Searches in the Long-Lived Particle and Dark Sectors

Juliette Alimena

On behalf of the ATLAS, CMS, and LHCb collaborations

31st Recontres de Blois

June 4, 2019

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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- **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.)

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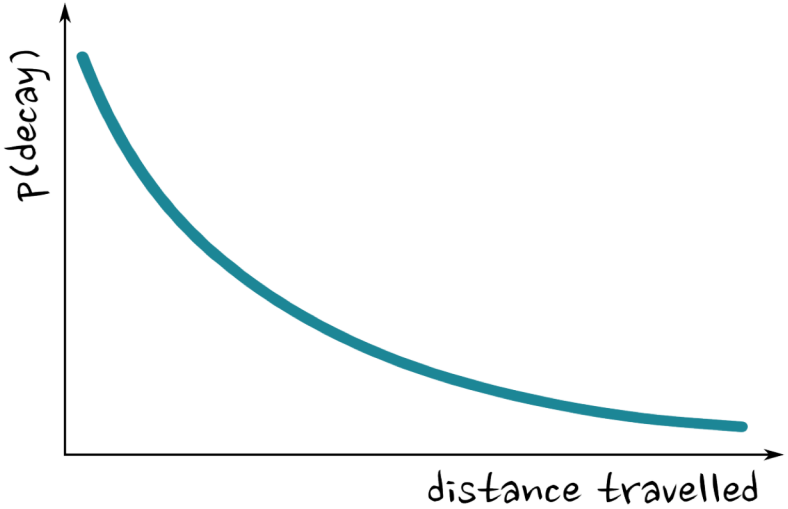
- **Can provide a dark matter candidate**
  - Dark matter must be a neutral, stable, BSM particle

Need a Variety of Searches

Any given particle's lifetime is sampled from an exponential



Adapted from Heather Russell

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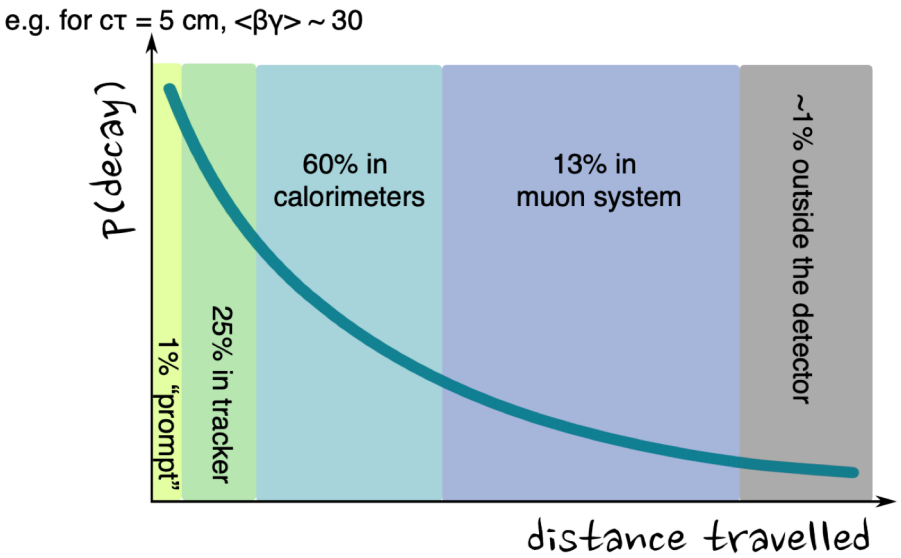
Any given particle's lifetime is sampled from an exponential

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



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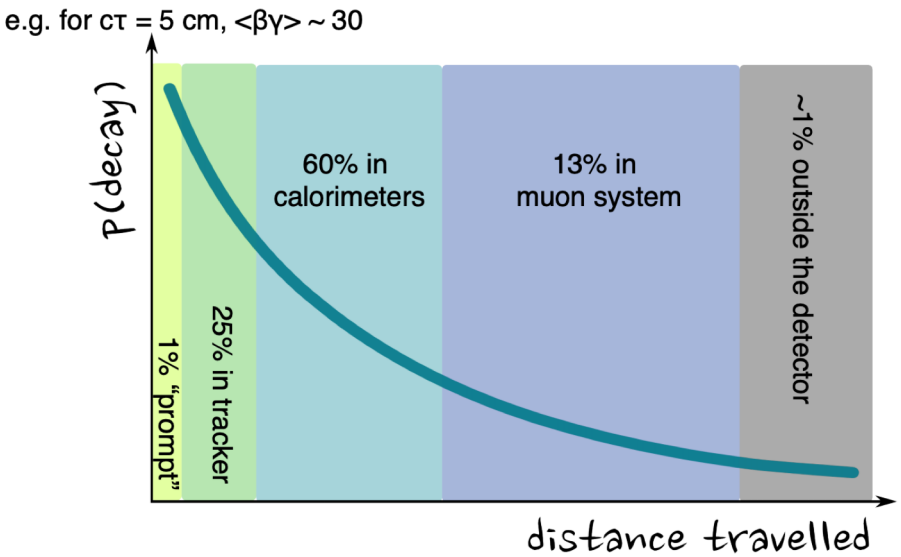
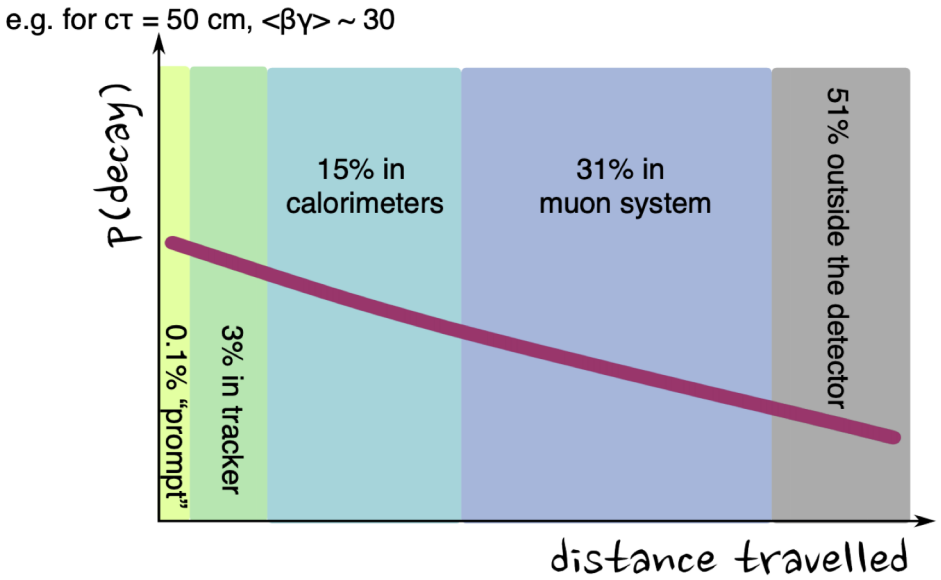


