# Searching for long-lived particles with CMS during Run-3 and at the HL-LHC

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*On behalf of the CMS Collaboration*

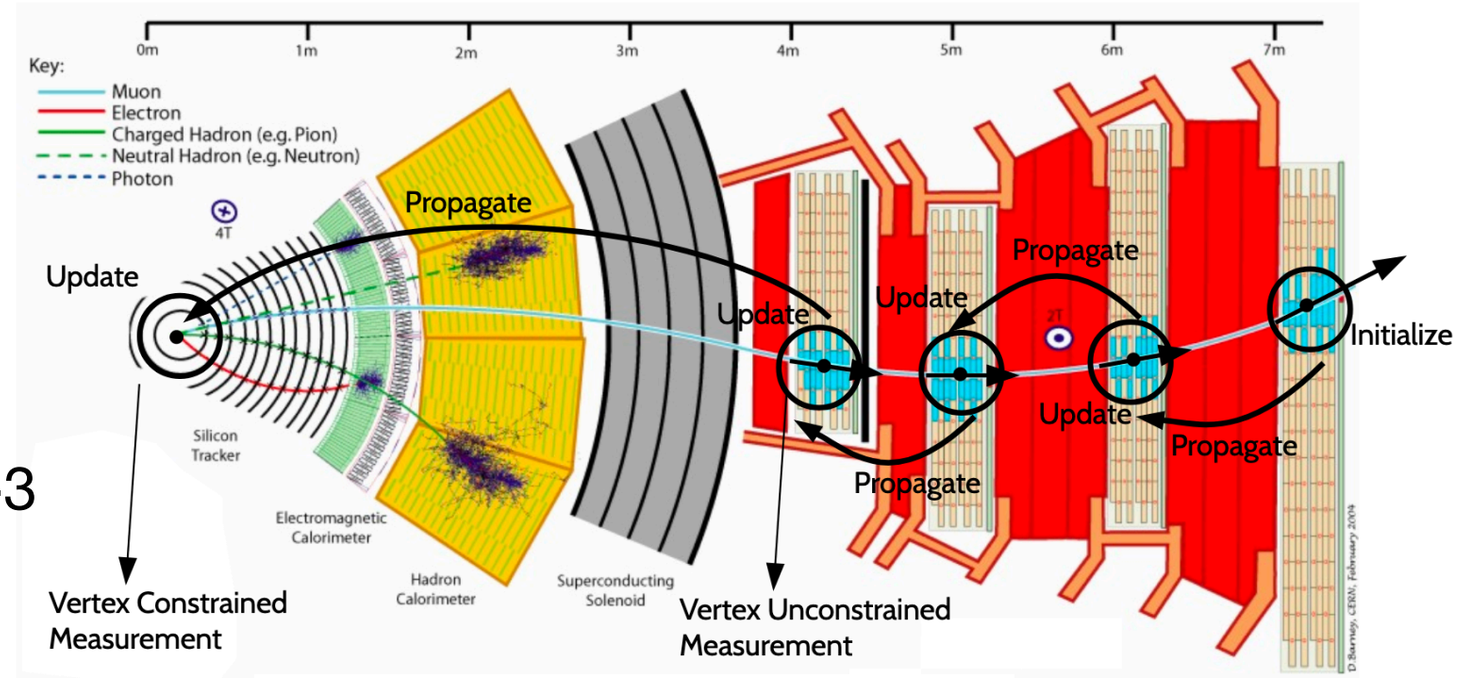
Phenomenology 2020 Symposium, 4-6 May 2020
University of Pittsburgh, Pittsburgh, PA (United States)

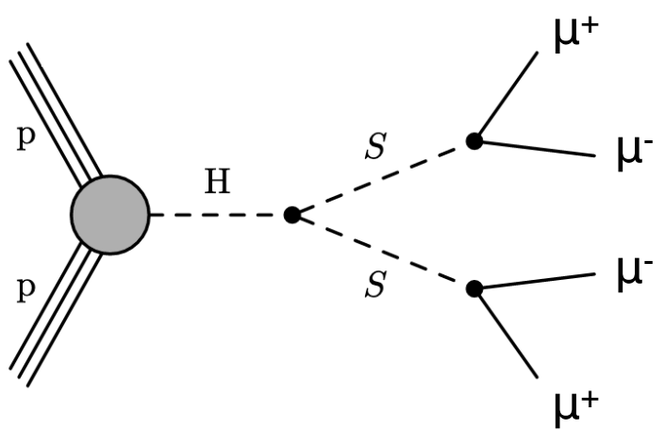
# Introduction

- Long-lived particles predicted in plenty of new physics models
  - ✓ Gauge mediated symmetry breaking, hidden valleys models, split-supersymmetry, R-parity violating supersymmetry
- Searches for long-lived particles are a hot topic at the LHC
  - ✓ Many CMS analyses ongoing on Run-2 data
- Lot of development ongoing for Run-3 and HL-LHC
  - ✓ New detectors, new trigger algorithms, better offline reconstruction, new analysis techniques
- In this presentation we will look at a few of those developments
- Not a complete list.
  - ✓ Discuss relevant topics under development within the CMS collaboration

# Displaced muons at L1T (Barrel)

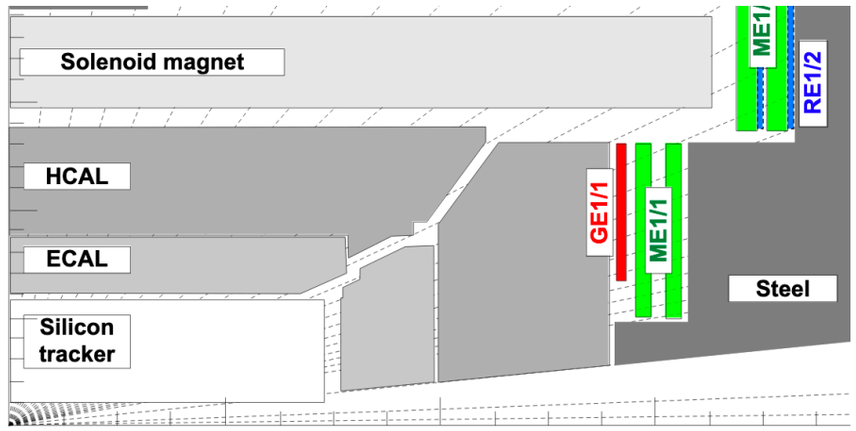
- In the CMS barrel a new track-finder based on a Kalman-filter has been developed
  - ✓ Efficient for both prompt and displaced muons
- Outside-in algorithm which starts at station 4,3 or 2 and propagates inwards
  - ✓ Two momentum measurements
    - ◉ Vertex unconstrained
    - ◉ Vertex constrained
- Commissioned during 2018 data taking. Recently improved for Run-3
- Simulations with H-> ss-> 4μ indicate KBMTF is >80% efficient up to impact parameter dxy~100 cm for $p_T$>10 GeV
  - ✓ Previously ~40% for dxy~100 at $p_T$>10 GeV, 20% at $p_T$>20 GeV



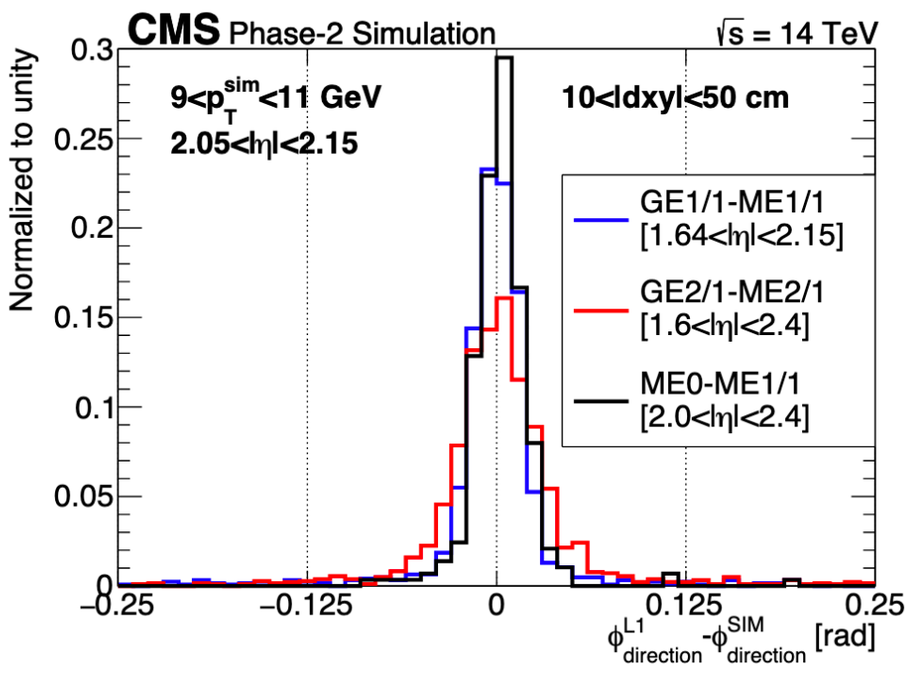
# Displaced muons at L1T (Endcap)

