Searches for Long-Lived Particles at the LHC

Juliette Alimena
On behalf of the ATLAS, CMS, and LHCb collaborations

New Physics with Exotic and Long-Lived Particles

July 2, 2019

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  or

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  - travel fast or slow
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- They often require dedicated searches

Why Search for Long-Lived Exotica?

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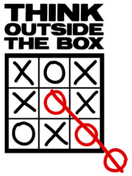

- **Why not?**
  - No sign of new physics yet! → **We should leave no stone unturned**
  - A new massive, long-lived particle would be a clear sign of new physics
  - **But challenging (exciting)!** We need to push our detectors, triggers, reconstruction, and analysis techniques to the limit

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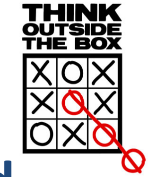

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- **Long-lived particles (LLPs) appear in many BSM scenarios**
  - Nearly mass-degenerate states (compressed SUSY, AMSB, etc.)
  - Heavy virtual mediators (split-SUSY, heavy neutral leptons, etc.)
  - Small couplings (dark photons, freeze-in DM, RPV SUSY, etc.)

  → **BSM searches need to be performed also considering the lifetime of the new particle**

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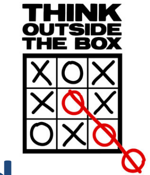

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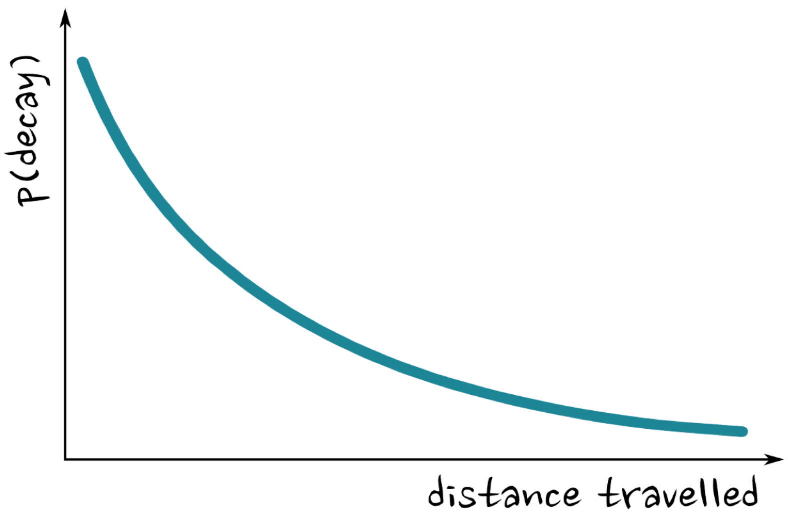
  →**BSM searches need to be performed also considering the lifetime of the new particle**
- **Can provide a dark matter candidate**
  - Dark matter must be a neutral, stable, BSM particle

Need a Variety of Searches

Any given particle's lifetime is sampled from an exponential

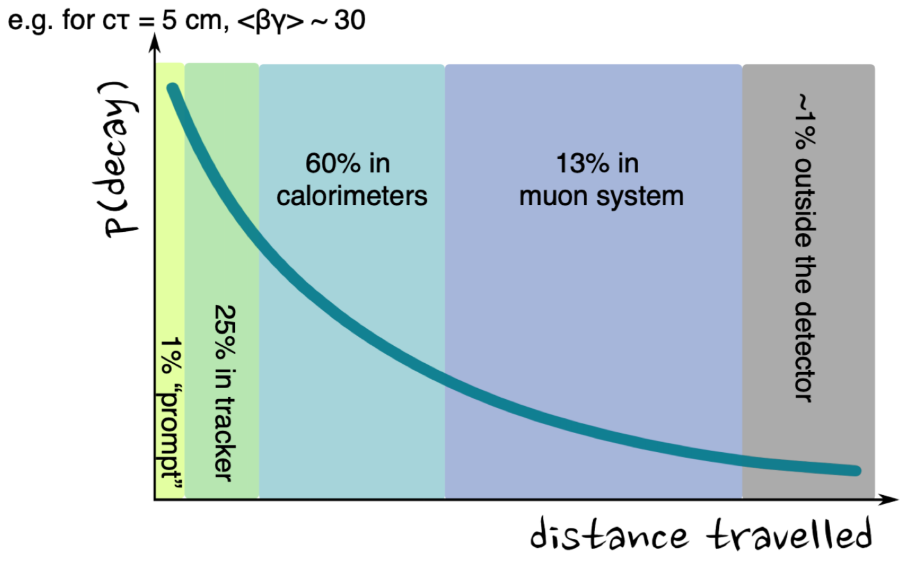


Adapted from Heather Russell

Need a Variety of Searches

Any given particle's lifetime is sampled from an exponential

Even particles with a **short proper lifetime can decay far** from the interaction:



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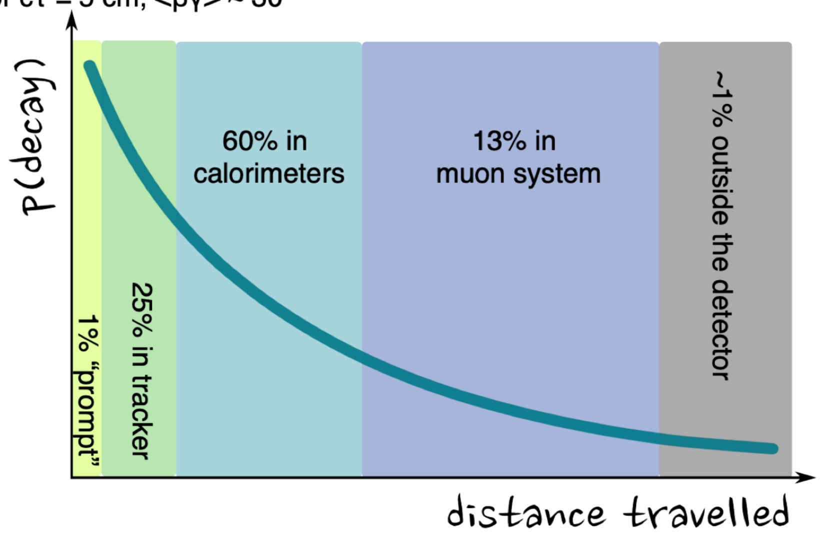
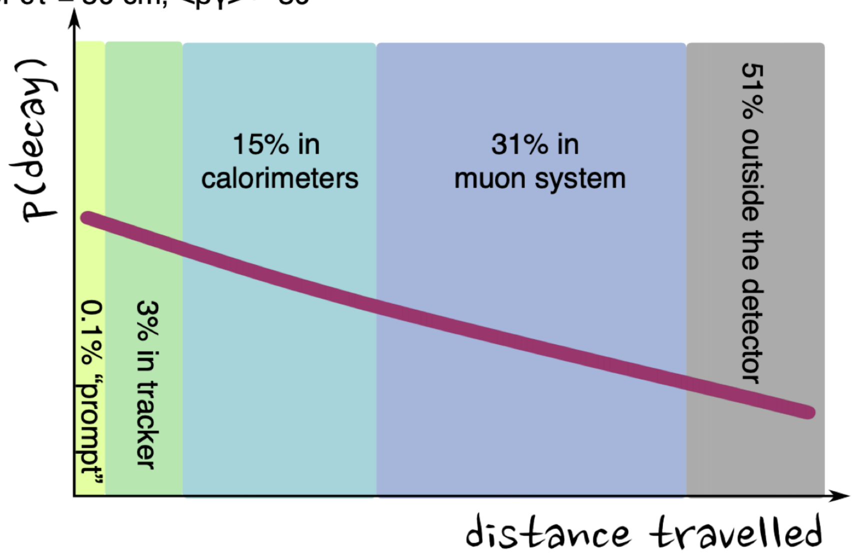
Even particles with a **short proper lifetime can decay far** from the interaction:

e.g. for cτ = 5 cm, <βγ> ~ 30



But if we want to consider particles with **longer lifetimes**, we could benefit from a **different search strategy**:

e.g. for cτ = 50 cm, <βγ> ~ 30



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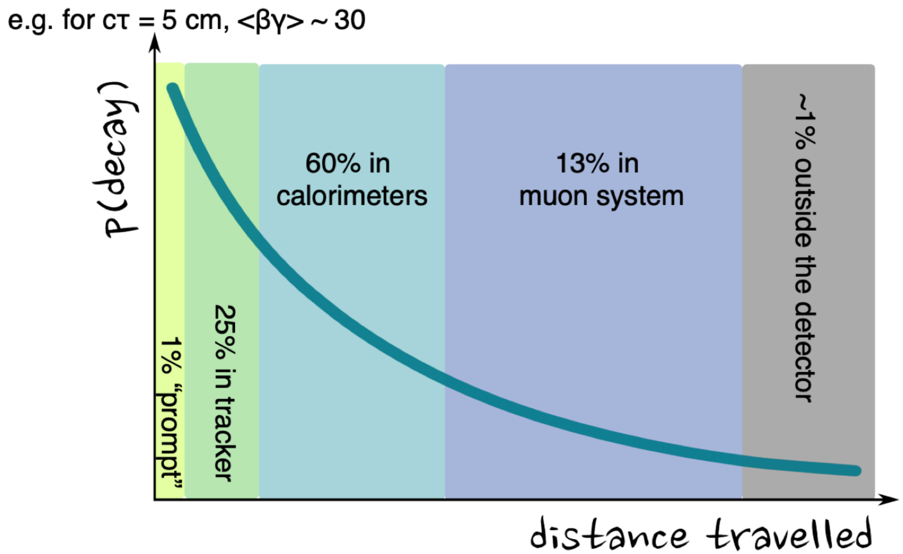

