Dark sector physics with LHCb

XIII meeting on B physics (Marseille; October 1 – 3, 2018)

Synergy between LHC and SuperKEKB in the Quest for New Physics

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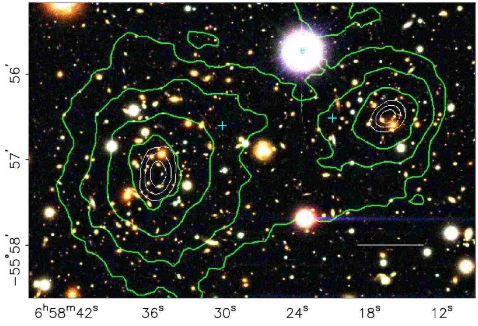
Introduction

What are and why dark sectors?

- The SM is the **most successful** theory describing subatomic **particles** and their **interactions.**
- But – also an **incomplete theory** → *i.e.* inability to explain **dark matter (DM):**
  - Very small fraction of the Universe composed by ordinary matter → DM is **very abundant.**
  - DM does **not interact with ordinary matter** but **exhibits gravitational effects.**
- Several proposals to tackle the DM problem → one of them are the **dark sectors:**
  - Collection of particles and forces **disconnected** from the SM:
    → Dark particles are **neutral under SM interactions** → no interaction with ordinary matter.
    → Dark particles are **massive** → affected by gravitational interactions.
  - Depending on the **complexity** of the dark sector → neutrino masses, baryon asymmetry, etc.



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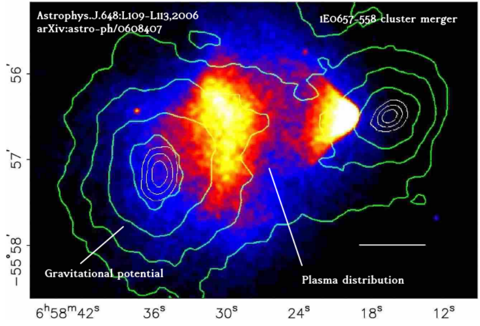
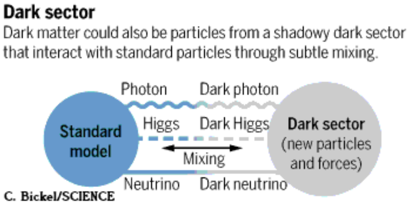


Introduction

Looks great... but how can we test this if there is no interaction with SM?

- Existence of a *mediator* coupled to SM → *portal* interactions:
  → Strongly constrained by SM symmetries → coupling to SM **strongly suppressed.**
- Encoded as a **mixing term** in the lagrangian (depends on mediator **spin** and **parity**):
  → Axion (pseudoscalar), vector, Higgs (scalar) and neutrino (lepton) portals.
- Look for **SM signatures from dark particle decays** via these portals:
  → Set limits in the **coupling strength to SM** → *i.e.* ϵ^2 (dark photons), f_a (ALPs)...
- Small couplings with SM typically lead to **longer lifetimes** (if stable in their dark sector):
  → Can elude current limits especially for **low masses and very displaced vertices**.
  → In general – dark sectors are poorly tested ☹ want to know more? ☺ **[arXiv:1608.08632]**



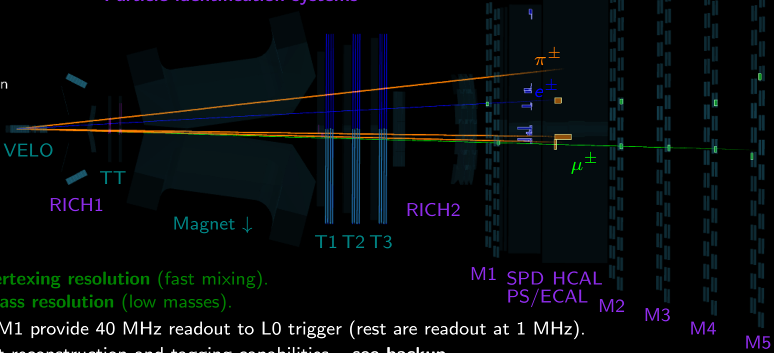
LHCb and Belle 2 can play a decisive role in this *intensity frontier!*

The LHCb detector **[IJMP A30 (2015) 1530022]**

Side view

Event 216853
Run 4052454
LHCb Simulation

LHCb is a 20×5 m GPD in the forward region (upgrade during LS2 – **see backup**).
Single-arm **forward** spectrometer ($2 < \eta < 5$) along the beamline (z).
Tracking and vertexing systems
Particle identification systems



Excellent **vertexing resolution** (fast mixing).
Excellent **mass resolution** (low masses).
HCAL and M1 provide 40 MHz readout to L0 trigger (rest are readout at 1 MHz).
Excellent jet reconstruction and tagging capabilities – **see backup.**

