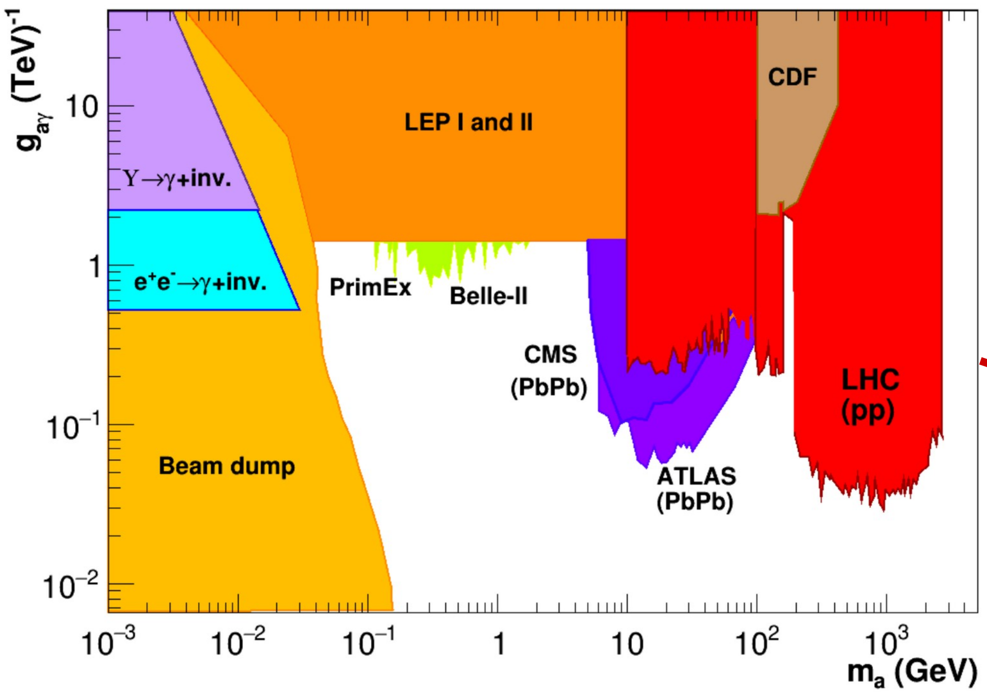
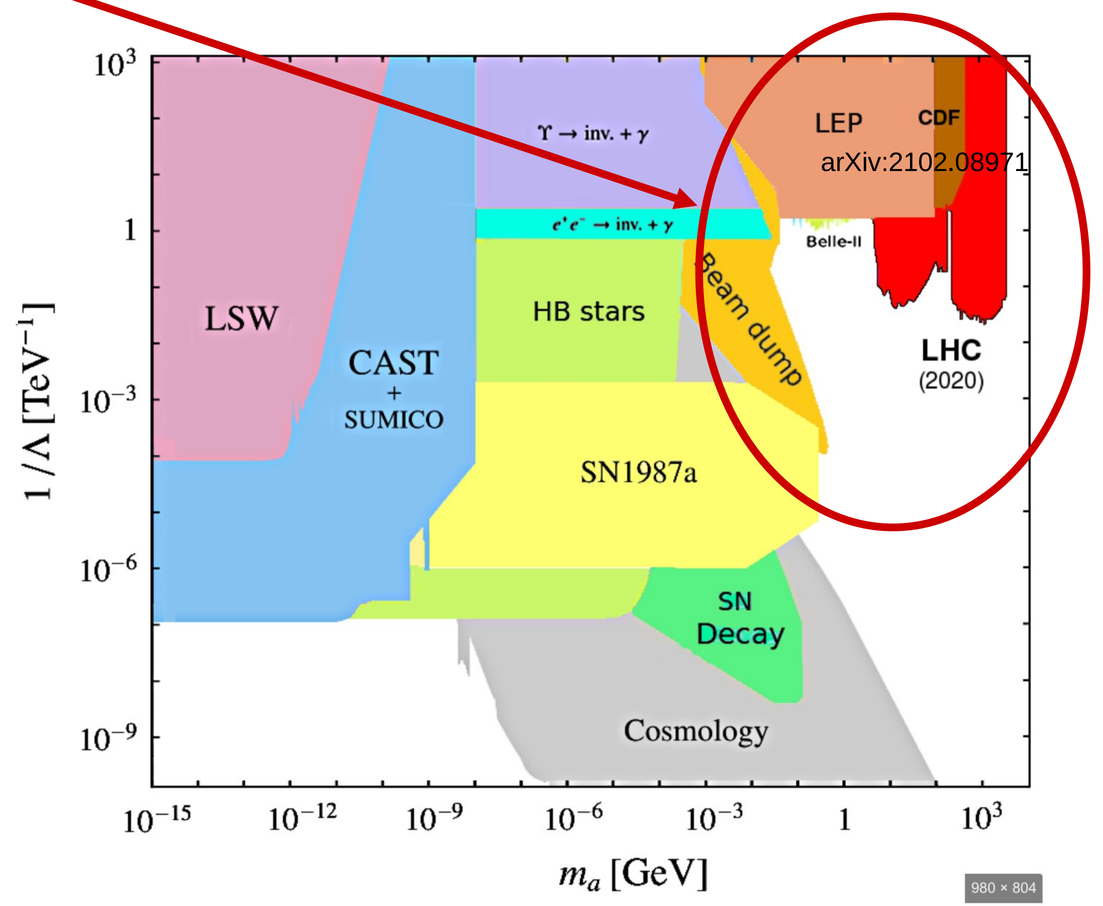
ALP searches at LHCb

Louis Henry, on behalf of the LHCb collaboration
Rencontres du Vietnam, 05/08/2024

