Higgs searches at LHCb

Higgs 2022 (Pisa; November 7 – 11, 2022)

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on behalf of the LHCb collaboration

European Organization for Nuclear Research (CERN)

November 9, 2022

The LHCb detector [IJMP A30 (2015) 1530022]

LHCb is a 20×5 m GPD in the forward region.

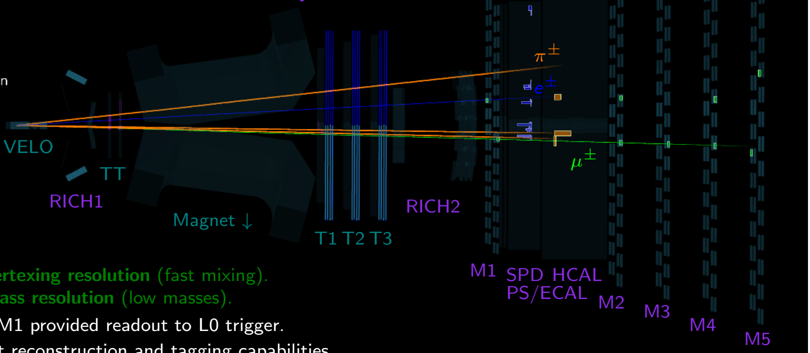
Single-arm **forward** spectrometer ($2 < \eta < 5$) along the beamline (z).

Tracking and vertexing systems

Particle identification systems

Side view

Event 216853
Run 4052454
LHCb Simulation



Excellent **vertexing resolution** (fast mixing).

Excellent **mass resolution** (low masses).

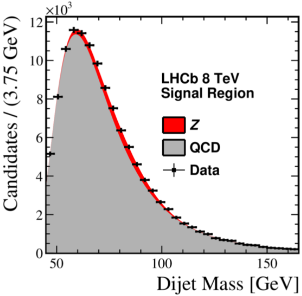
HCAL and M1 provided readout to L0 trigger.

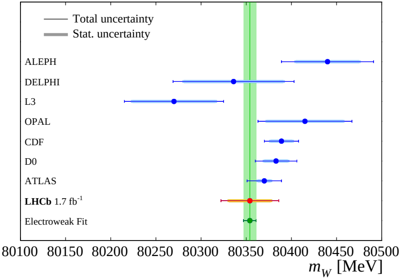
Excellent jet reconstruction and tagging capabilities.

Higgs searches at LHCb

LHCb is a General Purpose Detector:

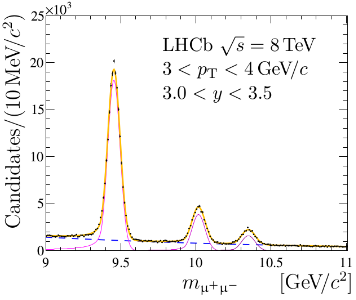
- Originally designed for heavy flavour physics → forward acceptance, reduced luminosity.
- Capable of **competitive** high p_T physics (*e.g.* Z, W): **[PLB 776 (2017) 430-439] [JHEP 01 (2022) 036]**

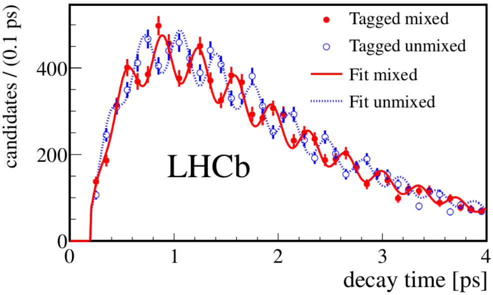




LHCb as a Higgs hunter: [IJMP A30 (2015) 1530022]

- **VELO:** excellent σ(IP)$\sim$ 20 μm and SV reconstruction $\rightarrow$ **crucial for jet flavor tagging.**
- **Tracking:** excellent spatial and momentum resolution $\rightarrow$ crucial for $H^0 \rightarrow$ LLP studies.
- **Trigger:** soft, full software trigger (GPUs) in Run 3 $\rightarrow$ expensive ML algorithms in HLT1.





Outline of this talk

Heavy flavor Higgs decays:

- Jet reconstruction and tagging at LHCb,
- Search for Higgs associated production into $b\bar{b}$ and $c\bar{c}$ [2016],
- Inclusive search for $b\bar{b}$ and $c\bar{c}$ resonances [2021],
- Prospects for $H^0 \to c\bar{c}$ searches.

Exotic Higgs decays:

- LFV decays of a Higgs-like boson [2018],
- Neutralino pair production decaying (semi-)leptonically [2021, 2022],
- Dark pion pair production decaying hadronically [2017],
- Hidden-sector bosons from B-meson decays [2017].

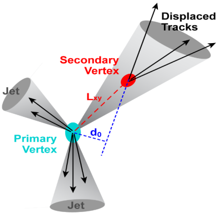
Searches for light Higgses:

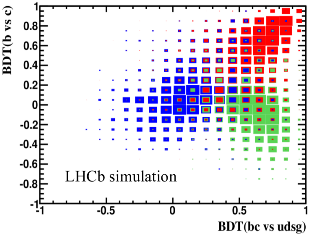
- Search for dimuon resonances in the Υ region (Run 1) [2018],
- Searches for low-mass dimuon resonances (Run 2) [2020].

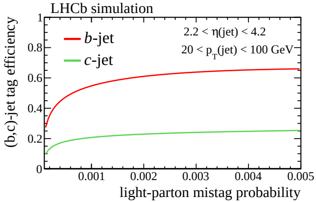
Heavy flavor

Jet reconstruction and identification at LHCb

- Jet reconstruction: **[JHEP (2014) 01 033]**
  - Particle flow algorithm (including neutral recovery) $\rightarrow$ jet input.
  - Anti-k_T algorithm for clustering (R = 0.5) $\rightarrow$ efficiency $> 95\%$ for $p_T > 20$ GeV.
  - Jet energy scale calibrated on data (using $Z \rightarrow \mu\mu$ + jets),
  - Energy resolution from 10 to 15% for a p_T range between 10 and 100 GeV.
- Secondary Vertex (SV) identification and jet tagging: **[JINST 10 (2015) P06013]**
  - Reconstruct SV from displaced tracks $\rightarrow$ kinematic and quality requirements on both,
  - Train two Boosted Decision Trees (BDTs) for a two-step jet flavour tagging:
    - SV displacement from PV, kinematics, charge and multiplicity;
    - SV corrected mass, defined as $\mathrm{M_{corr}(SV)} = \sqrt{\mathrm{M^2 + p^2 sin^2\theta}} + \mathrm{p sin\theta}$.
  - BDT(bc|udsg) to separate **light** and heavy flavour jets, BDT(b|c) to separate **b-jets** from **c-jets**.
  - Tagging efficiency of b(c)-jets of 65% (25%) with 0.3% contamination from light jets.

