Searches for Long-Lived Particles Using Muons in CMS

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Physics of
Dimuons
at the LHC

JINR
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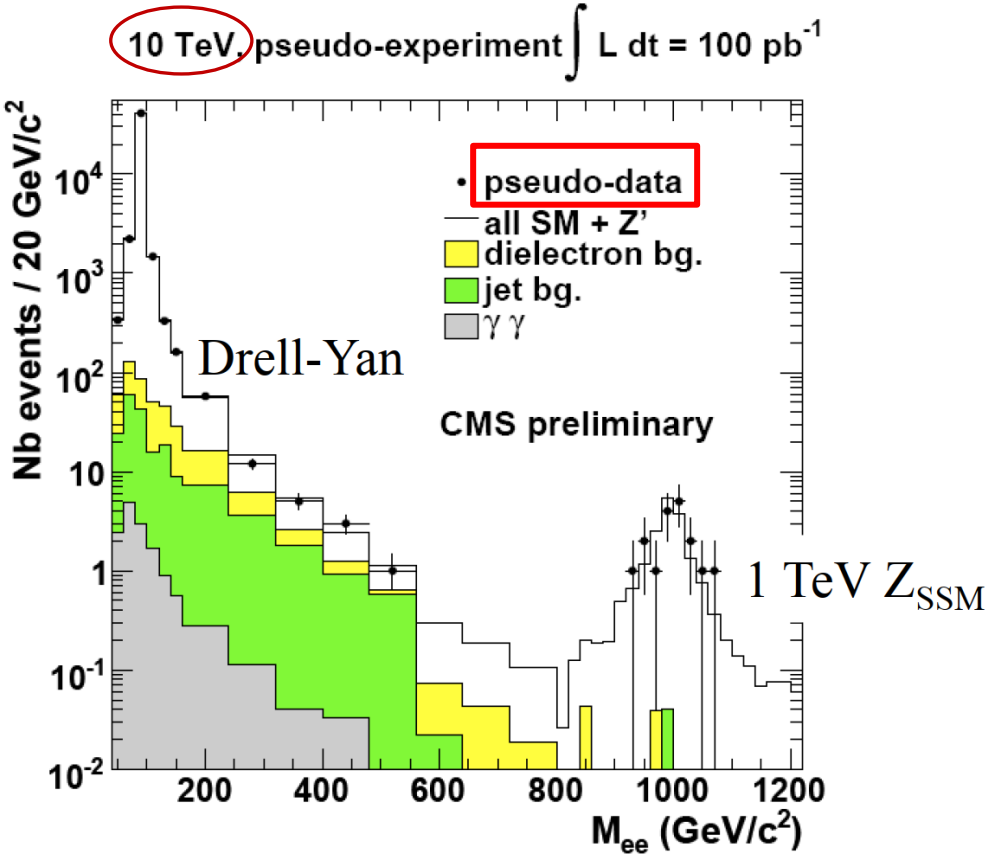
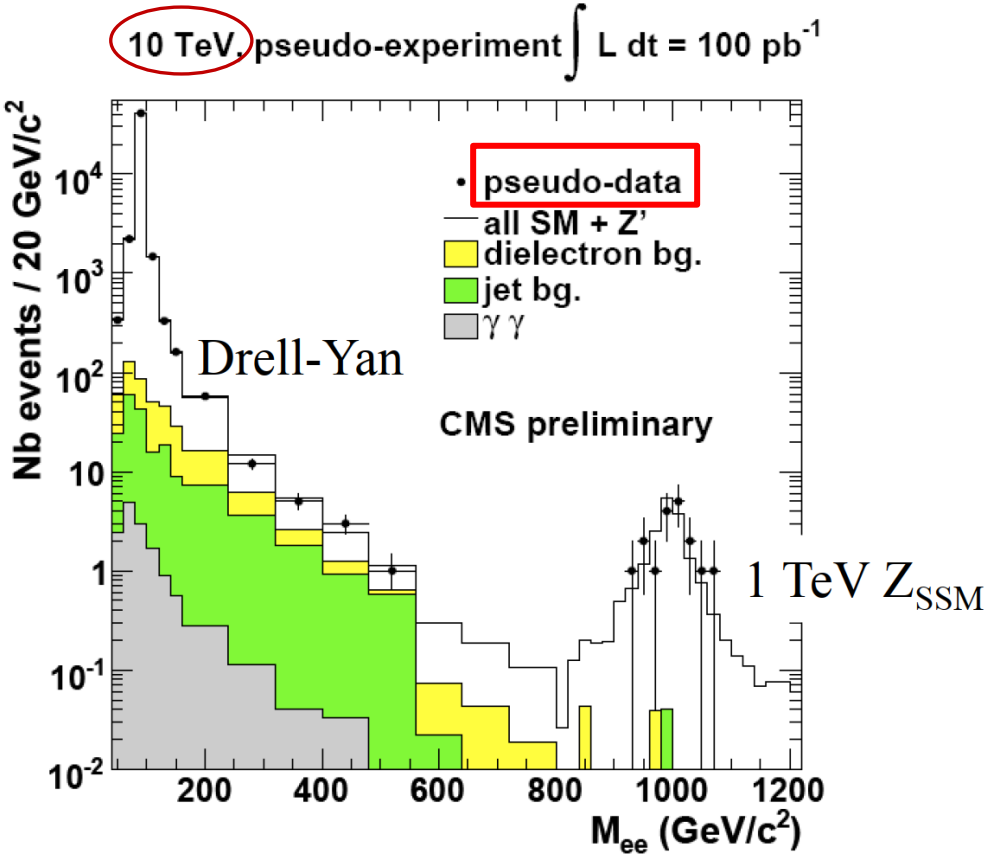
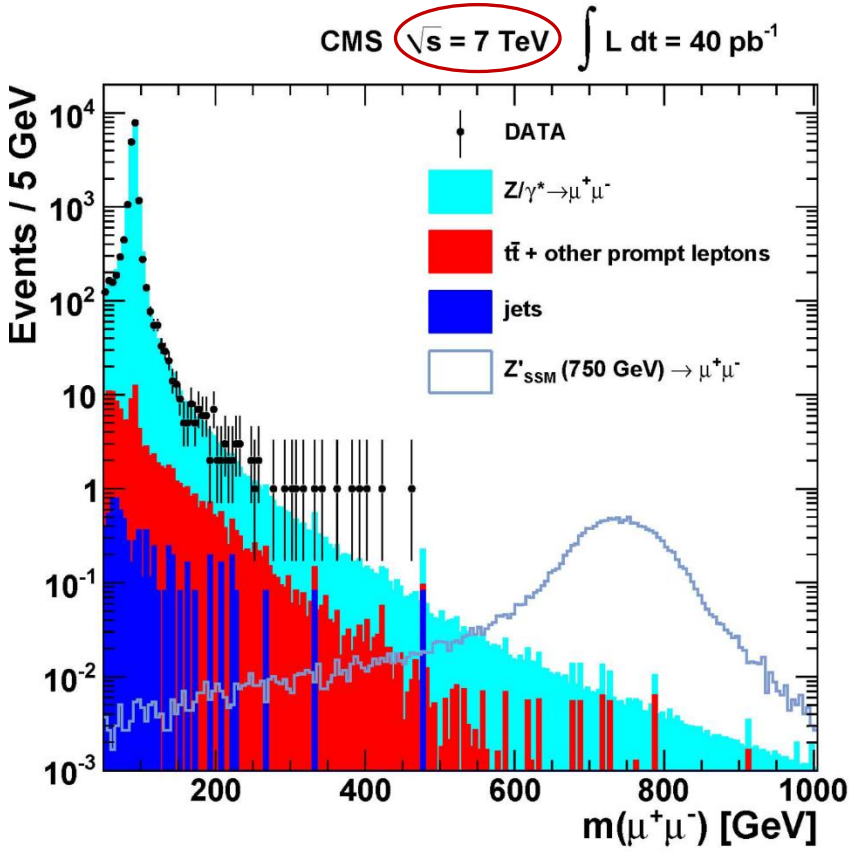
High-mass dimuons: expectations prior to Run 1



