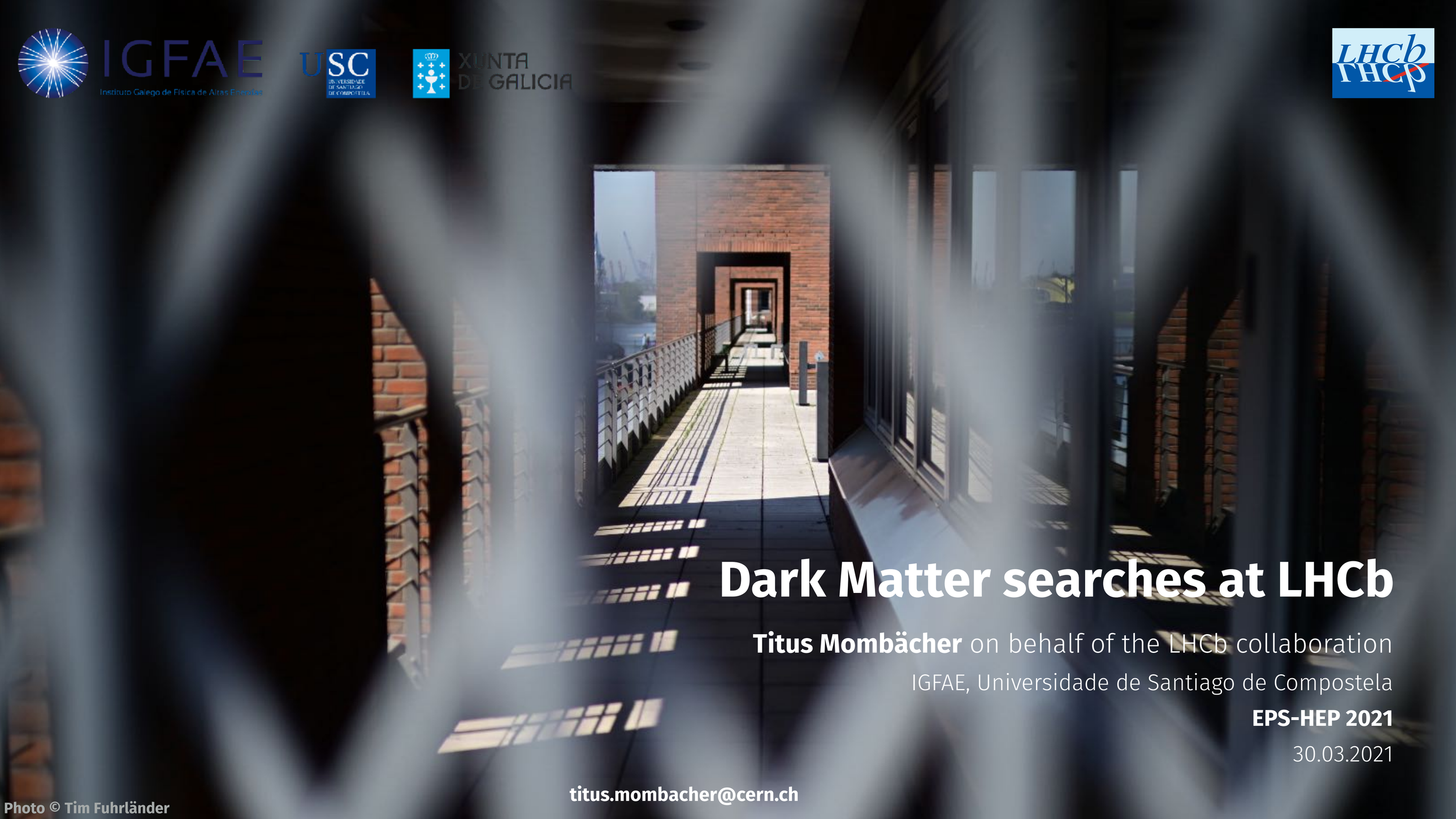

Dark Matter searches at LHCb

Titus Mombächer on behalf of the LHCb collaboration

IGFAE, Universidade de Santiago de Compostela

EPS-HEP 2021

30.03.2021

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Photo © Tim Fuhrländer

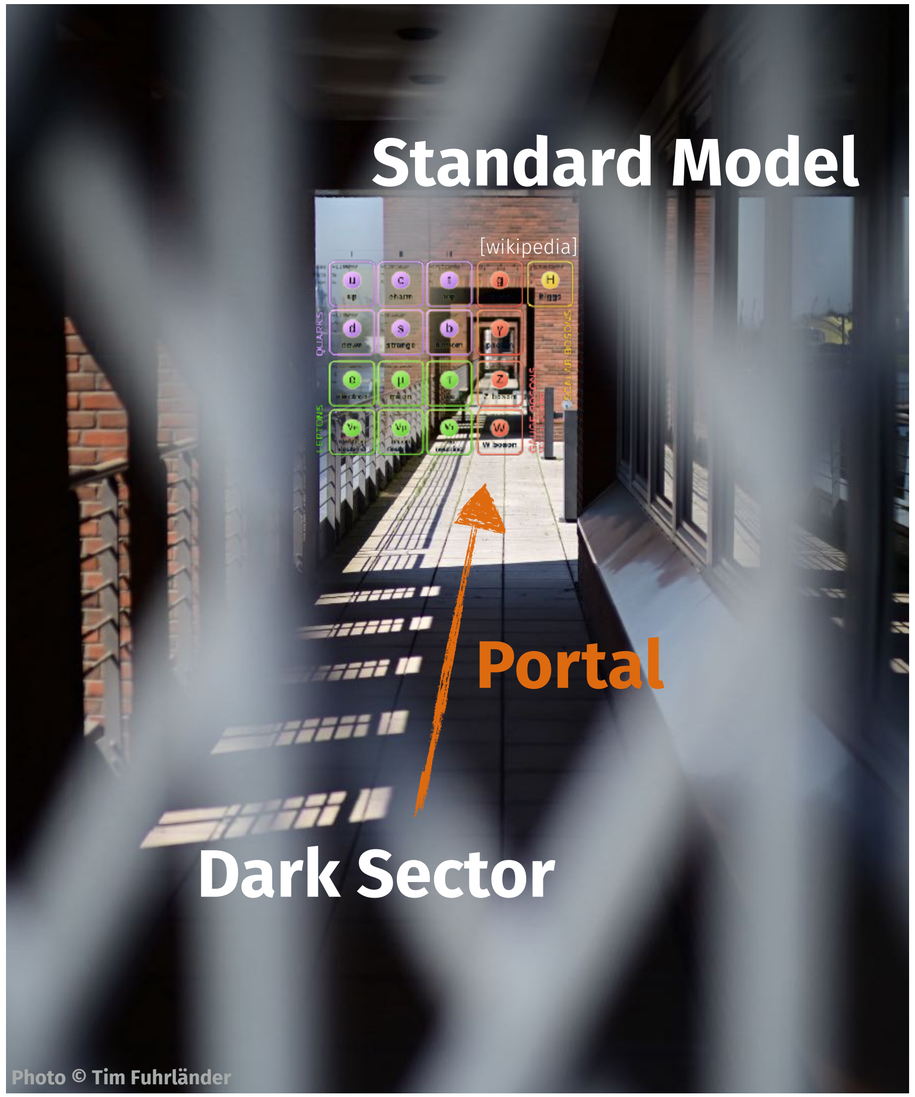
Dark Matter (DM) signatures at the LHC

- There are many models for dark matter

  → focus on signatures

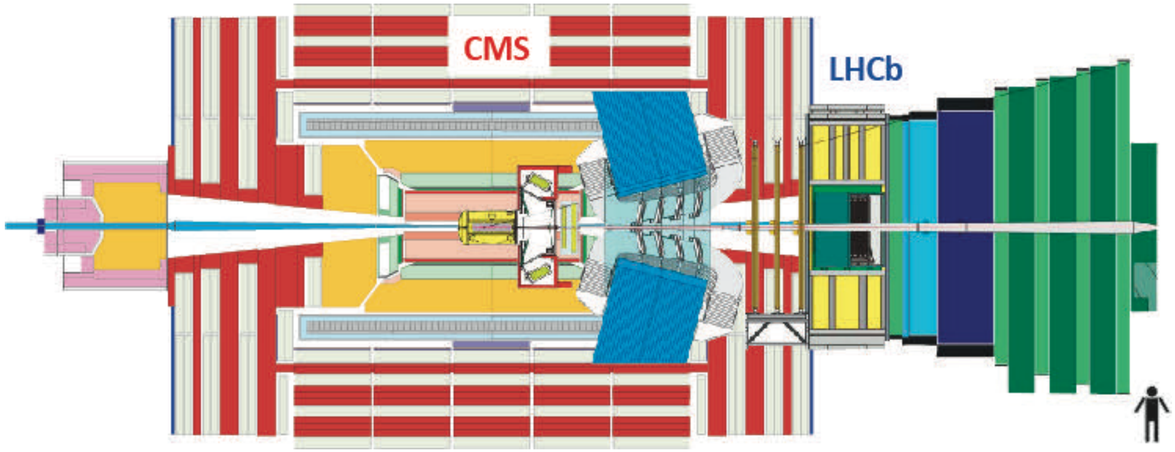
- Possible signatures:
  - Utilising portals that mix with the Standard Model → weakly coupled to SM
  - DM production → missing energy searches
  - Displaced signatures (long lifetimes), often evade current bounds → even for light masses

See also talk by Andrii Usachov, Tuesday NP session!

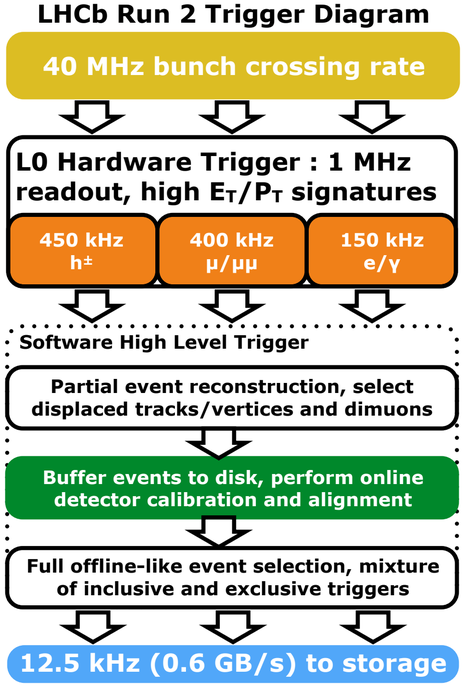


Why search for Dark Matter at LHCb?

[LHCb-PHO-GEN-2012-001]



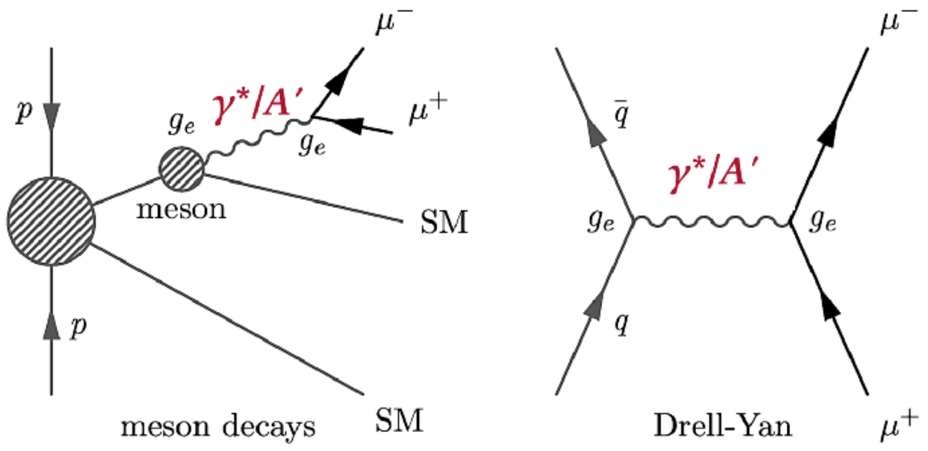
- Unique acceptance $2 < \eta < 5$
- Complementary to ATLAS and CMS
- Excellent vertex and mass resolution
- Soft trigger thresholds allow access to low masses
  - $p_{\mathrm{T}}(\mu) > 1.5\,\mathrm{GeV}$, $E_{\mathrm{T}}(e,h) > 3\,\mathrm{GeV}$
  - Can exploit Turbo trigger strategy:
    - Offline-quality reconstruction at trigger level → triggers tailored to analysis
    - Only save part of the event → broader physics range possible
    - Especially promising for the next data-taking period (Run 3)



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

Searches for $A' \to \mu^+\mu^-$

- Massive Dark Photon connects a Dark Sector to the SM by kinetic mixing with off-shell photon γ^*
- Kinetic mixing strength $\varepsilon^2 \in [10^{-12}, 10^{-4}]$ [Alexander et al, arXiv:1608.08632]
- Prompt and displaced searches
- Can normalise the expected yield to off-shell photon
  - Need to separate non-γ^* background
  - Can be fully data-driven (for prompt search)
- Analyse fully online selected (Turbo-trigger) data
  - Only partial event info saved → can cover larger physics range



