



# Long-lived particles searches at LHCb

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on behalf of the LHCb collaboration

July 27, 2021

A background image of a harbor at sunset, with buildings, ships, and a large crane visible. The sky is orange and red.

EPS-HEP Conference 2021

European Physical Society conference on high energy physics 2021

Online conference, July 26-30, 2021

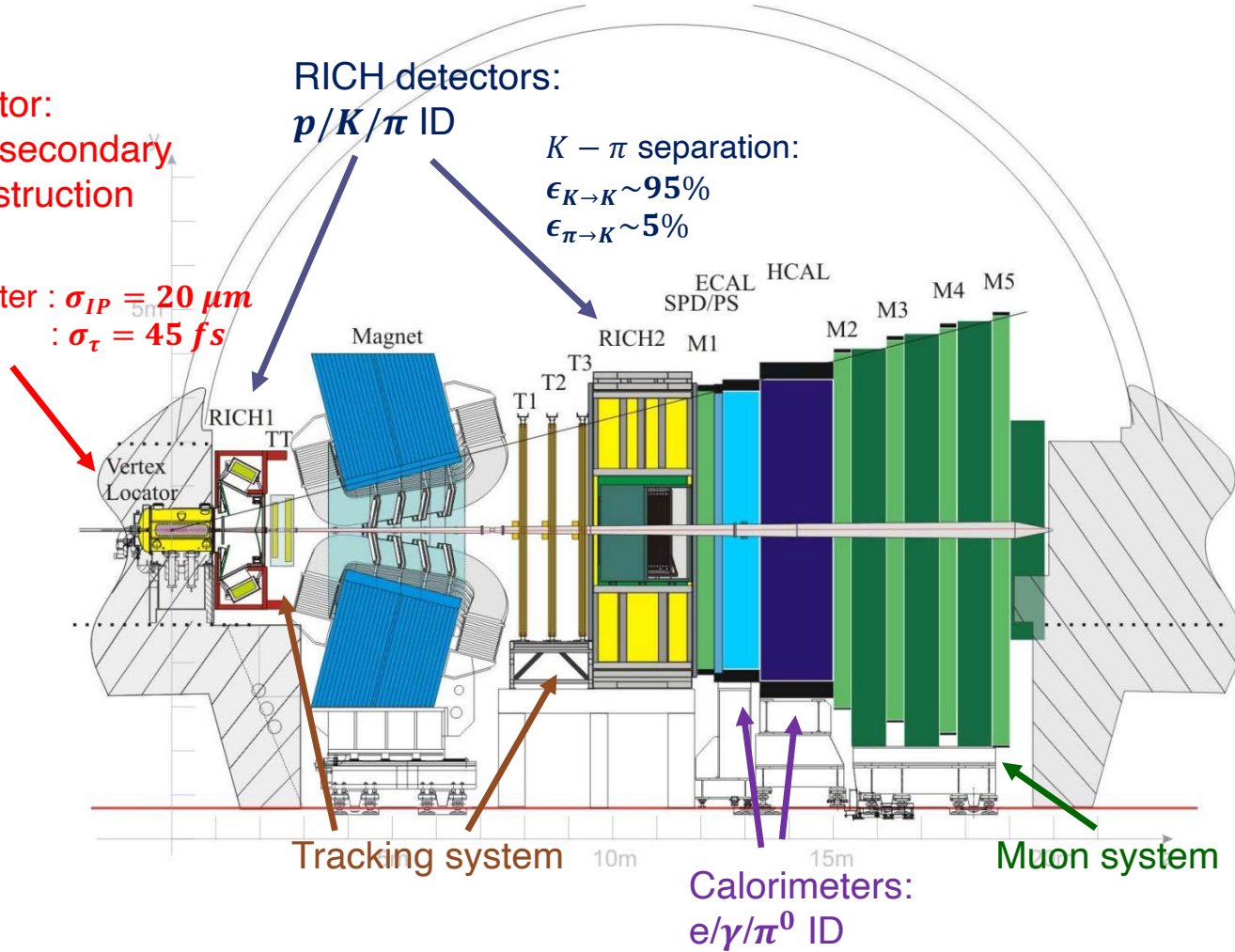
# LHCb detector

IJMPA 30, 1530022  
JINST 3, S08005

- Single-arm spectrometer for beauty and charm physics studies in forward region

Vertex LOcator:  
Primary and secondary  
vertex reconstruction

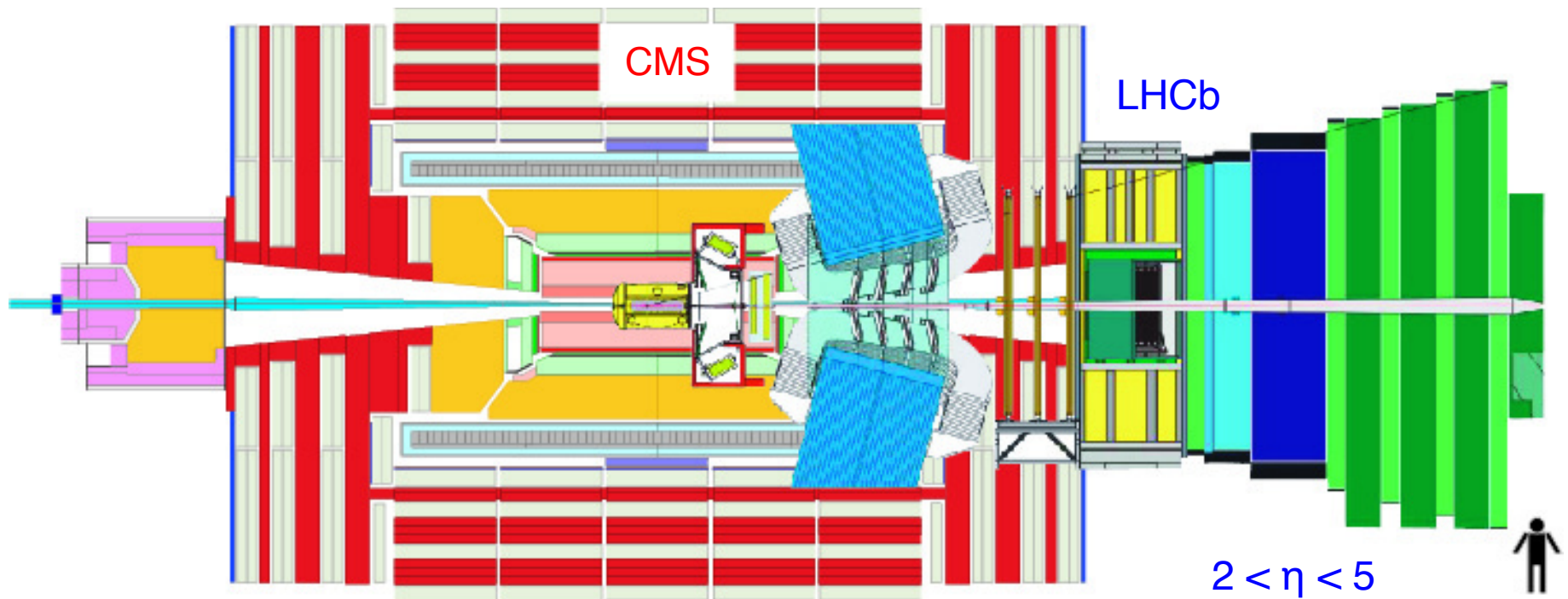
Resolution:  
Impact parameter :  $\sigma_{IP} = 20 \mu\text{m}$   
Lifetime :  $\sigma_{\tau} = 45 \text{fs}$



- Precise vertex reconstruction with VELO
- Powerful charged hadrons ID by RICH detectors

