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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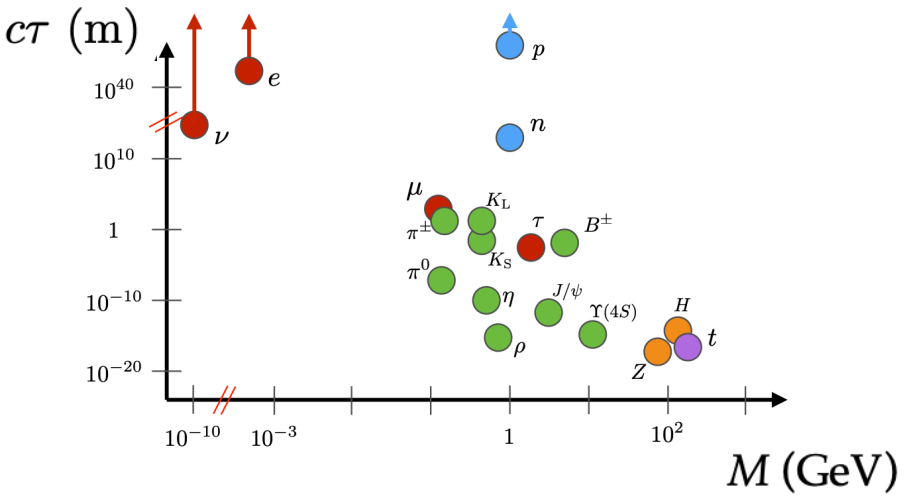
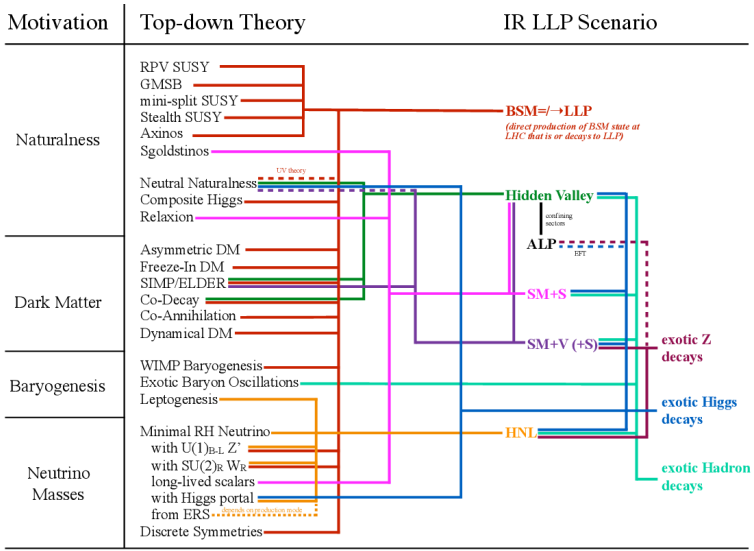
Why look for new long-lived particles (LLPs)?

Standard model particles span a wide range of lifetimes (τ)