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

Off-shell photon

Phase space

Efficiency ratio A'/γ^*

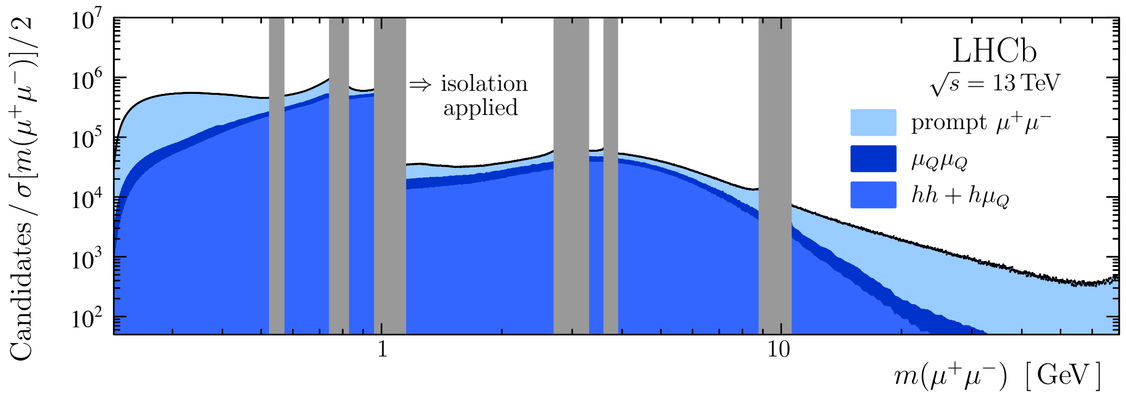
$\epsilon = 1$ **for prompt decays**

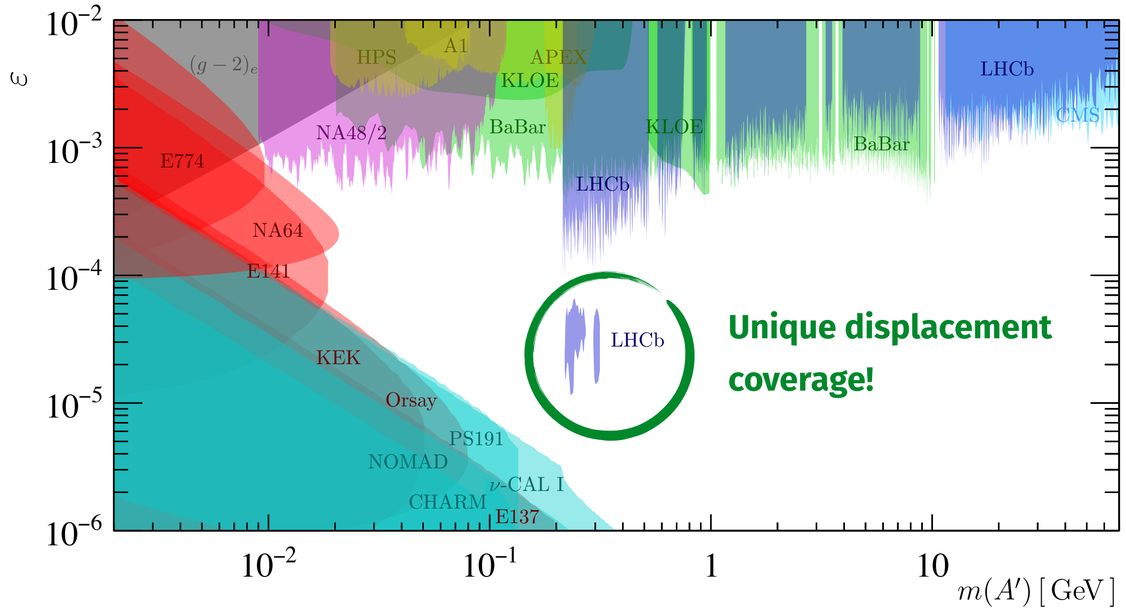
PRL 120 (2018) 061801
PRL 124 (2020) 041801

Searches for $A' \to \mu^+\mu^-$

- Bump hunt over large backgrounds
  - Scan the spectrum in steps and fit for the signal
  - Remove QCD resonances
  - Anti-k_T-based isolation
- Parameter regions tested:
  - Prompt: $m(A') \in [2m(\mu),\ 70\,\mathrm{GeV}]$
  - Displaced $\mathcal{O}(1\,\mathrm{ps})$: $m(A') \in [214,\ 350]\,\mathrm{MeV}$
- Will be able to cover $m(A') < 2m(\mu)$ with $D^{*0} \to D^0 A'(e^+e^-)$ in upcoming data-taking period (Run 3)

[Ilten et al., PRD 92 (2015) 115017]





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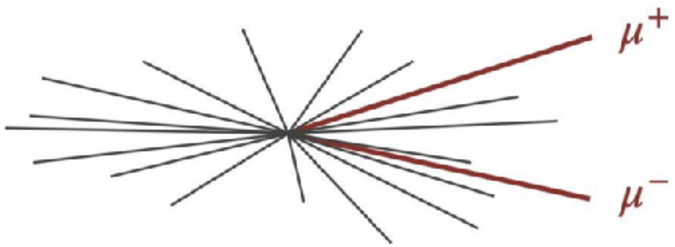
Beyond the non-minimal: inclusive $X \to \mu^+\mu^-$ search

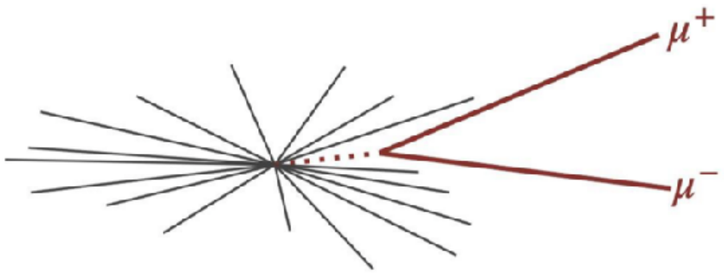
- Minimise production assumptions:
  - Drop assumption of kinetic mixing with γ^*
  - Obtain results in kinematic bins in tight fiducial regions

