Looking forward to Naturalness

Results and prospects for low-mass searches in the forward region at the LHC

Is There Still Room for Naturalness? NORDITA 2022

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European Organization for Nuclear Research (CERN)

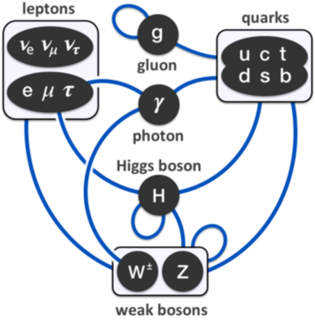
April 25, 2022

The Standard Model

The Standard Model (SM) of elementary particles:

- Most **successful theory** describing subatomic particles and their interactions.
- Accommodates strong, weak and electromagnetic interactions:

$$\mathrm{G}_{\mathrm{SM}} = \mathrm{G}_{\mathrm{QCD}} \times \mathrm{G}_{\mathrm{EW}} = \mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}}$$



SM is strongly predictive and precise:

- t predicted (observed) on 1973 (95),
- W/Z predicted (observed) on 1962 (83),
- g predicted (observed) on 1962 (78),
- H predicted (observed) on 1964 (2012),
- Good agreement with experimental results.

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But also an incomplete theory:

- Inability to explain gravity.
- Dark matter and dark energy.
- Baryogenesis problem (BNV, CPV).
- Towards a GUT (gauge unification).
- Neutrino masses.
- Hierarchy problem and fine-tuning.

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- Is there still room for Naturalness?

Still no New Physics at the LHC?

1. **NP is "collider-phobic"**: we need dedicated experiments (axions, dark photons, sub-GeV DM, sterile neutrinos), *e.g.* FASER, CODEX-b, MATHUSLA, LZ, DUNE, ADMX, etc.

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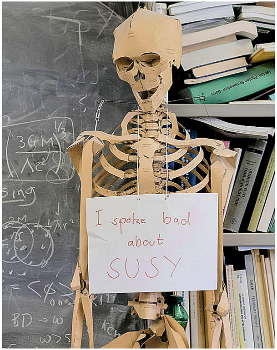

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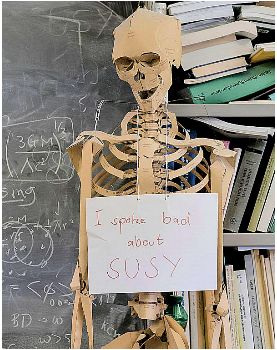

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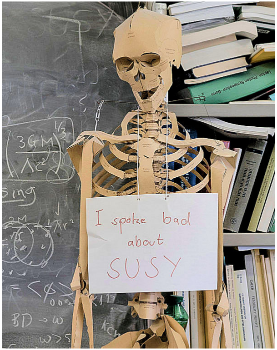
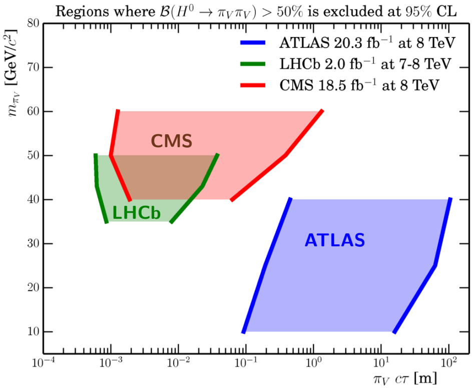
3. **The NP scale is $\sim$ EW scale but operating in "stealth mode"**: heavy mediators, tiny couplings, compressed spectra, large backgrounds $\rightarrow$ **ideal for LHCb to explore!**



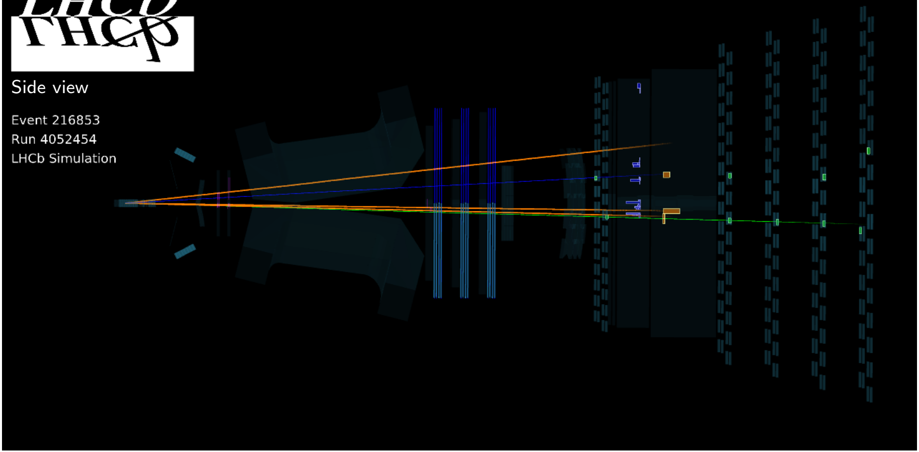
Hunting for Stealth New Physics

- The LHCb experiment is a **natural candidate** to search for stealth physics.
- Originally designed as a heavy-flavor experiment, but now a general purpose detector.
- Ability to deal with low-mass backgrounds, soft triggers and particle identification.
- Excellent vertex resolution and tracking capabilities.
- Unique coverage complementary to ATLAS and CMS:



The LHCb detector

LHCb is a 20$\times$5 m GPD in the forward region (originally designed for HF physics).



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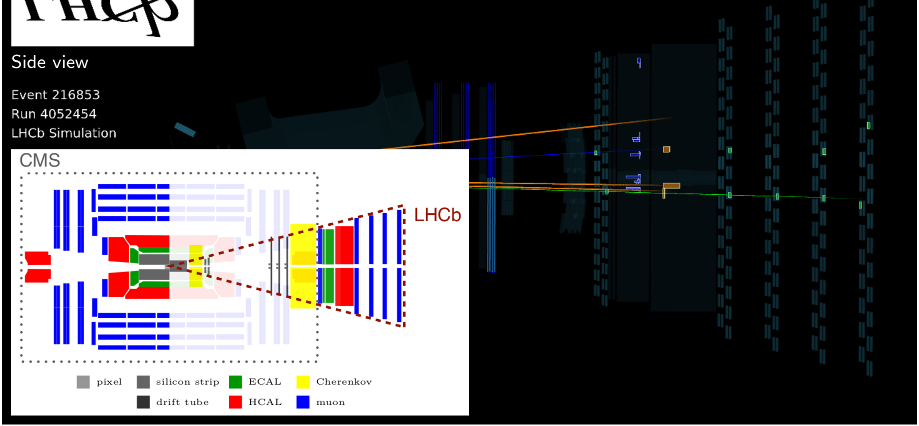

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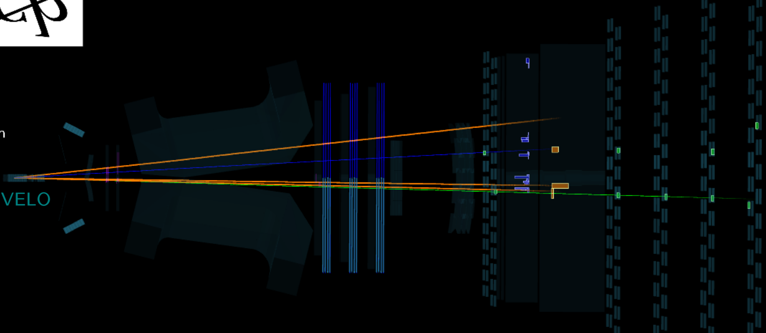
Side view

Event 216853
Run 4052454
LHCb Simulation



VErtex LOcator (VELO): excellent vertex resolution, $\sigma_{IP} \sim 20\mu m$ (high p_{T} tracks).

