LLP coverage at the LHC

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ECFA Focus topic: LLPs - round table
Towards the next update of the European Strategy for Particle Physics
29 April 2024

IFIC Instituto de Física Corpuscular
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IFIC ATLAS VLC Instituto de Física Corpuscular - Valencia
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Agencia Estatal de Investigación

Current coverage and limitations

- Hard to get a complete summary of all existing results. Separating them according to signatures:
- Neutral LLPs with…
  - **Hadronic** decays. Example benchmarks: Exotic decays of the Higgs or heavier bosons
    - Existing searches based on displaced vertices in inner tracker or muon system, displaced or delayed jets in the calorimeters, “lepton-jets” leading to jets in the calorimeters, stopped particles, etc.

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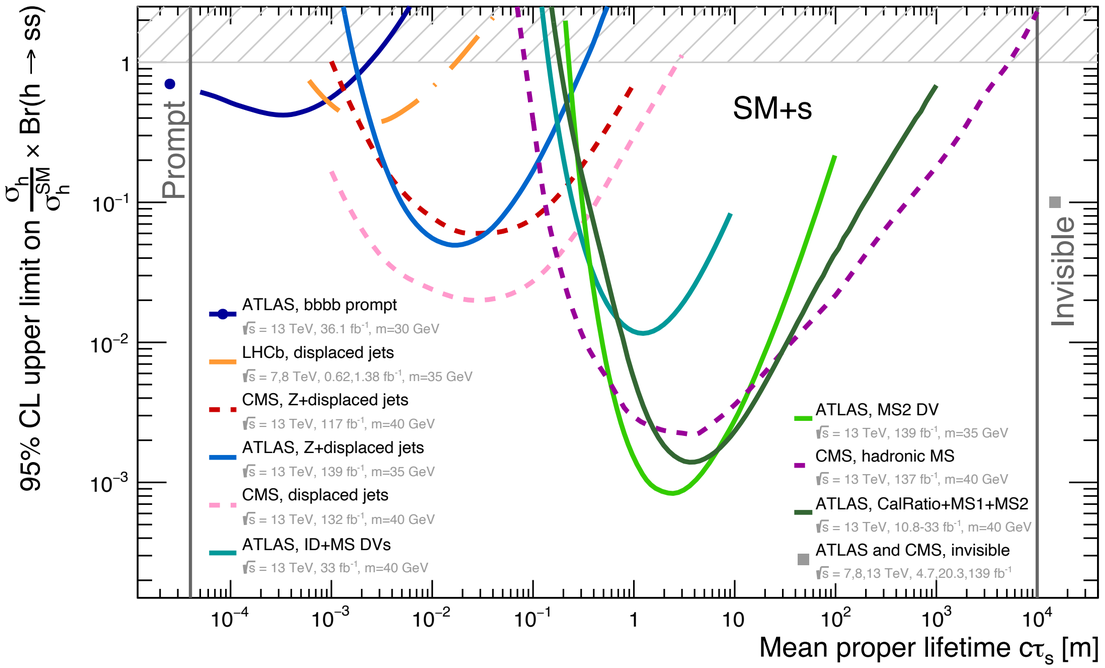
      - Higgs-like bosons decaying to LL scalars
        - Good coverage at ctau ~ 1m
        - Range prompt - 10^{-1} m could be improved
        - Range ctau > 10 m could be covered by dedicated experiments at the LHC