Where the wild things are: LHC & ALPs

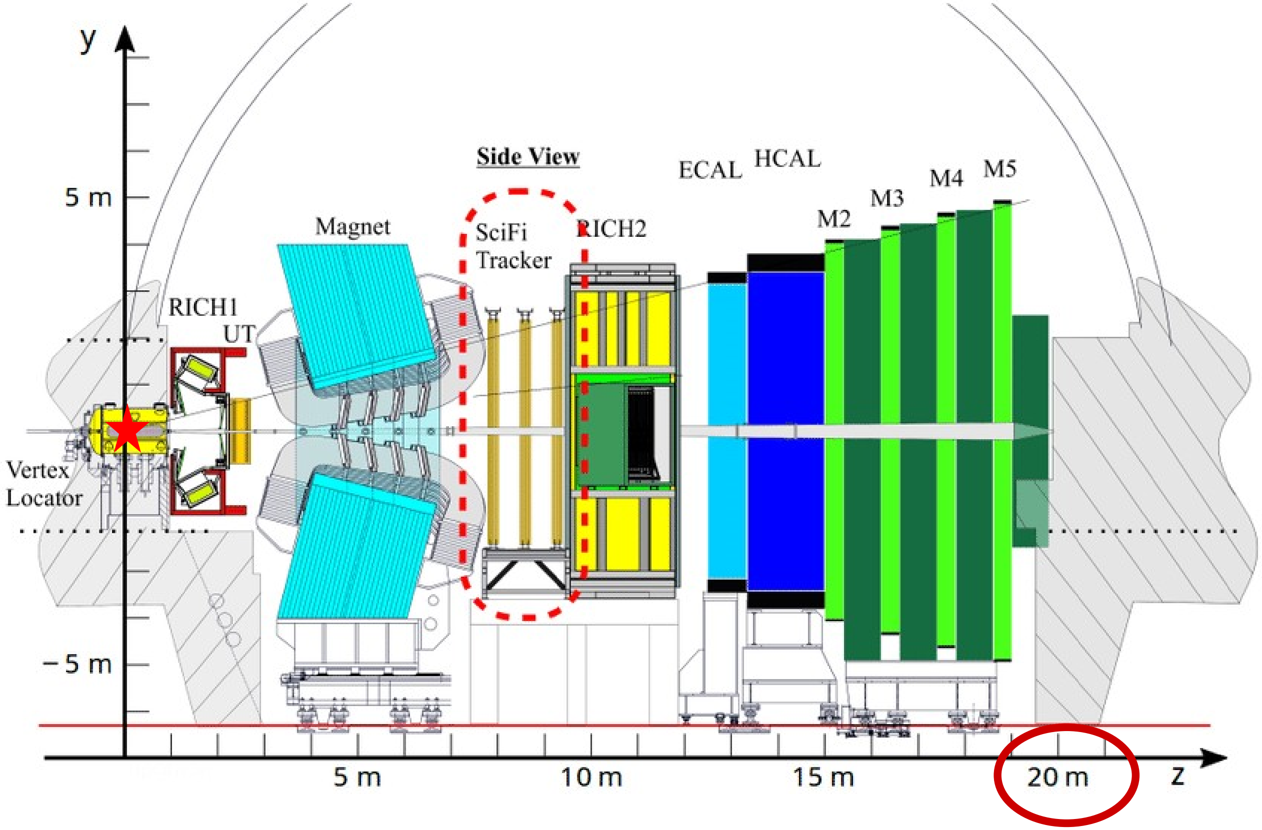


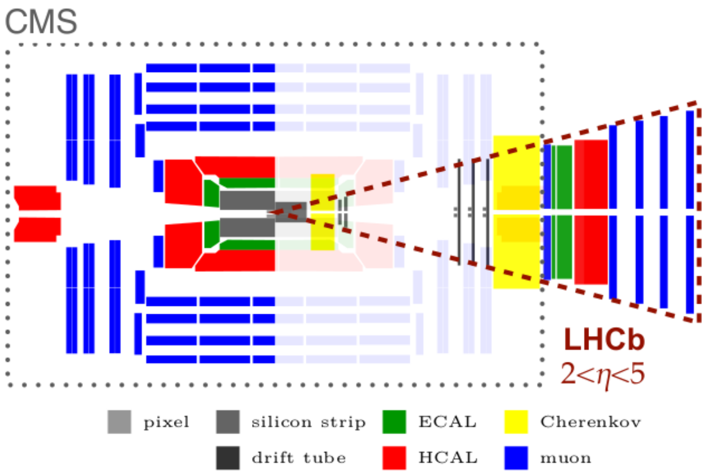
- "Low-energy" is E ~ [0.5-10] GeV
- "Displaced" is a few mms.



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.

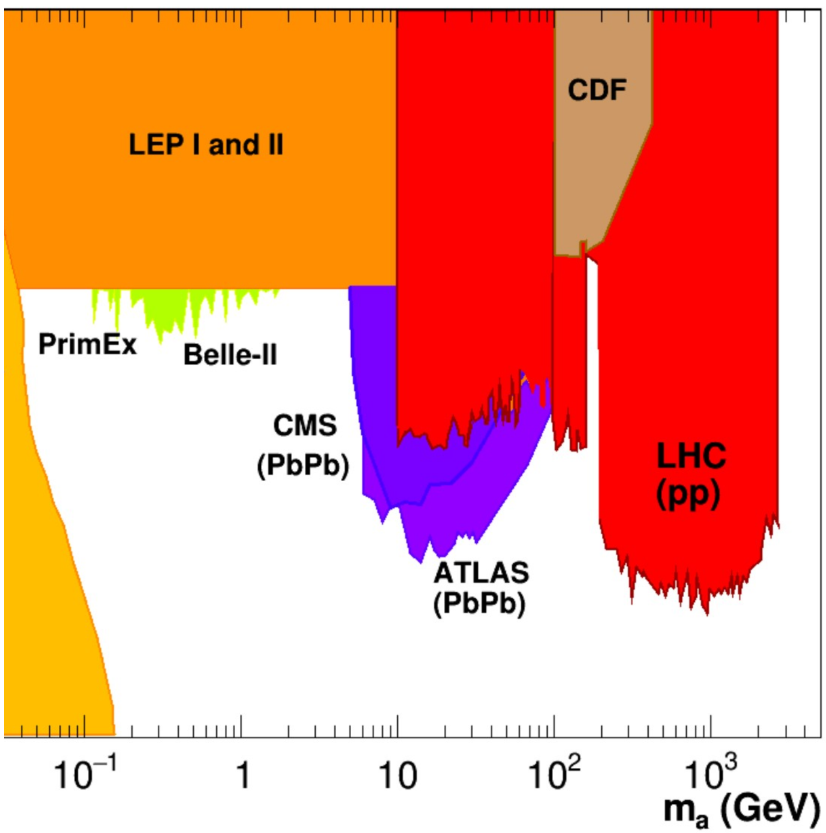




ALPs at the LHC: harder collisions, larger datasets

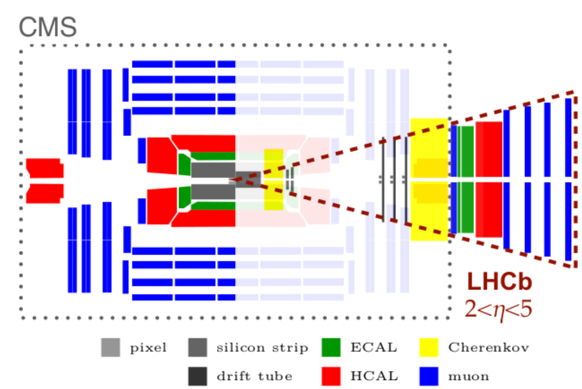
More energy

More data recorded



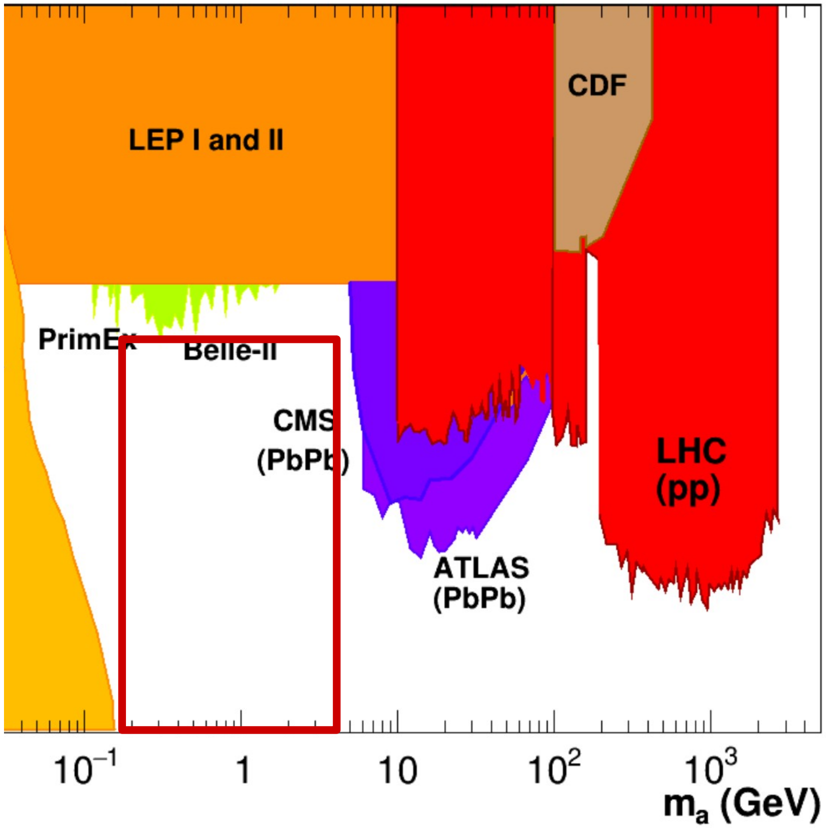
arXiv:2102.08971

- ATLAS/CMS have 20 times the luminosity of LHCb.
- Trigger rates way above, much better $\gamma\gamma$ reconstruction.
  - $\gamma\gamma$ is simply infeasible at LHCb.
- LHCb is not hermetic! No missing energy possible.