Inclusive prompt

- No isolation requirement
- Consider non-zero width

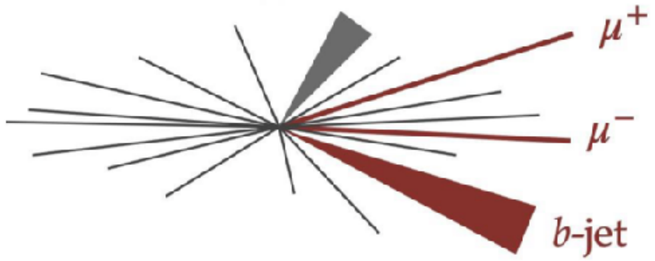


Displaced pointing

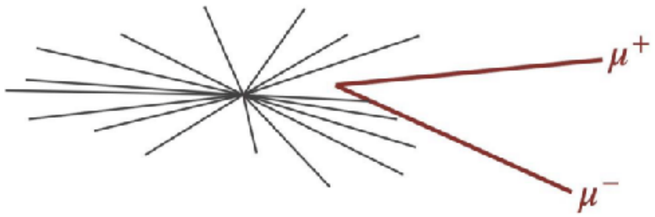


Prompt + b-jet

- Consider non-zero width

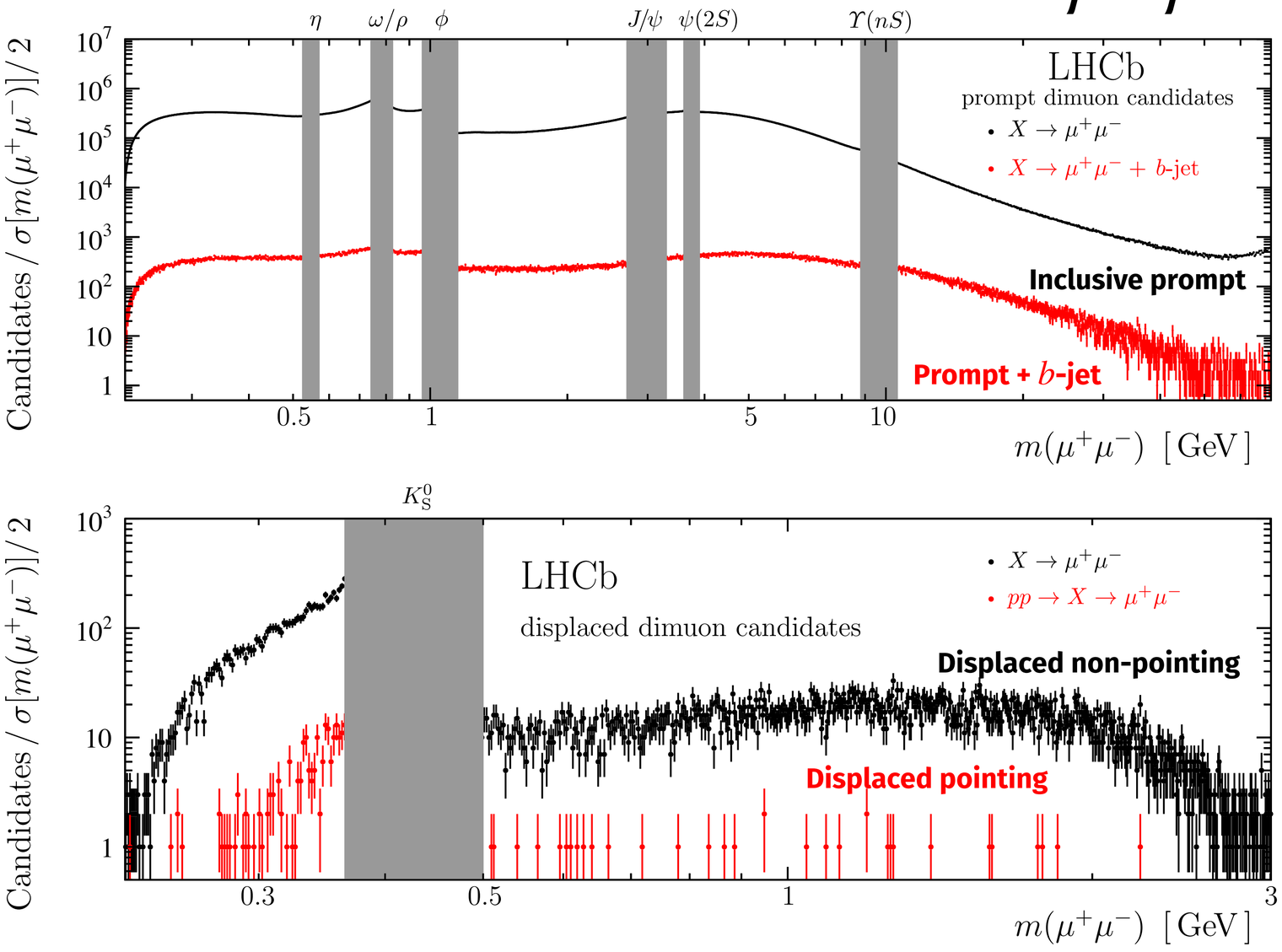


Displaced non-pointing



JHEP 10 (2020) 156

Beyond the non-minimal: inclusive $X \to \mu^+\mu^-$ search



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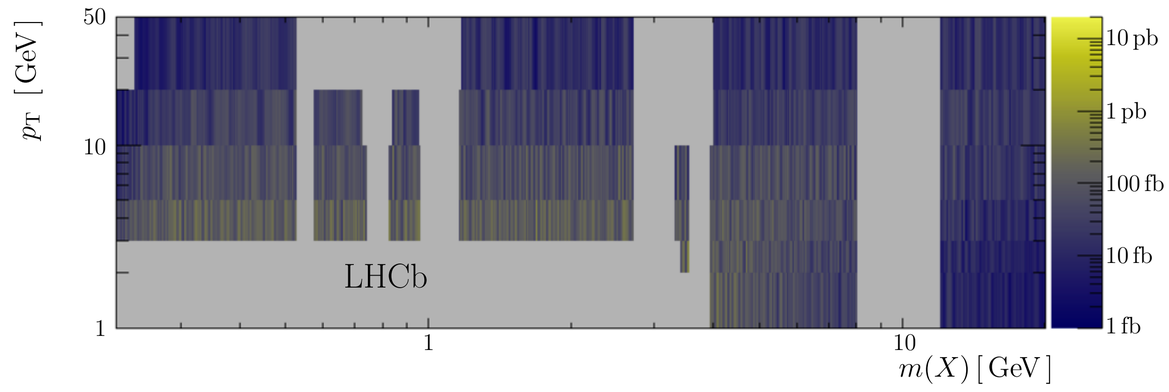
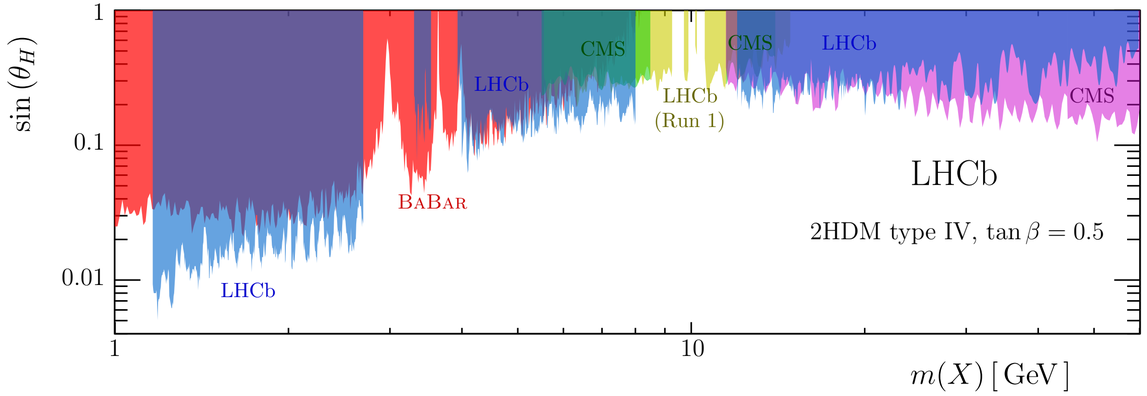
Make it your own: recastability

- **Can recast the results into any model!**
- Example: use the prompt search to impose limits on 2HDM + complex scalar singlet
  - World-best upper limit on mixing angle with SM Higgs
  - Exclude $X \to b\bar{b}$ excess seen by CMS [JHEP 11 (2018) 161] in this scenario (by x20)





NEW!