Projection *for 100 pb^{-1} (~2007)*

High-mass dimuons: first results

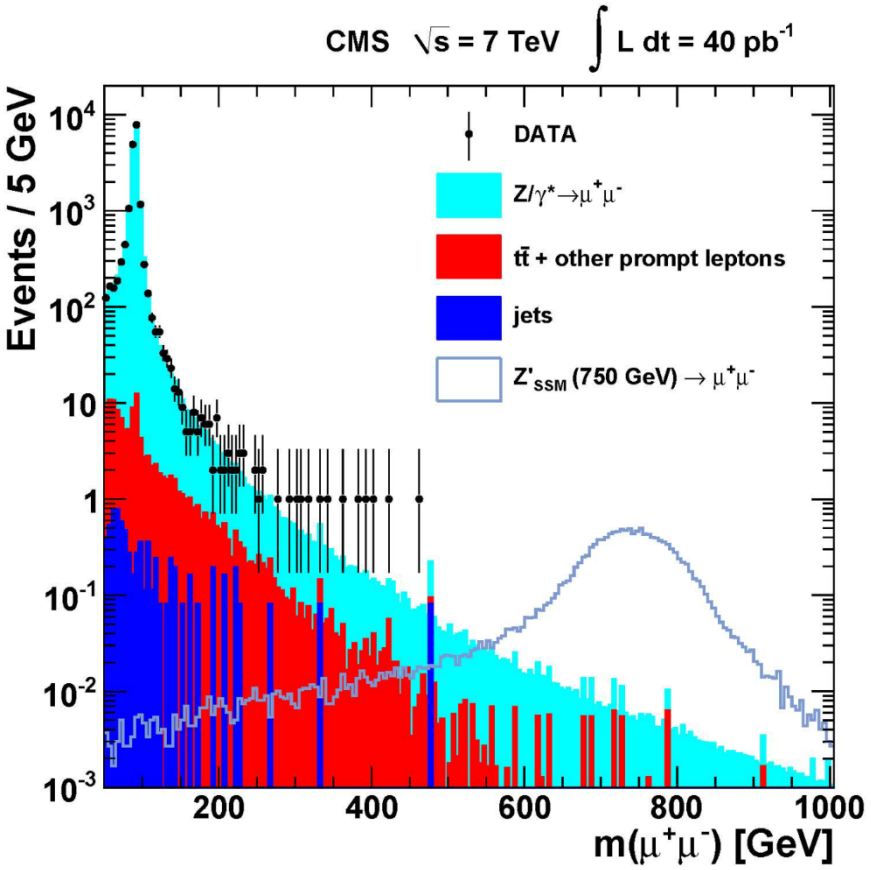


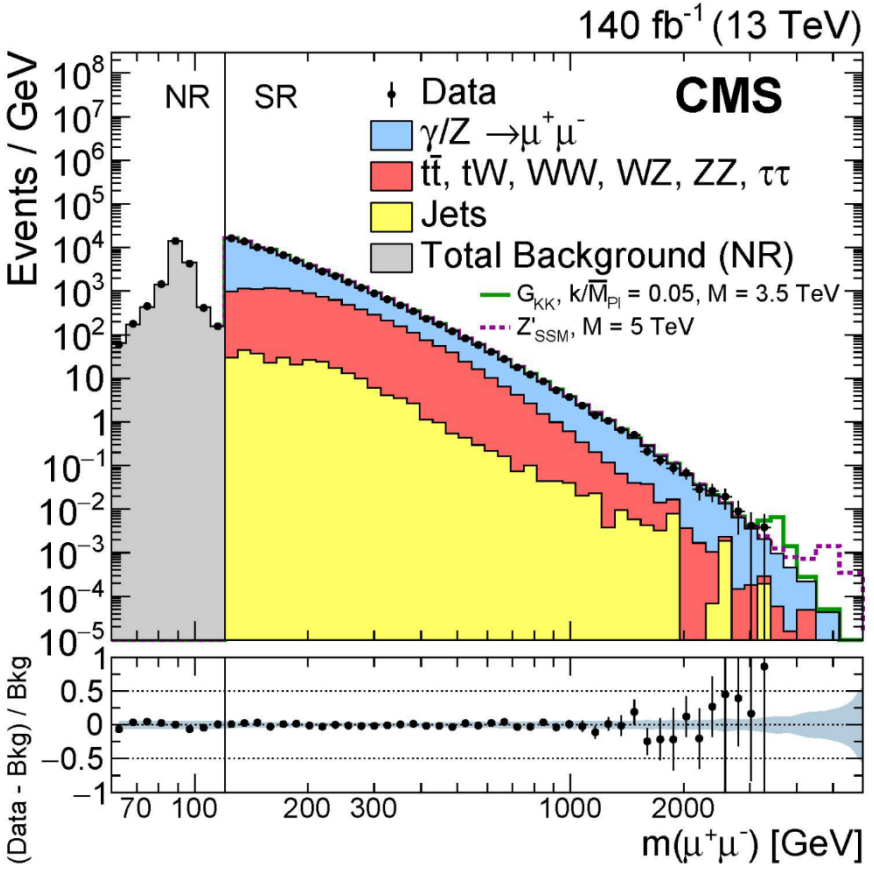


Projection *for 100 pb^{-1} (~2007)*

First CMS <u>paper</u> *on Z' → μμ/ee (2011)*

High-mass dimuons: progress in 10 years



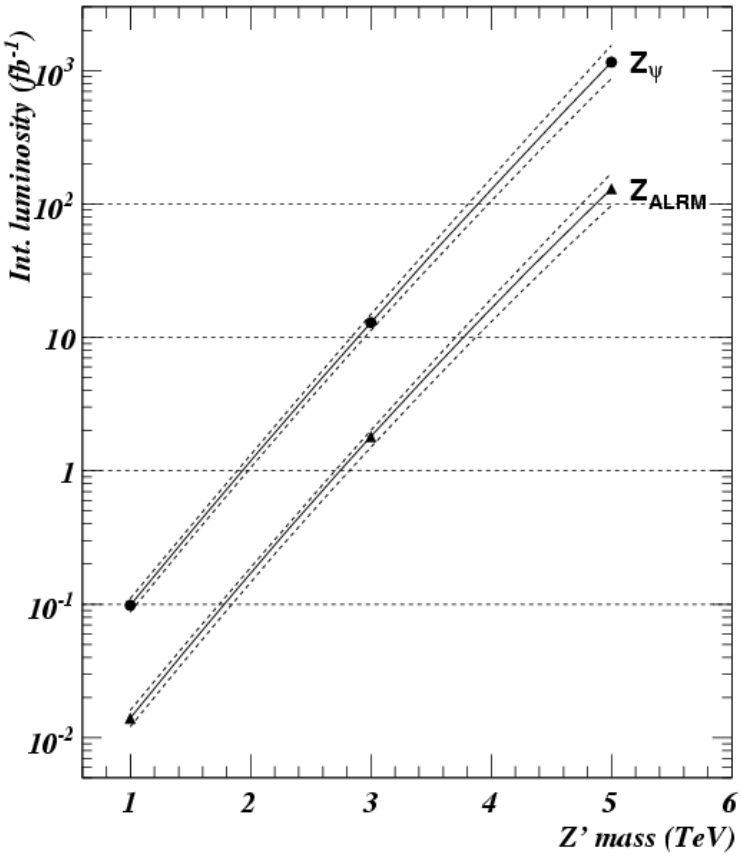


***First CMS <u>paper</u>** on Z' → μμ/ee (2011)*

***Latest CMS <u>paper</u>** on Z' → μμ/ee (2021)*

Mid-Run-2: new situation for BSM searches

- In 2017-18, experiments at the LHC entered the **new era** of relatively slow data accumulation at ~constant √s
- *Example of Z' → μμ searches: integrated luminosity needed to reach 5σ discovery significance at √s = 14 TeV; projection (~2007)*
  - **10x increase in integrated luminosity** is needed **to extend the probed mass range by about 1 TeV**
- This situation has led to an **increased interest in searches** for BSM signatures that are more difficult to detect at the LHC, notably searches for **long-lived particles** (LLPs)

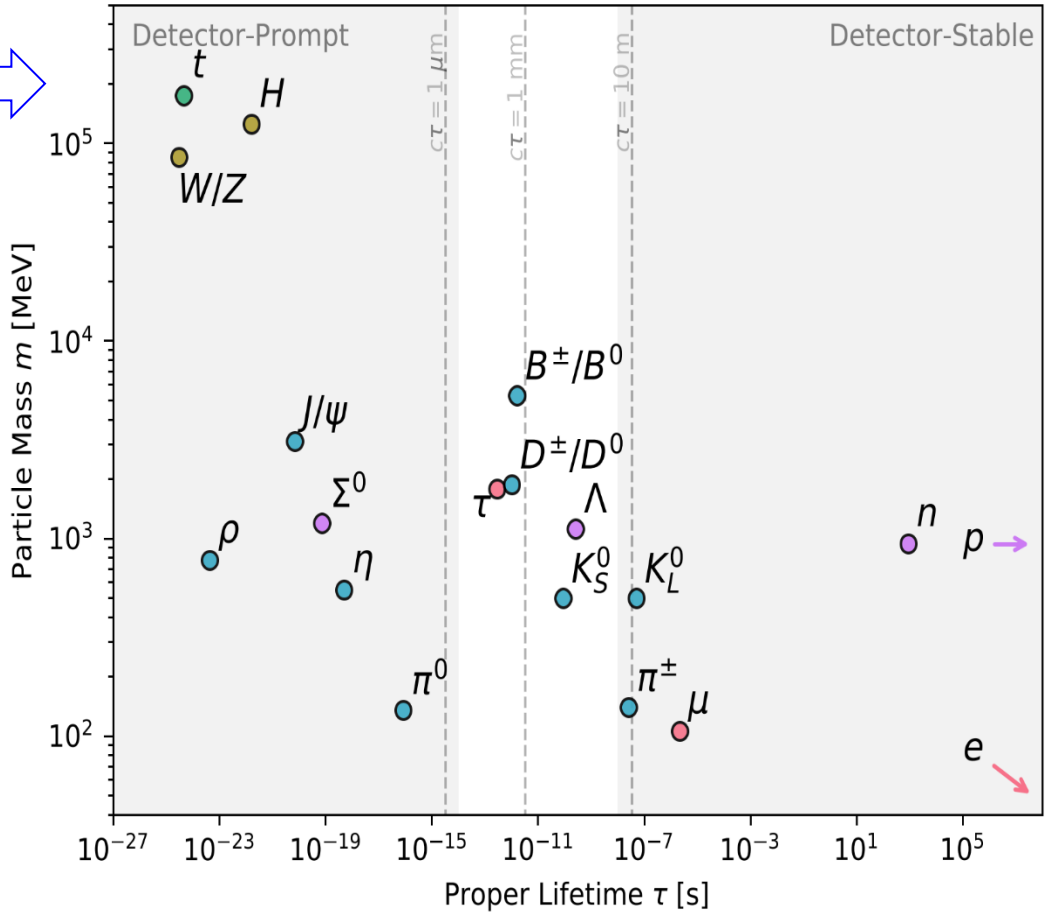


Long-lived particles (LLPs)

