Status and Prospect of LLP Searches at ATLAS and CMS

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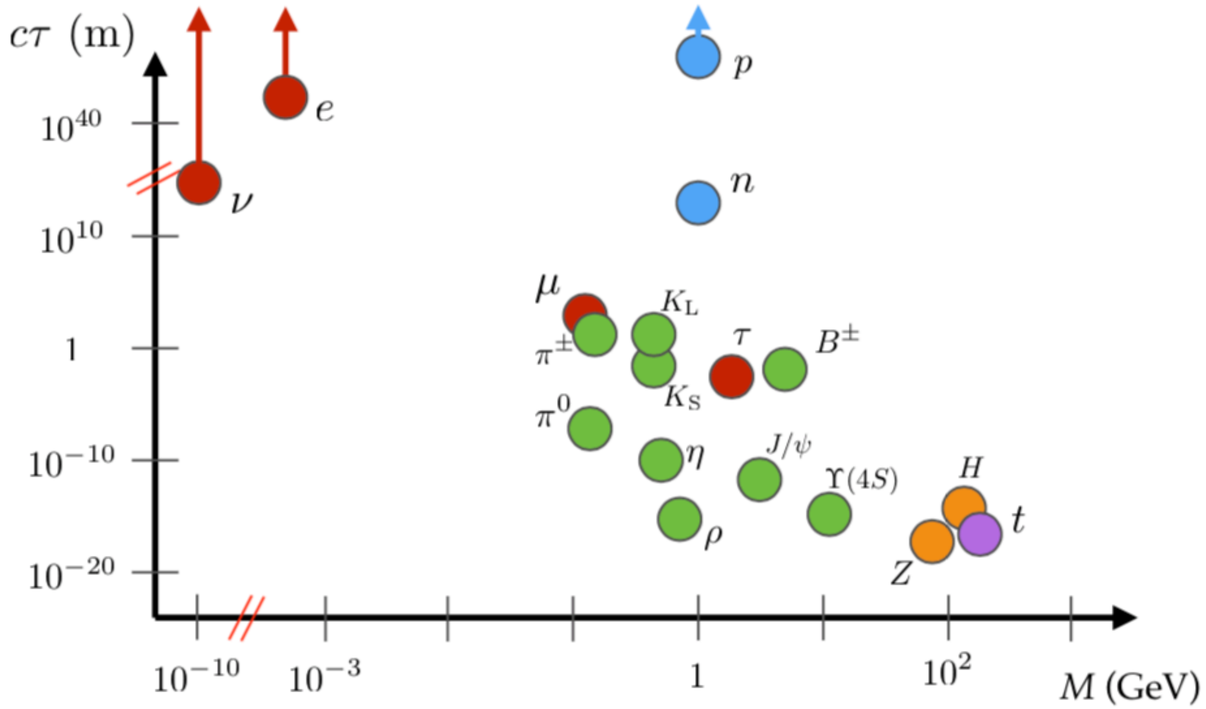
2022 Mitchell Conference
05/25/2022

Long-Lived Particles



$m \ll \Lambda$: Scale suppression

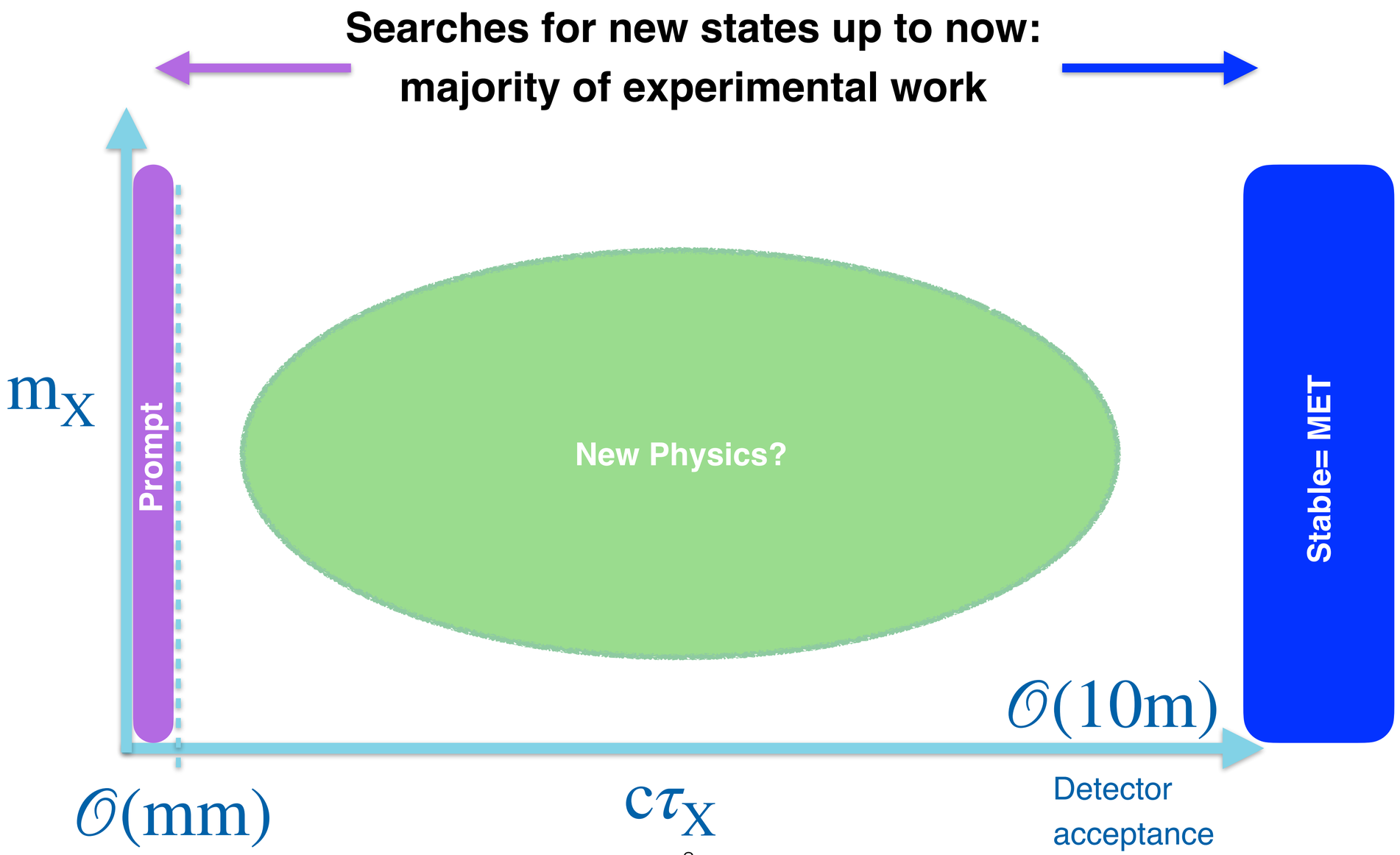
$$\tau^{-1} = \Gamma \sim y^2 (\frac{m}{\Lambda})^n \Phi$$

Small coupling

Small phase space

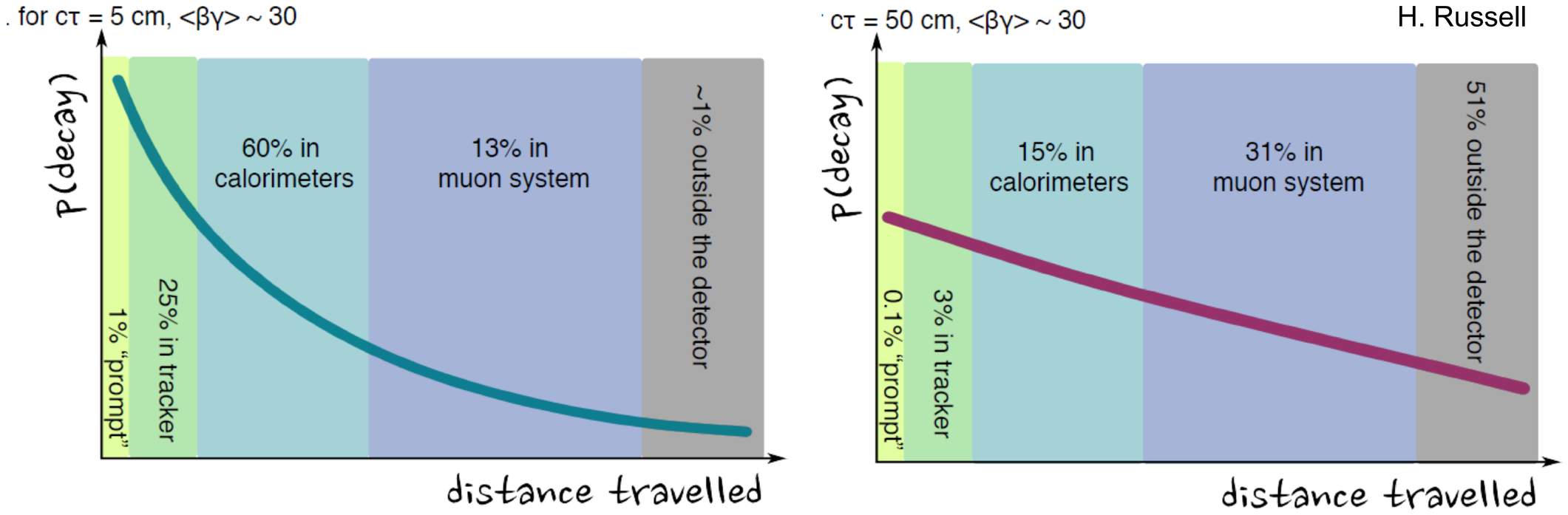
- Long-lived particles are common in SM as well as BSM theories
- Well motivated and predicted in many BSM models: SUSY, Heavy neutral leptons, Higgs portals …

New Physics at LHC: Long-lived particles



LLP Decay Region

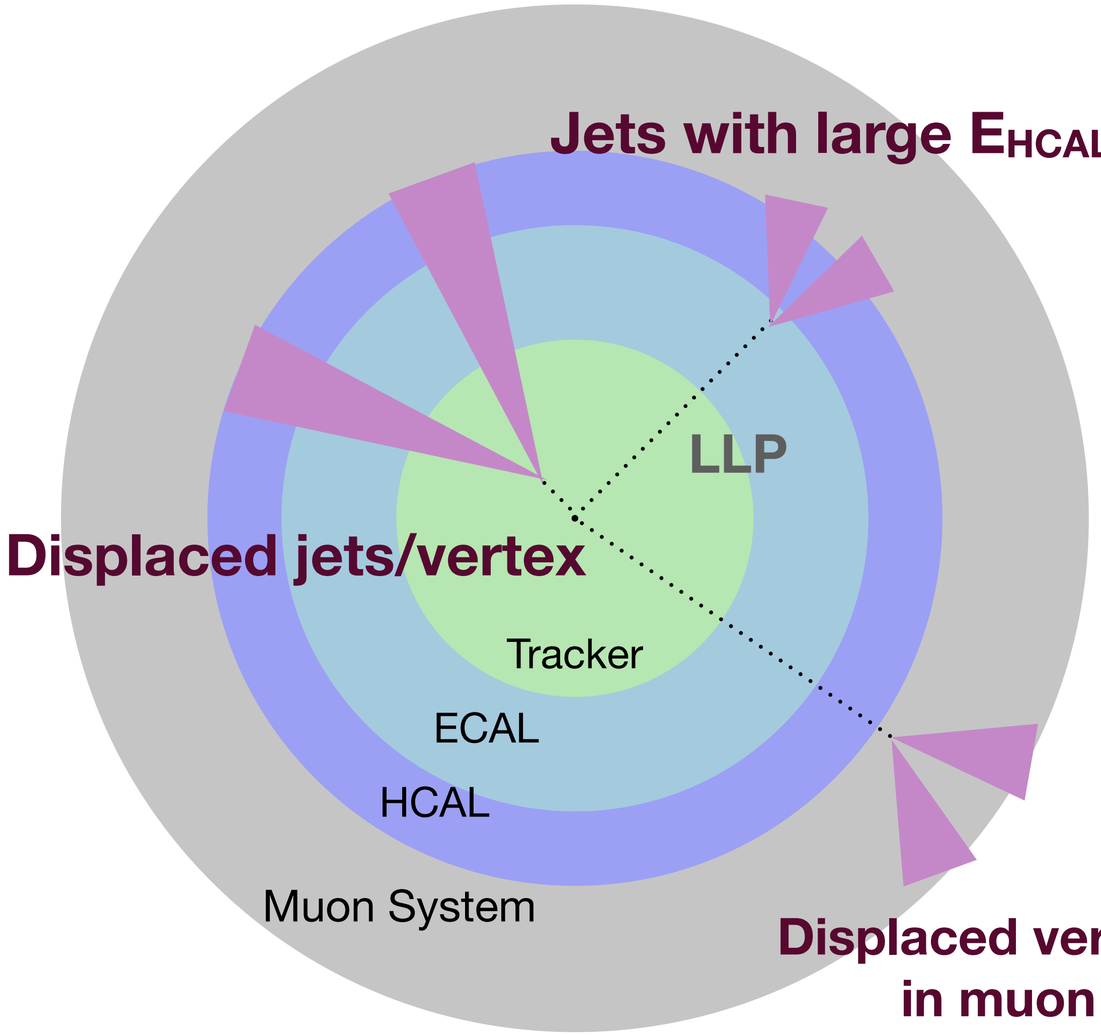
distance travelled $= \beta\gamma \times c\tau$



- Search strategy strongly depends on proper lifetime and boost of LLP
- Every sub-detector is important

Long-lived Particle Search @ LHC

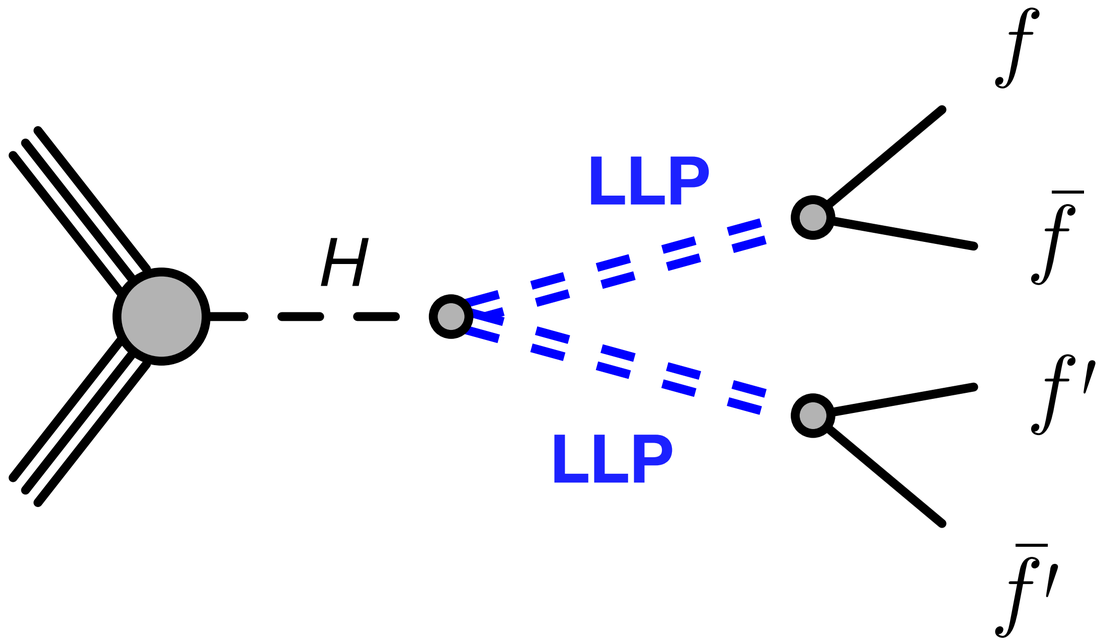
Displaced experimental signature



- Massive LLP program in LHC using Run 2 data covering LLP decays in different **detector volumes**
  - ~ 20 full Run 2 results from ATLAS & CMS
- Will give an overview with focus on hadronic decays
- **Analysis sensitivity primarily driven by LLP triggers**

