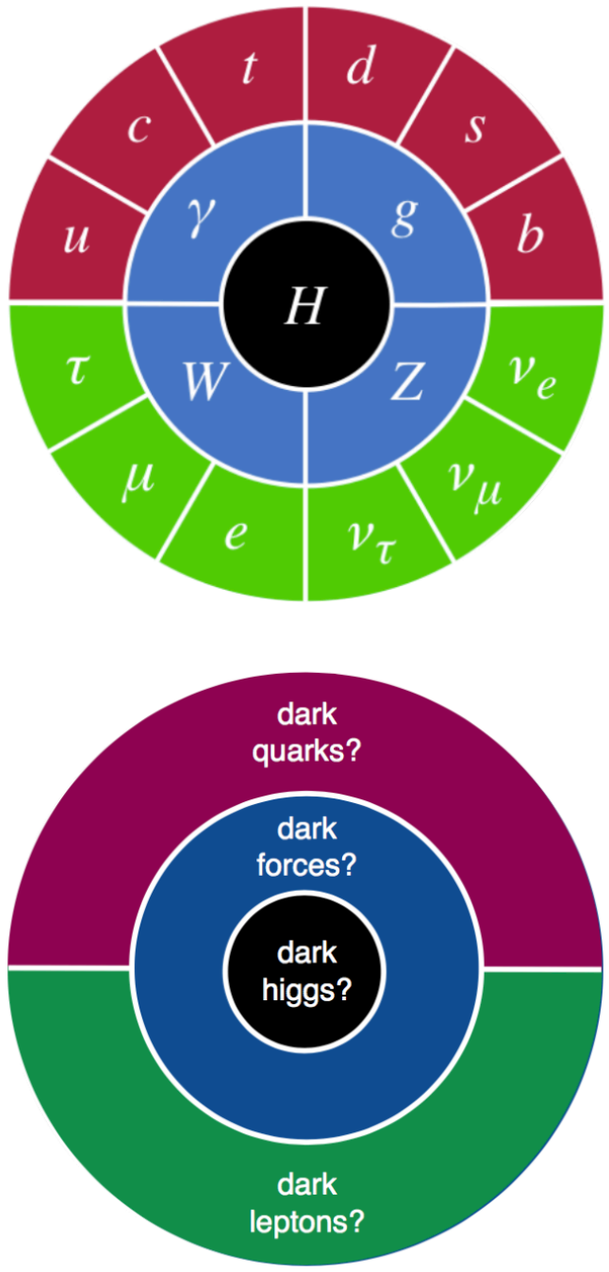
Dark photons at LHCb

2023 LHC Dark Matter Spring Meeting

May 16th, 2023

Blaise Delaney, on behalf of the LHCb Collaboration

Portals to the dark sector



4 portals: 4 new particles [arXiv:2209.04671]:

- Dark photons

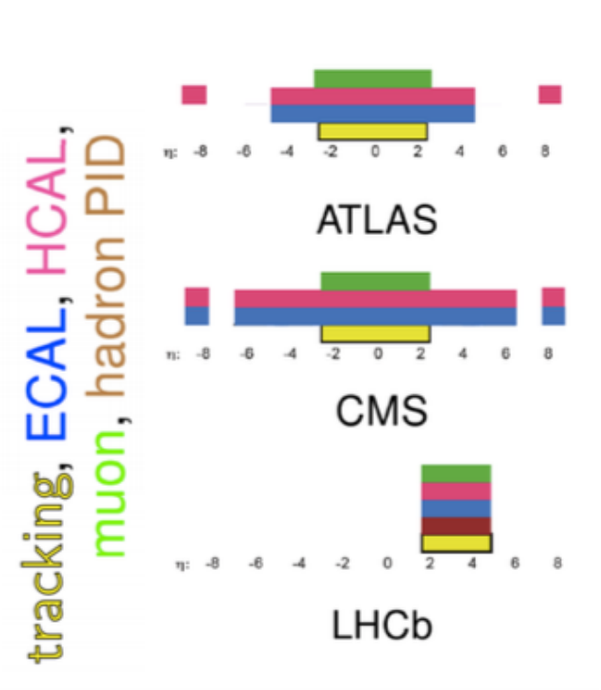
Appendix

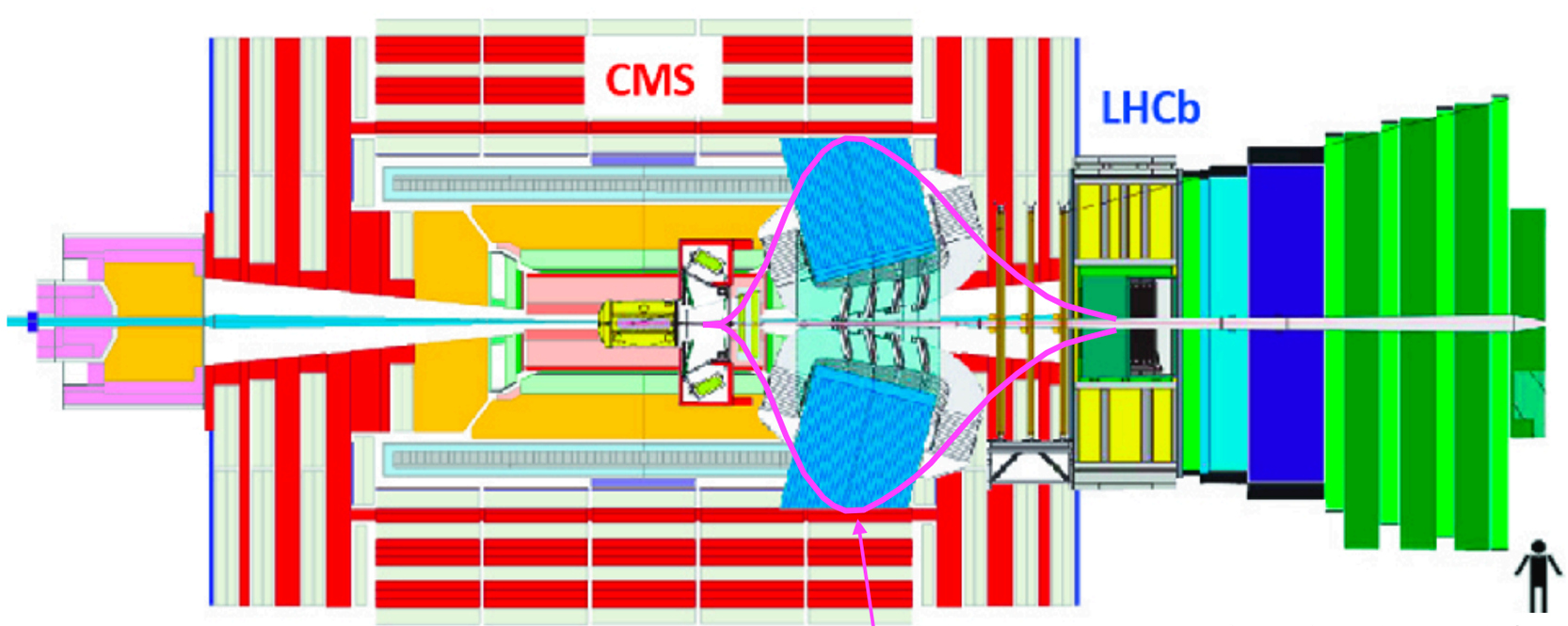
- Higgs-portal scalars
- Sterile neutrinos
- ALPs coupling to photons, fermions & gluons

LHCb: flavour *and* dark physics

JINST3(2008)S08005
Int J Mod Phys A30(2015)1530022
CERN-LHCC-2018-014 ; LHCB-TDR-018

- Only LHC experiment fully instrumented in the forward region
- Despite limited acceptance and lower $\mathcal{L}$ than ATLAS/CMS, *capacity for sensitivity to dark portals*:
  - Excellent vertex and momentum resolution
  - Capacity for *soft* triggers (*e.g.* trigger on $p_T \sim 1$ GeV on detached $\mu\mu$) → enhanced flexibility in Run 3 with a fully software trigger





Sketch adapted from Redi, LHCP '21
Not to scale

The LHCb trigger in Runs 2 & 3

JINST3(2008)S08005
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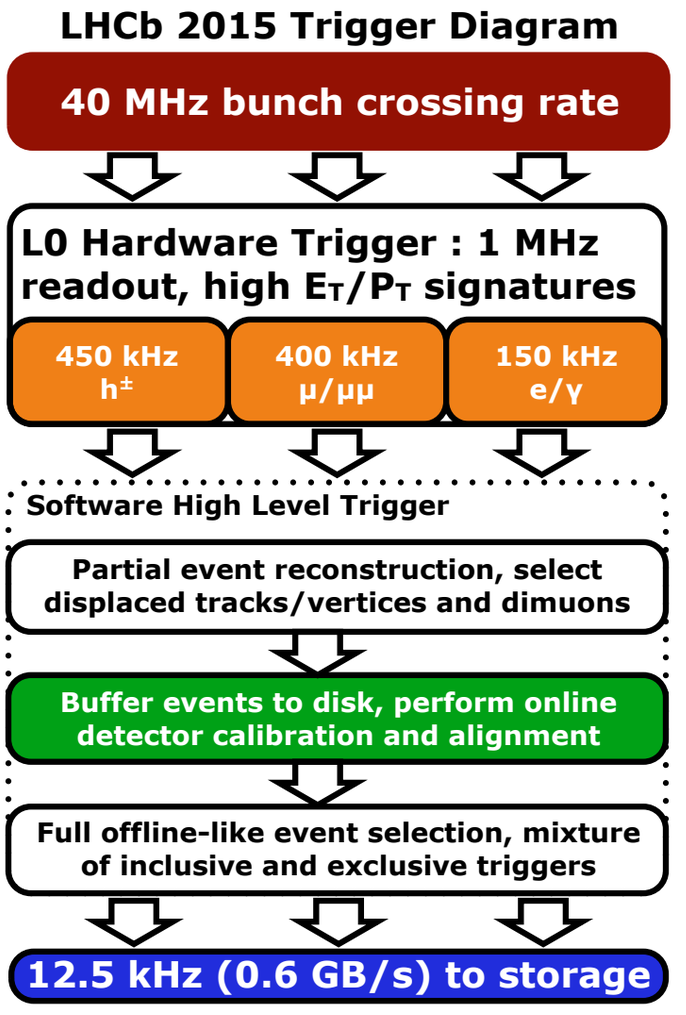
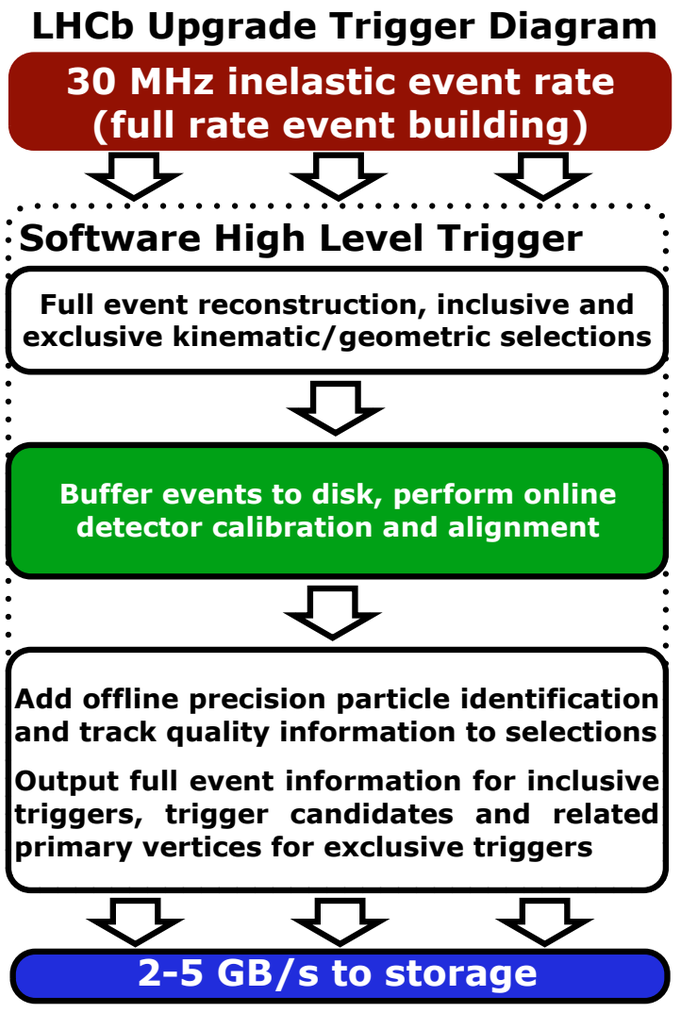


