FIP / LLP searches at LHCb

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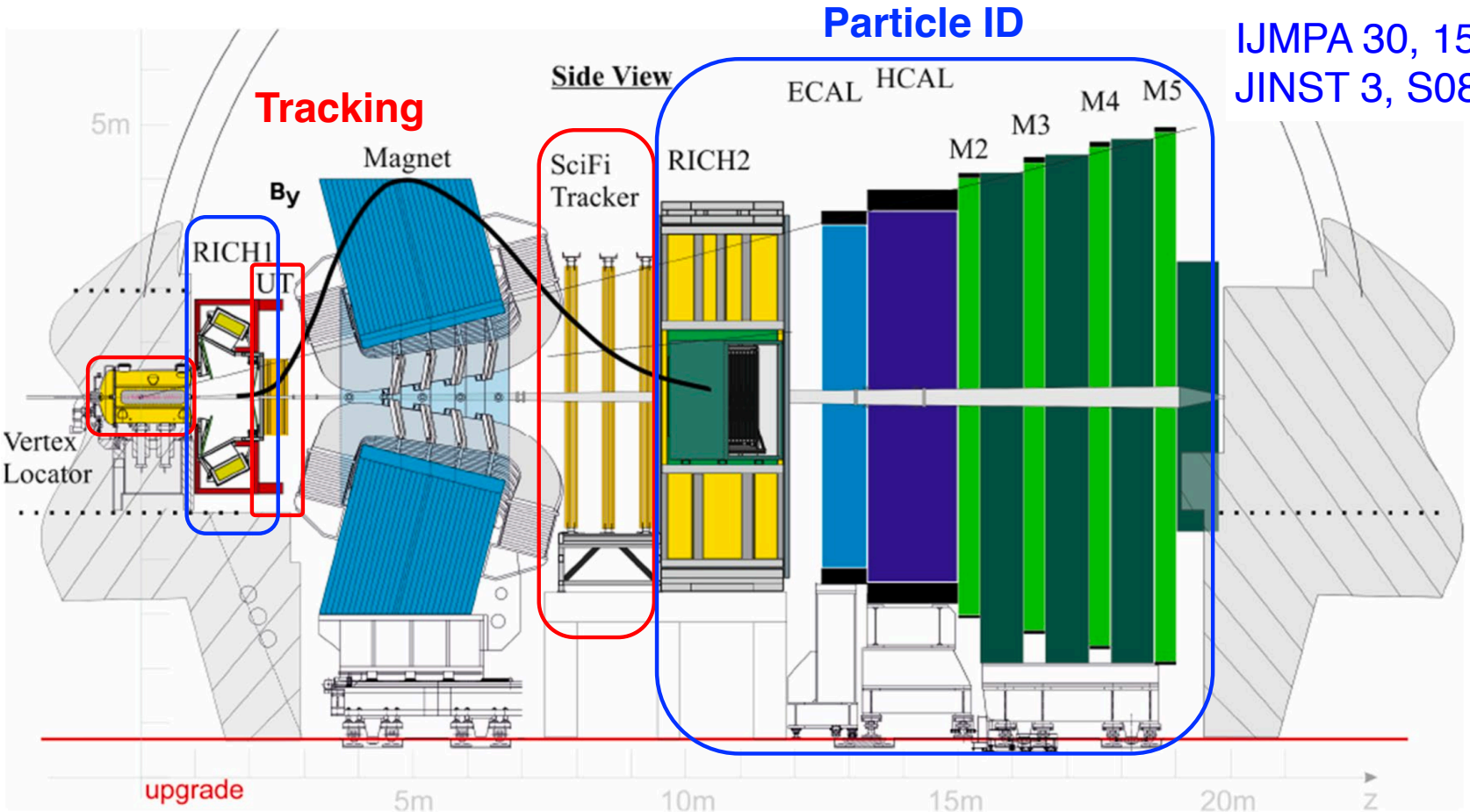
Nikhef, Amsterdam

on behalf of the LHCb collaboration

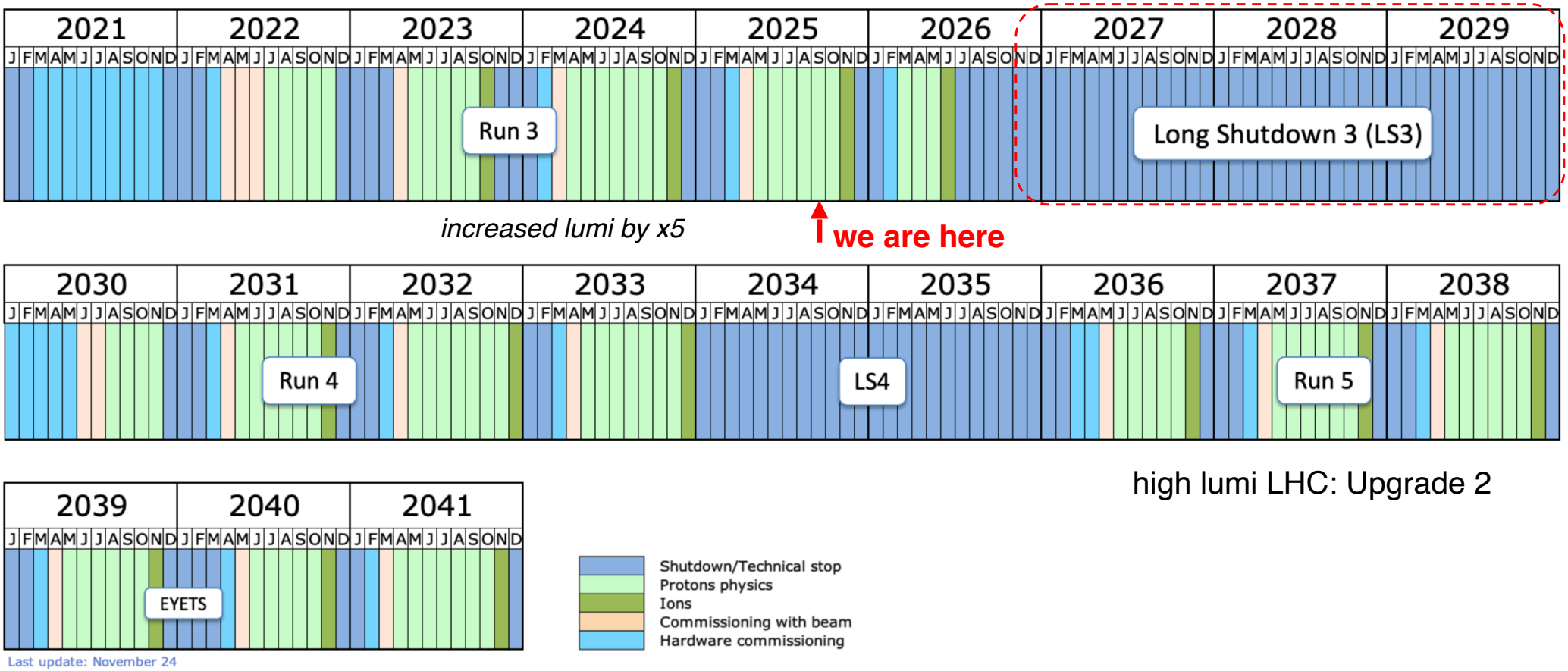
Light Dark World 2025
Madrid, September 16th, 2025

LHCb detector



- Forward spectrometer, designed as the *b*-physics experiment at the LHC
- Precise vertex reconstruction with VELO
- Powerful $p/K/\pi$ separation using RICH detectors
- Coverage complementary to ATLAS and CMS in p_{T} and η
- **Unique sensitivity for light LLPs / FIPs in O(GeV) range**

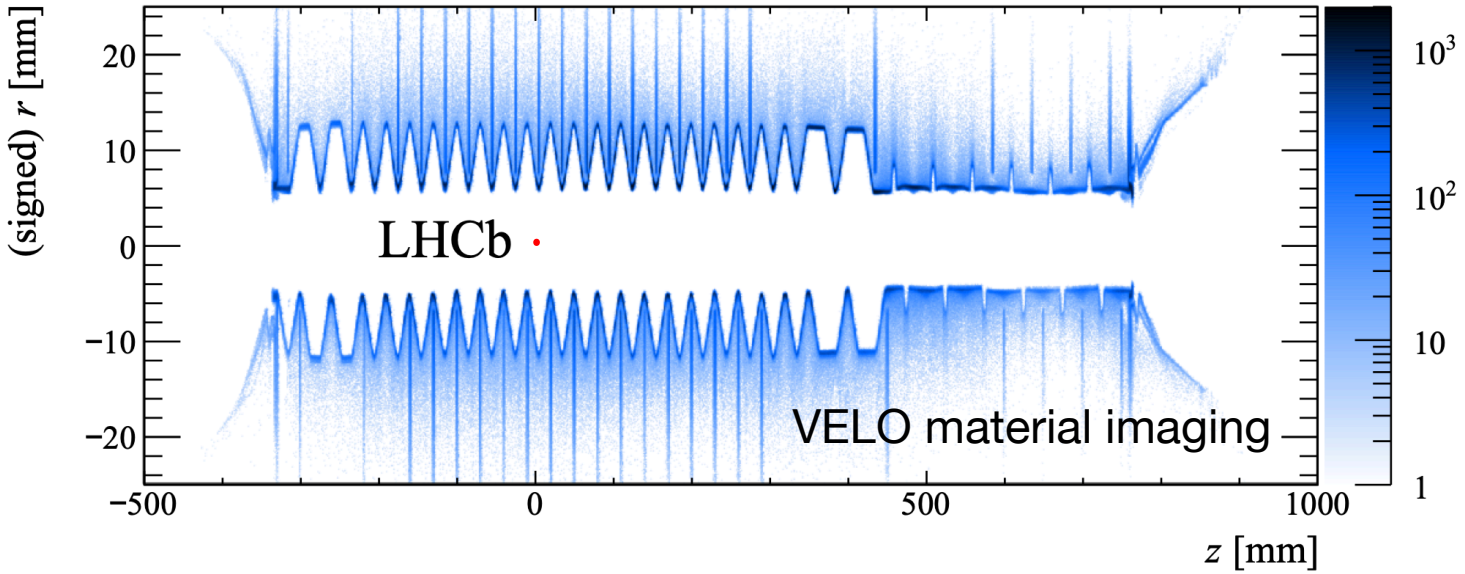
LHCb in long term



- Run 3: main physics using 2024 + 2025 + 2026 data
- Run 4: add new complex triggers on GPUs
- Run 5: Upgrade 2 – completely new detector, scoping document this year