But if we want to consider particles with **longer lifetimes**, we could benefit from a **different search strategy**:



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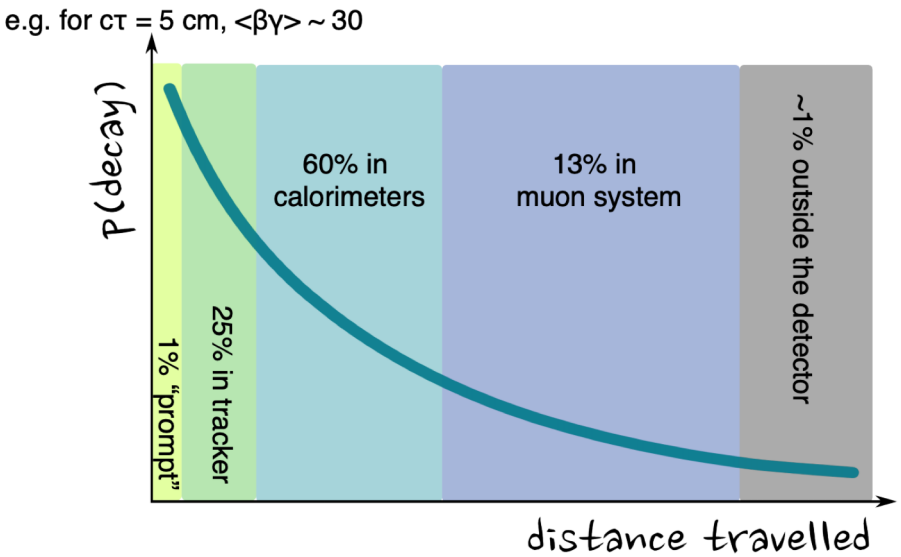

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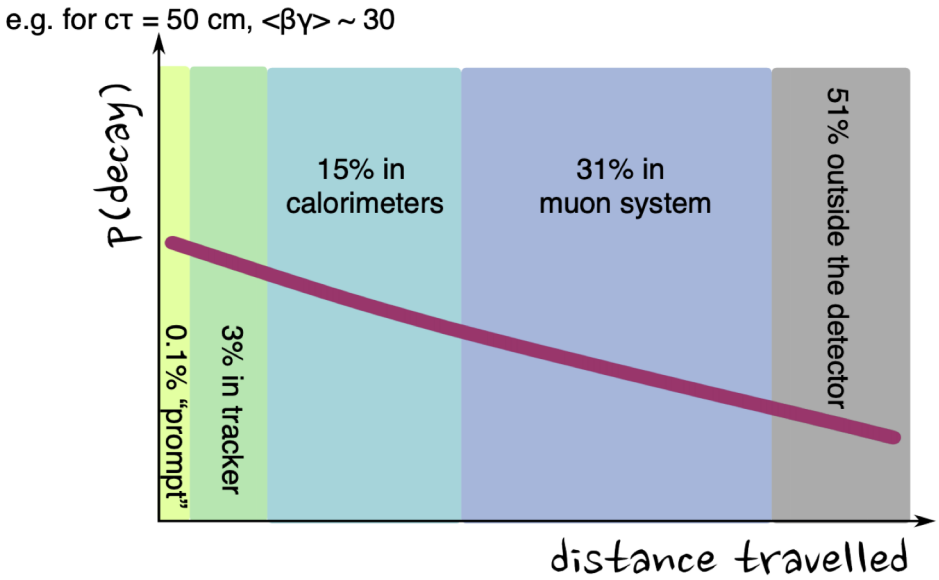


Lifetime, mass, decay products, boost, etc. dramatically affect the detector signature, and we need to use all subdetectors

Adapted from Heather Russell

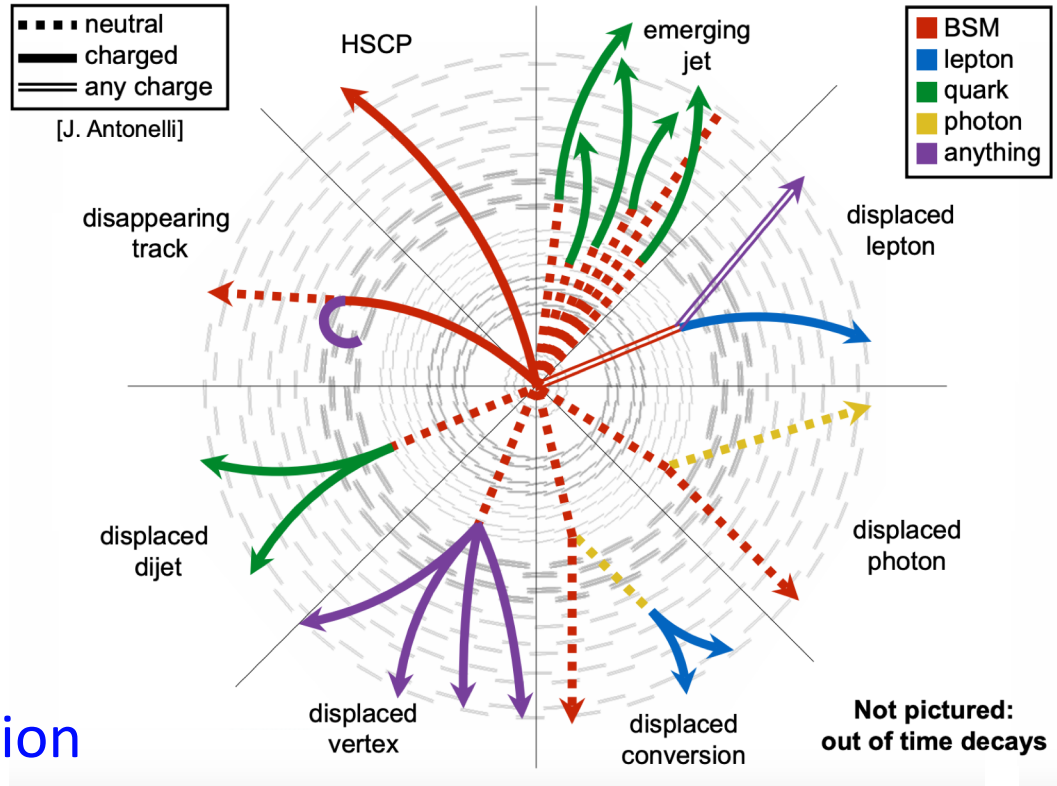
Long-Lived Particle Searches

Different LLP varieties:

- Charges
- Final states
- Decay locations
- Lifetimes

Some challenges:

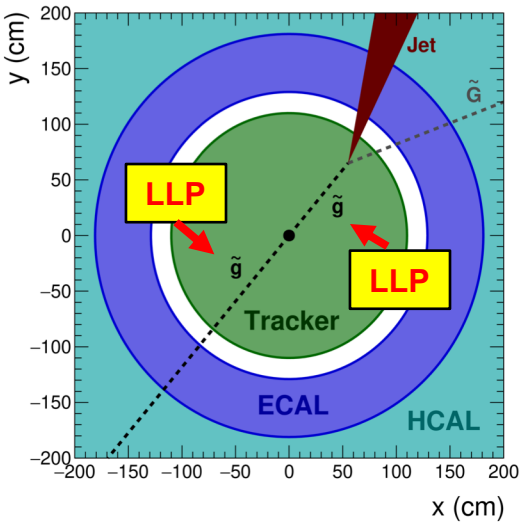
- Dedicated triggers
- Unique object reconstruction
- Atypical backgrounds
- Unusual discriminating variables



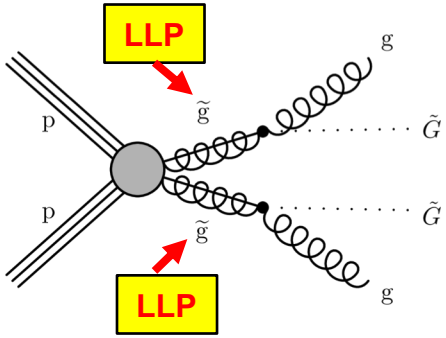
This talk will showcase a few recent example LLP searches to illustrate the variety of signatures and ~~challenges~~ **opportunities for innovation**

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:

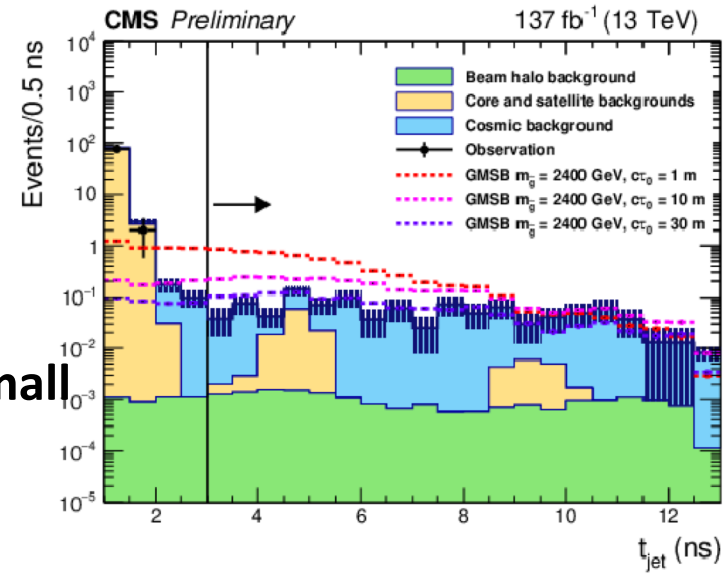


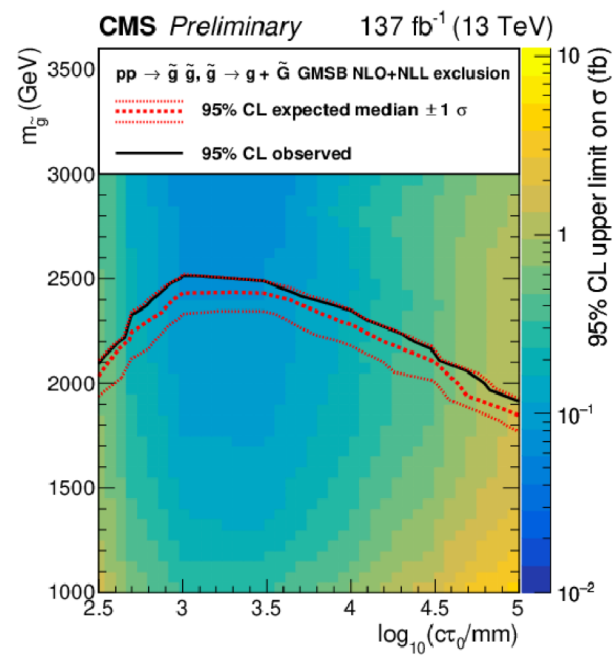
*If the **coupling is small**, the gluino can be long-lived*

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

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**
- Signal region: 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})**

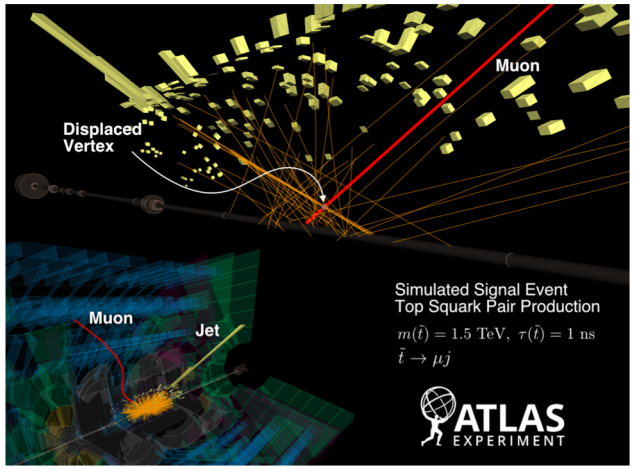




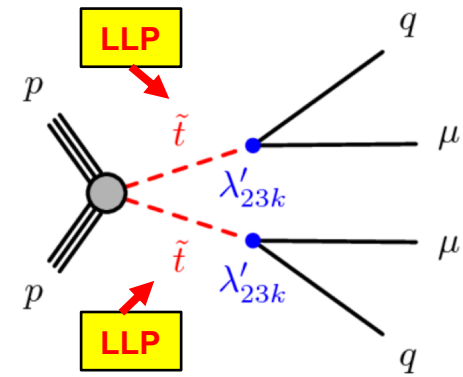
Displaced Vertex with Displaced Muon

ATLAS-CONF-2019-006

- Search for LLPs that decay to at least one displaced muon with a displaced vertex

