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Search for Dark Sector particles at LHCb

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Overview

The Dark Sector

The Dark Sector is a collection of hypothetical particles that feebly interact with Standard Model (SM) particles through new forces

What is the purpose of looking for the Dark Sector?

- The Dark Sector may include the cosmological Dark Matter
- The Dark Sector particles can address some problems of the Standard Model, such as the baryogenesis and the strong CP problem
- The Dark Sector can explain some experimental anomalies as $(g-2)_\mu$

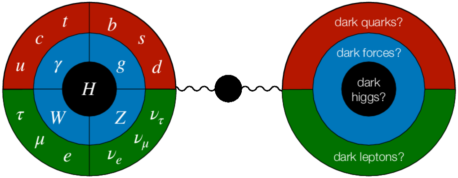
Image adapted from Symmetry

Minimal Dark Sector Portals

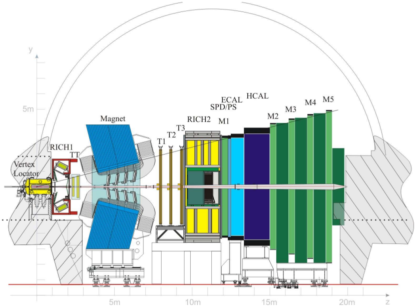
Minimal Dark Sector Portals are minimal extensions of the SM, featuring a single new mediator that feebly interacts with SM particles.

Due to the characteristics of the SM, four minimal portals are possible:

- Vector Portal - Dark Photon
- Higgs Portal - Dark Scalar
- Neutrino Portal - Heavy Neutral Lepton
- Axion-like Portal - Axion-like particles coupling to SM



The LHCb detector



Alves et al. [JINST3(2008)S08005]

LHCb is a single-arm forward spectrometer suited for Dark Sector searches

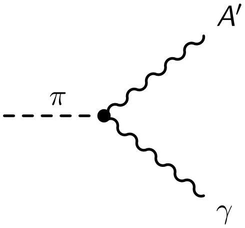
- Excellent vertex resolution ($(15+29/p_T[\text{GeV}])\mu$m)
- Very flexible trigger (fully software trigger after the upgrade)
- Good momentum resolution ($\Delta p/p$ from 0.5% to 1.0%)

Dark Sector particles at LHCb

LHCb can detect Dark Sector particles originating from different sources:

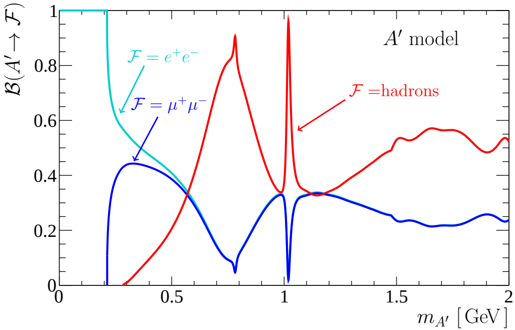
- Dark Sector New Physics ⟶ Strongly interacting massive particles; Flavour-violating axions
- In *pp* collisions, Dark Sector particles are produced via:
  - → Dark matter mix with mesons
  - → Drell-Yan ($q\bar{q}$ annihilation)
  - → Meson Decays ⟶ { DM prompt decays; DM displaced decays }

The Dark Photon



Pion decaying to a dark photon A' and a photon

Introduction to the Dark Photon



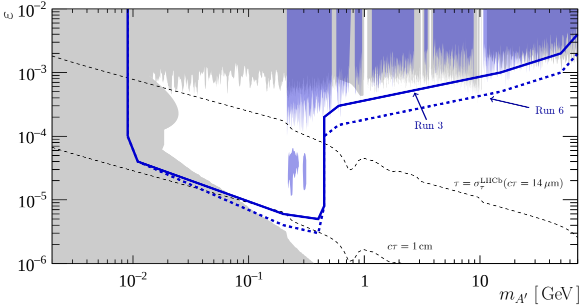
Ilten, Soreq, Williams, and Xue [JHEP06(2018)004]

- A' is a hypothetical massive spin-1 particle that can interact with EM current

$$\mathcal{L}_{\gamma A'} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu} + \epsilon e A'_{\mu}J^{\mu}_{EM}$$