- New GEM chambers (GE1/1) installed in front of existing cathode strip chambers
- Detectors made from copper-clad polyamide film perforated with holes under high voltage

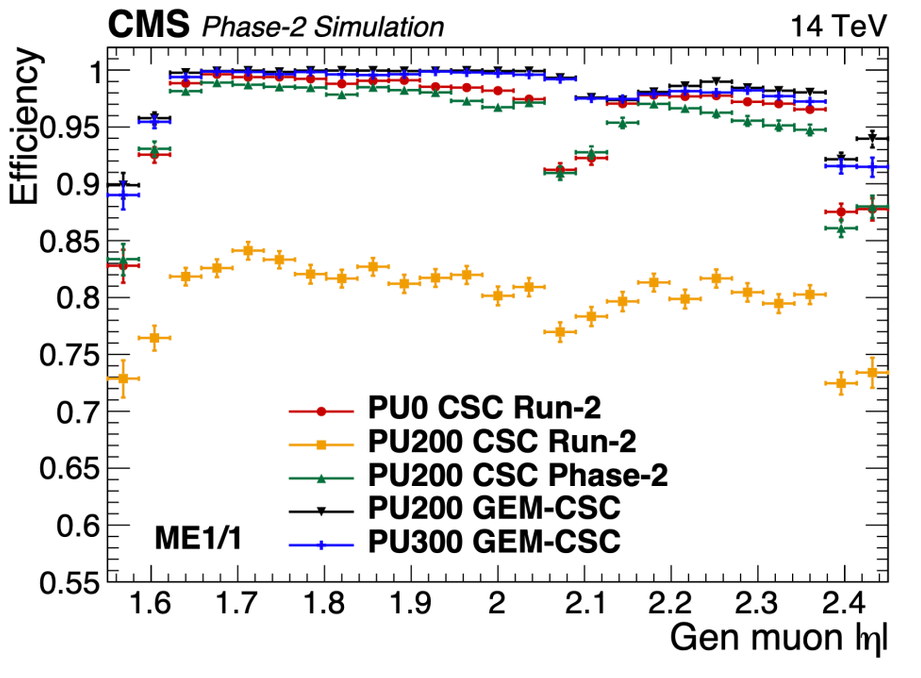



✓ Precision tracking (300 μrad), rate capability ~MHz/cm², efficiency >97%, timing ~8 ns

- Combining GEM with CSC trigger information crucial for displaced muon triggering




✓ GE1/1-ME1/1 bending angle to improve muon pT resolution



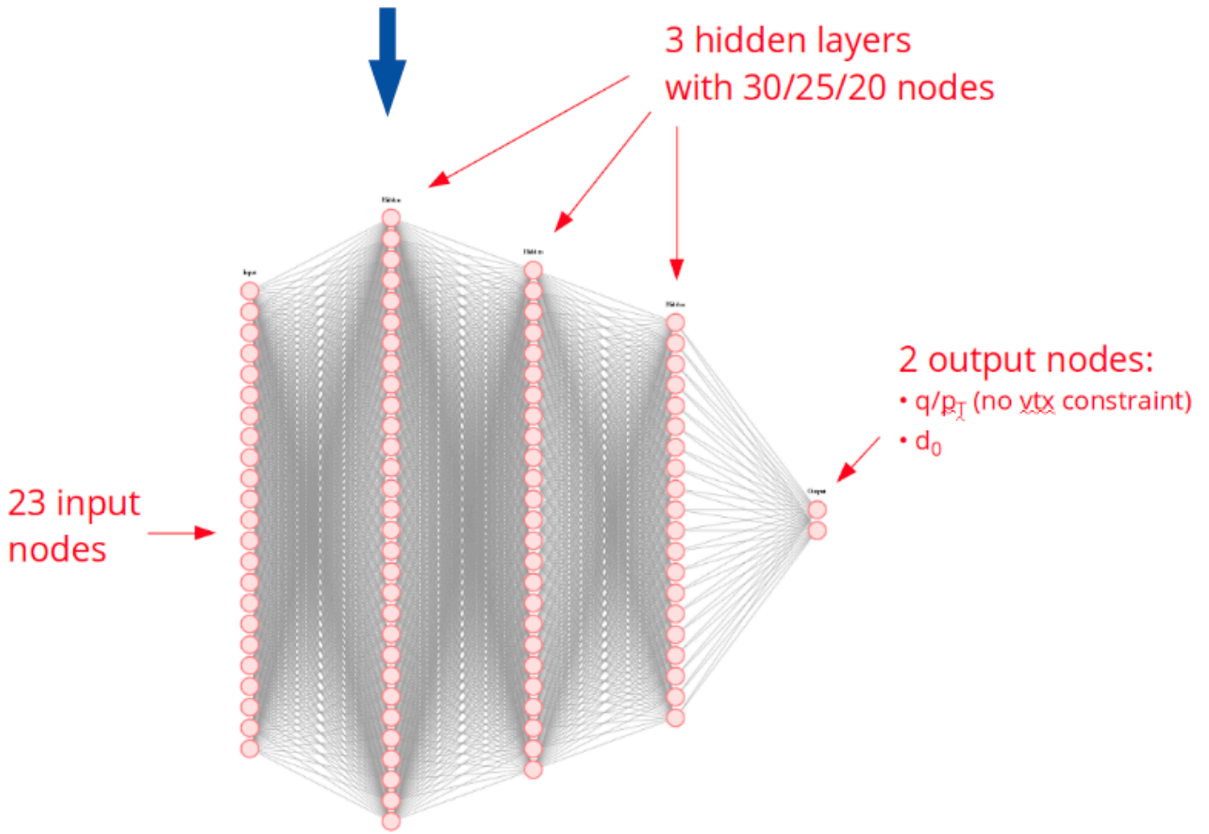

✓ Higher efficient track segments

**CMS-TDR-013**
**CMS-TDR-016**

# Displaced muons at L1 (Endcap)

- Upgrade of CSC local trigger algorithms (in each chamber)
  - ✓ Improved FPGAs for forward CSCs
  - ✓ New trigger patterns and trigger logic
    - ◉ Position resolution x4 (~0.2 mrad) compared to Run-2
    - ◉ Bending resolution x3 compared to Run-2
  - ✓ Expect significant improvements in displaced muon triggering

- Deployment of a displaced muon trigger in endcap for Run-3 and Phase-2
  - ✓ Prompt muon $p_T$ assignment uses on boosted-decision tree
  - ✓ Currently investigating a neural-net based track-finder in the endcap
    - ✓ 23 features (positions and bendings)



# LLPs decaying to hadronic showers in muon system

- Consider an LLP traveling several meter from the interaction point to the muon system before decaying into a shower of particles