M. Cepeda, S. Gori, V. Martínez-Outchoorn, J. Shelton. 2111.12751



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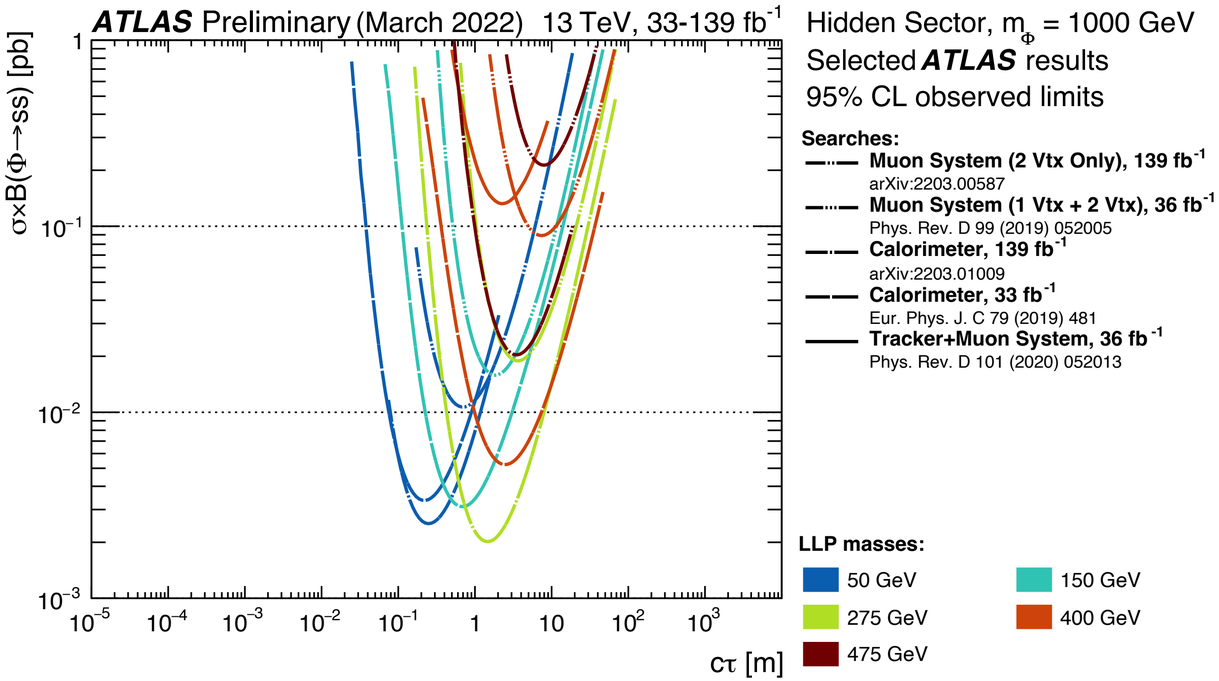
    - Existing searches based on displaced vertices in inner tracker or muon system, displaced or delayed jets in the calorimeters, “lepton-jets” leading to jets in the calorimeters, stopped particles, etc.
      - Heavier bosons decaying to LL scalars
        - Good coverage at ctau ~ 1m
        - Lower ctaus not as deeply investigated so far in ID DV searches
        - Range ctau > 10 m could be covered by dedicated experiments at the LHC



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    - Most searches limited by the triggers. E.g.
      - ATLAS Trackless low-EMF jets trigger (CalRatio) has low efficiency for low pT LLPs and decays in the ECal
      - ATLAS Muon vertex trigger requires multiple RoIs in a cone
      - CSC trigger in CMS limited to the endcaps
      - New ATLAS triggers in Run 3 including Large-Radius Tracking at HLT will greatly improve sensitivity to ID DV searches
      - New CMS triggers in Run 3 covering several signatures: delayed jet trigger using ECal timing, improved tracking for low-mass displaced jet triggers

