Status of LLPs searches at LHCb

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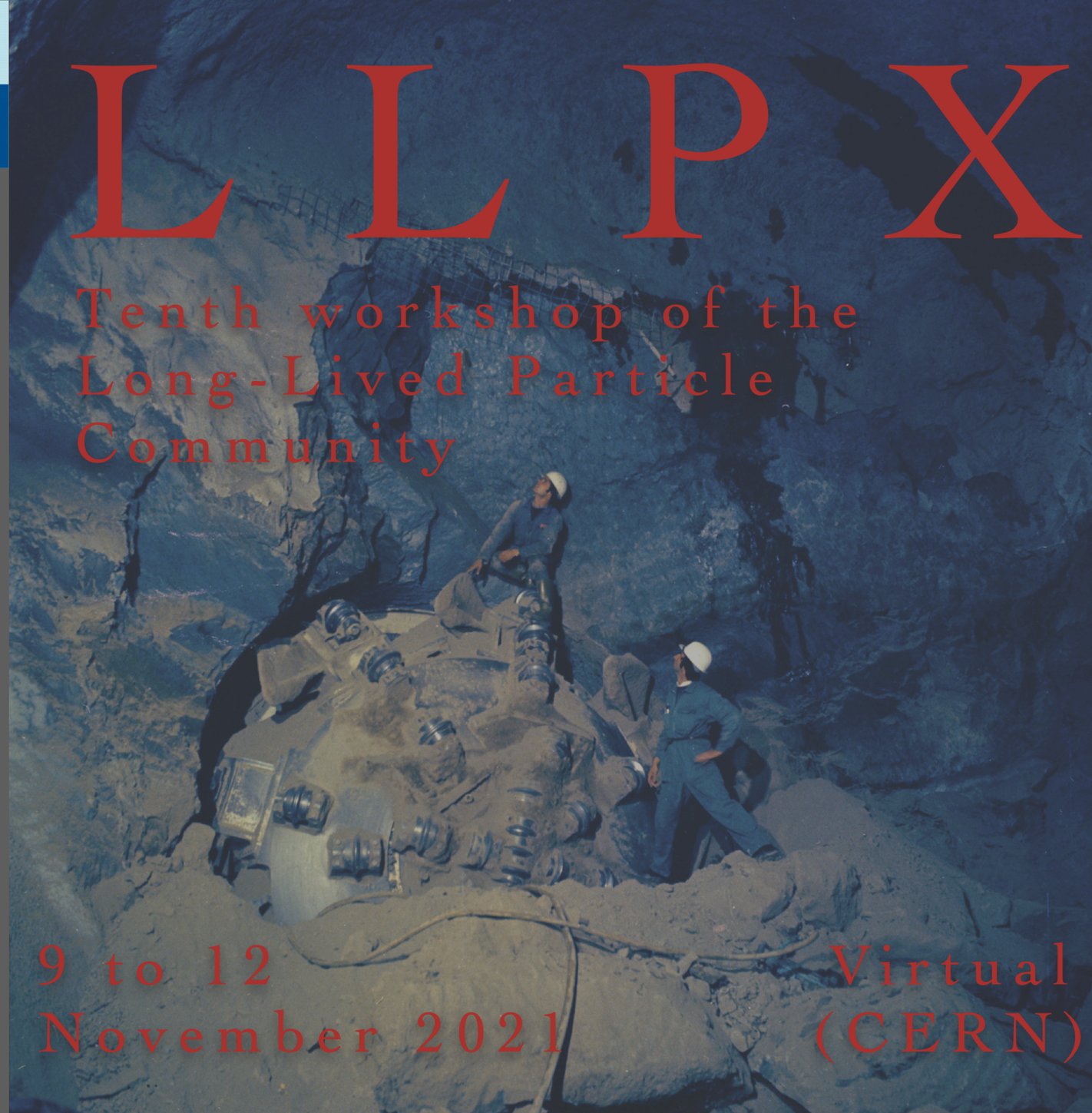
On behalf of the LHCb Collaboration



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Outline
What I am going to talk about

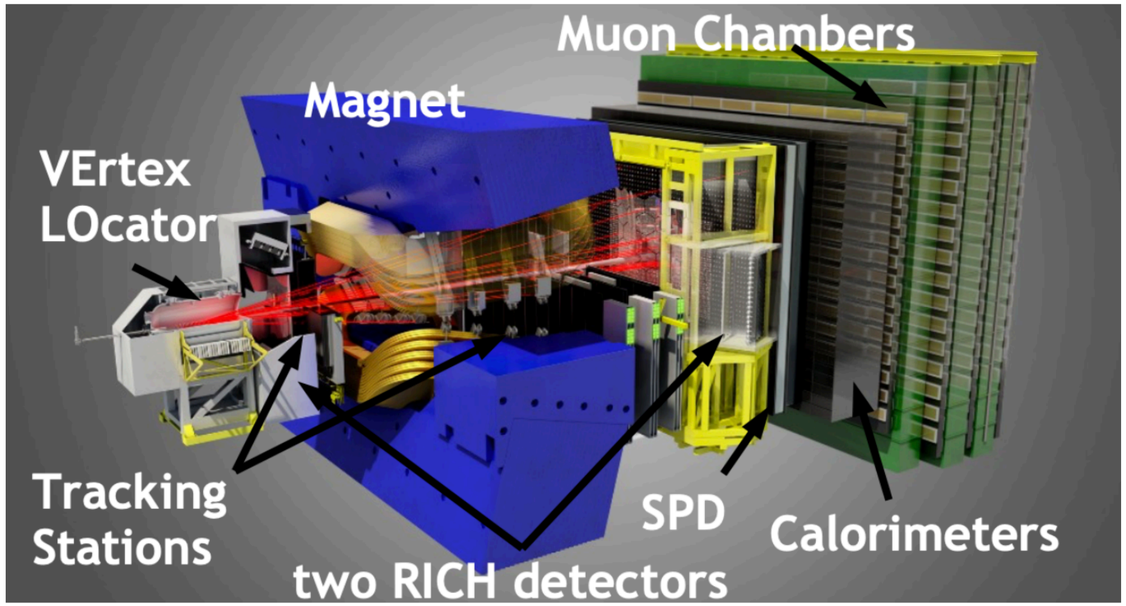
- LHCb experiment
- LLPs searches at LHCb
- Prospects for LLPs searches at LHCb
- Conclusions

