

Direct searches for new low-mass particles at LHCb

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The LHCb detector [IJMP A30 (2015) 1530022]



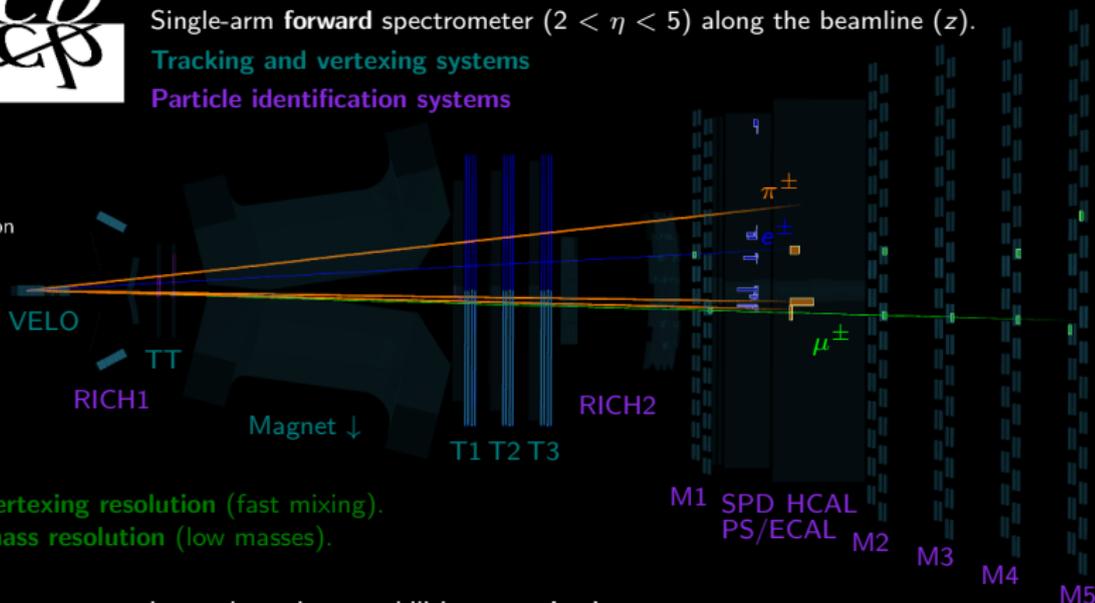
LHCb is a 20×5 m GPD in the forward region (upgrade during LS2 – see backup).
Single-arm forward spectrometer ($2 < \eta < 5$) along the beamline (z).

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).

Excellent jet reconstruction and tagging capabilities – see backup.

The LHCb detector [IJMP A30 (2015) 1530022]



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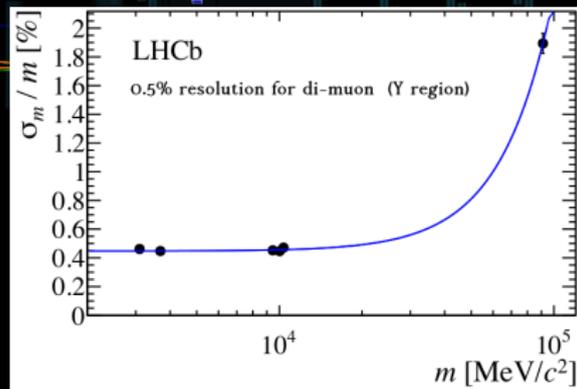
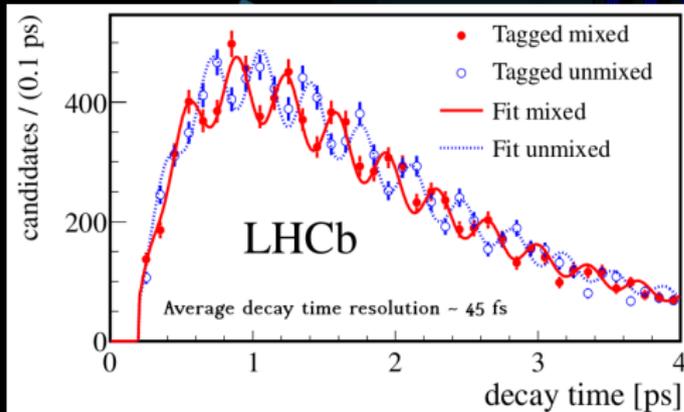
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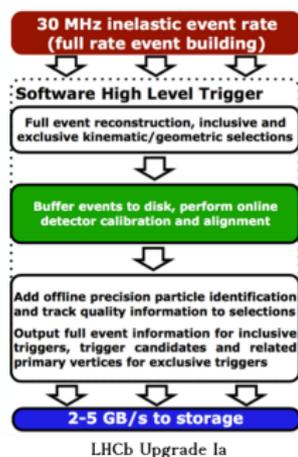
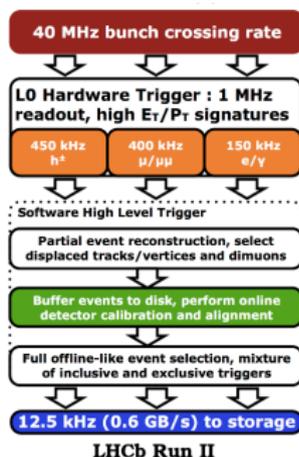
Event 216853

Run 4052454



The LHCb detector [IJMP A30 (2015) 1530022]

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

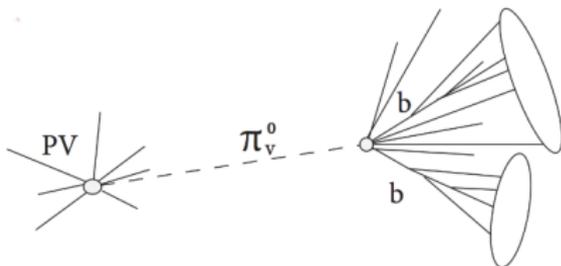
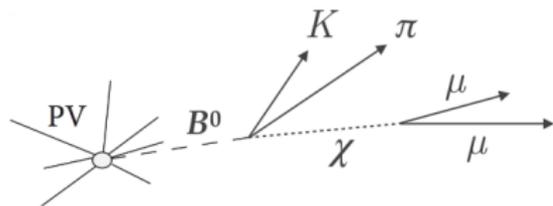


Unique coverage complementary to ATLAS/CMS:

- Soft trigger and forward acceptance \rightarrow **lower masses** (few GeV/MeV for jets/leptons).
- Excellent tracking and vertexing capabilities \rightarrow **lower lifetimes** (~ 1 ps).