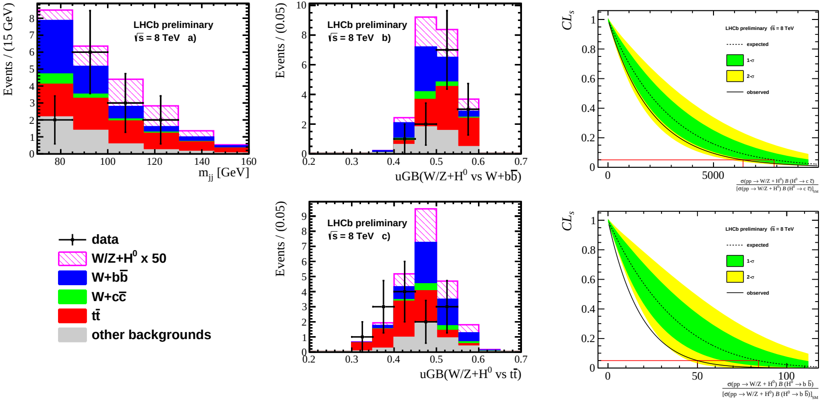






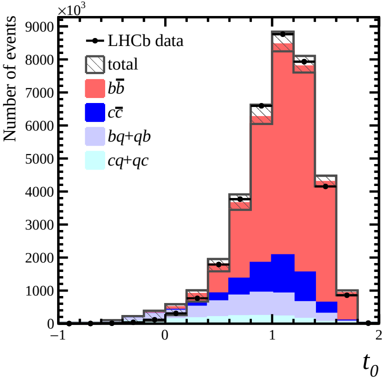
Search for W/Z + $H^0 \rightarrow b\bar{b}/c\bar{c}$ [LHCb-CONF-2016-006]

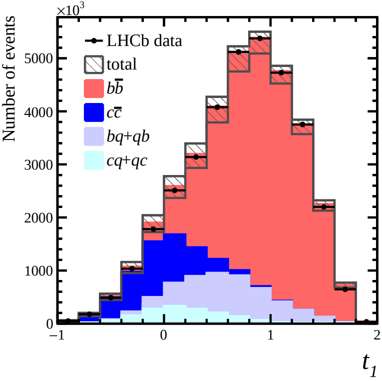
- Search for Higgs associated production using 2012 data (2 fb^{-1} at 8 TeV).
- Trigger on the high p_T μ, e from W/Z + **exploit jet tagging capabilities.**
- uGB to distinguish signal from backgrounds (W/Z + di-jet and $t\bar{t}$).
- CLs using m_{jj} + 2×uGB → compatible with background (no events) for $b\bar{b}$ ($c\bar{c}$).
- Upper limits on $H^0 \rightarrow b\bar{b}$ (69×SM) and **first limits** on $H^0 \rightarrow c\bar{c}$ (7900×SM).



Inclusive search for $c\bar{c}$ and $b\bar{b}$ resonances **[JHEP 02 (2021) 023]**

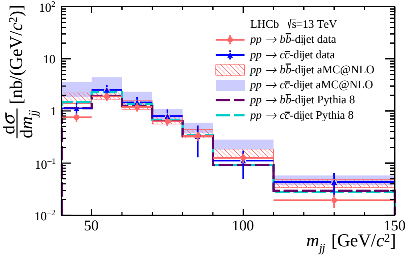
- Use 2016 data (1.6 fb^{-1} at 13 TeV) to test NLO pQCD predictions, test proton PDFs (access low Bjorken-x values), and search for resonances in m_{jj} (access low masses).
- Measure differential $c\bar{c}$- and $b\bar{b}$-dijet x-sections in the forward region and their ratio as a function of m_{jj}, $\eta(j_0)$, $p_T(j_0)$ and absolute difference in jet rapidities.
- Exploit **jet tagging capabilities** $\rightarrow$ fit to a linear combination (t_0, t_1) of tag observables.

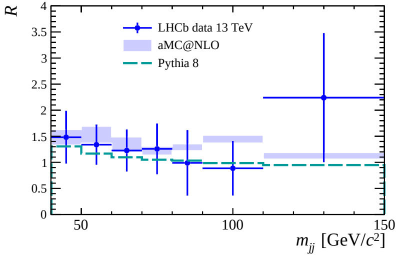




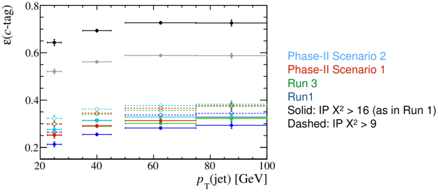
Inclusive search for $c\bar{c}$ and $b\bar{b}$ resonances [JHEP 02 (2021) 023]

- Results compatible with SM expectations → **first inclusive, direct measurement of differential $c\bar{c}$-dijet differential x-section at a hadron collider.**
- Understand backgrounds for future searches: search for $H^0 \to c\bar{c}$ and $H^0 \to b\bar{b}$.





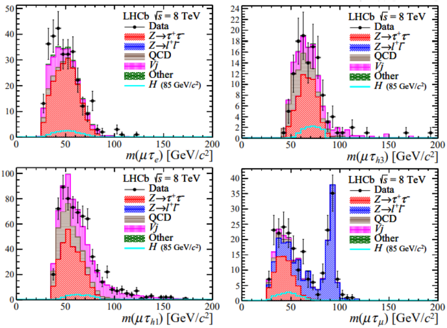
- Scale existing limits to 300 fb^{-1} and assume detector improvements affecting c-jet tagging (*e.g.* better IP resolution for SV separation): **[CERN-LPCC-2018-04]**
- No potential ML improvements considered. **Best LHC sensitivity on Yukawa coupling for c quark** (2-3 × y^c_{SM}).