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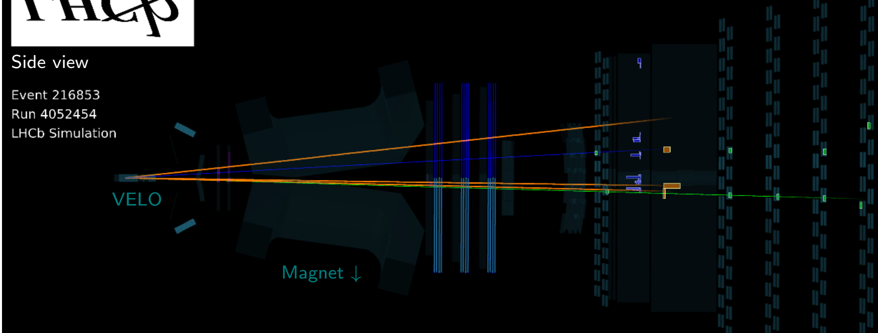

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Magnet: dipole magnet (4 T×m) for bending charged particle trajectories in the xy plane.

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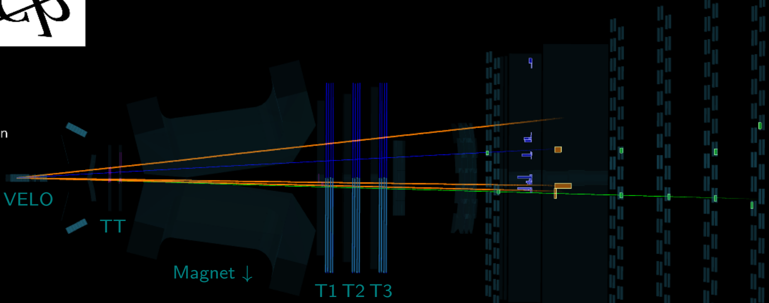

Tracking and vertexing systems:

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Magnet: dipole magnet (4 T$\times$m) for bending charged particle trajectories in the xy plane.
Silicon Tracker: one tracking station upstream and three stations ($\delta p/p \sim 0.4\%$) downstream the magnet.

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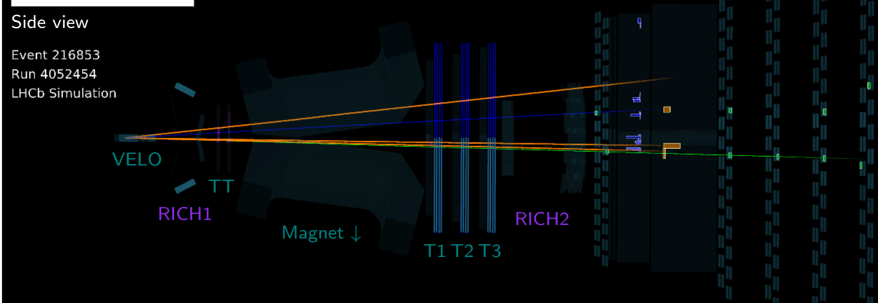

RICH: measure Cherenkov angle (rings) of charged particles.

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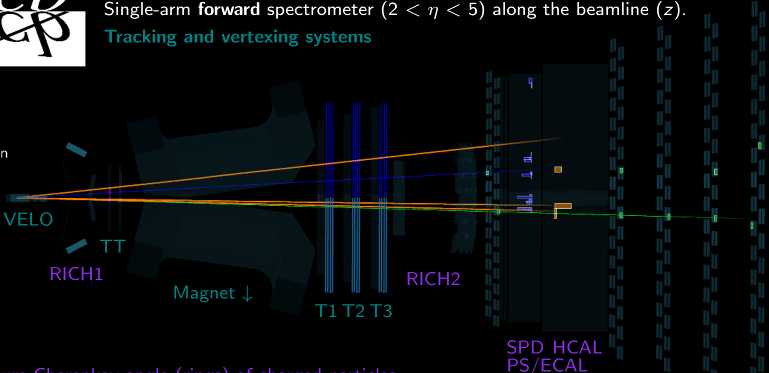

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Calorimeters: measure energy deposit of e, γ (ECAL) and hadrons (HCAL → L0 trigger).

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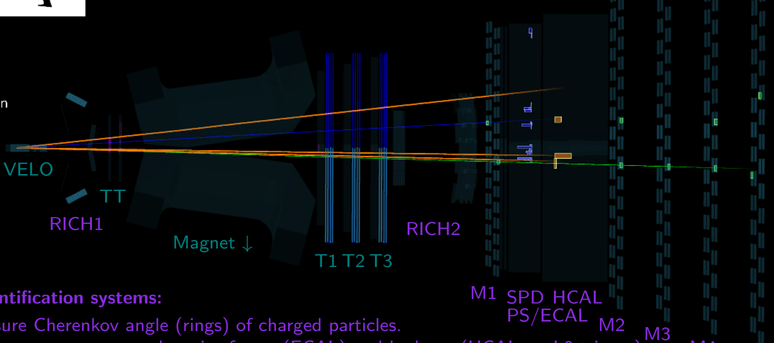

Particle identification systems:

RICH: measure Cherenkov angle (rings) of charged particles.
Calorimeters: measure energy deposit of e, γ (ECAL) and hadrons (HCAL → L0 trigger).
Muon system: measure energy deposit of μ, consisting of 5 stations (M1 → L0 trigger).