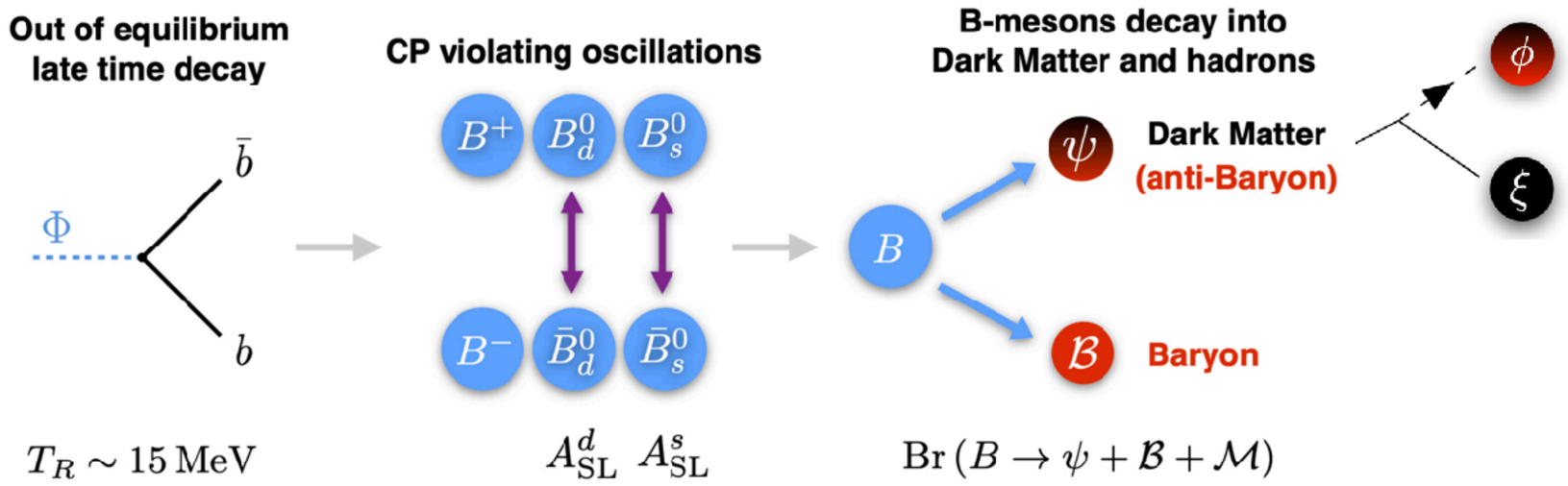
A. Brea Rodriguez, V. Chobanova, X. Cid Vidal, S.Lopez Soliño, D. Martínez Santos, TM, C. Prouvé, E.X. Rodríguez Fernández, C. Vázquez Sierra

arXiv:2106.12870

Prospects on searches for baryonic Dark Matter

- Recently proposed model combining B-mesogenesis with baryonic DM

[Escudero et al., PRD 99 (2019) 035031, arXiv:2101.02706]



$$Y_{\mathcal{B}} \simeq 8.7 \times 10^{-11} \frac{\mathrm{Br}(B \to \psi\, \mathcal{B}\, \mathcal{M})}{10^{-3}} \sum_q \alpha_q \frac{A^q_{\mathrm{SL}}}{10^{-3}}$$

$(0 \leq \alpha_q \leq 1.4)$

Mass and lifetime dep. of Φ

NEW!

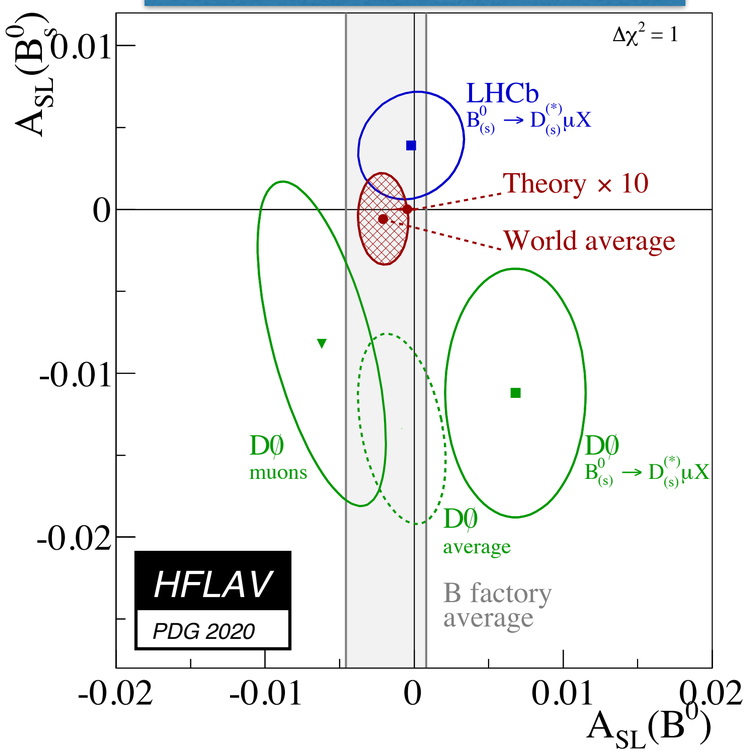
Brea et al., arXiv:2106.12870

Ingredients for the model

$$Y_B \propto \sum_{s,d} A_{SL}^{s,d} \times \mathscr{B}(B_{s,d}^0 \to \psi_{\mathrm{DS}} X)$$

- At least one of the two A_{SL} need to be be positive to produce baryon abundance
- A_{sl} determined directly and indirectly by LHCb and others
  - SM: $A_{SL}^d = (-4.7 \pm 0.4) \times 10^{-4}$, $A_{SL}^s = (2.1 \pm 0.2) \times 10^{-5}$ [Lenz & Tetlalmatzi-Xolocotzi, arXiv:1912.07621]
  - Direct: $A_{SL}^d = (-2.1 \pm 1.7) \times 10^{-3}$, $A_{SL}^s = (-0.6 \pm 2.8) \times 10^{-3}$ [HFLAV]
  - Indirect: $A_{SL}^d = (-3.3 \pm 1.4) \times 10^{-3}$, $A_{SL}^s = (-1.3 \pm 5.1) \times 10^{-4}$ [UTfit, NP-fit 2018]
- B_s^0 is the likeliest candidate for B-mesogenesis

Direct A_{SL} measurements [HFLAV]

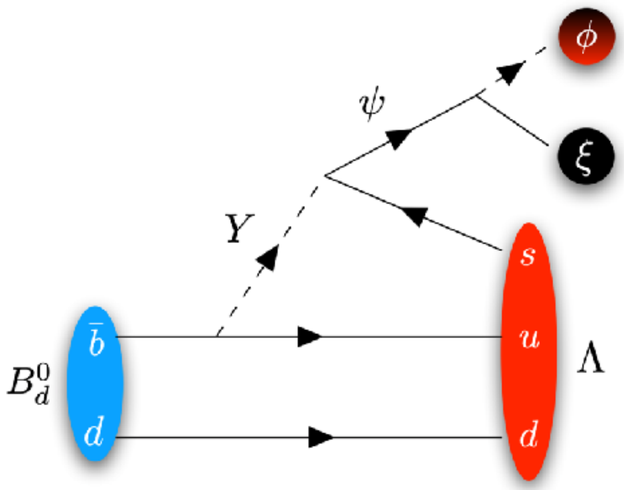


Can we search for these decays at LHCb?