Theoretical Motivation

- **Higgs portal** is a major focus in Run 2
  - Accessing lower LLP mass
  - Extending LLP lifetime, independent of LLP mass

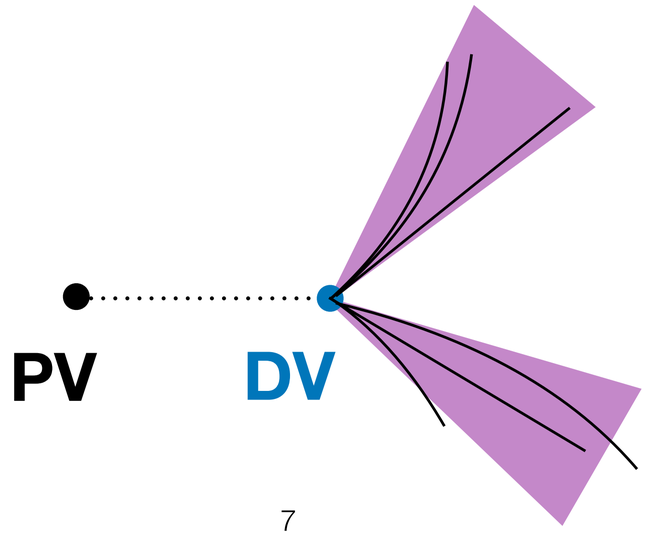


Decays in Tracker

- Analyses targeting different production modes due to **different trigger strategies**

Production mode	Trigger	Experiment	Reference
ggH	Displaced jets	CMS	2012.01581
ZH	ee/μμ	CMS	2110.13218
ZH	ee/μμ	ATLAS	2107.06092

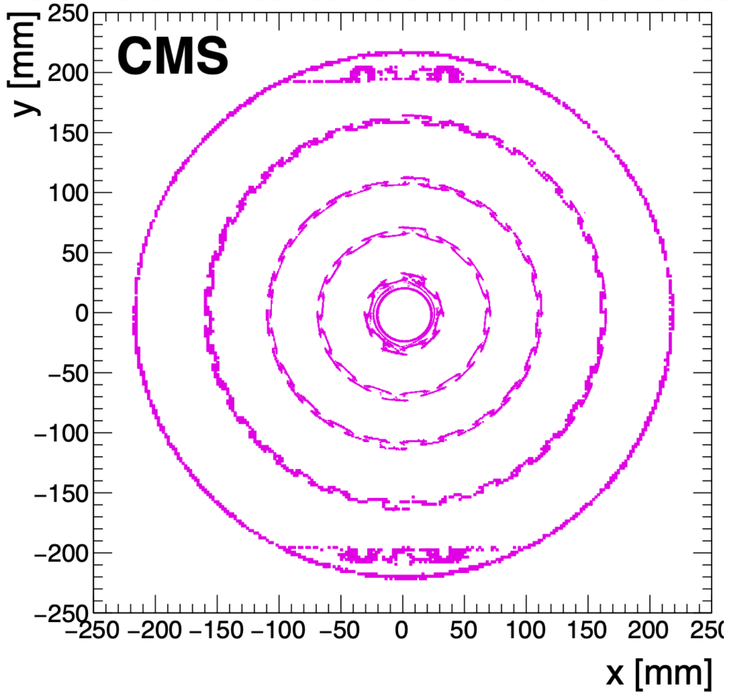
- Dedicated algorithm to reconstruct displaced vertices/jets
- Select for displaced vertices/jets passing quality cuts (p_T/IP)

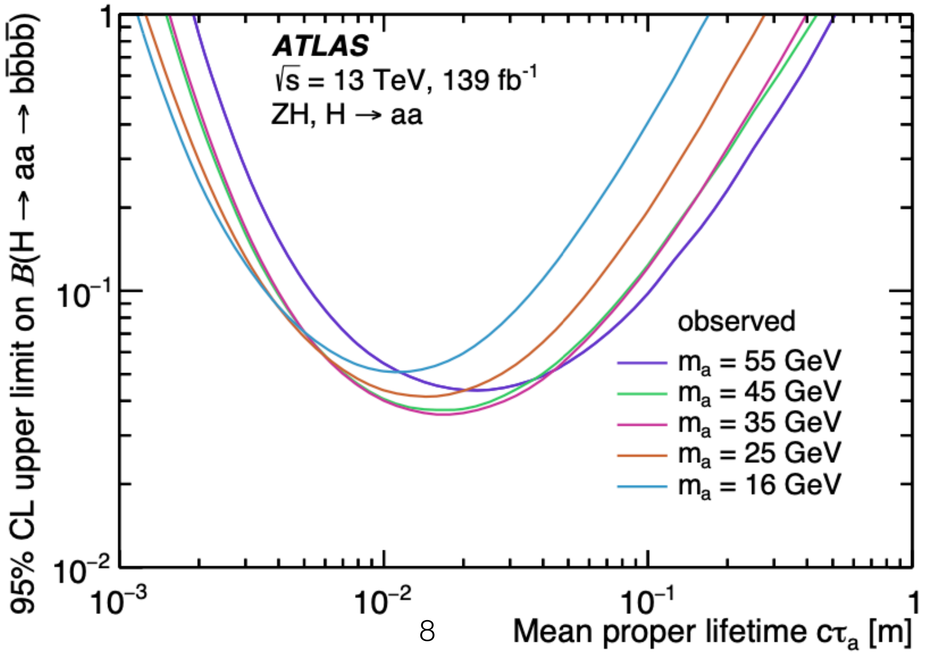


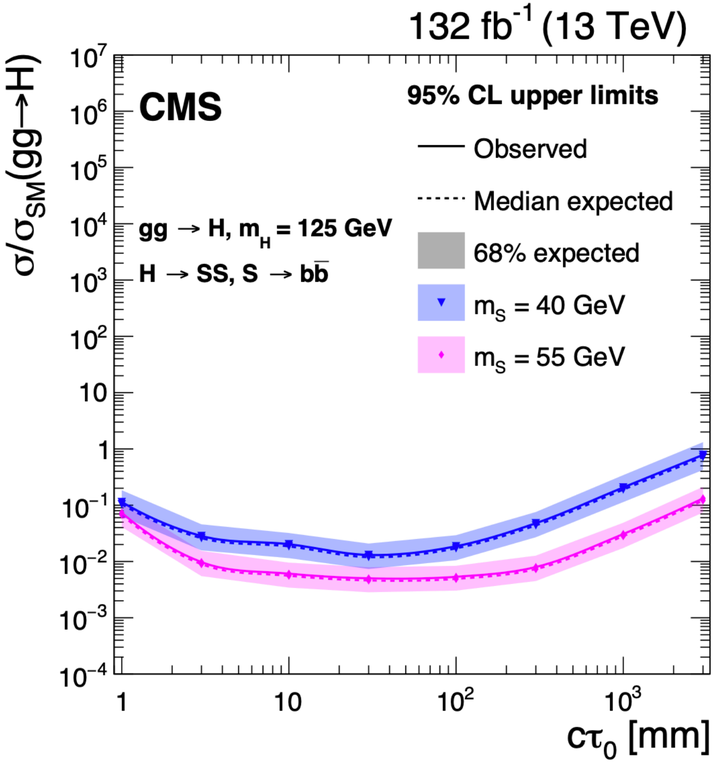
Decays in Tracker

- Data-driven background estimation:
  - SM multi-jet
  - Nuclear interaction in tracker materials
- **Analysis sensitivity driven by LLP trigger:**
  - Dedicated trigger improves analysis sensitivity → reach 0.5% BR
  - However, a high H_T cut in the trigger significantly decreases sensitivity for light LLPs

Background from nuclear interaction in tracker materials



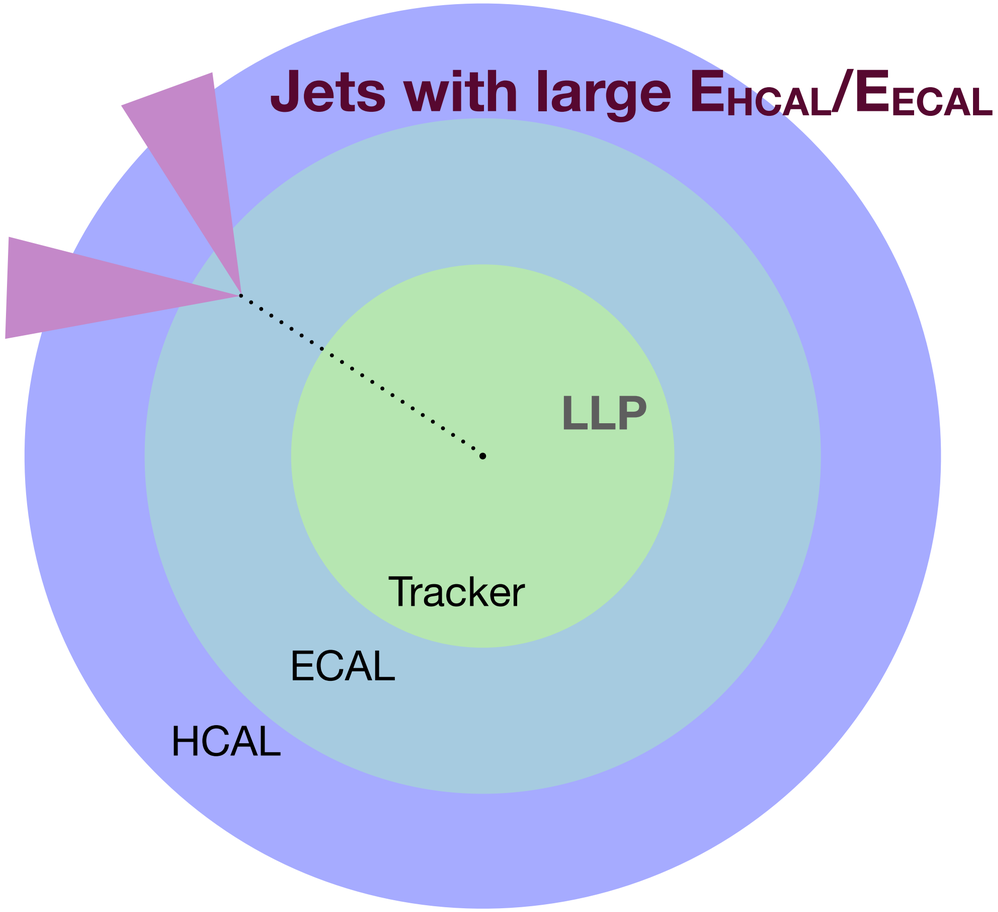




Decays in Calorimeter

NEW FULL RUN2 RESULT FROM ATLAS!

- Displaced jets with large E_{HCAL}/E_{ECAL}
- **Dedicated trigger** triggering on single displaced jets with low E_T of 30 GeV
- New **machine learning techniques** to train on low-level inputs (tracks, deposits in calorimeter, and segments from muon system)



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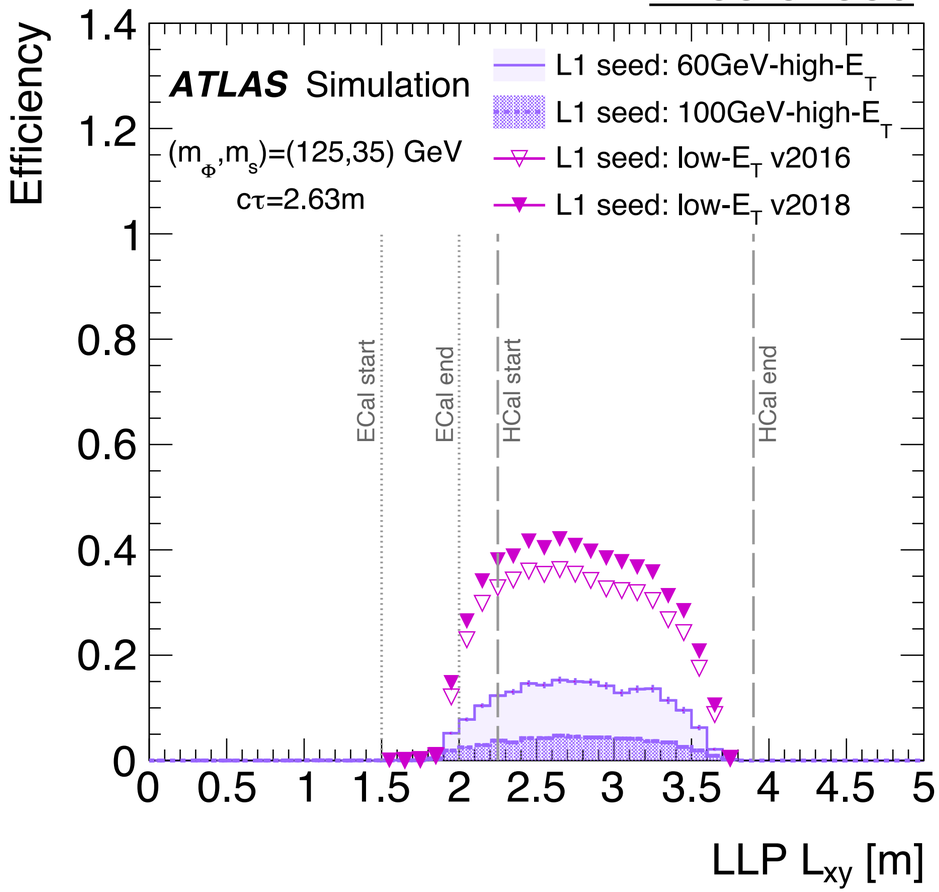
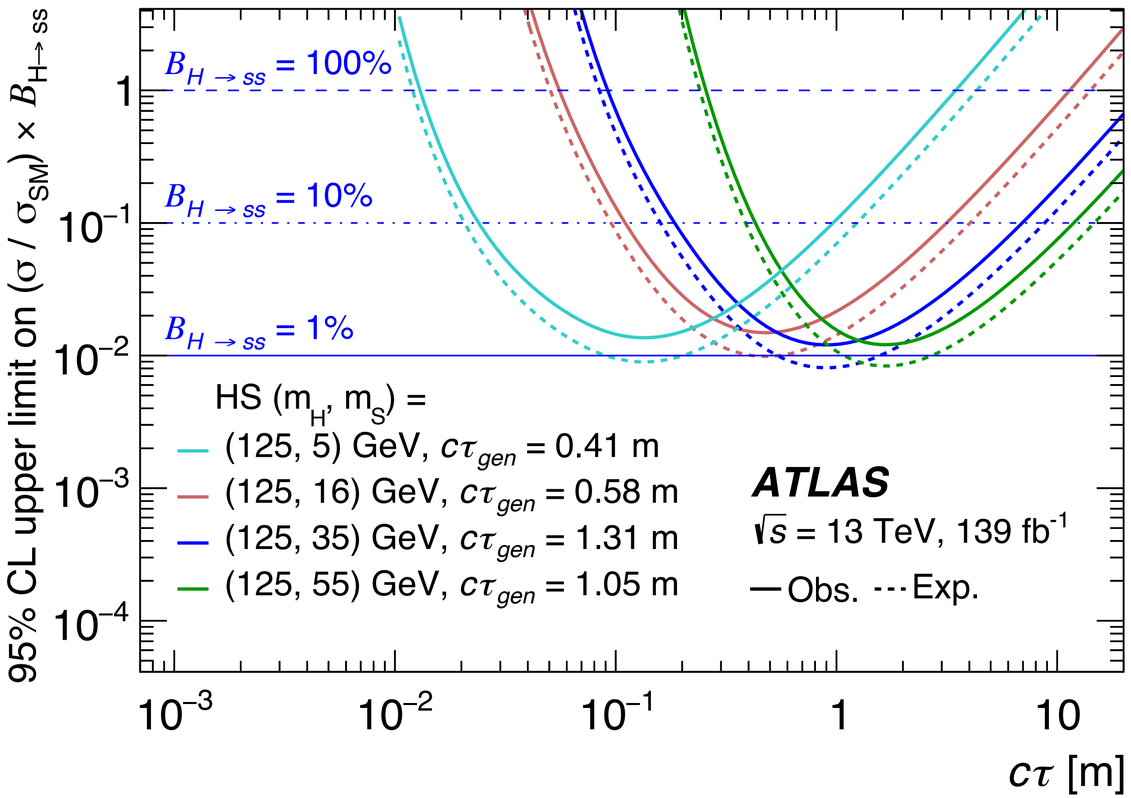