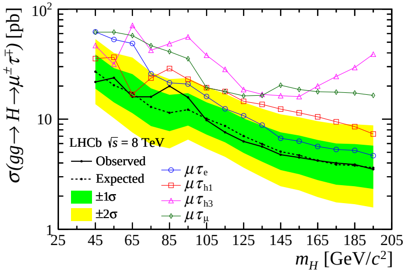


Exotic Higgs decays

Search for LFV decays of H^0-like bosons [EPJC (2018) 78 1008]

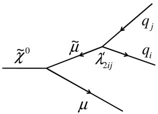
- Search for a H^0-like boson (45 to 195 GeV/c^2) into $\mu\tau$ in 2012 data (2 fb^{-1} at 8 TeV).
- High p_T muon + reconstruct leptonic and hadronic final states of the τ lepton.
- Selections optimised depending on the mass range (around m_H, below, and above).
- CLs limits at 95% C.L. with CLs, ranging from 22 pb at 45 GeV to 4 pb at 195 GeV.
- For Higgs, exclusion limit on the Yukawa coupling of $\sqrt{|Y_{\tau\mu}|^2 - |Y_{\mu\tau}|^2} < 1.7\times10^{-2}$.

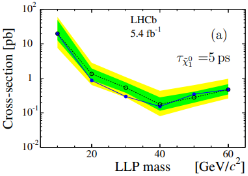


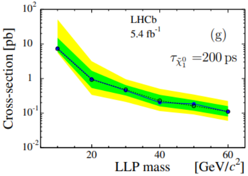


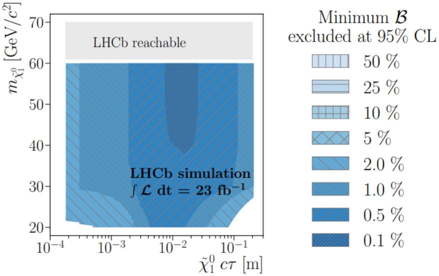
Pair produced $\tilde{\chi}_1^0 \rightarrow \mu q q'$ in Higgs decay **[EPJC 82 (2022) 4 373]**

- Search for RPV neutralino in 5.4 fb^{-1} of LHCb Run 1 and 2 data.
- Look for a **single displaced vertex** with several tracks + high p_T muon.
- Results interpreted in $H^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ benchmark model:





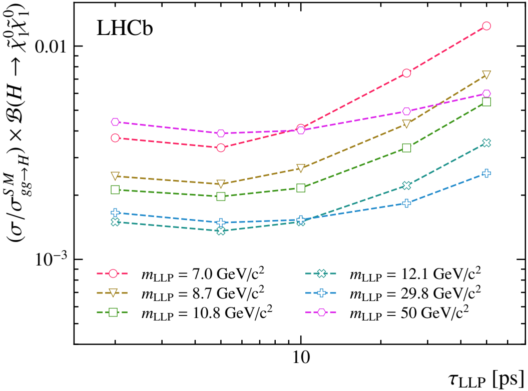




- Excluded production cross-section down to $\mathcal{O}(0.1)$ pb.
- Exclude $\mathcal{B}(H^0 \rightarrow \chi\chi)$ down to 0.1% by the end of Run 3 **[LHCb-CONF-2018-006]**

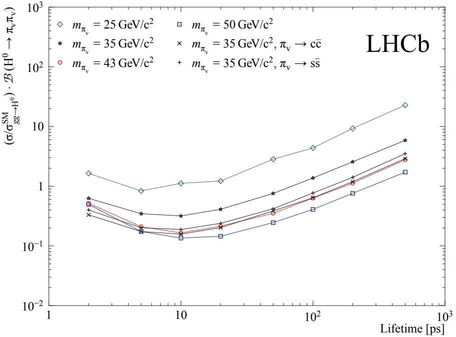
Pair produced $\tilde{\chi}_1^0 \to e^+\mu^-\nu$ in Higgs decay **[EPJC (2021) 81 261]**

- LHCb Run 2 (2016 – 2018) dataset (5.38 fb^{-1} at 13 TeV).
- Explore masses between and 7 and 50 GeV and lifetimes between 2 and 50 ps.
- Simultaneous ML fit to mass and LLP flight distance.
- UL at 95% C.L. on σB at 0.1 pb for $\tau < 10$ ps and $m > 10$ GeV – **no excess found**.



Pair produced dark pions in Higgs decay [EPJC (2017) 77 812]

- Search with full LHCb Run 1 (3 fb^{-1}) dataset published.
- **HV π_v decaying to $b\bar{b}$ – especially with SM-like $H^0 \to \pi_v \pi_v$ production.**
- Experimental signature is a **single displaced vertex** with two associated jets.
- Limits at 95% C.L. as a function of π_v lifetime for several π_v masses:



- Plan to analyse final state including kaons and pions (lower π_v masses).
- Improved simulation models including dark showers (multiple dark hadrons).

Confining Hidden Valley and dark showers: a proposal

- LHCb Run 1 search for $H^0 \to SS$, where $S \to b\bar{b}$ jets **[EPJC (2017) 77 812]**
- Improve simulation including dark QCD (multiple S) and intermediate resonances.
- Proposed search where $S \to K^+K^-$ (lower masses): **[JHEP (2020) 115]**

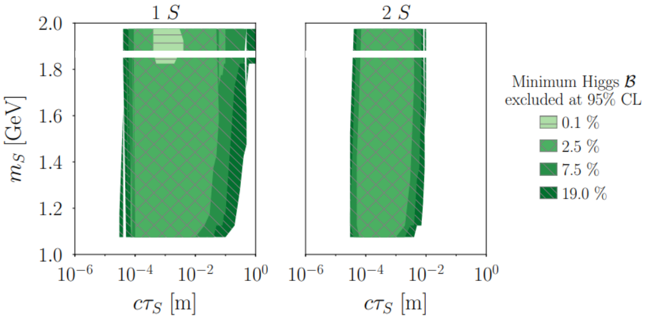
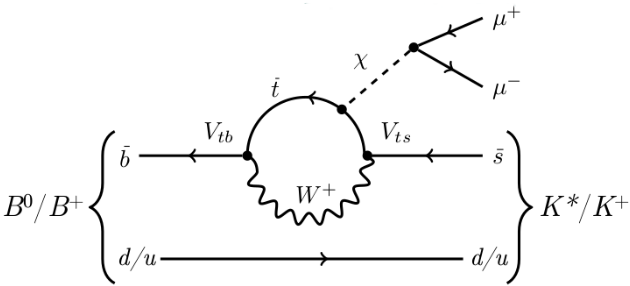


Figure 3. Range of S lifetime and mass for which a 95% CL exclusion of the branching fraction of the decay $h \to SS$ is possible at LHCb with an integrated luminosity of 15 fb^{-1} for different values of this branching fraction. We assume BR$(S \to K^+K^-) = 100\%$ in these plots. Left plot shows the limits when searching for just one S at the event, while right plot when searching for both of them.

