Energy Frontier Probes of the Dark Sector and Long-Lived Particles

Juliette Alimena

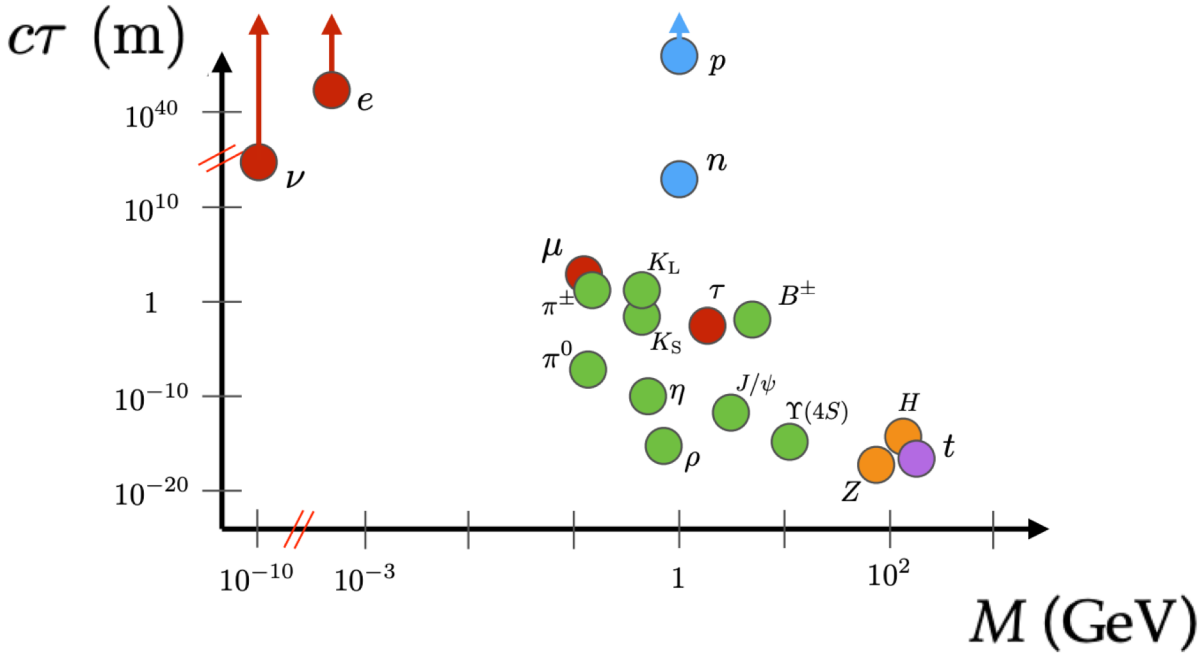
Cross-Frontier Meeting: Dark Sectors and Light Long-Lived Particles

