Displaced dimuons from a common vertex, in a wide range of displacements, at CMS

[arXiv:2205.08582]

LLP11; 31 May 2022

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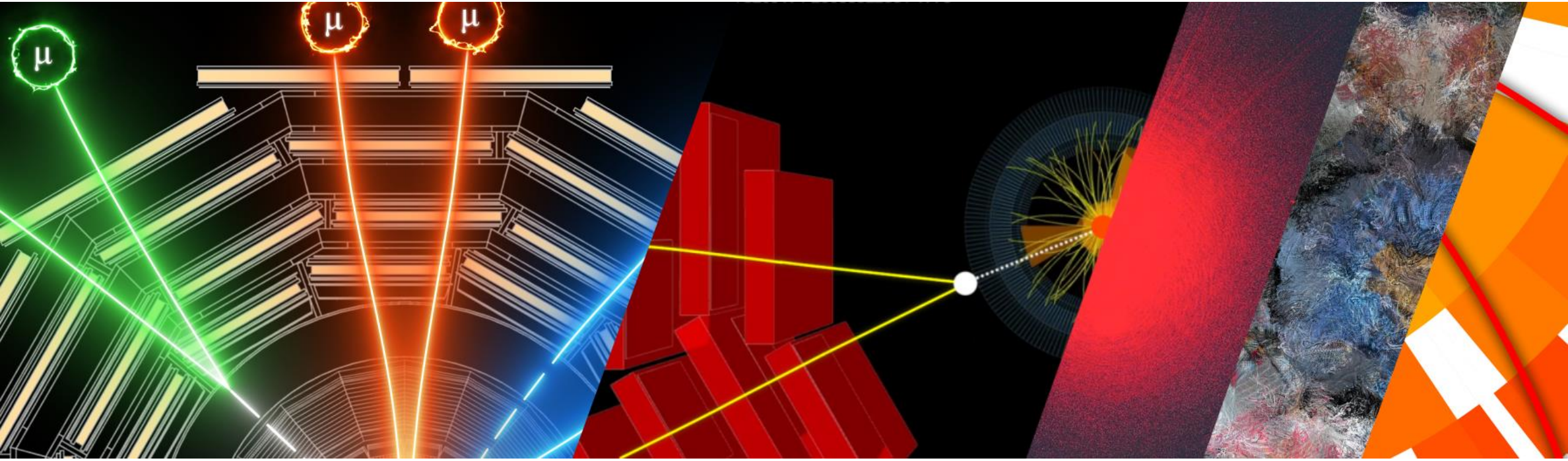
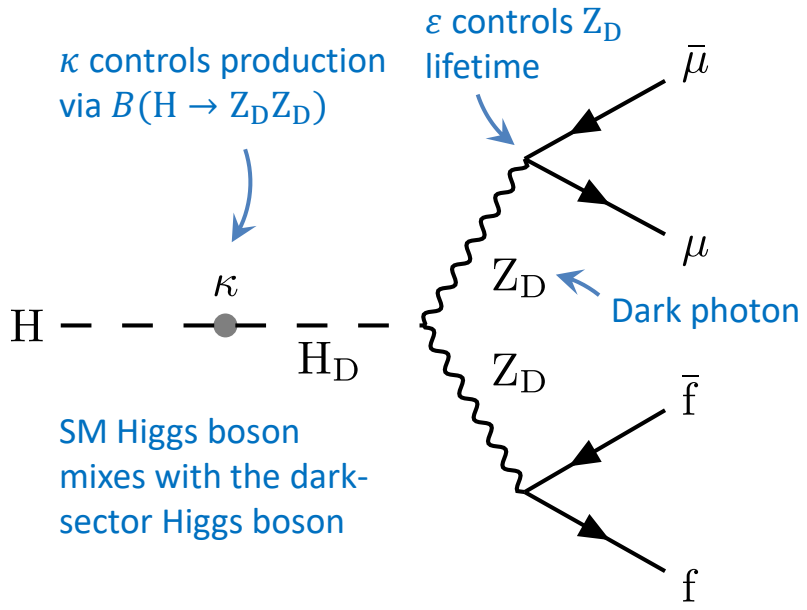
on behalf of the CMS collaboration



Introduction

- **Long-lived particles (LLPs)** could manifest via decay to detectable SM particles – e.g. **displaced dimuons** – at significant displacement from the interaction point
- **Presenting a new generic, inclusive CMS search** for LLPs decaying into pairs of oppositely charged muons: arXiv:2205.08582, submitted to JHEP
- Results interpreted in the framework of two commonly used benchmark models

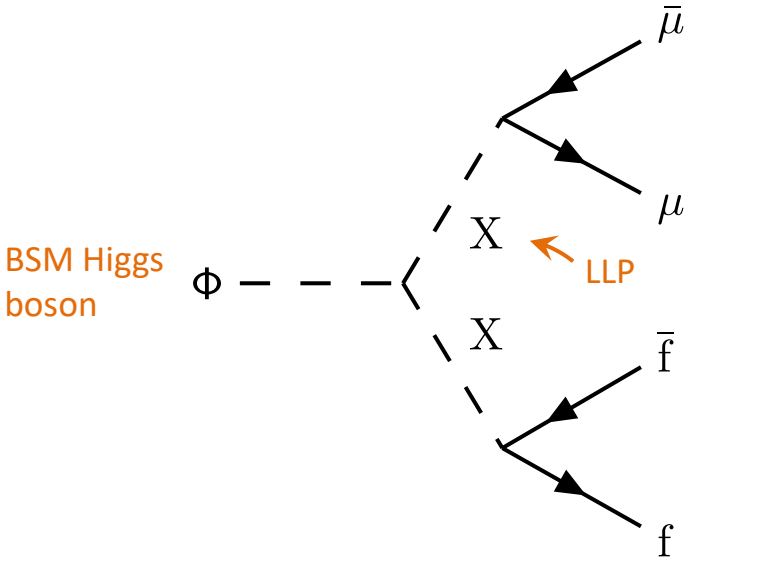


Hidden Abelian Higgs model (HAHM) $\mathrm{H} \to \mathrm{Z_D Z_D}, \mathrm{Z_D} \to \mu\mu$ [Curtin et al.]

- Introduces a **dark Higgs field** ($\mathrm{H_D}$) that mixes with the SM Higgs field
- $\mathrm{H_D}$ decays to two long-lived "**dark photons**" ($\mathrm{Z_D}$), which can decay into muons
- $B(\mathrm{H} \to \mathrm{Z_D Z_D})$ characterised by parameter κ, whilst $\mathrm{Z_D}$ lifetime by kinetic mixing ε

