

Search for long lived particles at the LHC

Jonas Floßmann | 16. April 2026

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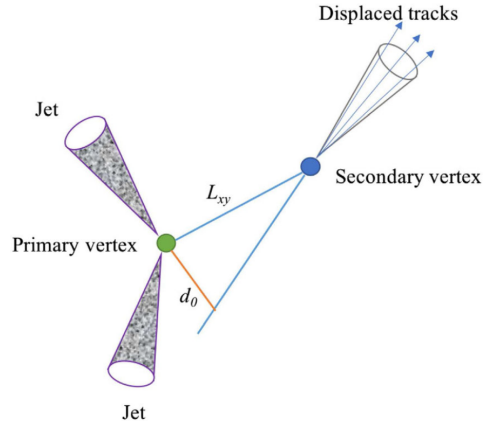
- Long lived particles
- Search for BSM particles at LHC
 - Search for long-lived particles decaying to final states with a pair of muons in proton-proton collisions at $\sqrt{s} = 13.6\text{TeV}$
 - Search for light scalar particles from Higgs boson decays in exclusive final states with two muons and two hadrons

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What Are Long-Lived Particles (LLPs)?

- Particles predicted by many BSM models with measurable decay lengths.
- Decay away from the interaction point \rightarrow displaced vertices.
- Typical in scenarios like:
 - Hidden sectors
 - Gauge-mediated SUSY breaking
- Lifetimes can range from picoseconds to seconds or more.



LLP signatures

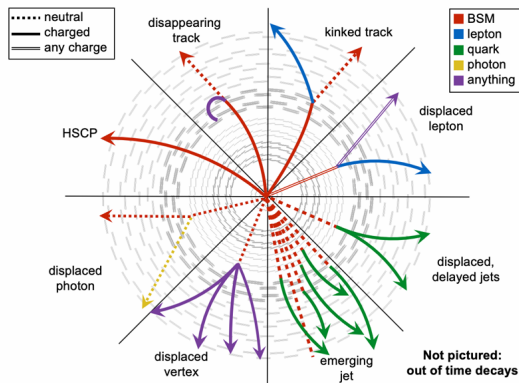


Figure: Possible interactions of LLP in the detector.

Why Are LLPs Important?

- LLPs give an alternative to conventional decays.
- Provide unique experimental signatures:
 - Displaced leptons/jets
 - Non-pointing photons
 - Delayed signals in detectors
 - etc.
- Can test otherwise inaccessible regions of BSM parameter space to leave no stone unturned.
- Increasing interest in high-energy particle physics.

Origins of Long-Lived Particles (LLPs)

- LLPs arise when particle decays are suppressed or delayed. Main mechanisms include:
 - **1. Small Couplings:**
 - Weak interaction strength or tiny mixing angles lead to long lifetimes.
 - Example: Neutrinos in SM, dark photons with small kinetic mixing.
 - **2. Small Mass Splittings:**
 - Phase space suppression when daughter particles are nearly degenerate with parent.
 - Example: Charged/neutral components in SUSY nearly degenerate.
 - **3. Heavy Mediators or Higher-Dimensional Operators:**
 - Decays proceed via off-shell heavy particles or suppressed effective operators.
 - Example: R-parity violating neutralino decays or exotic Higgs decays.

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What is R-Parity?

- R-Parity is a quantum number in SUSY:

$$R = (-1)^{3(B-L)+2s}$$

- Standard Model particles have $R = +1$, SUSY particles have $R = -1$.
- If R-parity is conserved:
 - Lightest Supersymmetric Particle (LSP) is stable
 - SUSY particles are produced in pairs
 - LSP is a candidate for dark matter

