Search for low-mass axion-like particles in LHCb

12th Large Hadron Collider Physics Conference

2024-06-03 @ Boston, USA

Blaise Delaney [blaise.delaney at cern.ch]

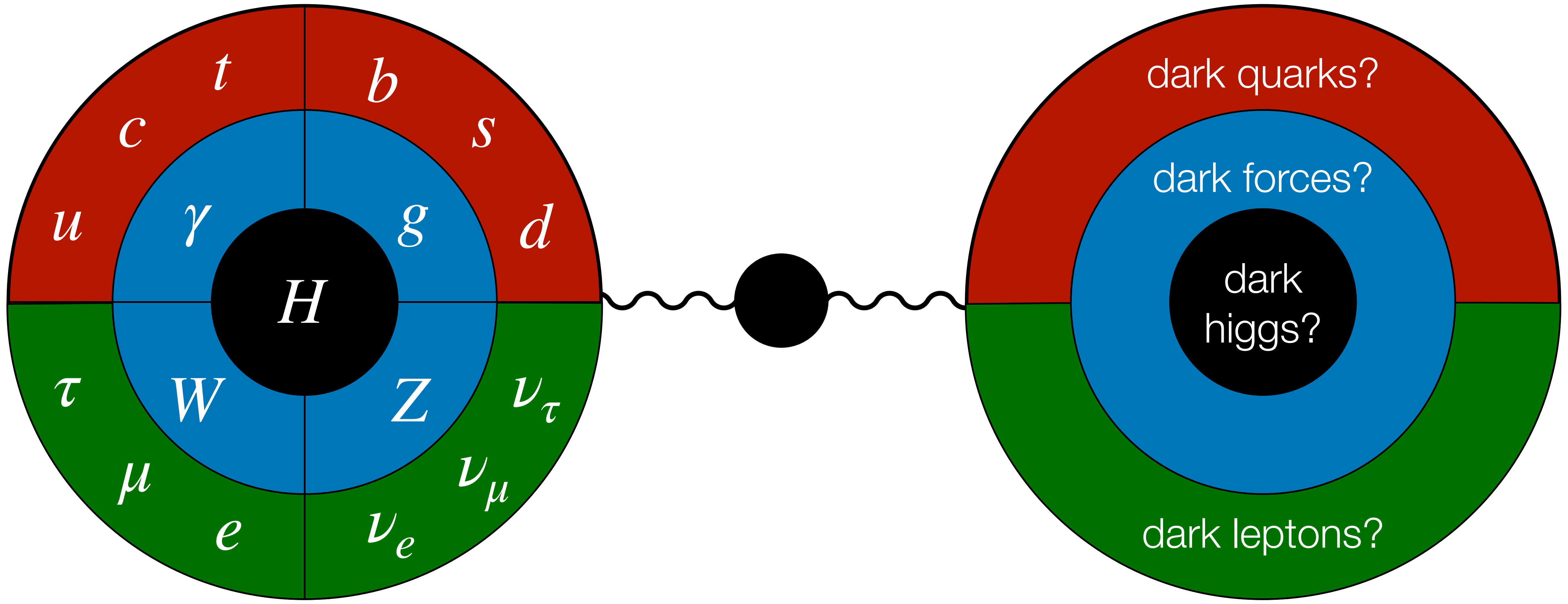
on behalf of the LHCb Collaboration

Portals to the dark sector

Dark-portal paradigm: New Physics **below the EW scale** with dark-sector particles are neutral wrt the SM and only couple indirectly to ordinary matter.

Gauge and Lorentz symmetries of the SM restrict how dark-sector mediators can couple to ordinary matter: 4 portals → 4 new particles:

- **Vector portal** (A'): $-\frac{\epsilon}{2\theta_W} F'_{\mu\nu} B^{\mu\nu}$
- **Axion portal** (a): $\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$
- **Scalar portal** (H): $(\mu S + \lambda S^2) H^\dagger H$
- **Neutrino portal** (N): $y_N LHN$



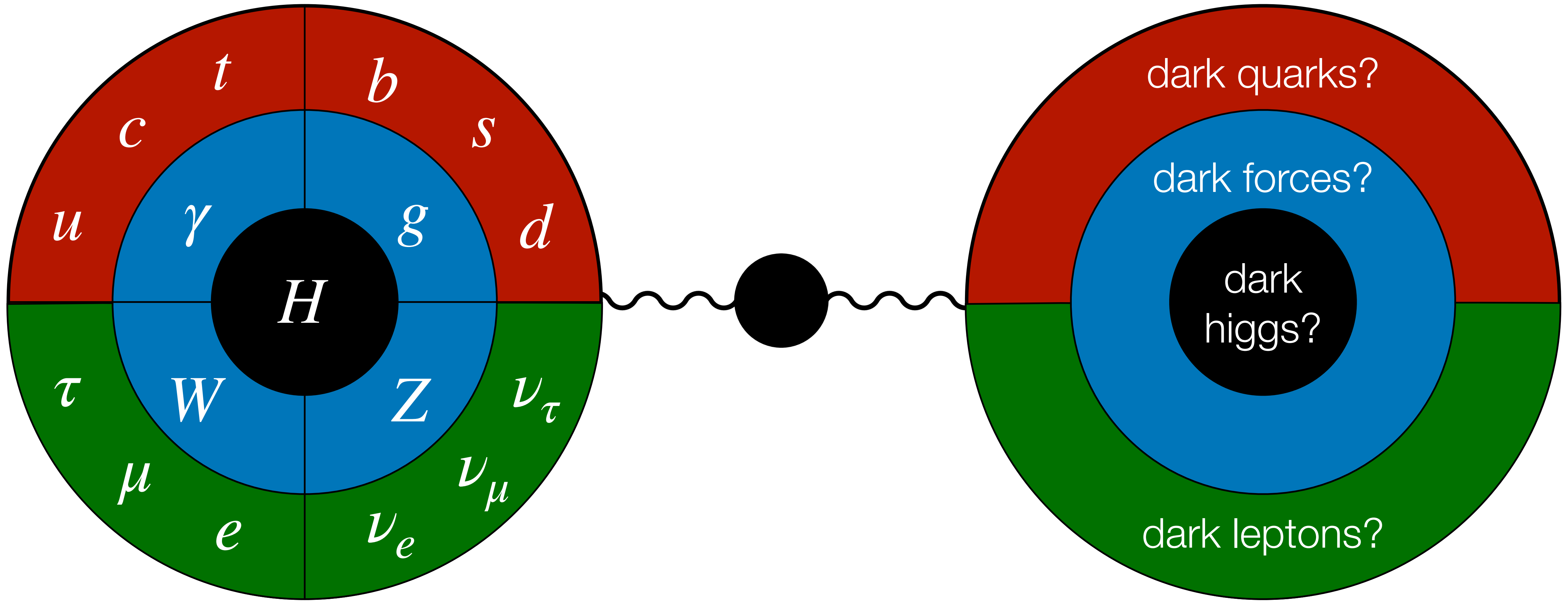
[Snowmass'21, arXiv:2209.04671]

Portals to the dark sector

Dark-portal paradigm: New Physics **below the EW scale** with dark-sector particles are neutral wrt the SM and only couple indirectly to ordinary matter.

Gauge and Lorentz symmetries of the SM restrict how dark-sector mediators can couple to ordinary matter: 4 portals → 4 new particles:

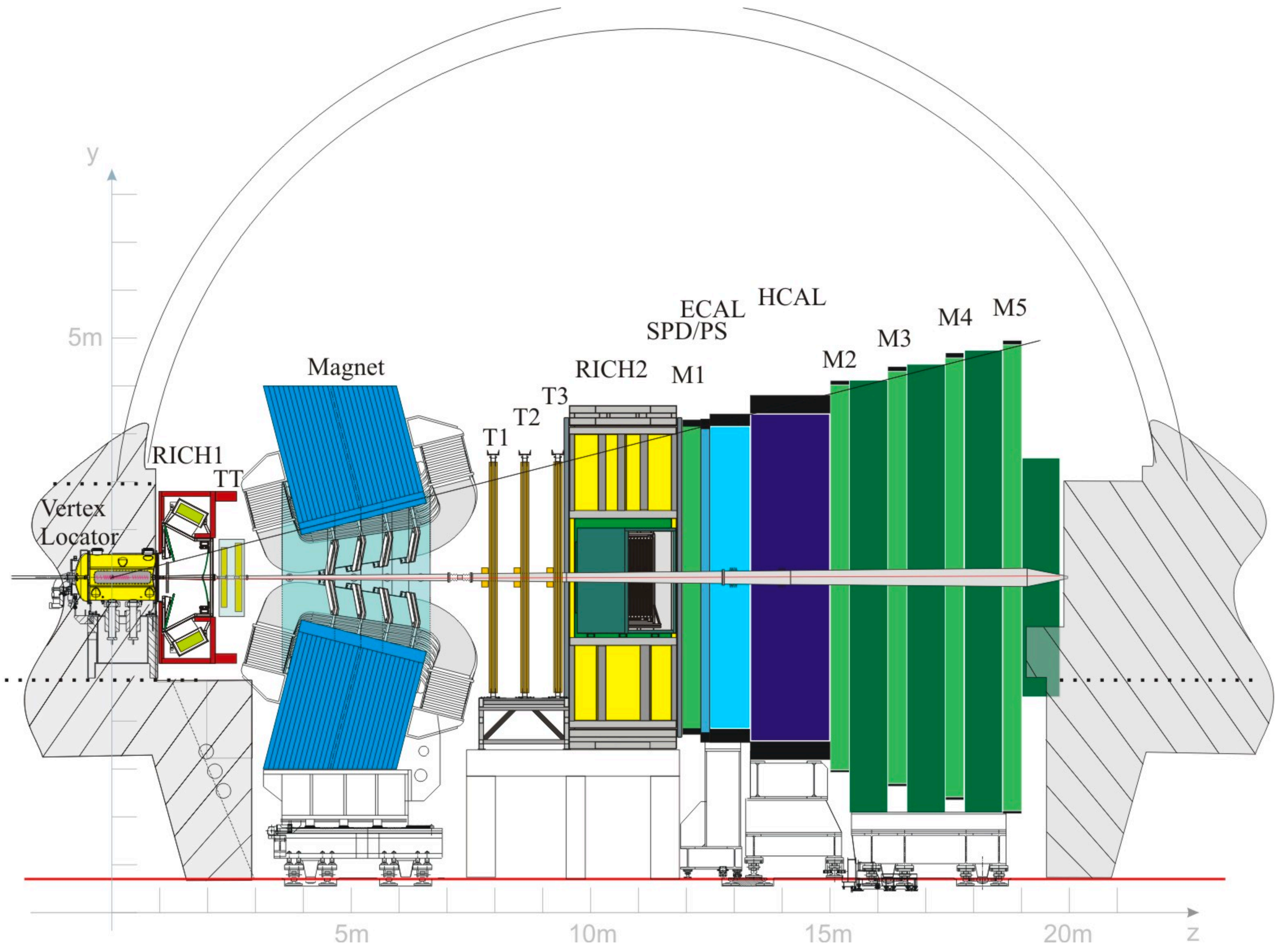
- **Vector portal** (A'): $-\frac{\epsilon}{2\theta_W}F'_{\mu\nu}B^{\mu\nu}$
- **Axion portal** (a): $\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$
- **Scalar portal** (H): $(\mu S + \lambda S^2)H^\dagger H$
- **Neutrino portal** (N): $y_N LHN$
  ↪ Louis Henry's talk on Friday morning



[Snowmass'21, arXiv:2209.04671]

LHCb: flavour *and* dark physics

[*JINST* 3 (2008) S08005]
[*JINST* 19 (2024) 05, P05065]



Capacity for sensitivity to dark portals:

- Excellent vertex resolution [IP resolution $\mathcal{O}(10\,\mu\text{m})$]