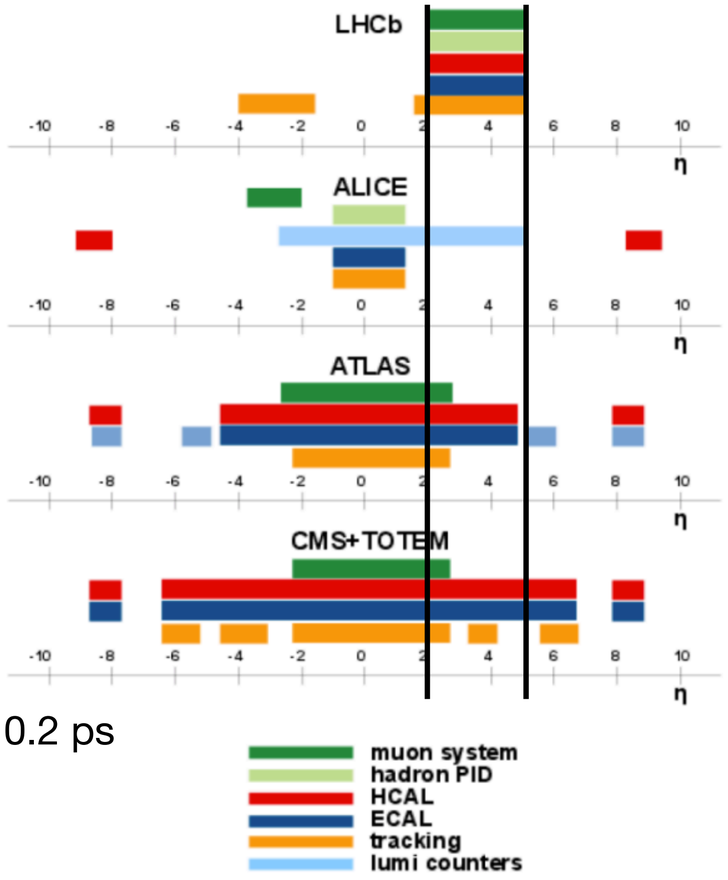
LHCb experiment

A General Purpose *Forward* Detector

JINST 3 (2008) S08005
Int. J. Mod: Phys. A 30, 1530022 (2015)
CERN-LPCC-2018-04

- LHCb, originally designed for b- and c-hadron physics, is now considered a **general purpose forward detector**
- Unique phase space region $(2 < \eta < 5)$ **complementary to General Purpose Detectors** (ATLAS & CMS)





- **Excellent track momentum resolution**: 0.4% at 5 GeV to 0.6% at 100 GeV
- Impact Parameter resolution $\sigma_{IP} = 20\ \mu$m for high-p_T tracks, lifetime resolution of $\sigma_\tau = 0.2$ ps
- Muon ID efficiency: 97% with 1-3% $\mu \to \pi$ misidentification
- Electron ID efficiency: 90% with 5% $h \to e$ misidentification

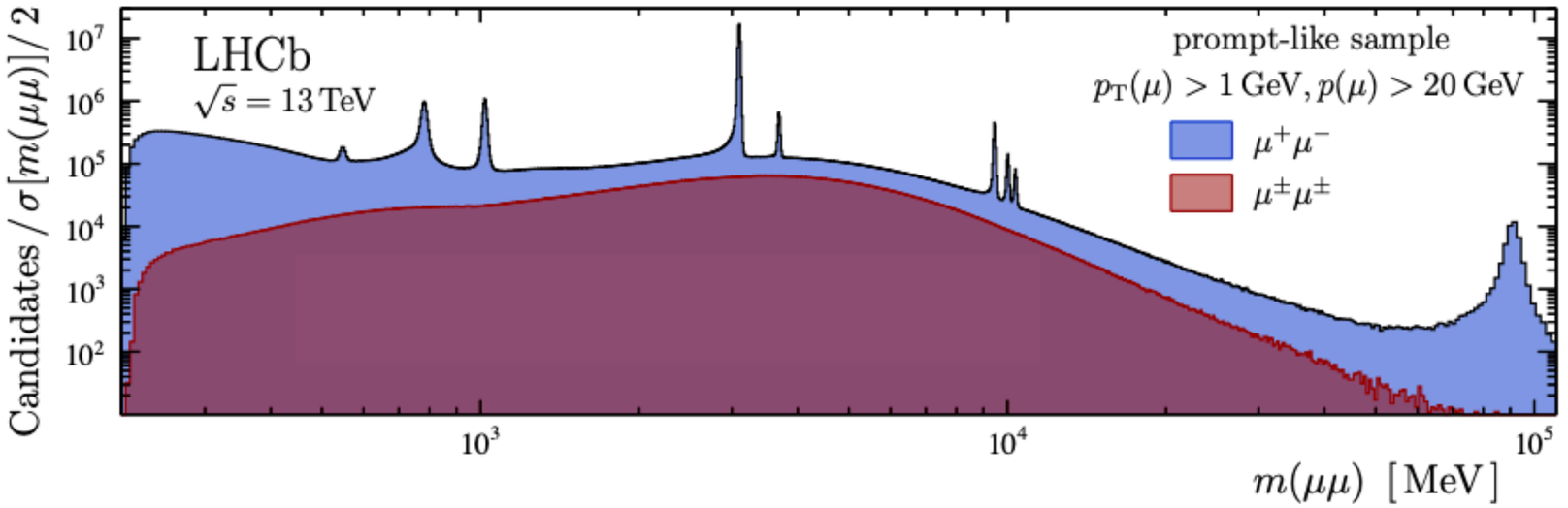
LHCb experiment
Trigger

Phys. Rev. Lett. 120, 061801 (2018)
J. Phys.: Conf. Ser. 664 082004 (2015)

- Soft triggers are needed
- Hardware level (L0):
  - Muons with $p_T > 1.5$ GeV
  - Calorimeter energy deposits with $E_T > 3$ GeV
- Software Level (HLT):
  - Topological triggers for displaced vertices
  - Triggers for PID and jets

new turbo lines since 2015:

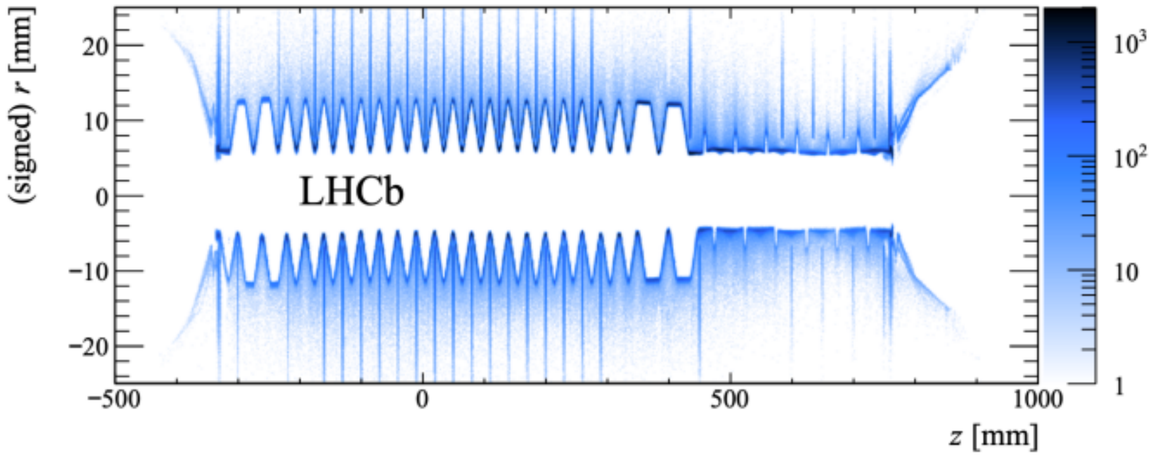
- store online reconstructed particles
- reduce event size by discarding lower level info
- output can be directly used for analysis

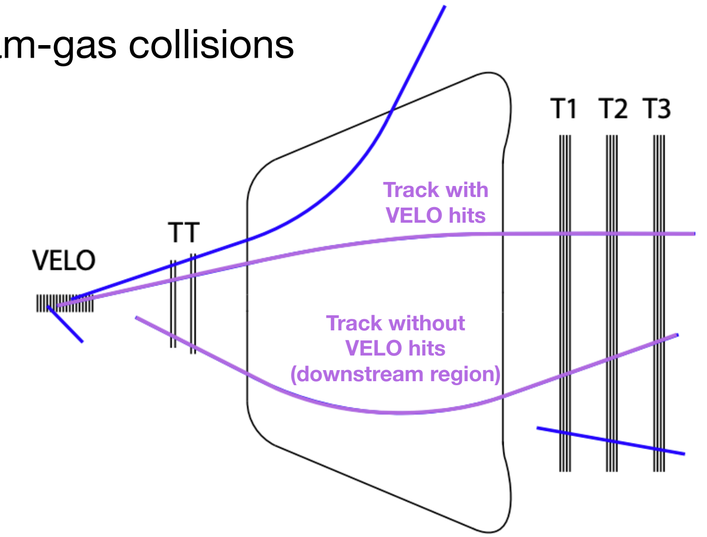


LHCb experiment
VELO material

JINST 13 (2018) 06, P06008

- Material map of VErtex LOcator (VELO) is fundamental for LLP searches:
  - Displacement up to 20 cm
  - Thin VELO envelope (RF foil) - background dominated by
    - heavy flavour decays at < 5 mm
    - material interactions at > 5 mm
- Precise material VELO map by secondary interactions of hadrons produced in beam-gas collisions





- So far only performed analyses on Run 1 and Run 2 data with LLPs decaying within the VELO
- Searches could be extended to LLPs decaying downstream of the VELO (displacement up to 200 cm)
  → much worse momentum resolution

LLPs searches at LHCb

A lot of studies!

- Displaced leptons:
  - Dark photon
  - Low-mass di-muon resonances
  - Majorana neutrino
  - **LLPs decaying to $e^{\pm}\mu^{\pm}\nu$** **NEW!**
  - Light boson from $b \to s$ decays
  - **LLPs decaying semileptonically** **NEW!**

- Displaced jets:
  - **HNL in $W^{\pm} \to \mu^{+}\mu^{\pm}$ jet** **NEW!**
  - LLP $\to$ jet jet
  - LLP $\to \mu$ + jets

LLPs searches at LHCb

Search for long-lived particles decaying to $e^{\pm}\mu^{\mp}\nu$

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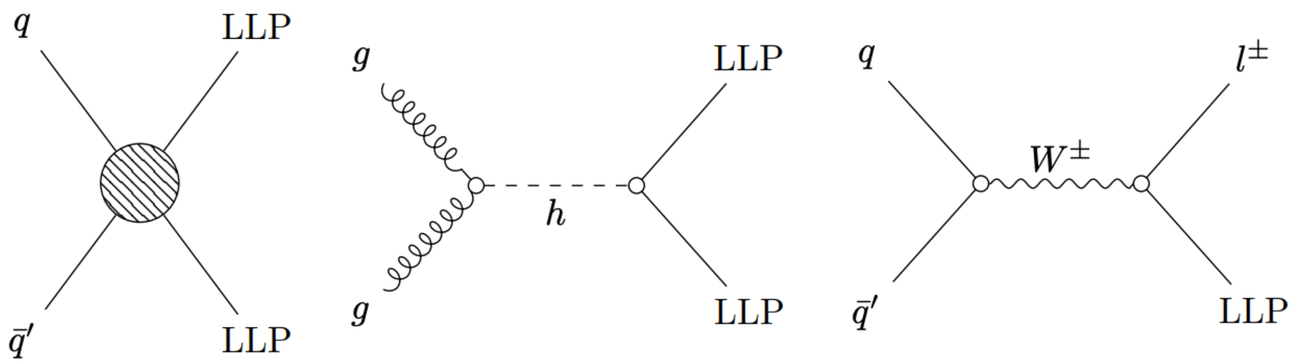
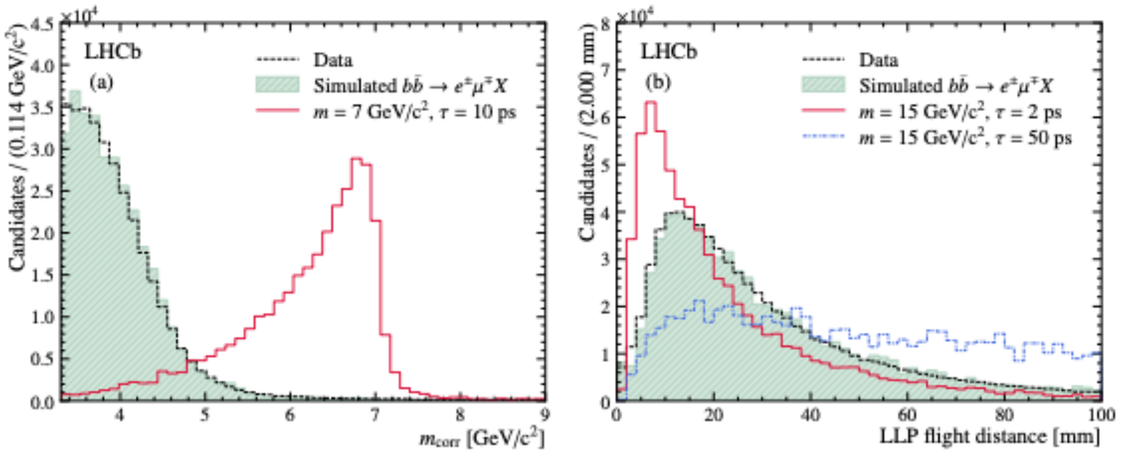
- Several productions mechanisms are considered:
  - Direct production
  - Pair production from SM-like Higgs boson decay
  - Charged current processes
- Signature: displaced vertices containing e and μ of opposite charges
- Analysis performed with full Run II data ($\sim 5\text{fb}^{-1}$)
- LLPs mass range [7,50] GeV and lifetime range [2,50] ps