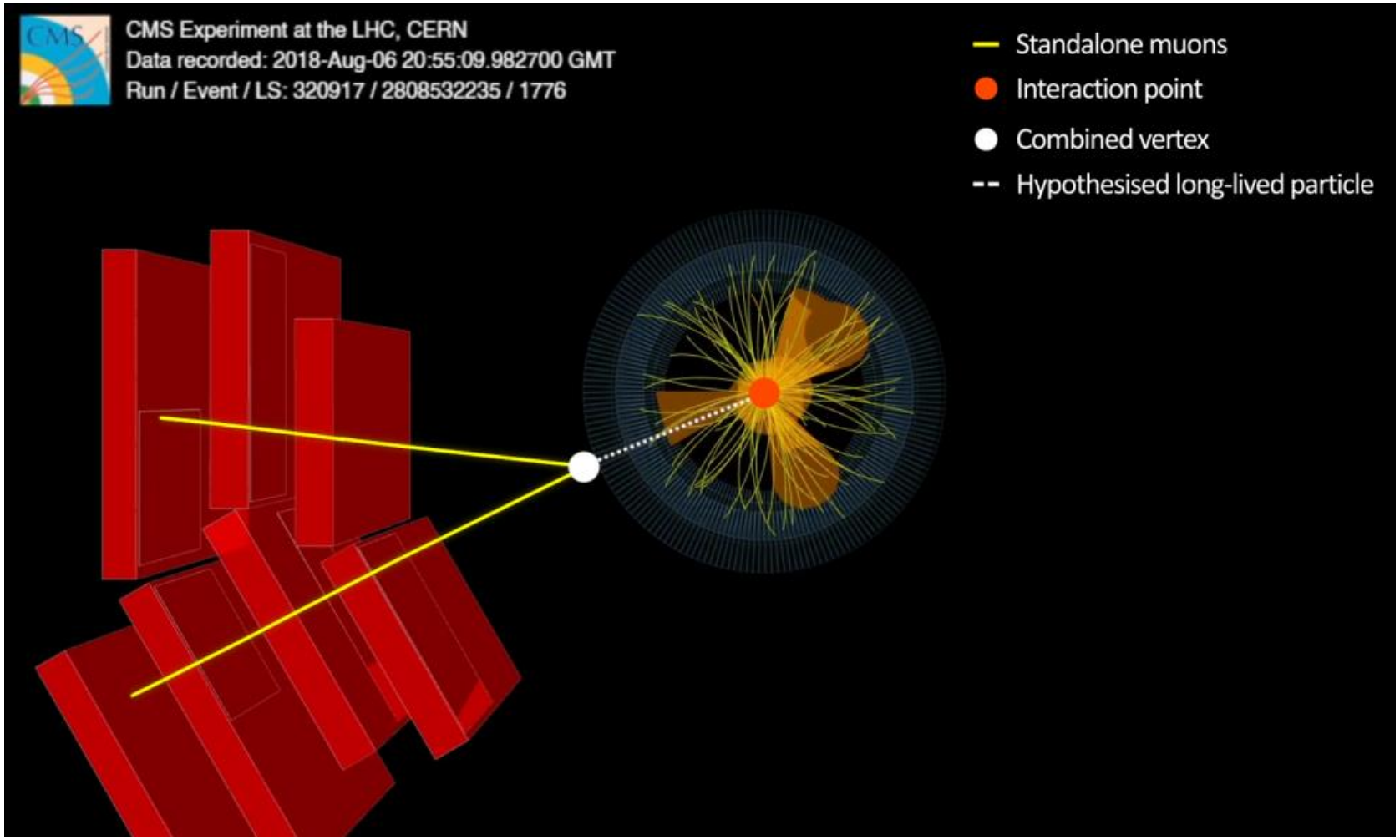
BSM Higgs boson decaying to LLPs $\Phi \to \mathrm{XX} \to \mu\mu + \text{anything}$ [Strassler & Zurek]

- Beyond SM Higgs boson decaying to two **scalar LLPs** (X), which may decay into muons
- A wide variety of possible kinematics: m_Φ, m_X, and $c\tau_\mathrm{X}$



Supplementary material for reinterpretation in HEPData record: 129518

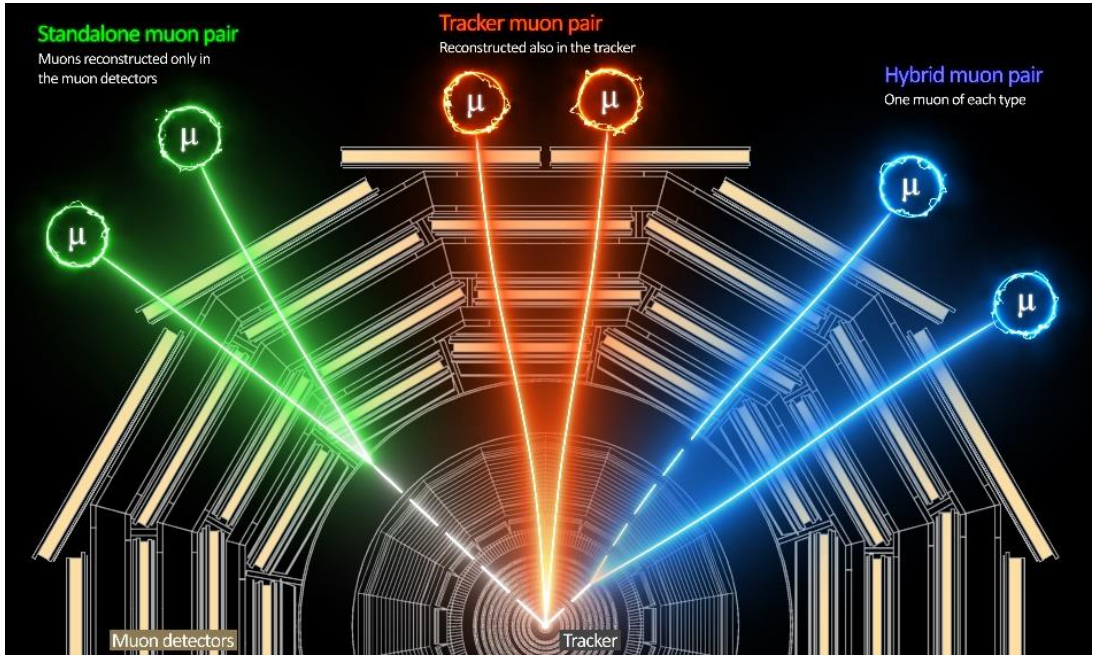
Displaced dimuons at CMS

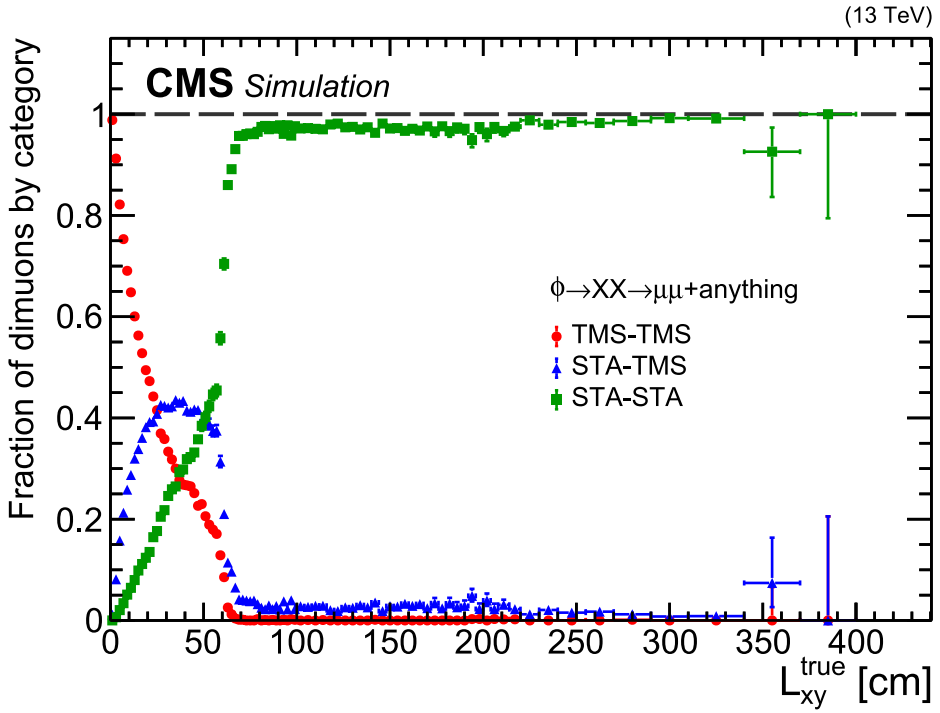


A candidate collision for a long-lived particle that decays into a pair of muons away from the interaction point, reconstructed in the 2018 data taking of the CMS detector.

