Long-lived particles @ LHC: present and future

Theory meets Experiment mini-workshop on **long-lived particles**

Carlos Vázquez Sierra

Nikhef, National Institute for Subatomic Physics,
Amsterdam, The Netherlands.

October 26, 2018

What is a long-lived particle (LLP)?

- A neutral particle that decays a macroscopic, reconstructable distance from the IP,
- or a charged particle that decays as above, or is quasistable on the scale of the detector.
- From "Flashes of Hidden Worlds at Colliders" (D. Curtin, R. Sundrum):
  [Physics Today 70 (2017) 6 46]

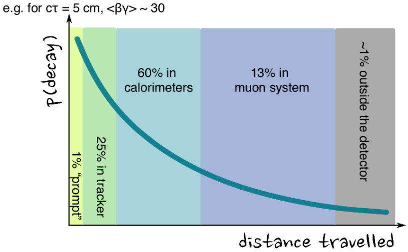
> The LHC main detectors are a busy place, with lots of hadronic shrapnel flying around. Luckily, neutral LLP decays are a spectacular signature, and the burst of energy appearing out of nowhere sets it apart from the mundane rubble emanating from the collision point. Look-

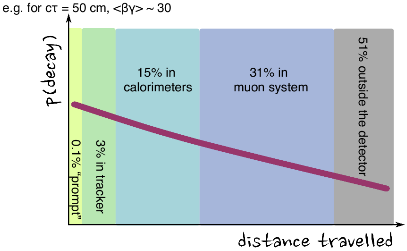
Introduction

- SM LLPs due to approximate symmetries, small couplings, mass degeneracies, etc.
- Same principles apply to BSM particles $\rightarrow$ easily get LLPs.
- Great opportunity for NP (direct searches) at LHC – **pretty much uncovered!**

Different signatures – different types of searches:

- Characterised by LLP mass, production + decay and lifetime.
- A graphic example for ATLAS by H. Russell:





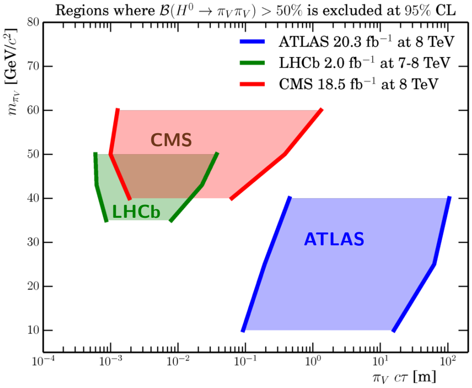
Experimental challenges for P2 – reach and coverage

2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	203+
			Run III						Run IV				Run V	
LS2						LS3					LS4			
LHCb 40 MHz UPGRADE Phase I			$L = 2 \times 10^{33}$		LHCb Consolidation				$L = 2 \times 10^{33}$ 50 fb^{-1}		LHCb Ph II UPGRADE *		$L = 2 \times 10^{34}$ 300 fb^{-1}	
ATLAS Phase I Upgr			$L = 2 \times 10^{34}$		ATLAS Phase II UPGRADE				HL-LHC $L = 5 \times 10^{34}$		ATLAS		HL-LHC $L = 5 \times 10^{34}$	
CMS Phase I Upgr			300 fb^{-1}		CMS Phase II UPGRADE						CMS		3000 fb^{-1}	
Belle II		5 ab^{-1}	$L = 8 \times 10^{35}$		50 ab^{-1}									

- **Challenging experimental conditions** – improve **detector performance and reach:**
  - Higher pile-up and occupancy → higher detector granularity.
  - Higher rate → improve discriminating power and trigger capabilities.
  - Higher fluence and radiation damage → higher radiation hardness.
- In particular – **trigger** and **tracking systems** are crucial for LLP searches.
- Increase the **physics coverage** of all the experiments:
  - We are open to new benchmark models we can use to produce physics projections.