ALPs at the LHC: softer modes, longer times

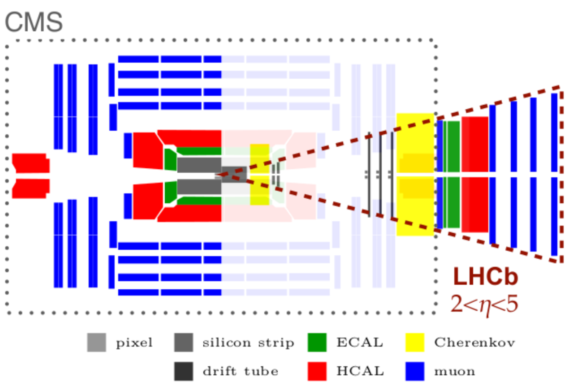
Better trigger for soft signatures



arXiv:2102.08971

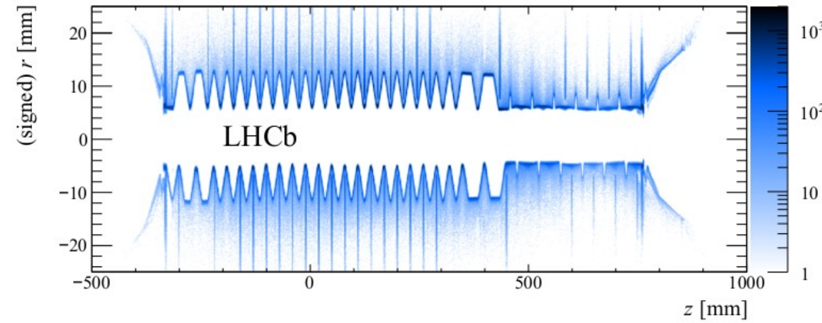
Longer decays!

- What LHCb does have:
  - Very good vertex resolution → possible to go for displaced decays;
  - Longer instrumented region;
  - Good PID → $\eta\pi\pi$ modes possible;
  - Specialised design for low-p_T decays;
  - Specialised design for B decays.

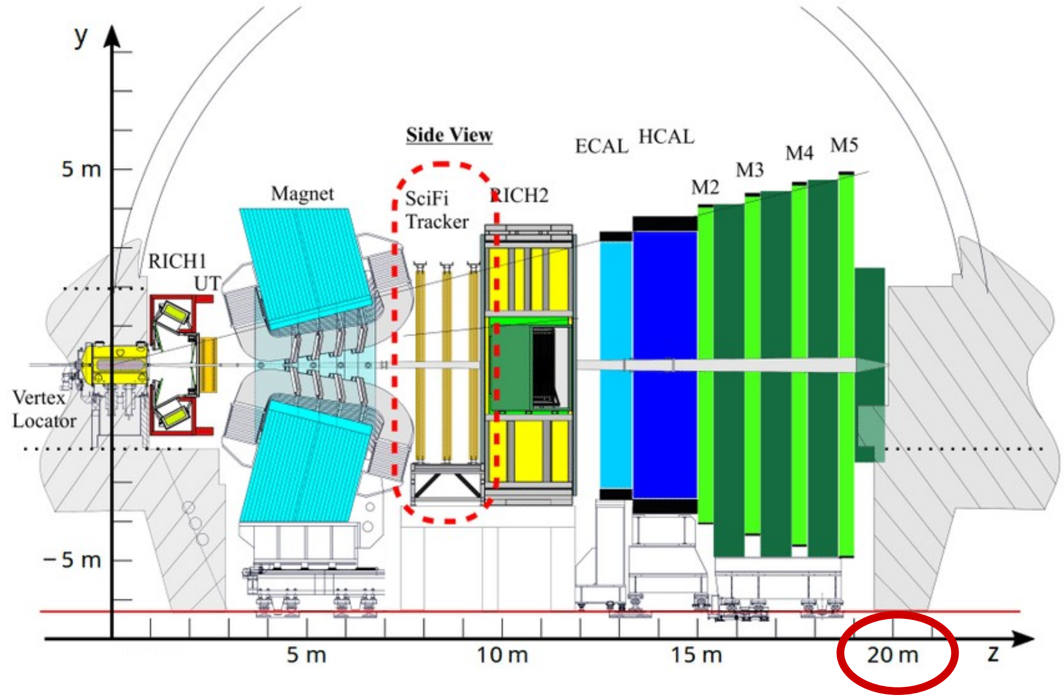


LHCb axions: two worlds

- Usual searches for axions in LHCb focus on the Vertex Locator (VELO).
  - Flight distances [few mm - 60-100cm]
  - Exploit vertex resolution to veto material interactions
  - Best track reconstruction efficiency.



- Axions are potentially long-lived particles → adding more detector length would corner the parameter space.
  - Yes but trigger challenge!
  - LHCb has been built mostly around the VELO

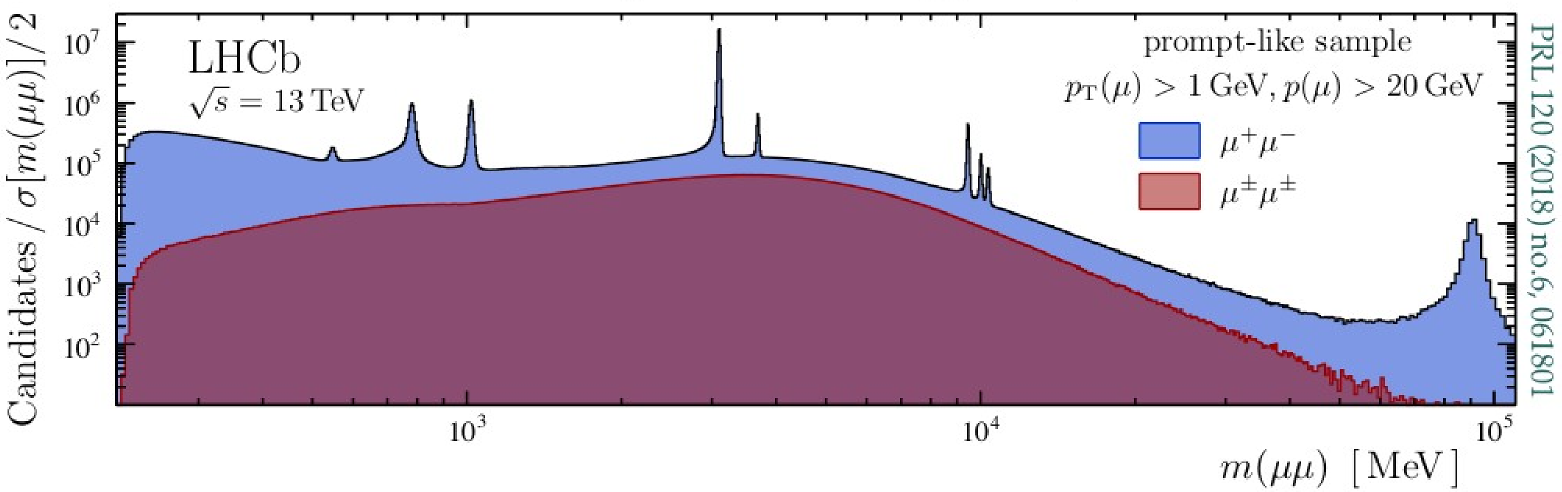


Searches for axions in the central region

- Several searches by LHCb of displaced particles → potential axions.
  - Search for $A' \to \mu^+\mu^-$ decays. [Phys. Rev. Lett. 124 (2020) 041801][LHCb page];
  - Searches for low-mass dimuon resonances [JHEP 10 (2020) 156][LHCb page];
  - Search for dark photons produced in 13 TeV pp collisions [PRL 120 (2018) 061801][LHCb page].

- All these searches tend to be in dimuon modes: easier to reconstruct and trigger on.
  - Fully online trigger in Run 3 → will be even more potent;
  - More flexible → hadronic modes?