- $\mathcal{O}(1\%)$ momentum resolution

- Capacity for *soft triggers* (*e.g.* trigger on $p_T \sim 1$ GeV on detached $\mu\mu$)

LHCb: flavour *and* dark physics

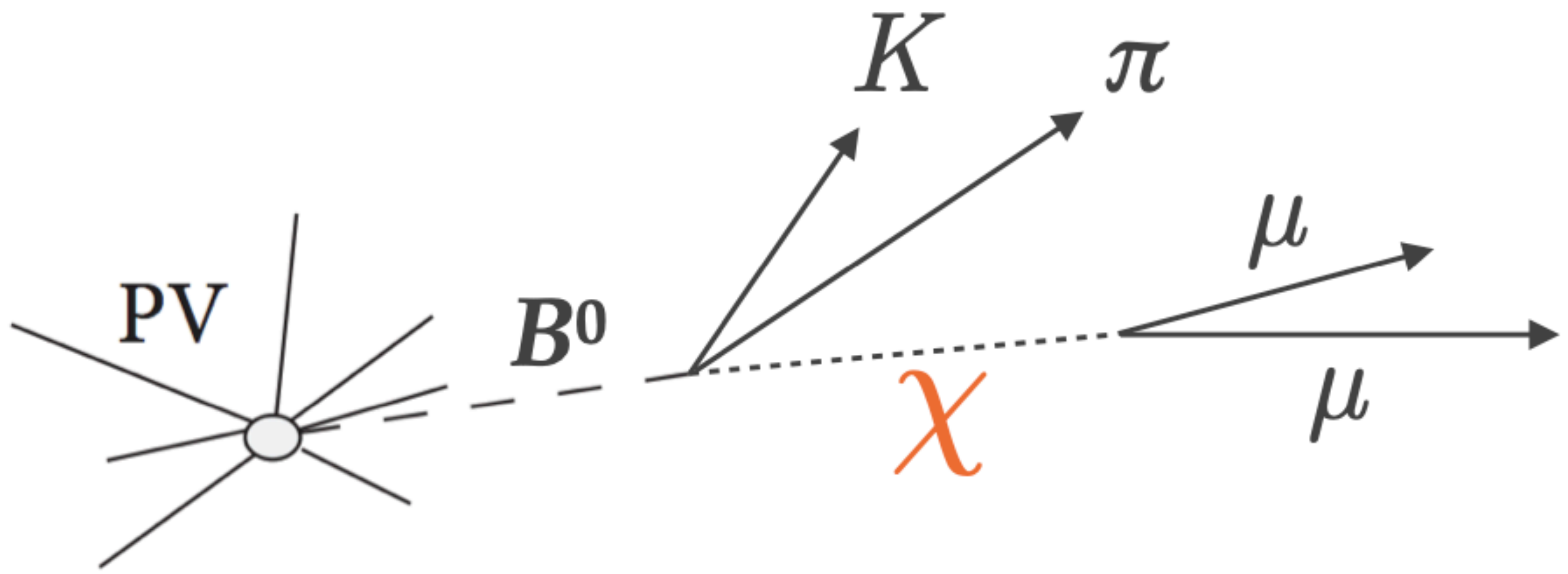
[*JINST* 3 (2008) S08005]
[*JINST* 19 (2024) 05, P05065]

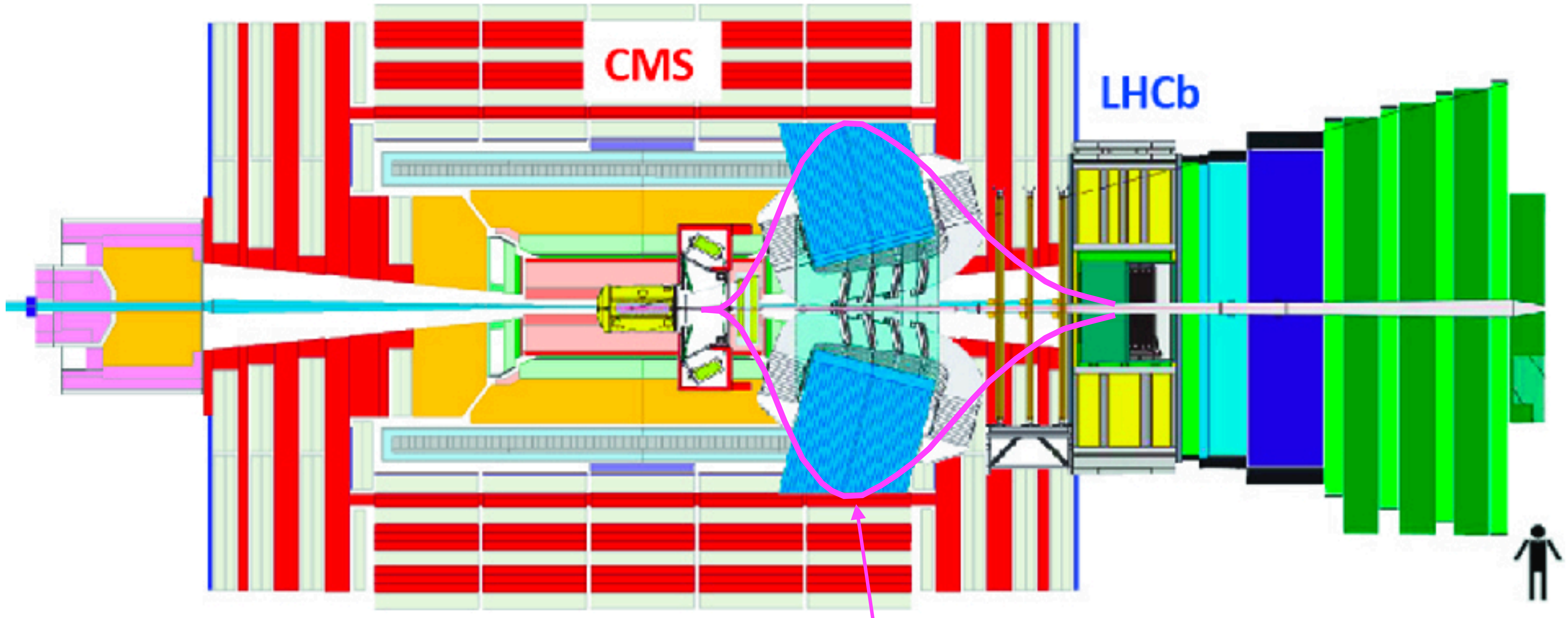
Advantages wrt ATLAS/CMS:

- Soft trigger selections → lighter masses

- Forward boost and $\sigma(\tau) \sim 50$ fs
  → low lifetimes (*prompt* vs *displaced* signatures)