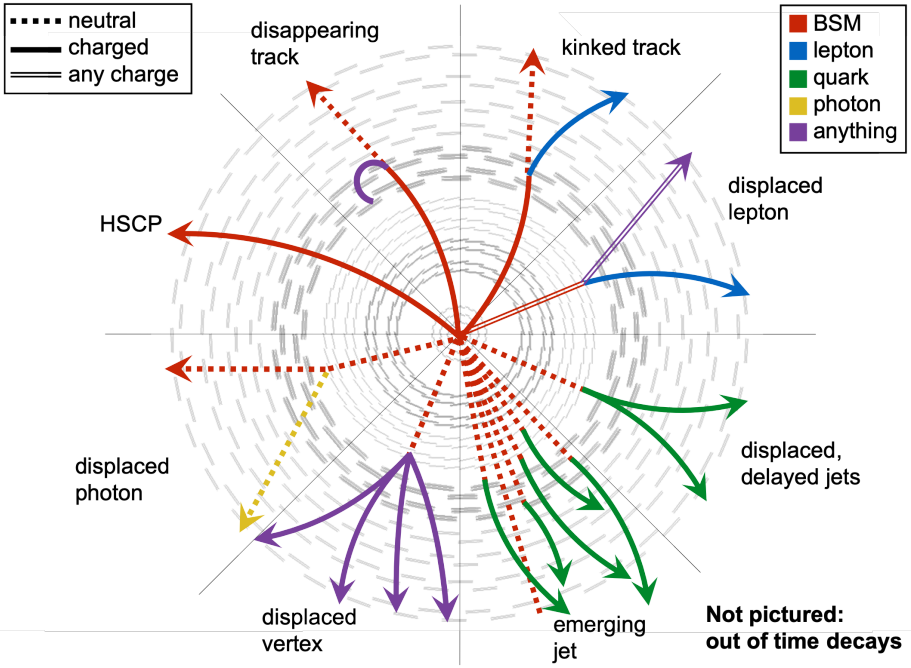


LLPs appear in many scenarios beyond the standard model

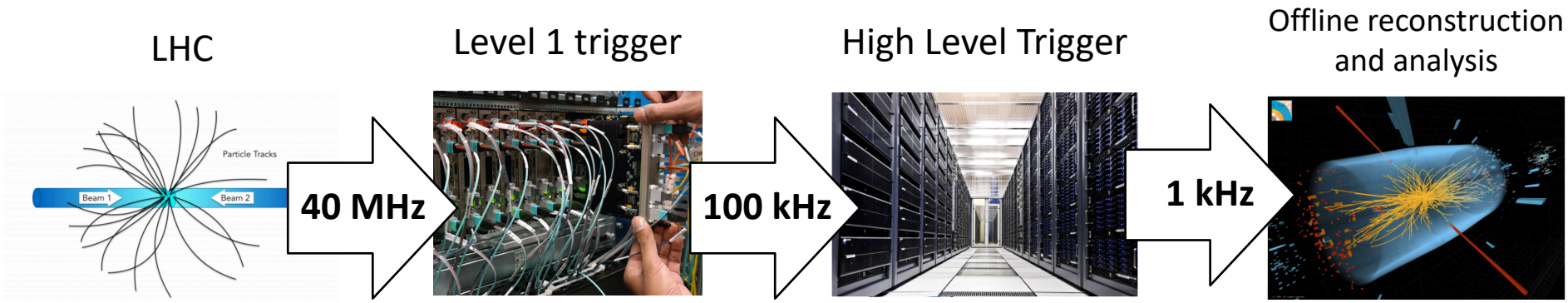


LLP Searches

- **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

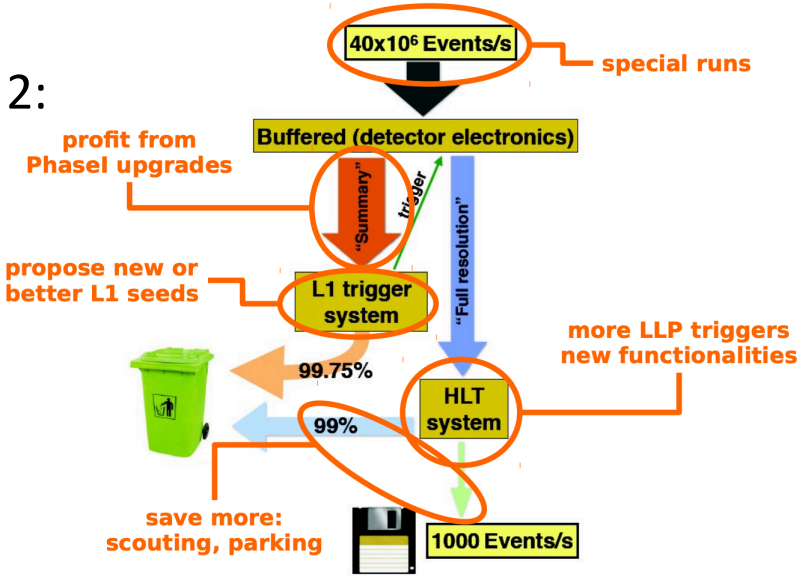


See Darin and Caterina's talks

- 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

Trigger Improvements in Run 3

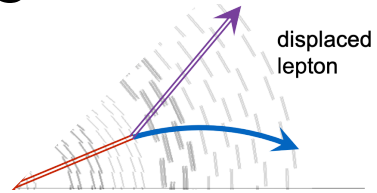
- Disclaimer: will focus on CMS, but some of these ideas are applicable for ATLAS as well
- Had a few dedicated LL triggers at CMS in Run 2:
  - Displaced dimuons (L2 and L3)
  - Displaced muon + photon
  - Single nonpointing photon
  - Displaced dijet
  - MET+isolated track
  - Jet/muon not coincident 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