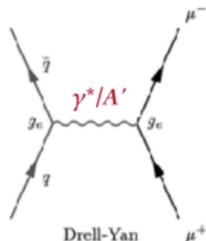
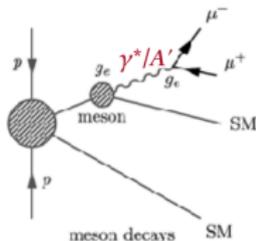
LHCb capabilities to exploit low masses and low lifetimes:

- Search for a di-muon resonance in $\Sigma^+ \rightarrow \rho \mu^+ \mu^-$ decays [PRL (2018) 120 221803]
- Search for candidates produced in B -hadron decays – see backup.
- Search for candidates **produced in the pp collision**:
 - **Dark photons decaying into pairs of muons,**
 - **Dark bosons in the mass region close to the Υ resonances,**
 - **Axion-like particles (ALPs) decaying into pairs of photons.**
 - Dark pions produced via SM Higgs decaying into jets (see L. Sestini talk today).



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 $A' \rightarrow \mu^+ \mu^-$ can be normalised to $\gamma^* \rightarrow \mu^+ \mu^-$.
 - 3 No use of MC \rightarrow no systematics from MC \rightarrow **fully data-driven analysis!**
- Separate γ^* signal from background and measure its fraction.
- **Prompt-like** search (up to 70 GeV/c²) \rightarrow **displaced** search (214 – 350 MeV/c²).
 - A' is long-lived only if the mixing factor is really small.
- Used 1.6 fb⁻¹ of 2016 LHCb data (13 TeV).



$$n_{\text{obs}}^{A'}[m(A'), \epsilon^2] = \epsilon^2 \left[\frac{n_{\text{obs}}^{\gamma^*}[m(A')]}{2\Delta m} \right] \mathcal{F}[m(A')] \epsilon_e^{A'}[m(A'), \tau(A')]$$

off-shell photon

phase-space

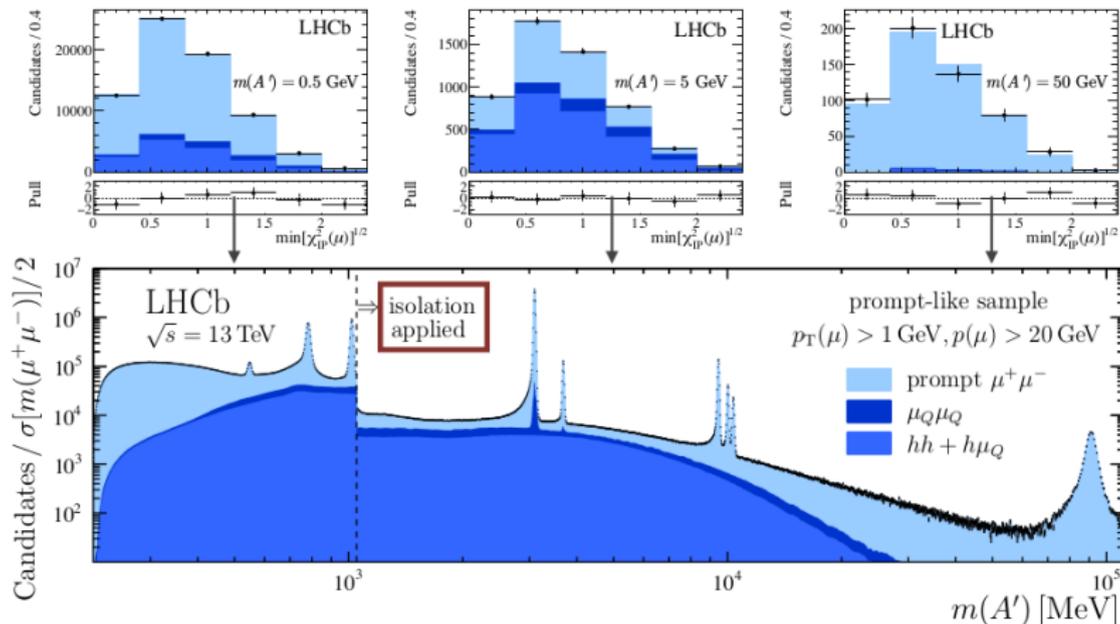
A'/γ^* eff ratio,
 $\epsilon=1$ for prompt

Dark Photons [PRL (2018) 120 061801]

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

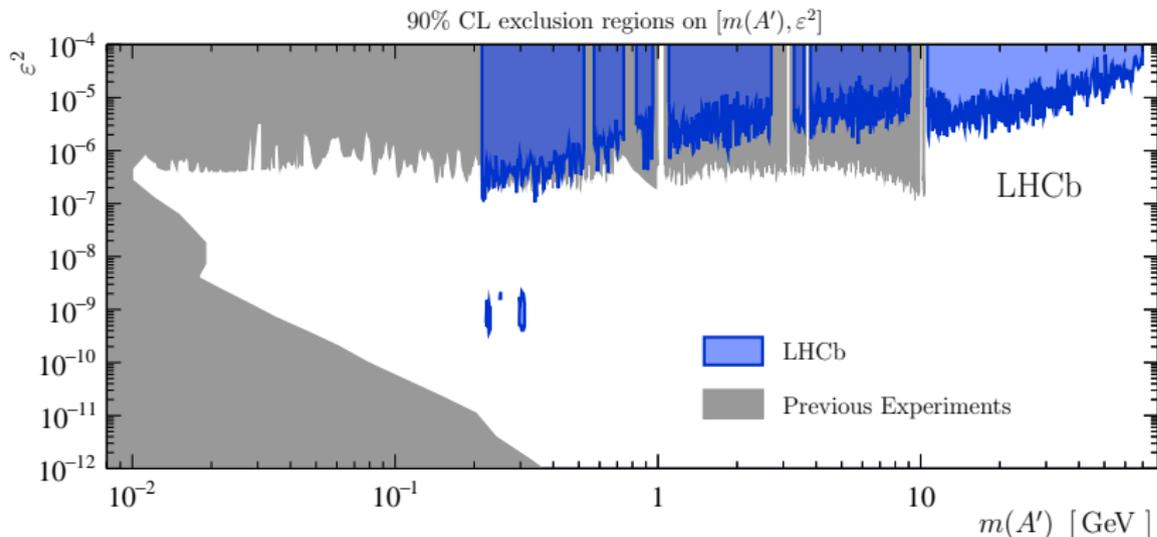
- prompt $\mu^+\mu^-$ → from data at $m(J/\psi)$ and $m(Z)$
- $\mu_Q\mu_Q$ → from simulation (validated)
- $hh + h\mu_Q$ → from same-sign dimuons (corrected)