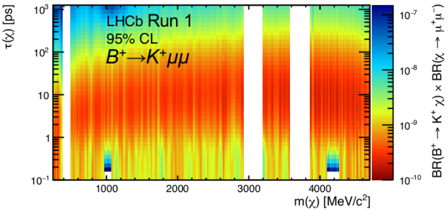
Hidden-sector bosons in $B \to K^{(*)}\chi(\mu^+\mu^-)$

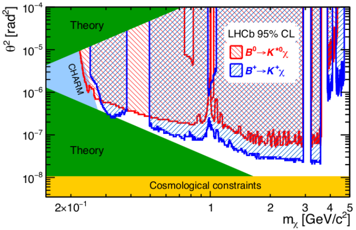
- $\mathrm{B}^0 \to K^{*0}\chi$ **[PRL 115 (2015) 161802]** / $\mathrm{B}^+ \to K^+\chi$ **[PRD 95 (2017) 071101 (R)]**
- Search for hidden-sector bosons $\chi \to \mu^+\mu^-$ in $b \to s$ penguin decays:
  - Axial-vector portal (χ as axion) **[LNP 741 (2008) 3]**
  - **Scalar** (Higgs) portal (χ as inflaton) **[JHEP 05 (2010) 10]**



Hidden-sector bosons in $B \to K^{(*)}\chi(\mu^+\mu^-)$

- Full LHCb Run I dataset (3 fb^{-1}) used for both searches.
- Allow for prompt and **detached** di-muon candidates.
- BR normalised to $\mathcal{B}(B^+ \to K^+ J/\psi)$ ($\sim 10^{-4}$) or $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$ ($\sim 10^{-7}$).
- Constraints on $\tau(\chi)$ between 0.1 and 1000 ps (left), **[PRD 95 (2017) 071101 (R)]**
- Constraints on mixing angle θ^2 between the Higgs and χ in the inflaton model (right):



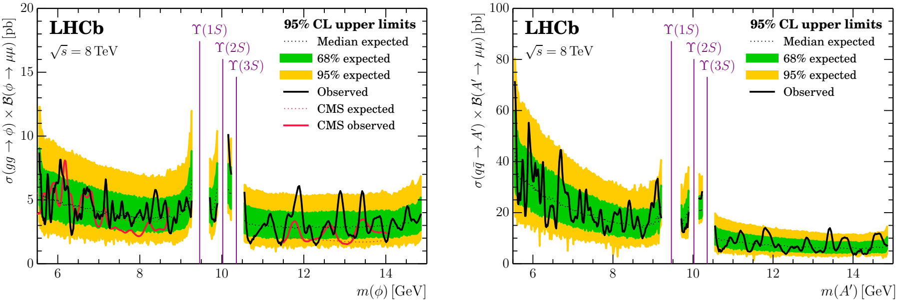


- **No evidence for signal observed.**
- **Large fraction of allowed inflaton parameter space ruled out.**

Light Higgses

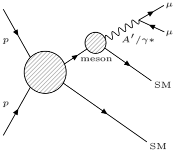
Search for $\mu\mu$ resonances in the Υ region [JHEP 09 (2018) 147]

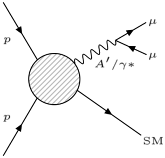
- Light spin-0 particles copiously produced in gluon-gluon fusion:
  - Many models: NMSSM, 2HDM+S, etc.
  - Review on LHC searches: **[arXiv:1802.02156]**
- Search using LHCb Run 1 (3 fb^{-1}) published in JHEP.
- Look for a di-muon resonance from 5.5 to 15 GeV/c^2 (also between Υ peaks):
  - Mass-interpolated efficiencies in bins of p_T, η (**model independent** results also given).
  - Production x-section (8 TeV) limits for a scalar (vector) boson on the left (right).
  - First scalar limits between 8.7 and 11.5 GeV/c^2 and competitive with CMS elsewhere.



Search for **dark photons** decaying into a pair of muons:

- Kinetic mixing of the dark photon (A') with off-shell photon (γ^*) by a factor ε:
  1. A' inherits the production mode mechanisms from γ^*.
  2. $A' \to \mu^+\mu^-$ can be normalised to $\gamma^* \to \mu^+\mu^-$.
- Separate γ^* signal from background and measure its fraction.
- **Prompt-like** search (up to 70 GeV/c^2) $\to$ **displaced** search (214 – 350 MeV/c^2):
  - A' is long-lived only if the mixing factor is really small.
- Used 5.5 fb^{-1} of Run 2 LHCb data (13 TeV).
- Great sensitivity (especially in the prompt region above 10 GeV and below 0.5 GeV).





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

off-shell photon

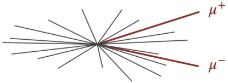
phase-space

A′/γ^* eff ratio, ϵ=1 for prompt

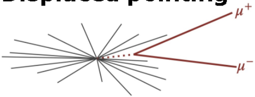
Search for di-muon low-mass resonances [JHEP 10 (2020) 156]

+ no isolation requirement
+ non-zero width considered

Inclusive Prompt

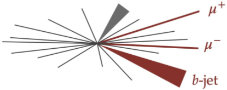


Displaced pointing

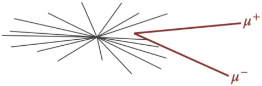


+ non-zero width considered

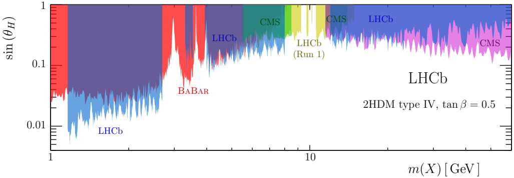
Prompt + b-jet



Displaced non-pointing



- 2HDM Higgs $\theta_H \to$ world-best limits:
  $\to$ LHCb R1 **[JHEP 09 (2018) 147]**
  $\to$ CMS R1 **[PRL 109 (2012) 121801]**
  $\to$ CMS R2 **[PRL 124, 131802 (2020)]**
  $\to$ Belle $Y \to X\gamma$ **[PRD 87 (2013) 031102]**
- Other scenarios covered too (*i.e.* HV).