Dimuon spectrum from **trigger output**



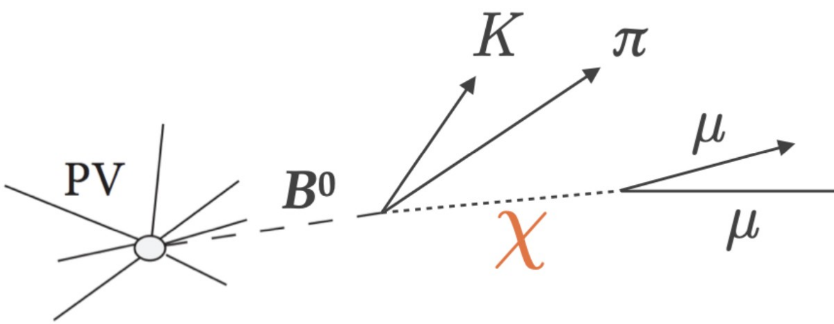
Let's go bump hunting

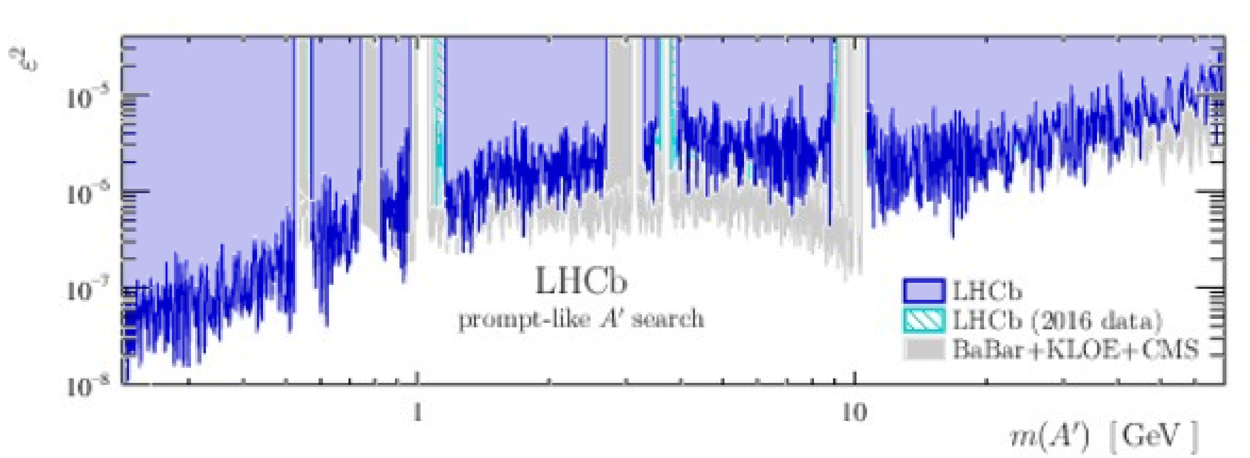
LHCb: searches for a ~~dark photon~~ axion (1)

PhysRevLett.120.061801

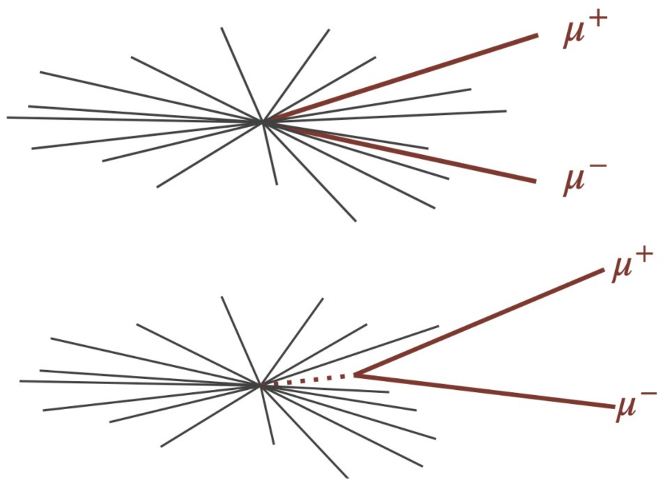
- Axions can be produced in B decays or in ‘direct’ production
- Pioneering search for a dark photon in two regions:
  - ‘Prompt’ (flight distance < 5 mm);
  - Displaced.