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



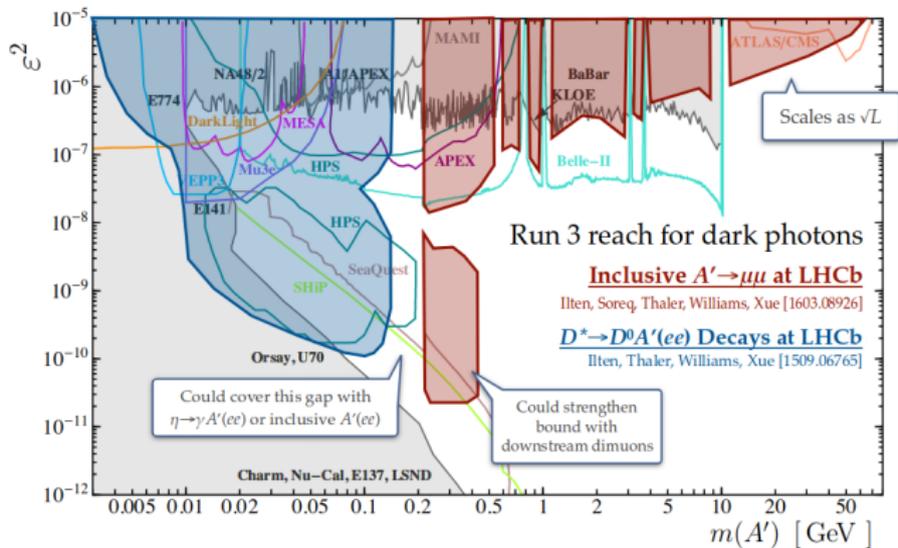
Dark Photons [PRL (2018) 120 061801]

- Displaced search is performed as well – see **backup** for details.
- **No significant excess found** - exclusion regions shown below:
 - First limits on masses above 10 GeV & competitive limits below 0.5 GeV.
 - Small displaced A' region excluded as well.
- Updated limits using full LHCb Run 2 **coming very soon** – stay tuned!



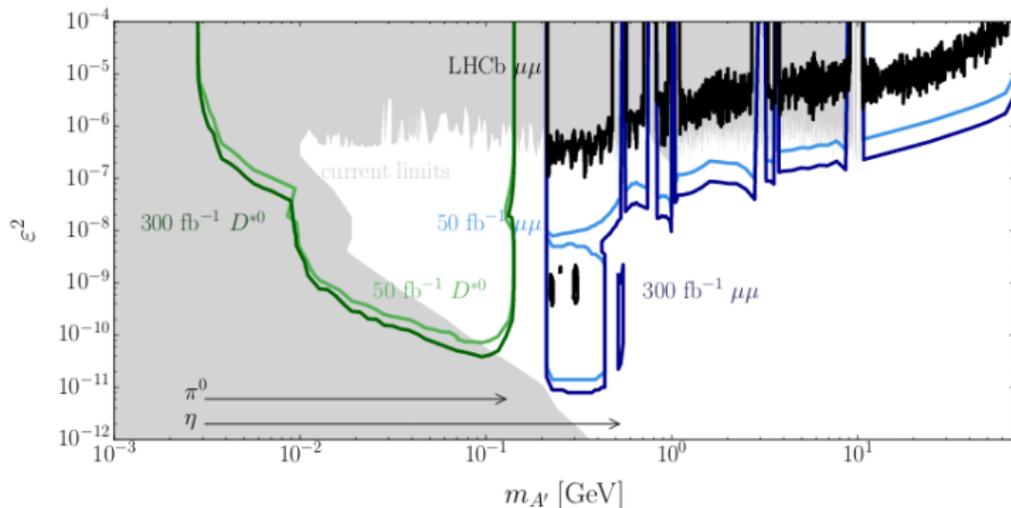
Dark Photons – the future

- Cover di-electron final states in $D^{*0} \rightarrow D^0 A'(ee)$ decays:
 - Hardwareless trigger is required (softer final state than in the di-muon mode),
 - High statistics → get $3 \times 10^{11} D^0$ per inverse fb!
- Extend searches model-independently:
 - Recast in other vector models [JHEP 06 (2018) 004]
 - Recast in (pseudo-)scalar models [arXiv:1802.02156]
- Prospected reach for **Run III** – comparison with other experiments:



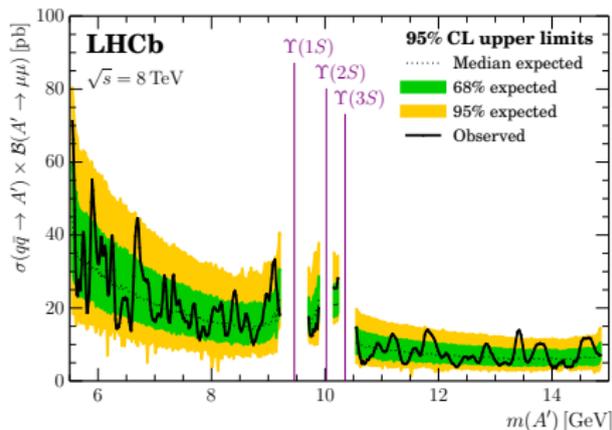
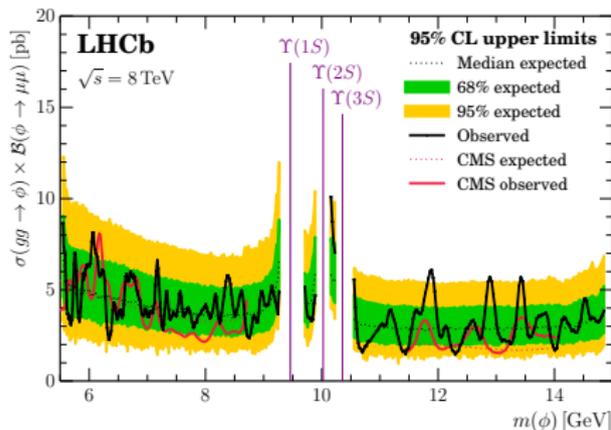
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 - Recast in (pseudo-)scalar models [[arXiv:1802.02156](#)]
- Prospected reach for **Run III and beyond**: [[arXiv:1812.07831](#)]



