Physics opportunities with BSM long-lived particles at LHCb

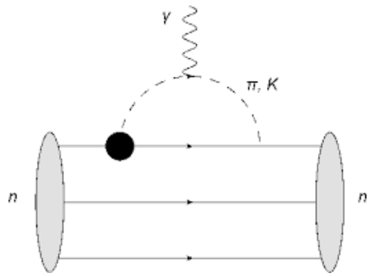
Louis Henry

3rd workshop on electronic dipole moments of unstable particles

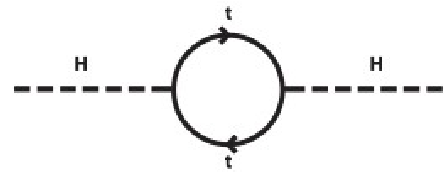
Orsay, 11/12/2023

Missing bricks in the Standard Model

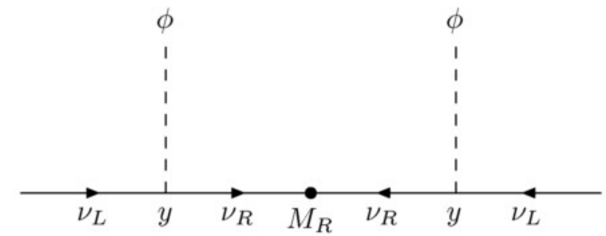
Strong CP problem

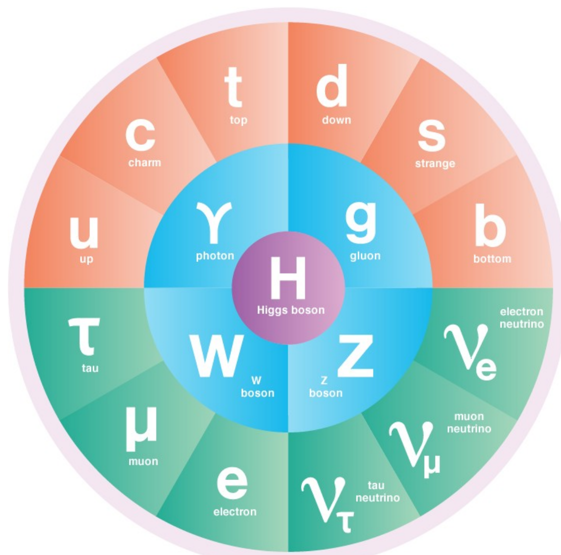


Higgs naturalness

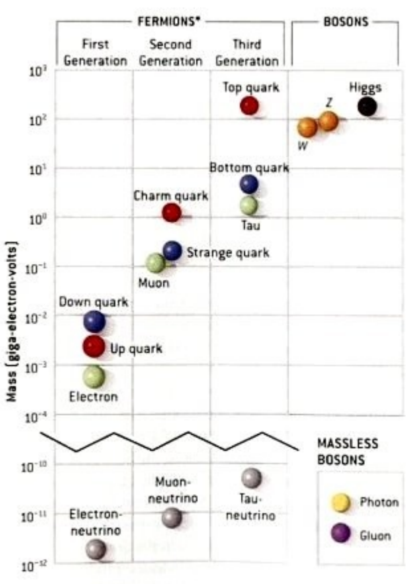


Neutrino mass

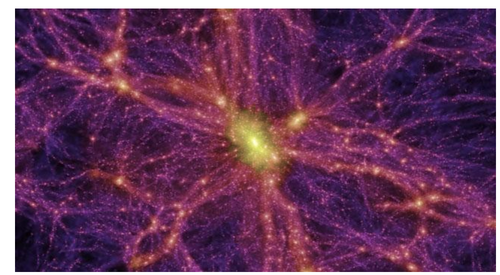




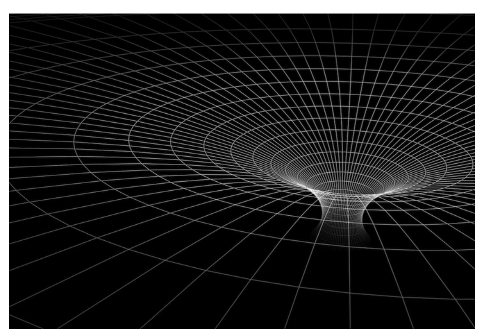
Mass hierarchy



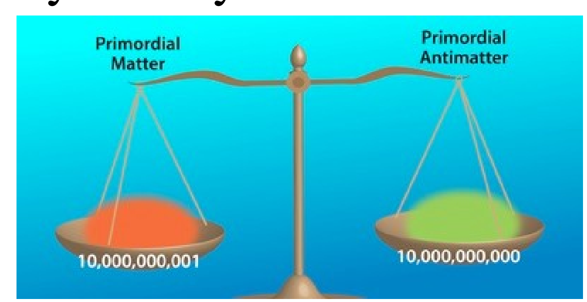
Dark matter candidate



Gravity

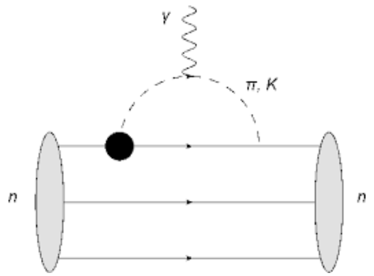


Baryon-antibaryon asymmetry of the Universe.

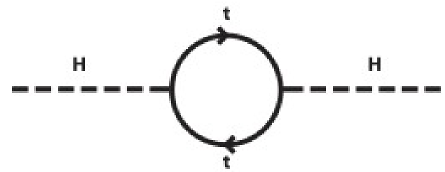


Come to the dark sector, we got CPV

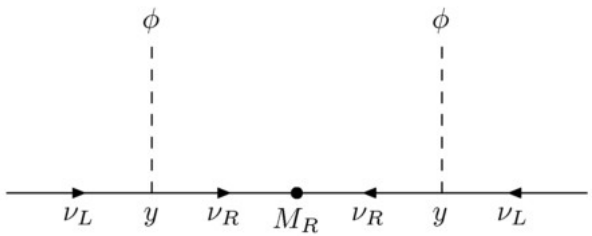
Strong CP problem



Higgs naturalness



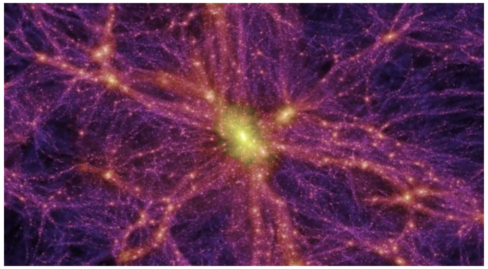
Neutrino mass



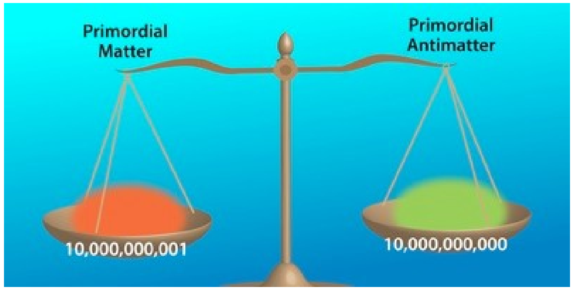
- Strong CP problem and Higgs naturalness hint at a (broken) symmetry.
- Neutrino mass requires a (massive) right-handed neutrino.
- Baryon-antibaryon asymmetry of the Universe needs more CP violation.
- Dark matter needs new particles that were coupled to the SM but are not (much) anymore.

Solution to one often involves a whole sector → impacts others

Dark matter candidate



Baryon-antibaryon asymmetry of the Universe.



Fantastic particles and where to find them

- Strongly depends on the problem considered and on what is considered 'natural'
  - After all, supersymmetry was thought to be around the corner at the LHC.

