Dark Matter searches at LHCb

Felicia Volle
for the LHCb Collaboration

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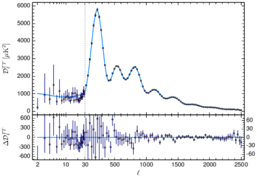
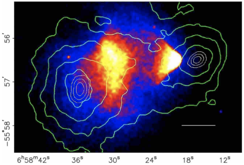
UNIVERSITY OF BIRMINGHAM

What do we know so far about Dark Matter?

Planck 2018



Bullet Cluster



- Dark Matter (DM) composes around 84% of matter content in our universe.

  Planck, A&A 641 (2020) A6

- Cosmologically stable.

  PRD 95 (2017) 2, 023010

- Neutral or only weakly charged under Standard Model forces.

  Otherwise would have been already detected.

- No or small self-interaction.

  "Bullet Cluster", AJ 648 (2006) L109-L113

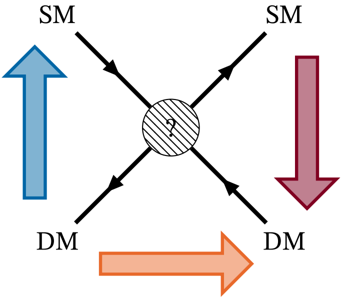
- Gravitationnally interacting; Thermal DM mass $\gtrsim 3$ keV.

  PRD 88 (2013) 043502

How to look for it?

Indirect detection

Credit: H.E.S.S. Collaboration



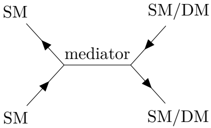
Direct detection

Credit: XENON Collaboration

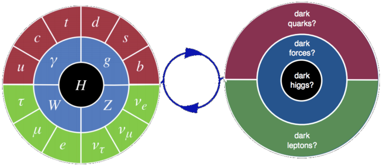
Collider searches

Credit: CERN

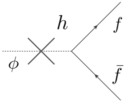
1. DM production
   (invisible final state)
2. Mediator resonances
   (peak search)



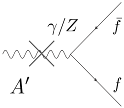
Portals between the visible and dark sectors



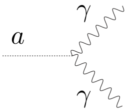
Examples:



Scalar portal (Φ)



Vector portal (A')



Axion portal (a)

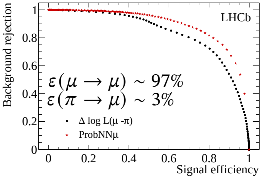
Neutrino portal (N)

Typically:

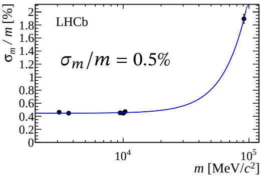
- Very weak couplings to SM particles.
- Long-lived, i.e. decay vertices displaced from primary interaction.

What do we need to detect such signatures?

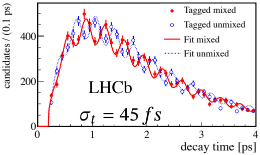
1. Particle identification



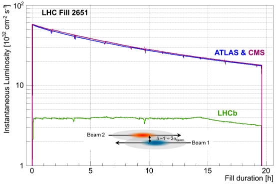
2. Mass resolution



3. Decay time resolution

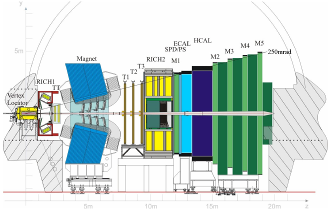


4. Balance between large luminosity and soft trigger thresholds, especially important for low-mass searches



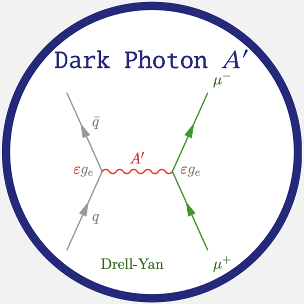
⟹

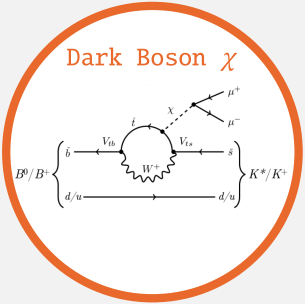
LHCb is excellent for low mass searches in pp collisions.

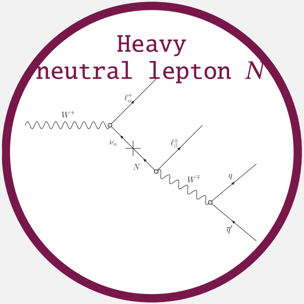


Int.J.Mod.Phys. A30(2015)1530022

Dark sector searches at LHCb





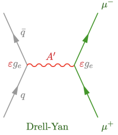


Non-exhaustive selection of results and future prospects!

