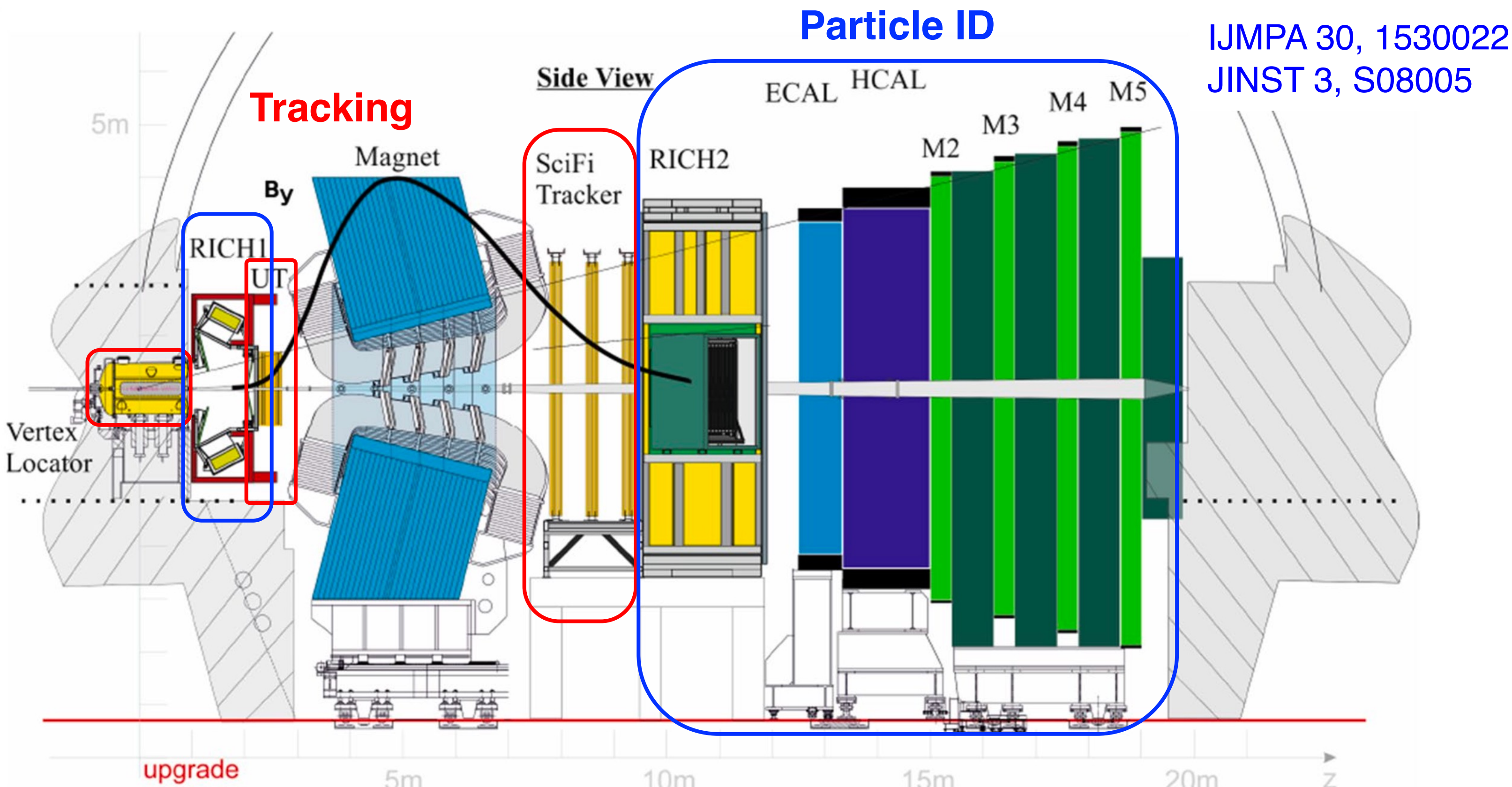
# LHCb results and prospects for feebly-interacting particles


Andrii Usachov
VU Amsterdam and Nikhef

on behalf of the LHCb collaboration


LDMA 2025
Genova, April 11th, 2025

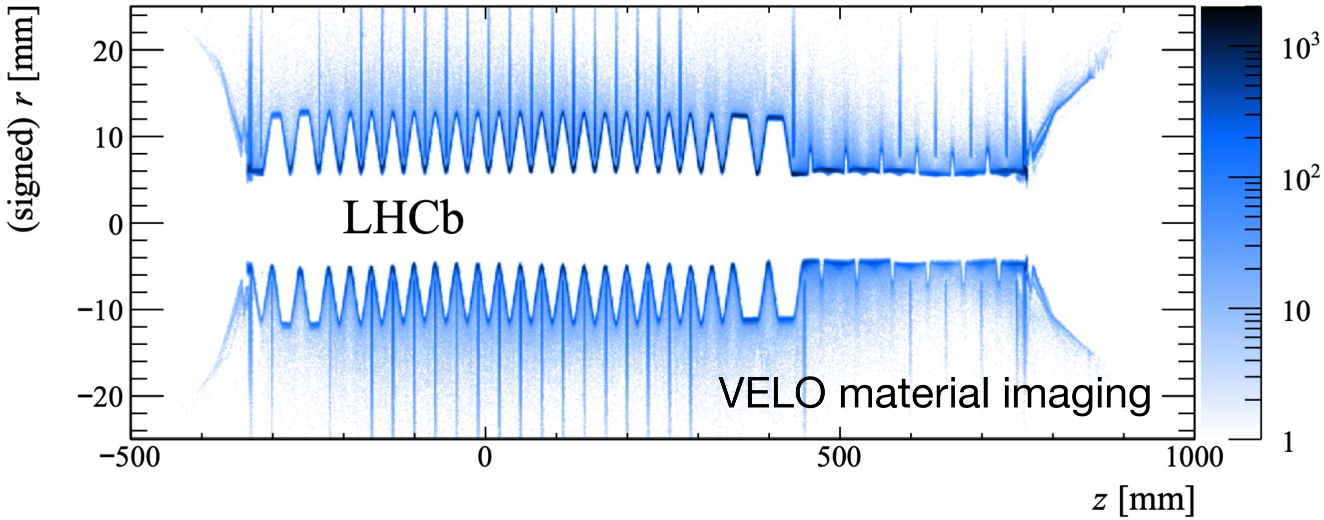
# LHCb detector




- 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 $p_{\mathrm{T}}$ and $\eta$
- **Unique sensitivity for light FIPs in O(GeV) range**

# FIPs searches at LHCb

**So far focused on signatures within VELO volume**




JINST 13 (2018) 06, P06008

- Displacement of ~20 cm

  **decays of B-mesons with* $\tau = 1.5\ ps$ *correspond to displacement of* $O(mm)$

- Thin VELO envelope (RF foil) - background dominated by
  - heavy flavor decays at *r < 5 mm*
  - material interactions at *r > 5 mm*

- Precise material veto thanks to beam-gas imaging

- **Can be extended to downstream region**

# FIPs 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**

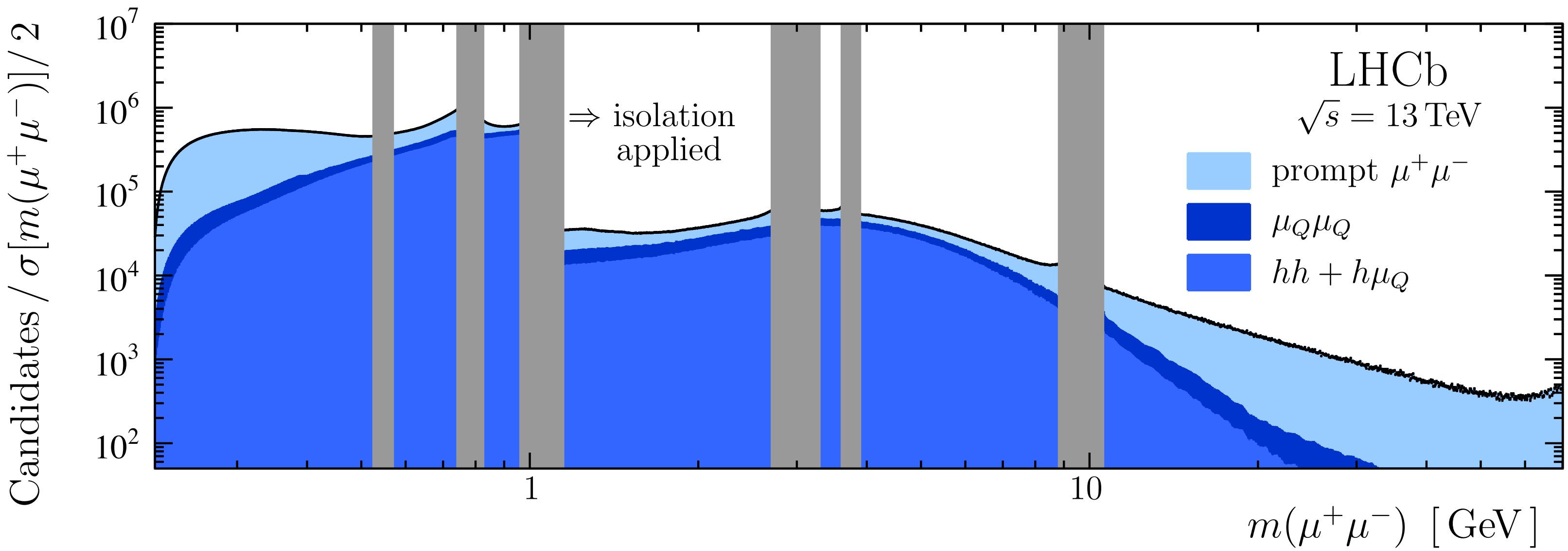
- HNL in $W^{\pm} \to \mu^{+}\mu^{\pm} jet$ — EPJC 81 (2021) 248
- LLP $\to$ *jet jet* — EPJC 77 (2017) 812
- LLP $\to \mu$ + *jets* — EPJC 77 (2017) 224