The LHCb detector

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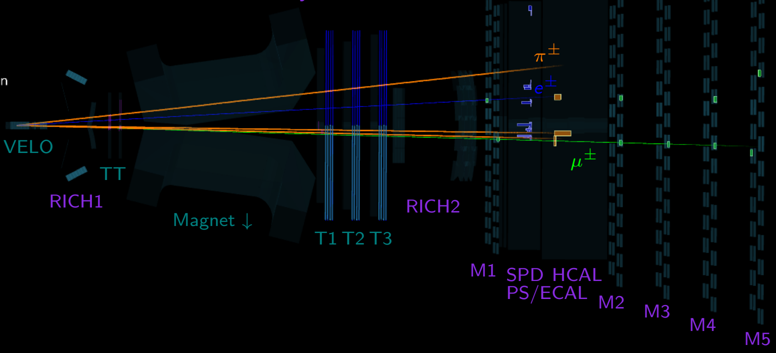

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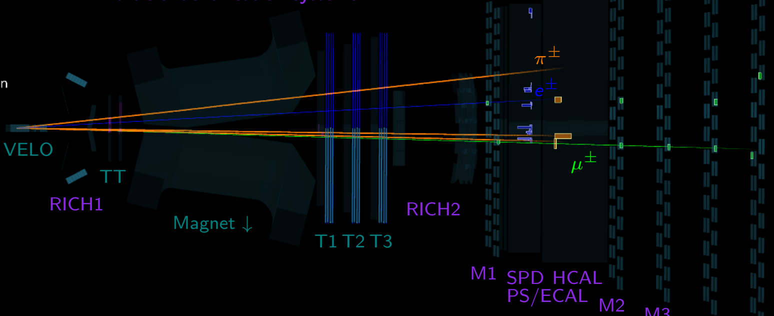

HCAL and M1 provide 40 MHz readout to L0 trigger (rest are readout at 1 MHz).
Good **jet tagging** efficiency: b(c) tagging efficiency of 65% (25%) with 0.3% contamination.

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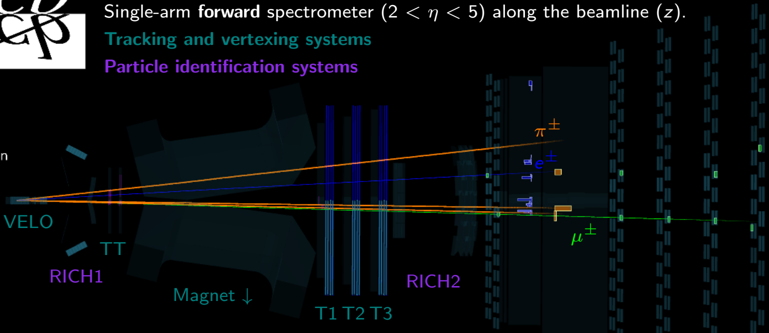

Excellent **vertexing** resolution ($\sim$ 40 fs for B_s^0 oscillations).
Excellent **mass resolution** ($\sim$ 0.5% for di-muon low mass resonances).
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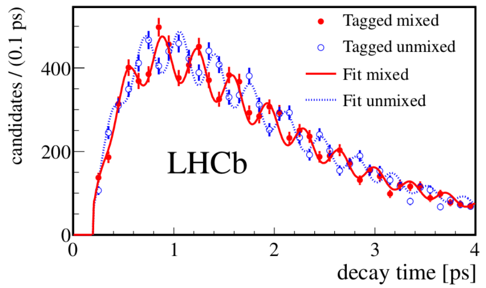
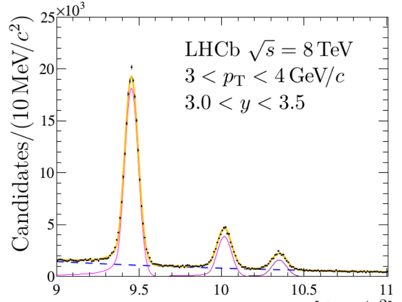
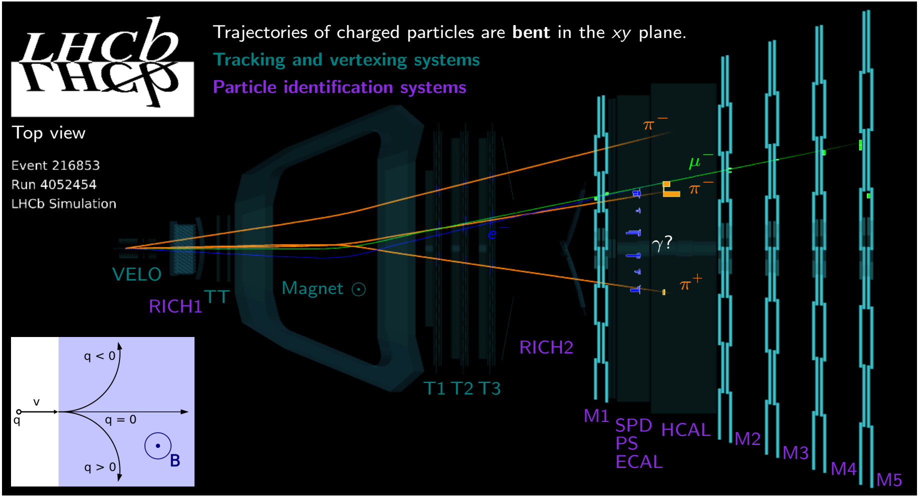




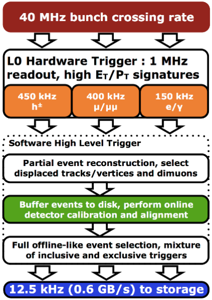
[JHEP (2015) 11 103]

The LHCb detector

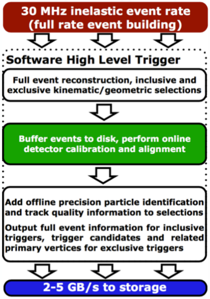


The LHCb trigger

- Hardware level L0:
  - → **removed** for Upgrade Ia (UIa).
  - → **benefit for low mass searches.**
- **Software level HLT:**
  - → Topological triggers on DV.
  - → Down to $p_T \sim 80$ MeV/c (μ).
  - → UIa: full event reco (30 MHz).
  - → **benefit for exotic searches.**
- **Turbo** (since 2015) lines:
  - → Any event part can be **saved.**
  - → Can work **directly** on them.
  - → **Online μ-ID and jets in turbo.**



LHCb Run II

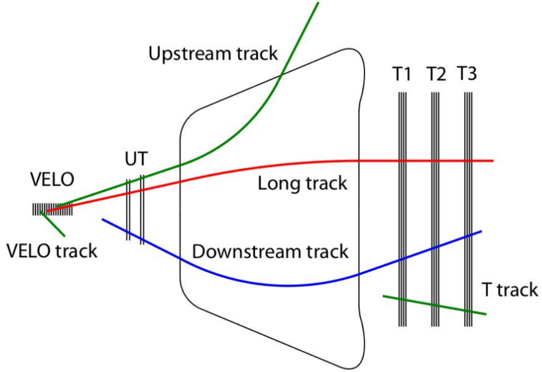


LHCb Upgrade Ia

- GPU-based HLT1 (Allen project) from UIa **[Comp Soft Big Sci (2020) 4 7]**

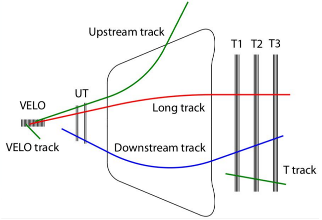
The LHCb reconstruction

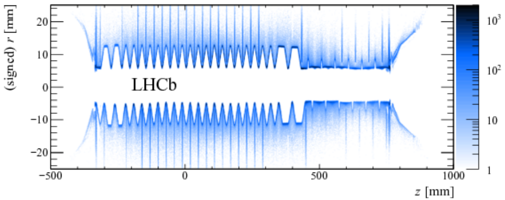
- **Long tracks:**
  - Tracks with hits in the tracking stations and in the VELO.
  - **Excellent spatial and momentum resolution.**
  - Reconstruction of particles decaying within VELO.
- **Downstream tracks** and **upstream tracks** – **see backup.**