R-Parity Violation and LLPs

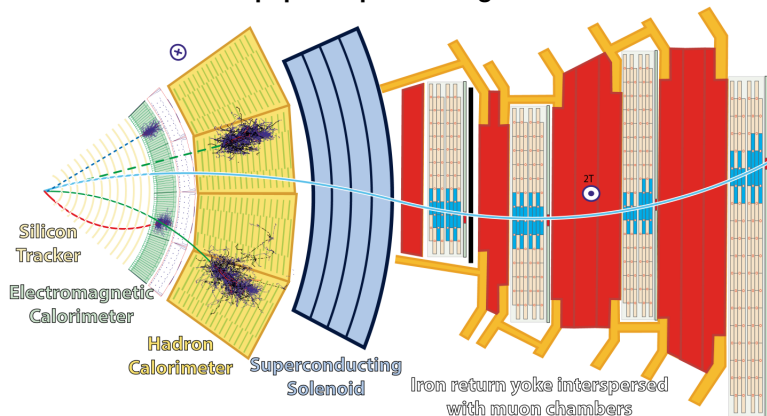
- **R-Parity Violation (RPV)** allows lepton or baryon number violation.
- Leads to unstable LSP \rightarrow visible decays
- Motivates searches for:
 - Displaced vertices from LSP decay in RPV SUSY scenarios
- Lifetime depends on size of RPV coupling; small couplings \Rightarrow LLPs.
- Example: $\tilde{\chi}_1^0 \rightarrow \mu^+ \mu^- \nu$ with displaced dimuons.

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CMS detector

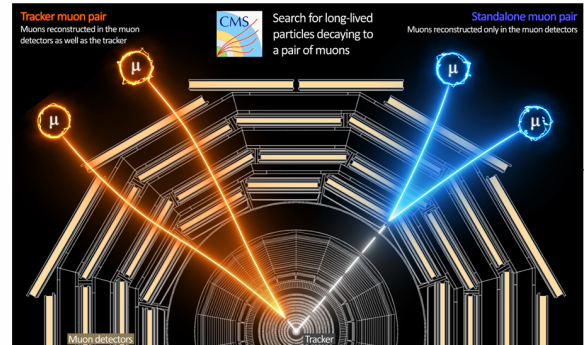
Discussion of the CMS paper <https://doi.org/10.48550/arXiv.2402.14491>



- Muon
- Electron
- Charged hadron (e.g. pion)
- - - Neutral hadron (e.g. neutron)
- - - Photon

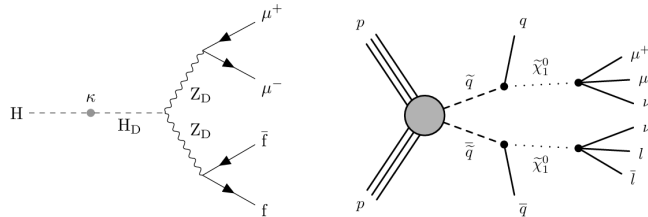
Displaced Muon Signatures

- Muons are clean probes due to minimal interaction with detector material.
- Displaced muons arise from LLP decays:
 - Can be far from the primary vertex
 - Often fail standard prompt muon selection criteria
- Signature in CMS:
 - **StandAlone Muons** reconstructed using only the muon system
 - **Tracker-Muon System Muons** reconstructed in the tracker as well as in the muon system



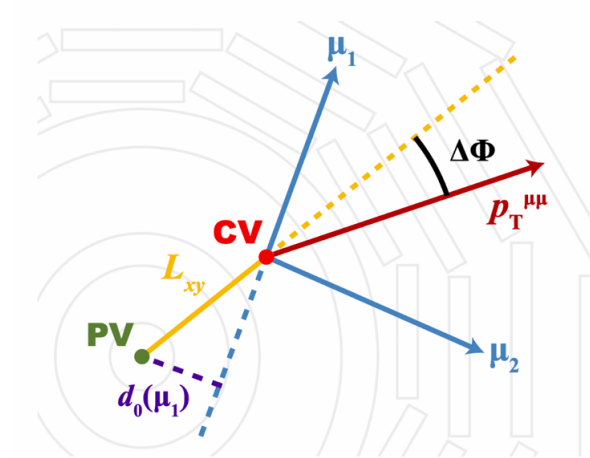
Signal Models and Simulated Samples

- **Goal:** Detect long-lived particles (LLPs) that decay into a pair of muons with macroscopic displacement.
- **Benchmark models:**
 - **Dark photon model (left):**
 - **RPV SUSY model (right):**



