Triggering on Long-Lived Particles:
Lessons Learned and Ideas for the Future

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PITT PACC Workshop: LHC physics for Run 3
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Why look for new long-lived particles (LLPs)?

Standard model particles span a wide range of lifetimes ($\tau$)

LLPs appear in many scenarios beyond the standard model
LLP Searches

• To make a discovery, look where no one has looked before!
• Wide variety of LLP signatures and strategies
• Often require **unusual and innovative techniques** at main LHC experiments
• Some challenges:
  – Dedicated triggers
  – Unique object reconstruction
  – Atypical backgrounds
  – Unusual discriminating variables
Triggers for LLPs

- LLP signatures are often **unusual** and **not covered** by “standard” triggers
- If your data is not triggered, it’s lost!
- **Dedicated triggers for LLPs are crucial!**
- Can be a key way to improve sensitivity of existing searches and/or expand our coverage

See Darin and Caterina’s talks
Trigger Improvements in Run 3

- Disclaimer: will focus on CMS, but some of these ideas are applicable for ATLAS as well
- Had a few dedicated LL triggers at CMS in Run 2:
  - Displaced dimuons (L2 and L3)
  - Displaced muon + photon
  - Single nonpointing photon
  - Displaced dijet
  - MET+isolated track
  - Jet/muon not coincident with collision
- Many ways we can improve triggers for LLPs in Run 3, at every stage of the trigger
- Work underway at L1 and ramping up on HLT
CMS Displaced Lepton Triggers

- Two types of muon reconstruction at the HLT:
  - L2 muon = muon system only
  - L3 muon = tracker + muon system

- Run 2 displaced lepton triggers:

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>At least <strong>two L2 muons</strong> with no vertex constraint</td>
<td>Displaced dimuons (forthcoming)</td>
</tr>
</tbody>
</table>
| At least **two L3 muons** with no vertex constraint | Displaced leptons without common vertex  
  - Two versions: Inclusive and muon transverse impact parameter $|d_0| > 0.1$ mm  
  - 2015, $e\mu$ channel: CMS-PAS-EXO-16-022  
  - Full Run 2 forthcoming |
| At least **one L3 muon** with no vertex constraint and at least **one photon** |  
  - Inclusive and muon $|d_0| > 0.1$ mm versions  
  - Photon used as proxy for displaced electron |
Improved muon algorithms at CMS L1 for Run 3

• Displaced muons in Run 2 were limited by the L1 trigger, which was not optimal for large displacements

• New Kalman filter outside-in sequential algorithm in the barrel:
  • Commissioned during 2018 data taking and more recently during cosmic runs
  • Recently improved for Run 3
  • Two options available:
    – Vertex-constrained for prompt muons
    – Vertex-unconstrained for displaced muons
  • Vertex-unconstrained algorithm shows > factor of 2 gain in efficiency for displaced muons (~40-100 cm)

• Other developments are also in progress that target improving the efficiency for displaced muons at L1 in the endcaps

See Darin’s talk
Displaced Lepton Trigger Ideas for Run 3

- Would be good to have a **coordinated approach** to displaced lepton triggers
  - Optimizing coverage in $p_T$ - $|d_0|$ (or $d_0$ significance) plane
  - Can optimize $p_T$ and $|d_0|$ thresholds at both L1 and HLT

- For example, in addition to what already existed in Run 2, could add:
  - **Electrons with minimum $|d_0|$ requirement**
    - Could be tuned to fill in lifetime coverage gap between prompt electron triggers and triggering on a photon
  - **Single and double leptons with larger $|d_0|$ thresholds but smaller $p_T$ thresholds**
    - Target soft leptons for compressed mass spectra searches or displaced semi-leptonic decaying taus

| $p_T$ [GeV] | $|d_0|$ [mm] |
|------------|-------------|
| ~30        | 0.1         |
|            | 1           |

Covered for muons

New trigger?
CMS Nonpointing Photon Trigger

• Single photon trigger from Run 2 was effective for delayed photons search ([doi:10.1103/PhysRevD.100.112003](https://doi.org/10.1103/PhysRevD.100.112003))
  - Photons from a displaced vertex strike the front face of the ECAL barrel at a non-normal incidence angle
  - Creates a more elliptical EM shower in the $\eta - \phi$ plane
  - Single photon HLT path makes requirements on major and minor axes of the shower to select elliptical shower shape
  - Other HLT requirements: photon $p_T > 60$ GeV, photon isolation, $H_T > 350$ GeV
  - Improves signal acceptance by about a factor of 2 over standard diphoton trigger for neutralino ctau>10 m