The LHCb reconstruction

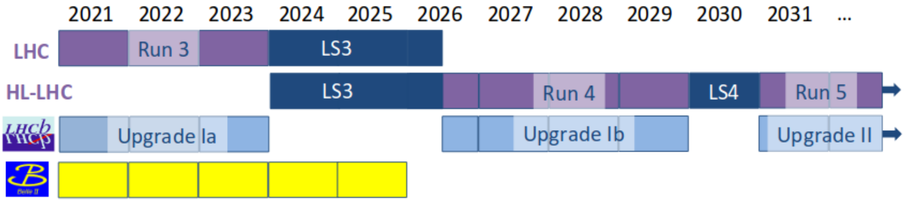
- **Long tracks:**
  - Tracks with hits in the tracking stations and in the VELO.
  - **Excellent spatial and momentum resolution.**
  - Reconstruction of particles decaying within VELO.
  - Presence of a **VELO envelope** (RF-foil) at $\sim$ 5 mm from beam:
    $\rightarrow$ Background dominated by heavy flavour below 5 mm.
    $\rightarrow$ 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]**
    $\rightarrow$ Sensitivity **improvement** by **one** to **two** orders of magnitude.
    $\rightarrow$ See **backup** for more details on the material veto map.
- **Downstream tracks** and **upstream tracks** – **see backup.**

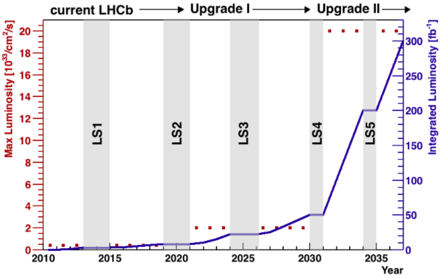




The future of LHCb

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



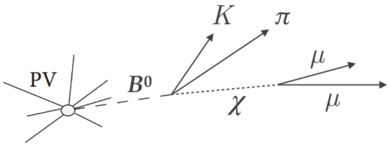


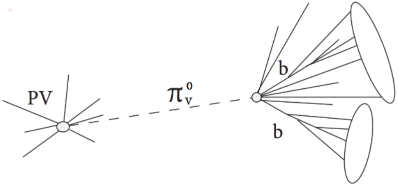
- Total dataset of 9 fb^{-1} collected during Run 1 and 2.
- Changes in Run 3: SciFi, UT, removal of M1, no L0 trigger, upgrade of subsystems.
- Expect to collect 300 fb^{-1} by the end of Upgrade 2.
- **Challenging conditions** – higher rate, pile-up, occupancy and fluence.
- Detector sub-systems have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

This talk

Selection of results and prospects on various signatures and models:

- **Low-mass dimuons:** dark photons, scalar resonances.
- **Long-lived particles:** decaying hadronically and semileptonically.
- **B-meson decays:** hidden sector bosons.
- **Other searches:** ALPs, CMSP.
- **Prospects:** Stealth major report, and CODEX-b.



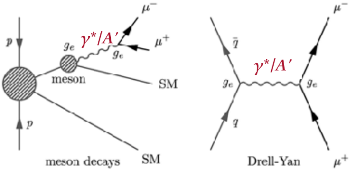


Low-mass dimuons

Dark Photons [PRL (2020) 124 041801]

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).



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

off-shell photon

phase-space

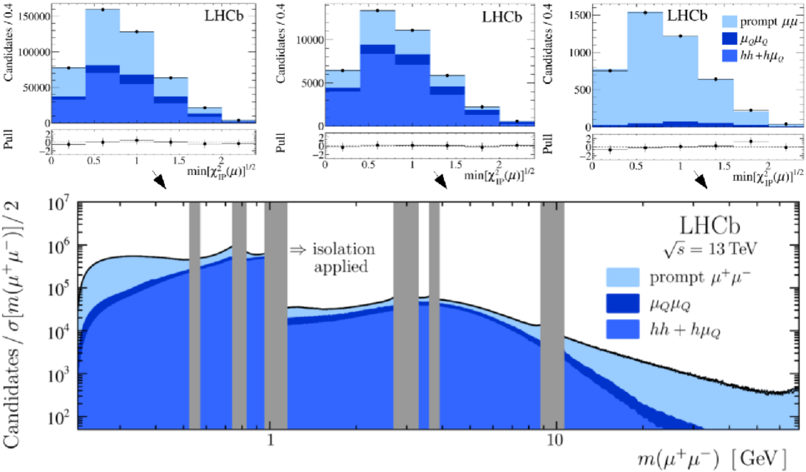
A$'$/γ^* eff ratio, ϵ=1 for prompt

Dark Photons [PRL (2020) 124 041801]

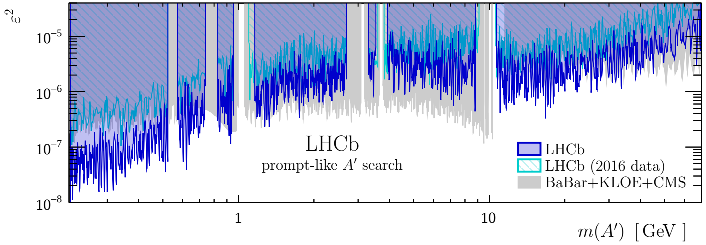
Using templates for min[χ^2_{IP}] (small mass dep)

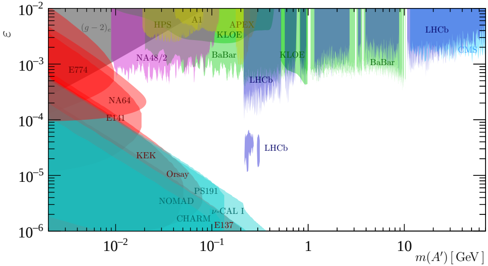
- prompt $\mu^+\mu^-$ → from data at $m(J/\psi)$ and $m(Z)$
- $\mu_Q\mu_Q$ → from simulation (validated)
- $hh + h\mu_Q$ → from same-sign dimuons (corrected)

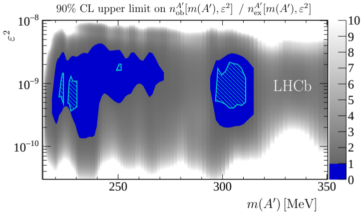
(μ_Q is a muon from a heavy-flavour decay)



Great sensitivity (especially above 10 GeV and below 0.5 GeV):