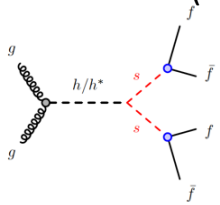
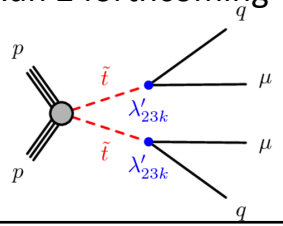
Steven Lowette

See Darin's talk

CMS Displaced Lepton Triggers

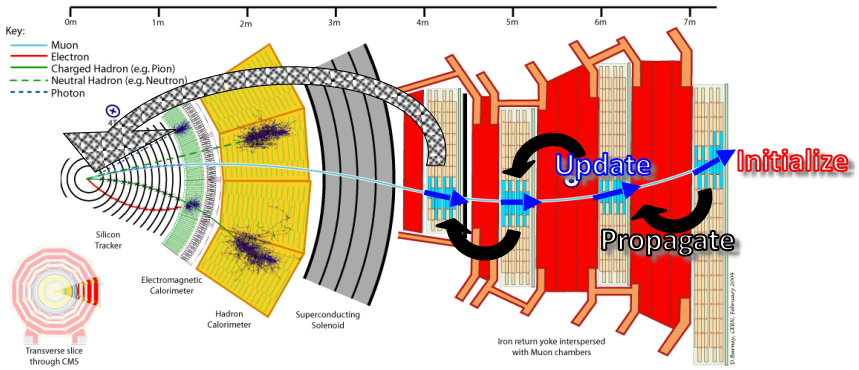


- Two types of muon reconstruction at the HLT:
  - **L2 muon** = muon system only
  - **L3 muon** = tracker + muon system
- Run 2 displaced lepton triggers:

Trigger	**Analysis**
At least **two L2 muons** with no vertex constraint	Displaced dimuons (forthcoming) 
At least **two L3 muons** with no vertex constraint • Two versions: Inclusive and muon transverse impact parameter $\|d_0\| > 0.1$ mm	Displaced leptons without common vertex • 2015, eμ 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:**



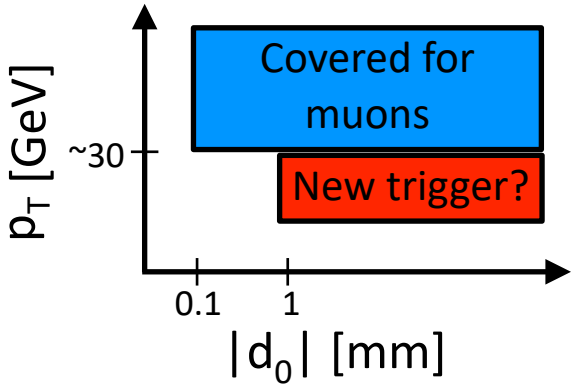
- Commissioned during 2018 data taking and more recently during cosmic runs
- Recently improved for Run 3
- Two options available:
  - Vertex-constrained for prompt muons
  - Vertex-unconstrained for displaced muons
- Vertex-unconstrained algorithm shows **> factor of 2 gain in efficiency** for displaced 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

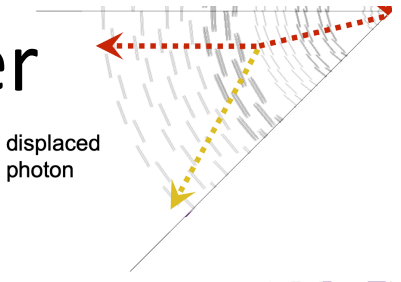
Displaced Lepton Trigger Ideas for Run 3