• Ideas for Run 3:
  - Can explore loosening/removing $H_T$ requirement when photon $p_T > 150$ GeV, to improve signal efficiency
  - Can try a similar trigger but for at least 2 photons, which will allow thresholds to be lowered and improvements to be made in the 2 photon channel
CMS Displaced Dijet Triggers

- Displaced dijet triggers used successfully in Run 2 for displaced jets search ([arxiv:2012.01581](https://arxiv.org/abs/2012.01581))
- **Core idea:** use displaced tracking iteration at the HLT to count the number of prompt and displaced tracks associated with jets
  - Allows for significant reduction in H_T threshold
- Two dedicated displaced dijet triggers in Run 2:

<table>
<thead>
<tr>
<th>“Displaced” trigger</th>
<th>“Inclusive” trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calo H_T &gt; 430 GeV</td>
<td>Calo H_T &gt; 650 GeV</td>
</tr>
<tr>
<td>At least 2 jets with:</td>
<td>At least 2 jets with:</td>
</tr>
<tr>
<td>• p_T &gt; 40 GeV</td>
<td>• p_T &gt; 60 GeV</td>
</tr>
<tr>
<td>• At most two prompt tracks (</td>
<td>d_0</td>
</tr>
<tr>
<td>• At least one displaced track (</td>
<td>d_0</td>
</tr>
</tbody>
</table>

Better efficiency for low-mass LLPs (< 500 GeV)  
Better efficiency for high-mass LLPs with small (< 3 mm) or large (>300 mm) ctau

- **Idea for Run 3:** use displaced and prompt tracks for other displaced objects at the HLT
- Displaced tracking at the HLT could benefit many LLP analyses!
CMS HCAL L1 Improvements for Run 3

Studying new L1 HCAL handles to target LLPs:

**$E_{\text{HCAL}}/E_{\text{ECAL}}$**

- Powerful discrimination
- Rates being studied for different $E_{\text{HCAL}}/E_{\text{ECAL}}$ and jet energy thresholds
- Already successfully used by ATLAS

**Depth**

- Could allow substantial reduction in jet energy threshold

**Timing**

- Decay products of heavy LLPs are delayed
- Time-to-digital converter (TDC) info available for each HBHE channel in Run 3
- Shows promise for ctau>1m

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CMS ECAL Timing at the HLT for Run 3

- But this analysis had to rely on high MET trigger since no ECAL timing reco at HLT in Run 2
  - MET trigger limits the sensitivity to low mass and compressed models
- A way to target lighter LLPs: make use of **ECAL timing at the HLT** in Run 3
  - Can seed with new L1 triggers targeting delayed signatures in the HCAL
    - Also investigating seeding with tau triggers at L1 and/or dedicated HCAL timing trigger
  - Can combine timing with **prompt track veto** (a la displaced dijets) to keep HLT thresholds low
  - Possibly also helpful for:
    - Delayed photons/electrons
    - Monopoles:
      - Detector signature: large, narrow energy deposits in calorimeter + large tracker ionization
      - Needs a dedicated trigger that avoids or mitigates the L1 spike cleaning
Hadronic Clusters in the Muon System

- **New LLP signature for CMS:**
  - Neutral LLPs with ctau> 1m could decay hadronically beyond the calorimeter with:
    - No tracks, no jets, high-multiplicity shower (>500 hits) in the muon system

- **Run 3 trigger idea:**
  - Current L1 muon trigger is limited to 2 track segments per chamber per BX
  - Could add a stub counter in the logic of the DT and CSC L1 trigger primitives
    - Takes advantage of recent CSC trigger upgrade
  - HLT: Cut on cluster properties to reduce the rate
  - Investigating available bandwidth at L1 and HLT
LL Scouting/ Trigger Level Analysis

- Performing an analysis on trigger objects can enable good sensitivity to $c\tau<10\,\text{cm}$ and low mass

In Run 2 at CMS:
- Scouting triggers do not explicitly require large displacement
- Search for displaced dimuons using scouting triggers underway

**Ideas for Run 3:**
- Can retain sensitivity to displaced objects by not applying strict ID
- Could add info for additional background rejection

- See Jakob, William, Darin’s talks
Other Thoughts about LLP Triggers in Run 3

**Other possible trigger developments for Run 3:**
- Displaced hadronic taus?
- Need to make smart use of cross triggers and triggering on prompt associated objects
- Should take advantage of GPUs in the HLT
  - Perfect for machine learning (see Maximilian, David, and Ben’s talks)
- Where can parked data be useful? Can B-parked dataset be useful for LLPs?

