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

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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
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: $H(125) \rightarrow ss \rightarrow bbbb$
  - 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 \( \mu \) decays
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
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
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 $R_{\mu\text{on}}$ 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 $\sim 10^{-7} - 10^{-8}$
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

![Graph showing CMS Phase-2 Simulation efficiency and fraction of events](image)
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 ($\sigma_{\text{pos}} = 12 \mu\text{m}$)
- Secondary Vertex ($\sigma_{\text{pos}} = 30 \mu\text{m}$ in transverse)
- Electron track timing ($\sigma_{\text{timing}} = 30 \text{ ps}$)

Neutralino velocity + decay particle kinematics

Neutralino mass

CMS Phase-2 Simulation

Neutralino mass distribution for $\tilde{t} \rightarrow \chi^0_1 + t$, $\chi^0_1 \rightarrow \tilde{G}$, $Z \rightarrow t\bar{t}$, $M(\tilde{t}) = 1000 \text{ GeV}$, $M(\chi^0_1) = 700 \text{ GeV}$, $M(\tilde{G}) = 1 \text{ GeV}$
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!

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