Displaced dimuons at CMS

- Search, with 97.6 fb^{-1} of data at $\sqrt{s} = 13$ TeV, for LLPs decaying into displaced dimuons **within and beyond the CMS silicon tracker**
- Two types of reconstructed muons:
  - **STA:** stand-alone (muon system only)
  - **TMS:** Tracker + muon system
- Therefore, search in three exclusive **dimuon categories**: STA-STA, STA-TMS, and TMS-TMS.
- Equivalent to **three separate searches**; unique selection requirements and background estimation procedures in each

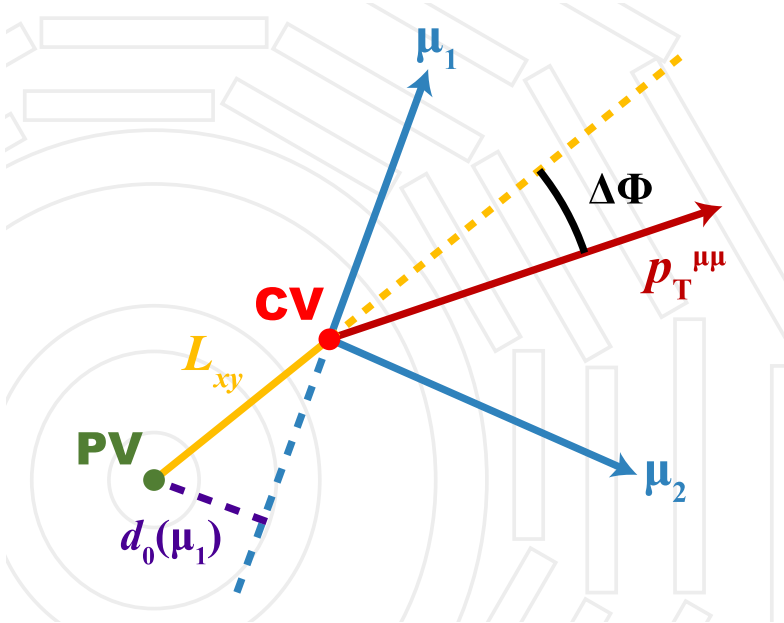




Triggers, and key variables utilised

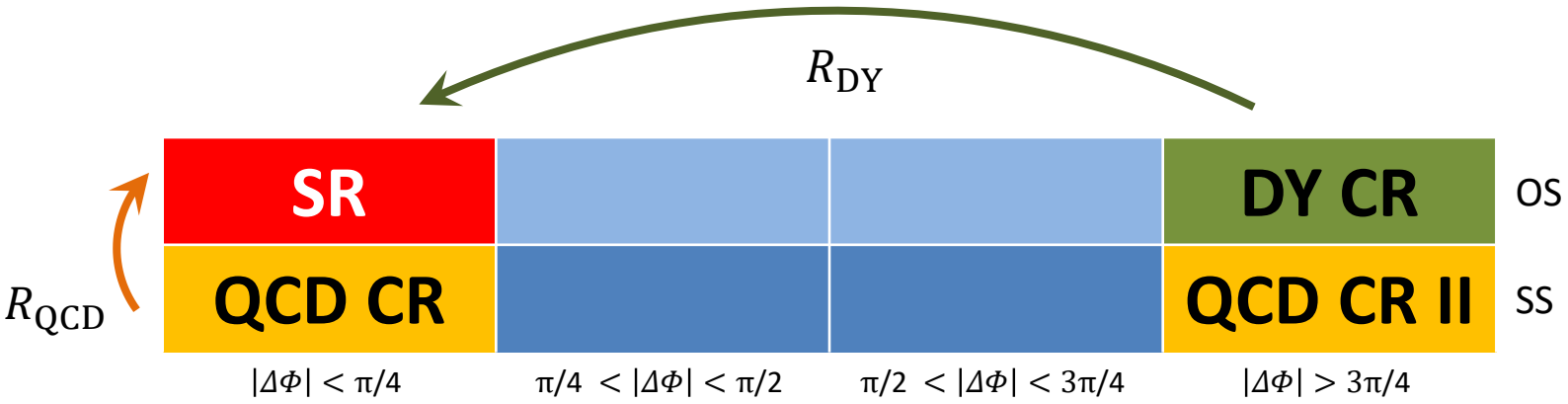
- **Dedicated triggers** requiring two muons only reconstructed in the muon system ($|\eta| < 2.0$ and $p_{\mathrm{T}} > 28$ (23) GeV for 2016 (2018))
- For 2016: 3D angle between the two muons $\alpha < 2.5$ rad to suppress cosmics, $m_{\mu\mu} > 10$ GeV
- For 2018: α and $m_{\mu\mu}$ requirements removed in 2018 to be optimised in the analysis, and have more control regions; signal efficiency improved by complementing with a different trigger with different "seeding"; **triggers studied using cosmics**

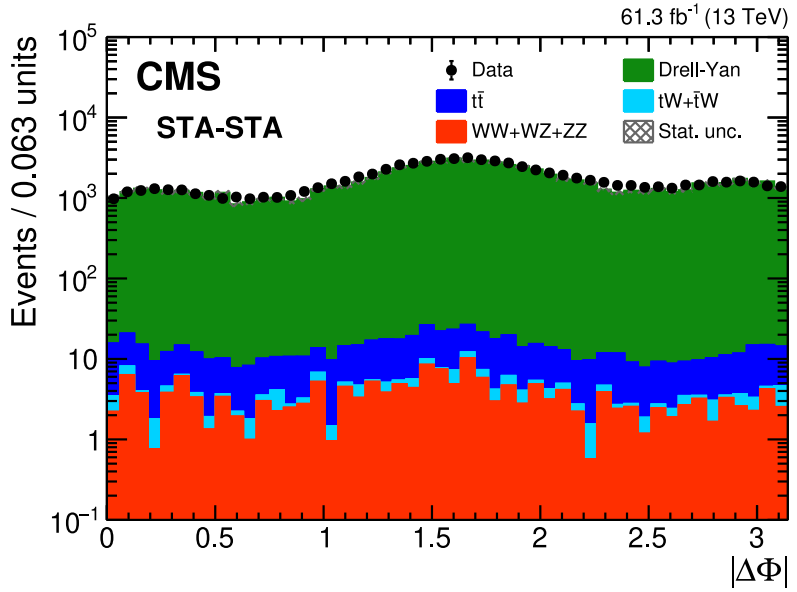
- **STA-to-TMS muon association:** Drastically suppress prompt background in the STA-STA and STA-TMS categories
- **L_{xy} significance ($L_{xy}/\sigma_{L_{xy}}$):** Transverse decay length, normalised to its uncertainty; expected to be **large** in signal
- **d_0 significance (d_0/σ_{d_0}):** Transverse impact parameter, normalised to its uncertainty; expected to be **large** in signal
- **Collinearity angle ($|\Delta\Phi|$):** The angle [0, π] in the transverse plane between the L_{xy} and dilepton p_{T} vectors; expected to be **small** ($< \pi/4$) in signal
- **Muon $p_{\mathrm{T}} > 10$ GeV, track quality, and dimuon vertex quality**
- **Dimuon invariant mass ($m_{\mu\mu}$):** Expected to be close to the hypothesised LLP mass
- **STA muon timing and direction**
- **TMS muon isolation**