  ✓ LLP produces a cluster of hits in chambers

- Most hadronic fragments would be stopped in steel return yoke

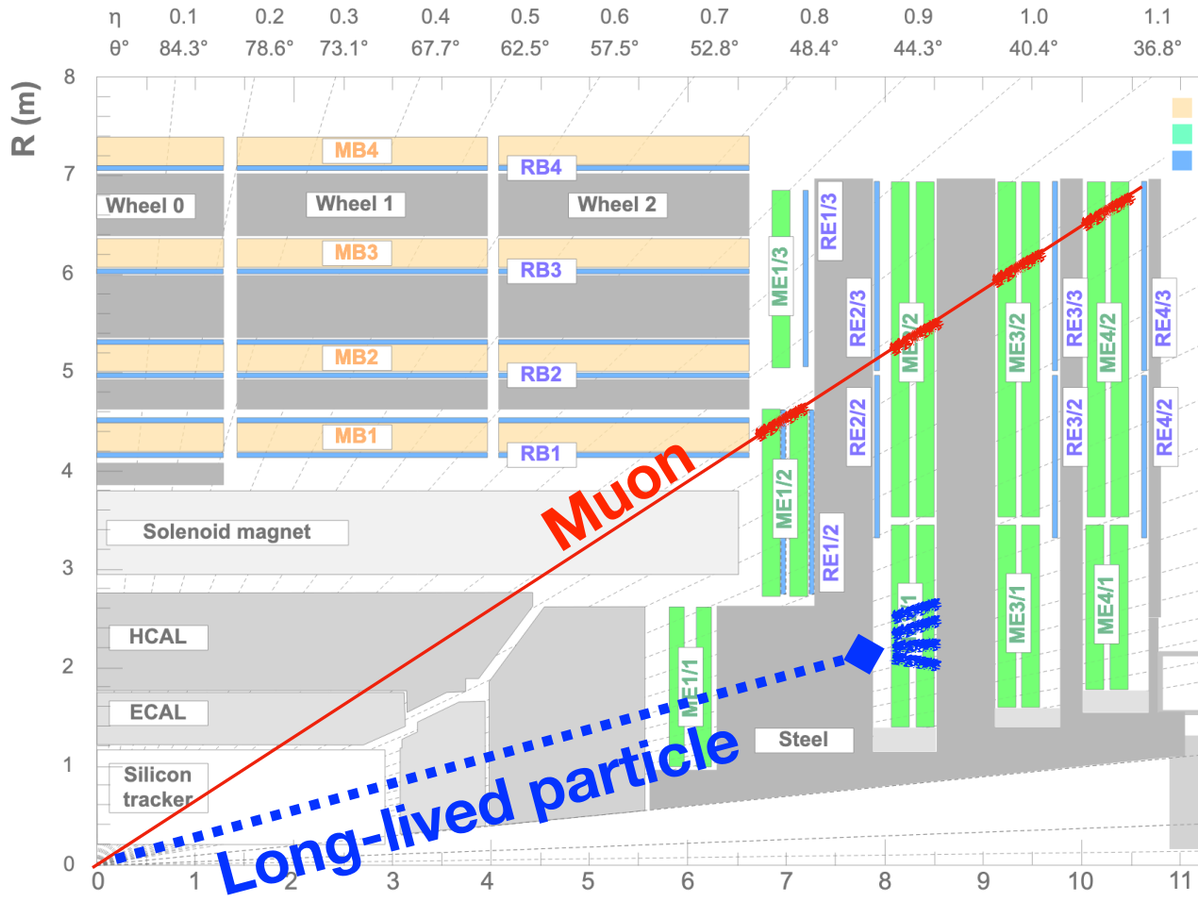
  ✓ Typically reconstruct large number of track segments in a single chamber (or two neighboring chambers)

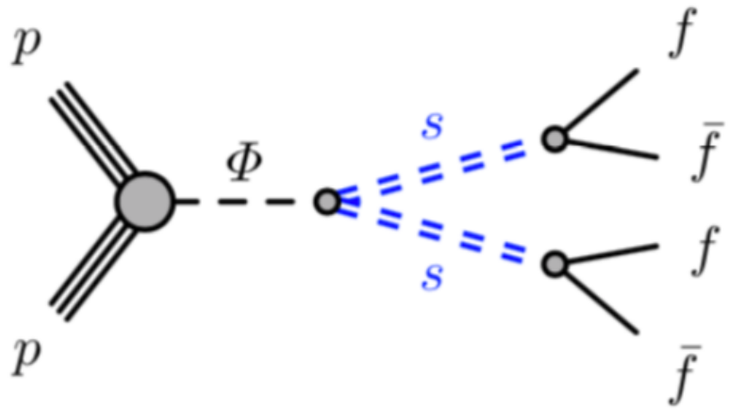
- Endcap muon can trigger on **max 2 track segments** per chamber per BX

  ✓ CMS not sensitive to such high-multiplicity events

- Benchmark model: H(125) → ss → bbbb

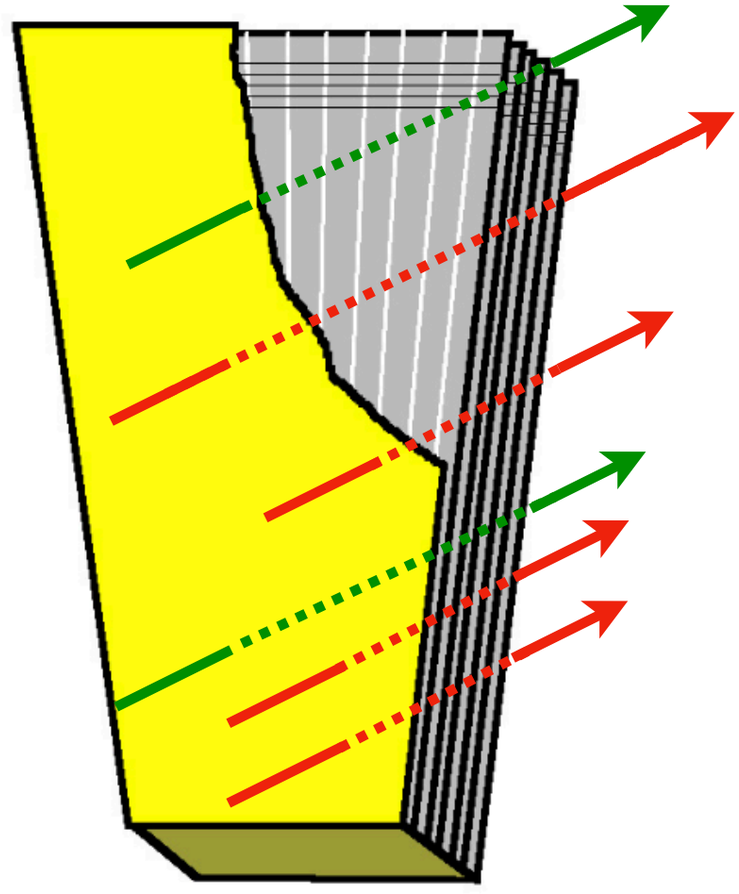
  ✓ 50 GeV “s” boson



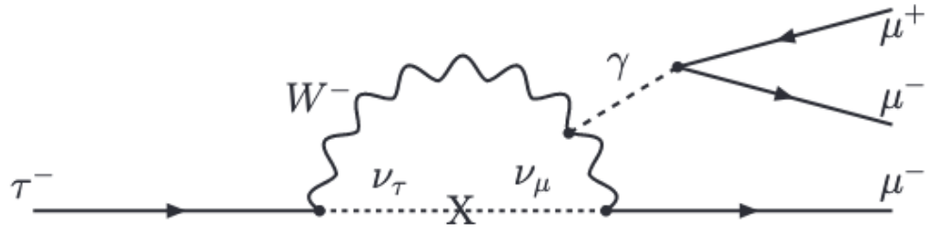
# LLPs decaying to hadronic showers in muon system

