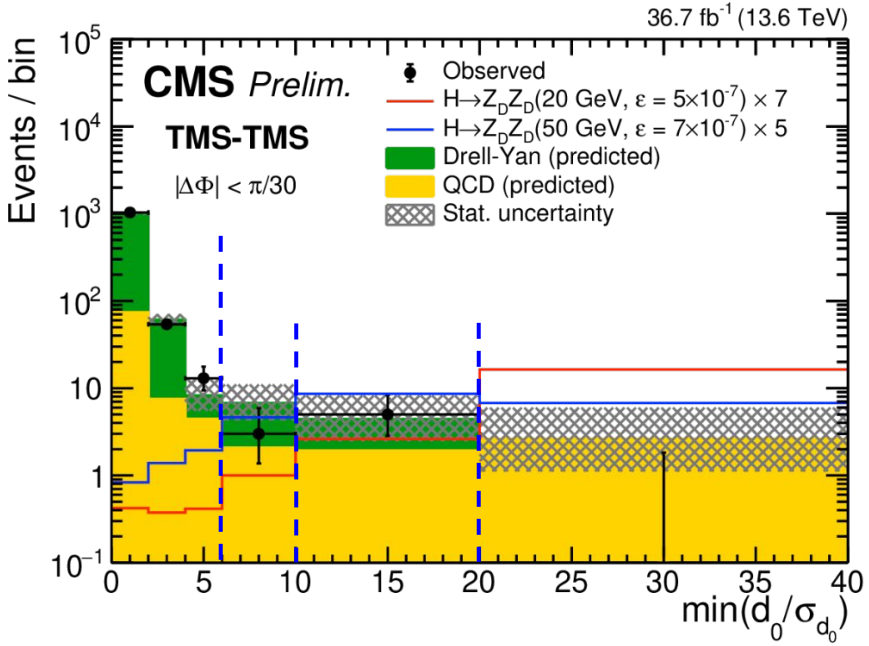


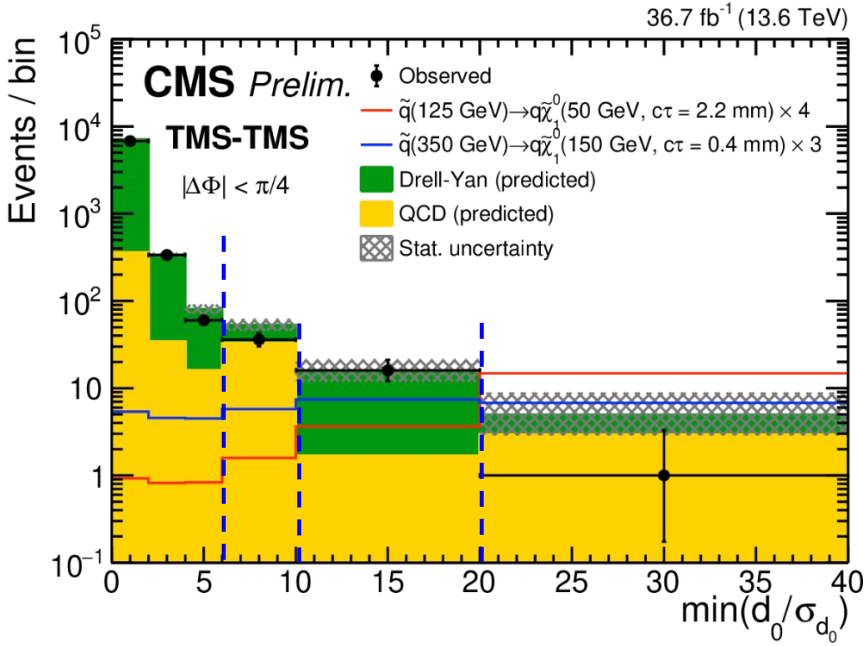


The background decreases rapidly as $\min(d_0/\sigma_{d0})$ increases (where signal is expected)

Signal region in **TMS-TMS** (II)

EXO-23-014 (new)