- New particles must be either **heavy**, **rare**, or **difficult to detect**.
  - Huge legacy of past experiments. For instance, Z decays.
  - This is not a XOR though: could be all at once.

Energy frontier

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

Intensity frontier

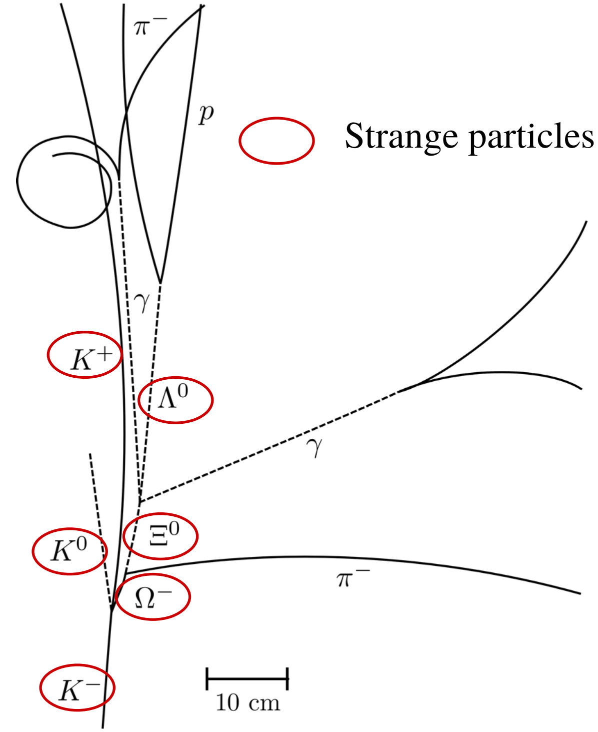
- More suited for indirect searches for NP.
- Missing CPV
- LHCb has its word on it.
- Can be transverse, longitudinal…

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.

What kind of physics gives long-lived particles

- Answer: most.
- Long-lived particles are not a fine-tuned answer to the question "Why did we not see new physics yet?".
- Result of any dark sector with a reduced coupling to the SM.
  - Familiar? This is the story of why 'strange' quarks are named thus.
- Small symmetry-breaking parameters can suppress decay rates.
- Either the messenger particle itself is long-lived, or coupling to the messenger particle is suppressed.

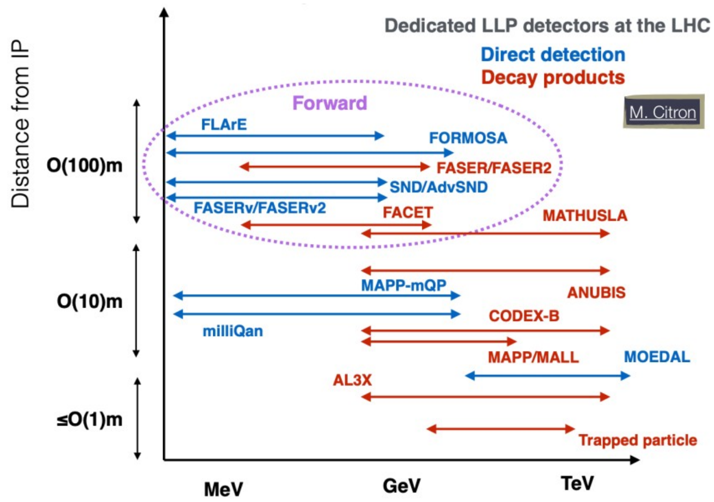


Oh look, a quasi-dark sector

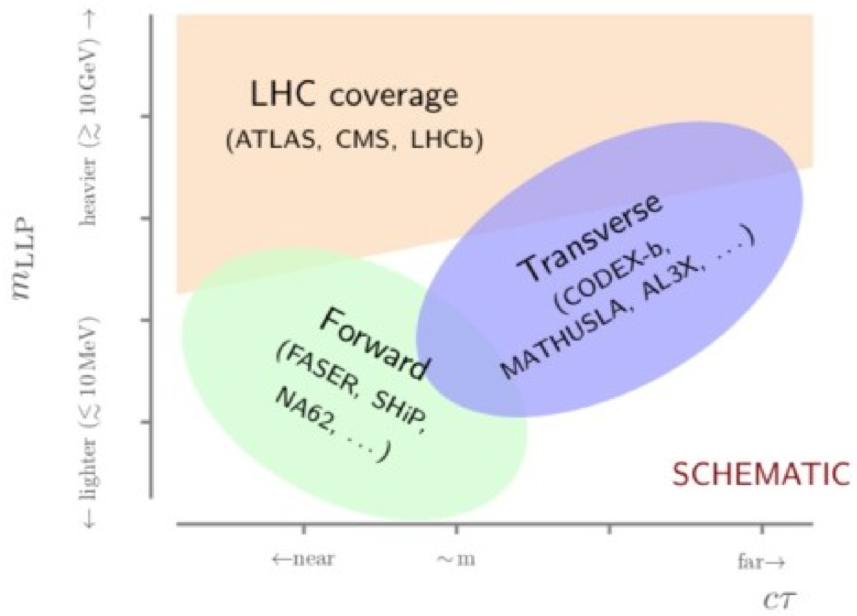
Dark sector → Messenger → SM

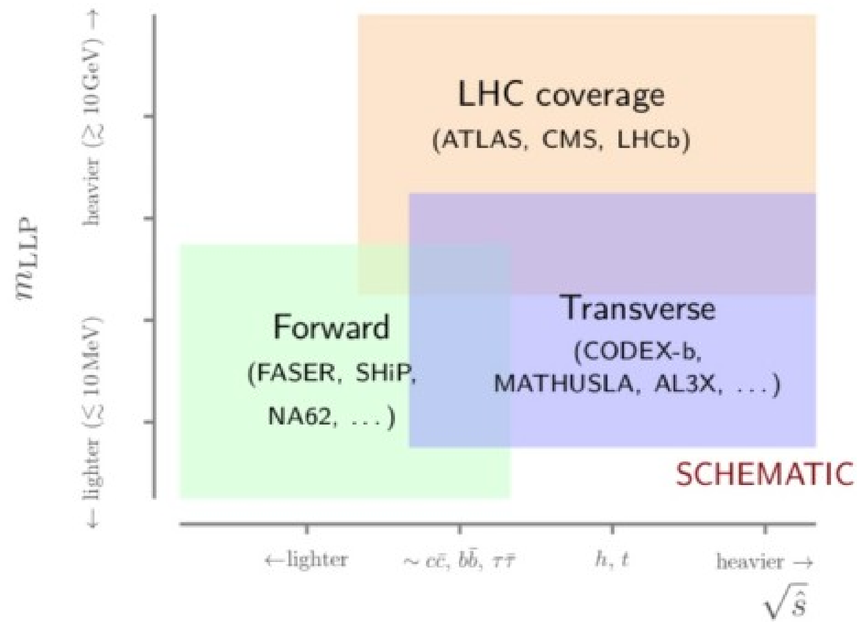
Current state of the art and experimental considerations

- Beam dump facilities achieve large boosts of **small masses** and **high luminosities**.
- ATLAS/CMS designed for transverse, heavy particles, close to IP.
- LHCb designed for more forward particles.