- 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

CMS Nonpointing Photon Trigger

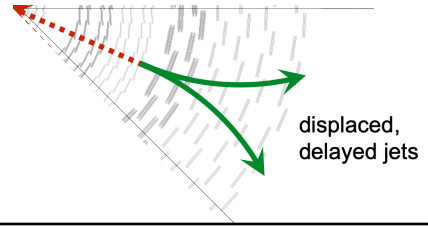


- Single photon trigger from Run 2 was effective for delayed photons search (doi:10.1103/PhysRevD.100.112003)
  - Photons from a displaced vertex strike the front face of the ECAL barrel at a non-normal incidence angle
  - Creates a more elliptical EM shower in the $\eta - \phi$ plane
  - Single photon 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)
- 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:



"Displaced" trigger	**"Inclusive" trigger**

• Calo H_T > 430 GeV
• At least 2 jets with:
  • p_T > 40 GeV
  • At most two prompt tracks ($\|d_0\|$ < 1 mm)
  • At least one displaced track ($\|d_0\|$ > 0.5 mm, d_0 sig <5)
	• Calo H_T > 650 GeV
	• At least 2 jets with:
	  • p_T > 60 GeV
	  • At most two prompt tracks ($\|d_0\|$ < 1 mm)

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

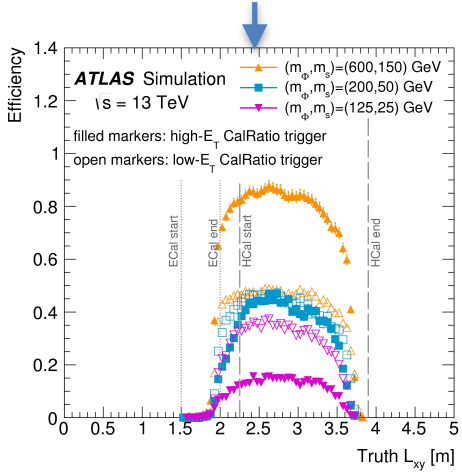
- **Idea for Run 3: use displaced and prompt tracks for other displaced objects at the HLT**
- **Displaced tracking at the HLT could benefit many LLP analyses!**

CMS HCAL L1 Improvements for Run 3

Studying new L1 HCAL handles to target LLPs:

E_{HCAL}/E_{ECAL}

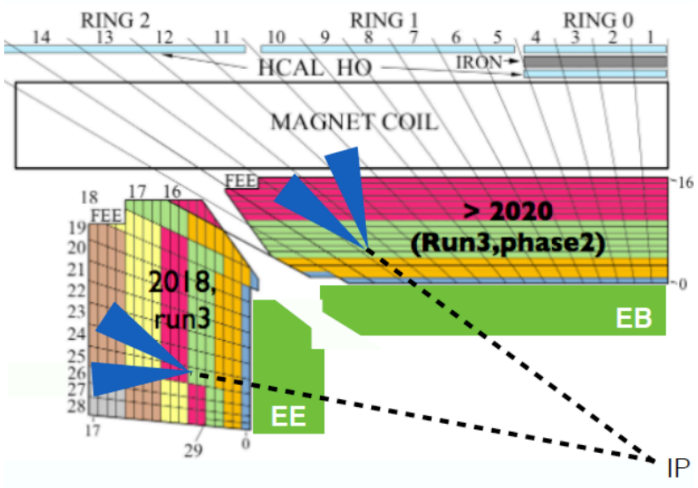
- Powerful discrimination
- Rates being studied for different E_{HCAL}/E_{ECAL} and jet energy thresholds
- Already successfully used by ATLAS