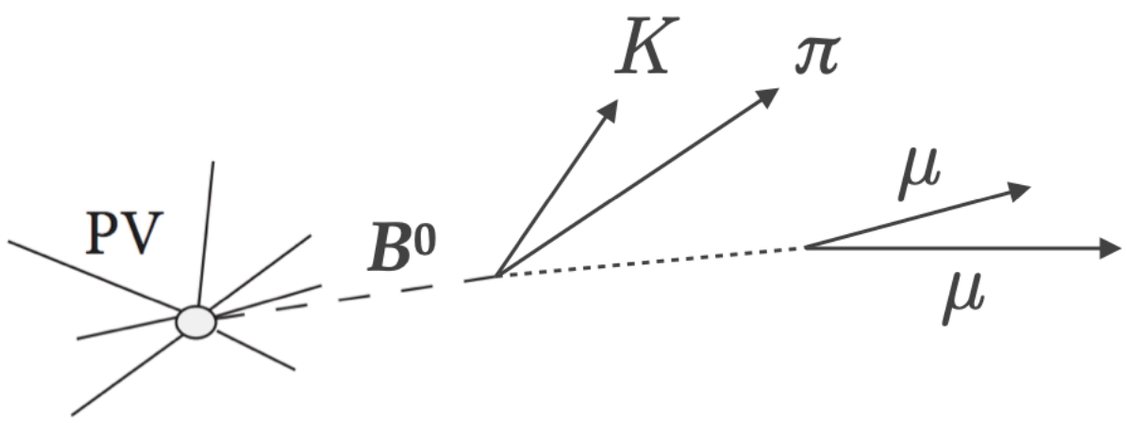


- **Run 2**: *consistent* online (HLT2) and offline reconstruction
- *A'* results based on HLT2 objects → no prescales on $\mu\mu$ down to threshold (~ 210 MeV)
- **Run 3**: fully software triggers with *enhanced sensitivity* to low-momentum candidates

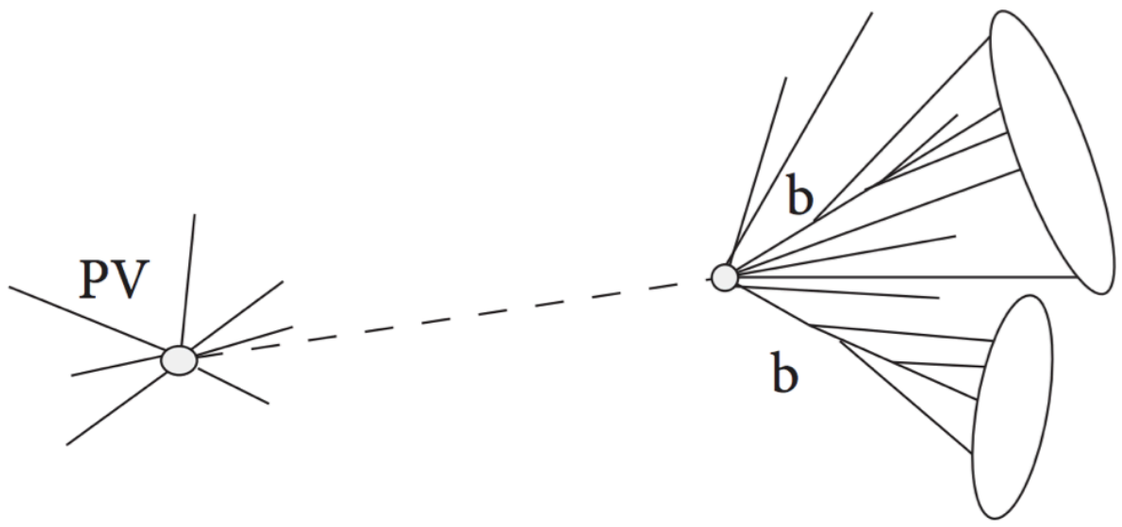
LHCb: flavour *and* dark physics

- Experimental programme:
  - Soft trigger & forward acceptance → lighter masses
  - Forward boost and $\sigma(\tau) \sim 50$ fs → low lifetimes (*prompt* vs *displaced* signatures)

Produced in heavy-flavor decays



Produced in *pp* collisions



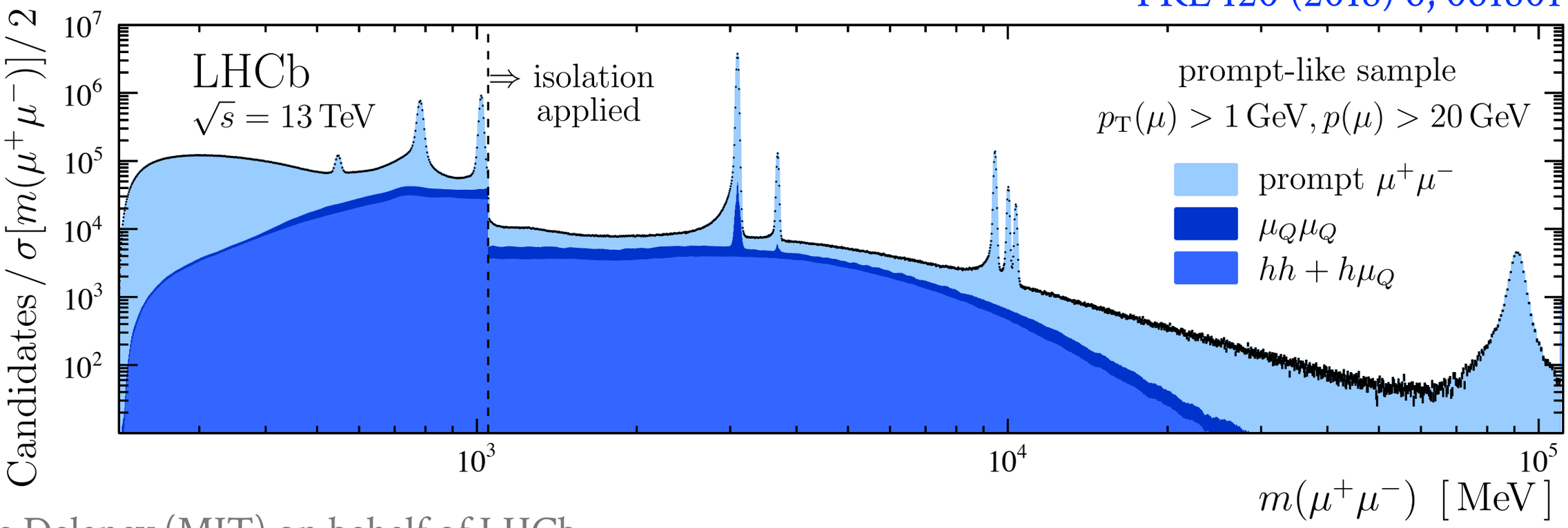
Sketch by Martino Borsato, LHCb Implications Workshop '20

Dark photons at LHCb

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

- A' production: anywhere a γ^* with A' mass: $\alpha' = \varepsilon^2 \alpha_{\mathrm{EM}}$
- Inclusive search of $A' \to \mu^+\mu^-$ with with Run 2 (5.5 fb^{-1})
- Updates search with 2016 data:
  - $3\times$ luminosity
  - Improved software trigger efficiency

PRL 120 (2018) 6, 061801

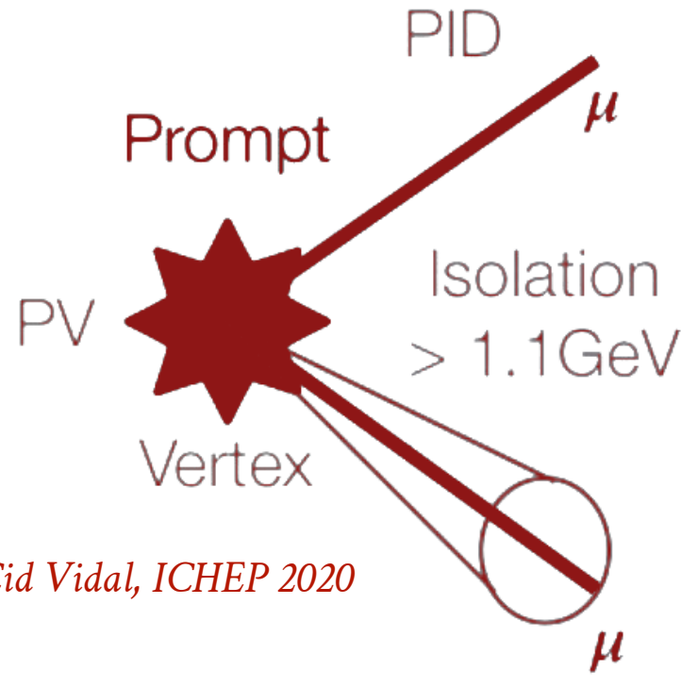


Dark photons at LHCb

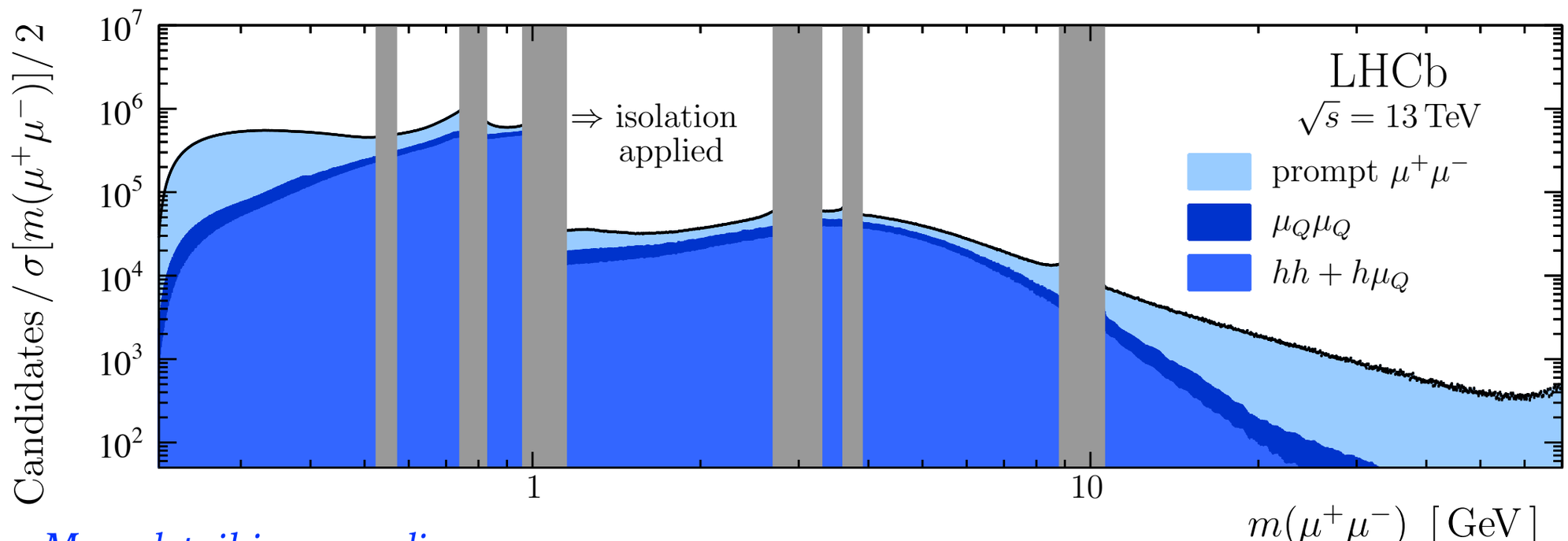
PRL 124 (2020) 041801

Analysis flow:

- Self-normalize to $\gamma^* \to \mu\mu$
- *Prompt* analysis:
  - Bkgs: prompt h & μ; μ from heavy flavour misID as prompt
  - Isolation applied for $m(\mu\mu) > 1.1$ GeV
  - Observed A' yields extracted via fits to $\min[\chi^2_{\mathrm{IP}}(\mu)]$



Credit: Cid Vidal, ICHEP 2020



More detail in appendix

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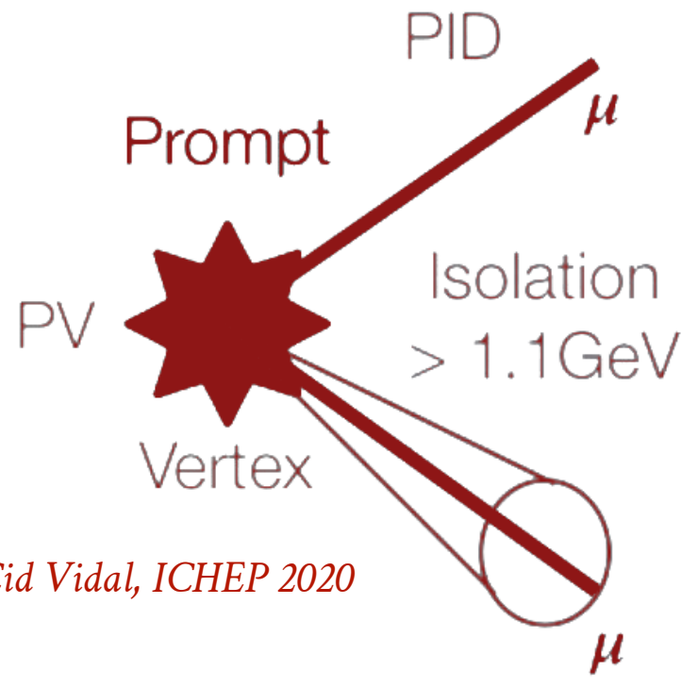
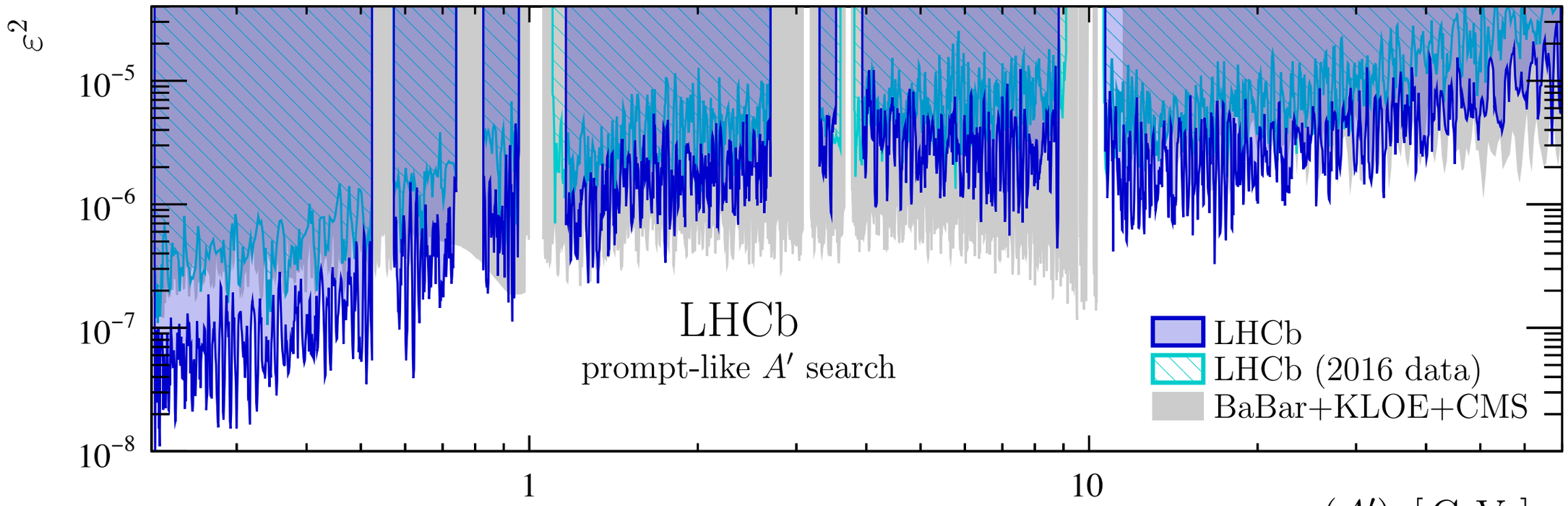