Snowmass 2021

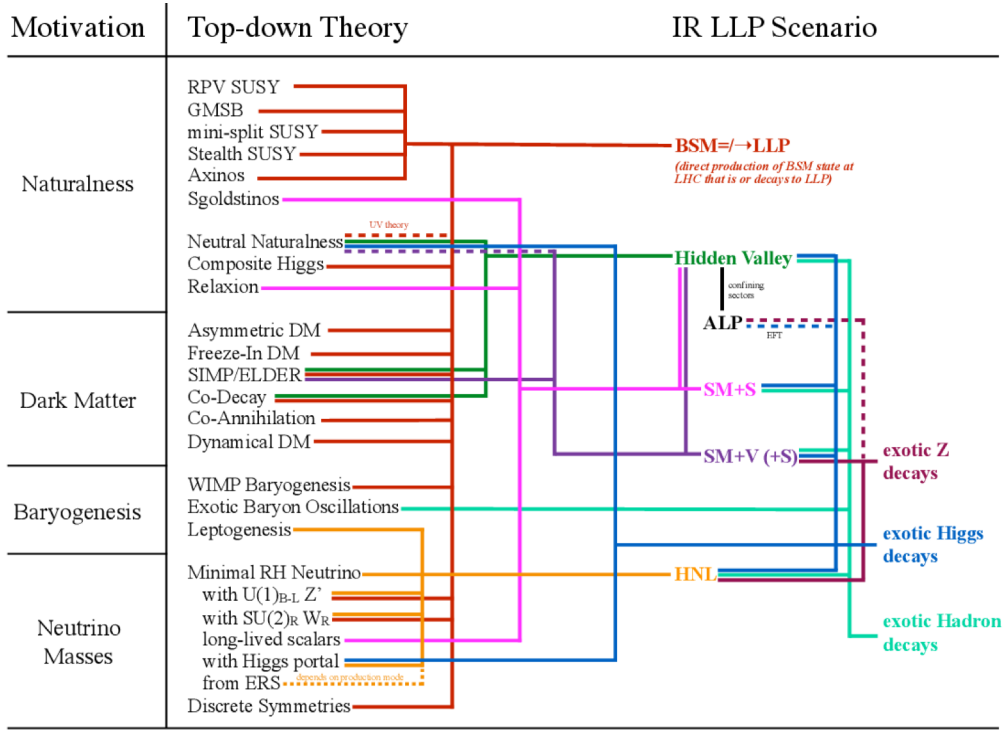
July 15, 2020

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

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

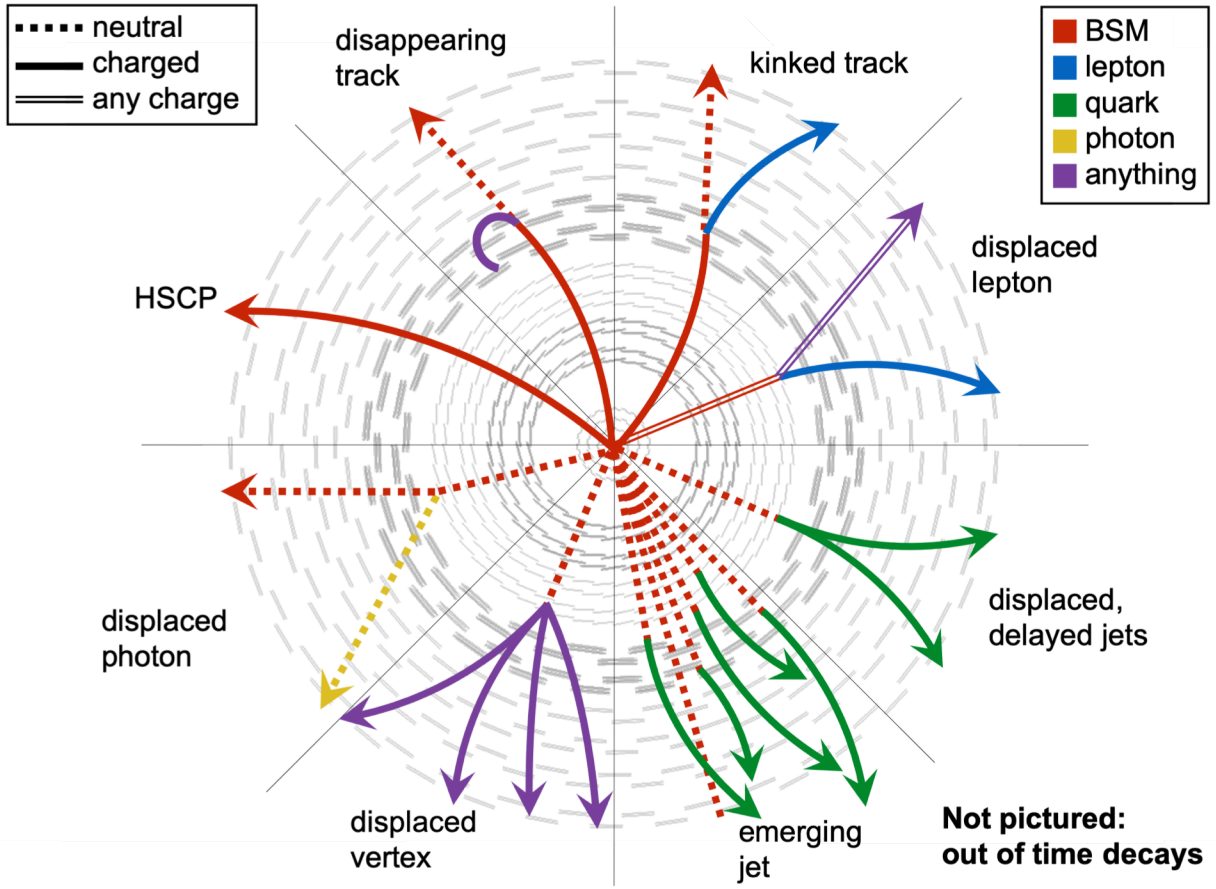


LLPs appear in **many scenarios beyond the standard model**, including the dark sector