Produced in heavy-flavour decays

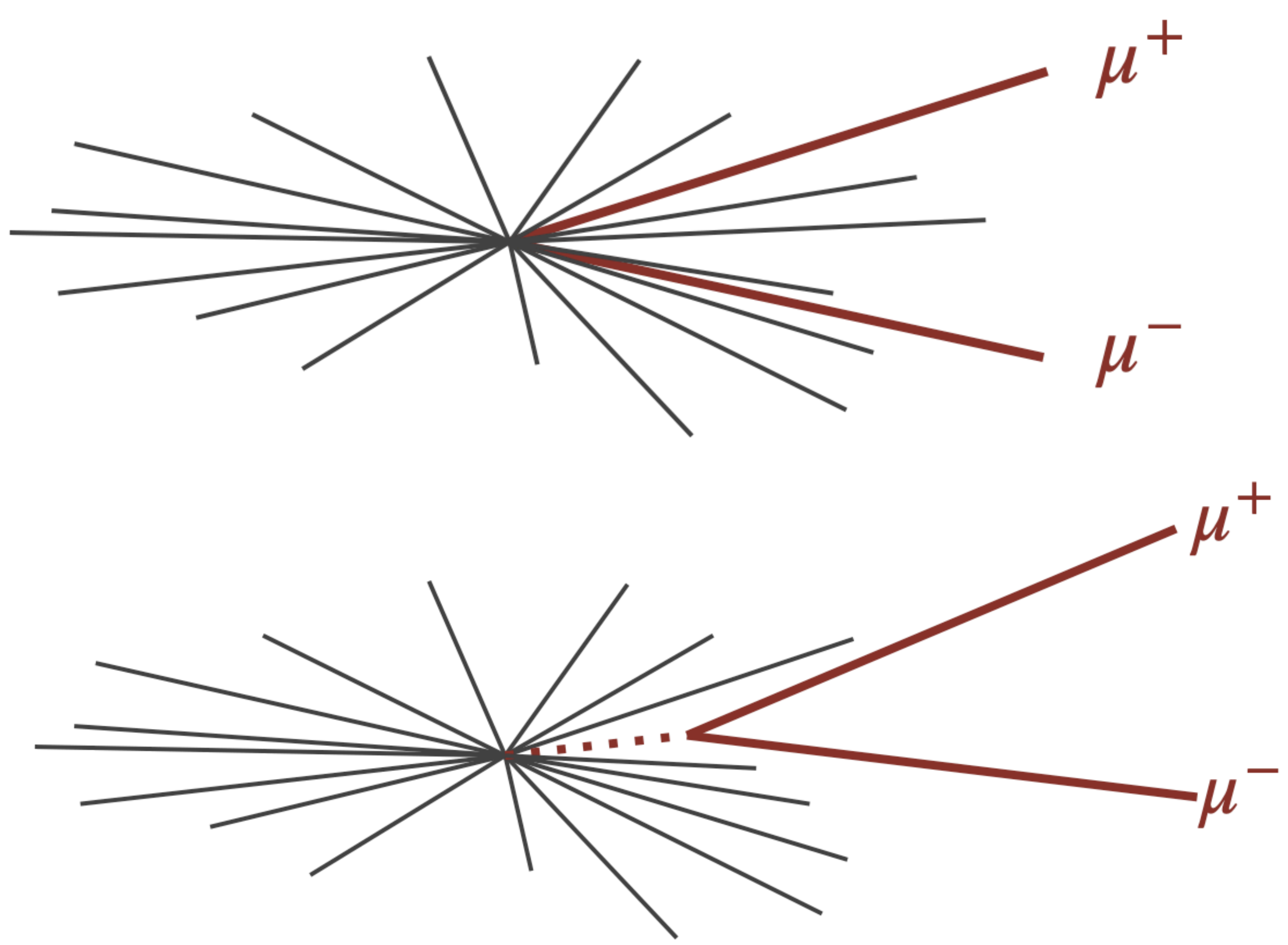




Sketch adapted from F. Redi, LHCP '21
not to scale

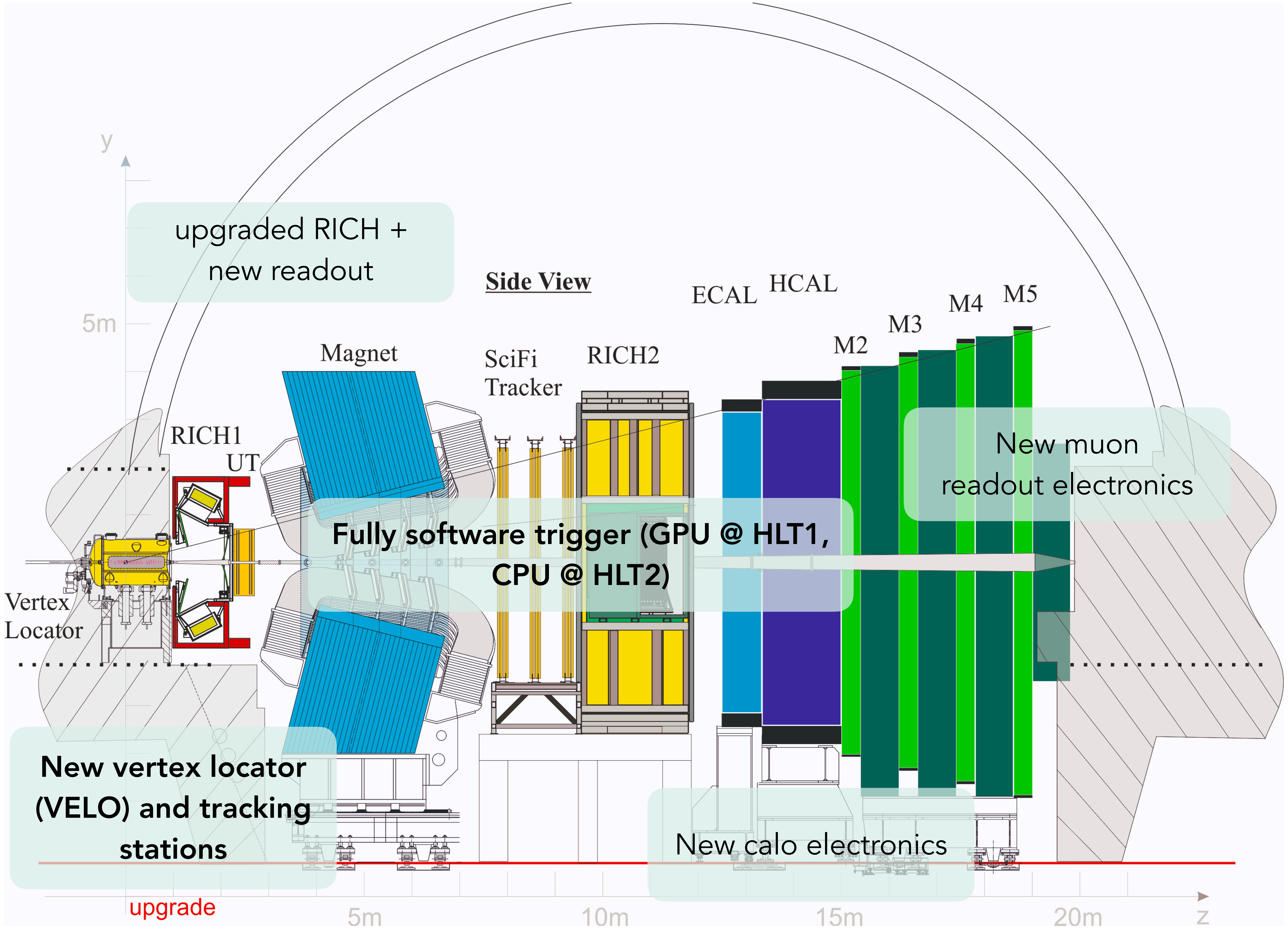
LHCb *B* field

Produced in *pp* collisions

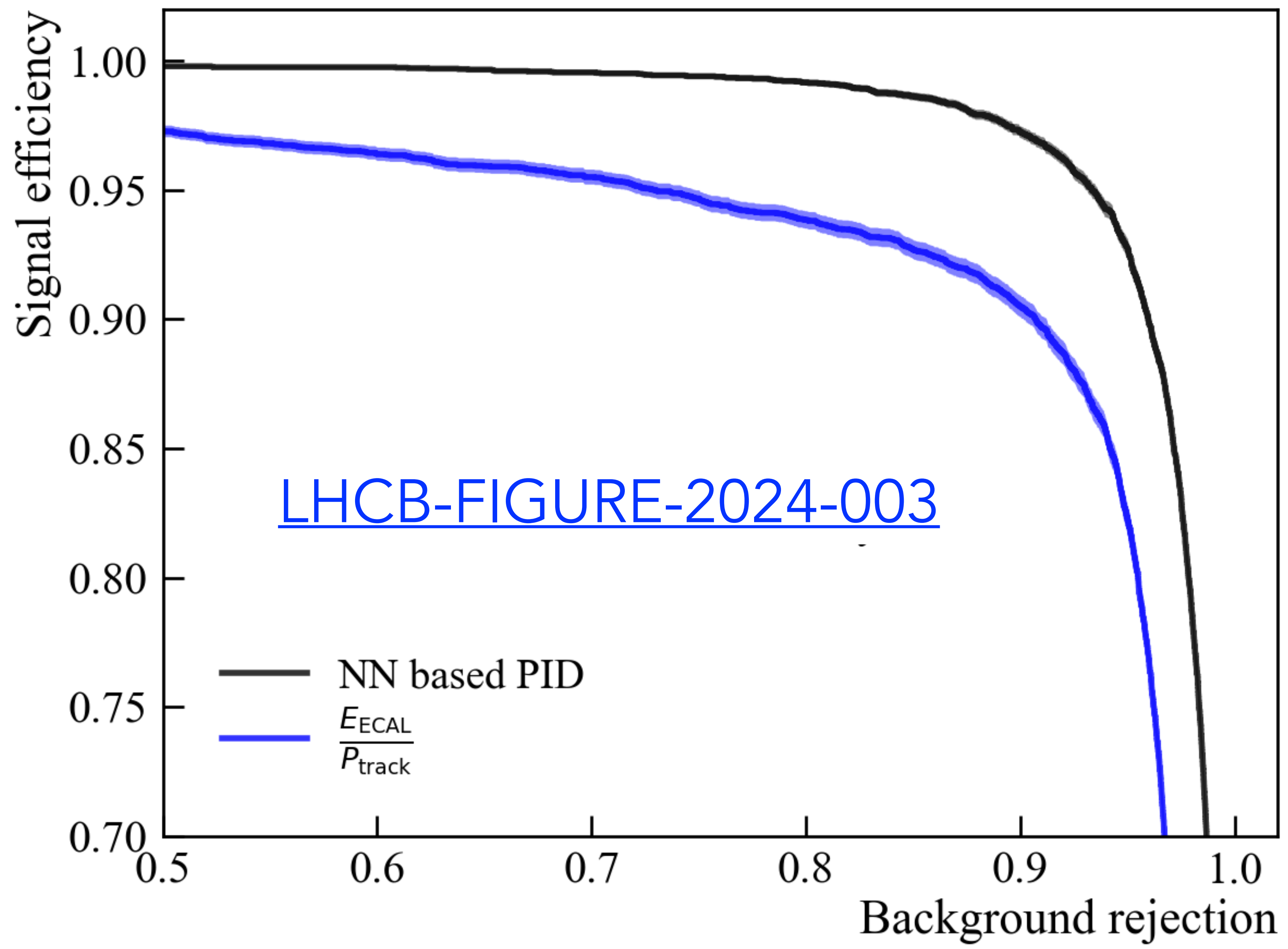


The upgraded LHCb detector for Run 3

[*JINST* 19 (2024) 05, P05065]



- Removal of L0 hardware trigger
- Triggerless readout: GPU @ HLT1, CPU @ HLT2
- Application of Lipschitz NNs [2112.00038] to enhance electron PID @ HLT1 and inclusive triggers @ HLT2 [2312.14265]



See talks by Kate and Michele on Friday

Dark Photons at LHCb

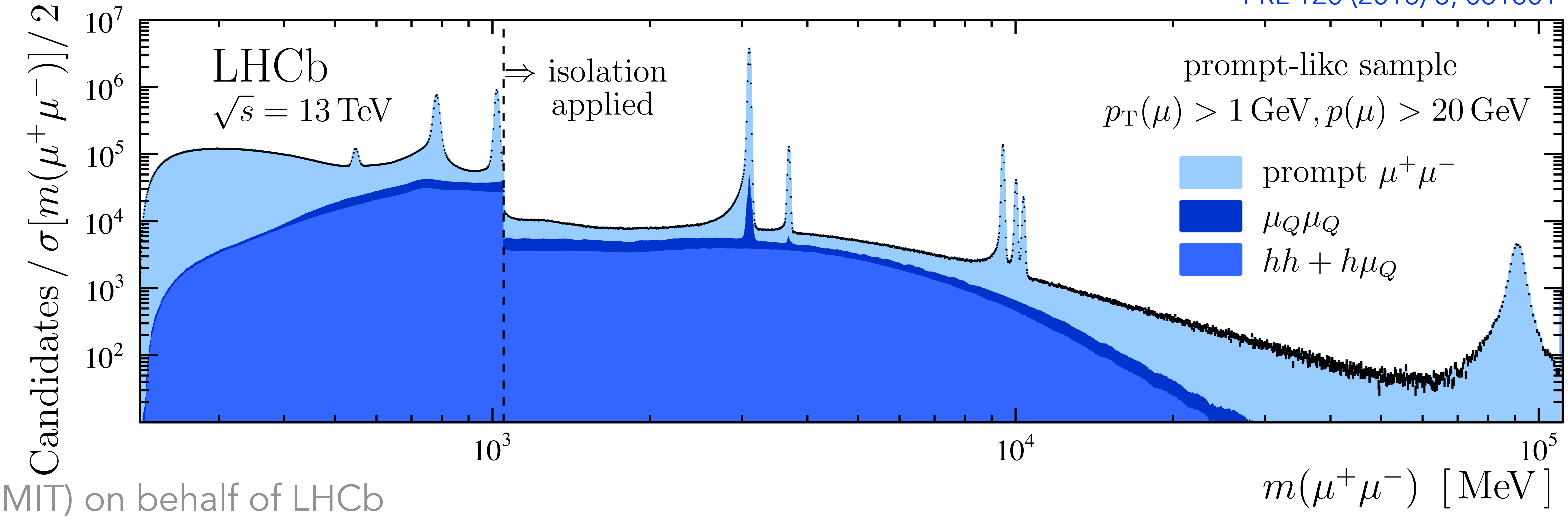
[PRL 120 (2018) 6, 061801]
[PRL 124 (2020) 041801]

- Inclusive search of $A' \to \mu^+\mu^-$ with Run 2 ($\mathscr{L} = 5.5\,\text{fb}^{-1}$)
- A' production & decay kinematics: anywhere a γ^* with A' mass: $\alpha = \varepsilon^2 \alpha_{\text{EM}}$
- Normalise to off-shell photon → just need to discriminate against non-γ^* background

$$n_{\text{ex}}^{A'}[m(A'), \varepsilon^2] = \varepsilon^2 \left[\frac{n_{\text{ob}}^{\gamma^*}[m(A')]}{2\Delta m} \right] \mathcal{F}[m(A')]\, \epsilon_{\gamma^*}^{A'}[m(A'), \tau(A')],$$