# LHCb detector

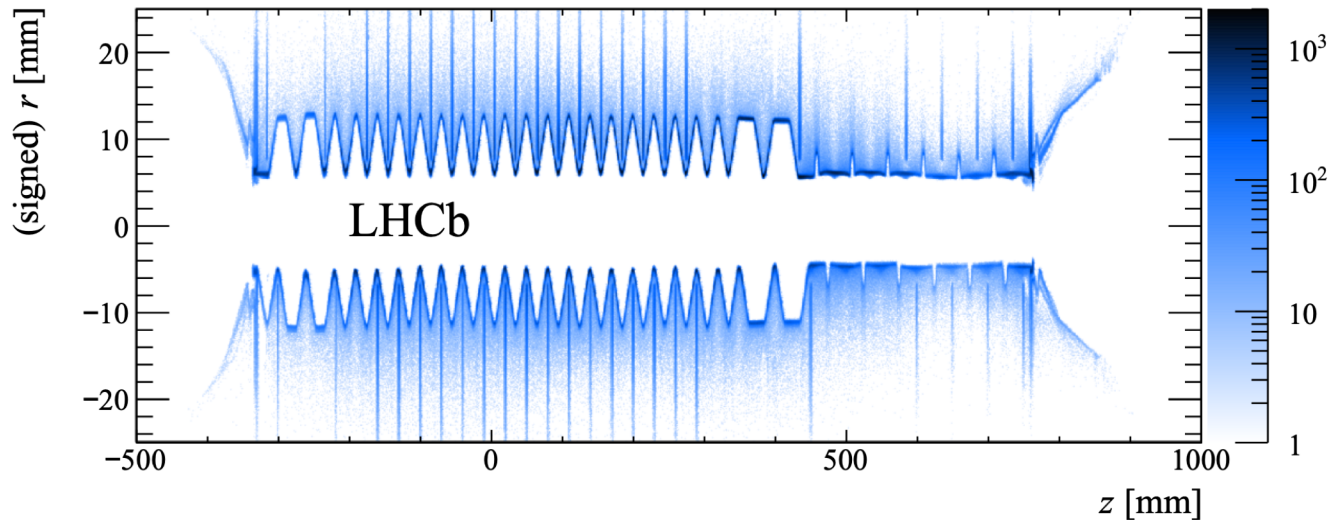
IJMPA 30, 1530022  
JINST 3, S08005



- Coverage complementary to ATLAS and CMS in  $p_T$  and  $\eta$
- Flexible software trigger allowing **soft selections**

# LLP searches at LHCb

- So far only within VELO



- Displacement up to 20 cm [JINST 13 \(2018\) 06, P06008](#)
  - \*decays of B-mesons with  $\tau = 1.5 \text{ ps}$  correspond to displacement of 0(mm)
- Thin VELO envelope (RF foil) - background dominated by
  - heavy flavour decays at  $< 5 \text{ mm}$
  - material interactions at  $> 5 \text{ mm}$
- Precise material veto thanks to imaging with reconstructed vertices
- Can be extended to downstream region
  - Displacement up to 200 cm
  - Much worse momentum resolution



# Recent LLP searches at LHCb

- LLP  $\rightarrow \mu + jets$  [LHCb-PAPER-2021-028](#) *new*  
[EPJC 77 \(2017\) 224](#)
- LLPs decaying to  $e^\pm \mu^\pm \nu$  [EPJ.C 81 \(2021\) 261](#) *new*
- HNL in  $W^\pm \rightarrow \mu^\pm \mu^\pm jet$  [EPJC 81 \(2021\) 248](#) *new*
- LLP  $\rightarrow jet jet$  [EPJC 77 \(2017\) 812](#)

Not in this talk:

- Dark photon [PRL 120 \(2018\) 061801](#),  
[PRL 124 \(2020\) 041801](#)
- Low-mass dimuon resonances [JHEP 10 \(2020\) 156](#)

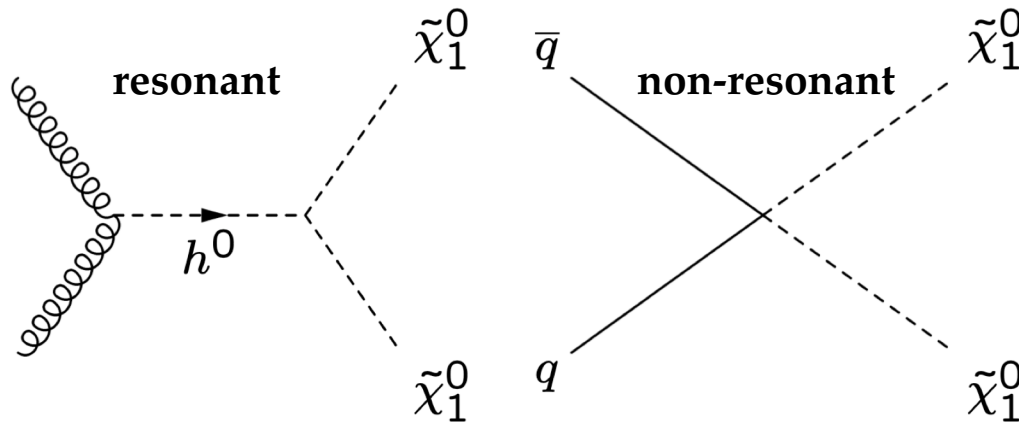
see [talk by T. Mombacher](#) for Dark matter searches at LHCb

# Search for LLPs decaying semileptonically

LHCb-PAPER-2021-028

**New !**

- LLPs may appear from MSSM Lagrangian with R-parity violation
- LHCb is capable to study LLPs down to relatively low masses
- Consider both resonant and non-resonant production processes



$h^0$  mass: 30 – 200  $GeV/c^2$   
LLP mass > 10  $GeV/c^2$   
(71 models)

LLP mass: 10 – 90  $GeV/c^2$   
(12 models)

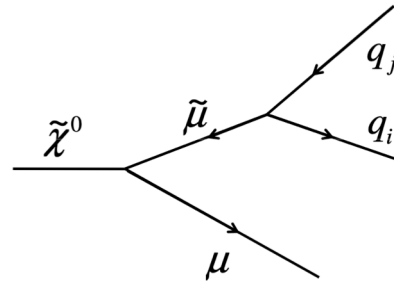
- LLP lifetime range: 5-200 ps
- Update of Run1 analysis [EPJC 77 \(2017\) 4, 224](#)
  - Later recasted by [Antush et. al, PLB 774 \(2017\) 114](#)

# Search for LLPs decaying semileptonically

LHCb-PAPER-2021-028

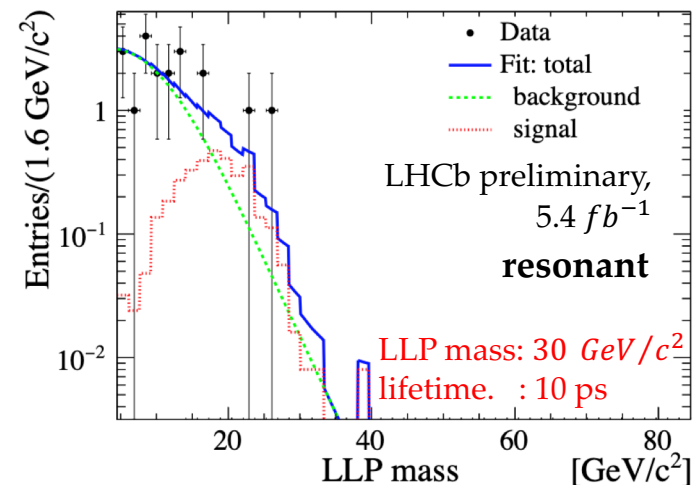
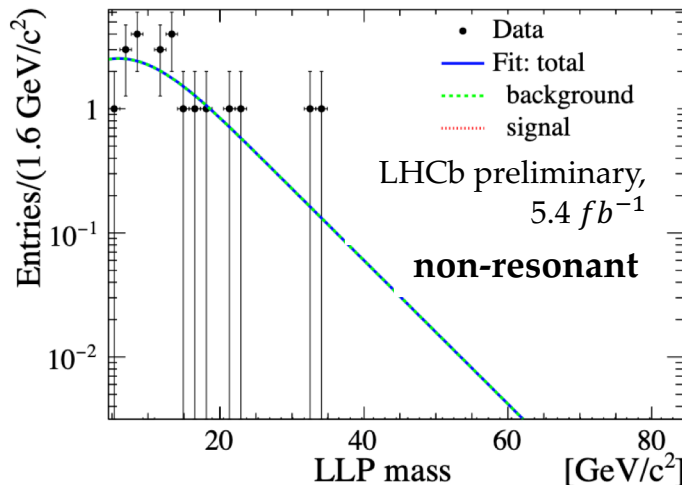
**New !**