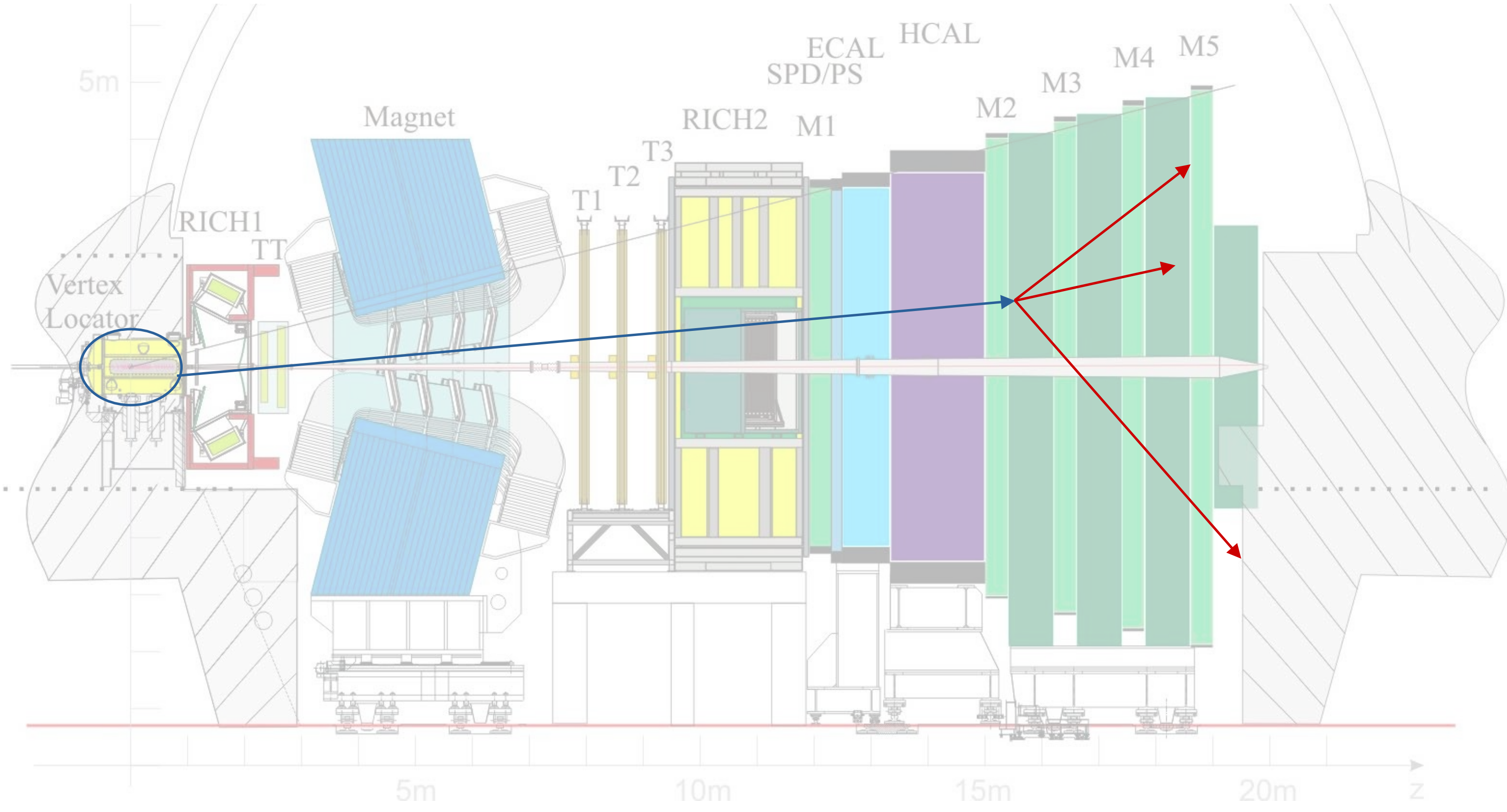


- Transverse experiments like ATLAS/CMS but further away.



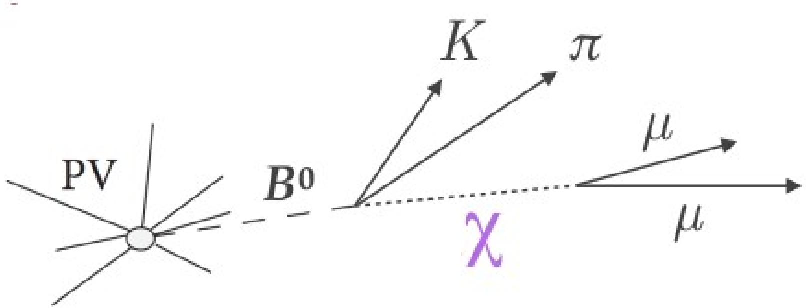


LHCb results and prospects on LLPs



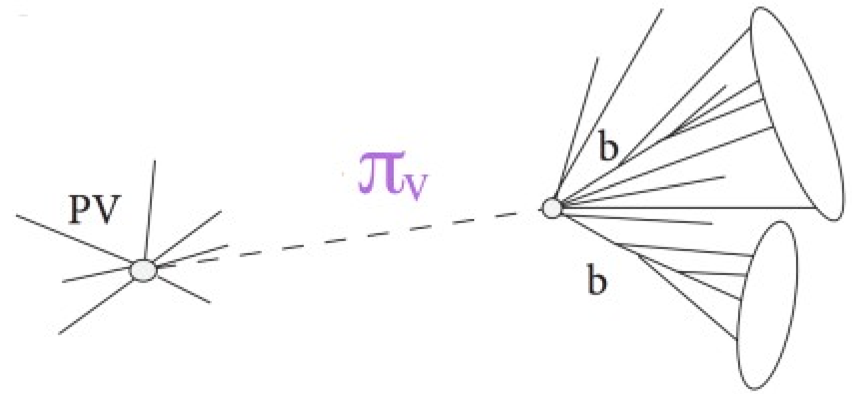
LLPs at LHCb: different worlds

- 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.

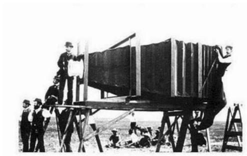


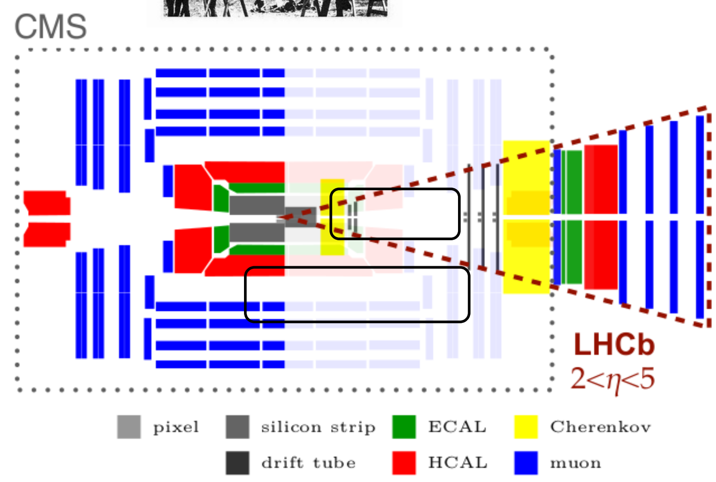
Produced in pp collisions

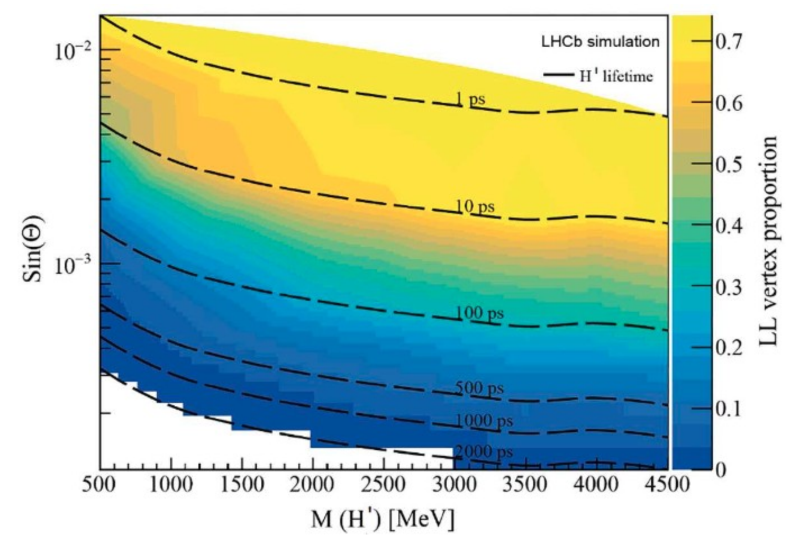
- No associated trigger.
- Displaced dileptons (e.g. dark photon), jets with possible μ associated.
- Larger energy range but need to be in acceptance.

