Long Lived Particles in LHCb Upgrade II

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on behalf of the LHCb collaboration

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LLPs at LHCb

- unique acceptance: $2 < \eta < 5$
- low pile-up (~1-2 visible interaction)
- excellent vertex resolution ($\sigma_T \sim 45$ fs for $B_s^0$)
- excellent mass resolution (0.5% in $\mu\mu$)

- good jet reconstruction
  - energy resolution $\sim 10\%$ for jets with $p_T > 10$ GeV
  - $b(c)$ tagging efficiency $\sim 65\%(25\%)$ for 0.3% light-parton contamination

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**CMS**

**LHCb**

$2 < \eta < 5$

- pixel
- silicon strip
- ECAL
- Cherenkov
- drift tube
- HCAL
- muon
LLPs at LHCb

- calibration + reconstruction in real time
- very soft triggers:

  at **hardware** level (L0):
  - muons with $p_T > 1.5$ GeV
  - calo deposits with $E_T > 3$ GeV

  at **software** level (HLT):
  - topological triggers on detached vertices
  - PID and jets in trigger
  - excellent for light dimuons (prompt and detached)

  new $\mu\mu$ turbo trigger with online muon id requirement (no pre-scale)

Many searches for LLPs performed and ongoing!

see Mike’s talk
LHCb Upgrades

Upgrade I

- no hardware trigger, full software trigger with readout of the full event at 40 MHz
- improved vertex resolution
- momentum resolution of the tracking system ~10-20% better
- reduced ghost rate

will extend LHCb reach for LLPs!
LHCb Upgrades

LHCb Upgrade I

- Run 3: \( L = 2 \times 10^{33} \)  
  - LS3: HL-LHC Installation, ATLAS/ CMS Phase 2 upgrades
  - \( L_{\text{int}} \approx 50 \text{ fb}^{-1} \)

LHCb Upgrade I(b)

- Installation starts
- Incremental improvements/prototype detectors

LHCb Upgrade II

- Run 5: \( L = 1-2 \times 10^{34} \)
- Run 6: \( L_{\text{int}} \approx 300 \text{ fb}^{-1} \)
- LS4
- LS5

Upgrade II (wrt Upgrade I)

- 10x higher vertex multiplicity
- 10x higher particle multiplicity
- 10x higher radiation damage
Detector improvements for LLPs?
within the LHCb acceptance from the initial interactions alone. These high multiplicities lead to challenging conditions for track and vertex reconstruction. Using the Phase-I Upgrade VELO detector design as a baseline, the performance of a number of potential modifications to the detector geometry and materials has been evaluated at the proposed Phase-II luminosity, and their effects on the final physics performance studied using full Monte Carlo simulations. Figure 4.2 summarises the tracking performance of the baseline (Phase-I) design under luminosities expected in the Phase-I and Phase-II Upgrade eras. The mean rate of reconstructing ghost tracks in the VELO alone from spurious hit combinations increases dramatically from 1.6% to 40% for the increased luminosity, even after tight track-quality requirements are imposed to limit the rate of these ghosts. There is a corresponding reduction in tracking efficiency, with the integrated value within the LHCb acceptance falling from $\sim 99\%$ to $\sim 96\%$. There is also a modest degradation in the impact parameter (IP) resolution, driven by the effect of the lowered tracking efficiency on the primary vertex (PV) resolution.

These losses in performance can be almost entirely recovered with a small number of design improvements. Most notably, by decreasing the pixel pitch from 55 µm to 27.5 µm and reducing the sensor silicon thickness from 200 µm to 100 µm, the ghost rate can be reduced back down to 2% while retaining a tracking efficiency of 96%, to choose one working point. Another potential design improvement would be the reduction of material. In the current and Phase-I Upgrade

How LHCb might look like…

- silicon and scintillating fibres based tracking detectors
- new sub-detectors (magnet stations, TORCH)
- high granularity ECAL with extended dynamic range
- HCAL removed

see Matt’s talk tomorrow

Tracking system and trigger crucial for LLP searches!
VELO plays a fundamental role in LLP searches:

- reconstruction of primary and secondary vertices
- part of the tracking system
- decay length accessible by LHCb ~20 cm (decay in the VELO)

In upgrade II, pixel timing becomes essential to reduce vertex mis-association in the high pile up environment!

**Example 1: Primary vertex association**

- Single PV: unambiguous flight distance
- Two PVs: ambiguous flight distance
- Two PVs + timing: clear assignment
RF box at ~5 mm from the beam:

- < 5 mm: background dominated by heavy flavour
- > 5 mm: background mainly from material interaction

...a material map of the VELO is essential to reduce the background in LLP searches!

- the removal of the RF foil is under study for upgrade II
- it would reduce the background and improve the IP resolution
- if not feasible it is crucial to veto the material interactions...

- beam-gas (helium) collisions
- material interaction along the full length of the VELO
- secondary interactions of hadrons used to map the material

...repeat for next runs?

- analysis performed for Run1 and Run2
- method already applied successfully on a LLP analysis (Phys. Rev. Lett. 120, 061801 (2018))
VELO in this high-radiation environment is clearly well motivated.