doi:10.1140/epjc/s10052-019-6962-6

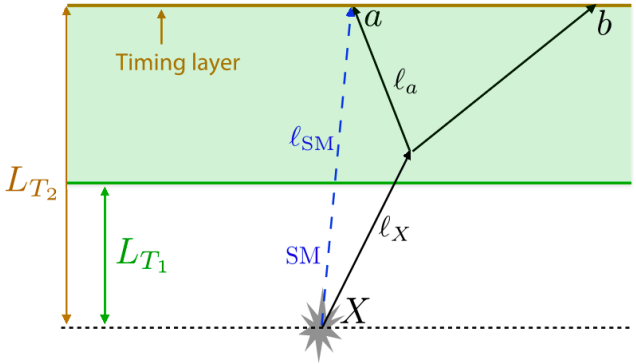
Depth

- Could allow substantial reduction in jet energy threshold

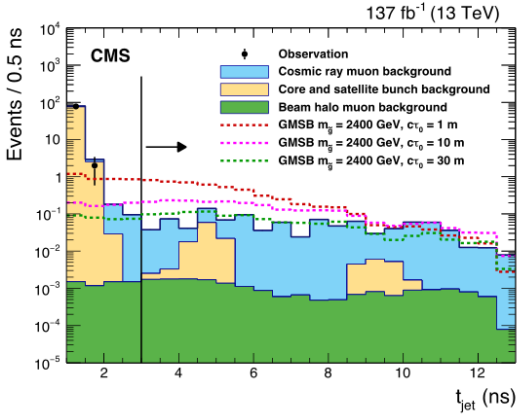


Timing

- 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



CMS ECAL Timing at the HLT for Run 3

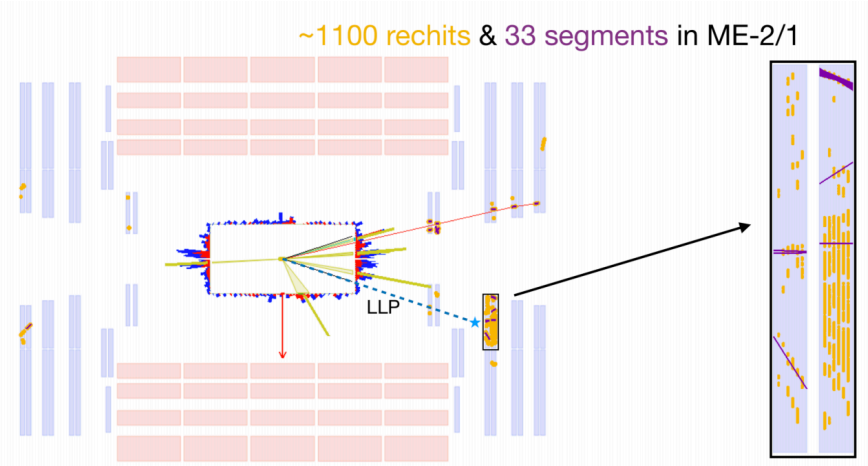


- **ECAL timing**: powerful offline tool for LLPs with successful Run 2 delayed jets search (**doi:10.1016/j.physletb.2019.134876**)
- But this analysis had to rely on high MET trigger since no ECAL timing reco at HLT in Run 2
  - MET trigger limits the sensitivity to low mass and compressed models
- **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

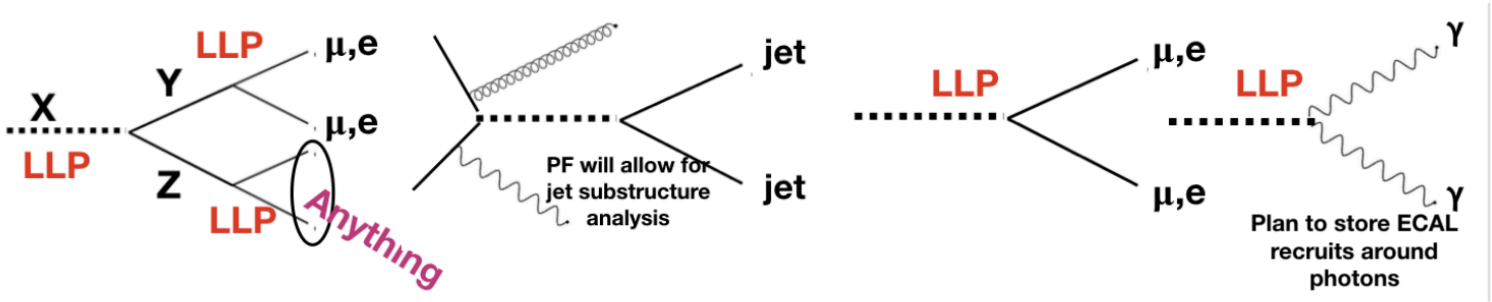
- New LLP signature for CMS:
- Neutral LLPs with ctau> 1m could decay hadronically beyond the calorimeter with:
  - No tracks, no jets, high-multiplicity shower (>500 hits) in the muon system