*expecting more results with Run 1-2 data*

# 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)

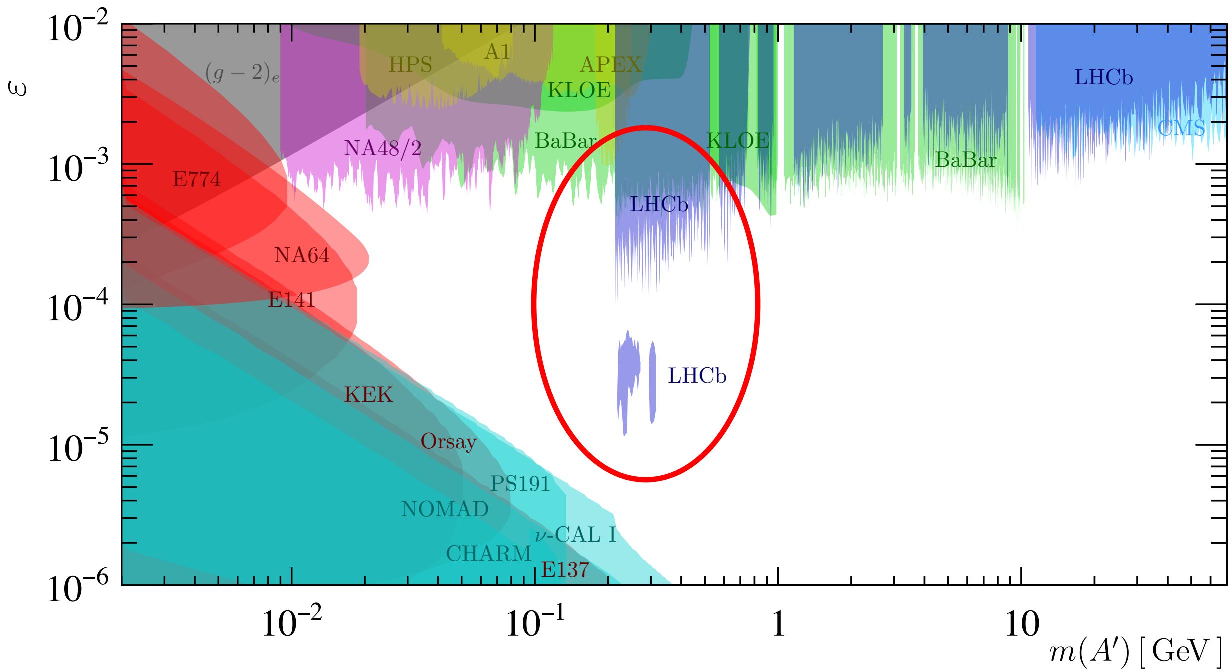
PRL 124 (2020) 041801

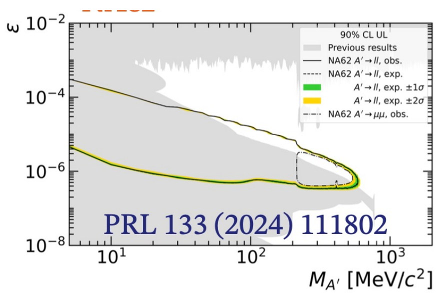


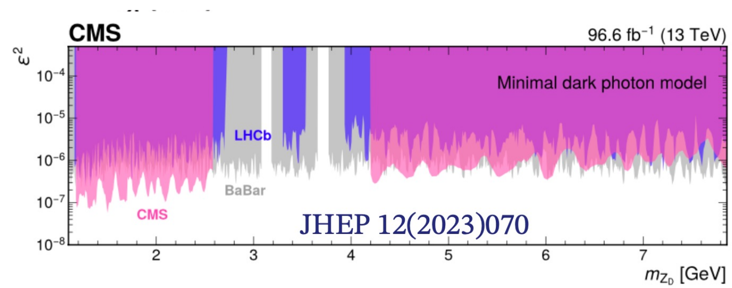

- Bump hunt analysis
- Regions of SM resonances removed
- Search for **both prompt and displaced** signatures using Run 2 data

# Dark photons in di-muon spectrum

PRL 124 (2020) 041801



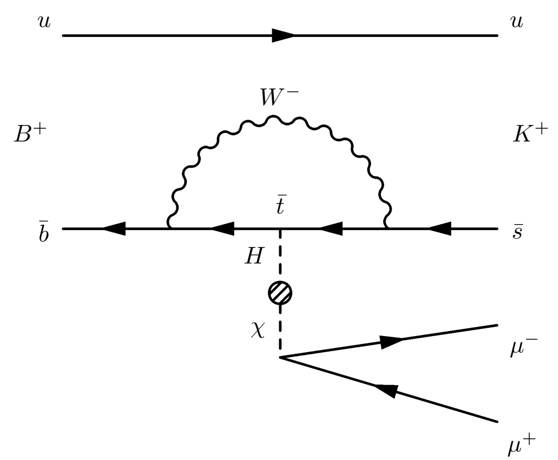




- World's best upper limits for inv. mass range of **~200-700 MeV (prompt)**
- First displaced search not from beam-dump experiments
  - explored invariant mass range: **214-350 MeV**
- Re-casted to non-minimal models

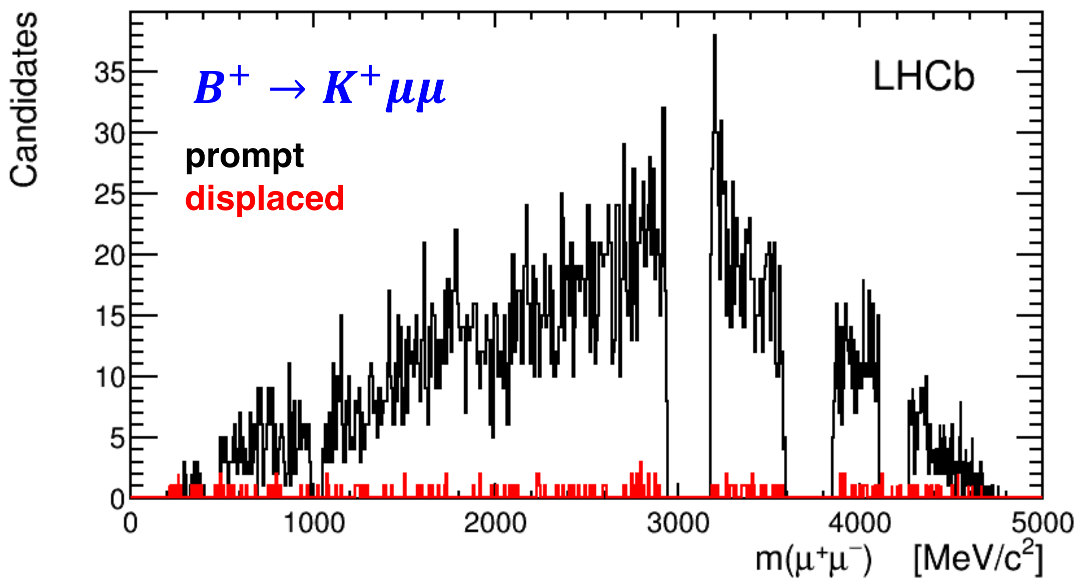
# Light boson in $b \to s$ decays

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

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



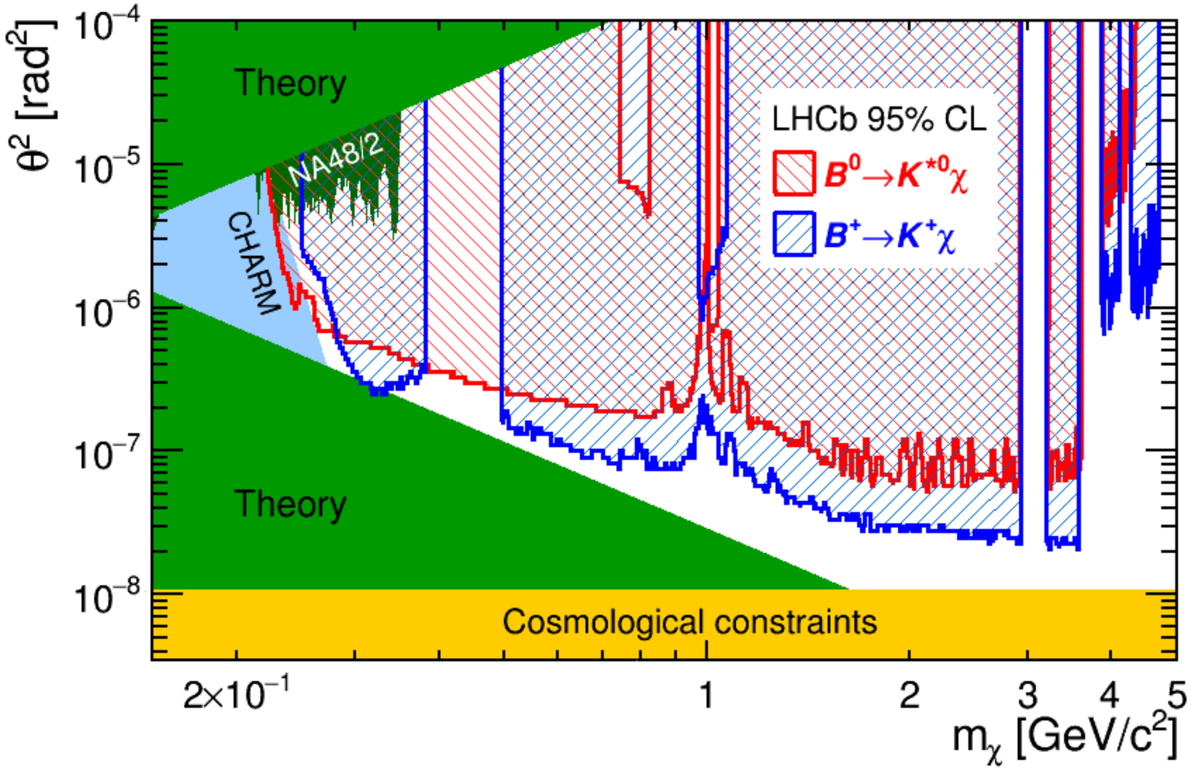

- LHCb has world's largest sample of $b \to s\mu\mu$ decays
- Study of di-muon spectrum