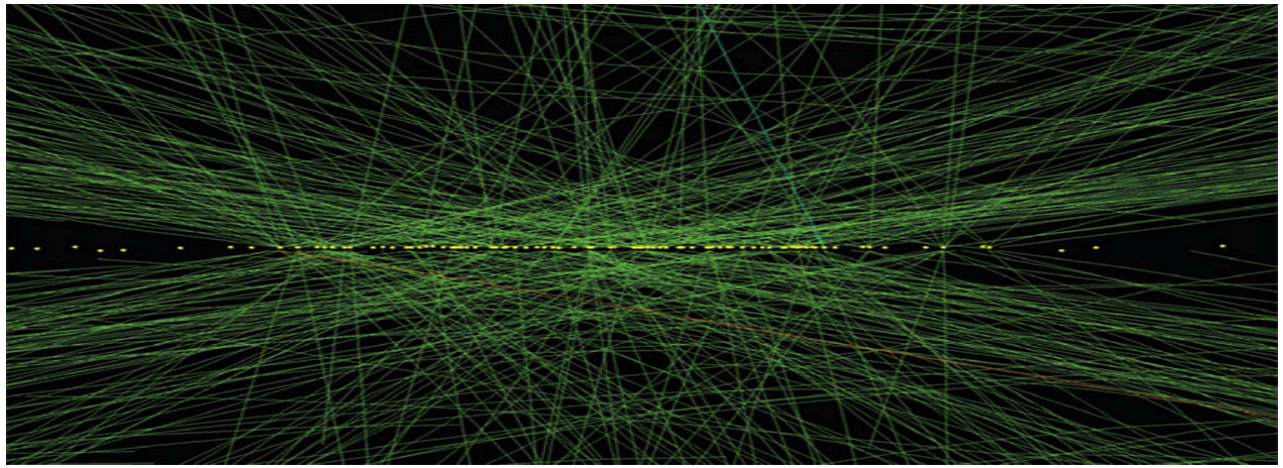
LLP Searches

- **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



High-Luminosity LHC

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

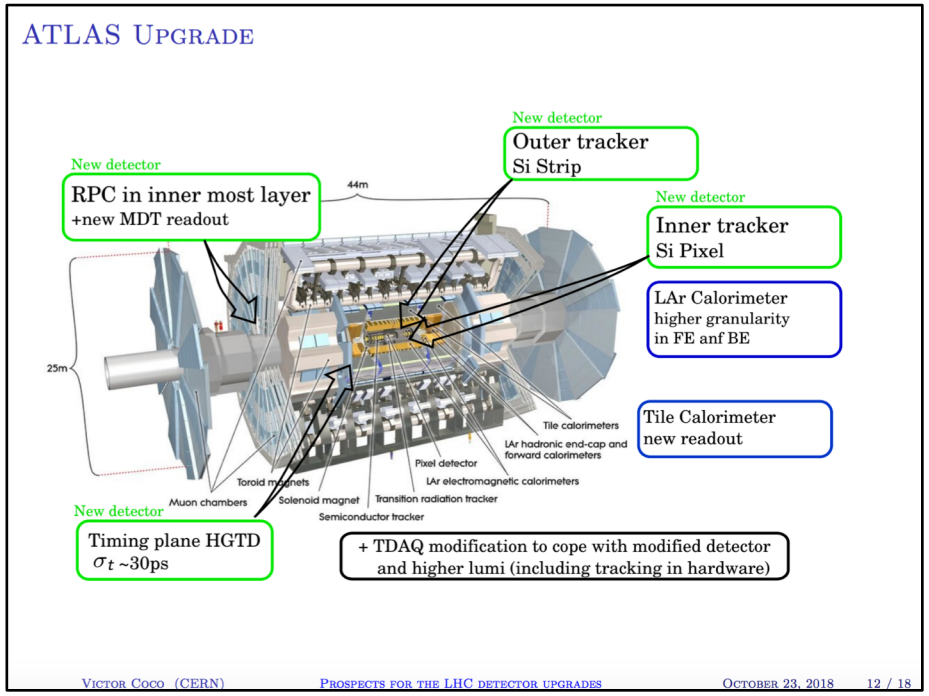


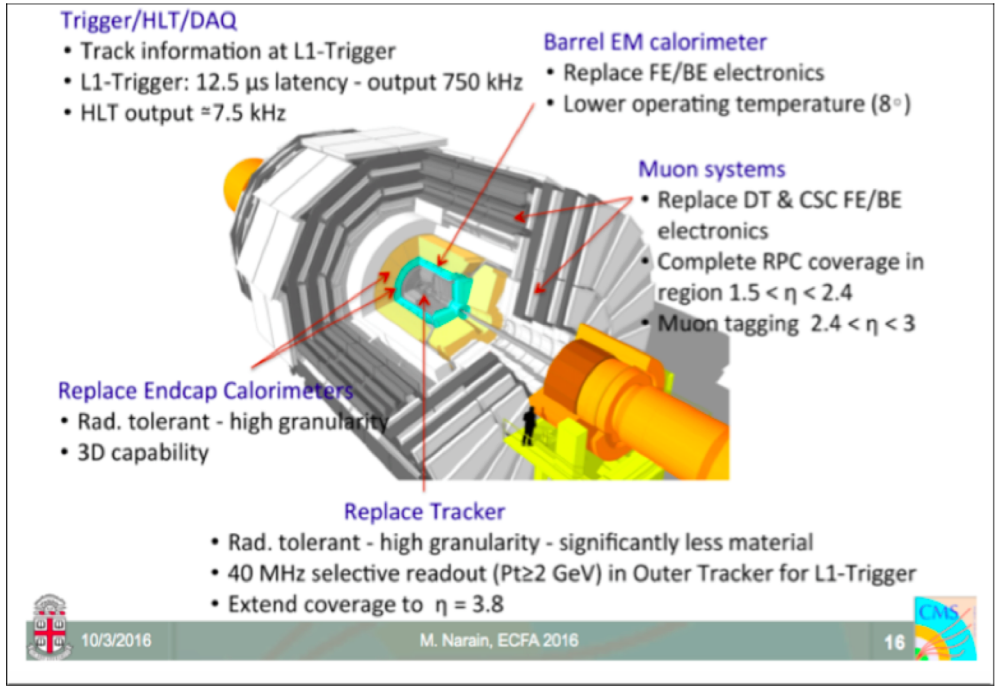
High pileup: about 200 additional proton collisions per bunch crossing

ATLAS and CMS Upgrades

- Higher geometrical coverage of all subdetectors
- High resolution for all subdetectors
- New L1 track trigger in CMS
- New timing detectors

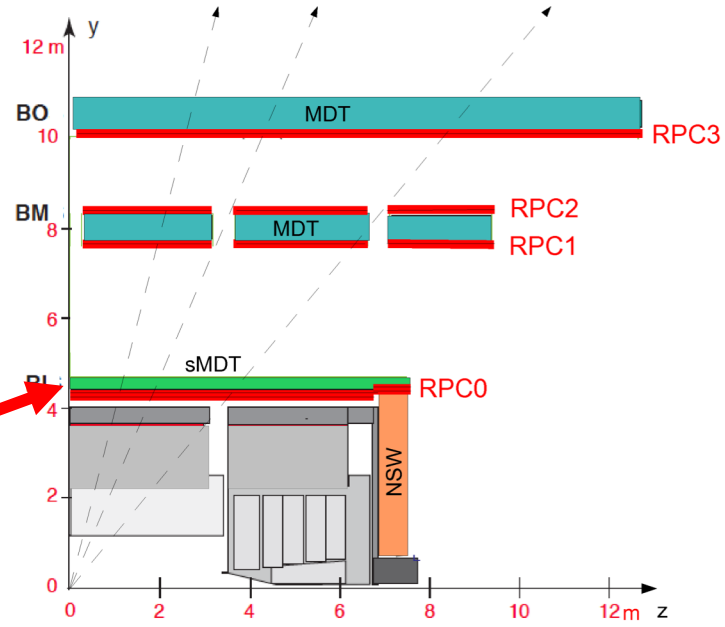
This talk will highlight some LLP projections that take advantage of the upgrades, and identify gaps that could be covered in Snowmass

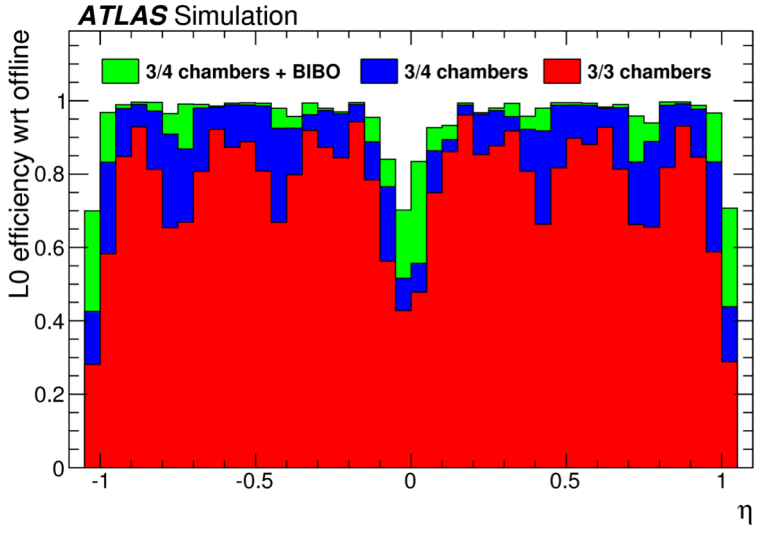




Muon System Upgrade

- Electronics for L0 trigger in Resistive Plate Chambers (RPCs) and Thin-Gap Chambers (TGC) will be upgraded to deal with increased trigger rate
- Replace Monitored Drift Tube (MDT) front-end readout
- New RPC layer in the barrel



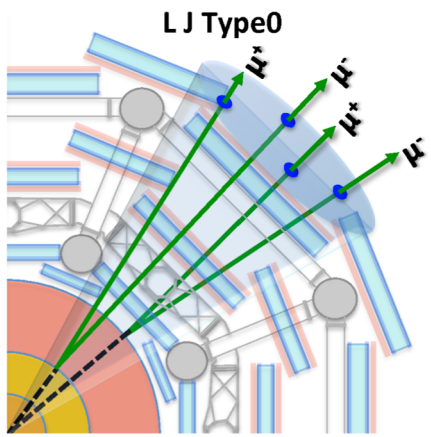


- **Increases efficiency of RPC triggers from 78% (Run 2) to 96% (HL-LHC)**

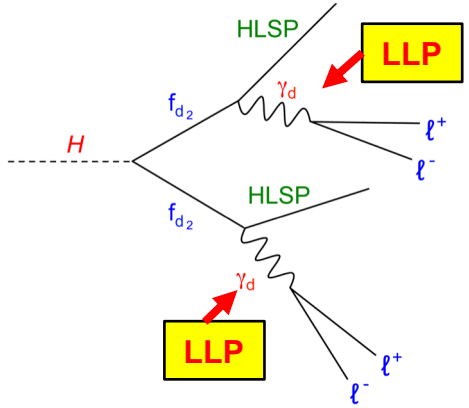
ATL-PHYS-PUB-2019-002

Displaced Lepton Jets at the HL-LHC (I)