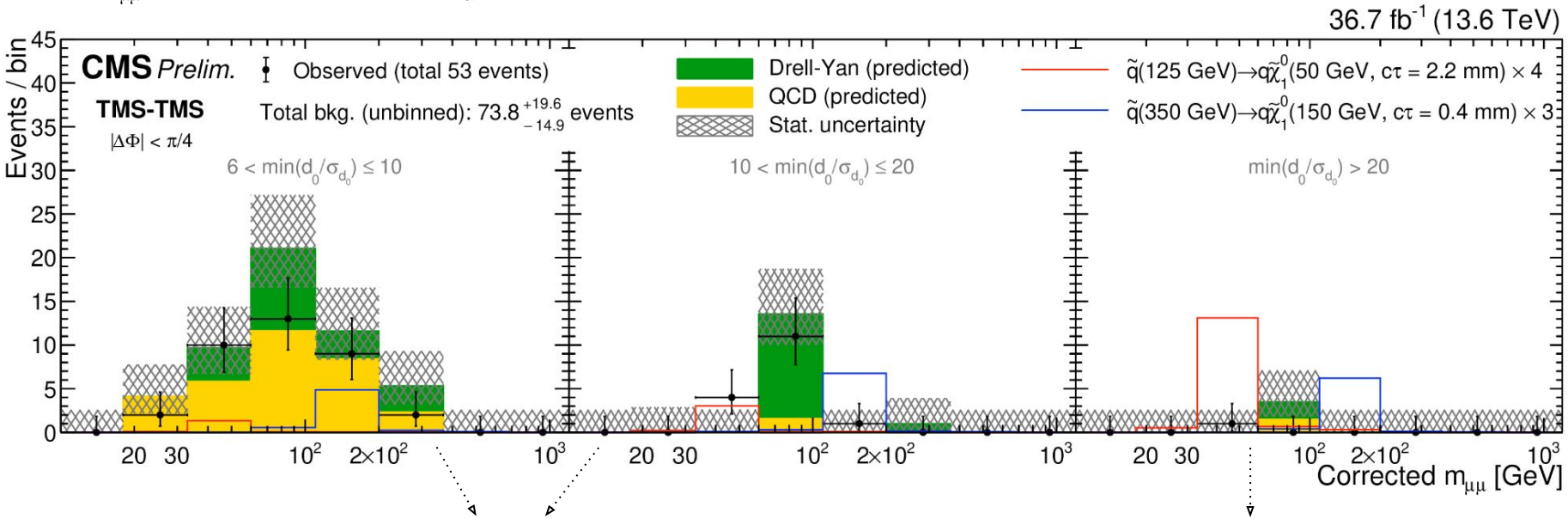
Look for excess of events **in the tail of min(d_0/σ_{d0})**

- [6, 10], [10-20] and >20 define the signal regions (next slide)

Signal region in **TMS-TMS** (III)

EXO-23-014 (new)

$m^{corr}_{\mu\mu}$ distribution in **min(d_0/σ_{d0}) intervals**



[6, 10] and [10, 20] → **target short $c\tau$**

>20 → **target large $c\tau$**

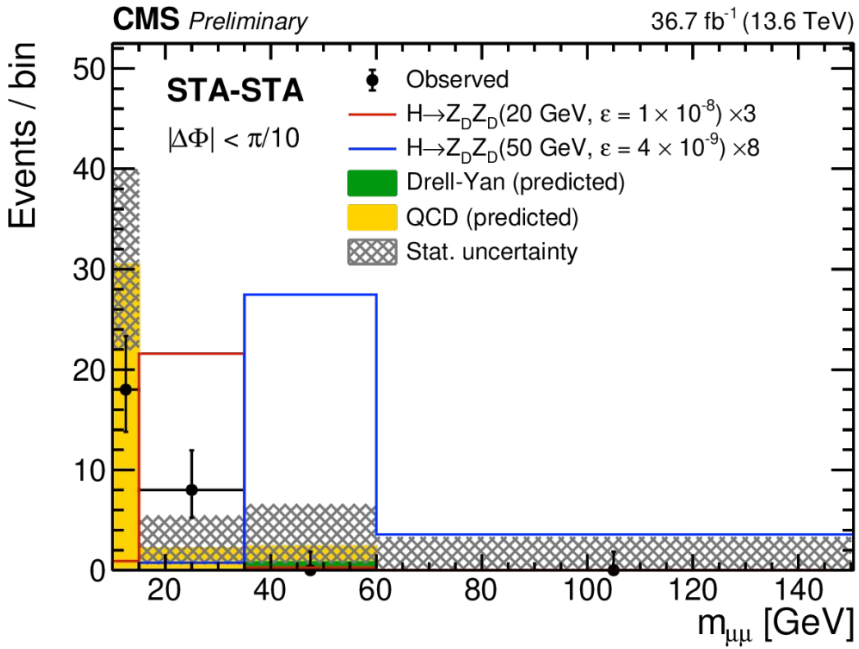
(most important signal region)