LHCb as a camera

- Concentrated around the beam axis.
  - Larger lever arm than ATLAS/CMS on pure tracking.
- Optimised for B physics:
  - Soft triggers (p_T ~ few GeV)
- By design, complementary to ATLAS/CMS
  - Lower lifetimes thanks to forward boost,
    lower masses due to trigger.
- Current searches are limited to decays no more than ~20 cm downstream from IP
  - In principle, can reconstruct tracks up to 8m

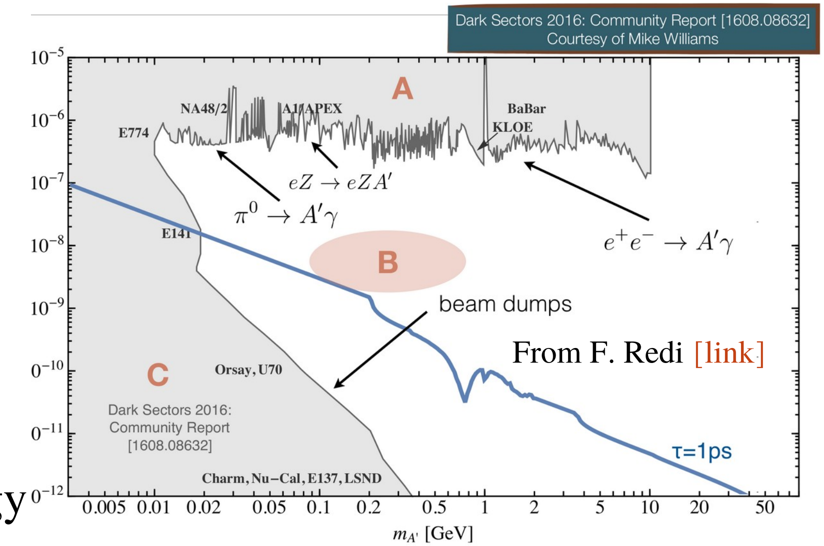






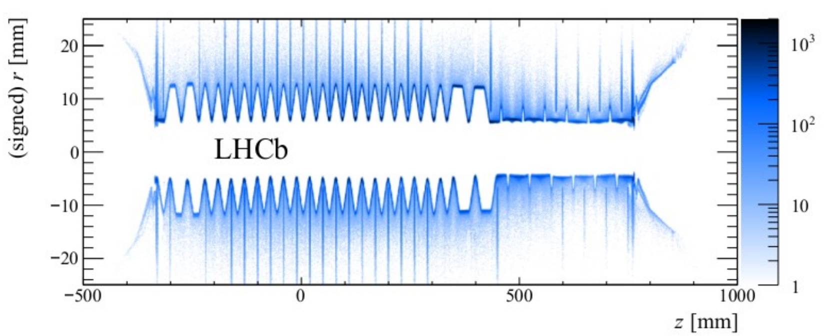
Acceptance for B → (H'→μμ)K
[Henry et al, Front. Big Data 2022.1008737]

Cornering the phase space



- **A**: bump hunts, visible or invisible modes.
  - Long-lived particle does not fly for long, background is heavy flavour.
  - Suited for generalistic experiments.
- **C**: displaced vertex searches, long decay lengths;
  - Flies very long, very rare → intensity frontier
  - Suited for beam-dump experiments: more lumi, less energy
- **B**: displaced vertex searches, short decay lengths.
  - Too short-lived for beam dumps, material interactions in generalistic detectors.

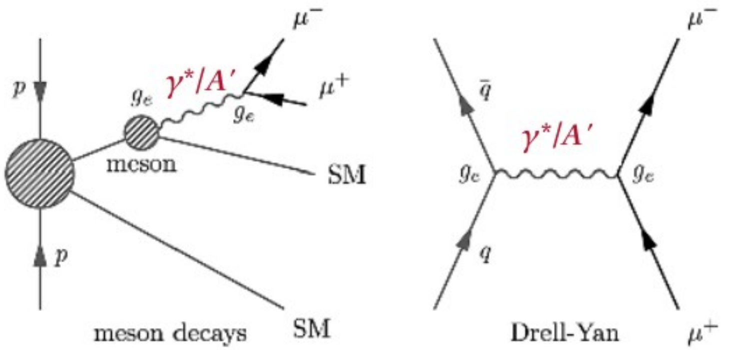
- Because of its geometry and the way we operate it, LHCb is both a ‘normal’ symmetric collision detector (albeit in forward region) AND a fixed-target experiment.
  - Unique hold on the ‘B’ region.
  - Largest background: material interactions → need precise knowledge of the detector.



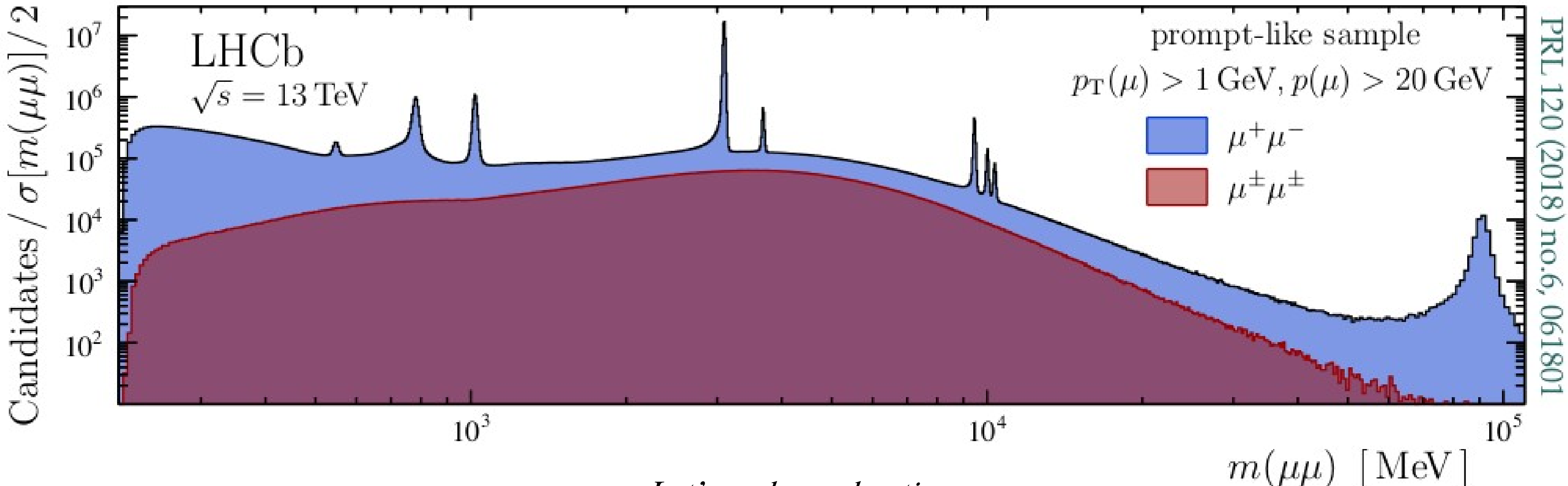
LHCb: searches for a dark photon (1)

PhysRevLett.120.061801

- Dark photon: unknown, possibly long-lived, boson that mixes with the SM photon.
- Pioneering search for a dark photon in two regions:
  - ‘Prompt’ (flight distance < 5 mm);
  - Displaced.
- Different backgrounds, efficiency corrections.
- Takes full advantage of the LHCb trigger scheme → huge dataset.