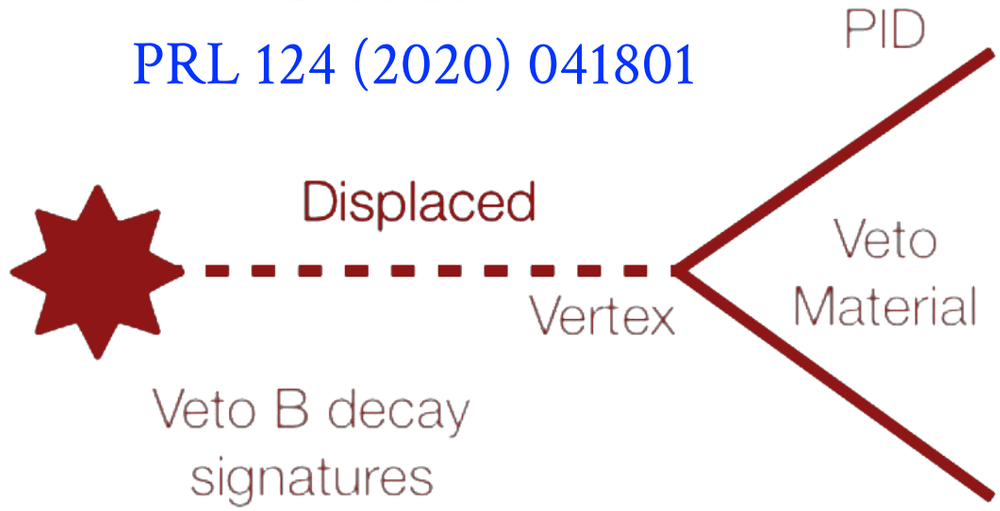
Credit: Cid Vidal, ICHEP 2020



More detail in appendix

Dark photons at LHCb

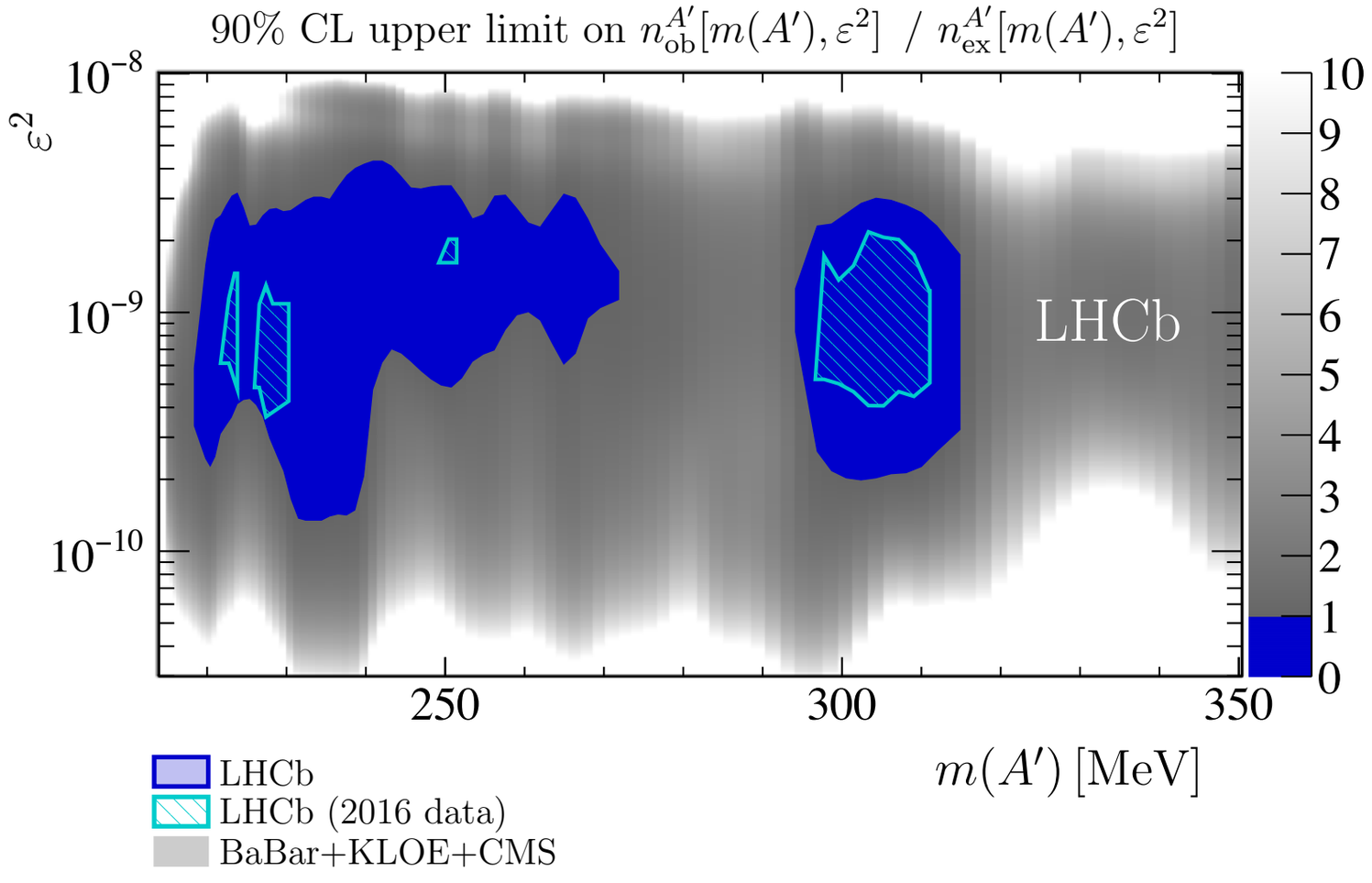
PRL 124 (2020) 041801



Credit: Cid Vidal, ICHEP 2020

Analysis flow:

- Self-normalize to $\gamma^* \to \mu\mu$
- *Displaced* analysis:
  - Photon conversion into $\mu^+\mu^-$ vetoed by $m(A')$ -dependent requirement on relevant *p*-value
  - Trigger requirements & BDTs to suppress $K_s \to \pi^+\pi^-$ and dimuons from *B decays*