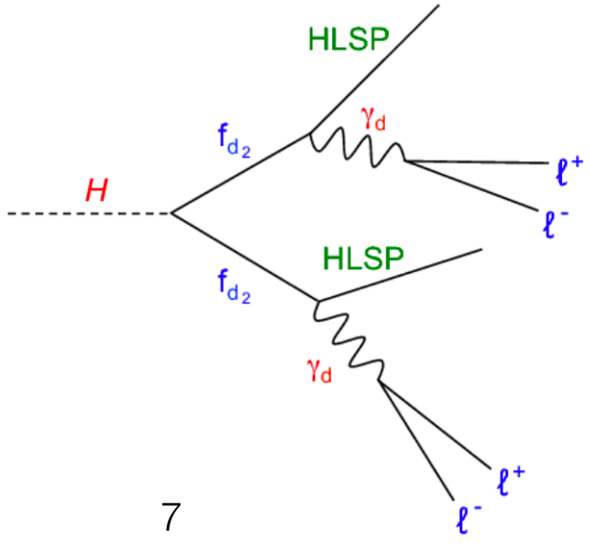
- Current studies focus on counting track segments and raw hits in each endcap muon chamber at L1T
- CSC trigger being upgraded during long shutdown 2 with new hardware and firmware
  - ✓ Additional usable bandwidth to identify high-multiplicity events
- At the high-level trigger, similar considerations can be made
  - ✓ Simple reconstructed hit counter offers significant rejection power of signal over background
  - ✓ More advanced techniques (BDT, DNN) are also considered
- Aside from hadronically bosons, other interesting signatures
  - ✓ Muon-jets
  - ✓ (Boosted) LFV tau -> 3 μ decays



**Sent to track-finder**

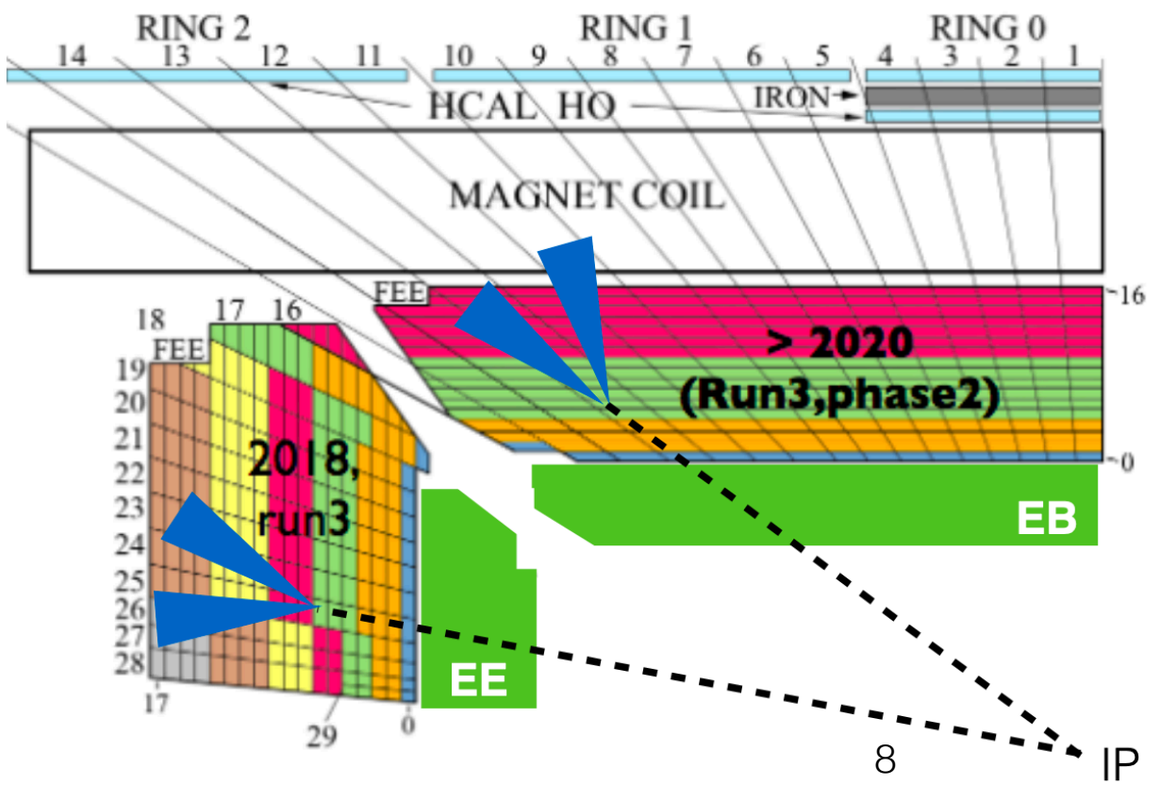
**Ignored in Run-2**
**Will be counted in Run-3**

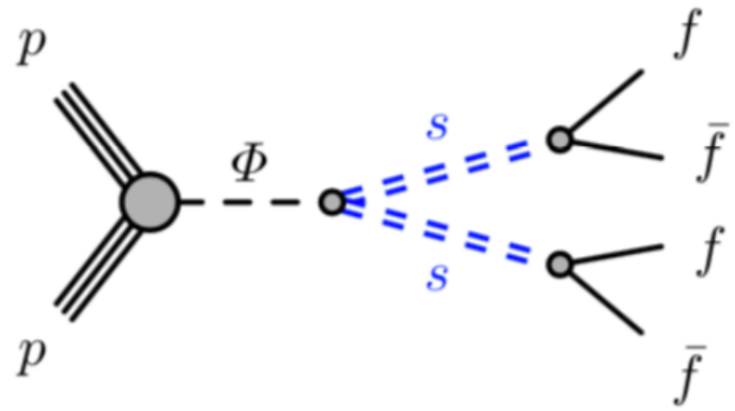


# Displaced Jets in HCAL

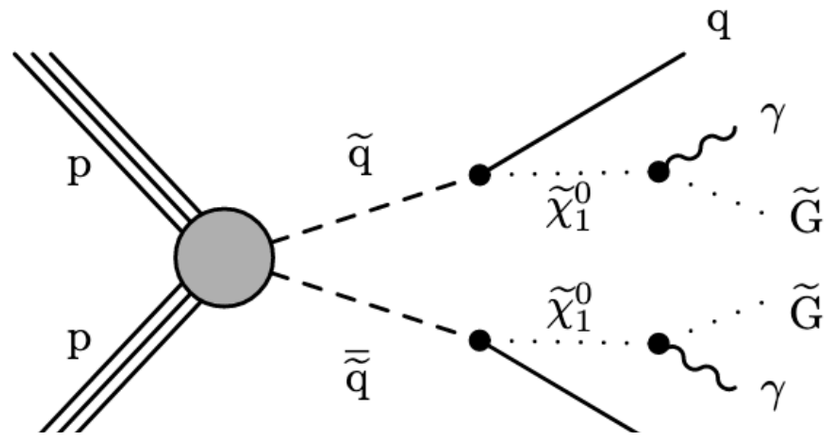
- Barrel HCAL is been equipped with new silicon photomultipliers
  - ✓ New front-end electronics delivering precision timing to the trigger
- Increased segmentation of the HCAL barrel and endcap systems at L1T
  - ✓ Depth of hadronic shower in HCAL and timing may be useful for triggering on long-lived particles
  - ✓ One of the benchmark models: Higgs to LLPs to fermions