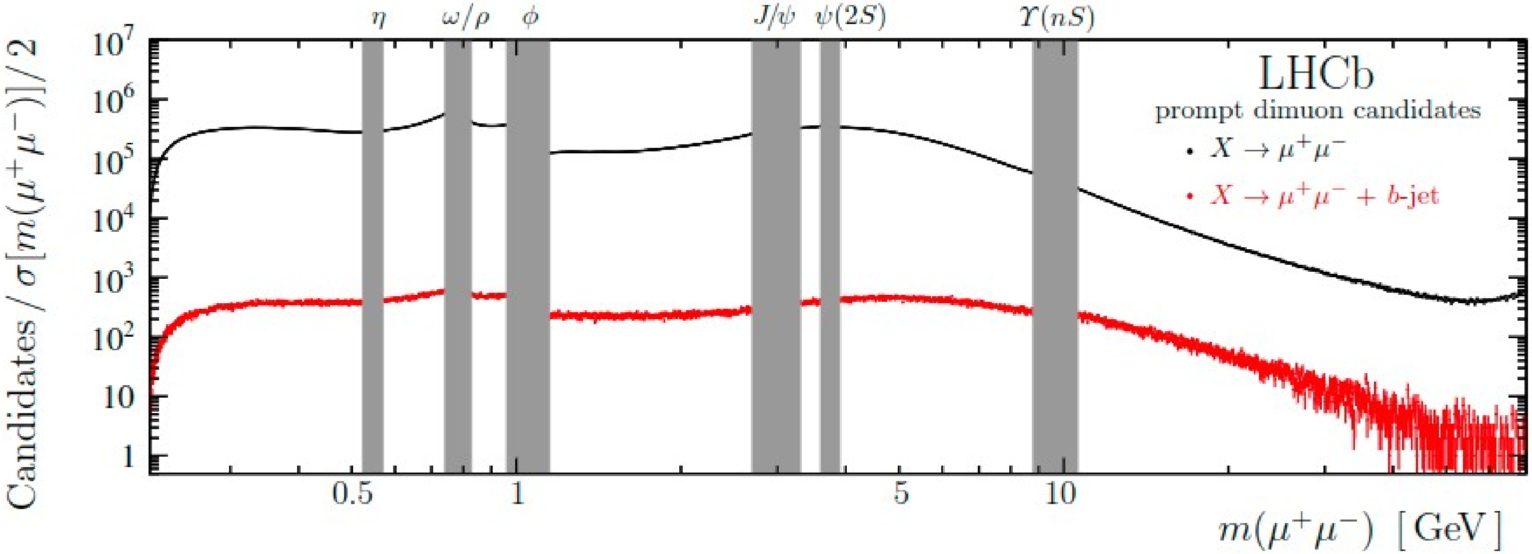


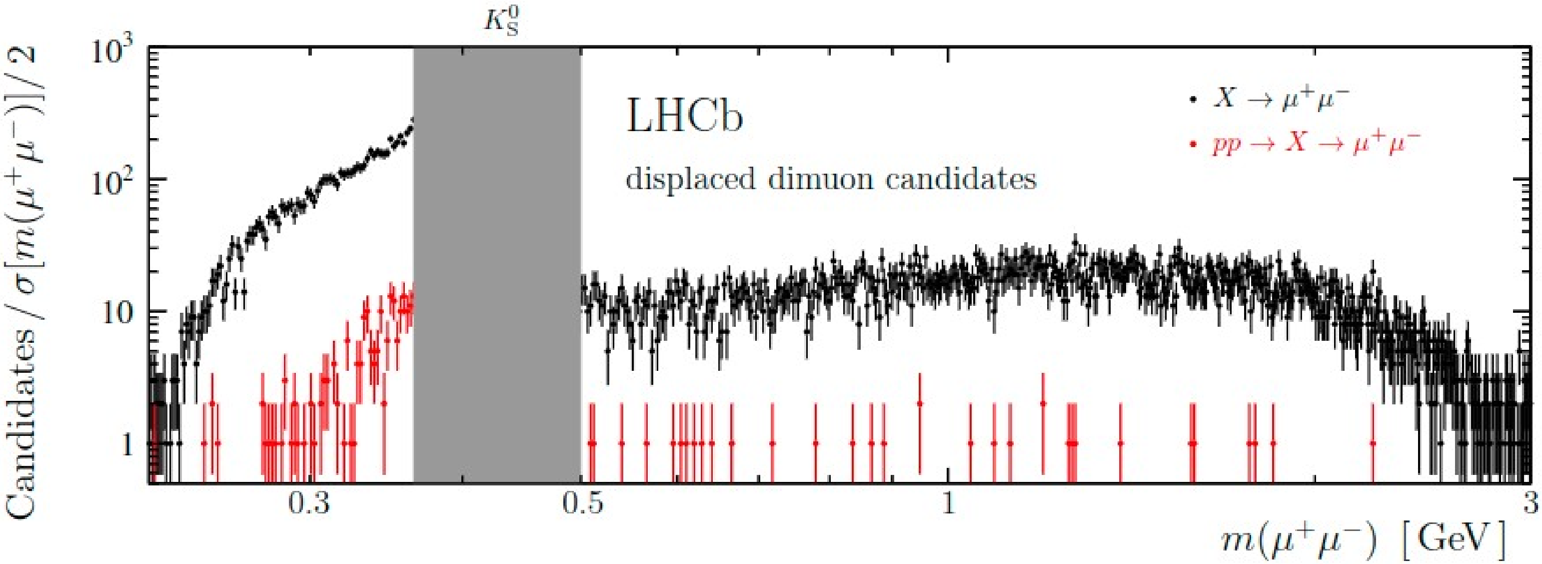
Dimuon spectrum from **trigger output**



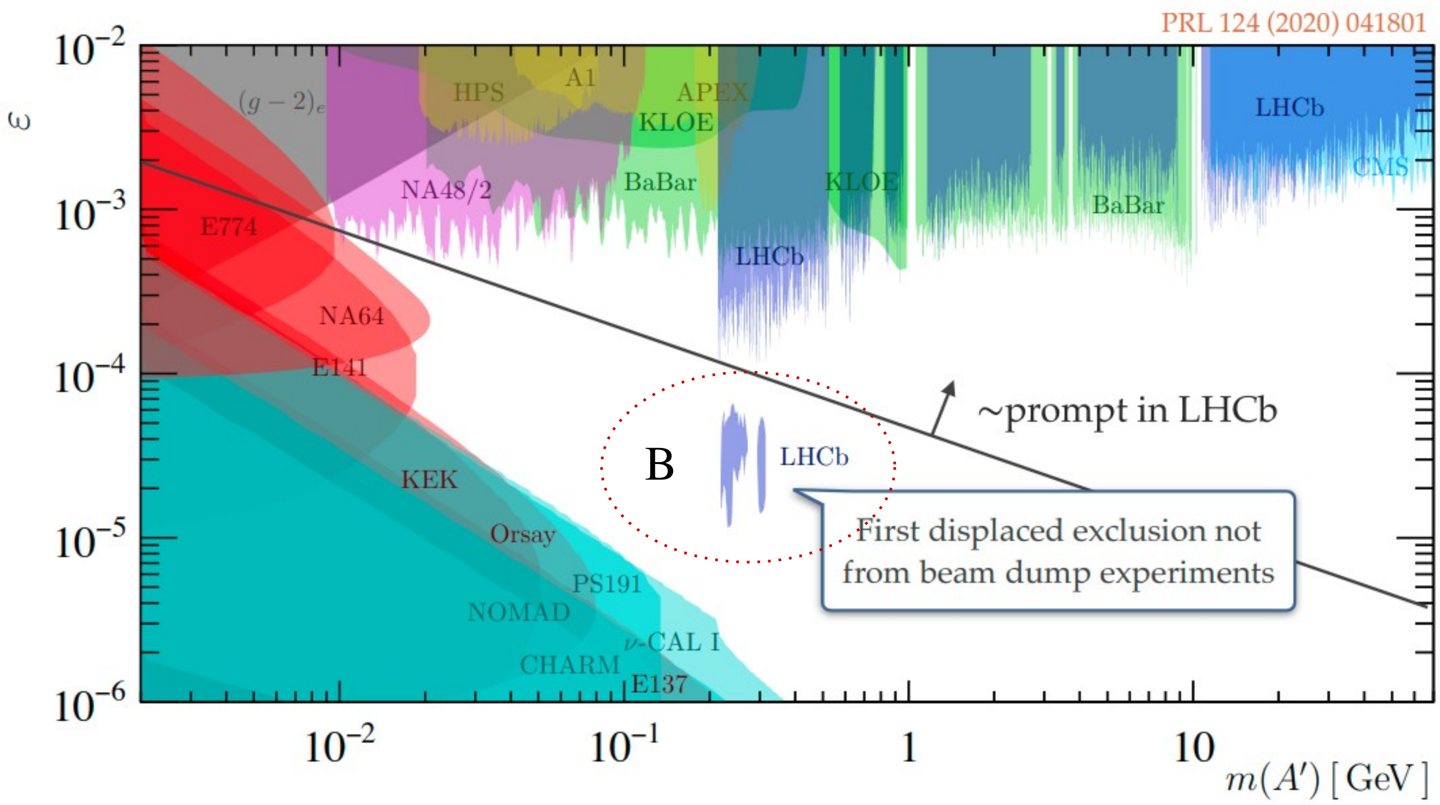
Let’s go bump hunting

LHCb: searches for a dark photon (2)





LHCb: searches for a dark photon (3)



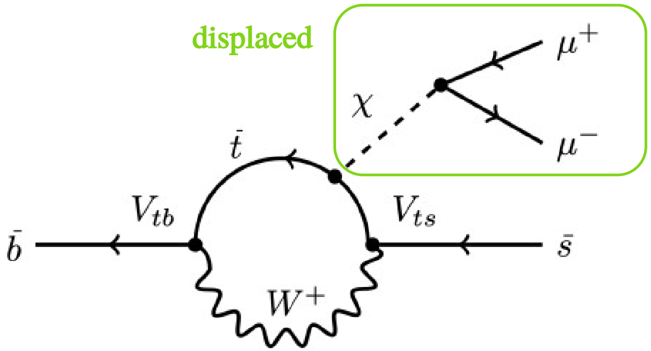
- First time we probe ‘B’ region.
- Improved detector material description, more statistics → explore unknown region.
- Huge impact of the trigger, reconstruction, operation strategy → Run 3, with its full software trigger, could be even better.

Searches in B decays

- LHCb has the world largest B meson sample.

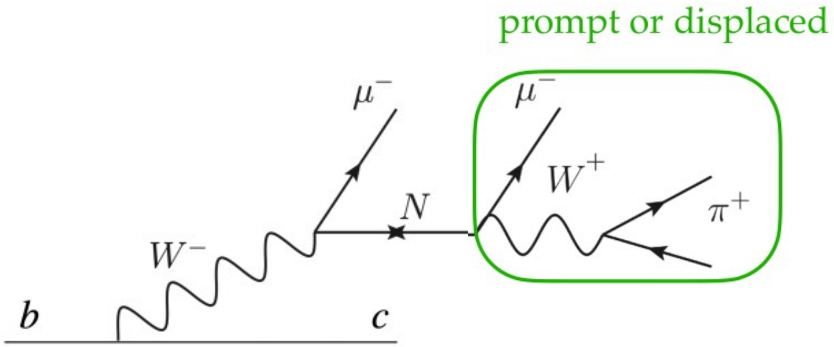
Scalar portal

- Uses b→s transition