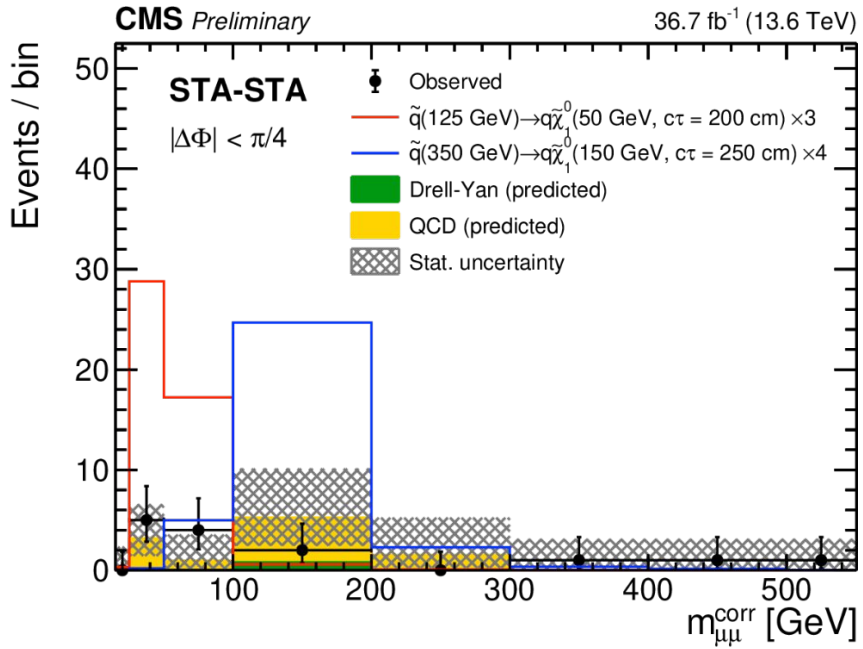
Data in agreement with expected SM background

[Plot for $m_{\mu\mu}$ in the paper]

Signal region in **STA-STA**

EXO-23-014 (new)





Small residual background in STA-STA, thanks to excellent TMS muon reconstruction in silicon tracker

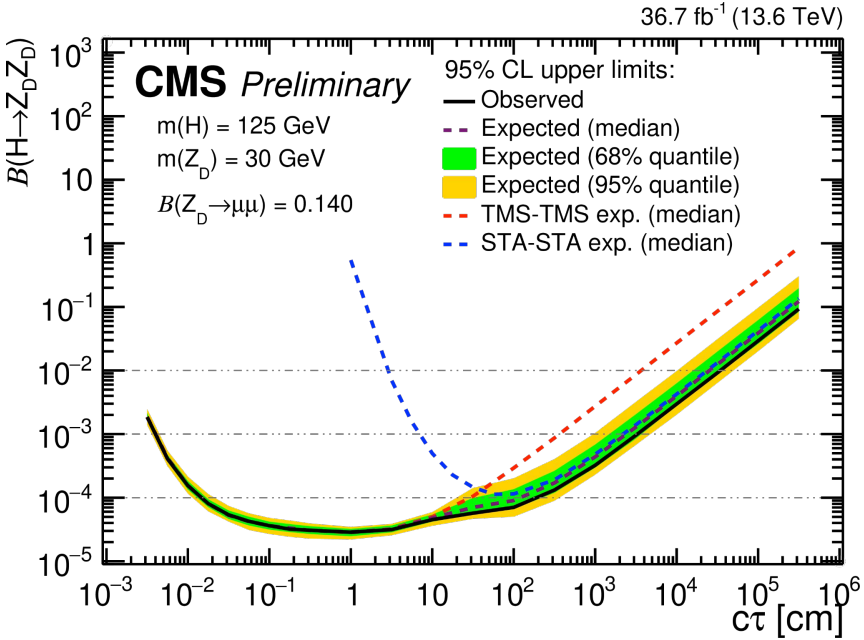
- cosmic ray muon background removed thanks to angular, timing, and direction criteria