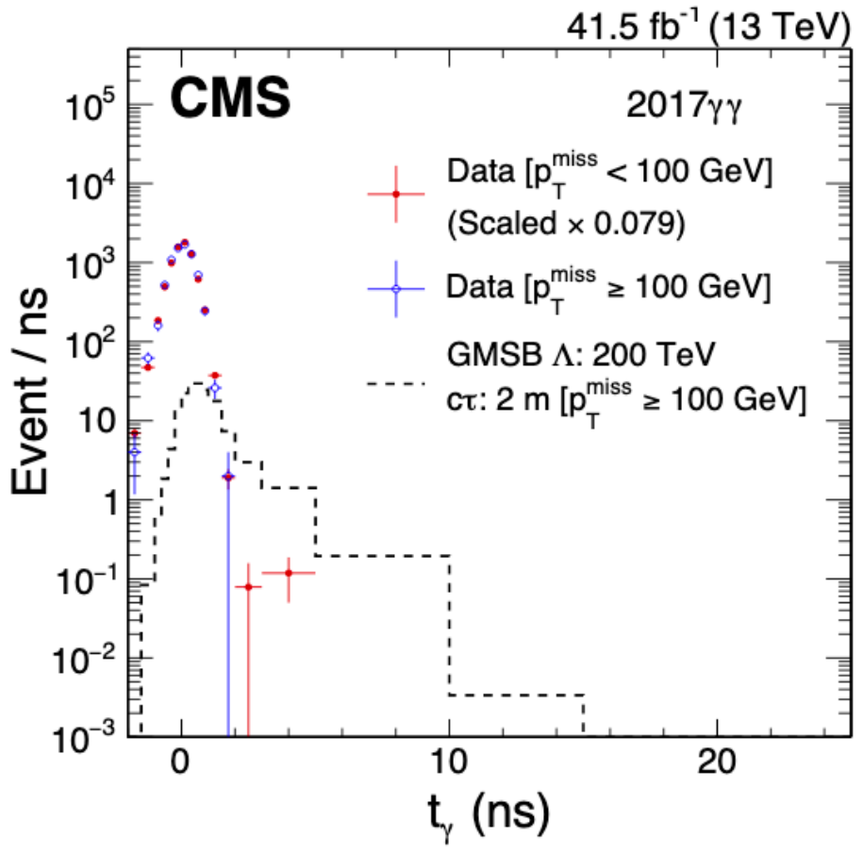


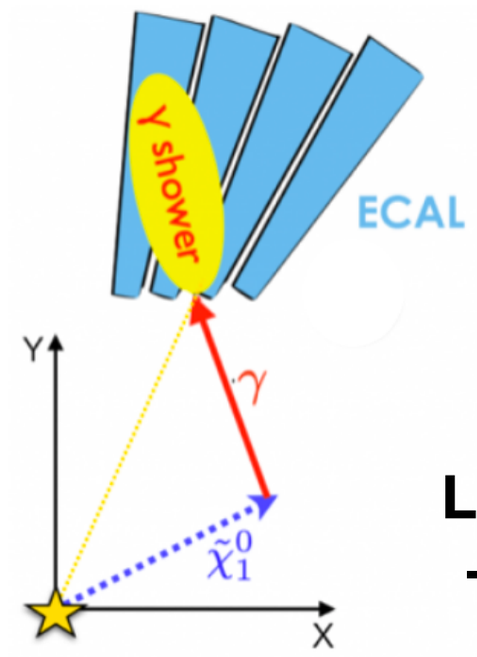



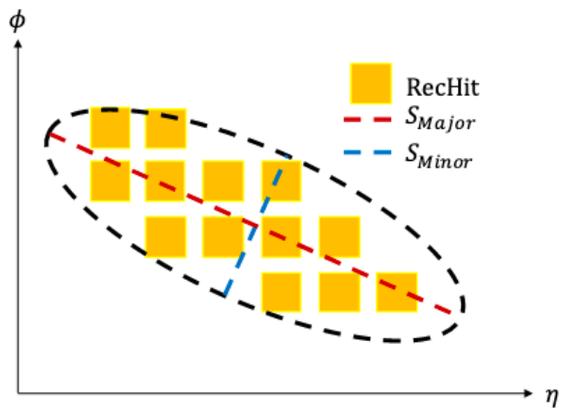
# Long-lived particles in HLT

- Big effort ongoing to implement special L1T “seeds” used in HLT algorithms for LLPs
- Example: Search for GMSB with displaced photons using Run-2 data
  - ✓ Two handles: photon time and photon impact parameter
- New L1T seeds for displaced photons in Run-3
  - ✓ Shower-shape in ECAL crystals is non-pointing



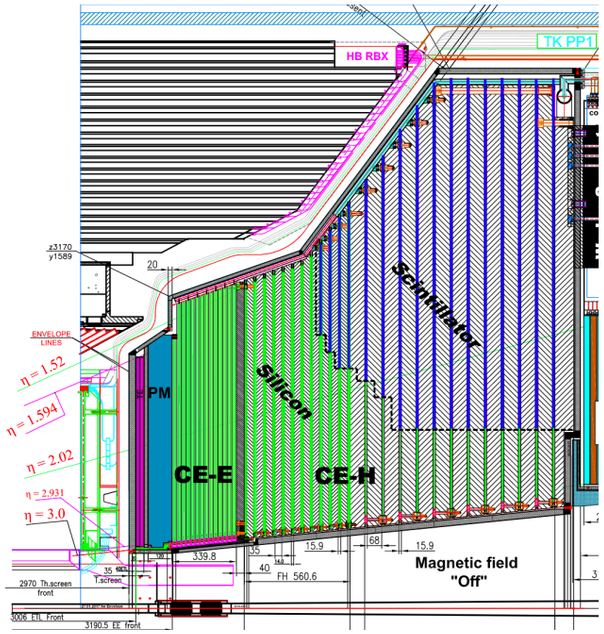



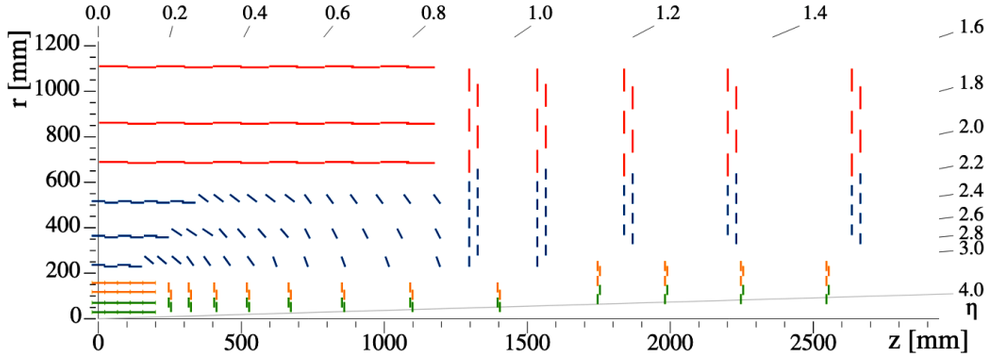

**LLP with significant lifetime -> Elliptical shower-shape**

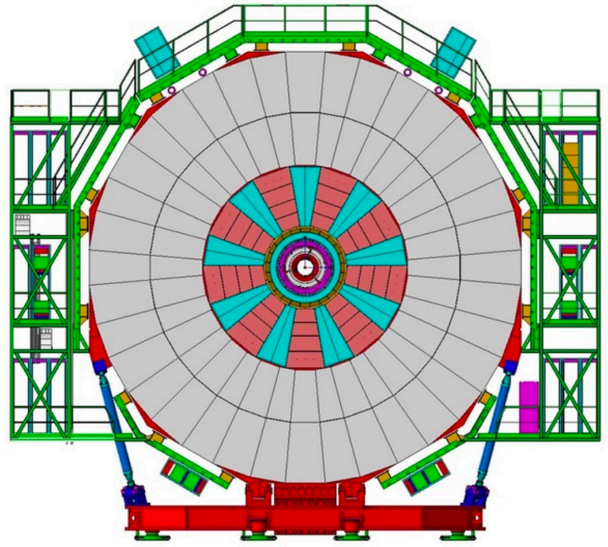
[CMS-EXO-19-005]