- Signature can be χ→ff, usually we take muons.
  - Easier experimentally;
  - Complementary to anomalies.



Heavy Neutral Lepton (HNL)

- Uses b→c transition
- Lots of different searches depending on N decay



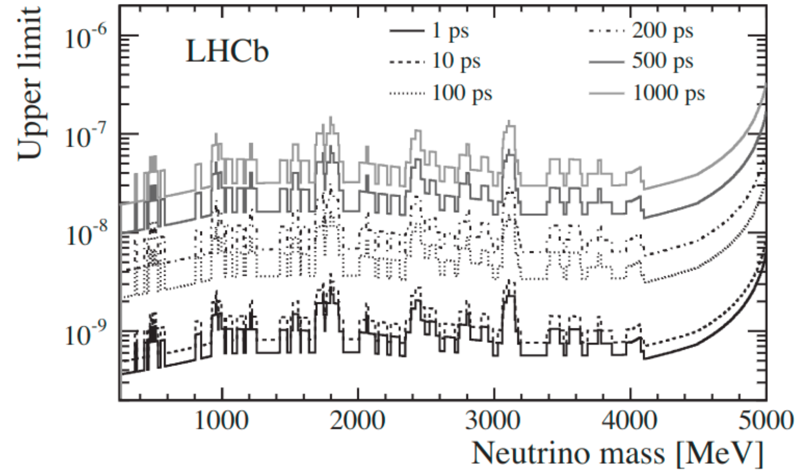
- Experimentally, both benefit from LHCb trigger on B, and many constraints.
  - B mass, B vertex if B→χK*, for instance
  - ‘Tagging’ muon

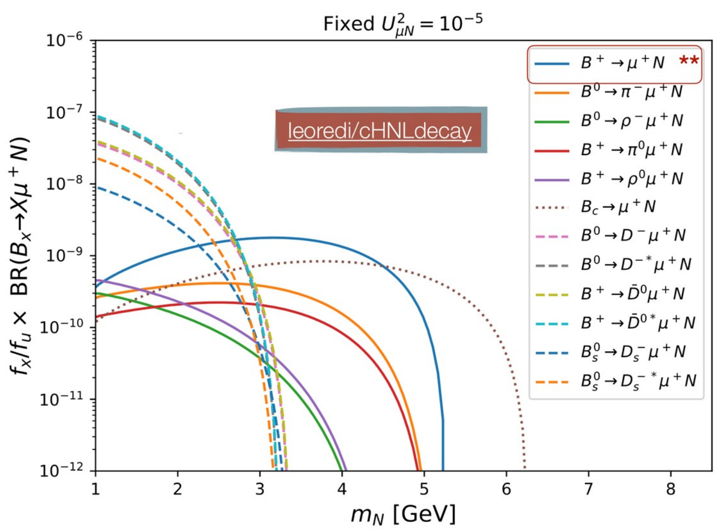
Searches in B decays: the HNL example

- LHCb published searches for HNLs, competitive with CMS.

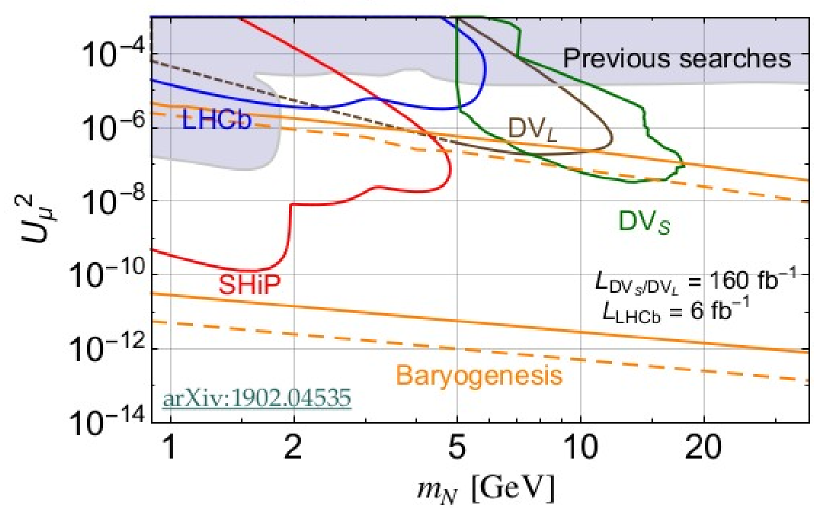
- Two issues:
  - Small detection region does not allow using the whole potential of LHCb;
  - Many decay modes → exclusive searches are limited.