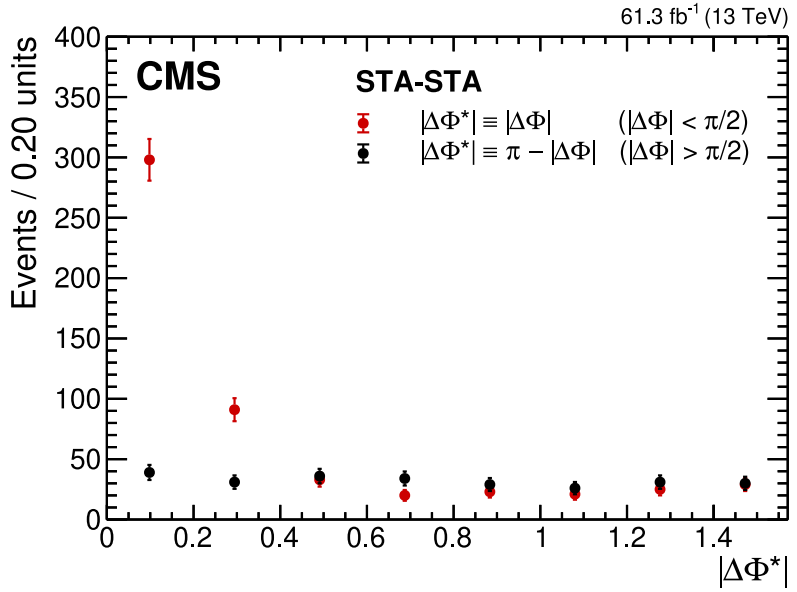


Background

- A displaced dimuon signature for $m_{\mu\mu} > 10$ GeV practically absent from the SM; the background in the search comes from **misreconstruction** of muons/dimuons
- **Prompt high-mass dimuons misreconstructed** as displaced due to instrumental or reconstruction failures; referred to as DY-like background; no preferred $\vec{L}_{xy}$ direction w.r.t. $\vec{p}_{\mathrm{T}}^{\mu\mu} \Rightarrow$ ~**symmetric in $|\Delta\Phi|$** (top right figure)
- Dimuon decays of non-prompt low mass resonances, cascade decays of b hadrons, unrelated non-prompt muons in the same or different jets; referred to as QCD-like background; ~**asymmetric in $|\Delta\Phi|$** (bottom right figure)
- Background evaluation using **large $|\Delta\Phi|$** and **same-sign** dimuons as proxies for DY- and QCD-like backgrounds, respectively, and transfer factors R_{DY} and R_{QCD}
- R_{DY} and R_{QCD} derived from measurement region dedicatedly designed for each category (discussed in the coming slides)

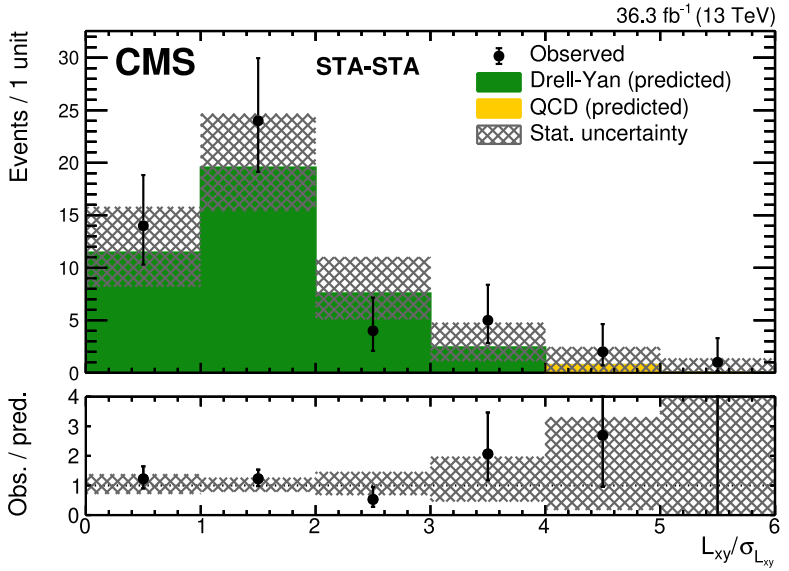




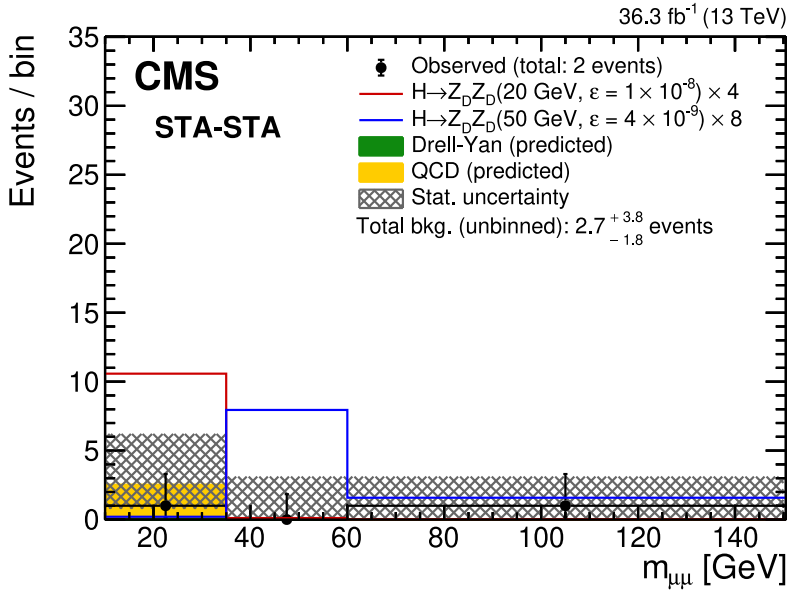


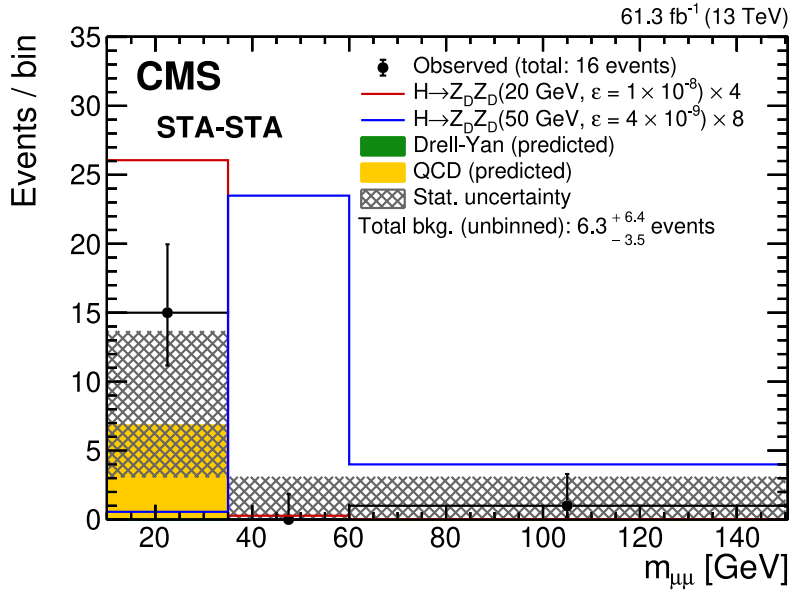
STA-STA dimuon category

- Provides sensitivity to LLP decays beyond the tracker volume
- Dedicated displaced standalone muon ID and reco., developed using cosmics
- Require $L_{xy}/\sigma_{L_{xy}} > 6$
- **Cosmic muons** an important background; suppressed by requiring muons with **good timing**, and **inside-out** direction, $\cos\alpha > -0.8\ (-0.9)$ in 2016 (2018), and conditions on **number of dimuon segments**, rejecting dimuons wherein a muon is **back-to-back** with a third muon with $p_T > 10$ GeV and $|\Delta t| > 20$ ns
- DY and QCD transfer factor measurement regions defined by inverting the STA-to-TMS muon association
- Background evaluation **validated** in $L_{xy}/\sigma_{L_{xy}} < 6$, $6 < m_{\mu\mu} < 10$ GeV, and small $|\Delta\eta_{\mu\mu}|$ regions
- **No significant excess** observed above the background-only hypothesis