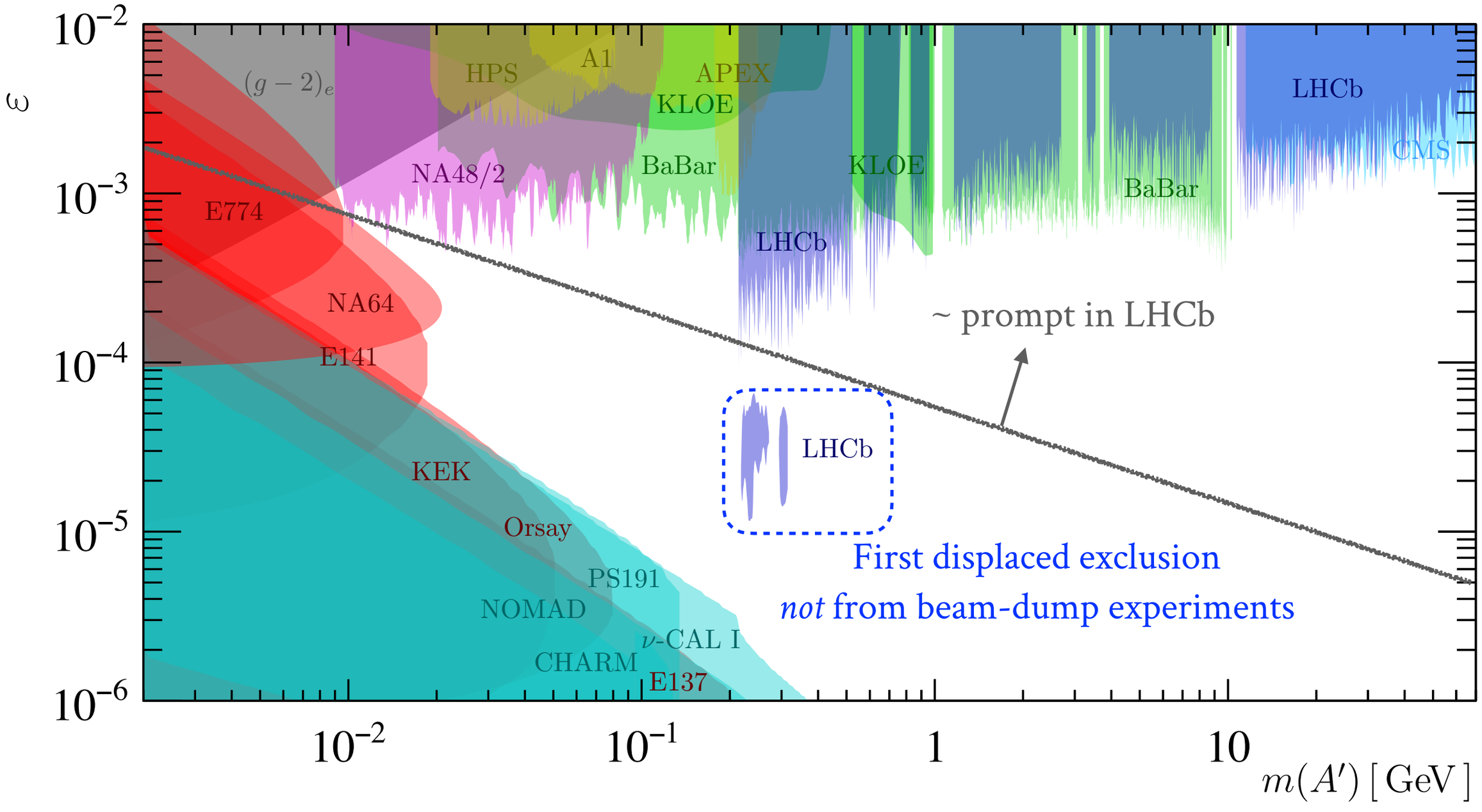


More detail in appendix

Dark photons at LHCb

PRL 124 (2020) 041801

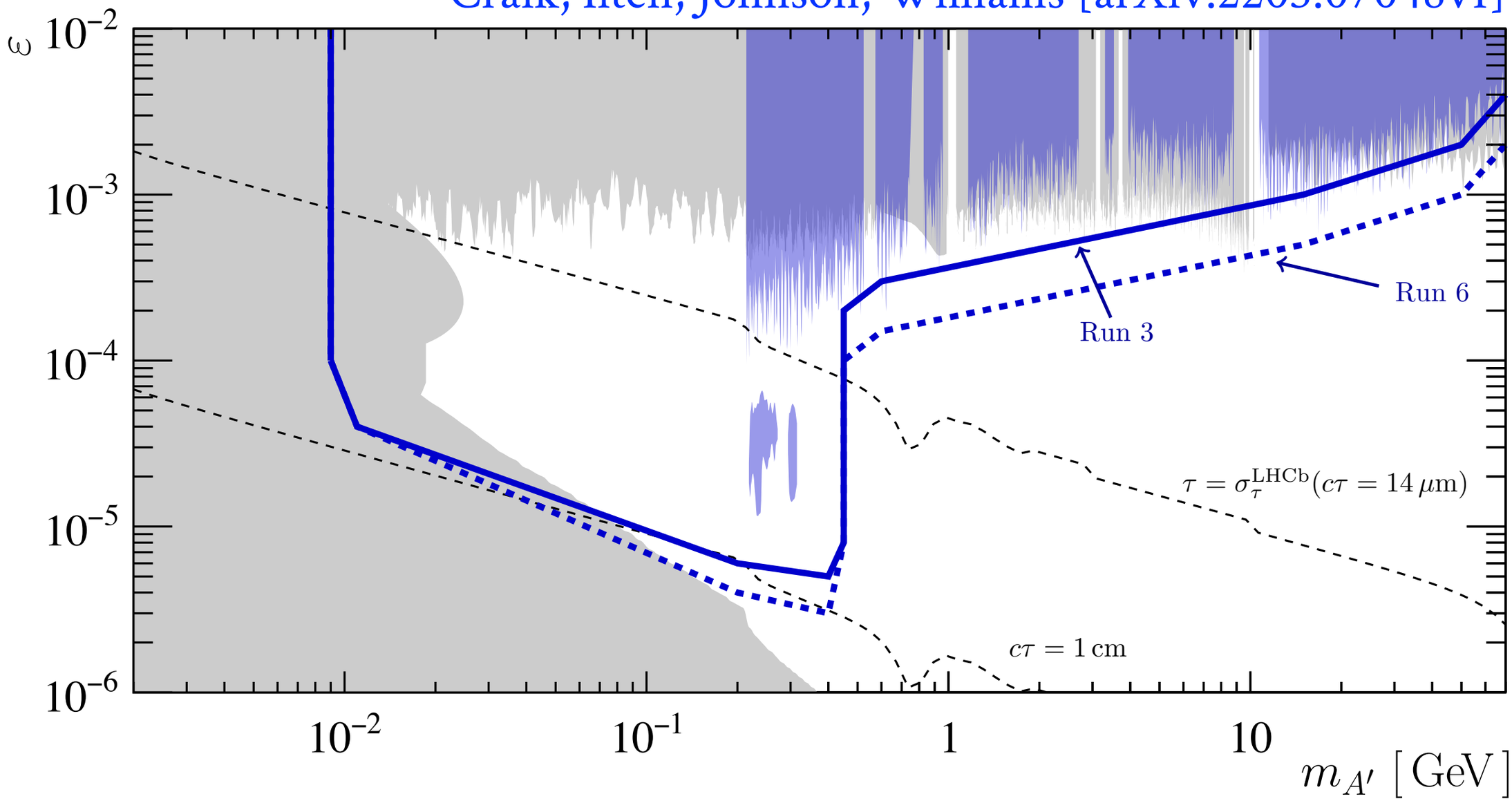
Putting it all together:*



*Update needed to include latest CMS results

The future of dark photons at LHCb

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



Non-minimal searches: inclusive $X \to \mu^+\mu^-$

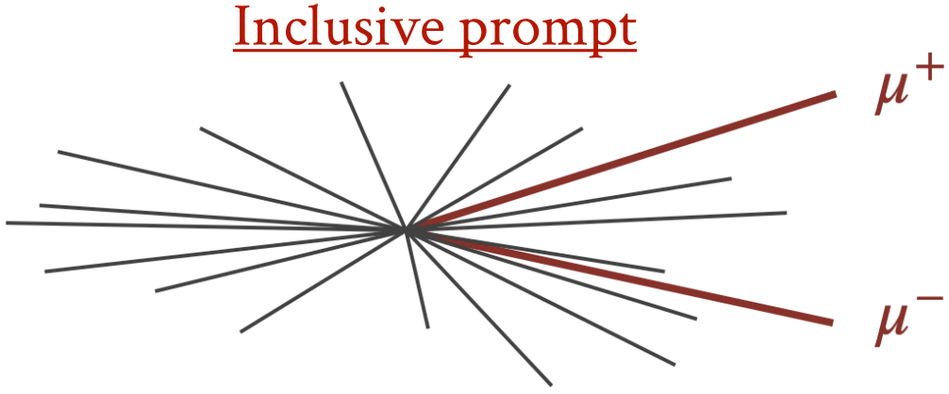
JHEP10(2020)156

Probe additional dark-sector particles using $\mu^+\mu^-$ data, dropping the assumption of a kinetic mixing with γ^*:

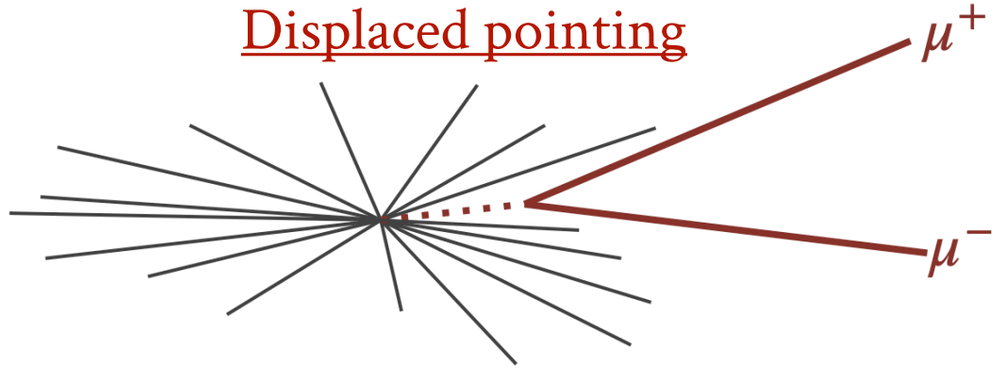
- Adopt same trigger as A' searches
- Model-independent search

Inclusive prompt

- No isolation requirements
- Non-zero width considered

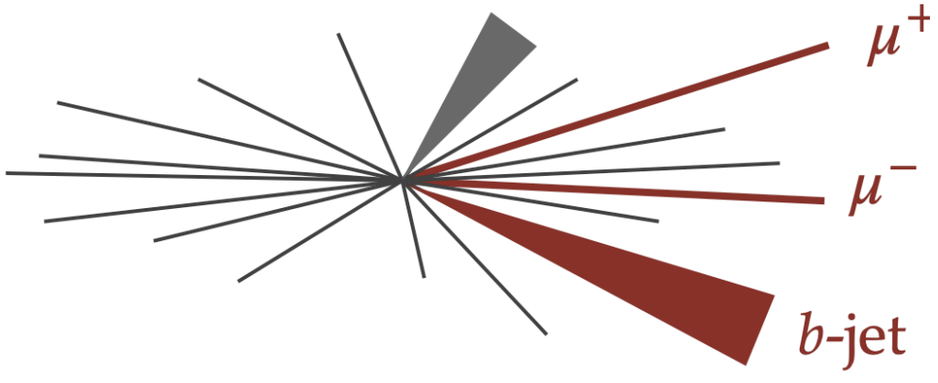


Displaced pointing

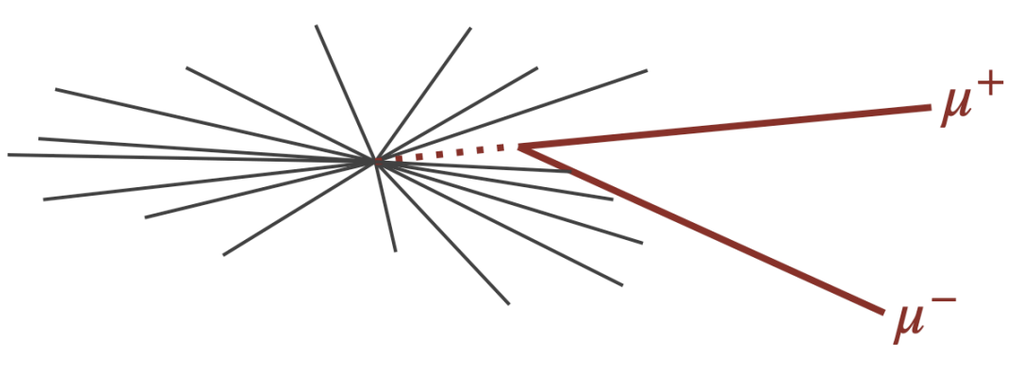


Prompt + b jet

- Non-zero width considered



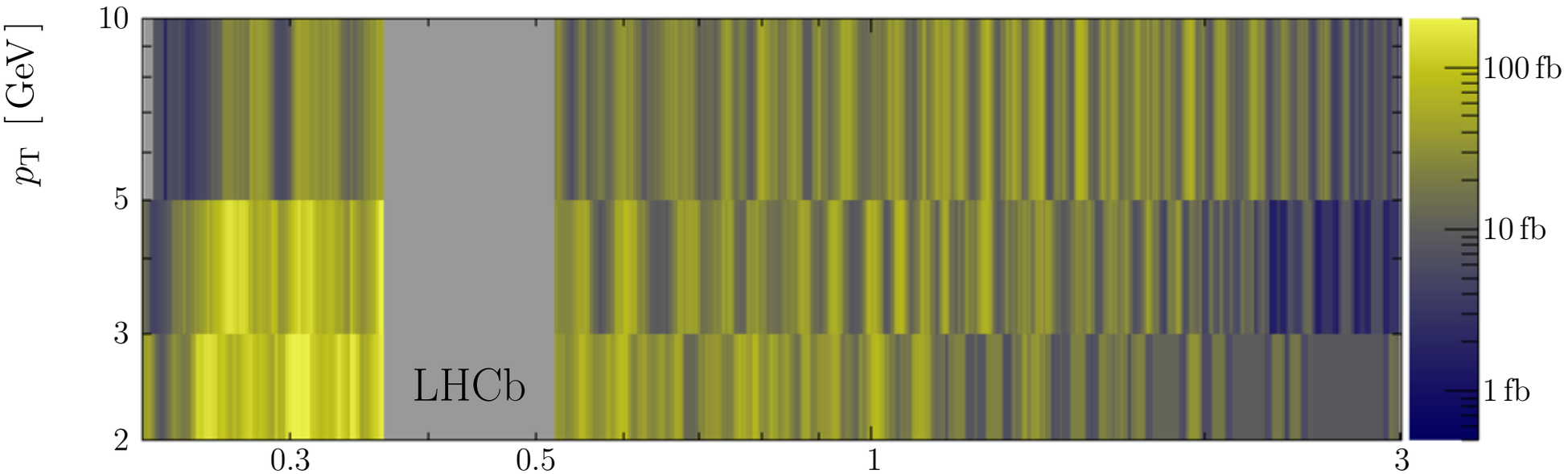
Displaced non-pointing



Non-minimal searches: inclusive $X \to \mu^+\mu^-$

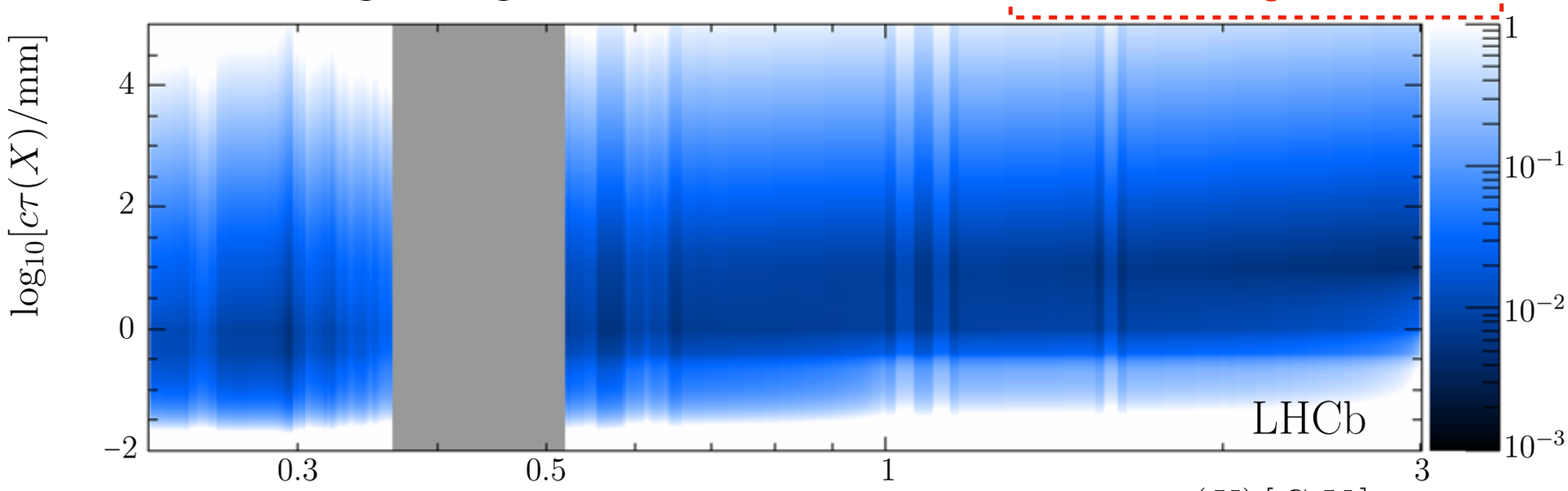
JHEP10(2020)156

- Upper limits at 90% CL on $\sigma(X \to \mu^+\mu^-)$ for the inclusive displaced search



- Upper limits at 90 % CL on $\gamma - Z_{HV}$ kinetic mixing for Hidden Valley (HV) model resulting in light hidden hadrons

World-leading constraints



LHCb is a *general-purpose* detector at the LHC

LHCb Run 3 → significant increase in discovery potential:

a) 5 × increase in *pp* collision rate

b) Fully software trigger

Appendix

Dark photons at LHCb

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

Analysis strategy:

Normalize to off-shell photon → just need to discriminate against non-γ^* background