PHYS. REV. LETT. 112 (2014) 131802





Future prospects for inclusive search



Essential to maintain competitivity to expand final states

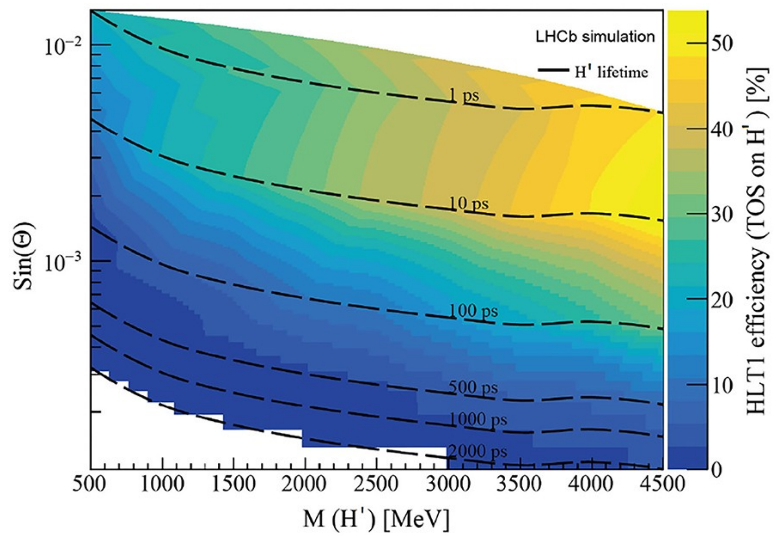
So what do we do?

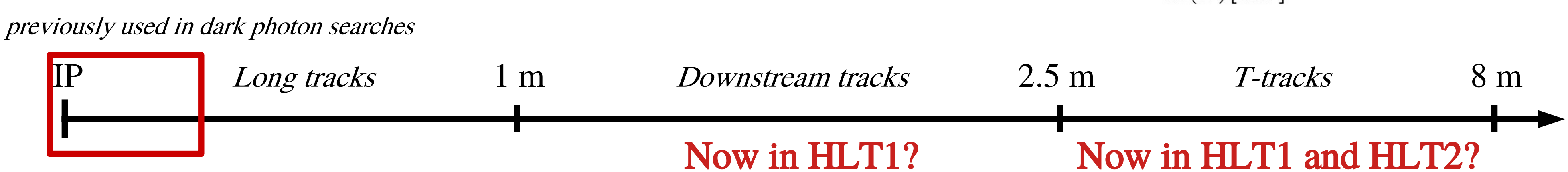
- Accumulate more data.
  - Not the whole story!
- LHCb not reaching its full potential yet as an LLP detector:
  - Trigger can be a bit limiting [2105.12668], [J. Phys. G: Nucl. Part. Phys. 47 090501 (2020)].
  - Searches focused on region around the IP.
- Right: impact of the first level of the LHCb trigger on efficiencies for the scalar portal.
- Currently worked on!
  - HLT1 now can support downstream tracking;
  - Groundbreaking work on using T tracks.

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.

Front. Big Data 2022.1008737



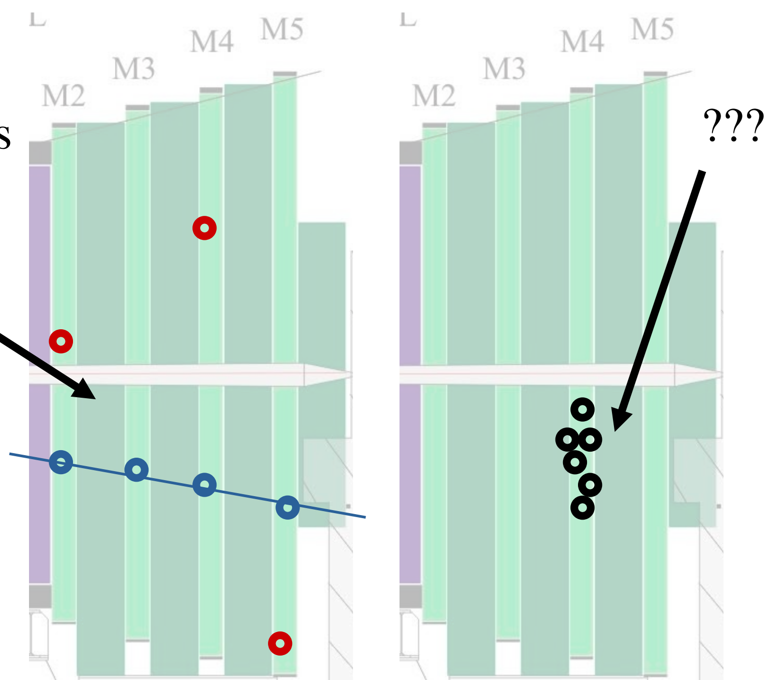


"Et puis, et puis encore?": Muon detector showers

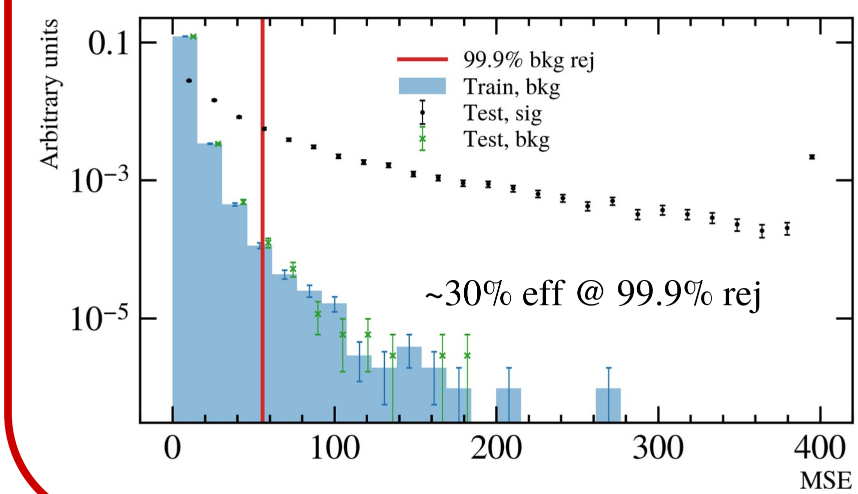
- Muon system is even further away from the IP and has few advantages:
  - Lots of advantages to operate there: low background environment, good tracking with large volume, shields.
  - BSM decaying in the muon system can create **hadrons** that then shower → characteristic profile.

- In other words: we expect nothing happens in the muon system apart from **noise** and **muon tracks**, whereas BSM can show up as **clusters of hits**.