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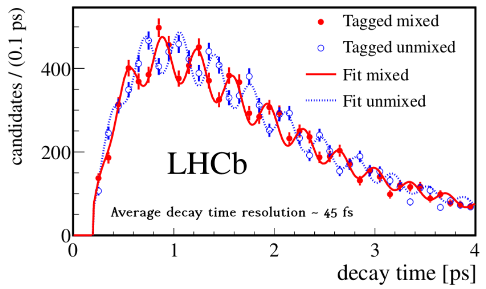
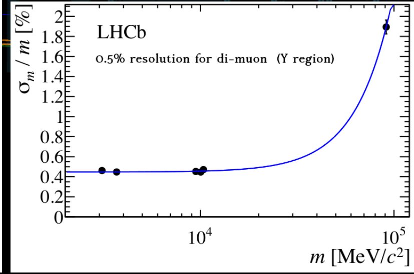
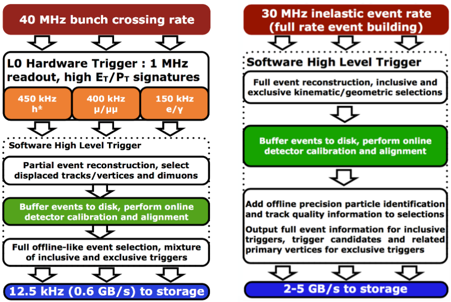




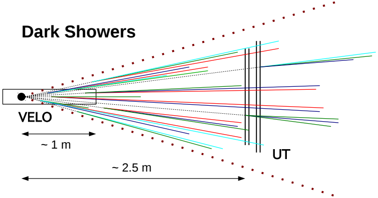
The LHCb detector [IJMP A30 (2015) 1530022]

- Very **soft** and **versatile** trigger system.
  - Hardware level L0:
    → to be **removed** for Upgrade Ia.
    → **benefit for low mass searches.**
  - **Software level HLT:**
    → Topological triggers on DV.
    → **Online μ-ID and jets in turbo.**
  - **Turbo** (since 2015) lines:
    → Full event reco can be saved.
    → Any event part is **persisted.**
    → Allow to work directly on them.



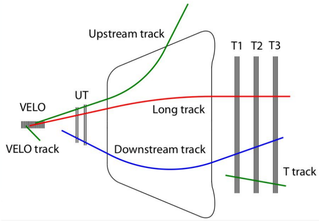
LHCb Run II LHCb Upgrade Ia

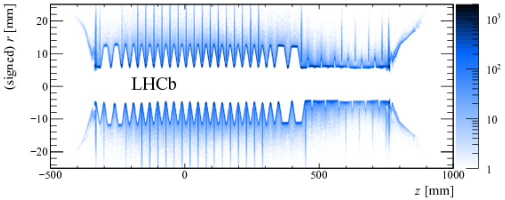
- Foreseen improvements for μ and e:
  → μ reco down to $p_T \sim 80$ MeV/c (Run II).
  → Dedicated $\mu\mu$ lines (efforts to also add e lines).
- **Trigger on dark showers** (no pointing to PV):
  → Characteristic of confining HV signatures.



The LHCb detector [IJMP A30 (2015) 1530022]

- **Tracks with tracking stations & VELO hits (a.k.a. long tracks):**
  - **Excellent spatial and momentum resolution.**
  - Reconstruction of particles decaying within VELO (most of our DS searches).
  - Presence of a **VELO envelope** (RF-foil) at $\sim$ 5 mm from beam:
    $\rightarrow$ Background dominated by heavy flavour below 5 mm.
    $\rightarrow$ Background dominated by **material interactions** above 5 mm.
  - Having a precise model of material interactions is **crucial**.
  - A **detailed VELO material veto map** is used: **[JINST 13 (2018) P06008]**
    $\rightarrow$ Sensitivity **improvement** by **one** to **two** orders of magnitude.
    $\rightarrow$ See **backup** for more details on the material veto map.
- **Downstream tracks** and **upstream tracks** – **see backup.**





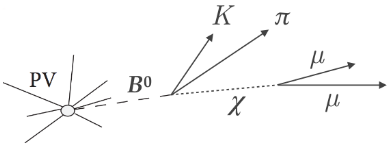
Direct searches at LHCb

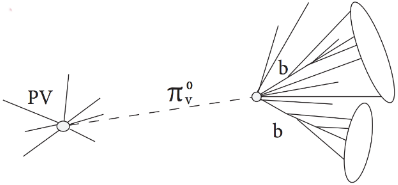
The two low-mass hunters – similar but different:

- Different **production** modes (*pp* collider → larger x-sections),
- Different **environment** (*ee* collider → much less background),
- Different **design** (LHCb is not hermetic → no MET → invisibles are difficult, *i.e.* ν),
- Different **capabilities** ($\beta\gamma$ much more smaller in Belle 2 → access to longer lifetimes).

High LHCb capabilities to exploit low masses and low lifetimes:

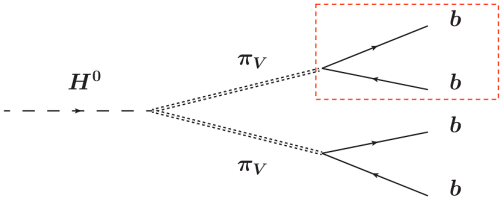
- Search for candidates **produced in the *pp* collision:**
  - Dark pions produced via SM Higgs and decaying into two jets,
  - Dark photons decaying into pairs of muons,
  - Dark bosons in the mass region close to the Υ resonances,
  - Axion-like particles (ALPs) decaying into pairs of photons.
- Search for candidates produced in B-hadron decays – **see backup.**





Dark pions decaying into jet pairs [EPJC (2017) 77 812]

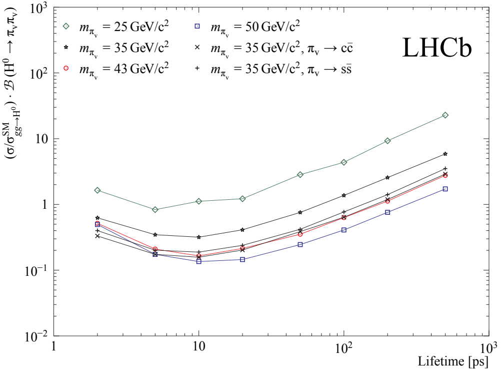
- Possible scenarios to accommodate this signature (LLP $\rightarrow$ jet pairs):
  - LSP in gravity mediated/BNV or LNV SUSY models,
  - **HV π_v decaying to $b\bar{b}$ – especially with SM-like $H^0 \rightarrow \pi_v \pi_v$ production.**
- In most of the cases **only one** of the two π_v decays into the LHCb acceptance.
- Experimental signature is a **single displaced vertex** with two associated jets.