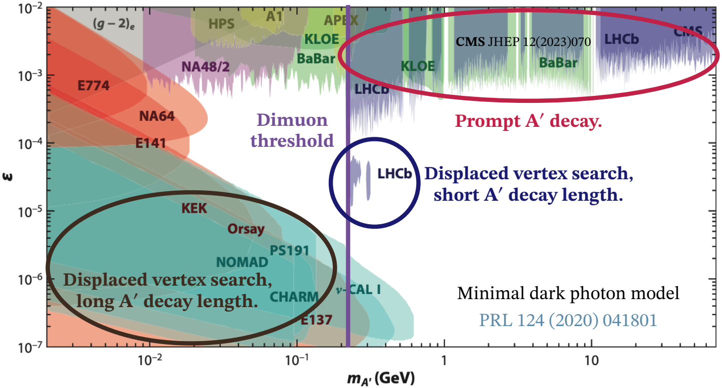
Dark Photon search

Kinematic mixing between dark and SM hypercharge fields:

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{{m_{A'}}^2}{2}A'_\mu A'^\mu + g_e J^\mu A_\mu + \varepsilon g_e J^\mu A'_\mu$$



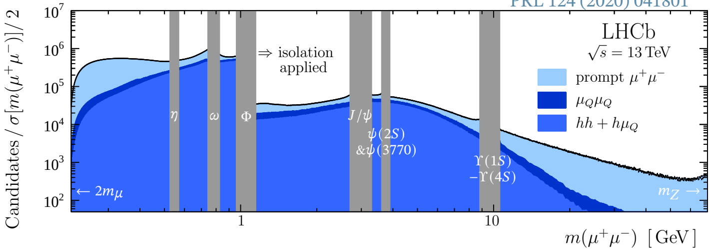
DP mass, $m_{A'}$, and kinetic-mixing strength, ε, are free parameters.



Prompt $A' \to \mu^+\mu^-$ search

- Prompt (displaced) means (in)consistency of A' production and decay vertex.
- Analysis exploits 5.5 fb^{-1} of Run 2 dataset.
- Normalisation to $\gamma^* \to \mu^+\mu^-$ yield cancels most experimental systematics.
- Templates from data (prompt $\mu\mu$, $hh + h\mu_Q$) and simulation ($\mu_Q\mu_Q$).
  - $\mu_Q = \mu$ from b/c-hadron decays
  - h = misidentified hadrons (mainly π's)
- Prominent resonance-peak regions are vetoed, and only tail modeled.

PRL 124 (2020) 041801



No significant excess found - exclusion regions at 90% C.L.
First limits on masses above 10 GeV & competitive limits below 0.5 GeV.

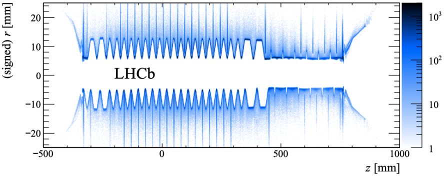
Displaced $A' \to \mu^+\mu^-$ search

- Search in $m_{A'} \in [214, 350]$ MeV/c^2.
- Even looser $p_T(\mu)$ requirement.
- Main background from photon conversions in VELO material.
- Material map to suppress decay vertices originating from material.
- Fit in bins of mass and lifetime.

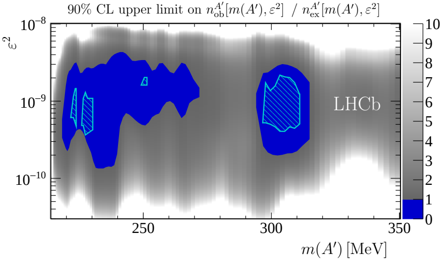
No significant excess found.
Small parameter space region excluded.

First limit ever not from beam dump in a displaced region.

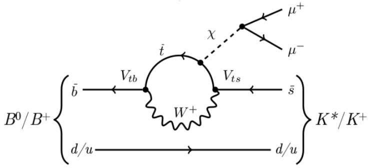
JINST 13 (2018) P06008



PRL 124 (2020) 041801

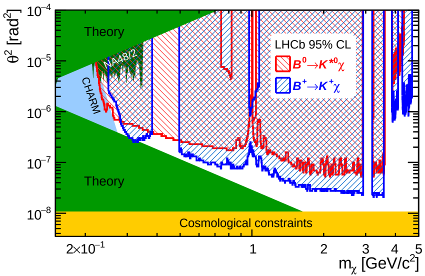


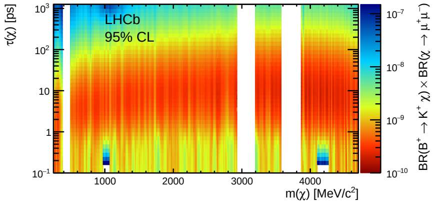
Dark boson searches in $B \to K^{(*)}\mu^+\mu^-$ decays