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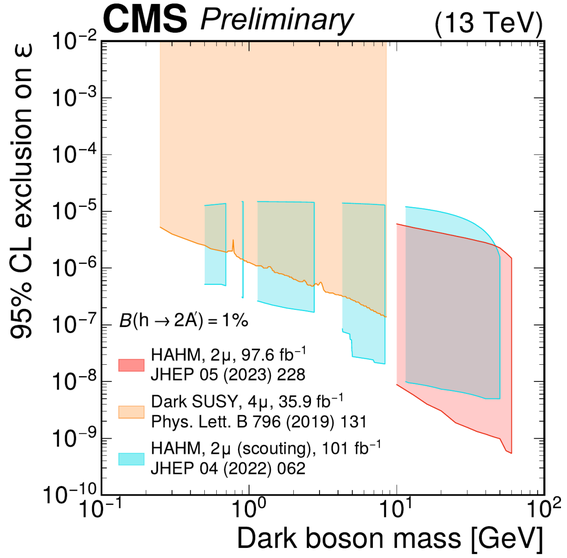
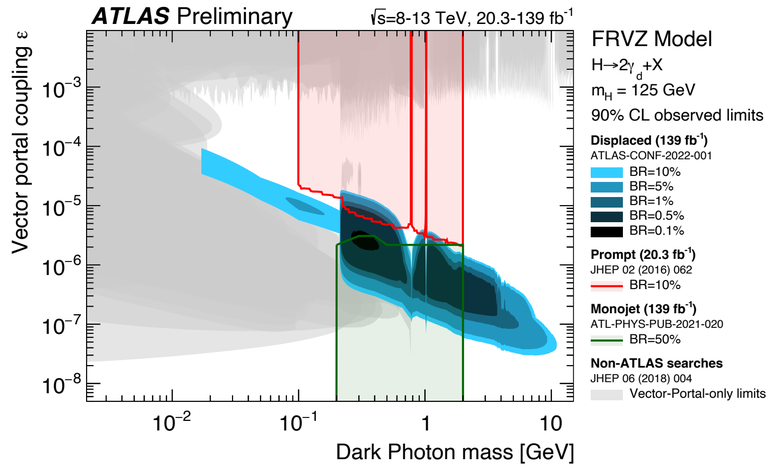
    - Most searches limited by the triggers.
    - Object identification needs dedicated algorithms. Limitations and complementarity among experiments:
      - ATLAS no good identification in the ECal. CMS has dedicated search using ECal timing!
      - Efficiency decreases for low pT or low DV mass
    - Backgrounds can be big (QCD) or unconventional (beam-induced, cosmics)
      - Most analysis involve 2 LLPs to reduce backgrounds.
      - Sensitivity to non pair-produced LLPs can be improved

Current coverage and limitations

- Hard to get a complete summary of all existing results. Showing a few examples based on signatures:
- Neutral LLPs with…
  - **Leptonic** decays (e, mu, tau). Benchmarks: several SUSY scenarios, dark bosons, HNLs, …
    - Existing searches based on displaced vertices in inner tracker looking for displaced leptons (vertex and non-vertex), “lepton-jets” leading to collimated pairs of muons with no ID tracks
      - Higgs-like bosons decaying to light dark bosons
        - Several models explored, different final states
        - Good coverage at mass ~ (1, 50) GeV depending on the model
          - Prompt - displaced - stable searches are complementary and cover most of the phase space
        - Lower masses could be improved for intermediate lifetimes