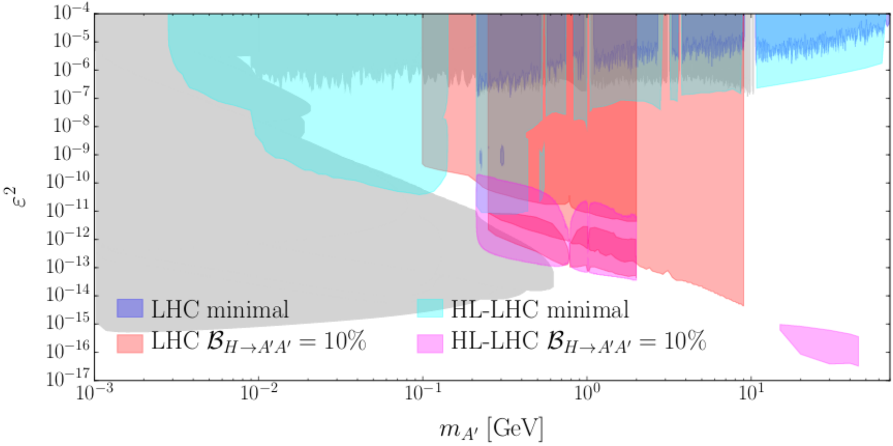






Dark Photons – **combined prospects**

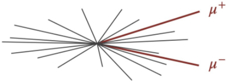
- Minimal scenario (LHCb) + Higgs portal (ATLAS/CMS):



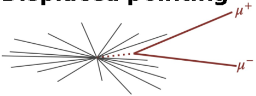
- **Signature sensitive to other models $\rightarrow$ model-independent search:**

+ no isolation requirement
+ non-zero width considered

Inclusive Prompt

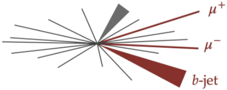


Displaced pointing

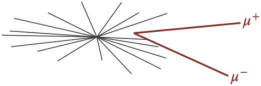


+ non-zero width considered

Prompt + b-jet

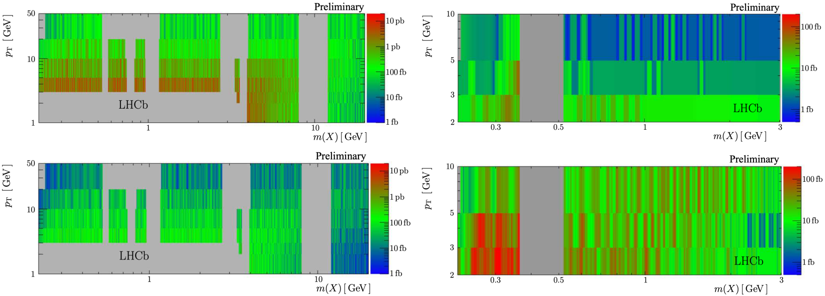


Displaced non-pointing

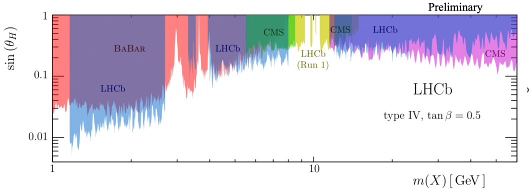


Dark Photons – **non-minimal searches** [JHEP 10 (2020) 156]

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



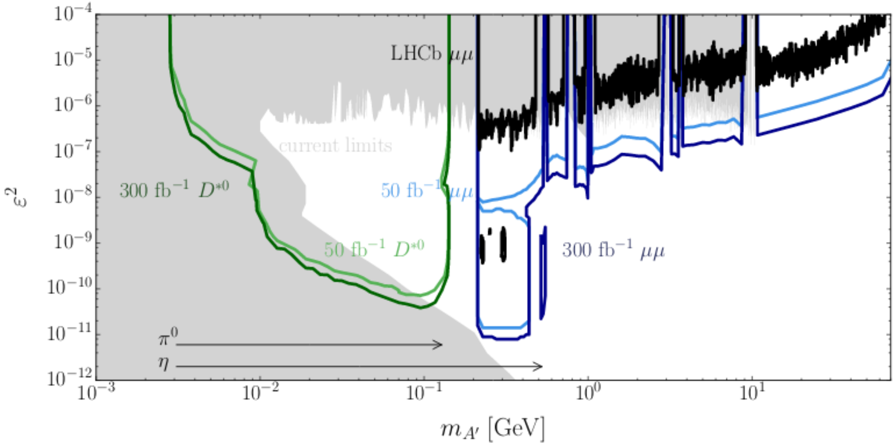
- 2HDM Higgs $\theta_H \to$ world-best limits:
  - $\to$ LHCb R1 **[JHEP 09 (2018) 147]**
  - $\to$ CMS R1 **[PRL 109 (2012) 121801]**
  - $\to$ CMS R2 **[PRL 124, 131802 (2020)]**
  - $\to$ Belle $\Upsilon \to X\gamma$ **[PRD 87 (2013) 031102]**
- Other scenarios covered too (*i.e.* HV).



Dark Photons – **the future**

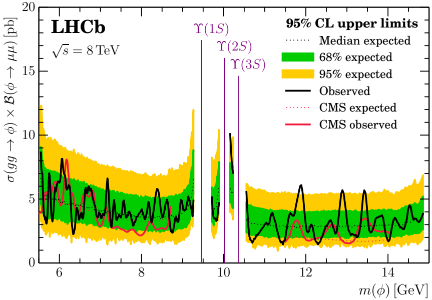
- Cover di-electron final states in $D^{*0} \to D^0 A'(ee)$ decays:
  $\to$ Hardwareless trigger is required (softer final state than in the di-muon mode),
  $\to$ High statistics $\to$ get $3\times10^{11} D^0$ per inverse fb!

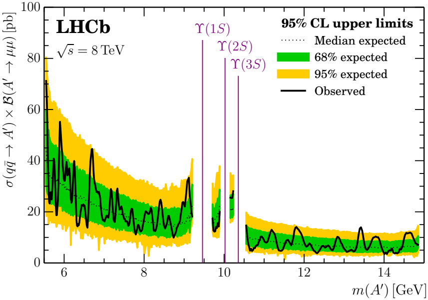
- Prospected reach for **Run III and beyond**: **[arXiv:1812.07831]**



Light dark bosons decaying into $\mu\mu$ **[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.
- **No excess observed** ☹ for more details → ask me during the coffee break ☺

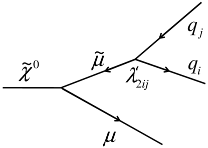


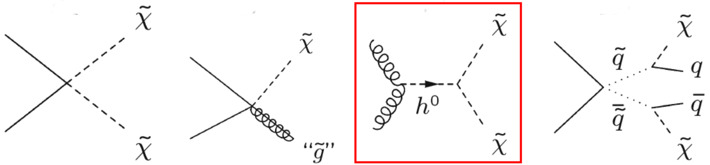


Long-lived particles

LLPs decaying into μ + jets [arXiv:2110.07293]

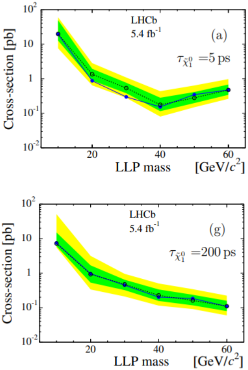
- **Massive LLP into μ + two quarks ($\rightarrow$ jets).**
- Signature sensitive to **several benchmark models:**
  - mSUGRA RPV neutralino,
  - Right-handed (Majorana) neutrinos,
  - Simplified MSSM production topologies:

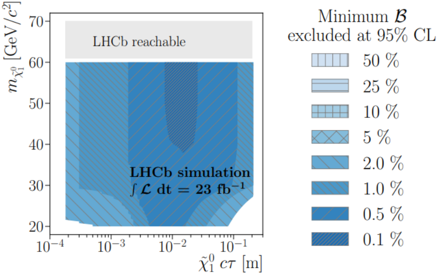




- One particular example: **decay of a Higgs-like particle** into two LLPs.
- Look for a **single displaced vertex** with several tracks + high p_T muon.
- Background dominated by $b\bar{b}$ events and material interactions.