$L_{xy}/\sigma_{L_{xy}} < 6$ VR

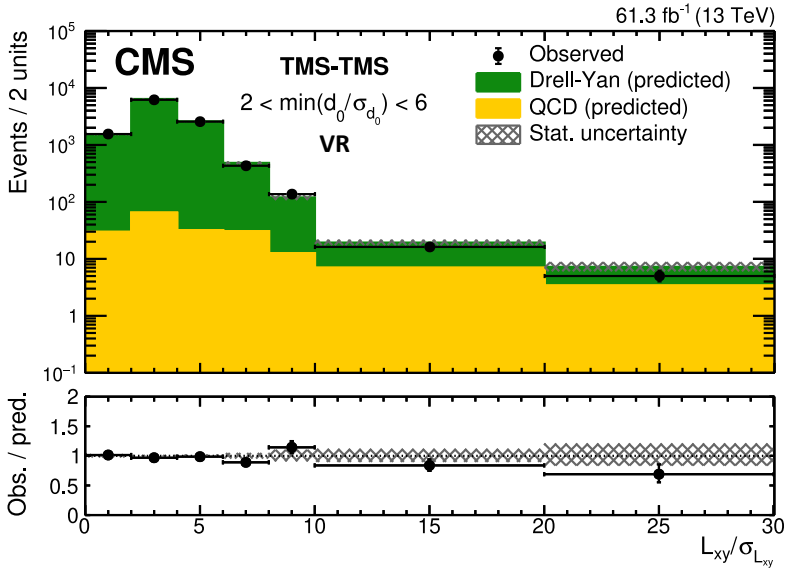




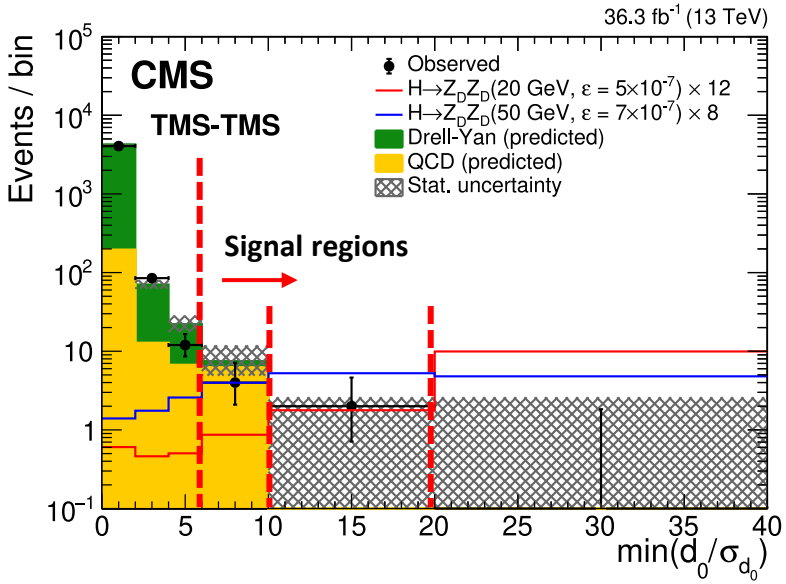
The uncertainties shown are statistical only; bin widths are indicative of the mass resolution at the central values.

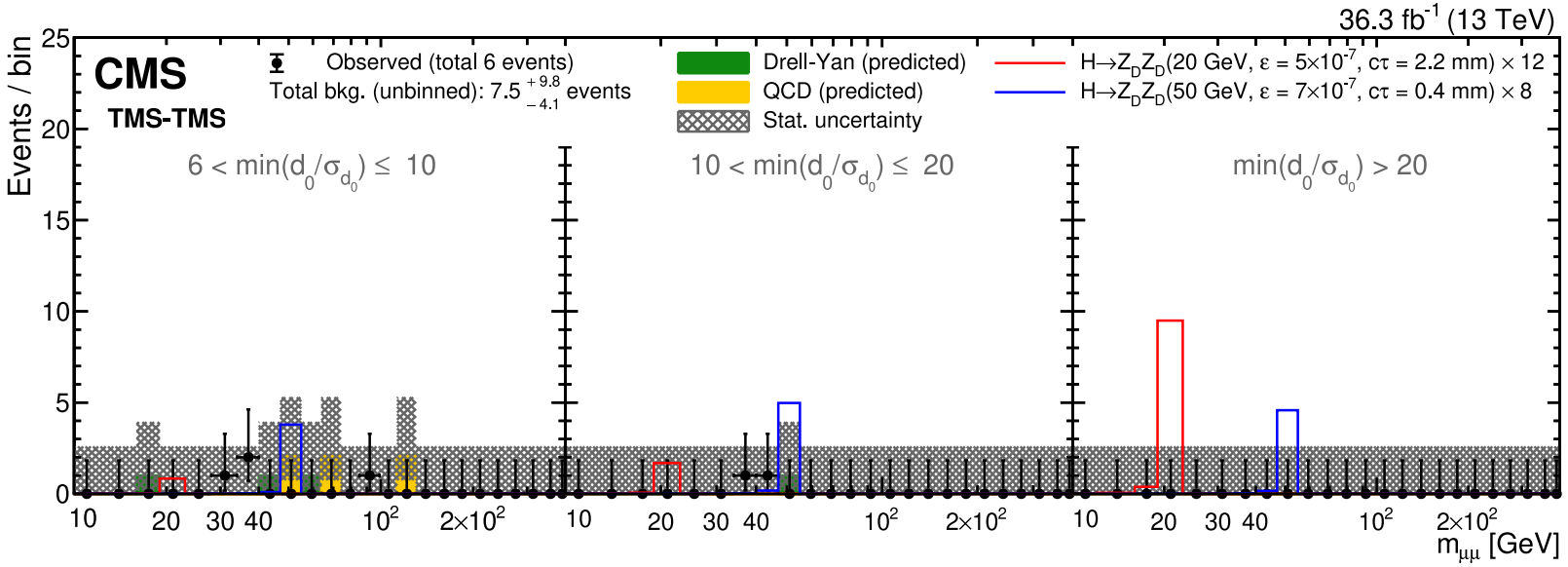
TMS-TMS dimuon category

- Much **better muon p_T resolution**, and **dimuon mass resolution** compared to the other categories; much **better d_0 resolution** (O(10 μm) compared to O(cm) for STA muons), which allows us to probe displacements smaller than a few cm
- **Muon isolation** great handle to suppress background; dedicated tracker isolation
- $L_{xy}/\sigma_{L_{xy}} > 6$ and $\min(d_0/\sigma_{d_0}) > 6$; split into **three subcategories** based on $\min(d_0/\sigma_{d_0})$ to enhance sensitivity
- DY transfer factor measured in inverted χ^2, and QCD transfer factor in inverted isolation region
- Background **validated** in $2 < \min(d_0/\sigma_{d_0}) < 6$ and $\pi/4 < |\Delta\Phi| < \pi/2$ regions
- **No significant excess** observed above the background-only hypothesis