# Light boson in $b \to s$ decays

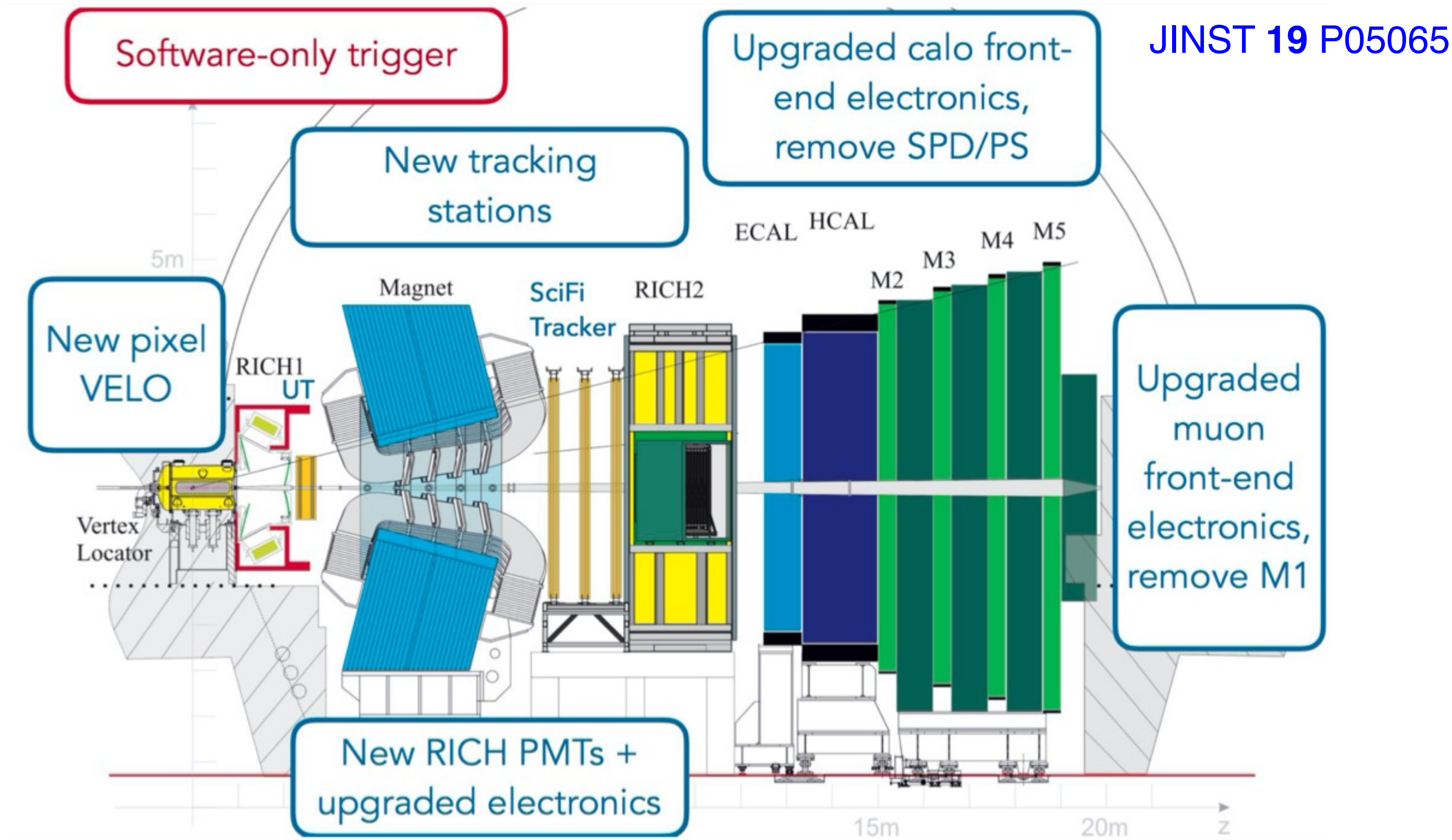
PRL 115 (2015)161802
PRD 95 (2017) 071101

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




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

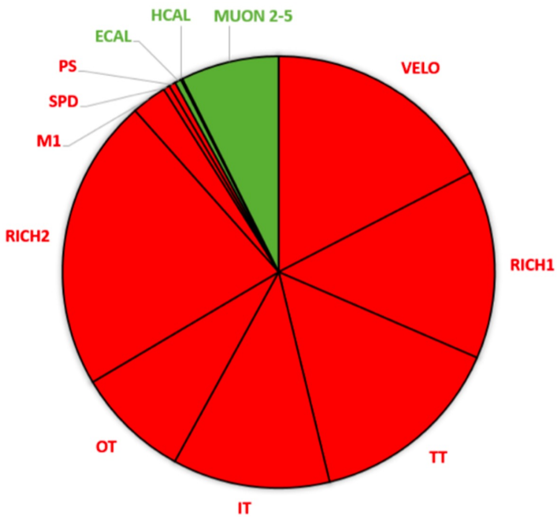
# Upgraded LHCb



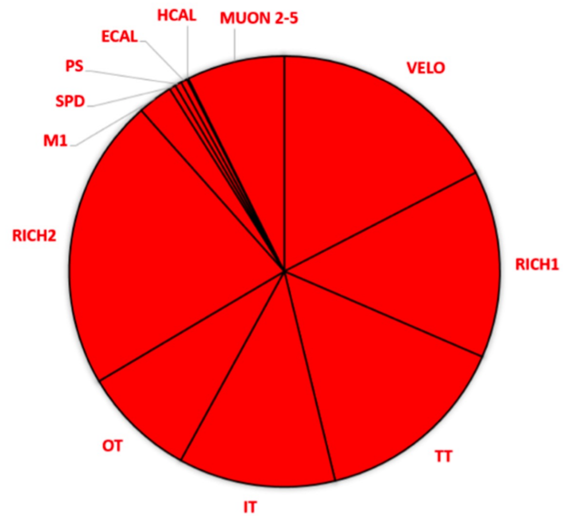

**Major detector upgrade for Run 3 and 4**

x5 larger instantaneous luminosity compared to Run 1 and 2

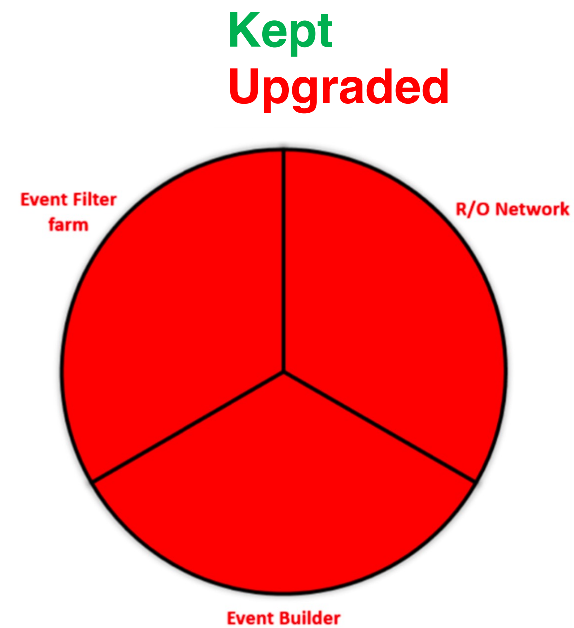
# Upgraded LHCb




**Detector channels**




**R/O electronics**



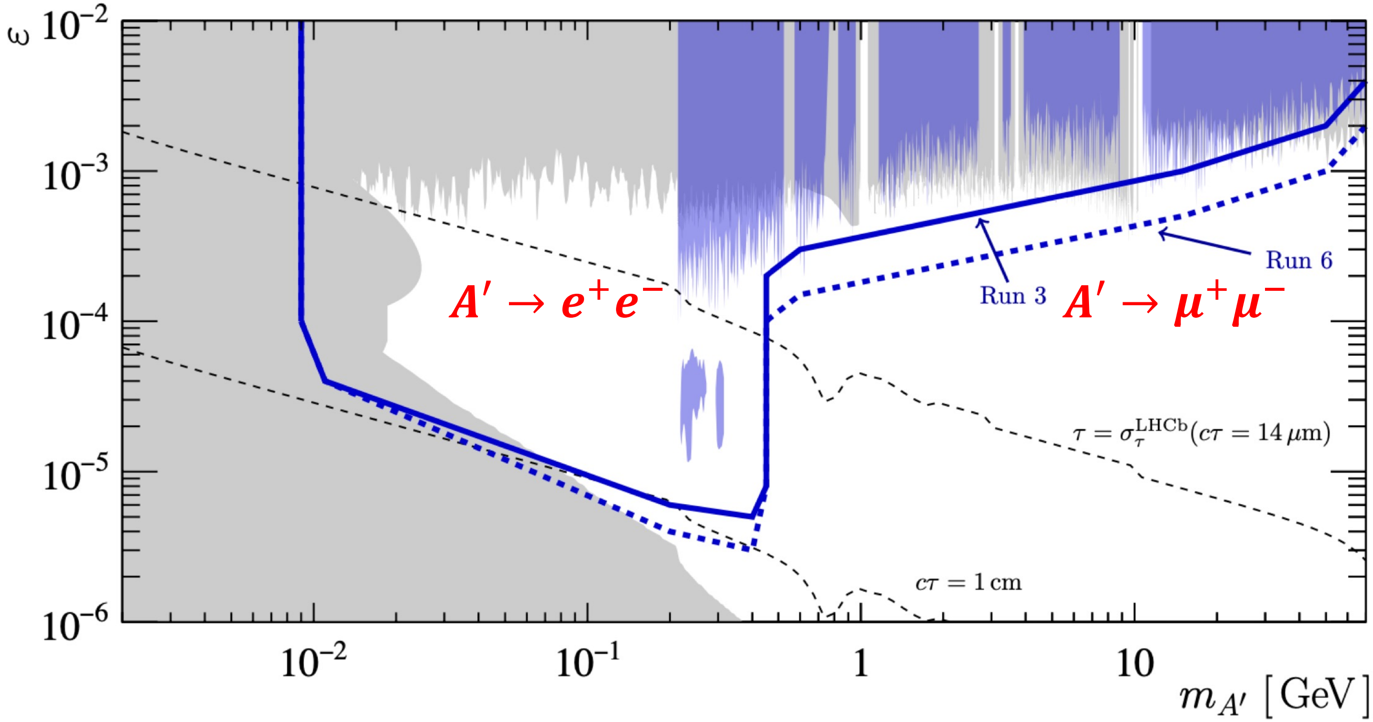

**DAQ**

- 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

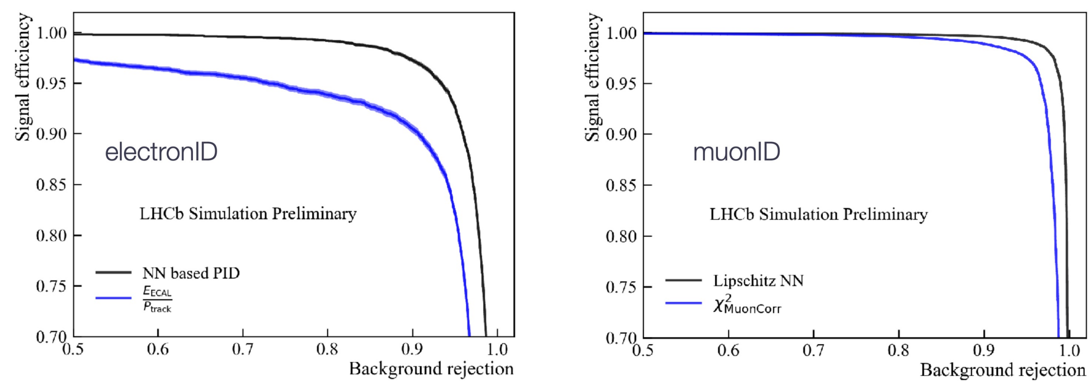



- Better tracking-based **muon ID** - large improvement at low momentum
- Much smaller mis-id for both muons and electrons
- **Expecting greatly improved sensitivity at very low masses**