- Data set: Run 2
- Decay signature: muon + 2 jets
- Selection:



- high-pt muon
- muon inside displaced vertex with at least 2 other tracks
- veto vertices in the VELO material
- MVA kinematical selection – separate for each model
  - *background: from fraction of data*

- Fit to invariant mass

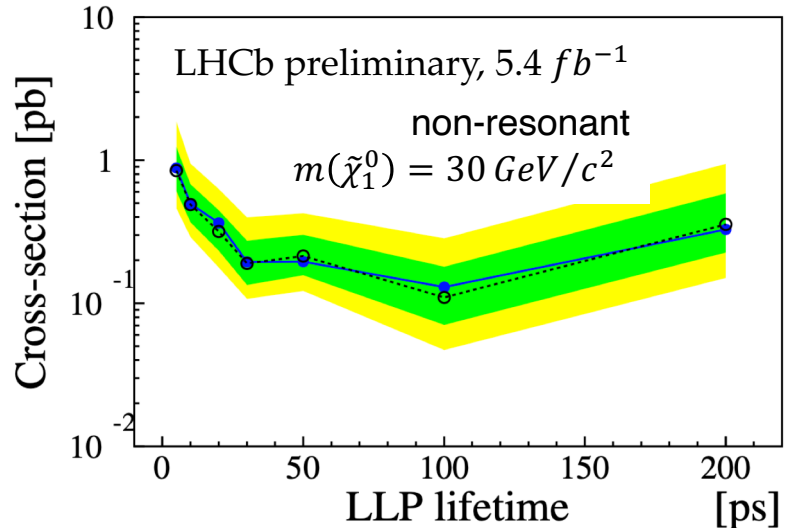
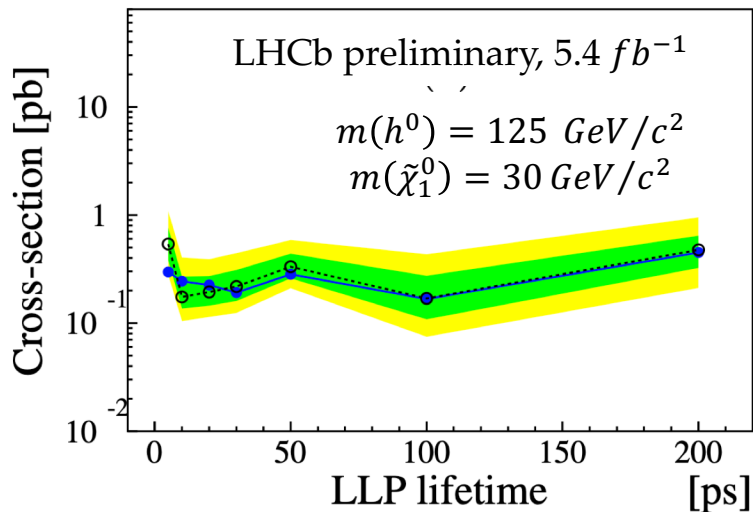
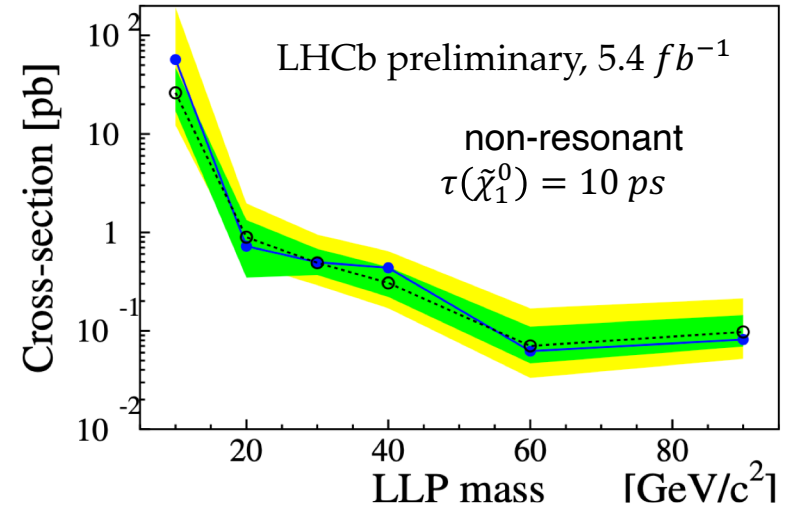
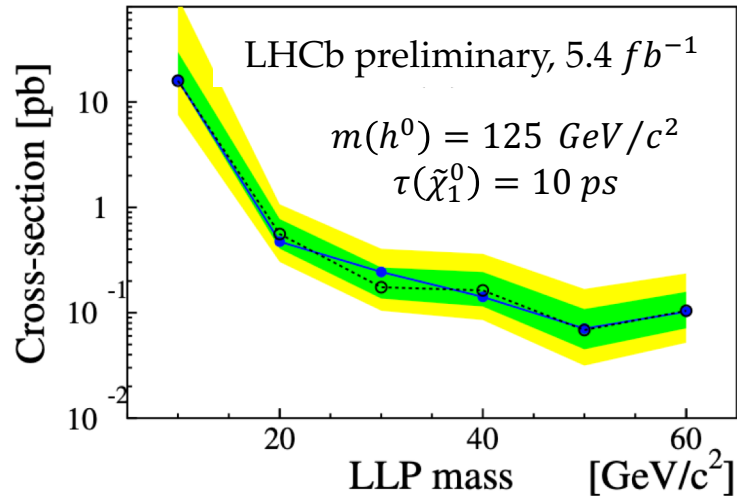


# Search for LLPs decaying semileptonically

LHCb-PAPER-2021-028

**New !**

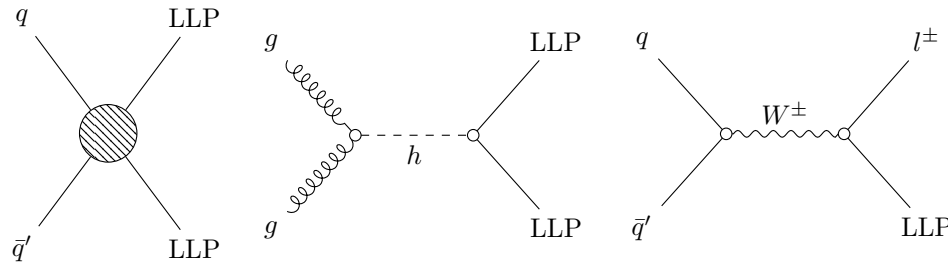
- Results: no signal(s) observed
- 95% CL upper limits on cross-section x BR
  - As function of LLP mass and lifetime, and  $h^0$  mass for resonant production





