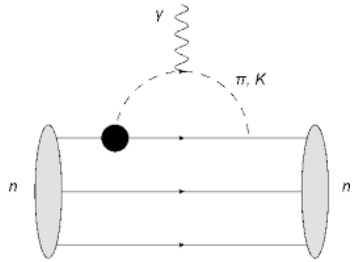

# Heavy neutral lepton searches at LHCb

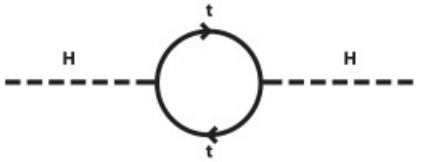
Louis Henry, on behalf of the LHCb collaboration
LHCP 2024, Boston, 03/06/2024

# Missing bricks in the Standard Model

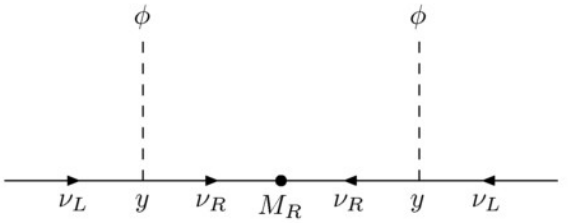
## Strong CP problem



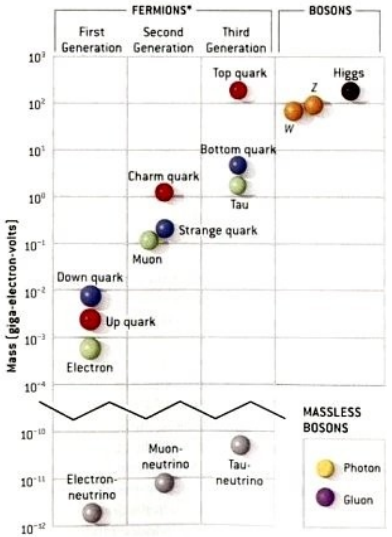

## Higgs naturalness

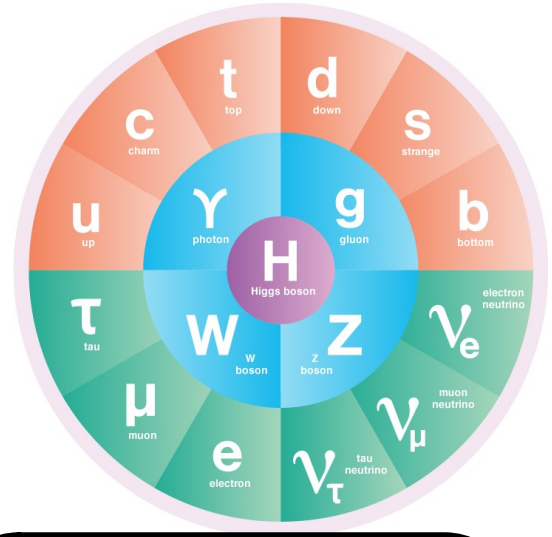



## Neutrino mass

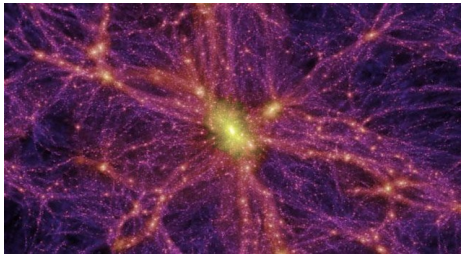



## Mass hierarchy

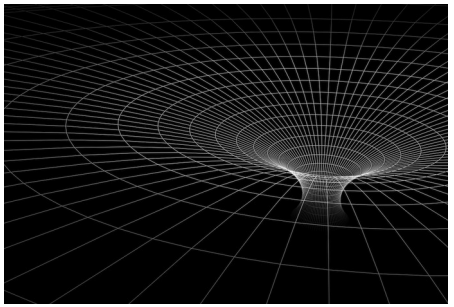


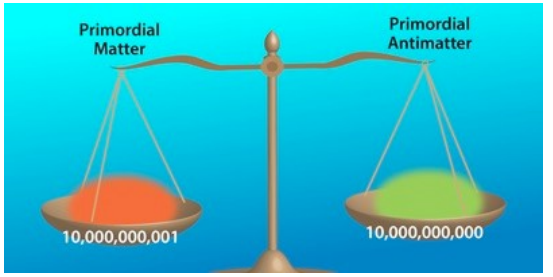

## Dark matter candidate



## Gravity



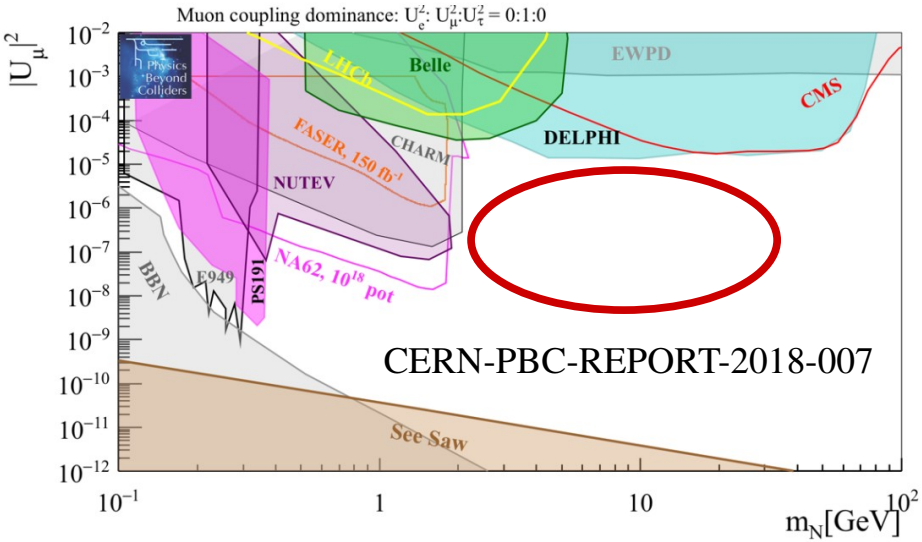
## Baryon-antibaryon asymmetry of the Universe.



# The heavy neutral lepton

- Heavy neutral leptons are a natural answer to a few outstanding puzzles.
  - Mostly, the nonzero mass of neutrinos.

- Where could we look for it?
  - Possibly long-lived! → evades traditional trigger and reco strategies.




## Energy frontier

- Missing symmetries (strong CP, Higgs naturalness).
- New physics produced mostly in transverse region.
- ATLAS/CMS most suited.

## Intensity frontier

- More suited for indirect searches for NP.
- Missing CPV
- LHCb has its word on it.
- Can be transverse, longitudinal…