- Searches for A' set constraints on $\epsilon - m_{A'}$ region $\left(\tau_{A'} \propto \frac{1}{\epsilon^2 m_{A'}}\right)$

Present and future of the Search for the Dark Photon

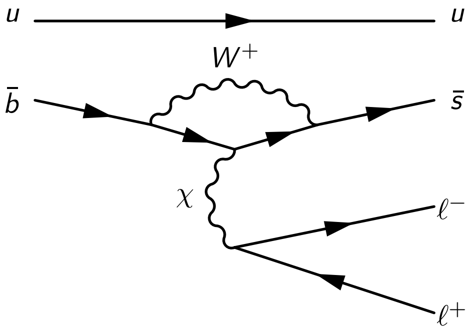


Craik, Ilten, Johnson, and Williams [arXiv:2203.07048 (2022)]

- LHCb has excellent sensitivity to dark photons
- Searches for long-lived and prompt $A' \to \mu^+\mu^-$ have been performed
  - $\to$ Competitive constraints on prompt-like dark photons
  - $\to$ World-leading constraints on low-mass dark photons with $\tau_{A'} \sim 1\,\text{ps}$
- Inclusive searches for $A' \to e^+e^-$ allowed in Run3

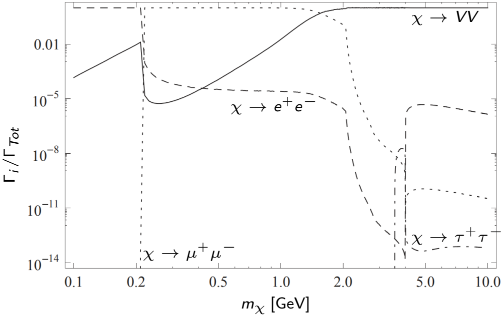
University of Zurich[UZH]

The Dark Scalar



Hypothetical B^+ meson decay chain:
$B^+ \rightarrow K^+ \chi (\rightarrow \ell^+ \ell^-)$

Introduction to the Dark Scalar



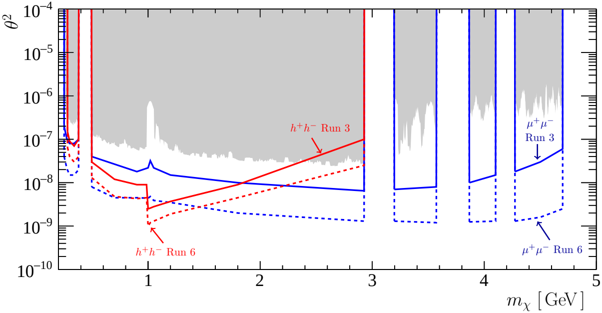
Batell, Pospelov, and Ritz [Phys. Rev. D79(2009)115008]

- The Higgs portal couples the SM Higgs to a gauge singlet scalar χ
- The dark scalar χ can mix with the SM Higgs boson with a mixing angle θ_χ

$$\mathcal{L}_\chi \supset \left(\mu\chi + \lambda\chi^2\right) H^\dagger H$$

- χ may be produced through flavour-changing meson decays ($B \to K\chi$)
  $\to$ LHCb can search for $\chi \to \mu^+\mu^-$

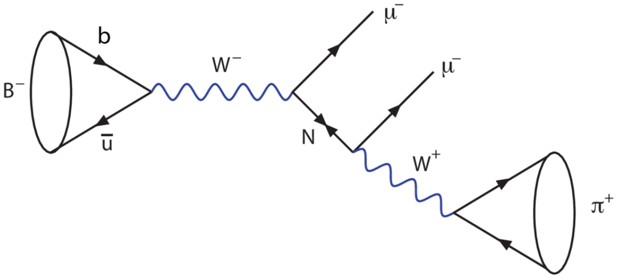
Present and future of the Search for the Dark Scalar



Craik, Ilten, Johnson, and Williams [arXiv:2203.07048 (2022)]