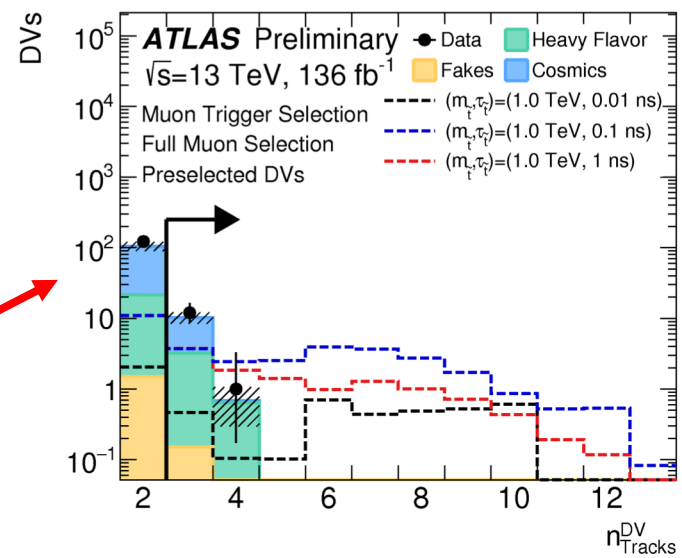


RPV SUSY benchmark:



If the λ'_{23k} ***coupling is small,*** *the top squark can be long-lived*

- Special event reconstruction:
  - **Large radius tracking** improves the efficiency for displaced tracks
  - Dedicated **secondary vertex algorithm** reconstructs displaced vertices
- Selection:
  - At least 1 displaced muon
  - At least 1 displaced vertex (at least 3 tracks, invariant mass > 20 GeV)



Displaced Vertex with Displaced Muon Results

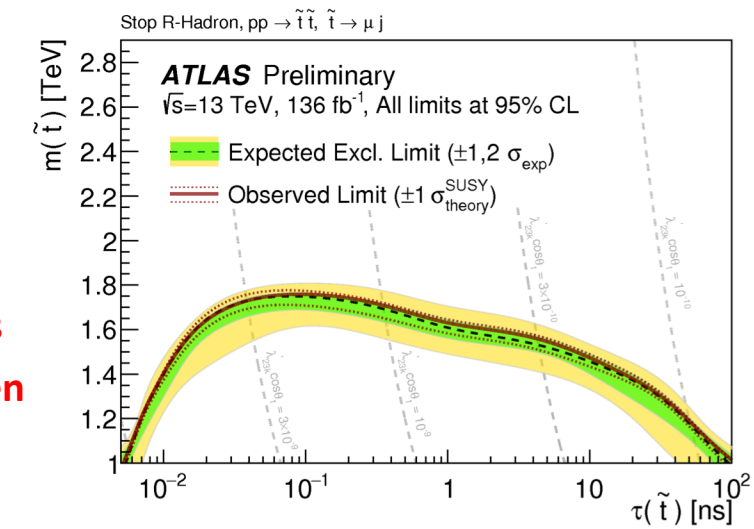
ATLAS-CONF-2019-006

- Backgrounds:
  - Cosmic rays
  - Reconstruction algorithm fakes
  - Muons from decays of heavy-flavor quarks
- Results with **full Run 2 data (136 fb^{-1})**:

- Largely removed by dedicated vetoes
- Residuals predicted by data-driven approach

	Background Prediction	Observation
Missing transverse momentum trigger signal region	0.43 ± 0.16 (stat) ± 0.16 (syst)	0
Muon trigger signal region	1.88 ± 0.20 (stat) ± 0.28 (syst)	1

- Set 95% confidence level limits on top squark mass and lifetime
- Exclude:
  - Top squark masses **up to 1.7 TeV** for lifetimes of **0.1 ns**
  - Top squark masses **below 1.3 TeV** for lifetimes **between 0.01 and 30 ns**



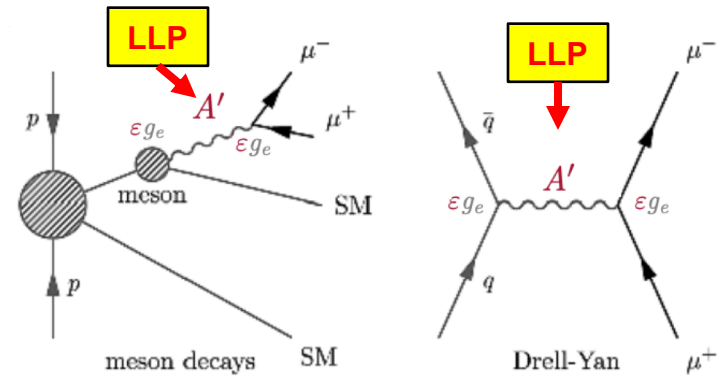
doi: 10.1103/PhysRevLett.120.061801

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:

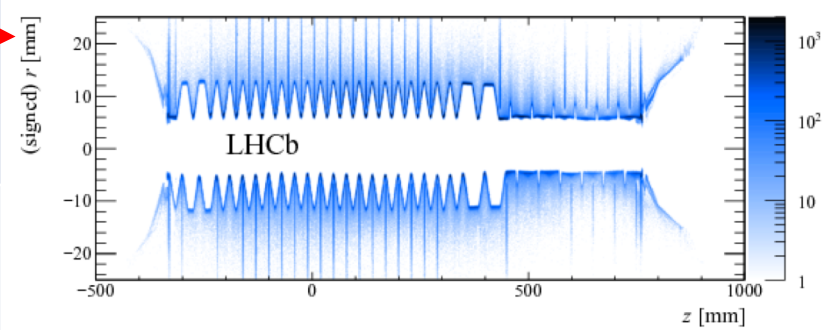
Contribution:	Reduced by:
Photon conversions to $\mu^+\mu^-$ in the silicon-strip vertex detector (VELO)	Using a material map
Two semileptonic b-hadron decays	Identifying other tracks coming from b-hadron decays with Boosted Decision Trees

Dark photon benchmark:



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

CERN-LHCB-DP-2018-002



Also see Monika's talk for more info!