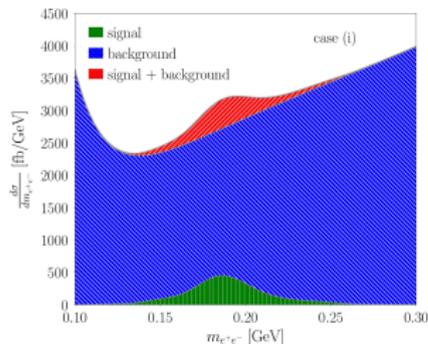
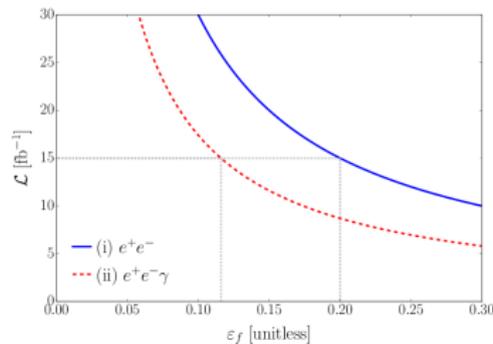
Light dark bosons decaying into $\mu\mu$ [JHEP 09 (2018) 147]

- Light spin-0 particles copiously produced in gluon-gluon fusion:
 - Many models: NMSSM, 2HDM+S, etc.
 - Recent 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 ☺



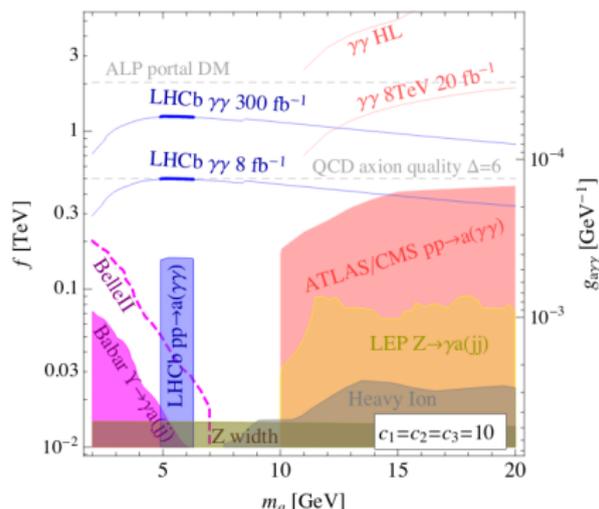
Discovering True Muonium at LHCb [arXiv:1904.08458]

- LHCb interested in vector (3S_1) state:
 - Direct production via kinetic mixing of TM with γ^* à la dark photon.
 - Dissociation factor estimated to be $\sim 50\%$ for Run 3 material budget.
- QED predicts $\tau \sim 1.8$ ps and mass ~ 211 MeV:
 - Very low mass \rightarrow off-shell γ production via $\eta \rightarrow \gamma\gamma^*$ (small BR but high σ).
 - Experimental signature \rightarrow **resolvable displaced vertex** decaying into e^+e^- pairs.
- **Inclusive search** – reconstruct only $\gamma^* \rightarrow e^+e^-$ (simpler, smaller systematics).
- Prospects (Run 3 & beyond) – different, conservative assumptions on reco ε :
 - Assume current LHCb e^+e^- mass resolution (~ 20 MeV at 211 MeV).
 - **Discovery potential** at 15 fb^{-1} ($5\sigma_{\text{stat}}$), inclusive search:



ALPs decaying into pairs of photons

- Constraints from LHC resonance searches above $m_a \sim 60 \text{ GeV}/c^2$ ($a \rightarrow \gamma\gamma, jj$).
- **But** – poor limits for low masses \rightarrow 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]
 - \rightarrow **B**: cut around $m(B_s^0)$ (since 2015).
 - \rightarrow **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

- LHCb proved to be **very competitive** for direct searches:
 - 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 → access softer kinematics.
 - Better vertex resolution and tracking capabilities.
 - New techniques under development for ideas on new signatures.
- We are looking forward to ideas for new signatures and techniques:
 - **Do not hesitate to contact us if interested!**

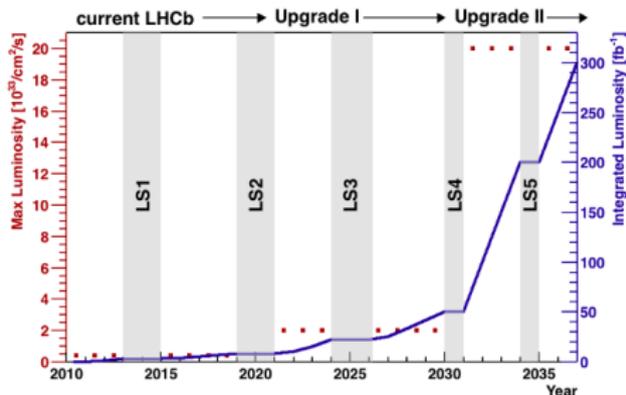
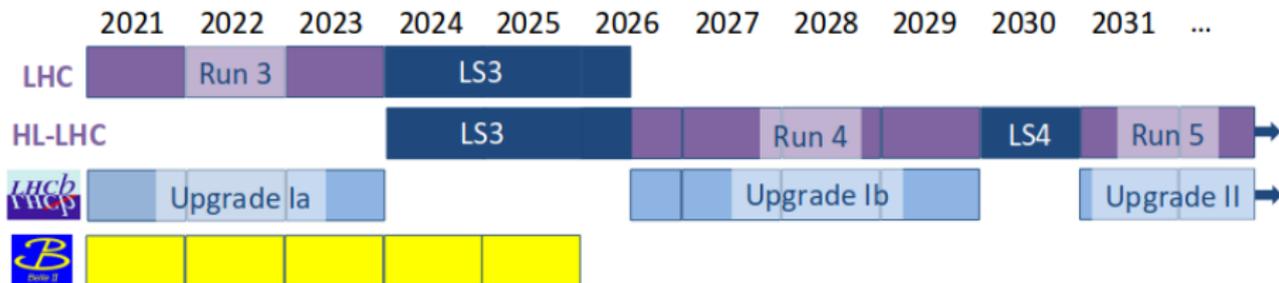