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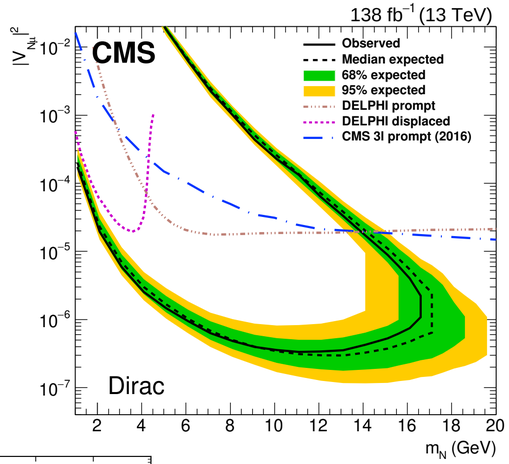
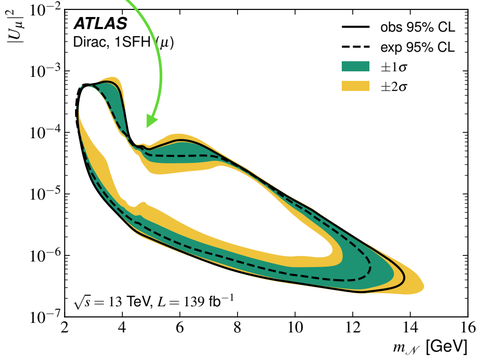
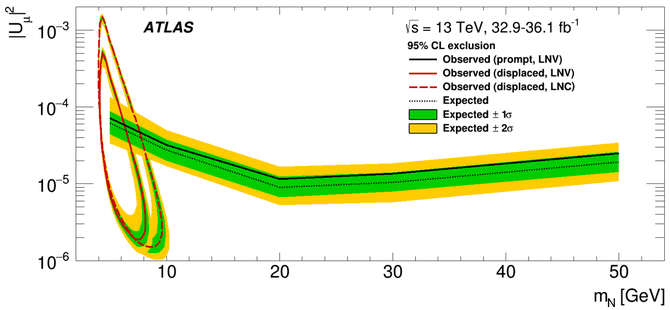
- Hard to get a complete summary of all existing results. Showing a few examples based on signatures:
- Neutral LLPs with…
  - **Leptonic** decays (e, mu, tau). Benchmarks: several SUSY scenarios, dark photons
    - Existing searches based on displaced vertices in inner tracker looking for displaced leptons (vertex and non-vertex), “lepton-jets” leading to collimated pairs of muons with no ID tracks
      - Heavy neutral leptons
        - Good coverage at m < 16 GeV where HNL is long-lived
          - Prompt - displaced searches are complementary
          - Displaced search more sensitive
        - Similar reach in ATLAS and CMS



- Veto on meta-stable regime