- Reconstruct the displaced vertex and find two associated jets.
- Use π_v detachment to **discriminate** between signal and background.
- Background dominated by $b\bar{b}$ events and **material interactions.**

Dark pions decaying into jet pairs [EPJC (2017) 77 812]

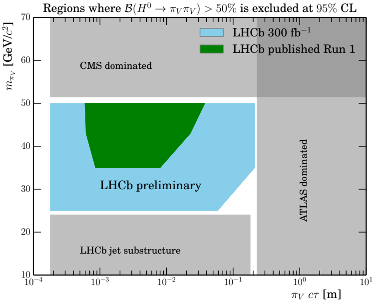
- Limits with partial LHCb Run I (2 fb^{-1}) dataset published (95% C.L. below):

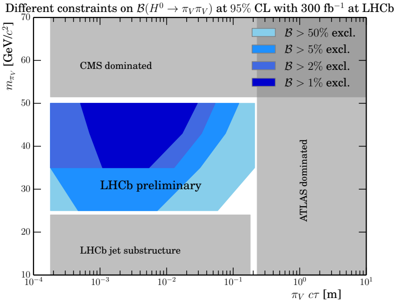


- **No excess found** – analyse LHCb Run II + lower π_v masses (jet substructure):
  → **New dedicated trigger selections for displaced jets** present during 2018 data-taking.
- Dark showers model → confining HV [PRD 97 (2018) 095033]:
  → Possible models with **few GeV Z'** (few MeV π_v with $\tau \sim \mathcal{O}(m)$) instead of SM H^0,
  → Also – π_v final states not only $b\bar{b}$ but also **leptons**.

Dark pions decaying into jet pairs **[EPJC (2017) 77 812]**

- Naive prospects for Upgrade II (loose assumptions):



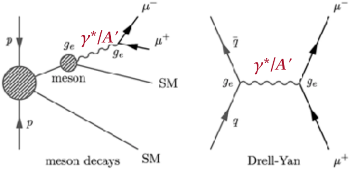


- **L0 removal (Upgrade Ia)** highly beneficial → access to lower jet masses.
- Higher pile-up in Upgrade II:
  - Impact of pile-up on jet reconstruction efficiencies needs to be studied in much detail.
  - We have reasons to be optimistic – preliminary studies ongoing + ideas (see below).
- Some possible improvements to mitigate the effect of the increased pile-up:
  - Remove neutrals (more pile-up dependent) from jet reco (only charged tracks).
  - Consider ML techniques to seize pile-up contributions as in ATLAS and CMS.

Dark Photons [PRL (2018) 120 061801]

Search for dark photons decaying into a pair of muons:

- Kinetic mixing of the dark photon (A') with off-shell photon (γ^*) by a factor ε:
  1. A' inherits the production mode mechanisms from γ^*.
  2. $A' \to \mu^+\mu^-$ can be normalised to $\gamma^* \to \mu^+\mu^-$.
  3. No use of MC $\to$ no systematics from MC $\to$ **fully data-driven analysis!**
- Separate γ^* signal from background and measure its fraction.
- **Prompt-like** search (up to 70 GeV/c^2) $\to$ **displaced** search (214 – 350 MeV/c^2).
  - A' is long-lived only if the mixing factor is really small.
- Used 1.6 fb^{-1} of 2016 LHCb data (13 TeV).



$$n_{\rm ex}^{A'}[m(A'),\varepsilon^2] = \varepsilon^2 \left[\frac{n_{\rm ob}^{\gamma^*}[m(A')]}{2\Delta m}\right] \mathcal{F}[m(A')]\,\epsilon_{\gamma^*}^{A'}[m(A'),\tau(A')]$$

off-shell photon

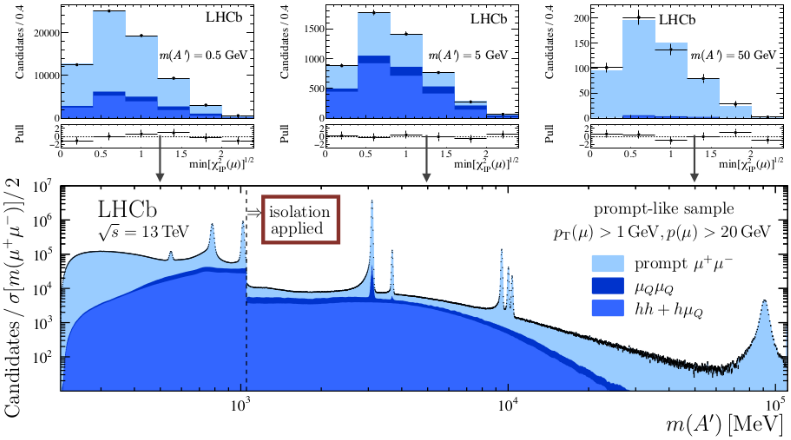
phase-space

A′/γ* eff ratio, ε=1 for prompt

Using templates for $\min[\chi^2_{IP}]$ (small mass dep)

