Search for low-mass axion-like particles in LHCb

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on behalf of the LHCb Collaboration
Portals to the dark sector

Dark-portal paradigm: New Physics **below the EW scale** with dark-sector particles are neutral wrt the SM and only couple indirectly to ordinary matter.

Gauge and Lorentz symmetries of the SM restrict how dark-sector mediators can couple to ordinary matter: **4 portals → 4 new particles:**

- **Vector portal** $(A')$: $-\frac{e}{2\theta_W} F'_\mu B^{\mu\nu}$
- **Axion portal** $(a)$: $\frac{a}{f_a} F^\mu_\nu \tilde{F}^{\mu\nu}$
- **Scalar portal** $(H)$: $(\mu S + \lambda S^2) H^\dagger H$
- **Neutrino portal** $(N)$: $y_N LHN$

[Snowmass'21, arXiv:2209.04671]
Portals to the dark sector

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- **Vector portal** \((A')\): \(-\frac{e}{2\theta_W}F'_\mu B^{\mu\nu}\)

- **Axion portal** \((a)\): \(\frac{a}{f_a}F^{\mu\nu}\bar{F}^{\mu\nu}\)

- **Scalar portal** \((H)\): \((\mu S + \lambda S^2)H^\dagger H\)

- **Neutrino portal** \((N)\): \(y_N L H N\)

Louis Henry’s talk on Friday morning

[Snowmass’21, arXiv:2209.04671]
LHCb: flavour and dark physics

Capacity for sensitivity to dark portals:

- Excellent vertex resolution [IP resolution $\mathcal{O}(10 \mu m)$]
- $\mathcal{O}(1\%)$ momentum resolution
- Capacity for soft triggers (e.g. trigger on $p_T \sim 1$ GeV on detached $\mu\mu$)

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LHCb: flavour and dark physics

Advantages wrt ATLAS/CMS:

- Soft trigger selections $\rightarrow$ lighter masses
- Forward boost and $\sigma(\tau) \sim 50$ fs $\rightarrow$ low lifetimes (prompt vs displaced signatures)

Produced in heavy-flavour decays

Produced in $pp$ collisions

Sketch adapted from F. Redi, LHCP '21
not to scale
The upgraded LHCb detector for Run 3

- Removal of L0 hardware trigger
- Triggerless readout: GPU @ HLT1, CPU @ HLT2
- Application of Lipschitz NNs to enhance electron PID @ HLT1 and inclusive triggers @ HLT2

See talks by Kate and Michele on Friday
Dark Photons at LHCb

- Inclusive search of $A' \rightarrow \mu^+\mu^-$ with Run 2 ($\mathcal{L} = 5.5 \text{ fb}^{-1}$)
- $A'$ production & decay kinematics: anywhere a $\gamma^*$ with $A'$ mass: $\alpha = \varepsilon^2 \alpha_{EM}$
- Normalise to off-shell photon $\rightarrow$ just need to discriminate against non-$\gamma^*$ background

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

Candidates / $[m(\mu^+\mu^-)]$ / 2

LHCb
$\sqrt{s} = 13 \text{ TeV}$

prompt-like sample
$p_T(\mu) > 1 \text{ GeV}, p(\mu) > 20 \text{ GeV}$

- prompt $\mu^+\mu^-$
- $\mu_1\mu_2$
- $h_1h_2 + h_1\mu_2$
Dark Photons at LHCb

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Dark photon sensitivity [Runs 3, 6]

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FIG. 1: Adapted from Ref. [14]: constraints on visible $A_{0}$ decays from (blue regions) LHCb [2] and (gray regions) all other experiments. The solid blue line is the union of Run 3 projections for LHCb from Refs. [9, 10], updated to include inclusive $A_{0} \to e^{+}e^{-}$ projections enabled by recent advances in the LHCb trigger. The dashed blue line projects further into the future to the end of Run 6.

- Reference [15] applied a constant scale factor to predict the future sensitivity based on the Run 1 results; however, this fails to account for the strong lifetime dependence of the LHCb limits. For example, at higher masses the Run 1 data sample only explored prompt decays which are contaminated by SM penguin and charmonium decays. With much greater luminosity, LHCb explores the long-lived region which is background free, improving the sensitivity.