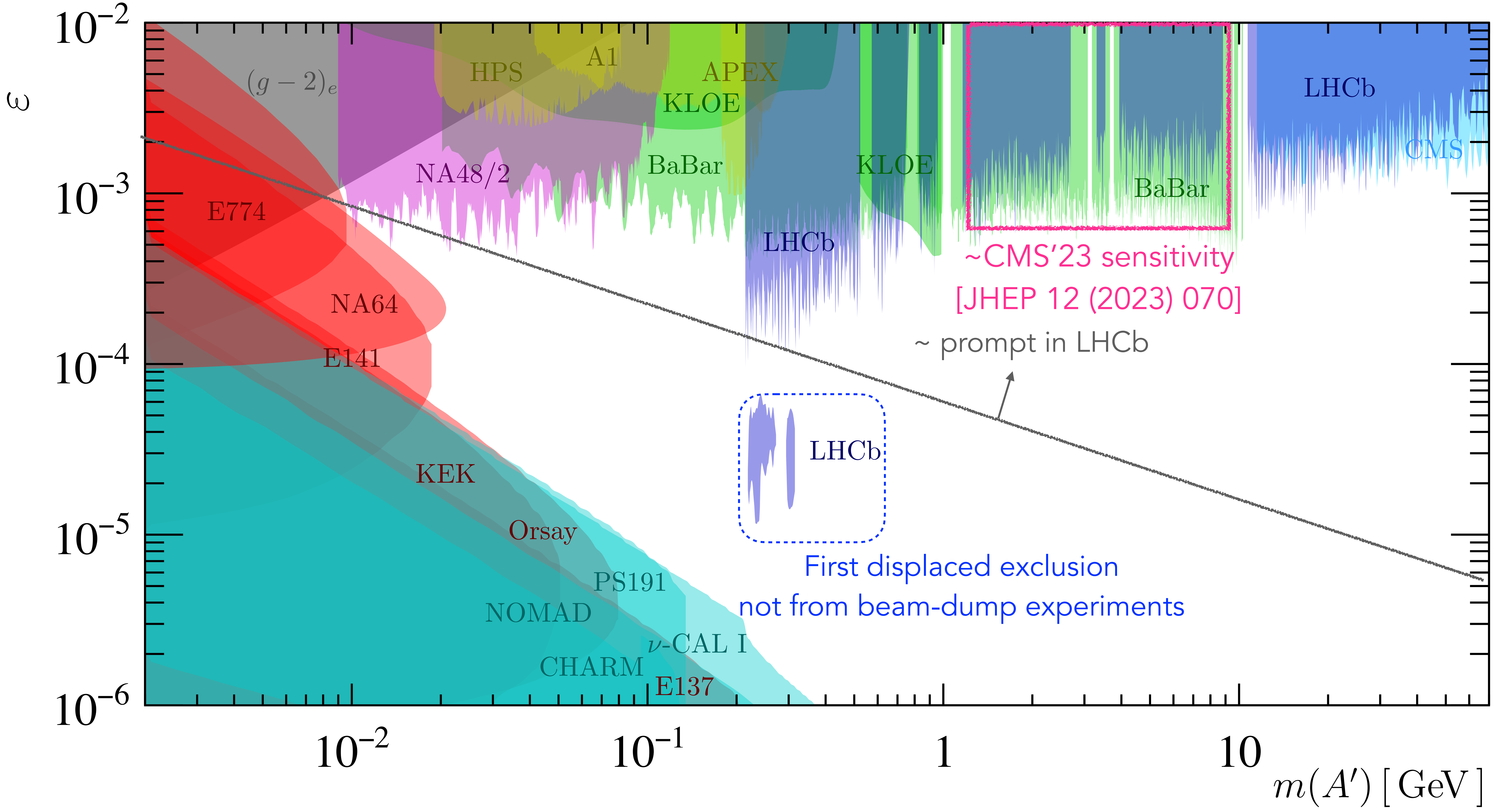
Off-shell photon; Phase space; A'/γ^* efficiency ratio

PRL 120 (2018) 6, 061801



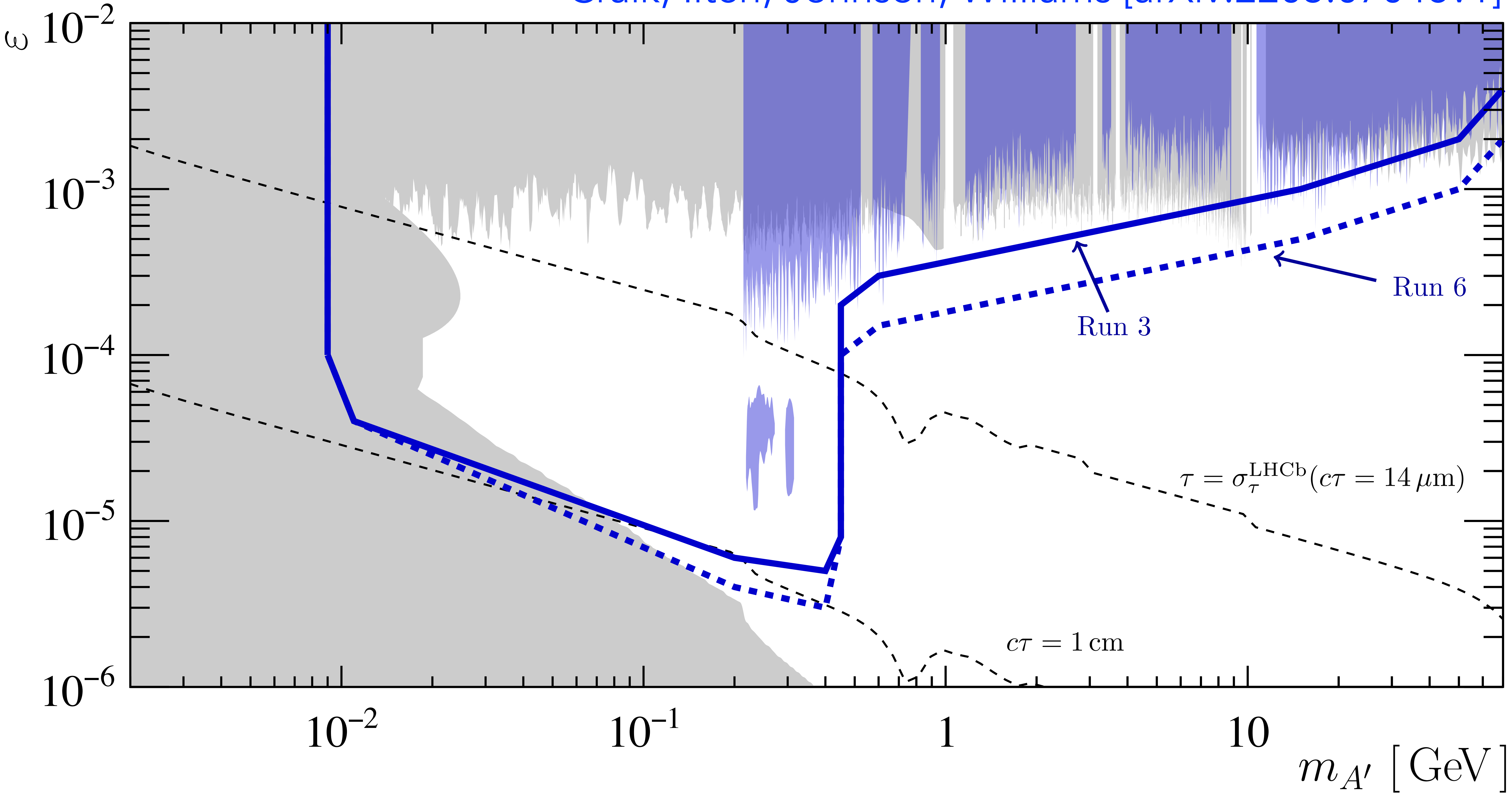
Dark Photons at LHCb

[PRL 124 (2020) 041801]



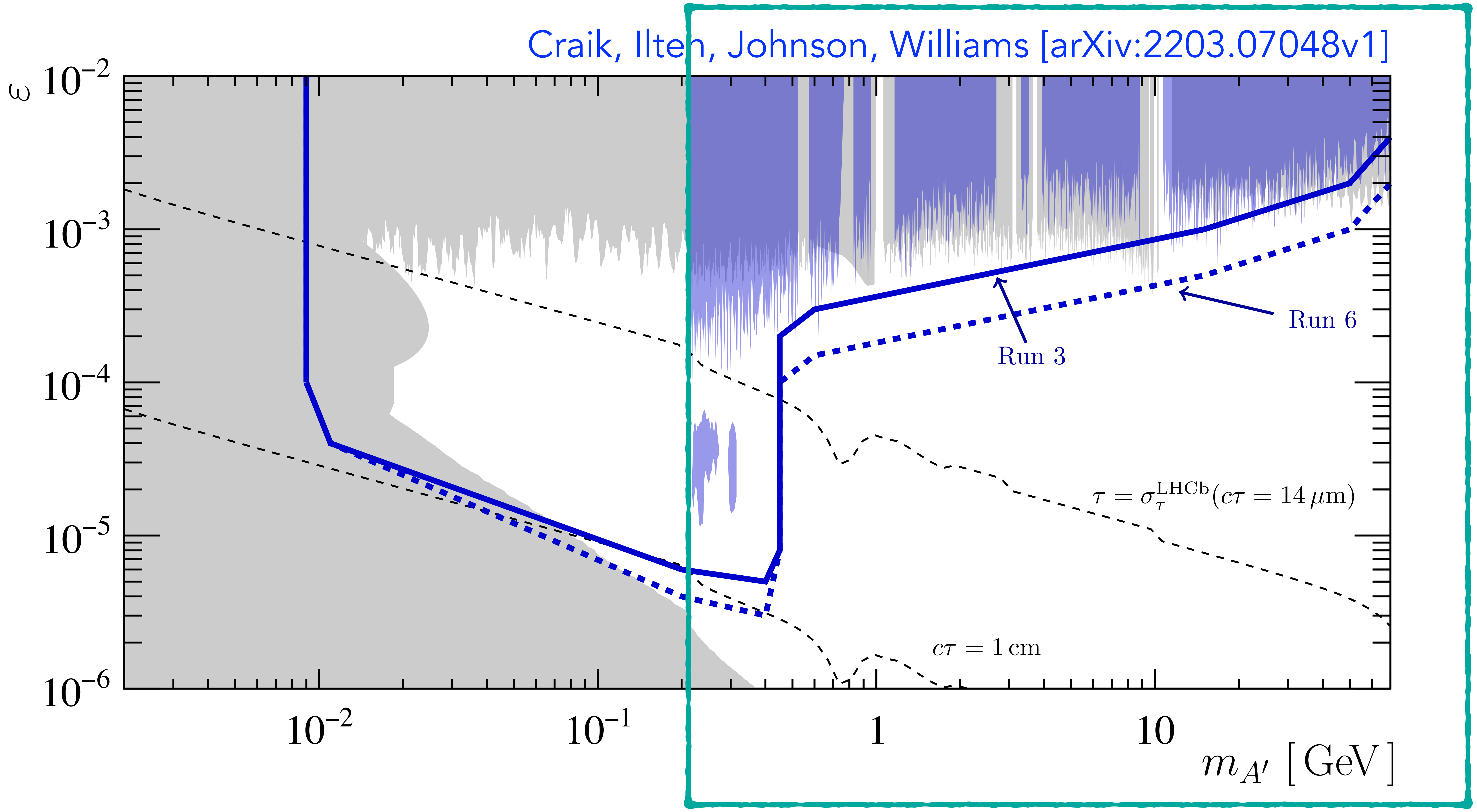
Dark photon sensitivity [Runs 3, 6]