LLP searches at LHCb

So far focused on signatures within VELO volume



JINST 13 (2018) 06, P06008

- Displacement of ~30 cm
  **decays of B-mesons with $\tau = 1.5\ ps$ correspond to displacement of $O(mm)$*
- Thin VELO envelope (RF foil) - backgrounds
  - heavy flavor decays at *r < 5 mm*
  - material interactions at *r > 5 mm*
- Precise material veto thanks to imaging using vertices from secondary particles
- **Can be extended to downstream region**

LLP searches at LHCb

Displaced leptons

- Dark photon — PRL 120 (2018) 061801, PRL 124 (2020) 041801
- Low-mass dimuon resonances — JHEP 10 (2020) 156
- (heavy) LLPs decaying to $e^{\pm}\mu^{\pm}\nu$ — EPJC 81 (2021) 261
- Majorana neutrino — PRL 112 (2014) 131802
- Light boson from $b \to s$ decays — PRL 115 (2015) 161802, PRD 95 (2017) 071101

Displaced jets

- HNL in $W^{\pm} \to \mu^{+}\mu^{\pm}jet$ — EPJC 81 (2021) 248
- LLP → *jet jet* — EPJC 77 (2017) 812
- LLP → μ + *jets* — EPJC 77 (2017) 224

Fully neutral:

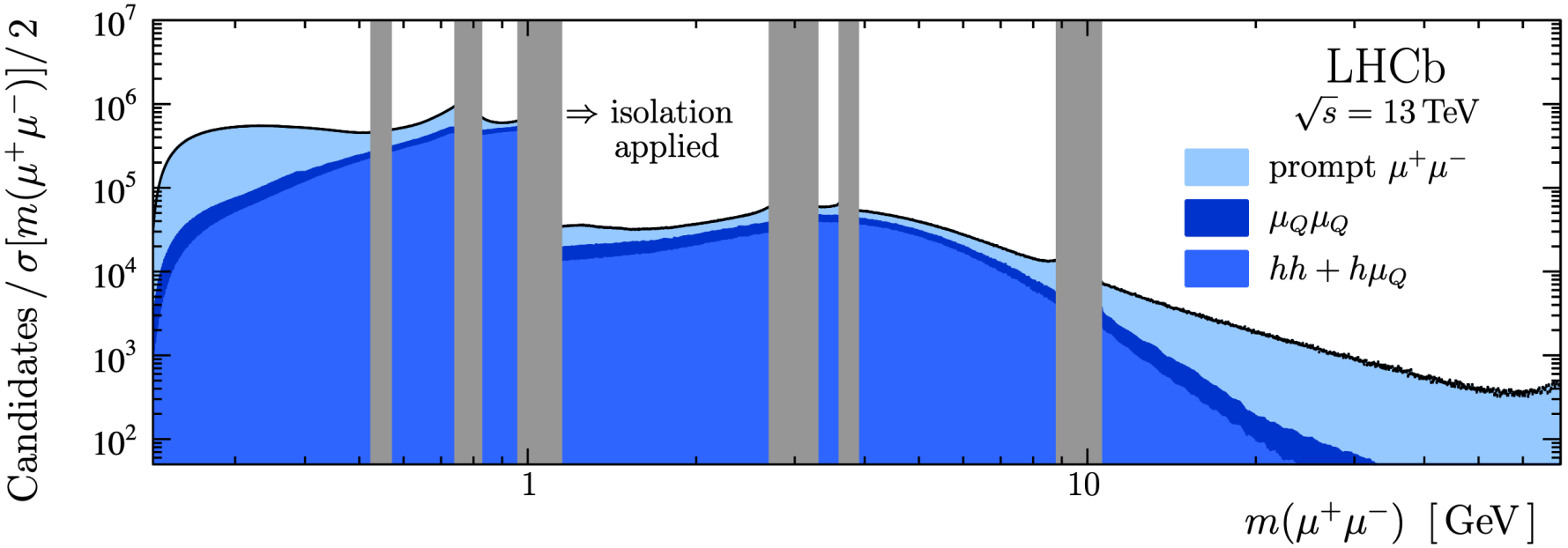
Low mass ALPs: Search for resonances decaying to photon pairs 2507.14390

Dark photons in di-muon spectrum

- Light dark photon can appear in a mixing with off-shell photon
  - large fraction in forward region, low p_T

- Normalized to off-shell photons
  - no need for efficiencies (for prompt search)

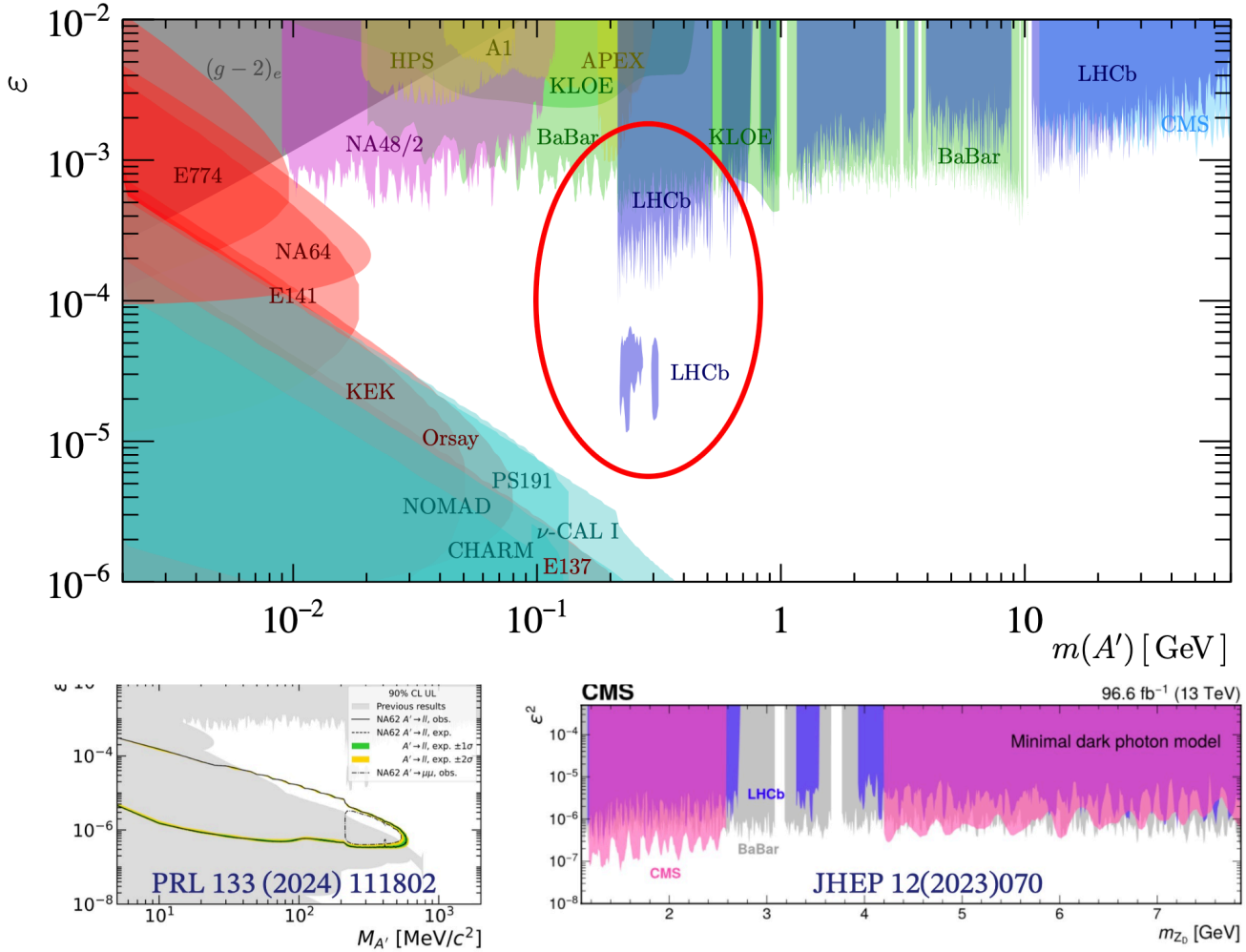
PRL 124 (2020) 041801



- Bump hunt analysis, regions of SM resonances removed
- Search for **both prompt and displaced** signatures using Run 2 data