- The published LHCb limits are based on older models for the coupling to hadrons. We update the existing limits to use the hadronic couplings in Ref. [16], which is the commonly used model employed by recent long-lived-particle experimental proposals. (This update also requires carefully considering the strong lifetime-dependence of the LHCb constraints.)

- Finally, we include new projections based on including the hadronic decays $B \to K(\pi(\pi))K(\pi(\pi))$ and $B \to K(\pi(\pi))K(\pi(\pi))$. We show that including these final states can improve the sensitivity in the $0.5 \rightarrow 1.5 \text{ GeV}$ region.

Figure 2 shows both our updated constraints using the published Run 1 results and our new projections. The Run 1 dimuon searches were background free in the displaced case, and we assume here that this continues to be true throughout the lifetime of LHCb data taking.

Updating the hadronic couplings to those of Ref. [16] weakens the existing constraints, largely due to the decreased $\mu^{+}\mu^{-}$ branching fraction. Figure 2 clearly shows that one cannot use a constant scale factor to predict future sensitivities. The LHCb dimuon search sensitivity improves more at higher masses. As stated above, going to Run 3 this is largely because the Run 1 data only probed prompt decays, whereas Run 3 will explore the nearly background-free long-lived decays even at higher masses.

For hadronic decays, we only consider the long-lived scenario, as larger couplings are ruled out by the dimuon data alone. To estimate the background, we consider the related hadronic final state $B^{\pm} \to K(\pi(\pi))\pi^{\pm}\pi^{\pm}$ studied by LHCb in Run 1 [17], which is dominated by random combinations of hadrons produced in heavy-flavor decays.

The motivation here is that we expect the background for long-lived bosons to largely arise due to combinations of hadrons produced in heavy-flavor decays that randomly satisfy the topological and kinematic constraints, which is also likely the case in our chosen background proxy. This assumption is expected to hold within an order of magnitude, which only affects the limits by up to a factor of two.

Craik, Ilten, Johnson, Williams [arXiv:2203.07048v1]
Dark photon sensitivity [Runs 3, 6]

LHCb Run 3: $\sigma(100)$ increase in $A' \rightarrow \mu^+\mu^-$ in the low-mass region [can collect the total Run 2 luminosity in $\sim 2$ months of data taking in Run 3]
Dark photon sensitivity [Runs 3, 6]

Sensitivity below the $\mu\mu$ threshold achieved by inclusive $A' \rightarrow ee$ search unlocked by electron ID in the first stage of the fully software trigger
ALP searches at LHCb

- Exploit $B \to K^{(*)} a$ decays to search for the MeV-to-GeV $m_a$ range, assuming ALP-gluon coupling dominant [PRL 123, 031803]

- Experimental target: $a \to \pi\pi\{\pi^0, \gamma, \eta\}$

- Currently being scrutinised with Run 2 data
ALP searches at LHCb

- Ongoing Run 2 analysis to probe ALPs produced by gluon fusion decaying to $\gamma\gamma$

- Current best limits in mass gap below the ATLAS/CMS sensitivity with 80 pb$^{-1}$ of LHCb 2016 data @ 13 TeV [LHCb-PUB-2018-006]

- Result expected public late ‘24
LHCb is a *general purpose* dark-sector experiment

LHCb Run 3: significant increase in discovery potential:
- $5 \times$ increase in $pp$ collision rate
- fully software trigger

$\Rightarrow$ *close the gap* in $[\varepsilon^2, m_{A^{'}}]$ to the beam-dump exclusion limits
$\Rightarrow$ achieve sensitivity in the $[1,3]$ GeV $m_{a}$-range
$\Rightarrow$ substantial increase in sensitivity to GeV-scale Higgs-portal scalars, especially for long-lived displaced candidates at high mass
Appendix
Dark scalars at LHCb

- Dark scalar coupling to the Higgs via mixing angle, $\theta$
- Exploit $B \rightarrow K^{(*)}\chi$ penguin decays to capitalise on enhancement due to $t$ mass in the loop

Most stringent constraints to in $250 < m(\chi) < 4700$ MeV and $0.1 < \tau(\chi) < 1000$ ps
Using LHCb Run 1 analyses of $B \rightarrow K^{(*)}\chi(\rightarrow \mu^+\mu^-)$

Craik, Ilten, Johnson, Williams [arXiv:2203.07048v1]
Dark Photons at LHCb

Prompt search results

LHCb (2016 data)
BaBar+KLOE+CMS

Displaced search results

90% CL upper limit on $n_{ob}^{A'}(m(A'),\varepsilon^2) / n_{ex}^{A'}(m(A'),\varepsilon^2)$
Dark Photons at LHCb