- Standard Model contains a large number of LLPs: π, K, D, B, τ…

- LLPs are predicted in many BSM scenarios, in models with
  - Nearly mass-degenerate spectra (e.g., compressed SUSY)
  - Particle decays via heavy virtual mediators (e.g., heavy neutral leptons)
  - Small couplings to SM particles (e.g., “hidden sector” models)

from arXiv:1810.12602

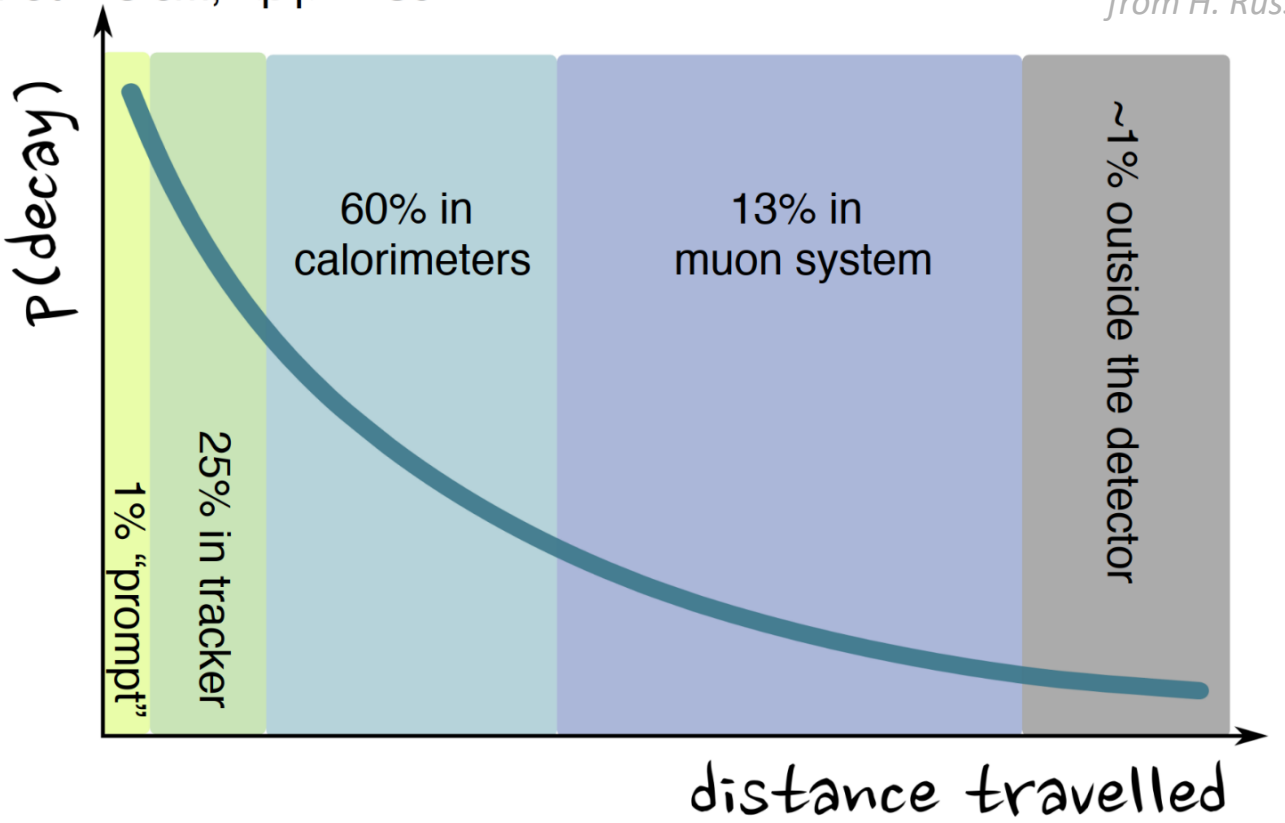


LLP lifetime

- N.B.: Any given particle's lifetime is sampled from an exponential
  - LLP lifetime τ is an important extra degree of freedom compared with searches for prompt particles, and leads to unconventional signatures

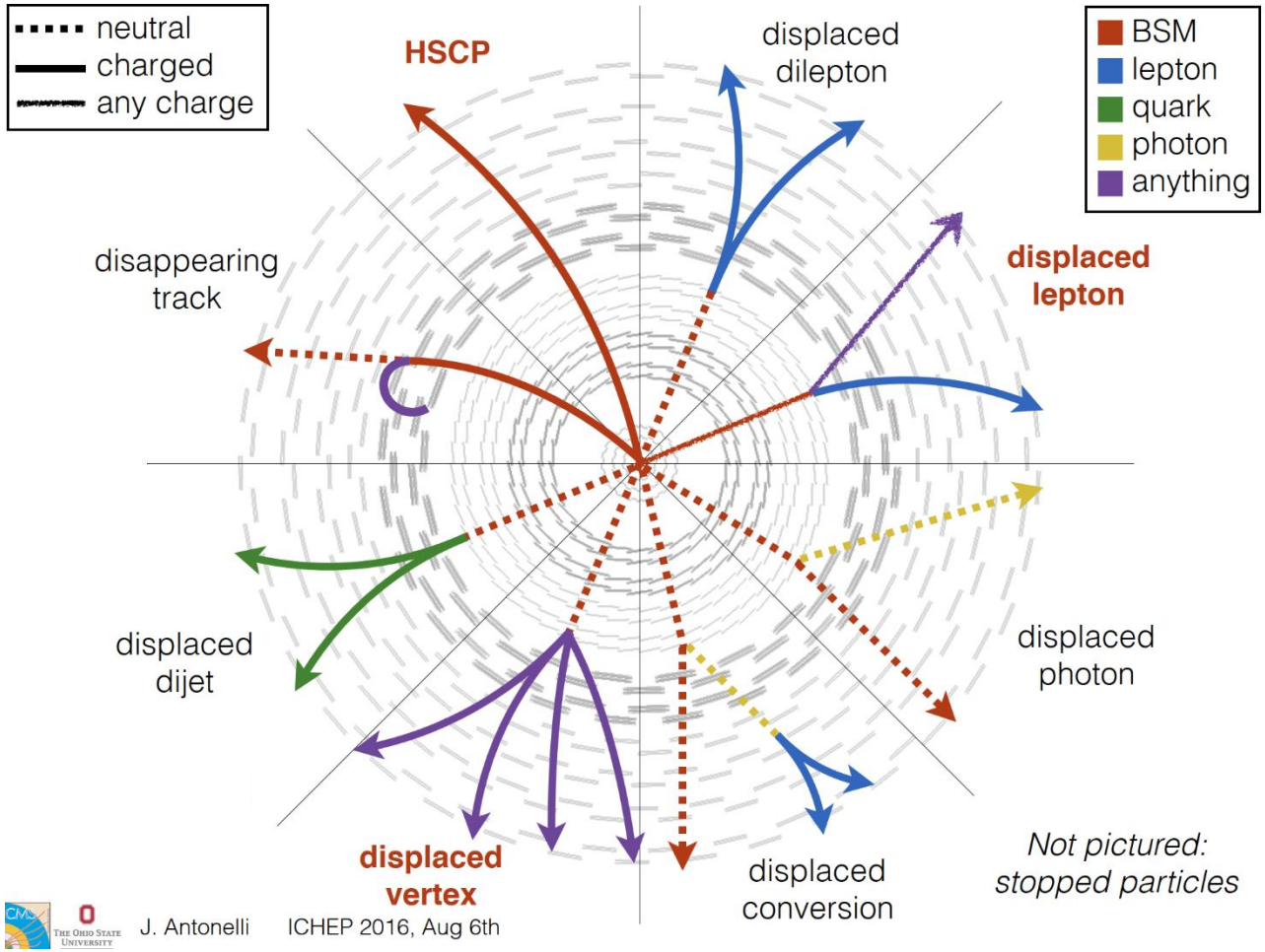
e.g. for $c\tau = 5$ cm, $\langle\beta\gamma\rangle \sim 30$

from H. Russell (link)



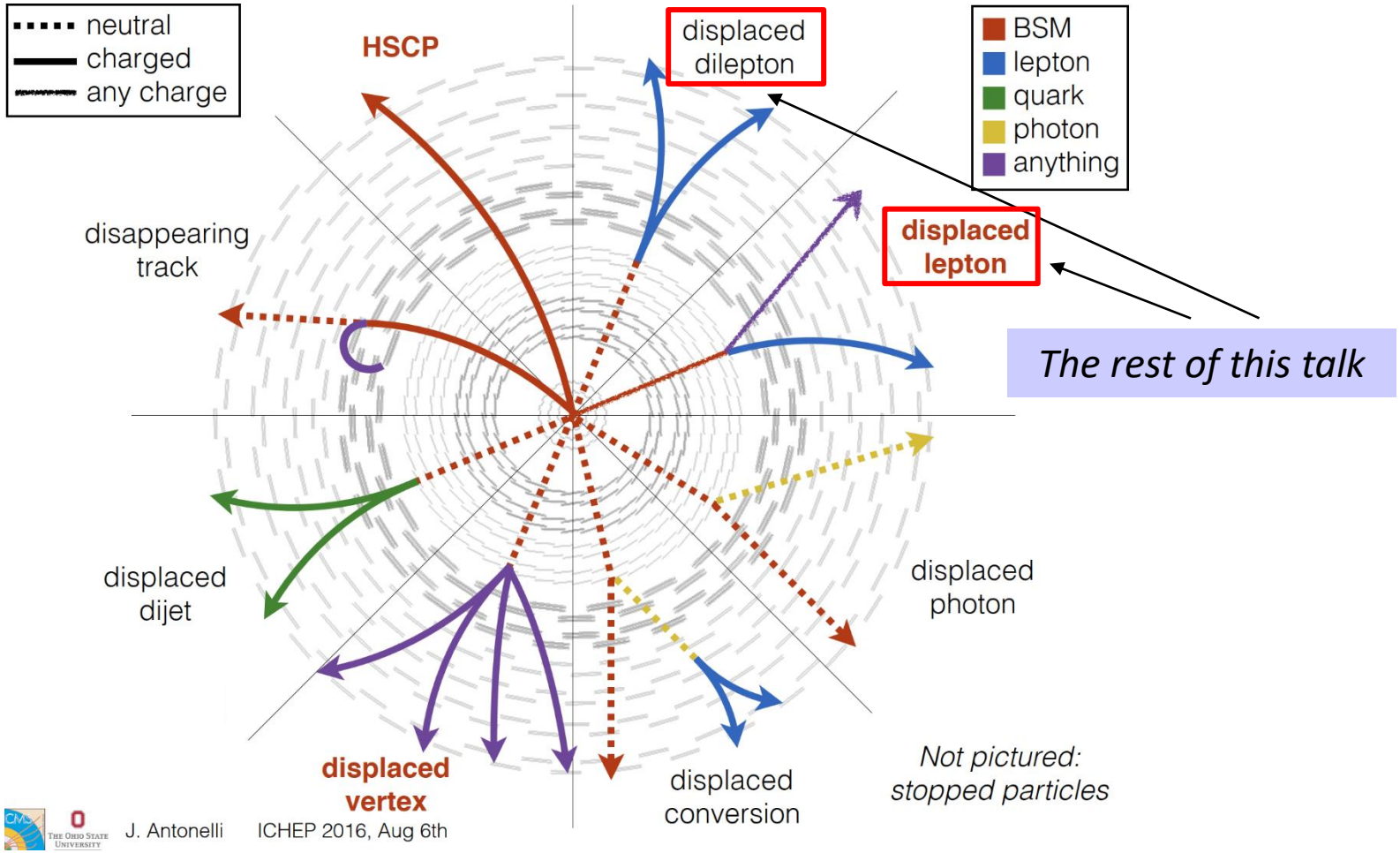
LLP experimental signatures

Different LLP properties (decay mode, cτ, mass, …) lead to a wide range of experimental signatures that often require dedicated searches