Dark photons in di-muon spectrum

PRL 124 (2020) 041801

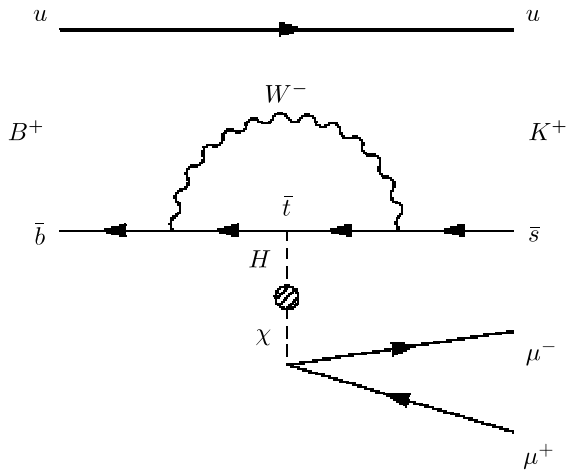


- World's best upper limits for inv. mass range of **~200-700 MeV (prompt)**
- First displaced search not from beam-dump experiments
  - explored invariant mass range: **214-350 MeV**
- Re-casted to non-minimal models

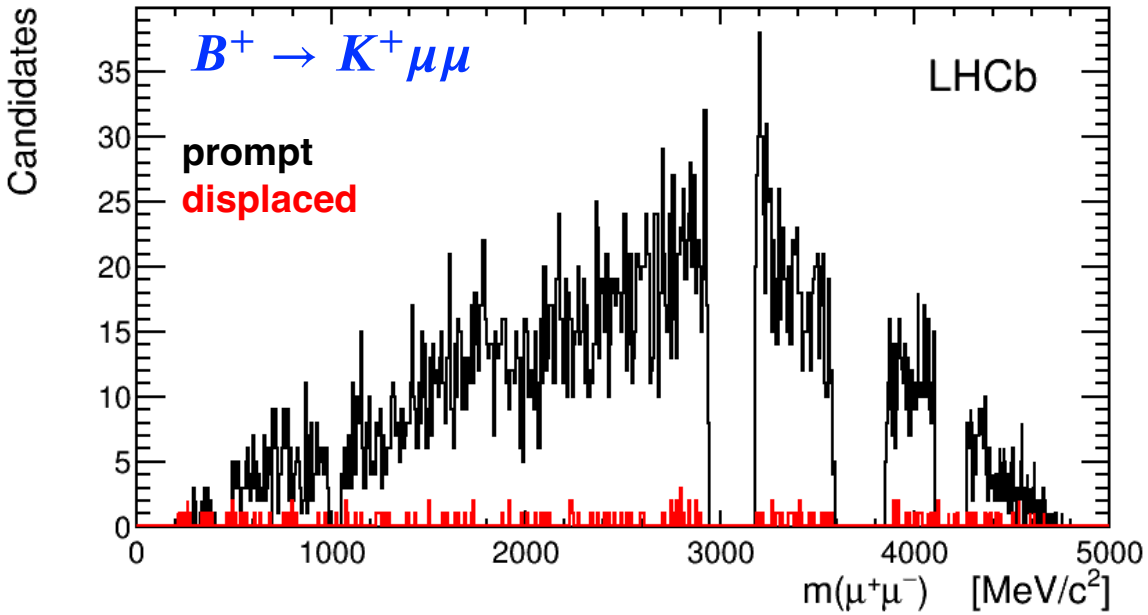
Light boson in $b \to s$ decays

- Light boson can contribute to $b \to s\mu\mu$ penguin decays

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



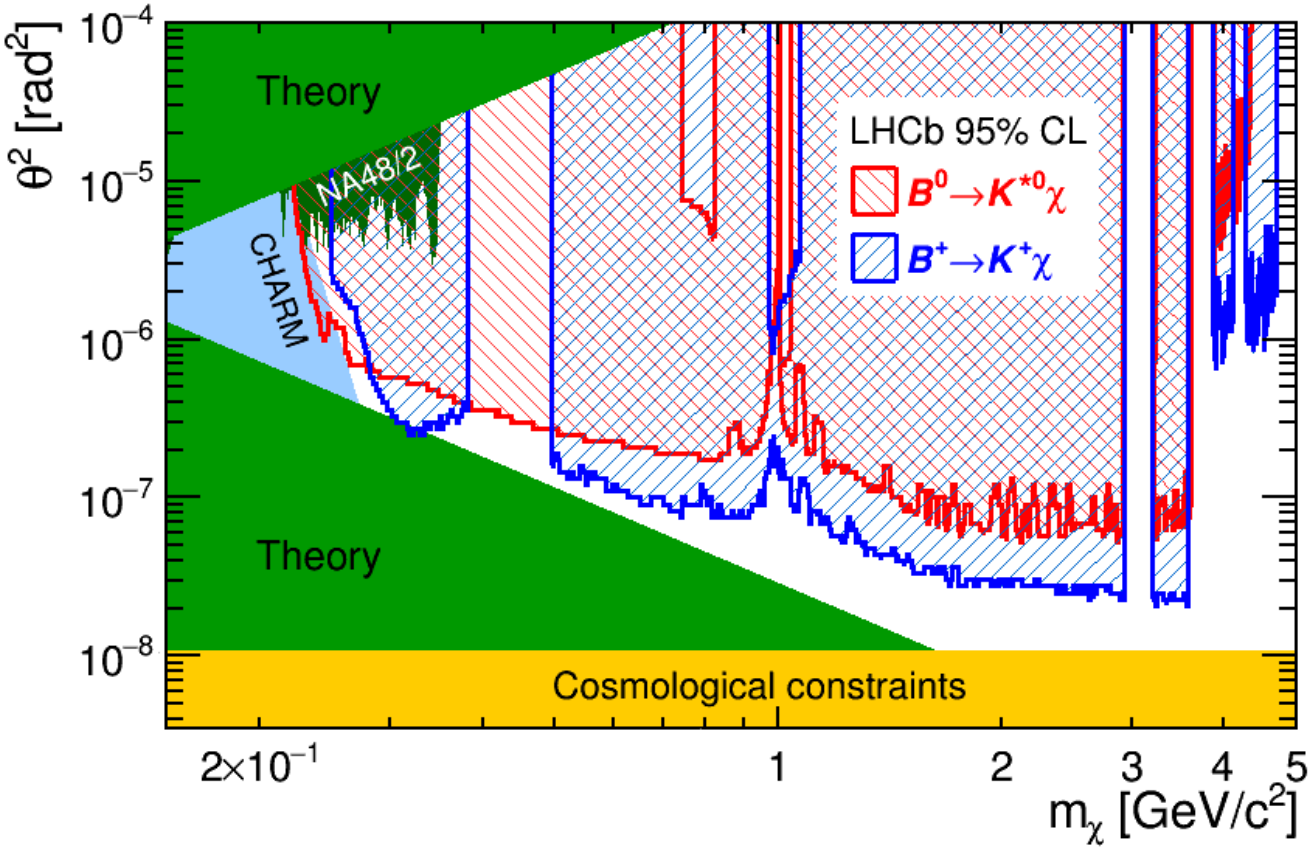
- LHCb has world's largest sample of $b \to s\mu\mu$ decays
- Study of di-muon spectrum



Light boson in $b \to s$ decays

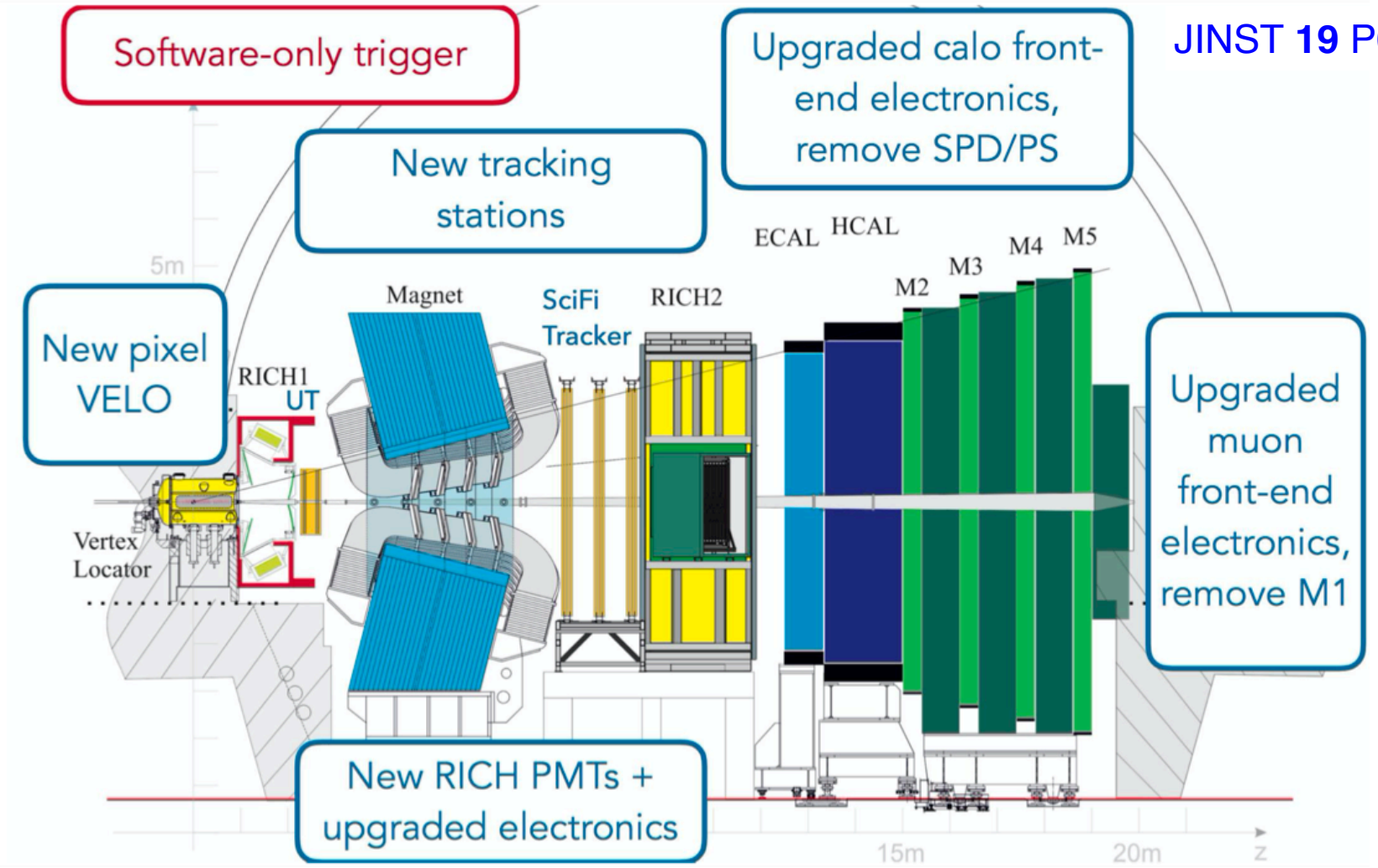
- Search for a narrow di-muon peak
- Displacement of muon pair is considered
- Upper limits on mixing with SM Higgs