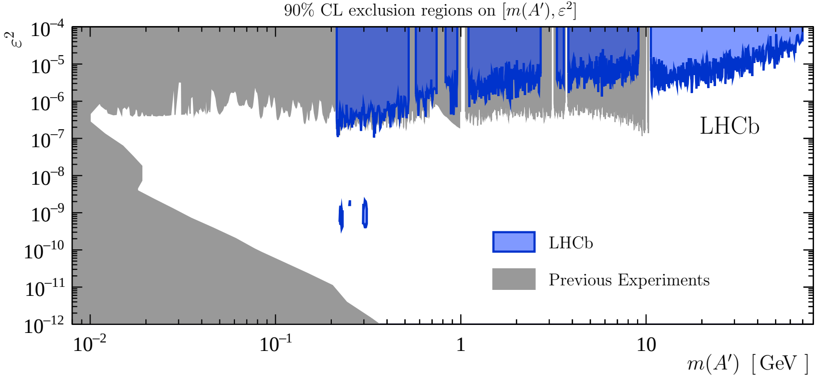
	prompt $\mu^+\mu^-$	$\rightarrow$ from data at $m(J/\psi)$ and $m(Z)$
	$\mu_Q\mu_Q$	$\rightarrow$ from simulation (validated)
	$hh + h\mu_Q$	$\rightarrow$ from same-sign dimuons (corrected)

(μ_Q is a muon from a heavy-flavour decay)



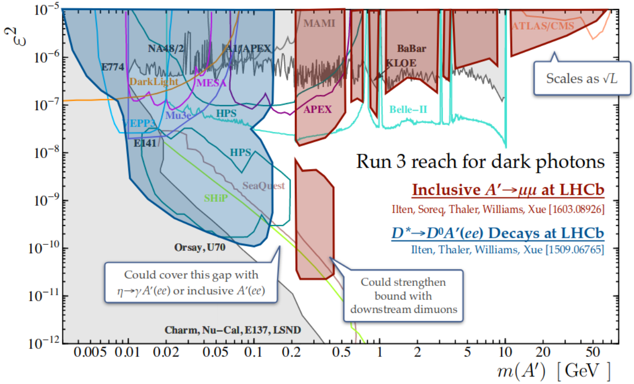
Dark Photons [PRL (2018) 120 061801]

- Displaced search is performed as well – see **backup** for details.
- **No significant excess found** - **exclusion regions at 90% C.L.:**
  → First limits on masses above 10 GeV & competitive limits below 0.5 GeV.
  → Small displaced A' region excluded → first limit ever **not from beam dump.**
- Future prospects for this search – see **backup**.



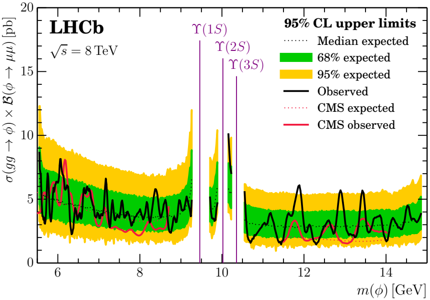
Dark Photons – the future

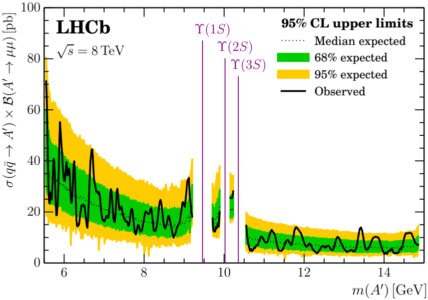
- Cover di-electron final states in $D^{*0} \to D^0 A'(ee)$ decays:
  $\to$ Hardwareless trigger is required (softer final state than in the di-muon mode),
  $\to$ High statistics $\to$ get $3 \times 10^{11} D^0$ per inverse fb!
- Extend searches model-independently:
  $\to$ Recast in other vector models **[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:



Light dark bosons decaying into $\mu\mu$ [JHEP 09 (2018) 147]

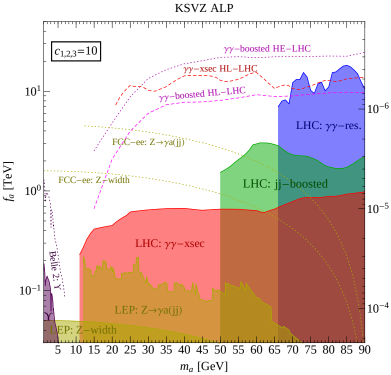
- Light spin-0 particles copiously produced in gluon-gluon fusion:
  - Many models: NMSSM, 2HDM+S, etc.
  - Recent review on LHC searches: [arXiv:1802.02156]
- Search using LHCb Run 1 (3 fb^{-1}) recently published in JHEP.
- Look for a di-muon resonance from 5.5 to 15 GeV/c^2 (also between Υ peaks):
  - Mass-interpolated efficiencies in bins of p_T, η (**model independent** results also given).
  - Production x-section (8 TeV) limits for a scalar (vector) boson on the left (right).
  - First scalar limits between 8.7 and 11.5 GeV/c^2 and competitive with CMS elsewhere.
- **No excess observed** ☹ for more details → ask me during the coffee break ☺





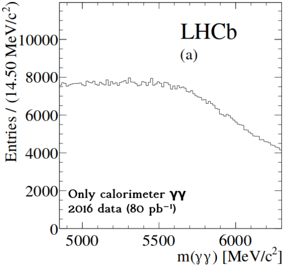
ALPs decaying into pairs of photons

- Constraints from LHC resonance searches above $m_a \sim 60$ GeV/c^2 ($a \to \gamma\gamma$, jj).
- **But** – poor limits for low masses → use $\gamma\gamma$ x-section measurements. **[PLB (2018) 06 039]**
- LHCb **could cover** the region between 3 and 10 GeV/c^2 (see **talk** by K. Tobioka).