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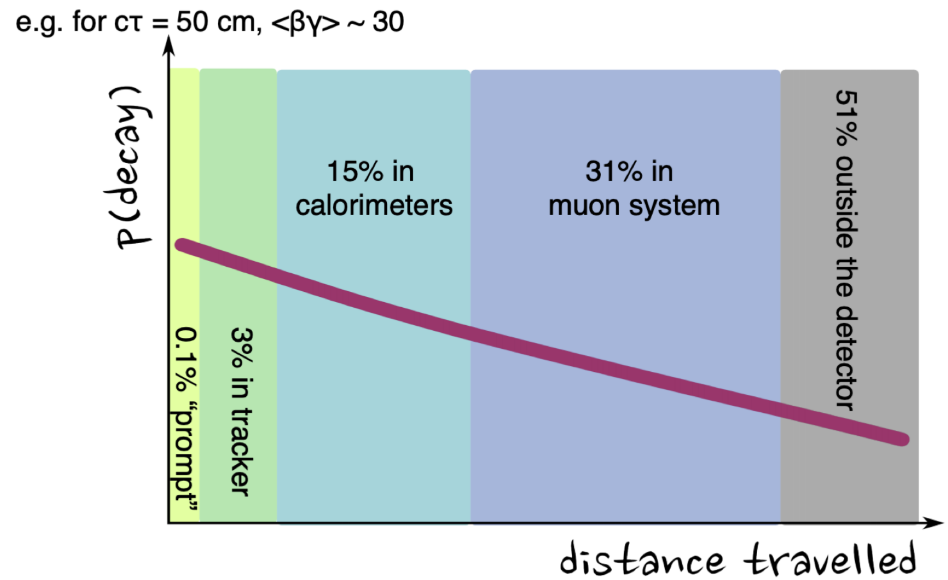


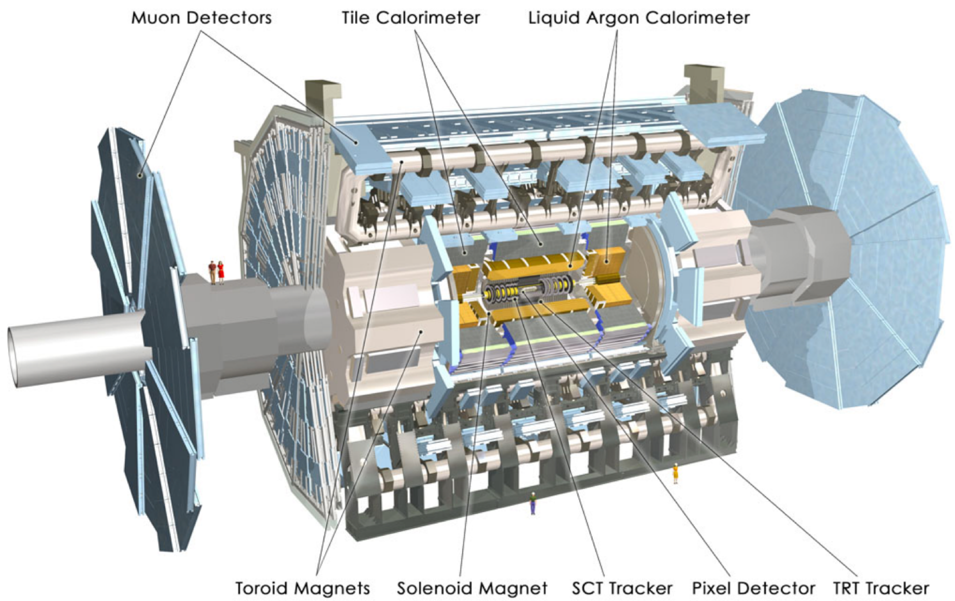
Lifetime, mass, decay products, boost, etc. dramatically affect the detector signature, and we need to use all subdetectors

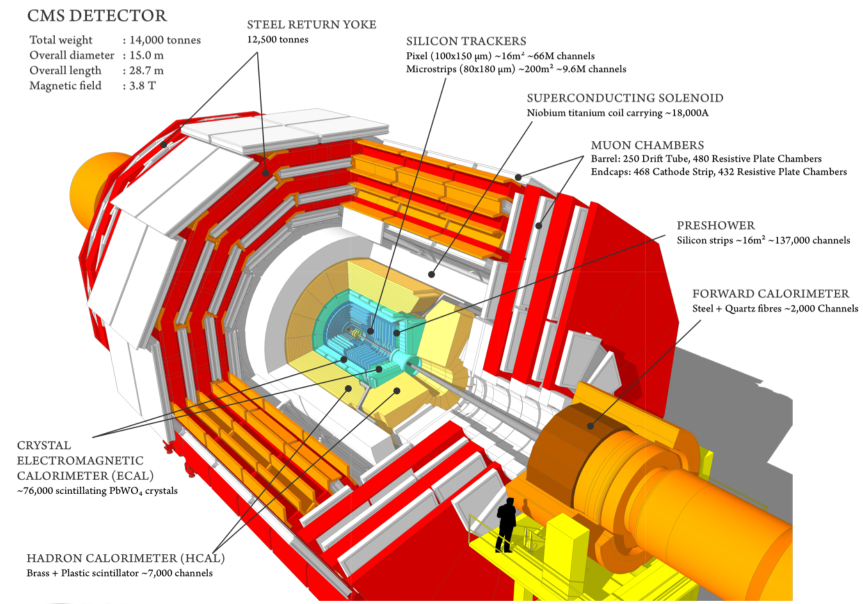
Adapted from Heather Russell

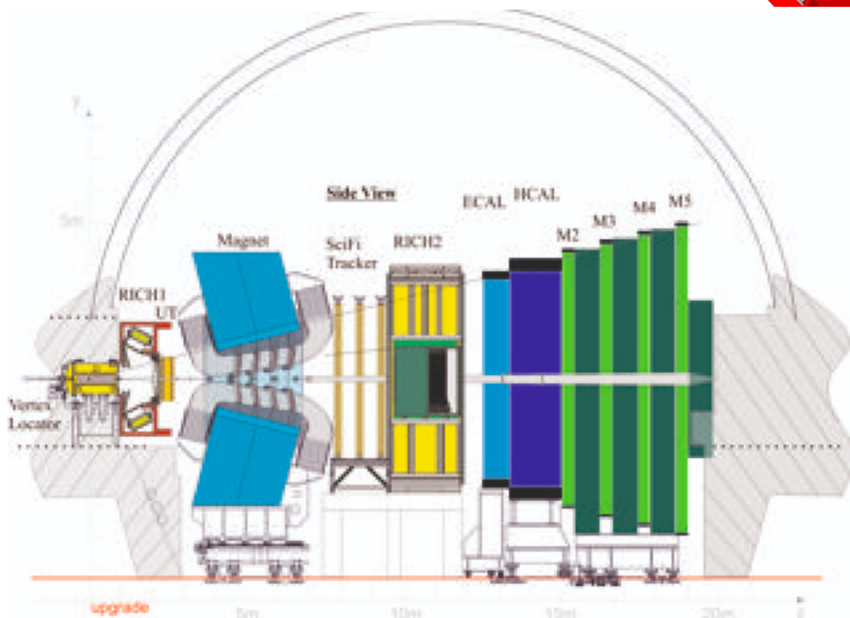
The Large Hadron Collider

- 10 years of successful operation of the LHC!
- Superb experiments operation efficiency
  - Greater than 90% efficient for both CMS and ATLAS (data taking + data quality)