Thanks for your attention!

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]

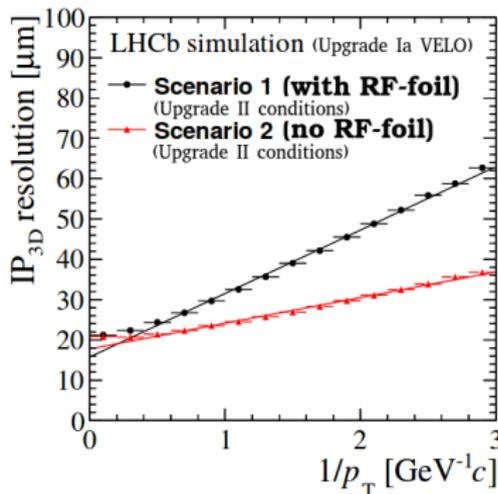
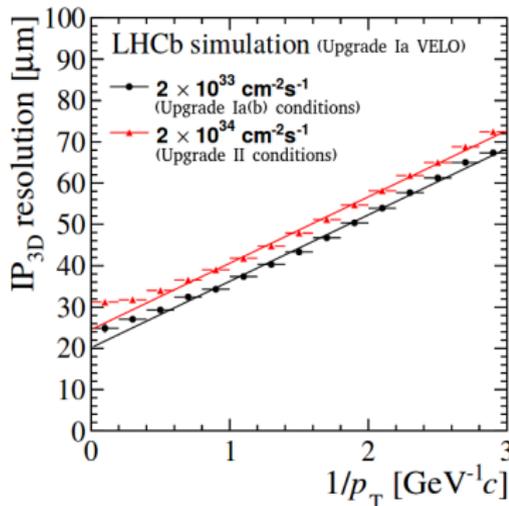


- **Challenging conditions** – higher rate, pile-up, occupancy and fluence.
- Expect to collect 300 fb^{-1} by the end of Upgrade II.
- Detector sub-systems have to be able to cope with such conditions.
- In particular – **trigger** and **tracking systems** are crucial for DS searches.

The upgraded LHCb VELO

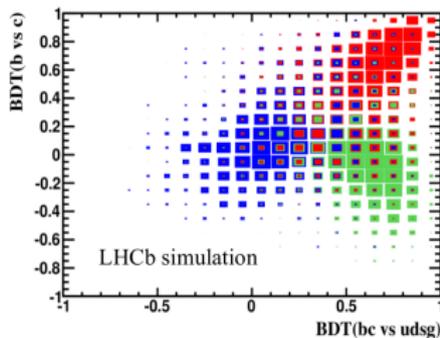
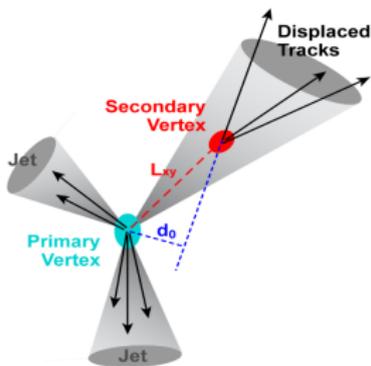
● Upgrade II VERTex LOcator: [CERN-LHCC-2017-003]

- 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:
 - better IP resolution + no material interactions.



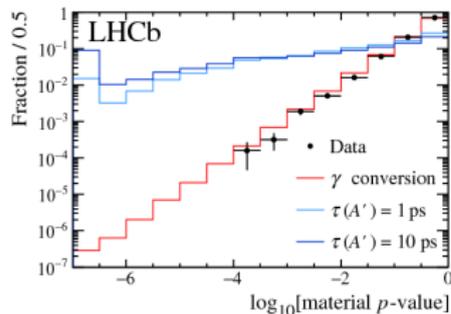
Jet reconstruction and identification at LHCb

- 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 $Z \rightarrow \mu\mu + \text{jets}$),
 - 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 $M_{\text{CORR}}(\text{SV}) = \sqrt{M^2 + p^2 \sin^2 \theta} + p \sin \theta$.
 - 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.

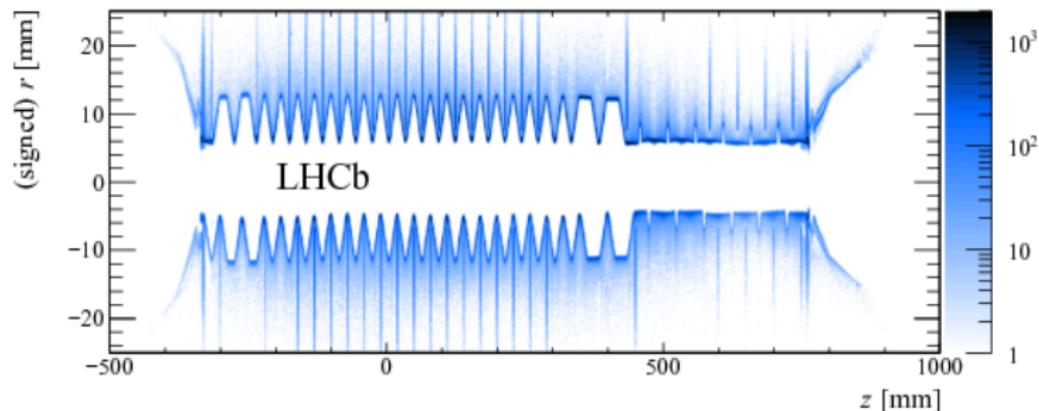


VELO material map [JINST 13 (2018) P06008]