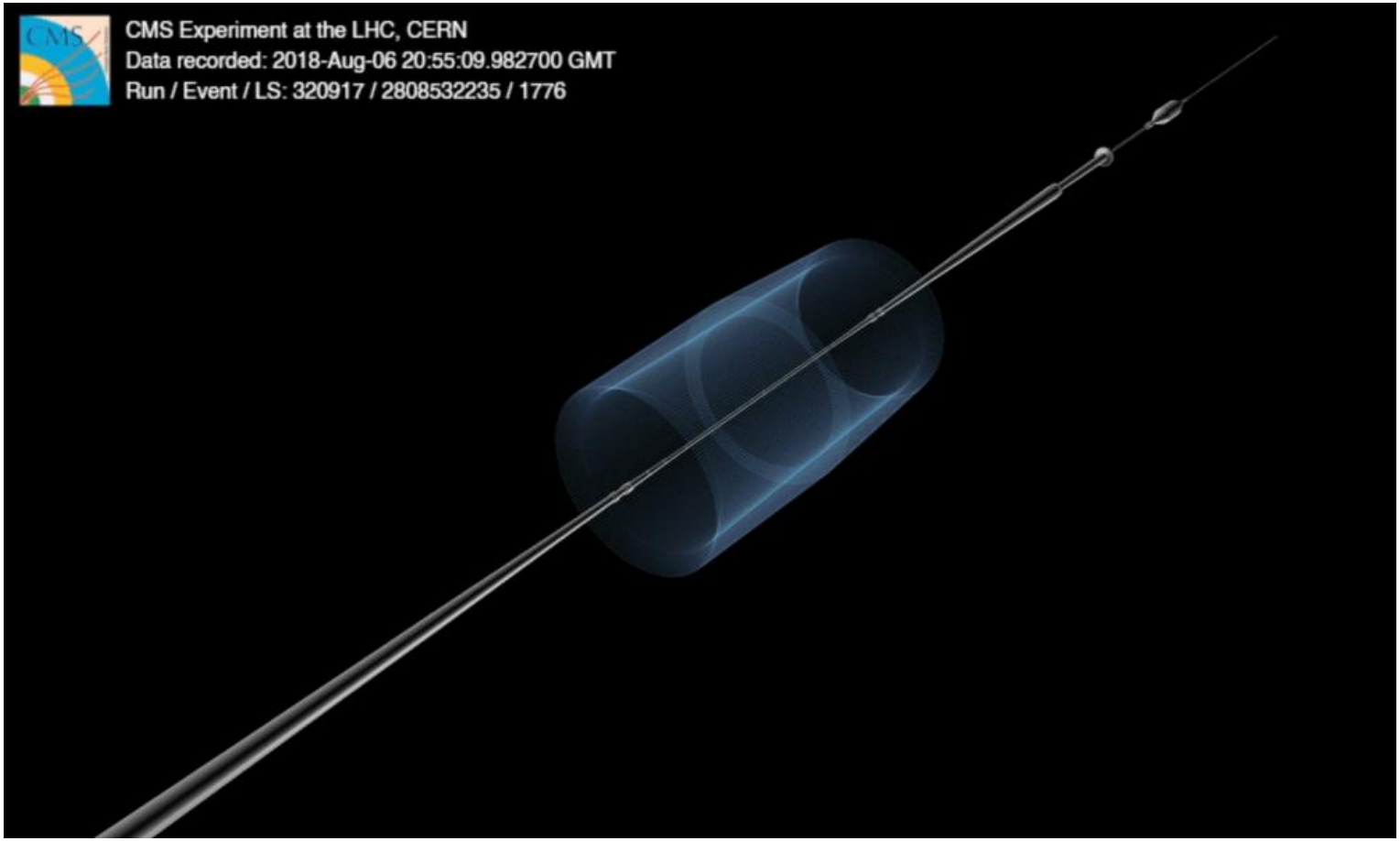


LLP experimental signatures

Different LLP properties (decay mode, cτ, mass, …) lead to a wide range of experimental signatures that often require dedicated searches



Displaced dimuons at CMS

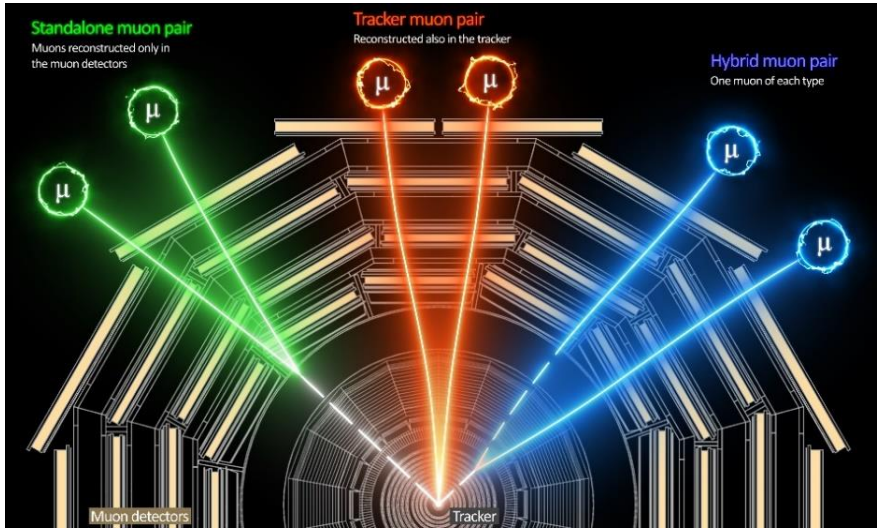


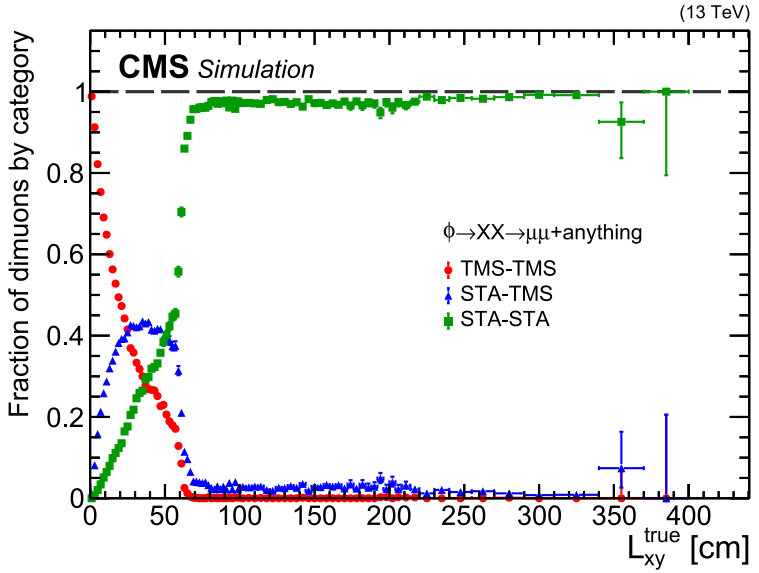
A candidate event for a long-lived particle that decays into a pair of muons away from the interaction point, reconstructed in the 2018 data taking of the CMS detector

Generic search for displaced dimuons at CMS

- **New generic, inclusive CMS search** for LLPs with m > 10 GeV decaying into pairs of oppositely charged muons: arXiv:2205.08582, submitted to JHEP
- The search targets LLP decays both **within and beyond the CMS silicon tracker**
- To maximize cτ coverage, we use two types of reconstructed muons:
  - **STA**: muons reconstructed in the muon system only ("**STA**ndalone" muons)
  - **TMS**: muons reconstructed both in the **T**racker and in the **M**uon **S**ystem

  resulting in **three** exclusive **dimuon categories**: **TMS-TMS**, **STA-TMS**, and **STA-STA**
- Equivalent to **three separate searches**; unique selection requirements and background estimation procedures in each

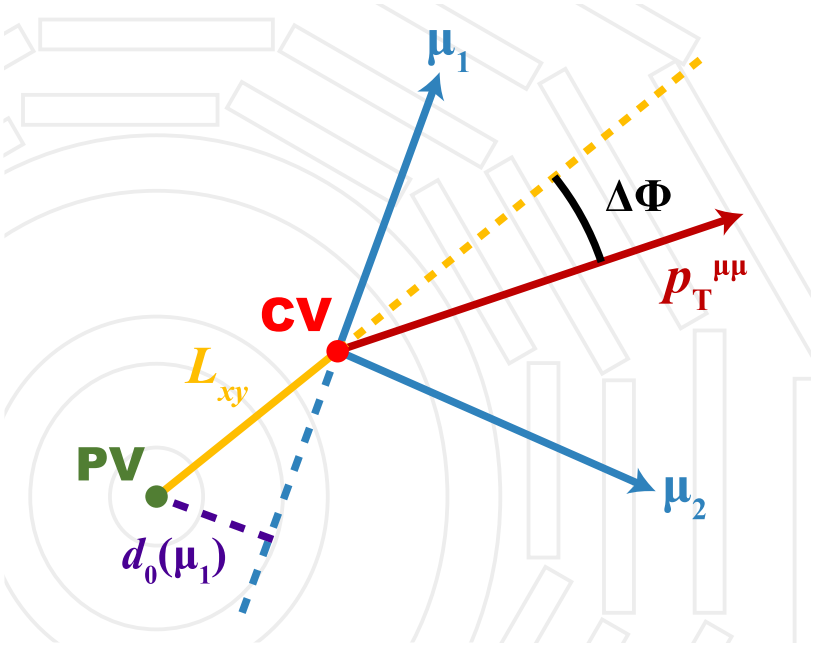




Displaced dimuons: triggers and key variables

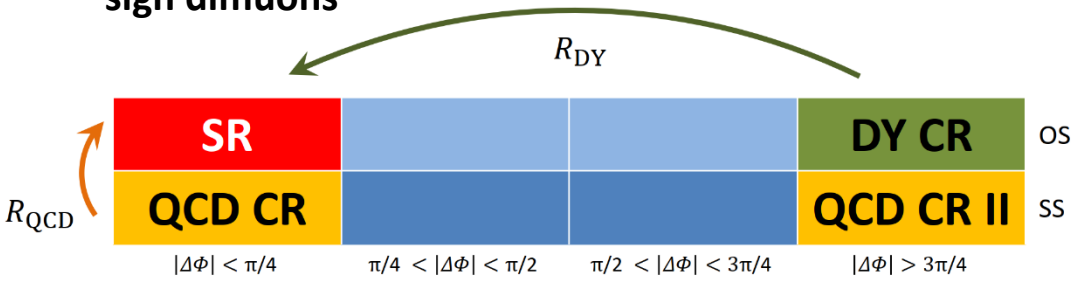
- **Dedicated** triggers requiring two muons reconstructed in the muon system alone ($p_T(\mu) > 28$ (23) GeV for 2016 (2018))
  - Deployed in 2016; dropped in 2017; re-deployed and further optimized in 2018
  - Performance studied using cosmic ray muons

