Searches for long-lived particles at LHCb
Workshop on the physics of HL-LHC, and perspectives at HE-LHC

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Phase-II LHCb Upgrade EoI: Opportunities in flavour physics, and beyond, in the HL-LHC era [CERN-LHCC-2017-003]

- **Challenging conditions** – higher rate, pile-up, occupancy and fluence.
- Expect to collect $300 \text{ fb}^{-1}$ by the end of (LHCb) Phase-II.
- Phase-II detector sub-systems have to be able to cope with such conditions.
- In particular – **trigger** and **tracking systems** are crucial for LLP searches.
The LHCb experiment

- Fully instrumented in $2 < \eta < 5$ (see comparison below) [IJMP A30 (2015) 1530022]
- Lower luminosity (1/8 of ATLAS/CMS during Run I) $\rightarrow$ **lower pileup**.
- **Particle identification** capabilities (RICH) and excellent **mass** resolution.
- Good **jet reconstruction**: [JINST 10 (2015) P06013] $\rightarrow$ Run I $b(c)$-tagging efficiency of 65(25)% – very reduced contamination (0.3%).
- **Will be even better for Phase-II** [CERN-LHCC-2017-003]
The LHCb trigger

- Very soft and versatile trigger system.
  - Hardware level L0:
    → to be removed for Phase-I.
    → benefit for low mass searches.
  - Software level HLT:
    → Topological triggers on DV.
    → Online $\mu$-ID and jets in turbo.
  - Turbo (since 2015) lines:
    → Full event reco can be saved.
    → Any event part is persisted.
    → Allow to work directly on them.

- Foreseen improvements for $\mu$ and $e$:
  → $\mu$ reco down to $p_T \sim 80$ MeV/c (Run II).
  → Dedicated $\mu\mu$ lines (efforts to also add $e$ lines).
- Trigger on emerging jets (no pointing to PV):
  → Characteristic of dark sector (shower) signatures.
**The LHCb reconstruction**

**Downstream tracks:**
- Reconstruction of LLP decaying beyond VELO.
- Tracks with worse vertex and momentum resolution.
- Trigger proposed on downstream tracks → better for LLP ($\leq 2$ m) signatures.
- Offline 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.
**The LHCb reconstruction**

- **Long tracks:**
  - Excellent spatial and momentum resolution.
  - Crucial for LLP decaying within VELO (most of our LLP searches).
  - 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 for LLP searches.
  - A **detailed material veto map** is used (paper in preparation):
    - Sensitivity improvement by one to two orders of magnitude.
The LHCb VELO

- **Phase-II VErtex LOcator:** [CERN-LHCC-2017-003]
  - Probably based on Phase-I 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. Phase-I.
  - **Possibility of removing RF-foil** for Phase-II:
    → better IP resolution + no material interactions.

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![IP resolution graphs](image-url)

- LHCb simulation (Phase-I VELO)
  - 2 × 10^{33} cm^2 s^{-1} (Phase-I conditions)
  - 2 × 10^{34} cm^2 s^{-1} (Phase-II conditions)

- Scenarios:
  - **Scenario 1 (with RF-foil)** (Phase-I conditions)
  - **Scenario 2 (no RF-foil)** (Phase-II conditions)

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HL/HE-LHC workshop
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Direct searches for LLPs at LHCb

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

**Exploit LHCb capabilities for direct searches:**
- Search for LLP produced in B and D decays $\rightarrow$ see talk tomorrow by Martino.
- Search for LLP produced in the $pp$ collision $\rightarrow$ **this talk**.
- Measure detachment ($\sim 0.1$ ps) of LLP decaying into hadrons (+leptons) $\rightarrow$ future?
- Proposal for a compact sub-detector (CODEX-b) $\rightarrow$ see next talk by David.
Massive LLPs decaying to $\mu + \text{jets}$

- **Massive LLP into $\mu + \text{two quarks (jets)}$.**

- **Signature sensitive to several benchmark models:**
  - mSUGRA RPV neutralino,
  - Right-handed (Majorana) neutrinos,
  - Simplified MSSM 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.
Massive LLPs decaying to $\mu + \text{jets}$