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



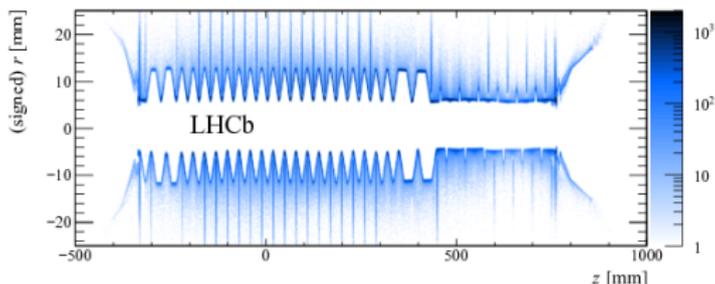
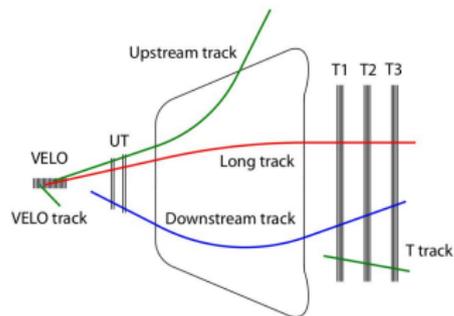
- Background mainly due to γ conversions (left plot).
- A new VELO material map has been developed:
 - Model in **great detail** both sensors & envelope.
 - Assign a **p-value** to material interaction hypothesis.
 - Sensitivity improvement by $\mathcal{O}(10)$ to $\mathcal{O}(100)$.
 - Based on data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



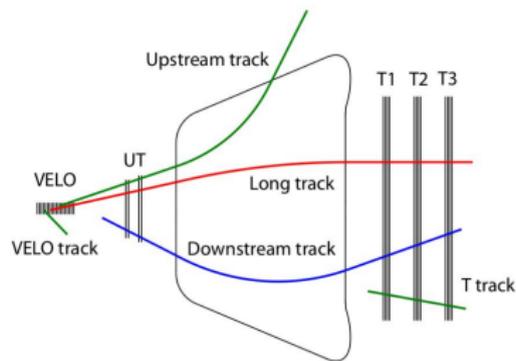
The LHCb reconstruction

- **Tracks with tracking stations & VELO hits (a.k.a. long tracks):**

- **Excellent spatial and momentum resolution.**
- Reconstruction of particles decaying within VELO.
- 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]**
 - Sensitivity **improvement** by **one to two** orders of magnitude.
 - See **backup** for more details on the material veto map.



The LHCb reconstruction



Downstream tracks:

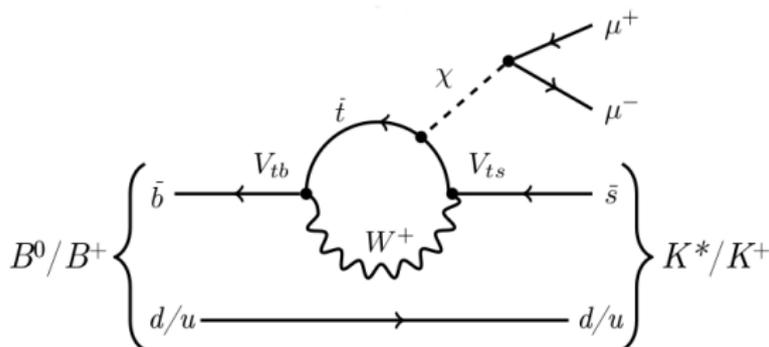
- Reconstruction of particles decaying beyond VELO.
- Tracks with worse vertex and momentum resolution.
- Trigger on downstream tracks \rightarrow better for LLP (≤ 2 m) signatures.
- Optimisation studies on-going [LHCb-PUB-2017-005]

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.

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

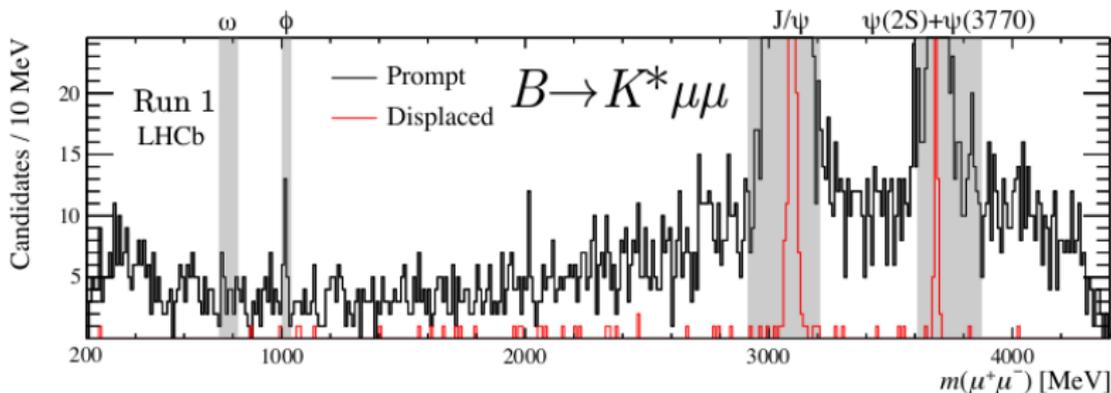
- $B^0 \rightarrow K^{*0} \chi$ [PRL 115 (2015) 161802] / $B^+ \rightarrow K^+ \chi$ [PRD 95 (2017) 071101 (R)]
- Search for hidden-sector bosons $\chi \rightarrow \mu^+ \mu^-$ in $b \rightarrow s$ penguin decays:
 - Axial-vector portal (χ as axion) [LNP 741 (2008) 3]
 - **Scalar** (Higgs) portal (χ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