NEW!

Brea et al., arXiv:2106.12870

Signatures and analysis



Exploit 4 different modes:

- $\Lambda_b^0 \to \psi K \pi$
- $\Lambda_b^0 \to \psi \pi \pi$
- $B^+ \to \psi \Lambda_c^+$
- $B_d^0 \to \psi \Lambda(1520)$

- Inclusive $\mathscr{B} \approx 0.1 - 0.0001$
- Exclusive $\mathscr{B} \approx 0.1 - 10^{-6}$
- No need to restrict to B_s^0, can test different b-transitions
- $m(\psi) \in [940,\ 4430]\,\mathrm{MeV}$

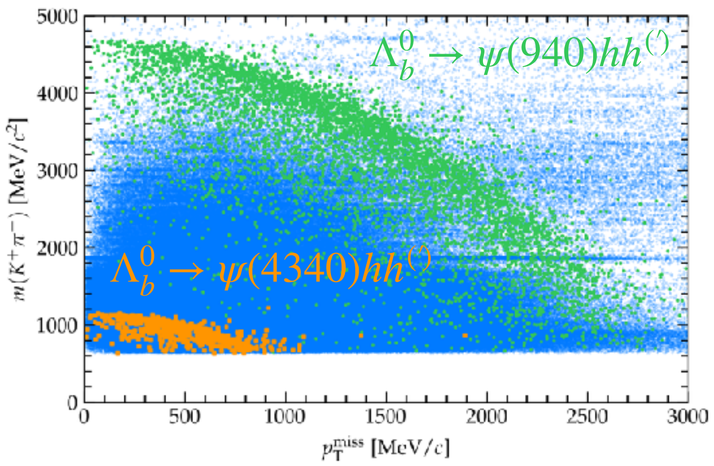
Simulation: Pythia + fast simulation of tracking system from [Chobanova et al, arXiv:2012.02692], particle identification from existing LHCb papers

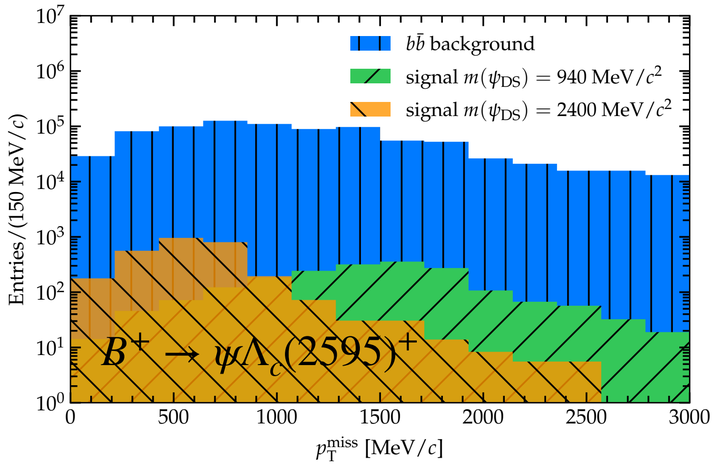
NEW!

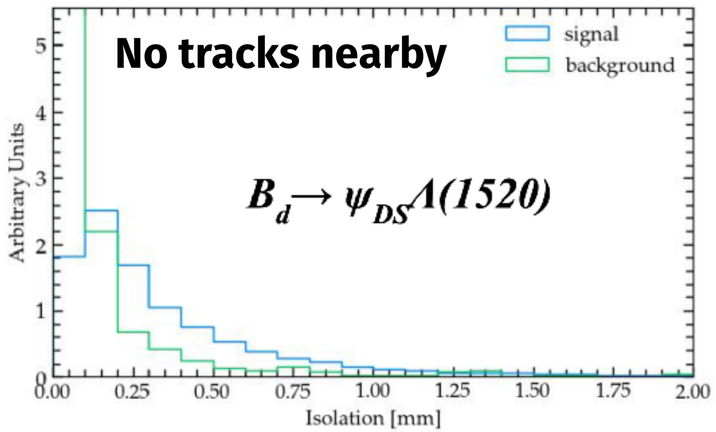
Brea et al., arXiv:2106.12870

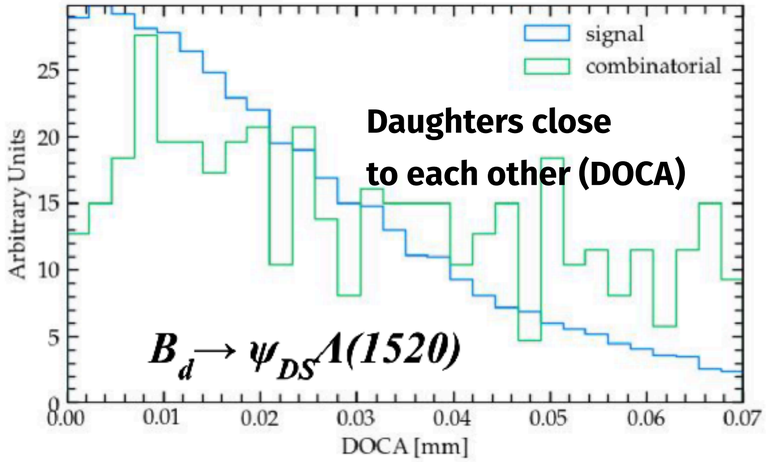
Selection

Requirements for b decay products: p_T, PV displacements, particle identification









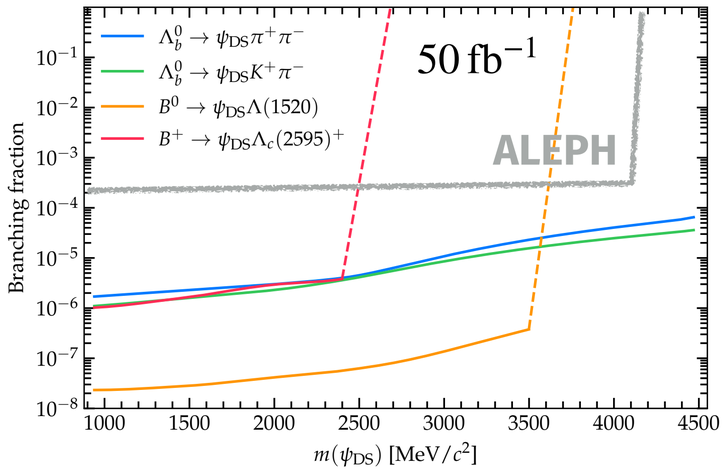
- Exploit sharp kinematic endpoints in $m(hh^{(\prime)})$ and p_T^{miss} transverse to flight direction
- Determine limits in bins of p_T^{miss} (and $m(hh^{(\prime)})$ for b-baryons), assuming known background

NEW!