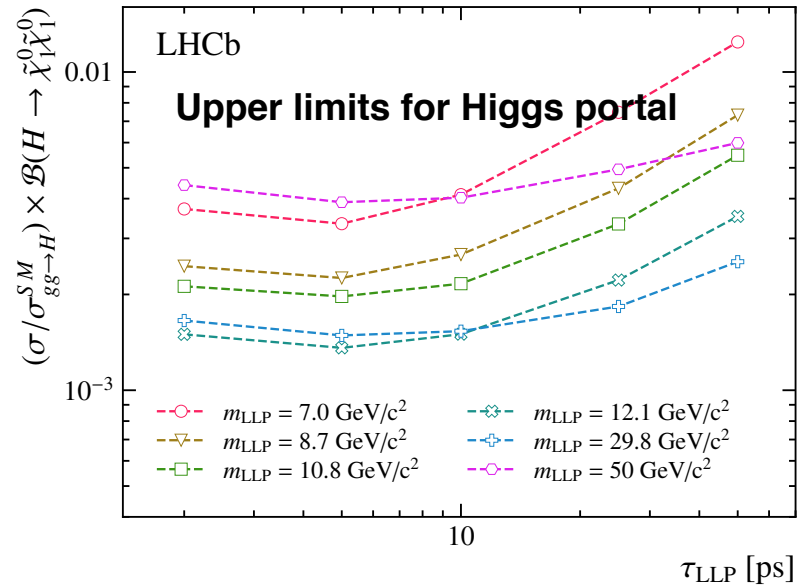
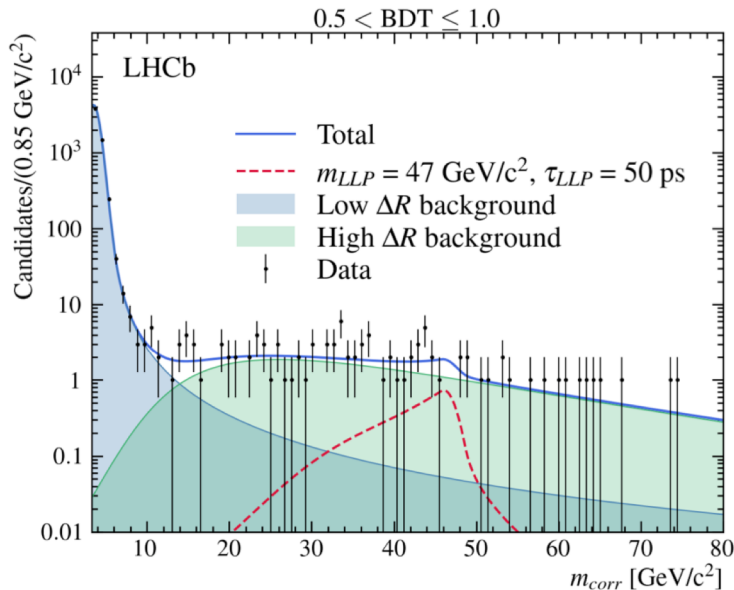
# LLPs decaying to $e^\pm \mu^\mp \nu$

- Production mechanisms considered:



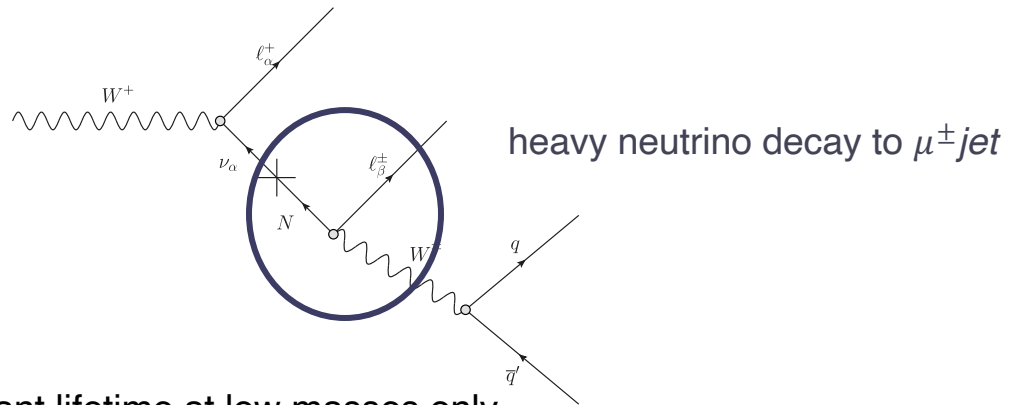
- Analysis with full Run 2 data
- LLP masses down to 7 GeV
- Correcting mass* wrt flight direction: a proof of concept analysis
- Simultaneous fit to corrected mass and lifetime

[EPJC 81 \(2021\) 248](#)



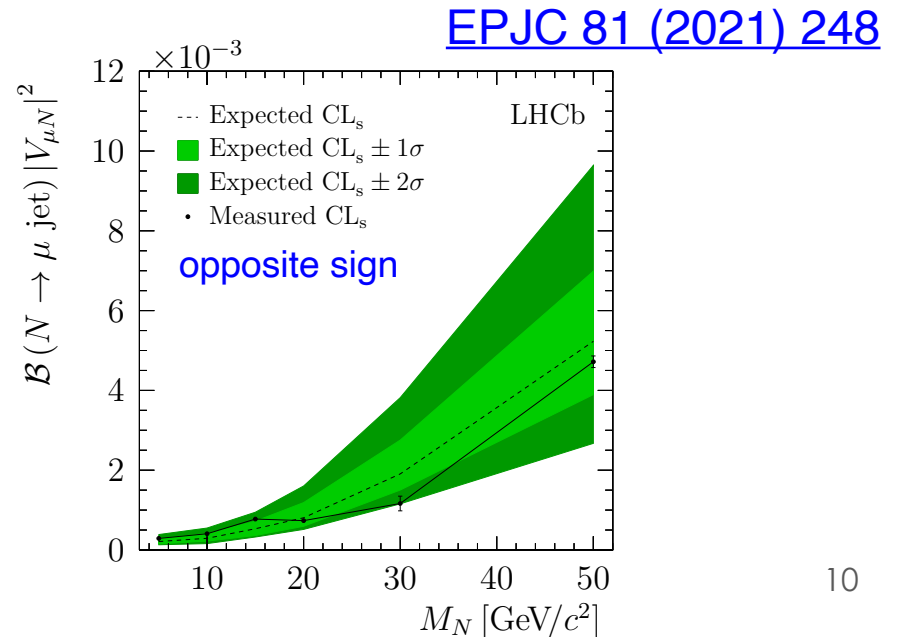
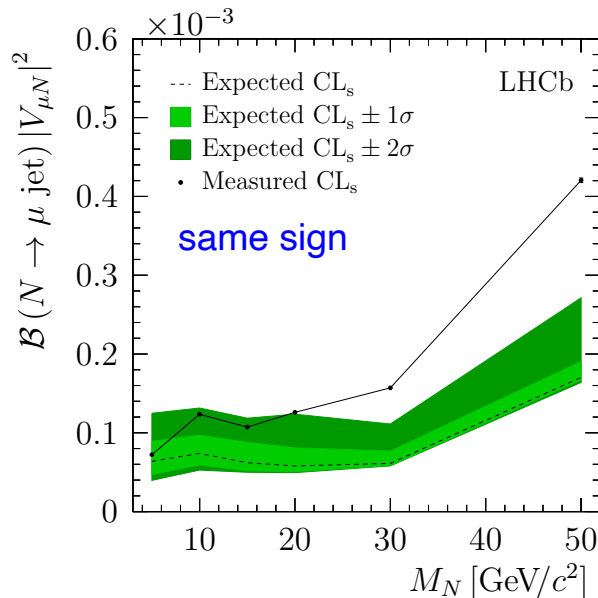
# HNL in $W^\pm \rightarrow \mu^\pm \mu^\pm jet$