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



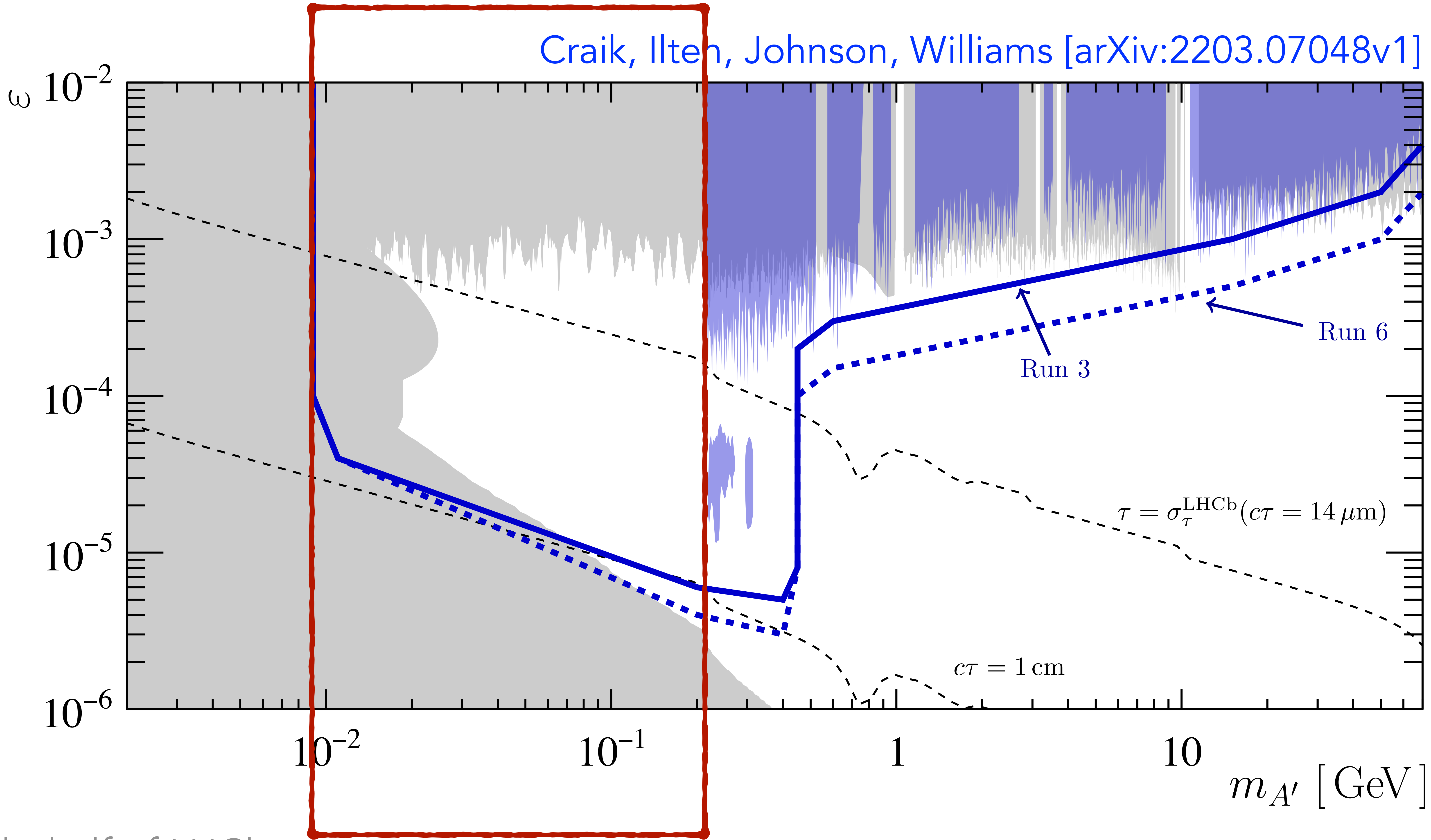
Dark photon sensitivity [Runs 3, 6]

LHCb Run 3: $\mathcal{O}(100)$ increase in $A' \to \mu^+\mu^-$ in the low-mass region [*can collect the total Run 2 luminosity in* ~ 2 *months of data taking in Run 3*]



Dark photon sensitivity [Runs 3, 6]

Sensitivity below the $\mu\mu$ threshold achieved by inclusive $A' \to ee$ search unlocked by electron ID in the first stage of the fully software trigger



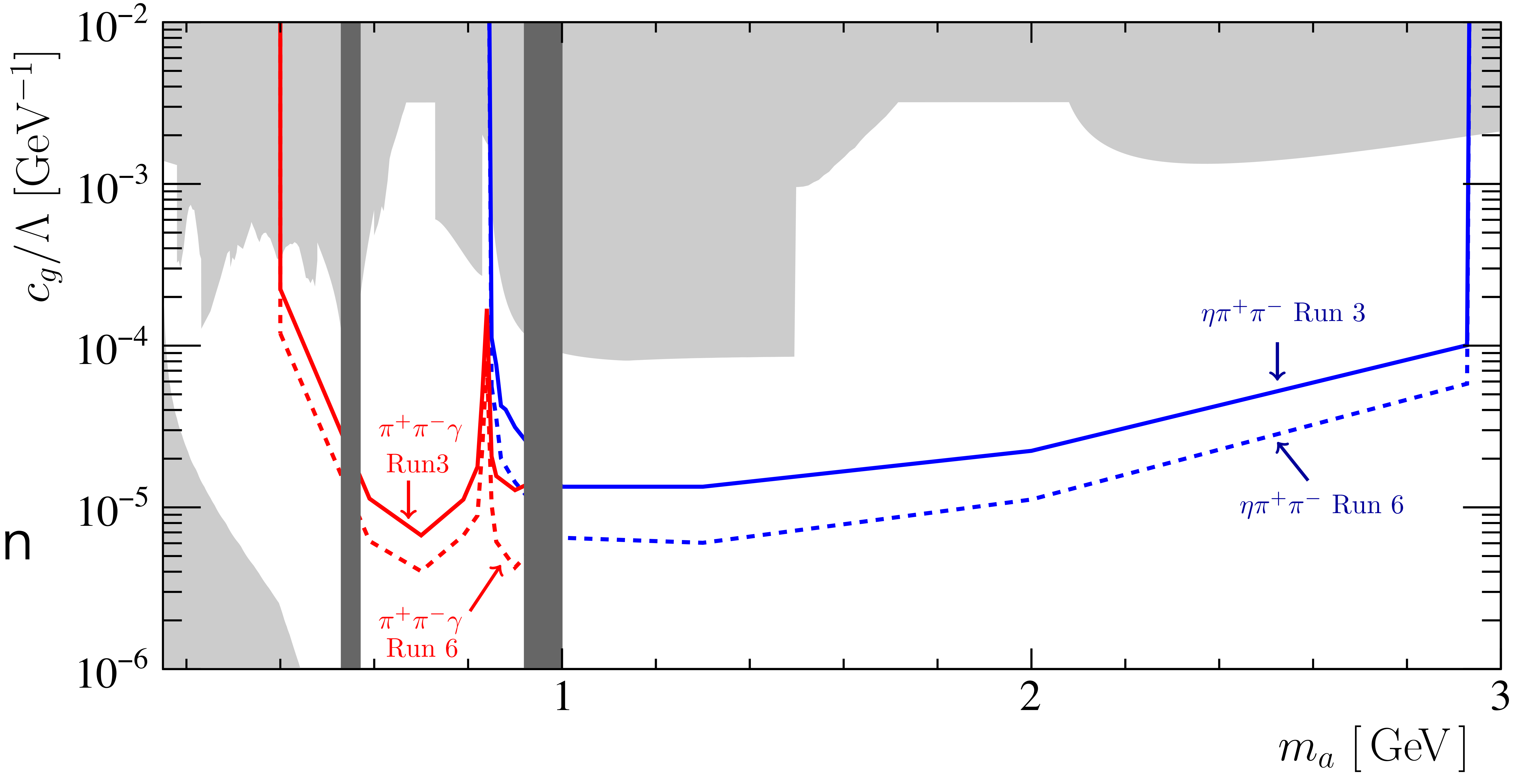
ALP searches at LHCb

- Exploit $B \to K^{(*)}a$ decays to search for the MeV-to-GeV m_a range, assuming ALP-gluon coupling dominant [PRL 123, 031803]

- Experimental target: $a \to \pi\pi\{\pi^0, \gamma, \eta\}$

- Currently being scrutinised with Run 2 data

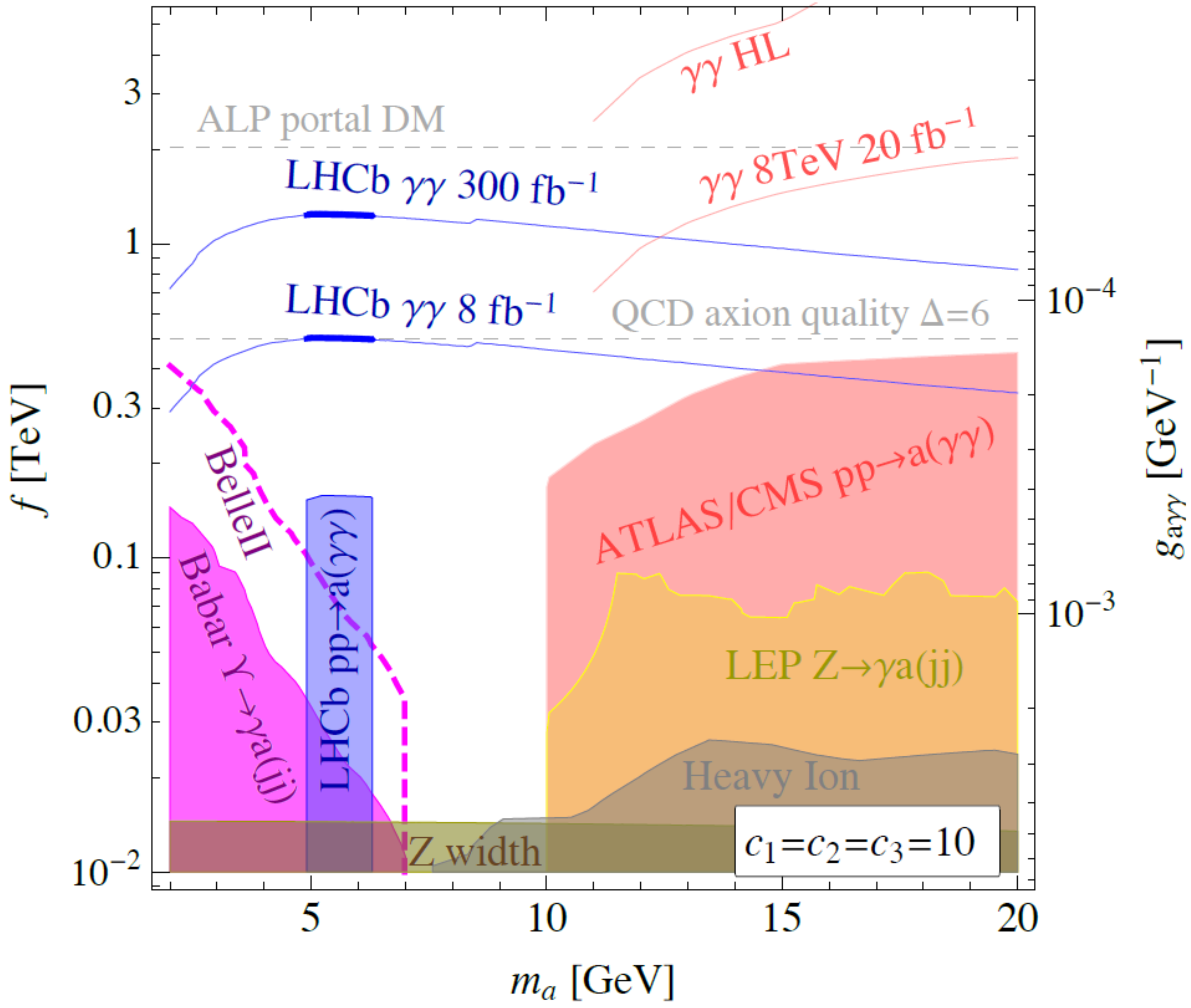
Craik, Ilten, Johnson, Williams [arXiv:2203.07048v1]



ALP searches at LHCb

[JHEP 1901 (2019) 113]

- Ongoing Run 2 analysis to probe ALPs produced by gluon fusion decaying to $\gamma\gamma$
- Current **best limits in mass gap below the ATLAS/CMS sensitivity** with $80\,\mathrm{pb}^{-1}$ of LHCb 2016 data @ $13\,\mathrm{TeV}$ [LHCb-PUB-2018-006]
- Result expected public late '24



LHCb is a *general purpose* dark-sector experiment

LHCb Run 3: significant increase in discovery potential:

- $5\times$ increase in *pp* collision rate
- fully software trigger

⇒ *close the gap in* $[\varepsilon^2, m_{A'}]$ to the beam-dump exclusion limits

⇒ achieve sensitivity in the [1,3] GeV m_a-range

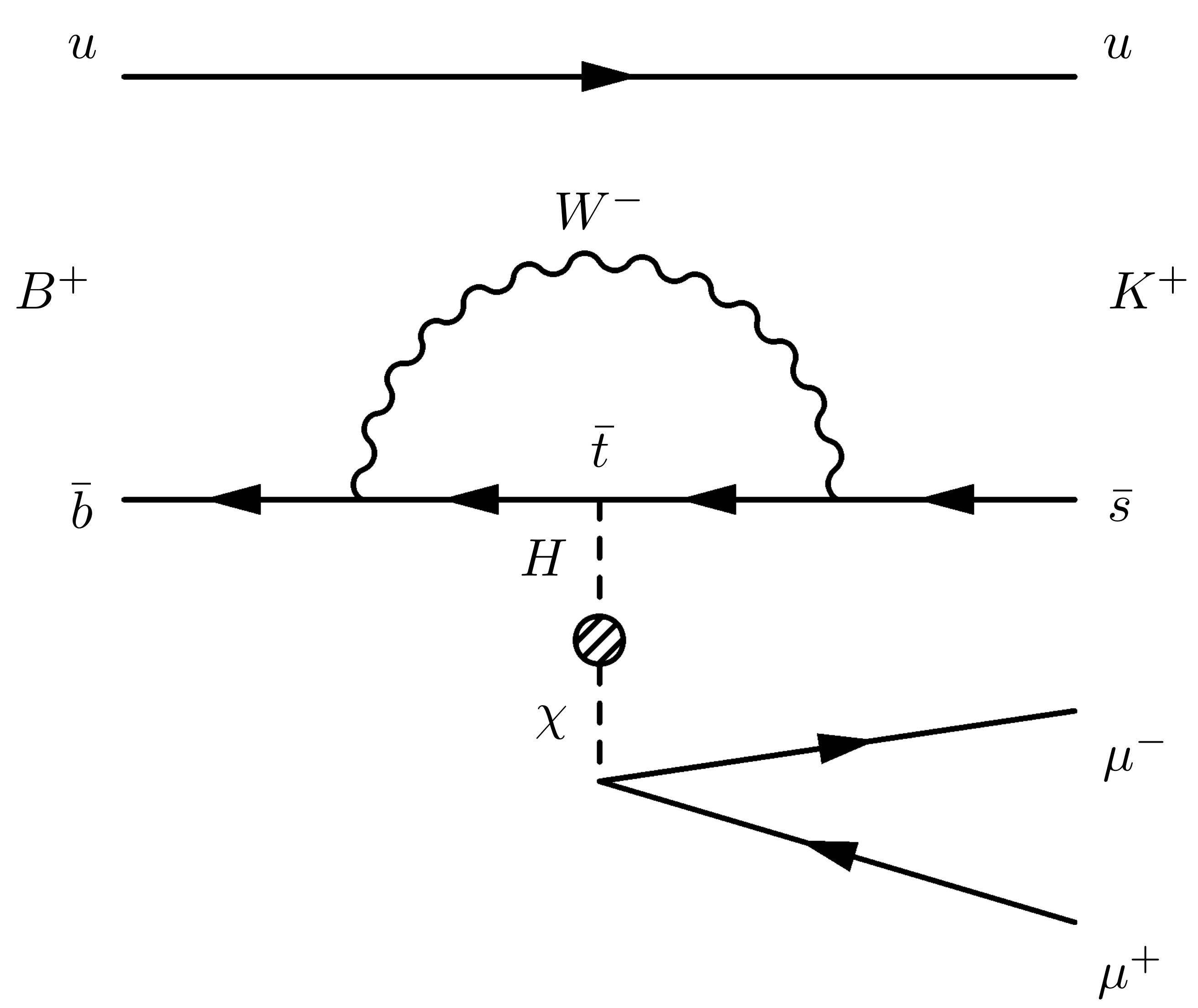
⇒ substantial increase in sensitivity to GeV-scale Higgs-portal scalars, especially for long-lived displaced candidates at high mass

Appendix

Dark scalars at LHCb

- Dark scalar coupling to the Higgs via mixing angle, θ

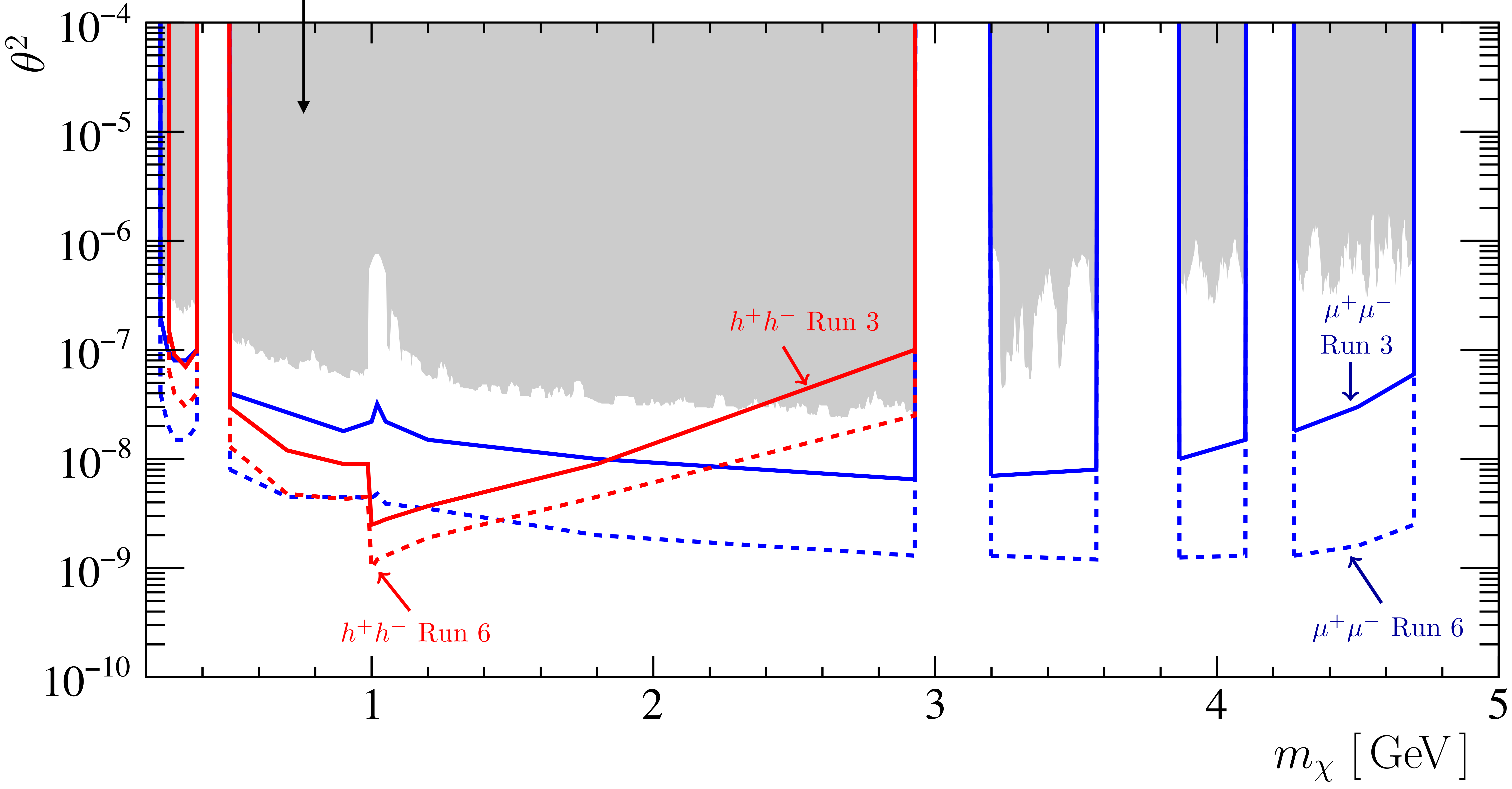
- Exploit $B \to K^{(*)}\chi$ penguin decays to capitalise on enhancement due to t mass in the loop



Most stringent constraints to in $250 < m(\chi) < 4700$ MeV and $0.1 < \tau(\chi) < 1000$ ps

Using LHCb Run 1 analyses of $B \to K^{(*)}\chi(\to \mu^+\mu^-)$

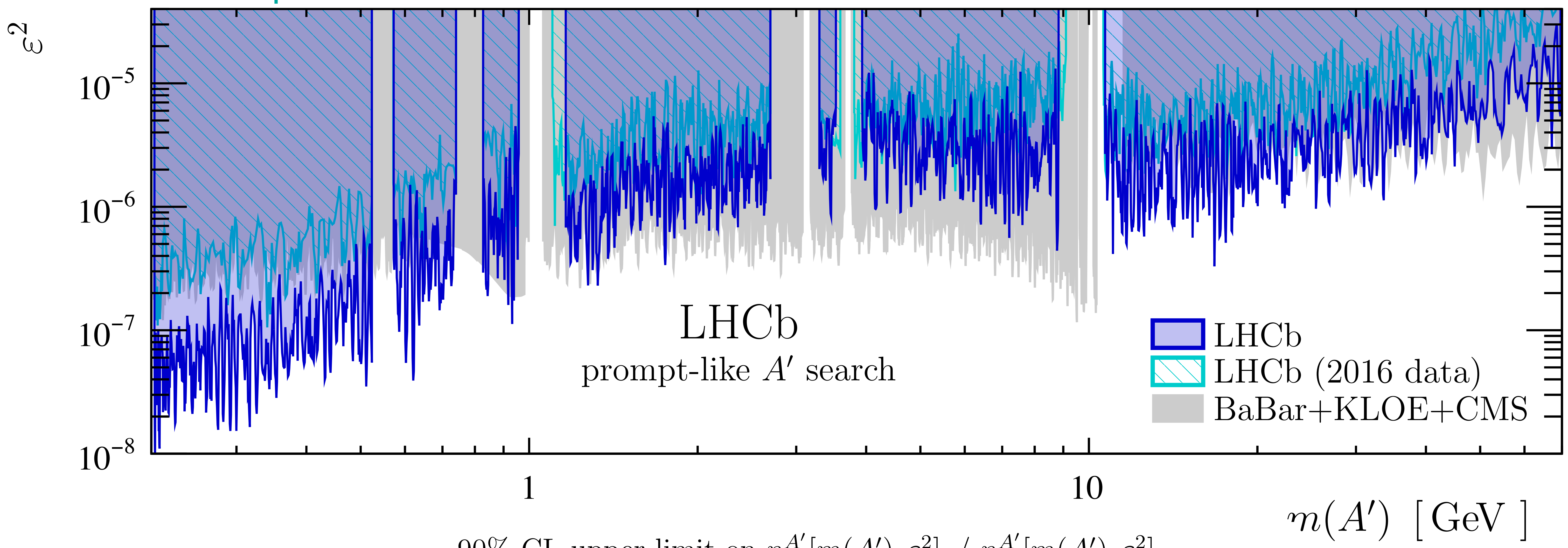
Craik, Ilten, Johnson, Williams [arXiv:2203.07048v1]