PRD 95 (2017) 071101, PRL 115 (2015) 161802

- Both analyses exploit full Run 1 dataset.
- Search for prompt and detached $\chi \to \mu\mu$ decays.
- $\mathcal{B}$ normalised to $\mathcal{B}(B^+ \to K^+ J/\psi)$ or $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$.
- In inflation model, mixing angle $\theta^2 \propto \mathcal{B}(B^+ \to K^+\chi)$ and $\tau_\chi \propto 1/\theta^2$.

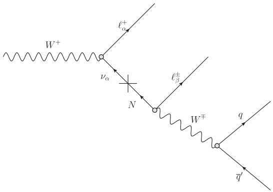




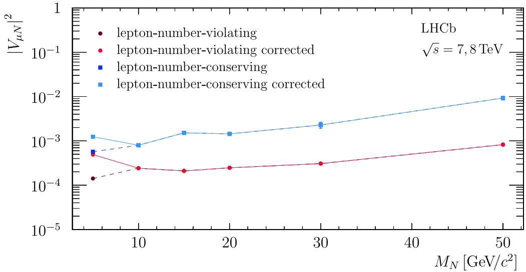
No evidence of signal observed. Constraints on θ^2 in inflation model and τ_χ.

Search for heavy neutral leptons

- Heavy neutral leptons (HNL) as explanation for smallness of m_ν.
- Mix with SM ν_ℓ with a coupling strength of $V_{\ell N}$.
- Searches for prompt HNL in $W^+ \to \mu^+ N(\to \mu^\pm q\bar{q}')$ decays with full Run 1 dataset.
- Cover $m_N \in [5, 50]$ GeV/c^2.



EPJC 81 (2021) 248



No excess observed. Upper limit for $|V_{\mu N}|^2$.

LHCb detector in Run 3

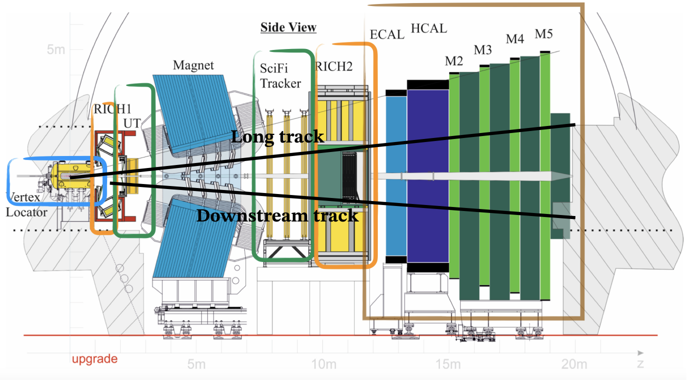
Increased instantaneous luminosity (pile-up ≈ 6).

New Vertex detector

New Particle Identification detector

New tracking system

New read-out



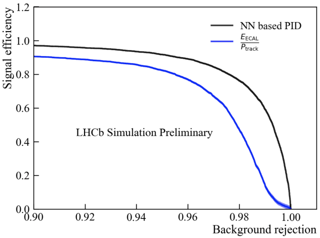
Removal of hardware trigger ⇒ Fully software-based trigger.

* Reconstruction of **all charged** particles.
* Potential for trigger on tracks starting outside of vertex detector ("downstream") ⇒ Advantageous for **long-lived** particles.

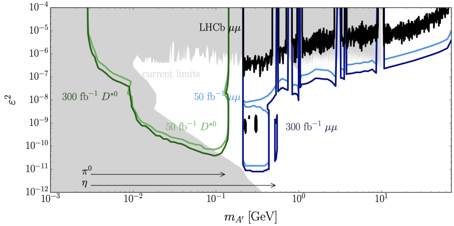
Future prospects of dark photon searches

- Search for $A' \to e^+e^-$ to access $m_{A'}$ below dimuon threshold.
- Background reduction via mass constraints of $D^{*0} \to D^0 A'(e^+e^-)$ decays. PRD 92 (2015) 115017
- Search of $\pi^0/\eta \to A'(e^+e^-)\gamma$ decays complementary.
- In Run 3, prompt $A' \to ee$ are saved to histograms without triggering, A''s from D^{*0} and π^0/η are kept for full analysis.