- Heavy neutral leptons can be found in W decays



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

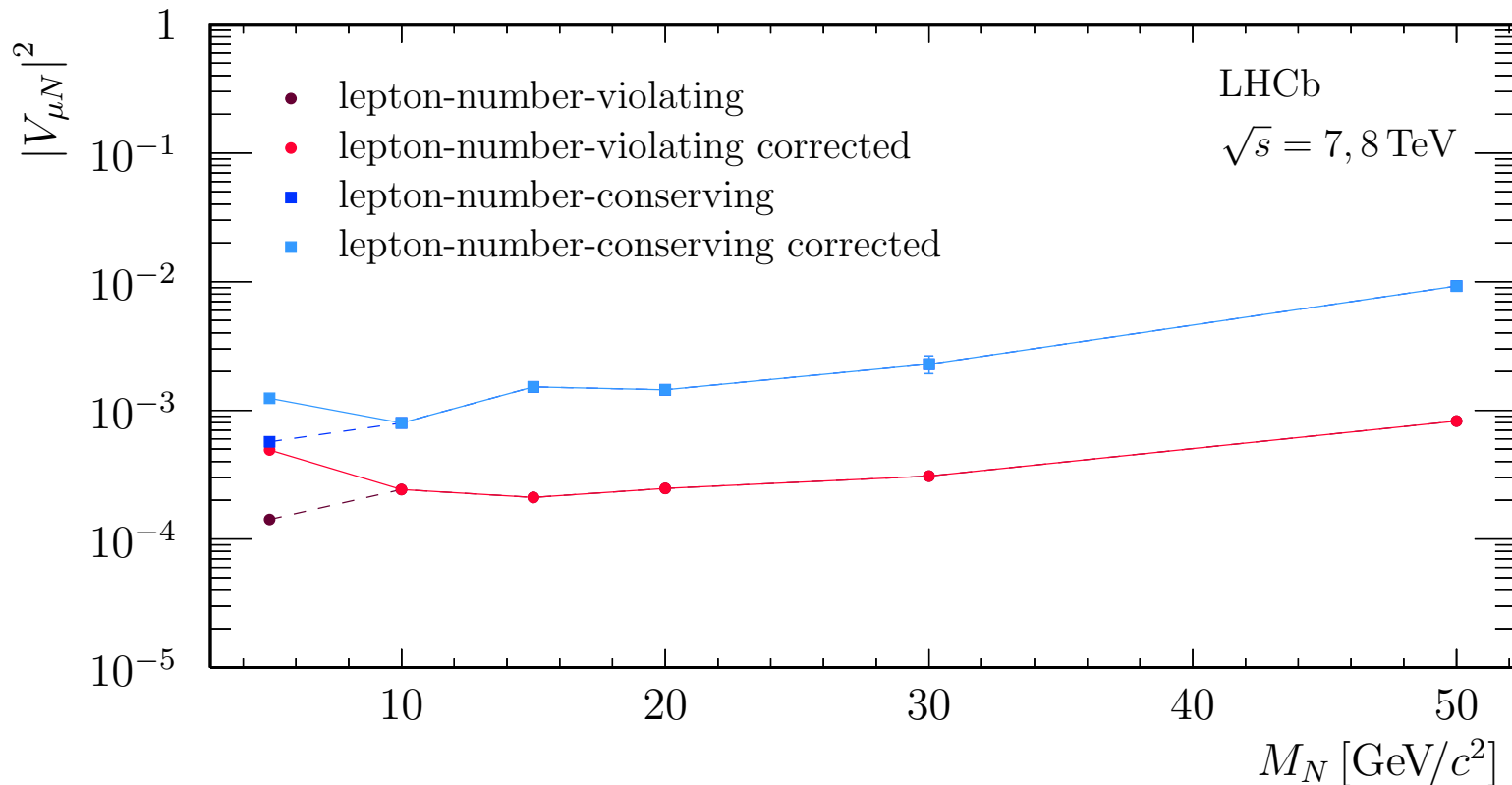
- Upper limits for both same and opposite sign muons using Run 1 data set



# HNL in $W^\pm \rightarrow \mu^\pm \mu^\pm jet$

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

[EPJC 81 \(2021\) 248](#)



- Lifetime corrections at low masses
- Not yet competitive with ATLAS, CMS and DELPHI searches  
[JHEP 10 265](#)   [JHEP 01 122](#)   [Z. Phys. C74 57](#)

# Searches for LLPs decaying to jets

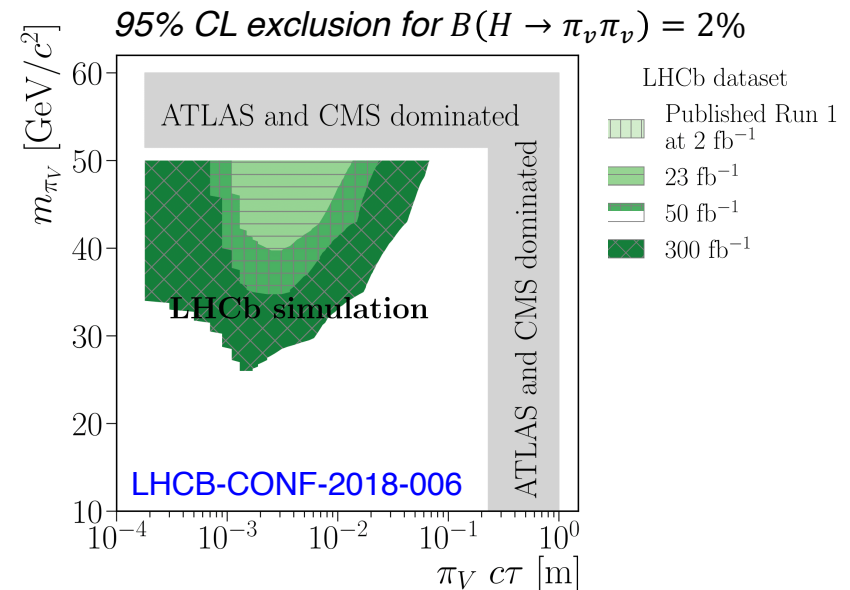
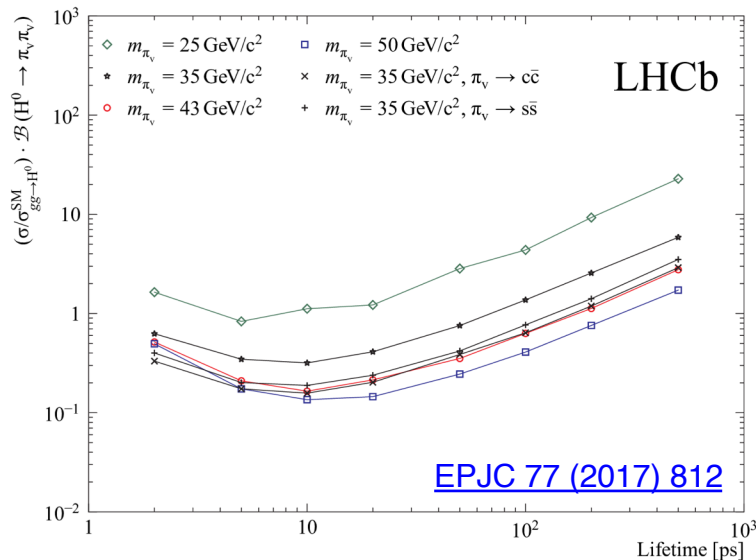
**Signature:** single displaced vertex with two (b-) jets

[EPJC 77 \(2017\) 812](#)

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

**Data set:** Run 1

- Analysis in bins of  $R_{xy}$  - radial distance to the beam axis
- Invariant mass range explored: 25-50 GeV
- No excess found, upper limit for lifetimes range 2-500 ps
- Complementary limits to ATLAS and CMS



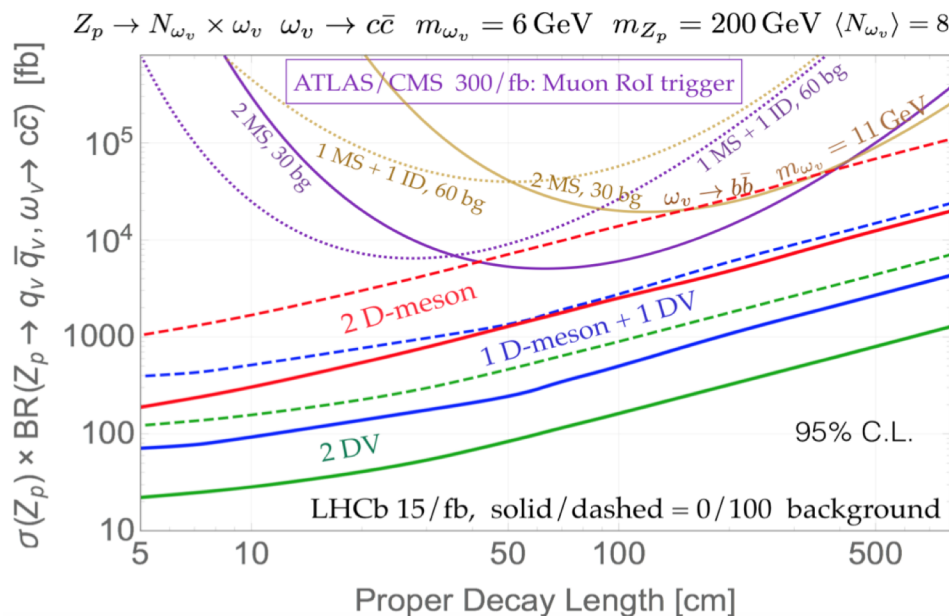
- Can be pushed to lower masses in Run 3 using jet substructure