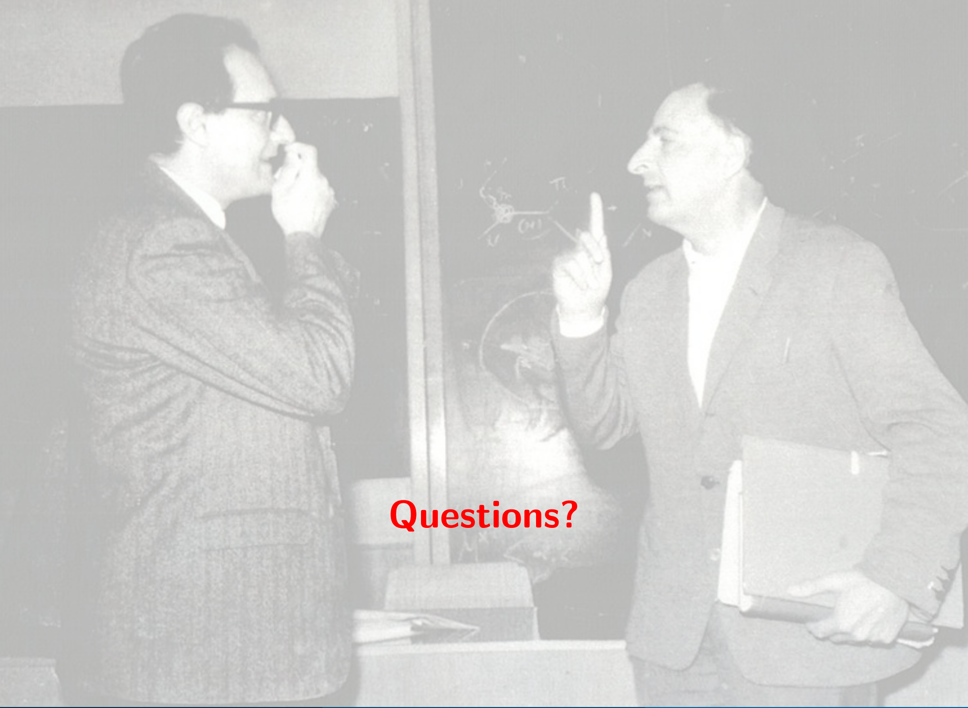


Conclusions

Conclusions

- LHCb proved to be **very competitive** for high p_T searches:
  - Excellent vertexing, tracking and soft trigger.
  - Especially competitive for jet tagging separation.
  - Rich variety of BSM models and signatures can be approached (see backup).
- **Bright prospects** for the future:
  - Interesting prospects for the $H^0 \to c\bar{c}$ mode.
  - Better vertex resolution and tracking capabilities.
  - New techniques under development for ideas on new signatures.
  - Extended reach with a new compact detector for LLPs $\to$ CODEX-b (see backup).

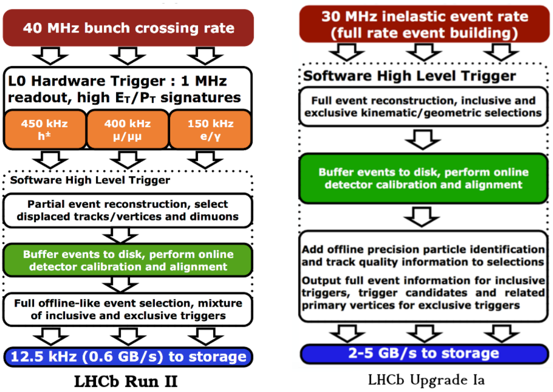
Thanks for your attention!



Questions?

Backup

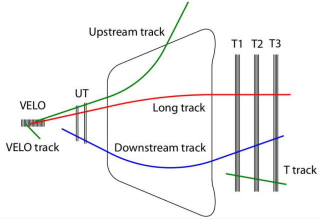
The LHCb trigger

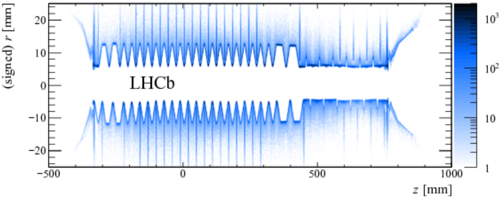


- L0 trigger removed for Run 3 $\rightarrow$ benefit for low-mass searches (no p_T bottleneck).
- Full event reconstruction from 30 MHz readout, able to select down to $p_T(\mu) \sim 80$ MeV/c.
- GPU-based HLT1 (Allen project) from Run 3 **[Comp Soft Big Sci (2020) 4 7]**

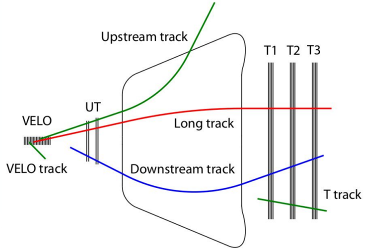
The LHCb reconstruction

- **Long tracks:**
  - Tracks with hits in the tracking stations and **in** the VELO.
  - **Excellent spatial and momentum resolution → 0.4% (0.6%) at 5 (100) GeV.**
  - Presence of a **VELO envelope** (RF-foil) at ∼ 5 mm from beam:
    → Background dominated by heavy flavour below 5 mm.
    → Background dominated by **material interactions** above 5 mm.
  - Having a precise model of material interactions is **crucial**.
  - A **detailed VELO material veto map** is used **[JINST 13 (2018) P06008]**





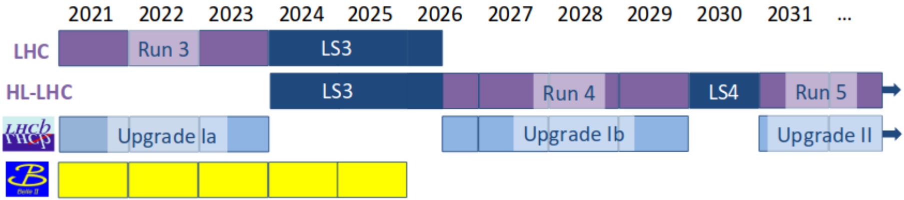
The LHCb reconstruction

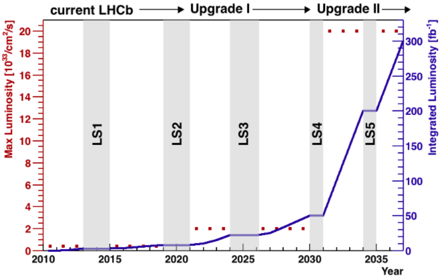


- **Downstream tracks:**
  - Reconstruction of particles decaying beyond VELO.
  - Tracks with worse vertex and momentum resolution.
  - Trigger on downstream tracks $\rightarrow$ better for LLP ($\lesssim 2$ m) signatures.
  - Optimisation studies on-going **[LHCb-PUB-2017-005]**
- **Upstream tracks:**
  - Reconstruction of soft charged particles bending out of the acceptance.
  - New tracker (UT) – high granularity, closer to beam pipe.
  - Proposal to add magnet stations (MS) inside the magnet $\rightarrow$ improve low p resolution.