OK, this looks like a muon



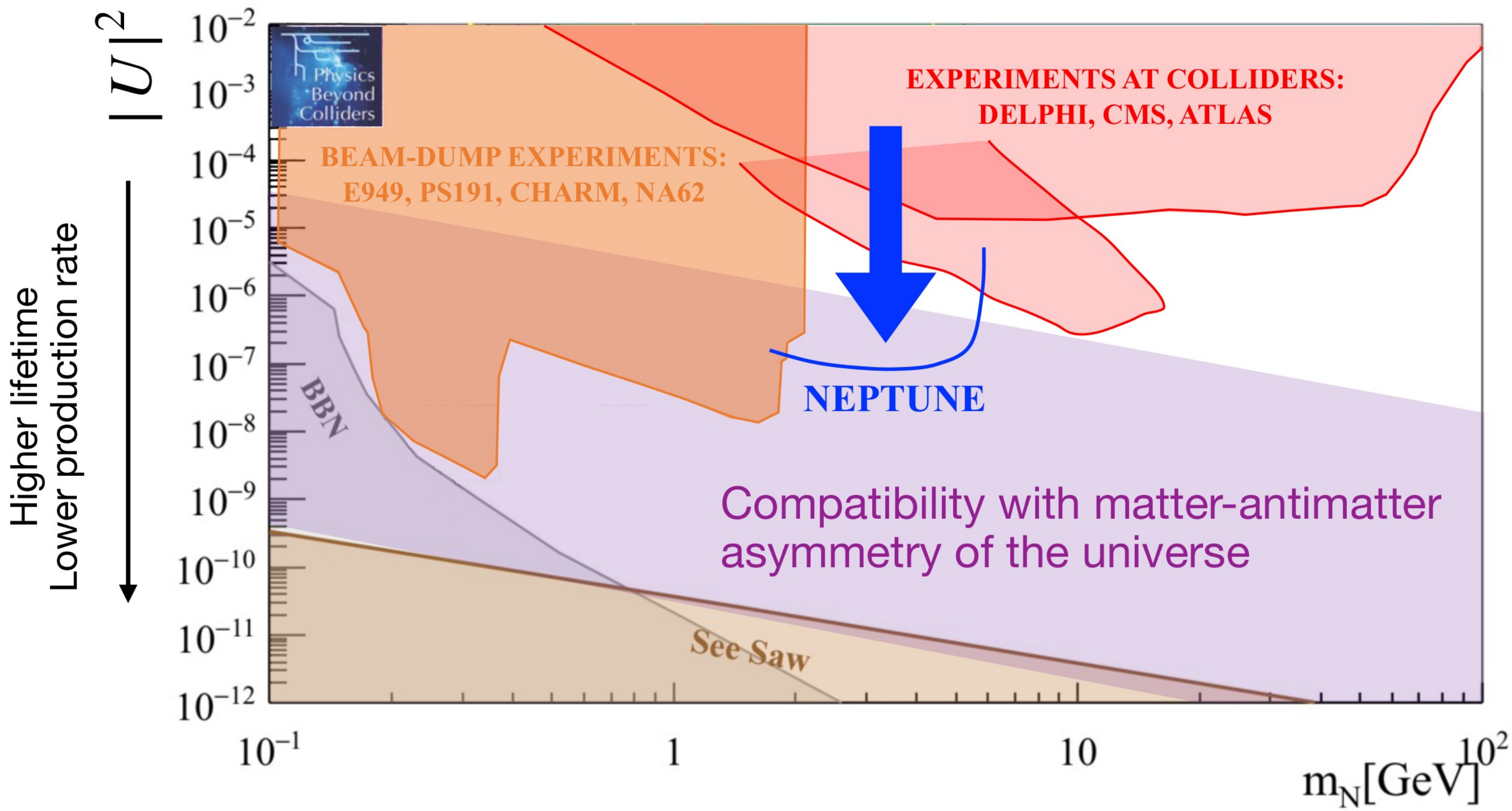
Possibility: anomaly detection
[2105.14027]



- Trigger already developed in ATLAS and CMS → work ongoing in LHCb and promising.

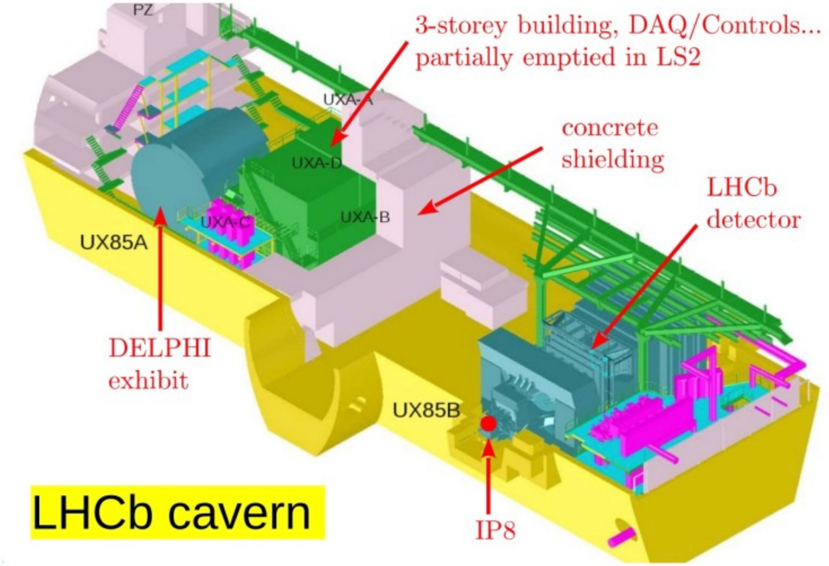
What is there to gain?

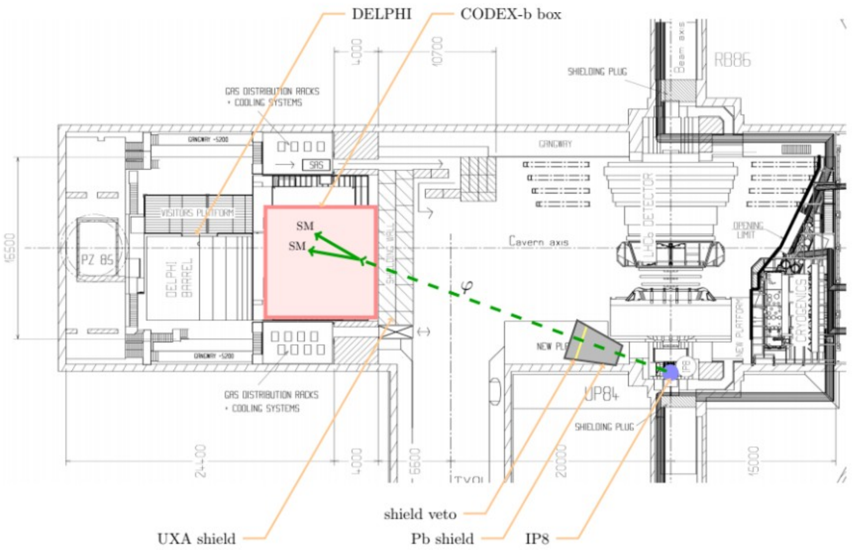
- Sensitivity gains are always a bit tricky to estimate.
- Searches requiring the VELO have a fiducial volume of 60 cm. If we end up adding muon stations ~ 13m (not contiguous).
- From A. Merli's NEPTUNE proposal, including Run 3-4 luminosity.
  - HNL parameter space.



Opportunites at ~~LHCb~~ → Point 8

- CODEX-b: COmpact Detector for EXotics at LHCb
  - Expression of interest: 1911.00481.
- Cheap, off-axis (transverse) tracker behind a huge shield and a long distance away from LHCb, in preexisting cavern.
- Trade-off between size and distance.
- Would be located either in the former D1 room or at the current location of DELPHI.
  - Possible some servers are still in the room, possibilities studied.





Demonstrator CODEX-β approved recently!

Conclusion

- Long-lived particles are an increasingly mainstream programme in current experiments.
  - Stay tuned: not only will we have more data, but do more with that data!
- Lots of dedicated experiments.
- With both **LHCb** and **CODEX-b**, Point 8 at the LHC will be sensitive to large portion of parameter space.
- Accumulating more data is not the whole story: increasing the lever arm of searches is essential to bridge the gap.