$2 < \min(d_0/\sigma_{d_0}) < 6$ VR





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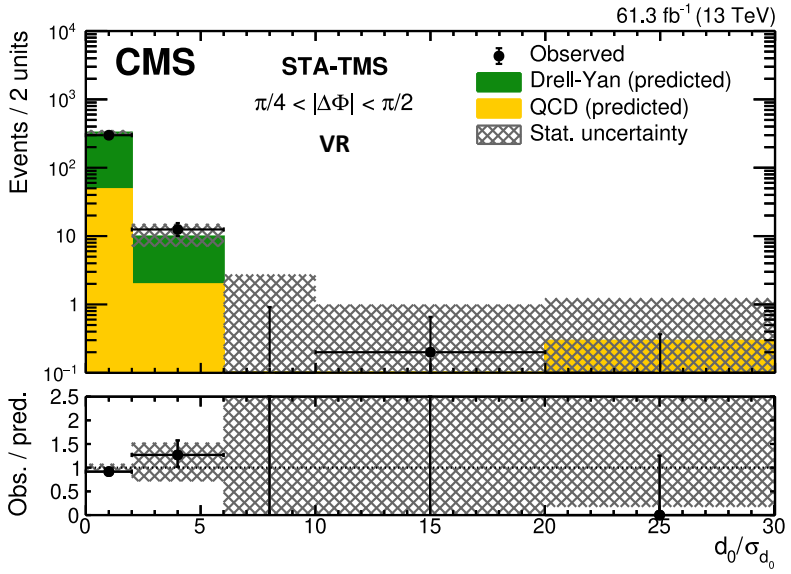
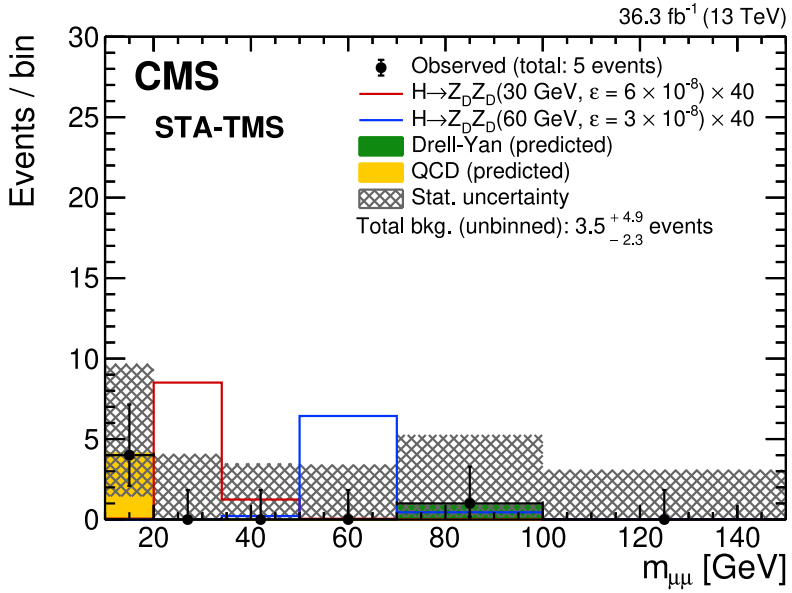
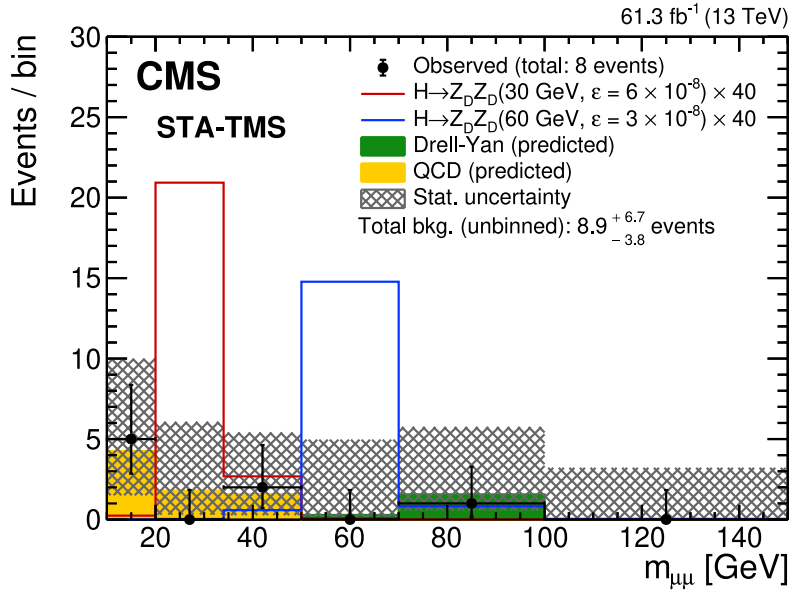
STA-TMS dimuon category

- Provides additional sensitivity at intermediate L_{xy}
- **Dimuon mass resolution in between** that of the other two categories, **muon p_T and d_0 resolution** drastically different between the two muons
- $L_{xy}/\sigma_{L_{xy}} > 3$ and $d_0/\sigma_{d_0} > 6$; inherits requirements from both the other categories, optimised independently
- Additional selection requirements, e.g. **tracker hits upstream of the CV**, **L_{xy}-dependent number of tracker layers**, and the **angle between $\vec{L}_{xy}$ and $\vec{p}_T^{\,TMS}$**
- DY and QCD transfer factor measurement regions defined by inverting the STA-to-TMS muon association
- Background evaluation **validated** in $2 < d_0/\sigma_{d_0} < 6$ and $\pi/4 < |\Delta\Phi| < \pi/2$ regions
- **No significant excess** observed above the background-only hypothesis



$\pi/4 < |\Delta\Phi| < \pi/2$ VR





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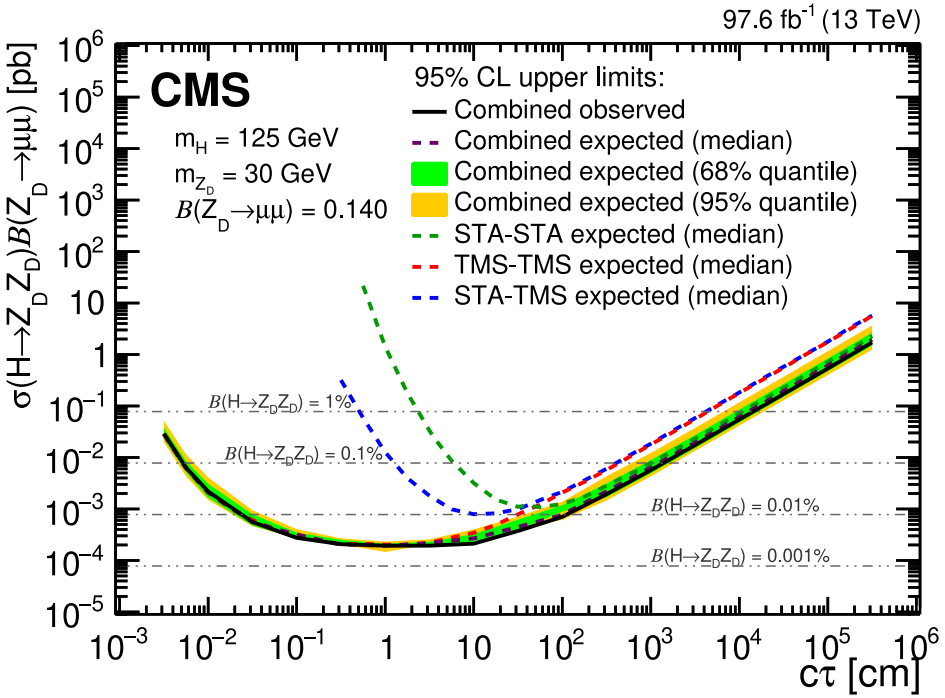
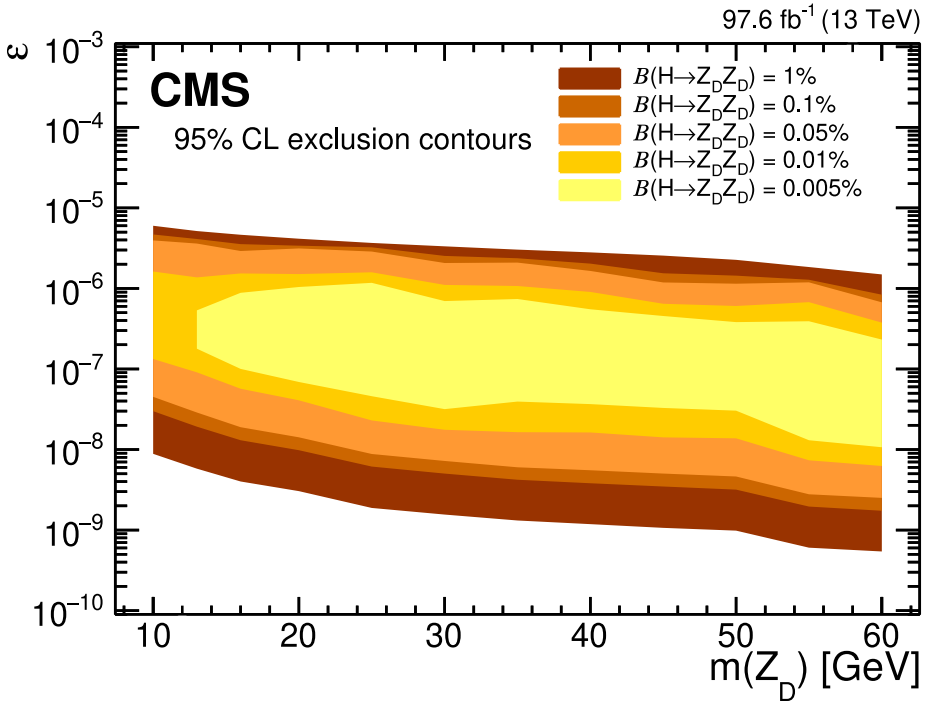
Results