Search for long-lived **dark photons** that decay to **displaced muon jets**



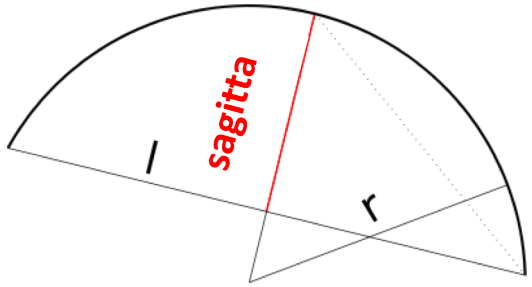
FRVZ vector-portal benchmark:



Developed two new L0 muon trigger algorithms:

1. Sagitta muon trigger:

- Momentum can be misreconstructed for non-pointing muons due to beam spot constraint
- New approach: cut on **sagitta** of muon trajectory
- Gives **~20% improvement in efficiency**

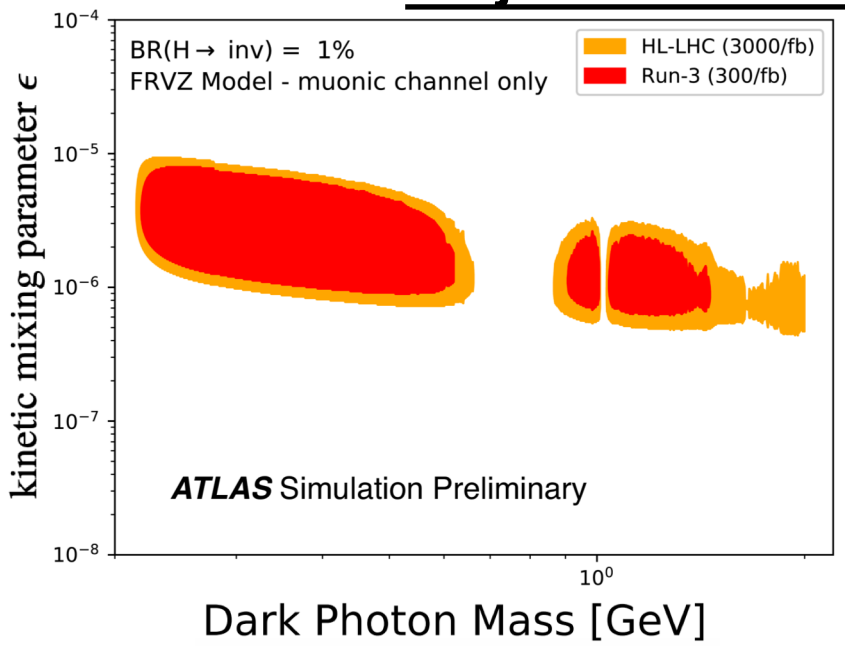


Displaced Lepton Jets at the HL-LHC (II)

2. Multi-muon scan trigger:

- If dark photon is highly boosted, decay muons can be close-by
- **New approach**: include **multiple muon** trigger candidates in the same **region of interest**
- Multi-muon scan improves signal efficiency **up to 7%** with p_T>20 GeV

Projection of 2015+2016 result (ATLAS-CONF-2016-042) :

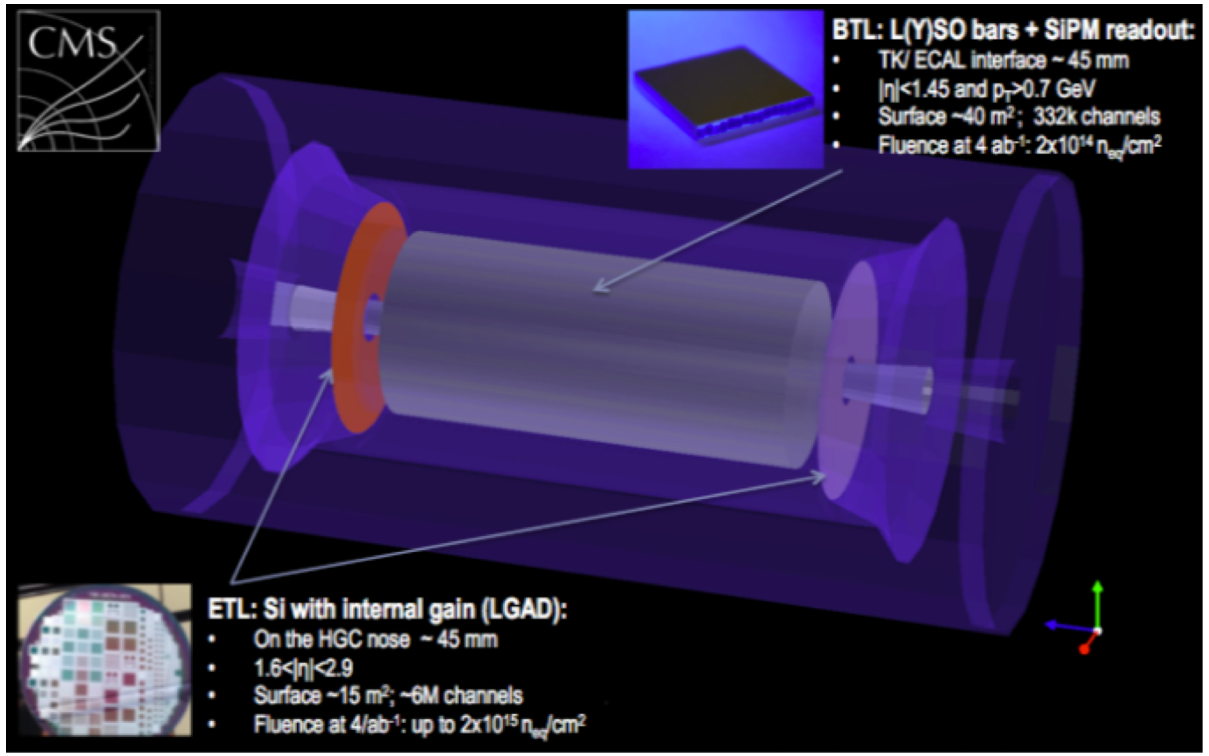


- **Run 3** (300 fb^{-1})
- **HL-LHC** (3000 fb^{-1})
- HL-LHC projection includes multi-muon scan trigger improvement
- HL-LHC projection will probe BR(H→$2\gamma_d$+X) down to ~1%: much further than Run 2 sensitivity!