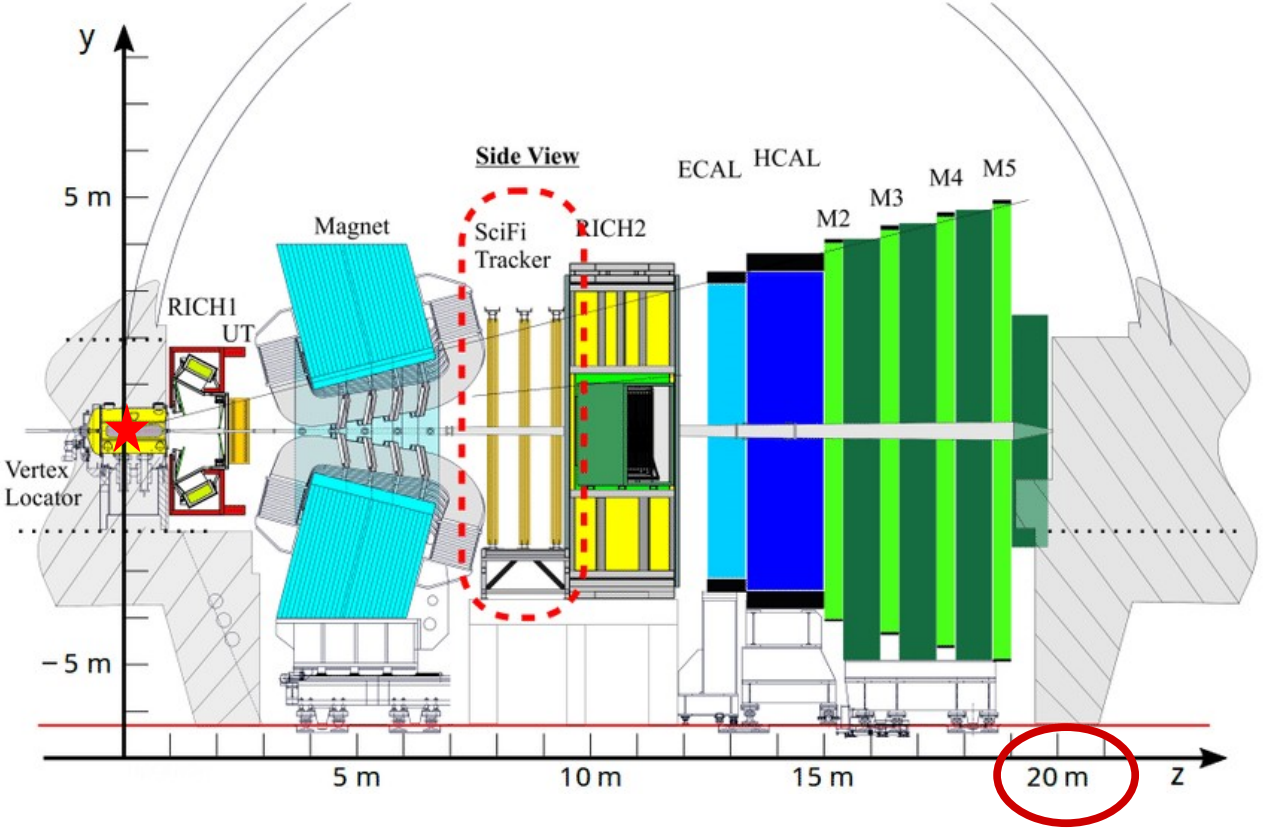
## Lifetime frontier

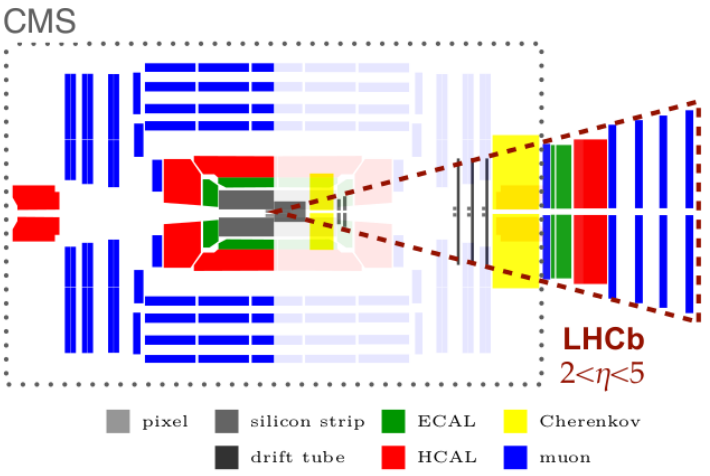
- New particles are there but too long-lived for current detectors.
- Necessarily low coupling to SM → related to intensity frontier.
- Transverse/longitudinal depends on mass of the mediator.

# The LHCb detector as a camera



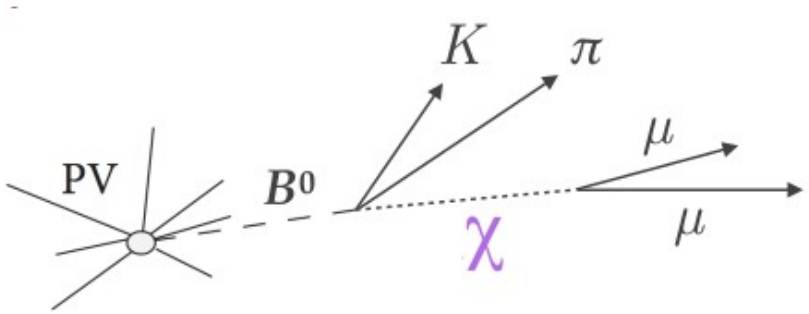
- LHCb is a detector along the LHC, specialised in the study of beauty and charm hadrons [JINST 3 (2008) S08005]
- High precision in the central region… but also a long instrumented region.