- Search with full Run I (3 fb$^{-1}$) LHCb data published. [EPJC (2017) 77:224]
- Results interpreted in $H^0 \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1$ benchmark model:

- Stringent limits – rejecting $\mathcal{B}(H^0 \rightarrow \chi\chi) > 10\%$ down to 30 GeV/c$^2$ (5 ps).
- No excess observed.
Massive LLPs decaying to $\mu + \text{jets}$

- **Prospects for Phase-II** → some **naive extrapolations** below:
  - Scale signal and background – consider increase of cross-sections,
  - Conservative assumptions for jet reco, trigger, and material interactions,
  - Optimistic assumptions for pile-up effect.

![Graph showing regions where $B(H^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) > 5\%$ is excluded at 95% CL](image)

**Regions where $B(H^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) > 5\%$ is excluded at 95% CL**

- LHCb reachable
- LHCb published Run 1
- LHCb jet substructure
- LHCb preliminary

**Different constraints on $B(H^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ at 95% CL with 300 fb$^{-1}$ at LHCb**

- $B > 5.0\%$ excl.
- $B > 1.0\%$ excl.
- $B > 0.5\%$ excl.
- $B > 0.1\%$ excl.

- **Our main aim is to reach lower masses and lower lifetimes.**
- **Removal of L0 trigger (Phase-I)** → much higher trigger efficiencies at the end!
- Jet reconstruction efficiencies will be better for lower masses.
- Expected a **better knowledge of material interactions** (or much less interactions!).
Massive LLPs decaying to jet pairs

- Possible scenarios to accommodate this signature:
  - LSP in gravity mediated SUSY,
  - LSP in SUSY models with BNV or LNV,
  - HV \( \pi_\nu \) decaying to \( b\bar{b} \) – especially SM-like \( H^0 \rightarrow \pi_\nu\pi_\nu \) production.
- In most of the cases only one of the two \( \pi_\nu \) 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 \( \pi_\nu \) detachment to discriminate between signal and background.
- Background dominated by \( b\bar{b} \) events and material interactions.
Massive LLPs decaying to jet pairs

- Search with full LHCb Run I (3 fb$^{-1}$) dataset published [LHCb-PAPER-2016-065]
- Limits at 95% C.L. as a function of $\pi_\nu$ lifetime for several $\pi_\nu$ masses:

![Graph showing limits at 95% C.L. as a function of $\pi_\nu$ lifetime for several $\pi_\nu$ masses.]

- No excess found – plan to analyse LHCb Run II + go to lower $\pi_\nu$ masses.
  → Working on new dedicated trigger lines for displaced jets.
- Develop jet substructure tools to study multi-jets at lower masses.
- Develop a selection for emerging jets → confining HV (dark showers) [arXiv:1708.05389]
Massive LLPs decaying to jet pairs

- Compare with recasted results from ATLAS and CMS (plot by M. Borsato):
  - CMS $18.5 \text{ fb}^{-1}$ [PRD 91 (2015) 012007], recast [PRD 92 (2015) 073008]
  - ATLAS $20.3 \text{ fb}^{-1}$ [PRD 92 (2015) 012010] [PLB 743 (2015) 15-34]

- Parameter space where $\mathcal{B}(H^0 \rightarrow \pi\nu\pi\nu) > 50\%$ is excluded at 95% C.L. is shown.
- Disclaimer: new 13 TeV results from CMS not included in the recast [CMS-PAS-EXO-16-003]
- Keep complementarity w.r.t. ATLAS and CMS in Phase-II searches.
- Consider similar strategy w.r.t. ATLAS and CMS in Phase-II searches.