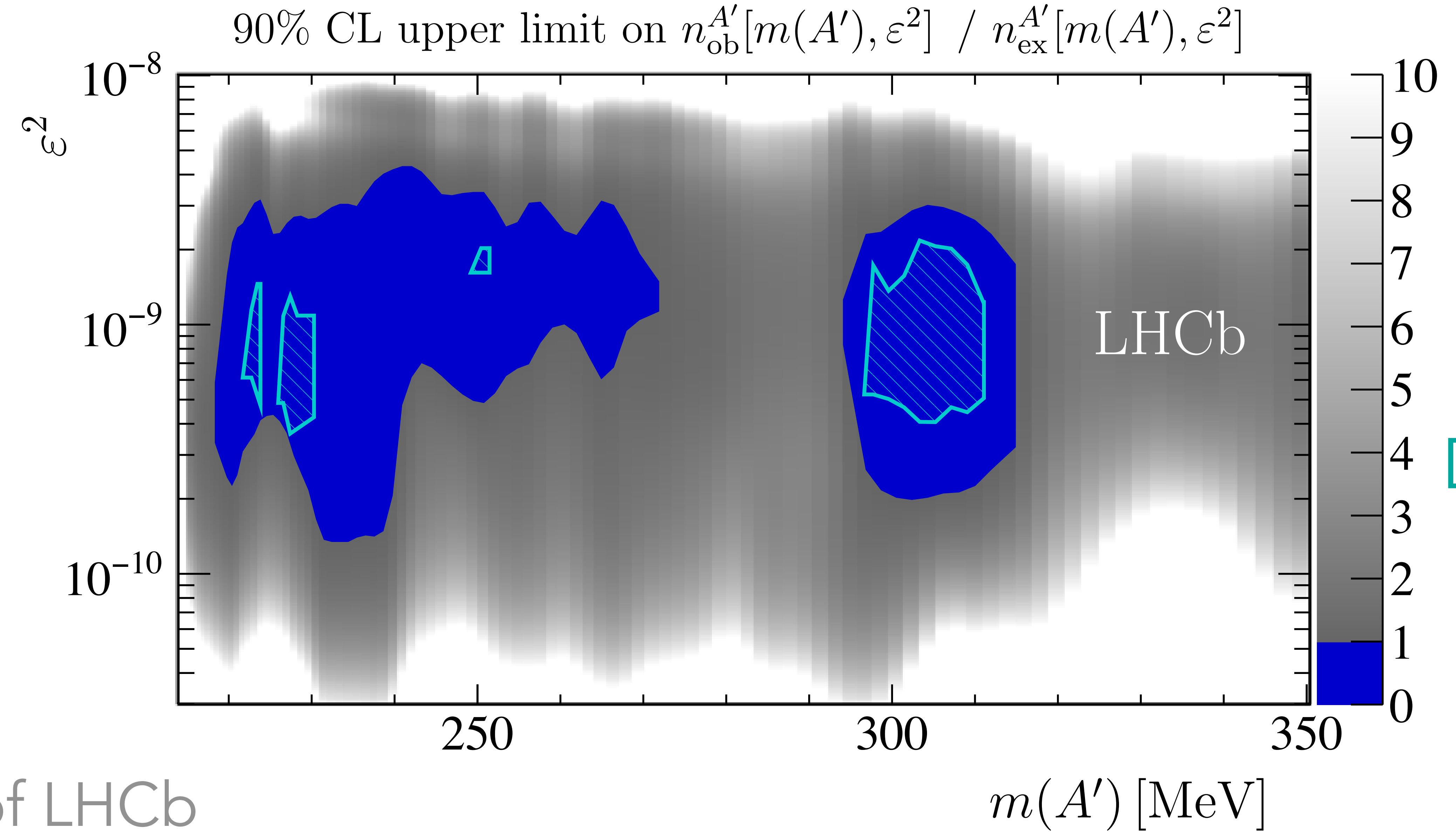


[PRL 124 (2020) 041801]

Dark Photons at LHCb

Prompt search results





Displaced search results

Dark Photons at LHCb

[PRL 124 (2020) 041801]

- **Event selection:**
  - Hardware trigger stage:
    - $p_T(\mu) > 1.8$ GeV || $p_T(\mu_1) p_T(\mu_2) > 1.5$ $(\mathrm{GeV})^2$
  - Software trigger stage:
    - MuonID criteria
    - Good quality vertex
  - Offline:
    - Dimuon isolation strategy

- Long-lived (prompt) search:
  - $p_T(\mu) > 0.5$ (1.0) GeV
  - $p(\mu) > 10$ (20) GeV
  - Inconsistency (consistency) with origin at the PV

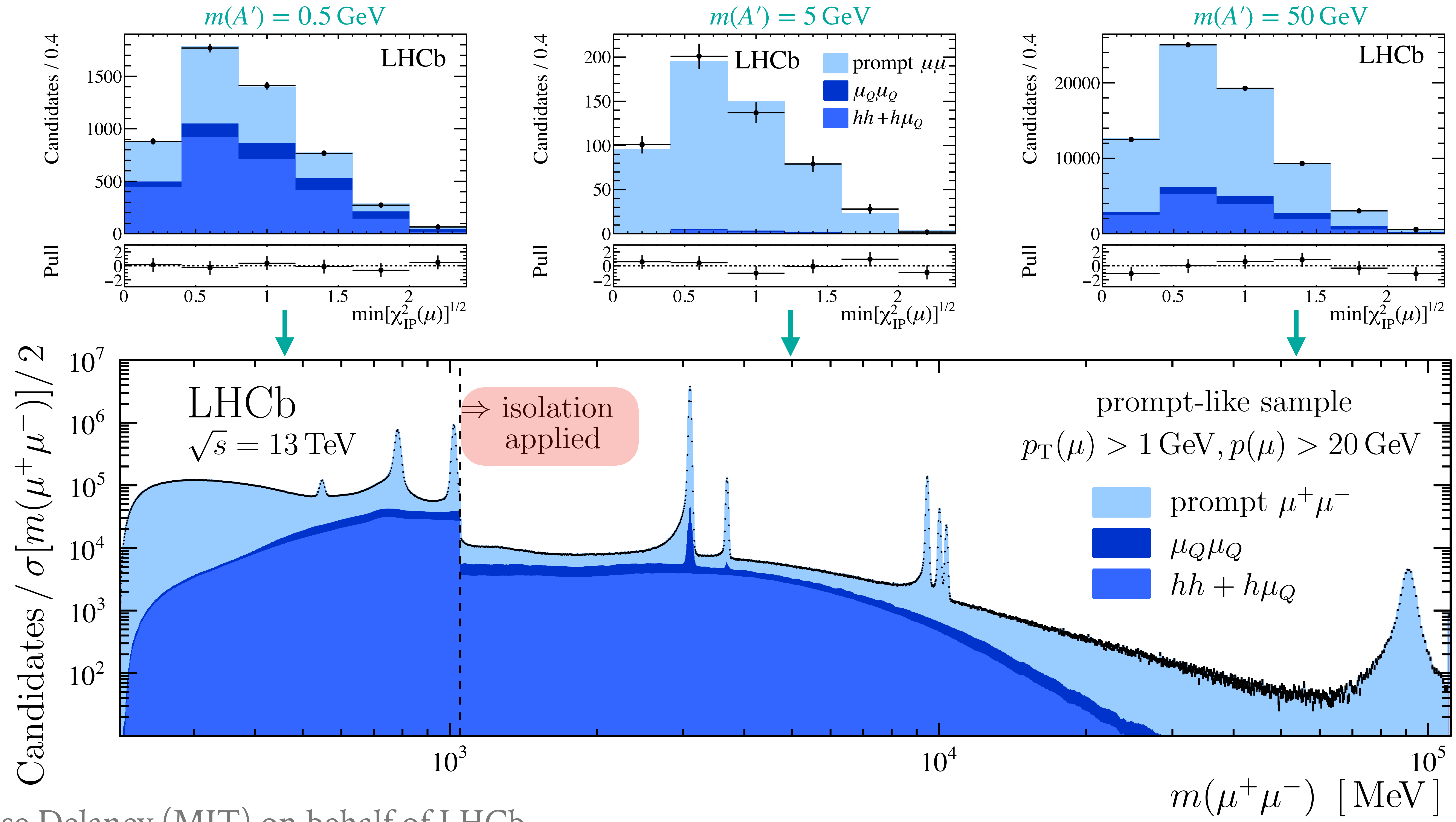
- **Prompt search misRECO backgrounds:**
  - Double mis ID (hh): μ as prompt hadron, most likely a pion
  - misID (h)+ misRECO (μ_Q): μ from *b(c)*-hadron decay and reconstructed as prompt
  - Double misRECO ($\mu_Q \mu_Q$)

- **Displaced search backgrounds:**
  - Photon conversions to $\mu\mu$ in the VELO (matter veto strategy in the back-up)
  - b-hadron decays with two muons produced in the decay chain
  - Low mass tail from $K_s^0 \to \pi\pi$ where both pions misidentified as muons

Prompt dark photons at LHCb

PRL 120 (2018) 6, 061801

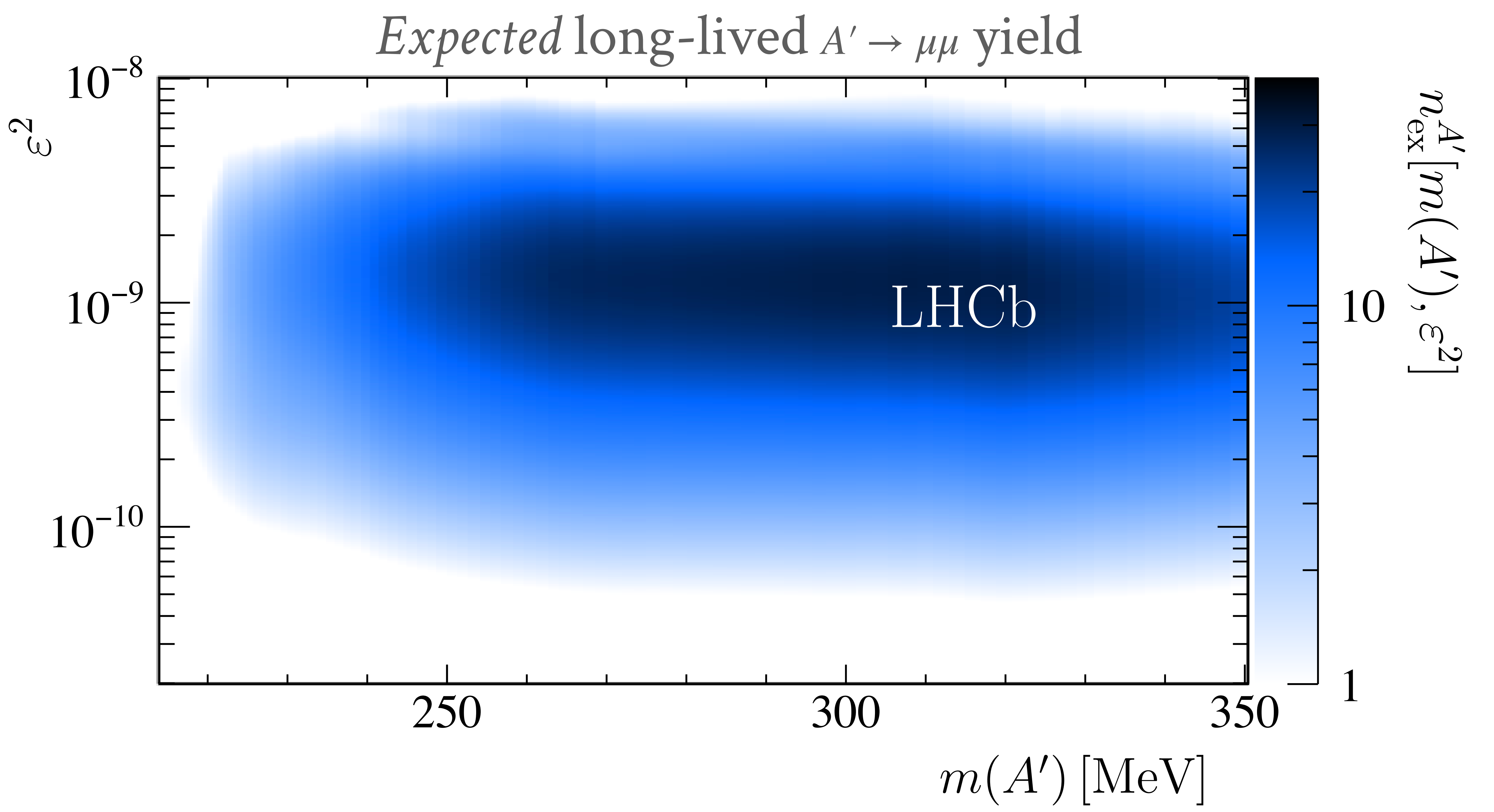
prompt $\mu^+\mu^-$	from data at $m(J/\psi)$ and $m(Z)$
$\mu_Q\mu_Q$	from simulation (validated)
$hh + h\mu_Q$	from same-sign $\mu^\pm\mu^\pm$ corrected