- **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 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

See Simon's talk for displaced vertex triggers at the HL-LHC

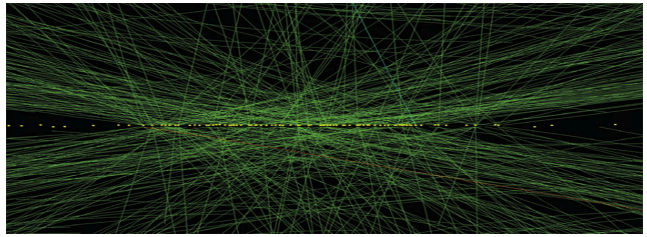
HL-LHC

- 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

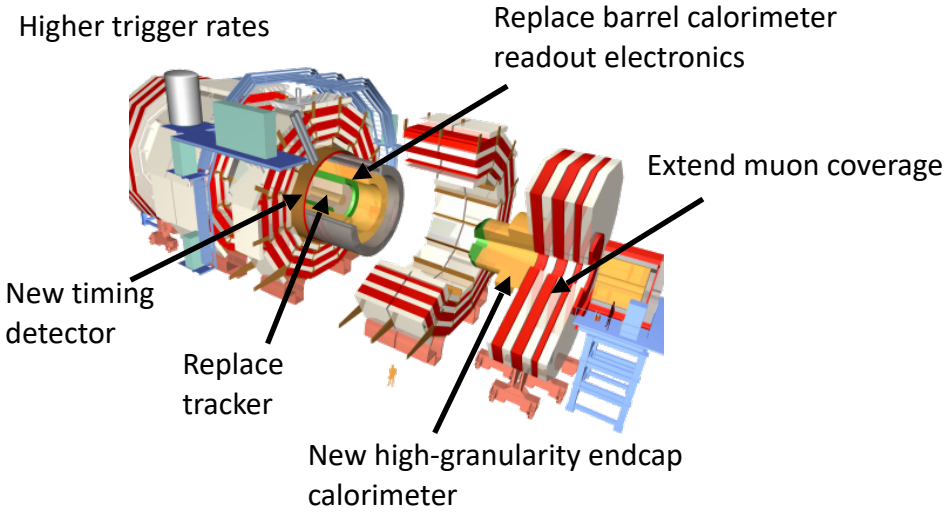
- Higher geometrical coverage, with high resolution for all subdetectors
- New timing detector
- **New L1 track trigger**
- **New high-granularity endcap calorimeter (HGCAL)**