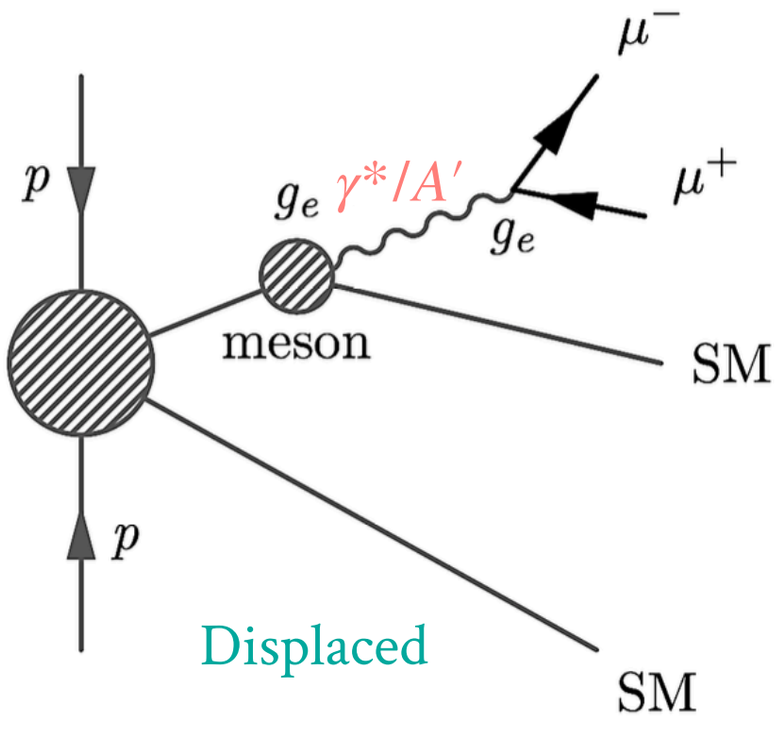
$$n_{\rm ex}^{A'}[m(A'),\varepsilon^2] = \varepsilon^2 \left[\frac{n_{\rm ob}^{\gamma^*}[m(A')]}{2\Delta m}\right] \mathcal{F}[m(A')] \epsilon_{\gamma^*}^{A'}[m(A'),\tau(A')],$$

Phase space

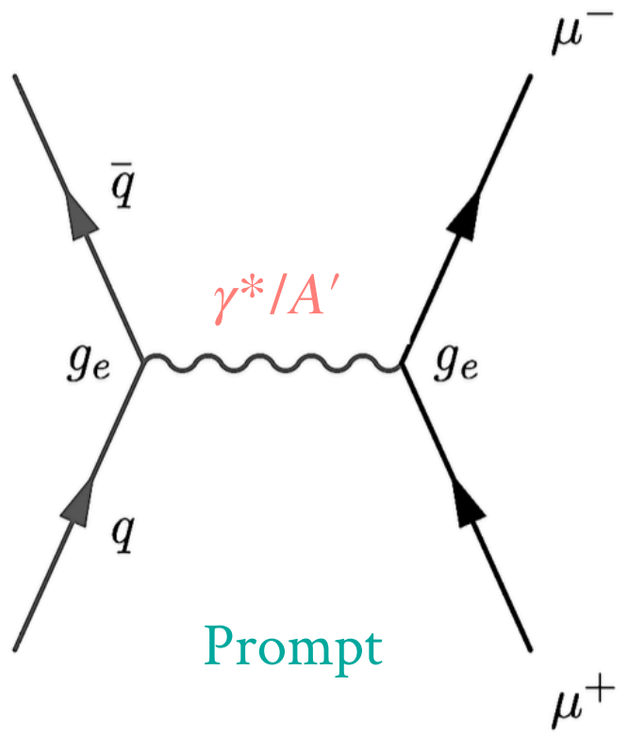
Off-shell photon

A'/γ^* efficiency ratio

1 for prompt



Displaced



Prompt

Prompt dark photons at LHCb

PRL 120 (2018) 6, 061801

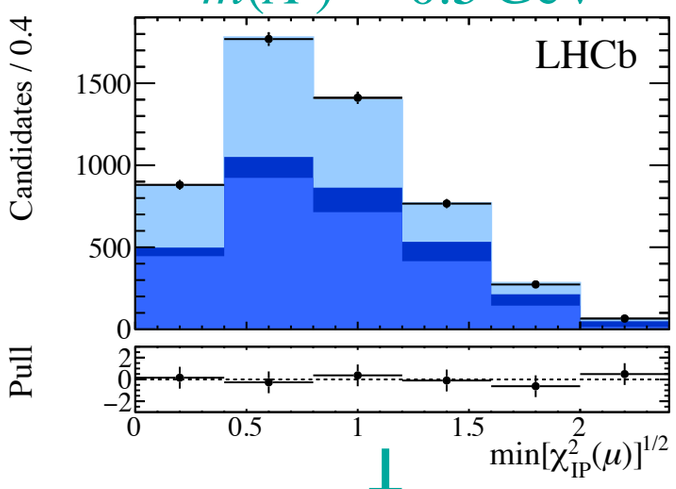
prompt $\mu^+\mu^-$ from data at $m(J/\psi)$ and $m(Z)$

$\mu_Q\mu_Q$ from simulation

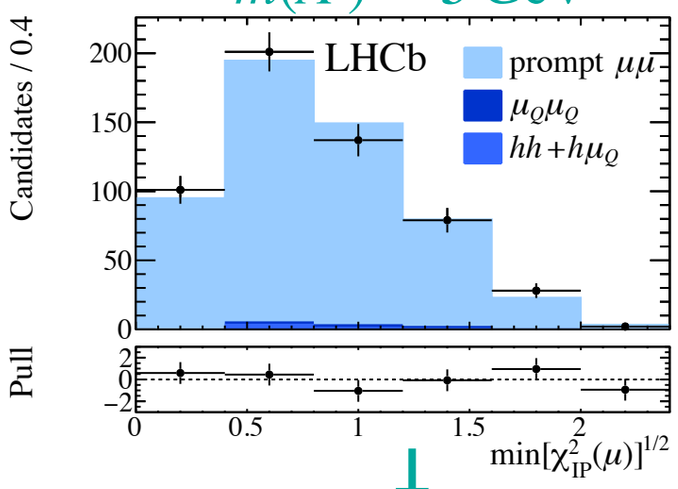
$hh + h\mu_Q$ from same-sign $\mu^\pm\mu^\pm$ corrected