[LHCb-CONF-2018-006](#)



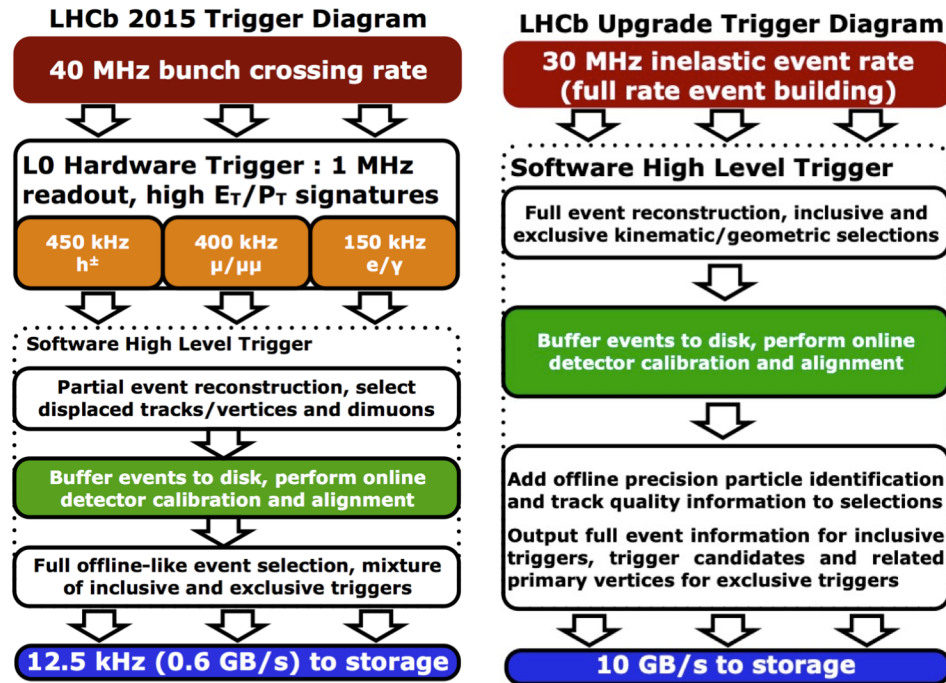
# LLP decays to light hadrons

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



credit: Y. Tsai

# Towards Run 3



- x5 luminosity compared to Run 2
  - fully-software trigger, 30 MHz event reconstruction
  - GPU-based first trigger stage (HLT1) [Comput.Softw.Big Sci. 4 \(2020\) 1, 7](#)
- convenient to trigger exotic signatures

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

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### 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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# Summary

LHCb provides unique capabilities for

- detecting **low-mass** particles and **soft** signatures
- complementing searches at ATLAS and CMS

**Available searches** for

- semi-leptonic and hadronic LLP decays
- heavy neutral leptons
- di-muon resonances

**Inspiring prospects for Run 3** with

- x5 larger luminosity
- fully-software trigger

Stay tuned

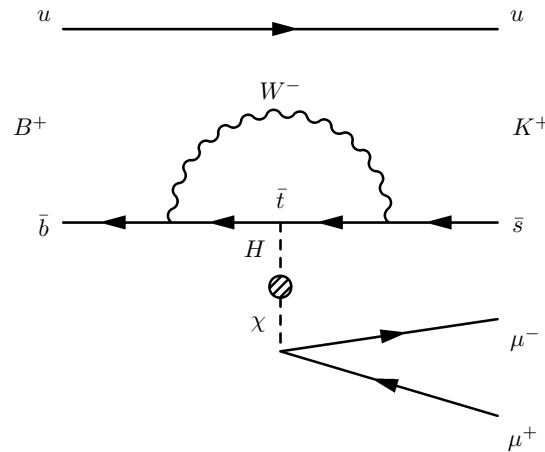




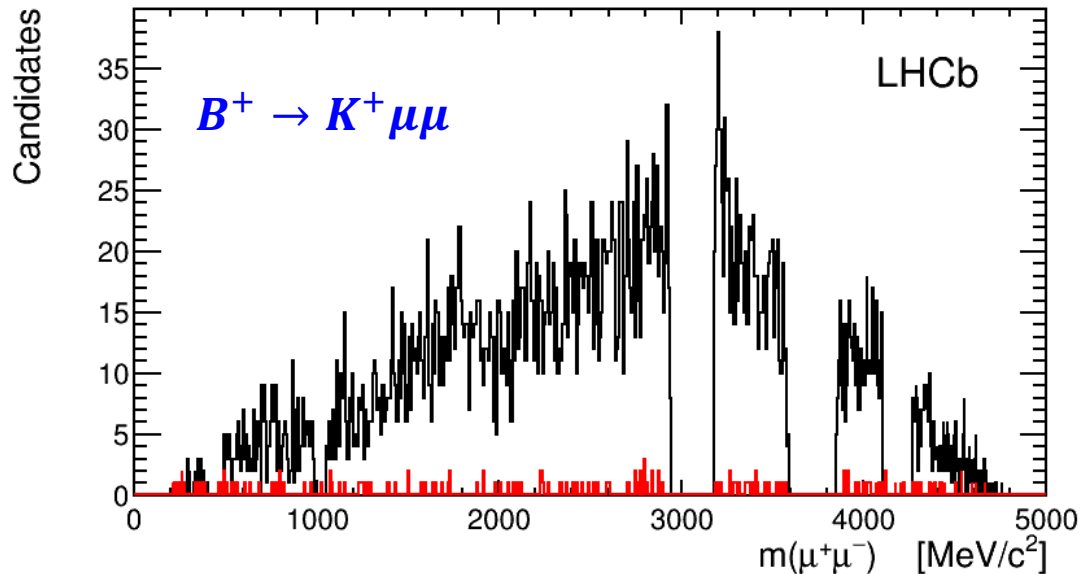
# Light boson from $b \rightarrow s$ decays

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

[PRL 115 \(2015\)161802](#)  
[PRD 95 \(2017\) 071101](#)