Produced in heavy-flavour decays



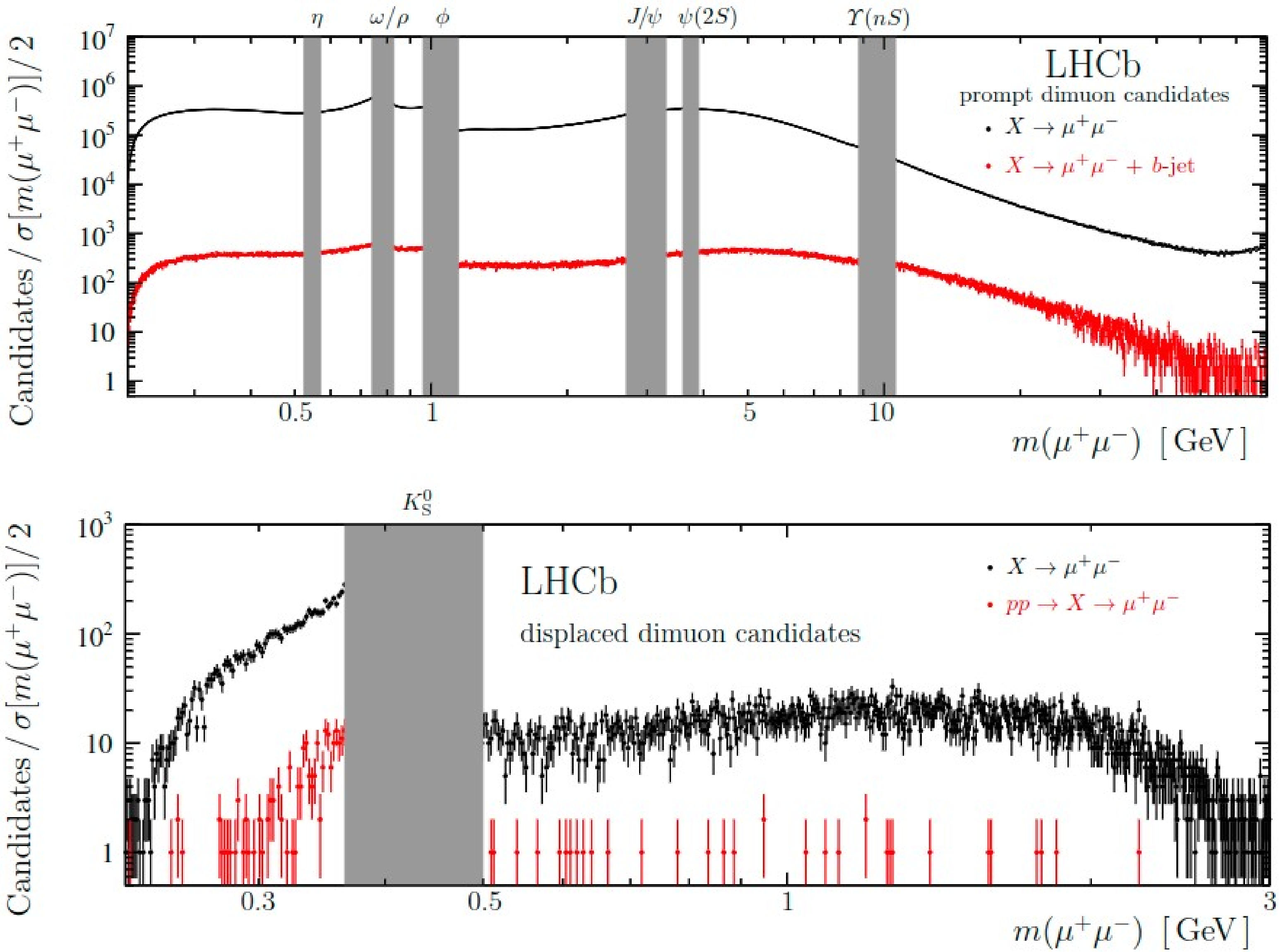


Produced in *pp* collisions

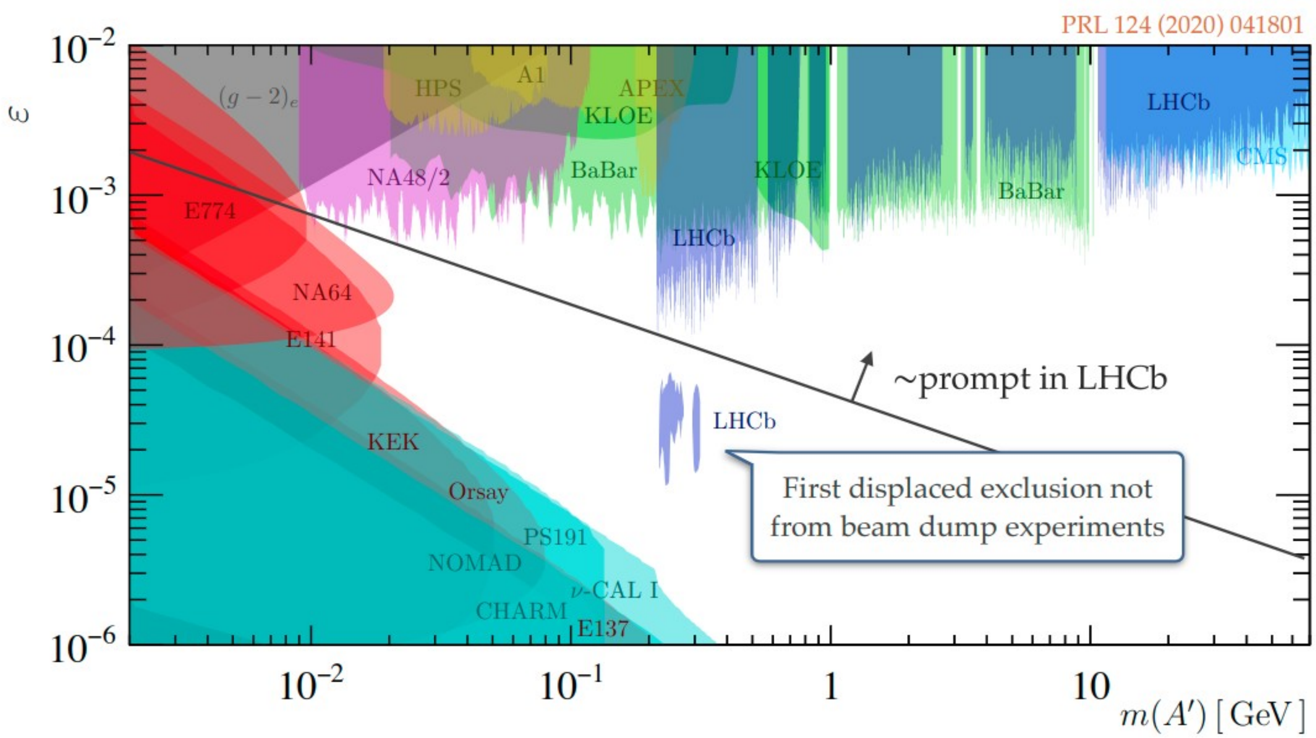


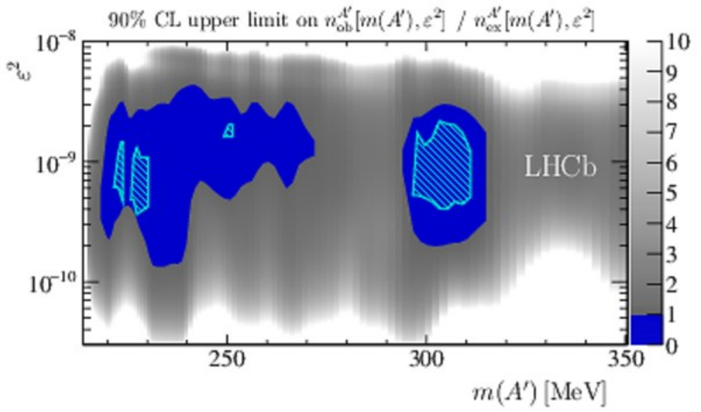
Let’s go bump hunting

LHCb: searches for a ~~dark photon~~ axion (2)



LHCb: searches for a ~~dark photon~~ axion (3)

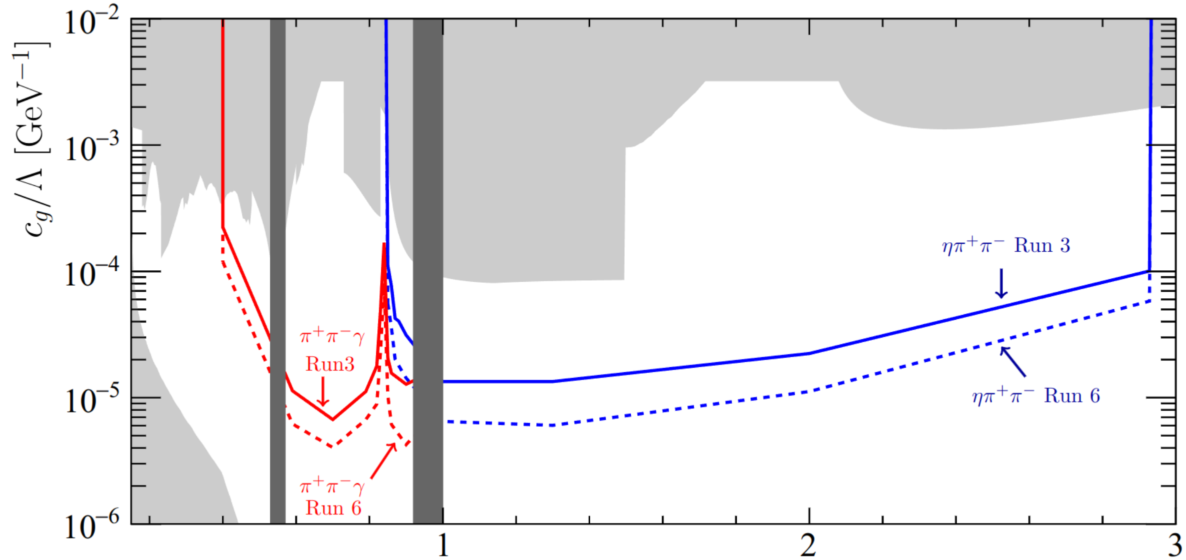




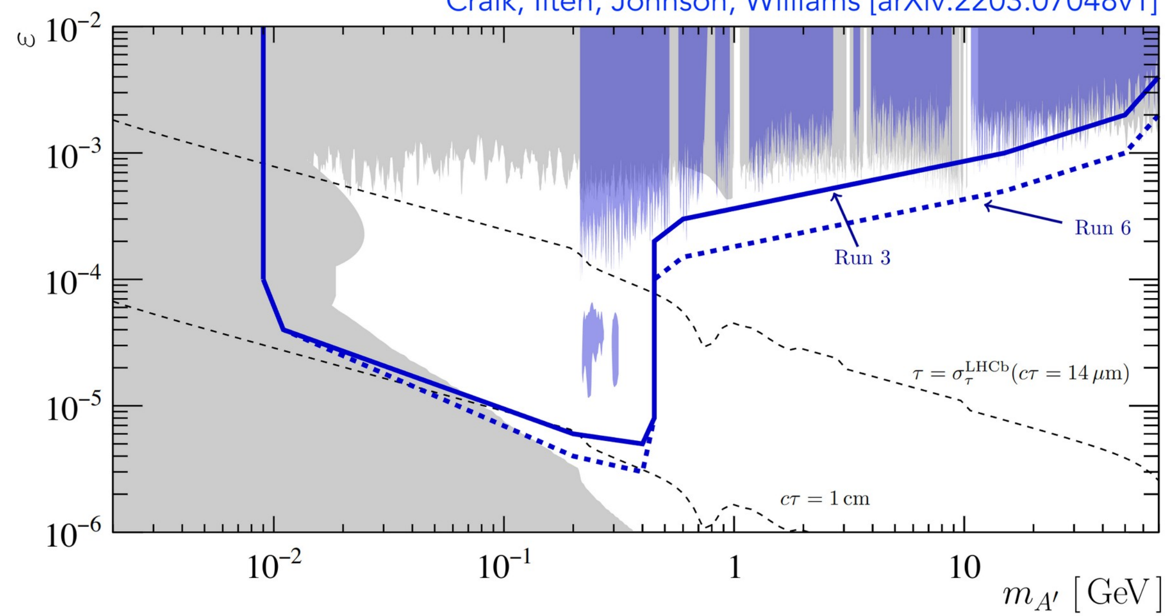
- First time we probe the intermediate region → not yet recast for axions.
- Improved detector material description, more statistics → explore unknown region.
- Huge impact of the trigger, reconstruction, operation strategy → Run 3, with its full software trigger, could be even better.