The future of LHCb

Physics case for an LHCb Upgrade II: Opportunities in flavour physics, and beyond, in the HL-LHC era [CERN-LHCC-2018-027]

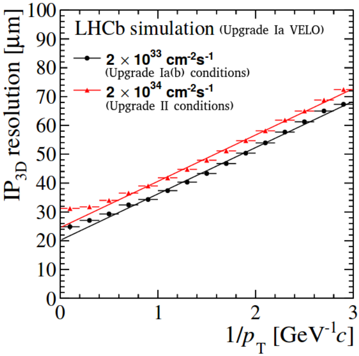


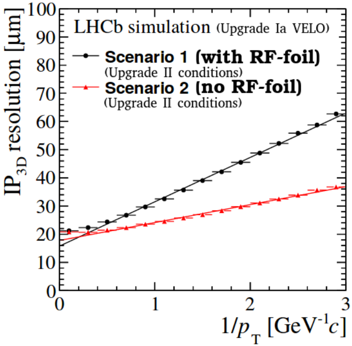


- Total dataset of 9 fb^{-1} collected during Run 1 and 2.
- Changes in Run 3: SciFi, UT, removal of M1, no L0 trigger, upgrade of subsystems.
- Expect to collect 300 fb^{-1} by the end of Upgrade 2.
- **Challenging conditions** – higher rate, pile-up, occupancy and fluence.
- Detector sub-systems have to be able to cope with such conditions.
- In particular – **trigger** and **tracking systems** are crucial for exotic searches.

The upgraded LHCb VELO

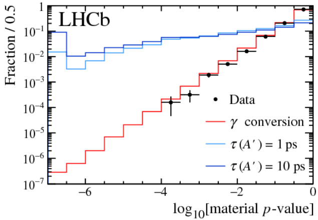
- **Upgrade II VErtex LOcator: [CERN-LHCC-2017-003]**
  - Probably based on Upgrade Ia VELO (silicon pixels).
  - Access to shorter lifetimes, better PV and IP resolution, and real-time alignment.
  - But – 10x multiplicity, pile-up and radiation damage w.r.t. Upgrade Ia(b).
  - **Possibility of removing RF-foil** for Upgrade II:
    $\rightarrow$ better IP resolution + no material interactions.



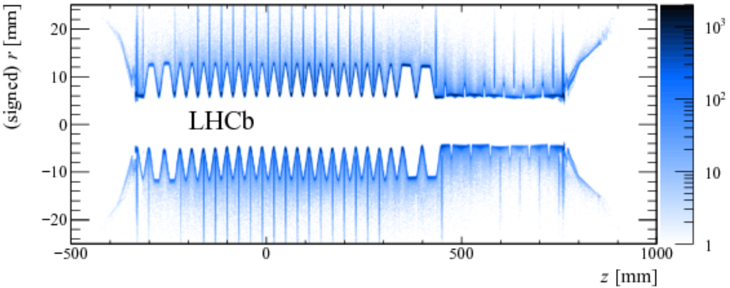


VELO material map [JINST 13 (2018) P06008]

- Background dominated by material interactions for displaced searches at LHCb.
- Mandatory to **keep control** of material interactions – veto them in an efficient way:

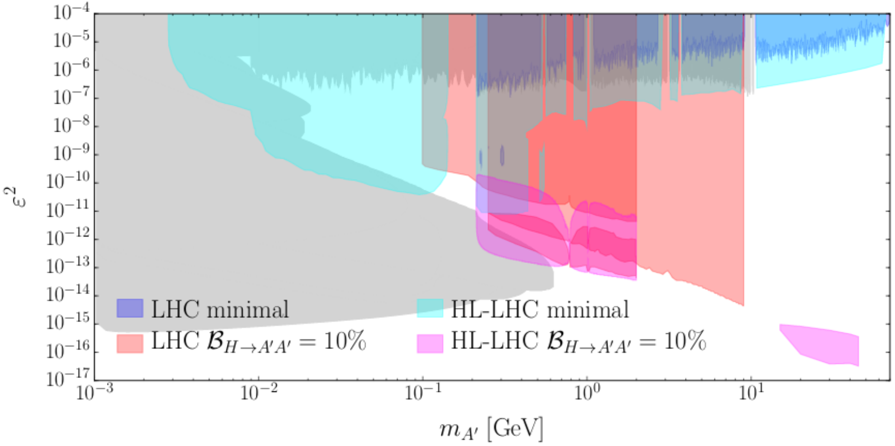


- Background mainly due to γ conversions (left plot).
- A new VELO material map has been developed:
  - Model in **great detail** both sensors & envelope.
  - Assign a **p-value** to material interaction hypothesis.
  - Sensitivity improvement by $\mathcal{O}(10)$ to $\mathcal{O}(100)$.
  - Based on data from **beam-gas collisions** (plot below).



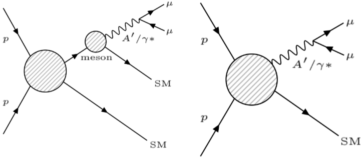
Dark Photons – **combined prospects**

- Minimal scenario (LHCb) + Higgs portal (ATLAS/CMS):



Search for dark photons decaying into a pair of muons:

- Kinetic mixing of the dark photon (A') with off-shell photon (γ^*) by a factor ε:
  1. A' inherits the production mode mechanisms from γ^*.
  2. $A' \to \mu^+\mu^-$ can be normalised to $\gamma^* \to \mu^+\mu^-$.
- Separate γ^* signal from background and measure its fraction.
- **Prompt-like** search (up to 70 GeV/c^2) $\to$ **displaced** search (214 – 350 MeV/c^2):
  - A' is long-lived only if the mixing factor is really small.
- Used 5.5 fb^{-1} of Run 2 LHCb data (13 TeV).
- Great sensitivity (especially in the prompt region above 10 GeV and below 0.5 GeV).



