Direct searches for new low-mass particles at LHCb

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

Tracking and vertexing systems

Particle identification systems

Excellent vertexing resolution (fast mixing).
Excellent mass resolution (low masses).

Excellent jet reconstruction and tagging capabilities – see backup.
LHCb is a $20 \times 5 \text{ m}$ 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**

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**Average decay time resolution ~ 45 fs**

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**LHCb**

0.5% resolution for di-muon (Y region)
Hardware level L0:
→ to be removed for Upgrade Ia.
→ benefit for low mass searches.

Software level HLT:
→ Topological triggers on DV.
→ Down to $p_T \sim 80$ MeV/c ($\mu$).

Turbo (since 2015) lines:
→ Any event part can be saved.
→ Can work directly on them.
→ Online $\mu$-ID and jets in turbo.
Direct searches at LHCb

Unique coverage complementary to ATLAS/CMS:
- Soft trigger and forward acceptance → **lower masses** (few GeV/MeV for jets/leptons).
- Excellent tracking and vertexing capabilities → **lower lifetimes** (∼ 1 ps).

LHCb capabilities to exploit low masses and low lifetimes:
- Search for a di-muon resonance in $\Sigma^+ \to p\mu^+\mu^-$ 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 $\Upsilon$ 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 ($\gamma^*$) by a factor $\varepsilon$:
  1. $A'$ inherits the production mode mechanisms from $\gamma^*$.
  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 $\gamma^*$ signal from background and measure its fraction.
- Prompt-like search (up to 70 GeV/$c^2$) $\rightarrow$ displaced search (214 – 350 MeV/$c^2$).
  - $A'$ is long-lived only if the mixing factor is really small.
- Used 1.6 fb$^{-1}$ of 2016 LHCb data (13 TeV).
Using templates for \( \min[\chi^2_{\text{TP}}] \) (small mass dep)

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

(\( \mu_Q \) is a muon from a heavy-flavour decay)

**Graphs**

- LHCb
  - \( m(A') = 0.5 \text{ GeV} \)
  - \( m(A') = 5 \text{ GeV} \)
  - \( m(A') = 50 \text{ GeV} \)

**Graphs**

- LHCb
  - \( \sqrt{s} = 13 \text{ TeV} \)
  - Prompt-like sample
    - \( p_T(\mu) > 1 \text{ GeV}, p(\mu) > 20 \text{ GeV} \)

- Candidates: \( \sigma[m(\mu^+\mu^-)] \)
  - \( \min[\chi^2_{\text{TP}}]^{1/2} \)

**Graphs**

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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 $\rightarrow$ 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:

![Diagram](image.png)
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- 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 $\Upsilon$ peaks):
  - Mass-interpolated efficiencies in bins of $p_T, \eta$ (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 🙂
LHCb interested in vector \(^{(3S_1)}\) state:
- Direct production via kinetic mixing of TM with \(\gamma^*\) 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 \(\sim 211\) MeV:
- Very low mass \(\rightarrow\) off-shell \(\gamma\) production via \(\eta \rightarrow \gamma \gamma^*\) (small BR but high \(\sigma\)).
- 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 \(\varepsilon\):
- Assume current LHCb \(e^+e^-\) mass resolution \(\sim 20\) MeV at 211 MeV.
- **Discovery potential** at 15 \(\text{fb}^{-1}\) (5\(\sigma_{\text{stat}}\)), inclusive search:
ALPs decaying into pairs of photons

- Constraints from LHC resonance searches above $m_a \sim 60$ 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]
  - B: cut around $m(B_s^0)$ (since 2015).
  - ALP: up to 11 GeV/c$^2$ (only 2018).

**Planned search** using 2018 LHCb data.

<table>
<thead>
<tr>
<th>Requirement (2x2 cell clusters)</th>
<th>B</th>
<th>ALP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T(\gamma)$ [GeV]</td>
<td>$&gt; 3.5$</td>
<td>$&gt; 5$</td>
</tr>
<tr>
<td>$E_T(\gamma_1) + E_T(\gamma_2)$ [GeV]</td>
<td>$&gt; 8$</td>
<td>$&gt; 11$</td>
</tr>
<tr>
<td>$M(\gamma_1\gamma_2)$ [GeV/c$^2$]</td>
<td>[3.5, 6.0]</td>
<td>[6.0, 11.0]</td>
</tr>
<tr>
<td>$p_T(\gamma_1\gamma_2)$ [GeV/c]</td>
<td>$&gt; 2$</td>
<td>$&gt; 5$</td>
</tr>
</tbody>
</table>
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
**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 $Z \rightarrow \mu\mu +$ 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 $M_{corr}(SV) = \sqrt{M^2 + p^2\sin^2\theta + p\sin\theta}$.
  - 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.
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 $\gamma$ 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 \( \sim 5 \) 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 → better for LLP ($\leq 2$ 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 → 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 ($\chi$ as axion) [LNP 741 (2008) 3]
  - Scalar (Higgs) portal ($\chi$ 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 ($\sim 30$ 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 $\chi$ mass and decay time (uBoost).
Hidden-sector bosons in $B \rightarrow K^{(*)}\chi(\mu^+\mu^-)$

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

No evidence for signal observed.
Large fraction of allowed inflaton parameter space ruled out.
- 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. $\mu$ from $b$-hadron decays.
- Fit in bins of mass and lifetime – use consistency of decay topology $\chi^2$.
- 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 → 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.
ALPs decaying into pairs of photons

- Trigger algorithm (MVA-based) for soft $\gamma\gamma$ searches:
  1. Uses converted and calorimeter $\gamma$.
  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.

LHCb

(a)

Entries / (14.50 MeV/c²)

Only calorimeter $\gamma\gamma$
2016 data (80 pb⁻¹)

m($\gamma\gamma$) [MeV/c²]