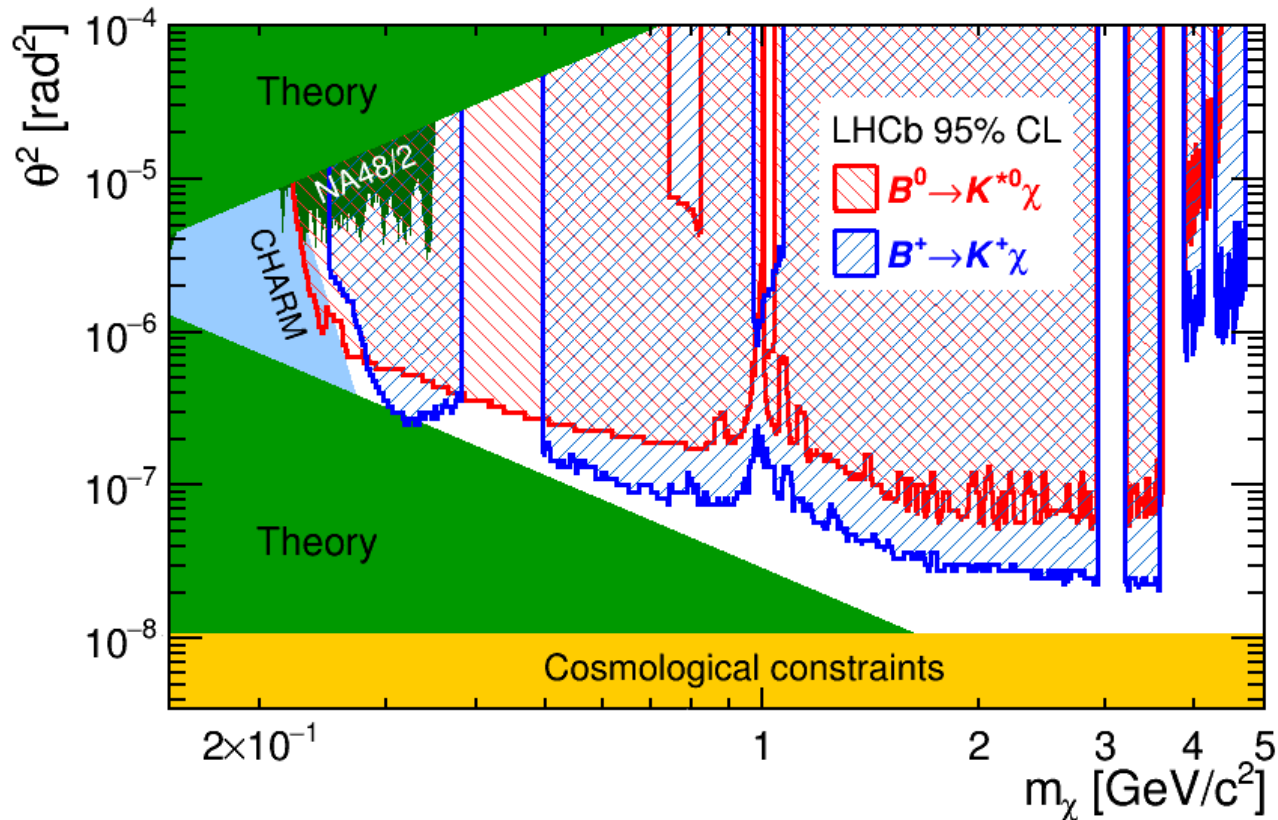
- LHCb has world's largest sample of  $b \rightarrow s\mu\mu$  decays
- Study of di-muon spectrum



# Light boson from $b \rightarrow s$ 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

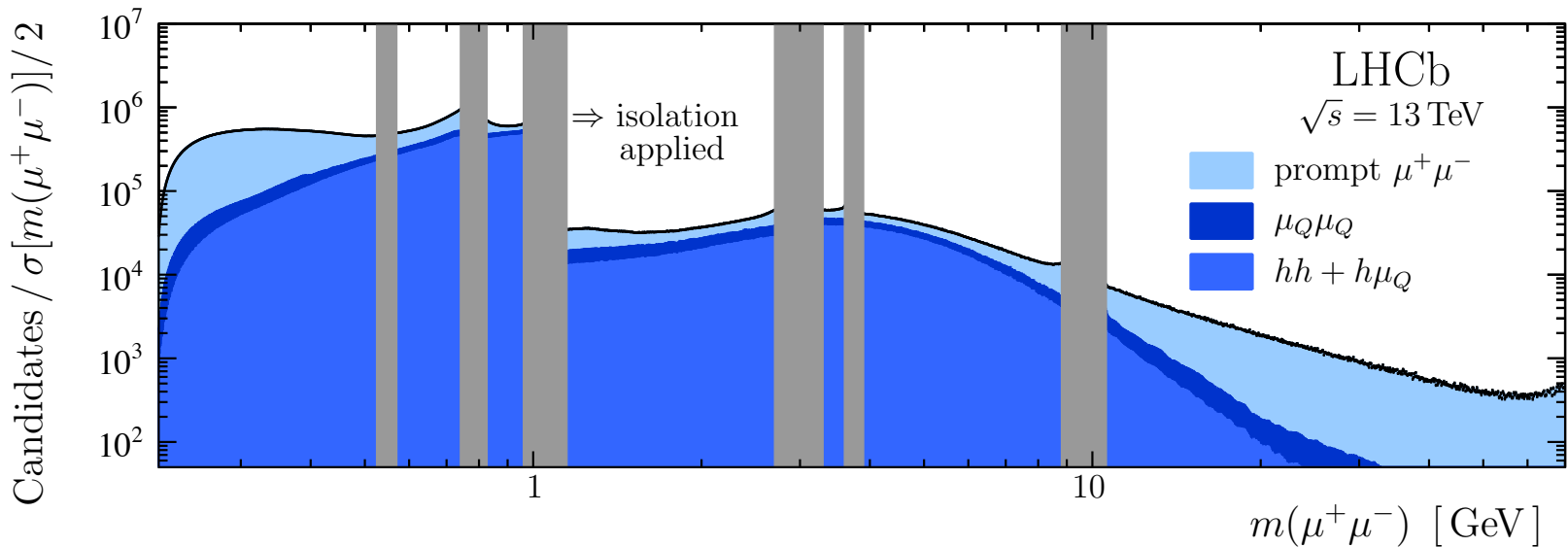


- **World's best upper limits below  $2m_\tau$**

# 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](#)

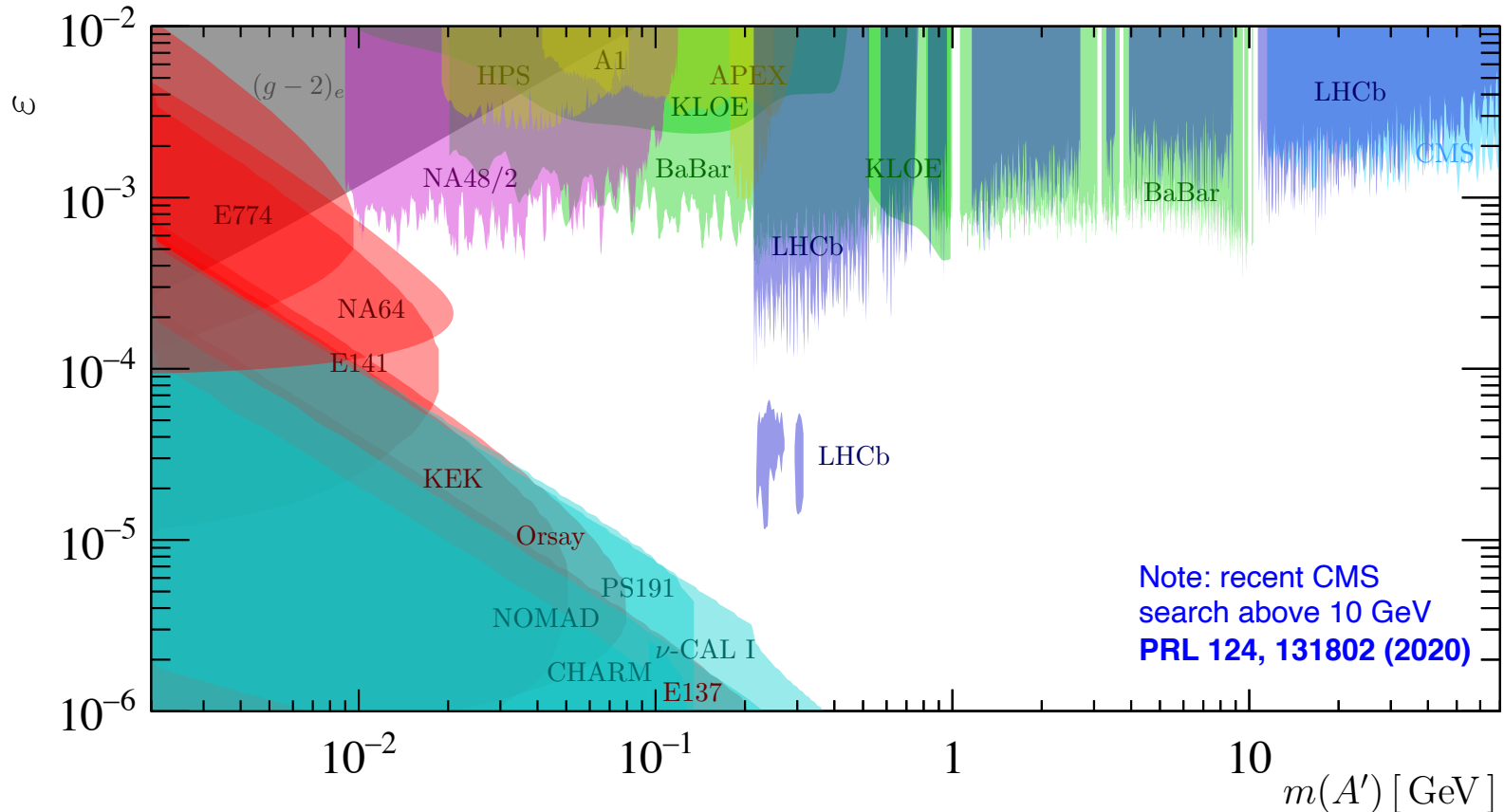


- Bump hunt analysis
- Regions of SM resonances removed
- Search for **both prompt and displaced** signatures using Run 2 data