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

off-shell photon

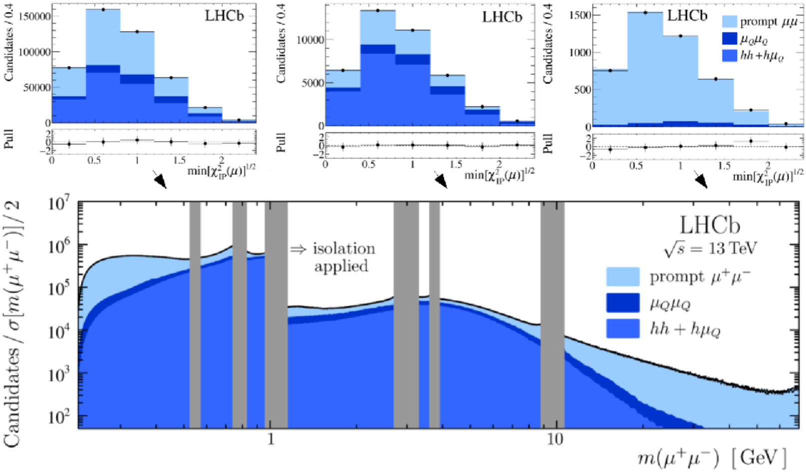
phase-space

A'/γ^* eff ratio, ϵ=1 for prompt

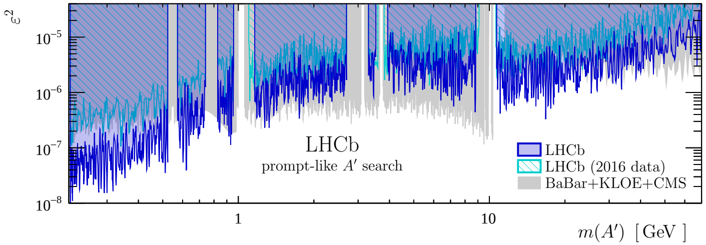
Using templates for min[χ^2_{IP}] (small mass dep)

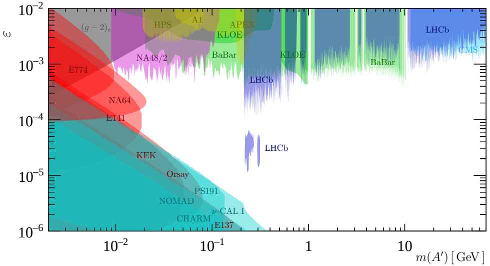
prompt $\mu^+\mu^-$	→ from data at $m(J/\psi)$ and $m(Z)$
$\mu_Q\mu_Q$	→ from simulation (validated)
$hh + h\mu_Q$	→ from same-sign dimuons (corrected)

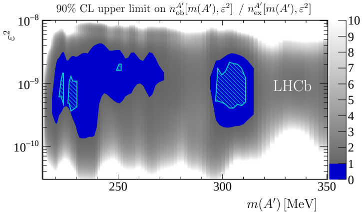
(μ_Q is a muon from a heavy-flavour decay)



Dark Photons **[PRL (2020) 124 041801]**



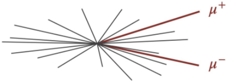




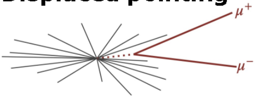
Dark Photons – **non-minimal searches** [JHEP 10 (2020) 156]

+ no isolation requirement
+ non-zero width considered

Inclusive Prompt

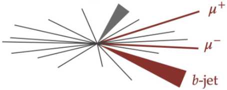


Displaced pointing

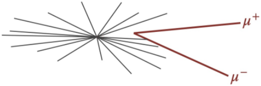


+ non-zero width considered

Prompt + b-jet

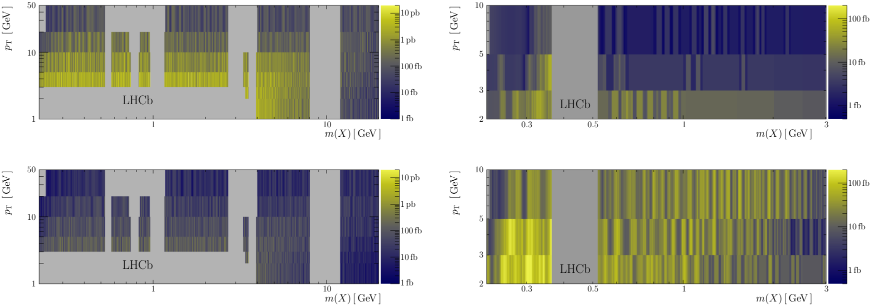


Displaced non-pointing

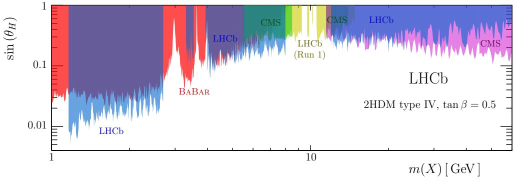


Dark Photons – **non-minimal searches** [JHEP 10 (2020) 156]

- UL @ 90% C.L. on $\sigma(X \to \mu\mu)$ (top: inclusive, bottom: b-associated):

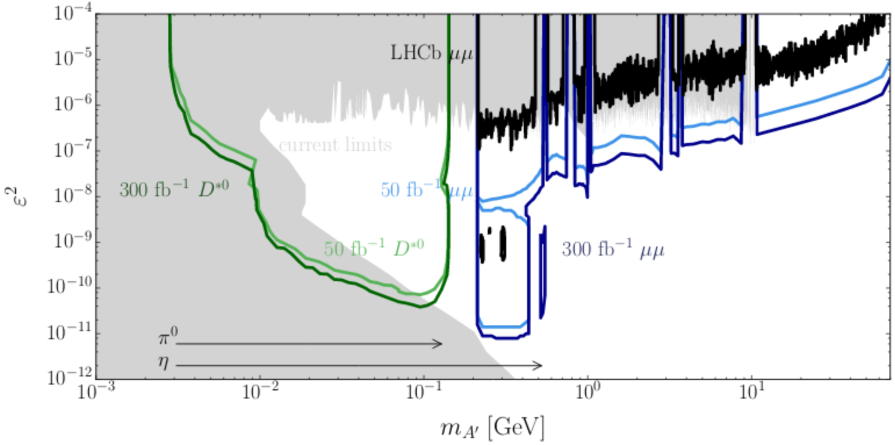


- 2HDM Higgs $\theta_H \to$ world-best limits:
  - $\to$ LHCb R1 **[JHEP 09 (2018) 147]**
  - $\to$ CMS R1 **[PRL 109 (2012) 121801]**
  - $\to$ CMS R2 **[PRL 124, 131802 (2020)]**
  - $\to$ Belle $Y \to X\gamma$ **[PRD 87 (2013) 031102]**
- Other scenarios covered too (*i.e.* HV).