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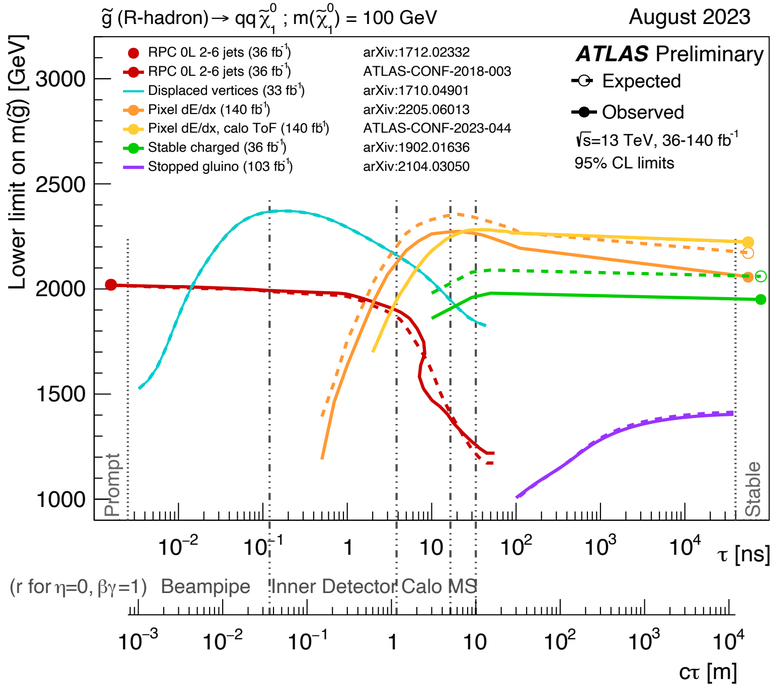
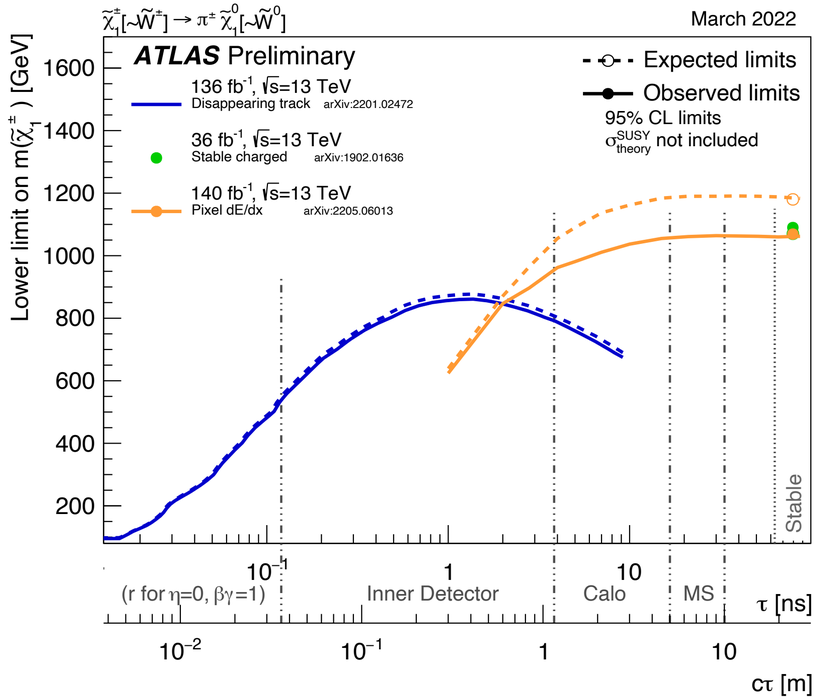
    - Existing searches based on displaced vertices in inner tracker looking for displaced leptons (vertex and non-vertex), “lepton-jets” leading to collimated pairs of muons with no ID tracks
    - Triggers can also be limiting:
      - ATLAS Mu-scan trigger looking for collimated pairs of muons, no good sensitivity for intermediate phase space between very collimated and resolved scenarios
    - Object identification needs dedicated algorithms: LRT, tracking for DV, DV mass, pT, eta, timing, ML techniques
      - Limitations: more and more complicated in high pileup environment
    - Most backgrounds are instrumental (random track crossings, interaction with material, etc.) or cosmics (for lepton jets)