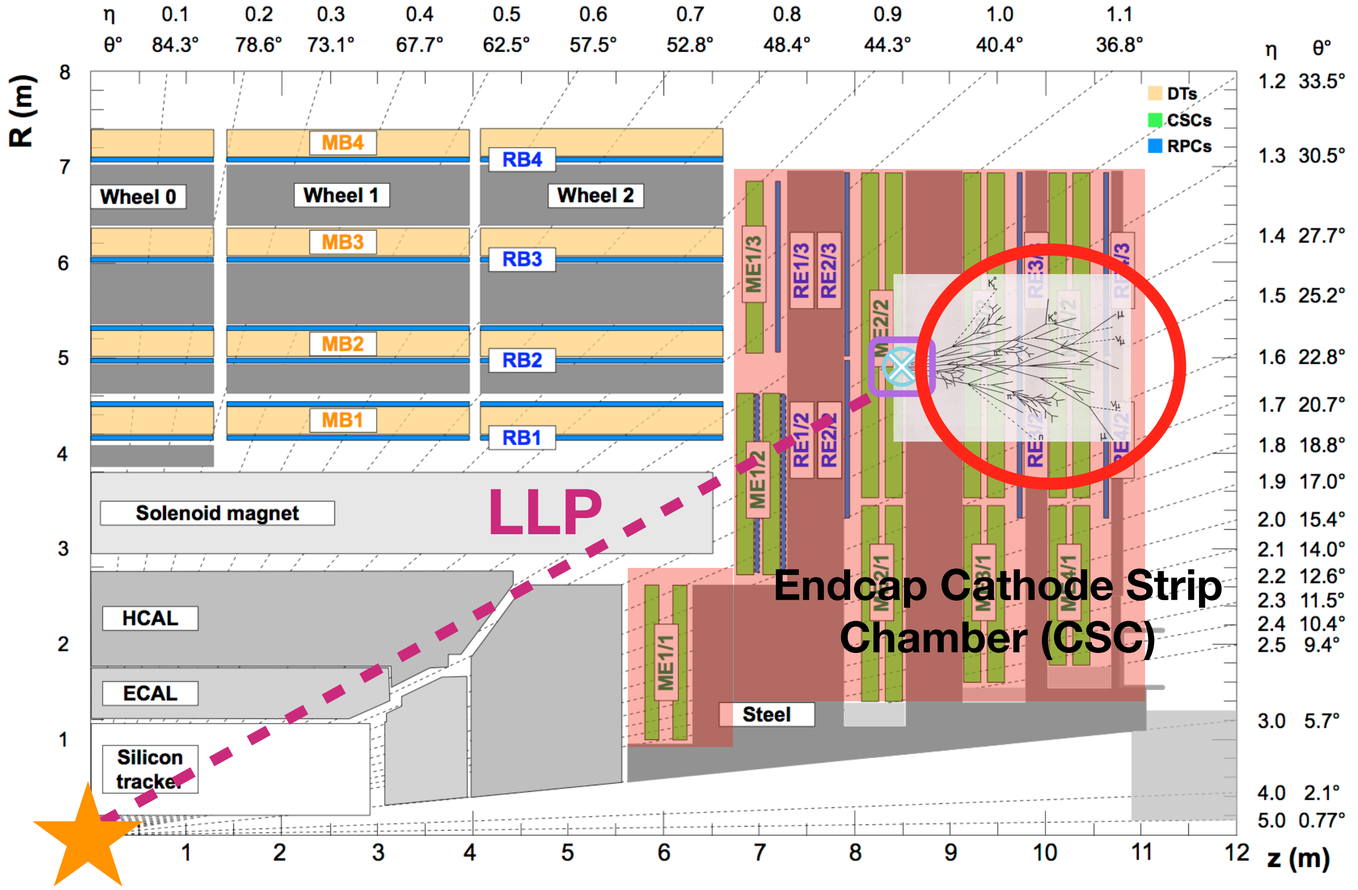
Decays in Calorimeter

Expected: 20.6 ± 4.0 events; observed: 23 events

- Dedicated boosted decision tree to remove **beam-induced background**
- Use data-driven estimation method to estimate **multi-jet background** in signal region
- Reach BR ~ 1.5% for LLP masses from 5 - 55 GeV
- 3-5x improvement from previous iteration



LLP Decays in Muon System

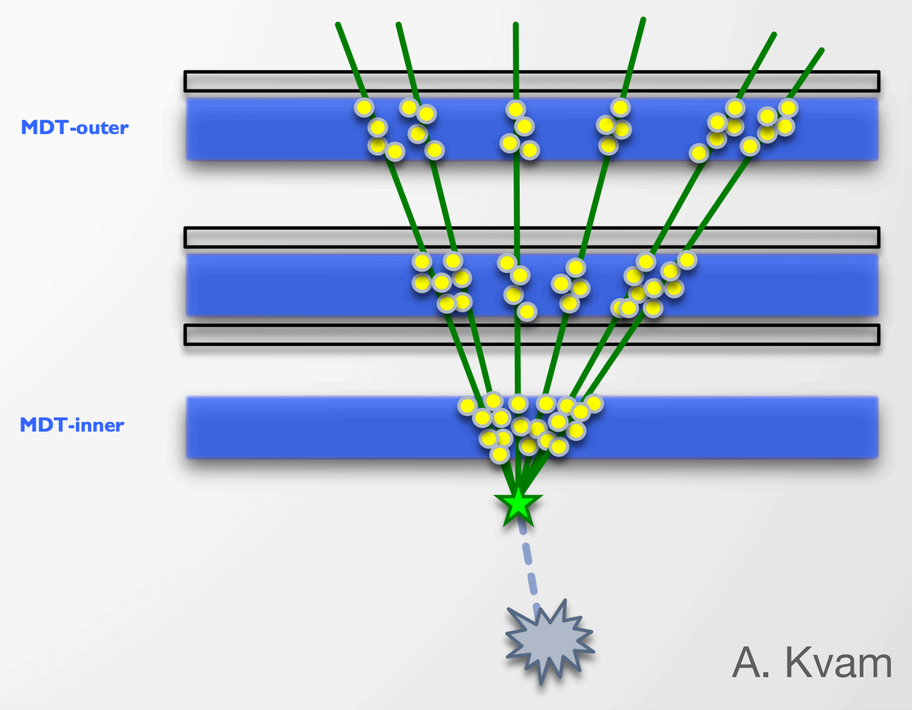


- **Large amount of shielding** from inner detectors and materials in front
- Very different designs of the ATLAS and CMS muon system
  - ATLAS: gas between stations → tracker → **displaced vertex**
  - CMS: steel between station → sampling calorimeter → **displaced shower**

Displaced Vertices in the ATLAS Muon System

NEW FULL RUN2 RESULT FROM ATLAS!

- **Dedicated trigger** for displaced vertices in the muon system
- Looks for **2 displaced vertices** in the muon system that are isolated from tracks and jets
  - Require both LLPs to decay in the muon system
  - Very small background by requiring 2 DV



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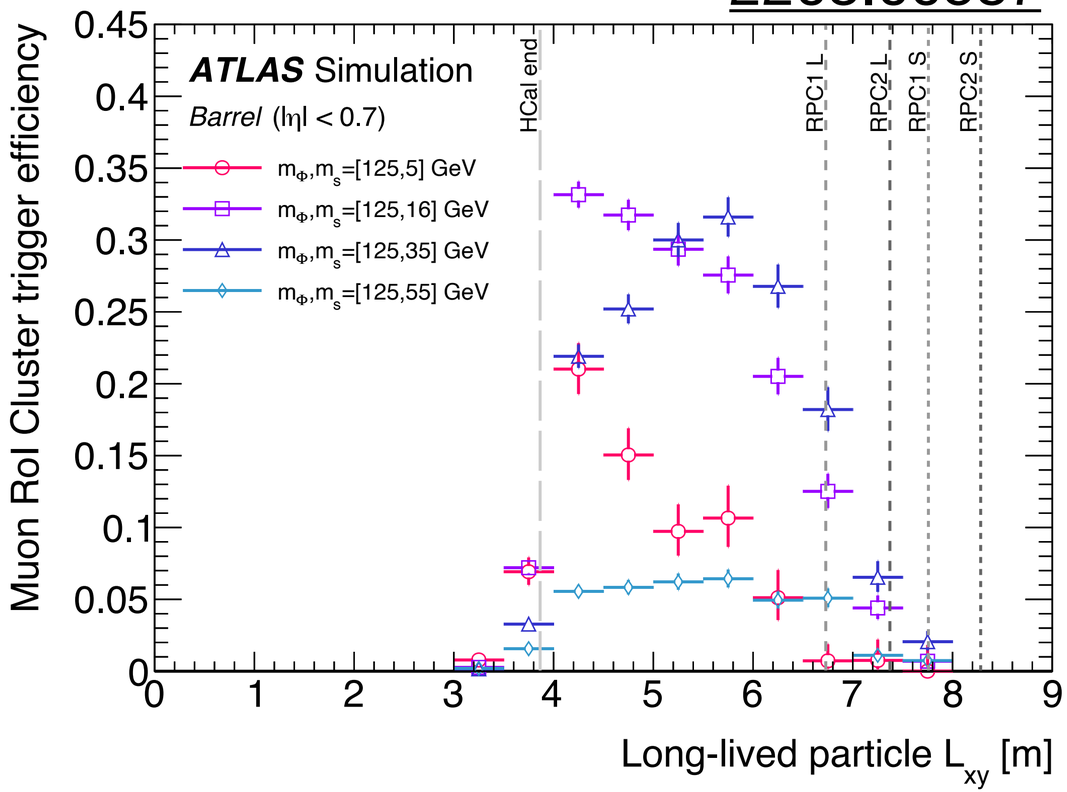
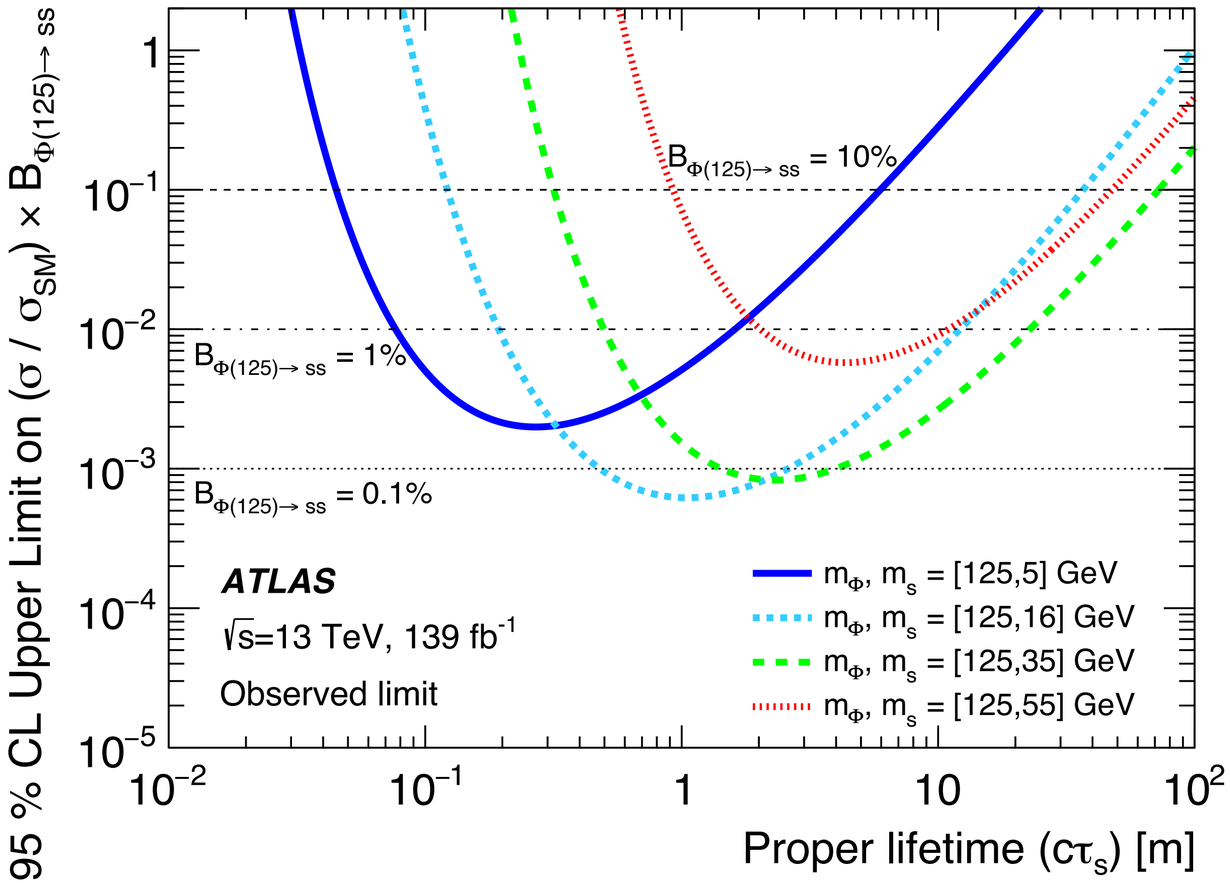


Displaced Vertices in the ATLAS Muon System

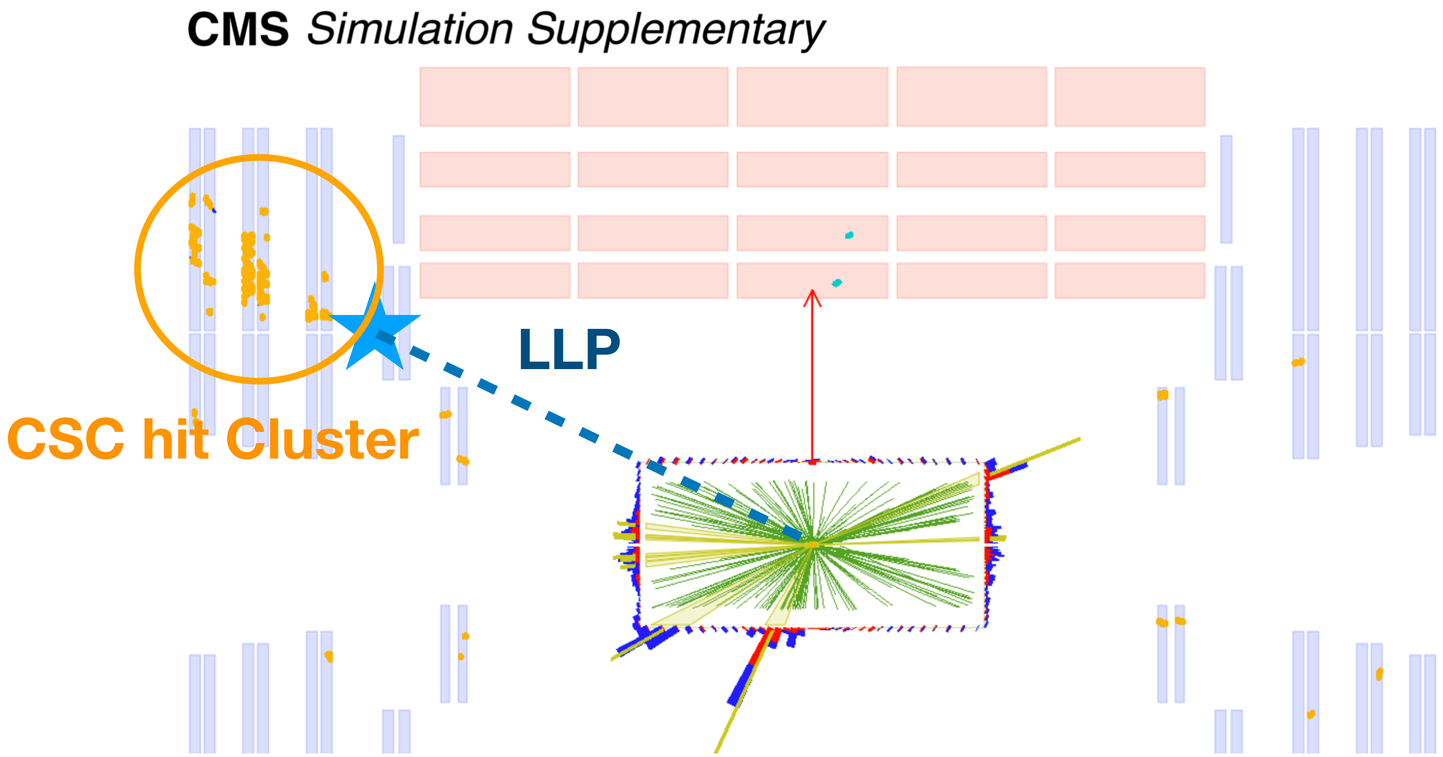
Expected: 0.32 ± 0.05 events; observed: 0 events