Analysis Strategy and Event Selection

- **Dataset:** 36.6 fb^{-1} of CMS Run 3 data at $\sqrt{s} = 13.6 \text{ TeV}$.
- **Signature:** Two muons from a common displaced secondary vertex.
- **Key observables:**
 - Transverse decay length L_{xy}
 - Invariant mass of the dimuon system
 - Transverse impact parameters d_0



Displaced muon triggers

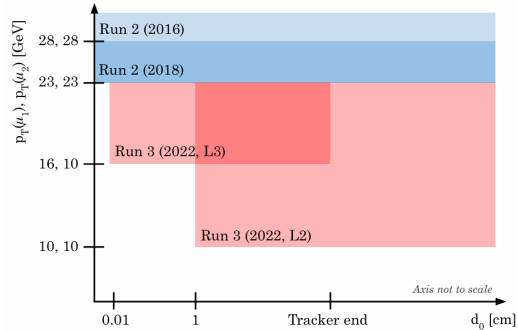


Figure: p_T and d_0 coverage of the used trigger.

Key Selection Cuts for Displaced Dimuons

■ Kinematic Cuts

- Muon $p_T > 10$ GeV, $|\eta| < 2.4$
- Dimuon invariant mass $m_{\mu\mu} > 10$ GeV (to suppress J/ψ , low-mass backgrounds)

■ Vertex Displacement

- Transverse decay length L_{xy} required to be significant
- $L_{xy}/\sigma_{L_{xy}} >$ threshold depending on category
- $\sigma_{L_{xy}} < 20$ cm (for STA-STA category)
- Binning in $\min(d_0/\sigma_{d_0})$: ranges of 6–10, 10–20, >20

■ Isolation Cuts

- STA: $I_{\text{rel, trk}} < 0.15$ (tracks in $\Delta R < 0.3$ cone)
- TMS: $I_{\text{rel, trk}} < 0.075$

■ Angular Cuts

- Azimuthal angle between $p_T^{\mu\mu}$ and decay vector \vec{L}_{xy} :
 - HAHM: $|\Delta\phi| < \pi/10$ (STA), $< \pi/30$ (TMS)
 - RPV SUSY: $|\Delta\phi| < \pi/4$

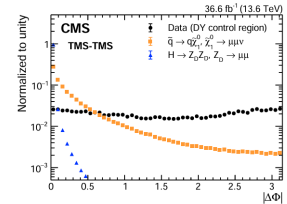
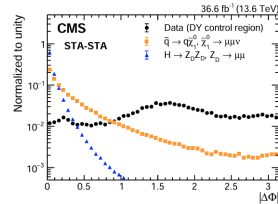
■ Additional Suppression Criteria

- Reject STA dimuons with $|\Delta\eta_{\mu\mu}| < 0.1$ if track quality poor
- Reject events with same-sign dimuons (background control)

Background Estimates and Systematic Uncertainties

■ Background sources:

- Prompt Drell–Yan production
 - Heavy-flavor decays (e.g., $b\bar{b} \rightarrow \mu\mu X$)
 - Cosmic-ray muons
 - Beam halo and fake muons
- Mitigated using vertex displacement, isolation, and timing.
- Background from DY processes peak at $\Delta\Phi = \frac{\pi}{2}$ and signal muons peak at $\Delta\Phi = 0$ due to their collinear nature



