How LHCb is shedding light on the existence of dark sector portals

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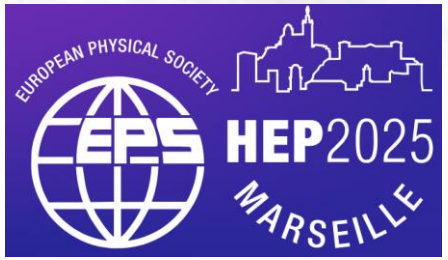
on behalf of the LHCb Collaboration

EPS-HEP 2025, Marseille
9th July 2025



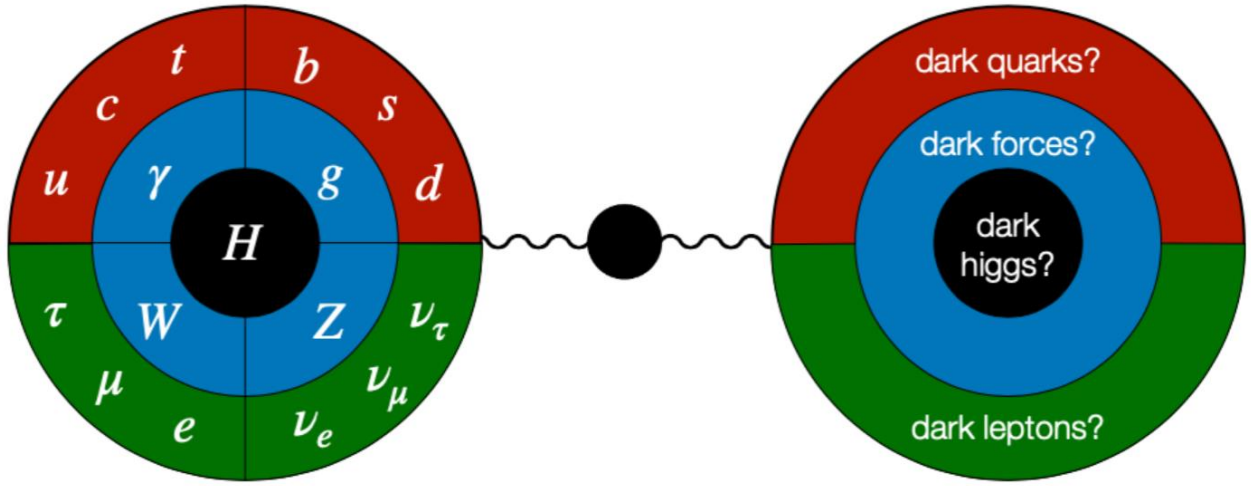
Dark sector portals

- Dark sector: set of new particles neutral under SM forces, only weakly coupled to SM through portals
- Dark matter might arise from dark sector, which could also explain other open questions (e.g., neutrino masses, matter-antimatter asymmetry)
- Coupling constrained by gauge and Lorentz symmetries
  → only **4 portals** allowed:

This talk

- Vector portal: dark photon
- Scalar portal: Higgs-like particle
- Axion portal: Axion-like particle

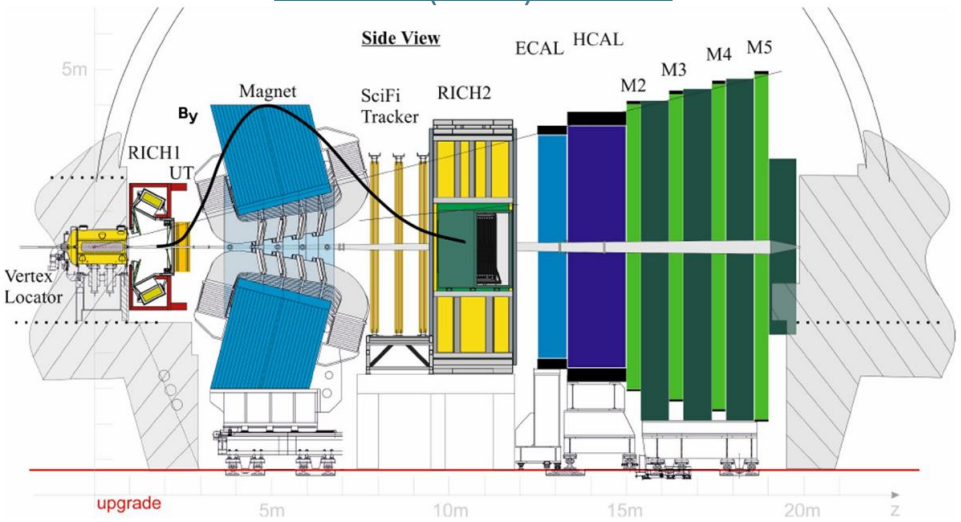
- Neutrino portal: sterile neutrino



SM Dark sector

Dark sector at LHCb

JINST 19 (2024) P05065

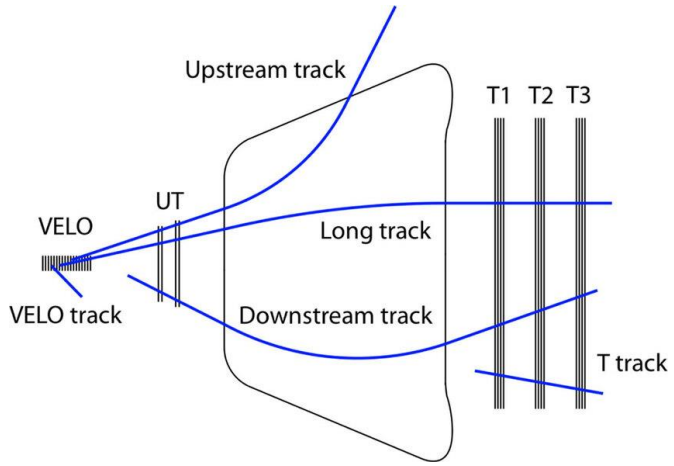


Sensitivity to dark portals already in Run 2:

- Only LHC experiment fully instrumented in forward direction
- Excellent vertex and momentum resolution
- Balance between large luminosity and soft trigger thresholds
  → important for low-mass searches

Run 3 upgraded detector:

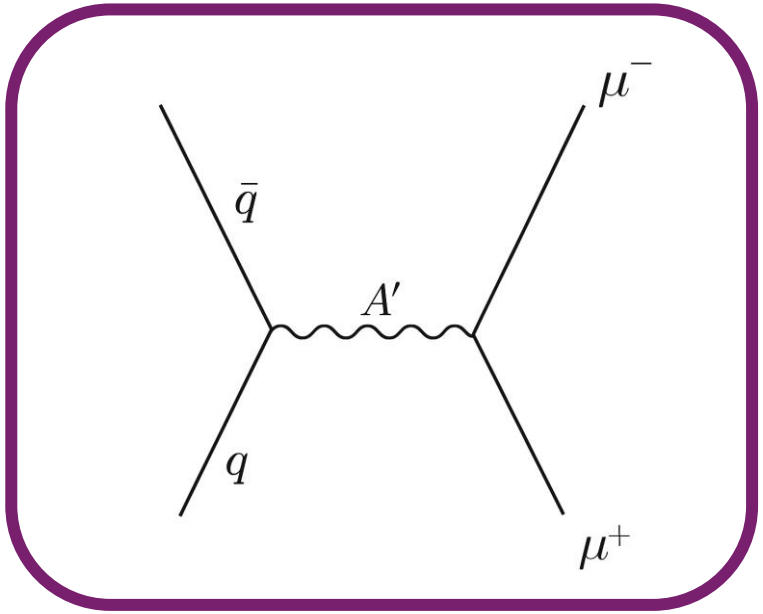
- New vertex detector and tracking system
- New particle identification detector
- **Fully software-based trigger**
  - Softer selection thresholds
  - Potential for trigger on tracks starting outside vertex detector (downstream and T-tracks) → long-lived particles



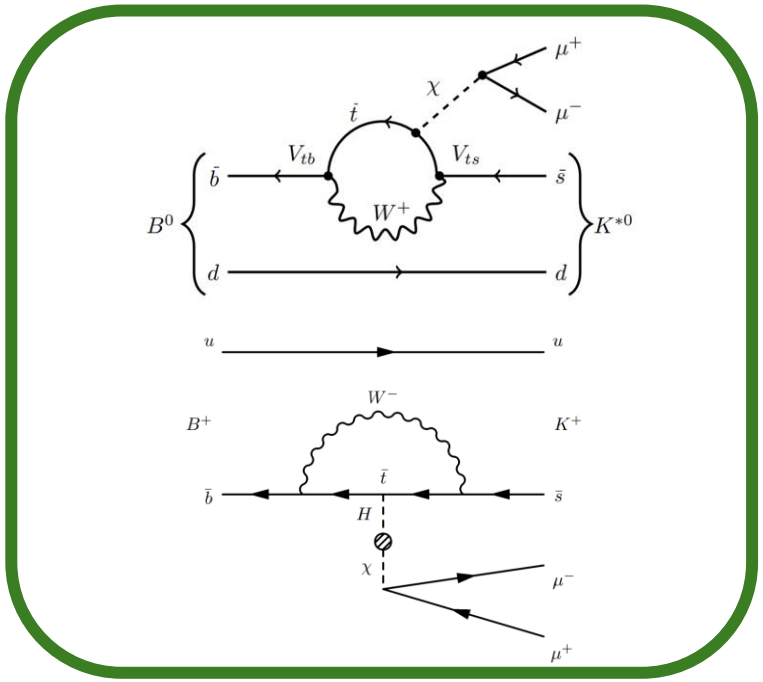
arXiv:2312.14016v3

In this talk

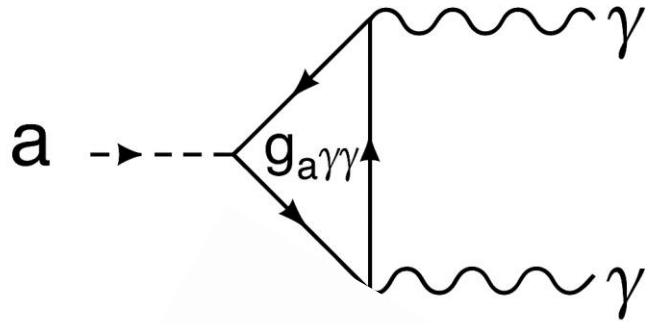
Dark photon A'



Dark boson χ



Axion-like particle a (ALP)



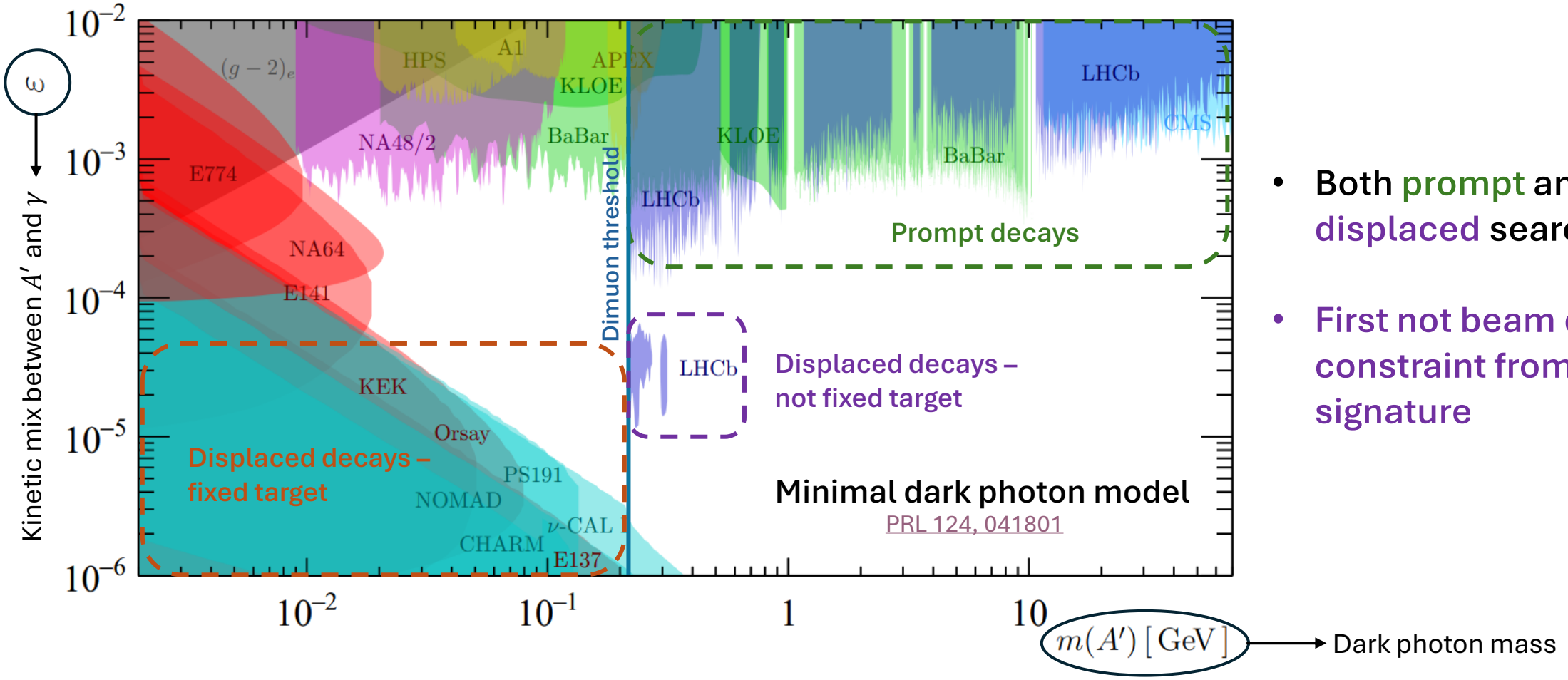
NEW!

Non-exhaustive overview of Run 1-2 results and Run 3 prospects!

Dark photon searches

PRL 120 (2018) 061801
PRL 124, 041801

LHCb conducted inclusive searches of $A' \to \mu^+\mu^-$ with Run 2 data ($5.5\ \mathrm{fb}^{-1}$)

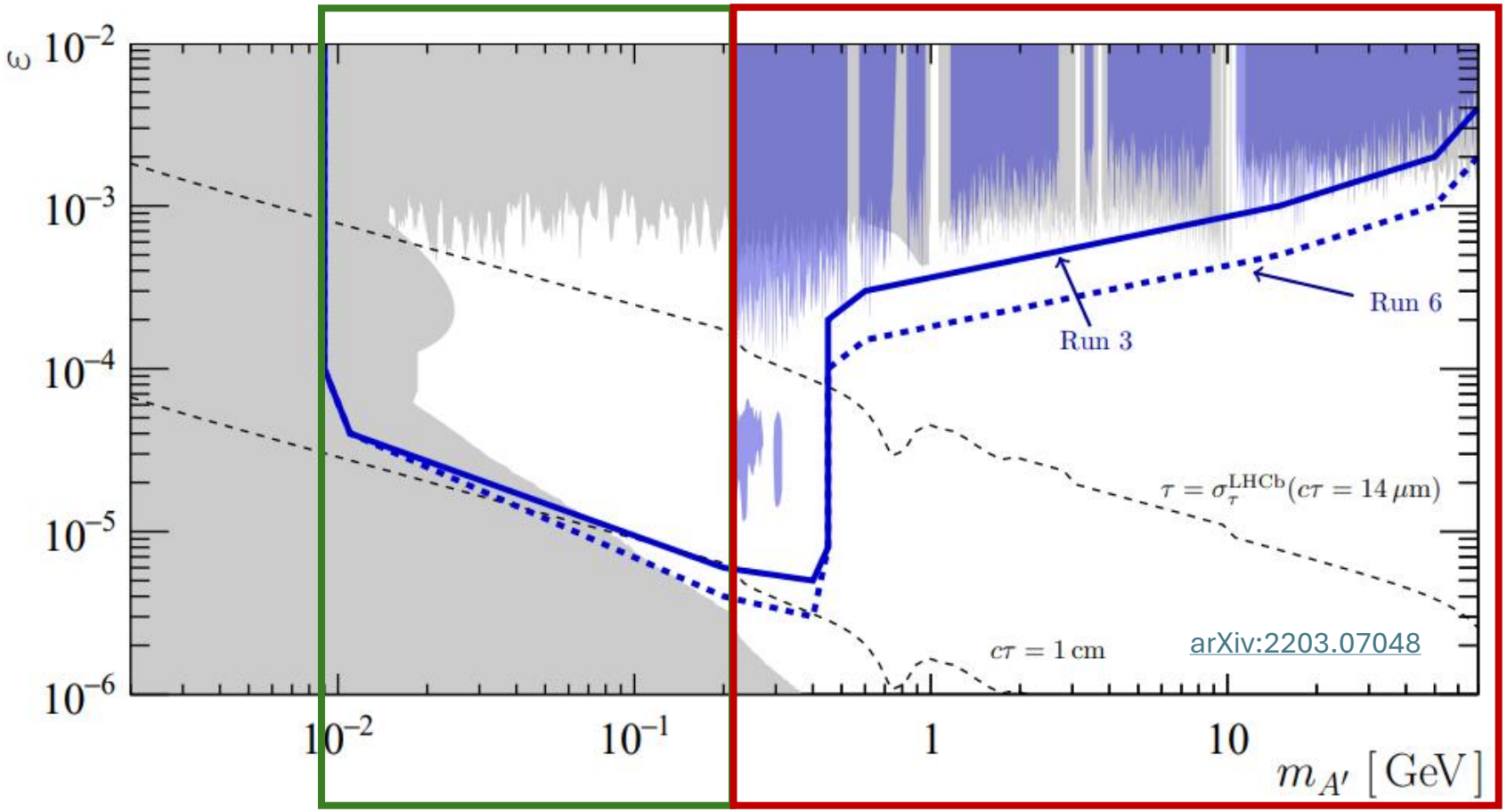


- Both prompt and displaced searches
- First not beam dump constraint from displaced signature

arXiv:2203.07048

Dark photon future: Run 3 and beyond

LHCb can extend its coverage to both di-muon and di-electron final states



$A' \to \mu^+\mu^-$:

- Yield increase in low-mass region thanks to software trigger
- Improved muon ID

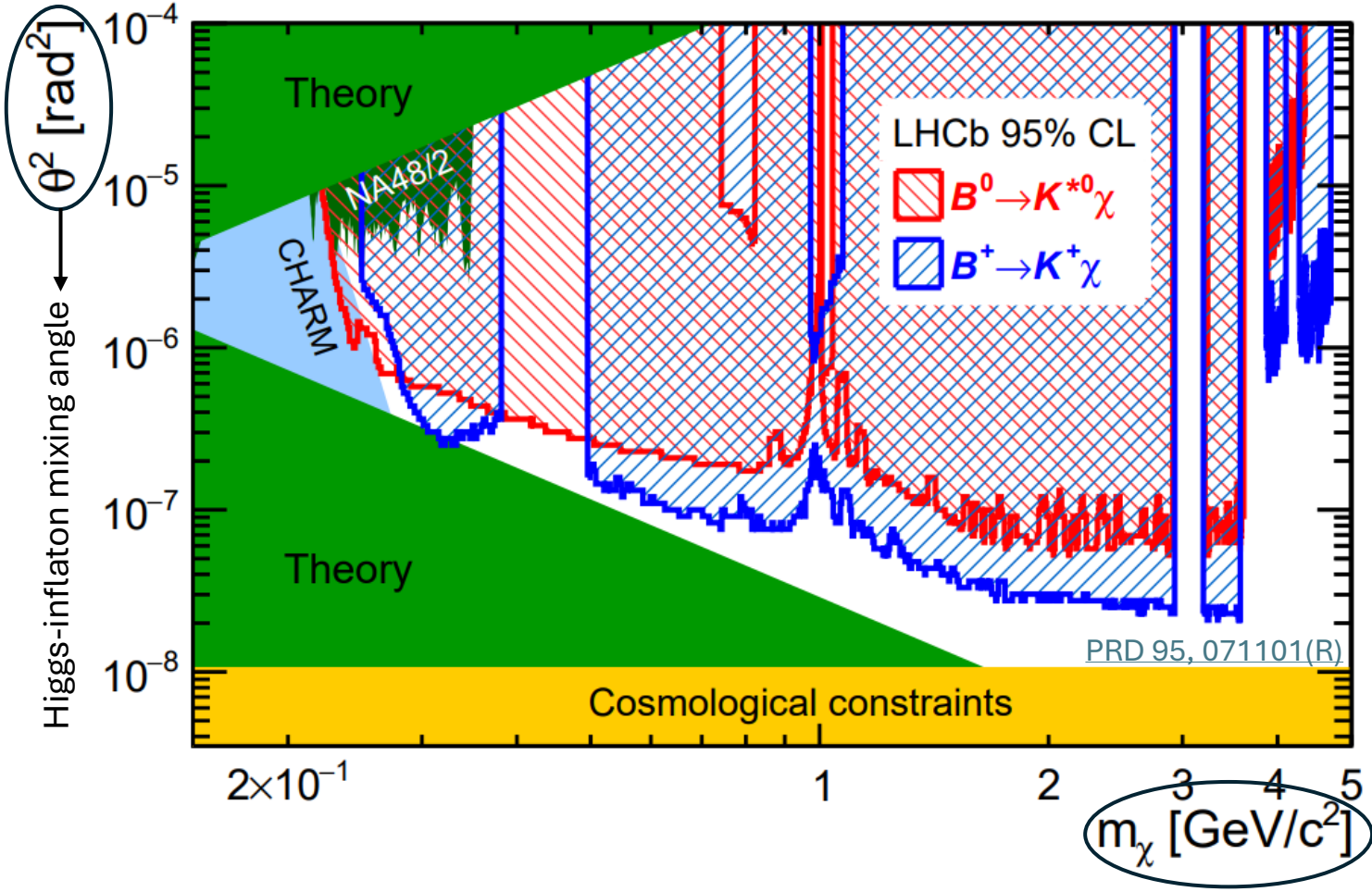
$A' \to e^+e^-$: new sensitivity range below $\mu\mu$ threshold, unlocked by

- Improved electron ID
- Fully software-based trigger

Dark boson in $b \to s\,\mu^+\mu^-$ transitions

PRL 115, 161802
PRD 95, 071101(R)

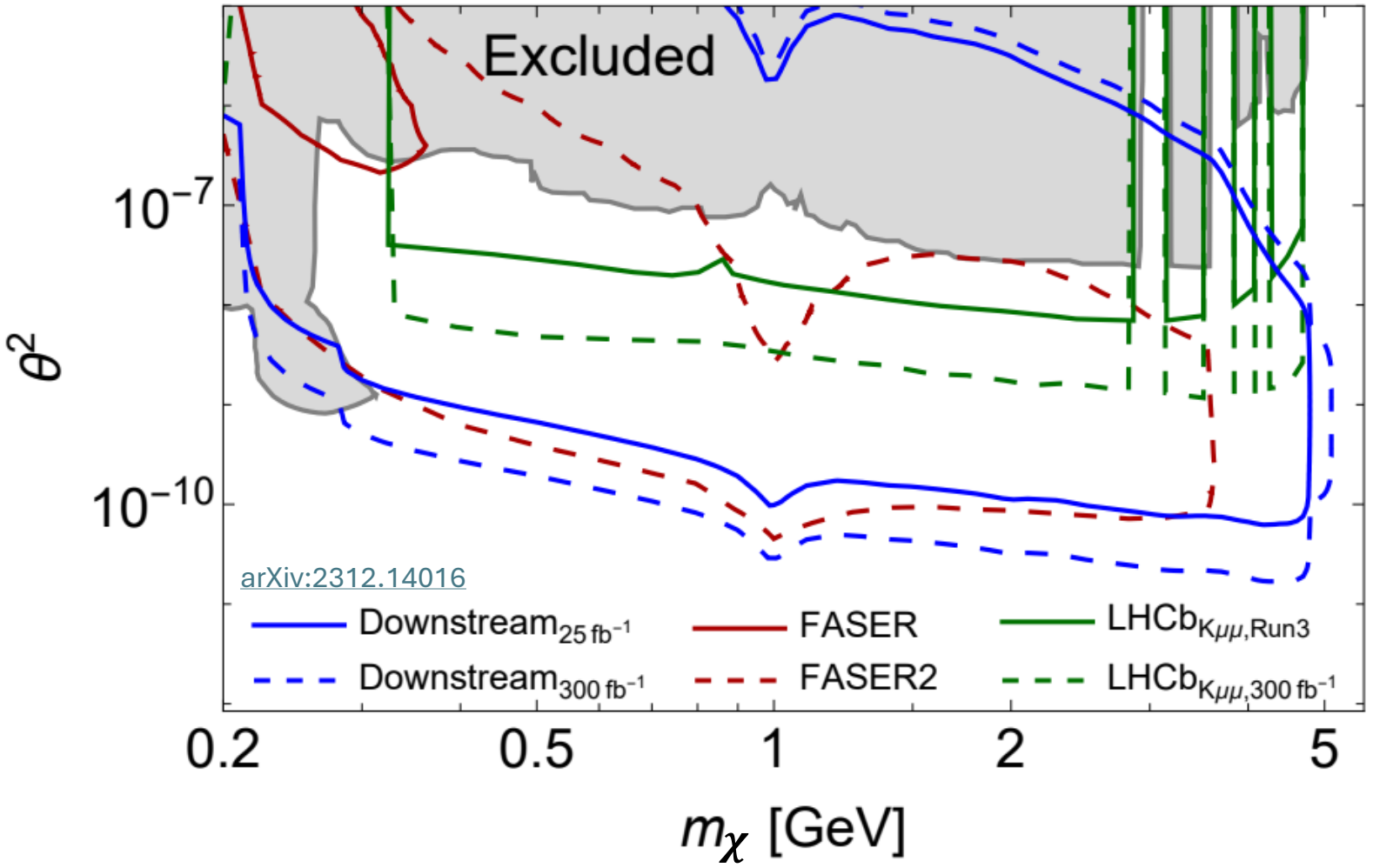
LHCb performed searches for light scalar particle decaying to muons with Run 1 data ($3\ \mathrm{fb}^{-1}$)



Channels:

- $B^0 \to K^{*0}(\to K^+\pi^-)\chi(\to \mu^+\mu^-)$
- $B^+ \to K^+\chi(\to \mu^+\mu^-)$
- **Both prompt and displaced $\chi \to \mu^+\mu^-$ decays**
- **Upper limits within inflation model**
- **World's best upper limits below $2m_\tau$**

Dark boson in $b \to s$ future: Run 3 and beyond



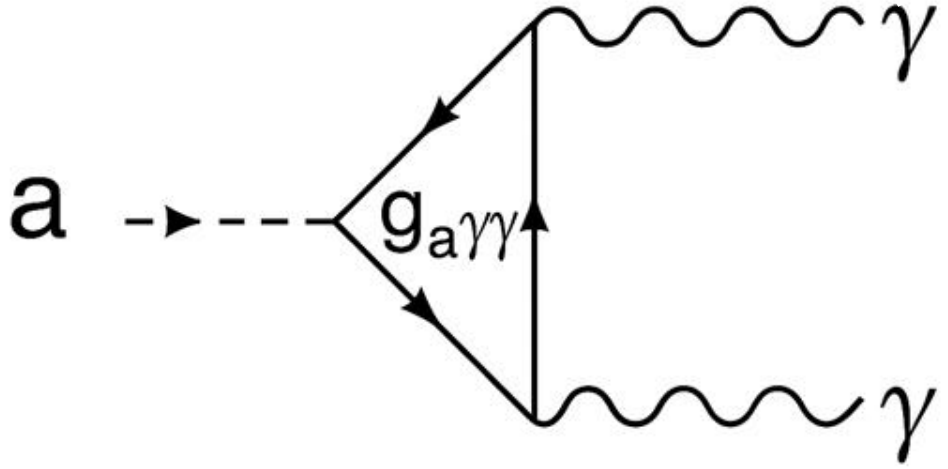
LHCb can improve sensitivity already in Run 3:

- Even with long-track muons only
- Further improvement with downstream and T-tracks reconstruction
  → **more on this in S. Libralon's and J. Zhuo's talks**

Search for ALP $\rightarrow \gamma\gamma$

New LHCb search in fully neutral final state with 2018 data ($2.1\ \mathrm{fb}^{-1}$)

- Clean signature enabling study of coupling to photons
- Production via gluon-gluon fusion



ALP symmetry breaking scale

Coupling with gluon

Coupling with photon

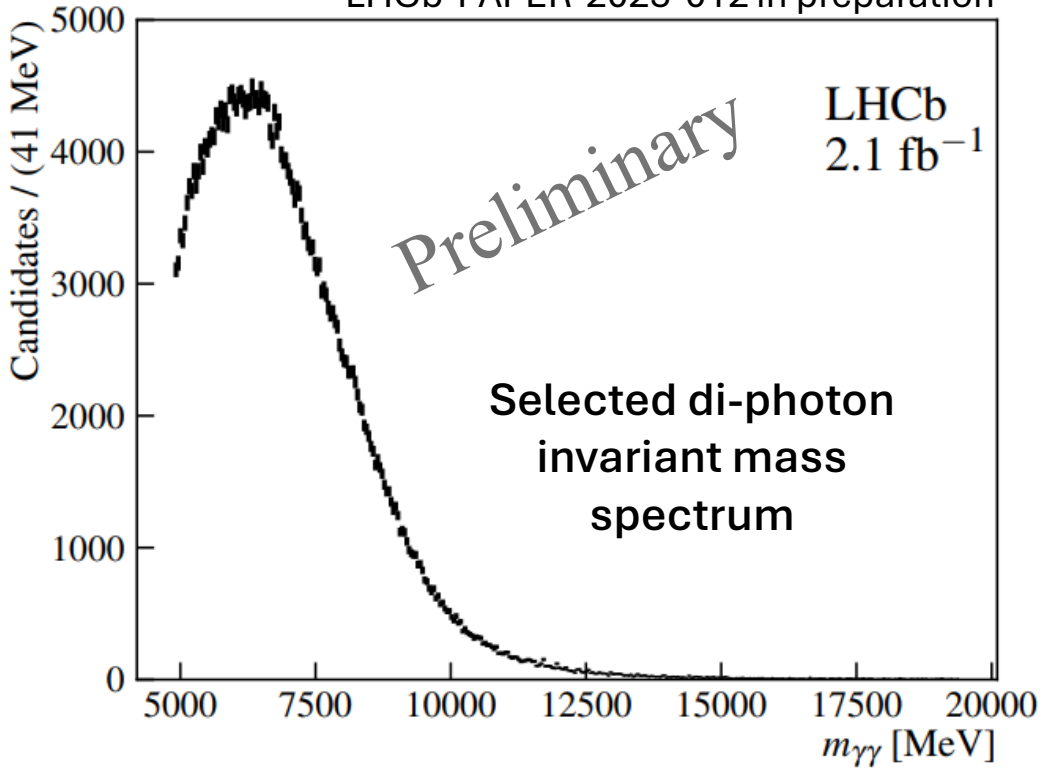
Mass term

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

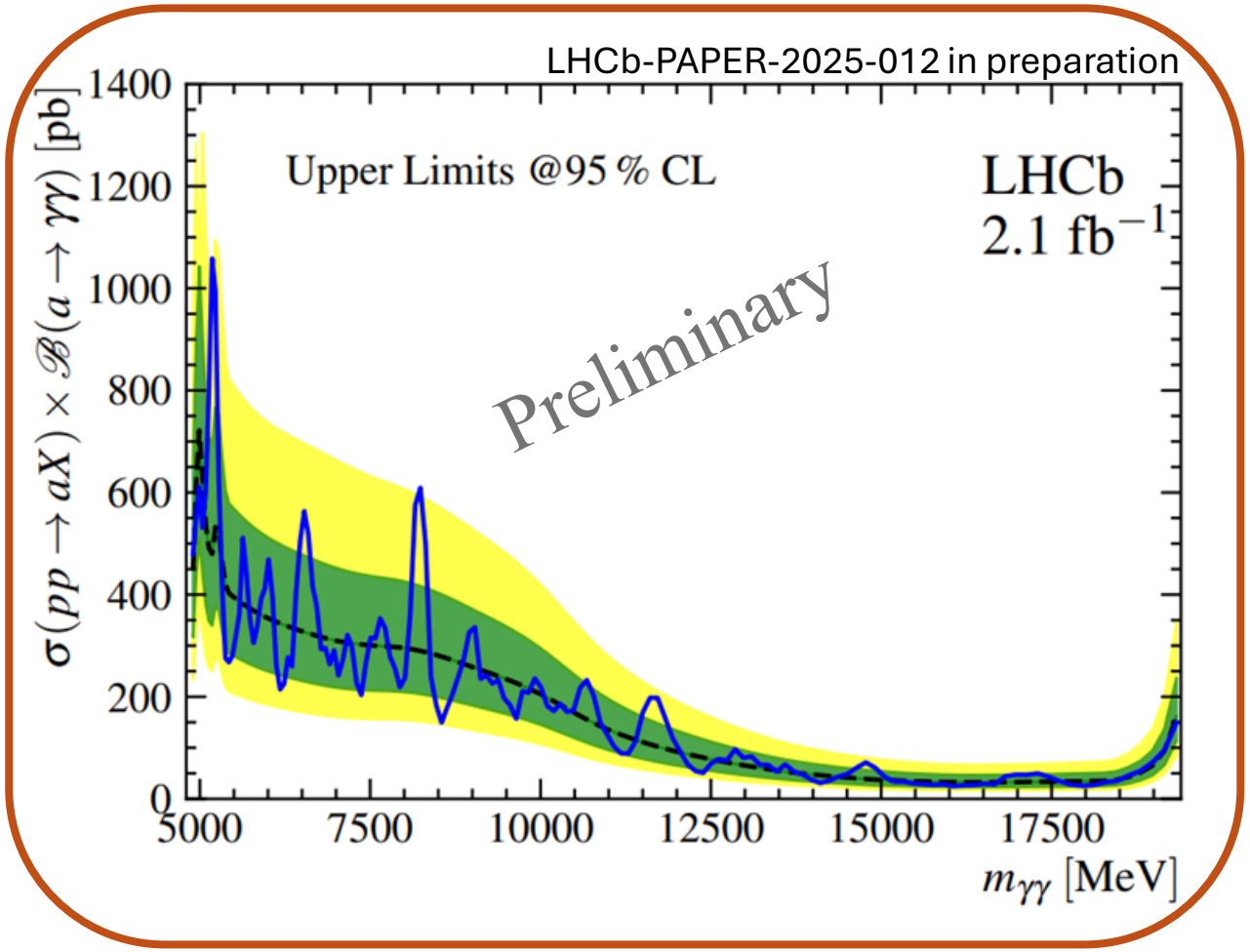
Search for ALP $\rightarrow \gamma\gamma$: analysis strategy

- Studied di-photon mass range: [4.9, 19.4] GeV
- Dedicated trigger lines for photons selection
- Signal candidates built from two ECAL clusters, corresponding to photons produced in *pp* collision
- Main backgrounds:
  - Combinatorial (e.g., $\pi^0 \rightarrow \gamma\gamma$, hadronic decays, misID photons)
  - Merged $\pi^0 \rightarrow \gamma\gamma$ (overlapping showers)
- Multivariate selection based on isolation variables: photons required to be isolated from nearby tracks and neutral calorimetric activity

LHCb-PAPER-2025-012 in preparation



Search for ALP $\rightarrow \gamma\gamma$: results



NEW!
LHCb-PAPER-2025-012

Model independent upper limit @95% CL on $\sigma(pp \to aX) \times \mathcal{B}(a \to \gamma\gamma)$ as function of di-photon mass

Additional results exploiting similar strategy and signal selection:

- **Search for $B^0_{(s)} \to \gamma\gamma$ decays, sensitive to NP contributions**

  $\mathcal{B}(B^0_s \to \gamma\gamma) < 2.68 \times 10^{-5}$

  $\mathcal{B}(B^0 \to \gamma\gamma) < 0.83 \times 10^{-5}$

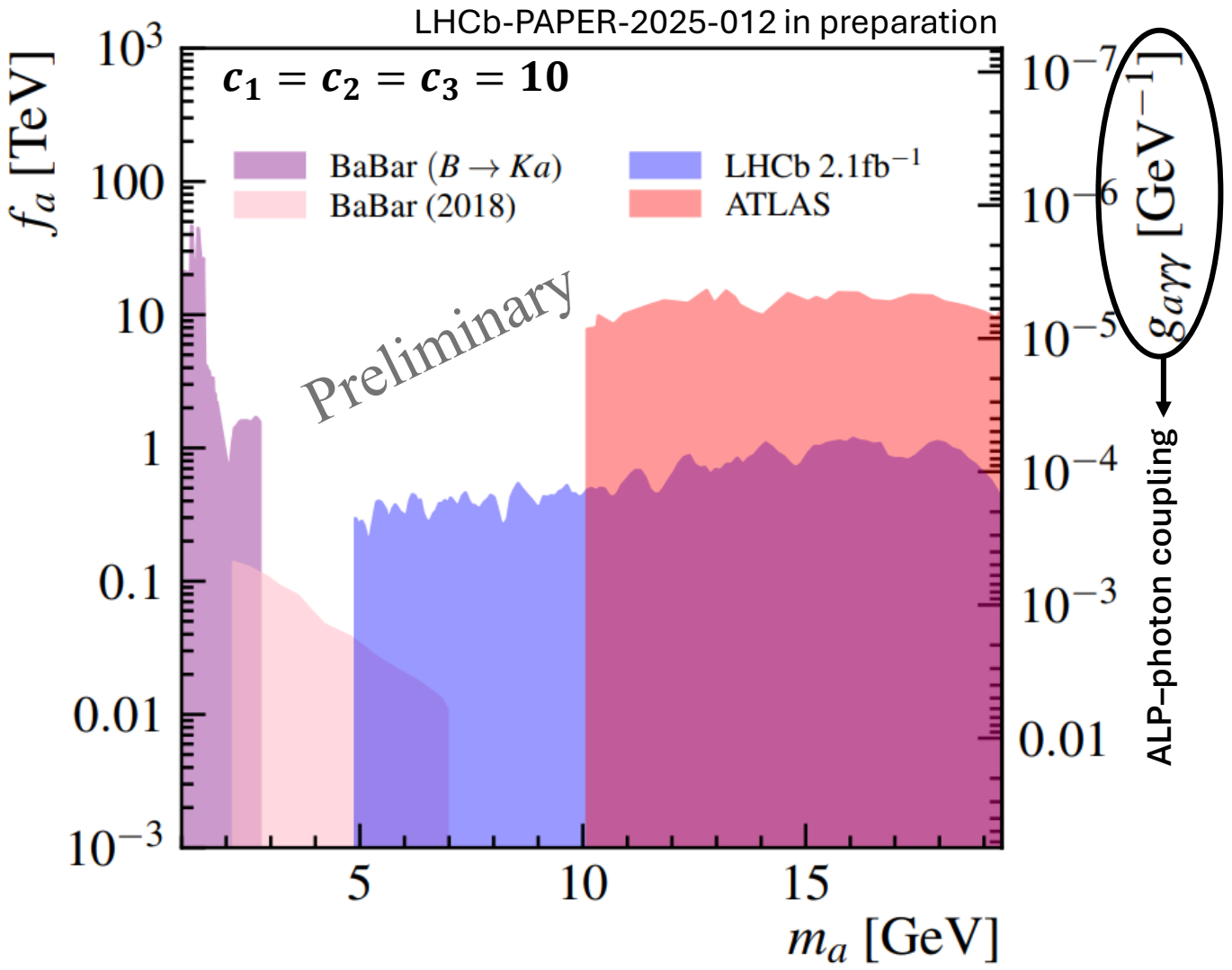
  @95% CL
  Improves previous LHCb limit

- **Search for $\eta_b \to \gamma\gamma$ decay**

  $\sigma(pp \to \eta_b X) \times \mathcal{B}(\eta_b \to \gamma\gamma) < 765\,\text{pb}$ @95% CL

  First search in hadronic environment

Search for ALP $\rightarrow \gamma\gamma$: interpretation



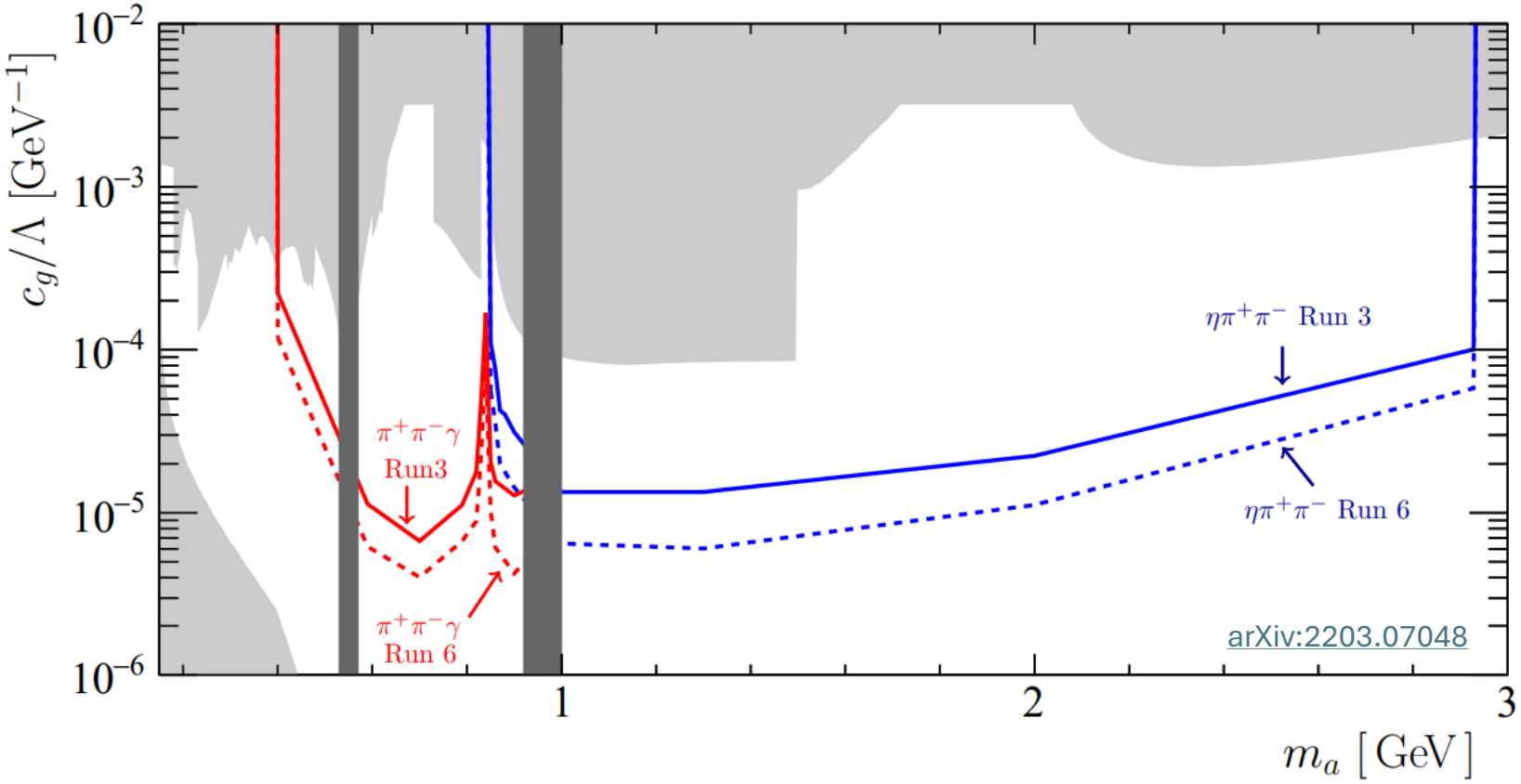
- Results interpreted as lower limits on symmetry breaking scale as function of ALP mass
- Probes of wide region of parameter space not explored so far

Best limit in the [4.9, 10] GeV mass range

arXiv:2203.07048

ALPs future: Run 3 and beyond

LHCb can extend sensitivity exploiting different decay channels



- **ALP coupling to gluons**

$$\mathcal{L} \supset -\frac{4\pi\alpha_s c_g}{\Lambda} a G^{\mu\nu}\tilde{G}_{\mu\nu}$$

- **Searches for**
  $a \rightarrow \pi\pi\{\pi^0, \gamma, \eta\}$

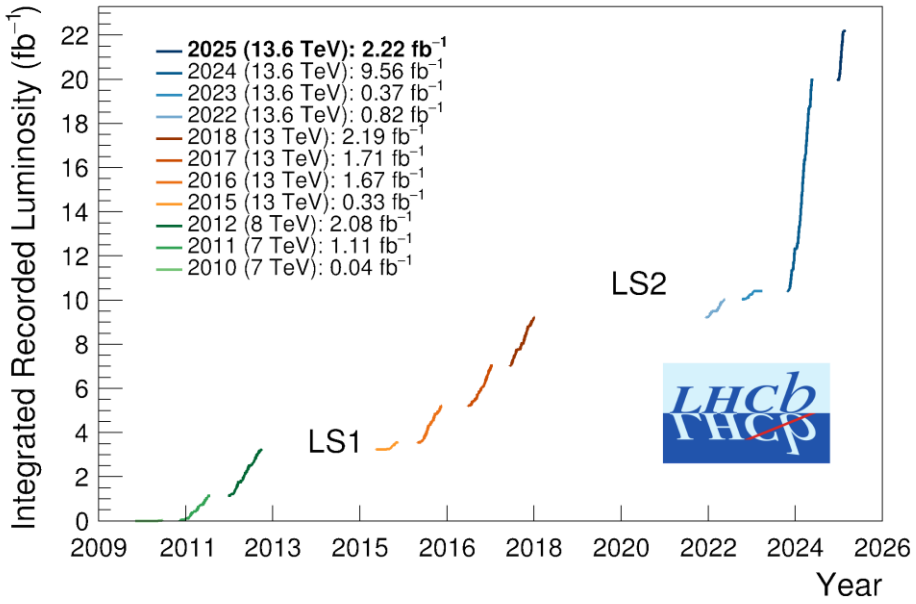
Conclusions

- LHCb has an extensive program of searches in dark sector
  - Excellent vertexing and tracking
  - Unique ability to trigger low-pT and low-mass signatures

- Performed searches for dark photon and dark scalar from b-decays using Run 1-2 datasets

- New search for ALPs in di-photon final state with 2018 data

- Exciting prospects for searches with Run 3 data:
  - Larger statistics
  - Removal of hardware trigger
  - Increased vertex resolution and tracking capabilities
  - Better ID on muons and electrons



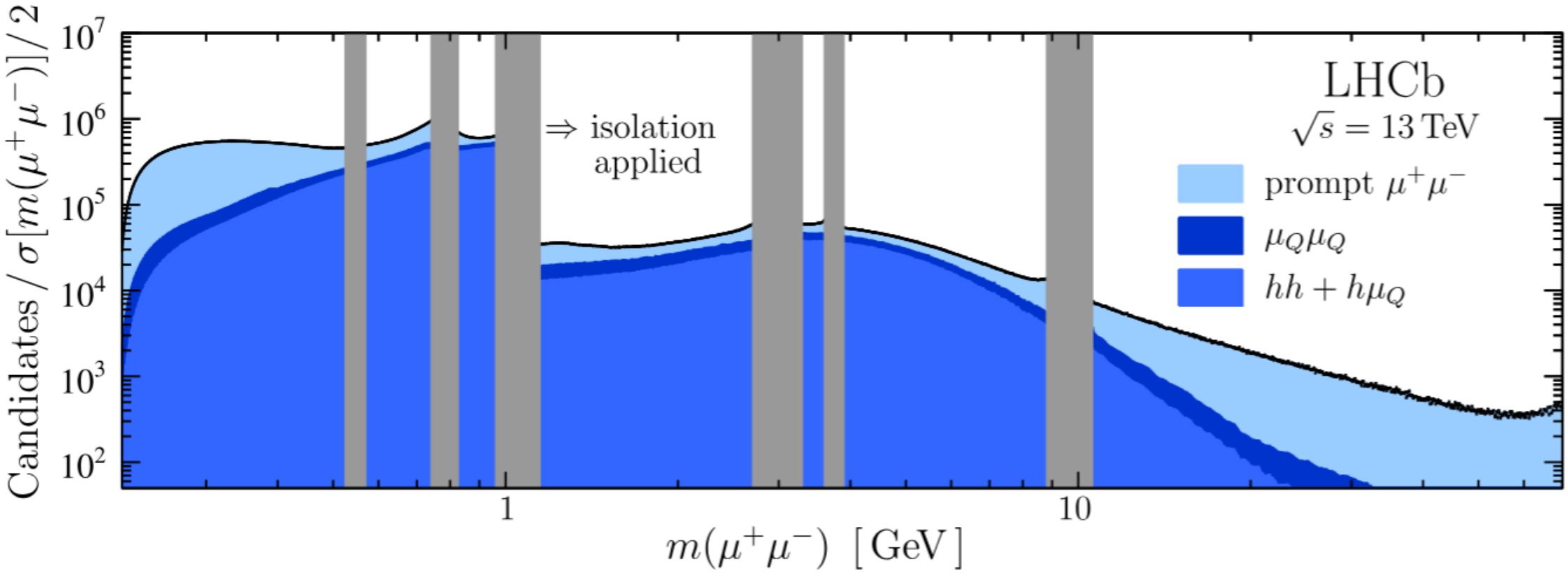
Backup slides

Dark photon kinetic mixing

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

- The kinetic mixing term induces an effective coupling between dark photon and the electromagnetic current of the SM
- The dark photon can be produced in processes where one would normally have a virtual photon, with a rate reduced by a factor ε

Dark photon: prompt mass spectrum



Scalar portal

$$\mathcal{L} \supset -\frac{1}{2} m_\chi^2 \chi^2 - \theta\, \chi H^\dagger H$$

- The electroweak symmetry breaking induces mixing between H and χ, with amplitude proportional to θ
- The χ boson inherits the couplings of the Higgs boson, but suppressed by a factor of θ
- In particular, it interacts with SM fermions with a Yukawa-like term