Fits executed @ in steps of $\sigma[m(\mu^+\mu^-)]/2$

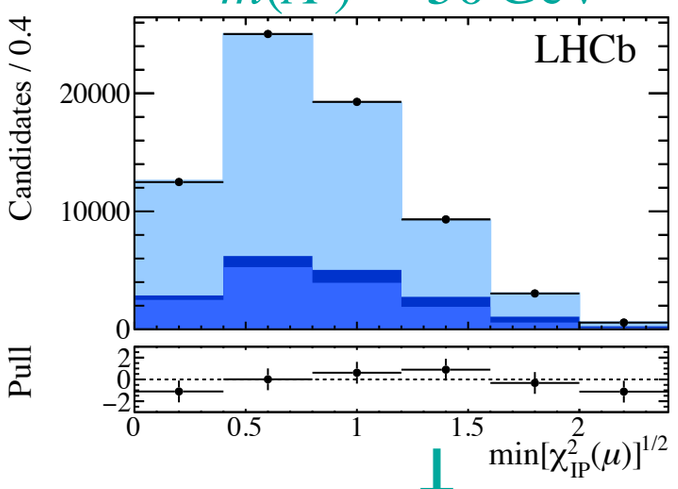
$m(A') = 0.5$ GeV

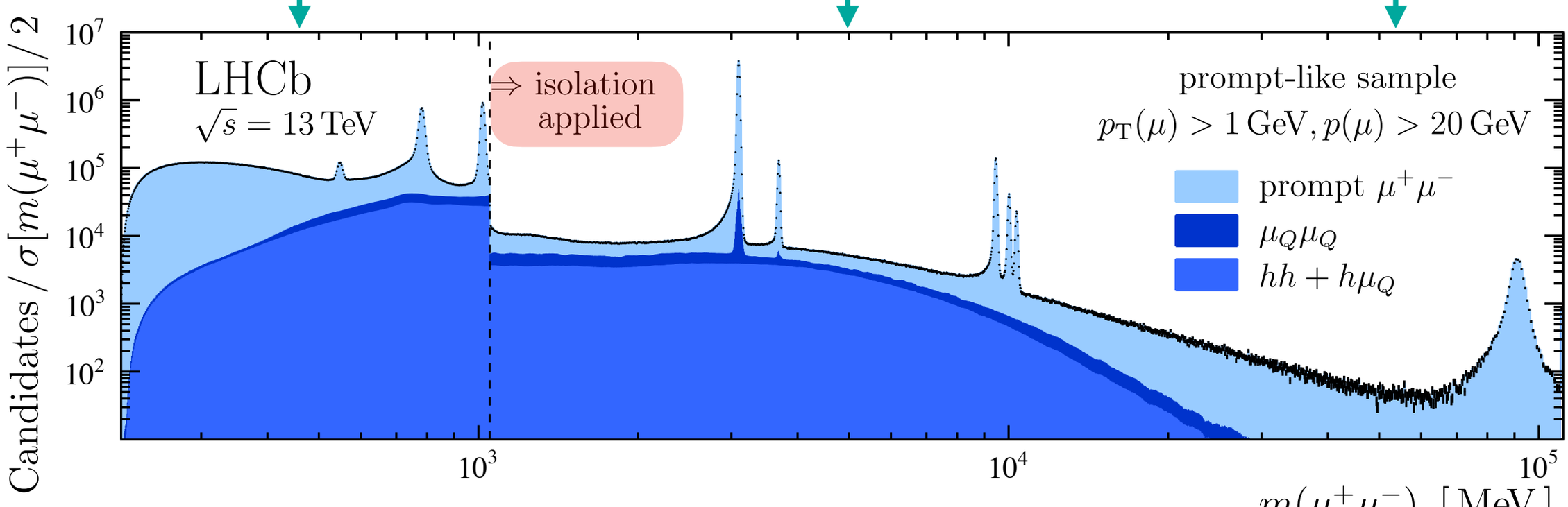


$m(A') = 5$ GeV



$m(A') = 50$ GeV

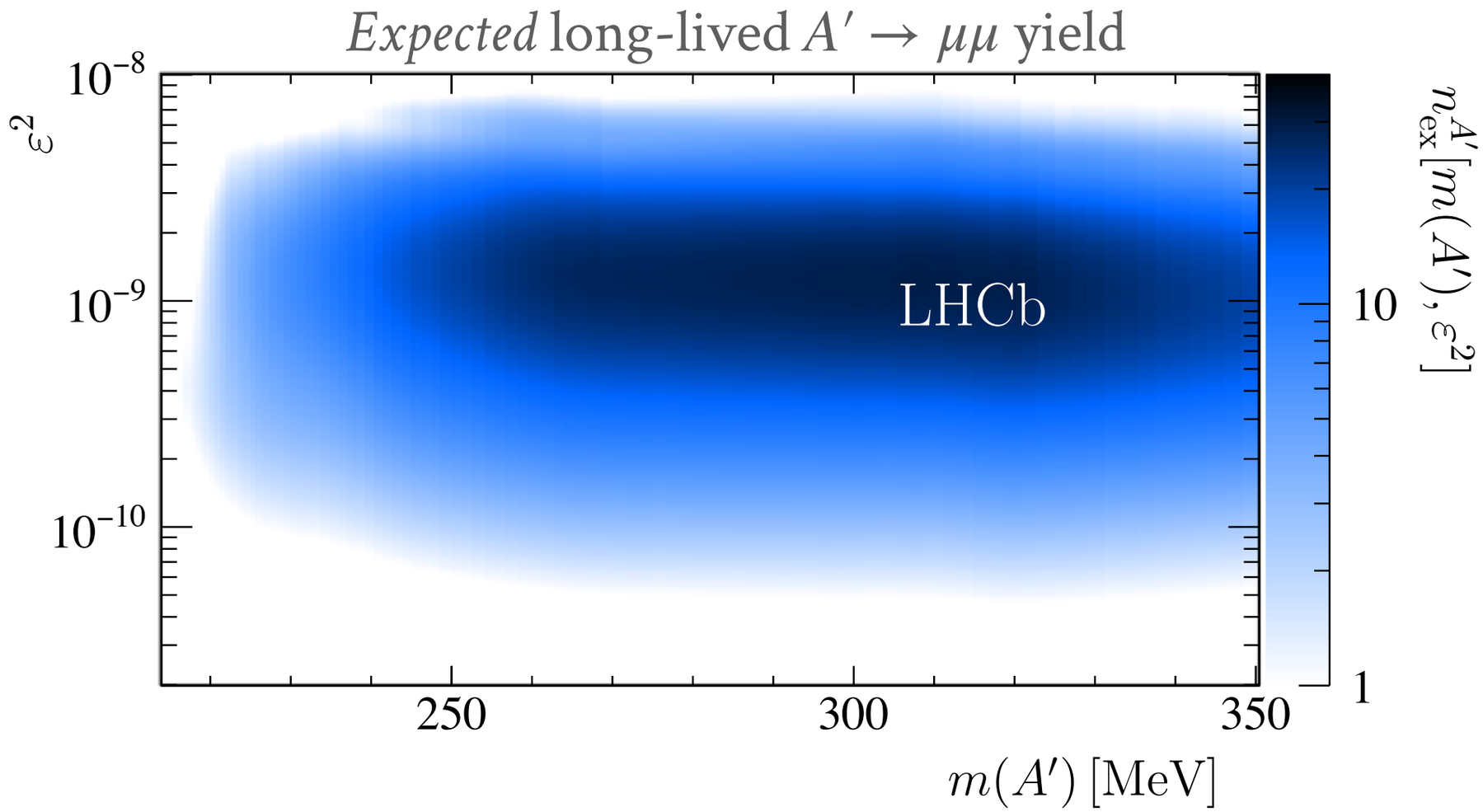




Displaced dark photons at LHCb

PRL 120 (2018) 6, 061801

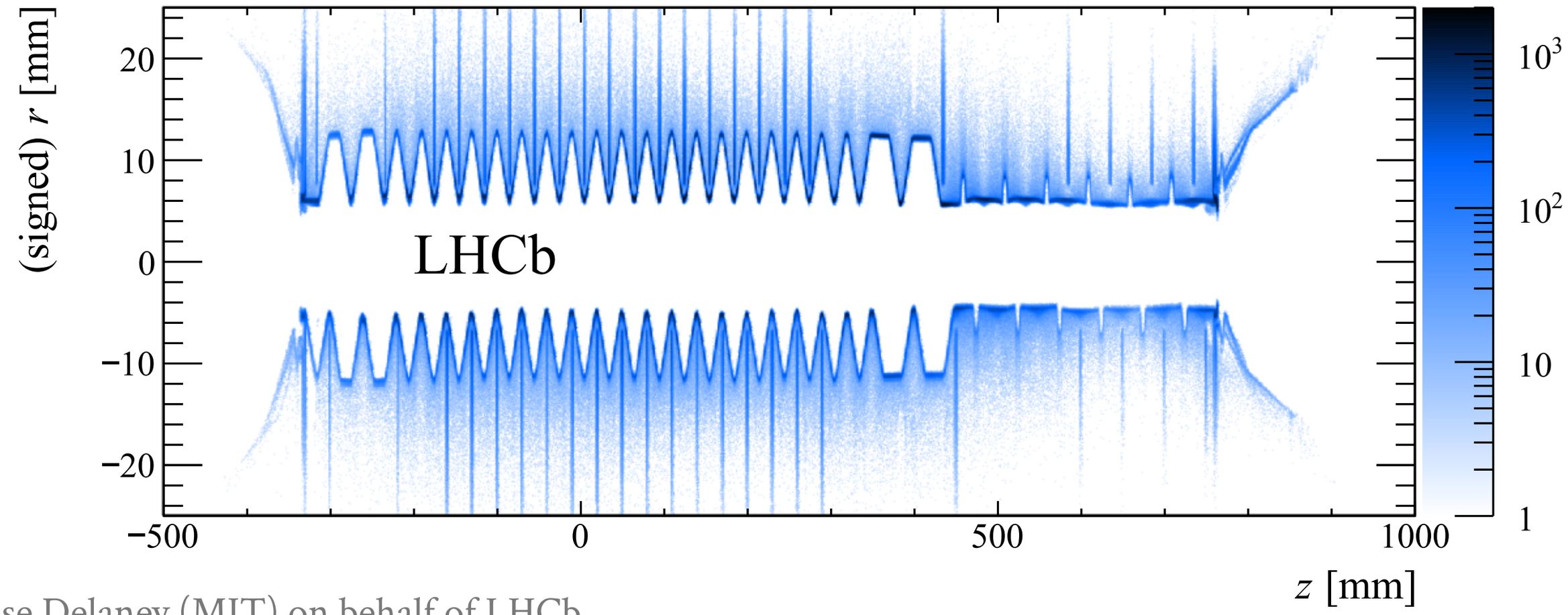
- Only region $m(A') < 350$ MeV is sensitive
- Comparatively looser $p_T(\mu)$ requirements
- Main background from γ conversion in the VErtex LOcator



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



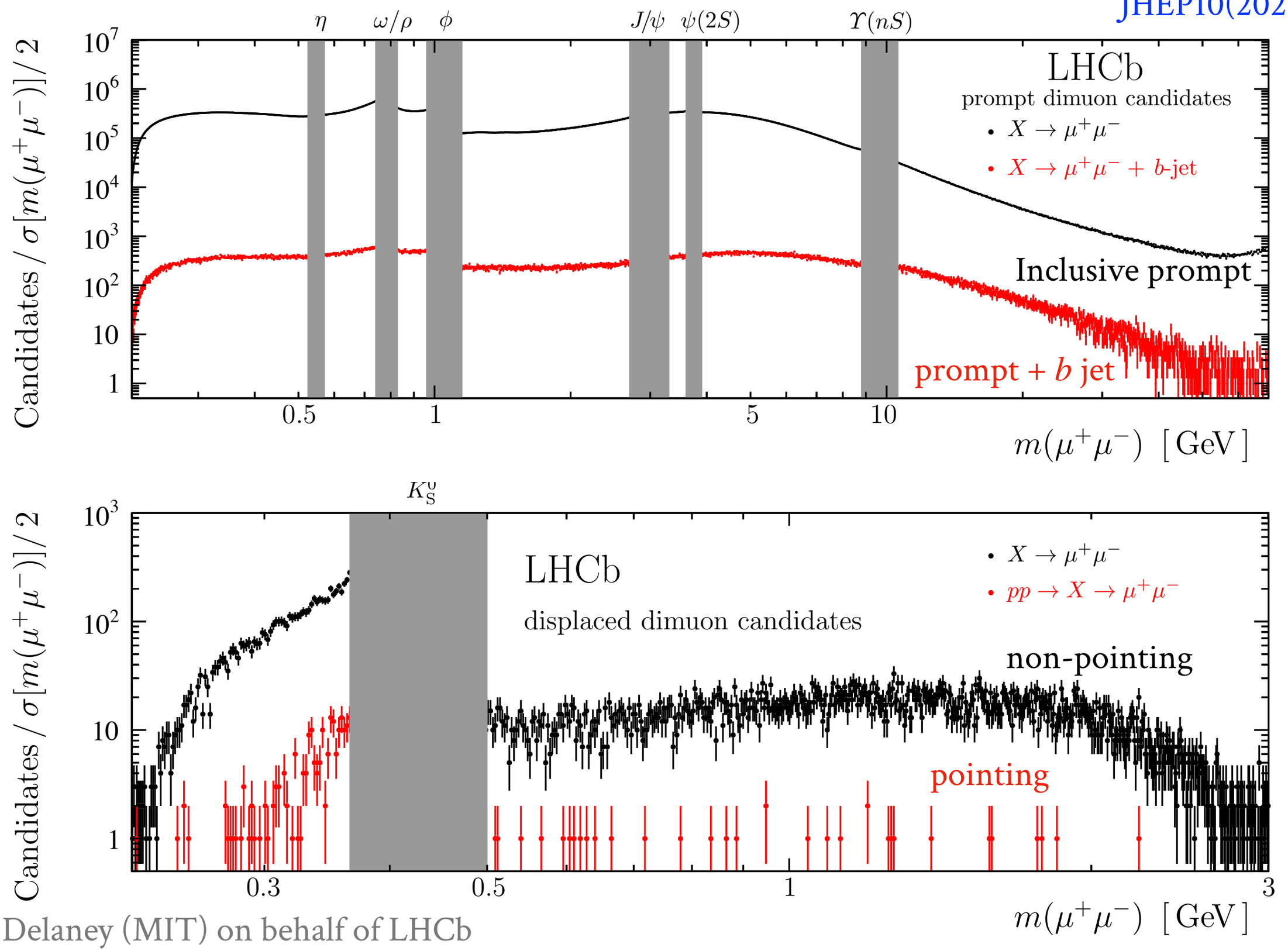
$X \to \mu^+\mu^-$: fiducial region

JHEP10(2020)156

All searches	$p_{\mathrm{T}}(\mu) > 0.5\,\mathrm{GeV}$ $10 < p(\mu) < 1000\,\mathrm{GeV}$ $2 < \eta(\mu) < 4.5$ $\sqrt{p_{\mathrm{T}}(\mu^+) p_{\mathrm{T}}(\mu^-)} > 1\,\mathrm{GeV}$ $5 \leq n_{\mathrm{charged}}(2 < \eta < 4.5, p > 5\,\mathrm{GeV}) < 100$ (from same PV as X)
Prompt $X \to \mu^+\mu^-$ decays	$1 < p_{\mathrm{T}}(X) < 50\,\mathrm{GeV}$ X decay time $< 0.1\,\mathrm{ps}$ $\alpha(\mu^+\mu^-) > 1\,\mathrm{mrad}$ $20 < p_{\mathrm{T}}(b\text{-jet}) < 100\,\mathrm{GeV},\ 2.2 < \eta(b\text{-jet}) < 4.2$ ($X + b$ only)
Displaced $X \to \mu^+\mu^-$ decays	$2 < p_{\mathrm{T}}(X) < 10\,\mathrm{GeV}$ $2 < \eta(X) < 4.5$ $\alpha(\mu^+\mu^-) > 3\,\mathrm{mrad}$ $12 < \rho_{\mathrm{T}}(X) < 30\,\mathrm{mm}$ X produced in pp collision (promptly produced X only)

Non-minimal searches: inclusive $X \to \mu^+\mu^-$

JHEP10(2020)156



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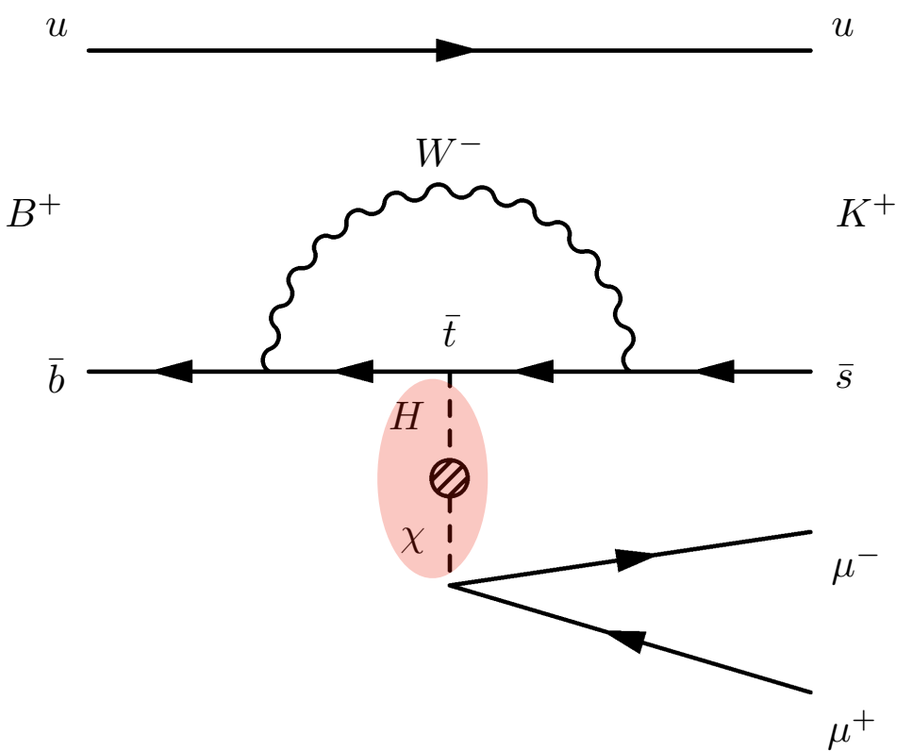
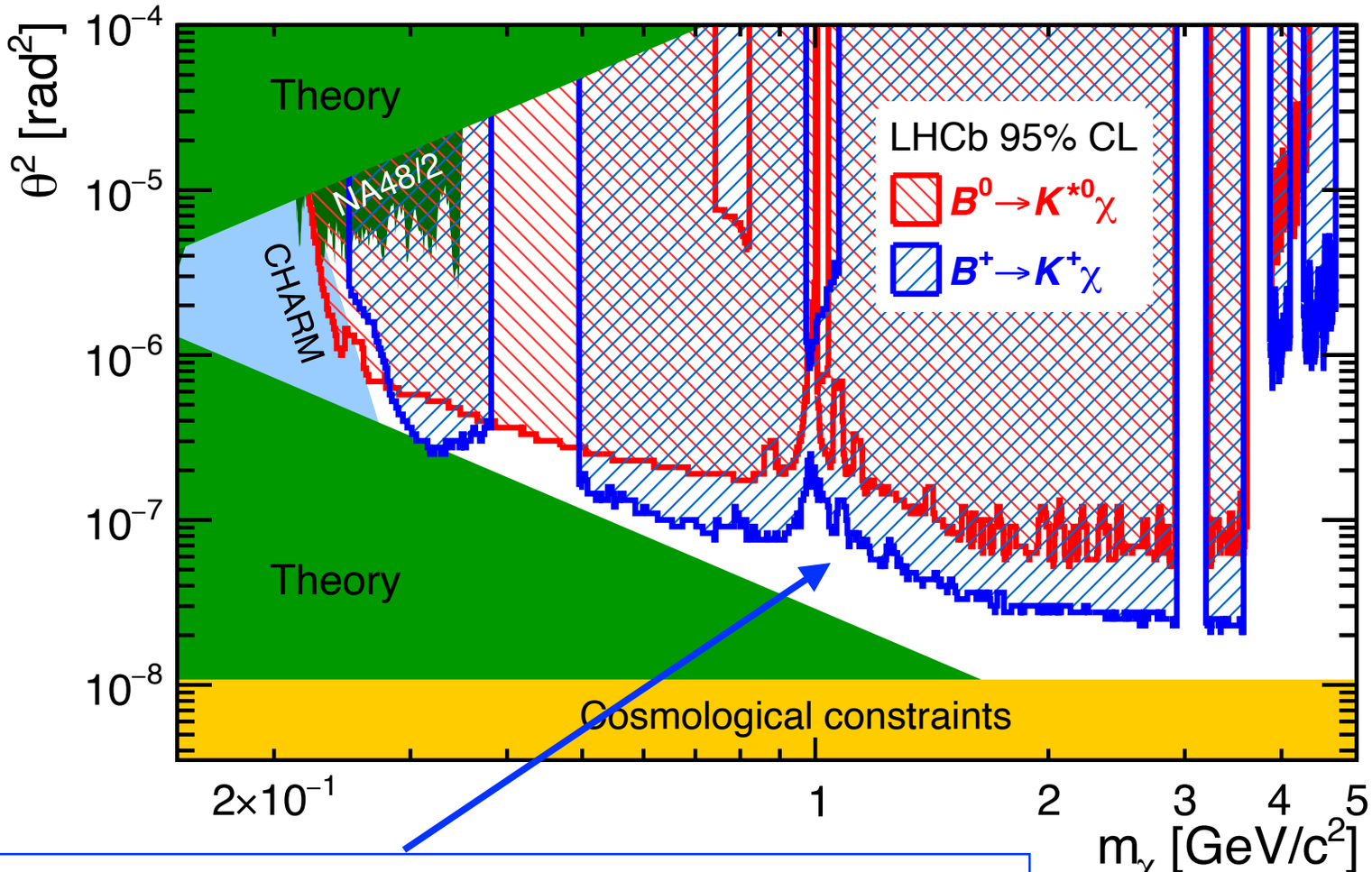
Higgs portal at LHCb