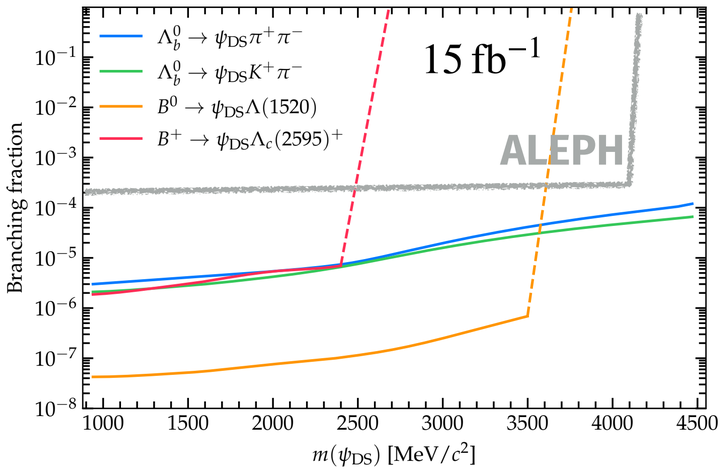
Brea et al., arXiv:2106.12870

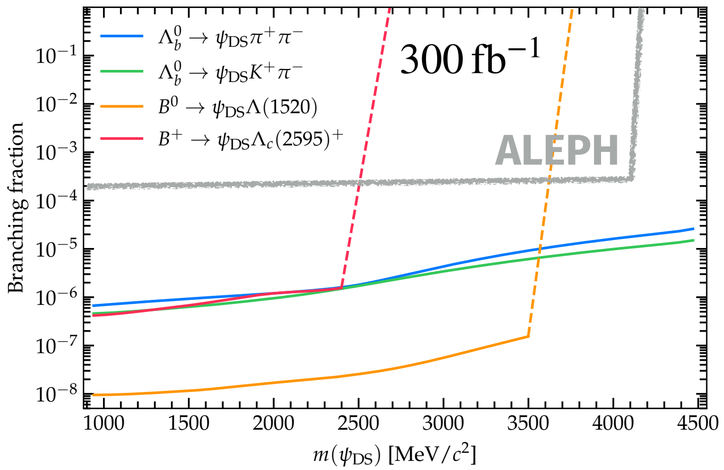
Sensitivity

LHCb Upgrade (Phase I)



LHCb Upgrade (Phase II)





[ALEPH: EPJC 19 (2001) 213]

- Cleaner signal at lower masses→stronger sensitivity
- If ψ is heavy, expected exclusive BF's are higher → can probe theory with less sensitivity
- **LHCb Upgrade has the potential to cover the full phase space of the model**
- Crucial systematics: background knowledge

  →even with per mil systematics the search would be systematically limited for $> 10\,\mathrm{fb}^{-1}$

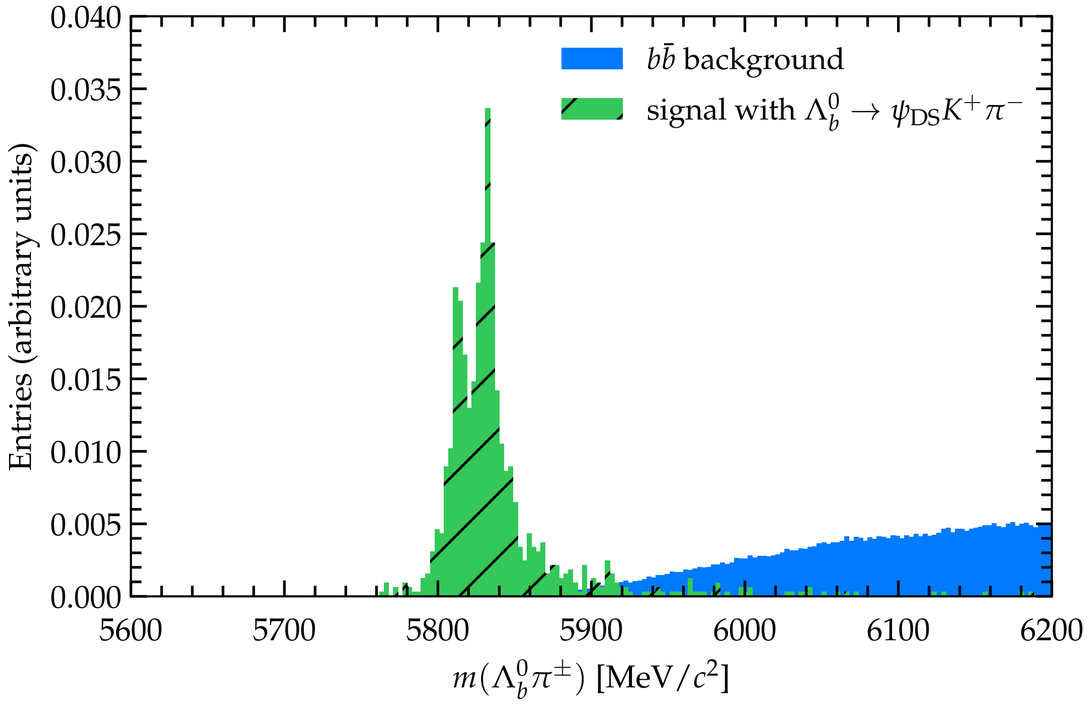
NEW!

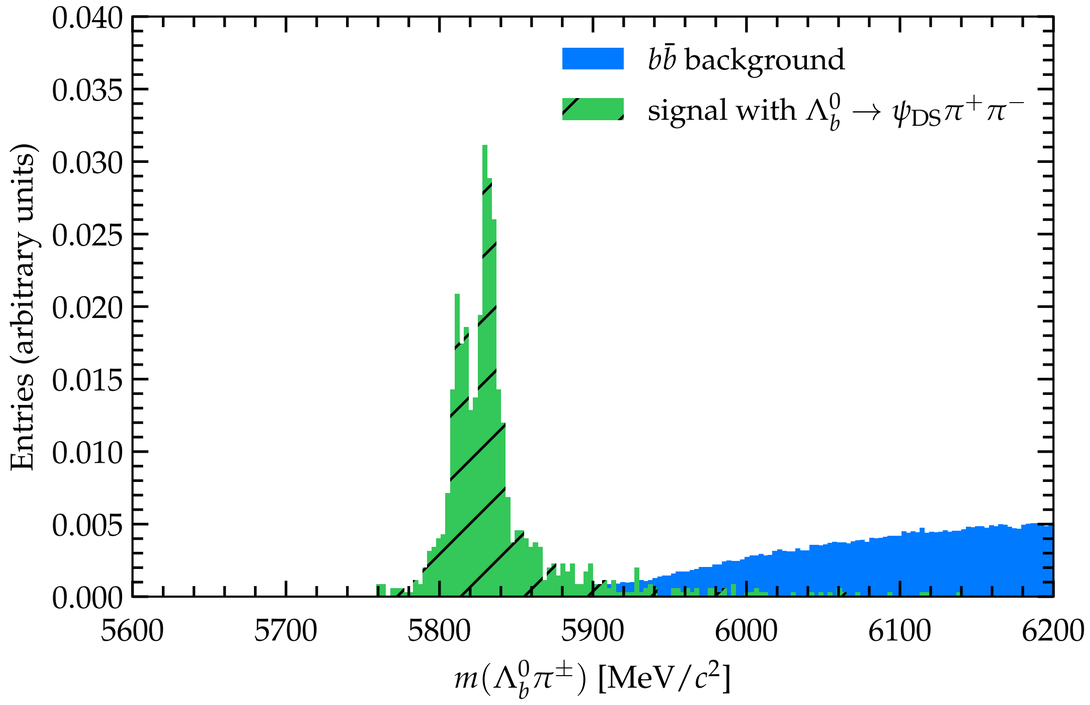
Brea et al., arXiv:2106.12870

Better background control: use ancestor resonances

Further background suppression (and peak confirmation) with identification of b-hadron mother, e.g. $\Sigma_b^+ \to \Lambda_b^0 \pi^+$