Data in agreement with expected SM background

Run 3 results

EXO-23-014 (new)

First LHC constraints using 13.6 TeV data

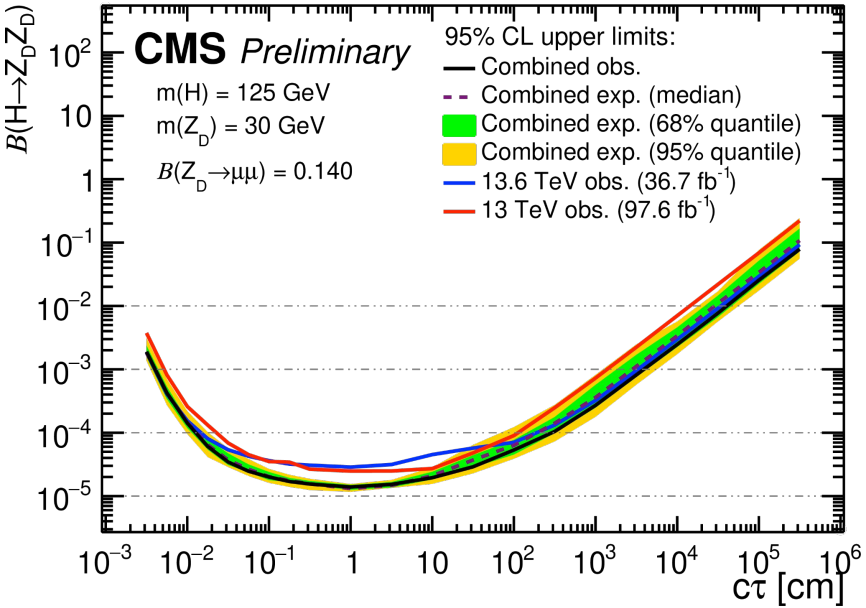


- Sensitivity dominated by TMS-TMS at small and STA-STA at large cτ
- Thanks to a combination of categories, **analysis is sensitive to a wide range of cτ from μm to km!**
- Similar results for other m(Z$_D$)

Run 2 + Run 3 results

EXO-23-014 (new)

Run 2 (**97.6 fb^{-1} at 13 TeV**) + Run 3 (**36.7 fb^{-1} at 13.6 TeV**) combination