- First search to exclude **BR(h→SS) < 0.1%**
- Previous work with 2016 data (1DV+2DV): 1811.07370
- Ongoing effort to work on a full Run 2 result with 1 DV and a combination with the 2 DV result

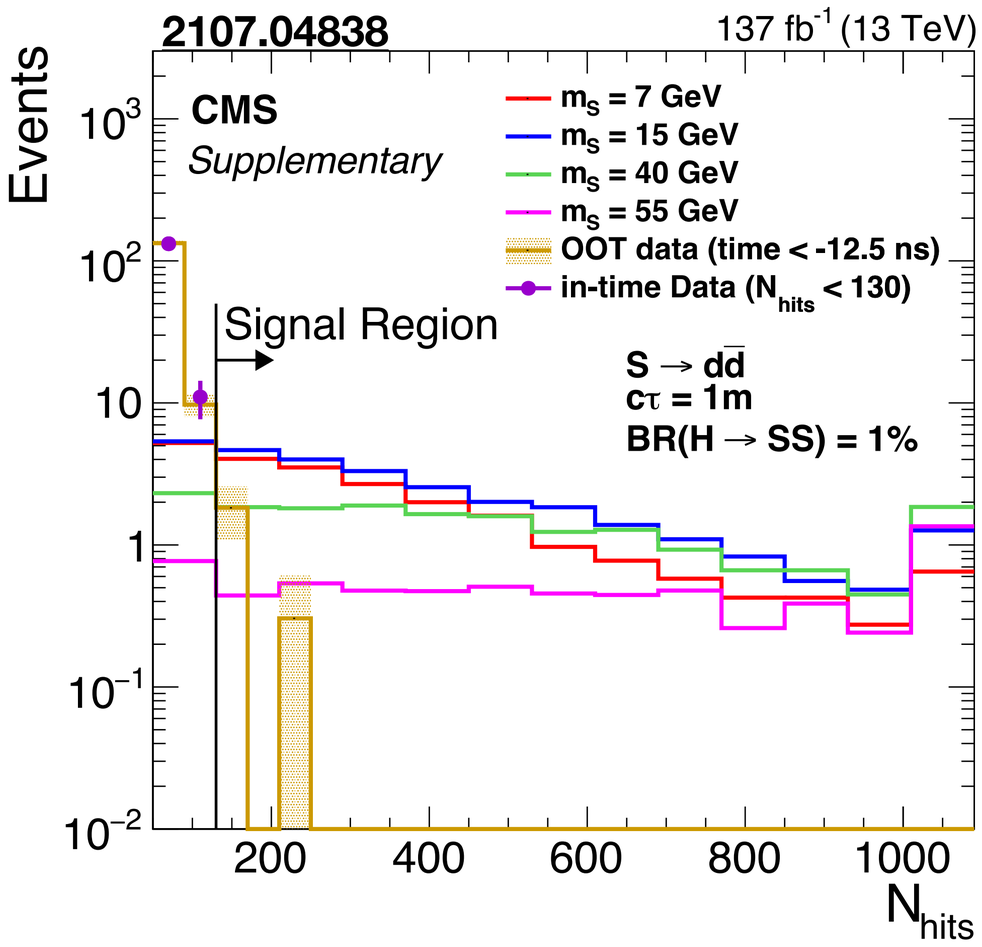
Displaced Showers in the CMS Endcap Muon System

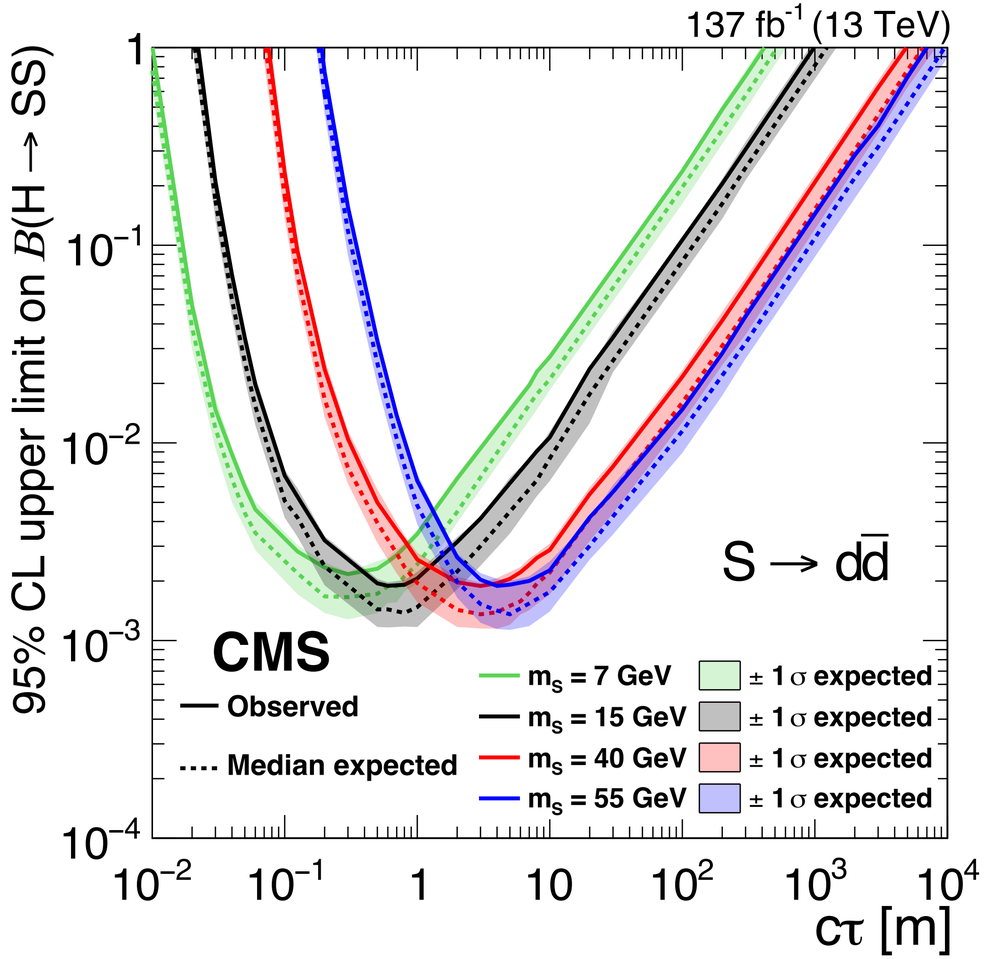
- Excellent **background suppression** from shielding material → unique to CMS
- Trigger with high MET due to lack of dedicated trigger (~1% efficiency)
- Looks for **1 displaced shower with high multiplicity (>130 hits)** isolated from jets and muons



* Note: only endcap is used in this analysis

Displaced Showers in the CMS Endcap Muon System

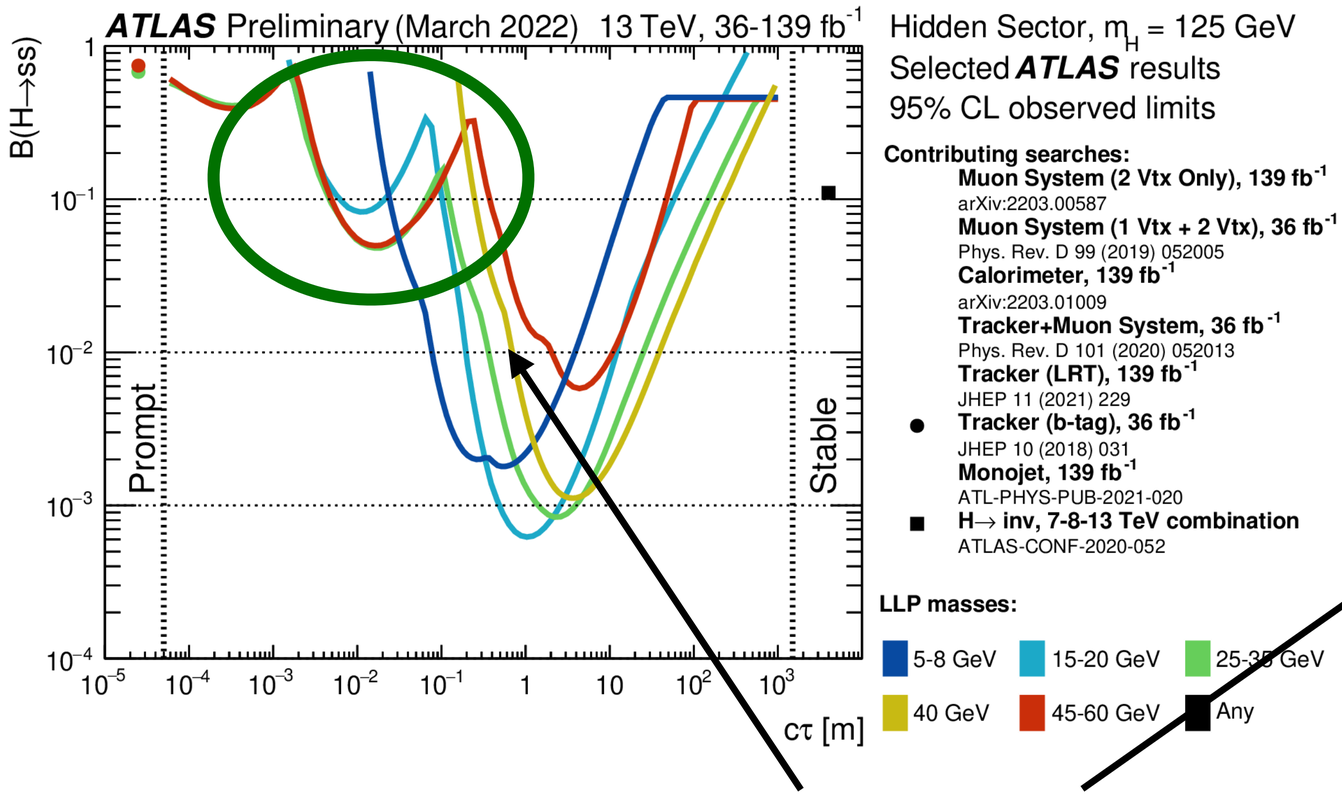




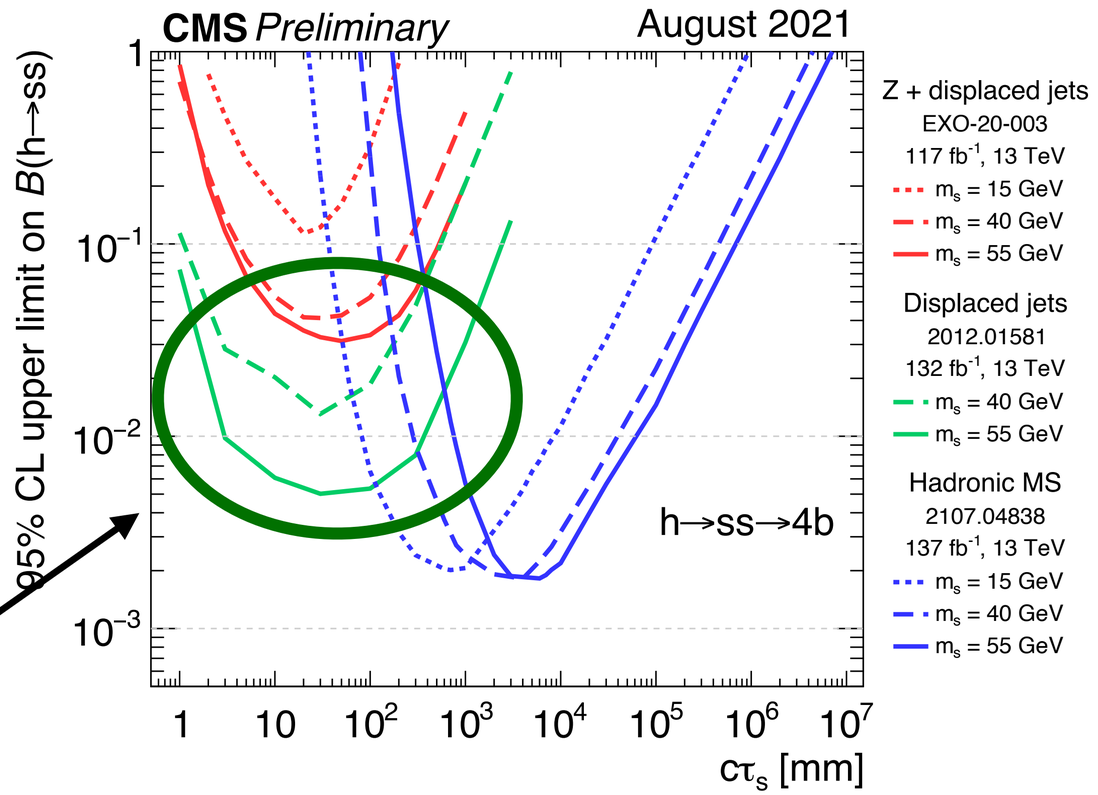
- Expected 2 ± 1 background events, 3 events observed
- Analysis sensitivity is **independent of LLP mass** → only sensitive to LLP energy
- A combination paper searching for 1 and 2 displaced shower in barrel + endcap is undergoing internal CMS review