see [Zhang,Stone, arXiv:1402.4205] or $B_{s2}^{0*} \to B^+ K^-$





Conclusion

- LHCb has a unique coverage for Dark Matter searches
  - Not accessible to other experiments
  - Consequently several world-best limits
- Broad program being pursued
  - Searches for prompt and displaced particle decays into leptons, also hadrons/jets
  - Missing energy searches
- Unique trigger system gives bright prospects for the future
  - For baryonic DM model can cover the full phase space!

See also arXiv:2105.12668 for more prospects for the LHCb experiment

Backup

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

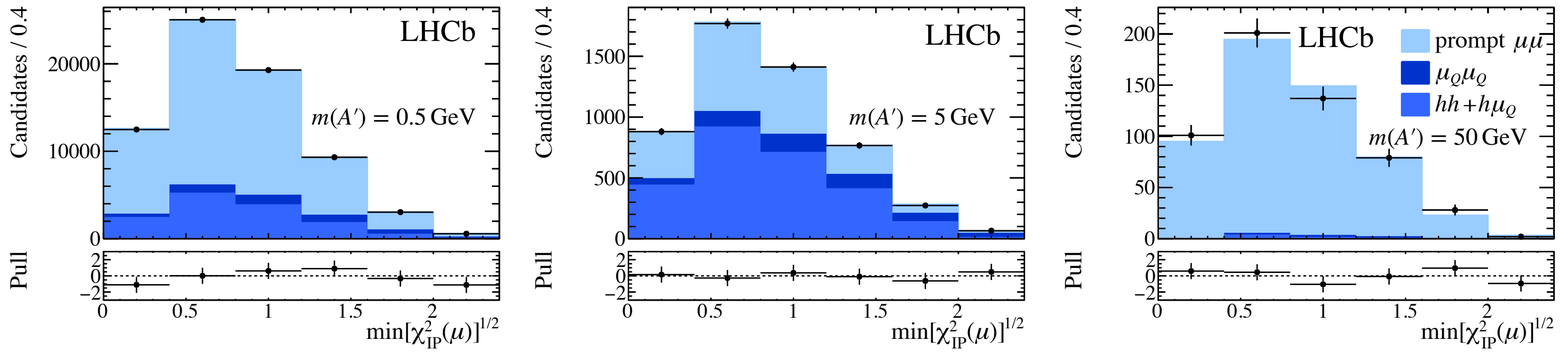
Search for prompt $A' \to \mu^+\mu^-$

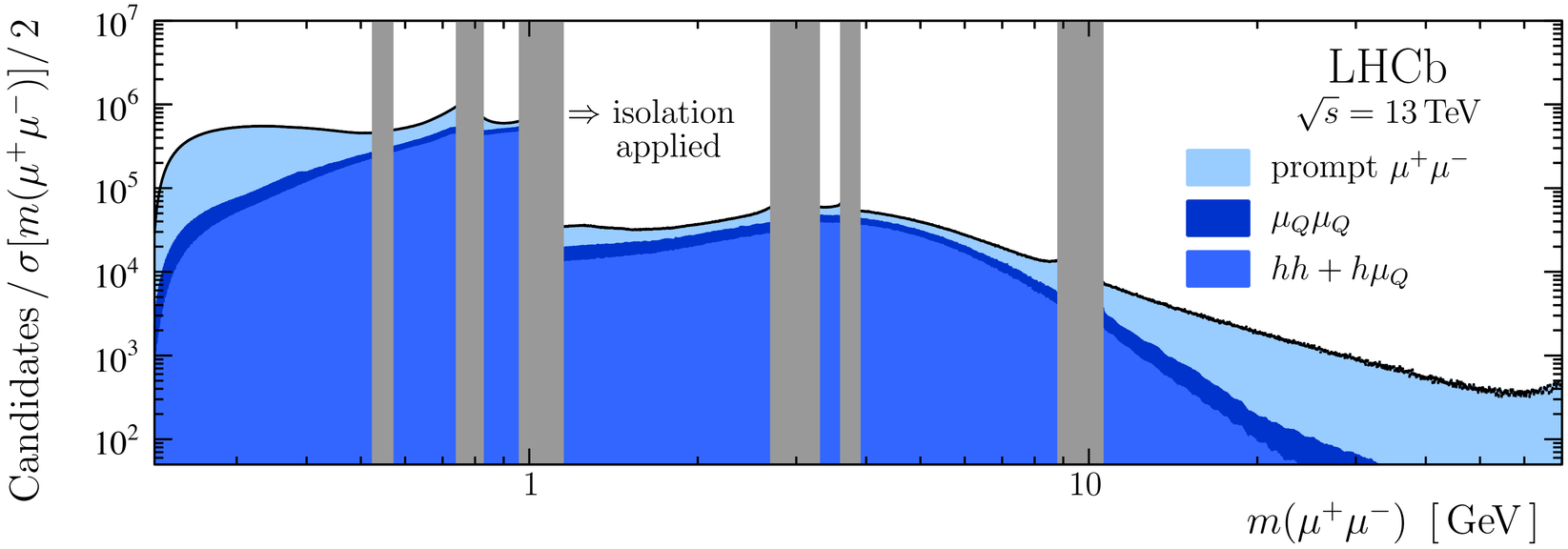
$n_{\text{ob}}^{\gamma^*}$ from templates for $\min[\chi^2_{\text{IP}}(\mu)]$

$\to$ only small correlation to $m(\mu^+\mu^-)$

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

μ_Q coming from heavy flavour decay





Inclusive $X \to \mu^+\mu^-$ search

Fiducial regions

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

$\alpha(\mu^+\mu^-) > 1(3)\,\text{mrad} \to \varepsilon(\mu^+\mu^-) \approx \varepsilon(\mu^+)\varepsilon(\mu^-)$,

Only works for $p_T(X) < 50\,\text{GeV}$

b-jet with anti-k_T $(R = 0.5)$

$12 < \rho_T(X) < 30\,\text{mm} \to \varepsilon(\tau_X) \approx \varepsilon$,

Inclusive $X \to \mu^+\mu^-$ search

Systematics

Source	Relative uncertainty
Signal model	5%
Background model	data driven
Trigger, reconstruction, selection	2–5% (bin dependent)
Charged-particle multiplicity	5%
X kinematics	10–30% (bin dependent)
b-jet selection	11% ($X + b$ only)
SV selection	5% (SV-based only)
X SV distribution	10% (SV-based only)
Luminosity	6%
Total	11–30% (bin dependent)