- Signal selection:
  - $p(e/\mu) > 10$ GeV/c and $p_T(e/\mu) > 1.6$ GeV
  - Good quality vertex inside VELO
  - Lifetime of the candidate > 0.5 ps
- Mass correction to account for not reconstructing neutrino
  - $m_{corr} = \sqrt{m(e\mu)^2 + p(e\mu)^2 \sin^2\theta}$
  - Candidates with $m_{corr} < 3.3$ GeV/c^2 are discarded

LLPs searches at LHCb

Search for long-lived particles decaying to $e^{\pm}\mu^{\mp}\nu$

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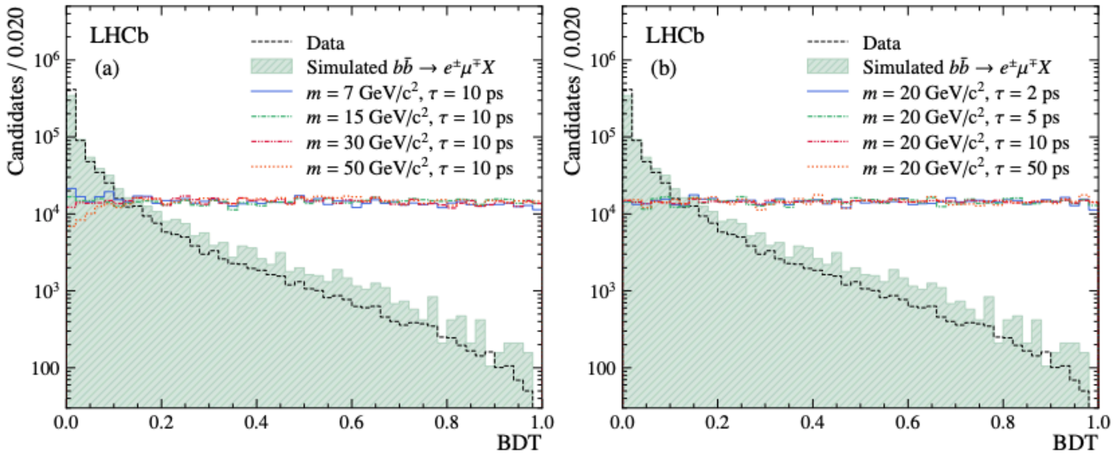
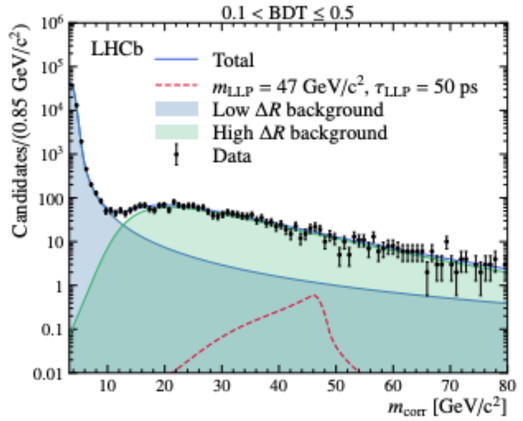
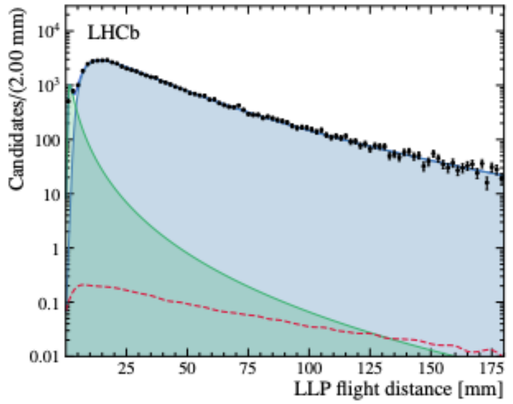
- A BDT is further used to purify LLP $\rightarrow e^{\pm}\mu^{\mp}\nu$ candidates