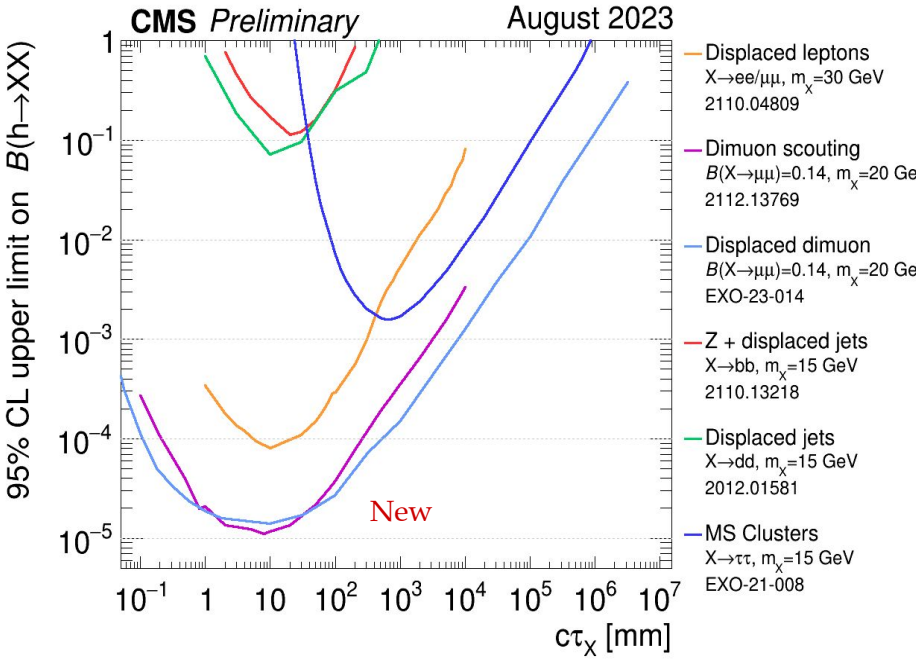


- Similar sensitivity compared to Run 2 despite about 2.5 smaller dataset, **thanks to new Run 3 triggers**
- **After Run 2 + Run 3 combination**, depending on m(Z_D) and cτ(Z_D), **~2 tighter B(H → Z_DZ_D) constraints**

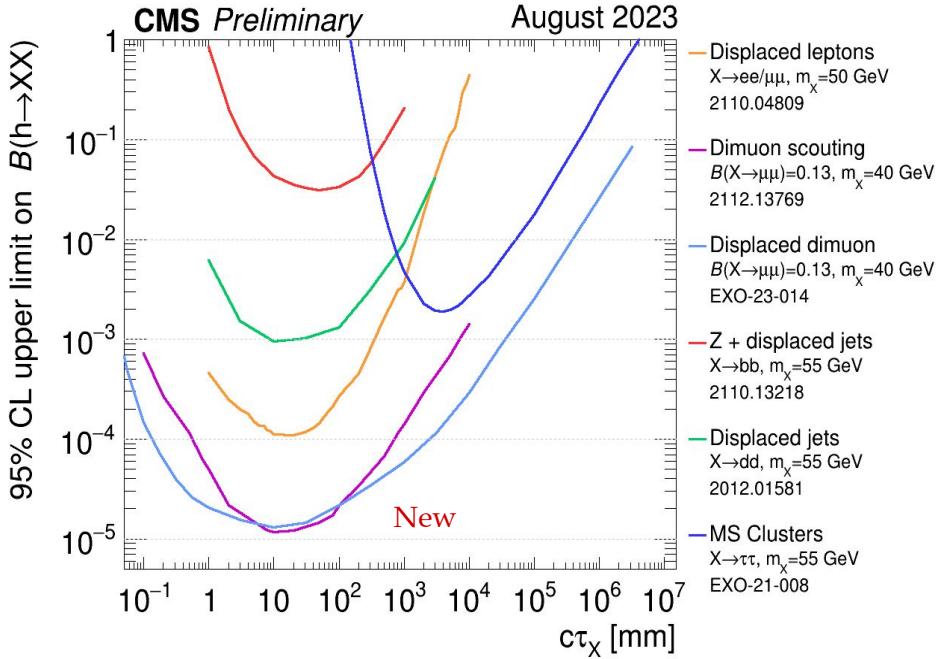
Comparison to other LLP searches: H → XX

EXO-23-014 (new)