Experimental challenges for P2 – complementarity

- Keep complementarity between LHCb, ATLAS and CMS:
  - Detector acceptance and vertexing capabilities play an important role.
  - LHCb can reach lifetime and masses that ATLAS & CMS can not – and vice-versa.
- An example – Run 1 search for pair produced Hidden Valley π_v via SM Higgs decay:
  - CMS 18.5 fb^{-1} **[PRD 91 (2015) 012007]**, recast **[PRD 92 (2015) 073008]**
  - ATLAS 20.3 fb^{-1} **[PRD 92 (2015) 012010] [PLB 743 (2015) 15-34]**
  - Parameter space where $\mathcal{B}(H^0 \to \pi_v \pi_v) > 50\%$ is excluded at 95% confidence level:

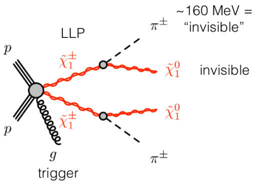


ATLAS outline

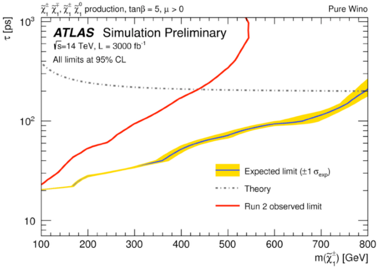
- Interplay between searches and upgraded detector:
  - Performance of ID, ITk, calo and muon triggers.

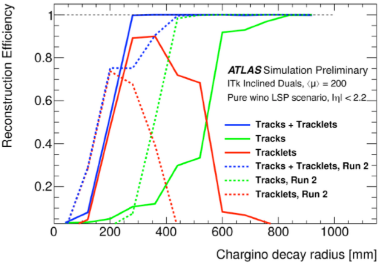
- **Disappearing tracks:**
  - Physics projection studies in Pixel TDR.
- **Multi-track displaced vertices in ID + MET:**
  - Tracking studies in Pixel TDR.
  - Physics projection studies to be done.
- **Displaced vertices in muon spectrometer:**
  - Muon trigger studies in TDAQ TDR.
- **Jets in HCAL with low EM fraction:**
  - Calo trigger studies in Tile TDR.

Disappearing tracks

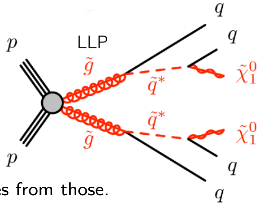


- Charged particle decaying into invisible:
  - Sensitivity in lifetime from 10 ps to 10 ns.
  - Pure wino (higgsino) SUSY LSP, $\tau = 0.2$ (0.05) ns.
- Selection (in Pixel TDR - **to be reoptimised**):
  - MET > 450 GeV + one jet > 300 GeV.
  - Tracklet with 4 pixel hits and $p_T > 250$ GeV disappearing in strips.
  - Background is mostly **fake tracklets** (estimated using Upgrade MC & Run 2 data).
- HL-LHC projection for pure wino LSP & tracking efficiency below:
  - Standard tracking produces more kinked tracks for pions than current ID.
  - **Fakes significant** $\rightarrow$ further optimisation of selection to reject fakes.
  - Expect to exclude > 800 GeV (> 250 GeV) for pure wino (higgsino) with 3000 fb^{-1} data.

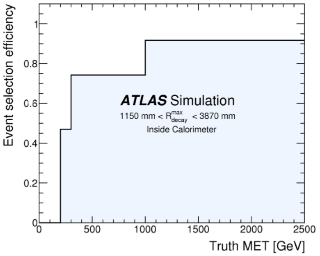


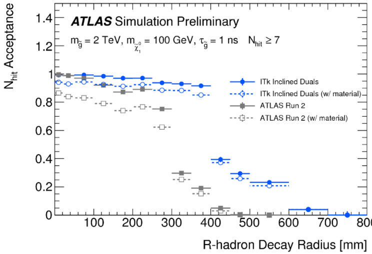


Multi-track displaced vertices in ID + MET



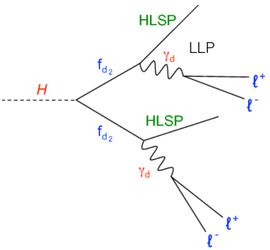
- Neutral or charged LLP decaying within ID:
  - Sensitivity in lifetime from 10 ps to 10 ns.
  - Gluino R-hadrons decaying into neutralino + jets.
- Selection (taken from Run 2 analysis → **can be tuned**):
  - Relies on reconstructing displaced tracks and displaced vertices from those.
  - Veto of vertices in detector material & MET above 200 GeV.
  - Requires at least one vertex with at least 5 tracks & DV mass at least of 10 GeV.
- Run 2 efficiency versus truth MET & tracking efficiency below:
  - Reconstruction efficiency (reach) for displaced tracks **increases up** to 400 (500) mm.
  - Physics reach **to be estimated** (material veto in ITk, MET and vertexing efficiency).