CMS-TDR-19-002

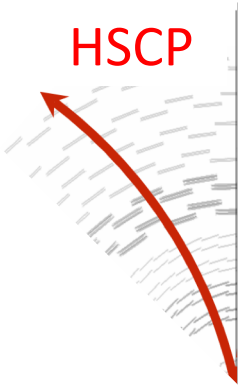
MIP Timing Detector (MTD)

- Detector dedicated to precisely measuring the production time of minimum ionizing particles (MIPs)
- **30 ps** resolution at the start of the HL-LHC
- Allows to precisely measure **vertices in 4D**, at 200 PU
- **Provides unique opportunity for LLPs**



Heavy Stable Charged Particles with the MTD

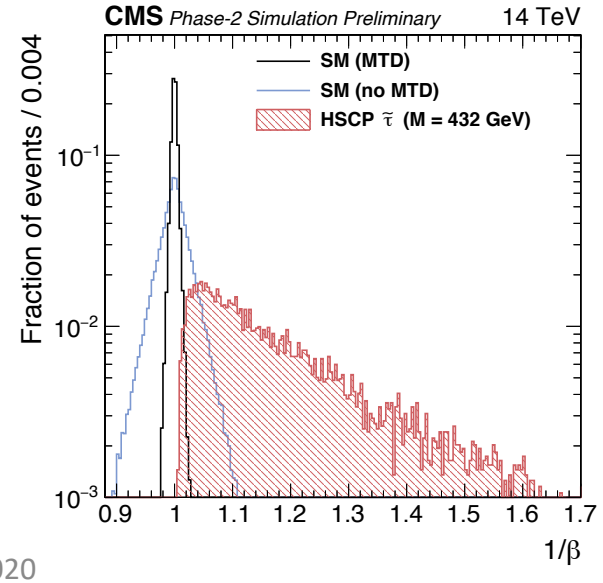
- Search for **heavy**, slow-moving, highly-ionizing particles that pass through the detector
- Studied the HSCP **β** (velocity/speed of light) measured with the particle path length and time difference between the primary vertex and MTD hits



mGMSB benchmark:

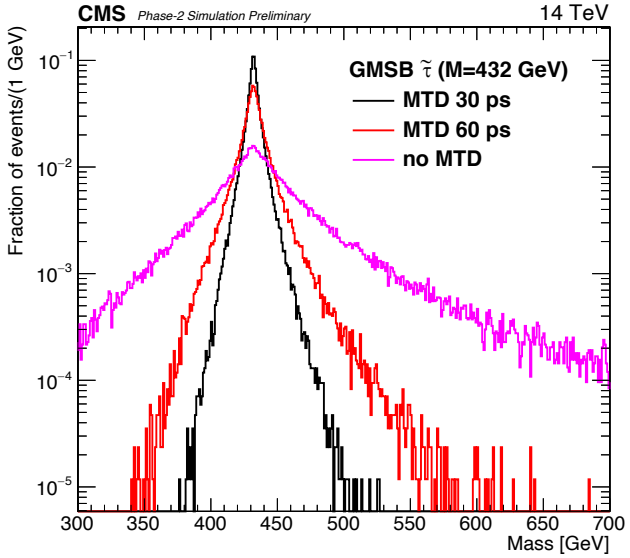
*If the **coupling** of the stau to the gravitino **is small**, the stau can be long-lived*

MTD greatly improves 1/β resolution



Can estimate the **HSCP mass** from the momentum and β as measured by the MTD

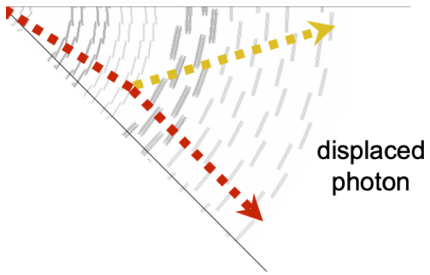
- MTD, 30 ps resolution
- MTD, 60 ps resolution
- no MTD, 1/β resolution from 2016 HSCP analysis



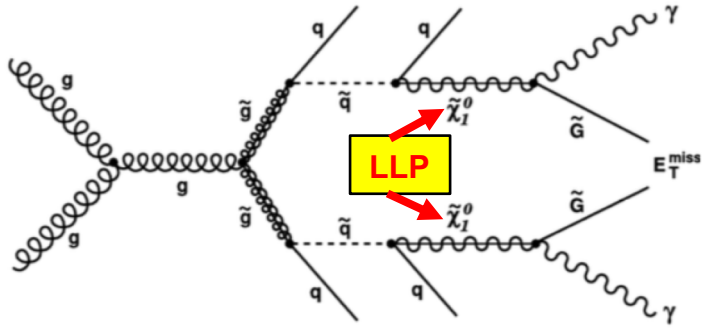
The MTD greatly improves long-lived particle velocity measurements and thus analysis sensitivity

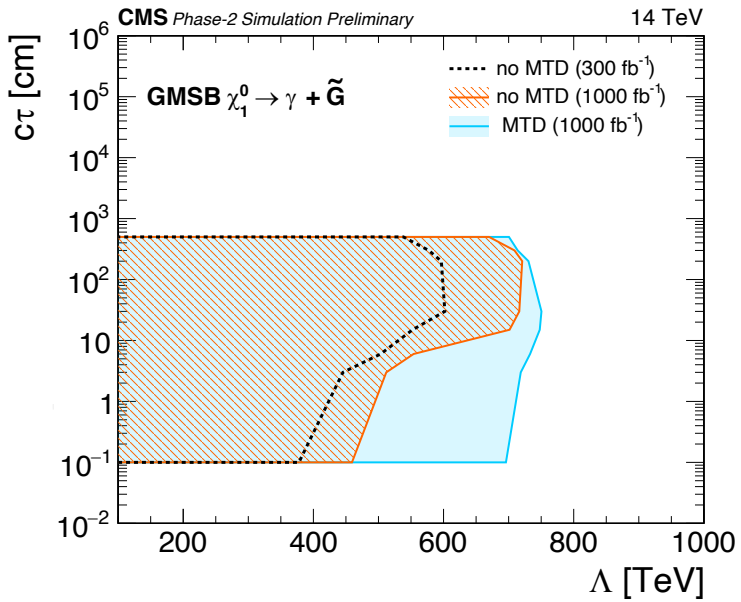
Delayed Photons with the MTD

- Search for LLPs that decay to **delayed photons + missing transverse momentum**
- Photon time estimated using the ECAL and compared to the PV time using the MTD



GMSB benchmark:



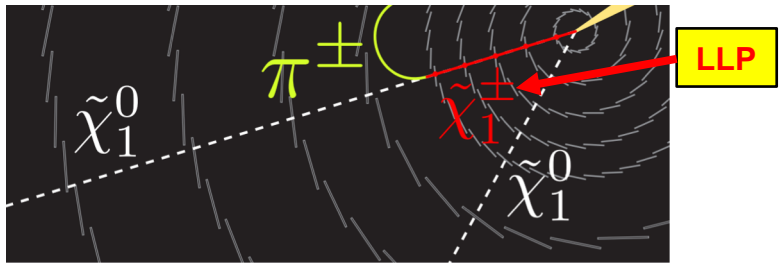


- **Run 3 detector (300 fb^{-1})**
  - 300 ps time resolution in ECAL
- **Phase-2 detector without MTD (1000 fb^{-1})**
  - 180 ps time resolution dominated by beamspot uncertainty
- **Phase-2 detector with MTD (1000 fb^{-1})**
  - **30 ps time resolution**