Dark Photons – **the future**

- Cover *ee* in $D^{*0} \to D^0 A'(ee)$ decays (high statistics, no L0), and with inclusive *ee* triggers.
- Prospected reach for **Run III and beyond**: **[arXiv:1812.07831]**



Dark Photons – **Snowmass projections**

- Projections from [arXiv:2203.07048]:

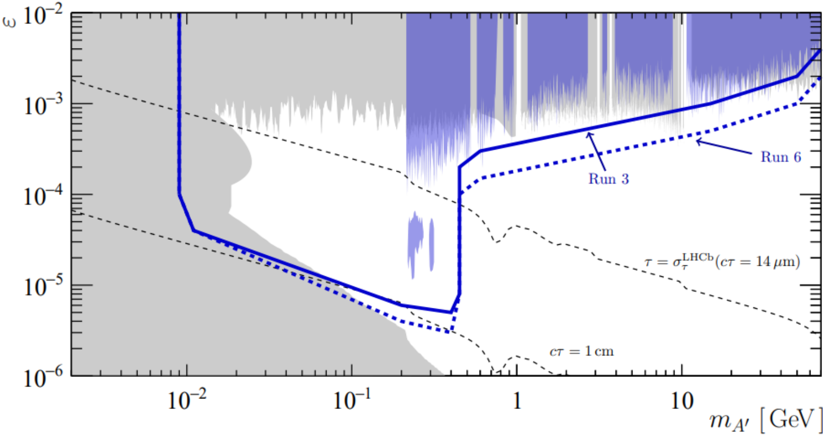


FIG. 1: Adapted from Ref. [14]: constraints on visible A' decays from (blue regions) LHCb [2] and (gray regions) all other experiments. The solid blue line is the union of Run 3 projections for LHCb from Refs. [9, 10], updated to include inclusive $A' \to e^+e^-$ projections enabled by recent advances in the LHCb trigger. The dashed blue line projects further into the future to the end of Run 6.

LLPs decaying into $e^+\mu^-\nu$ [EPJC (2021) 81 261]

Simulation:

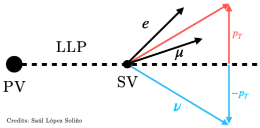
- Signal (DPP and HIG) using MSSM RPV model – LLP as $\tilde{\chi}_0^1$ light neutralino,
- Signal (CC) using LRSM model – LLP as a HNL from on-shell W boson decay,
- Several **signal samples** per model for different LLP mass and lifetimes.
- **Background sample** simulated for QCD $b\bar{b}$ events.

Selection:

- Require good quality DVs with minimum displacement and kinematic requirements.
- Leptons isolated to suppress QCD background – isolation optimised with same-sign data.
- After full selection $\rightarrow$ 60k $b\bar{b}\rightarrow e\mu X$ events (consistent with observed yield).

Corrected mass approach:

- LHCb is a non-hermetic spectrometer $\rightarrow$ we **can not do invisibles.**
- However, we can compute a proxy to X+invisible invariant mass $\rightarrow$ **corrected mass**.
- **Required** to have only one **massless** invisible in the final state (ν).
- **Required** to know the **direction of flight** of the parent particle.



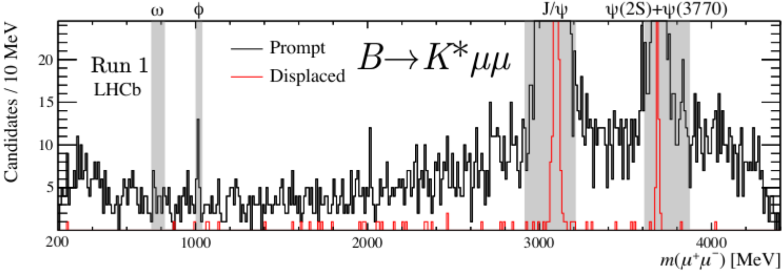
1. Assume LLP origin vertex approximately be the same as the *pp* collision.
2. Obtain a (pseudo) decay vertex using the di-lepton systems.
3. Project the di-lepton system momenta to the LLP direction of flight.

$$m_{\mathrm{corr}} = \sqrt{m(e\mu)^2 + p(e\mu)^2 \sin^2\theta} + p(e\mu)\sin\theta$$

Corrected mass as a good proxy to real mass $\rightarrow$ discriminating variable.

Hidden-sector bosons in $B \to K^{(*)}\chi(\mu^+\mu^-)$

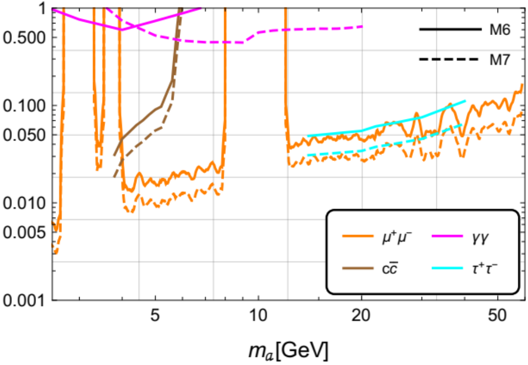
- Full LHCb Run I dataset ($3\ \mathrm{fb}^{-1}$) used for both searches.
- Allow for prompt and **detached** di-muon candidates – up to 1000 ps ($\sim$ 30 cm).
- Look for a narrow di-muon peak (mass resolution between 2 and 9 MeV/c^2).
- Exclude narrow QCD resonances - mass distribution: **[PRL 115 (2015) 161802]**



- MVA selection almost independent of χ mass and decay time (uBoost).

Search for a composite ALP at LHCb

- Axion-like particle in the context of Composite Higgs models: **[EPJC (2022) 82 3]**
- Low-mass pseudoscalar decaying into pairs of leptons, quarks or photons.
- Reinterpreation of existing $\gamma\gamma$ (QCD axion projections) and $\mu\mu$ (experimental) boundaries.
- Studies for final states consisting of $\tau\tau$ and $c\bar{c}$ into D mesons.



STEALTH white paper

- Major report on STEALTH physics at LHCb published in Reports on Progress in Physics **[ROPP (2022) 85 024201] [arXiv:2105.12668]**
- More than 20 proposed searches on different models are described:

- **B-mesogenesis:** baryonic DM from *B*-hadron decays **[EPJC (2021) 81 964]**
- **Confining HV:** dark hadrons decaying into SM light hadrons **[JHEP (2020) 115]**
- **Composite ALP:** light pseudoscalar in Composite Higgs models **[EPJC (2022) 82 3]**

Extended reach for LLPs (CODEX-b + LHCb)

- Compact detector for exotics: **[PRD 97 (2018) 015023]**
  - Box of tracking layers to search for decays-in-flight of LLPs generated at IP8.
  - Interface with LHCb for identification and partial reconstruction of possible LLP events.
- Prospects for several benchmark models studied:
  - Prospects (various detectors) for $B \to X_s \varphi$ (φ as a light scalar) shown below (original paper).
  - Updated limits including other models in the Snowmass white paper **[arXiv:2203.07316]**