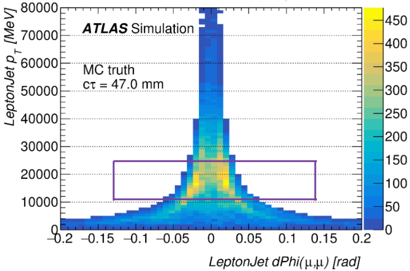




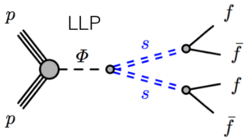
Displaced vertices in muon spectrometer

- Neutral LLP decays before muon spectrometer:
  - Decays into pairs of multiple pairs of collimated leptons.
  - HV models with **dark photon decays into leptons:**
    - Produce **physics projections** for this search $\rightarrow$ [ATLAS-CONF-2016-042] for Run 2 results.
- Current trigger:
  - Di-muon resolution limited to $\Delta\phi \sim 0.2$ & single muon p_{T} threshold ~ 25 GeV.
- Upgraded (Phase 2) trigger:
  - New muon sector logic and trigger processors $\rightarrow$ **di-muon trigger with RoI.**
  - Threshold **reduced** to $\sim$10 GeV for $\Delta\phi = 0.01$ (see right plot below).
  - Significant **gain** for close muons in trigger efficiency.
  - Further optimisations foreseen for di-muon $\Delta\phi$ with the new algorithm.

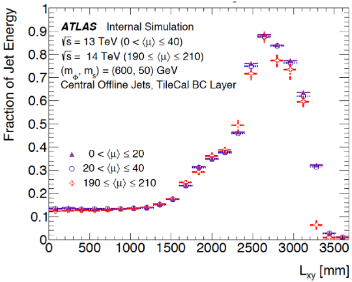


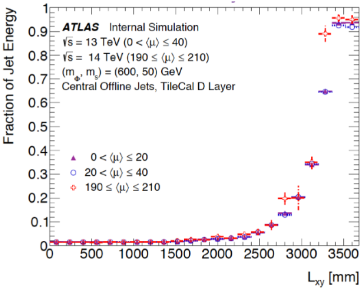


Jets in hadronic calorimeter with low EM fraction



- Neutral LLP → jets inside the hadronic calorimeter:
  - HS scalar boson → HS particles → heavy SM fermions.
- Current trigger:
  - Dedicated L1 trigger based on τ candidates + low EMfrac.
- Upgraded (Phase 2) trigger ideas:
  - Pile-up activity in EM calorimeter → low EMfrac will **become problematic.**
  - Increased longitudinal L1 granularity in Tile:
    - Compare energy deposit per layer → **reduce sensitivity** to pileup.
  - Deposited energy fraction versus decay radius for Tile BC (left) and D (right) layer:



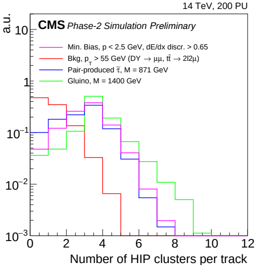


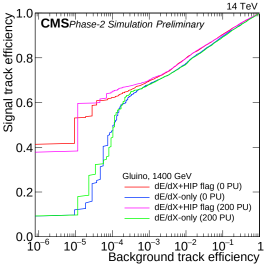
CMS outline

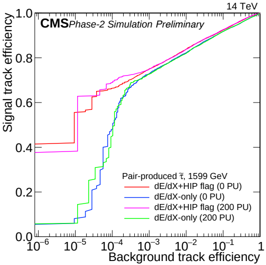
- **Tracker & RPC upgrade for HSCP:**
  [CMS-TDR-17-001] [CMS-TDR-17-003]
  - HSCPs have a distinct signature in the detector.
  - Exploit RPC time resolution & OT capabilities.
- **Displaced muons:**
  [CMS-TDR-17-003]
  - New forward muon detectors to improve trigger.
  - New tracking algorithms for displaced muons.
- **Signatures with delayed photons/Z^0 bosons:**
  - Sensitivity strongly limited by time resolution.
  - New MTD $\rightarrow$ new possibilities for LLP searches.