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



- **World's best upper limits below $2m_\tau$**

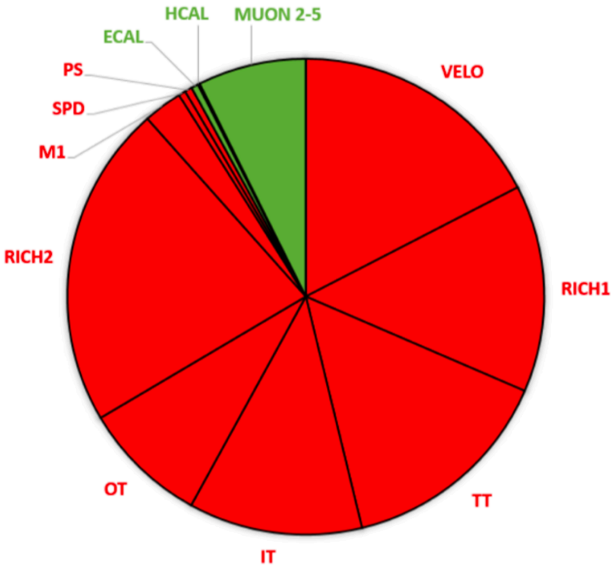
Upgraded LHCb



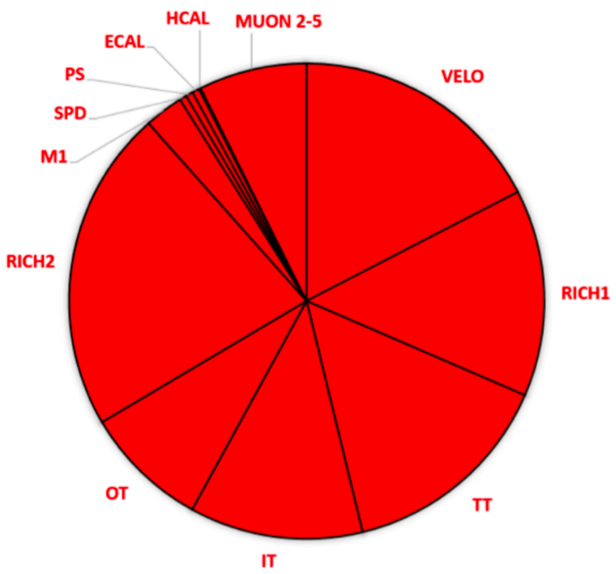
Major detector upgrade for Run 3 and 4

x5 larger instantaneous luminosity compared to Run 1 and 2

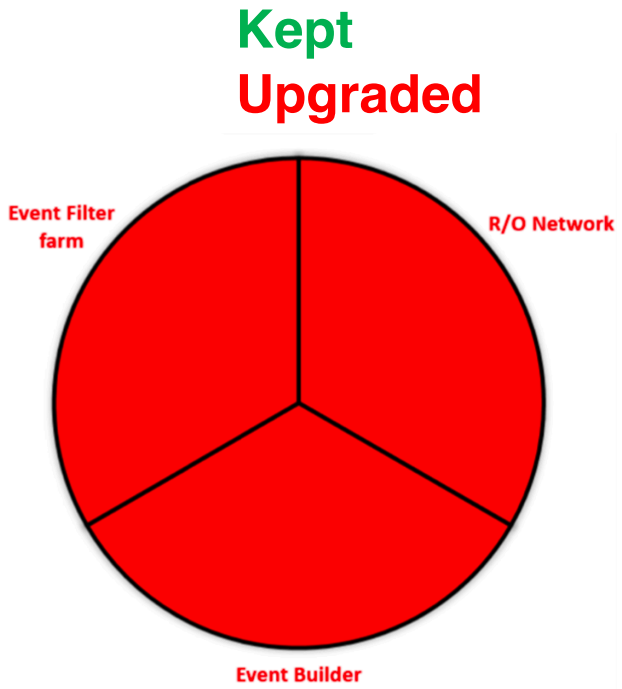
Upgraded LHCb



Detector channels



R/O electronics



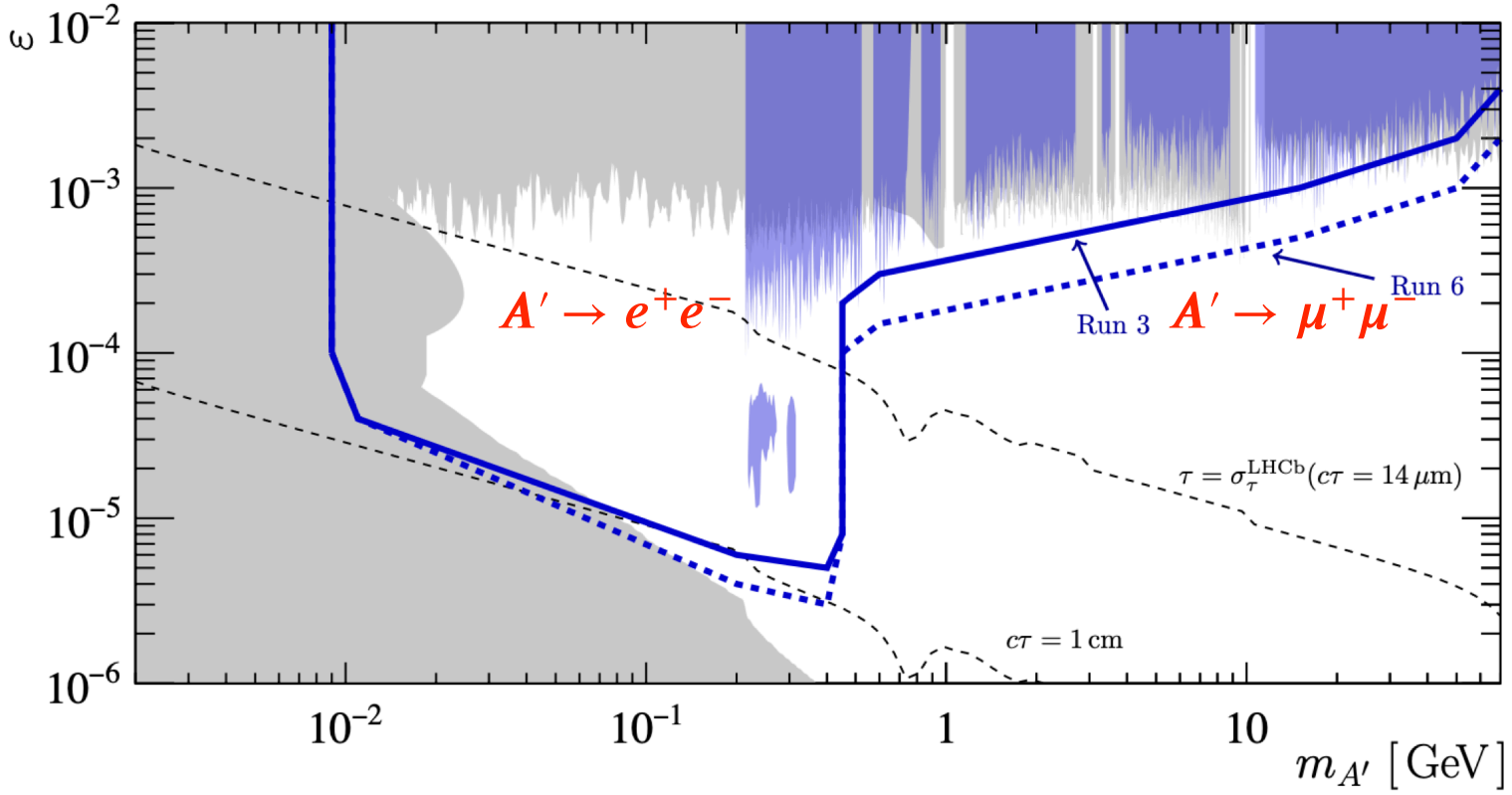
DAQ

- Most of electronics replaced
- No hardware trigger, read-out at 30 MHz
- **Fully software online trigger on GPUs**
- Allows much increased sensitivity for LLP searches with dedicated triggers

Dark photons: new muon and electron ID

- In Run 3 LHCb is covering both di-muon and di-electron modes

arXiv:2203.07048



- Better tracking-based **muon ID** - large improvement at low momentum
- Much smaller mis-id for both muons and electrons
- **Expecting greatly improved sensitivity at very low masses**