  - Specialised in displaced vertices in the central region → interesting for "small" lifetimes.
  - Can we act as a specialised camera in the very displaced region?



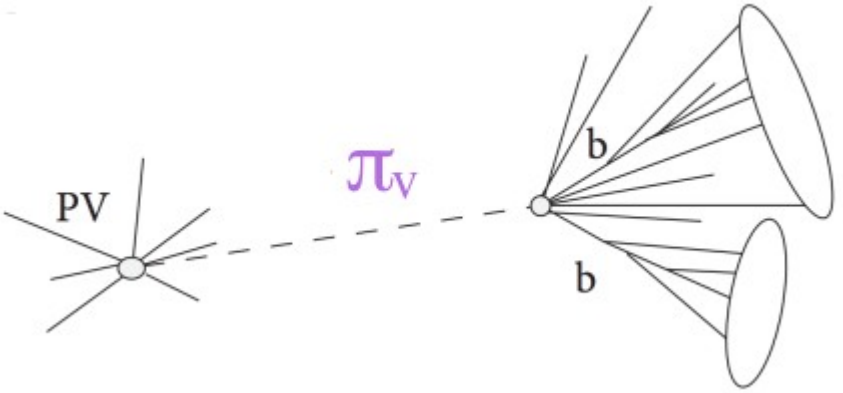
# LLPs at LHCb: different worlds

- Final states and accompanying particles are crucially important.
- At LHCb, two types of production:




Produced in B/D decays

- Benefit more from LHCb trigger, acceptance.
- Light boson, majorana neutrino
- Limited energy range
- Possible to use constraints on mass to reduce beackgrounds.