What does the future look like?

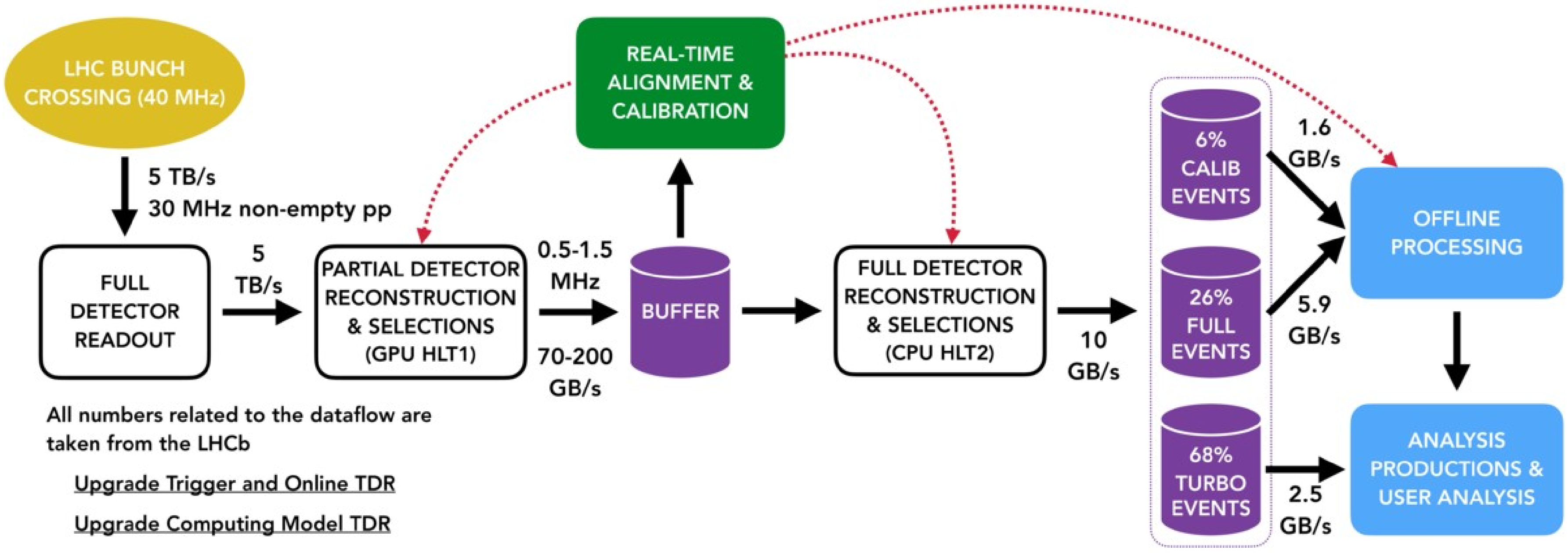
- From 2203.07048.
- Run 3 LHCb will have:
  - 5x the luminosity;
  - Fully software trigger.
- Increase in dark-photon partly due inclusion of electron ID in the first stage of the trigger!
- Large impact of these developments.



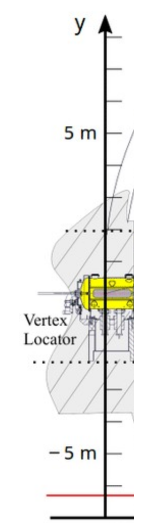
Craik, Ilten, Johnson, Williams [arXiv:2203.07048v1]



A matter of trigger: the LHCb trigger system in Run 3



- In Run 1&2, “L0” hardware trigger killing soft & displaced signatures.
- No very-displaced (>60cm away from PV) track in the HLT1.
- No far track (>2.5m away from PV) track in any analysis.
- Right: the essential ingredient of Run 1&2 trigger.



Down the far end

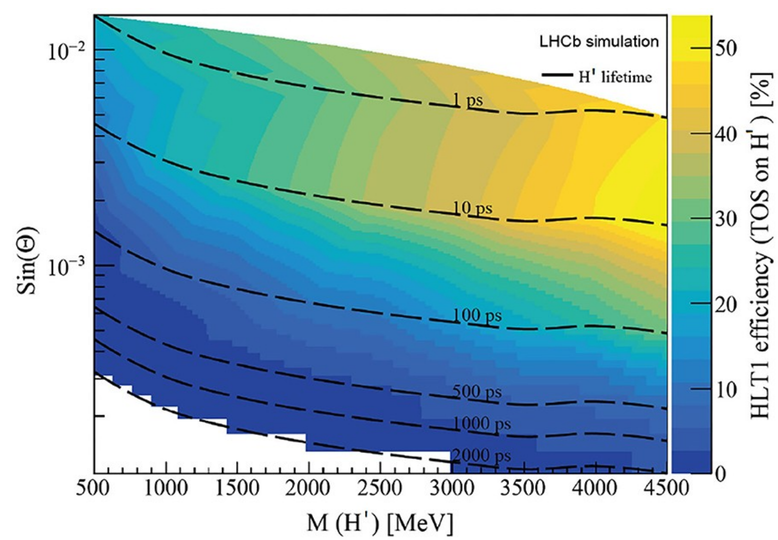
- LHCb not reaching its full potential yet as an LLP detector:
  - Trigger can be a bit limiting [2105.12668], [J. Phys. G: Nucl. Part. Phys. 47 090501 (2020)].
  - Searches focused on region around the IP.

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.

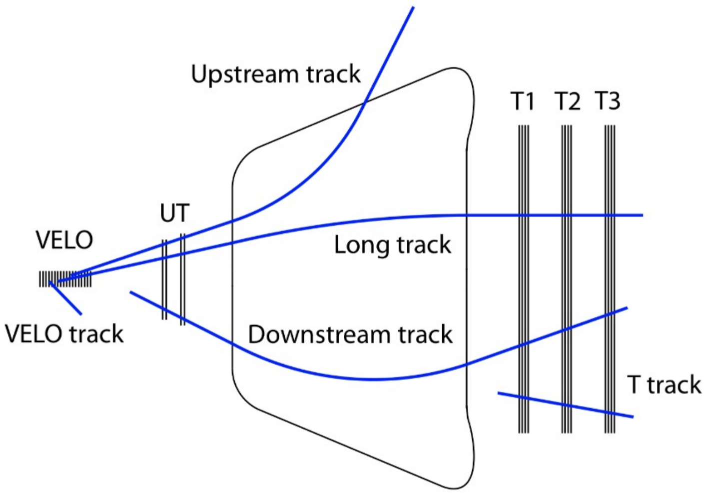
Front. Big Data 2022.1008737



- 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.