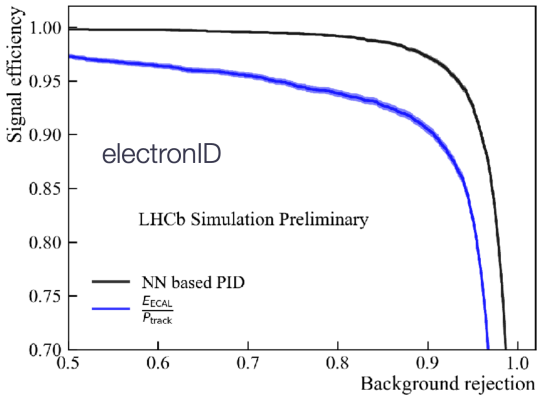
Dark photons: new muon and electron ID

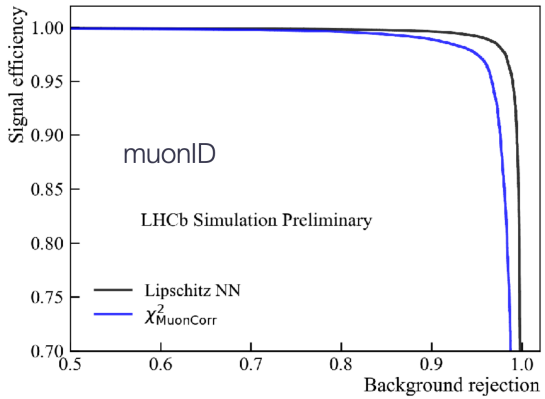
- Performance of lepton ID

  with smooth and fast Lipshitz NN

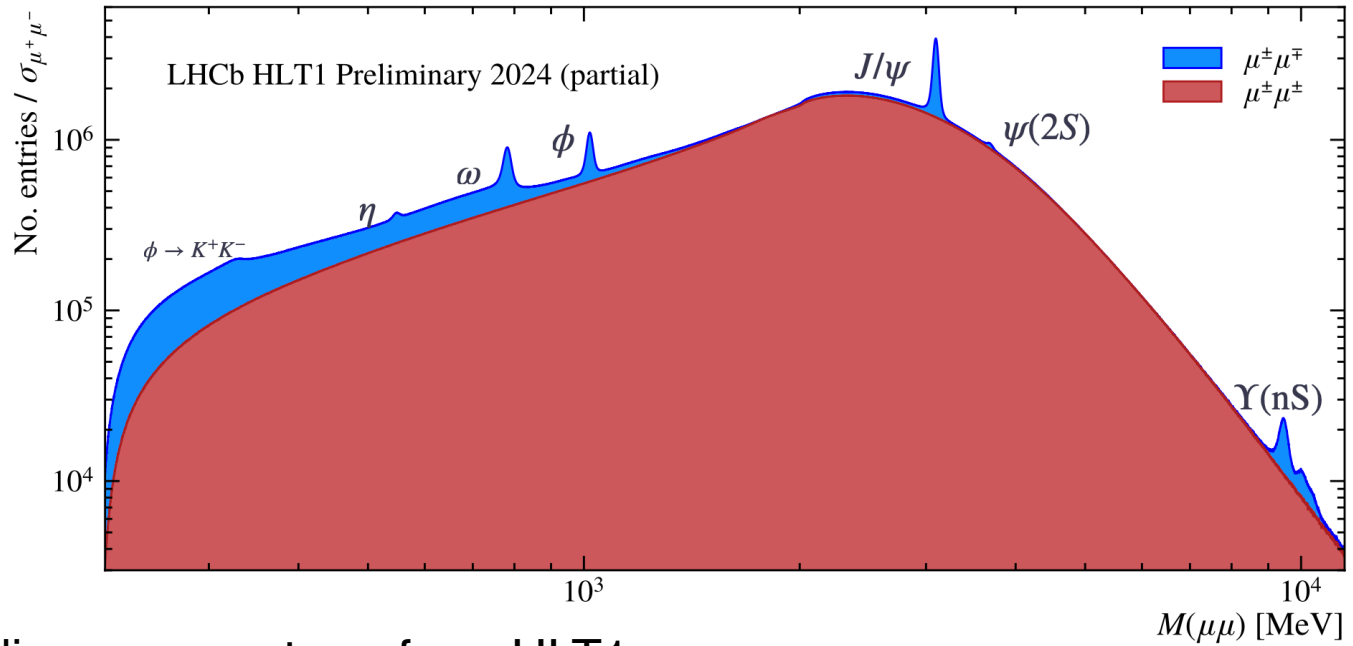
Run 3, PID in real time

LHCb-FIGURE-2024-029





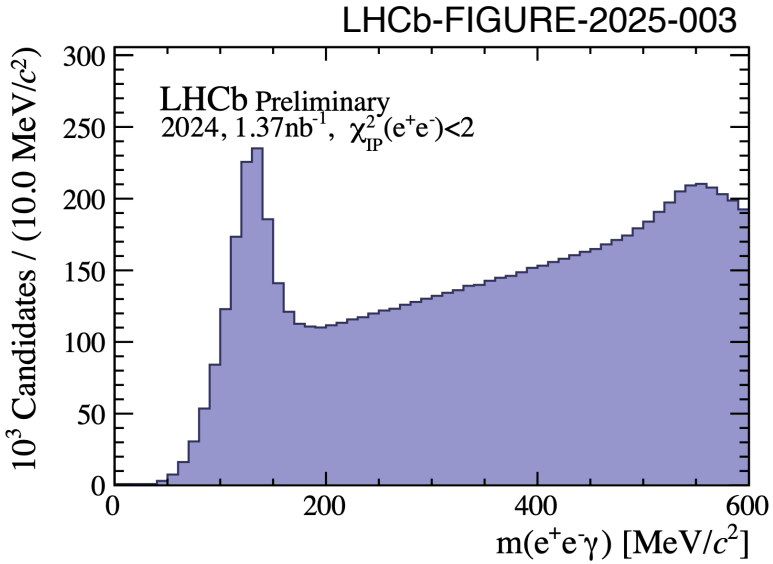
LHCb-FIGURE-2024-029



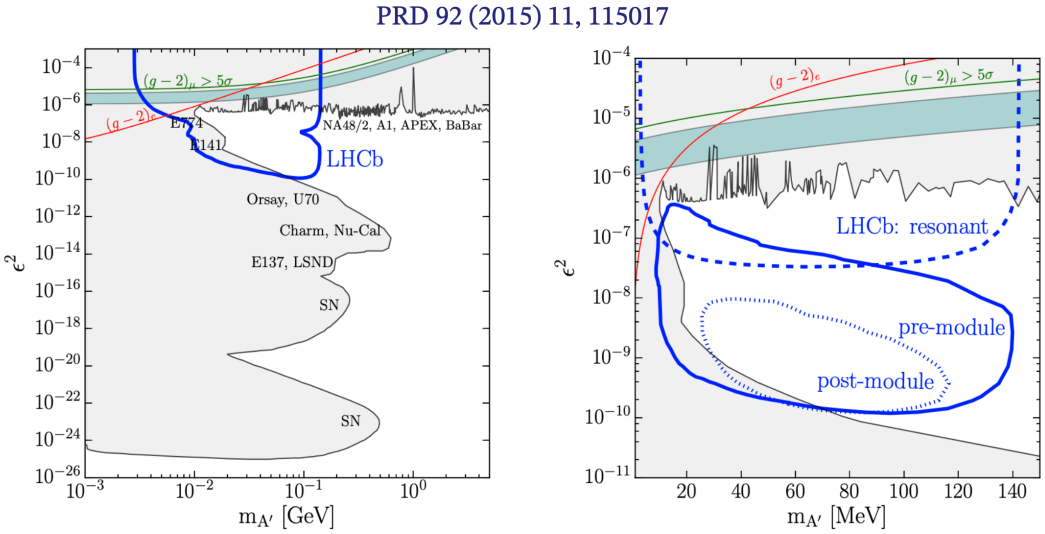
- Prompt di-muon spectrum from HLT1
- **x20 more $\eta \to \mu\mu$ per fb^{-1} compared to Run 2**