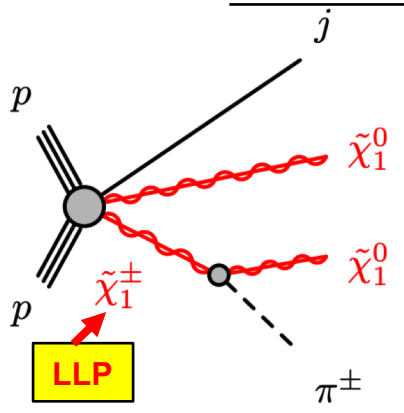
The MTD greatly improves the sensitivity to LLPs with short lifetimes and large masses

Disappearing Tracks at the HL-LHC

- Search for charged LLPs that decay to neutral particles with a disappearing track signature

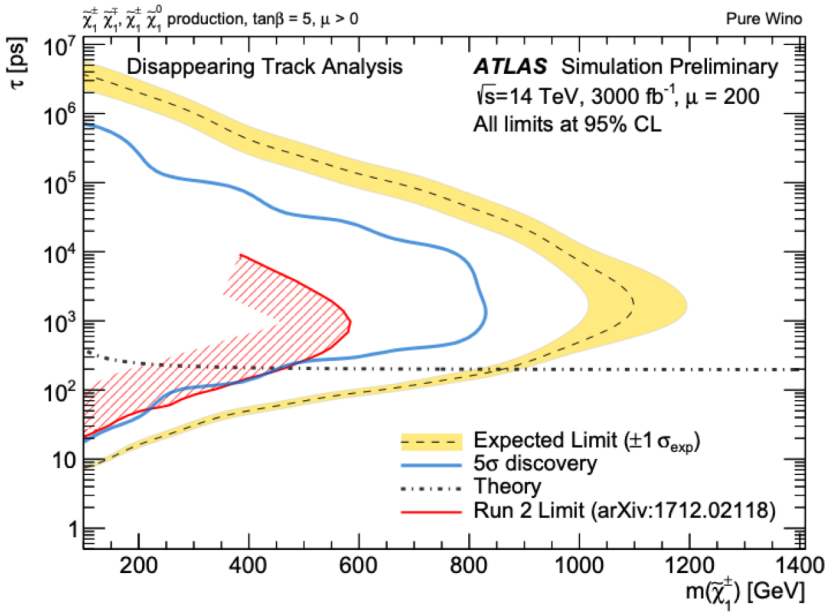


AMSB benchmark:



*If chargino and neutralino are **almost mass degenerate**, the chargino can be long-lived*

Pure wino LSP scenario



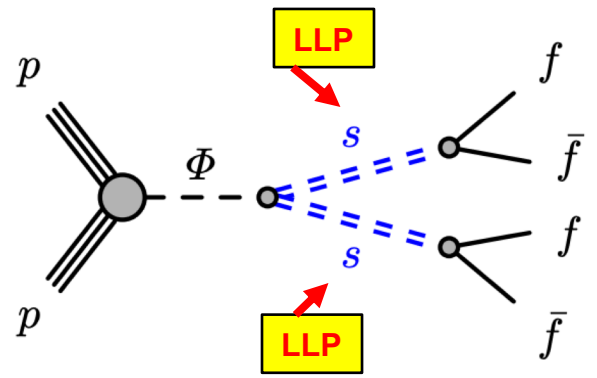
- Truth-level analysis with parameterized detector response
- Select events with short tracks, no leptons, and large missing transverse momentum
- **Large gain in disappearing track sensitivity at the HL-LHC with 3 ab^{-1}**

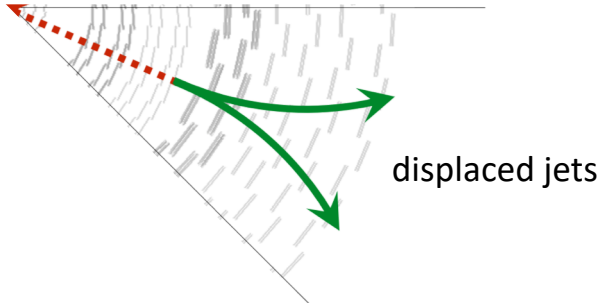
CMS-PAS-FTR-18-018

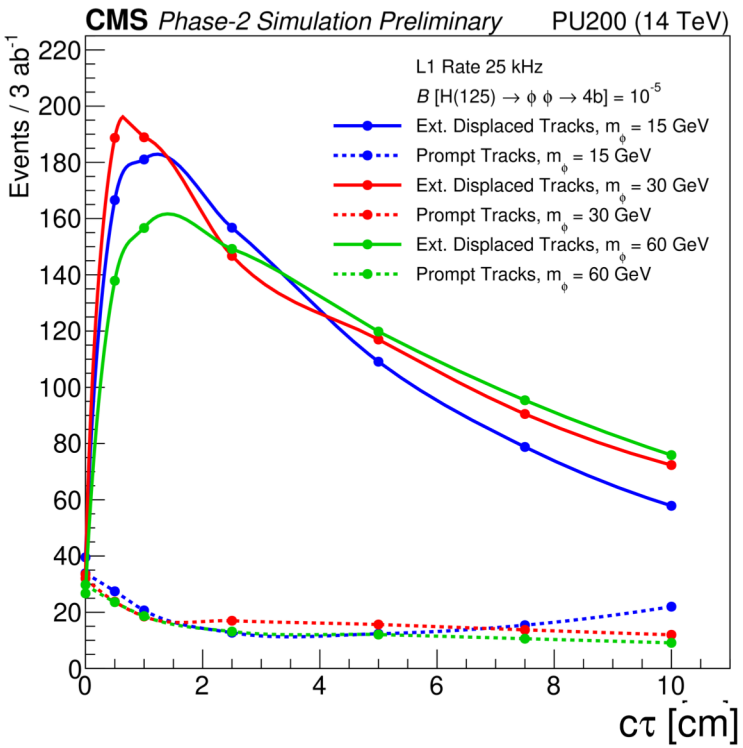
Triggering on Displaced Jets

- Search for long-lived scalars that decay to displaced jets
- Many displaced tracks <u>currently missed</u> at trigger level, but could be found with L1 **track trigger**

<u>Exotic Higgs boson decays to LL scalars:</u>







Enough events for discovery!