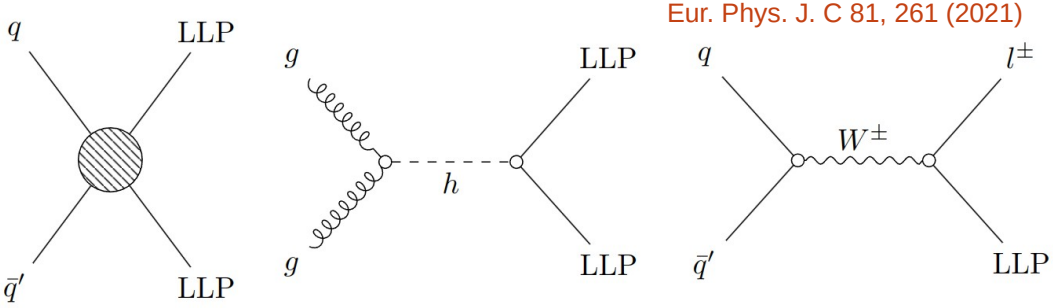

Produced in pp collisions

- No associated trigger.
- Displaced dileptons (e.g. dark photon), jets with possible μ associated.
- Larger energy range but need to be in acceptance.

# Search for long-lived particles decaying to $e^{\pm}\mu^{\mp}\nu$



- Production modes considered: direct-pair production, Higgs decay, and charged current.

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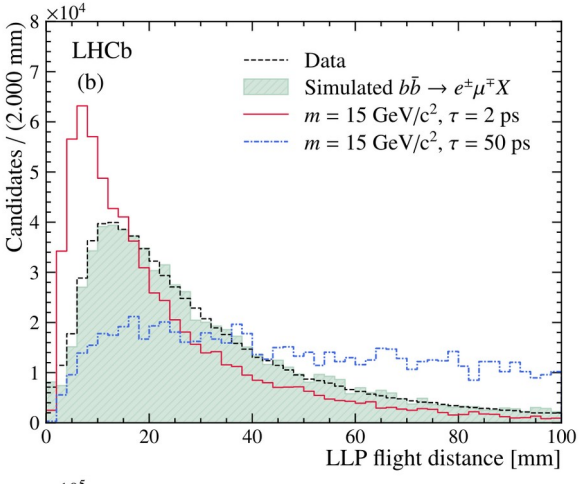
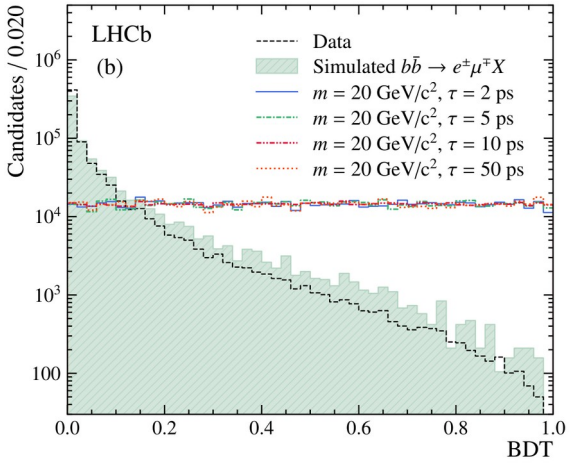
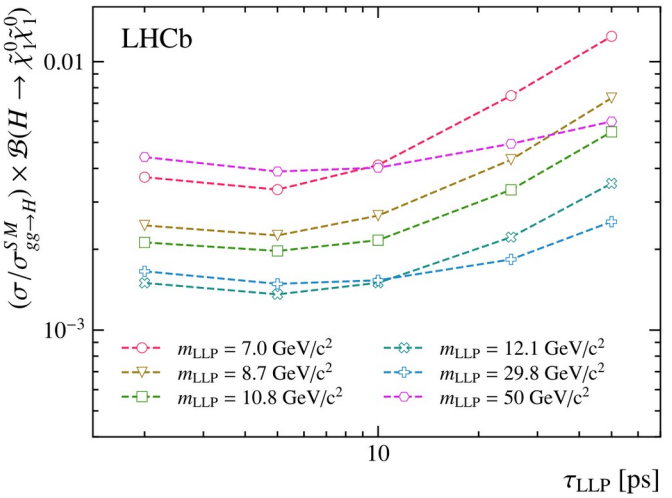
- Looks for displaced vertex → fully exploits LHCb vertexing capabilities in inner region.
- Templates from simulation to look for signal, BDT method to reject background further.
  - No significant excess observed.
  - Good data/MC agreement.