# New detectors at HL-LHC



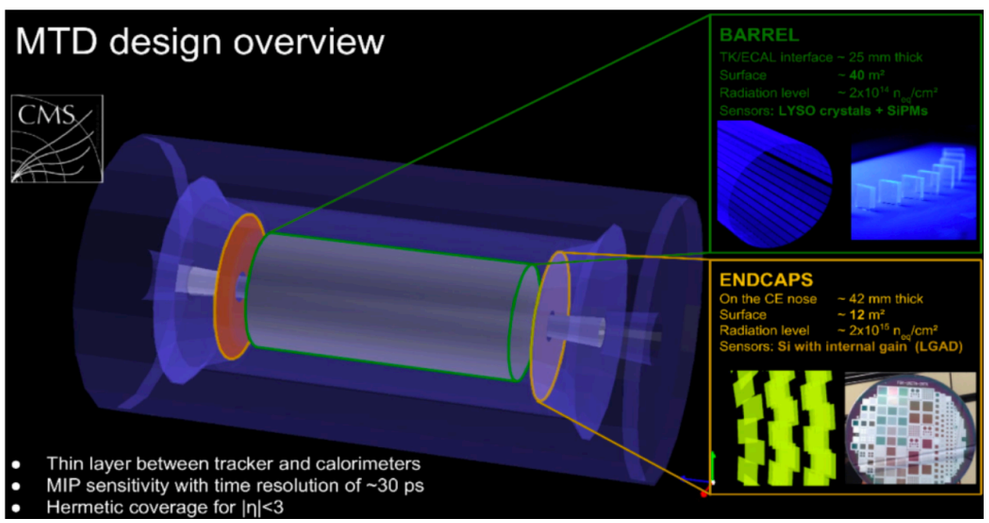

## High Granularity Calorimeter



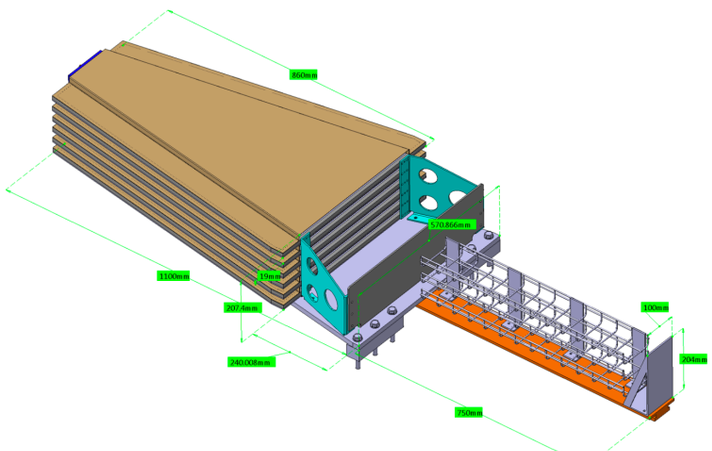



## Phase-2 Tracker

## MIP Timing Detector (MTD) between tracker and ECAL

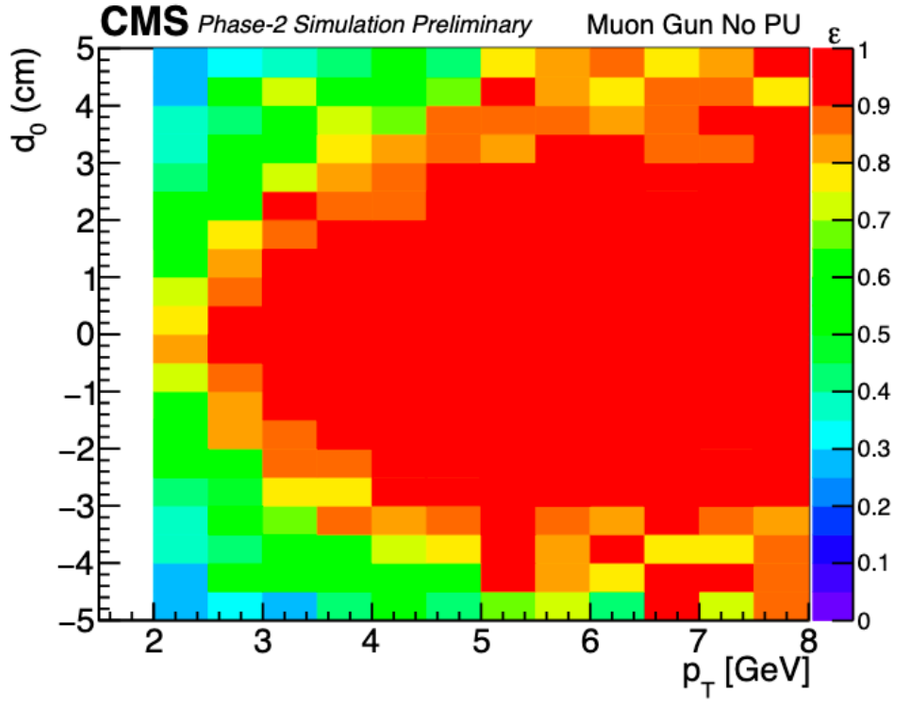



## GEMs in station 2 (GE2/1) and very forward region (ME0)

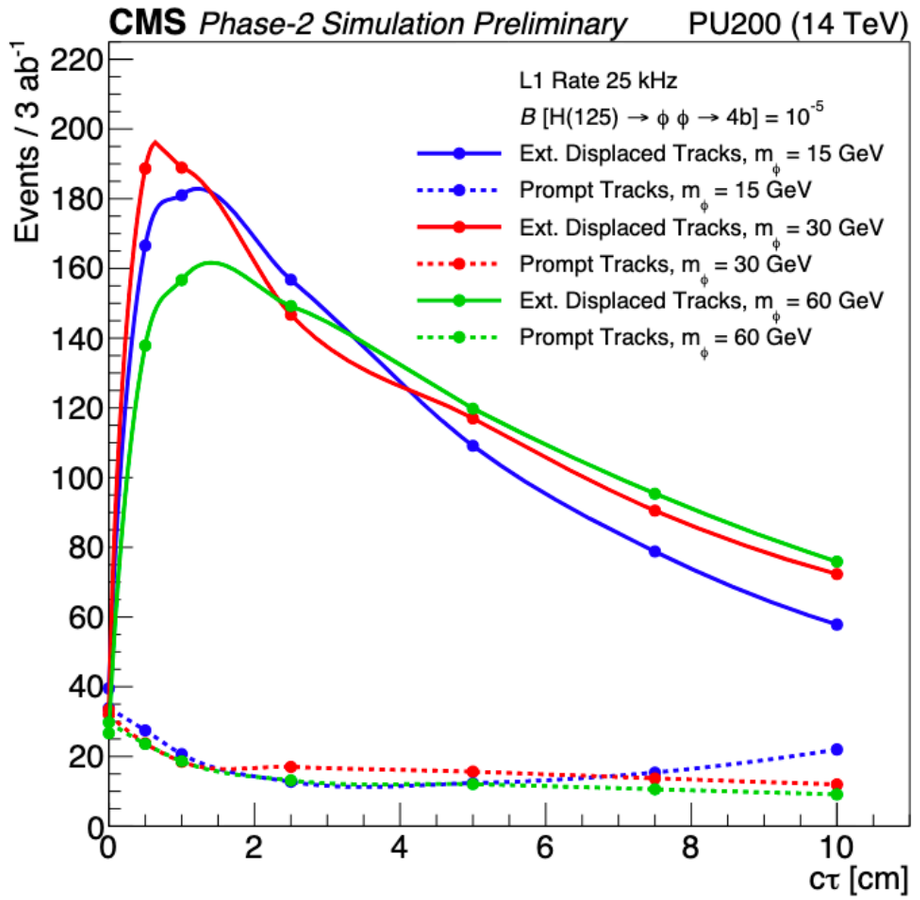


# LLPs with the Phase-2 Tracker

- Phase-2 Tracker will be equipped with L1T system
  - ✓ Prompt tracks can be combined with muon/ calorimeter information
  - ✓ Also displaced tracking algorithms developed
    - ◉ Good trigger efficiency with impact parameter up to 5 cm and low pT




- Higgs boson decays to two new light scalars that in turn decay to jets (H(125) → ss → bbbb)
  - ✓ With significant lifetime for scalar “s”, zero-background analysis. BR(H(125) → ss) ~ $10^{-5}$
  - ✓ New $H_T$ triggers using displaced tracks
  - ✓ Much higher sensitivity to H(125) → ss → bbbb processes with displaced L1T tracks