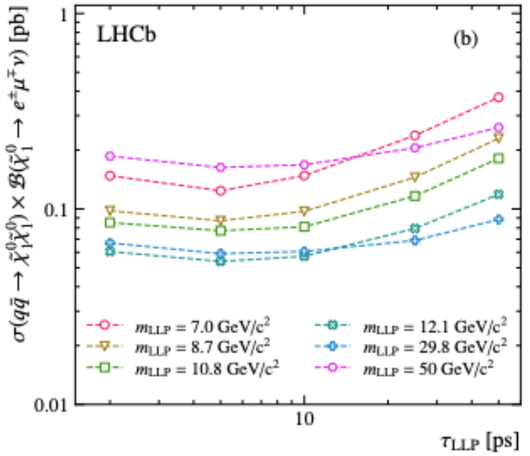


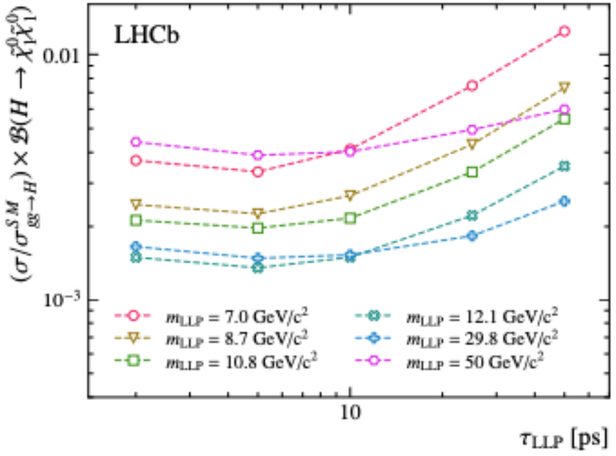
- Results are found to be compatible with background-only hypothesis
- Upper limits at 95% Confidence Level (CL) on the production cross-sections times branching fraction are computed for each production mechanism
- Best limit for lifetimes below 10 ps and masses above 10 GeV/c^2

- The signal yield is obtained by means of a simultaneous fit of m_{corr} and LLP flight distance into two BDT intervals







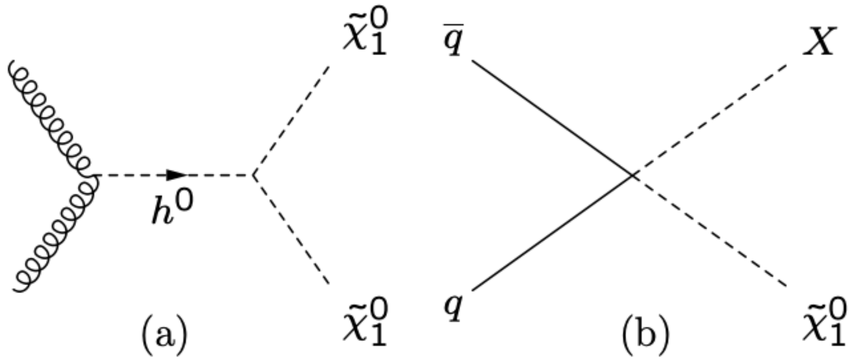


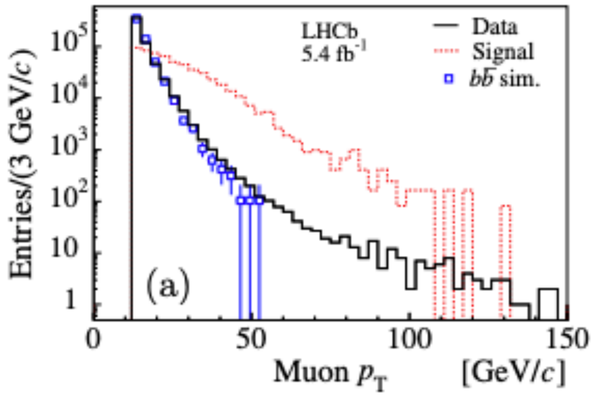
LLPs searches at LHCb

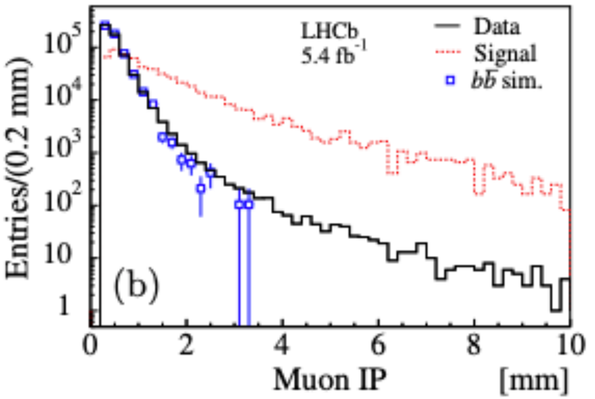
LHCb-PAPER-2021-028

Search for massive long-lived particles decaying semileptonically at $\sqrt{s} = 13$ TeV

- Search for massive long-lived particles (LLP) decaying into a muon and two quarks
- LLPs lifetimes considered range goes from 5 ps to 200 ps
- Two searches are performed:
  a. Higgs-like bosons from gluon fusion (with mass $m \in [30,200]$ GeV/c^2) decaying into 2 LLPs
  b. Direct production from quark interaction, with LLPs masses $m \in [10,90]$ GeV/c^2
- Analysis performed with full Run II data ($\sim 5\text{fb}^{-1}$)
- Signal selection:
  - Displaced vertex from any PV and one isolated high-p_T muon
  - Muon impact parameter > 0.25 mm and $p_T^\mu > 12$ GeV/c
  - LLP candidate $\rightarrow$ 3 or more tracks and $m_{inv} > 4.5$ GeV/c^2
  - Requirements on muon isolation





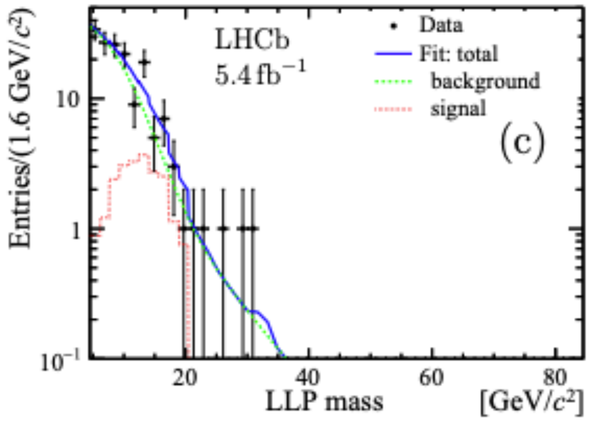


LLPs searches at LHCb

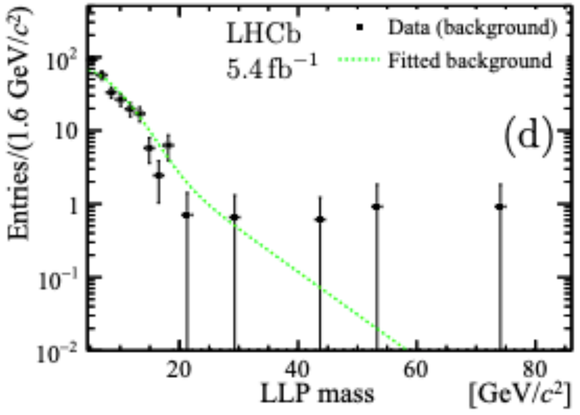
LHCb-PAPER-2021-028

Search for massive long-lived particles decaying semileptonically at $\sqrt{s} = 13$ TeV