The LHC Main Experiments

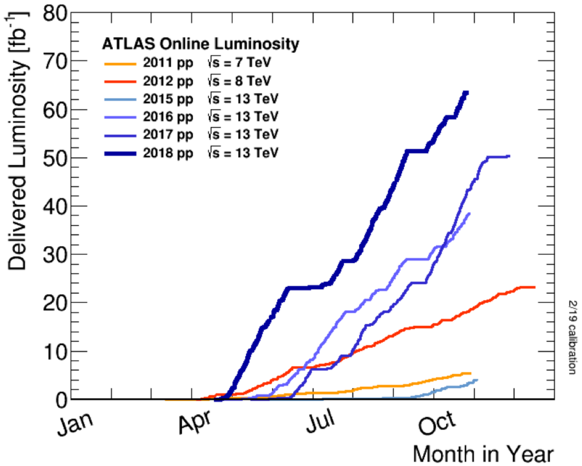






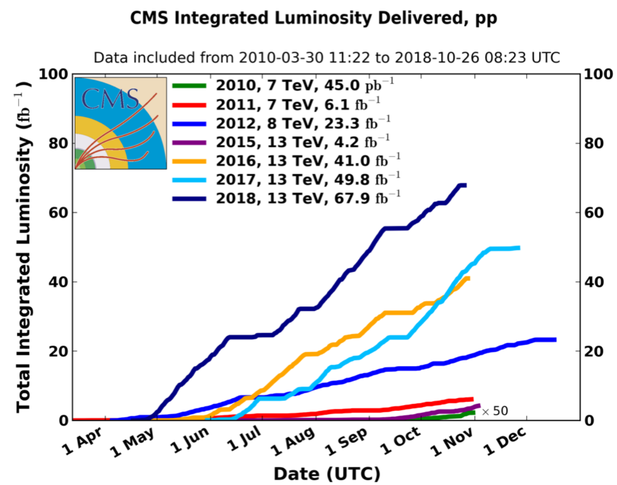
Run 2

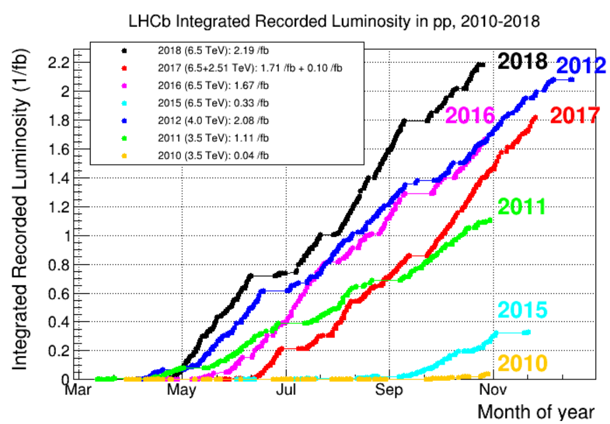
- 13 TeV center-of-mass energy, bunch spacing of 25 ns
- ATLAS and CMS:
  - ~140 fb^{-1} of integrated luminosity, 30-40 pileup interactions



Record year in 2018!

>60 fb^{-1} collected by CMS and ATLAS





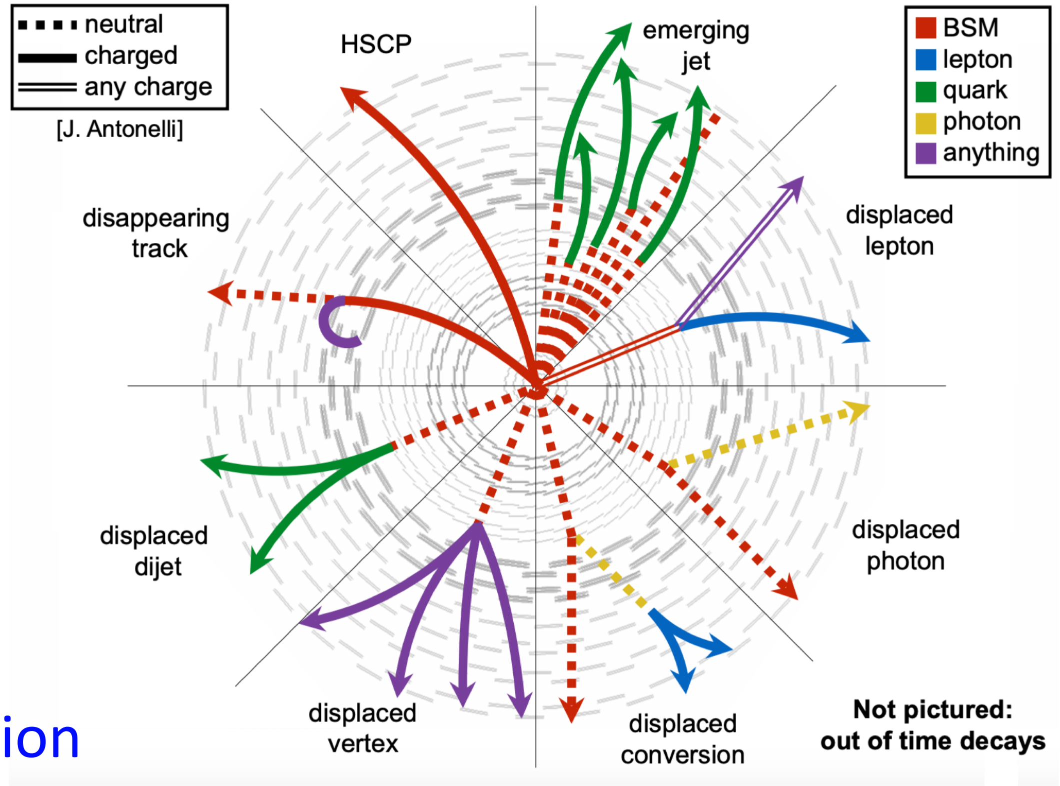
Long-Lived Particle Searches

<u>Different LLP varieties:</u>

- Charges
- Final states
- Decay locations
- Lifetimes

<u>Some challenges:</u>

- Dedicated triggers
- Unique object reconstruction
- Atypical backgrounds
- Unusual discriminating variables

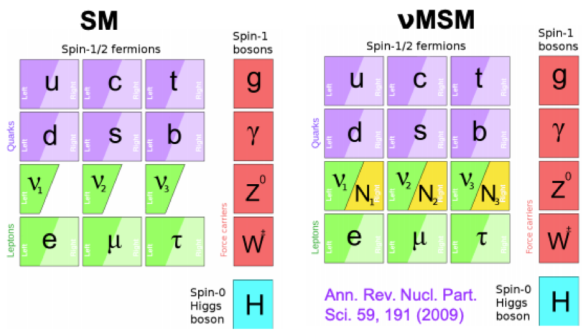


This talk will showcase a few recent example LLP searches to illustrate the variety of signatures and ~~challenges~~ **opportunities for innovation**

Prompt and Long-Lived Heavy Neutral Leptons

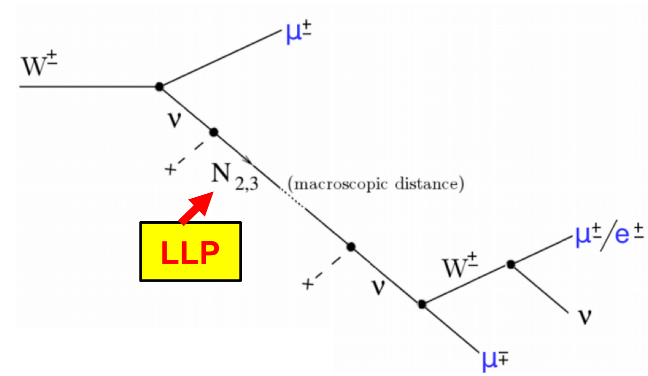
arXiv:1905.09787

- Search for heavy neutral leptons (HNLs) that are produced through mixing with muon or electron neutrinos



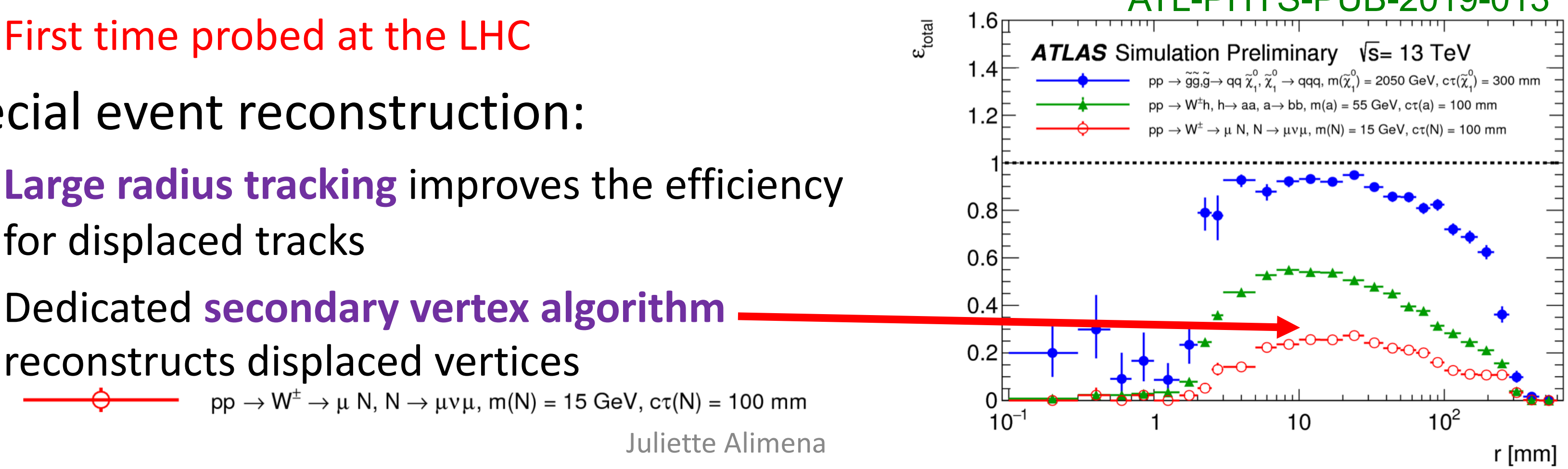
- Signature for LL HNLs:
  - Prompt μ + displaced dilepton vertex (μμ or μe)
  - First time probed at the LHC
- Special event reconstruction:
  - **Large radius tracking** improves the efficiency for displaced tracks
  - Dedicated **secondary vertex algorithm** reconstructs displaced vertices