PRL 115 161802 (2015), PRD 95, 071101(R) (2017)

- Exploit ability of LHCb of studying $b \to s$ penguin decays to search for hidden-sector bosons, χ using Run 1 data (3 fb^{-1})

- Allow detached $\mu\mu$ within VELO → bump hunt for long-lived χ candidates in $B \to K^{(*)}\chi,\ \chi \to \mu^+\mu^-$





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

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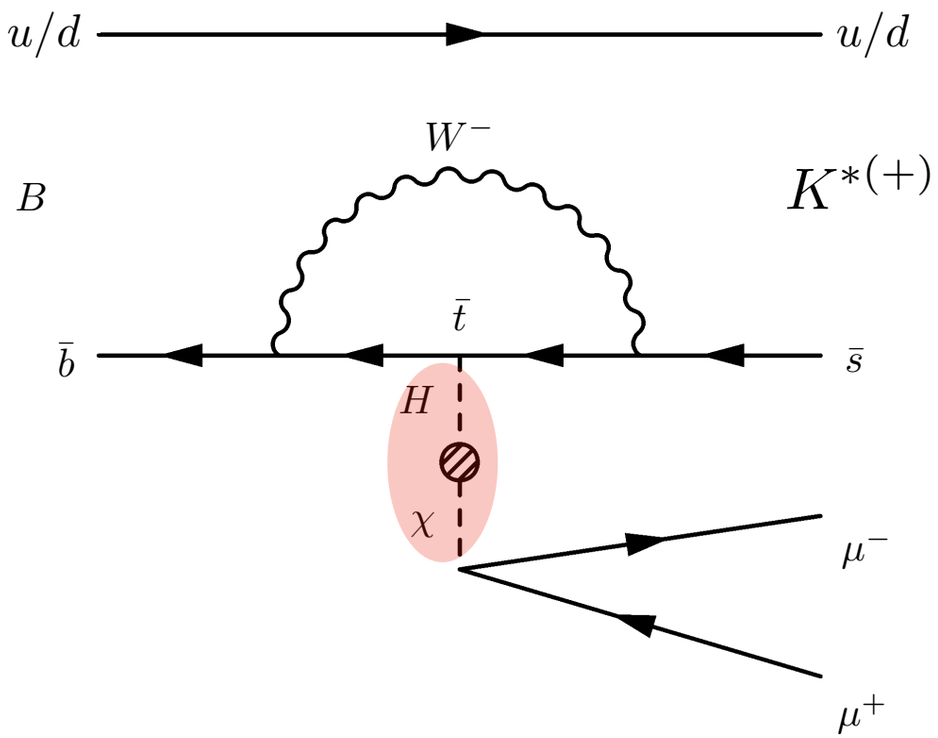
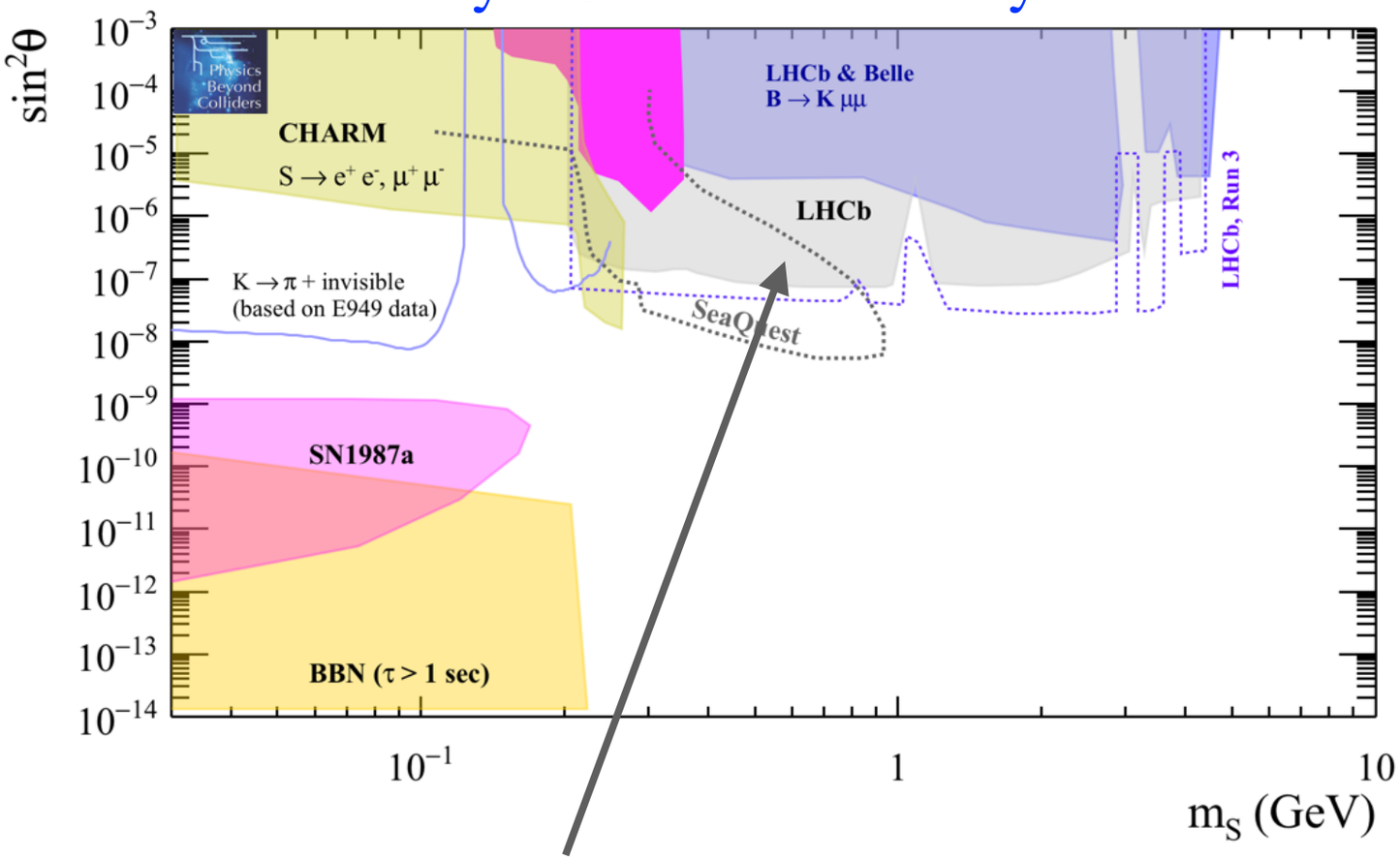


J. Phys. G: Nucl. Part. Phys. 47 010501



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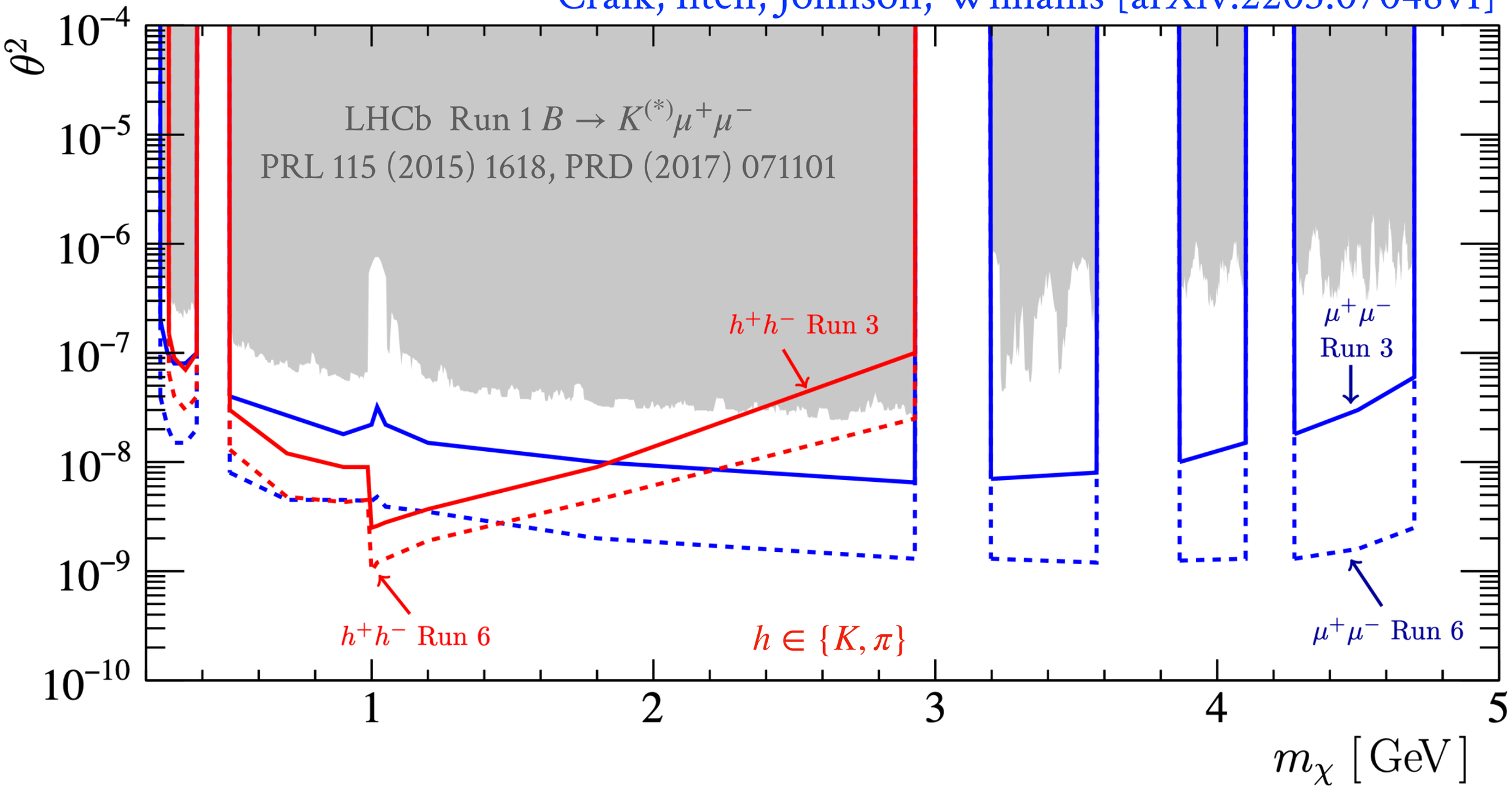
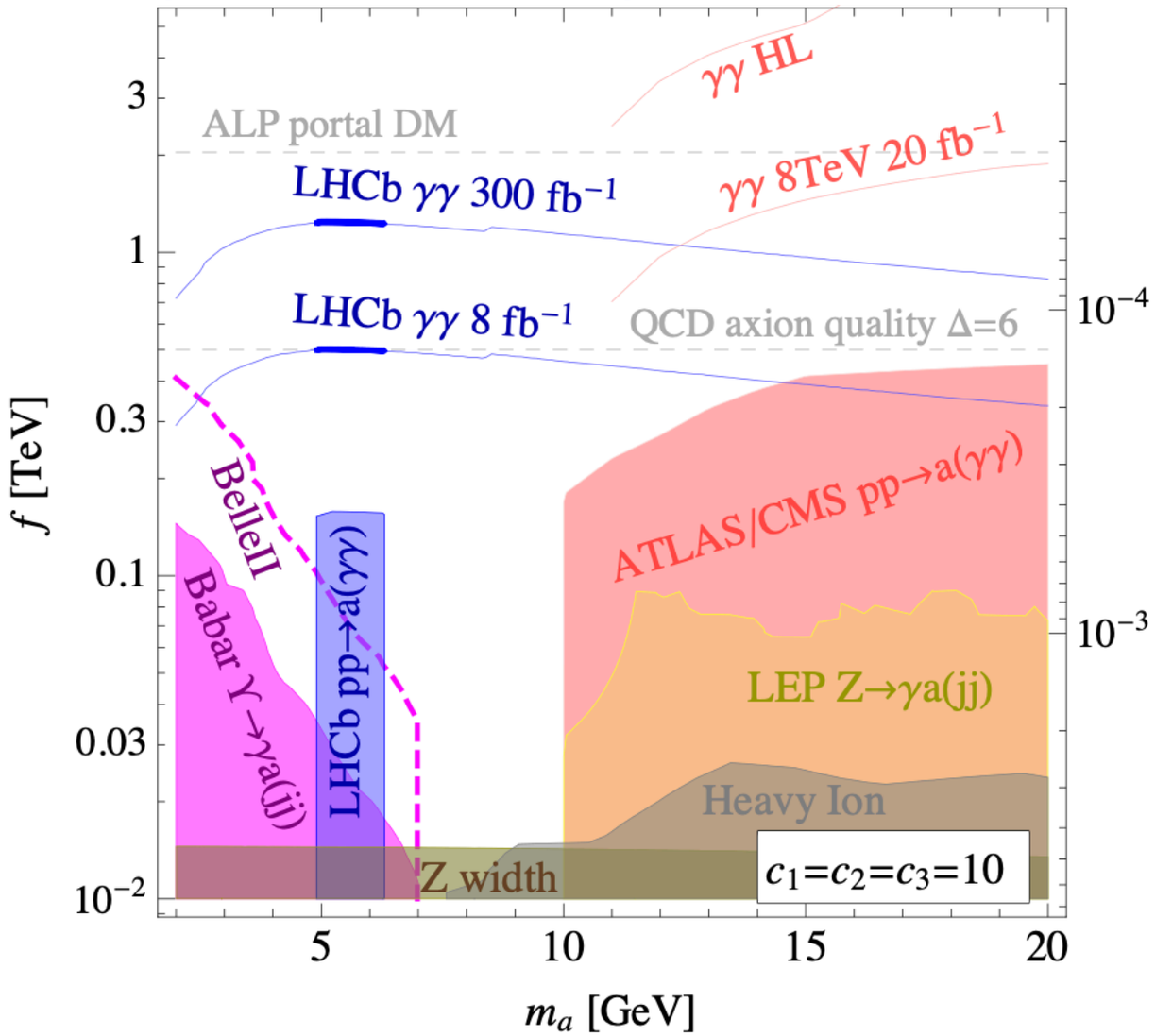
Future sensitivity to the Higgs portal at LHCb