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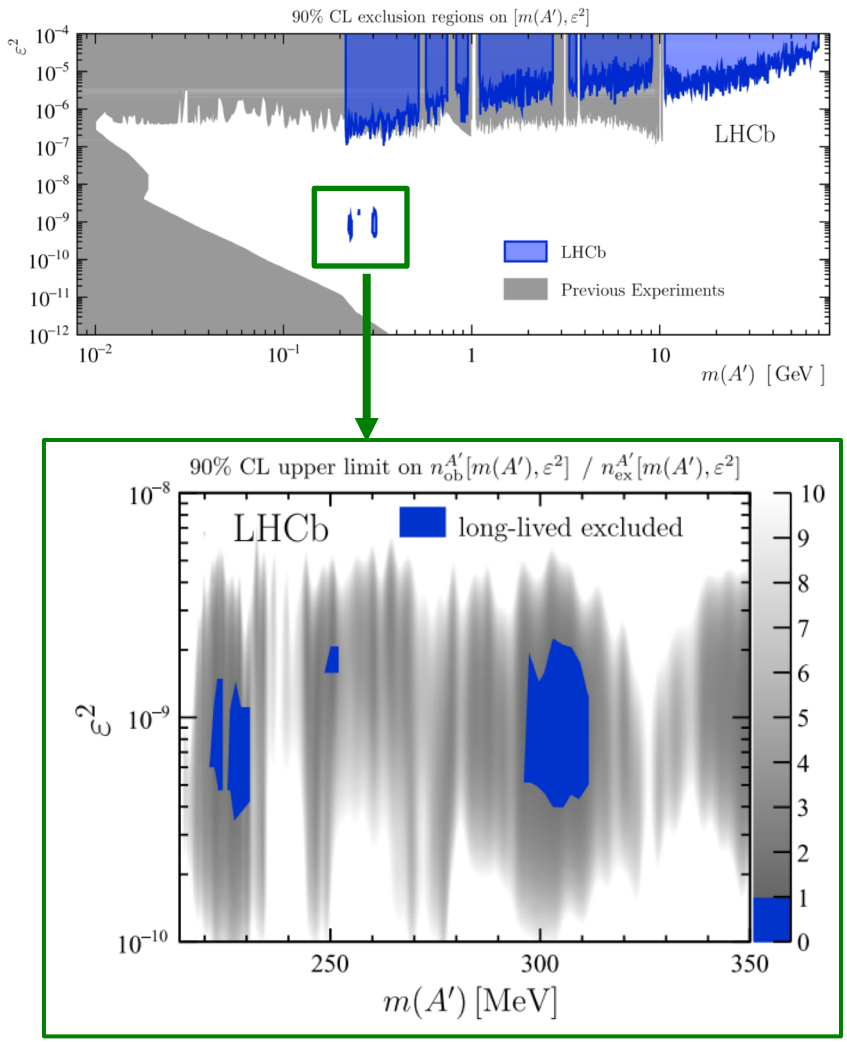
Prompt and Long-Lived Dark Photons Results

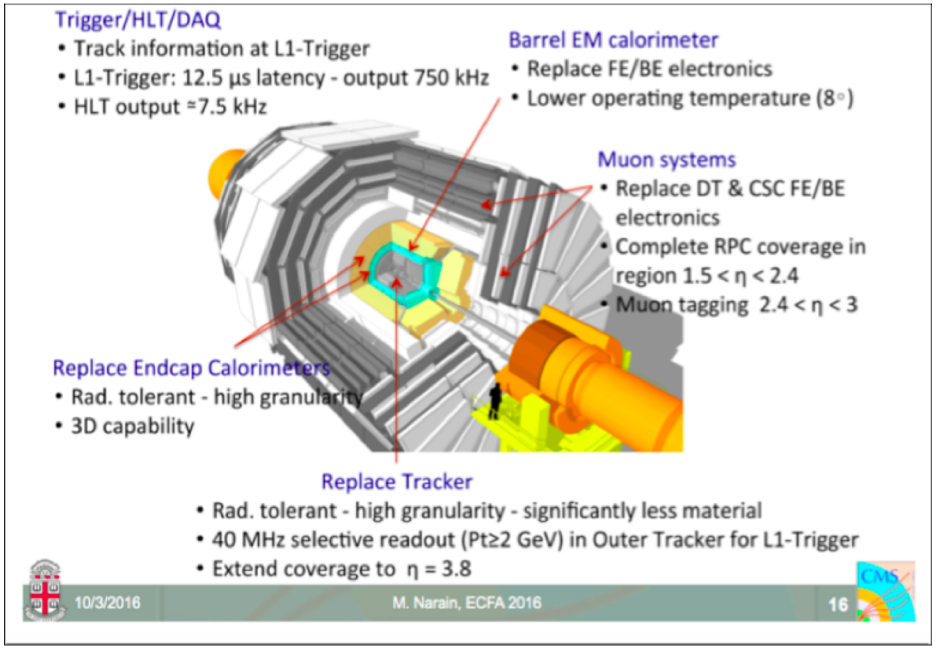
Also see Monika's talk for more info!

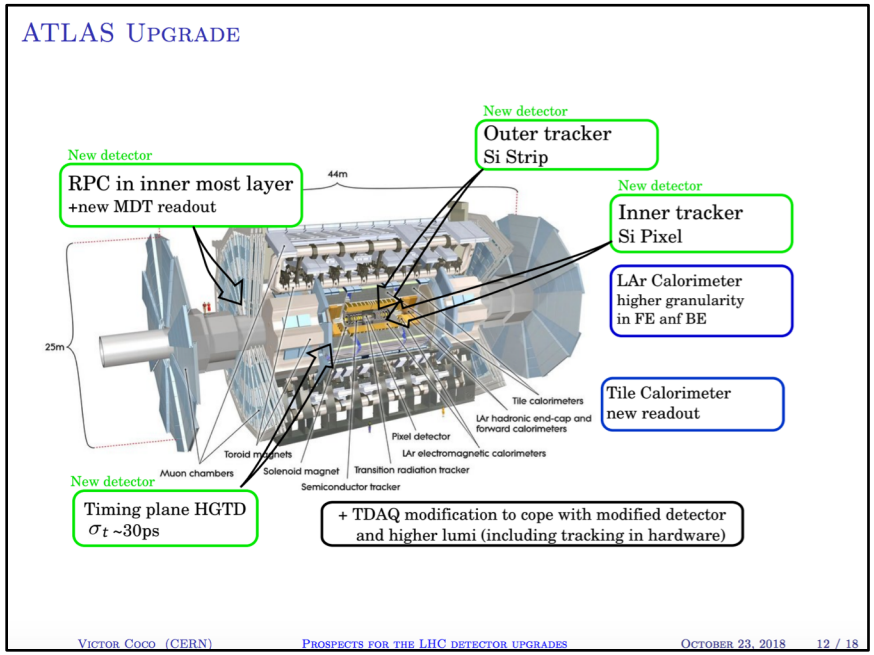
- Scan dimuon mass, bin in A' lifetime and decay fit χ^2
- <u>Results with 2016 data (1.6 fb^{-1}):</u>
  - Set 90% confidence level limits on A' mass and ε^2
  - First search to achieve sensitivity to LL dark photons using a displaced-vertex signature
- <u>Future improvements:</u>
  - Trigger already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