Tracker & RPC upgrade for HSCP [CMS-TDR-17-001] [CMS-TDR-17-003]

- Heavily ionising LLPs moving slowly in the detector:
  - Masses $\sim \mathcal{O}(1)$ TeV with $\beta \sim 0.3 - 0.5$.
- Exploit **intrinsic time resolution** of the RPC system:
  - HSCPs look like slow μ propagating through CMS.
  - Use RPC $\rightarrow$ allow to trigger HSCPs with $\beta \sim 0.25$.
- Use **IT** and **OT** to identify signal tracks:
  - Anomalously high energy loss measurements (IT).
  - New threshold in OT (see right plot) $\rightarrow$ **HIP flag.**
- Performance of **dE/dx discriminator** for Phase 2:
  - HIP flag **critical** to restore tracker sensitivity in Phase 2.
  - ROC for gluino (1.4 TeV) and stau (1.599 TeV):

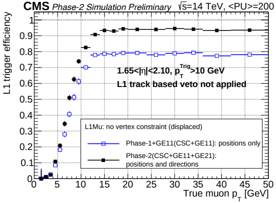




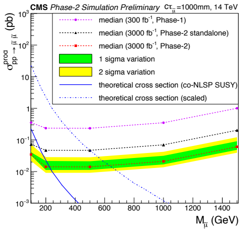


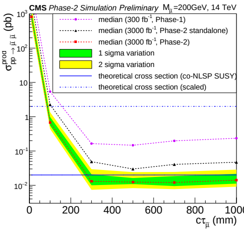
Displaced muons **[CMS-TDR-17-003]**

- L1 inefficient for tracks with few mm displacement:
  - Beamspot as constraint $\rightarrow$ less rate, higher resolution.
- Inclusion of new GE2/1 forward muon detectors:
  - Will improve measurement of bending angle.
  - **Highly efficient trigger** for displacements up to 15 cm.
- **Displaced stand-alone** algorithm (no IP constraint):
  - Tracks reconstructed from **only hits in muon chambers.**
  - Benefit from additional hits from upgraded μ system.



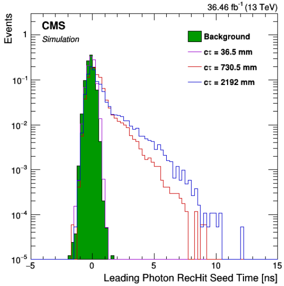
- Consider GMSB model with smuon as NLSP (2 displaced OS-μ & MET $>$ 50 GeV):
  - **Impact parameter significance** as **background discriminator.**
  - Signal efficiency 5% versus 10^{-4} for SM (QCD, $t\bar{t}$, DY) background.
  - Sensitivity **without** DSA algorithm (black line) $\rightarrow$ reconstruction efficiency reduced by factor 3:

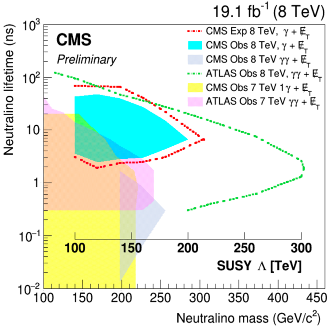


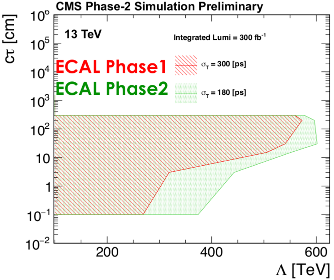


Signatures with delayed photons/Z^0 bosons

- $\gamma/Z^0(\rightarrow ee)$ from the decay of a long-lived neutralino:
  - Non standard EM objects that arrive **in delay** to ECAL.
- Higher lifetime bound $\rightarrow \tilde{\chi}_1^0$ decays outside CMS.
- Lower lifetime bound $\rightarrow$ limited by **time resolution:**
  - Beamspot size in HL-LHC $\sim 180-200$ ps.
  - Resolution dominated by **uncertainty from beamspot.**
  - ECAL P2 improves performance but still **not optimal.**