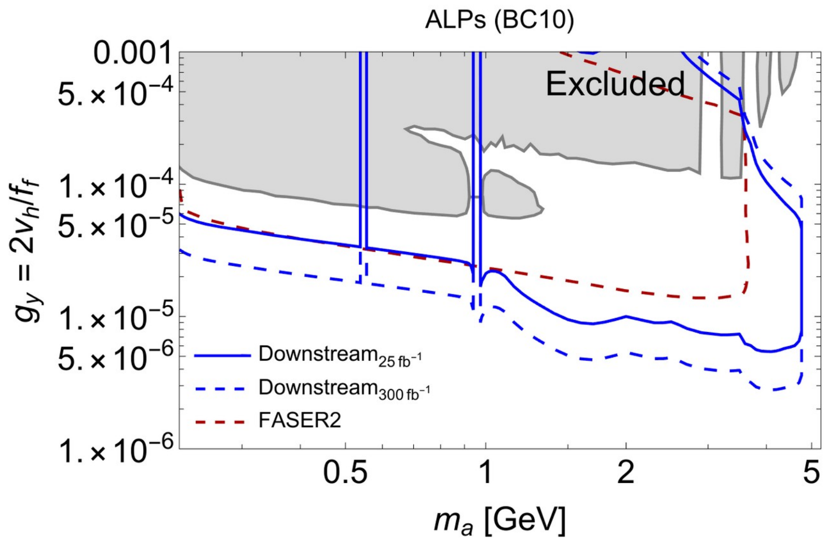
Downstream & T tracks

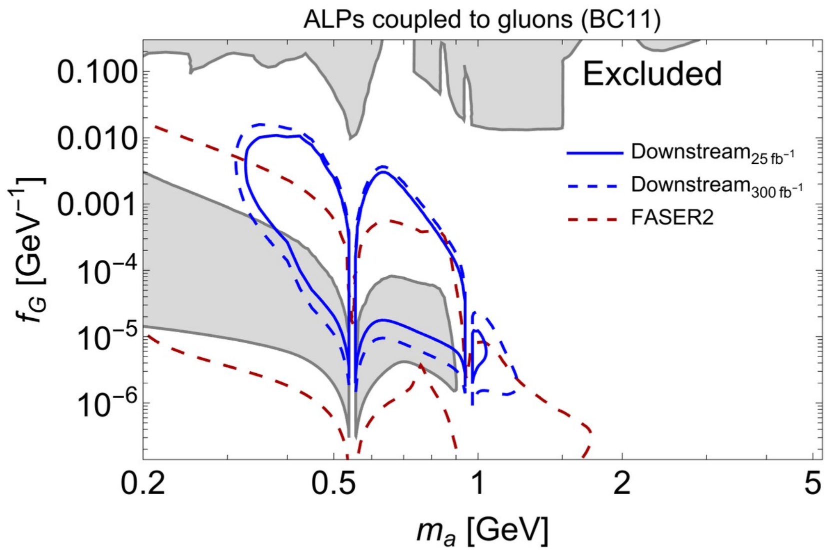
- Downstream and T tracks not (fully) present in Run 2 trigger → loss of statistics.
  - Run 3 trigger adapted → now possible to trigger early on downstream tracks.
  - Large (up to x5) statistical gain expected.



- First analysis ever using T tracks being approved.
  - Go from 2.5 to 8m possibly!

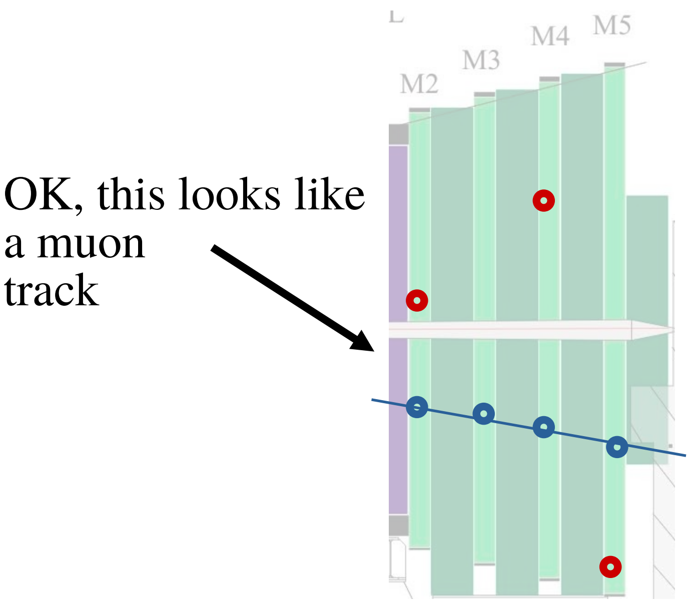
- Below: gain in sensitivity on an ALP, including downstream. [Eur.Phys.J.C 84 (2024) 6, 608]

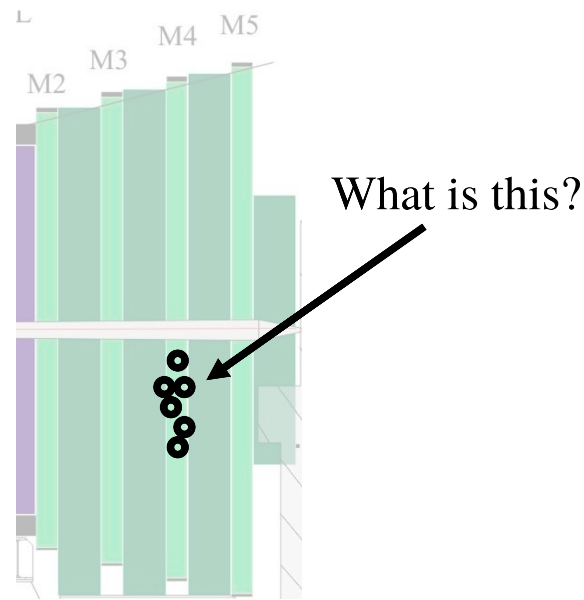




The case for muon detector showers at LHCb

- For very long-lived particles, detection efficiency is basically a function of the length of the detector.
- Muon stations offer 4 more metres and a large volume to detect axions in.
- Conversely, axions will decay into hadronic modes that may shower inside the muon shieldings, and thus create an unexpected and characteristic energy deposit.