HL-LHC + CMS/ATLAS Upgrades

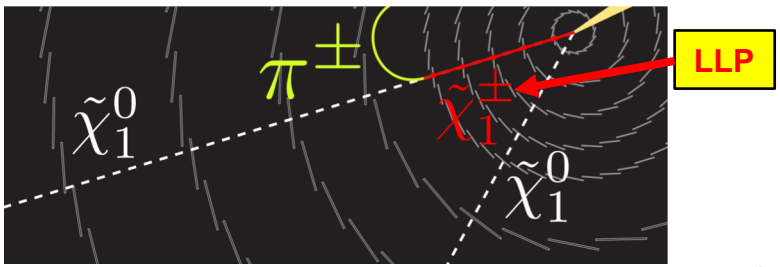
- 14 TeV center-of-mass energy, 3 ab^{-1} of luminosity, 200 pileup
- Higher geometrical coverage of all subdetectors
- High resolution for all subdetectors
- New L1 track trigger in CMS
- New timing detectors



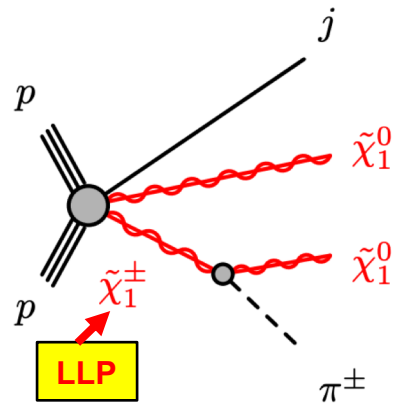


Disappearing Tracks at the HL-LHC

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

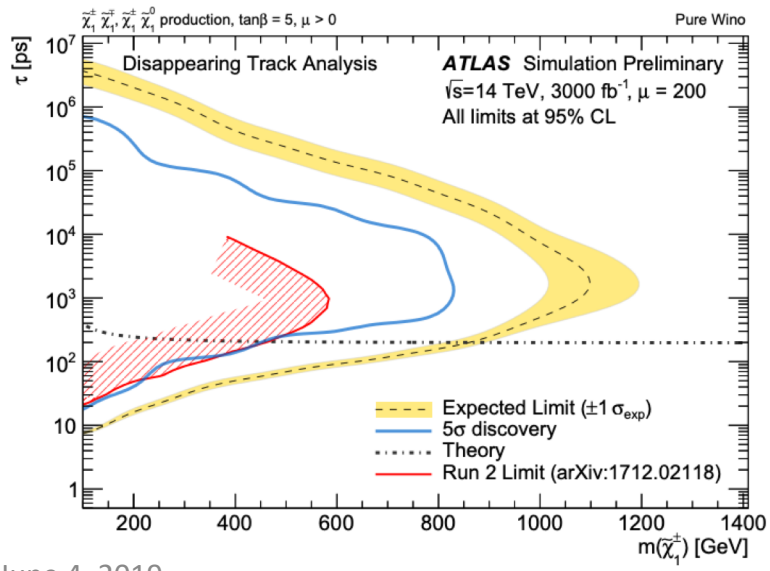


AMSB benchmark:



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

Pure wino LSP scenario



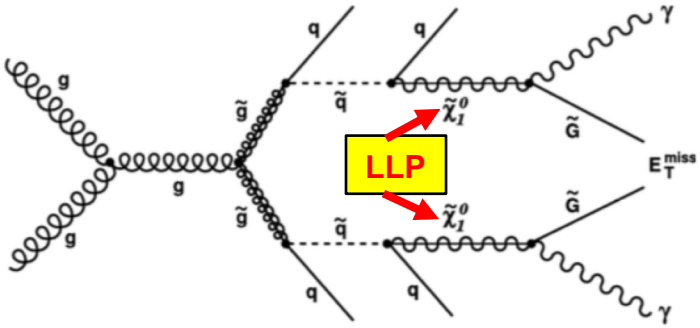
- Truth-level analysis with parameterized detector response
- Select events with short tracks, no leptons, and large missing transverse momentum
- **Large gain in disappearing track sensitivity at the HL-LHC with 3 ab^{-1}**
- Even **more** tracking and vertexing improvements for disappearing tracks: ATL-PHYS-PUB-2019-011
  - **E.g. reconstructing the soft pion track!**

CMS-TDR-17-006

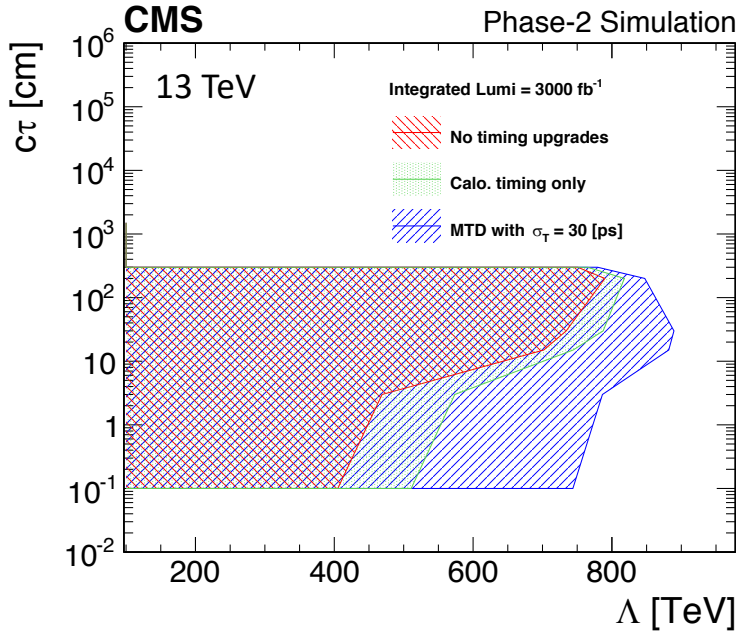
Delayed Photons at the HL-LHC

- Search for LLPs that decay to **delayed photons + missing transverse momentum**
- Generator-level study with smeared photon time distribution