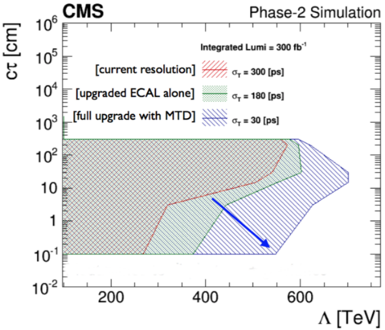


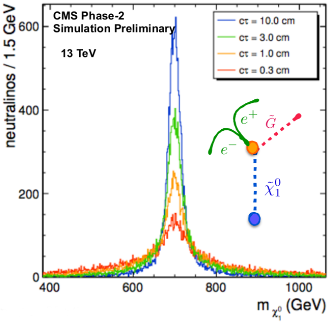




Signatures with delayed photons/Z^0 bosons

- New **precision MIP Timing Detector (MTD)** for Phase 2 (see Lindsey's talk at LHCC):
  - Hermetic timing detector (MIP + barrel & endcap layers) with 30 ps precision.
  - Acceptance of $|\eta| < 3.0$ with $p_T > 0.7$ GeV in barrel and $p > 0.7$ GeV in endcap.
  - Rejects **spurious SVs** & **remove pileup tracks** from isolation cones.
- ECAL P2 + MTD (blue region) **increases sensitivity to short lifetimes** (left plot below).
- Precision timing allows to reconstruct LLP SV → measure LLP β → measure **LLP mass:**
  - Example for a complementary out-of-time channel is shown (right plot below).
  - For details and numbers from simulation see Alexander's talk at Trieste.





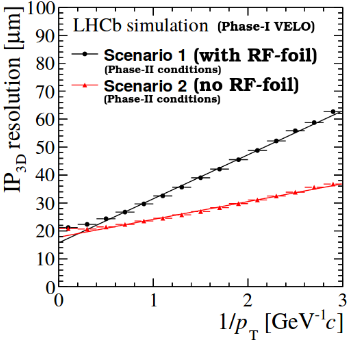
LHCb outline

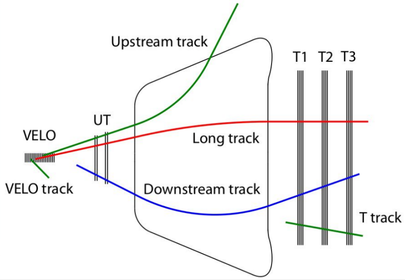
- Aim for complementarity w.r.t. ATLAS and CMS:
  - Forward acceptance $\rightarrow$ low masses.
  - Excelling vertexing capabilities $\rightarrow$ low lifetimes.

- **Upgraded trigger, tracker and VELO:**
  - Instrumentation studies for Phases 1 and 2.
- **Massive LLPs decaying to μ + jets:**
  - Physics projection studies for yellow report.
- **Massive LLPs decaying to jet pairs:**
  - Physics projection studies for yellow report.
  - Interest in pile-up studies (jet reco efficiencies).
- **Dark photons:**
  - Interest in other possible final states.
  - Ability to recast results in other models.
- **Extended reach for LLPs (CODEX-b + LHCb):**
  - New detector to operate interfaced with LHCb.
  - Greatly extend reach for LLP searches.

Upgraded trigger, tracker and VELO

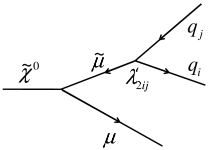
- Remove hardware L0 for Phase 1 $\rightarrow$ **fully software-based trigger:**
  - **Huge improvements** expected for low mass searches (main bottleneck).
  - Develop dedicated lines for displaced jets, di-muons and di-electrons.
- Exploit **LHCb tracking capabilities** – not only **long tracks:**
  - Trigger on **downstream tracks** $\rightarrow$ better for LLP ($\lesssim$ 2m) signatures. **[LHCb-PUB-2017-005]**
  - New tracker for **upstream tracks (UT)** – high granularity, closer to beam pipe.
  - Proposal to add magnet stations (MS) inside the magnet $\rightarrow$ improve low p acceptance.
- Phase 2 **VErtex LOcator** – challenging conditions: **[CERN-LHCC-2017-003]**
  - Access to shorter lifetimes, better PV and IP resolution, and real-time alignment.
  - Better knowledge of material interactions (dedicated material veto map).
  - Possibility of removing RF-foil for Phase 2 (better IP resolution, no material interactions).