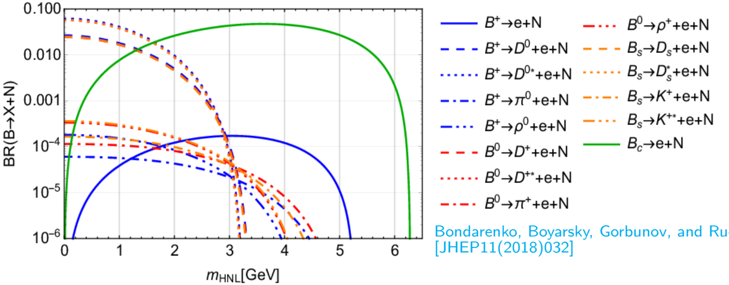
- Search for long-lived scalar particle in $B^+ \to K^+\chi(\mu^+\mu^-)$
  - $\to$ World-leading constraints on Higgs-portal scalar for $m_S < 2m_\tau$
- Huge improvements expected for Run 3:
  - $\to$ searching for long-lived χ and explore new parameter space $(\tau_S \propto \theta_S^2)$
  - $\to$ including $B^+ \to K^+\chi(\pi^+\pi^-)$ and $B^+ \to K^+\chi(K^+K^-)$

The Heavy Neutral Lepton



B^- decay chain including a hypothetical heavy neutral lepton

Introduction to the Heavy Neutral Lepton



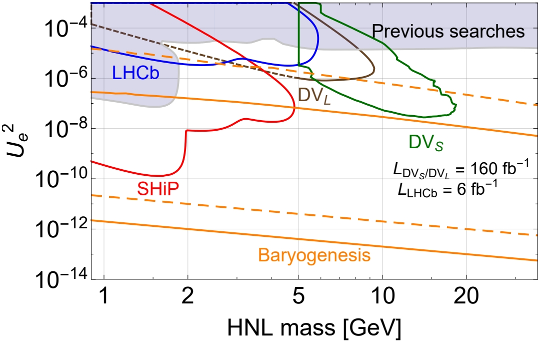
Bondarenko, Boyarsky, Gorbunov, and Ruchayskiy [JHEP11(2018)032]

- The neutrino portal refers to the coupling of the gauge singlet N to the SM
- The N couples with LH operator formed of the lepton and the Higgs

$$\mathcal{L}_N \supset -y^{\alpha} L_{\alpha} H N + \text{h.c.}$$

- The phenomenology of N is related to m_N and the mixing angles $|U_\ell|^2$
  - → HNL can be produced in beauty mesons weak decays
  - → HNL can be detected through its semi-leptonic weak decays

Present and future of the Search for the HNL

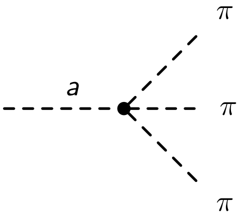


Boiarska, Bondarenko, Boyarsky, et al. [arXiv:1902.04535 (2019)]

DV_S: ATLAS
DV_L: CMS

- LHCb searched for HNL in $B^- \to N(\pi^+\mu^-)\mu^-$
  - → New results using 2016-2018 data are coming out soon!
- Plan to search for HNL in inclusive B and B_c decays
  - → Improve the detection efficiency of particles down to $p_T \sim 0.5\,\text{GeV}$
  - → Exploit the removal of the hardware trigger

Axion-like Particles



A hypothetical decay mode for an axion-like particle: $a \to \pi\pi\pi$

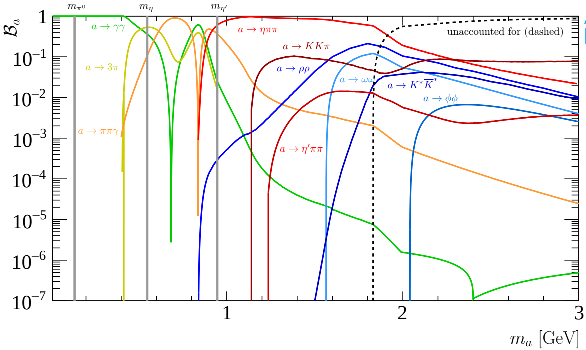
Introduction to the axion-like particles

- Axions are pseudoscalar particles postulated by the Peccei-Quinn mechanism to solve the *strong CP problem*
- Axion-like particles (ALPs) are hypothetical particles, similar to axions, arising from spontaneously broken global symmetries
- ALPs are pseudo-Nambu-Goldstone bosons whose couplings to the Standard Model gauge bosons are highly suppressed
- ALPs can couple (not exclusively) to photons and gluons:

$$\mathcal{L} \supset c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu} + c_{GG}\frac{\alpha_S}{4\pi}\frac{a}{f}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