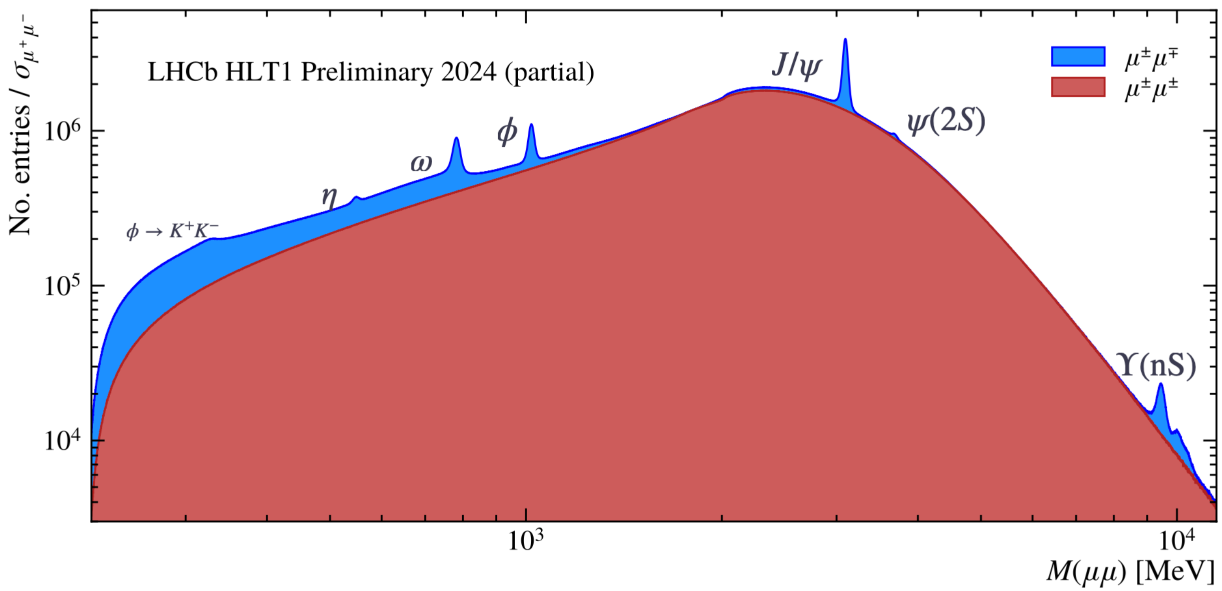
# Dark photons: new muon and electron ID

- Performance of lepton ID with smooth and fast Lipsitz NN

Run 3, PID in real time LHCb-FIGURE-2024-029




LHCb-FIGURE-2024-029

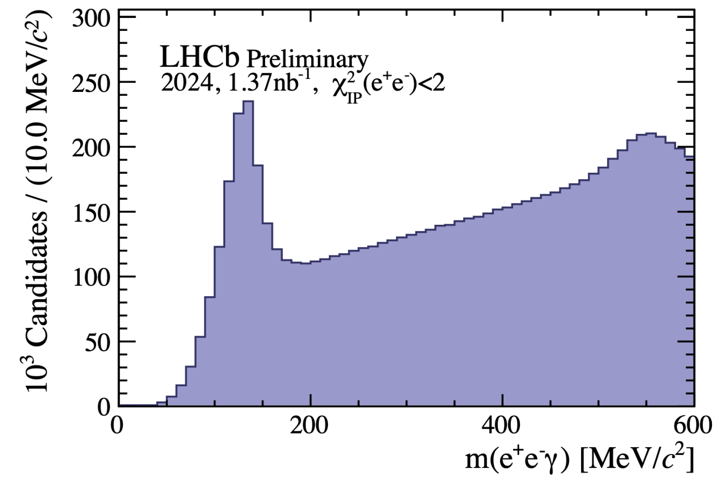



- Prompt di-muon spectrum from HLT1
- **x20 more $\eta \to \mu\mu$ per $fb^{-1}$ compared to Run 2**

# Dark Photons in di-electron

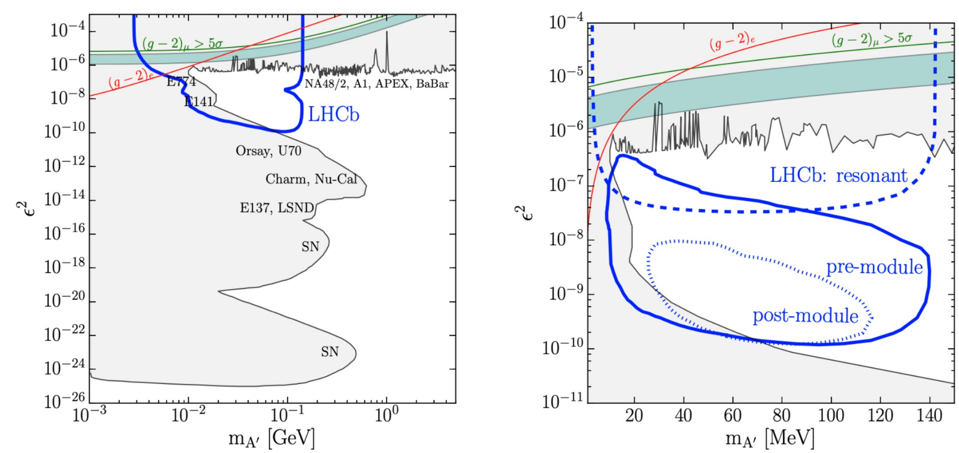
- Search in $\pi^0/\eta \to \gamma(A \to e^+e^-)$

LHCb-FIGURE-2025-003



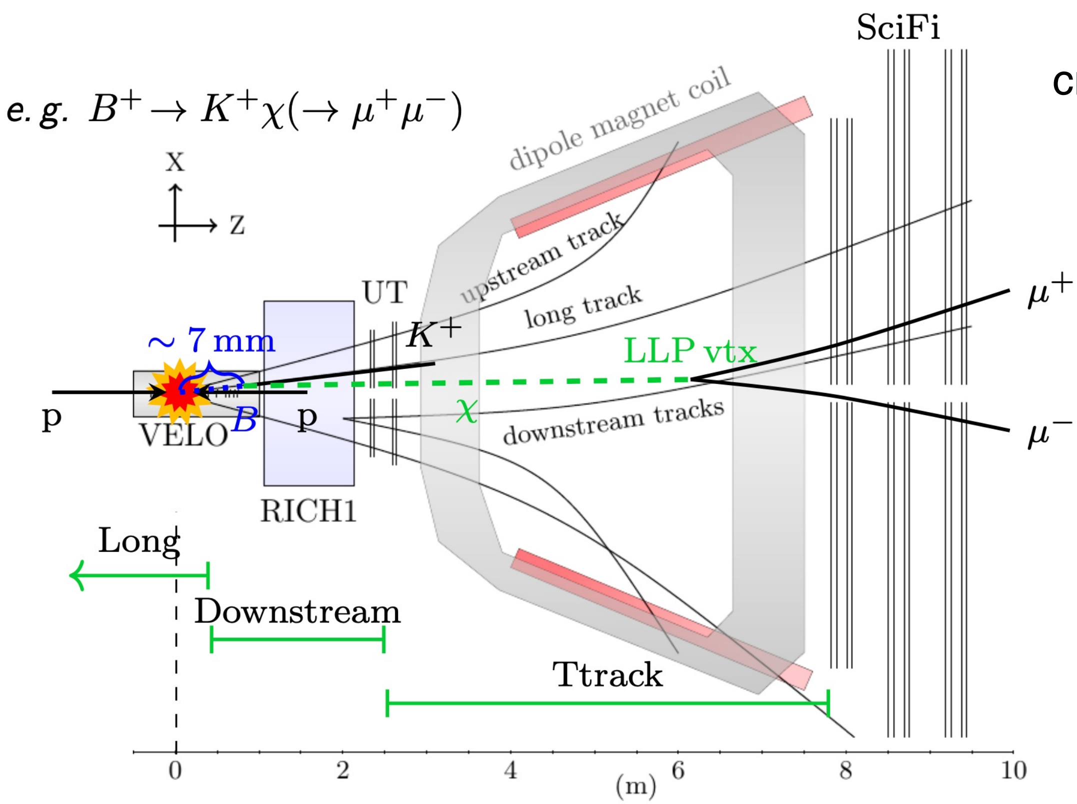

- Search in $D^* \to D^0(A \to e^+e^-)$

PRD 92 (2015) 11, 115017



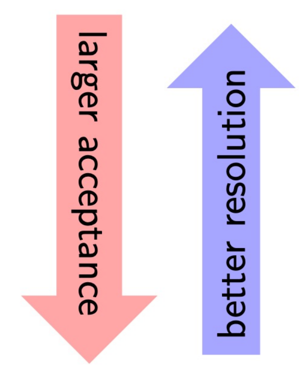

- Possible observation of True Muonium with Run 3 data [PRD 100, 053003 (2019)]

# Long-lived particles in Run 3




credit: C. Langenbruch

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



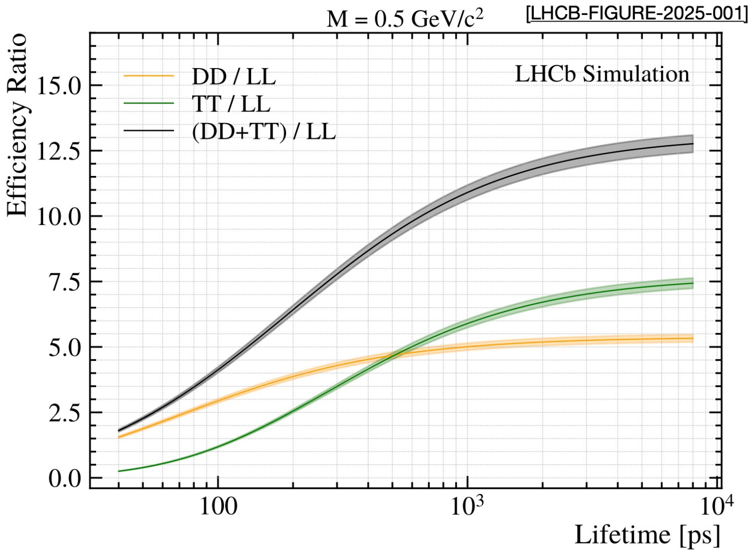
# T- tracks : Dark Higgs

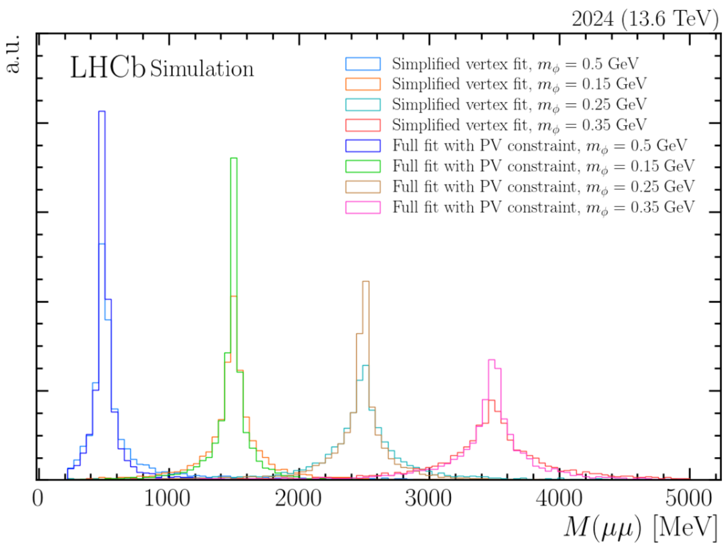
- Dark Higgs in $b \to s$ **transitions**
- Sensitivity for lifetimes of O(10 ns):