- 95% CL upper limits set on $\sigma(\Phi \to XX)B(X \to \mu\mu)$ for the BSM Higgs model, and $\sigma(H \to Z_D Z_D)B(Z_D \to \mu\mu)$ for the dark photon model (example below left)
- Sensitivity dominated by TMS-TMS at small and STA-STA at large lifetimes, with STA-TMS contributing at intermediate lifetimes
- Two-dimensional exclusion contours in the m_{Z_D}-ϵ space also derived (example below right)
- The search able to cover:
  - **a large range of LLP masses** – from 10 GeV to several hundred GeV
  - **a large range of boson masses m_Φ** – up to 1 TeV – for the BSM Higgs model
  - **many orders of magnitude of displacements** (evident from the plots below)

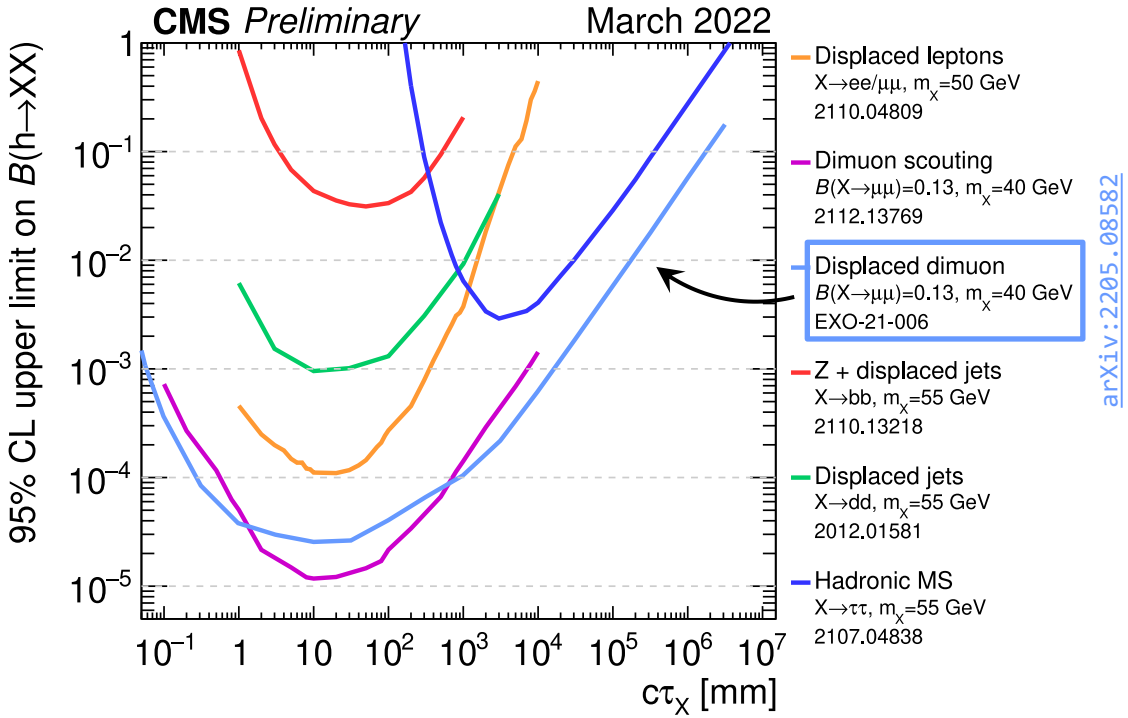


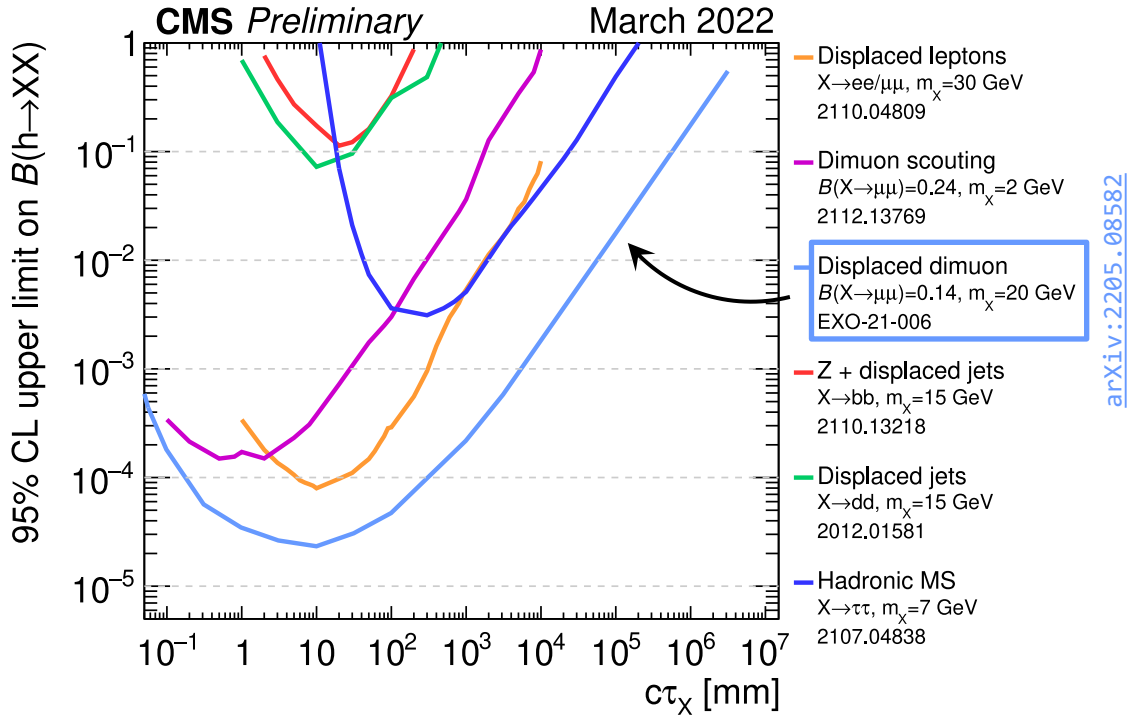


Results

Best limits yet for most considered masses and lifetimes

- For the Hidden Abelian Higgs model with m_{Z_D} greater than 20 GeV up to half the mass of the Higgs boson: for $c\tau_{Z_D}$ values between 0.03 and ~0.5 mm (varying with m_{Z_D}), and above ~0.5 m
- In the complementary range, between 0.03 ~0.5 mm (varying with m_{Z_D}), best limits by another CMS search – JHEP04(2022)062 (**dimuon scouting**, i.e. with a dedicated high-rate data stream)
- For exotic scalar boson masses larger than the Higgs boson mass, for all considered LLP masses and lifetimes