- ALPs interactions are strongly model-dependent
  $\rightarrow$ LHCb can look for both gluon-coupled and photon-coupled ALPs

The ALPs coupling to gluons

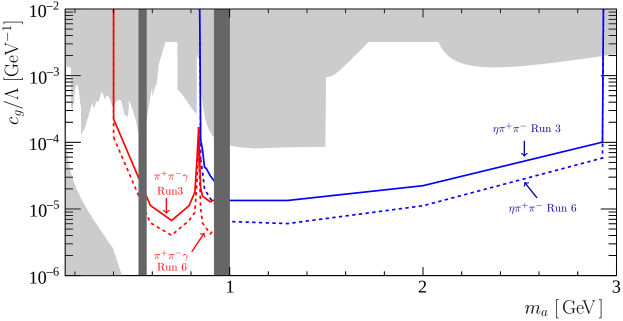


Aloni, Soreq, and Williams [arXiv:1811.03474 (2019)]

Consider a scenario where the ALP-gluon coupling is dominant ($c_{GG} >> c_{\gamma\gamma}$)

- $a \to 3\pi$ and $a \to \pi\pi\gamma$ are dominant in the $0.55 \lesssim m_a \lesssim 0.95$GeV region
  - $\to$ Search for $B^0 \to a\,(\to 3\pi)\,K\pi$ and $B^0 \to a\,(\to \pi\pi\gamma)\,K\pi$
- $a \to \eta\pi\pi$ is dominant in the $0.95 \lesssim m_a \lesssim 1.85$GeV region
  - $\to$ Search for $B^0 \to a\,(\to \eta\pi\pi)\,K\pi$

Present and future of the Search for the ALPs-gluon



Craik, Ilten, Johnson, and Williams [arXiv:2203.07048 (2022)]

- Searches ongoing for ALPs coupling to gluons using Run2 data
- Expected improvements for Run3:
  - → Exploit the removal of the hardware trigger
  - → Explore long-lived ALPs below 1 GeV

Conclusions

- The LHCb experiment can leverage the advantages of both the energy and intensity frontiers to look for Dark Sector particles
- A broad program of searches is planned for the future:
  - $\rightarrow$ Dark photon to dielectron
  - $\rightarrow$ Long-lived dark scalar to pions and kaons
  - $\rightarrow$ Massive neutrinos in beauty meson decays
  - $\rightarrow$ ALPs coupling to the gluons
- For Run3, the LHCb detectors have been upgraded, and with the new software trigger, exciting results are expected in the coming years!

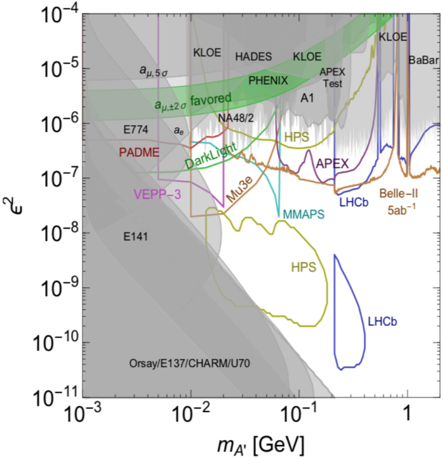
Acknowledgements

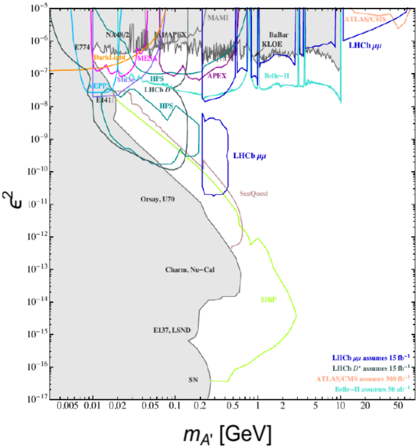
Thanks for your attention!