**Lessons learned, in general:**
- Need to make sure HLT paths give high efficiency, particularly vs displacement
- Need to develop L1/HLT trigger DQM and validation to spot trigger problems early
- In addition to staying within rate budgets, need to make sure CPU time is within constraints as well
- Should explore porting offline developments to the HLT
- Should think about skims and the event content needed
- ... stay vigilant!
High-Luminosity LHC

HL-LHC
- 14 TeV center-of-mass energy
- About 20 times more data by the end
- Expect up to 200 interactions per pp collision, unprecedented amount of radiation

CMS Detector
- Higher geometrical coverage, with high resolution for all subdetectors
- New timing detector
- New L1 track trigger
- New high-granularity endcap calorimeter (HGCAL)

High pileup: about 200 additional proton collisions per bunch crossing

See Simon’s talk for displaced vertex triggers at the HL-LHC
CMS L1 Track Trigger and LLPs

- **Baseline** track trigger targets prompt tracks
- **Extended** track trigger targets displaced tracks (~1 cm)
  - Baseline algorithms + few modules to target large displacements

**Large improvement in efficiency with extension for displaced tracks:**

**Enough events for discovery!**

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**Benchmark model:**

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**Extension for displaced tracks**

**Baseline track trigger**
CNN Trigger for LLP Decays in HGCal

- Realized there is currently no way to trigger at L1 on displaced/delayed signatures in the forward region with CMS at the HL-LHC
- Developed a **fast convolutional neural network** (CNN) to find **nonpointing showers** in a **high-granularity calorimeter** (HGCal)
  - Current HGCal L1 reconstruction assumes pointing showers
- Computer vision image recognition can easily differentiate between nonpointing and pointing showers
- Proof of concept paper with toy calorimeter: doi:10.1088/1748-0221/15/12/P12006

**Chart:**
- **Nonpointing shower**
- **Pointing shower**
- Colors indicate calorimeter layer number
- Marker size indicates deposited energy

**Good performance already at low energy (this is energy, not p_T):**

- E = [10, 30] GeV
- E = [30, 50] GeV
- E = [50, 70] GeV
- E = [70, 200] GeV
Summary

- Run 3 will be a very exciting time for LLP searches!
- Developments ongoing for L1 and HLT
- What else? Keep the ideas coming! **Now** is the time to work on this!
- Don’t forget about the HL-LHC: New detectors provide explicit opportunities for LLPs, besides the increased physics reach and more data
- **Plenty of phase space still to explore! Triggers are the KEY**
Backup
Displaced Particles in CMS Phase 2 at Level 1

- Can we trigger at level 1 (L1) on displaced/delayed particles in the CMS at the HL-LHC?

- **Track trigger:**
  - Only for charged particles
  - Only for $|\eta|<2.1$
  - Only for $|d_0|<10$ cm, with the track trigger extension

- **MIP Timing Detector (MTD):**
  - Will not be used at L1

- **ECal and HCal barrel:**
  - Timing available at L1

- **High-Granularity Calorimeter (HGCal):**
  - No timing at L1
  - Current HGCal L1 reconstruction assumes pointing showers

- **Displaced/delayed signatures from LLPs in the forward region could be completely missed with CMS in Phase 2, without a dedicated trigger**
- **Example LLP signature:** Emerging jets (t-channel production)
Efficiency vs Energy and Angle

- Select a working point of 15 kHz based on previous slide
- Promising, model-independent results:

![Graph](image)

- Now working with CERN High Level Synthesis for Machine Learning (HLS4ML) group to see how feasible this would be for FPGAs in the real Phase 2 CMS HGCal at L1
- Ultimate goal is to have this as a trigger for the CMS HGCal