Displaced dark photons at LHCb

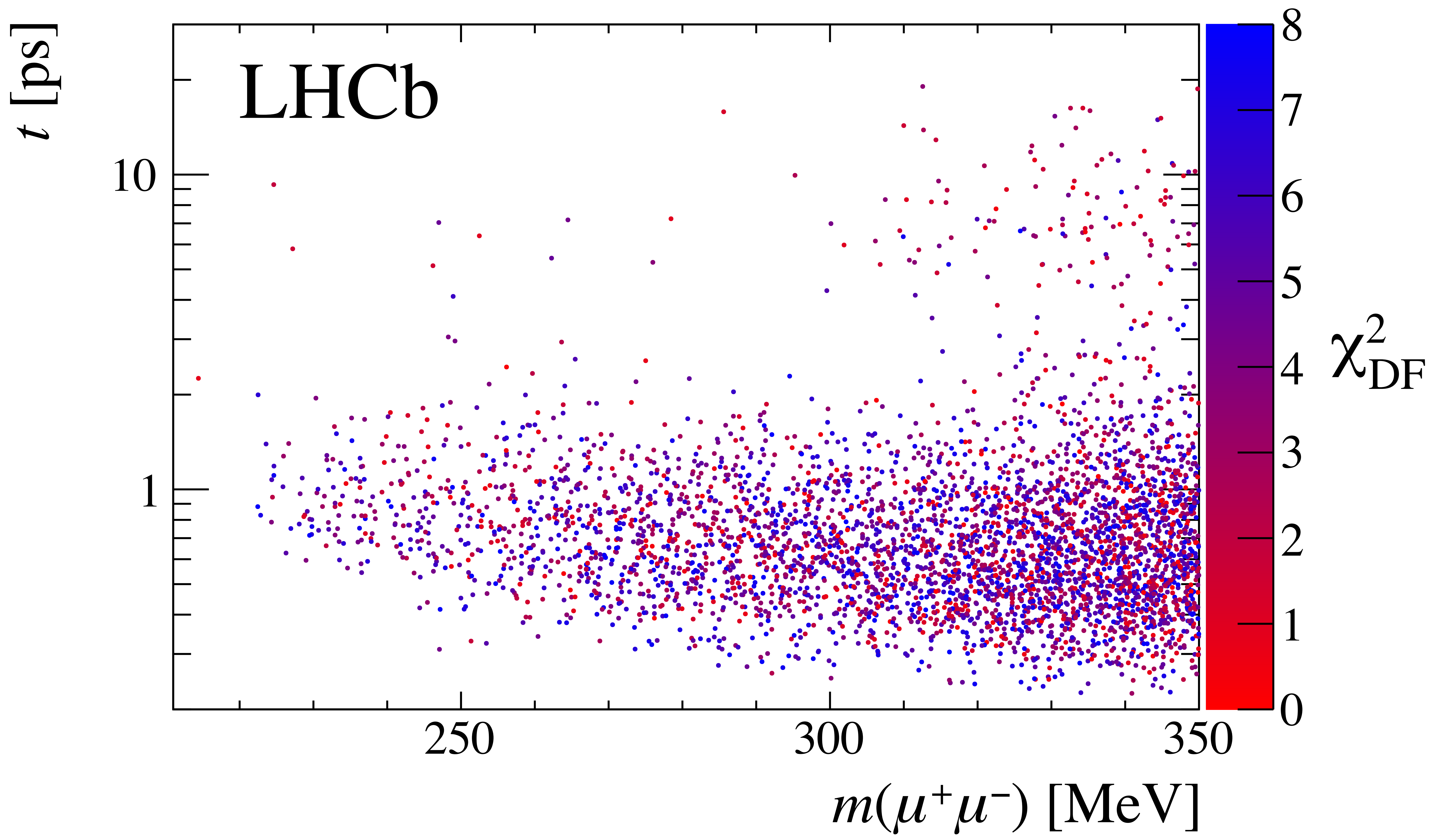
PRL 120 (2018) 6, 061801

- Only region $m(A') < 350$ MeV is sensitive
- Comparatively looser $p_T(\mu)$ requirements
- Main background from γ conversion in the VErtex LOcator



Displaced dark photons at LHCb

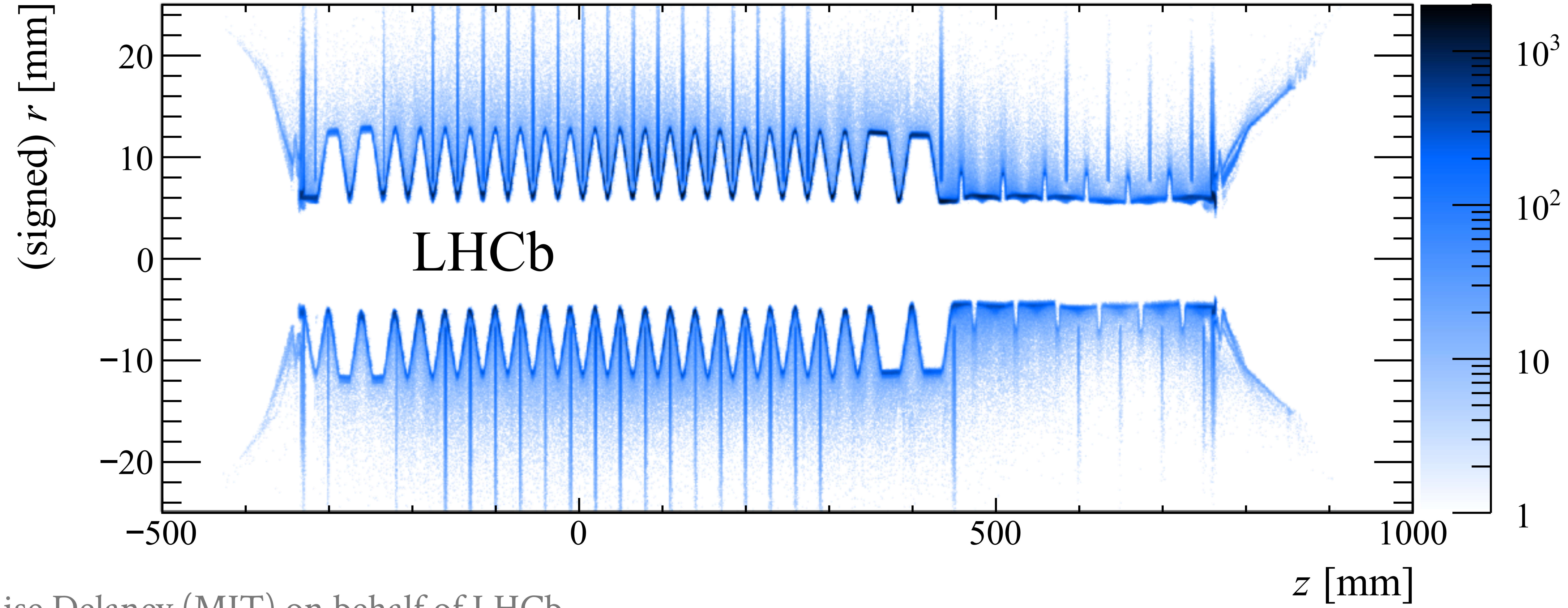
PRL 120 (2018) 6, 061801



VELO Material Map

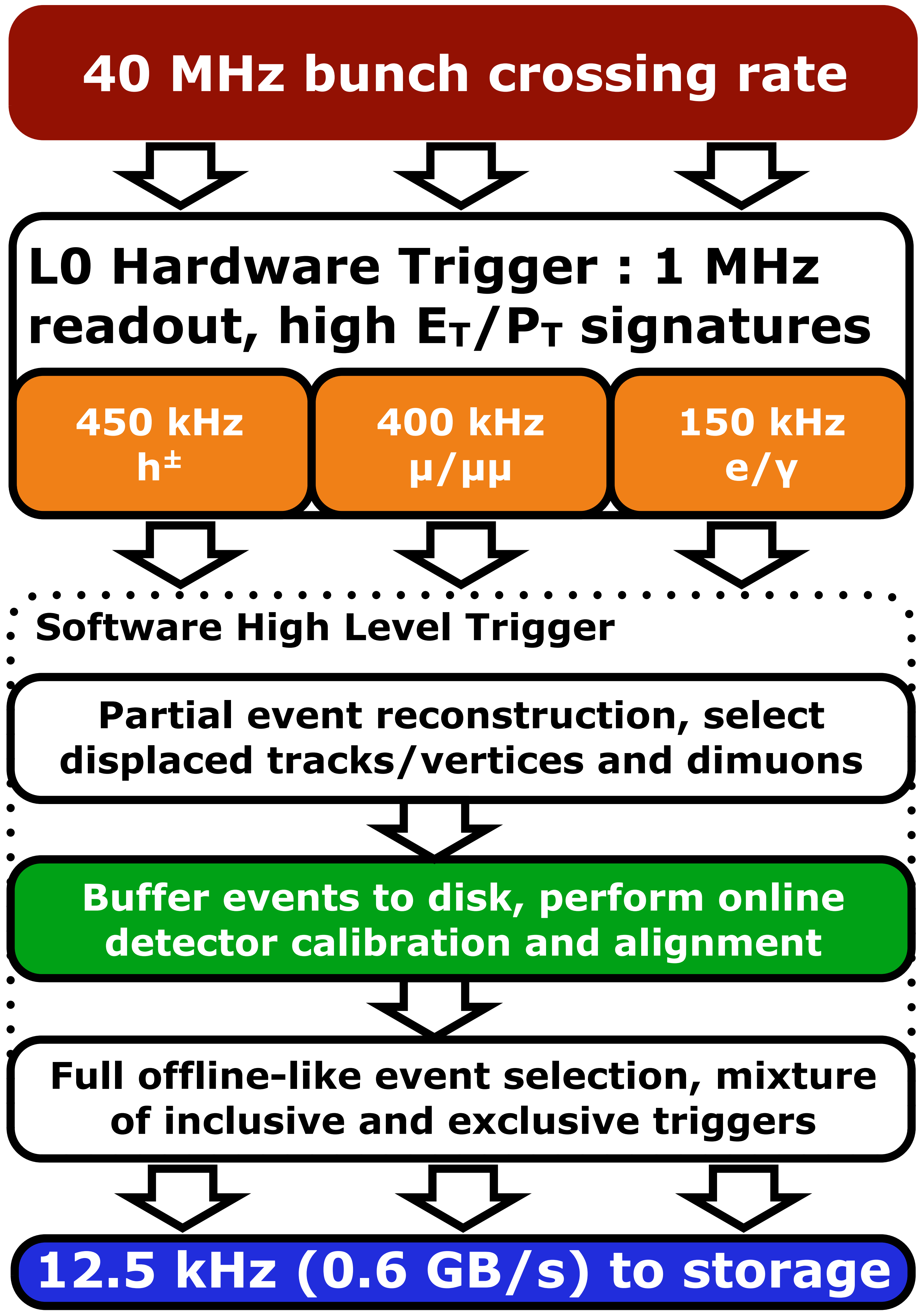
JINST 13 (2018) 06, P06008

- Beam-gas collisions can be distinguished from hadrons produced in heavy-flavor decays
  → map the whole VErtex LOcator geometry
- Can assign p-value to material interaction hypothesis
- Effective veto of γ conversions to $\mu\mu$ in the material
  → veto main background displaced A' searches at low mass



The LHCb Trigger

LHCb 2015 Trigger Diagram



LHCb Upgrade Trigger Diagram