Current coverage and limitations

- Hard to get a complete summary of all existing results. Showing a few examples based on signatures:
- Charged LLPs with…
  - Existing searches based on disappearing tracks, unconventionally high or low dE/dx in the Inner trackers and/or Muon system
  - Triggers can also be limiting: dedicated triggers for many of them
  - Object identification requires very good understanding of the detector's response as a function of charge and mass





Current Gaps

- Still several gaps in coverage. See Chapter 3 of the LLP White paper
- Many have been or are being covered with Run 3 data but others still to be studied

Journal of Physics G: Nuclear and Particle Physics

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3.6. Discovery opportunities: overview of gaps in coverage

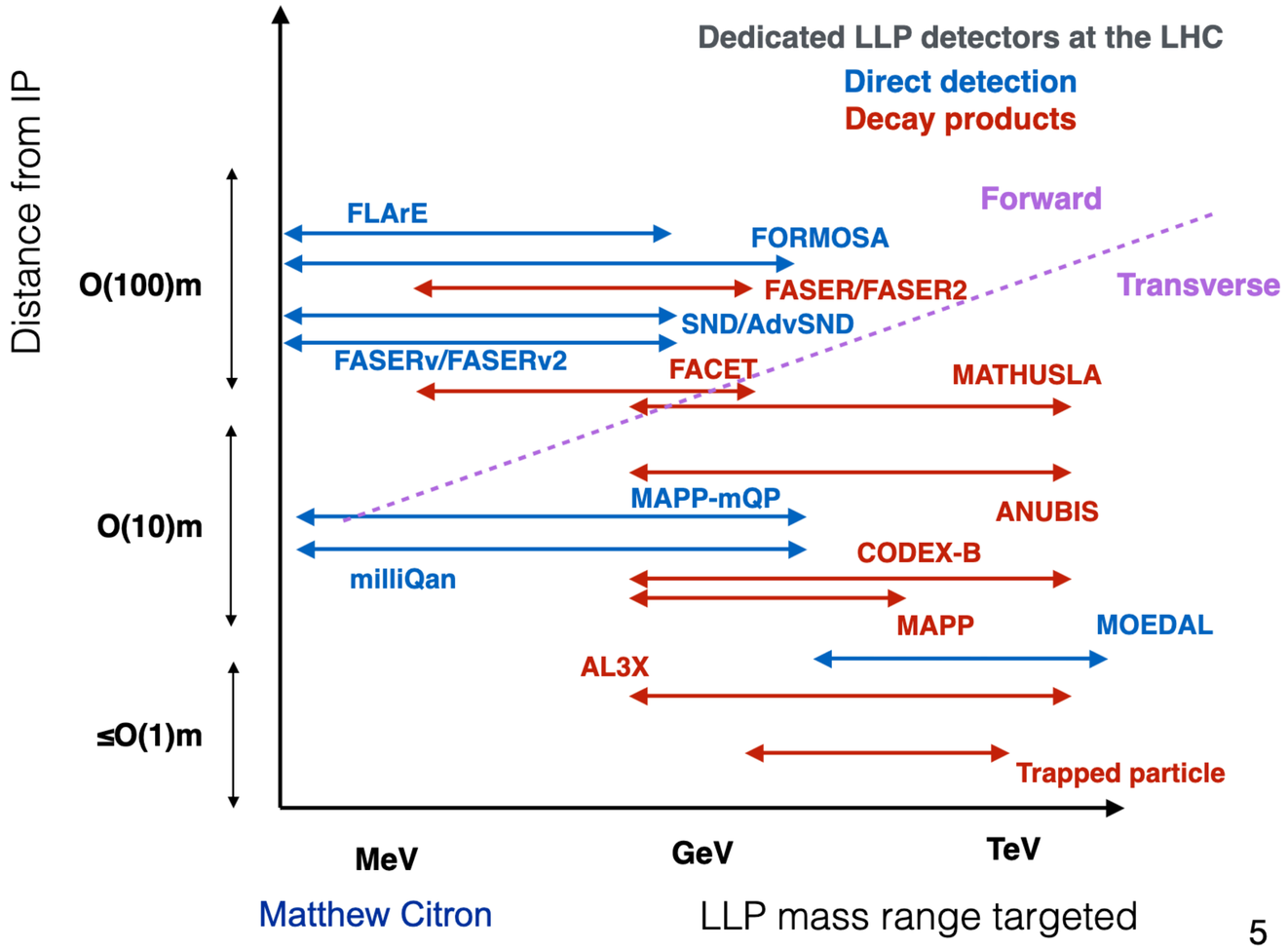
In the preceding sections 3.1–3.5.3, we have examined the so-called 'coverage' of existing searches for LLPs at the LHC with the explicit and express purpose of identifying uncovered realms and places where discoveries could be hiding. Here, we summarize these gaps and potential opportunities for LLP discovery in bullet form, as a to-do list for the experimental community.