# Search for heavy neutral leptons in $W^+ \to \mu^+\mu^\pm$jet decays



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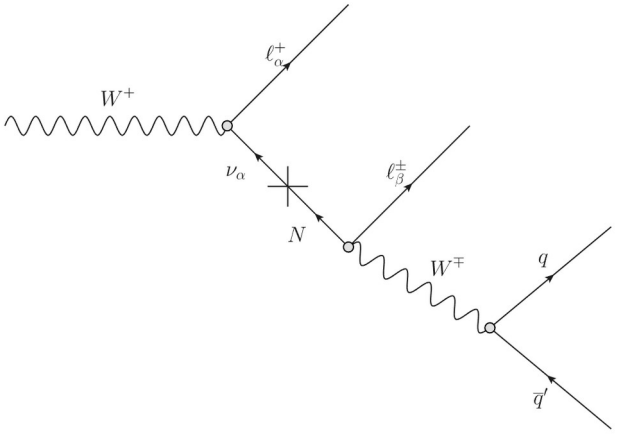
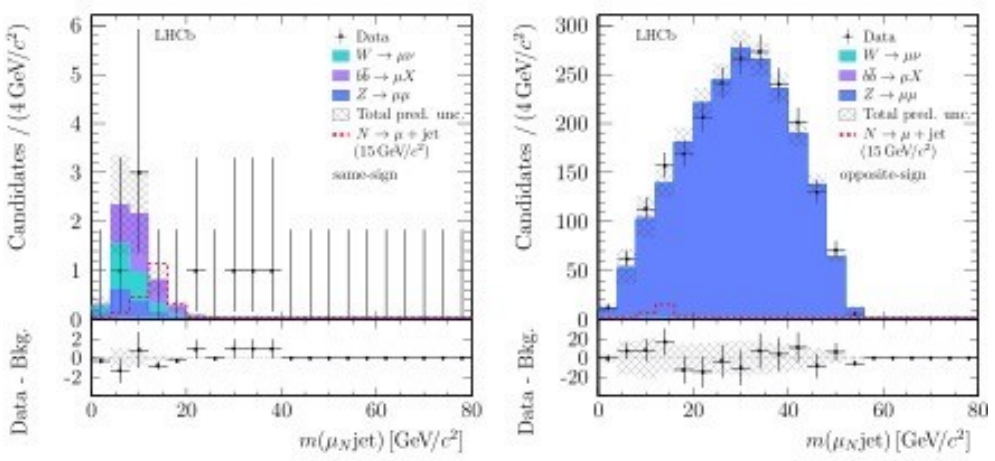
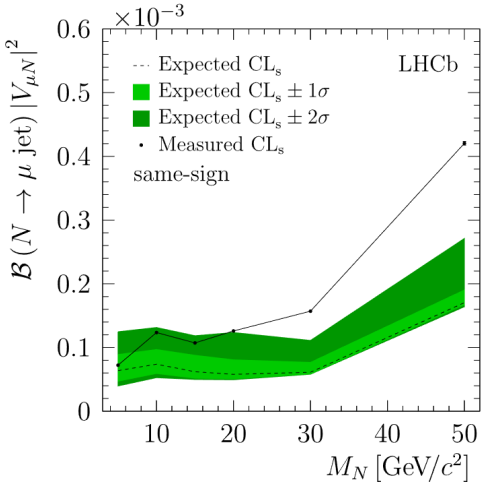
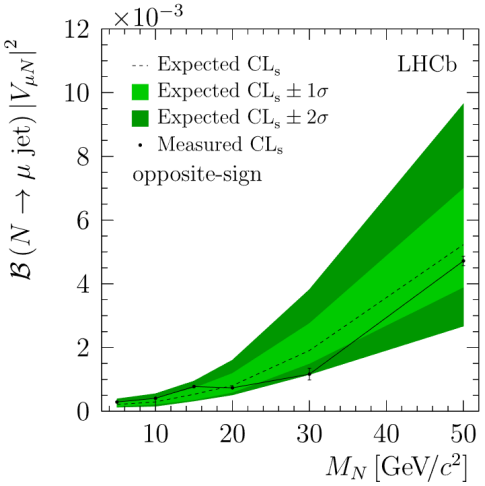
- Prompt HNL decays, allowing for Majorana.
- Background normalised via $W \to \mu\nu$ and $Z \to bb$
- Constrained to prompt in order to suppress heavy-flavour background.