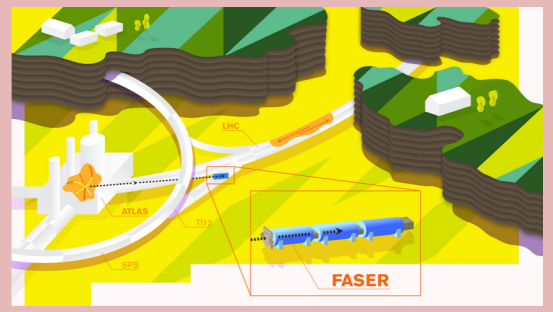
← Track trigger extension for displaced tracks

← Baseline track trigger

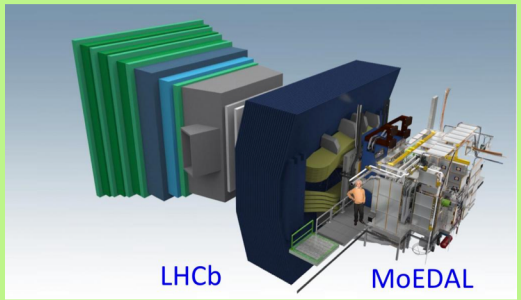
Some Dedicated LLP Experiments

- Besides the more general purpose LHC experiments, there are approved and proposed **experiments dedicated to looking for LLPs**
- Just a few examples (**see more later today**):

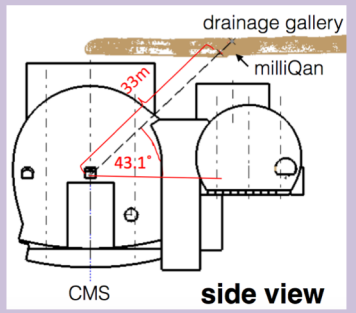
FASER: searches for long-lived dark photons and similar particles in the extreme forward direction

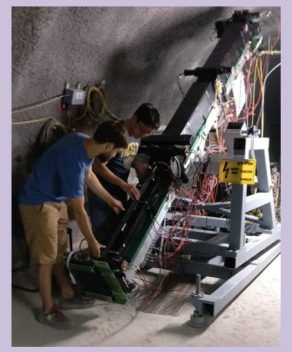


MoEDAL: searches for monopoles stopped in the beampipe with a SQUID precision magnet

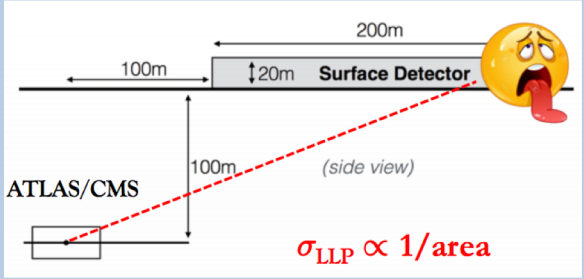


MilliQan: searches for millicharged particles with a detector pointed at the CMS interaction point



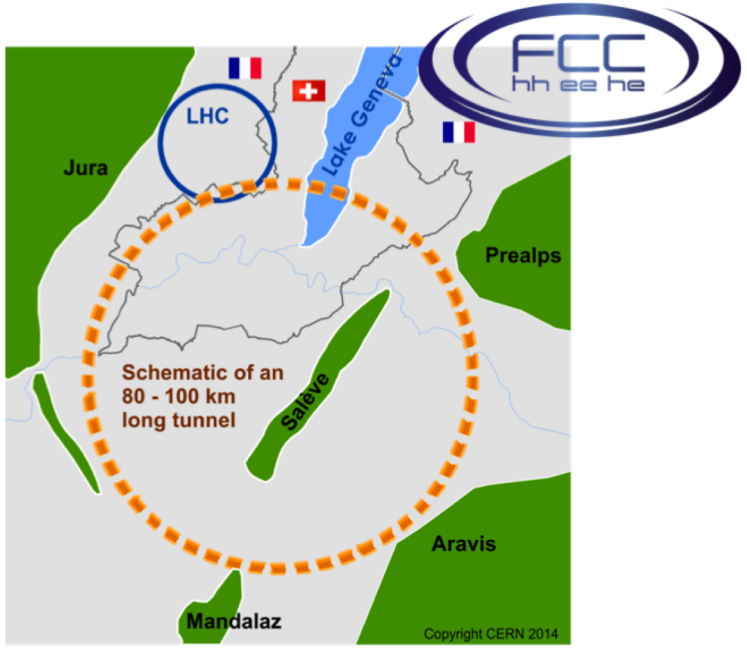


MATHUSLA: searches for (very) long-lived weakly interacting neutral particles with a large-volume, air-filled surface detector



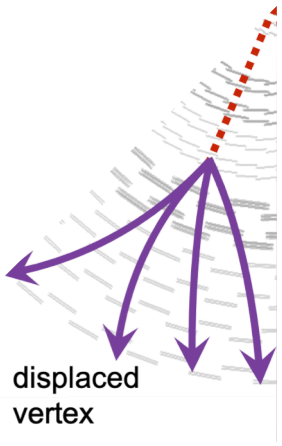
LLPs at Lepton Colliders

- Besides future hadron colliders, there are also opportunities for LLPs at future lepton colliders, for example:
  - Compact Linear Collider (CLIC)
  - Future Circular Collider (FCC-ee)
- Lepton colliders have a cleaner collision environment than hadron colliders
  - Possibility of readout without a trigger
  - First layers of pixels could be closer to the interaction point

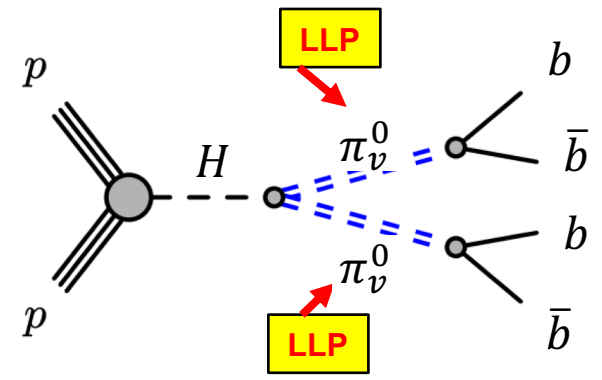


Displaced Vertices at CLIC

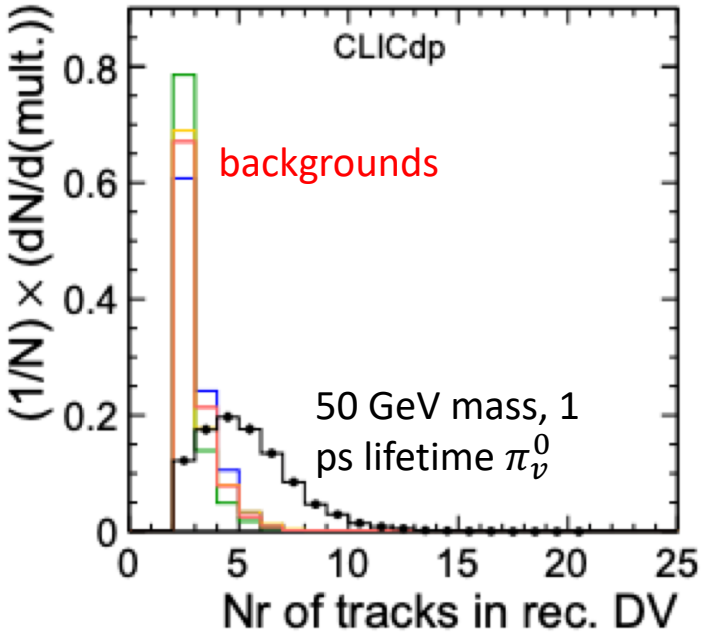
- Search for Higgs bosons that decay to long-lived particles that decay to b quarks with a signature of displaced, multi-track vertices
- Results with full CLIC_ILD detector simulation
- Use BDT to separate signal from background