Background Estimates and Systematic Uncertainties

- **Estimation:** Fully data-driven.
 - Control regions with relaxed cuts or same-sign muon pairs
 - Scaled to predict events in signal regions
- **Systematic uncertainties:**
 - Vertex reconstruction and muon ID:
 - Modeling of background mis-ID rates
 - Luminosity uncertainty: 2.3%

Background Estimates and Systematic Uncertainties

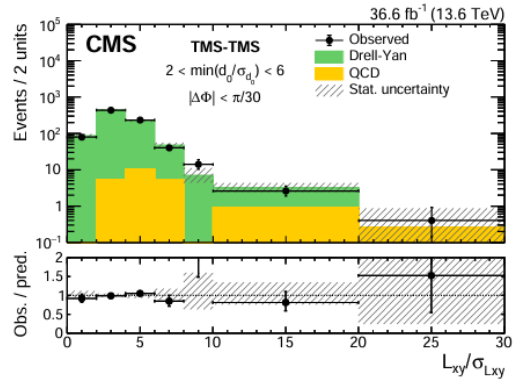
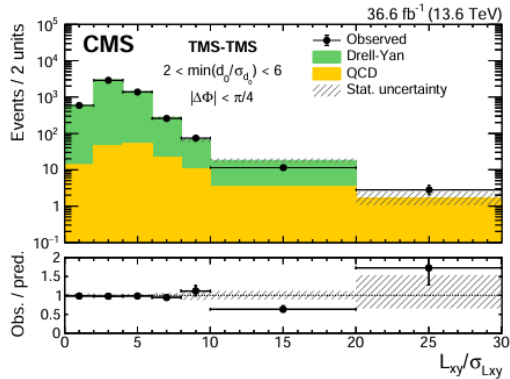


Figure: Background prediction in the validation region (VR) compared to measured data for TMS muons.

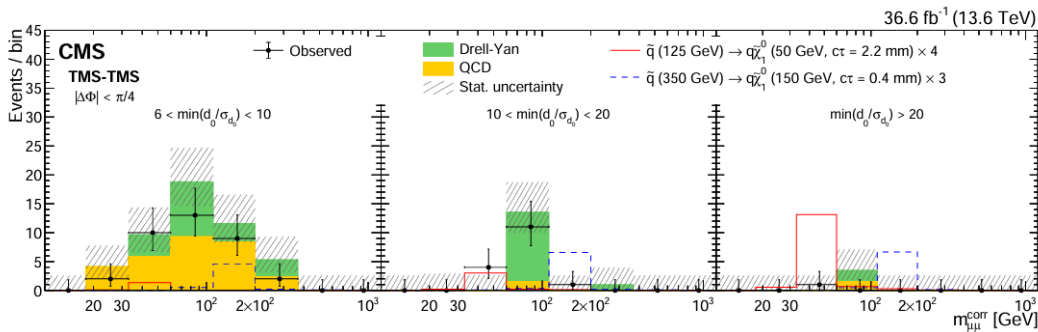


Figure: Results of the RPV model for the TMS muons.