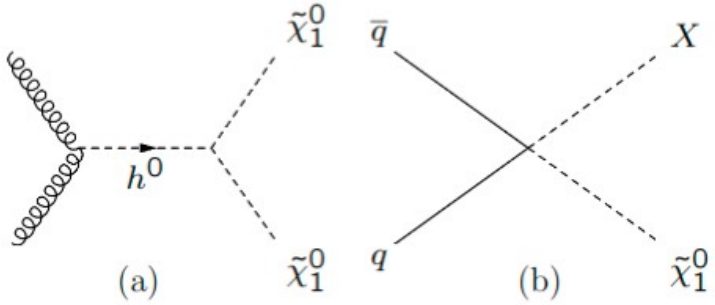



# Search for massive long-lived particles decaying semileptonically at √s= 13 TeV



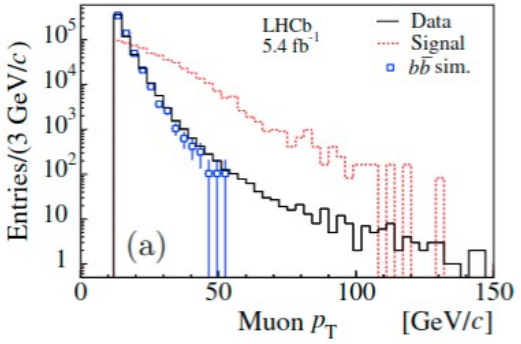
[Eur. Phys. J. C 82 (2022) 373]

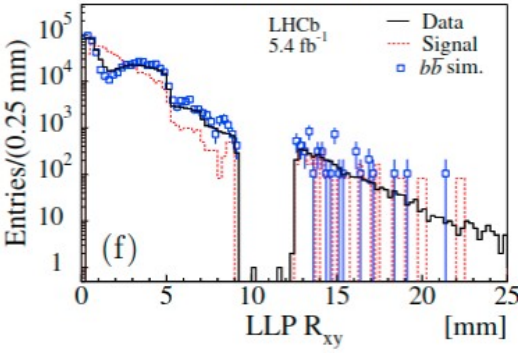
- Analysis focusing on SUSY particles, either produced through a scalar portal $h^0$, or in nonresonant fashion. **Possible to recast though!**
  - (a) $m_{h0}$ in [30 - 200] GeV range, $m_{\chi}$ in [10 GeV - $0.5m_{h0}$] range, and lifetime in [5 - 200] ps range.
  - (b) $m\chi$ in [10 - 90] GeV range, lifetime in [5 – 200] ps range.




$$\tilde{\chi}_1^0 \to \mu^+ q_i q_j (\mu^- \bar{q}_i \bar{q}_j)$$

- LHCb: probing a rapidity region more difficult to barrel experiment.
- Triggering on the high $p_T$ ($> 10$ GeV/c) muon
  - Then offline, adding an IP criterion & tightening the $p_T$ cut.
- Remove primary vertices through distance to the beam axis.
- Vertex needs to have three or more tracks with the muon, regions with material are vetoed.