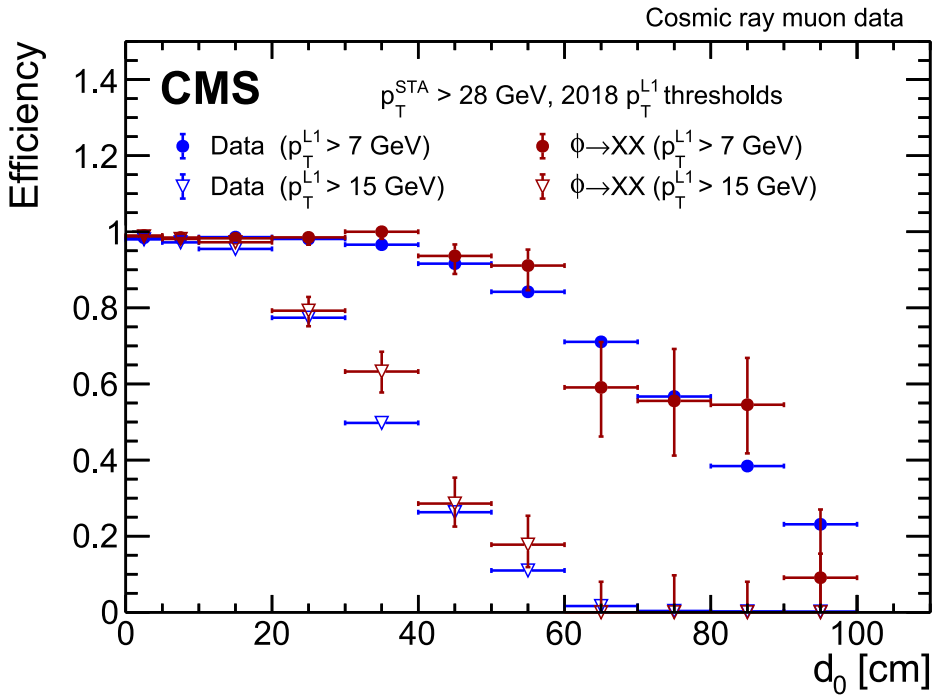




Conclusion and outlook

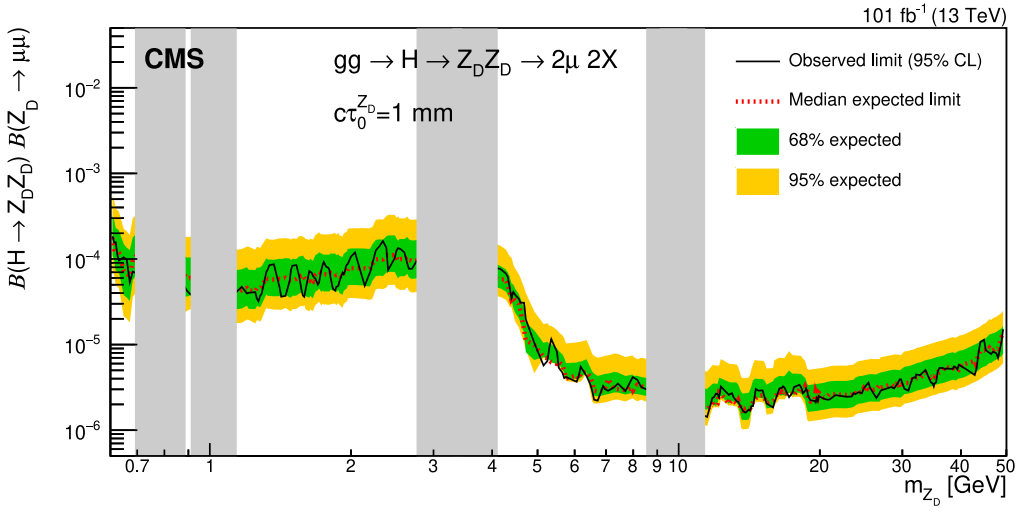
- Presented a new generic search for LLPs decaying into **displaced dimuons** over a wide range of displacements
- Search divided into STA-STA, STA-TMS, and TMS-TMS dimuon categories to enhance sensitivity
- Dedicated **event selection** and **background estimation** in each category
- Results **compatible with the standard model** predictions
- The derived 95% CL upper limits **best constraints** to date for most considered masses and lifetimes

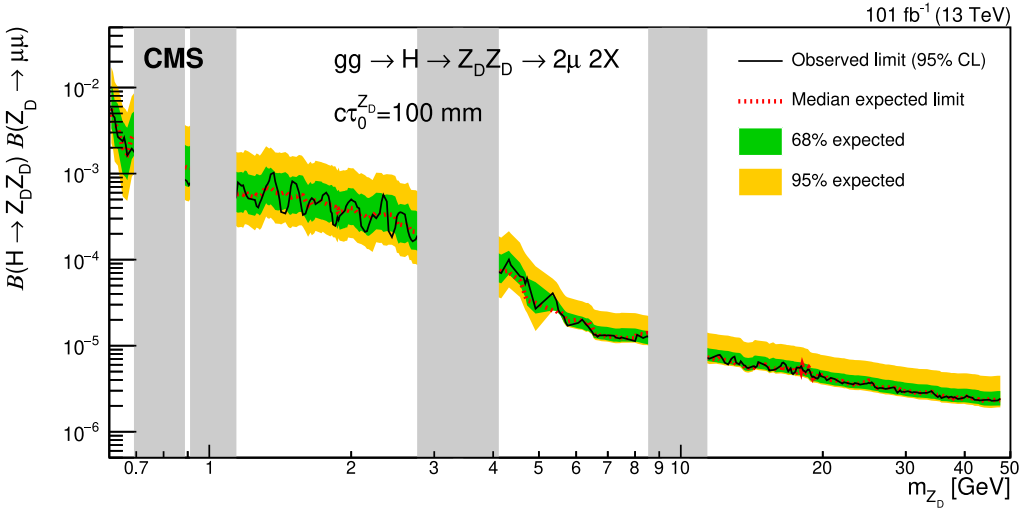
- Sensitivity of the search **limited by the trigger**
- Exploring **trigger improvements** for the upcoming data taking to allow improve the sensitivity of the search beyond just gains from increased luminosity

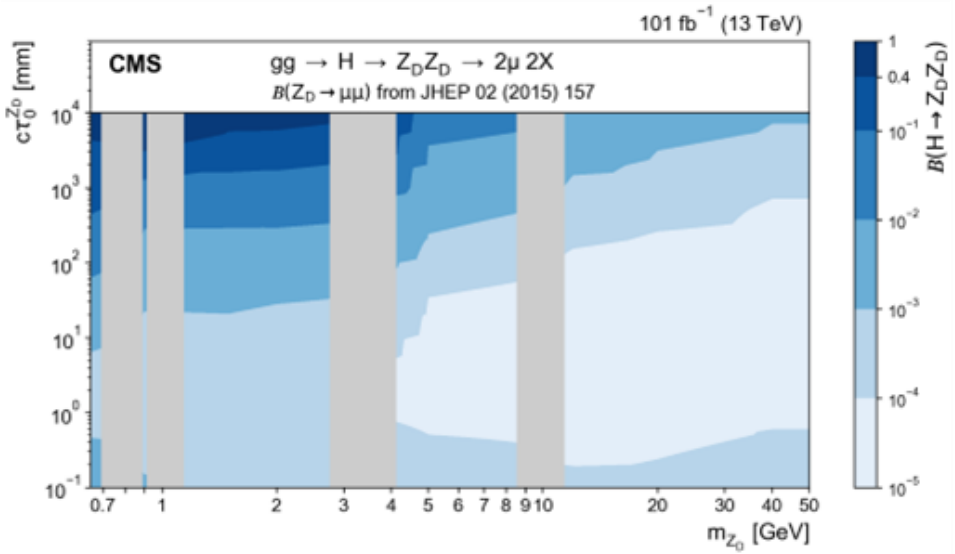


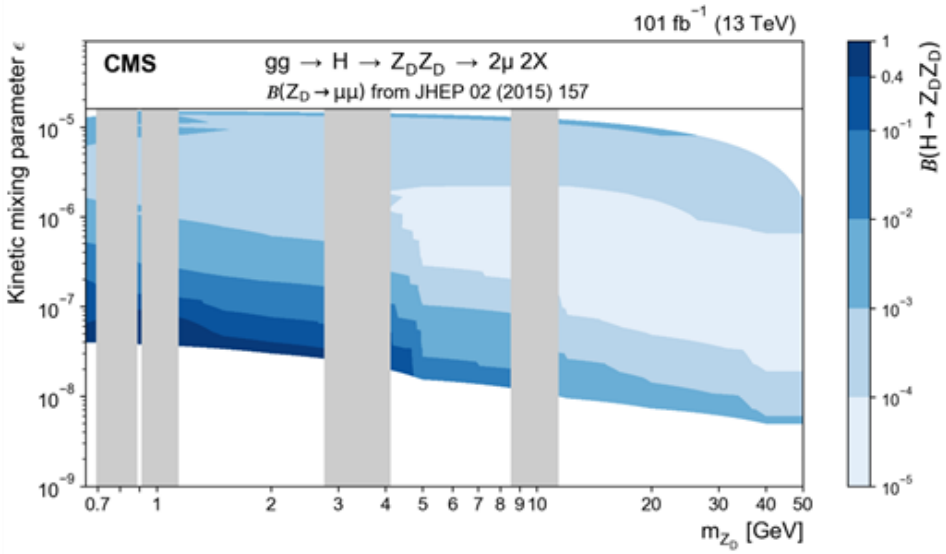
Backup slides

Recap of results from the CMS dimuon scouting analysis









JHEP04(2022)062