Dark Photons in di-electron mode

- Search in $\pi^0/\eta \to \gamma(A \to e^+e^-)$

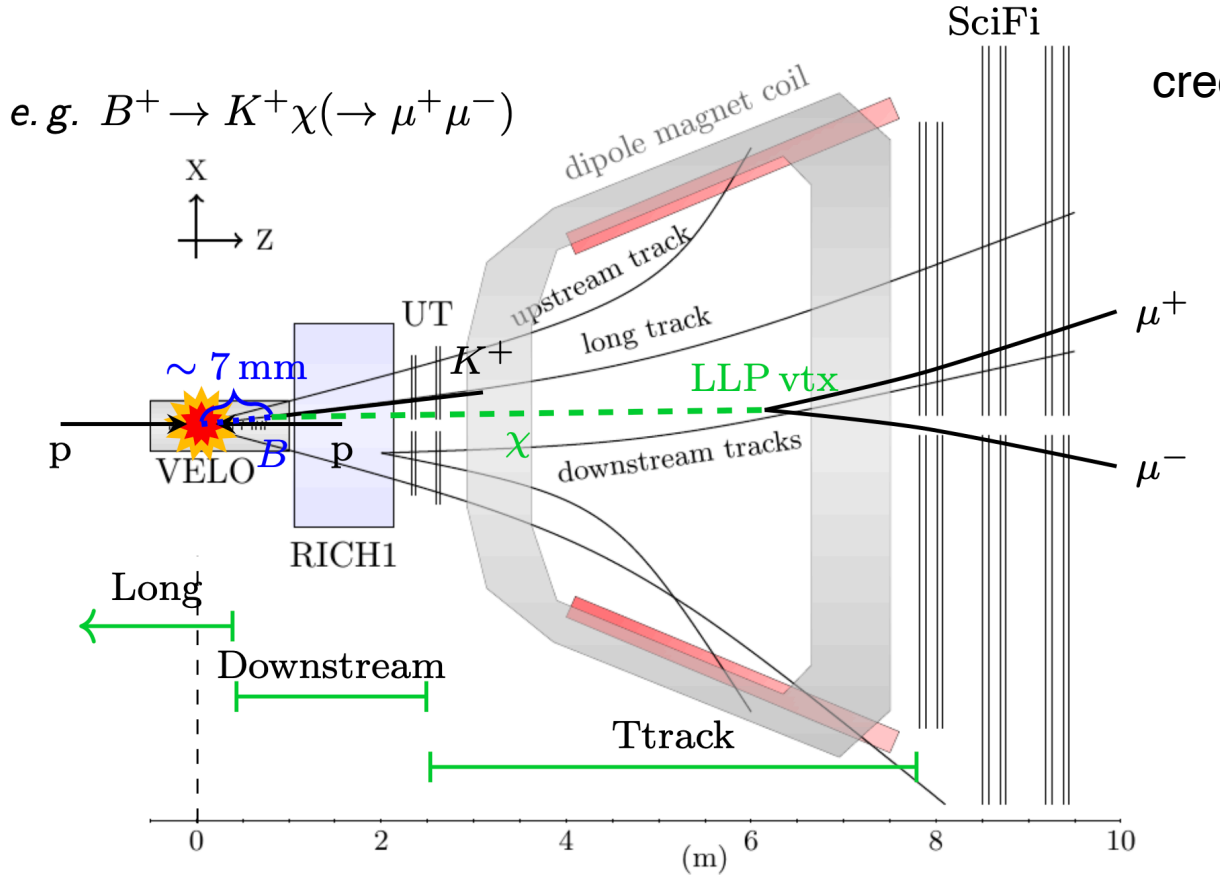


- Search in $D^* \to D^0(A \to e^+e^-)$



- Possible observation of True Muonium with Run 3 data PRD 100, 053003 (2019)

Long-lived particles in Run 3



credit: C. Langenbruch

- Long tracks (Velo+[UT]+SciFi): $z_{\mathrm{LLP\,vtx}} \lesssim 40\,\mathrm{cm}$
- Downstream tracks (UT+SciFi): $z_{\mathrm{LLP\,vtx}} \lesssim 250\,\mathrm{cm}$
- Ttracks (SciFi only): $z_{\mathrm{LLP\,vtx}} \lesssim 780\,\mathrm{cm}$
- In all cases control of backgrounds is crucial

larger acceptance

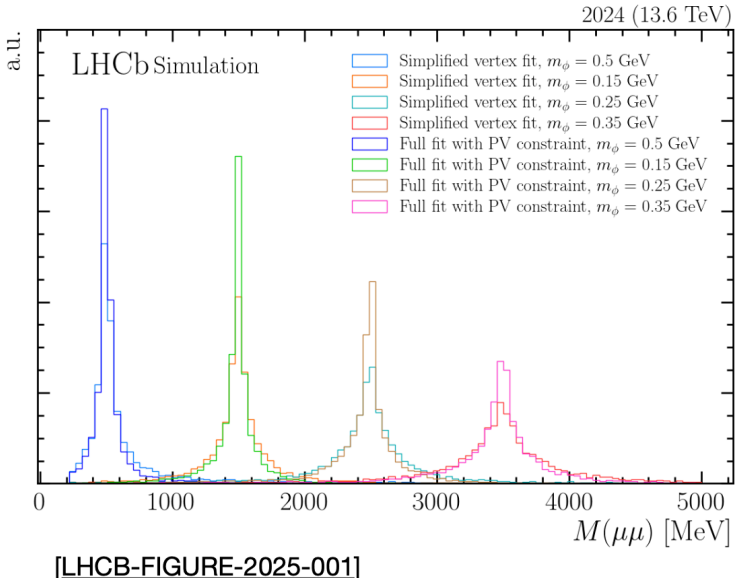
better resolution

Very long-lived particles : Dark Scalar

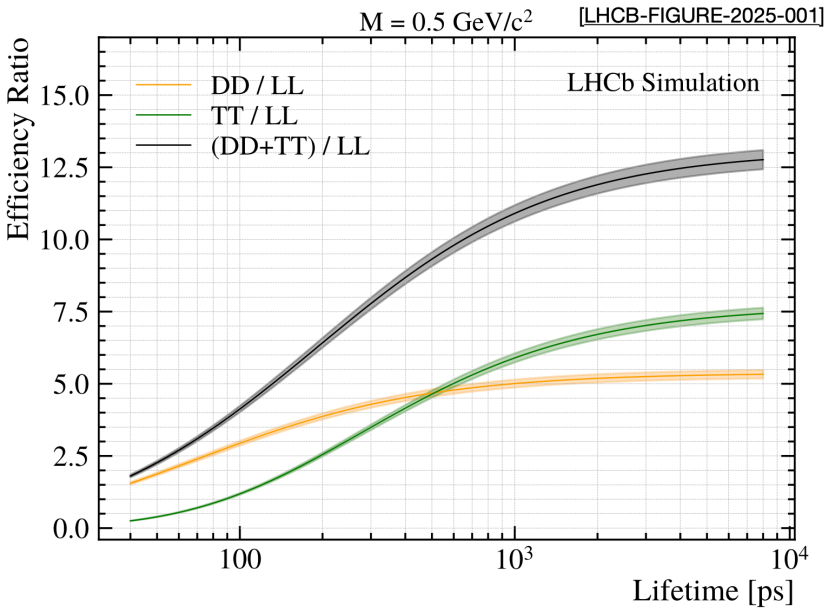
- Following on Dark Scalar in $b \to s$ **transitions**
- Focus on **di-muon signature** at first

- The invariant mass resolution is limited

- Sensitivity for **lifetimes of O(10 ns)**:
  up *x10* gain in efficiency



[LHCB-FIGURE-2025-001]

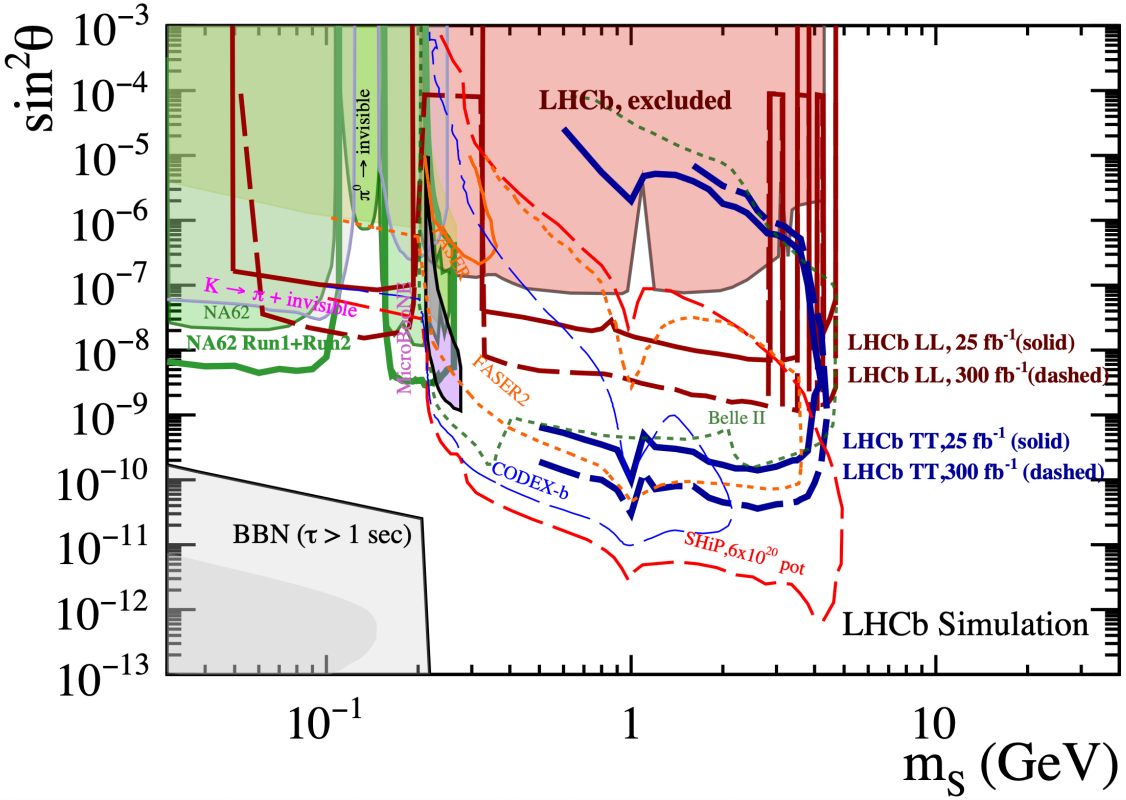


Very long-lived particles : Dark Scalar

- Dark Scalar can be found in $b \to s$ **transitions**
- Focus on **di-muon signature** at first