# Search for massive long-lived particles decaying semileptonically at √s= 13 TeV

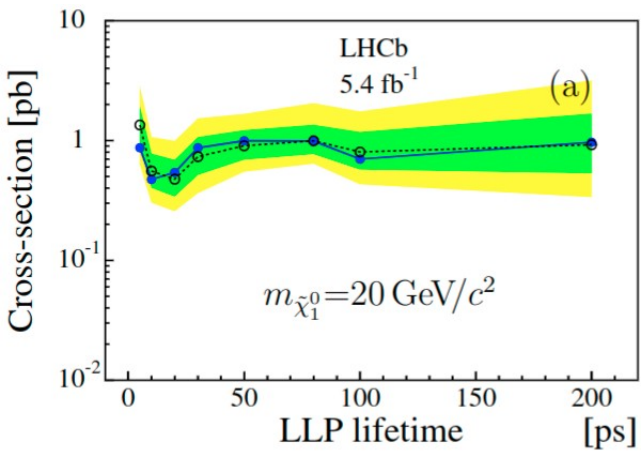


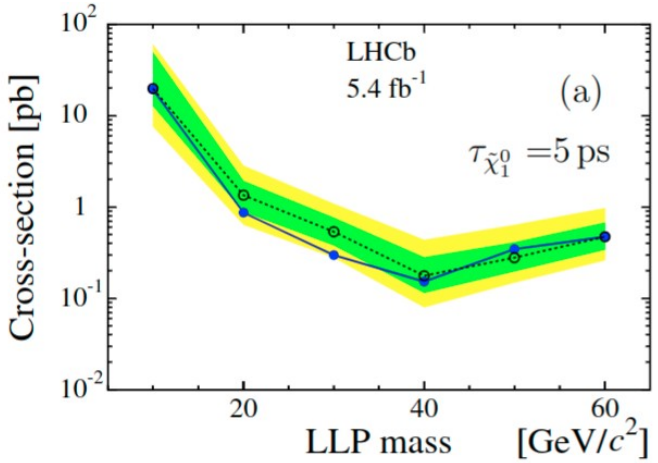
[Eur. Phys. J. C 82 (2022) 373]

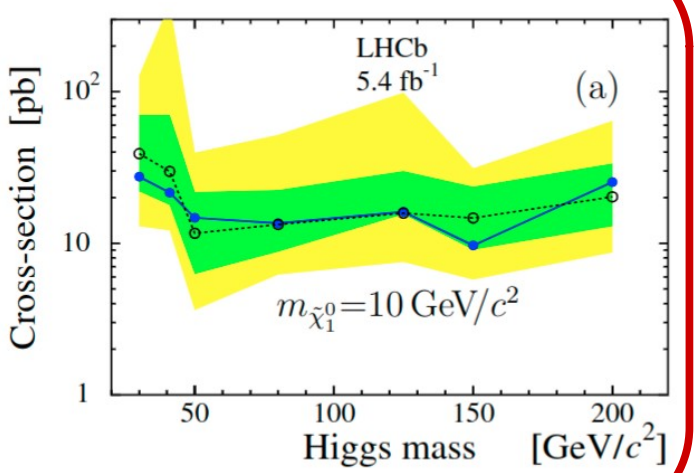
- Systematic uncertainties are dominated by the parton fusion and uncertainties on the MVA.

| Source | Contribution [%] |
|---|---|
| Integrated luminosity | 2.0 |
| Parton luminosity gluons fusion (quarks) | 6.0 (3.0) |
| Simulation statistics | 2.0–4.0 |
| Muon reconstruction | 2.0–3.7 |
| $p_T^\mu$ | 1.0 |
| $IP^\mu$ | 1.0 |
| Vertex reconstruction | 2.0 |
| Beam line uncertainty ($R_{xy}$) | 0.9 |
| Muon isolation | 1.7 |
| MVA | 1.7-16 |
| Mass calibration | 1.4 |
| Total | 7.3–18.9 |

- Results given as function of the χ mass, the χ lifetime, and the Higgs mass.