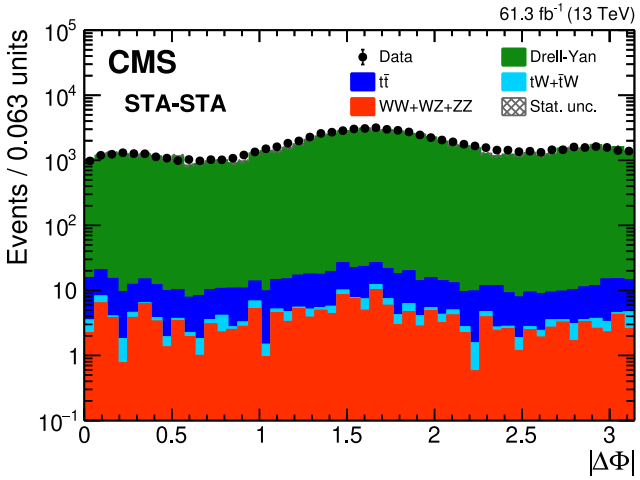
- **Key S/B discriminating variables:**
  - **L_{xy} significance ($L_{xy}/\sigma_{L_{xy}}$):** transverse decay length normalised to its uncertainty; expected to be **large** in signal
  - **d_0 significance (d_0/σ_{d_0}):** muon transverse impact parameter (IP) normalised to its uncertainty; expected to be **large** in signal
  - **Collinearity angle (|ΔΦ|):** angle between the L_{xy} and dilepton p_T vectors; expected to be **small** in signal

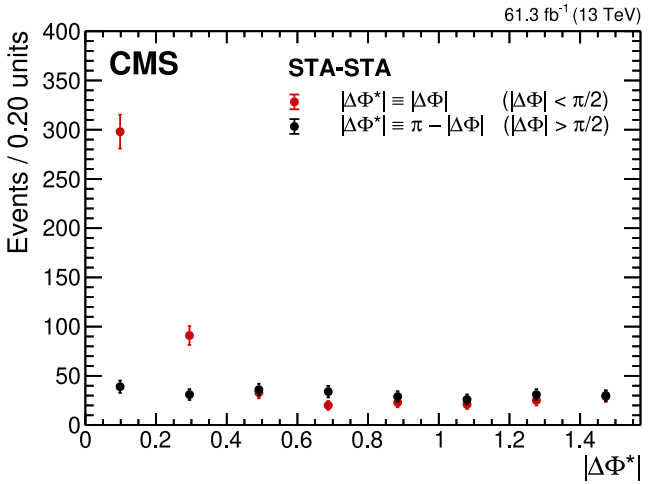


Displaced dimuons: background evaluation

- In SM, no LLPs with m > 10 GeV decaying to dimuons → **background is due to** instrumental or reconstruction **mistakes**
- **DY-like backgrounds:** prompt high-mass dimuons misreconstructed as displaced. ~**Symmetric in |ΔΦ|** (no preferred $\vec{L}_{xy}$ direction w.r.t. $\vec{p}_{\mathrm{T}}^{\mu\mu}$).
- **QCD-like backgrounds:** dimuons from decays of non-prompt low-mass resonances, cascade decays of b hadrons, and two unrelated non-prompt muons. **Asymmetric in |ΔΦ|.**
- Evaluate **DY-like** backgrounds from **large-|ΔΦ| dimuons** and **QCD-like** backgrounds from **same-sign dimuons**



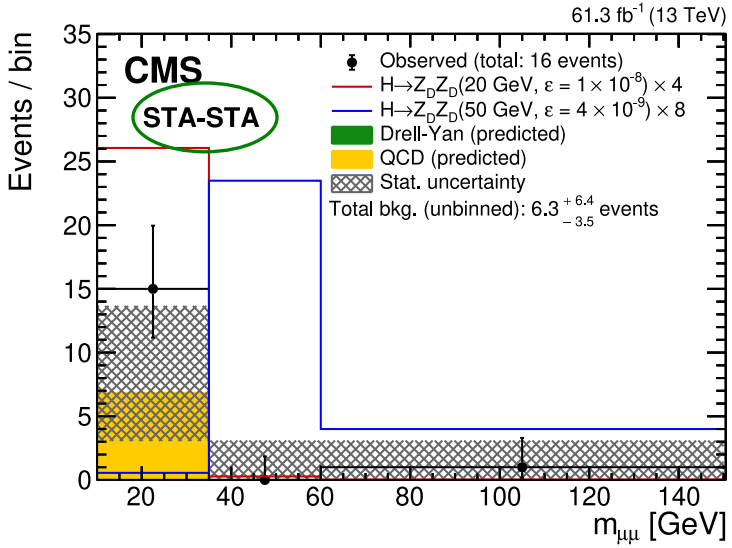


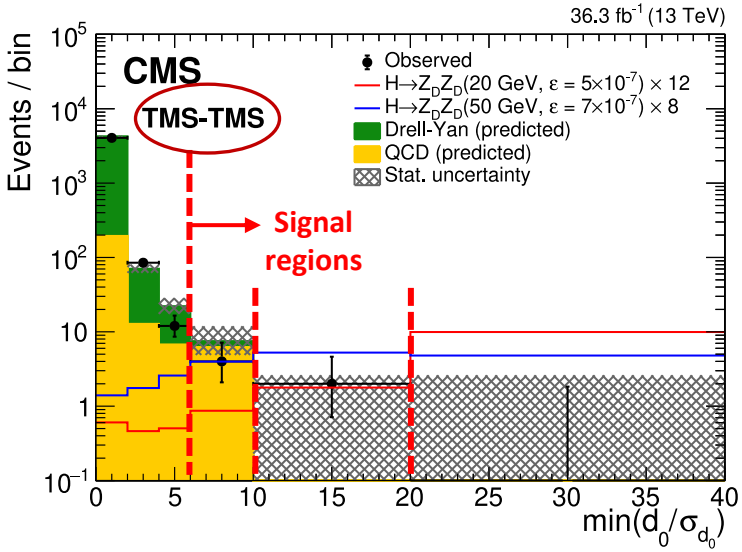


- **Transfer factors R_{DY} and R_{QCD}** derived from various dedicated control regions

Displaced dimuons: analysis summary and results

- Developed **dedicated displaced muon ID and custom muon isolation**
- **Suppress collision backgrounds** by track quality, dimuon vertex quality, |ΔΦ|, and displacement cuts (typically $L_{xy}/\sigma_{L_{xy}} > 6$ and/or $d_0/\sigma_{d_0} > 6$)
- **Get rid of cosmic ray muon background** with the help of angular, timing, and direction criteria
- Split selected events into **m(μμ) and d_0/σ_{d_0} bins**
- **Validate background predictions in control regions** obtained by inverting selection criteria