- A MVA based on BDT is used to further purify data
- The background shape is obtained with a data-driven method:
  - Signal region: muon isolation < 1.2
  - Background region: muon isolation ∈ [1.4, 2.0]
- The signal yield is obtained by a unbinned extended maximum-likelihood fit to the reconstructed LLP mass

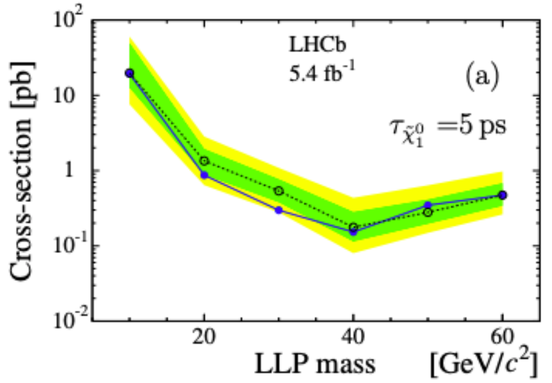


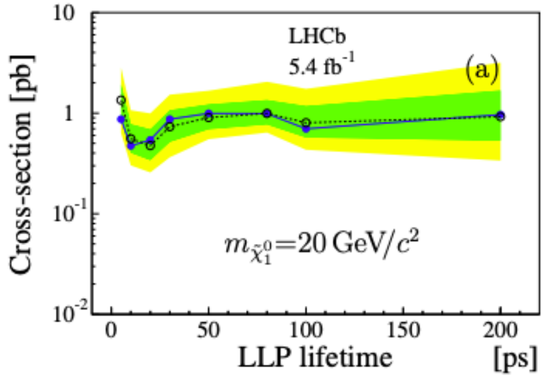
Signal region

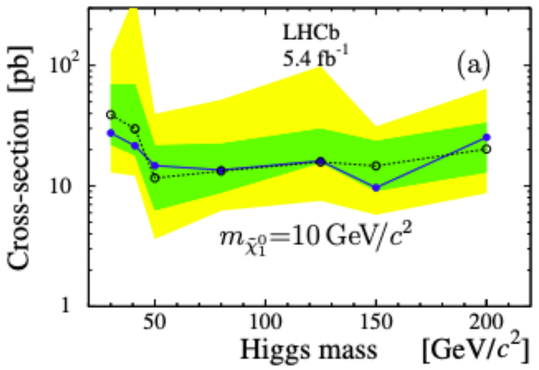


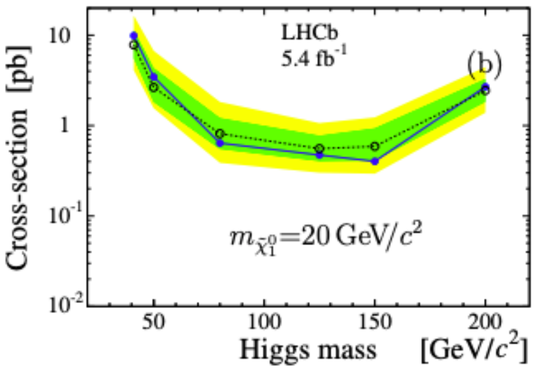
Background region

- 95 % CL upper limits are set on $\sigma(\text{LLPs}) \times \mathcal{B}(\text{LLPs} \to q\bar{q}\mu)$ for both searches → sensitivity of the order $O(1$ pb$)$









LLPs searches at LHCb

Search for heavy neutral leptons in $W^{\pm} \to \mu^{+}\mu^{\pm}$ jet decays

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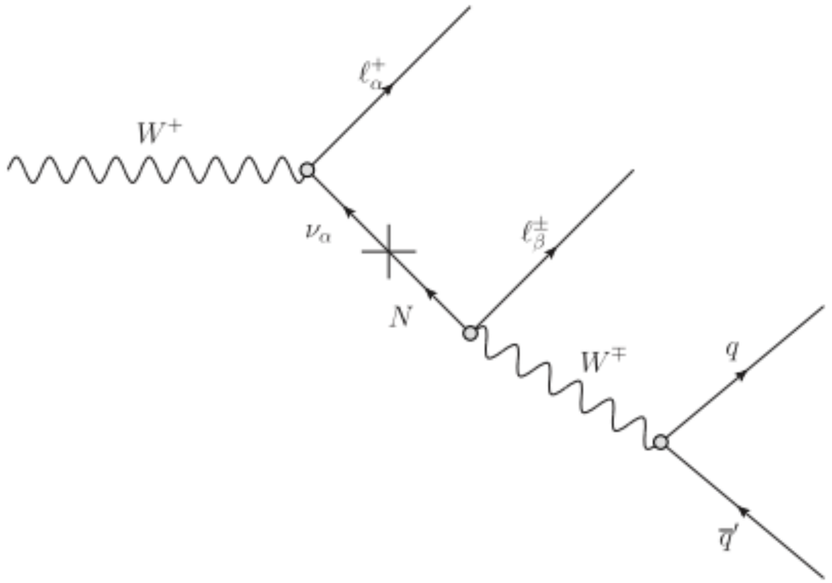
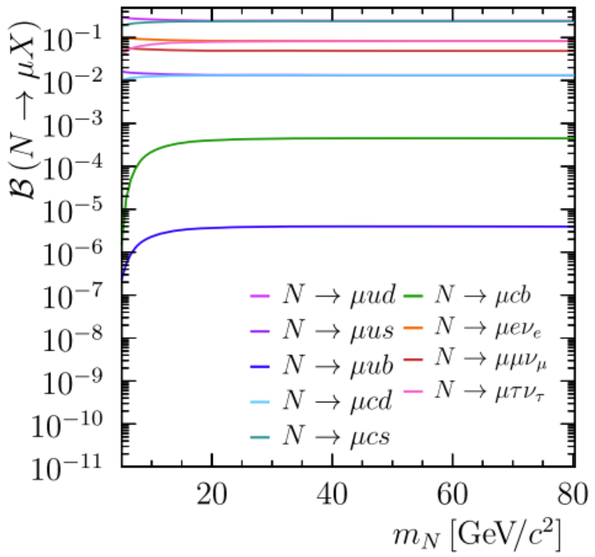
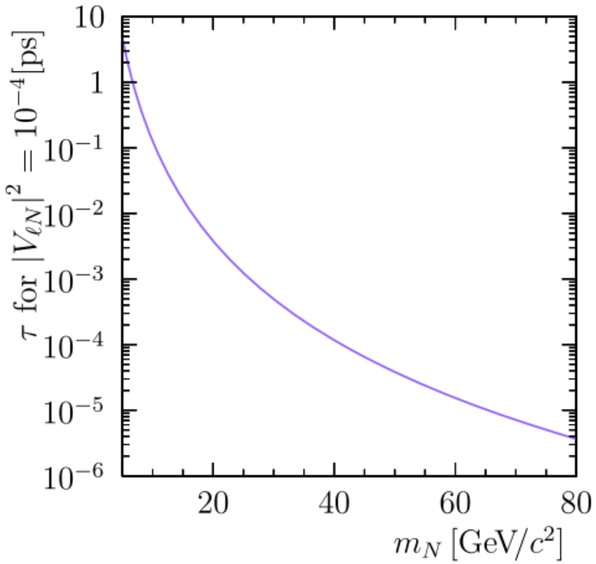
- Prompt heavy neutrino decay to $\mu^{\pm}$ jet
- HNL mass range between 5 and 50 GeV/c^2
- Significant lifetime expected at low masses
- Analysis performed with full Run I data ($\sim 3\text{fb}^{-1}$) at $\sqrt{s} = 7$ and $\sqrt{s} = 8$ TeV