[EPJC (2016) 76:664]
Massive LLPs decaying to jet pairs

- Prospects for Phase-II → same naive assumptions as before:

- Again – our main aim is to reach lower masses and lower lifetimes.
- Removal of L0 (Phase-I) will be beneficial as well → access to lower jet masses.
- Higher pile-up in Phase-II:
  - Impact of pile-up on jet reconstruction efficiencies needs to be studied in much detail.
  - We have reasons to be optimistic – preliminary studies ongoing + ideas (see below).
- Some possible improvements to mitigate the effect of the increased pile-up:
  - Remove neutrals (more pile-up dependent) from jet reco (only charged tracks).
  - Consider ML techniques to seize pile-up contributions as in ATLAS and CMS.
Conclusions

- Expect to collect $300 \text{ fb}^{-1}$ by the end of Phase-II.
- A lot of potential in Phase-I triggers and VELO $\rightarrow$ also potential for Phase-II.
- Ace up our sleeve $\rightarrow$ our complementarity w.r.t. other LHC experiments.
- Plenty of prospects from existing results and ideas of new searches:
  - LLP searches at lower masses and lifetimes $\rightarrow$ $\pi_v$, $\tilde{\chi}_1^0$, RH neutrinos...
  - Develop jet substructure tools to study multi-jets at lower masses.
  - More realistic models for HV searches – dark showers (emerging jets).
  - $e$ in final states – sensitive to lower masses (no sensitivity anywhere else at the LHC).
  - Fractional charge particles, monopoles, quirks – sensitivity studies needed.
- Encouraging proposals (increasing interest!) from the theory community:
  - Confining HV at LHCb [arXiv:1708.05389]
  - Soft bombs [JHEP 08 (2017) 076]
  - Rare Z decays to a hidden sector [arXiv:1710.07635]
- We are looking forward to new ideas $\rightarrow$ do not hesitate to contact us!
Is there anything beyond the Standard Model?

Thanks for your attention!
Backup
Massive LLPs decaying to $\mu + \text{jets} – \text{recast}$

- Limits from this analysis recasted to look into sterile neutrinos [arXiv:1706.05990]

- Could we get best world-limit (5–10 GeV/c$^2$) with same kind of search?
- Dedicated search with Run II data in preparation.
Confining HV at LHCb [arXiv:1708.05389]

FIG. 1: Left panel: $Z'_p$ cross section reach. Green line: cross section for a photon-like coupling, suppressed by $\epsilon = 0.02$. Right panel: Projected upper bounds on $\text{BR}(h \rightarrow \text{twin bottom quarks})$ using the 1DV search. This process produces lighter twin mesons $\hat{\omega}/\hat{\eta}$ followed by $\hat{\omega} \rightarrow \mu^+\mu^-$. Horizontal green line: prediction in a variation of the Fraternal Twin Higgs model (see text); in this context $\omega_v$ is a mixture of $c'$ and $s'$. Green curve: reach for the corresponding decay topology (see text for details).
FIG. 2: Projected bounds from various ATLAS/CMS displaced muons search strategies, see text for details. The brown curve represents an extrapolation of a current analysis, while the green curve represents only a minor modification. The orange and purple projections have aggressive assumptions about backgrounds and will likely weaken following detailed detector simulations. The band widths correspond to $10 \leq \langle N_v \rangle \leq 30$. The blue band is derived from the LHCb search proposed in this work.
FIG. 3: Projected bounds from various displaced $c\bar{c}$ search strategies, see text. Purple curves: ATLAS/CMS reach estimate for DV decays into $\geq 5$ charged tracks, with either two DV in the muon spectrometer (solid) or one DV in the inner detector and one in the muon spectrometer (dotted). Brown: analogous ATLAS/CMS reach for $\omega_v \rightarrow b\bar{b}$, $m_{\omega_v} = 11$ GeV.
Turbo stream in Run II

- only exclusive decays (and nothing else) saved

Turbo++:
- Full event reconstruction can be persisted
- Variables such as isolation, objects for jets reconstruction, can be saved

Turbo SP:
- New intermediate solution between Turbo and Turbo++
- Trigger candidate + subset of reconstruction saved

\[ [\text{JHEP03(2016)159}] \]