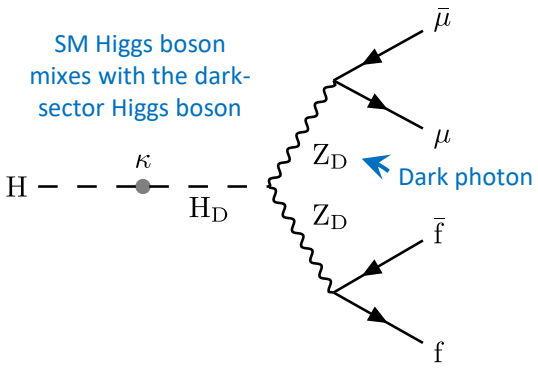


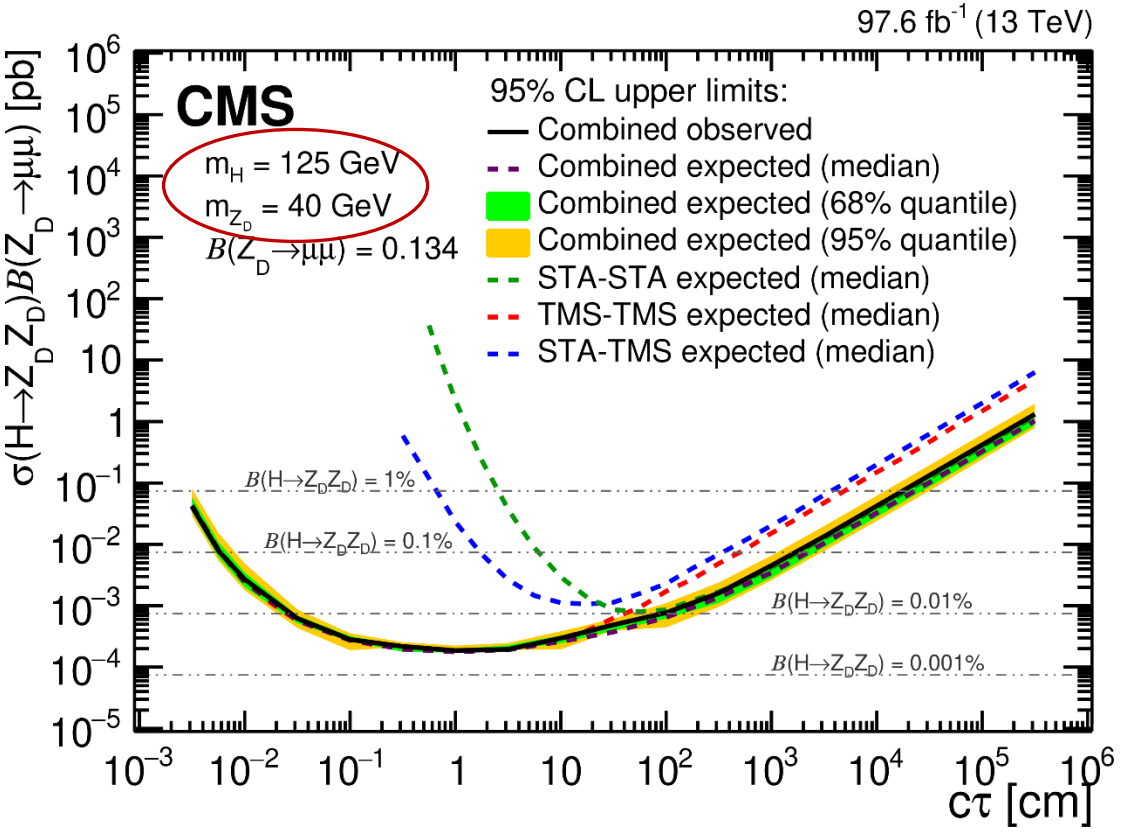


No significant excess observed above the background-only hypothesis

Displaced dimuons: m(LLP) < m(H)/2

Interpretation in the framework of the hidden Abelian Higgs model (Curtin et al.)

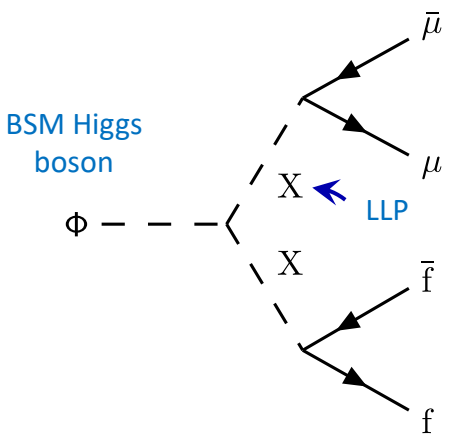


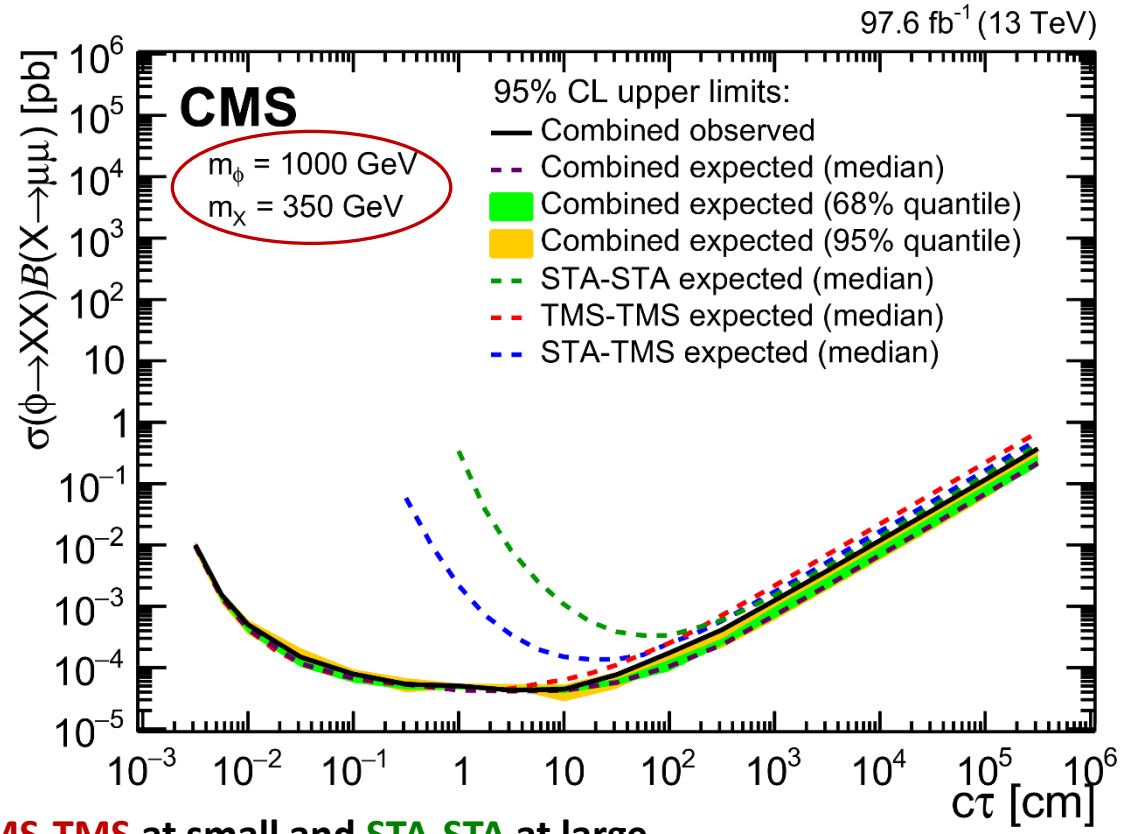


- Thanks to a combination of dimuon categories, analysis is sensitive to a **wide range of cτ from μm to km!**
- Probes **Br(H→Z_DZ_D) as low as 10^{-4}–10^{-5}** at m(Z_D) = 10–62 GeV

Displaced dimuons: m(LLP) > m(H)/2

Interpretation in the framework of the "heavy scalar" model (Strassler, Zurek)

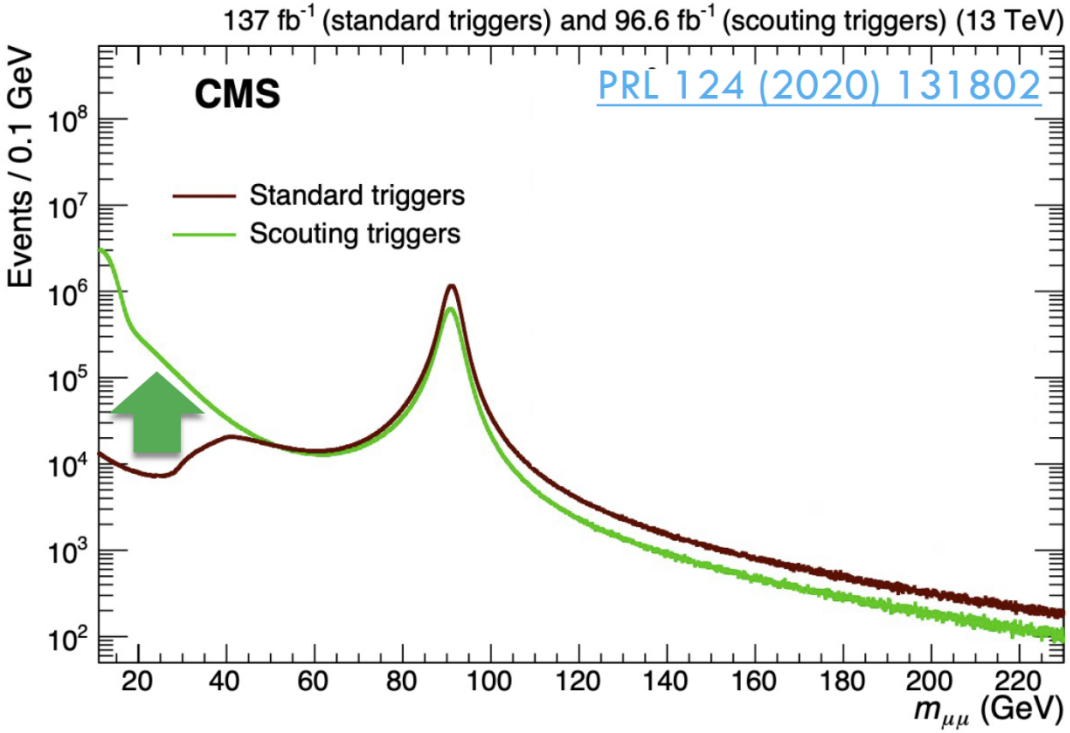




- Sensitivity dominated by **TMS-TMS at small and STA-STA at large lifetimes**, with STA-TMS contributing at intermediate lifetimes
- The search covers **a large range of LLP masses** (from 10 to several hundred GeV) and **a large range of boson masses** (up to 1 TeV)

Displaced low-mass dimuons: data scouting

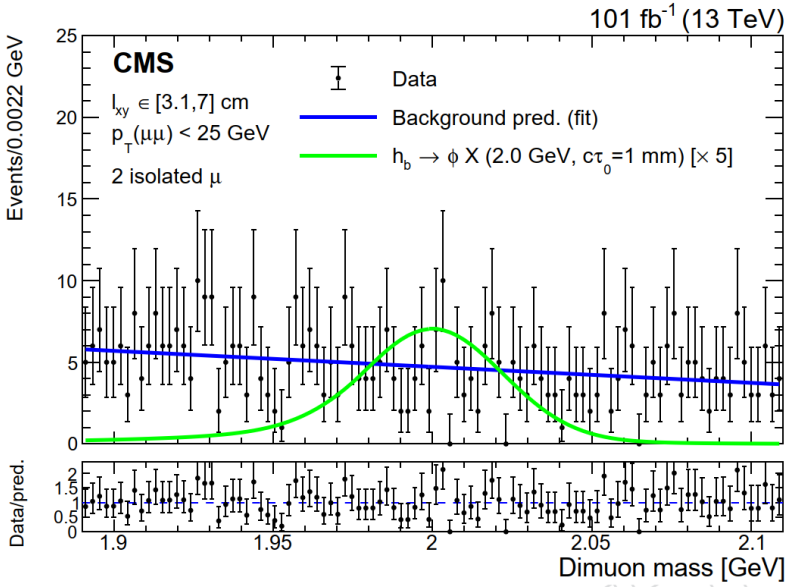
- Neither triggers discussed above (requiring $p_T(\mu) > 23$-28 GeV) nor standard triggers allow access to **low-mass regime**, m(LLP) < ~10 GeV
  - The way out is to **use** dedicated high-rate data stream (aka "**data scouting**")