# Dark photons in di-muon spectrum

[PRL 124 \(2020\) 041801](#)



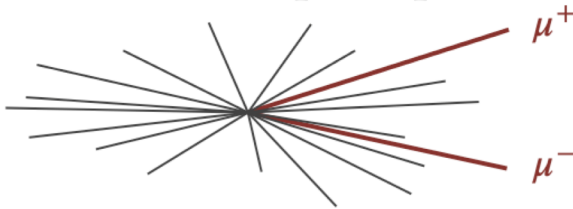
- World's best upper limits for inv. mass range of  $\sim 200\text{-}700$  MeV (prompt)
- First displaced search not from beam-dump experiments
  - *explored invariant mass range: 214-350 MeV*
- *Can be extended with di-electron search at very low masses in  $D^* \rightarrow Dee$*   
[PRD92 \(2015\) 115017](#)

# Non-minimal search

[JHEP 10 \(2020\) 156](#)

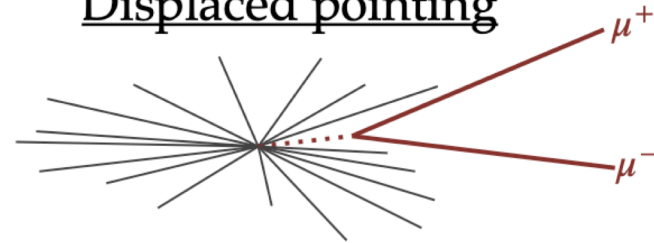
- No assumption on mixing with off-shell photon
- Production categories

## Inclusive prompt

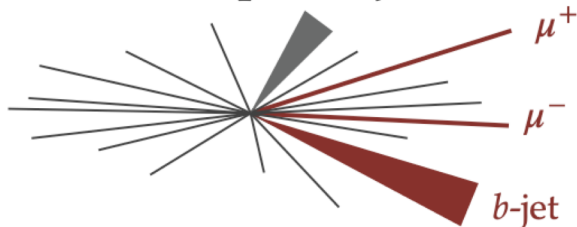


- No isolation requirements
- Non-zero width considered

## Displaced pointing

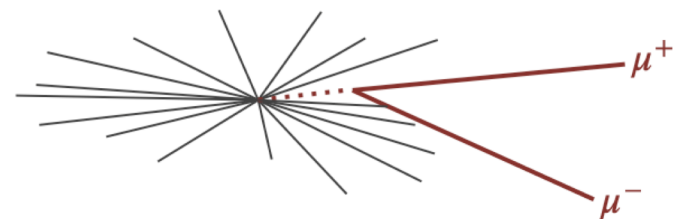


## Prompt + $b$ -jet



- Non-zero width considered

## Displaced non-pointing

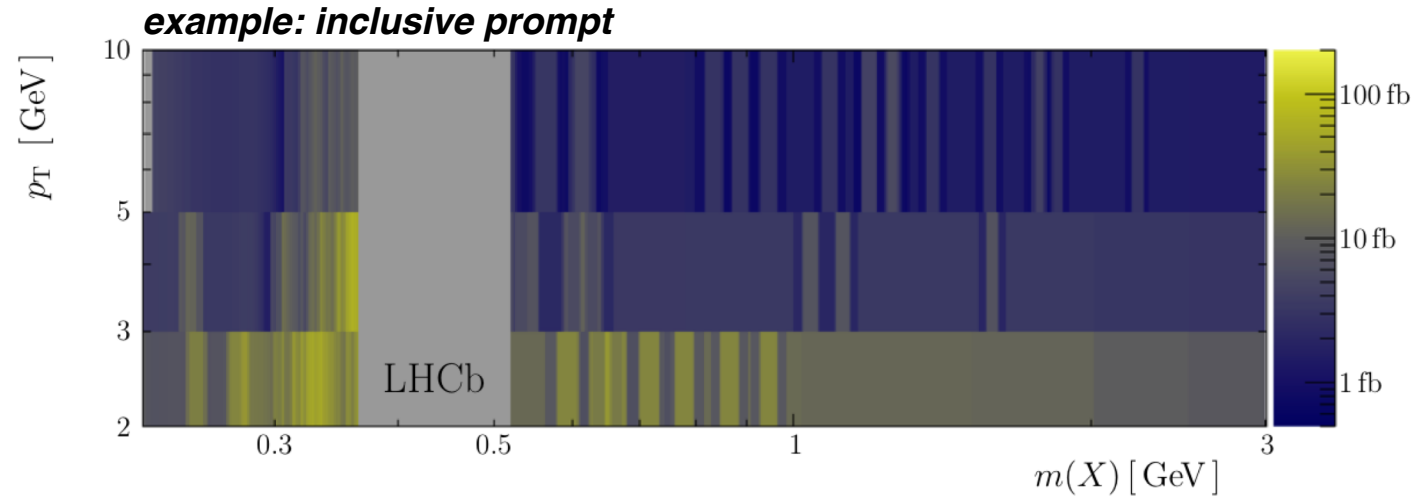


# Inclusive di-muon search

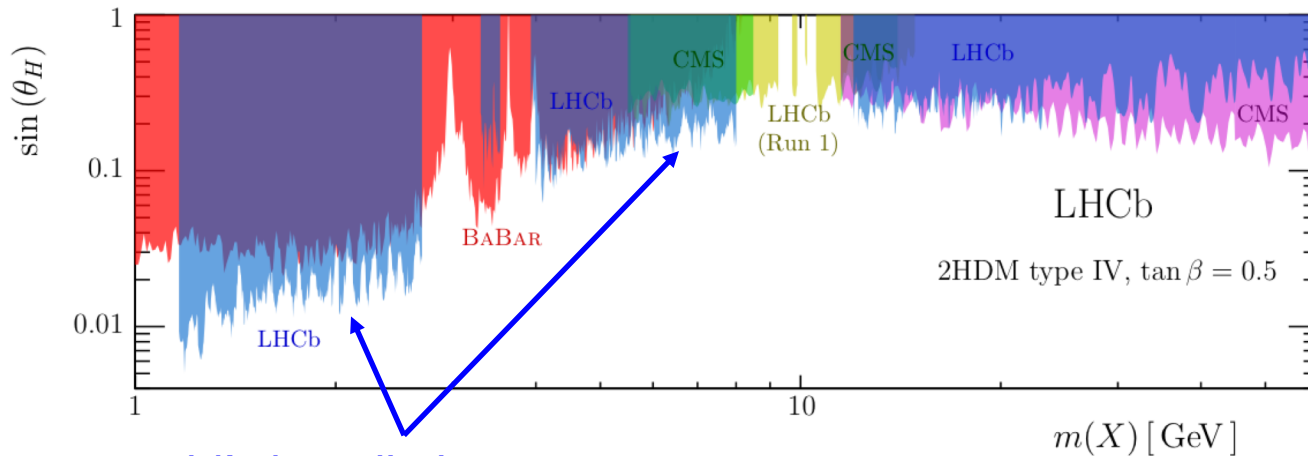
- Results in kinematics bins for each category

*\*numbers available at supplementary material for interpretations*

[JHEP 10 \(2020\) 156](#)



- 2 HDM scenario



world's best limits on  $\sin(\theta_H)$