νMSM benchmark:



If the mixing angles between HNLs and neutrinos are small, the HNLs can be long-lived

ATL-PHYS-PUB-2019-013



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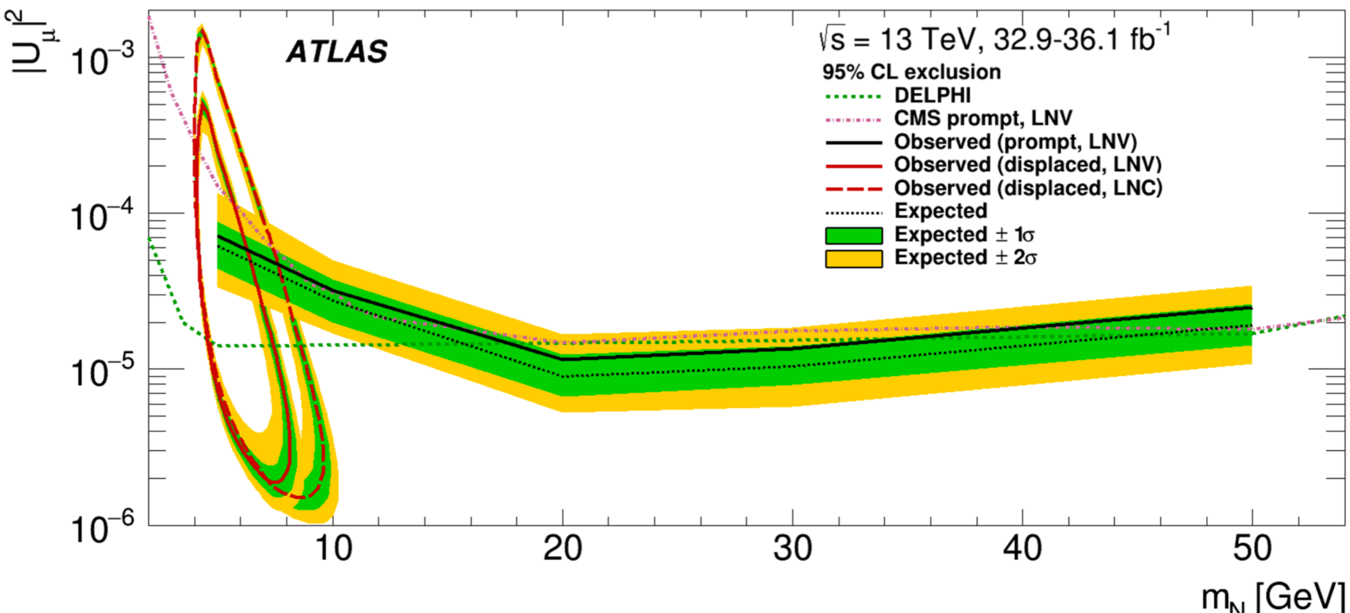
Prompt and LL HNL Results

- Many backgrounds **significantly reduced** by requiring prompt lepton and by requiring "tight" lepton identification for objects matched to tracks from displaced vertex
- Data-driven studies show that backgrounds from hadronic interactions, metastable particle decays, J/Ψ, and Ψ(2S) are **minimal** when m_{DV}> 4 GeV (signal region)
- Estimate residual background in signal region (2 leptons with opposite charge) using transfer factors from control region (2 leptons with same charge)
- Estimate < 2.3 background events, observe 0

Set 95% confidence level limits on HNL mass and coupling strength ($|U_\mu|^2$) :



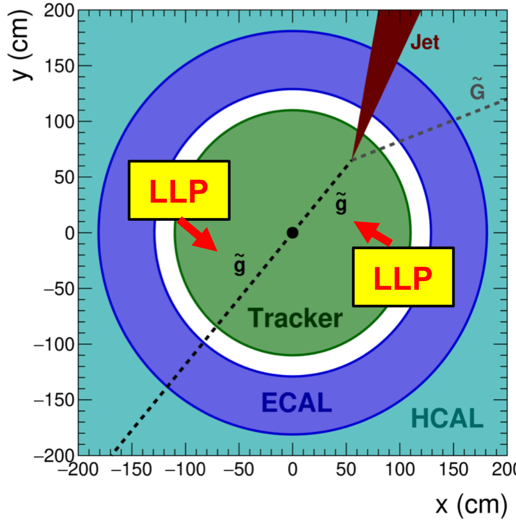
Exclude down to $|U_\mu|^2$ ~ $2*10^{-6}$ ($1.5*10^{-6}$) assuming LNV (LNC) with **2016 data (32.9 fb^{-1})**

Probe coupling **1 order of magnitude** lower than DELPHI result, for 5 < m_N < 10 GeV

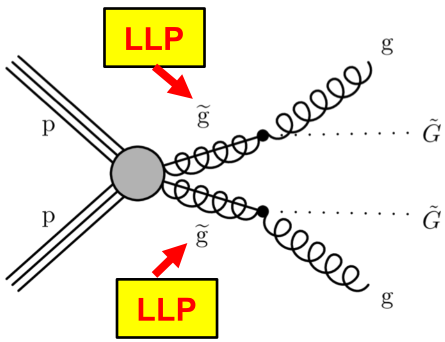
arXiv:1906.06441

Delayed Jets

- Search for heavy neutral LLPs that decay to at least one delayed jet + missing transverse momentum
- First use of timing from the electromagnetic calorimeter (ECAL) to identify delayed jets
- Backgrounds:
  - Core timing resolution effects (e.g. scintillation time differences due to radiation)
  - Satellite bunches (collisions of very low luminosity bunches at ~2.5 ns steps from main bunches)
  - Beam halo muons (muons from beam interacting with collimators)
  - Cosmic ray muon deposits in the ECAL



GMSB benchmark:



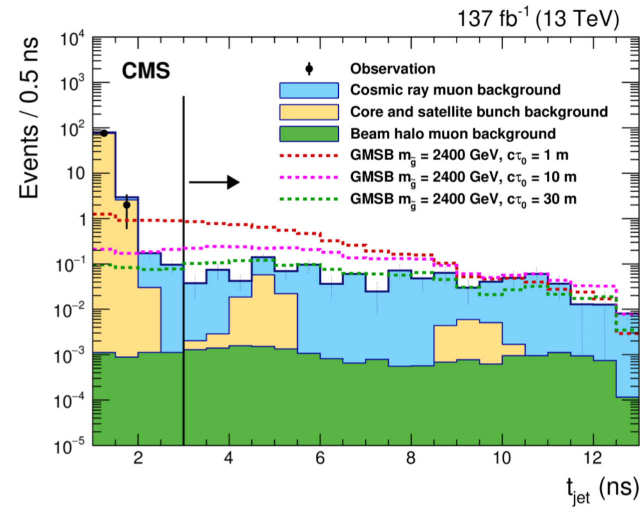
*If the **coupling is small**, the gluino can be long-lived*

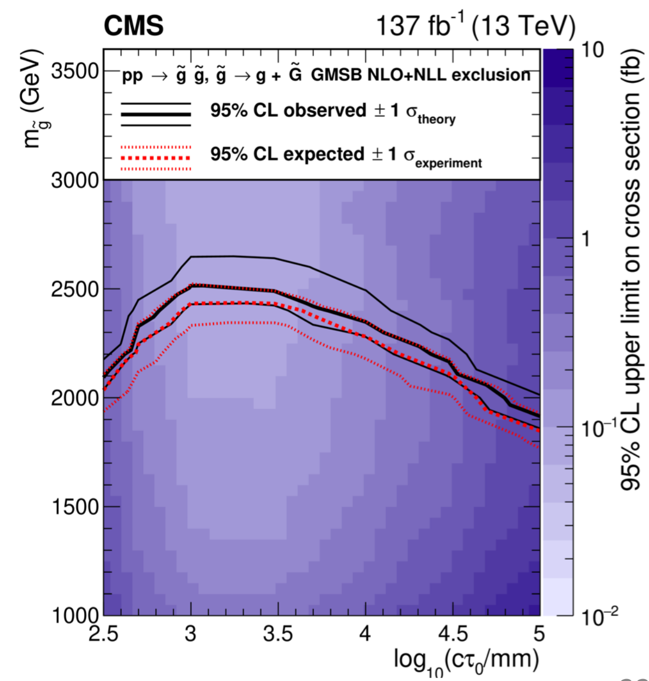
- Cleaning selections reject contributions from dominant backgrounds
- Remaining backgrounds predicted with data-driven methods (not modelled in simulation)

arXiv:1906.06441

Delayed Jets Results

- Jet time (t_{jet}) is the main discriminating variable
  - t_{jet} is the median time of all matched ECAL cells satisfying quality criteria
  - **Most of the background** (core effects) **at small t_{jet} (prompt)**
  - **Signal benchmark** has **long t_{jet} tail**
- <u>Signal region</u>: single bin **t_{jet}> 3ns**
  - **Plot for illustration only**
  - Predict $1^{+2.5}_{-1}$ events
  - **Observe 0 events**
- Set 95% confidence level limits on gluino mass and lifetime
- Exclude gluino masses up to **2.5 TeV** for **$c\tau$ of 1 m** with **full Run 2 data (137 fb^{-1})**