Results

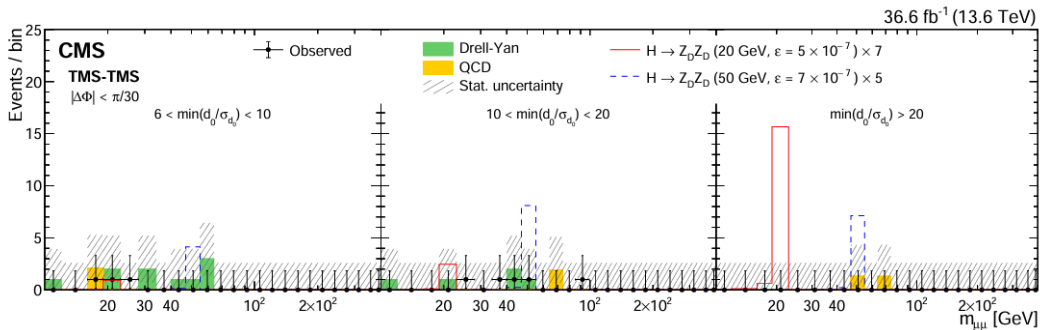
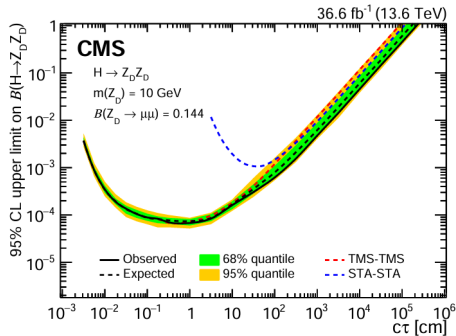
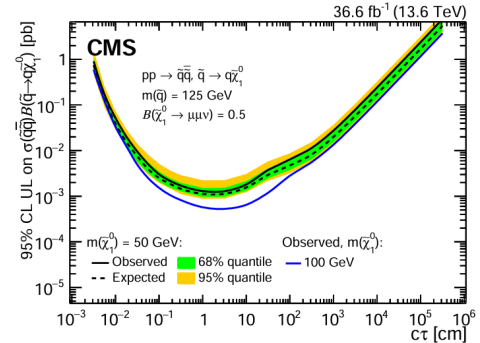


Figure: Results of the HAHM model.

Results



((a)) HAHM model.



((b)) RPV model.

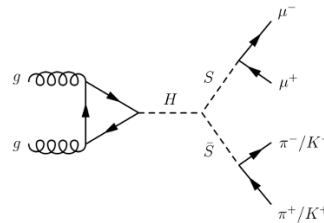
Figure: Limits on the used models to describe new physics. Taken into account are not only the TMS results shown in the slides before, but also the STA results.

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Signal Mode

- Signal has 2 OS muons and 2 OS hadrons
- Final state particles can come from a displaced vertex
- For $m_S < 1.1$ GeV the scalar particle is assumed to decay into pions otherwise the decay into Kaons is dominant
- 138 fb^{-1} of 2016-2018 data



Triggers and offline reconstruction

- Single-Muon-Triggers for prompt decays are used $p_T > 24, 27$ GeV
- Displaced-Muon-Triggers are only available for the 2018 dataset
- Offline reconstruction:
 - " Muons and hadrons: $p_T > 5$ GeV and $|\eta| < 2.4$ as well as a light cut on the di-system with $m_{**} > 5$ GeV
- Vertex reconstruction done with a Kalman-vertex-fit

Triggers and offline reconstruction

- Signal mass window is defined $m_{\mu\mu} \sim m_{hh}$
- In the $m_{\mu\mu hh}$ spectrum CR and SR are defined
- The events are clustered in region depending on $\frac{L_{xy}}{\sigma_L}$
 - prompt: $\left(\frac{L_{xy}}{\sigma_L}\right)_{\mu\mu} < 40$ and $\left(\frac{L_{xy}}{\sigma_L}\right)_{hh} < 30$
 - displaced muons: $\left(\frac{L_{xy}}{\sigma_L}\right)_{\mu\mu} > 40$ and $\left(\frac{L_{xy}}{\sigma_L}\right)_{hh} < 30$
 - displaced hadrons: $\left(\frac{L_{xy}}{\sigma_L}\right)_{\mu\mu} < 40$ and $\left(\frac{L_{xy}}{\sigma_L}\right)_{hh} > 30$
 - displaced: $\left(\frac{L_{xy}}{\sigma_L}\right)_{\mu\mu} > 40$ and $\left(\frac{L_{xy}}{\sigma_L}\right)_{hh} > 30$
- The QCD background is suppressed by requiring a rel. isolation cut on the muons