Requirement (Transverse energies computed w/ 2x2 cell clusters)	Value
$E_T(\gamma)$ [GeV]	> 3.5
$E_T(\gamma_1) + E_T(\gamma_2)$ [GeV]	> 8
$M(\gamma_1\gamma_2)$ [GeV/c^2]	$[3.5, 6.0]$
$p_T(\gamma_1\gamma_2)$ [GeV/c]	> 2

- Trigger algorithm for **soft** $\gamma\gamma$ searches:
  1. Uses converted **and** calorimeter γ,
  2. Pre-filters candidates by E_T,
  3. Combines two candidates to form $\gamma\gamma$,
  4. Filters again by E_T, p_T and $\gamma\gamma$ mass.
- **Two** trigger selections so far: **[LHCb-PUB-2018-006]**
  - → Cut around $m(B_s^0)$ (since 2015).
  - → Mass range extended to 12 GeV/c^2 (only 2018).
- **Planned search** using 2018 LHCb data.



Conclusions

- LHCb proved to be **very competitive** for dark sector searches:
  - Excellent vertexing, tracking and soft trigger.
  - Especially competitive for low masses and lifetimes.
  - Rich variety of models and signatures can be approached.
- **Bright prospects** for the future:
  - Removal of hardware trigger $\rightarrow$ access softer kinematics.
  - Better vertex resolution and tracking capabilities.
  - New techniques under development for ideas on new signatures.
- Exploit **complementarity** with Belle 2 in the hunt of dark sectors:
  - Different machines $\rightarrow$ different limitations and capabilities.
  - **But** – different regions in dark sector parameter spaces can be covered.
- LHC LLP workshop at Nikhef (23rd-25th October 2018) $\rightarrow$ indico **here**.
- We are looking forward to ideas for new signatures and techniques:
  - **Do not hesitate to contact us if interested!**

Thanks for your attention!

Backup

Example of a vector portal

- Portal = communication between SM and HS via a spontaneously broken U(1) group.
- Several mechanisms depending on the nature of the gauge bosons are involved.

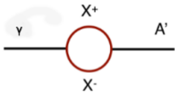
Example of a vector portal (dark photon):

- Consider a basic HS with a new gauge group U(1)' spontaneously broken:

$$-\frac{1}{4}X^{\mu\nu}X_{\mu\nu} + \frac{1}{2}m^2_{A'}A'_{\mu}A'^{\mu} \longrightarrow \boxed{-\frac{\epsilon}{2}F^{\mu\nu}X_{\mu\nu}}$$

- Get rid of the **kinetic mixing** term by diagonalising :
  - "Mass" basis → changes particles mass → A interacts with EM charged SM particles → **NO!**
  - "Interaction" basis → A' - γ oscillation due to small mass mixing → **OK! Interaction via loop:**

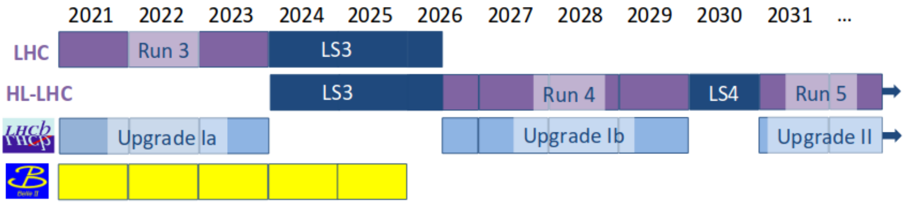
$$-\epsilon m^2_{A'}A_{\mu}A'^{\mu} \longrightarrow$$

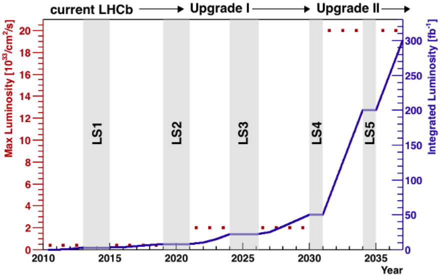


$\varepsilon \sim eg_D/16\pi^2 \sim O(10^{-3})$

The future of LHCb

Physics case for an LHCb Upgrade II: Opportunities in flavour physics, and beyond, in the HL-LHC era [CERN-LHCC-2018-027]



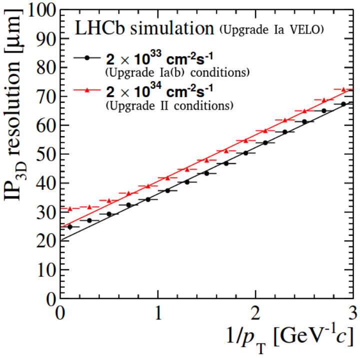


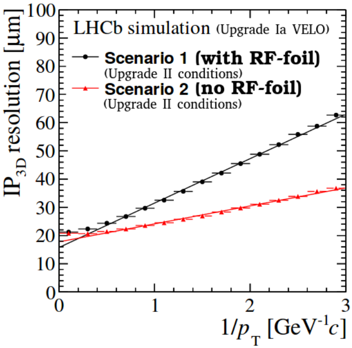
- **Challenging conditions** – higher rate, pile-up, occupancy and fluence.
- Expect to collect 300 fb^{-1} by the end of Upgrade II.
- Detector sub-systems have to be able to cope with such conditions.
- In particular – **trigger** and **tracking systems** are crucial for DS searches.