  up *x*10 gain in efficiency

  using real trigger **settings from 2024**

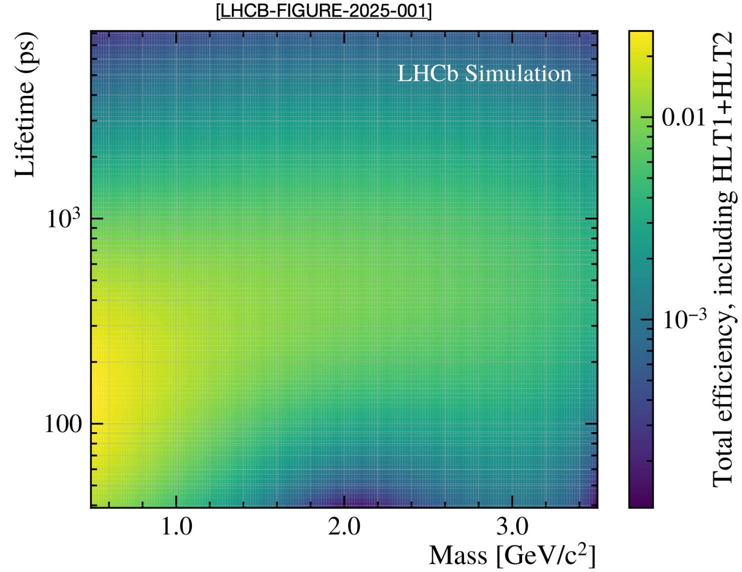
- though limited invariant mass resolution




[LHCB-FIGURE-2025-001]

[LHCB-FIGURE-2025-001]

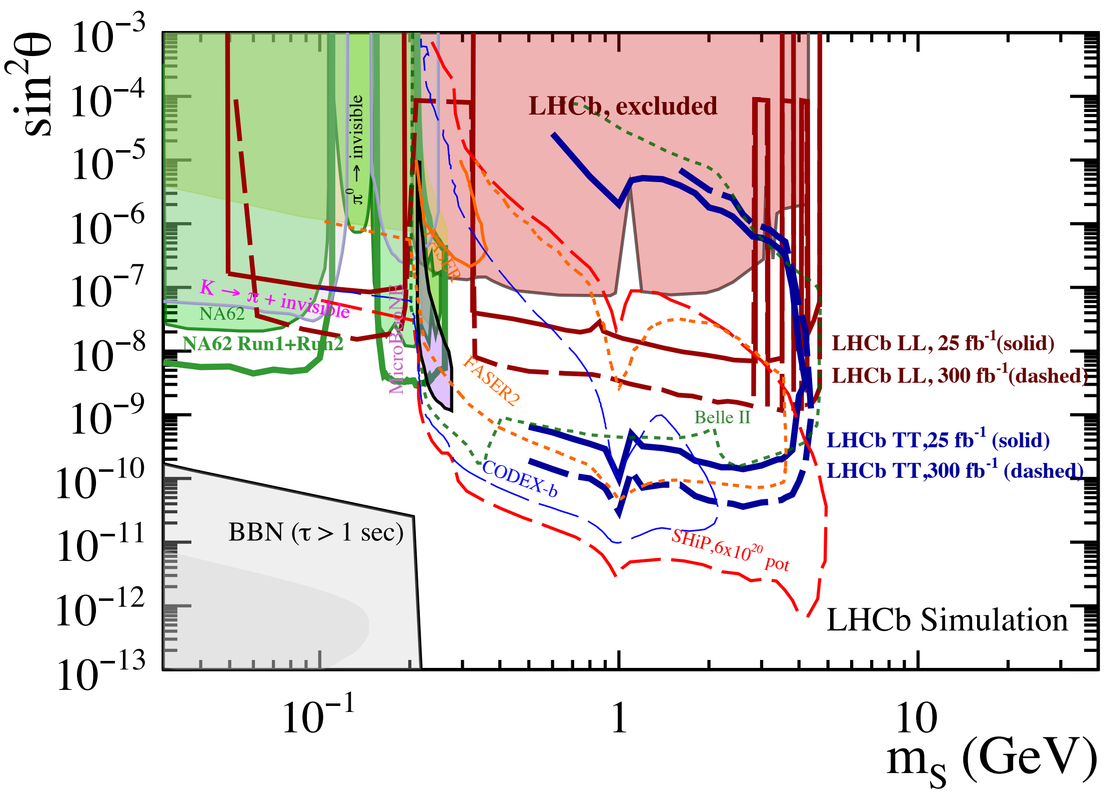


# T- tracks : Dark Higgs

- Dark Higgs in $b \to s$ **transitions**
- Sensitivity for lifetimes of O(10 ns):

  up *x*10 gain in efficiency

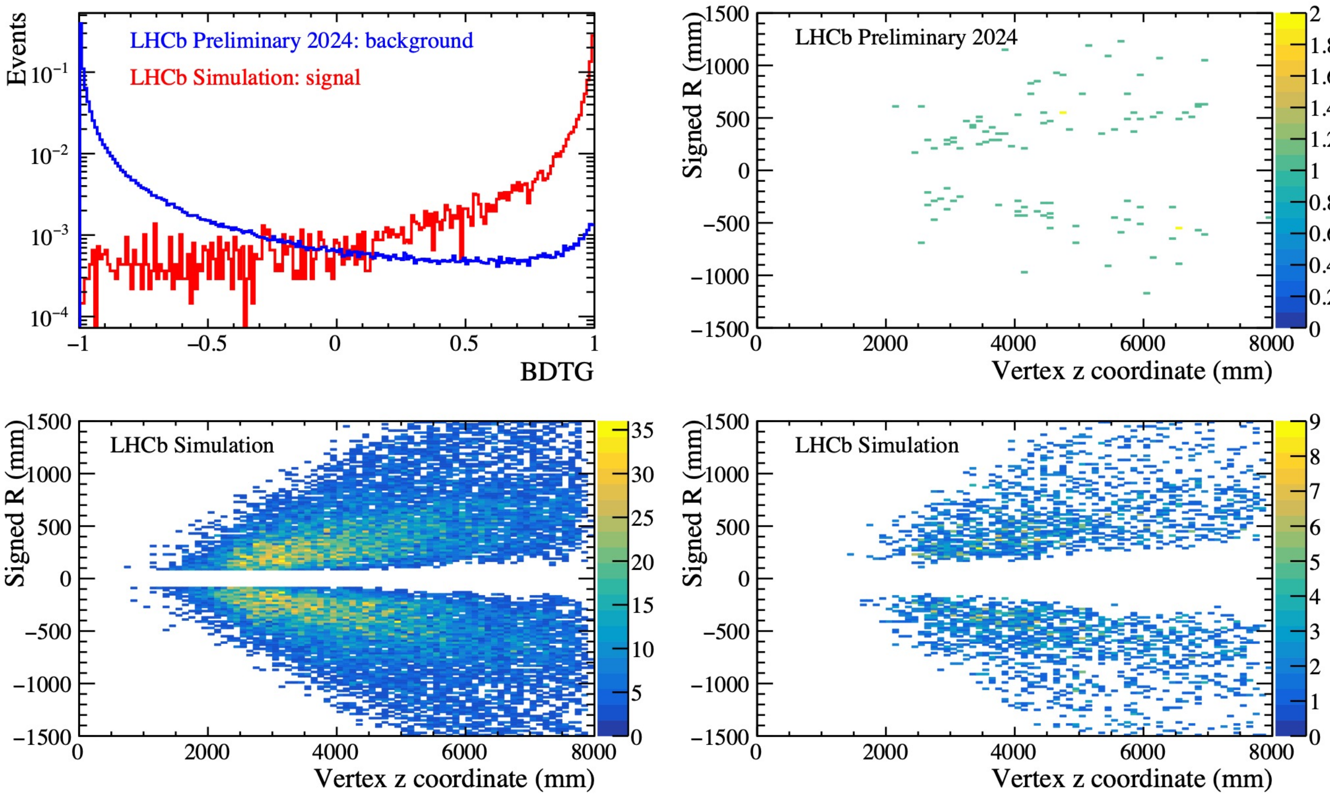
  using real trigger **settings from 2024**
- **Efficiency projection:**



# T- tracks : Dark Higgs

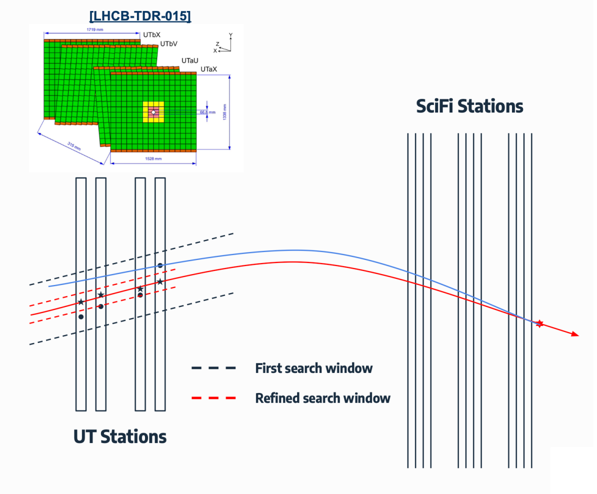
- Background reduction is essential
- First BDT using small sample of data
- $10^5$ suppression at the cost of about 50% of the signal
- Not yet using full power of geometry, PID and downstream tracks