Summary of Run 2 LLP Search Results

ATLAS



CMS



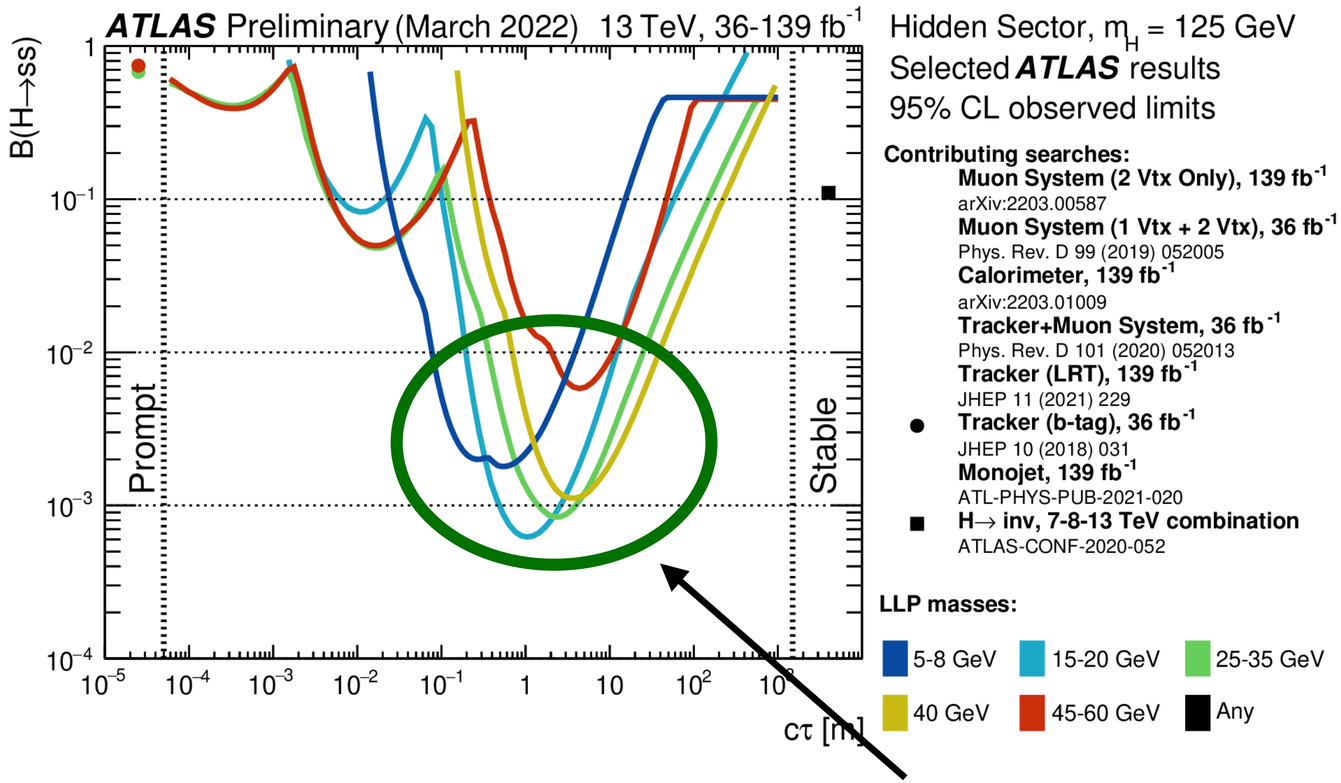
LLP decay in tracker

Tracker-based LLP trigger allow CMS to reach significantly lower BR for LLP decays in tracker

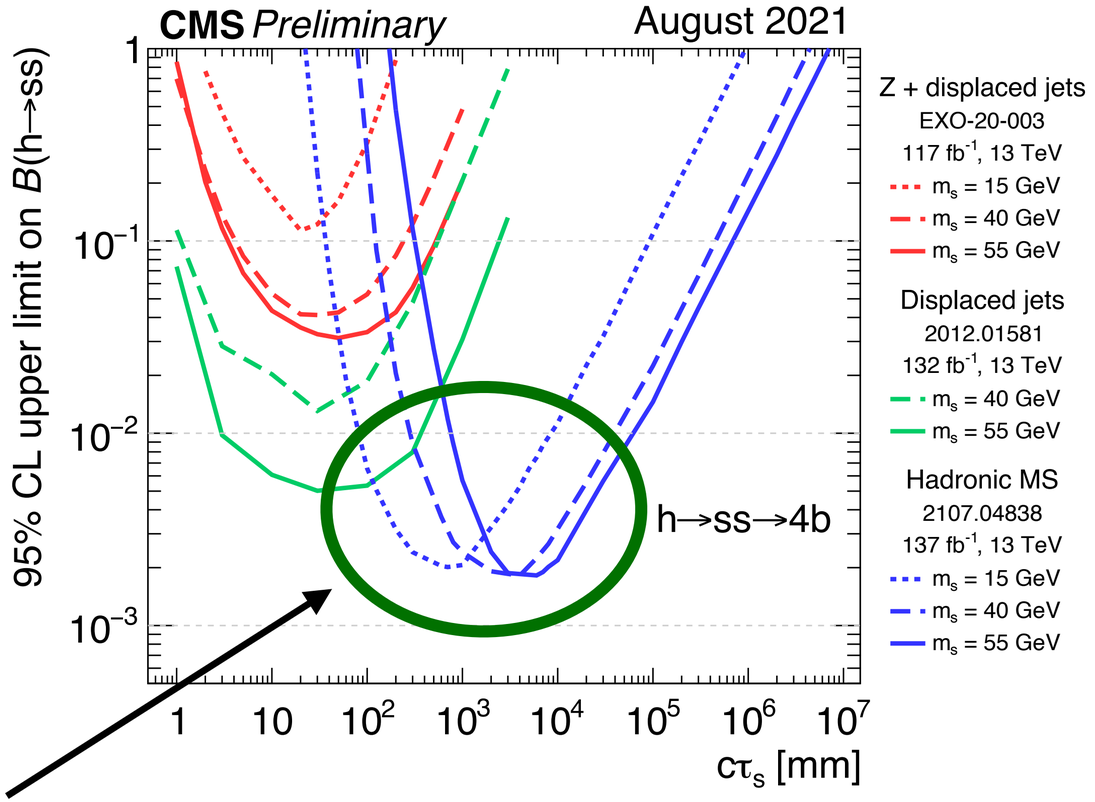
- Note the differences in branching ratio assumption

Summary of Run 2 LLP Search Results

ATLAS



CMS

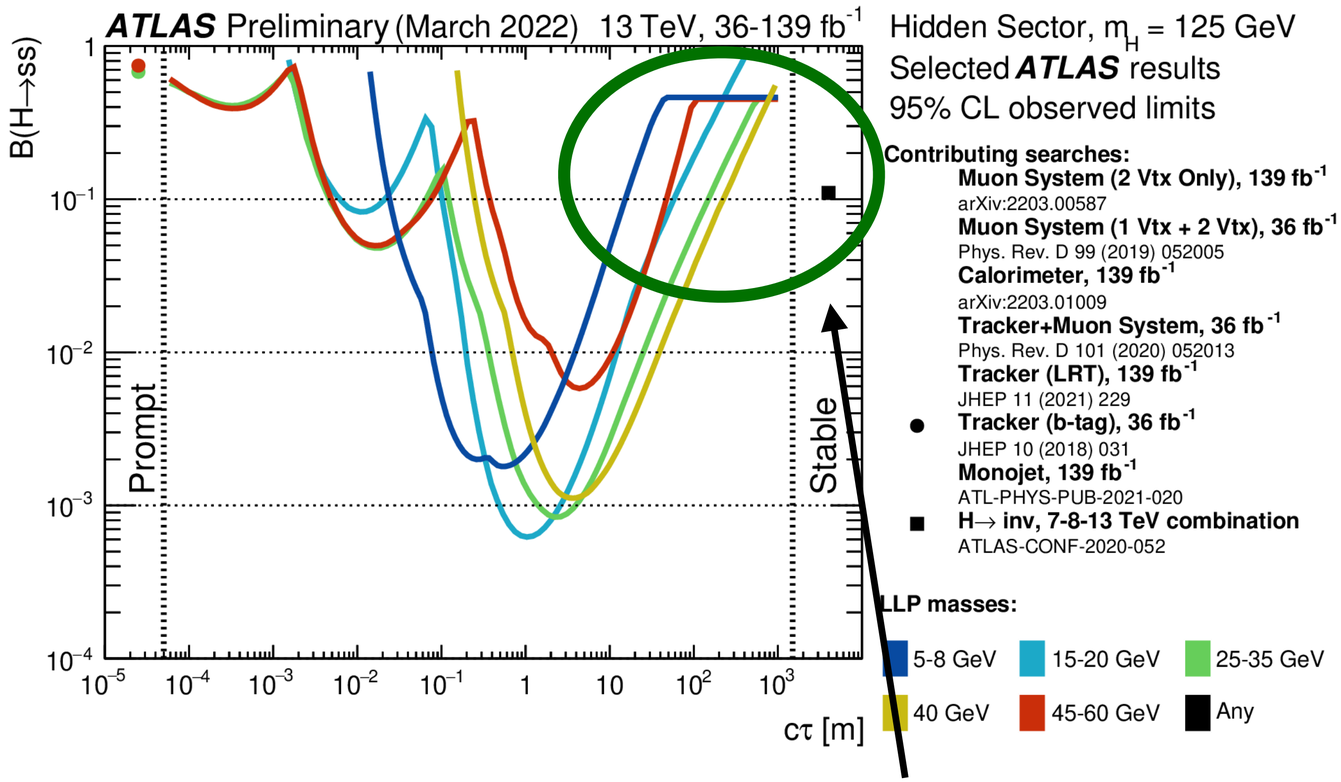


LLP decay in muon system

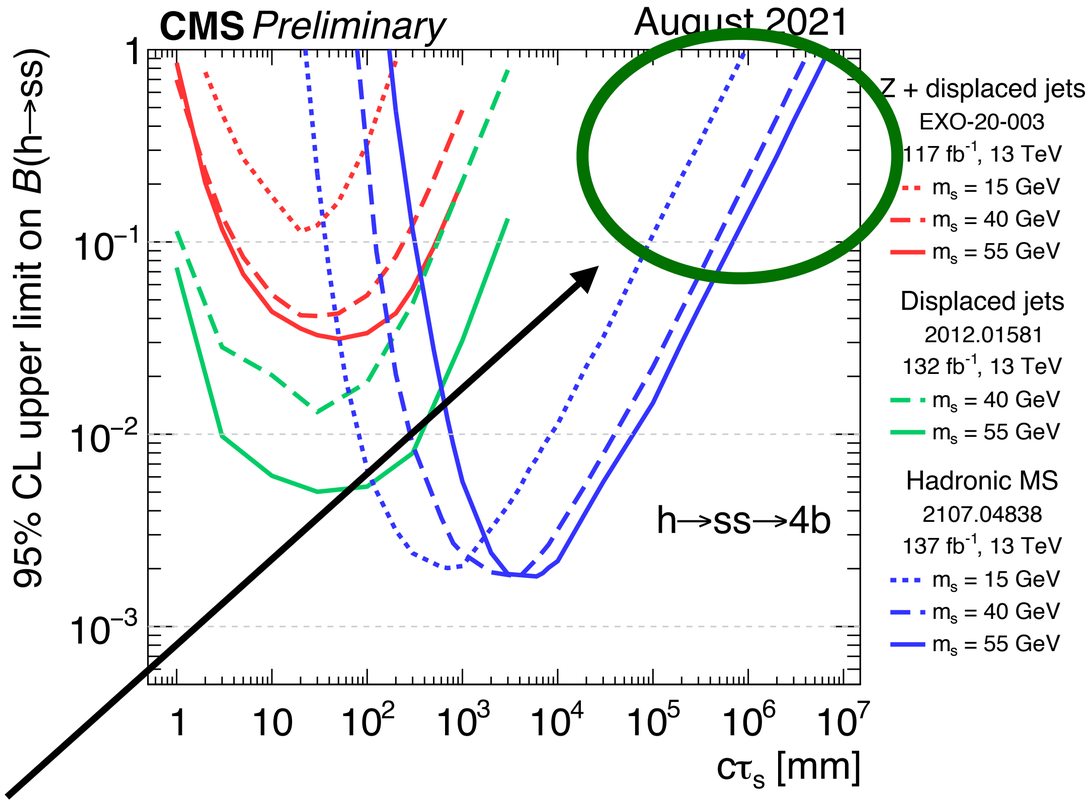
- **ATLAS reaches lower BR (< 0.1%) due to dedicated trigger in muon system**
- CMS extends to longer cτ due to the 1 displaced shower requirement
- For both detectors, the muon system analysis set the most stringent limits
  - Note the differences in branching ratio assumption

Summary of Run 2 LLP Search Results

ATLAS



CMS



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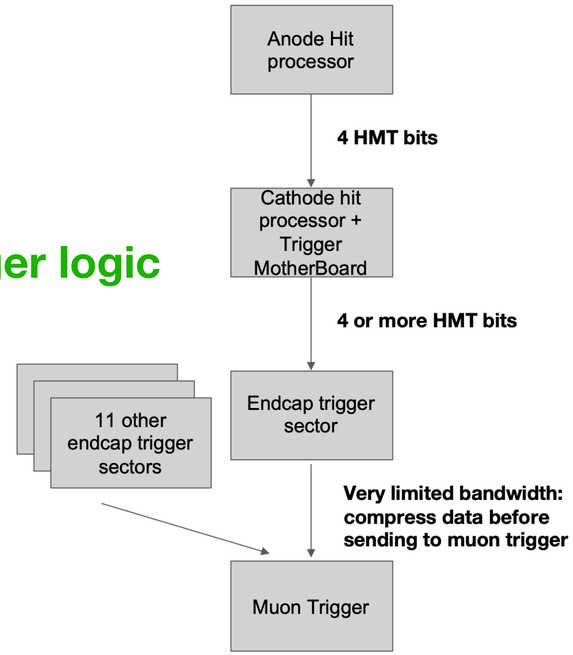
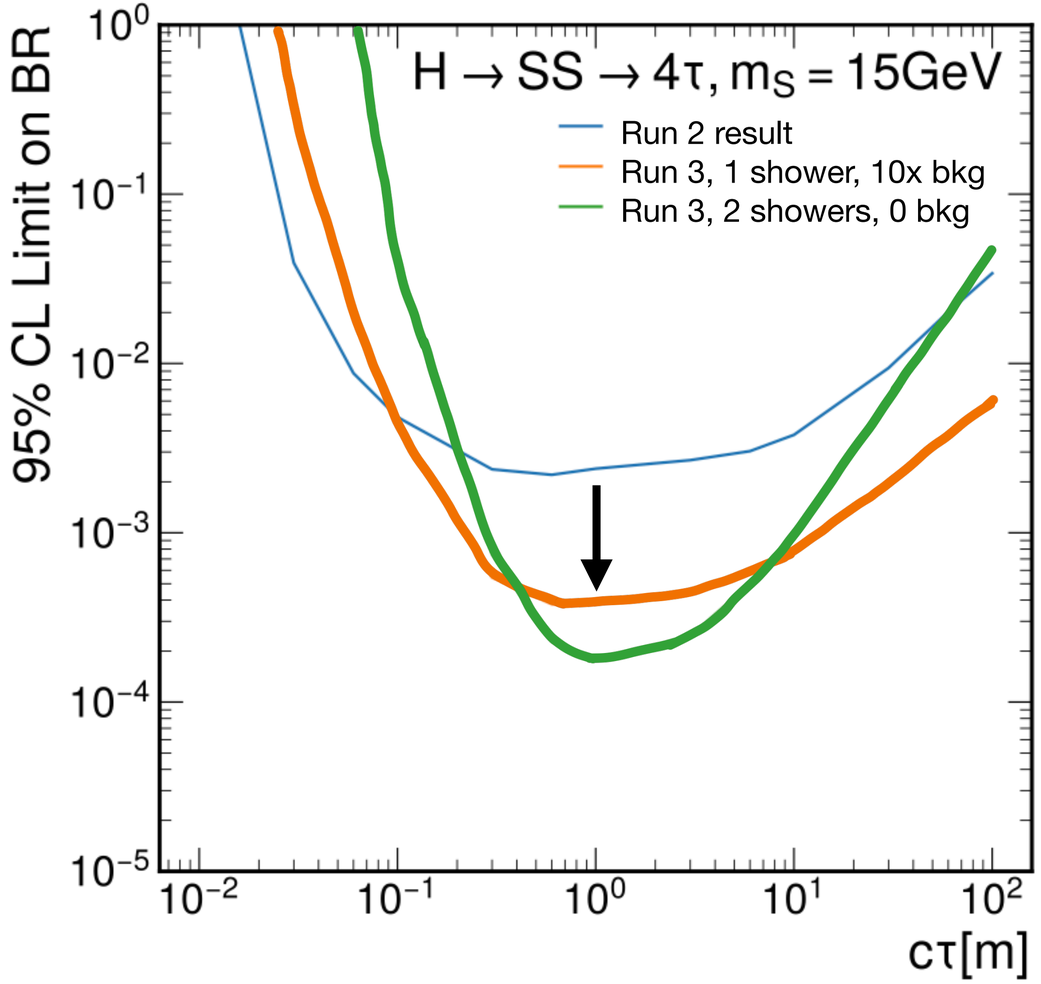
  - Note the differences in branching ratio assumption