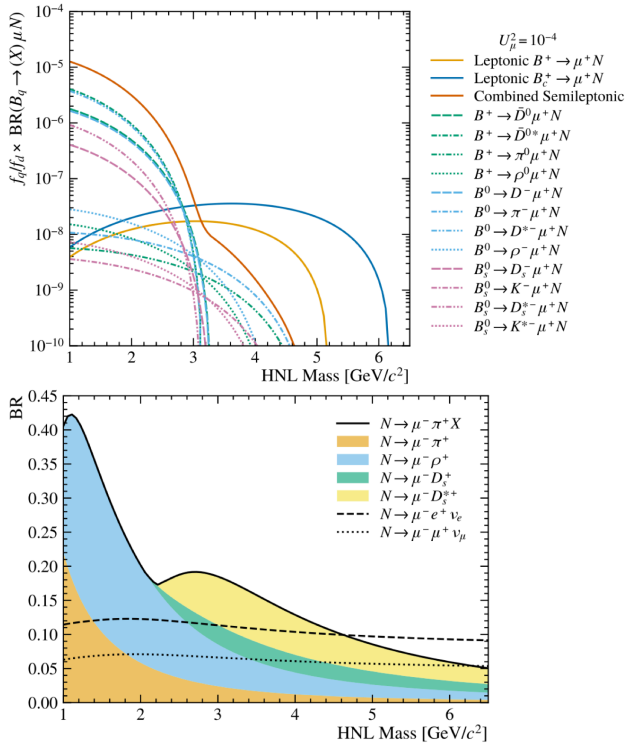
- The invariant mass resolution is limited

- Sensitivity for **lifetimes of O(10 ns)**:
  up *x10* gain in efficiency
- **Efficiency projection** (zero background)

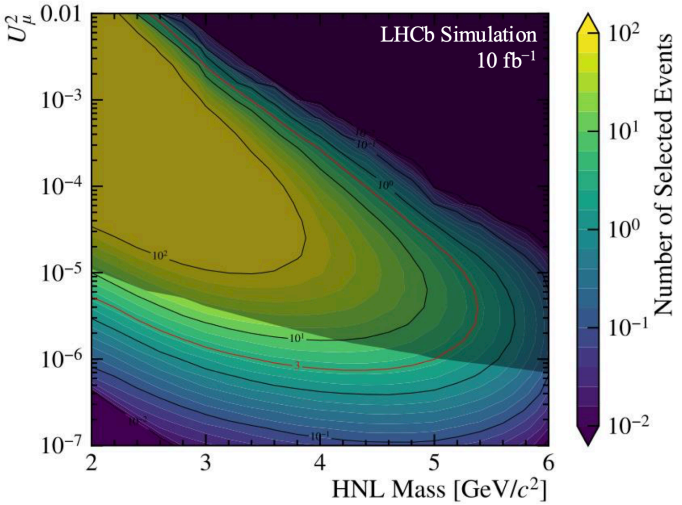


Very displaced Heavy Neutral Leptons

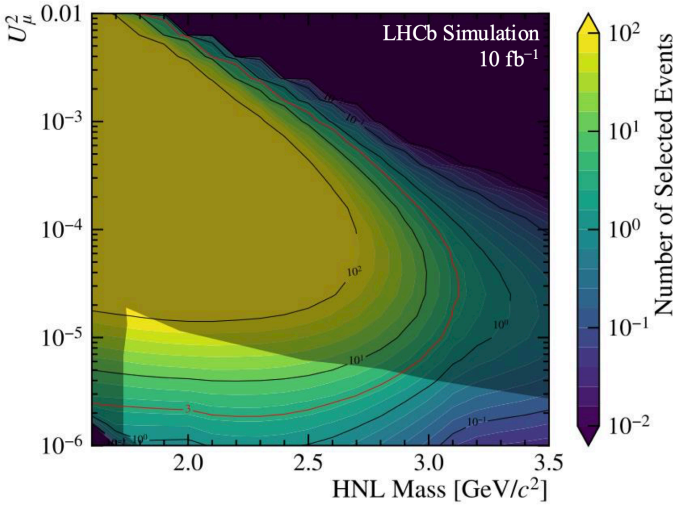
- Theory input on HNL production in *b*-decays
- Similar benefits at very large lifetimes with downstream and T-tracks
- **Best sensitivity around 2-5 GeV**
- Sensitivity for HNL originating from B_c decays : unique opportunities at LHCb



Data: Bondarenko *et al.* 2018 [10.1007/JHEP11(2018)032]



Leptonic B_c and B_u production with downstream tracks, $N \to \mu\pi[X]$, $N \to \mu\mu\nu_\mu$ and $N \to \mu e\nu_e$

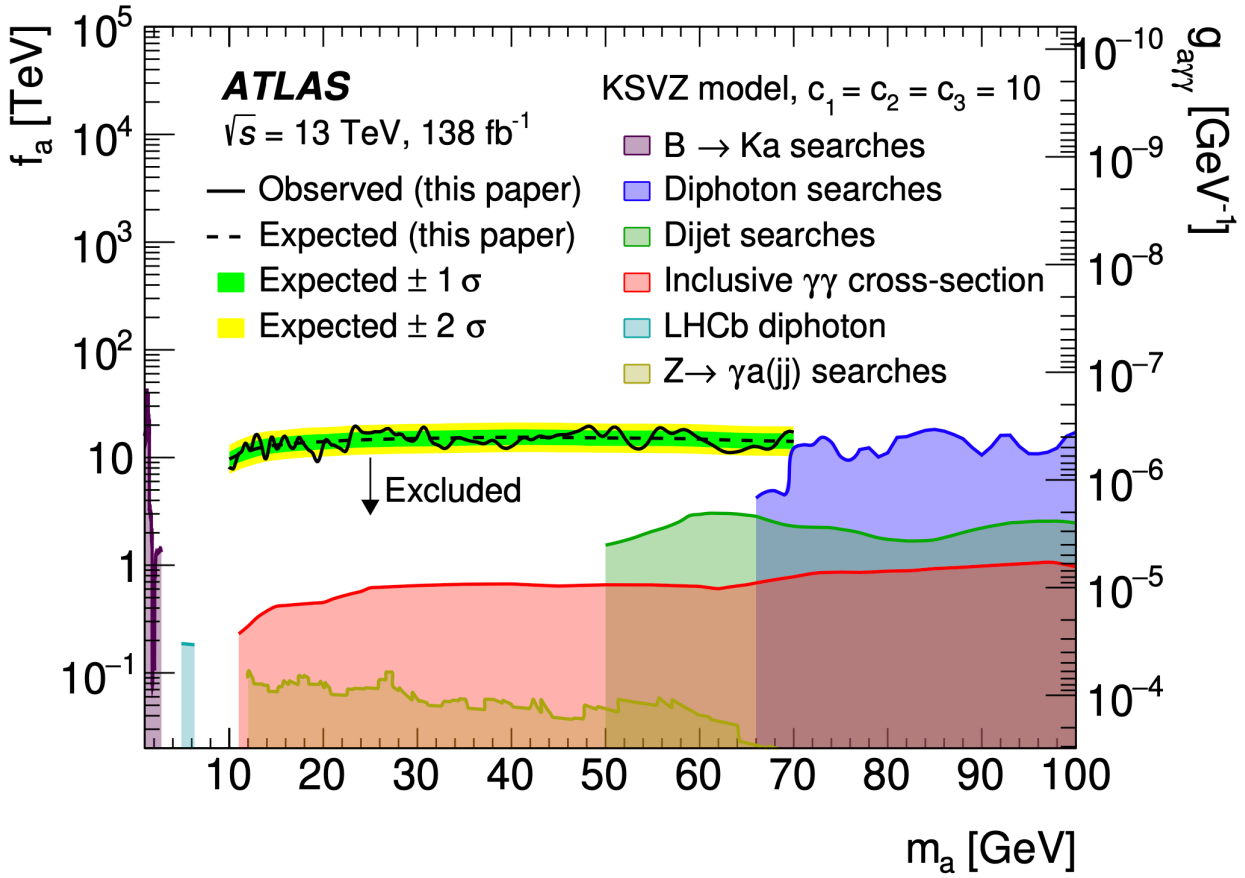


Semileptonic combined production with T tracks, $N \to \mu\pi[X]$, $N \to \mu\mu\nu_\mu$ and $N \to \mu e\nu_e$

Non leptonic signatures

Low mass ALP searches at LHC

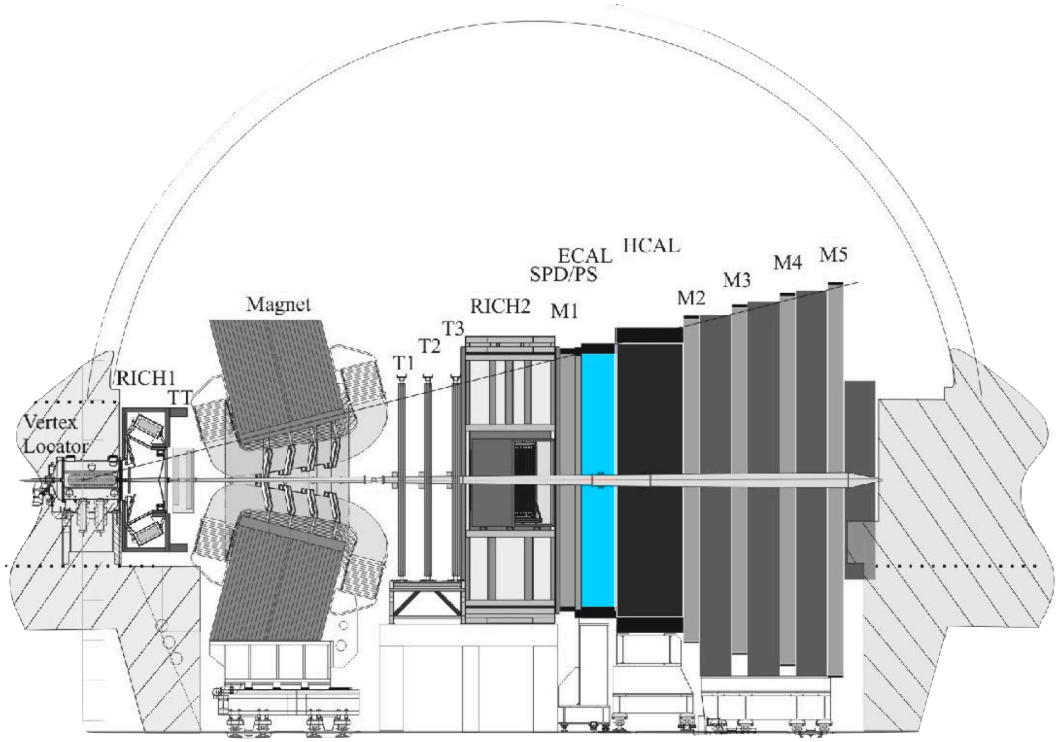
2507.14390



- Recent search by ATLAS using $\gamma\gamma$ provides **strong limits down to ~10 GeV**
  JHEP 07 (2023) 155
- Best limits around 5 GeV JHEP 01 (2019) 113
  using (small) LHCb open data set intended for the $B_s^0 \to \gamma\gamma$ **search**
- LHCb to cover broader low mass range below 10 GeV with **dedicated di-photon search**
- Future opportunities at LHCb and Belle 2 by exploiting hadronic signatures of ALPs