The upgraded LHCb VELO

- **Upgrade II VErtex LOcator:** **[CERN-LHCC-2017-003]**
  - Probably based on Upgrade Ia VELO (silicon pixels).
  - Access to shorter lifetimes, better PV and IP resolution, and real-time alignment.
  - But – 10x multiplicity, pile-up and radiation damage w.r.t. Upgrade Ia(b).
  - **Possibility of removing RF-foil** for Upgrade II:

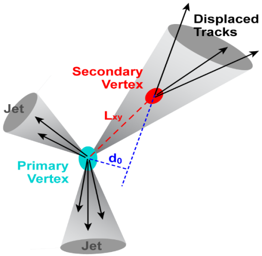
    $\rightarrow$ better IP resolution + no material interactions.

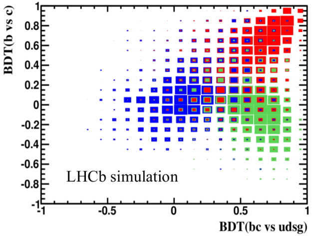




Jet reconstruction and identification at LHCb

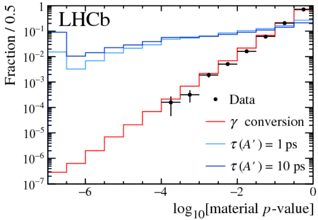
- Jet reconstruction: **[JHEP (2014) 01 033]**
  - Particle flow algorithm (including neutral recovery) $\rightarrow$ jet input.
  - Anti-k_T algorithm for clustering ($R = 0.5$) $\rightarrow$ efficiency $> 95\%$ for $p_T > 20$ GeV.
  - Jet energy scale calibrated on data (using $Z \rightarrow \mu\mu$ + jets),
  - Energy resolution from 10 to 15% for a p_T range between 10 and 100 GeV.
- Secondary Vertex (SV) identification and jet tagging: **[JINST 10 (2015) P06013]**
  - Reconstruct SV from displaced tracks $\rightarrow$ kinematic and quality requirements on both,
  - Train two Boosted Decision Trees (BDTs) for a two-step jet flavour tagging:
    - SV displacement from PV, kinematics, charge and multiplicity;
    - SV corrected mass, defined as $\mathrm{M_{corr}(SV)} = \sqrt{\mathrm{M}^2 + \mathrm{p}^2\sin^2\theta} + \mathrm{p}\sin\theta$.
  - BDT(bc|udsg) to separate light and heavy flavour jets, BDT(b|c) to separate b from c-jets.
  - Tagging efficiency of b(c)-jets of 65% (25%) with 0.3% contamination from light jets.



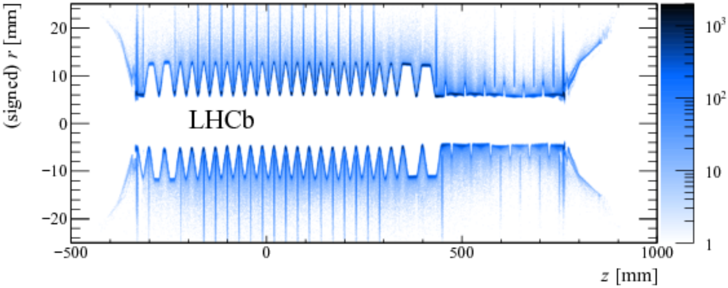


VELO material map **[JINST 13 (2018) P06008]**

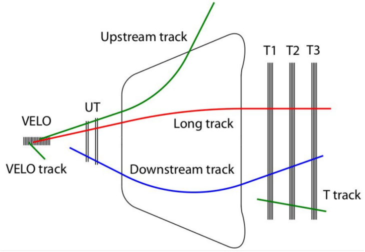
- Background dominated by material interactions for displaced searches at LHCb.
- Mandatory to **keep control** of material interactions – veto them in an efficient way:



- Background mainly due to γ conversions (left plot).
- A new VELO material map has been developed:
  - Model in **great detail** both sensors & envelope.
  - Assign a **p-value** to material interaction hypothesis.
  - Sensitivity improvement by $\mathcal{O}(10)$ to $\mathcal{O}(100)$.
  - Based on data from **beam-gas collisions** (plot below).



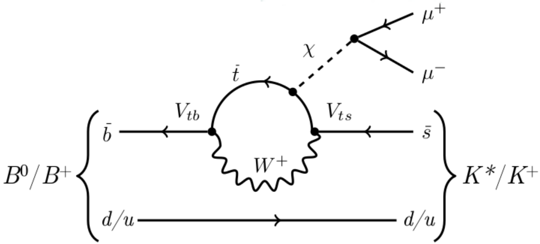
The LHCb reconstruction



- **Downstream tracks:**
  - Reconstruction of particles decaying beyond VELO.
  - Tracks with worse vertex and momentum resolution.
  - Trigger on downstream tracks $\rightarrow$ better for LLP ($\leqslant$ 2 m) signatures.
  - Optimisation studies on-going **[LHCb-PUB-2017-005]**
- **Upstream tracks:**
  - Reconstruction of soft charged particles bending out of the acceptance.
  - New tracker (UT) – high granularity, closer to beam pipe.
  - Proposal to add magnet stations (MS) inside the magnet $\rightarrow$ improve low p resolution.