The large number of multiple interactions per beam crossing at Phase-II presents particular hits. Consequently R&D on achieving high-granularity 4D spatial and timing information in the VELO is required.

Hadron samples are based on their flight distance, as determined by the VELO. This measurement requires the correct association of the production (PV) and decay vertices of the heavy flavour hadron. Using a Phase-I Upgrade design detector 13% of hadron decays would be mismatched to the wrong PV as a function of the time resolution.

Potential design improvements to recover performance losses:

- smaller pixels and thinner silicon sensor
  - scenario1
- removal of RF box (biggest contributor to material budget)
  - scenario2

Most likely to get additional gain (timing for reconstruction? timing for extrapolation?)

VELO Upgrade I performance at HL-LHC luminosity:

- ghost rate explodes
- tracking efficiency decreases
- spatial resolution degrades
Tracks in LHCb Now

**Long tracks**
- excellent spatial resolution close to PV
- excellent momentum resolution in magnitude and direction

**Downstream tracks**
- reconstruction of daughters of LLPs that decay beyond VELO acceptance (20 cm<SV<200 cm)
- good momentum resolution

**Upstream tracks**
- reconstruction of charged particles bent out of the acceptance
- excellent directional resolution
- approximate estimation of the momentum possible

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**most relevant tracks for LLP searches**

- VELO track
- Long track
- Downstream track
- T track
- UT
- T1, T2, T3

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HL/HE LHC - 04/04/2018
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Tracks in LHCb Upgrade II

Upstream tracks

- tracking acceptance can be significantly increased for soft tracks by **tracking stations on the magnet**
- the momentum resolution will improve
- a large fraction of track now lost will be recovered

Downstream tracks

- downstream timing with **TORCH** (Time Of Internally Reflected CHERenkov light)
- target: precision per track ~15 ps
- track matching will improve with consequent suppression of ghosts
- it will allow to timestamp LLP decaying after the VELO and match it to the correct vertex
- it will provide particle id to lower momenta through the ToF
same strategy as Upgrade I:

- no hardware trigger
- triggerless readout at the LHC bunch crossing rate
- fully software-based trigger with no further offline processing
- signal classification at the trigger level

- more flexibility
- higher efficiency for low mass searches and electron modes
- possibility to access lower jet masses (emerging jets, jet substructures…)

what can be further improved?

- studies ongoing on adding downstream reconstruction at HLT1 (‘retina’ scheme with dedicated processors in the DAQ)

EPJ Web Conf. 127 (2016) 00005
What sensitivity can we reach with HL-LHC?
LLPs Decaying to Jet Pairs

- search for hidden sector LLP decays via SM Higgs portal
- **mass range**: 25-50 GeV
- **lifetime range**: 2-500 ps
- **dataset**: run 1 (2 fb⁻¹)
- **signature**: single displaced vertex with 2 associated jets

### Strategy
- trigger on displaced vertex
- requirements on jet pointing and material interaction veto to reduce main backgrounds:
  - vertex from heavy flavour decay or material interaction
  - SM dijet events
- fit of the di-jet mass in bins of lateral displacement $R_{xy}$

### Background

![Graph showing background and best fit in di-jet mass distribution]

- $LHCb$
- $3.0 < R_{xy} < 5.0$ mm
- $\sqrt{s} = 8$ TeV
- $BR=1$

### Mass and Lifetime
- **mass range**: 25-50 GeV
- **lifetime range**: 2-500 ps
upper limits set on SM-Higgs BR to dark pions
upper limits set on SM-Higgs BR to dark pions

competitive and complementary limits to ATLAS and CMS!

what about HL-LHC?

Regions where $\mathcal{B}(H^0 \rightarrow \pi_V \pi_V) > 50\%$ is excluded at 95% CL

- ATLAS 20.3 fb$^{-1}$ at 8 TeV
- LHCb 2.0 fb$^{-1}$ at 7-8 TeV
- CMS 18.5 fb$^{-1}$ at 8 TeV

pushing to low mass and lifetime
LLPs Decaying to Jet Pairs

extrapolation to 300 fb$^{-1}$

- signal and background scaled to 14 TeV
- conservative assumptions on detector performance (trigger, material interaction, jet reco)
- optimistic assumptions on the effect of pile-up

Regions where $B(H^0 \to \pi\nu\nu) > 50\%$ is excluded at 95\% CL

Different constraints on $B(H^0 \to \pi\nu\nu)$ at 95\% CL with 300 fb$^{-1}$ at LHCb
LLP Decaying Semileptonically

• search for massive LLP decaying semileptonically into SM particles

• 2 approaches:
  ‣ RPV mSUGRA neutralino as benchmark
    • mass range: 23-198 GeV
  ‣ simplified topologies, less model dependent
    • mass range: 25-50 GeV

• lifetime range: 5-100 ps

• dataset: run I (1+2 fb⁻¹)

• signature: single displaced vertex with several tracks and a high $p_T\mu$

• background dominated by $b\bar{b}$
**strategy**

- trigger on $\mu +$ displaced vertex
- exploit $\mu$ isolation to define a signal and a control region enhanced in background
- simultaneous fit of the LLP candidate mass in the 2 regions to extract number of candidates