- Signal selection:
  - $p_T(\mu_N) > 3$ GeV/c and $m_{inv}(\mu_N, \mu_W) \in [20,70]$ GeV/c^2
  - Jet reconstructed with $\Delta R = 0.5$ and $p_T > 10$ GeV/c^2
  - Heavy-flavour background suppression: IP of μ_N and μ_W
  - Candidates are classified as same-sign (SS) and opposite-sign (OS)

LLPs searches at LHCb

Search for heavy neutral leptons in $W^{\pm} \to \mu^{+}\mu^{\pm}$ jet decays

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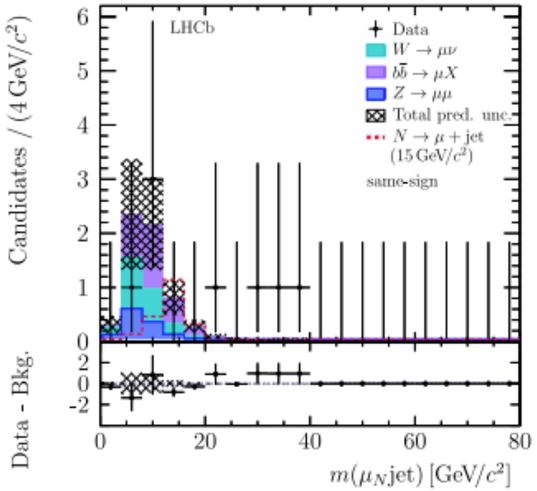
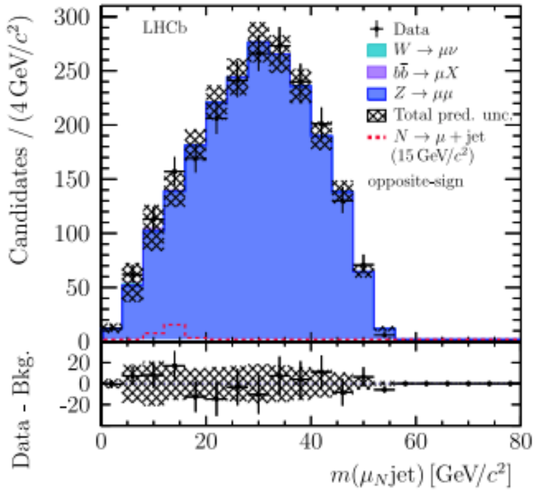
- Three different BDTs are used for μ_N, μ_W and kinematics
- Definition of signal and control regions:

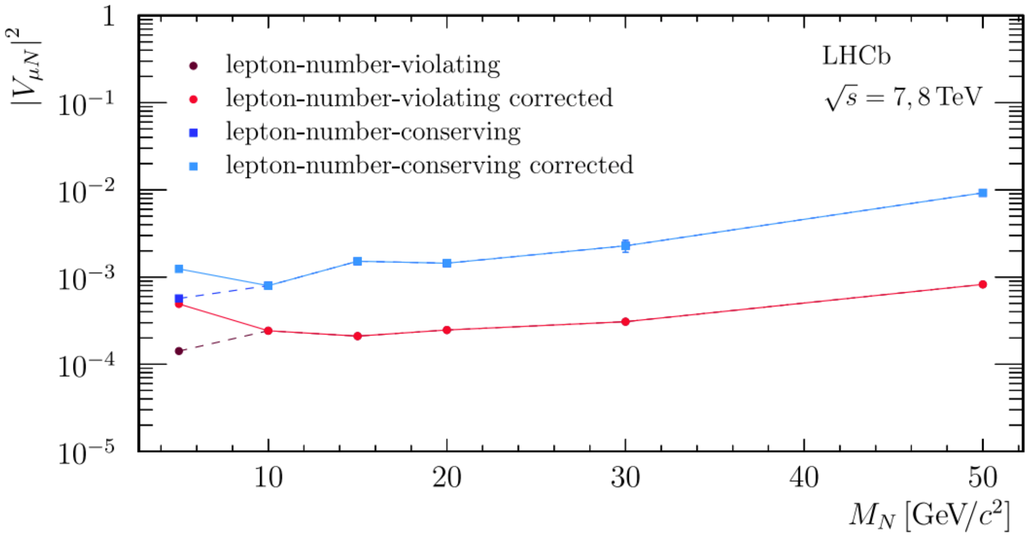
	IP(μ_W) (mm)	μ_W uBDT	μ_N uBDT	Kinematic uBDT	IP(μ_N) (mm)
Signal	< 0.04	> 0.55	> 0.60	> 0.62	< 0.1
W region	< 0.04	> 0.55	< 0.60	< 0.62	< 0.1
$b\bar{b}$ region	> 0.04	< 0.55	< 0.60	< 0.62	> 0.1
QCD region	< 0.04	< 0.55	> 0.60	> 0.62	< 0.1