- Search with 5.4 fb^{-1} of LHCb Run 1 and 2 data published.
- Results interpreted in $H^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ benchmark model:

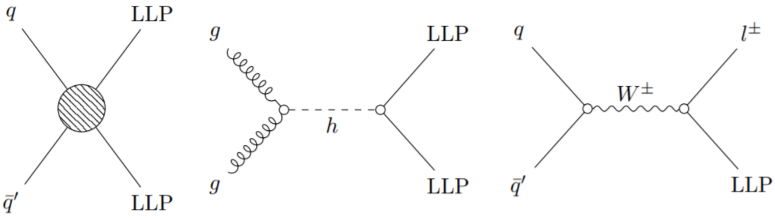




- Excluded production cross-section down to $\mathcal{O}(0.1)$ pb.
- Exclude $\mathcal{B}(H^0 \to \chi\chi)$ down to 0.1% by the end of Run 3 **[LHCb-CONF-2018-006]**

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

- Search for a long-lived particle decaying into $e^+\mu^-\nu$, and produced:
    - via direct pair production (DPP) from *pp* collisions,
    - from an exotic Higgs decay (HIG), produced in pairs,
    - or from a charged current process (CC).



- 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.
- Leptonic triggers with low p_T requirements → allow to access small LLP masses.

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.

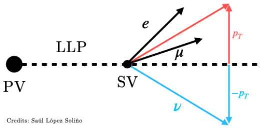
Selection:

- 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).

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

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.



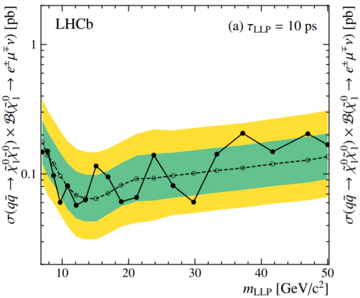
1. Assume LLP origin vertex approximately be the same as the *pp* collision.
2. Obtain a (pseudo) decay vertex using the di-lepton systems.
3. Project the di-lepton system momenta to the LLP direction of flight.

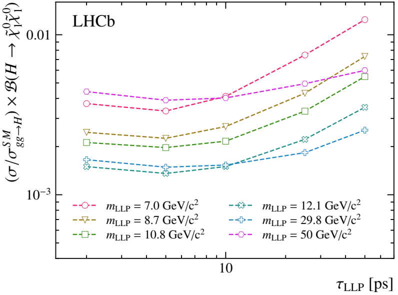
$$m_{\text{corr}} = \sqrt{m(e\mu)^2 + p(e\mu)^2 \sin^2\theta} + p(e\mu)\sin\theta$$

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

Results:

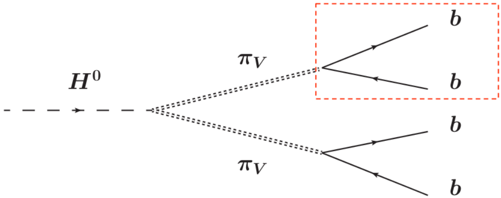
- Simultaneous ML fit to m_{corr} and LLP flight distance in two BDT bins.
- Systematics dominated by choice of signal models.
- UL at 95% C.L. on σB per model – **no excess found**.
- Best UL for DPP with lifetimes below 10 ps and masses above 10 GeV $\rightarrow$ order of 0.1 pb.





LLPs decaying into jet pairs **[EPJC (2017) 77 812]**

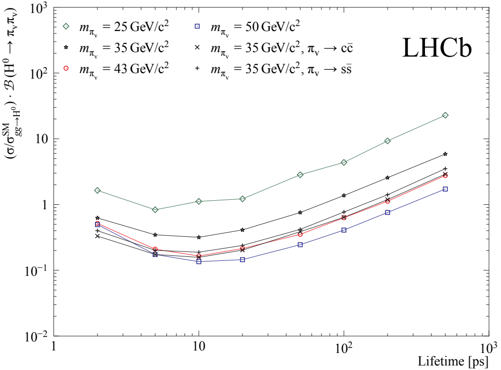
- Possible scenarios to accommodate this signature:
  - LSP in gravity mediated/BNV or LNV SUSY models,
  - **HV π_v decaying to $b\bar{b}$ – especially with SM-like $H^0 \to \pi_v \pi_v$ production.**
- In most of the cases **only one** of the two π_v decays into the LHCb acceptance.
- Experimental signature is a **single displaced vertex** with two associated jets.



- Reconstruct the displaced vertex and find two associated jets.
- Use π_v detachment to **discriminate** between signal and background.
- Background dominated by $b\bar{b}$ events and **material interactions.**

LLPs decaying into jet pairs **[EPJC (2017) 77 812]**

- Search with full LHCb Run 1 (3 fb^{-1}) dataset published.
- Limits at 95% C.L. as a function of π_v lifetime for several π_v masses:

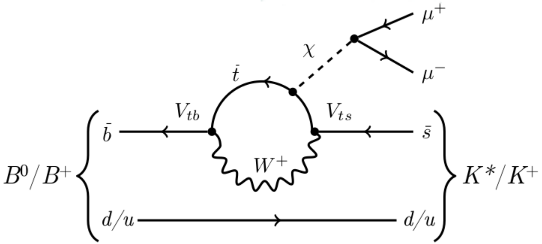


- Plan to analyse final state including kaons and pions (lower π_v masses).
- Improved simulation models including dark showers (multiple dark hadrons).

B-meson decays

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

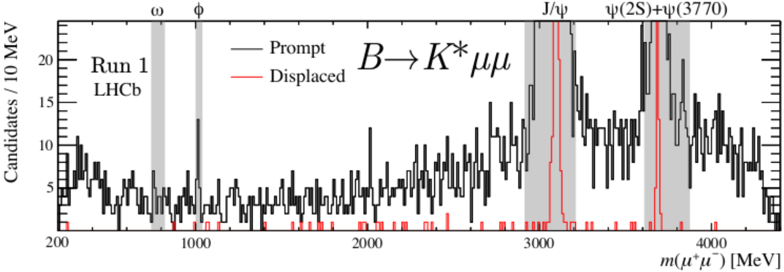
- $\mathrm{B}^0 \to K^{*0}\chi$ **[PRL 115 (2015) 161802]** / $\mathrm{B}^+ \to K^+\chi$ **[PRD 95 (2017) 071101 (R)]**
- Search for hidden-sector bosons $\chi \to \mu^+\mu^-$ in $b \to s$ penguin decays:
  - Axial-vector portal (χ as axion) **[LNP 741 (2008) 3]**
  - **Scalar** (Higgs) portal (χ as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



- First dedicated search ($K^{*0}\chi$) over such a large mass range:
  - **Pro:** $K^{*0} \to K^+\pi^-$ vertex leads to better $\tau(\chi)$ resolution and less background.
  - **Con:** $\mathrm{B}^0 \to K^{*0}\chi$ has smaller branching fraction than the $\mathrm{B}^+ \to K^+\chi$ mode.
- Allow for prompt and **detached** di-muon candidates – up to 1000 ps ($\sim$ 30 cm).