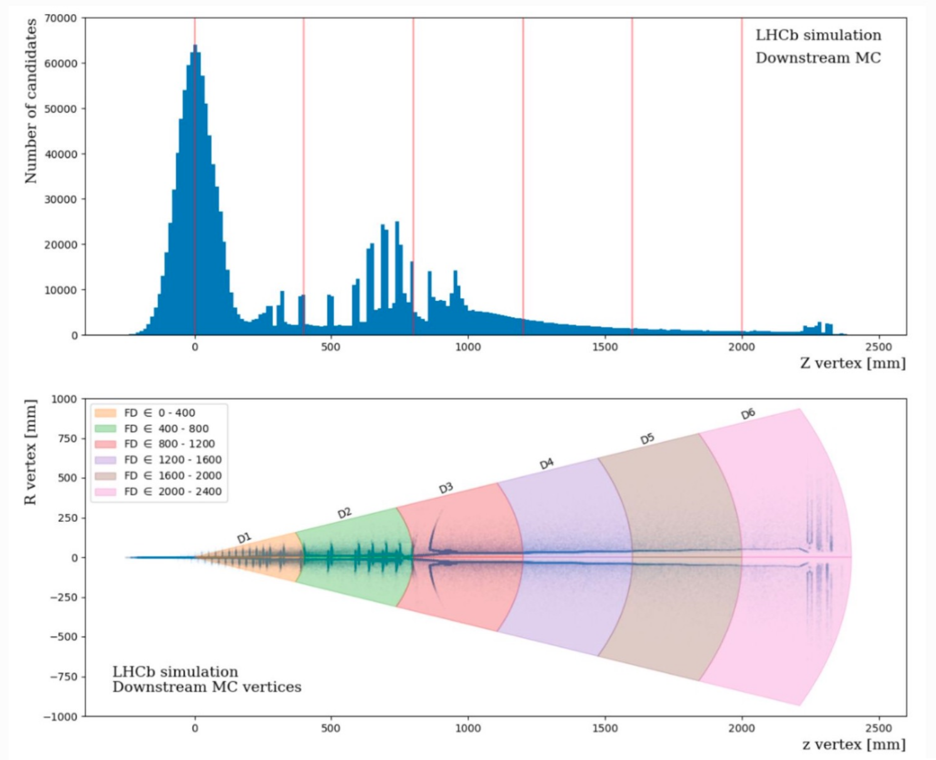
[LHCB-FIGURE-2025-001]



# LLPs with downstream tracks

- Trigger software project: **BuSca (Buffer Scanner)**
- **Already taking data**
- Focused on **two-track downstream** vertices
- Powerful for LLP signatures without involving b-decays
- Understanding of material interactions is essential

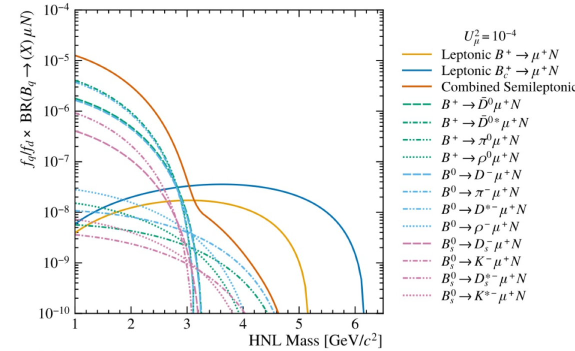


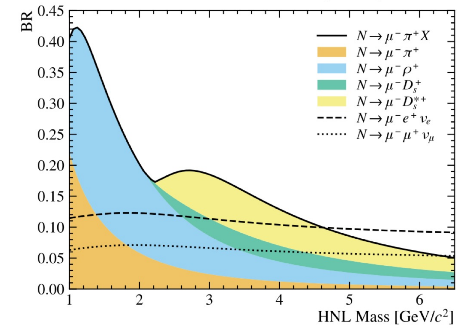




[LHCB-FIGURE-2024-036]

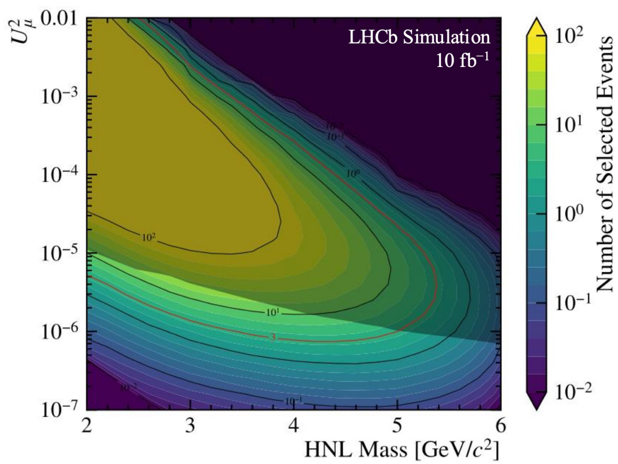
# Very displaced Heavy Neutral Leptons

- 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 under study: unique opportunities at LHCb

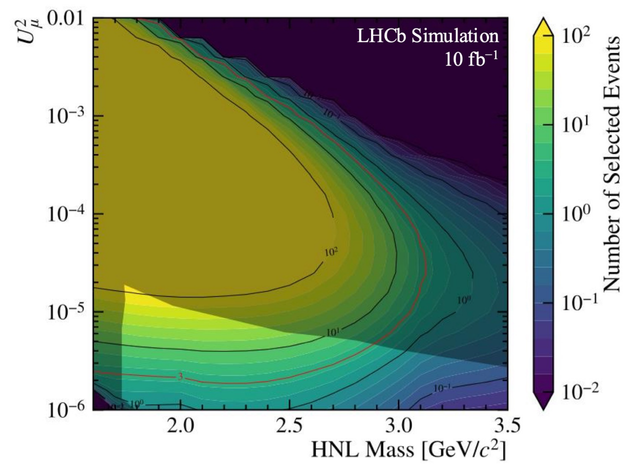



Data: Bondarenko *et al.* 2018 [10.1007/JHEP11(2018)032]




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



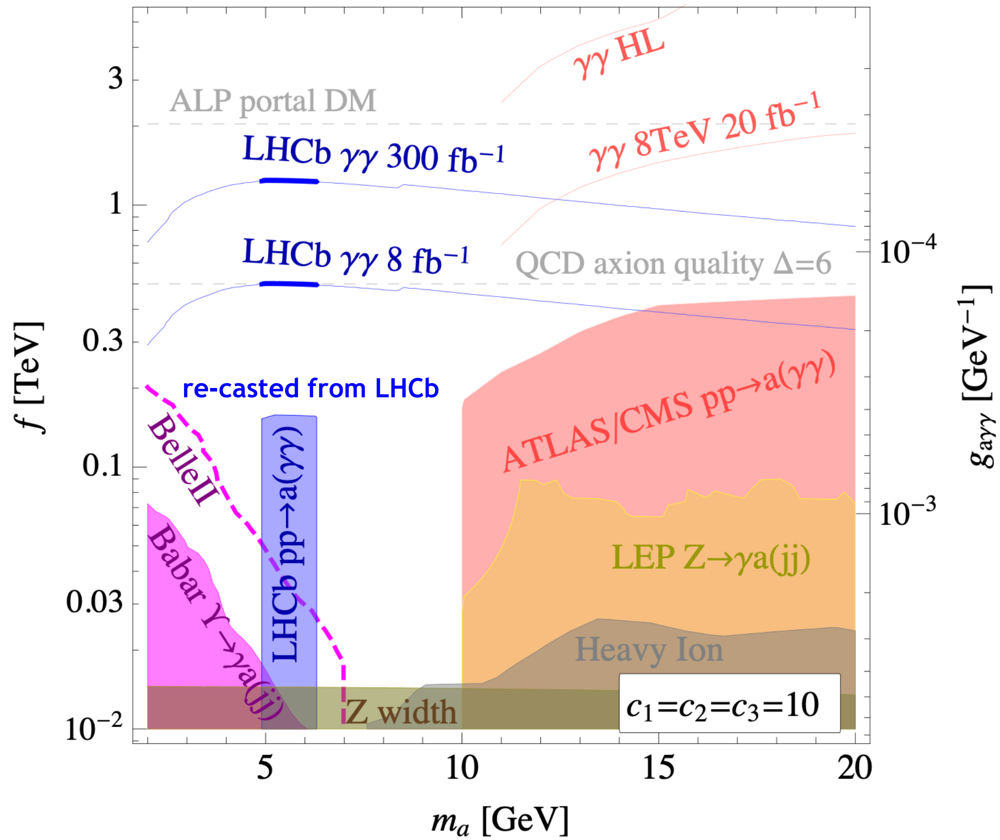

Semileptonic combined production with T tracks, $N \to \mu\pi[X]$, $N \to \mu\mu\nu_\mu$ and $N \to \mu e \nu_e$

# Non leptonic signatures

# Di-photons: ALP search

- ALPs can be produced and detected via $gg \to ALP \to \gamma\gamma$
- Light ALPs with **mass of O(GeV)** are not accessible by ATLAS and CMS
- LHCb has already provided best limits in narrow mass window using *(small)* open data set for $B_s^0 \to \gamma\gamma$

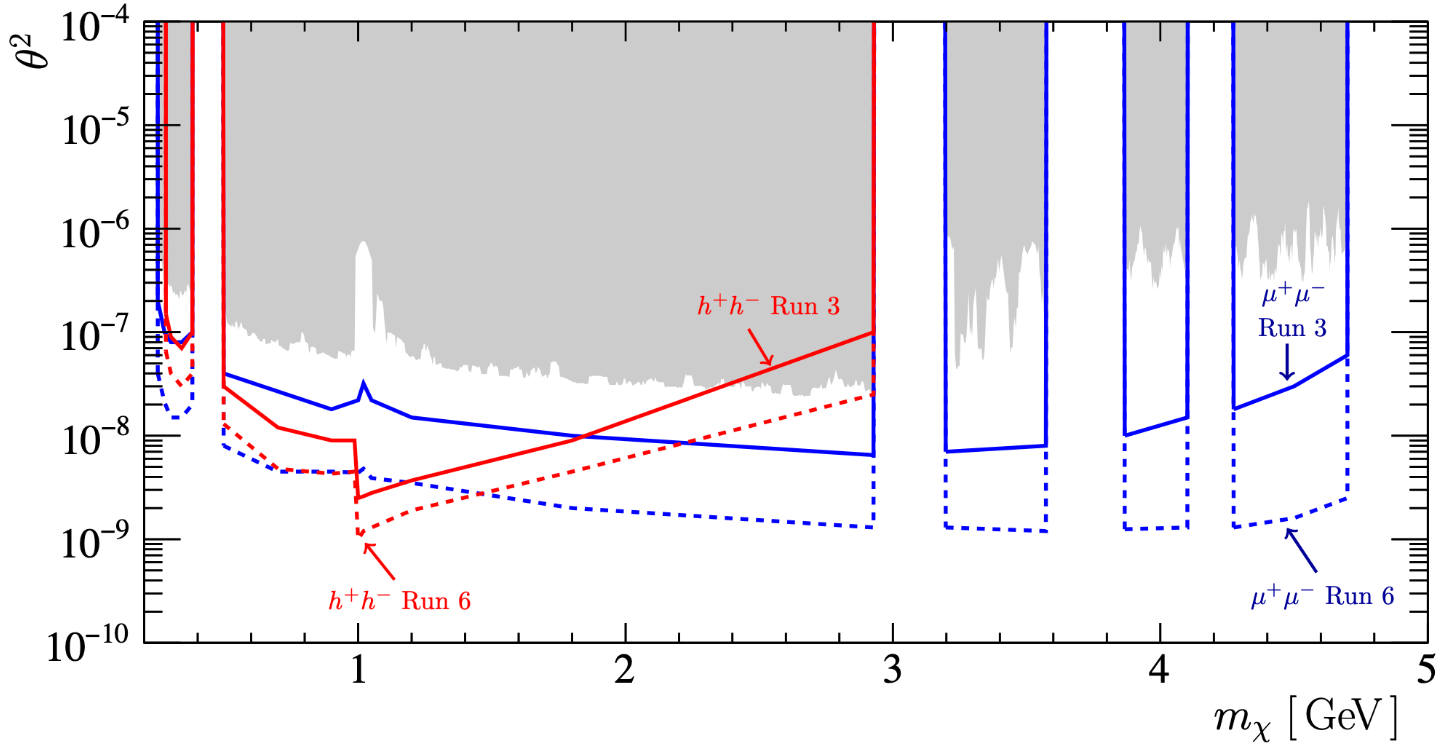
JHEP 1901 (2019) 113




**Expecting much better sensitivity in broader mass range using Run 2 data set**

# Dark scalar from *b*-decays: hadronic decays

arXiv:2203.07048




- Searches can be completed with hadronic signatures
- Better sensitivity around 1 GeV with $h^+h^-$
- Similarly searches for ALPs decay in *b*-decays
- Both Run 2 and Run 3 data can be used