Hidden-sector bosons in $B \to K^{(*)}\chi(\mu^+\mu^-)$

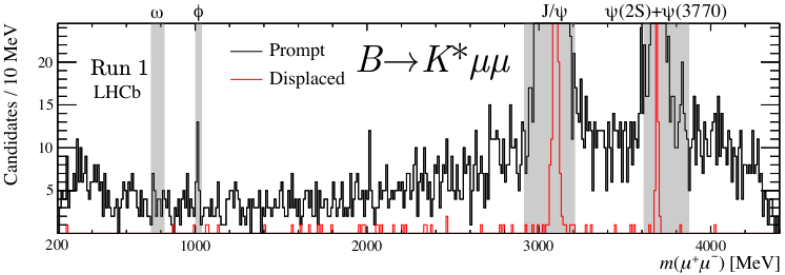
- $\mathrm{B}^0 \to K^{*0}\chi$ **[PRL 115 (2015) 161802]** / $\mathrm{B}^+ \to K^+\chi$ **[PRD 95 (2017) 071101 (R)]**
- Search for hidden-sector bosons $\chi \to \mu^+\mu^-$ in $b \to s$ penguin decays:
  - Axial-vector portal (χ as axion) **[LNP 741 (2008) 3]**
  - **Scalar** (Higgs) portal (χ as inflaton) **[JHEP 05 (2010) 10]**



- First dedicated search ($K^{*0}\chi$) over such a large mass range:
  - **Pro:** $K^{*0} \to K^+\pi^-$ vertex leads to better $\tau(\chi)$ resolution and less background.
  - **Con:** $\mathrm{B}^0 \to K^{*0}\chi$ has smaller branching fraction than the $\mathrm{B}^+ \to K^+\chi$ mode.
- Allow for prompt and **detached** di-muon candidates – up to 1000 ps ($\sim$ 30 cm).

Hidden-sector bosons in $B \to K^{(*)}\chi(\mu^+\mu^-)$

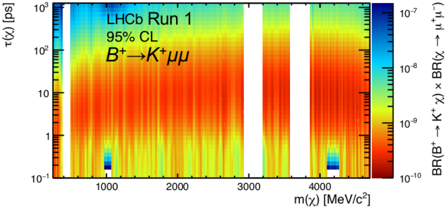
- Full LHCb Run I dataset (3 fb^{-1}) used for both searches.
- Look for a narrow di-muon peak (mass resolution between 2 and 9 MeV/c^2).
- Exclude narrow QCD resonances - mass distribution: **[PRL 115 (2015) 161802]**

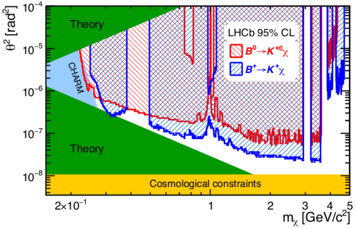


- MVA selection almost independent of χ mass and decay time (uBoost).

Hidden-sector bosons in $B \to K^{(*)}\chi(\mu^+\mu^-)$

- BR normalised to $\mathcal{B}(B^+ \to K^+ J/\psi)$ ($\sim 10^{-4}$) or $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$ ($\sim 10^{-7}$).
- Constraints on $\tau(\chi)$ between 0.1 and 1000 ps (left), **[PRD 95 (2017) 071101 (R)]**
- Constraints on mixing angle θ^2 between the Higgs and χ in the inflaton model (right):

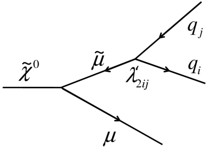


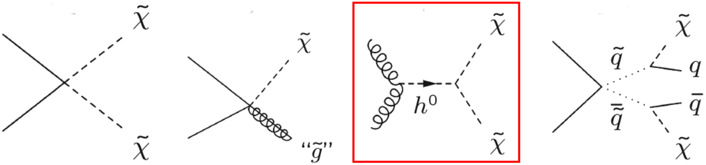


- **No evidence for signal observed.**
- **Large fraction of allowed inflaton parameter space ruled out.**

Massive LLPs decaying to μ + jets [EPJC (2017) 77:224]

- **Massive LLP into μ + two quarks ($\rightarrow$ jets).**
- Signature sensitive to **several benchmark models:**
  - mSUGRA RPV neutralino,
  - Right-handed (Majorana) neutrinos,
  - Simplified MSSM production topologies:

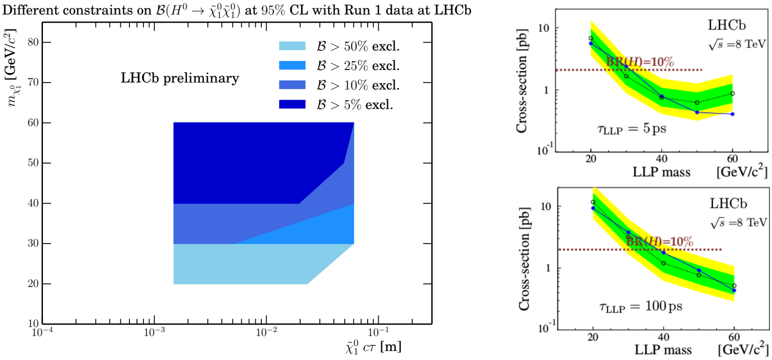




- One particular example: **decay of a Higgs-like particle** into two LLPs.
- Look for a **single displaced vertex** with several tracks + high p_T muon.
- Background dominated by $b\bar{b}$ events and material interactions.