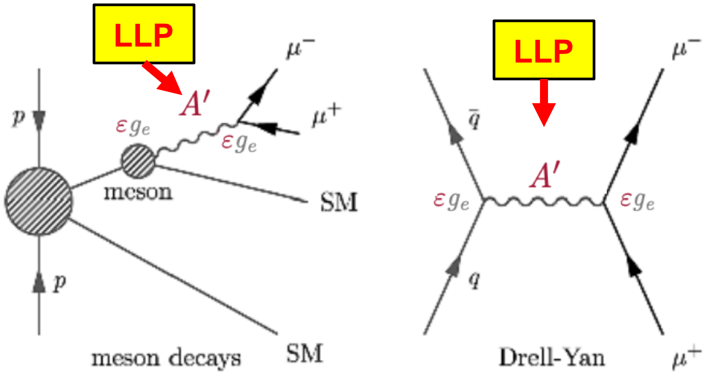
doi: 10.1103/PhysRevLett.120.061801

Prompt and Long-Lived Dark Photons

- Search for prompt and long-lived dark photons (A') that decay to opposite-sign muons
- Prompt search: $2m_{\mu} < m_{A'} < 70$ GeV
- LL search: $214 < m_{A'} < 350$ MeV (maximize sensitivity)
- Backgrounds in LL search:

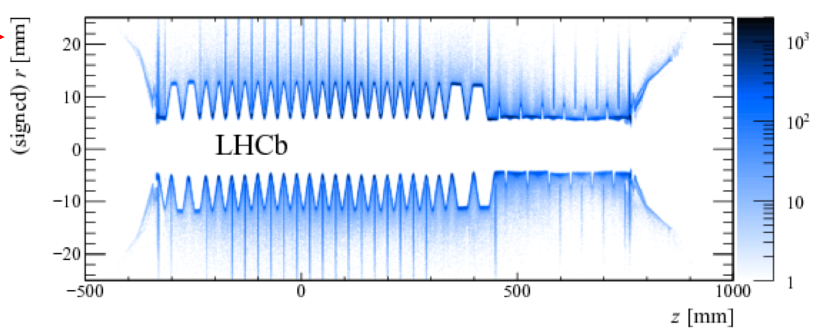
Contribution:	**Reduced by:**
Photon conversions to $\mu^+\mu^-$ in the silicon-strip vertex detector (VELO)	Using a material map →
Two semileptonic b-hadron decays	Identifying other tracks coming from b-hadron decays with Boosted Decision Trees

Dark photon benchmark:



*If **m(A')*ε² is small**, the dark photon can be long-lived*

CERN-LHCB-DP-2018-002



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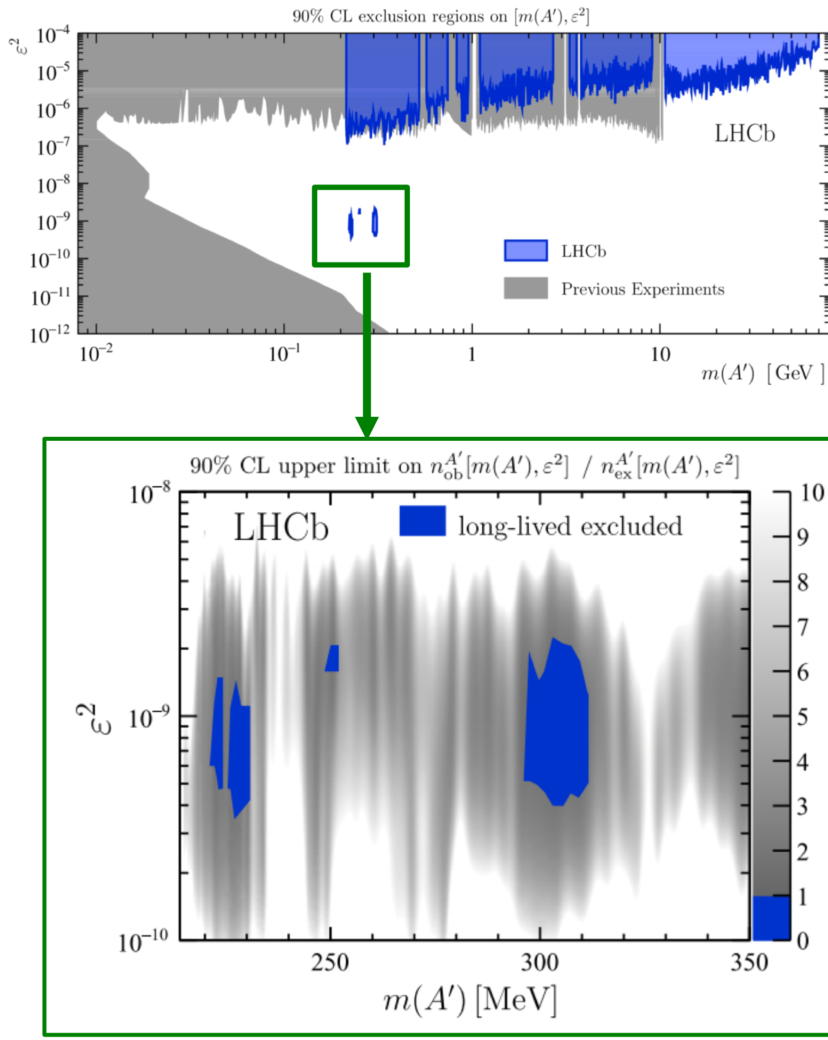
Prompt and Long-Lived Dark Photons Results

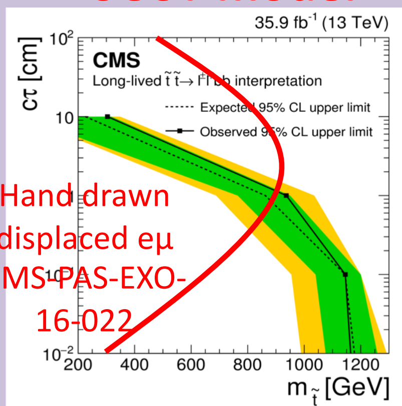
- Scan dimuon mass, bin in A' lifetime and decay fit χ^2
- <u>Results with 2016 data ($1.6\ fb^{-1}$):</u>
  - Set 90% confidence level limits on A' mass and ε^2
  - First search to achieve sensitivity to LL dark photons using a displaced-vertex signature
- <u>Future improvements:</u>
  - Trigger already improved for 2017 run
  - Expect large improvement in sensitivity in Run 3, due to increased luminosity and removal of the hardware trigger



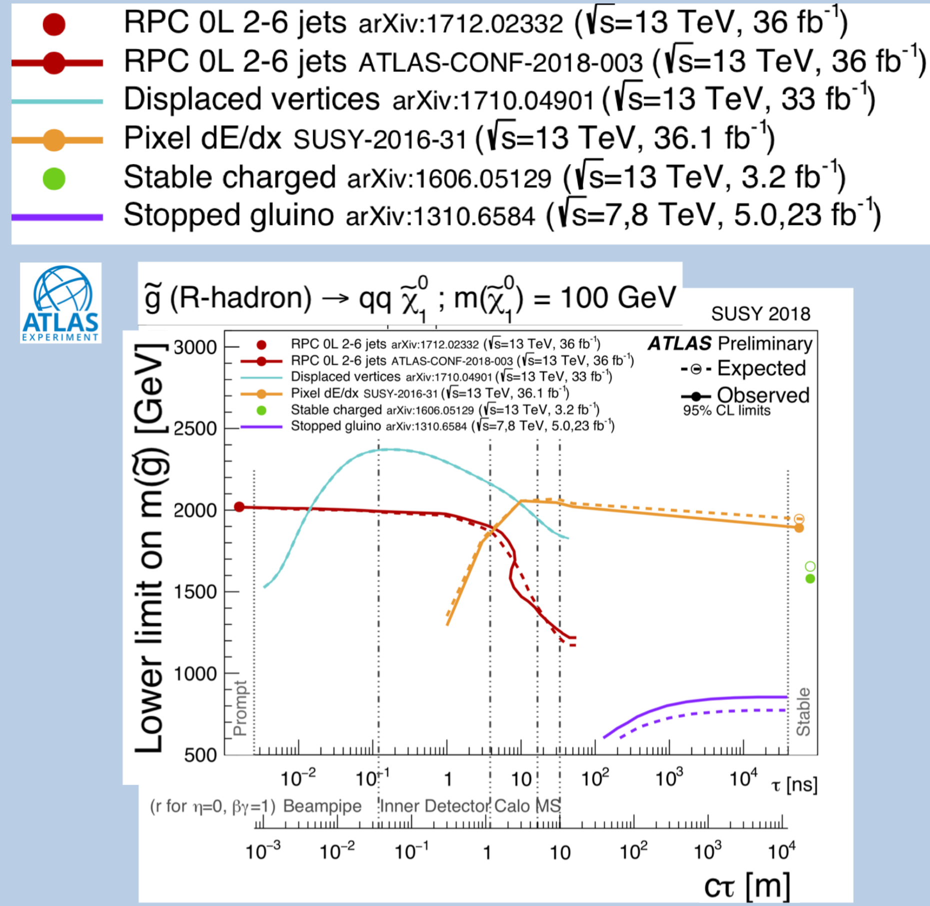
Prompt Searches Sensitive to LLPs

Search for 2nd-gen LQs, arXiv:1808.05082

reinterpreted using a long-lived RPV SUSY model



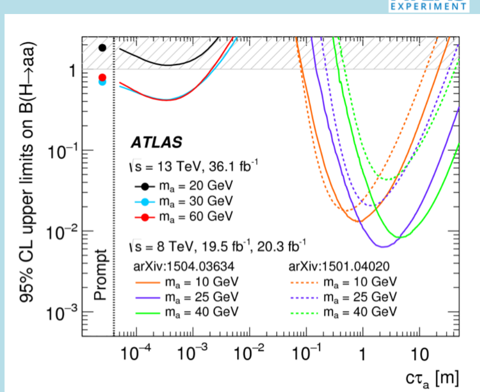
LL gluino results:



Search for H->aa->4b decays,

doi:10.1007/JHEP10(2018)031

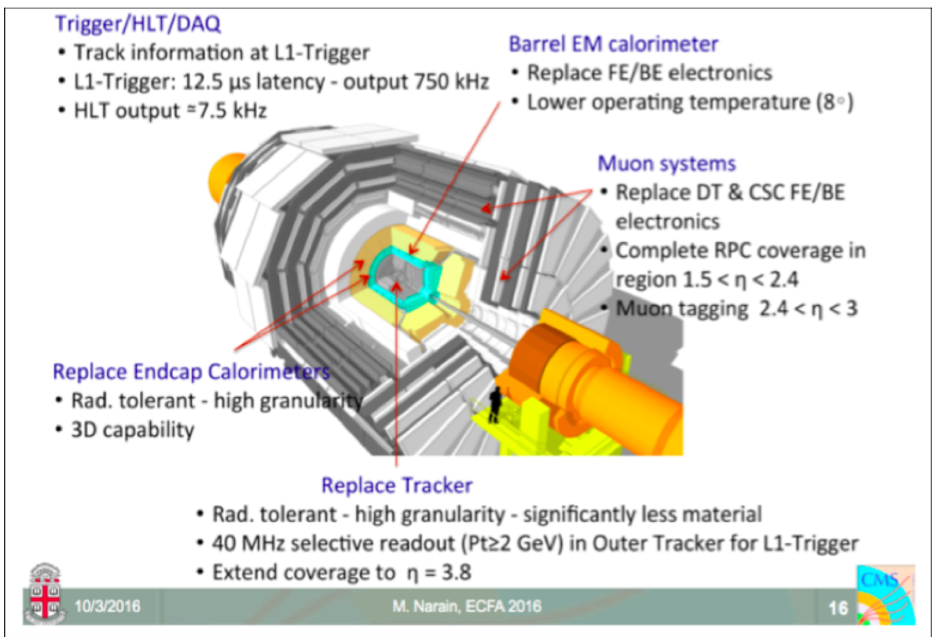
Shows what lifetime range is accessible with standard b-tagging

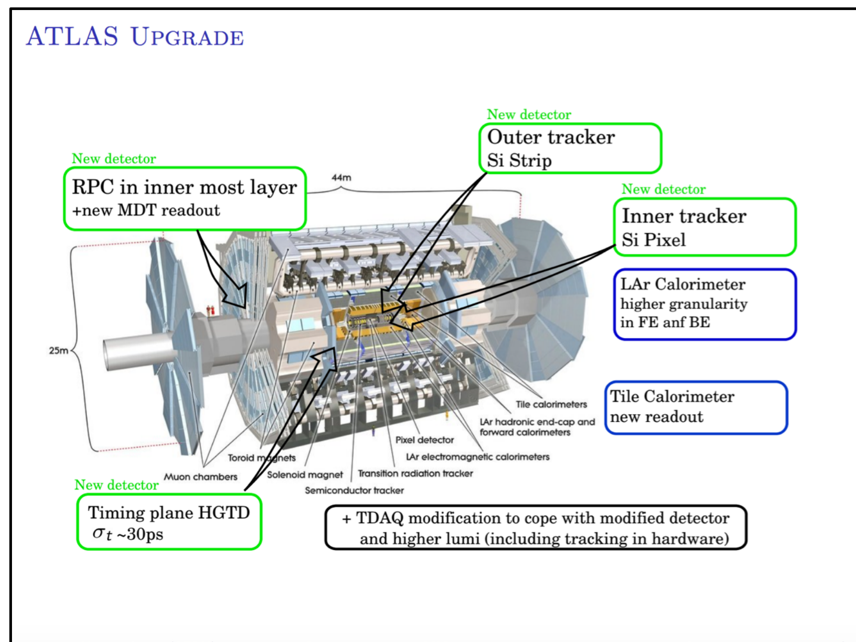


Interplay between prompt and dedicated LLP searches can help identify the gaps in coverage

HL-LHC + CMS/ATLAS Upgrades

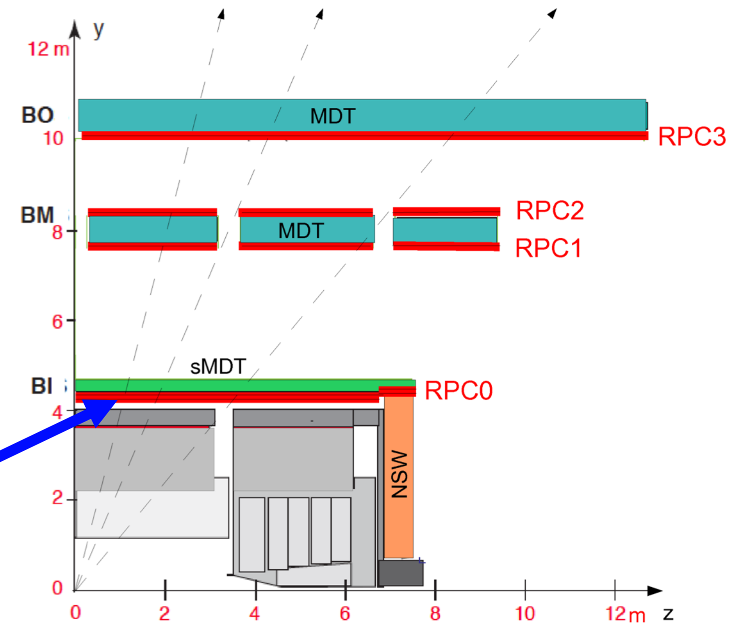
- 14 TeV center-of-mass energy, 3 ab^{-1} of luminosity, 200 pileup
- Higher geometrical coverage of all subdetectors
- High resolution for all subdetectors
- New L1 track trigger in CMS
- New timing detectors





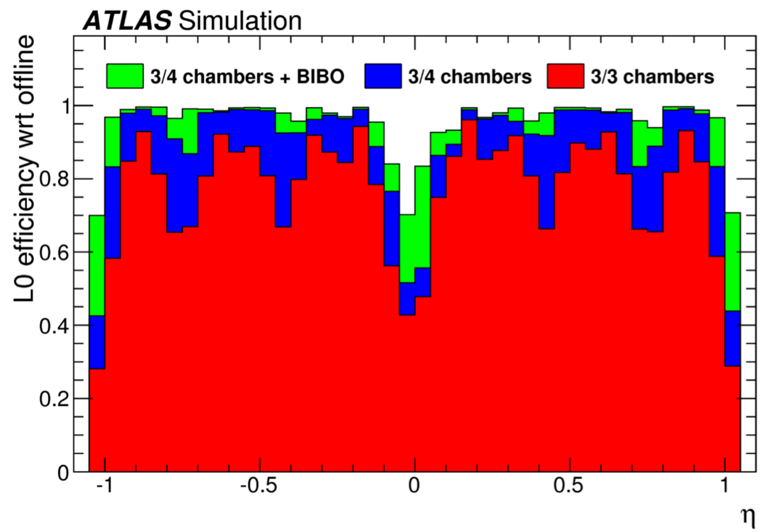
Muon System Upgrade

- 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



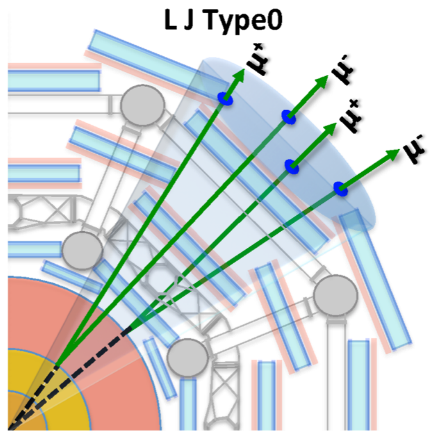
Efficiency of the RPC trigger system:

- Run 2 "3/3 chambers" trigger
- HL-LHC "3/4 chambers" trigger
- HL-LHC "3/4 chambers + BI-BO" trigger
- **Increases efficiency from 78% (Run 2) to 96% (HL-LHC "3/4 chambers + BI-BO")**