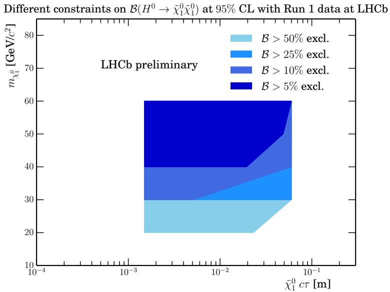


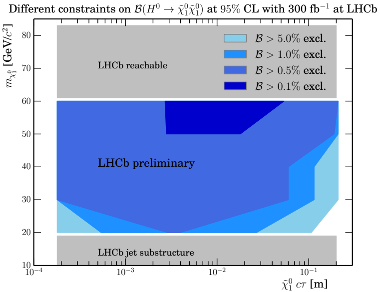
Massive LLPs decaying to μ + jets

- **Massive LLP into μ + two quarks ($\rightarrow$ jets):**
  - Look for a **single DV** with several tracks + high p_T muon.
  - Background dominated by $b\bar{b}$ & material interactions.
- Sensitive to **several benchmark production models:**
  - Focus on the **decay of a Higgs-like particle** into two LLPs.



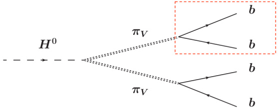
- Run 1 results **[EPJC (2017) 77:224]** and Phase 2 prospects below:
  - Scale signal and background (increase of x-sections) & optimistic assumptions for pile-up.
- **Conservative assumptions** for jet reconstruction, trigger and material interactions:
  - Better knowledge of material interactions + better jet reconstruction efficiencies for lower masses.
  - **Removal of L0 trigger (Phase-I)** $\rightarrow$ much higher trigger efficiencies at the end.



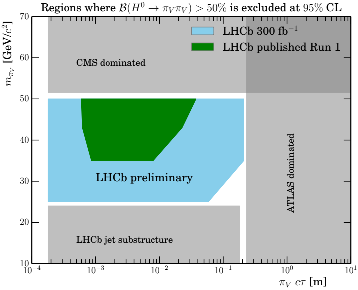


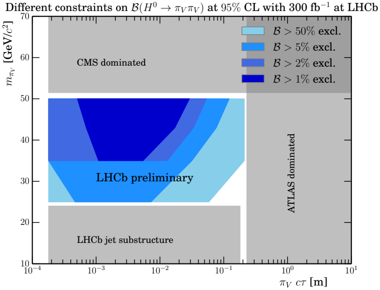
Massive LLPs decaying to jet pairs

- **DV with two associated heavy flavour jets:**
  - Most of the cases → only one LLP decays inside LHCb.
  - Reconstruct DV (LLP R_{xy} as discriminator) & find the jets.
  - Background dominated by $b\bar{b}$ & material interactions.



- Sensitive to **several benchmark production models:**
  - Focus on the **decay of a Higgs-like particle** into two HV π_v.
  - Others, i.e. confining HV sector (multi-jet final state).
- Run 1 results **[EPJC (2017) 77:812]** and Phase 2 prospects below:
  - Same assumptions as with LLP into μ + jet analysis.
  - Dedicated trigger lines for displaced jets & jet substructure tools to reach lower masses.
  - Pile-up in Phase 2 will probably **affect** jet reconstruction (studies on-going).