**no significant excess observed**

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![Graph](image)

- $\tau_{LLP} = 5 \text{ ps}$
- $m_{\tilde{q}} = 1300 \text{ GeV/c}^2$
- $\sqrt{s} = 8 \text{ TeV}$
- $\sqrt{s} = 8 \text{ TeV}$
- $\tau_{LLP} = 50 \text{ ps}$
- $\tau_{LLP} = 10 \text{ ps}$
- $m_{\tilde{q}} = 1575 \text{ GeV}$
- $m_{\tilde{q}} = 500 \text{ GeV}$
strategy

- trigger on $\mu +$ displaced vertex
- exploit $\mu$ isolation to define a signal and a control region enhanced in background
- simultaneous fit of the LLP candidate mass in the 2 regions to extract number of candidates
Extrapolation to 300 fb$^{-1}$

- Signal and background scaled to 14 TeV
- Conservative assumptions on detector performance (trigger, material interaction, jet reco)
- Optimistic assumptions on the effect of pile-up

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

![Graph 1: Regions where $B(H^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) > 5\%$ is excluded at 95% CL.]

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

![Graph 2: Different constraints on $B(H^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ at 95% CL with 300 fb$^{-1}$ at LHCb.]

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Summary

With the upgrade II we have…

• 10x luminosity

• significant changes in the detector to cope with the challenging conditions: many proposals/ideas! (3rd Workshop on LHCb Upgrade II)

• LHCb reach for LLPs significantly improves beyond luminosity scaling: pushing towards low masses and low lifetimes

• proposal for a new dedicated detector (CODEX-b) to further extend physics reach and capabilities for LLPs (see Mike’s talk)

• unique coverage complementary to ATLAS and CMS

• many inputs coming from the theory community:
  ‣ confining Hidden Valley  arXiv:1708.05389
  ‣ soft bombs  JHEP 08 (2017) 076
  ‣ rare Z decays to a hidden sector  arXiv:1710.07635

…growing interest for LLPs at LHCb!
Back Up
strategy:
look for decays-in-flight of LLPs from IP8

Five benchmark LLP scenarios:
- Massive dark photon γd (kinetic mixing)
- Light O(GeV) scalar φ (Higgs mixing)
- Heavy neutral lepton (mixing with the active neutrinos)
- h → dark glueballs (twin Higgs mixing portal)
- QCD coupled ALP m_φ < 3π (diphoton channel!)
Extrapolation to HL-LHC

**assumptions:**

the pile-up won't affect much neither the jet reconstruction neither the backgrounds

For **jet reconstruction**, we think we can have it under control by either:

- applying the same ML techniques to mitigate the pile up already used by ATLAS/CMS
- removing neutrals from jets (resolution would degrade but this is done already for Turbo jets)

For the **backgrounds**, for LLPs there are two main sources, heavy flavour and material interactions:

- heavy flavour should be about the same
- material interactions: the understanding of the VELO material significantly increased in the last year, and hopefully this will be also the case in the HL-LHC. If RF foil thinner or even completely removed, background drastically reduced
Turbo stream in Run II

**Turbo:**
- only exclusive decays (and nothing else saved)

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

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

**Event size:**
- TURBO (since 2015): Event size: 15 kB
- TURBO SP new 2017: Event size: 70 kB
- TURBO++ (since 2016): +γ, π⁰

Candidate fit + Sec. Comb. bkg.

- only exclusive decays (nothing else saved)
- new intermediate solution
- trigger candidate + subset of reconstruction saved
- full event reconstruction can be persisted
- variables such as isolation, objects for jet reconstruction can be saved

\[ (K^p +) \[ MeV/c^2 \]

LHCb \( p_s = 13\, \text{TeV} \)

\[ \text{JHEP03(2016)159} \]
Confining Hidden Valley Model

**di-muon channel**

signature: a displaced vertex well separated from beamline

**heavy flavour decay channel**

signature: 2 vertices with large separation from PV and significant separation between each other

potential better sensitivity than ATLAS/CMS
Soft Bombs

- large multiplicity of soft particles
- spherical event shape
- multiplicity scales linearly with energy
- might be signature of strongly-coupled hidden valleys

“given that LHCb will eventually operate fully in the trigger-less mode, it will have unique sensitivity to soft signatures of new physics”
Rare Z Decays to a Hidden Sector

- rare decays of the Standard Model Z boson are powerful probes of hidden sectors
- Z decays into hidden-sector particles typically give rise to large multiplicities of soft particles

![Graph](image)

**FIG. 4:** Sensitivity projections for the $Z \rightarrow h_D A' \rightarrow 4\ell + X$ search for integrated luminosity of 300 fb$^{-1}$ (upper dark lines) and 3000 fb$^{-1}$ (lower faint lines) at $\sqrt{s} = 13$ TeV and $\alpha_D = 0.1$. The dotted green line shows the projected LHCb sensitivity with 15 fb$^{-1}$ from Ref. [29], while the dashed lines show the projections for the proposed Drell-Yan search from Ref. [32]. Notation and existing bounds are the same as in Fig. 3.