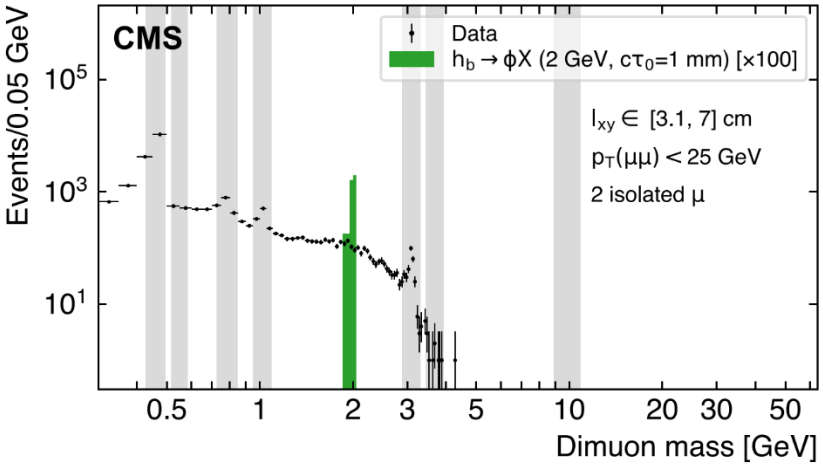


- Dimuon "scouting" triggers: require two opposite-sign muons with $p_T(\mu) > 3$ GeV
  - Thus, **allow probing LLP mass range down to 2m(μ)**
- On the other hand, data scouting has important **limitations**:
  - Very limited amount of (HLT-level) information available
  - In Run 2, presence of at least 2 hits in pixel tracker was required, limiting the available Lxy range to 11 cm

Displaced dimuons with data scouting: analysis summary

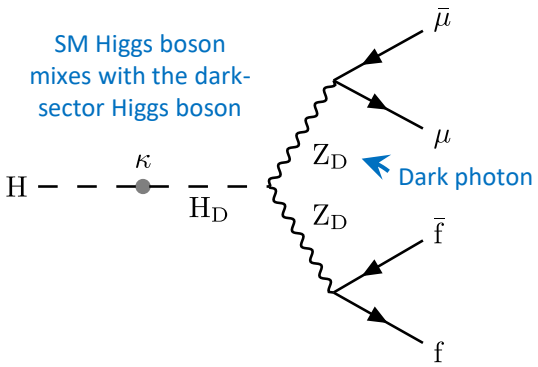
- Event selection:
  - Similarly to the above analysis, includes cuts on displacement and $|\Delta\Phi|$
  - Also rejects vertices near pixel modules and applies some other low-m-specific cuts
- Signal extraction:
  - Fit to dimuon mass spectrum in $\pm 5\sigma$ window around the probed signal mass
  - Mask mass ranges containing known SM resonances

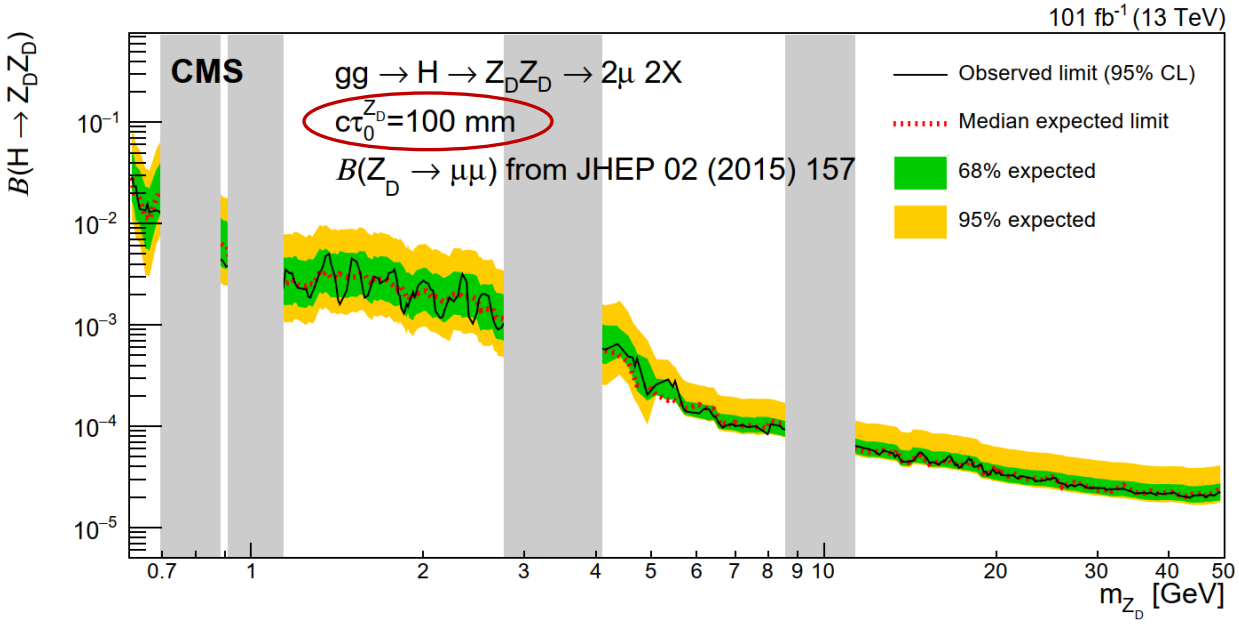




Displaced dimuons with data scouting: results

Interpretation in the framework of the hidden Abelian Higgs model (Curtin et al.)



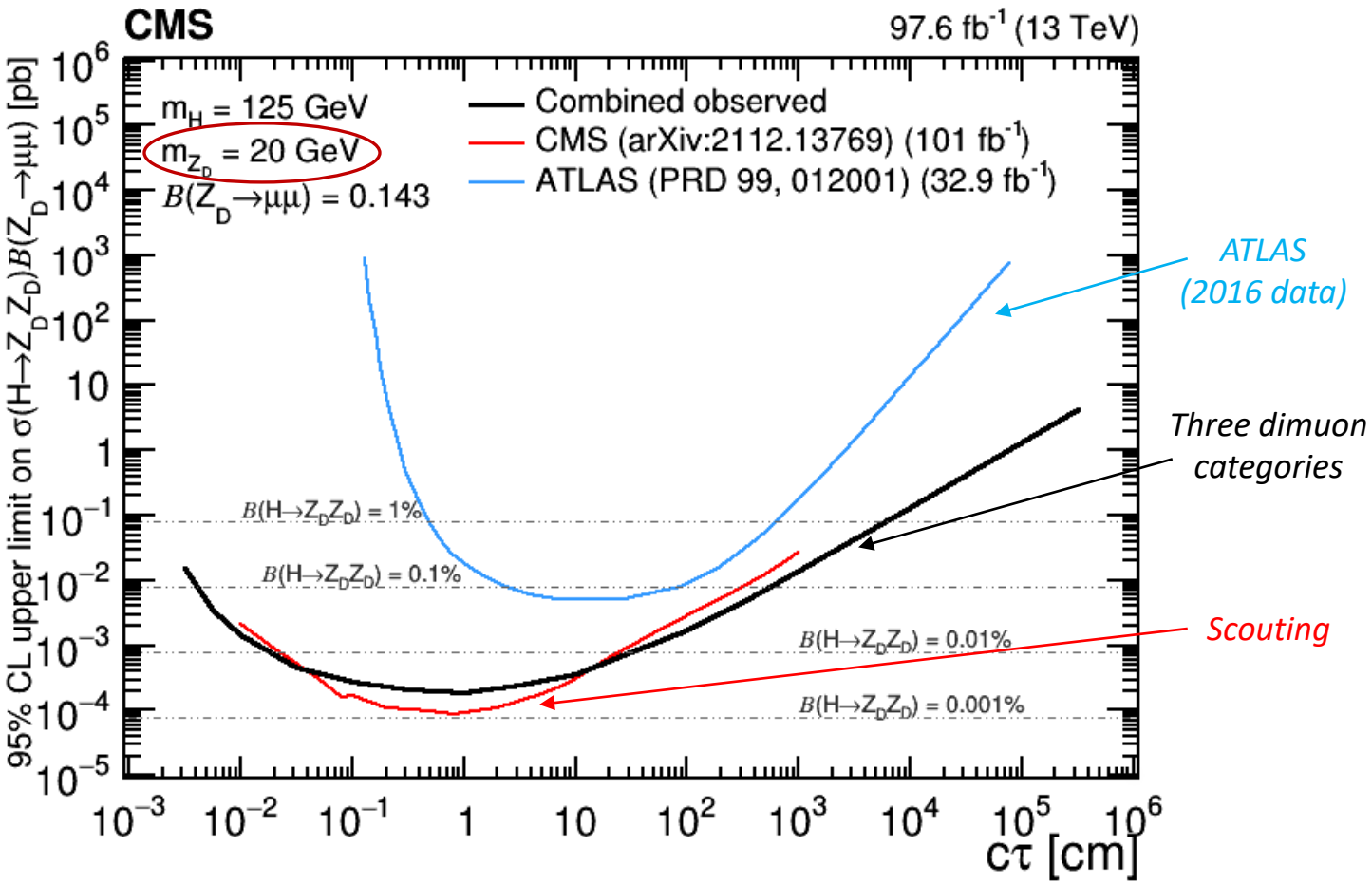


- Probes **Br(H→$Z_D Z_D$) down to O(10^{-5})** at **m(Z_D) = 0.6–50 GeV**
- Most sensitive to cτ = 1–100 mm