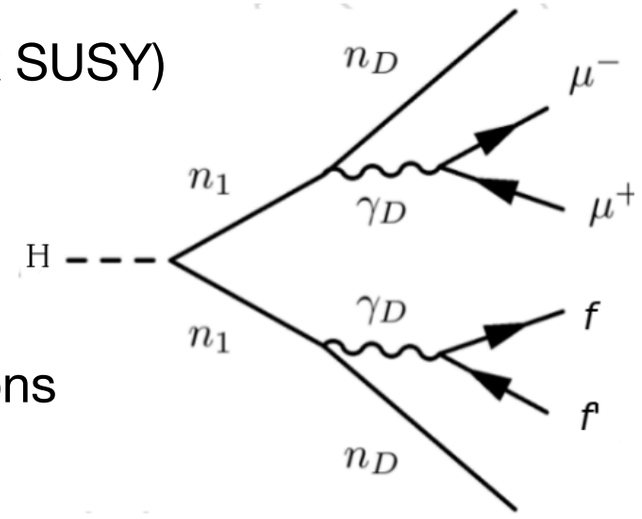



[CMS-FTR-18-018]

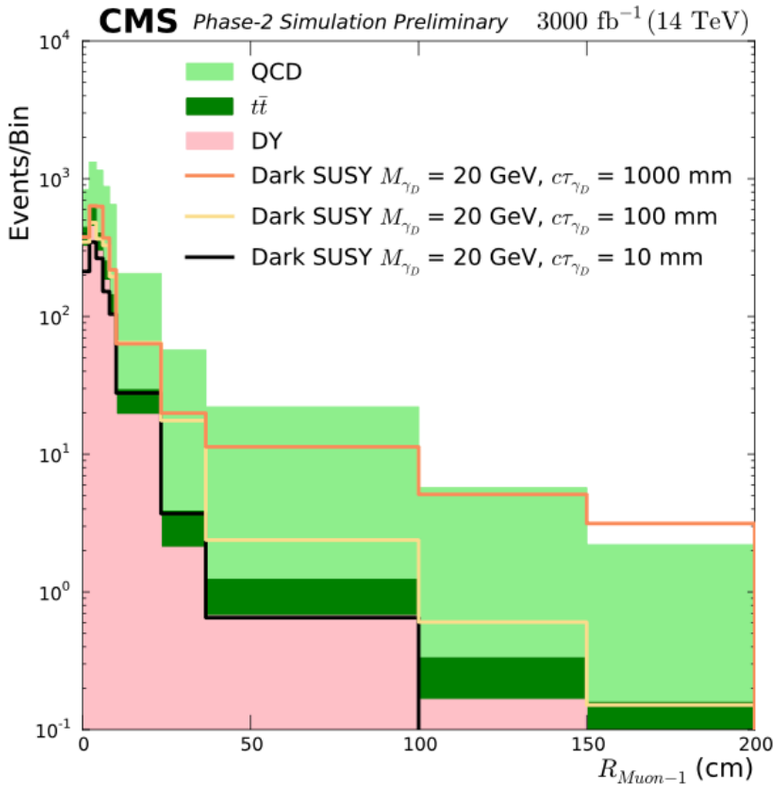
CERN-2019-007

# Long-lived dark photons

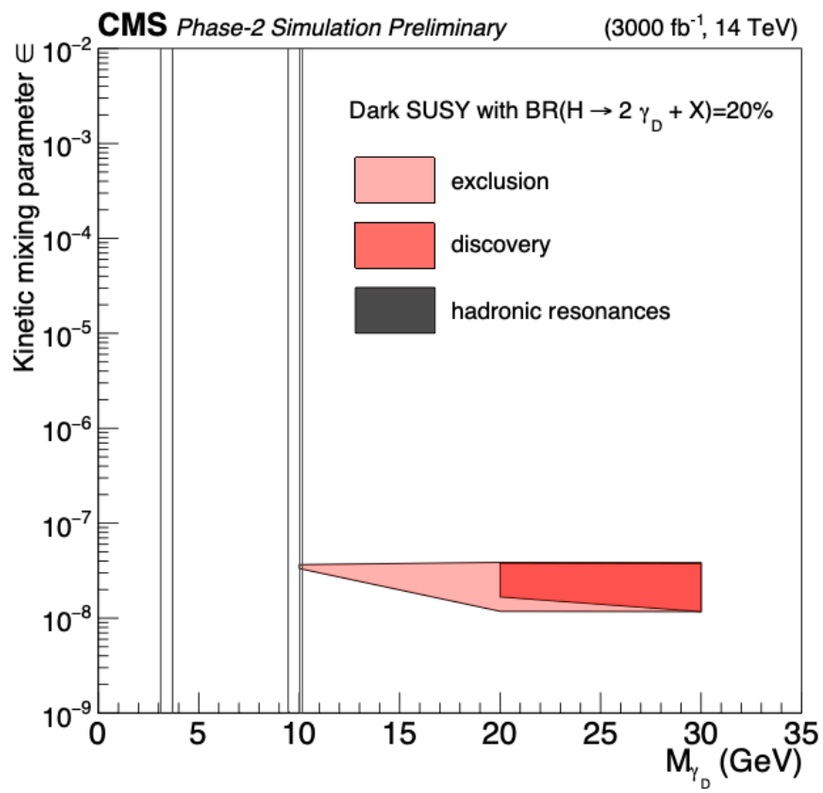
- Dark photons appear naturally in models with hidden sectors (e.g. dark SUSY)
  - ✓ Weak coupling with SM particles through kinetic mixing
  - ✓ Pairs of displaced muons
- Dominant bkg from QCD, with (non-prompt) b-quarks decaying to muons
- Analysis is done with $R_{\text{muon}}$ key observable in search
  - ✓ 3D distance between interaction point and extrapolated muon track




- Expect further improvements in sensitivity on the kinetic mixing parameter with Phase-2 upgrade of the L1 muon trigger




Sensitivity in region 20-30 GeV for epsilon ~$10^{-7}$-$10^{-8}$



# Heavy Stable Charged Particles

- Slow moving particles in the detector (v/c ~ 0.5 to 1)

  ✓ Predicted in supersymmetric extensions of SM

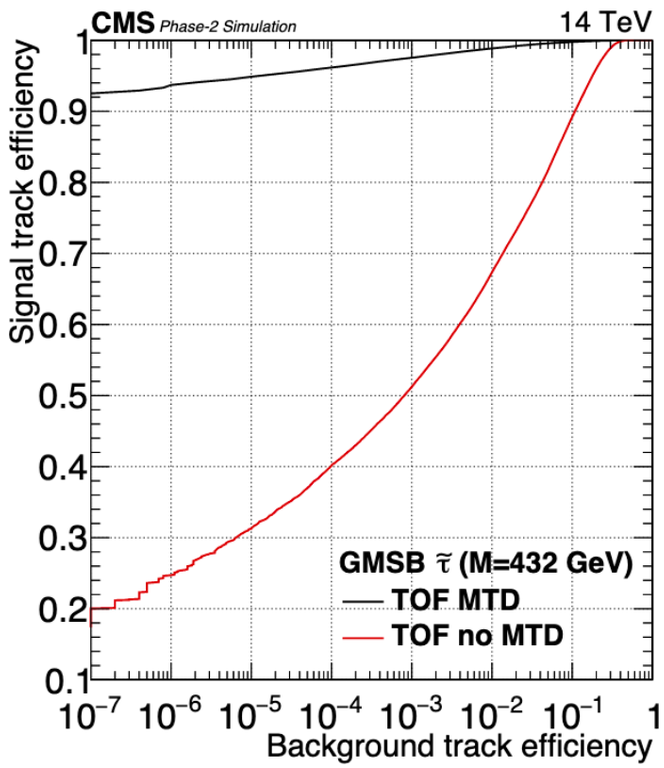
- Case study: SUSY tau lepton propagating through CMS muon system