GMSB benchmark:



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



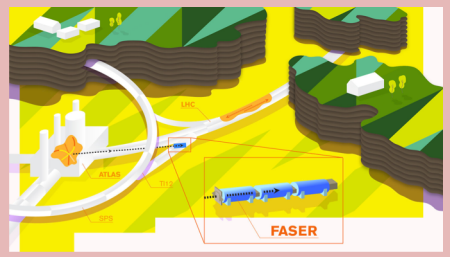
- Current CMS detector
  - 300 ps time resolution in ECAL
- Phase-2 detector without precision timing
  - 180 ps time resolution dominated by beamspot uncertainty
- Phase-2 detector with precision timing
  - **30 ps time resolution**

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

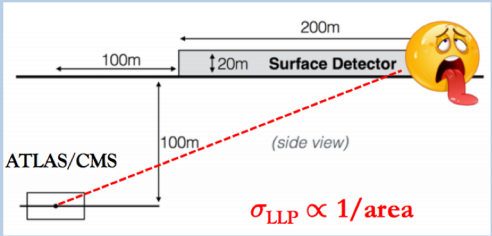
Some Dedicated LLP Experiments

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

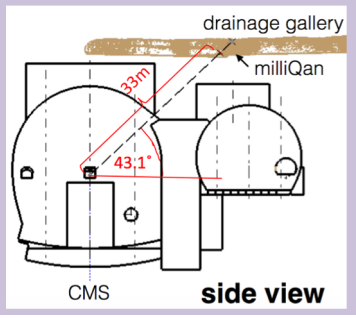
FASER: searches for long-lived dark photons and similar particles in the extreme forward direction



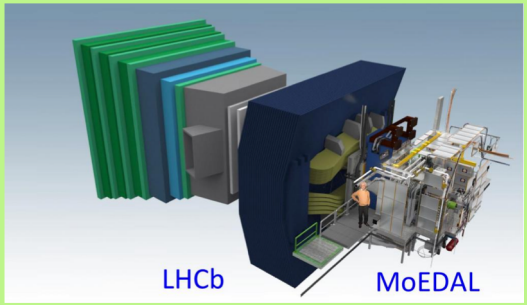
MATHUSLA: searches for (very) long-lived weakly interacting neutral particles with a large-volume, air-filled surface detector



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



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



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
  - Heavy neutral leptons
    - ***See Jan Hajer's talk later today***
    - *Also see new ATLAS result: EXOT-2017-26*
  - 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
- Exotic long-lived particle searches often require non-standard techniques to collect, reconstruct, and analyze the data → **different/challenging/FUN!**
- 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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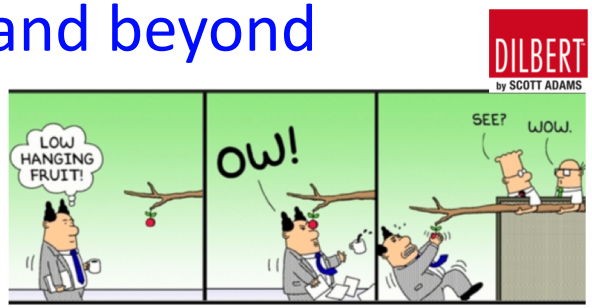


Backup

LHC LLP White Paper and Workshops

Aim of the LHC LLP community:

Make sure we don't miss BSM LLPs!

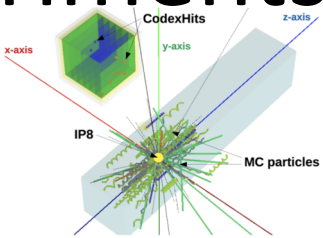
LHC LLP community workshops:

- Latest workshop at CERN, May 27-29, 2019
- https://indico.cern.ch/e/LHC_LLP_May_2019

LHC LLP community White Paper submitted to arXiv

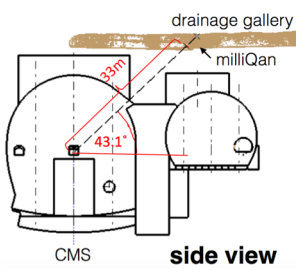
- **White Paper Chapters:**
  - **Simplified Models** Yielding LLPs
  - **Experimental Coverage** of LLP Signatures
  - Common Sources of **Backgrounds** for LLP Searches
  - **Detector Upgrades**
  - **Reinterpretation and Recommendations** for the Presentation of Search Results
  - New Frontiers: **Dark Showers**

Approved and Proposed LLP Experiments



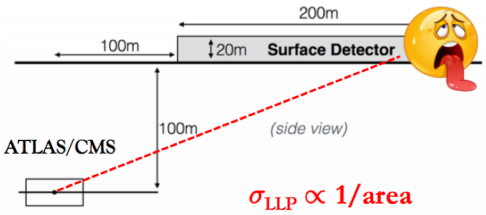
CODEX-b: searches for long-lived weakly interacting neutral particles with a new detector near LHCb

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



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

MAPP: searches for low-charged particles and long-lived neutrals that decay outside of LHCb



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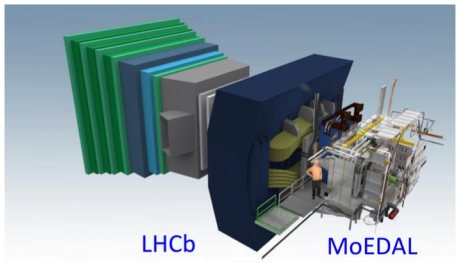
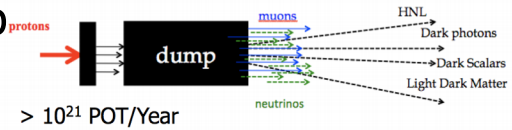