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

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

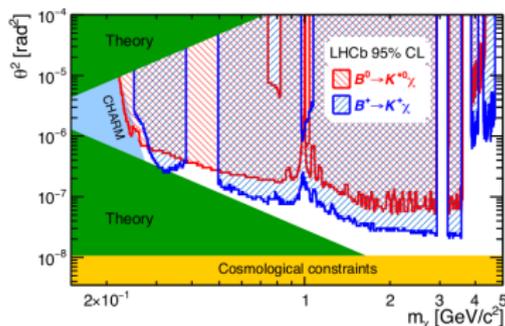
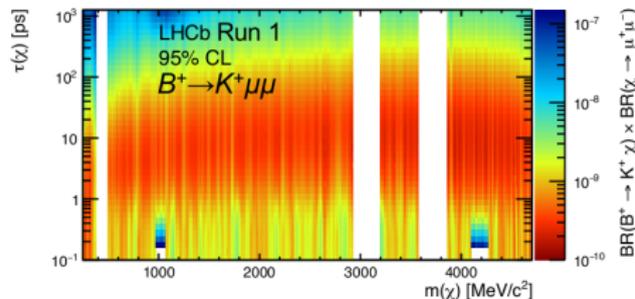
- Full LHCb Run I dataset (3 fb^{-1}) used for both searches.
- Look for a narrow di-muon peak (mass resolution between 2 and 9 MeV/c^2).
- Exclude narrow QCD resonances - mass distribution: [\[PRL 115 \(2015\) 161802\]](#)



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

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

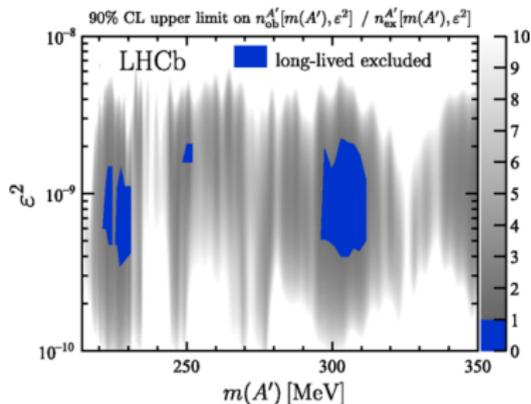
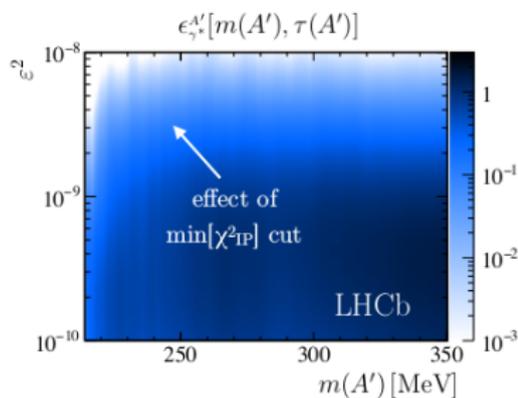
- BR normalised to $\mathcal{B}(B^+ \rightarrow K^+ J/\psi)$ ($\sim 10^{-4}$) or $\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$ ($\sim 10^{-7}$).
- Constraints on $\tau(\chi)$ between 0.1 and 1000 ps (left), [PRD 95 (2017) 071101 (R)]
- Constraints on mixing angle θ^2 between the Higgs and χ in the inflaton model (right):



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

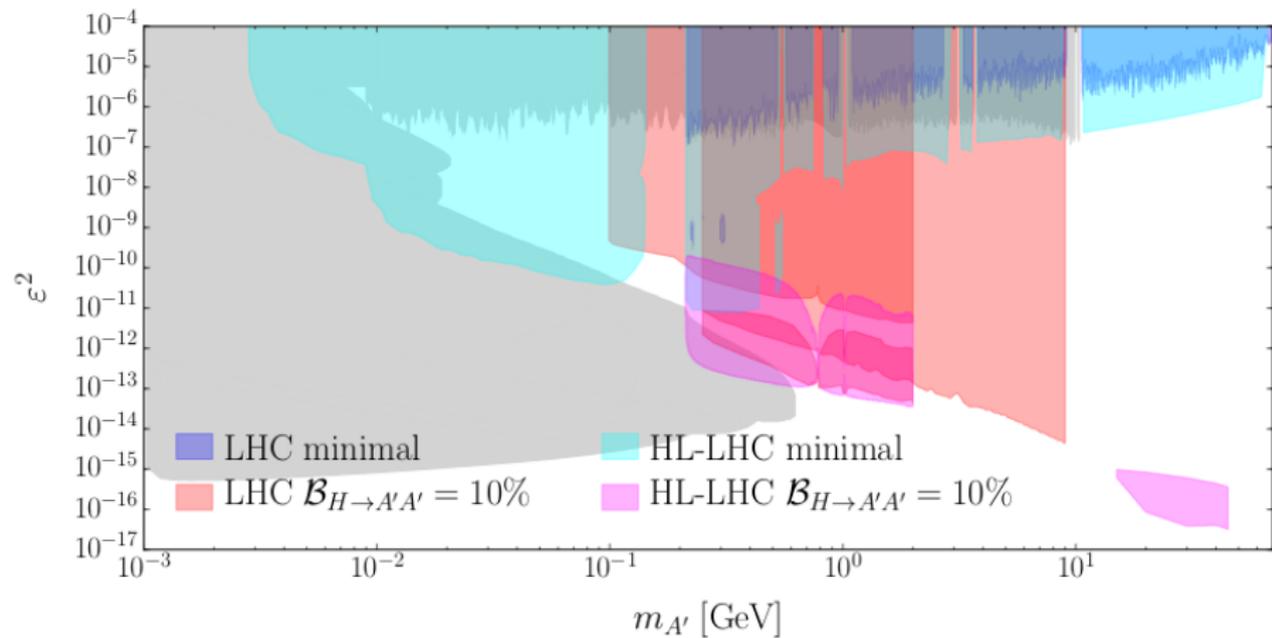
Dark Photons – displaced search [PRL (2018) 120 061801]

- Looser requirements on muon transverse momentum.
- Material background mainly from photon conversions [JINST 13 (2018) P06008]
- Isolation decision tree from $B_s^0 \rightarrow \mu^+ \mu^-$ search: [PRL (2018) 118 191801]
→ Suppress events with additional number of tracks, i.e. μ from b -hadron decays.
- Fit in bins of mass and lifetime – use consistency of decay topology χ^2 .
- Extract p-values and confidence intervals from the fit:



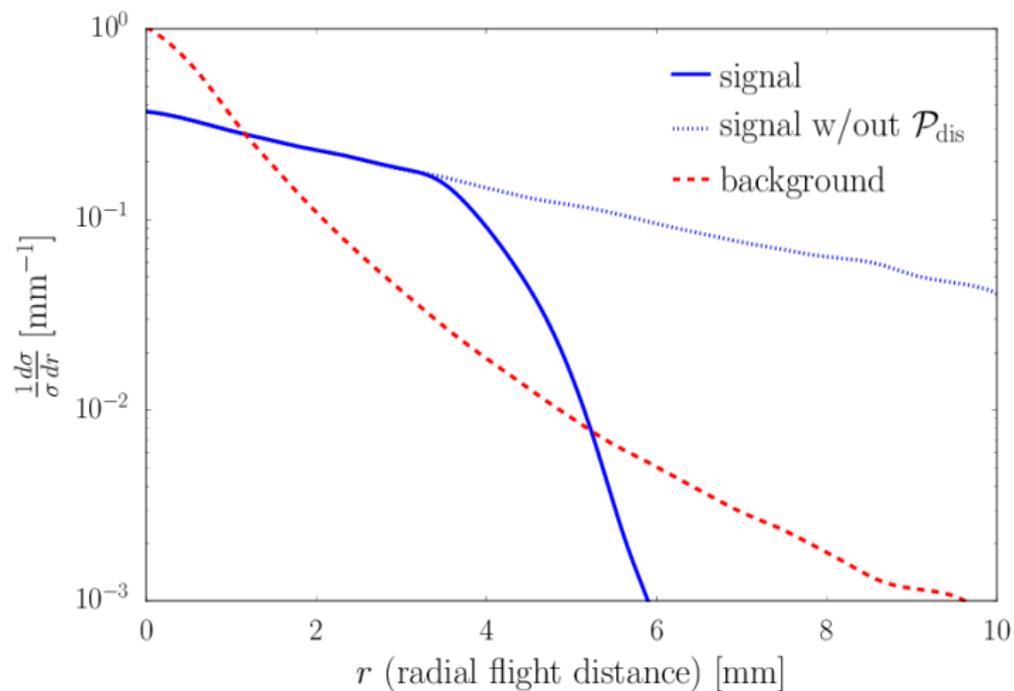
Dark Photons – combined prospects

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

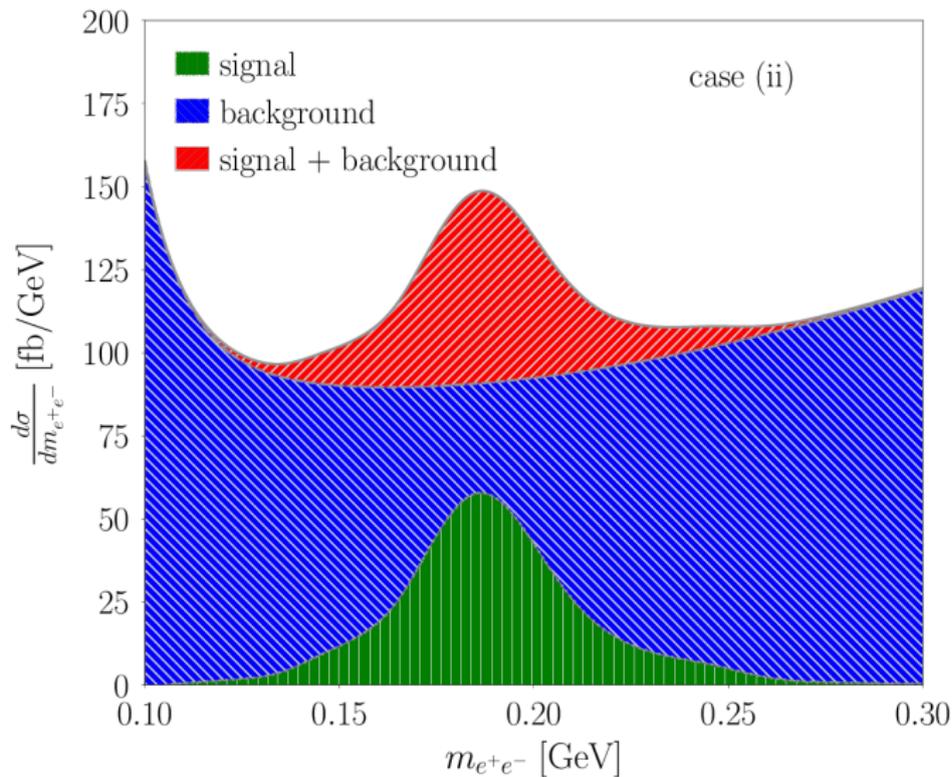


- True muonium (TM), or $\mu^+\mu^-$ bound state (analogous to positronium):
 - *para*TM: 1S_0 pseudoscalar state, decays predominantly into $\gamma\gamma$ pairs.
 - *ortho*TM: 3S_1 vector state, decays predominantly into e^+e^- pairs.
- Properties well predicted by QED:
 - Provide **precision tests** of QED,
 - Sensitive to BSM \rightarrow deviations in the TM decay rate.
- However – TM is a fragile bound state:
 - TM could **dissociate** into $\mu^+\mu^-$ before decaying due to material interactions,
 - LHCb has an aluminium (AlMg3) foil enveloping the VELO.
 - Dissociation factor is calculated and included in these calculations.

Discovering True Muonium (3S_1) at LHCb [arXiv:1904.08458]



Discovering True Muonium (3S_1) at LHCb [arXiv:1904.08458]



ALPs decaying into pairs of photons

- Trigger algorithm (MVA-based) for **soft** $\gamma\gamma$ searches:
 - 1 Uses converted **and** calorimeter γ ,
 - 2 Pre-filters candidates by E_T ,
 - 3 Combines two candidates to form $\gamma\gamma$,
 - 4 Filters again by E_T , p_T and $\gamma\gamma$ **mass**.

