

Searches for exotic particles at LHCb

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on behalf of the LHCb collaboration



Implications of LHCb measurements and future prospects

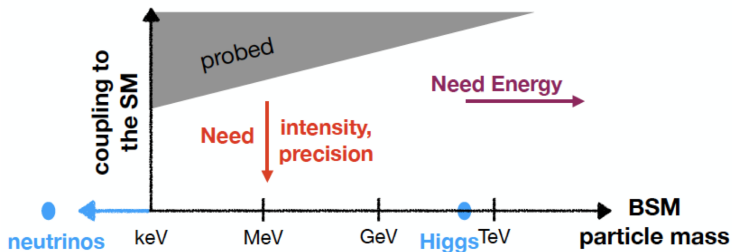
25th October 2024



UNIVERSITY OF
BIRMINGHAM



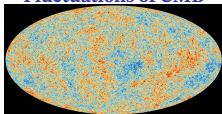
Where to search for New Physics at colliders?



- * Direct and indirect searches did not reveal NP, yet.
- * New Physics (NP) scale is unknown.
- * Exploration of uncovered parameter space is important.
- * Potential for new light particles feebly coupled to the Standard Model (SM).
 - ⊕ Could be a dark matter (DM) candidate, as well.

What do we know so far about Dark Matter?

Fluctuations of CMB



Gravitational lensing



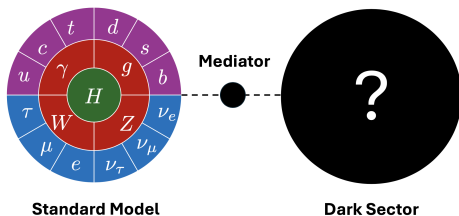
Rotation curves of spiral galaxies



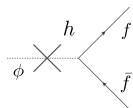
- Dark Matter (DM) composes around 27% of matter and energy content of our universe.
- Gravitationally interacting.
- Neutral or only weakly charged under SM forces.
- No or small self-interaction.
- Stable on cosmological scales.

Proposal of “dark sector”, interacting with the SM through a new mediator.

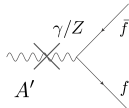
The dark sector



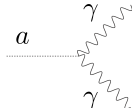
Portal examples:



Higgs portal
 $(\mu S + \lambda S^2)H^\dagger H$



Vector portal
 $\varepsilon F_{\mu\nu} F'^{\mu\nu} / \varepsilon B_{\mu\nu} F'^{\mu\nu}$



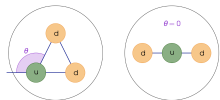
Axion portal
 $\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu},$
 $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}^{i,\mu\nu}$



Neutrino portal
 $y_N \bar{L} H N$

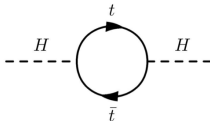
Dark sector particles could address...

Strong CP problem



⇒ axion

Hierarchy problem



⇒ dark scalar

Baryon number asymmetry



⇒ dark scalar, HNL

Neutrino masses



⇒ heavy neutral lepton
(HNL)

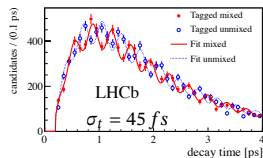
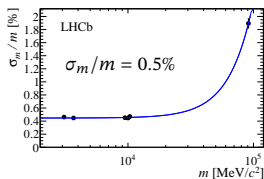
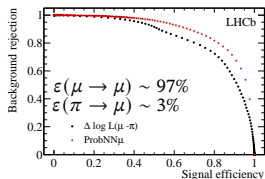
DM candidate



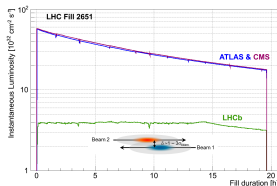
⇒ dark photon, axion,
dark scalar, HNL

What do we need to detect such signatures?

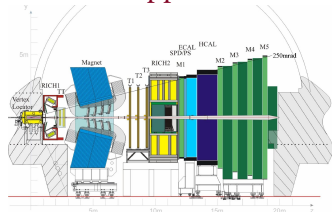
1. Particle identification
2. Mass resolution
3. Decay time resolution



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

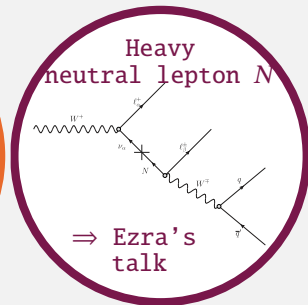
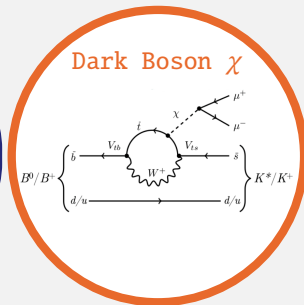
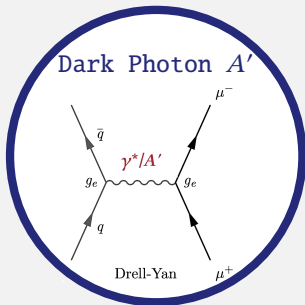


LHCb is excellent for low mass searches in pp collisions.



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

Dark sector searches at LHCb



Non-exhaustive selection of results and future prospects!

The Dark Photon

IDEA: Extend SM with new $U(1)_D$ gauge symmetry.

Kinetic mixing of $U(1)_D$ with $U(1)_Y$:

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{m_{A'}^2}{2}A'_\mu A'^\mu - \epsilon e J^\mu A'_\mu - e' J'^\mu A'_\mu + O(\epsilon^2)$$

Couplings to fermions
inherited from mixing
with γ .

Mass term via dark
Higgs or Stueckelberg
mechanism

DP couplings to
dark current.

- 1 $m_{A'} > m_{DM}$: Prompt A' decay to DM \rightarrow invisible
- 2 $m_{A'} < m_{DM}$: A' decay to SM particles \rightarrow visible

The Dark Photon

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Couplings to fermions inherited from mixing with γ .

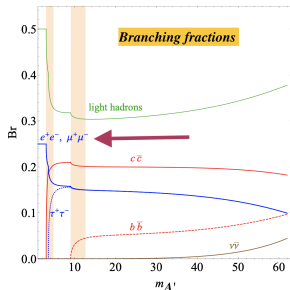
Mass term via dark Higgs or Stueckelberg mechanism

DP couplings to dark current.

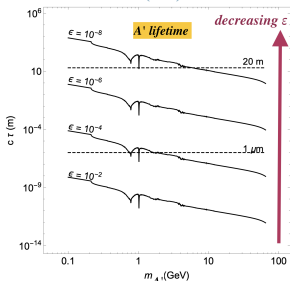
Vanishes in minimal DP model.

- 1 $m_{A'} > m_{DM}$: Prompt A' decay to DM \rightarrow invisible
- 2 $m_{A'} < m_{DM}$: A' decay to SM particles \rightarrow visible
- 3 Minimal DP model \rightarrow only A' in dark sector

Chin.Phys.C 41 (2017) 6, 063102

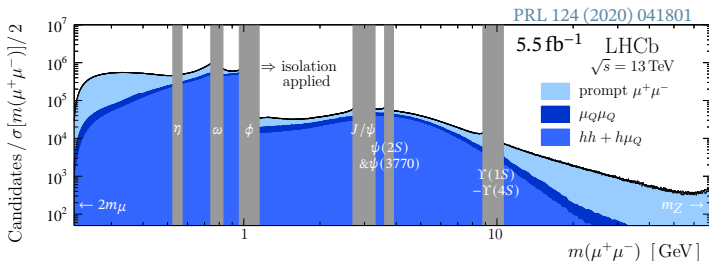
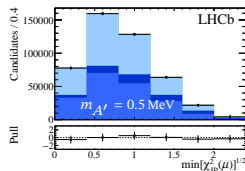


JHEP 02 (2015) 157



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

- * Normalisation to $\gamma^* \rightarrow \mu^+ \mu^-$ yield cancels most experimental systematics.
- * Templates from data and simulation.
- * Scan $m_{\mu\mu}$ in steps of $\sigma_{m_{\mu\mu}}/2$.
- * Prominent resonances vetoed, tail modeled.



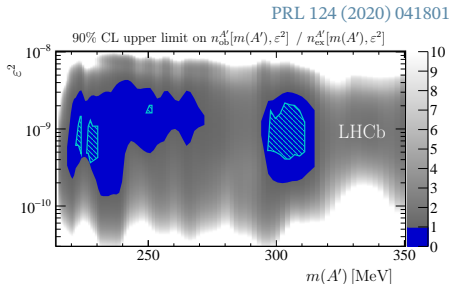
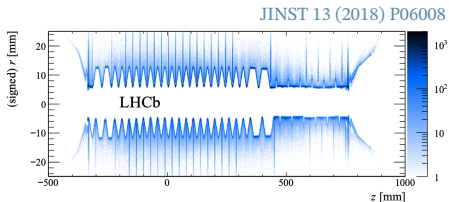
No significant excess found - exclusion regions at 90% C.L.
First limits on masses above 10 GeV & competitive limits below 0.5 GeV.

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

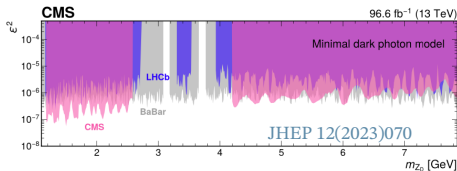
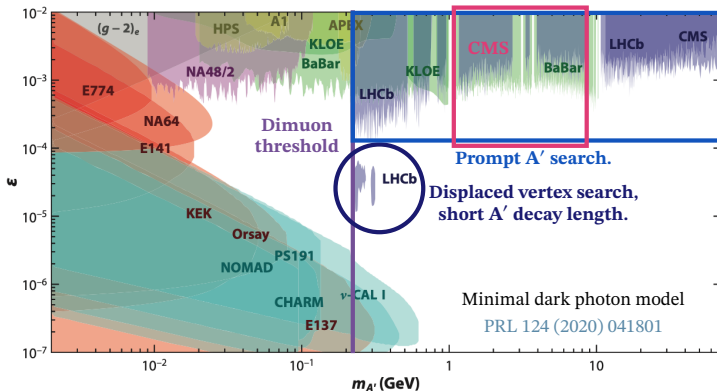
- ▶ Search in $m_{A'} \in [214, 350]$ MeV.
- ▶ Even looser $p_T(\mu)$ requirement.
- ▶ Main background from photon conversions in VELO material.
- ▶ Material map to suppress decay vertices originating from material.
- ▶ Fit in bins of mass and lifetime.

No significant excess found.
Small parameter space region excluded.

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



Resulting limits on A' mass and kinetic mixing strength

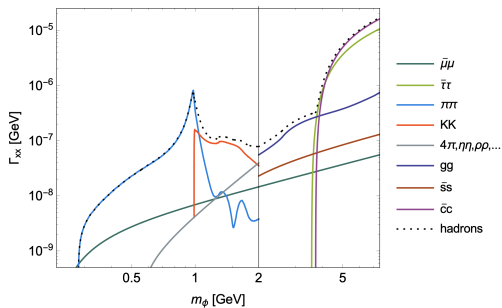


Dark scalar searches

IDEA: Extend SM with scalar singlet, mixing with the Higgs-boson.

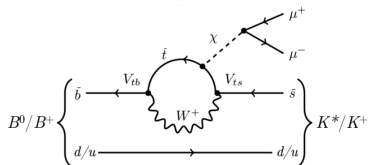
- ▶ If $m_S \ll$ EWK scale, coupling to fermions proportional to Higgs-scalar mixing angle $\sin \theta$.
- ▶ Leptonic decay rate of S well known, but large theoretical uncertainties on hadronic decay rates.

PRD 99 (2019) 1, 015018



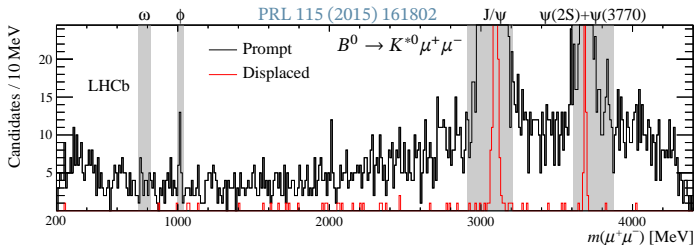
Theoretical predictions show disagreements.

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



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

- ▶ Both analyses exploit full Run 1 dataset.
- ▶ Search for prompt and displaced $\chi \rightarrow \mu\mu$ decays.
- ▶ \mathcal{B} normalised to $\mathcal{B}(B^+ \rightarrow K^+ J/\psi)$ or $\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)$.
- ▶ Scan $m_{\mu\mu}$ in steps of $\sigma_{m_{\mu\mu}}/2$.
- ▶ B -mass constraint improves $\sigma_{m_{\mu\mu}}$.

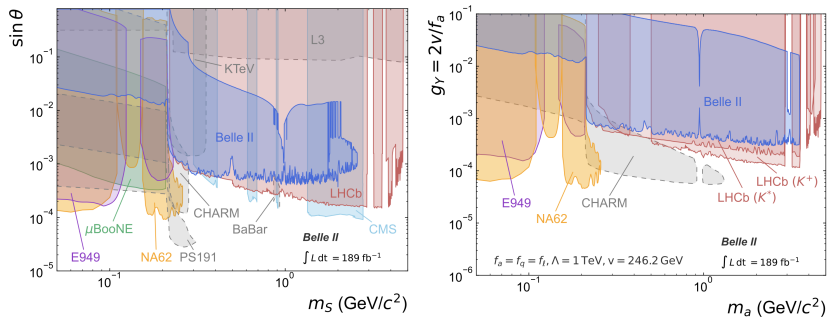


No evidence of signal observed.

Resulting limits on ALP and dark sector models

- Results published as limits on $\mathcal{B}(B \rightarrow K\chi(\mu\mu))$ as function of τ_χ and m_χ .
- Setting limits on dark scalar and ALP models.
- While LHCb exploits $\mu\mu$ final state only, Belle II combines ee , $\mu\mu$, $\pi\pi$ and KK .

PRD 108 (2023) 11, L111104



LHCb's dark boson searches set stringent limits.

LHCb detector in Run 3

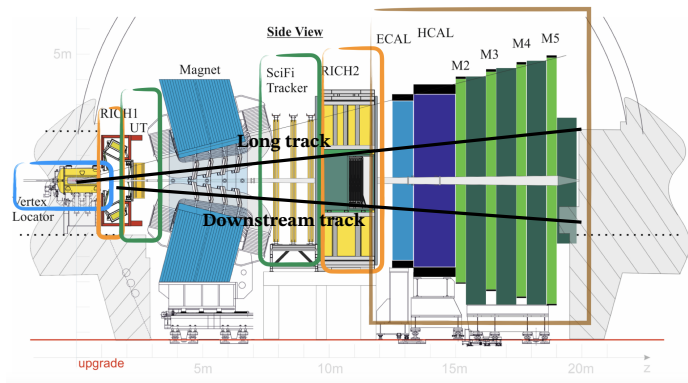
New Vertex detector

New Particle Identification detector

New tracking system

New read-out

Increased instantaneous luminosity (pile-up ≈ 6).

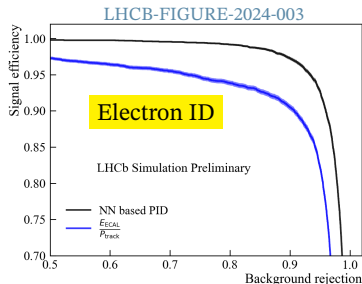
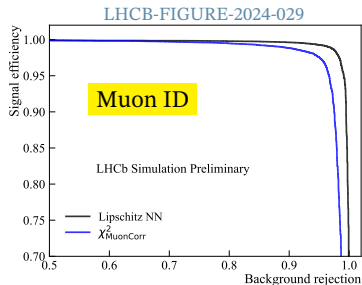
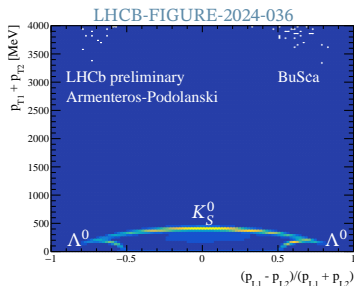


Removal of hardware trigger \Rightarrow Fully software-based trigger.

- * Reconstruction of **charged** particles.
- * Potential for trigger on tracks starting outside of vertex detector (“downstream”) \Rightarrow Advantageous for **long-lived** particles.

Neural networks at the first trigger steps

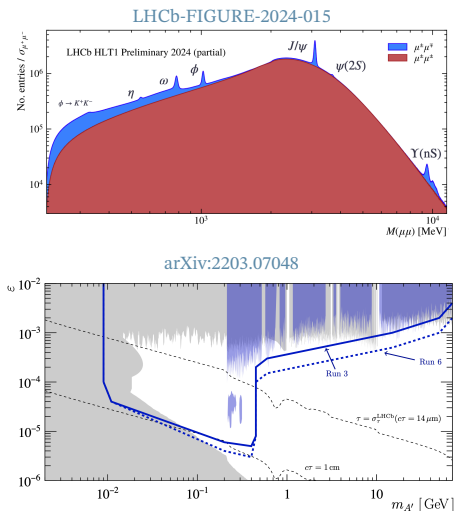
- ▶ Buffer scanner at first trigger level to detect long-lived particles is running on 2024 data.
- ▶ Improved muon and electron identification at first trigger level via Lipschitz constraint NN.



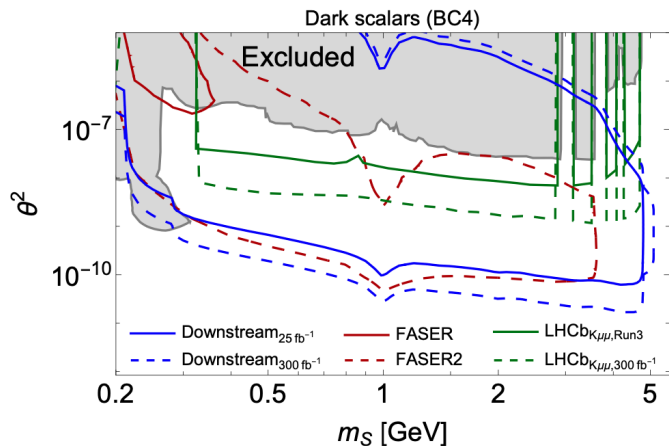
Future prospects of dark photon searches

- Clean dimuon mass spectrum in 2024 data out of first trigger step.
- Search for $A' \rightarrow e^+e^-$ to access $m_{A'}$ below dimuon threshold and normalise to $\gamma^* \rightarrow e^+e^-$.
 - Prompt $A' \rightarrow ee$ has high yields but large backgrounds.
 - In abundant $\pi^0/\eta \rightarrow e^+e^-\gamma$ decays. [arXiv:2203.07048](https://arxiv.org/abs/2203.07048)
 - Better resolution via mass constraints in $D^{*0} \rightarrow D^0 e^+e^-$ decays, but rarer. [PRD 92 \(2015\) 115017](https://arxiv.org/abs/1507.01151)

LHCb could cover unexplored parameter space.



Future prospects of dark scalar searches



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



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

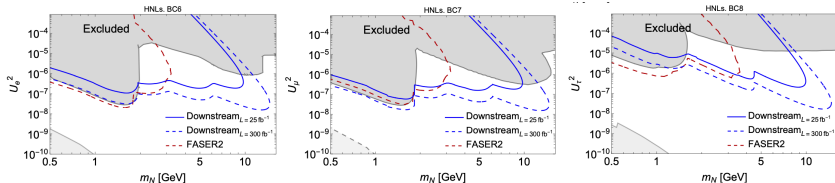
EPJC 84 (2024) 6, 608

Several ideas to exclude free parameter space with LHCb data.

Prospects for HNL searches

- ▶ 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 ($\sim 2\text{m}$ displacement).
- ▶ HNL's produced in D -meson or τ decays ($m_N \lesssim 2\text{ GeV}$) not competitive.
- ▶ Promising HNL search in b -hadron ($2\text{ GeV} \lesssim m_N < m_{B_c} - m_\ell$) and W decays ($m_N > m_{B_c}$).