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



m(X) ≥ 40 GeV

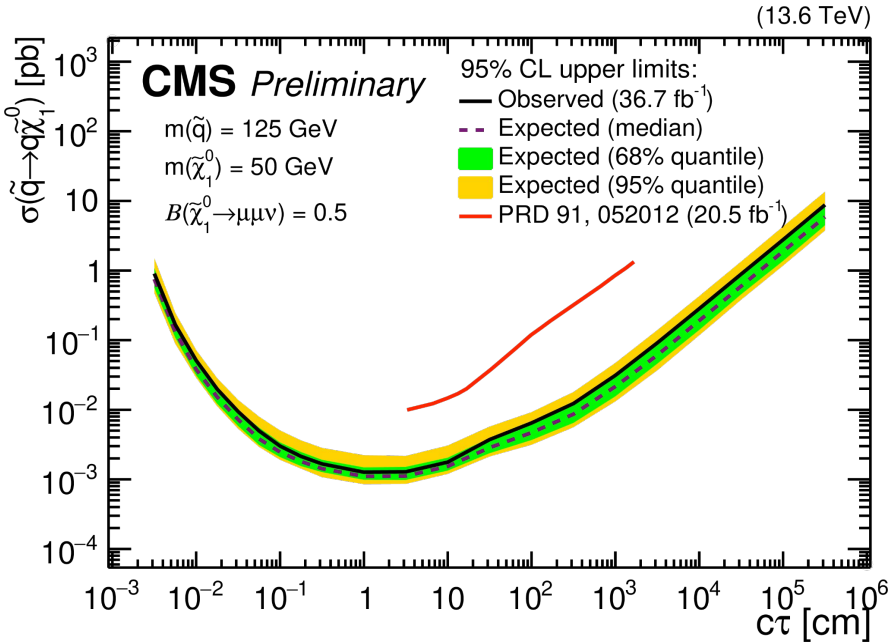


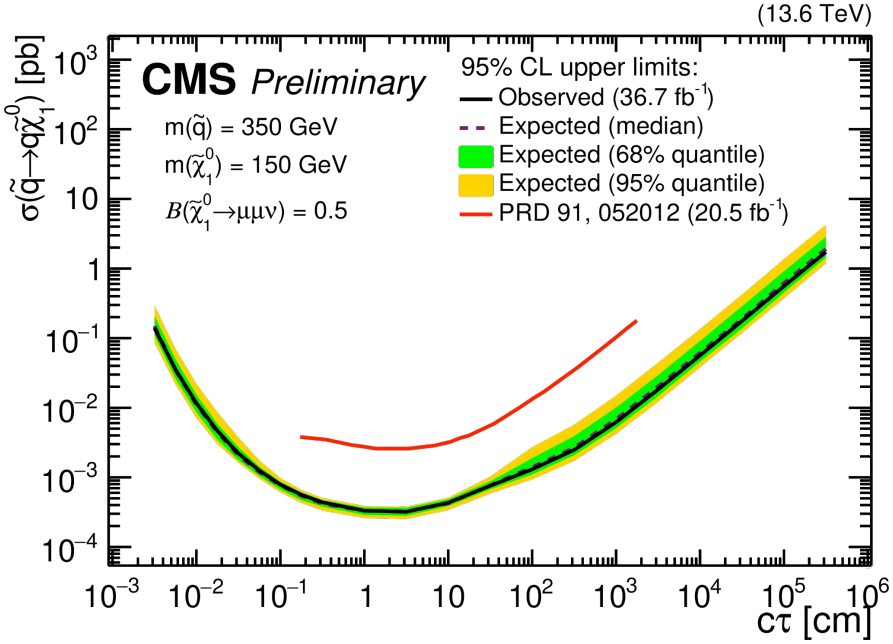
10 GeV < m(X) < 40 GeV

Comparison to other LLP searches: RPV SUSY

EXO-23-014 (new)

Significant improvements in $\sigma(\tilde{q} \to q\tilde{\chi}_1^0)$ constraints in RPV SUSY over previous Run 1 search in CMS [ref]





Wrap-up

Presented the first search for new physics at 13.6 TeV

- Thanks to an innovated set of new triggers, achieved unique sensitivity already with 36.7 fb^{-1}
- Results combined with Run 2 data
- Best constraints to date to B(H→ $Z_D Z_D$) in broad range of $c\tau(Z_D)$ for m(Z_D)>10 GeV
- Significant improvements in constraints to $\sigma\left(\tilde{q} \rightarrow q\,\tilde{\chi}_1^0\right)$ in RPV SUSY

Numerous ongoing R&D efforts to improve LLP searches in CMS

- Other new triggers implemented for Run 3 (see CMS-DP-2023-043 for details)

Stay tuned for more LLP results with 13.6 TeV