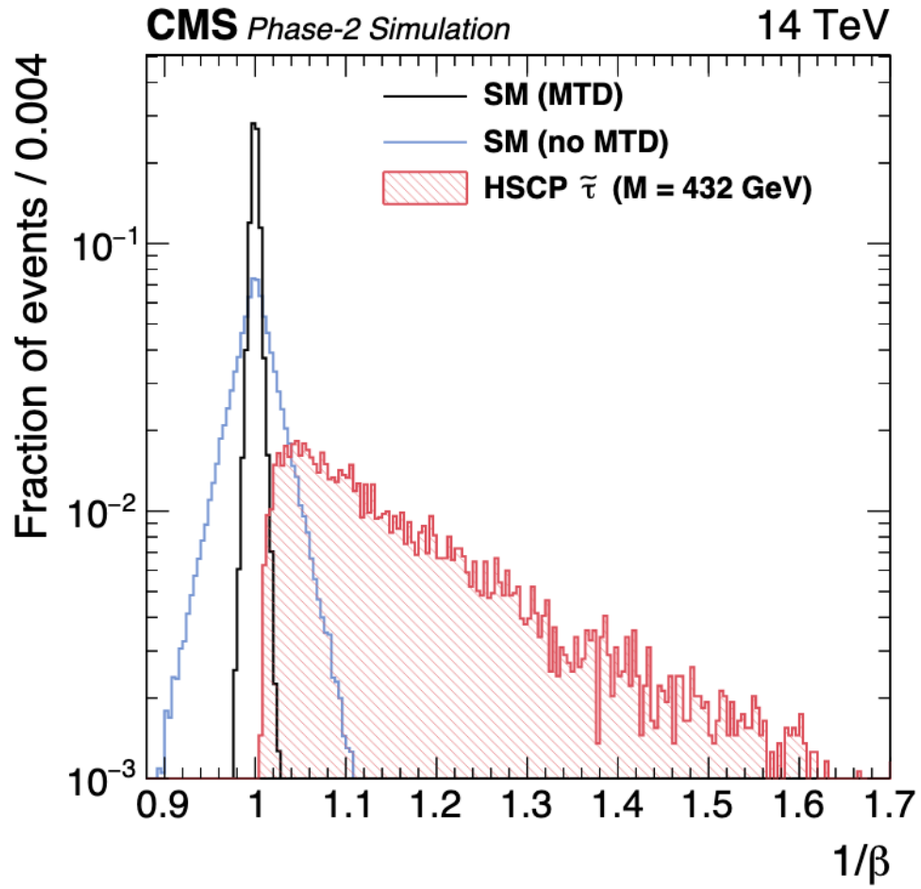
  ✓ Hits in several stations in linear pattern hit-position vs hit-time

- HSCP trigger developed using time-of-flight in MTD (~30 ps) and RPC (~1 ns)

  ✓ Clear distinction of HSCP signal from Drell-Yan+jets background

  ✓ >90% efficient with MTD included



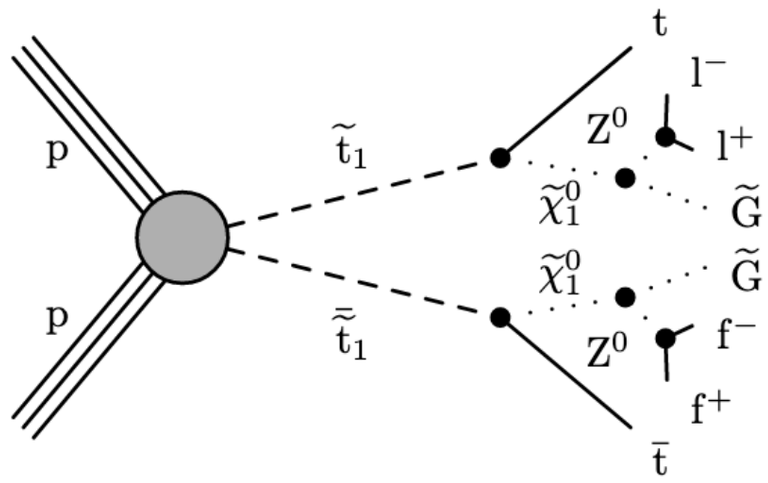




[CMS-TDR-020]

# Long-lived neutralinos with MTD

- Another signature where MTD proves to be very useful
- Gauge mediated SUSY breaking stop production to long-lived neutralinos

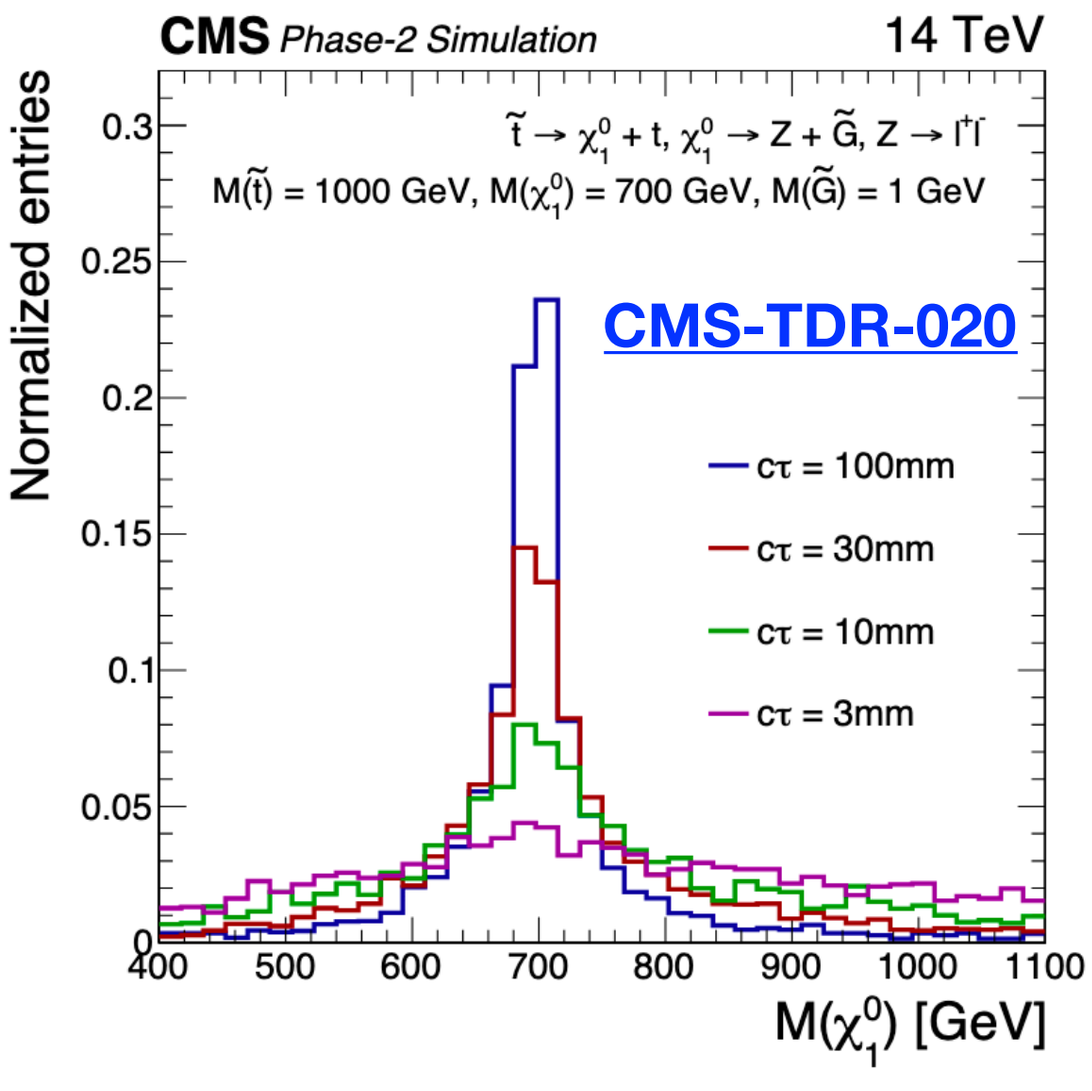
  ✓ Considering $e^+e^-$ final states




- Primary vertex ($\sigma_{pos}$ = 12 μm)
- Secondary Vertex ($\sigma_{pos}$ = 30 μm in transverse)
- Electron track timing ($\sigma_{timing}$ = 30 ps)

**Neutralino velocity + decay particle kinematics**

**Neutralino mass**



# Summary

- Searches for long-lived particles are a very challenging and interesting research field at the LHC

- Upgrades of CMS detector systems for Run-3 and HL-LHC provide new ways to exploit the unique features of long-lived particle decays in physics searches

- Looking forward to seeing Run-3 results!

**The speaker acknowledges funding from the US Department of Energy Grant #DE-SC0010103**