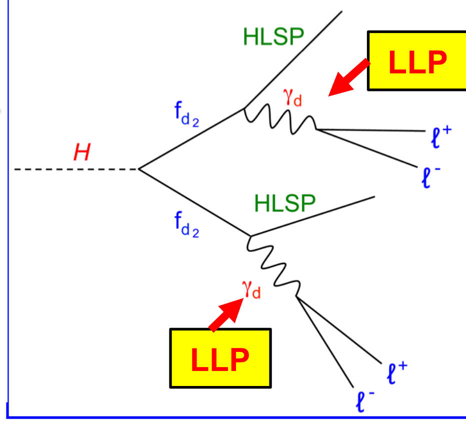


Displaced Lepton Jets Prospects (I)

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

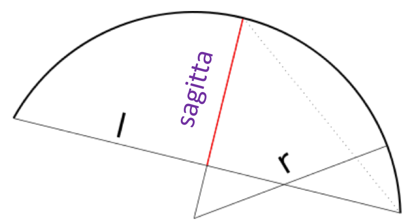


FRVZ vector-portal benchmark:



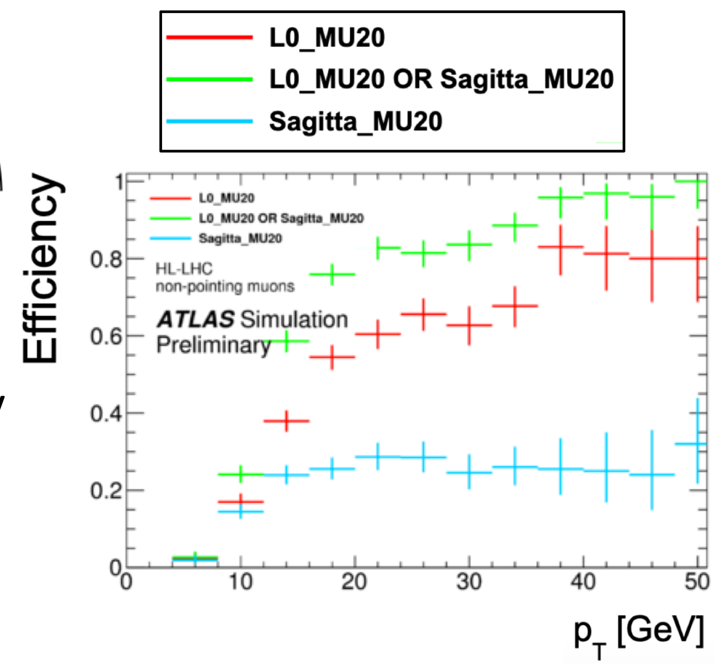
If the kinetic mixing is small, the dark photon can be long-lived

Developed two new L0 muon trigger algorithms:



1. Sagitta muon trigger:

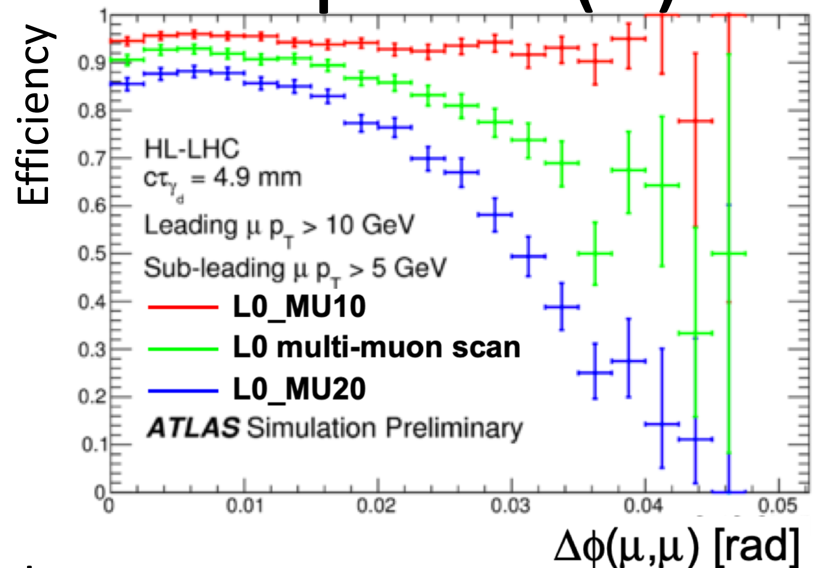
- **Momentum** can be **misreconstructed** for non-pointing muons due to **beam spot constraint**
- New approach: cut on **sagitta** of muon trajectory
- **L0_MU20 OR Sagitta_MU20** gives **~20% efficiency improvement** over L0_MU20 for FRVZ benchmark model



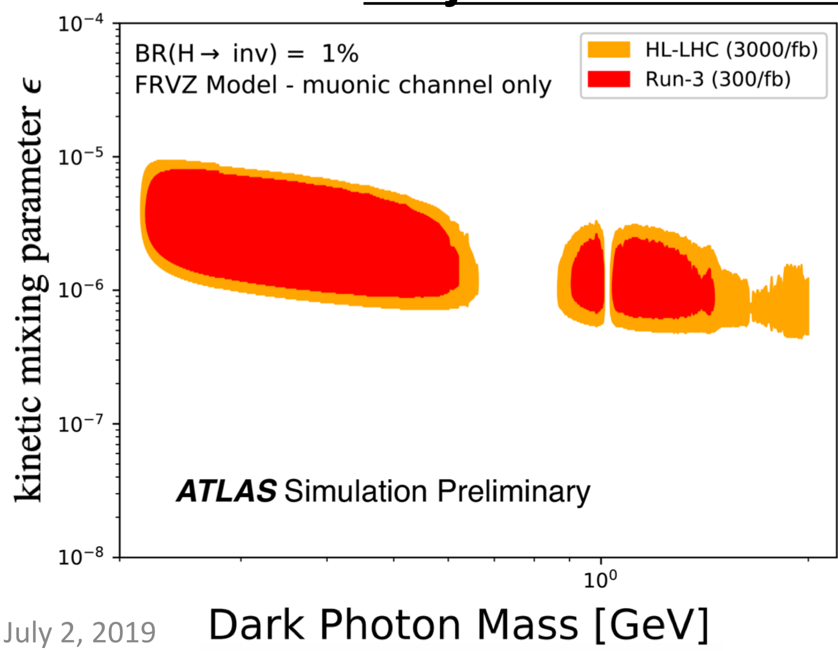
Displaced Lepton Jets Prospects (II)

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 efficiency for FRVZ model **up to 7%** wrt single muon trigger with p_T>20 GeV



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

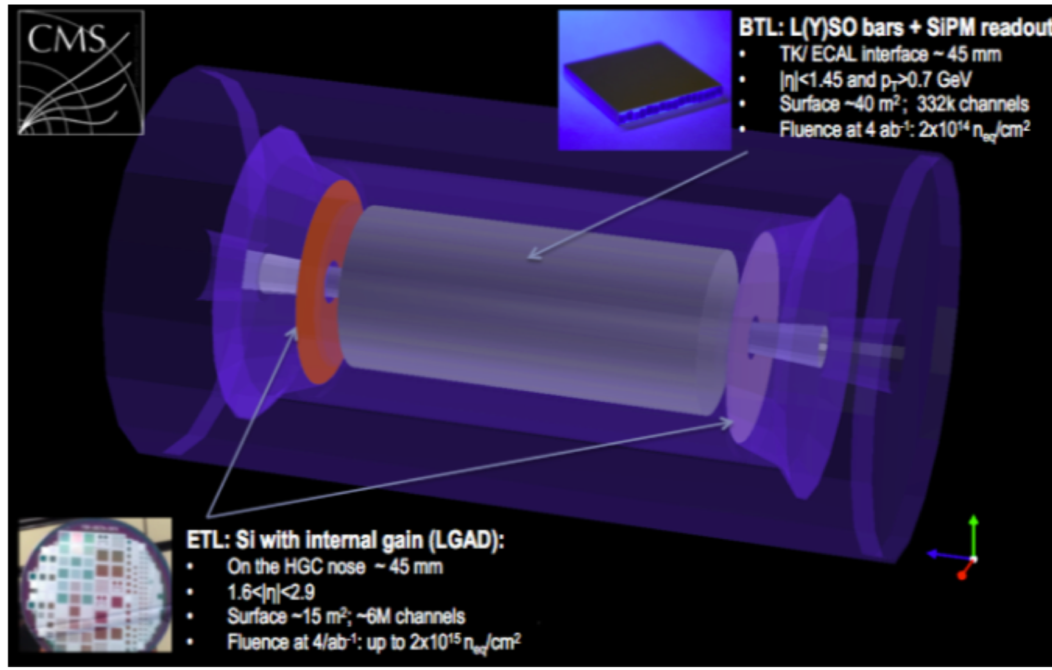


- **Run 3** (300 fb^{-1})
- **HL-LHC** (3000 fb^{-1})
- HL-LHC projection includes multi-muon scan trigger improvement
- HL-LHC projection will probe BR(H→2γ_d+X) down to ~1%: much further than Run 2 sensitivity!