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

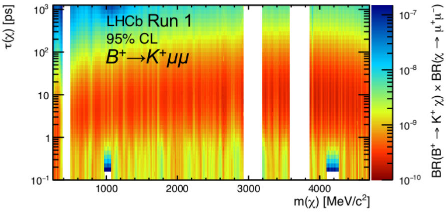
- Full LHCb Run I dataset (3 fb^{-1}) used for both searches.
- Look for a narrow di-muon peak (mass resolution between 2 and 9 MeV/c^2).
- Exclude narrow QCD resonances - mass distribution: **[PRL 115 (2015) 161802]**

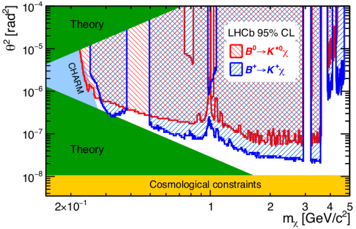


- MVA selection almost independent of χ mass and decay time (uBoost).

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

- 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):



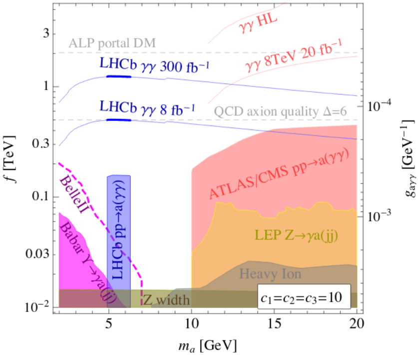


- **No evidence for signal observed.**
- **Large fraction of allowed inflaton parameter space ruled out.**

Other searches

ALPs decaying into pairs of photons

- Constraints from LHC resonance searches above $m_a \sim 60$ GeV/c^2 ($a \to \gamma\gamma$, jj).
- **But** – poor limits for low masses → use $\gamma\gamma$ x-section measurements. **[PLB (2018) 06 039]**
- LHCb **could cover** the region between 3 and 10 GeV/c^2 (recast): **[JHEP 1901 (2019) 113]**

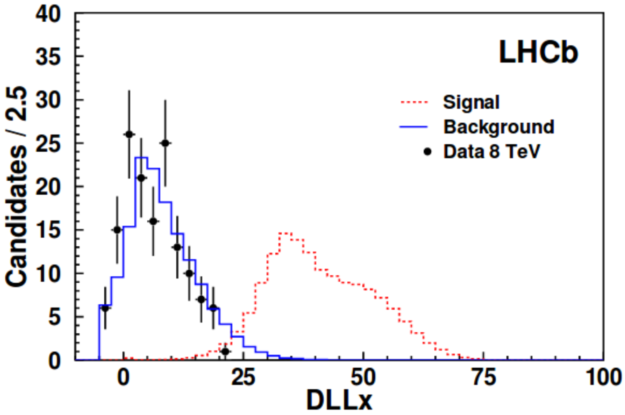


- Trigger (MVA) for **soft** $\gamma\gamma$ searches.
- **Two** selections **[LHCb-PUB-2018-006]** **[arXiv:1906.09058]**
  - → **B**: cut around $m(B_s^0)$ (since 2015).
  - → **ALP**: up to 11 GeV/c^2 (only 2018).
- **Planned search** using 2018 LHCb data.

Requirement (2x2 cell clusters)	B	ALP
$E_T(\gamma)$ [GeV]	> 3.5	> 5
$E_T(\gamma_1) + E_T(\gamma_2)$ [GeV]	> 8	> 11
$M(\gamma_1\gamma_2)$ [GeV/c^2]	[3.5, 6.0]	[6.0, 11.0]
$p_T(\gamma_1\gamma_2)$ [GeV/c]	> 2	> 5

Identify exotic signatures using RICH sub-detectors

- Use likelihoods to separate particles according to their masses, β, energy loss...
- Proof of concept (search for CMSP particles at LHCb) **[EPJC (2015) 75:595]**
- An example – distinguish between exotic heavy particles from Drell-Yan muons:



Prospects

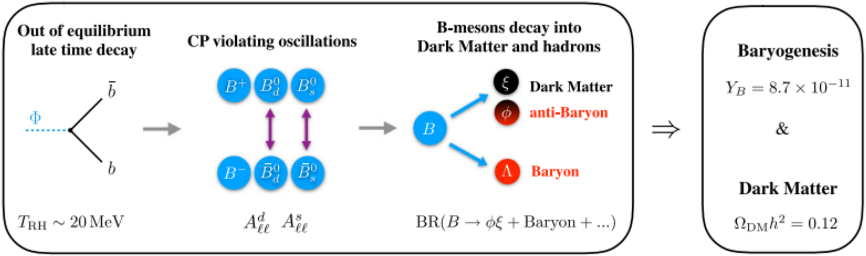
Stealth white paper

- 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]**

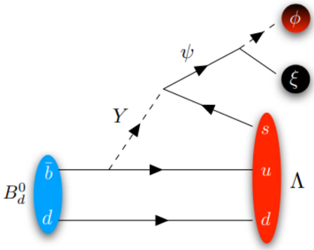
S1: B-mesogenesis

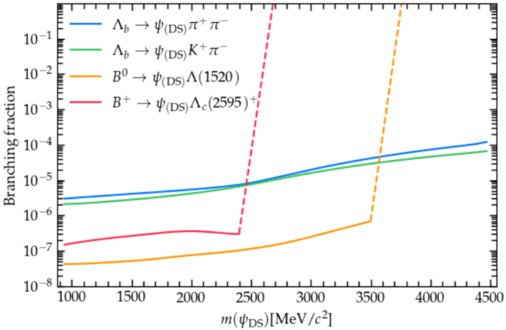
- Explain baryon asymmetry and DM abundance at the same time.
- Propose a DM candidate with baryon number: **[PRD 99, 035031]**
- Observables in the model are $A_{SL}^{s,d}$ and $\mathcal{B}(H_b \to \Psi_{(DS)} + X)$.