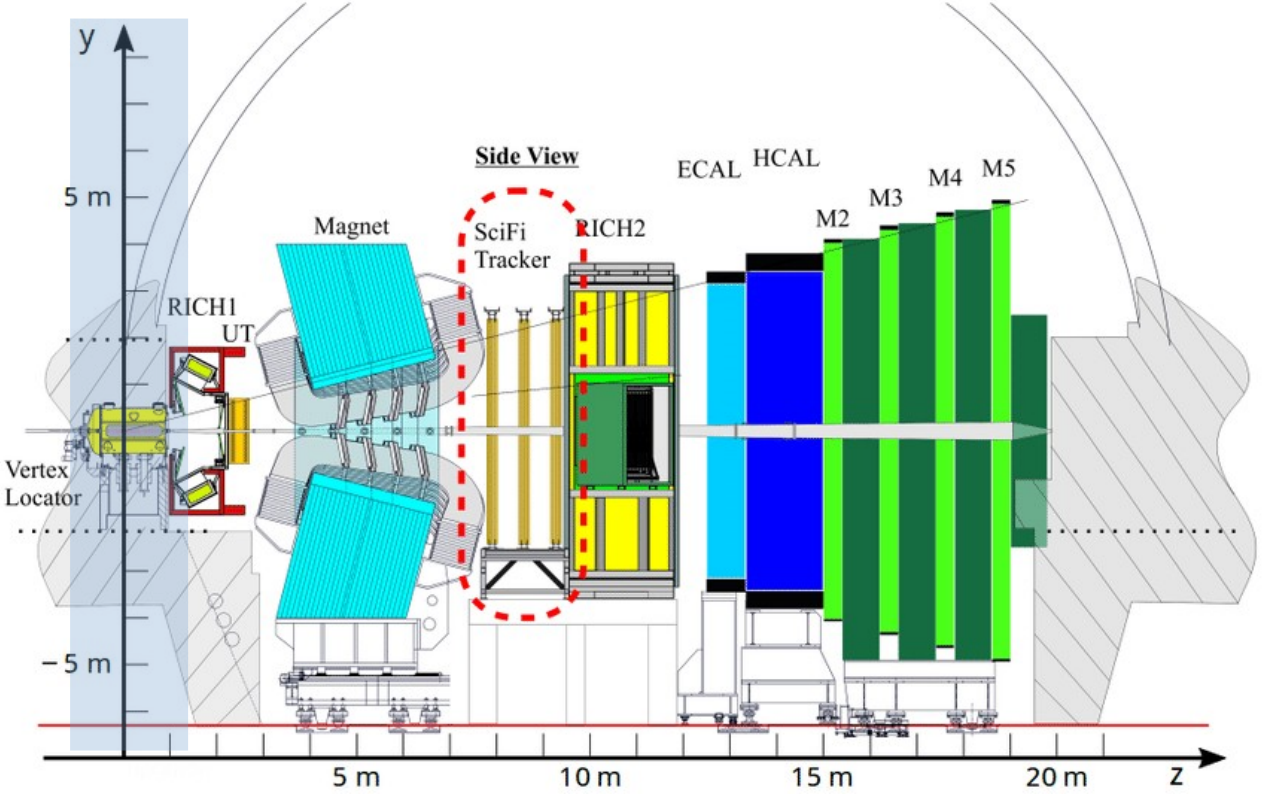


# What's to come?

- Presented results are rather old → more analyses are in advanced development stage.
  - Still Run 2 though.
- We are, in Run 2, limited by statistics and by the available reconstruction modes.
- With Run 3, LHCb changed to full software trigger → unprecedented flexibility!



# So what do we do?

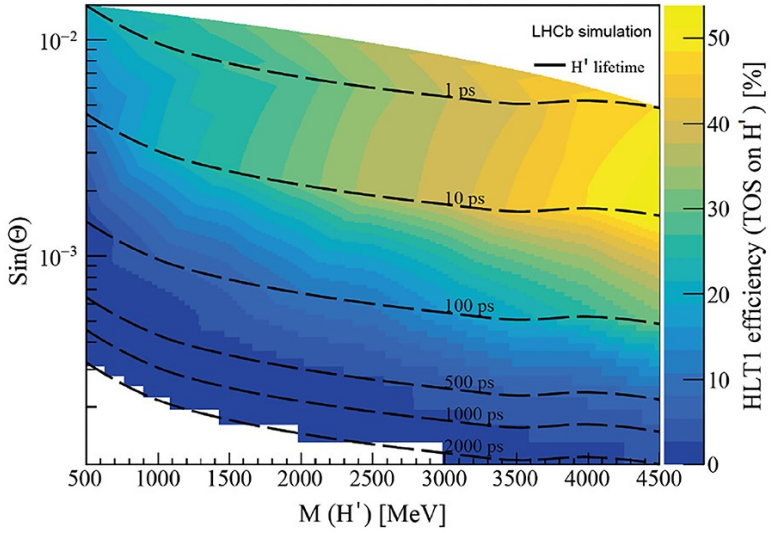
- LHCb not reaching its full potential yet as an LLP detector:
  - Trigger can be a bit limiting [2105.12668], [J. Phys. G: Nucl. Part. Phys. 47 090501 (2020)].
  - Searches focused on region around the IP.

2203.07048

Reference [9] showed that ultimately the reach of LHCb is limited by the size of its vertex detector (VELO); *i.e.*, that the sensitivity is not limited by the signal rate or backgrounds, but instead by the lifetime acceptance. This results in a minimal gain in sensitivity for dark photons going from Run 3 to Run 6, even though the integrated luminosity will increase by a factor of 20.

- Right: impact of the first level of the LHCb trigger on efficiencies for the scalar portal.

Front. Big Data 2022.1008737




- Currently worked on!
  - Trigger now fully adapted to downstream tracking;
  - Even more displaced tracks now included;
  - Efforts to include "muon-only" (up to 18m disp. from PV!) in trigger, see L. Hartman's talk.

*previously used in dark photon searches*

# Conclusion

- Heavy neutral leptons are well motivated and a lot of the parameter space still needs to be explored.
- LHCb has shown the capacity to look for HNLs in two very different regimes: prompt decay and displaced vertices.
  - Different background, physics reach.
- More analyses to come with Run 2 data!
- Adding more data is only one of the facets of the experiment's future → large increase in fiducial volume planned.
  - From [0-1m] to up to 18m away from the PV!

2312.14016