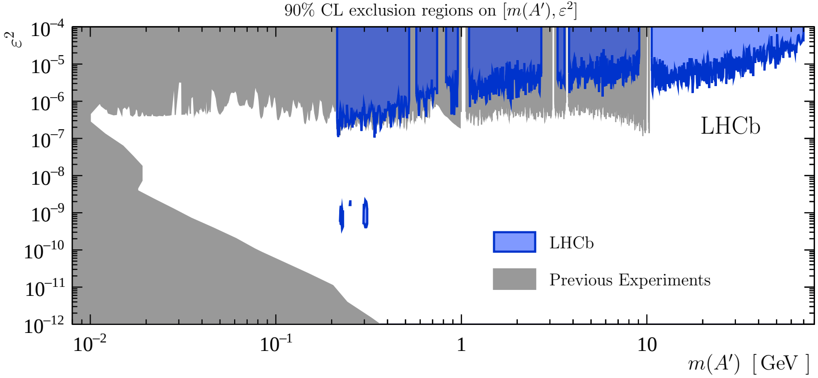




Dark Photons

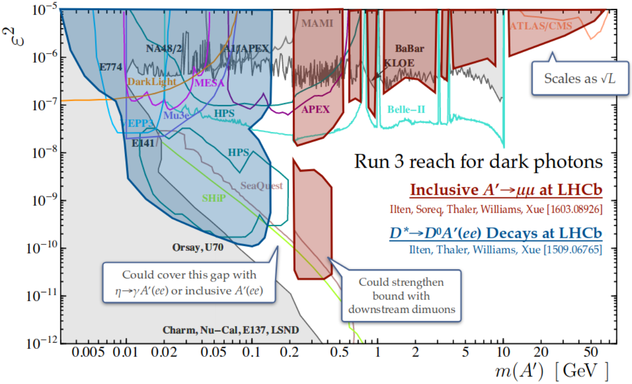
Search for dark photons decaying into a pair of muons:

- Used 1.6 fb^{-1} of 2016 LHCb data (13 TeV) **[PRL (2018) 120 061801]**
- **Prompt-like** search (up to 70 GeV/c^2) $\rightarrow$ **displaced** search (214 – 350 MeV/c^2).
- **No significant excess found** - **exclusion regions at 90% C.L.:**
  $\rightarrow$ First limits on masses above 10 GeV & competitive limits below 0.5 GeV.
  $\rightarrow$ Small displaced A' region excluded $\rightarrow$ first limit ever **not from beam dump.**



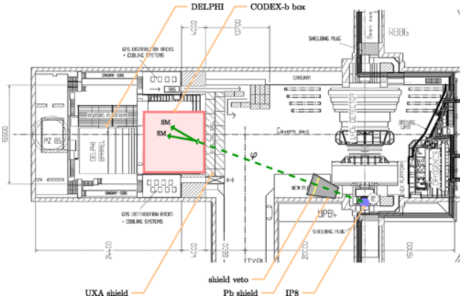
Dark Photons

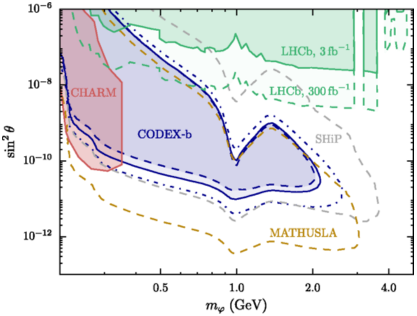
- Cover di-electron final states in $D^{*0} \to D^0 A'(ee)$ decays:
  $\to$ Hardwareless trigger is required (softer final state than in the di-muon mode),
  $\to$ High statistics $\to$ get $3 \times 10^{11} D^0$ per inverse fb!
- Extend searches model-independently:
  $\to$ Recast in other vector models **[JHEP 06 (2018) 004]**
  $\to$ Recast in (pseudo-)scalar models **[arXiv:1802.02156]**
- Prospected reach for **Run III** – comparison with Belle 2 and other experiments:



Extended reach for LLPs (CODEX-b + LHCb)

- Compact detector for exotics: **[PRD 97 (2018) 015023]**
  - Box of tracking layers to search for decays-in-flight of LLPs generated at IP8.
  - Interface with LHCb for identification and partial reconstruction of possible LLP events.
- Prospects for several benchmark models studied:
  - Prospects (various detectors) for $B \to X_s \varphi$ (φ as a light scalar) shown below.
  - LHCb has already provided limits for this signature using Run 1 data **[PRD 115 (2015) 161802]**





Conclusions

- Significant effort to extend our **experimental reach and coverage**:
  - Keep an excellent detector performance during Phase 2.
  - Cope with the challenging conditions of a high luminosity machine.
  - Develop new successful techniques for a new high luminosity scenario.
- Exploit **complementarity** of ATLAS, CMS and LHCb:
  - Each detector has unique capabilities $\rightarrow$ acceptance, vertexing, trigger...
  - Make sure no corner of the parameter space remains unveiled.

Is there anything beyond the Standard Model?