NEW LLP L1 Trigger for CMS Run 3

- **CMS is catching up with ATLAS in implementing LLP triggers**
- **Displaced shower in muon system**
  - Select for high multiplicity in muon system
  - **~10-20x** improvement in trigger efficiency
  - Enable new search signatures **MS-ECAL, MS-Tracker** and models: **τ-type HNL**

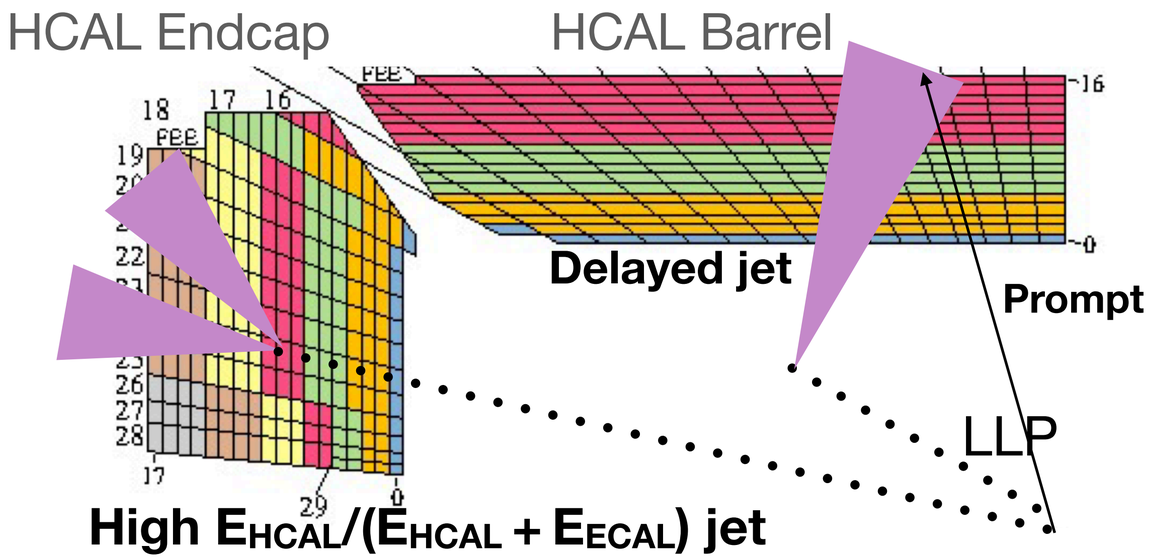
Level 1 trigger logic





NEW LLP L1 Trigger for CMS Run 3

- **LLP decays using upgraded HCAL (Phase 1)**
  - **Timing** to select LLPs that are delayed wrt collision
  - **Depth information** to select LLPs that deep in HCAL, requiring high E_{HCAL}/E_{ECAL}
  - Enable new searches with LLPs decay using calorimeter for CMS

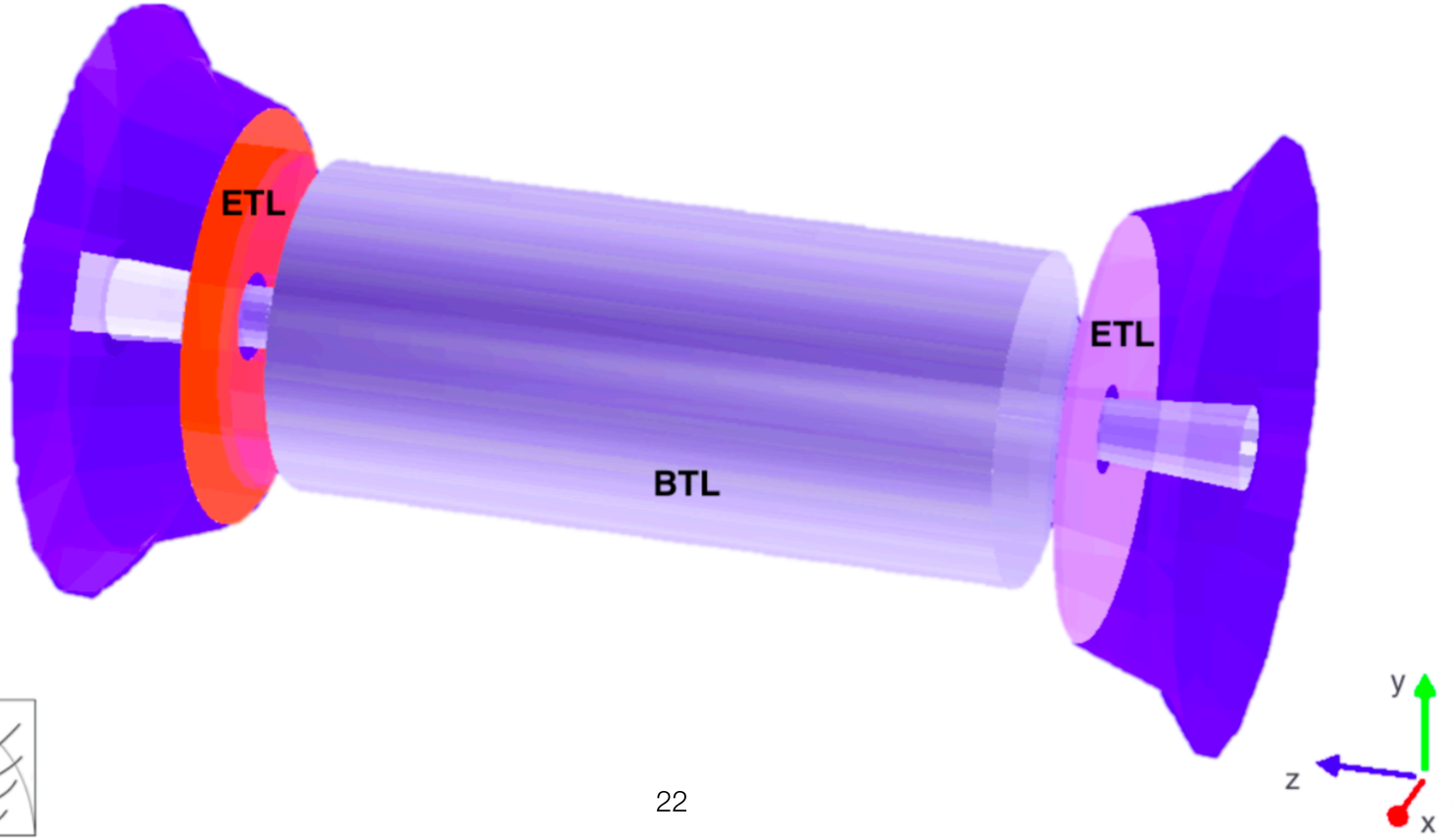


Towards HL-LHC

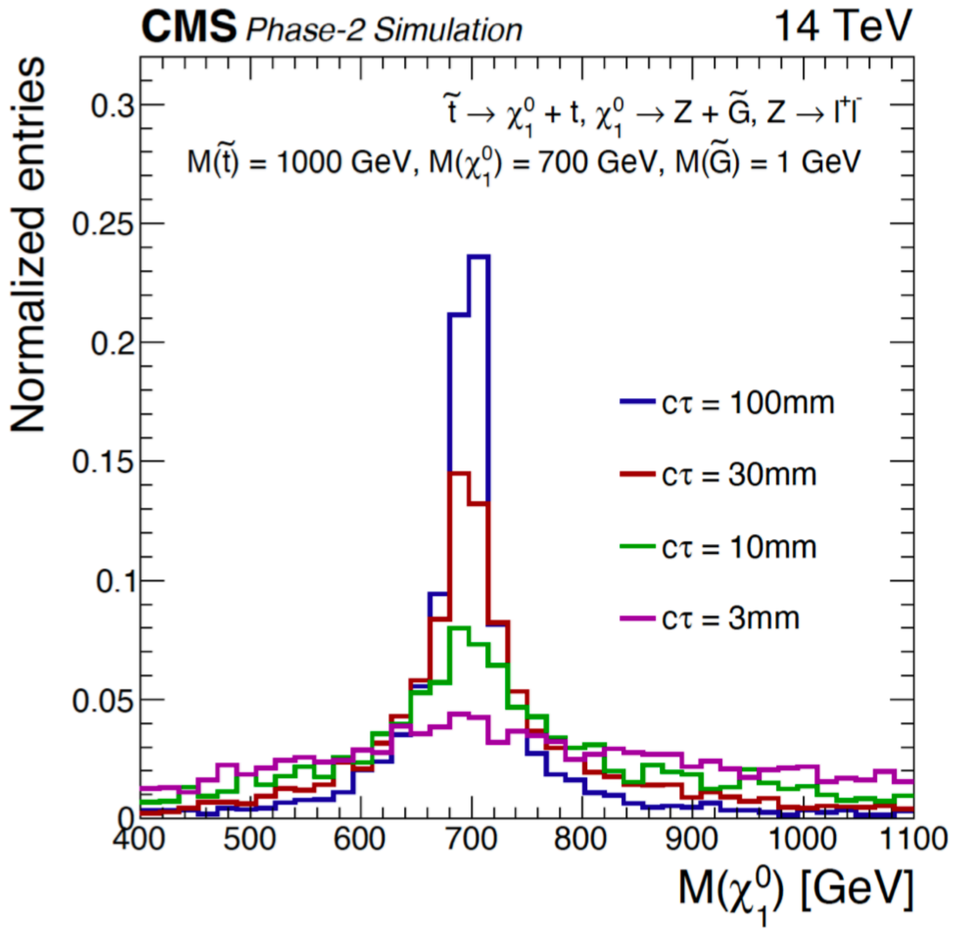
- LHC will be upgraded to deliver higher beam intensity (30 → 200 pileup), delivering a total of 3000 fb^{-1} of data (20x more data)
- **Significant upgrade** to ATLAS & CMS:
  - Increased granularity
  - Higher bandwidth and capabilities in trigger
  - New sub-detectors extending coverage
- Sensitivity of LLP searches can be extended significantly by **improvement in detector performance**

NEW Timing Capabilities

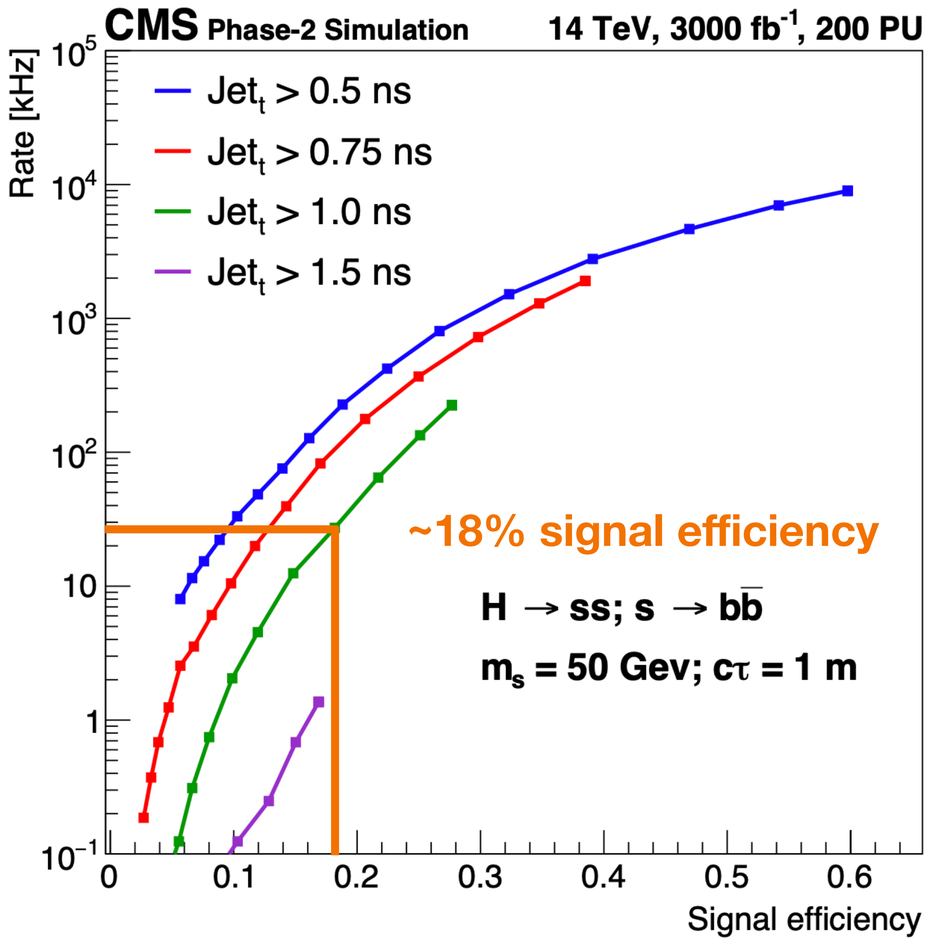
- Both CMS & ATLAS will have a new timing detector with **30ps** for minimum ionizing particles (MIP)
  - Thin layer (~4 cm) between tracker and ECAL
- CMS ECAL will have a 30ps timing resolution at the trigger level
  - Upgraded readout electronics and higher-bandwidth shaping amplifiers



LLP Physics Impact



New mass reconstruction capabilities



New L1 trigger on delayed jets using ECAL timing

Summary

- Presented overview of hadronic LLP searches at CMS and ATLAS
- A large, complimentary, and evolving program of searches utilizing special capabilities of all sub-detectors
- New Run 3 trigger capabilities will maximize discovery potential for existing detectors
- HL-LHC and Phase-2 detector upgrades will enable entirely new LLP search signatures

CMS Phase2 Upgrade

Trigger/HLT/DAQ

- Track information in L1-Trigger
- L1-Trigger: 12.5 ms latency – output 750 kHz
- HLT output 7.5 kHz

Barrel ECAL/HCAL

- Replace FE/BE electronics
- Lower ECAL operating temp. (8 °C)

Muon Systems

- Replace DT & CSC FE/BE Electronics
- Complete RPC coverage in region 1.5<h<2.4
- Muon tagging 2.4<h<3