1. All-hadronic LLP decays
   - Associated-object triggers (especially motivated by Higgs-like VBF and VH production modes) need to be more comprehensively used to improve sensitivity to low-p_{T} objects.
   - Improvements are needed in sensitivity at lower masses and lifetimes (e.g. for LLPs produced in Higgs decays).
   - Single hadronic DVs need to be looked for in searches that currently use two (such as decays in ATLAS HCAL and MS).
   - Possibilities need to be explored for ATLAS and CMS for online reconstruction of hadronic displaced objects, as the inclusive H_{T} triggers used by the two collaborations miss these objects unless they have a large p_{T}. (By constrast, LHCb can trigger on a displaced hadronic vertex [253, 254].)
   - Low-mass hadronically decaying LLPs can look somewhat like tau leptons, so the question remains as to whether there is any possibility of using, for example, L1 tau triggers to seed displaced jet triggers at HLT and improve trigger efficiency; studies need to be performed by the experimental collaborations.
   - The prospects for dedicated searches for displaced hadronic taus need to be investigated, since no dedicated searches currently exist.
   - The potential for flavor-tagging displaced jets (b-displaced jets, c-displaced jets, etc) needs to be explored.
2. Leptonic
   - Coverage needs to be provided for the intermediate region between boosted, low-mass LLPs (lepton jets) and high-mass, resolved LLPs (resolved ATLAS/CMS searches).
   - Improvements need to be made to extend coverage to lower masses and to lower p_{T} thresholds. Currently no prescription or plan for this exists, and so dedicated studies need to be done.
   - Searches need to be done for different combinations of charge and flavor of displaced leptons (e.g. same-sign versus opposite-sign, opposite-flavor versus same-flavor).
   - Searches need to be done for tau leptons in LLP decays, in particular if they come from the ID; an unanswered question remains as to whether displaced-jet triggers can be used for this purpose.
3. Semi-leptonic
   - Searches do not exist and need to be done for LLP masses below about 30 GeV; this mass range is theoretically well motivated by Majorana neutrinos.
   - Searches need to be performed for all flavor combinations (for example, one CMS search only covers $e^{\pm}\mu^{\mp}$), as well as same-sign versus opposite-sign leptons.
   - Currently unknown improvements need to be made to relax or modify isolation criteria wherever possible to recover sensitivity to boosted semi-leptonic decays.
   - Searches need to be done that better exploit triggering on associated objects for improved sensitivity to low-mass objects, or to employ high-multiplicity lepton triggers if there are multiple LLPs.
4. Photonic
   - There is currently no coverage for LLPs decaying into $l\gamma$, $j\gamma$, or without $\not{E}_{\mathrm{T}}$, and searches urgently need to be performed for this decay topology.
   - There is currently poor coverage (i.e. there exists no dedicated search) for single-γ topologies. The only searches with sensitivity require two jets to be present in addition to $\not{E}_{\mathrm{T}}$ [303]. Studies are needed to assess the sensitivity of this search to signals with only one delayed photon and different jet multiplicities.
   - There is currently no coverage for softer non-pointing or delayed photons, and searches need to be performed for these kinematic realms.
   - Studies need to be performed to determine if triggers on associated objects may improve sensitivity to signals with a single photon, without $\not{E}_{\mathrm{T}}$, or for lower-p_{T} photons
5. Other exotic long-lived signatures
   - Disappearing tracks with $c\tau \sim$ mm are very hard to probe, and new ideas and detector components are needed to extend sensitivity to this potential discovery regime. It is unclear if the ATLAS insertable B-layer will be present in HL-LHC run and how sensitivity to the DT topology will improve with the replacement of the current ID with the new inner tracker (ITk), or whether new tracking layers very close to the beam line can be added. It is an open question as to what is the lowest distance at which new layers (or double layers) can be inserted. Another open question that needs to be answered is whether there are any prospects for DTs at LHCb with an upgraded detector.

   - No dedicated searches for quirks exist at the LHC, a huge, open discovery possibility for ATLAS, CMS, and LHCb. Some LHC constraints exist by reinterpreting HSCP searches, but dedicated searches need to be performed. There are significant challenges in modeling the propagation and interaction of quirks with the detector, as well as in fitting tracks to their trajectories, but new ideas have been proposed that need to be explored by the experimental collaborations that might allow improved sensitivity to quirks with less ambitious analysis methods.

Current Gaps

- Dedicated experiments for LLPs at the LHC will cover some of them.
  - A few already approved and taking data
  - Others in good path towards HL-LHC



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Where could we gain with future colliders?

- Points for improvement:
  - In leptonic colliders, “smaller” backgrounds (pileup, BIB)
    - Loosened triggers
    - Better sensitivity
  - Longer lifetimes:
    - Higher energies mean higher masses, so slower particles. Better chances for decays within detectors
    - Bigger detectors mean decay positions further away

- At the (HL-)LHC there are lots of work on new signatures to reach so-far uncovered or barely covered models
  - Single LLP + prompt activity (e.g. ALP + X)
  - Emerging / semi-visible jets
  - Need to investigate where the limitations are and where future accelerators will help