Triggers and offline reconstruction

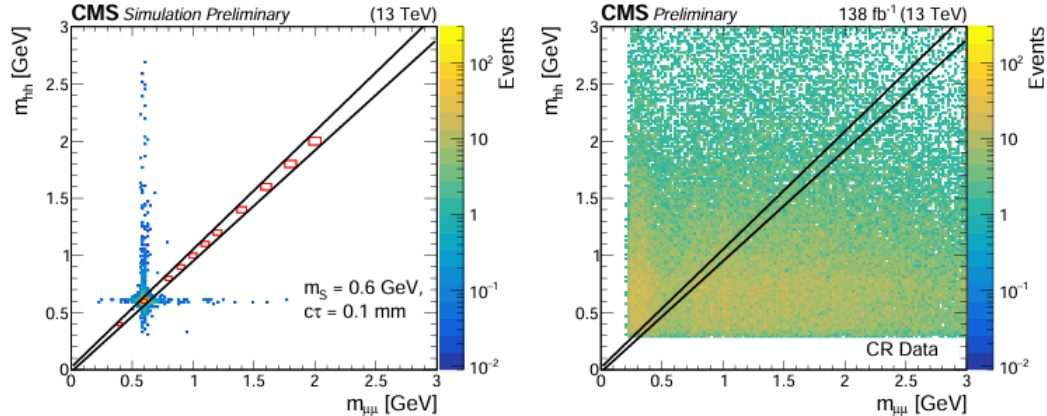


Figure: 2d plot for $m_{\mu\mu}$ against m_{hh} for MC and CR region.

Merging the Categories

- In the displaced categories not enough events are available to fit the background properly
- → the prompt categories are merged and rel. isolation cuts are thrown out to gain more statistics
- must account for the otherwise ruled out events with a transfer factor
- exponential fit to the sidebands and extrapolated in the signal region
- search is done in mass regions around each m_S hypothesis, since signal would be in a narrow average mass region
- statistical uncertainties dominate for the low event displaced categories
- systematic uncertainties are added to the evaluation

Signal mass region

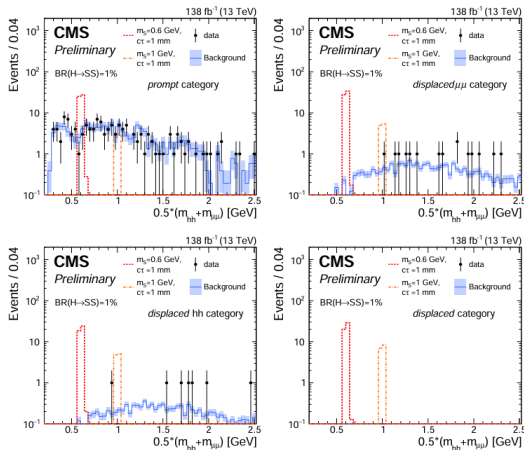


Figure: The average di-object invariant mass is shown for the events in the signal region and background prediction.

Results

- Results are evaluated as limits on the Branching ratio of $H \rightarrow SS$ with the $CL_{95\%}$ interval method.

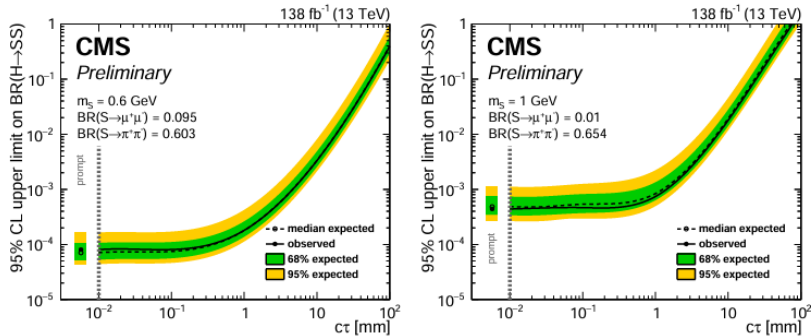


Figure: Limits on the branching ratio of $H \rightarrow SS$ dependent on m_S and lifetime $c\tau$.