# STEALTH white paper

arXiv.2105.12668

# Unleashing the full power of LHCb to probe Stealth New Physics

**Editors:** M. Borsato[1], X. Cid Vidal[2], Y. Tsai[3 4], C. Vázquez Sierra[5], J. Zurita[6]

**Authors:** G. Alonso-Álvarez[7], A. Brea Rodríguez[2], D. Buarque Franzosi[9,10], G. Cacciapaglia[11,12], A. Casais Vidal[2], M. Du[13], G. Elor[14], M. Escudero[15], G. Ferretti[9], T. Flacke [16], P. Foldenauer[17], J. Hajer[18,19], L. Henry[5], P. Ilten[20], J. Kamenik[21,22], B. Kishor Jashal[6], S. Knapen[5], F. L. Redi[23], M. Low[24], Z. Liu[13,25,26], A. Oyanguren Campos[6], E. Polycarpo[27], M. Ramos[28,29], M. Ramos Pernas[30], E. Salvioni[5], M. S. Rangel[27], R. Schäfer[8], L. Sestini[31], Y. Soreq [32], V. Q. Tran[13], I. Timiryasov[23], M. van Veghel[33], S. Westhoff[8], M. Williams[34], J. Zupan[20]

### Abstract

In this paper we describe the past, present and future potential of LHCb to find Stealth physics. This refers to Beyond the Standard Model signatures with excellent theory motivation and not falling in the category of "flavor physics". Examples of these signatures include Long-Lived particles, light resonances or hadronic final states where particle identification can play an important role. We will describe why LHCb is very well equipped to discover this kind of physics at the Large Hadron Collider, and provide good examples of well motivated theoretical models that can be probed with great detail at the experiment.

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# First LHCb FIPs workshop

- 3-day workshop this February
- Nice discussions with both theory and experiment colleagues
- Focus on the future

- **Aiming to continue FIPs workshops in the future at LHCb**
- You are very welcome!

# Summary

- LHCb made searches for **dark photon**, **HNLs**, **dark scalar** from *b*-decays using Run 1-2 data set, based on *displaced muon signature*
- *Hadronic* and *di-photon* signatures, so far, remain to be explored with Run 2 and 3 data

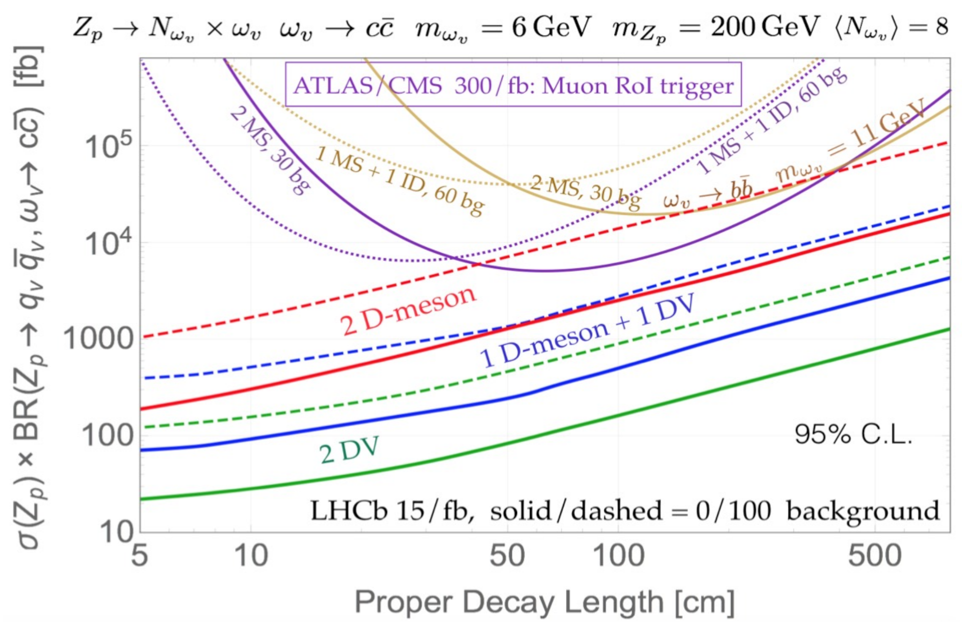
- Greatly improved sensitivity thanks to new online GPU trigger with:
  - new lepton ID (both muons and **electrons**)
  - tracking for **very long-lived particles**
  - larger statistics

  and has capabilities to study more complex signatures with dedicated trigger

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

# LLP / ALP decays to light hadrons

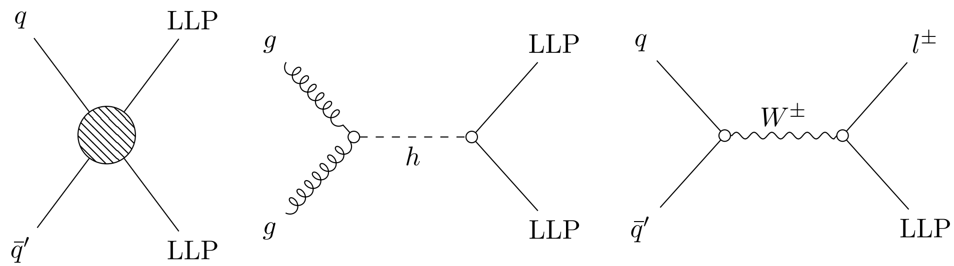
- Access to low masses O(GeV)
- Unique sensitivity by using charged hadron ID from RICH
- Complicated **mixture of heavy flavor background**
- Several searches suggested:
  - Model-independent search for $H \to SS, S \to K^+K^-$
    *LHCb projections:* JHEP 01 (2020) 115
  - Dark hadrons via decays to *D*-mesons / displaced vertices
    *LHCb projections:* PRD 97 (2018) 9, 095033




- **Not yet explored at LHCb**

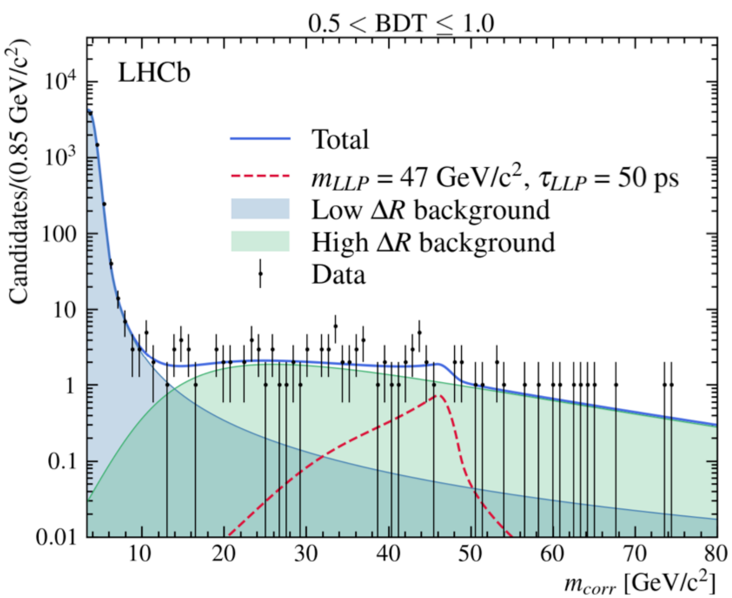
# LLPs decaying to $e^{\pm}\mu^{\mp}\nu$

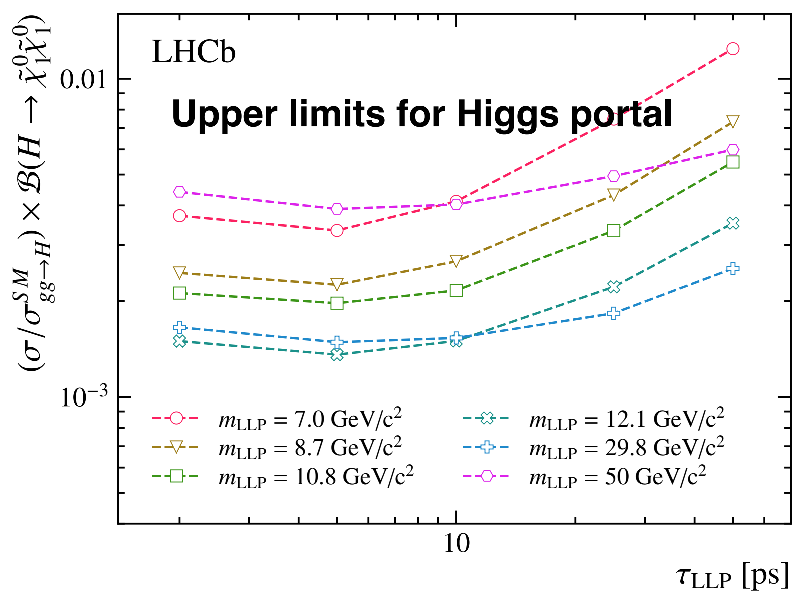
- Production mechanisms




- Analysis with full Run 2 data
- LLP masses down to 7 GeV
- *Correcting mass* to flight direction: a proof-of-concept analysis
- Simultaneous fit to corrected mass and lifetime

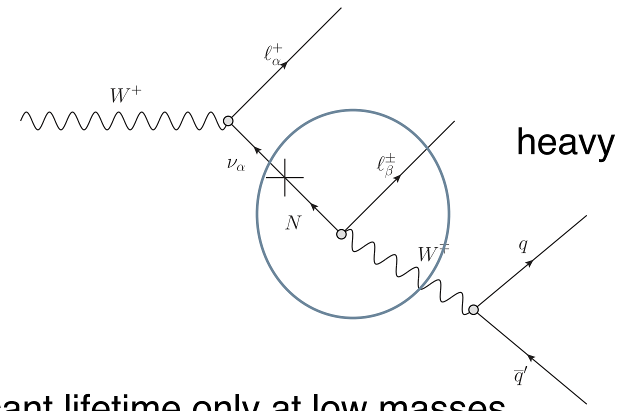
[EPJC 81 (2021) 248](#)