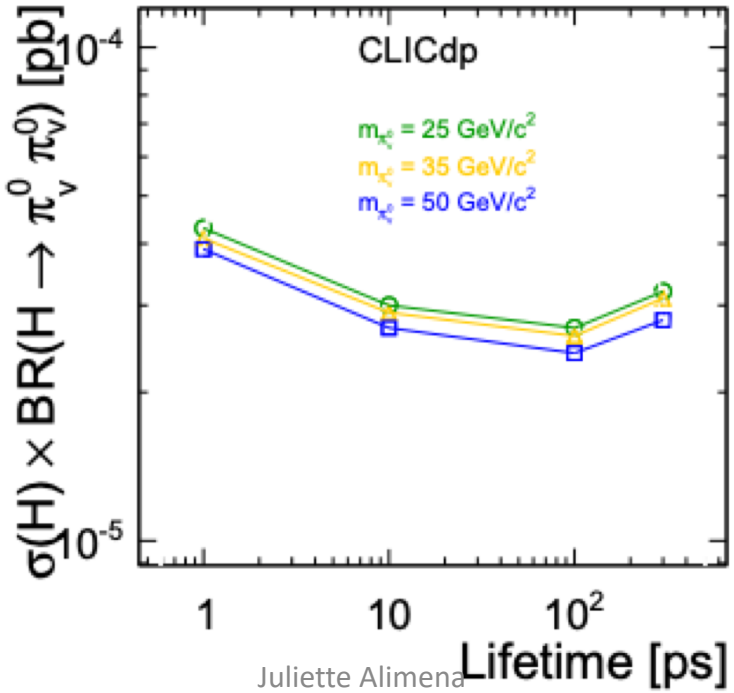


Hidden Valley benchmark:



An input variable to the BDT:



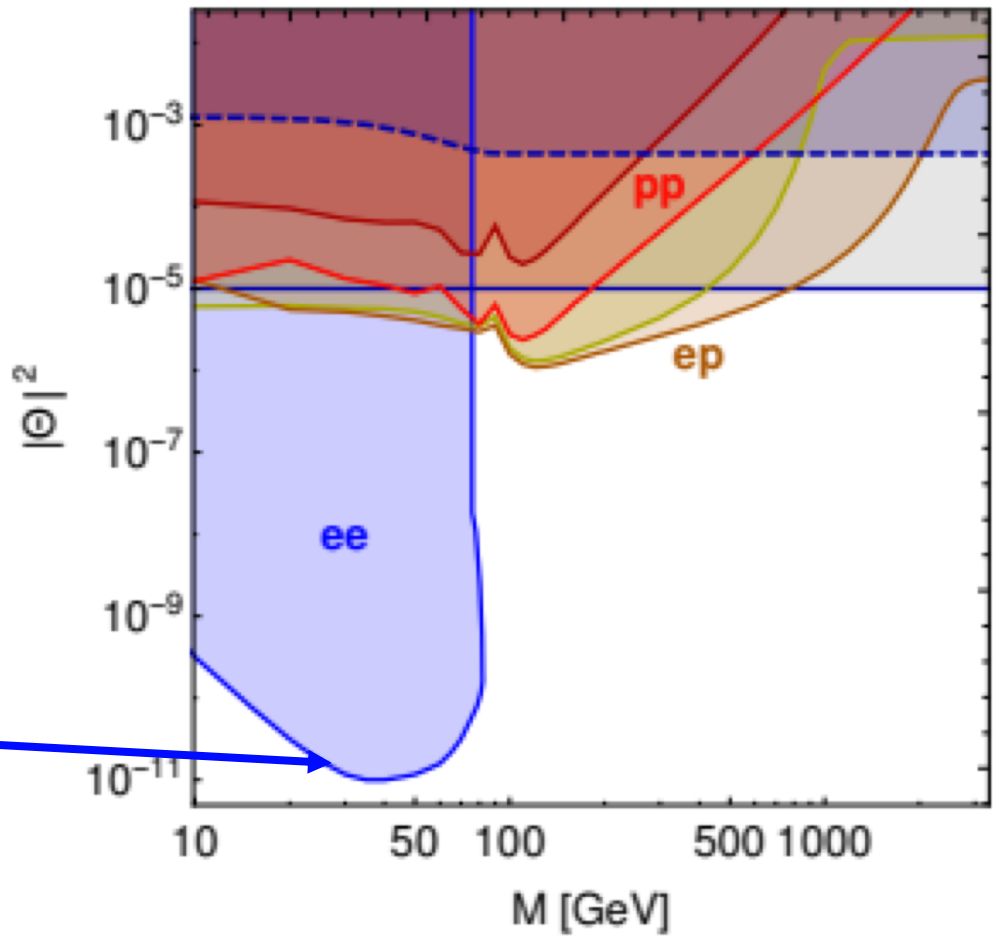


Good sensitivity to long-lived Higgs bosons in clean environment at CLIC

arXiv:1612.02728v2

Sterile Neutrinos at ee, pp, and ep Colliders

- Search for sterile heavy neutrinos (aka heavy neutral leptons)
- Systematic study of different possible signatures (prompt and displaced) and sensitivity at various future colliders
- Best sensitivity for heavy neutrino masses $M < m_W$ is obtained from displaced vertex searches at the Z pole run of the FCC-ee



Summary

- Can and should perform a variety of searches for exotic long-lived particles at future colliders
- Showed how LLP searches will benefit from of ATLAS and CMS Phase-2 upgrades and increased physics potential at future hadron collider, as well as some prospects for LLPs at lepton colliders
- More can be done, particularly to explore the LLP potential with the HGCal, with dedicated detectors, and with lepton colliders, for example
  - What else?
- Exotic long-lived particle searches often require non-standard techniques to collect, reconstruct, and analyze the data → **different/challenging/FUN!**
- **Need to be sure we don't miss new physics!**