New Endcap Calorimeters

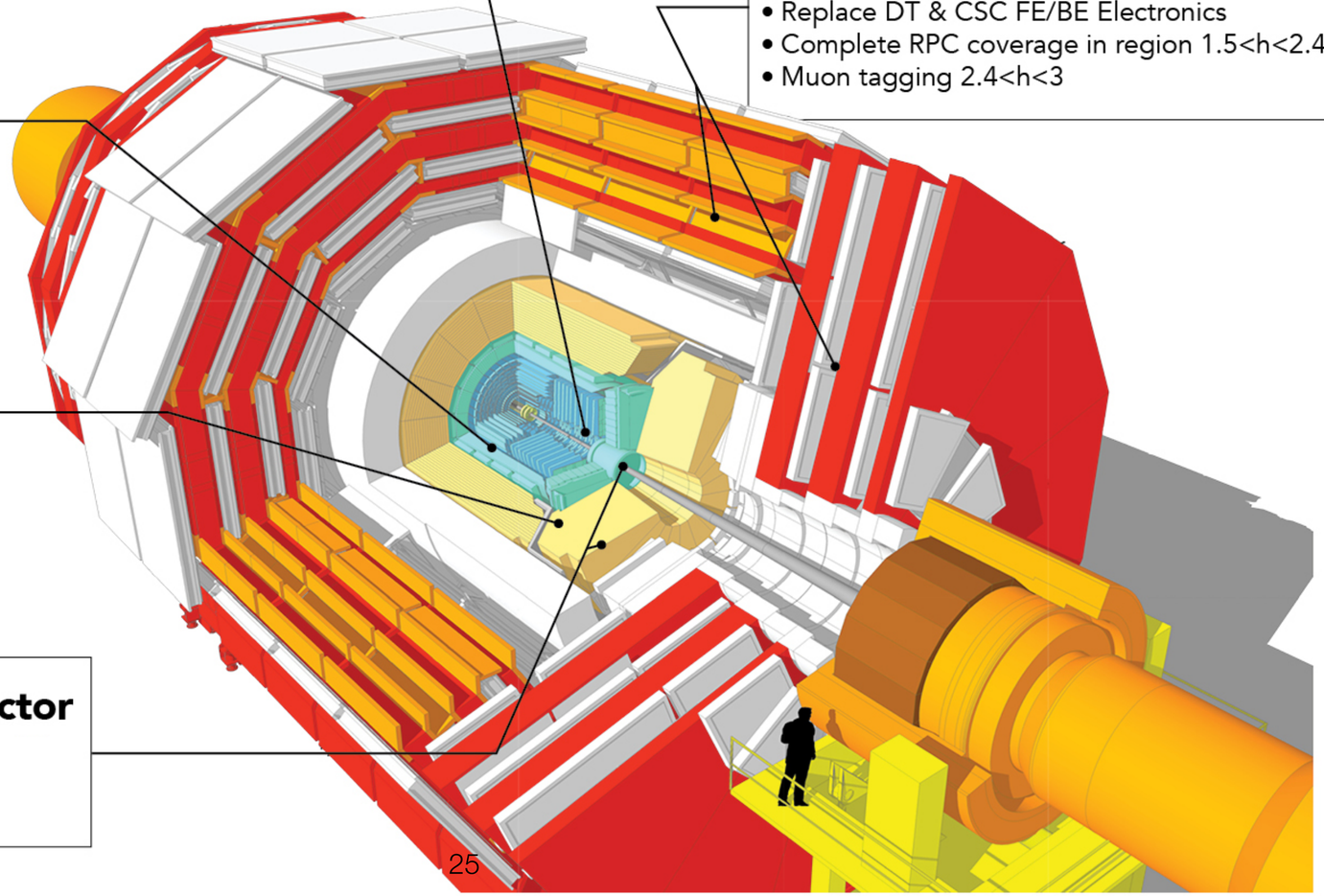
- Rad. tolerant – high granularity
- 3D capable

New Tracker

- Rad. tolerant – high granularity – significant less material
- 40 MHz selective readout (pT>2 GeV) in Outer Tracker for L1 -Trigger
- Extended coverage to h=4

MIP Precision Timing Detector

- Barrel: Crystal +SiPM
- Endcap: Low Gain Avalanche Diodes

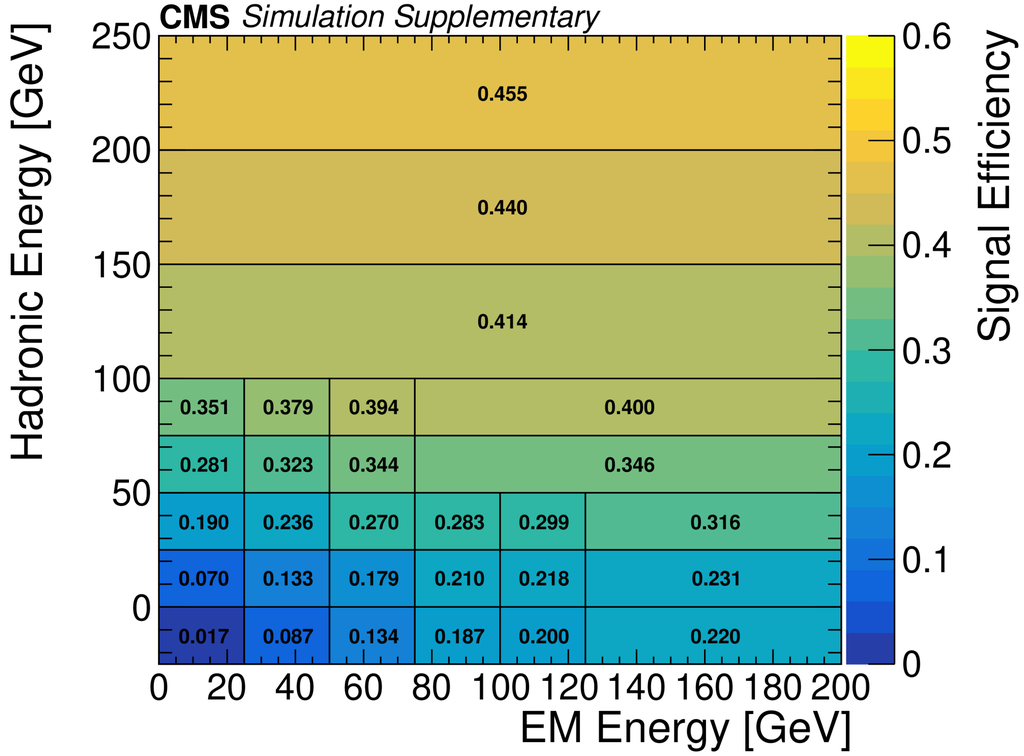


Reinterpretation Materials

- LLPs can arise in MANY other models…
- These searches are driven by the displaced signatures and are **model independent**
- Efforts to provide parametrized object-level efficiencies and detailed instructions on HEPData, which would allow anyone to recast the search with any theoretical models

CMS MS search provided cluster reconstruction efficiency as a function of LLP energy

https://www.hepdata.net/record/104408



CMS trigger system

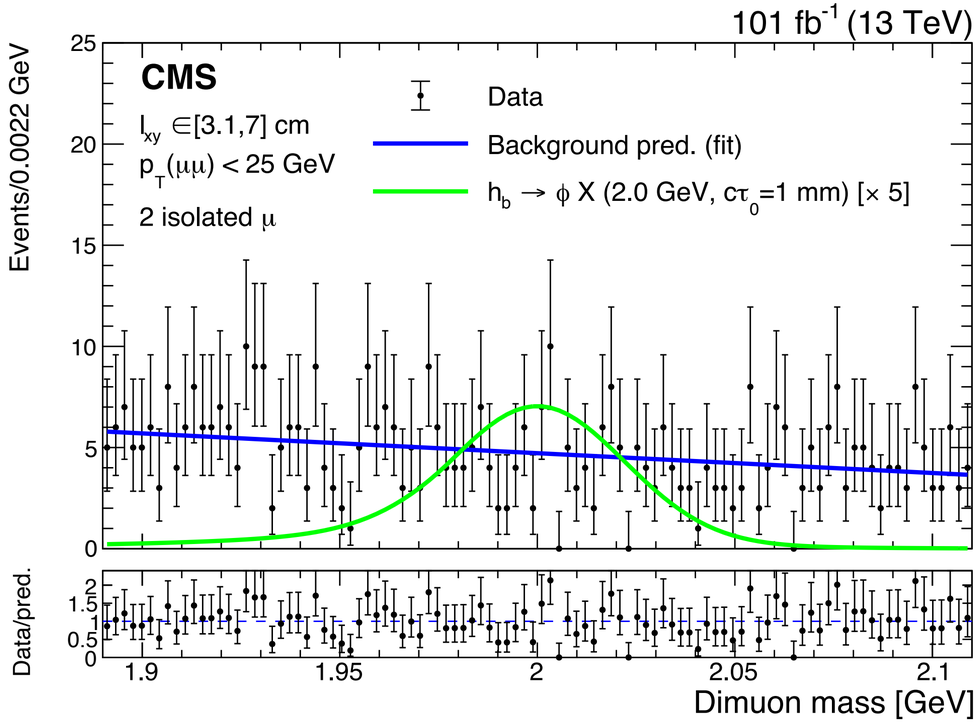
- 2-tier trigger system
- L1 trigger: custom electronics
  - up to 100 kHz, with 4us latency
  - Only calorimeter and muon system detector information available (limited number of bits)
- HLT: commercial PC
  - 1-2kHz, 300 ms latency
  - All sub-detectors available, possible to run complex algorithm, PF algorithm
  - Limited by CPU time and disk space

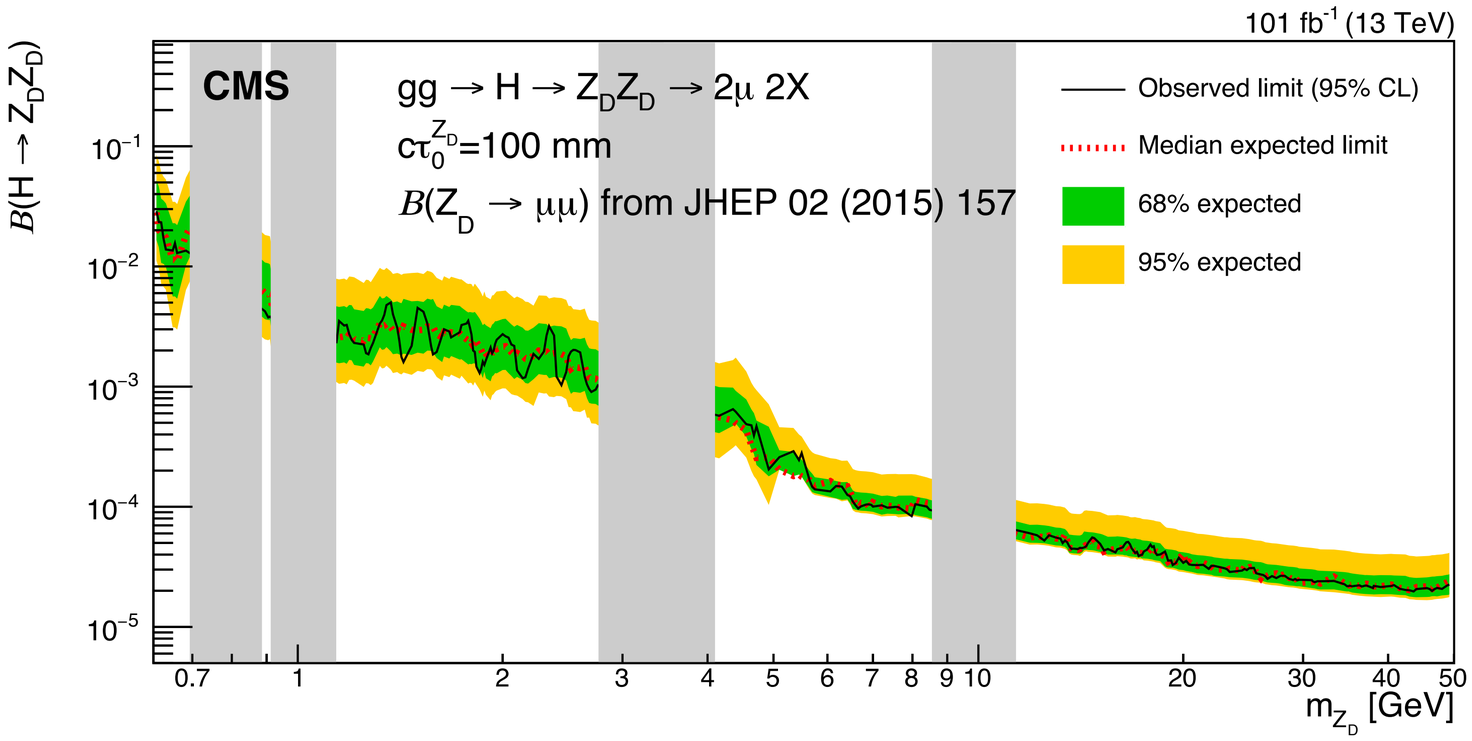
CMS Scouting Stream

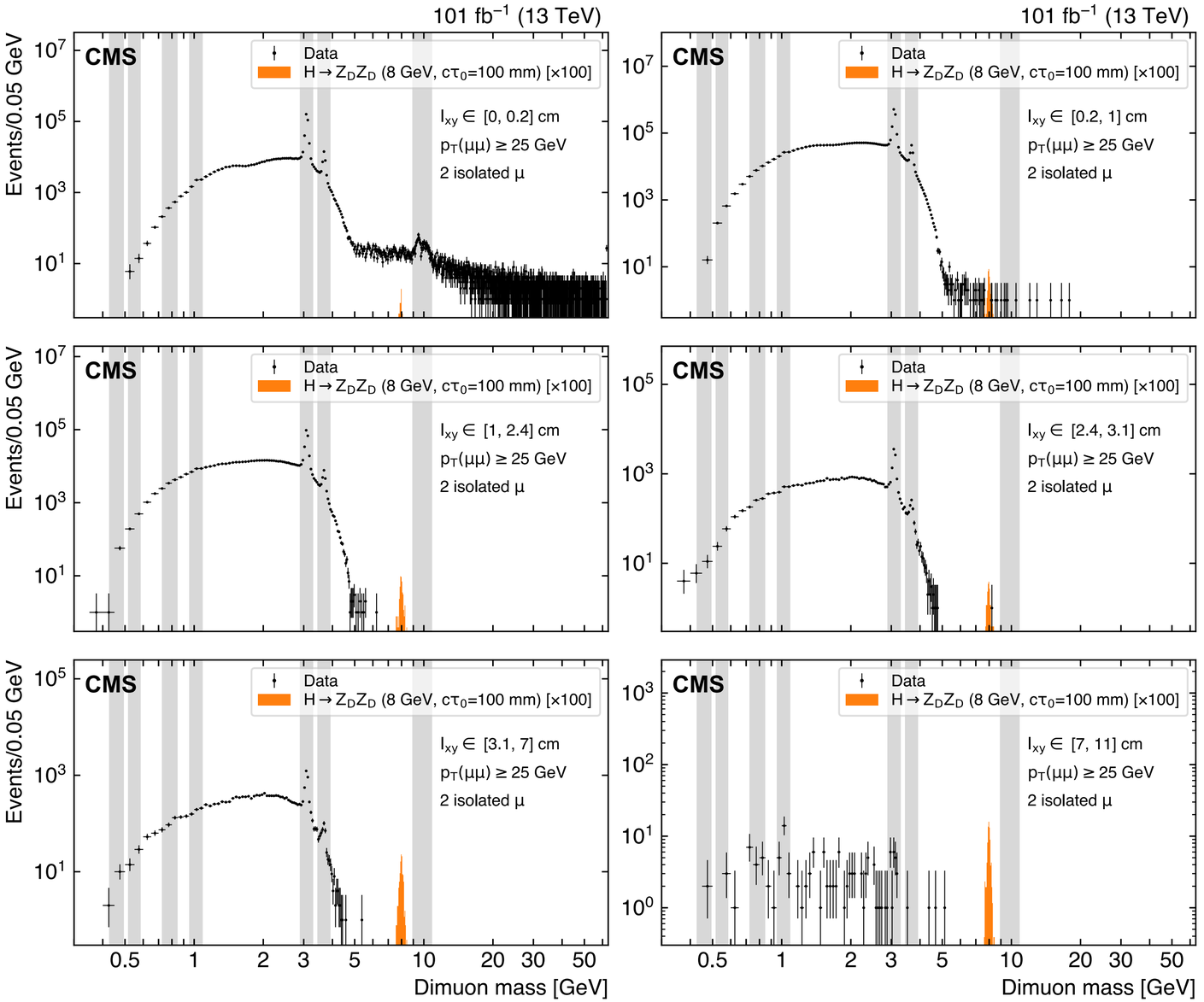
- CMS trigger mostly select for high pT and prompt events
- bandwidth = event rate × event size
- To increase the rate (decrease threshold), we need to decrease event size
- Rate is about 3kHz, event size is reduced by up to 1000x by only retaining limited HLT information