Massive LLPs decaying to μ + jets **[EPJC (2017) 77:224]**

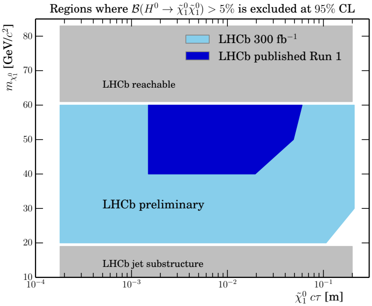
- Search with full Run I (3 fb^{-1}) LHCb data published last year.
- Results interpreted in $H^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ benchmark model:

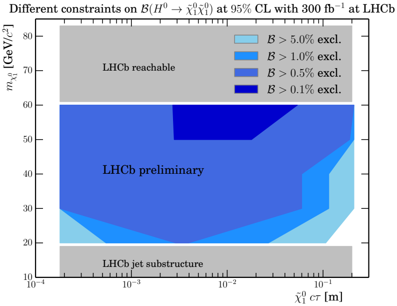


- Stringent limits – rejecting $\mathcal{B}(H^0 \to \chi\chi)$ >10% down to 30 GeV/c^2 (5 ps).
- **No excess observed.**

Massive LLPs decaying to μ + jets [EPJC (2017) 77:224]

- Prospects for Phase-II → some **naive extrapolations** below:
  - Scale signal and background – consider increase of cross-sections,
  - Conservative assumptions for jet reco, trigger, and material interactions,
  - Optimistic assumptions for pile-up effect.

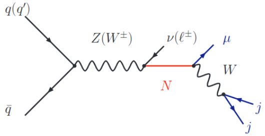




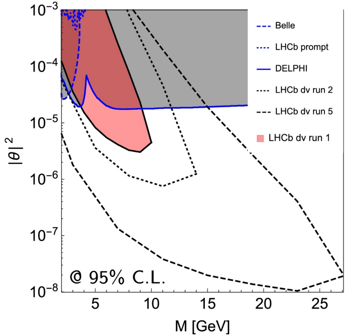
- Our main aim is to reach **lower masses** and **lower lifetimes.**
- **Removal of L0 trigger (Phase-I)** → much higher trigger efficiencies at the end!
- Jet reconstruction efficiencies **will be better for lower masses.**
- Expected a **better knowledge of material interactions** (x3 less for UIa VELO).

Massive LLPs decaying to μ + jets (recast)

- Limits recasted to look into sterile neutrinos **[PLB (2017) 774 114-118]**

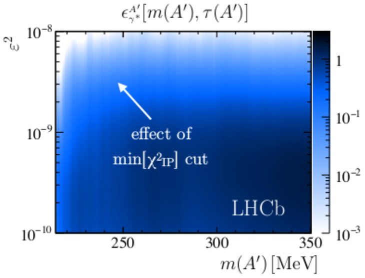


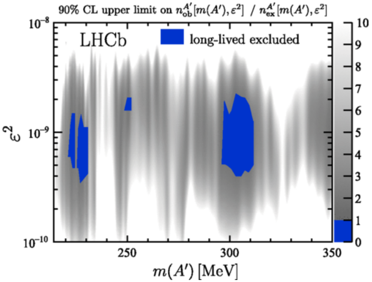
- Could we get best world-limit (5–10 GeV/c^2) with same kind of search?
- Dedicated search with Run II data **in preparation.**



Dark Photons – displaced search **[PRL (2018) 120 061801]**

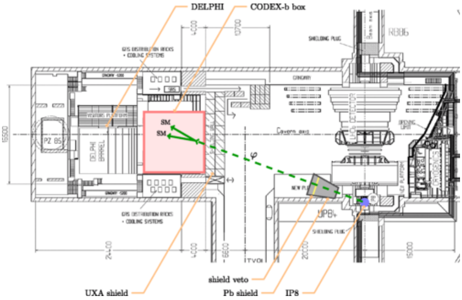
- Looser requirements on muon tranverse momentum.
- Material background mainly from photon conversions **[JINST 13 (2018) P06008]**
- Isolation decision tree from $B_s^0 \to \mu^+\mu^-$ search: **[PRL (2018) 118 191801]**
  $\to$ Supress events with additional number of tracks, i.e. μ from b-hadron decays.
- Fit in bins of mass and lifetime – use consistency of decay topology χ^2.
- Extract p-values and confidence intervals from the fit:

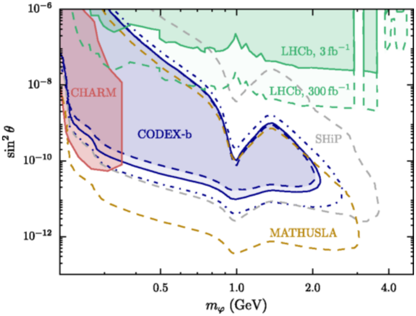




Extended reach for LLPs (CODEX-b + LHCb)

- 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]**





Complementarity with ATLAS and CMS

- 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: