What rare decays and dark sector searches have in common

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for the LHCb Collaboration

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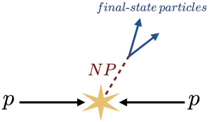
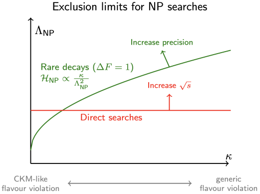
How to search for New Physics (NP) in colliders?

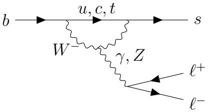
Direct searches



* Search for theoretically well-motivated NP candidates.
* Aim to produce NP particle in collider.
* Limited by beam energy.



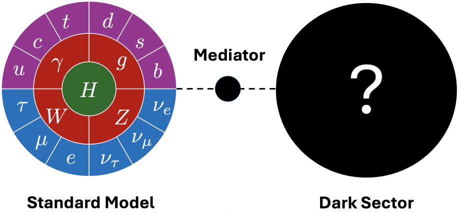
Indirect searches



* Precision measurements of Standard Model (SM) processes.
* Dependent on the flavour structure of NP, could probe higher NP scales.

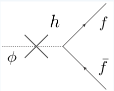
$\Longrightarrow$ Complementarity of direct and indirect searches.

Mediators between the visible and dark sector



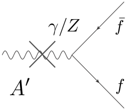
Credits to E.Whiter.

Portal examples:



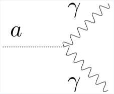
Higgs portal

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



Vector portal

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



Axion portal

$\frac{a}{f_a}F_{\mu\nu}\widetilde{F}^{\mu\nu}$,

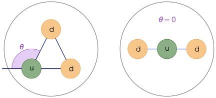
$\frac{a}{f_a}G_{i,\mu\nu}\widetilde{G}^{i,\mu\nu}$

Neutrino portal

$y_N \bar{L} H N$

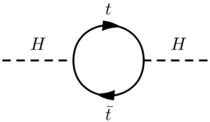
Those dark sector mediators could address...

Strong CP problem



$\Rightarrow$ axion

Hierarchy problem

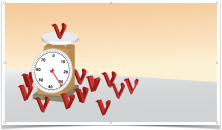


$\Rightarrow$ dark scalar

Baryon number asymmetry

$\Rightarrow$ dark scalar, HNL

Neutrino masses



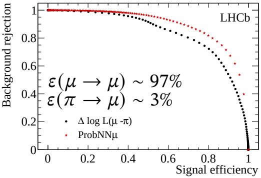
$\Rightarrow$ heavy neutral lepton (HNL)

DM candidate

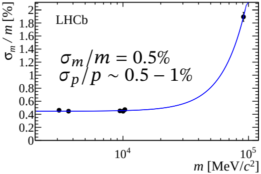
$\Rightarrow$ dark photon, axion, dark scalar, HNL

What do we need to detect such signatures?

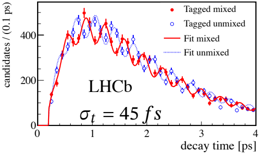
1. Particle identification



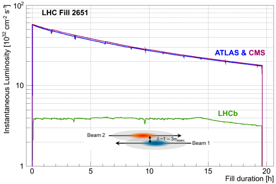
2. Mass resolution



3. Decay time resolution

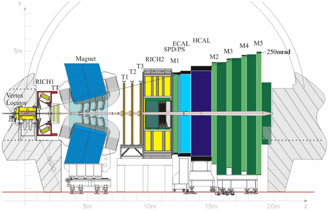


4. Balance between large luminosity and soft trigger thresholds, especially important for low-mass searches



$\Longrightarrow$

LHCb is excellent for low mass searches in pp collisions.

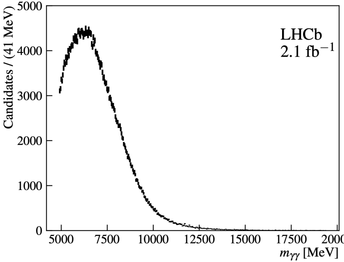


Int.J.Mod.Phys. A30(2015)1530022

Search for ALP$\to \gamma\gamma$

NEW arXiv:2507.14390

- Search for axion-like particles (ALP) in 2018 dataset.
- Production via gluon-gluon fusion, and decay to photons.
- Covered mass range of $m_{\gamma\gamma} \in [4.9, 19.4]$ GeV/c^2.



After electroweak symmetry breaking:

ALP symmetry breaking scale

Coupling to gluons

Coupling to photons

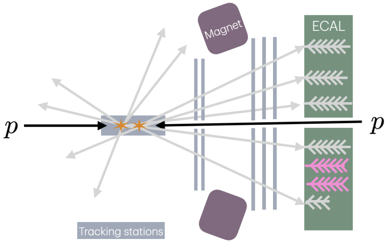
Mass term

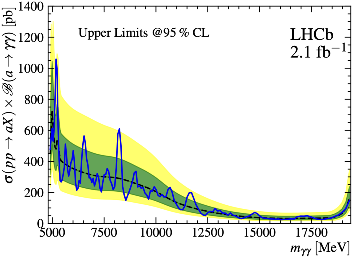
$$\mathcal{L} \supset \frac{a}{4\pi \boxed{f_a}}\left[\boxed{\alpha_3 c_3 G\tilde{G}} + \boxed{\alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}}\right] + \boxed{\frac{1}{2} m_a^2 a^2}$$

ALP$\rightarrow \gamma\gamma$ analysis strategy

NEW arXiv:2507.14390

- Candidates built from two calorimeter deposits, identified as γ's from pp collision.
- Candidate required to be in fiducial region $\eta \in [1.8, 5.2]$ and $p_{\mathrm{T}} > 6\,\mathrm{GeV}$
- Multivariate methods against misidentification, and for signal isolation.
- Combinatorial background of γ's and merged $\pi^0 \rightarrow \gamma\gamma$ decays remain.





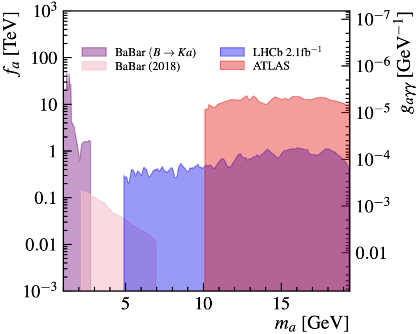
EXTRA:

Search for $B^0_{(s)} \rightarrow \gamma\gamma$ and $\eta_b \rightarrow \gamma\gamma$.

Rates of FCNC enhanced in 2HDM PRD58 (1998) 095014, SUSY PRD70 (2004) 035008, ...

Results of the ALP$\to \gamma\gamma$ search

NEW arXiv:2507.14390



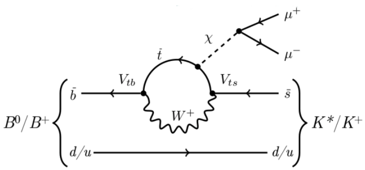
Upper limits at 95% CL:

- f_a vs. m_a (left) using $c_1 = c_2 = c_3 = 10$.
- $\mathcal{B}(B^0 \to \gamma\gamma) < 0.83 \times 10^{-5}$.
- $\mathcal{B}(B_s^0 \to \gamma\gamma) < 2.68 \times 10^{-5}$.
- $\sigma(pp \to \eta_b X)\mathcal{B}(\eta_b \to \gamma\gamma) < 765$pb First time at hadron collider.

Best limits on f_a in $m_a \in [4.9, 10]$ GeV.

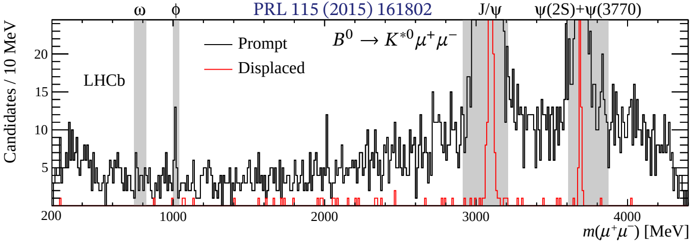
Beautiful example of a direct search for ALPs and indirect search for NP via FCNC decays in one analysis.

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 displaced $\chi \to \mu^+\mu^-$ decays.
- $\mathcal{B}$ normalised to $\mathcal{B}(B^+ \to K^+ J/\psi)$ or $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$.
- Scan $m_{\mu\mu}$ in steps of $\sigma_{m_{\mu\mu}}/2$.
- B-mass constraint improves $\sigma_{m_{\mu\mu}}$.

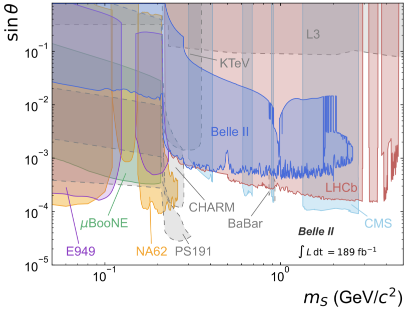


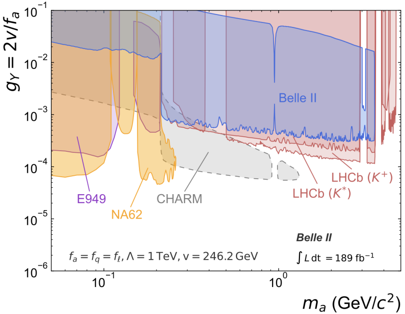
No evidence of signal observed. Direct search for NP in FCNC decay.

Resulting limits on dark scalar and ALP models

- Results published as limits on $\mathcal{B}(B \to K\chi(\mu^+\mu^-))$ as function of τ_χ and m_χ.
- LHCb exploits $\mu^+\mu^-$ final state, while Belle II combines e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$ and K^+K^-.
- ALP universal coupling to fermions; none to bosons and itself (BC10).

PRD 108 (2023) 11, L111104



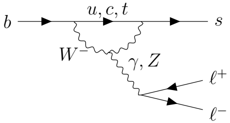


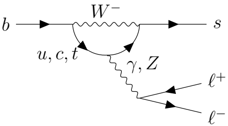
LHCb's dark boson searches set stringent limits via $b \to s\ell^+\ell^-$ decays.

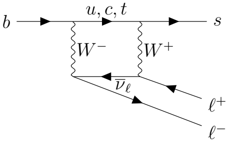
No evidence of NP in direct searches, yet. What to learn from indirect searches?

Indirect searches for NP via $b \to s\ell^+\ell^-$ transitions

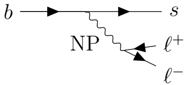
$b \to s\ell^+\ell^-$ transitions are CKM- and loop-suppressed in the Standard Model.

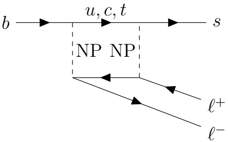






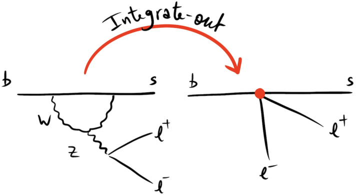
New Physics processes could contribute significantly.



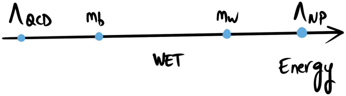


Precision measurements of those **rare decays** are crucial tests of the SM.

Indirect measurements are key to NP

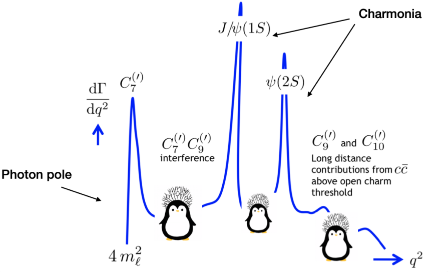


$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i (\mathcal{C}_i\mathcal{O}_i + \mathcal{C}_i'\mathcal{O}_i')$$



Sketches provided by Y.Amhis

Parametrisation of NP via
Wilson Coefficients (WCs) $C_i^{(\prime)}$.



WCs can be accessed
in the rare mode.

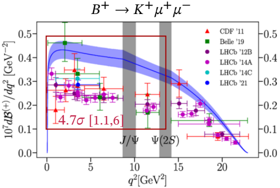
$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}$$

$$\mathcal{O}_9 = \frac{e^2}{16\pi^2} m_b (\bar{s}\gamma_\mu P_L b)\bar{\ell}\gamma^\mu \ell$$

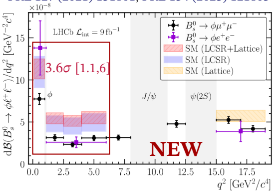
$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2} m_b (\bar{s}\gamma_\mu P_L b)\bar{\ell}\gamma^\mu \gamma_5 \ell$$

Experimental measurements of $b \to s\ell^+\ell^-$ decays

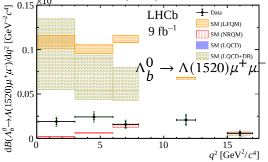
PRD 107, 119903 (2023)



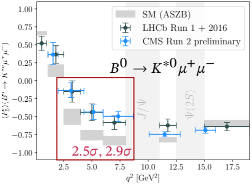
PRL 127 (2021) 151801, PRL 134 (2025) 121803



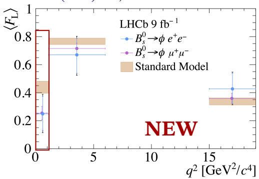
PRL 131 (2023) 151801



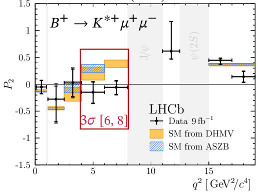
PRL 125 (2020) 011802, CMS-PAS-BPH-21-002



JHEP 11 (2021) 043, LHCb-PAPER-2025-006



PRL 126 (2021) 161802



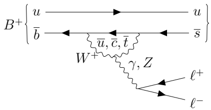
Belle II reports excess of $B \to K\nu\bar{\nu}$ wrt SM of 2.7σ. PRD 109 (2024)11, 112006

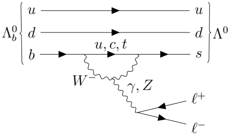
Deviations in differential branching fractions and angular observables.

LFU tests are mostly in agreement with SM hypothesis.

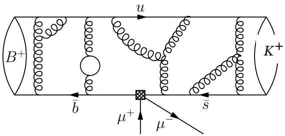
But b-quarks hadronise ...

... into mesons and baryons ...





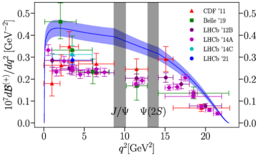
...and interact hadronically.



Theoretical "cleanness" depends on hadronic uncertainties.

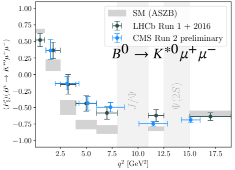
PRD 107, 119903 (2023)

$B^+ \to K^+\mu^+\mu^-$



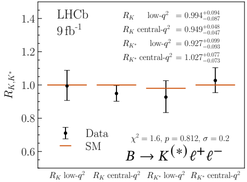
(a) Differential branching fractions

PRL 125 (2020) 011802, CMS-PAS-BPH-21-002



(b) Optimised angular observables

PRD 108 (2023) 032002



(c) Lepton flavour universality tests

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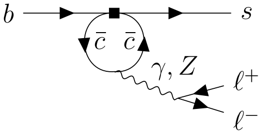
What about the non-local contributions?

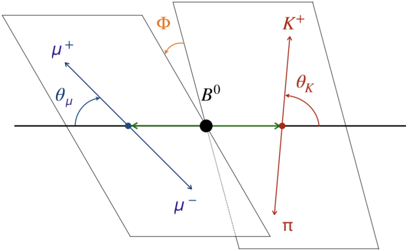
- Theoretical debate if mimicked by non-local hadronic contributions.

Idea: Perform another model-dependent unbinned angular analysis by parametrising form factors, WCs and nonlocal amplitudes.

→ Model-dependent unbinned angular analysis confirmed tensions in partial q^2 range PRD 109 (2024) 052009.

New: Fit in $q^2 \in [0.1, 18.0]\ \mathrm{GeV}^2/c^4$ including J/ψ and $\psi(2S)$ resonances.





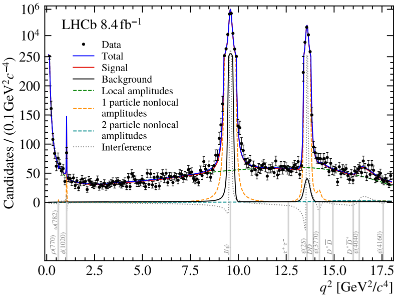
Credits to L.Carus.

Analysis of local and nonlocal amplitudes in $B^0 \to K^{*0}\mu^+\mu^-$ decays

NEW JHEP09(2024)026

- Nonlocal contributions modelled via dispersion relations.
- Models all known vector resonances coupling to muons.
- Include for the first time two-particle contributions from $D^{(*)}\bar{D}^{(*)}$ and $\tau^+\tau^-$ loops, as well.

$\Rightarrow$ Parametrised in $C_9^{eff,\lambda}(q^2)$ contained in angular coefficients.

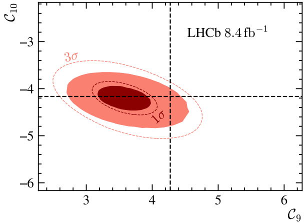


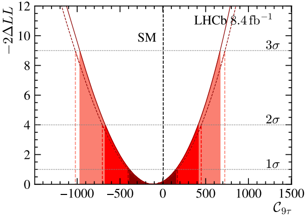
$$\frac{\mathrm{d}^4 \overset{(-)}{\Gamma}(B^0 \to K^+\pi^-\mu^+\mu^-)}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i \underbrace{\boxed{\overset{(-)}{J}_i(q^2)}}_{\text{Angular coefficients}} \underbrace{\boxed{f_i(\cos\theta_\ell, \cos\theta_K, \phi)}}_{\text{Spherical harmonics}} \underbrace{\boxed{G_i}}_{m(K\pi)\text{ line shape}}$$

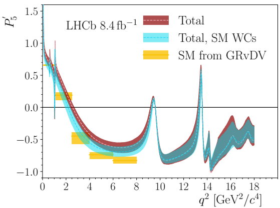
Analysis performed with 8.4 fb^{-1} (Run 1+2, w/o 2015).

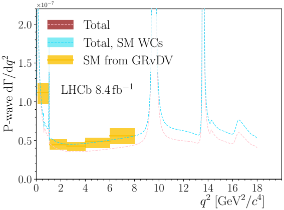
Results of amplitude analysis

- Results sensitive to form factor constrains.
- Nonlocal contributions matter, but do not account for all the tensions.
- C_9 in tension with SM at 2.1σ.
- Compatibility with PRD 109 (2024) 052009.
- First indirect measurement of $B^0 \to K^{*0}\tau^+\tau^-$.
- First result of $C_{9\tau}$.



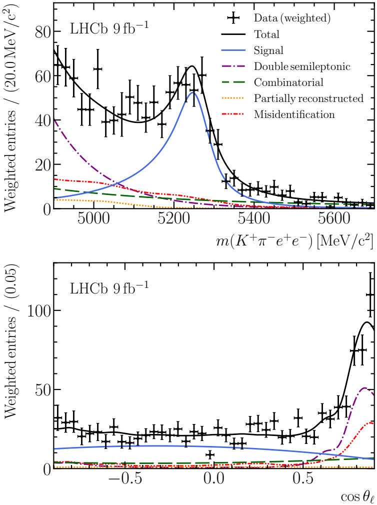






Angular analysis of $B^0 \to K^{*0} e^+ e^-$

- Most angular analyses of $b \to s\mu^+\mu^-$ decays since better resolution. $\Rightarrow$ Test $B^0 \to K^{*0} e^+ e^-$ decays.
- Performed in $q^2 \in [1.1, 6]$ GeV$^2/c^4$ with 9 fb^{-1} (Run 1+2).
- Non-resonant $K^+\pi^-$ contribution in $m(K^-\pi^+)$ window around K^{*0} mass neglected.
- Model signal and background components in 4D angular fit.
- Measurement of CP-averaged observables S_i, and theoretically optimised P_i observables.



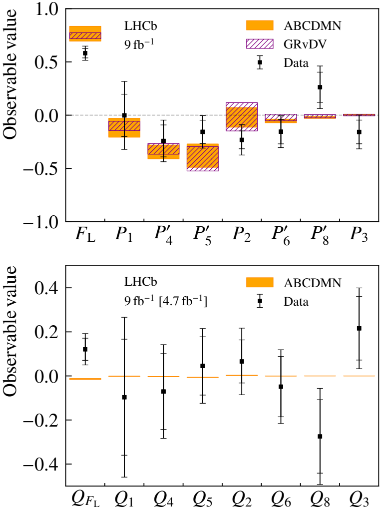
$B^0 \to K^{*0}e^+e^-$ angular observables

NEW JHEP06(2025)140

- Largest systematic uncertainties originating from background description.
- Most precise measurements of $B^0 \to K^{*0}e^+e^-$ angular observables in $q^2 \in [1.1, 6]\ \mathrm{GeV}^2/c^4$ to date.
- Agreement with SM prediction, with maximal deviation of 2σ in F_L and A_{FB}.
- Lepton Flavour Universality test in angular observables performed via

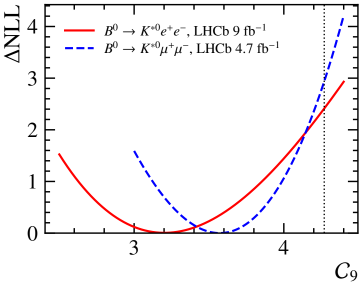
$$Q_i = P_i^{\mu} - P_i^{e}.$$

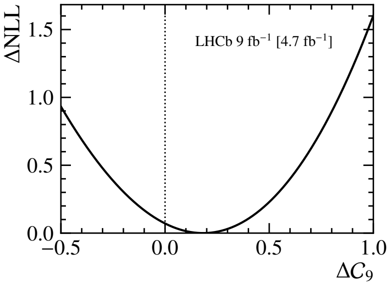
No sign of LFU violation.



EFT interpretation

NEW JHEP06(2025)140



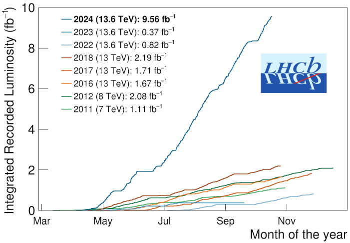


Negative shift in C_9 in electron and muon mode in $B^0 \to K^{*0}\ell^+\ell^-$ decays.

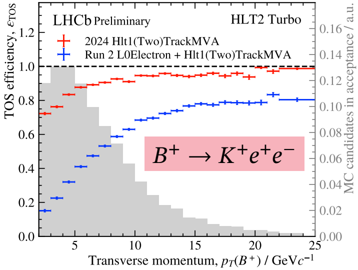
$\Delta C_9 = C_{9\mu} - C_{9e}$ compatible with zero within one standard deviation.

Takeaway message

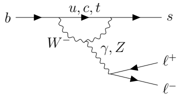
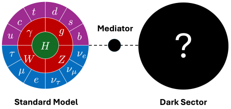
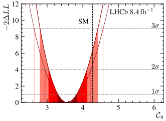
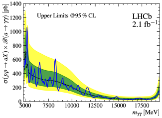
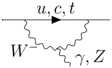
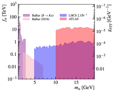
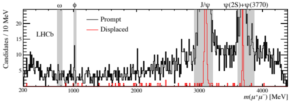
- Complementarity of direct and indirect searches for NP.
- New upper limits set by search for ALP $\to \gamma\gamma$ decays.
- Same decays can be exploited for direct & indirect searches.
- Discrepancies with SM seen in BFs and angular observables in rare decays.
- Analysis of local and nonlocal amplitudes in $B^0 \to K^{*0}\mu^+\mu^-$ decays shed light into theoretical discussions about nonlocal contributions.
- Tension in C_9 remain.
- Negative shift in C_{9e} compatible with shift in $C_{9\mu}$ observed in $B^0 \to K^{*0}\ell^+\ell^-$ angular analysis.



LHCb-FIGURE-2024-030



What have rare decays and searches for dark sector mediators in common?

<table>
<tr><th></th><th>
</th><th>
</th></tr>
<tr><td>Search for NP?</td><td>Indirect</td><td>Direct</td></tr>
<tr><td>Consistent with SM?</td><td>
</td><td>
</td></tr>
<tr><td>Suspression?</td><td>$V^{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$ 
</td><td>$g_{a\gamma\gamma} \equiv \dfrac{\alpha_{\text{EM}}(c_2 + \frac{5}{3}c_1)}{\pi f_a}$ </td></tr>
<tr><td>Displacement?</td><td>$\tau_{B,\Lambda_b} \approx 1.5 \times 10^{-12}\ s$</td><td>
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</table>

Appendix

BC4 model

Lagrangian of the interaction of the dark scalar S with the Standard Model fermions and gauge bosons after electroweak symmetry breaking (from J. Phys. G: Nucl. Part. Phys. 47 010501):

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

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

BC10 model

Lagrangian for ALPs coupling to fermions with universal and flavor diagonal couplings (from PRD 109, 055042):

$$\mathcal{L} \supset \frac{\delta_\mu a}{f_a}\left(C_\ell \sum_\ell \bar{\ell}\gamma^\mu\gamma_5\ell + C_q \sum_q \bar{q}\gamma^\mu\gamma_5 q\right)$$

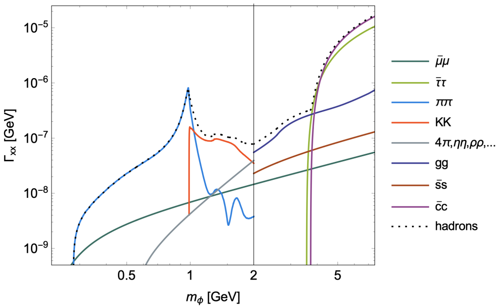
- C_ℓ Hermitian matrix of ALP-lepton coupling strengths.
- C_q Hermitian matrix of ALP-quark coupling strengths, in “BC10 model” equal to C_ℓ (from J. Phys. G: Nucl. Part. Phys. 47 010501).
- f_a ALP symmetry breaking scale.

Theoretical prediction of dark scalars

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

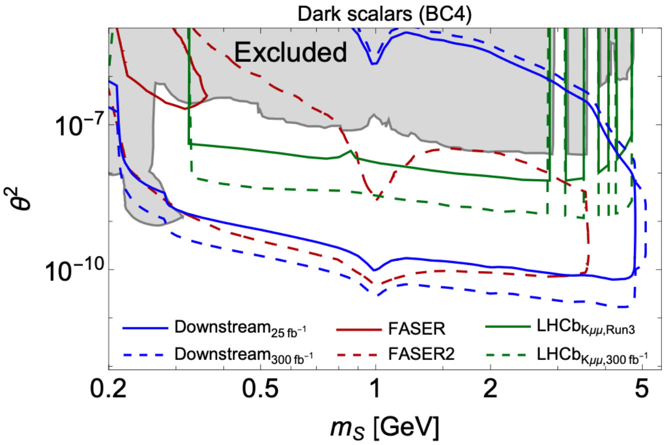
- If $m_S \ll$ EWK scale, coupling to fermions proportional to Higgs-scalar mixing angle $\sin\theta$.
- Leptonic decay rate of S well known, but large theoretical uncertainties on hadronic decay rates.

PRD 99 (2019) 1, 015018



Theoretical predictions of hadronic decay rates show disagreements.

Future prospects of Higgs portal searches



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

↓

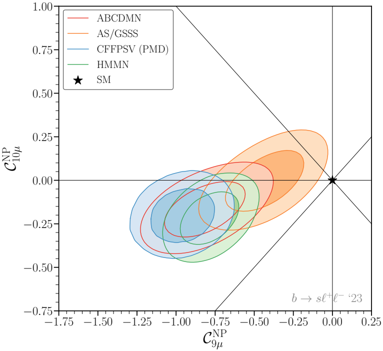
Further improvement if μ's reconstructed as **downstream tracks**.

EPJC 84 (2024) 6, 608

Several ideas to exclude free parameter space with LHCb data.

Global Effective Field Theory fits

Global fits from four different theory groups, using different predictions, observables, assumptions about non-local matrix elements and statistical frameworks.



PoS (FPCP 2023) 010

Consistent deviations of $b \to s\mu^+\mu^-$ observables with respect to SM prediction.

Decay width parametrisation

NEW JHEP09(2024)026

Angular coefficients

$m(K\pi)$ line shape

$$\frac{\mathrm{d}^4 \overset{(-)}{\Gamma}(B^0 \to K^+\pi^-\mu^+\mu^-)}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i \boxed{\overset{(-)}{J}_i(q^2)}\,\boxed{f_i(\cos\theta_\ell, \cos\theta_K, \phi)}\,\boxed{G_i}$$

Spherical harmonics

Angular coefficients are bilinear combinations of decay amplitudes $\mathscr{A}_\lambda^{\mathrm{L,R}}(q^2)$:

Form factors

$$\mathscr{A}_\lambda^{\mathrm{L,R}}(q^2) = N_\lambda\left\{\left(\boxed{C_9^{eff,\lambda}(q^2)} \pm C_9'\right) \mp \left(C_{10} \pm C_{10}'\right)\boxed{F_\lambda^A(q^2)} + M_\lambda\left(\boxed{C_7^{eff,\lambda}} - C_7'\right)\boxed{F_\lambda^T(q^2)}\right\}$$

WCs with non-local contributions

Fit acceptance and resolution corrected signal decay width and combinatorial background in B^0-mass region.

Optimised angular observable definitions

$$P_1 = \frac{2S_3}{(1 - F_{\mathrm{L}})}\,,$$

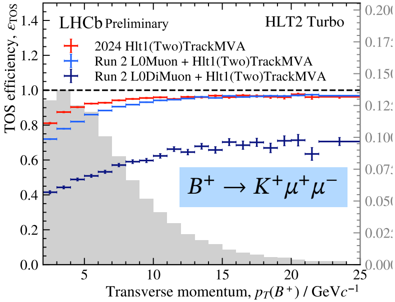
$$P_2 = \frac{2}{3}\frac{A_{\mathrm{FB}}}{(1 - F_{\mathrm{L}})}\,,$$

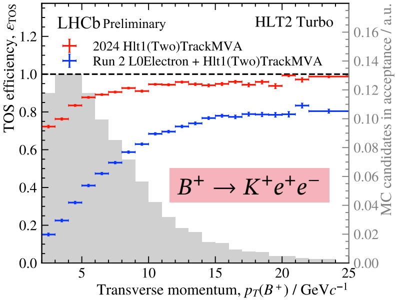
$$P_3 = \frac{-S_9}{(1 - F_{\mathrm{L}})}\,,$$

$$P'_{4,5,6,8} = \frac{S_{4,5,7,8}}{\sqrt{F_{\mathrm{L}}(1 - F_{\mathrm{L}})}}\,.$$

HLT 1 efficiencies of decays containing electrons

LHCb-FIGURE-2024-030





Improved HLT 1 efficiencies of decays containing electrons in Run 3.