Backup

Backup Slides

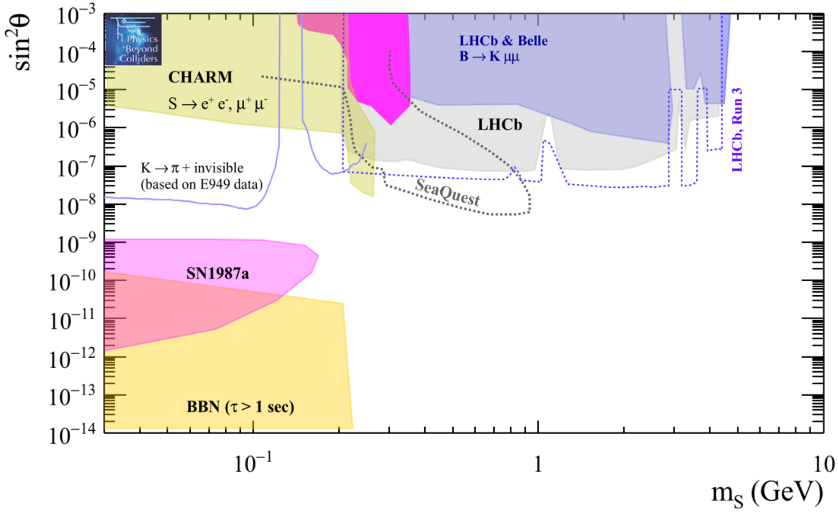
Current status of the search for the dark photon





Filippi and De Napoli
[arXiv:2006.04640 (2020)]

Current status of the search for the dark scalar



Filippi and De Napoli
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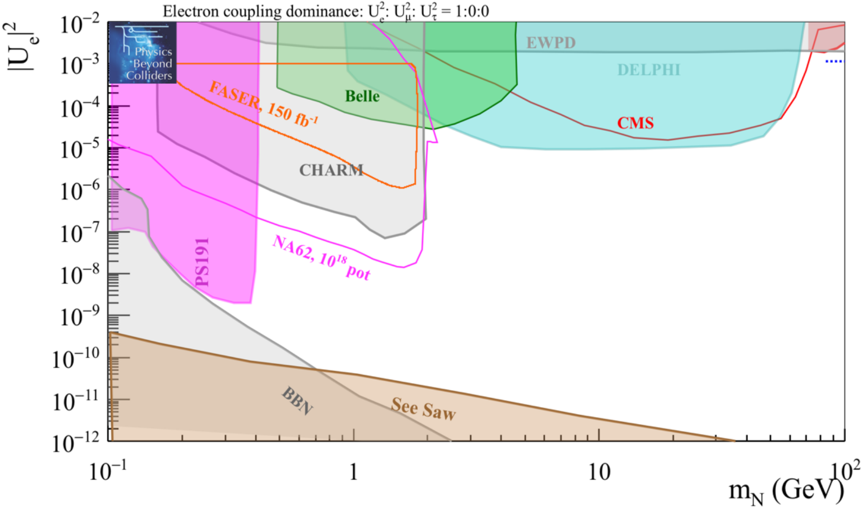
Current status of the search for the HNL



Filippi and De Napoli
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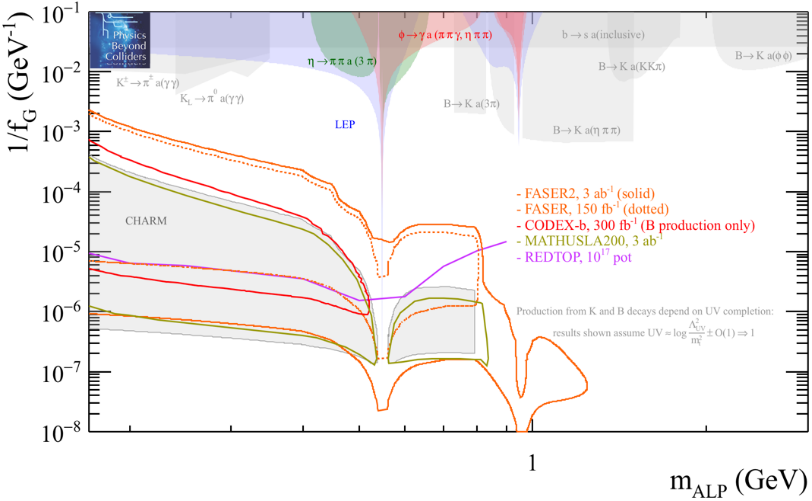
Current status of the search for ALPs



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References II

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