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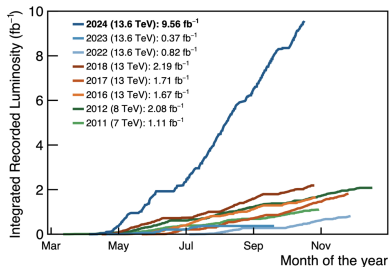


HNL searches could profit from downstream tracking.

Conclusion

Broad spectrum of searches at LHCb:

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

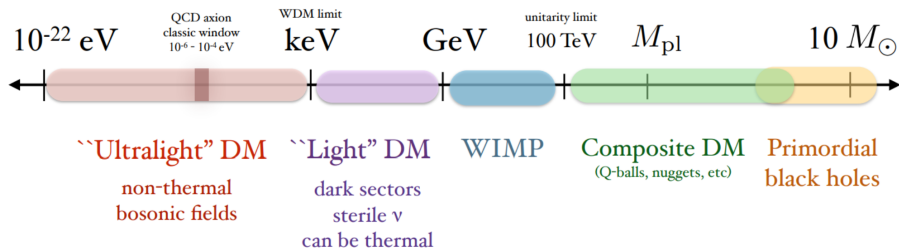


Exciting prospects for dark sector searches:

- Large data sample via luminosity increase in Run 3.
- New ideas to explore uncovered parameter space.
- Higher purity already at first trigger step via lepton identification neural network.
- Downstream tracking offers new possibilities for long-lived particles.

Appendix

Mass range of dark matter candidates



“Dark matter models and direct detection” TASI Lectures 2018 by T.Lin

BC4 model

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

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

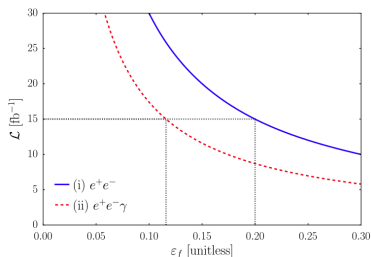
S Higgs-like dark scalar.

θ S -Higgs mixing angle.

α coupling of the hSS operator. $\alpha = 0$ in “BC4 model”.

Sensitivity study of true muonium search

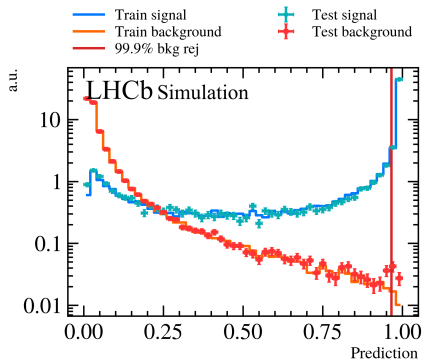
- Standard Model $\mu\mu$ true muonium bound state, $\mathcal{T}\mathcal{M}$.
- Kinematically mixing with photon.
- Study vector state 1^3S_1 , predominantly decaying to e^+e^- .
- Proposed search for displaced $\eta \rightarrow \gamma\mathcal{T}\mathcal{M}(e^+e^-)$ and inclusive $\mathcal{T}\mathcal{M}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



PRD 100 (2019) 053003

Anomaly detection for showers in muon detectors

- Muon detectors as sampling detectors to select showers.
- Trigger on such showers, allows to be less impacted by data and simulation differences.
- BDT used to compare performances (right) using $H \rightarrow AA$ with the axion A decaying to hadronically decaying τ -leptons.



LHCb-FIGURE-2024-015

Bibliography

S.1: Illustration by Sandbox Studio, Chicago with Ana Kova.

S.2: Illustration by Stefania Gori at ICHEP '24 “Exploring the frontier: Theoretical insights into the physics of dark sectors”.

S.3: CMB picture from ESA/Planck Collaboration. Bullet Cluster from NASA/CXC/CfA/M.Markevitch (X-ray), NASA/STScI, Magellan/U.Arizona/D.Clowe (Optical and lensing map), ESO WFI (Lensing map). Spiral galaxy NGC 5248/Caldwell 45 from NASA/ESA Hubble Space Telescope.

S.4: Illustration by Ellie Whiter. Diagrams from Martino Borsato.

S.5: Illustration in Cem Eröncel's [Lecture about axions](#); PRD (2013) 88, 12; Sandbox Studio, Chicago.

S.7: DP diagram from Martino Borsato.