High pileup: about 200 additional proton collisions per bunch crossing



Track information at level 1 trigger

Higher trigger rates

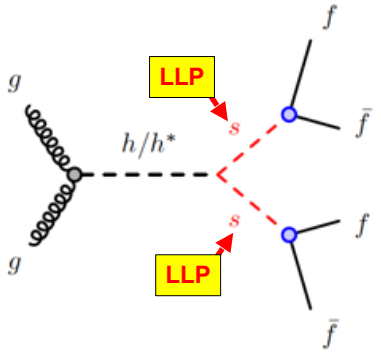


CMS L1 Track Trigger and LLPs

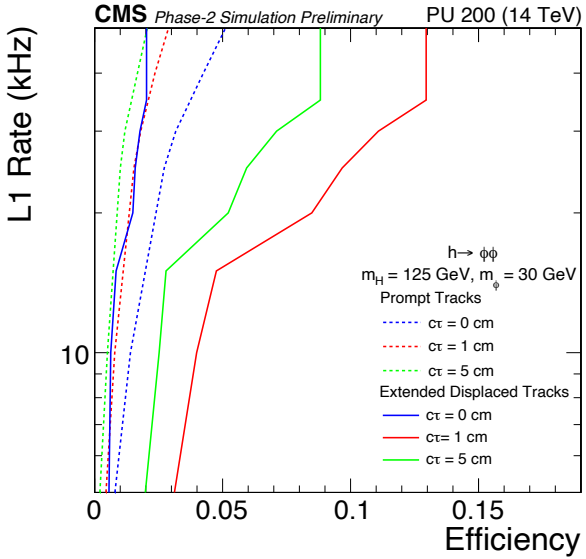
CMS-PAS-FTR-18-018

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

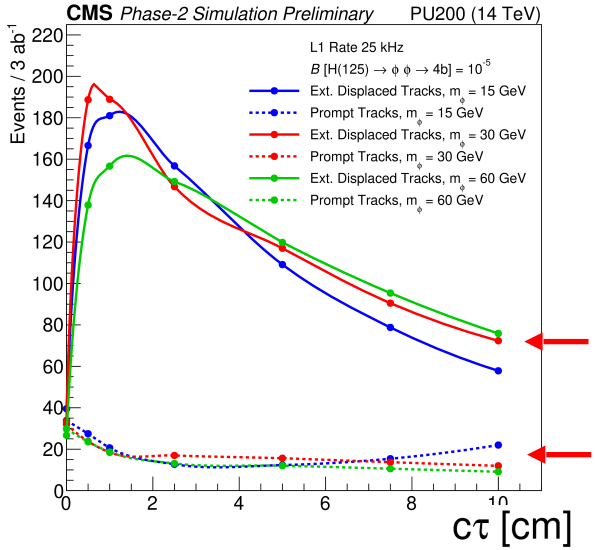
Benchmark model:



Large improvement in efficiency with extension for displaced tracks:



Enough events for discovery!

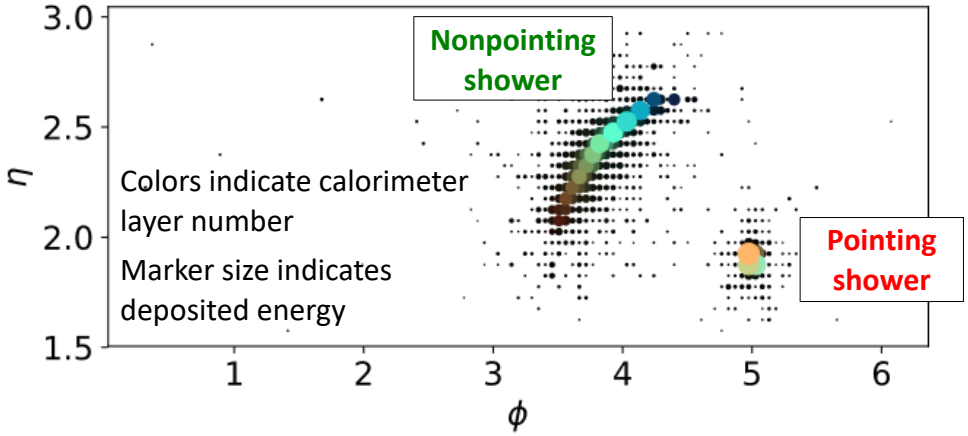


Extension for displaced tracks

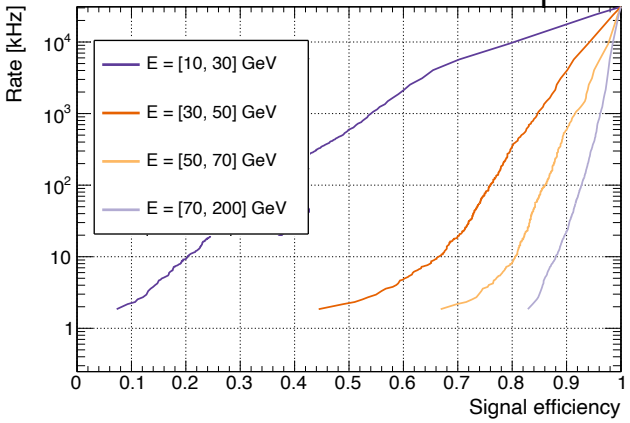
Baseline track trigger

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](doi:10.1088/1748-0221/15/12/P12006)