Published in JHEP 04 (2022) 062

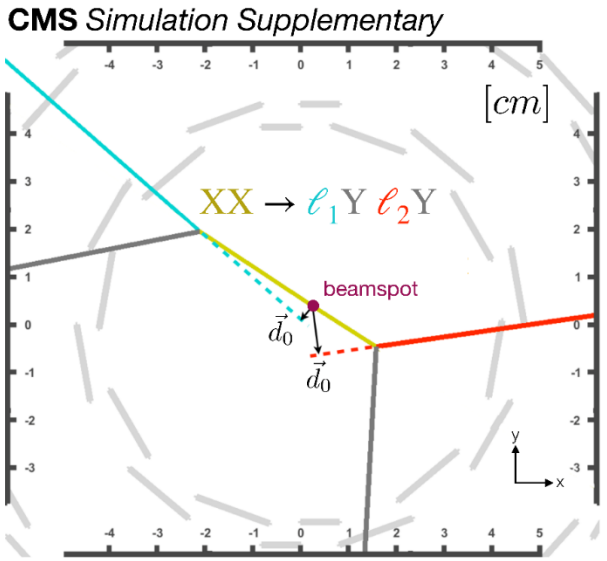
Displaced dimuons: comparison of the results

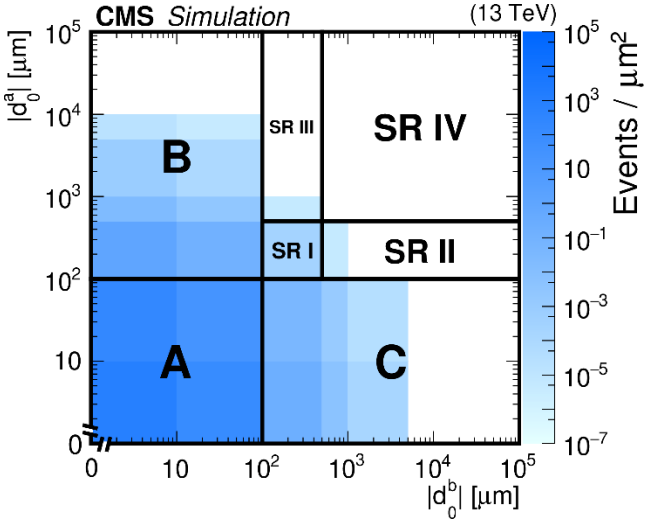
Both described searches probe the LLP mass region of 10-40 GeV; here is the comparison for m(LLP) = 20 GeV (the HAHM model)



Search for leptons with large impact parameter

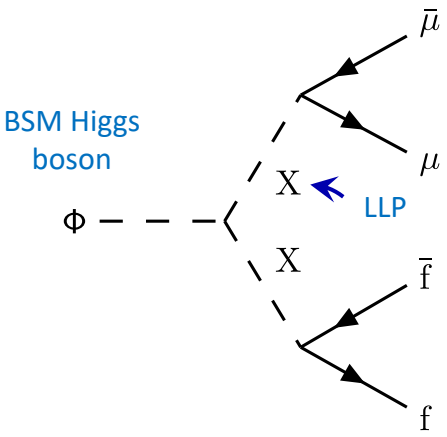
- Inclusive search for **LLPs decaying to displaced leptons**: Eur. Phys. J. C 82 (2022) 153
- Look for μμ, eμ, ee final states where **both leptons have large transverse impact parameter (d_0)**
- **Leptons** are allowed but **not required to originate from a common vertex**
- Dimuon channel: two isolated high-p_T (p_T > 40-45 GeV) muons with d_0 > 100 μm reconstructed in tracker
- Background evaluated using ABCD method based on two lepton d_0 values
- **No excess** of events in data over predicted background

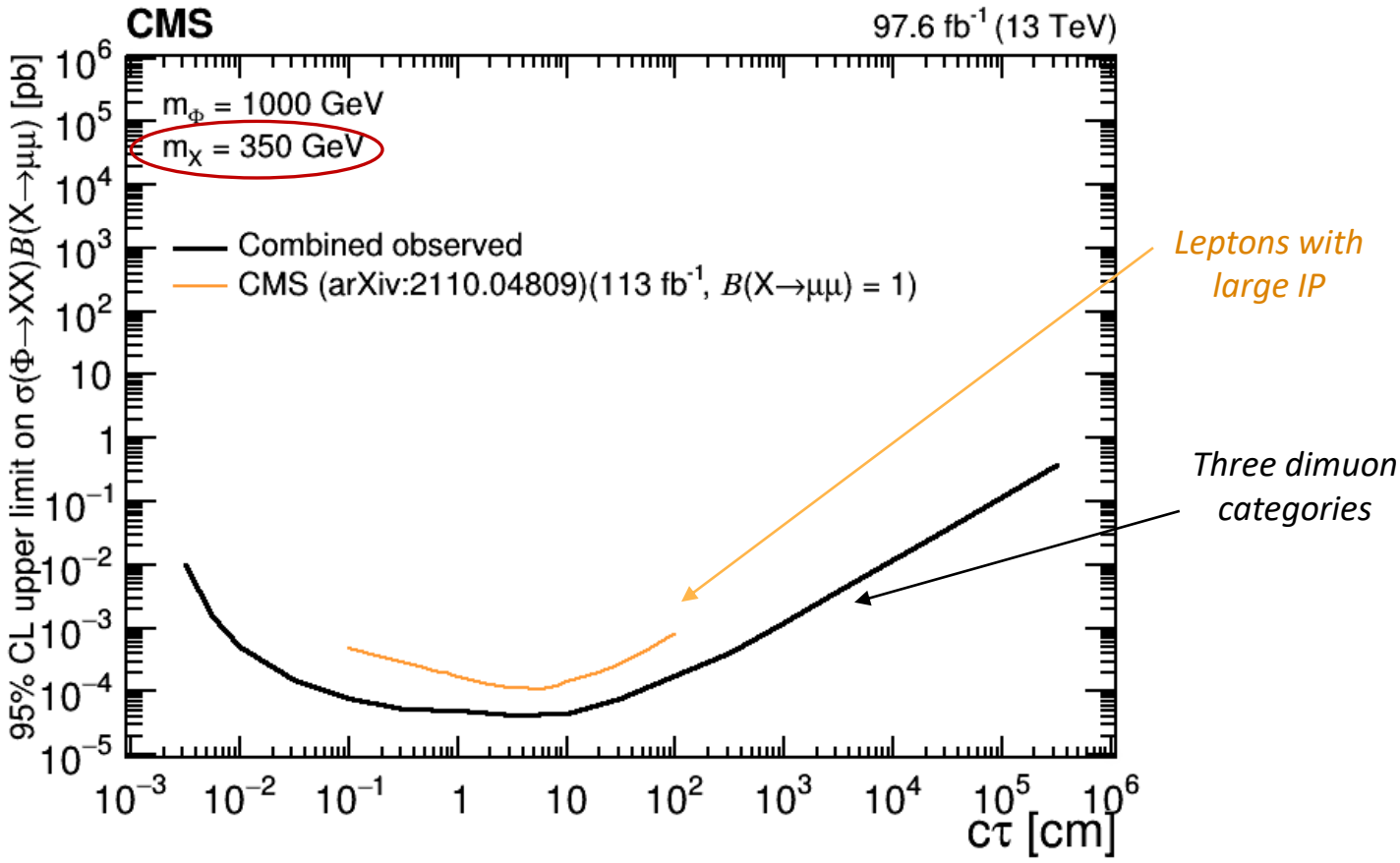




Leptons with large IP vs displaced dimuons

The results of the "leptons with large IP" search are less stringent than dedicated dimuon searches for models featuring displaced dimuons (such as the heavy-scalar model shown here)

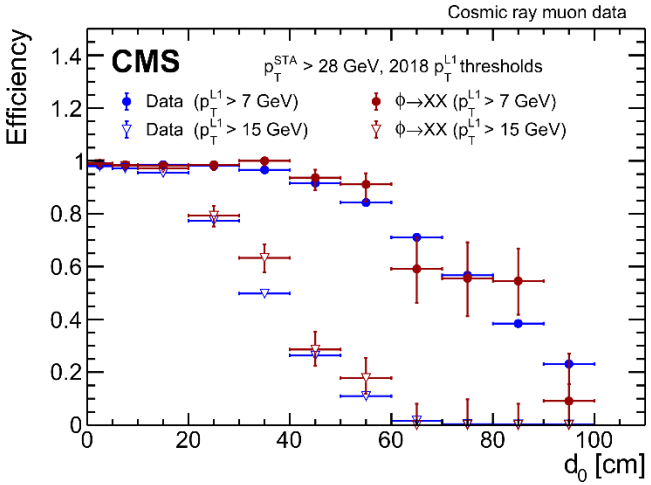




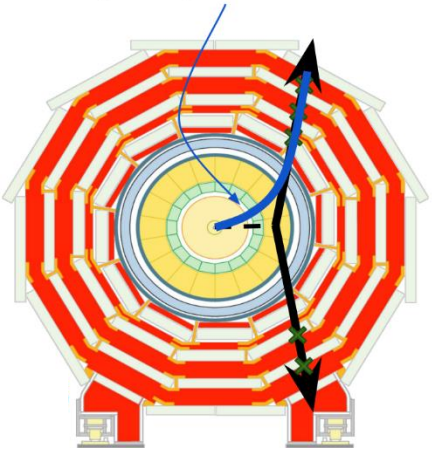
Preparations for Run 3

The main limiting factor for described Run-2 searches is trigger efficiency

- Level-1 efficiency drop at large d_0 caused by beamspot bias in muon-p_T assignment



mis-reconstructed L1 muon track with artificially small p_T as a result of the implicit beamspot requirement at L1



  - Largely resolved for Run 3 thanks to new Level-1 algorithms (kBMTF, EMTF NN)
- Low efficiency at low masses because of high p_T thresholds at HLT
  - New paths implemented in Run-3 trigger menu, with p_T thresholds lowered to ~10 GeV
- Requirement of at least two pixel hits removed from scouting triggers

Expect large boost in signal efficiency at Run 3!

Summary and outlook

- Long-lived particles: extensive search program at the LHC
- Searches for displaced dimuons/muons are its important part
  - Briefly described three recent CMS analyses today
- Exciting times for LLP searches ahead, with numerous R&D projects on the way (trigger, dedicated object reconstruction and ID, analysis methods, etc.)

Want to contribute to LLP searches at CMS? Contact Karri.Folan.Di.Petrillo@cern.ch and Slava.Valouev@cern.ch