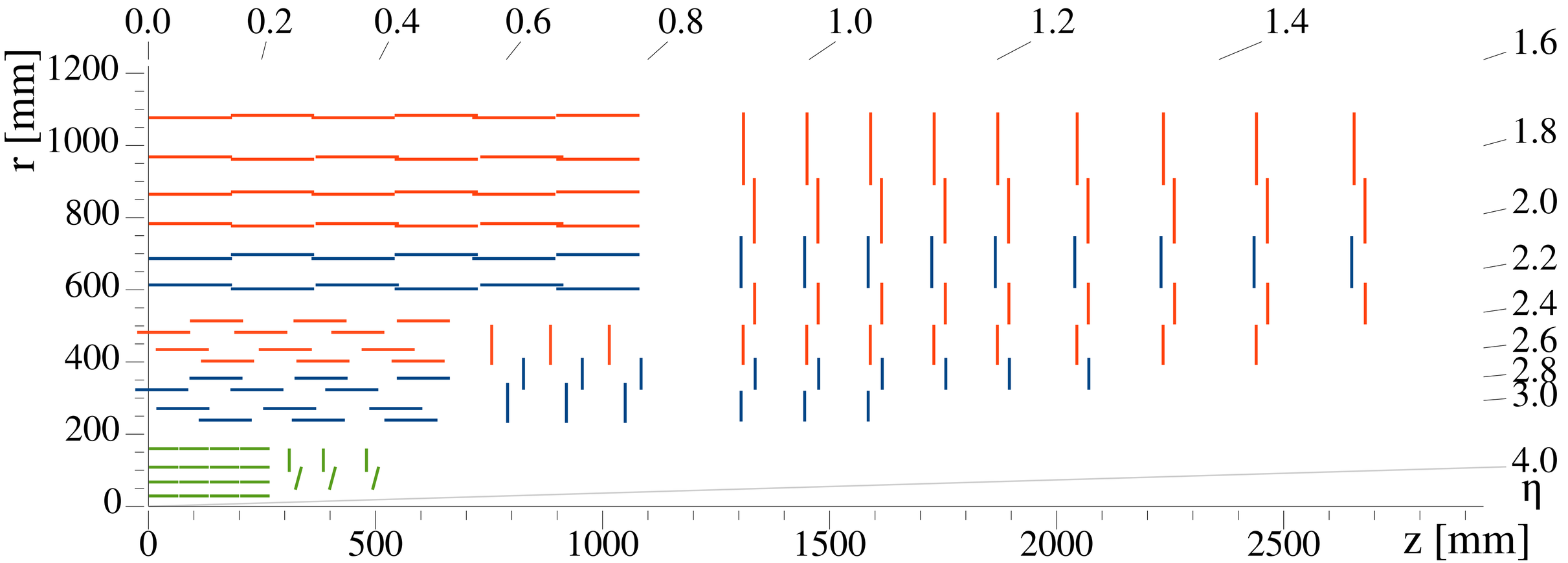
Displaced Low-Mass Dimuons

- Scouting data stream allow unprecedented mass reach of $m_{\mu\mu} > 200$ MeV
- Select events with 2 displaced muons and 1 associated DV [l_{xy}~0-11cm]
- Look for narrow resonant peak over the background continuum by simultaneous fit in all event categories in steps of signal mass resolution

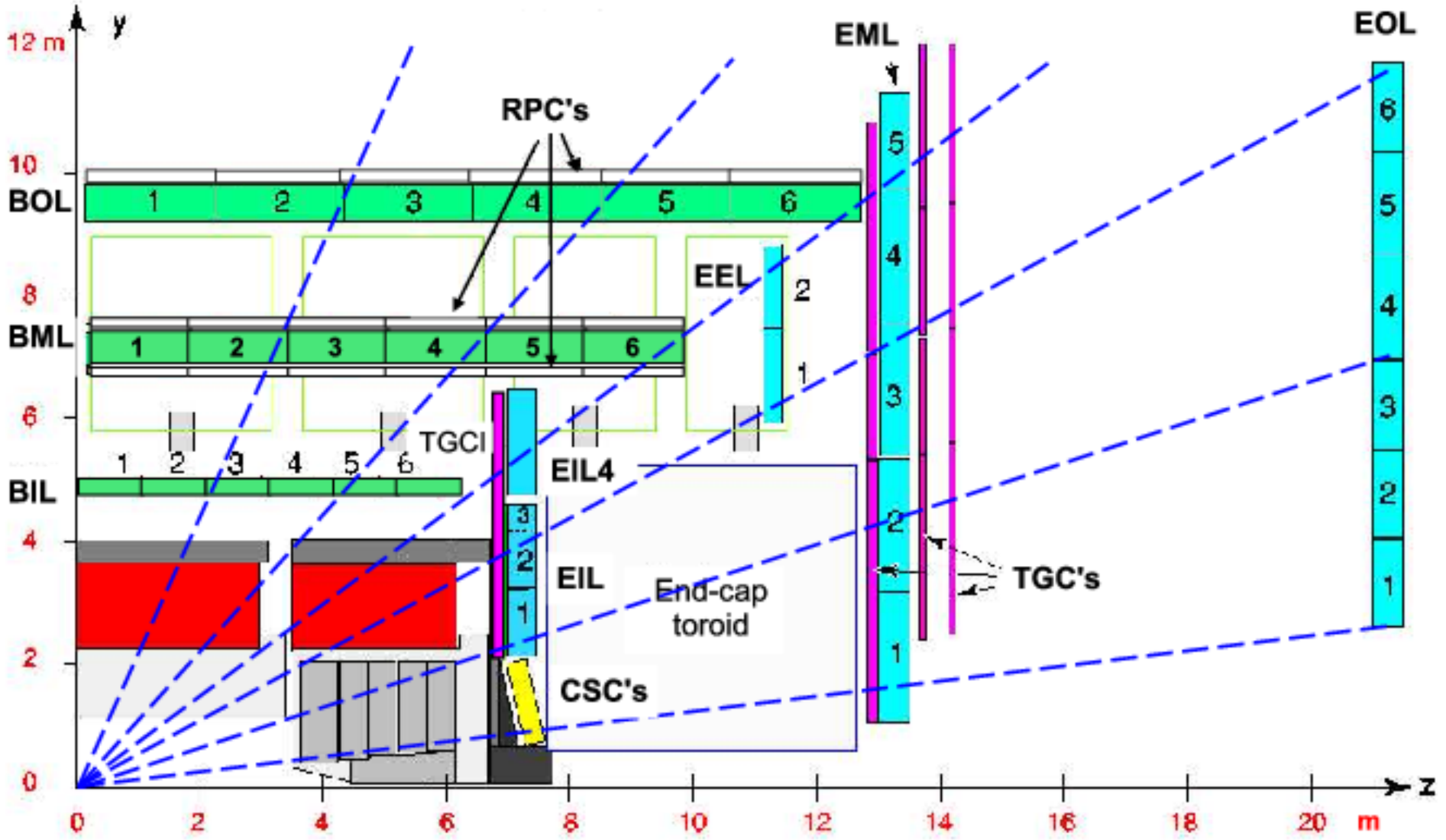





101 fb^{-1} (13 TeV)
CMS
Data
H → $Z_D Z_D$ (8 GeV, cτ$_0$=100 mm) [×100]
l_{xy} ∈ [0, 0.2] cm
$p_T(\mu\mu) \geq 25$ GeV
2 isolated μ
l_{xy} ∈ [0.2, 1] cm
l_{xy} ∈ [1, 2.4] cm
l_{xy} ∈ [2.4, 3.1] cm
l_{xy} ∈ [3.1, 7] cm
l_{xy} ∈ [7, 11] cm
Events/0.05 GeV
Dimuon mass [GeV]



- The pixel detector is shown in green, while single-sided and double-sided strip modules are depicted as red and blue segments, respectively.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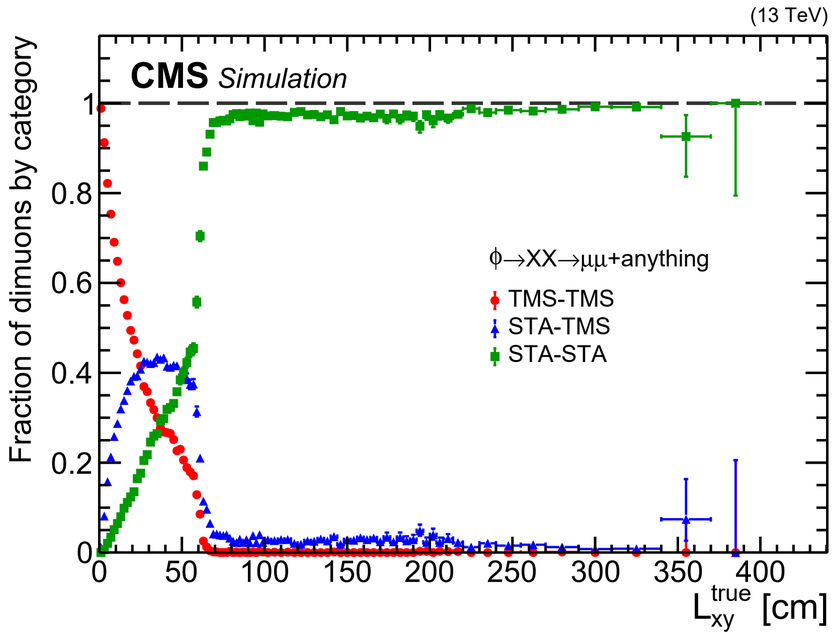
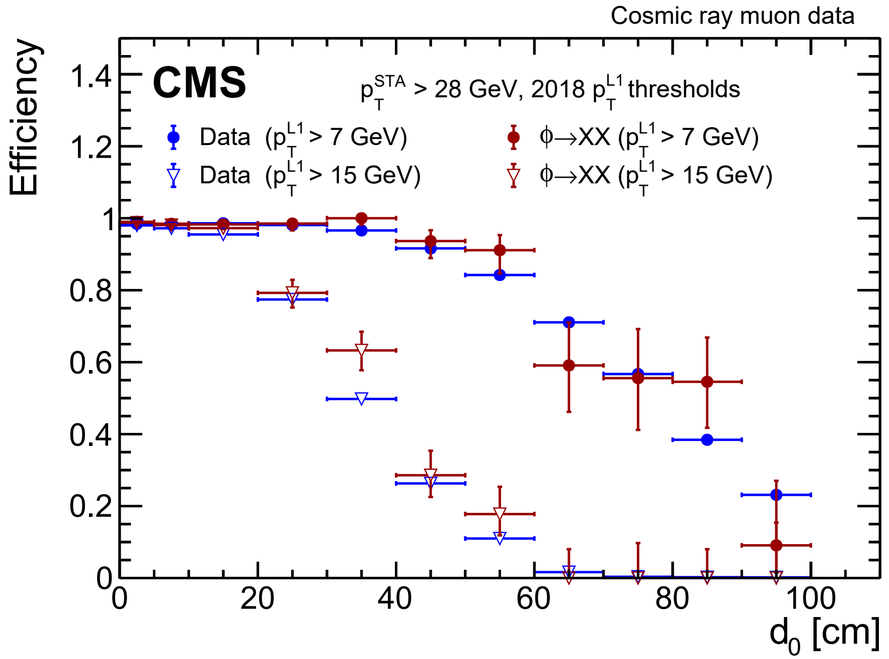
Displaced Dimuon Search

- Look for 2 muons, the muon can be reconstructed with tracker and muon system or muon system only
- Only 2016+2018 data, 97fb-1





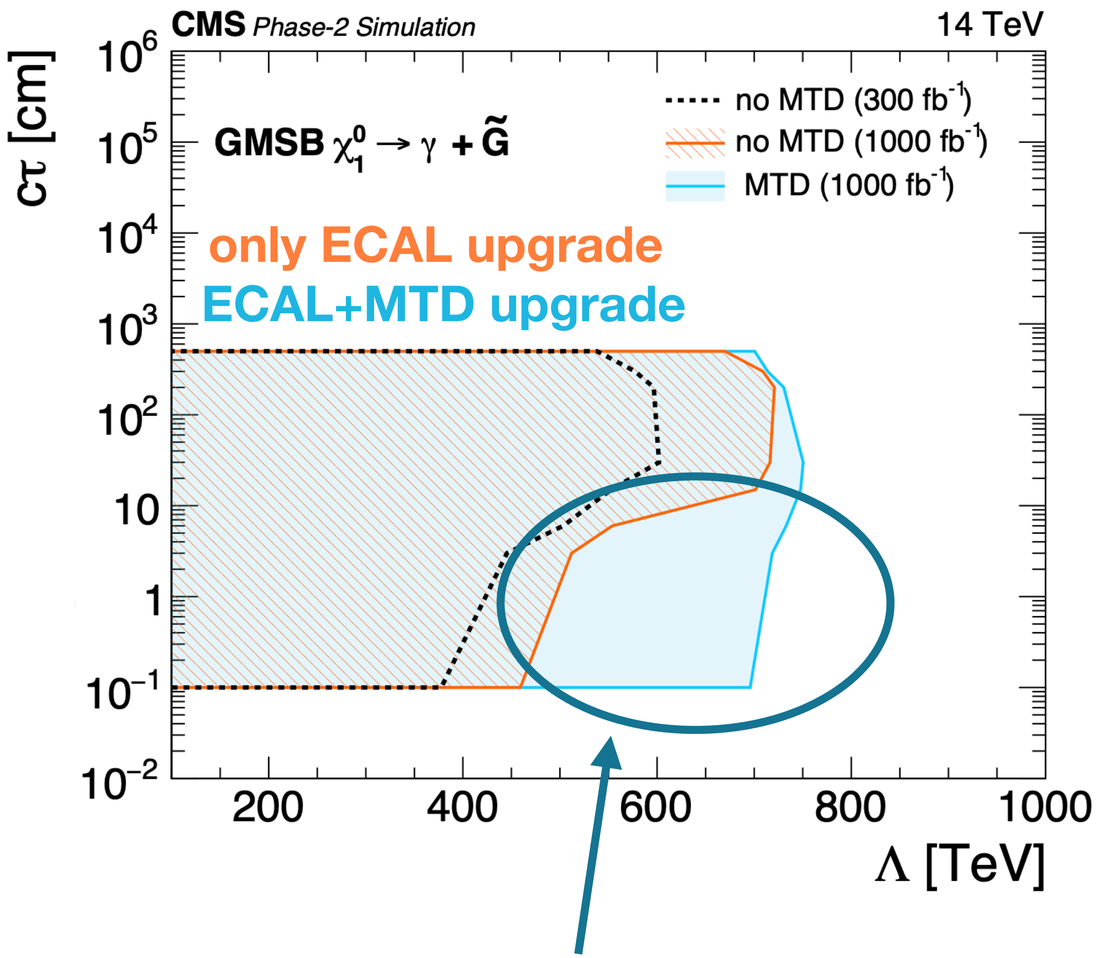
Phase2 Trigger Upgrade

- L1 trigger: up to 750 kHz, with 12.5us latency
  - Use of more sophisticated algorithms
  - Tracker information will be available at L1
- HLT: 7.5kHz
  - All sub-detectors available, possible to run complex algorithm
  - Limited by CPU time and disk space

Displaced jet analysis

- HT>500 GeV, each jet > 50 GeV, eta < 2
- pT and mass requirement suppress SM long-lived baryon and meson
- SVs in background events tend to have only one track with a high value IP

Selections	Observed events	Signal efficiency (%) $m_X = 1000\,\text{GeV}$ $c\tau_0$		
		3 mm	30 mm	300 mm
Displaced-jet triggers, offline H_T selections	17758640	69.4	91.2	80.5
Offline jet p_T and η selections, vertex $\chi^2/n_{dof} < 5.0$	8387775	68.9	90.7	73.5
Vertex $p_T > 8\,\text{GeV}$	3794960	68.2	90.3	69.4
Vertex invariant mass $> 4\,\text{GeV}$	1129531	66.5	89.3	61.6
Second largest Sig[IP_{2D}] > 15	422449	66.0	89.0	60.9
Charged energy fraction from the SV $\epsilon > 0.15$	93873	64.3	87.6	58.4
Energy fraction from the PVs $\zeta < 0.20$	15891	63.6	86.9	57.9
Veto using the NI-veto map	13721	63.6	84.9	55.4
$N^{3D}_{tracks} < 3$ for each jet	2753	54.6	76.4	48.4
GBDT > 0.988	1	51.5	73.5	42.5



Significantly increases sensitivity at short cτ