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



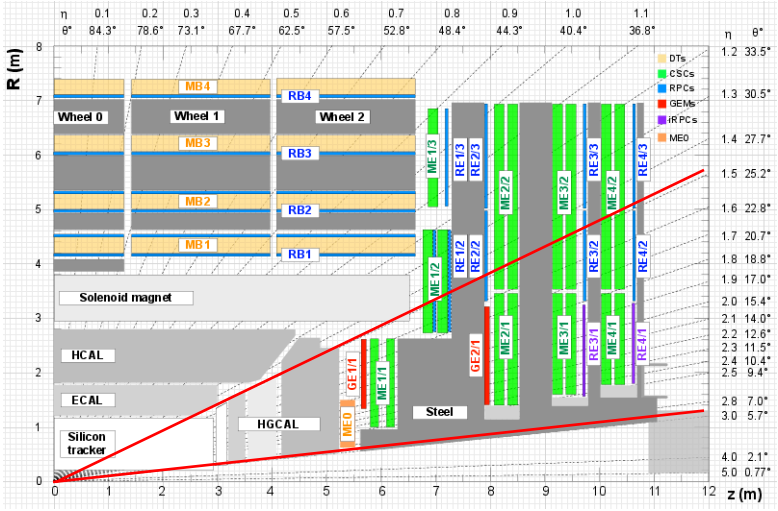
Summary

- 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**

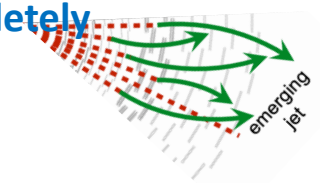
Backup

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

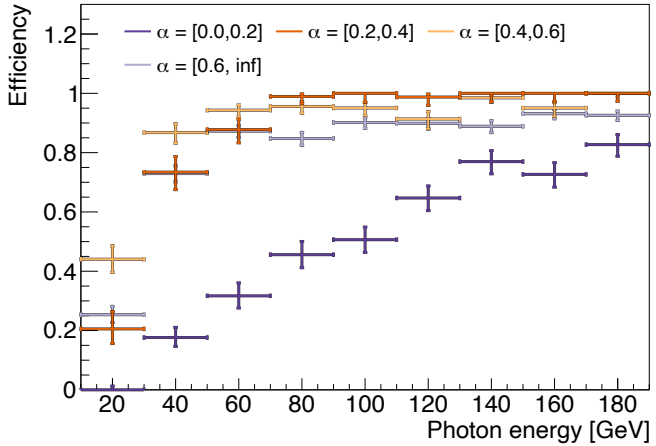


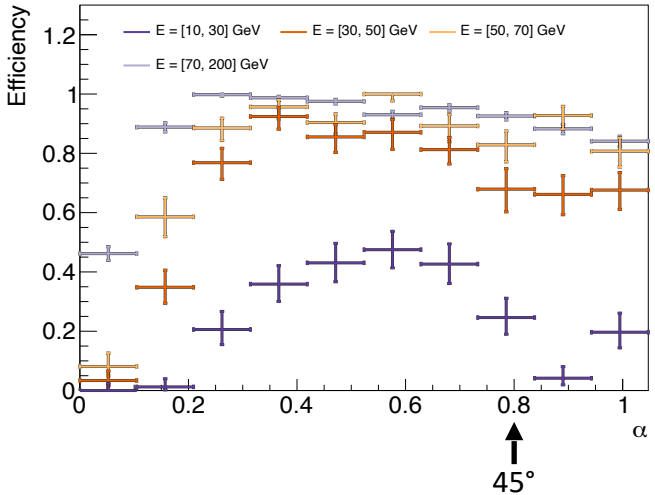
- **Displaced/delayed signatures from LLPs in the forward region could be completely missed with CMS in Phase 2, without a dedicated trigger**
- Example LLP signature: Emerging jets (t-channel production)



Efficiency vs Energy and Angle

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





- 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