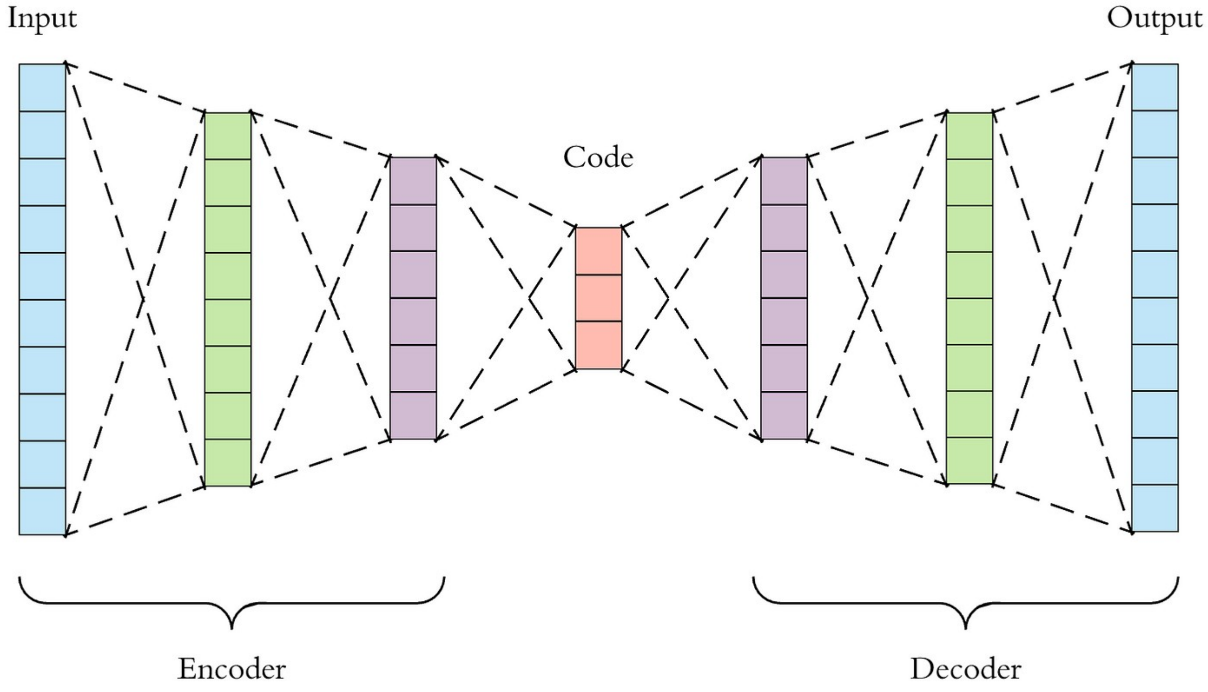


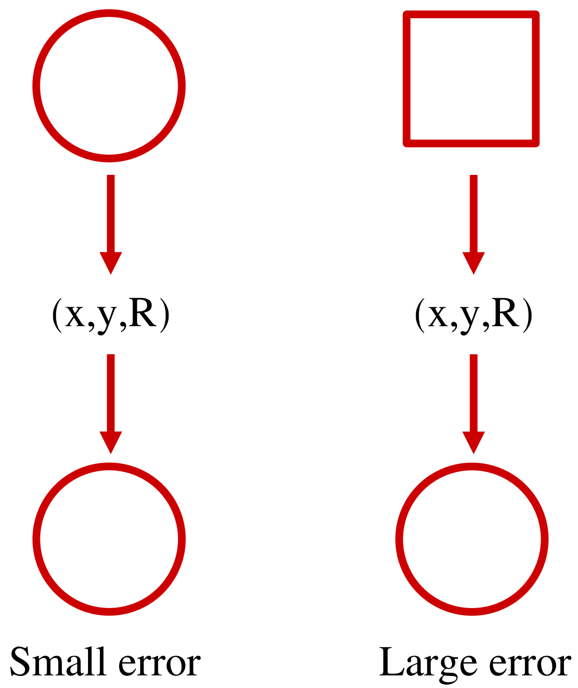


- Idea already developed by ATLAS [1] and CMS [2,3].
- Before we dream of an analysis, we need to see if we can even trigger on those “muon detector showers”.

Autoencoder

- An autoencoder is a neural network made of two parts:
  - Encoder: projects the parameter space into a latent space of lower dimensionality;
  - Decoder: reconstitutes the latent space into the parameter space.
- The idea is to train this autoencoder to encode/decode minimum bias events with minimal loss, whereas other types of events would have a large loss



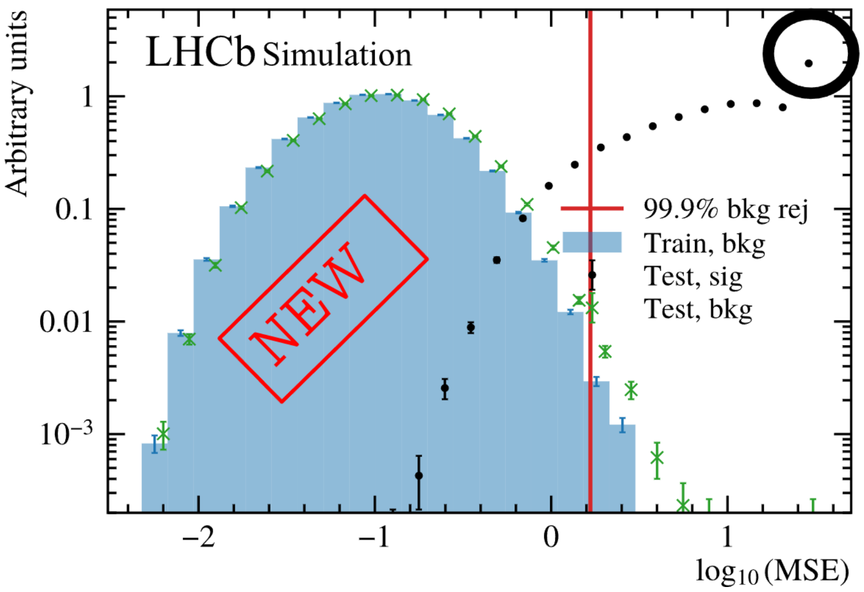


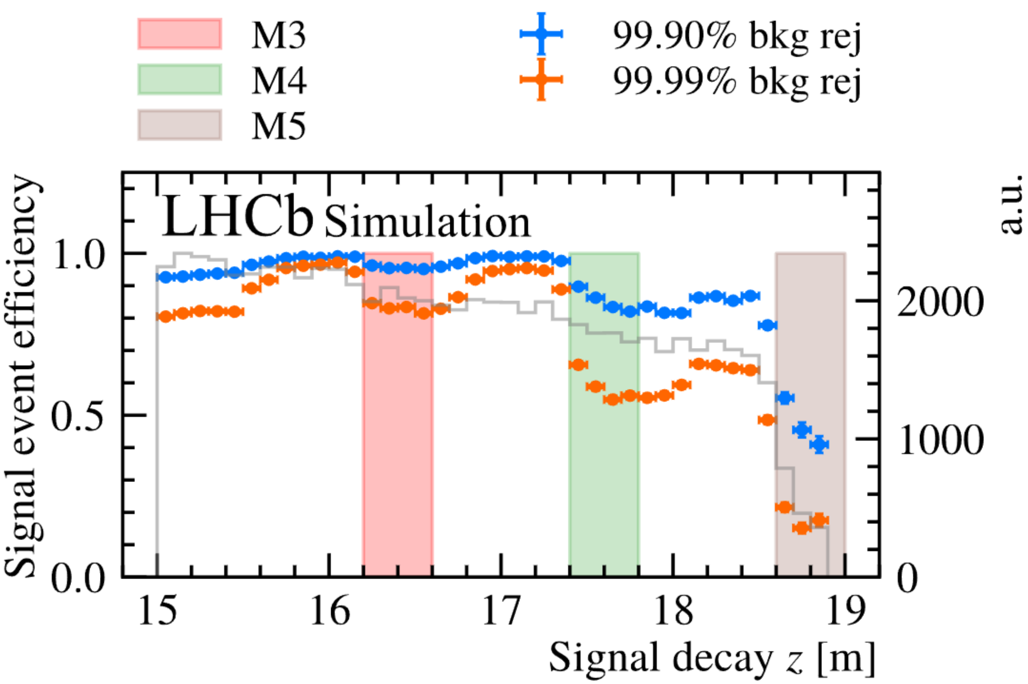
Muon detector showers: encouraging results

- Axions decaying to pairs of taus are favoured → hadronic final states.
- Results with A→ππη still pending but would also be good wrt, e.g., muon modes.

LHCb-FIGURE-2024-015

Including bin overflow





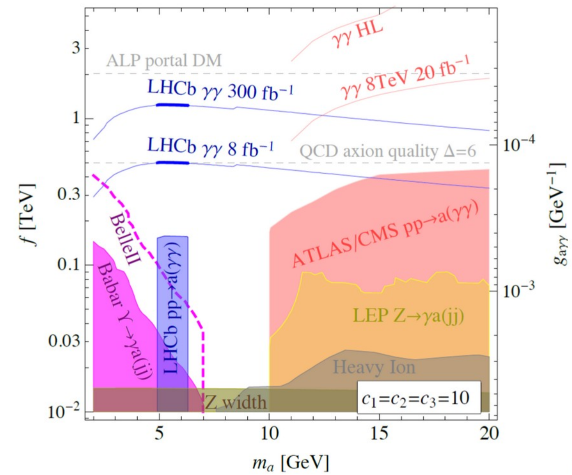
- Reaching ~80% efficiency for rejections compatible with an HLT1 line, and ~60% for rejections compatible with HLT2 line.
- HLT2 line already implemented, HLT1 in work.

Conclusion

- ALPs are well motivated and a lot of the parameter space still needs to be explored.

[JHEP 1901 (2019) 113]

- LHCb has shown the capacity to look for ALPs in two very different regimes: prompt decay and displaced vertices.
  - Different background, physics reach.
  - Able to reach world-best sensitivity below the ATLAS/CMS limit.



- 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