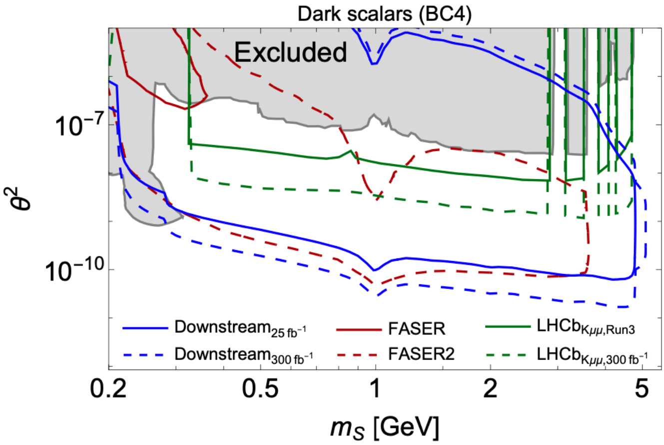
LHCb could cover unexplored parameter space.



arXiv:1812.07831



Future prospects of dark scalar searches



Improved sensitivity for $B^+ \to K^+\chi(\mu\mu)$ search in Run 3, where the μ's are **long tracks**.

↓

Further improvement if μ's reconstructed as **downstream tracks**.

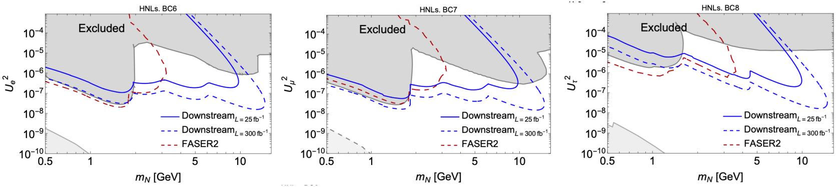
EPJC 84 (2024) 6, 608

Several ideas to exclude free parameter space with LHCb data.

Prospects for heavy neutral leptons

- HNL coupled to active neutrino ν_e (BC6), ν_μ (BC7) or ν_τ (BC8) with mixing angle U_α.
- Unexplored U_α vs. m_N phase space can be tested with downstream tracks ($\sim$ 2m displacement).
- HNL's produced in D-meson or τ decays ($m_N \lesssim 2\,\text{GeV}$) not competitive.
- Promising HNL search in b-hadron ($2\,\text{GeV}/c^2 \lesssim m_N < m_{B_c} - m_\ell$) and W decays ($m_N > m_{B_c}$).

EPJC 84 (2024) 6, 608

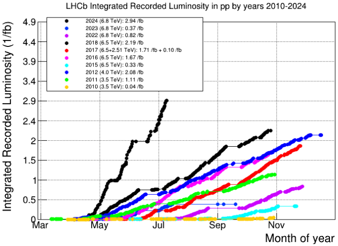


Heavy neutral leptons searches could profit from downstream tracking.

Conclusion

Broad spectrum of searches at LHCb:

- Prompt and displaced decay topologies.
- From resonance searches in dilepton mass to exploitation of electroweak penguin decays.



Exciting prospects for dark sector searches in Run 3:

- Large data sample via luminosity increase.
- Expected efficiency increase for decays with electronic final states.
- Downstream stream tracking offers new possibilities for long-lived particles.

Appendix

BC4 model

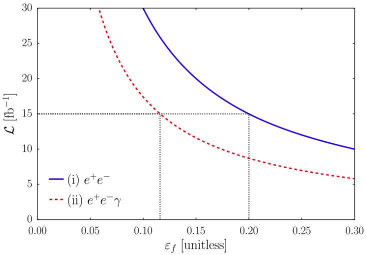
Lagrangian of the interaction of the dark scalar S with the Standard Model fermions and gauge bosons after electroweak symmetry breaking:

$$\mathcal{L} \supset -\theta \frac{m_f}{v} S\bar{f}f + 2\theta \frac{m_W^2}{v} SW^+W^- + \theta \frac{m_Z^2}{v} SZ^2 + \alpha \left(\frac{1}{4v} S^2 h^2 + \frac{1}{2} S^2 h \right)$$

- S Higgs-like dark scalar.
- θ S-Higgs mixing angle.
- α coupling of the hSS operator. $\alpha = 0$ in "BC4 model".

Sensitivity study of true muonium search

- Standard Model $\mu\mu$ true muonium bound state, $\mathcal{TM}$.
- Kinematically mixing with photon.
- Study vector state 1^3S_1, predominantly decaying to e^+e^-.
- Proposed search for displaced $\eta \to \gamma\mathcal{TM}(e^+e^-)$ and inclusive $\mathcal{TM} \to e^+e^-$.
- Required integrated luminosity for a $5\sigma_{\text{stat}}$ discovery as function of the reconstruction efficiency ε_f (figure right).



PRD 100 (2019) 053003