Search for resonances decaying to photon pairs

2507.14390



Photon reconstruction

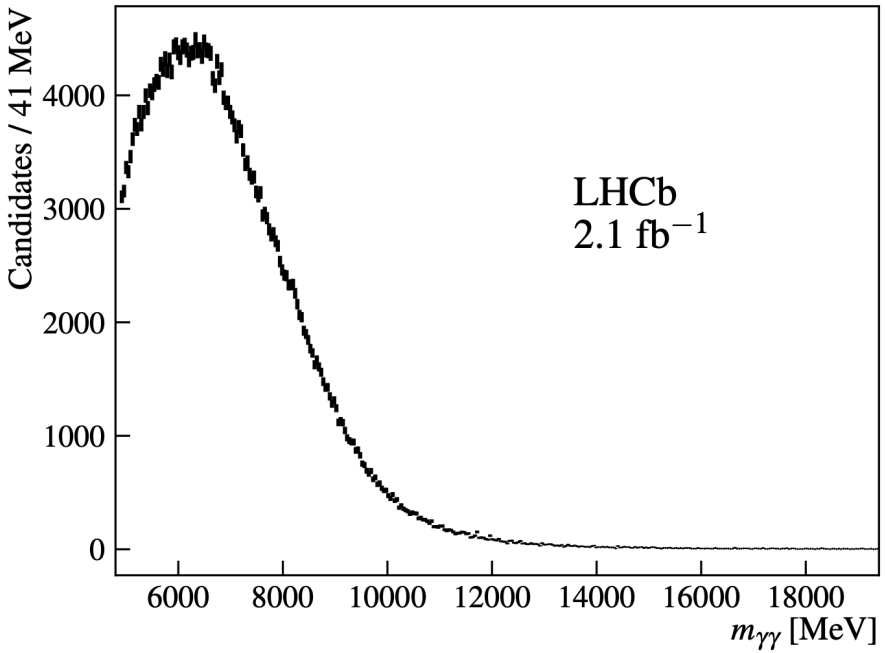
- Reconstructed from energy deposits in ECAL
- No secondary vertex information – photons are assumed to come from the PV
- No significant energy smearing for lifetimes up to 20 ps
- Nominal resolution: $\frac{\sigma_E}{E}$~3%
- Dedicated low mass di-photon triggers in 2018

Search for resonances decaying to photon pairs

2507.14390

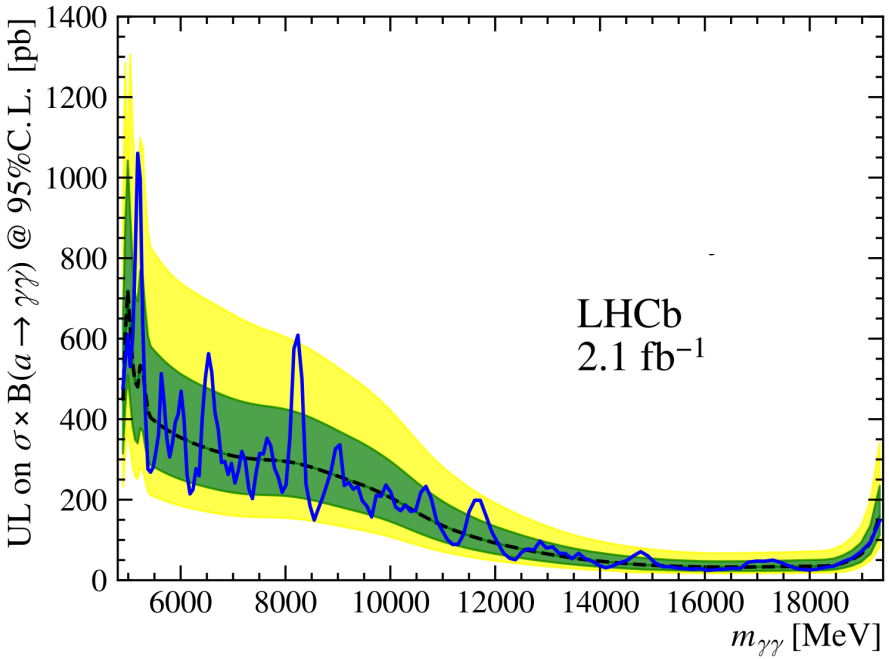
Backgrounds

- No substantial peaking backgrounds are in the considered inv. mass window
- Contributions from *b*- and *c*- hadrons found to be negligible compared to the background level
- Combinatorial photons mostly coming from π^0 and η decays



Bump hunt

- Upper limits using CLs method to the [4.9 GeV, 14.9 GeV] range
- The first LHCb analysis using only neutrals in the final state



Search for resonances decaying to photon pairs

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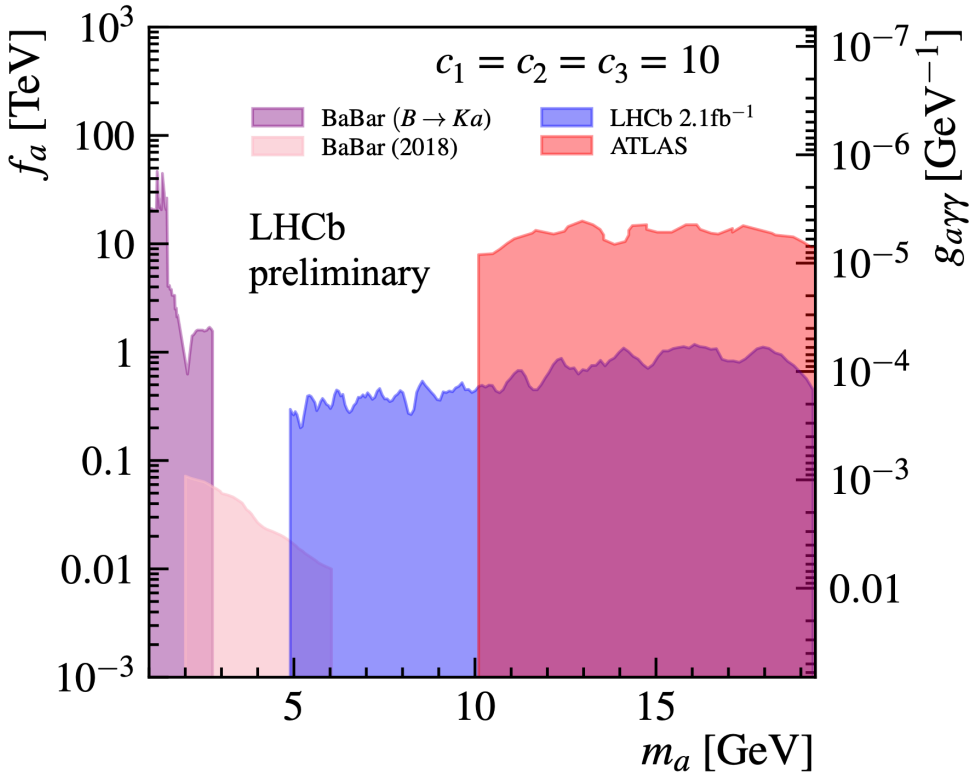

- **Strongest limits by LHCb for ALPs decaying to $\gamma\gamma$ between 4.9 and 10 GeV**
- Stronger limits by ATLAS above 10 GeV
- Also, limits for the SM decays @ 95% CL

$$BR\left(B_s^0 \to \gamma\gamma\right) < 2.68 \times 10^{-5}$$
$$BR\left(B^0 \to \gamma\gamma\right) < 0.8 \times 10^{-5}$$
$$\sigma\left(pp \to \eta_b X\right) \times BR\left(\eta_b \to \gamma\gamma\right) < 765\ pb\ (84\ pb)_{fiducial}$$

first direct limit on ground-state bottomonium production in *pp* collisions

Summary

- LHCb made searches for **dark photon**, **HNLs**, **dark scalar** from *b*-decays using Run 1-2 data set, based on *displaced muon signature*
- **First fully neutral search for ALPs in di-photon mode - best limits below 10 GeV**
- Hadronic signatures remain to be explored with Run 2 and 3 data

- Greatly improved sensitivity thanks to new online GPU trigger with:
  - new lepton ID (both **muons** and **electrons**)
  - tracking for **very long-lived particles**
  - larger statistics

  and has the capabilities to study more complex signatures with dedicated triggers

- **Expecting powerful new searches with Run 3 data**
- **Theory guidance is crucial and very welcome !**