- **Event selection:**
  - Hardware trigger stage:
    - $p_T(\mu) > 1.8 \text{ GeV} \parallel p_T(\mu_1)p_T(\mu_2) > 1.5 \text{ (GeV)}^2$
  - Software trigger stage:
    - MuonID criteria
    - Good quality vertex
  - Offline:
    - Dimuon isolation strategy

- **Prompt search misRECO backgrounds:**
  - Double mis ID ($hh$): $\mu$ as prompt hadron, most likely a pion
  - misID ($h$)+ misRECO ($\mu_Q$): $\mu$ from $b(c)$-hadron decay and reconstructed as prompt
  - Double misRECO ($\mu_Q\mu_Q$)

- **Displaced search backgrounds:**
  - Photon conversions to $\mu\mu$ in the VELO (matter veto strategy in the back-up)
  - $b$-hadron decays with two muons produced in the decay chain
  - Low mass tail from $K_s^0 \rightarrow \pi\pi$ where both pions misidentified as muons

- **Long-lived (prompt) search:**
  - $p_T(\mu) > 0.5 \text{ (1.0) GeV}$
  - $p(\mu) > 10 \text{ (20) GeV}$
  - Inconsistency (consistency) with origin at the PV
Prompt dark photons at LHCb

Blaise Delaney (MIT) on behalf of LHCb

PRL 120 (2018) 6, 061801

(prompt $\mu^+\mu^-$ from data at $m(J/\psi)$ and $m(Z)$)

(muQ$\mu_Q$ from simulation (validated))

(hh + h$\mu_Q$ from same-sign $\mu^+\mu^-$ corrected)

$m(A') = 0.5 \text{ GeV}$

$m(A') = 5 \text{ GeV}$

$m(A') = 50 \text{ GeV}$

Candidates / 0.4

Pull

Candidates / 0.4

Pull

Candidates / 0.4

Pull

$m(\mu^+\mu^-)$ from data at $m(J/\psi)$ and $m(Z)$

from simulation (validated)

from same-sign $\mu^+\mu^-$ corrected

prompt-like sample

$\sqrt{s} = 13 \text{ TeV}$

$\mu^+\mu^-$ [MeV]

$\sigma(m(\mu^+\mu^-)) / 2$

$\mu^+\mu^- / \sigma(\mu^+\mu^-)$

$\mu^+\mu^-$ isolation applied

$\mu_T > 1 \text{ GeV}, \mu > 20 \text{ GeV}$

LHCb

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Displaced dark photons at LHCb

- Only region $m(A') < 350$ MeV is sensitive
- Comparatively looser $p_T(\mu)$ requirements
- Main background from $\gamma$ conversion in the VERTex LOcator

Expected long-lived $A' \rightarrow \mu\mu$ yield

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Displaced dark photons at LHCb

PRL 120 (2018) 6, 061801

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![Graph showing the relationship between $t$ [ps] and $m(\mu^+\mu^-)$ [MeV] with LHCb data. The graph includes a color scale for $\chi^2_{DF}$.]

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Beam-gas collisions can be distinguished from hadrons produced in heavy-flavor decays
→ map the whole VERtex LOcator geometry

Can assign \( p \)-value to material interaction hypothesis

Effective veto of \( \gamma \) conversions to \( \mu \mu \) in the material
→ veto main background displaced \( A' \) searches at low mass

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The LHCb Trigger

**LHCb 2015 Trigger Diagram**

- **40 MHz bunch crossing rate**
- **L0 Hardware Trigger**: 1 MHz readout, high $E_{T}/P_{T}$ signatures
  - 450 kHz $h^{\pm}$
  - 400 kHz $\mu/\mu\mu$
  - 150 kHz $e/\gamma$

**Software High Level Trigger**
- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers
- **12.5 kHz (0.6 GB/s) to storage**

**LHCb Upgrade Trigger Diagram**

- **30 MHz inelastic event rate (full rate event building)**
- **Software High Level Trigger**
  - Full event reconstruction, inclusive and exclusive kinematic/geometric selections
  - Buffer events to disk, perform online detector calibration and alignment
  - Add offline precision particle identification and track quality information to selections
  - Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers
- **2-5 GB/s to storage**

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