# HNL in $W^{\pm} \rightarrow \mu^{+}\mu^{\pm} jet$

- Search neutral leptons can be found in W decays

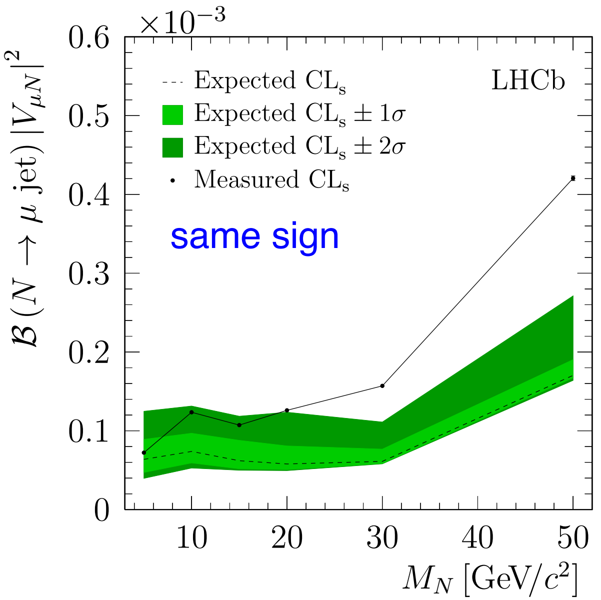


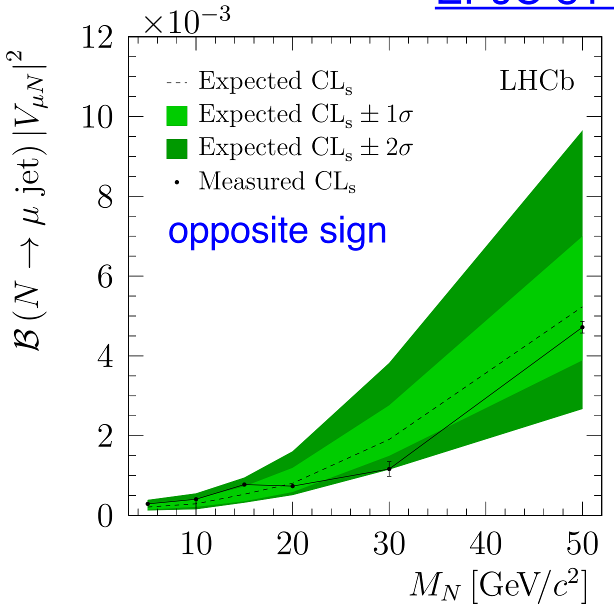

heavy neutrino decay to $\mu^{\pm} jet$

*HNL is expected to have significant lifetime only at low masses

- Upper limits for both *same* and *opposite sign* muons using Run 1 data set

EPJC 81 (2021) 248

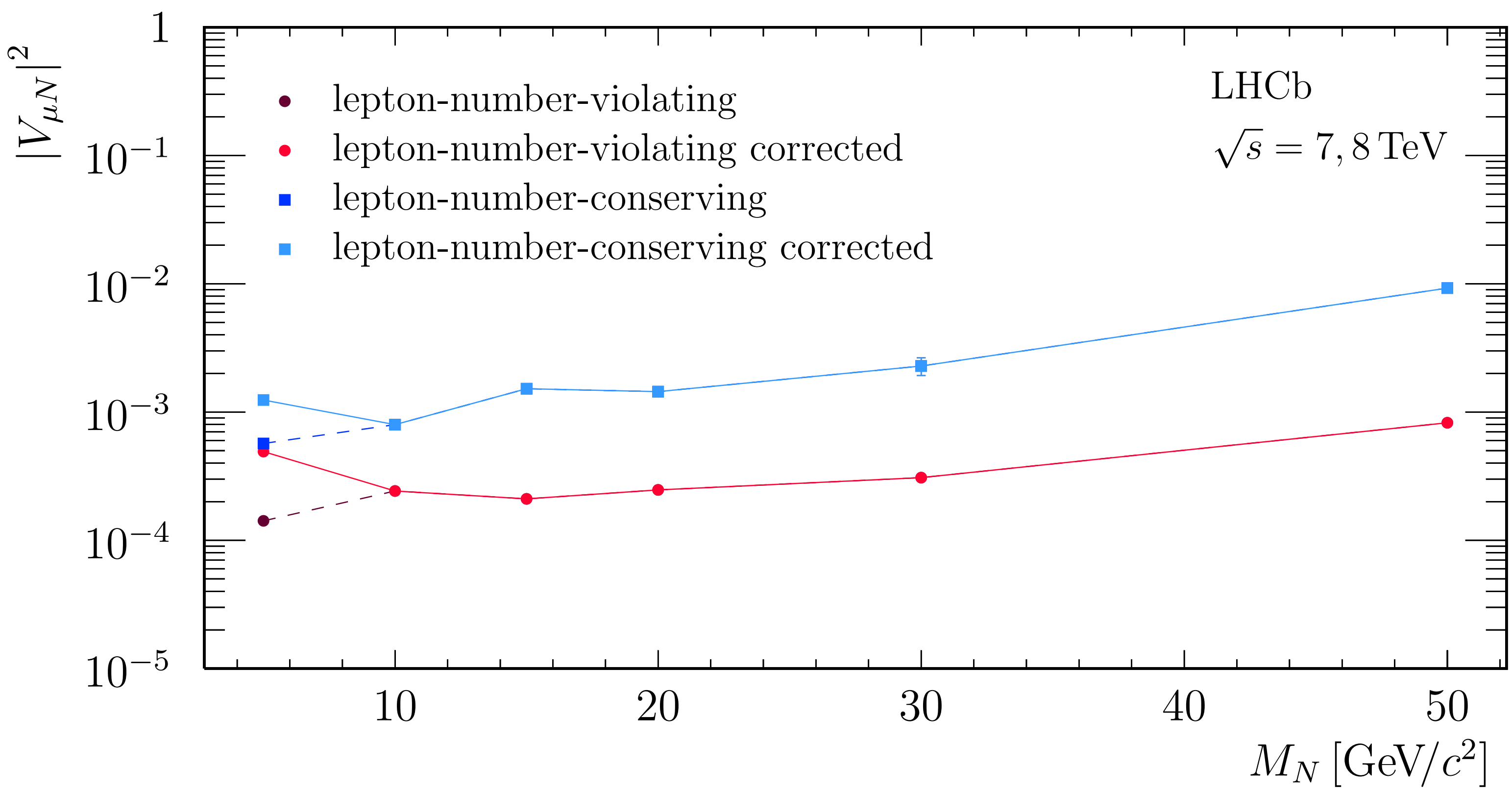


# HNL in $W^{\pm} \rightarrow \mu^{+}\mu^{\pm} jet$

- Upper limits on mixing with muon neutrino - $|V_{\mu N}|^2$

EPJC 81 (2021) 248




- Lifetime corrections at low masses
- Not very competitive with ATLAS, CMS and DELPHI searches

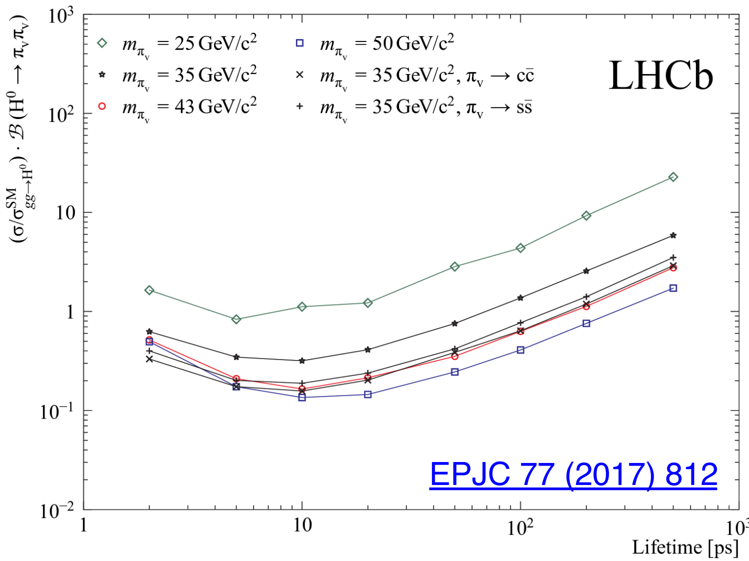
JHEP 10 265 JHEP 01 122 Z. Phys. C74 57

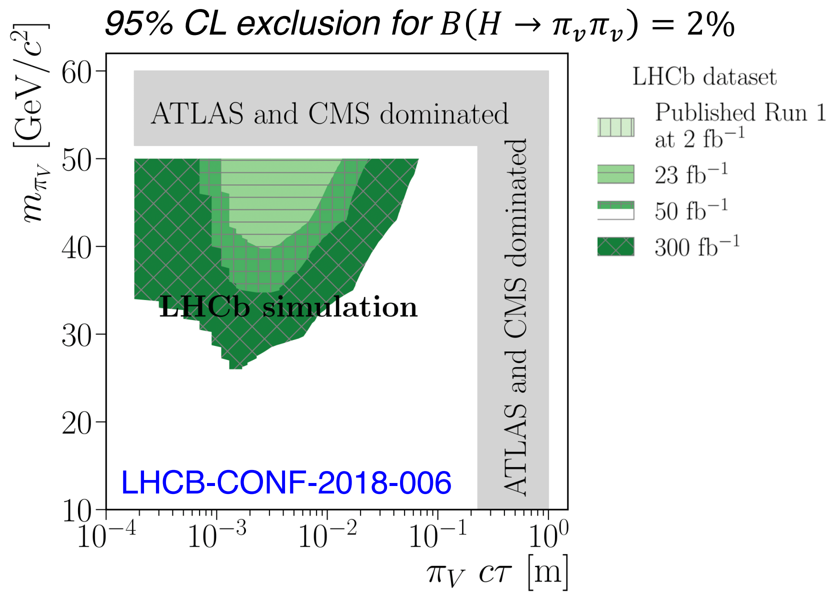
# Searches of LLPs decaying to jets

**Signature**: single displaced vertex with two (*b*-) jets EPJC 77 (2017) 812

**Model:** Hidden Valley dark pions produced through Higgs portal

- Analysis in bins of $R_{xy}$ - radial distance to the beam axis
- Invariant mass range explored: 25-50 GeV
- Upper limit for lifetimes range 2-500 ps
- Complementary limits to ATLAS and CMS




- Can be pushed to lower masses in Run 3 using jet substructure

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