S1: B-mesogenesis

- Predictions of $\mathcal{B}$ down to 10^{-6} and $A_{SL}^{s,d}$ between 10^{-5} and 10^{-3}.
- $A_{SL}^{s,d}$ is measured with high precision, while $\mathcal{B}(H_b \to \Psi_{(DS)} + X)$ has been never studied.
- LHCb can constrain the alowed space by the end of Run 3 (15 fb^{-1}) **[EPJC (2021) 81 964]**





S2: Confining HV

- Generic search for $H \to SS$ where $S \to K^+K^-$ instead of to HF: **[JHEP (2020) 115]**

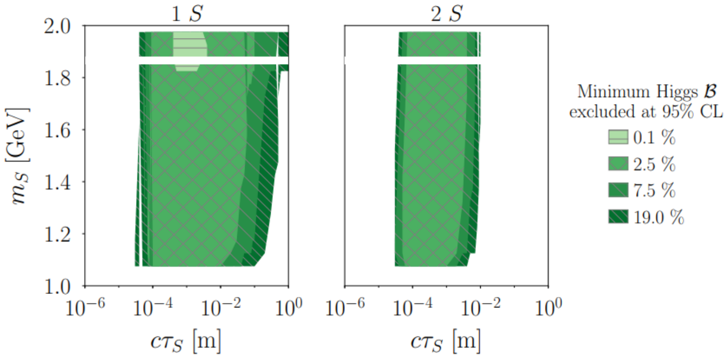
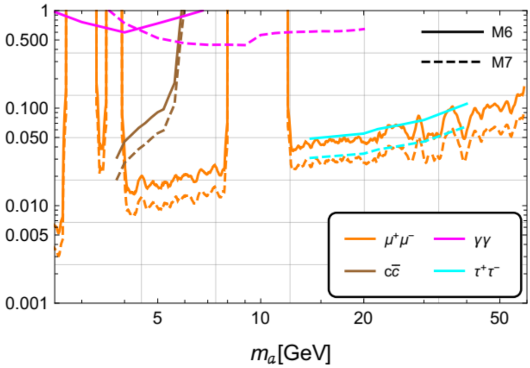


Figure 3. Range of S lifetime and mass for which a 95% CL exclusion of the branching fraction of the decay $h \to SS$ is possible at LHCb with an integrated luminosity of 15 fb^{-1} for different values of this branching fraction. We assume BR($S \to K^+K^-$) = 100% in these plots. Left plot shows the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

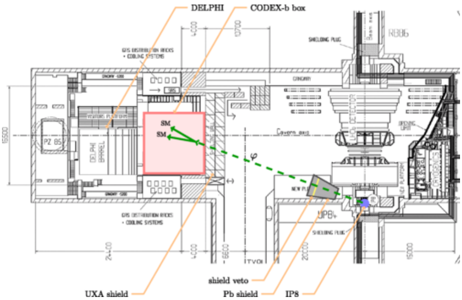
S3: Composite ALP

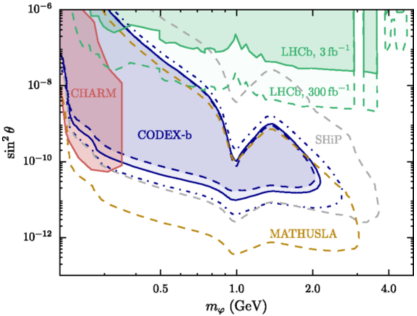
- Axion-like particle in the context of Composite Higgs models: **[EPJC (2022) 82 3]**
- Low-mass pseudoscalar decaying into pairs of leptons, quarks or photons.
- Reinterpreation of existing $\gamma\gamma$ (QCD axion projections) and $\mu\mu$ (experimental) boundaries.
- Studies for final states consisting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



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.
  - LHCb has already provided limits for this signature using Run 1 data **[PRD 115 (2015) 161802]**





Conclusions

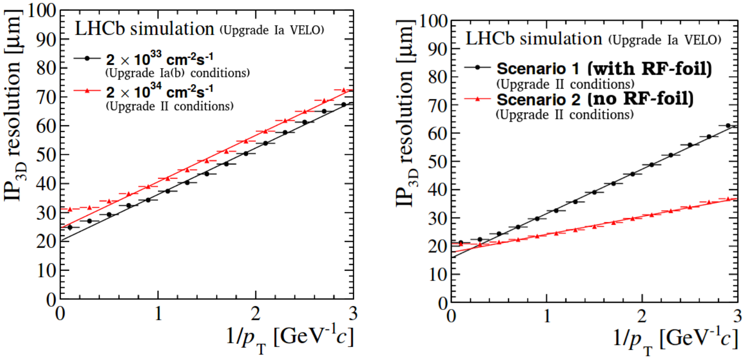
- LHCb proved to be **very competitive** for Stealth physics:
  - Excellent vertexing, tracking and soft trigger.
  - Especially competitive for low masses and lifetimes.
  - Rich variety of models and signatures can be approached.
- **Bright prospects** for the future:
  - Removal of hardware trigger $\rightarrow$ access softer kinematics.
  - Better vertex resolution and tracking capabilities.
  - New techniques under development for ideas on new signatures.
- **Many other existing results and proposed studies** not covered:
  - LFV Higgs decays **[EPJC (2018) 78 1008]**
  - HNLs from B and D meson decays, or prompt W decays **[EPJC (2021) 81 248]**
- **Major report** on Stealth physics at LHCb: more than 20 models covered.

Thanks for your attention!

Backup

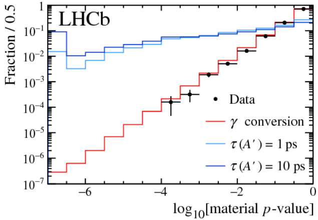
The upgraded LHCb VELO

- **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.

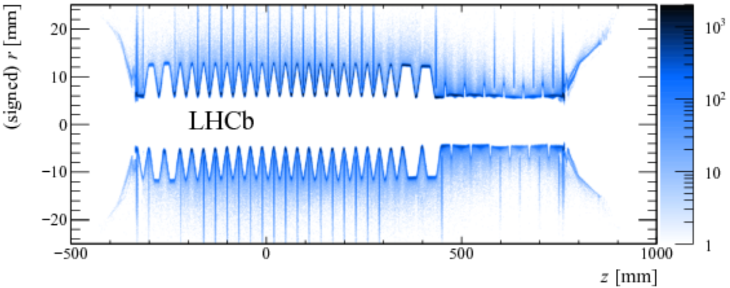


VELO material map [JINST 13 (2018) P06008]

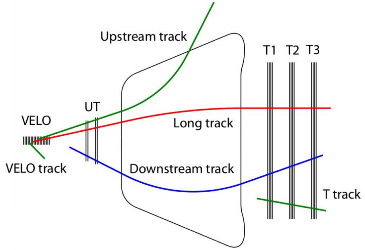
- Background dominated by material interactions for displaced searches at LHCb.
- Mandatory to **keep control** of material interactions – veto them in an efficient way:



- 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).



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.

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 $\mathrm{M_{corr}(SV)} = \sqrt{\mathrm{M^2 + p^2 sin^2\theta}} + \mathrm{psin}\theta$.
  - BDT(bc|udsg) to separate light and heavy flavour jets, BDT(b|c) to separate b from c-jets.
  - Tagging efficiency of b(c)-jets of 65% (25%) with 0.3% contamination from light jets.