NA62: searches for vertices of long-lived neutral particles

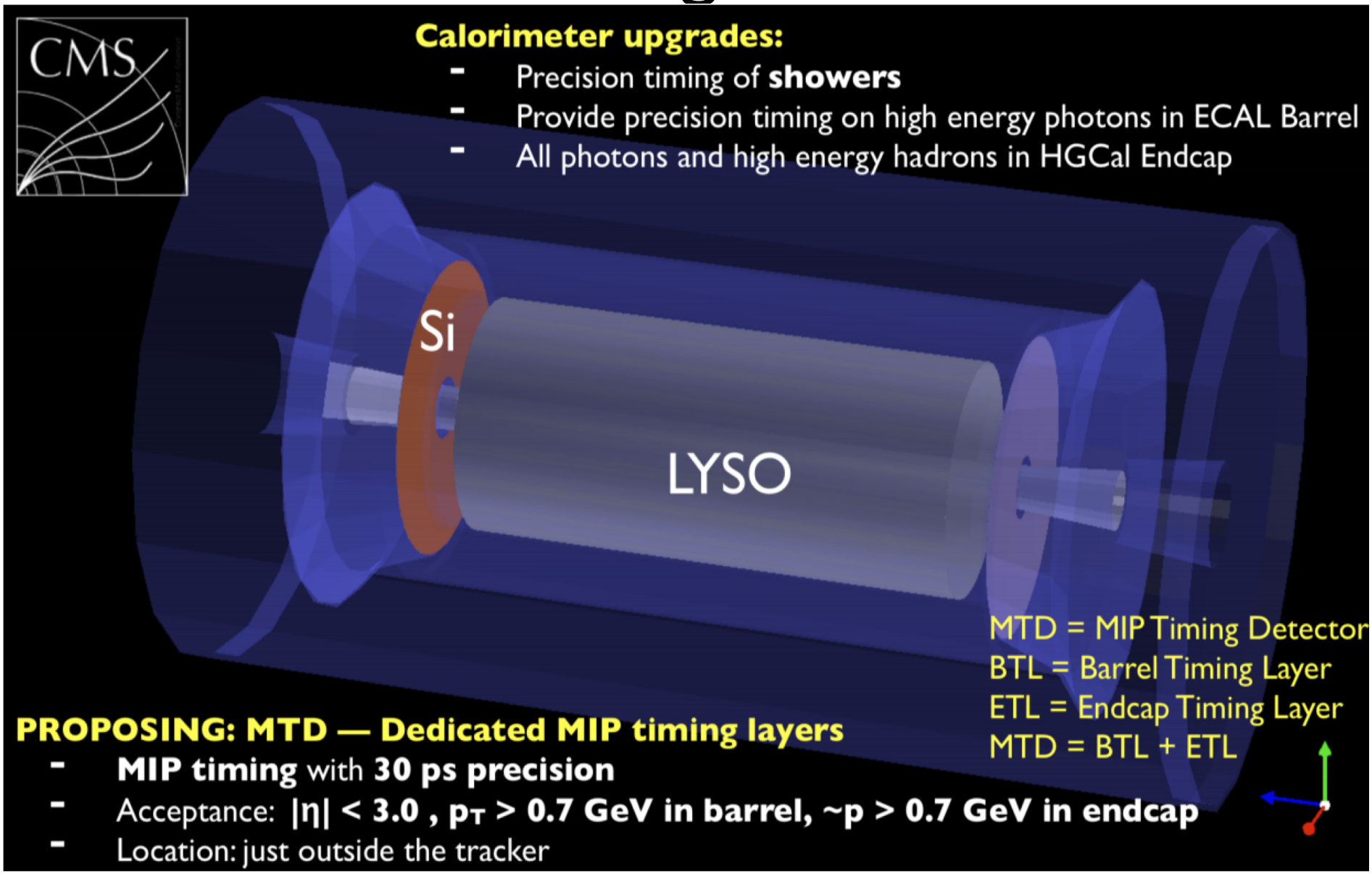
SeaQuest: dark-sector searches

SHIP: searches for neutral hidden particles at the beam dump



And more!

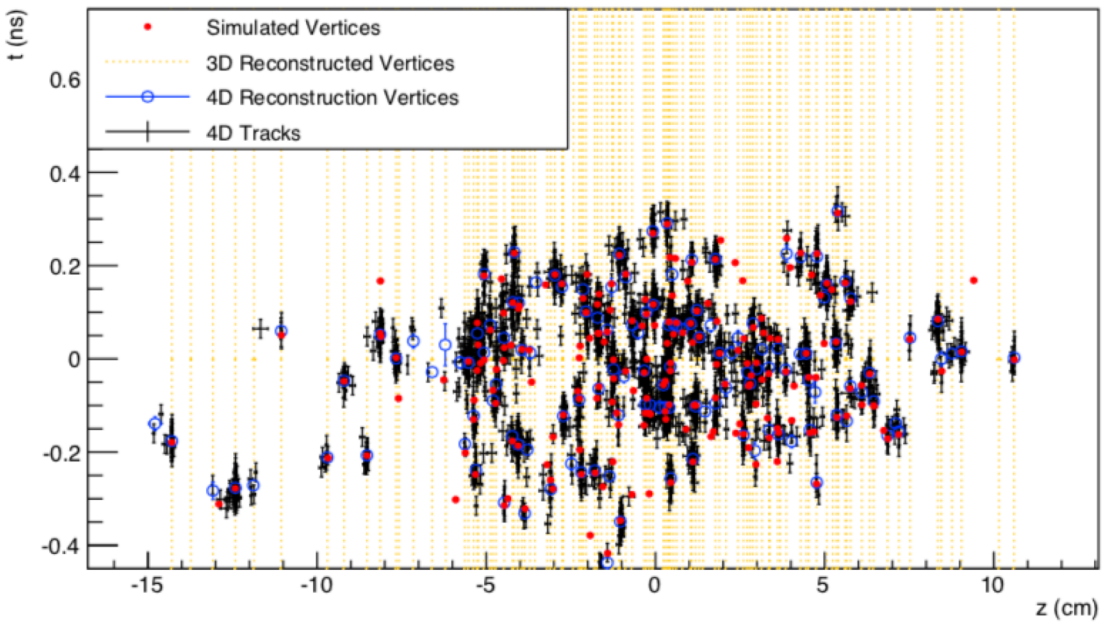
MIP Timing Detector



MTD Allows for 4D Vertexing

In 200 PU, we can precisely reconstruct vertices in 4D

- Vertex merging:
  - 15% in space
  - 1% in space-time



- Other benefits of the MTD:
  - Improved track and vertex reconstruction
  - Improved lepton identification efficiency
  - Improved MET resolution