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

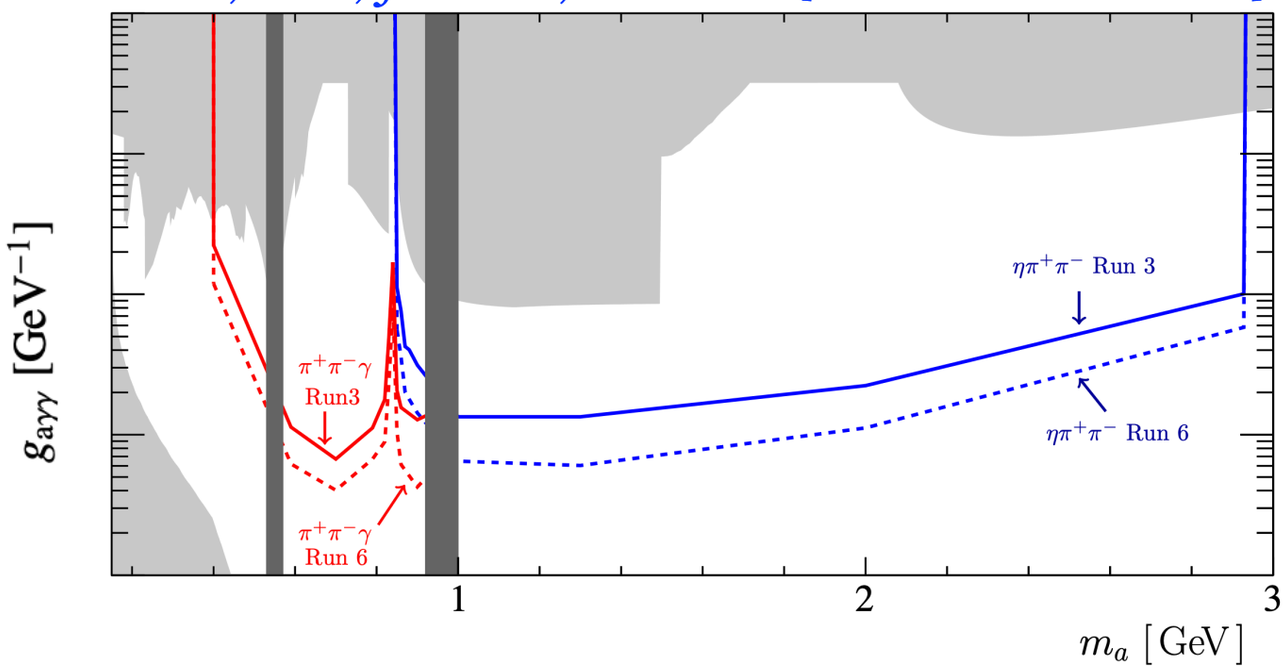


Planned searches for ALPs

Cid Vidal, Mariotti, Redigolo, Sala, Tobioka
[JHEP 01 (2019) 113, JHEP 06 (2020) 141]



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



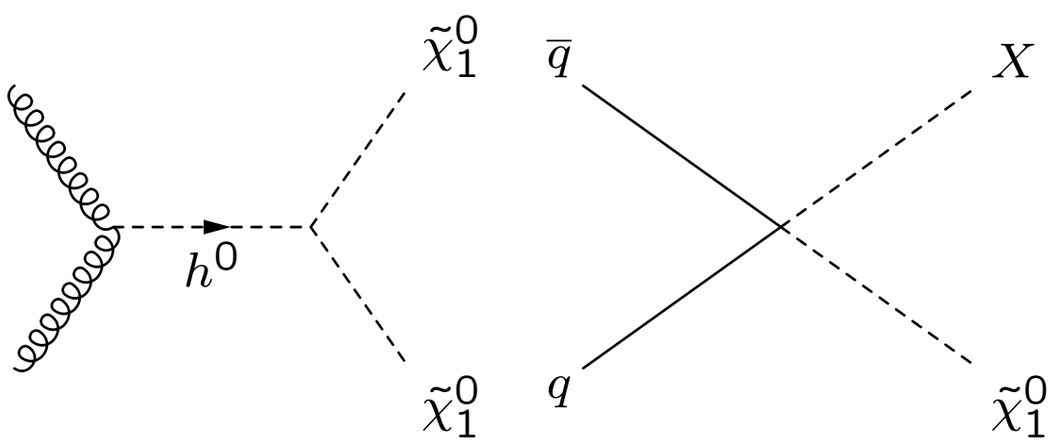
Predicted sensitivity to ALP-gluon coupling via

$$B \to K^{(*)} a(\to \pi\pi\{\eta, \gamma\})$$

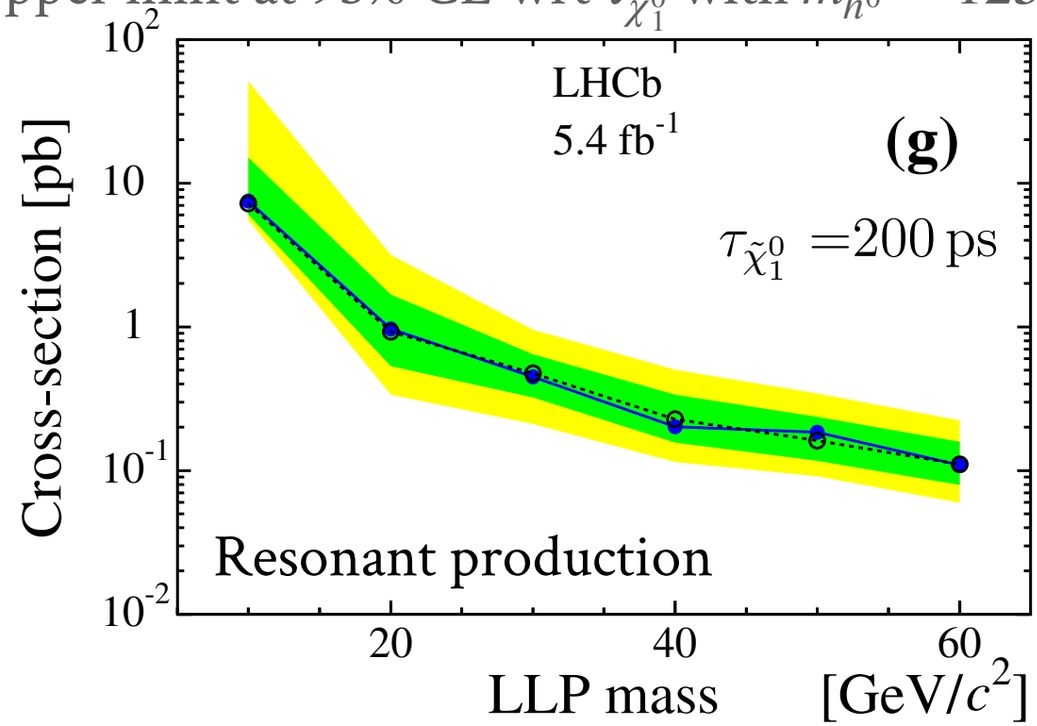
Search for massive LLP decaying semileptonically at $s = \sqrt{13}$ TeV

EPJC 82 (2022) 4, 373

- Target massive long-lived particles (LLP) $\tilde{\chi}_1^0$ with a measurable flight distance and decaying via $\tilde{\chi}_0^1 \to \mu q_i q_j$
- LLP lifetime range between 5 ps (above B lifetime) and 200 ps (within Vertex Locator)



Upper limit at 95% CL wrt $\tau_{\tilde{\chi}_1^0}$ with $m_{h^0} = 125$ GeV



Overcoming the LHCb acceptance limit with CODEX-b

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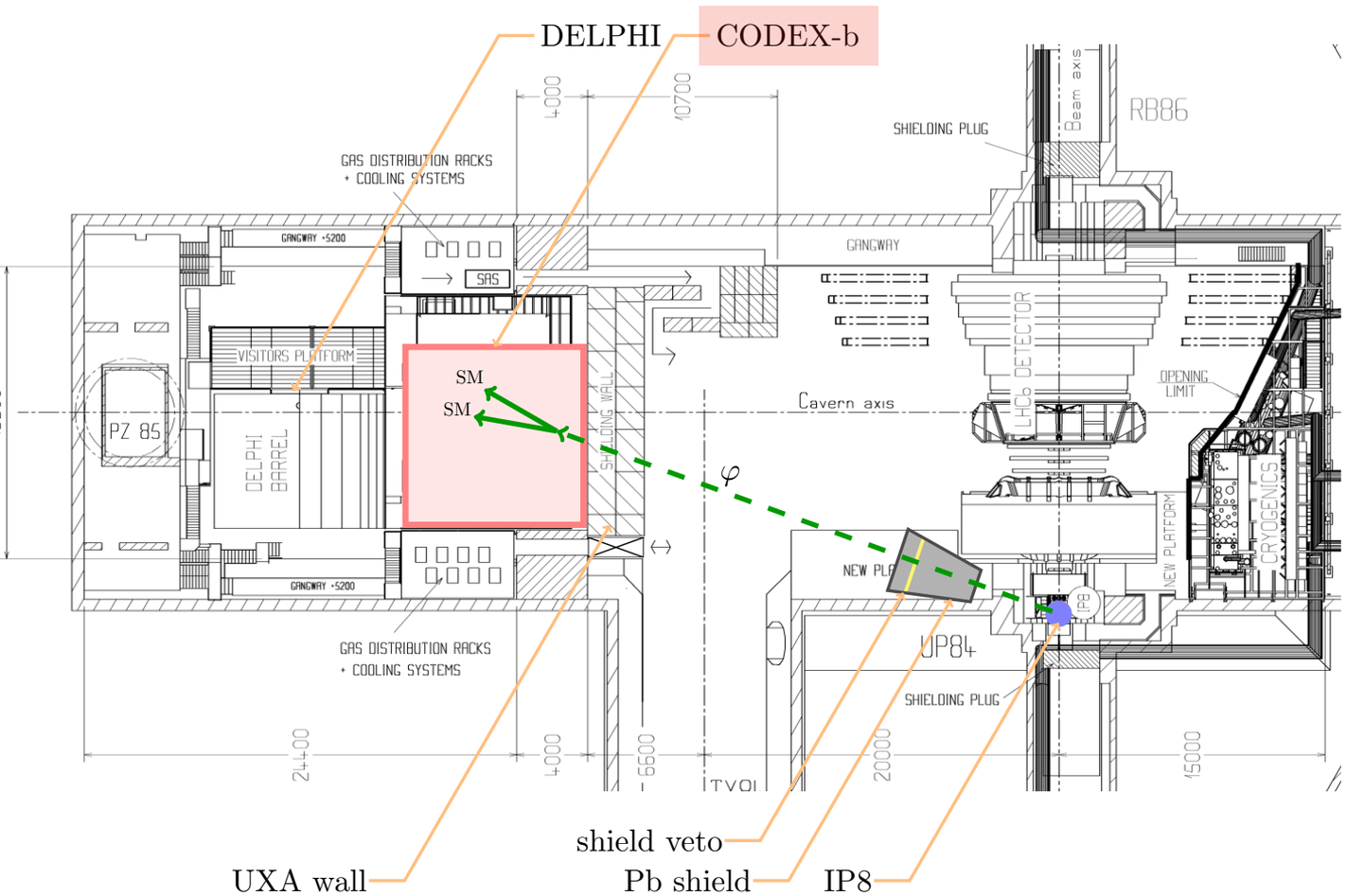

arXiv:1903.04497