CMS-TDR-19-002

MIP Timing Detector (MTD)

- Detector dedicated to precisely measuring the production time of minimum ionizing particles (MIPs)



- **Barrel:** LYSO crystal scintillators read out with silicon photomulitpliers
- **Endcaps:** Silicon sensors with internal gain

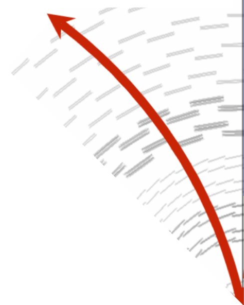
- **30 ps** resolution at the start of the HL-LHC
- Allows to precisely measure **vertices in 4D**, at 200 PU
- **Provides unique opportunity for LLPs**

Heavy Stable Charged Particles with the MTD (I)

CMS-TDR-19-002

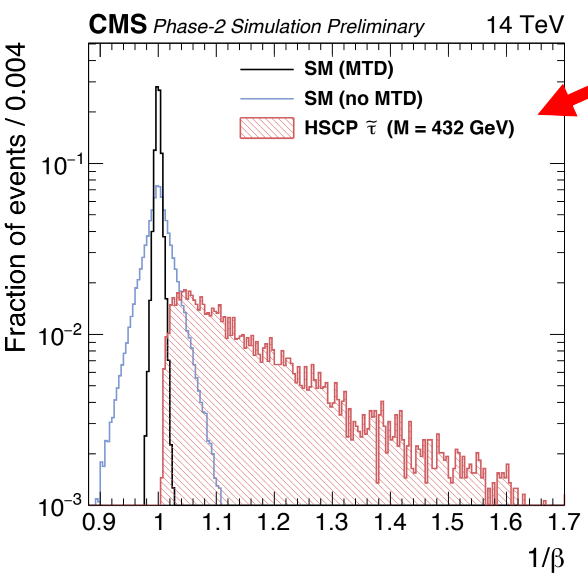
- Search for **heavy**, slow-moving, highly-ionizing particles that pass through the detector
- Studied the HSCP **β** (velocity/speed of light) measured with the particle path length and time difference between the primary vertex and MTD hits

HSCP



mGMSB benchmark:

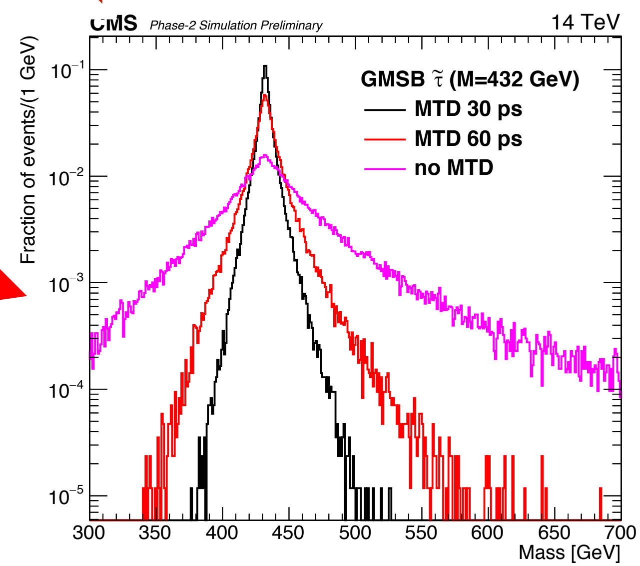
*If the **coupling** of the stau to the gravitino **is small**, the stau can be long-lived*



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

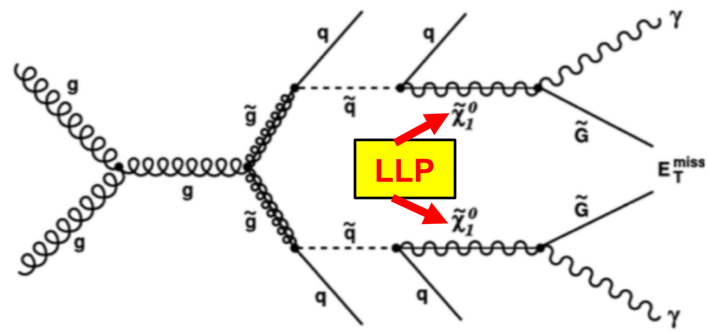


The new timing detector greatly improves long-lived particle velocity measurements and thus analysis sensitivity

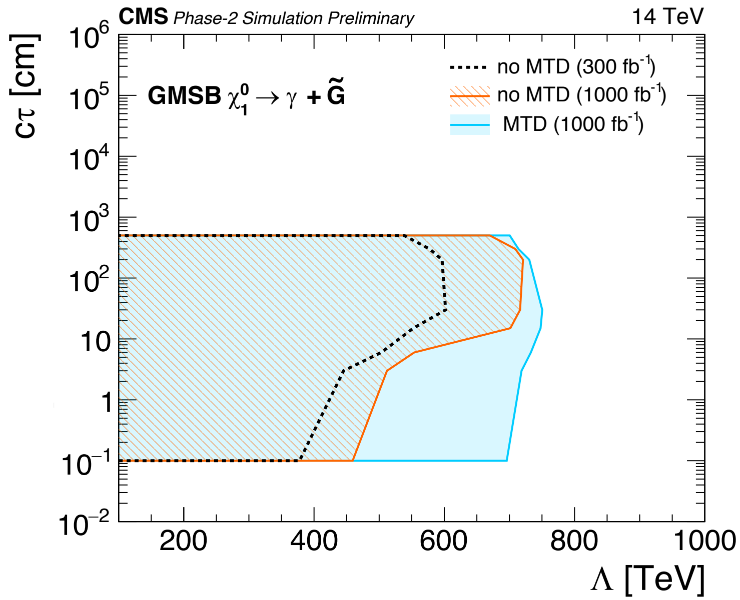
Delayed Photons at the HL-LHC

- 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:



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



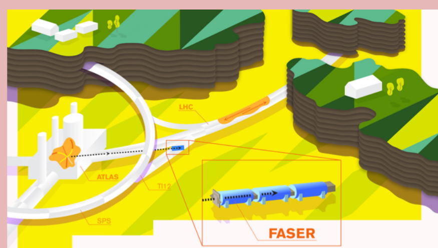
- **Run 3 detector (300 fb^{-1})**
  - 300 ps time resolution in ECAL
- **Phase-2 detector without MTD (1000 fb^{-1})**
  - 180 ps time resolution dominated by beamspot uncertainty
- **Phase-2 detector with MTD (1000 fb^{-1})**
  - **30 ps time resolution**

The new timing detector greatly improves the sensitivity to LLPs with short lifetimes and large masses

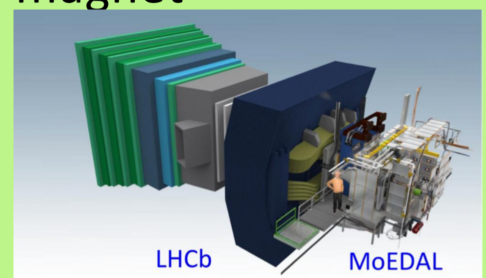
Some Dedicated LLP Experiments

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

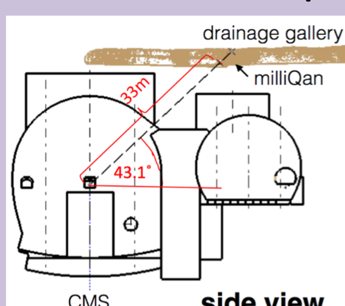
FASER: searches for long-lived dark photons and similar particles in the extreme forward direction

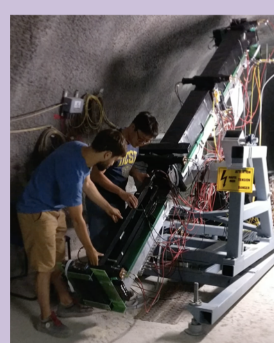


MoEDAL: searches for monopoles stopped in the beampipe with a SQUID precision magnet

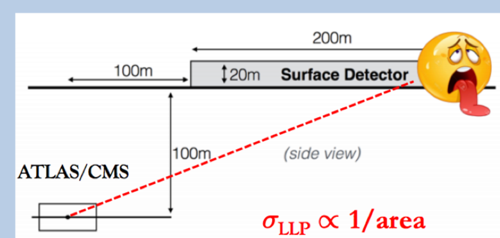


MilliQan: searches for millicharged particles with a detector pointed at the CMS interaction point





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



What Else?

- The previous slides were **far from exhaustive** – **many other searches** for LLPs have been done or are in progress
- **But here are some other things we can try:**
  - Soft displaced objects
  - Displaced taus
  - Kinked tracks
  - Quirks
  - Take advantage of **data scouting** and **data parking**
  - Particular opportunity for LLPs in **Run 3**
    - **Trigger** improvements? Completely new triggers?
  - **And many more!**

Summary

- Performing a variety of searches for exotic long-lived particles at ATLAS, CMS, LHCb, and dedicated LLP experiments
  - *See more in e.g. talks from* ***Alice, Haifa and Leandro***
- Exotic long-lived particle searches often require non-standard techniques to collect, reconstruct, and analyze the data → **<u>different/challenging/FUN!</u>**
- No signal observed yet, but more to do!
- Let's make sure we don't miss new physics! Need to look everywhere
- LLP searches will benefit from Phase-2 upgrades and increased physics potential at the HL-LHC and beyond
- We've already eaten the low-hanging fruit

→ time to expand our palate!

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