SS candidates



OS candidates

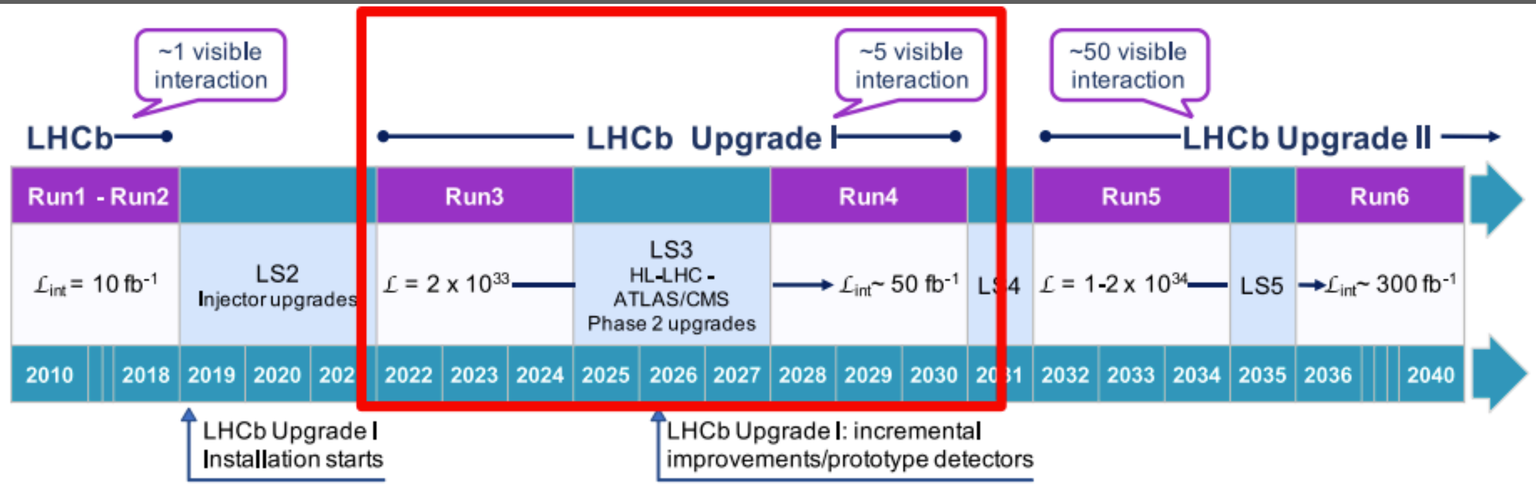




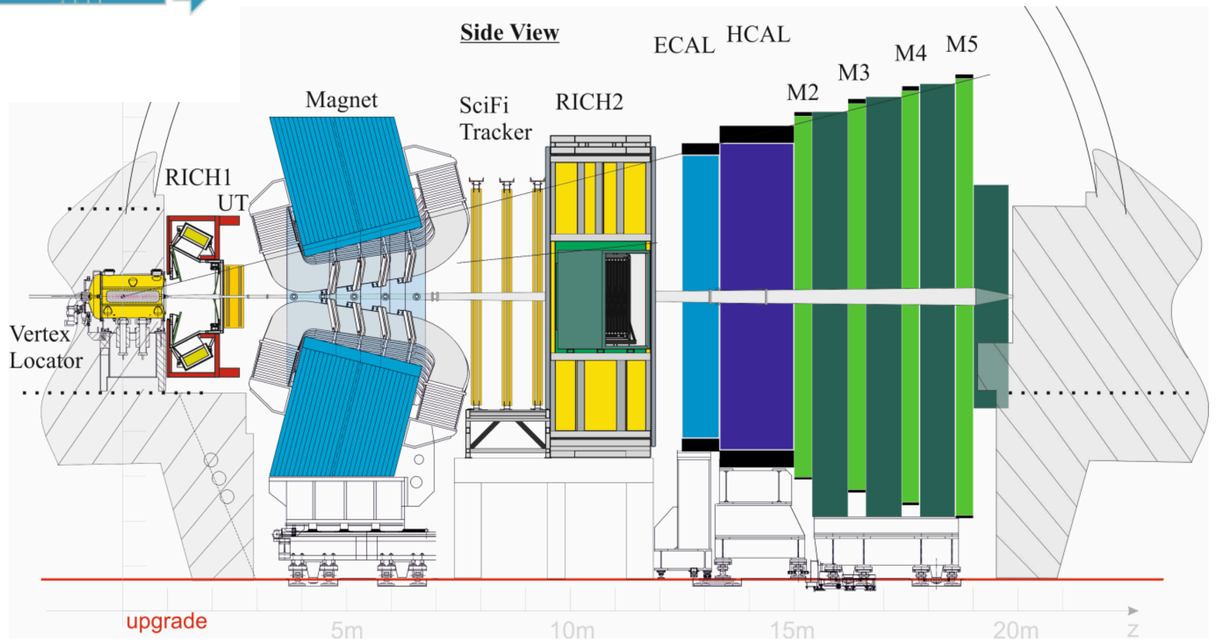
- Binned fit to $p_T(\mu_N)$ in eight pseudorapidity bins
- No excess is found, upper limits on $\mathcal{B}(N \to \mu\text{jet}) \, | \, V_{\mu N} |^2$
- Up to now results are not competitive with ATLAS, CMS and DELPHI searches
- With integrated luminosity of 50 fb^{-1} → better sensitivity for the same-sign muons channel
- Here search for prompt HNL, better sensitivity at low mass can be reached with displaced search!

Prospects for LLPs searches at LHCb

What to expect for the future!



- LHCb is getting ready for the Run 3 with a **whole new detector**:
  - upgraded VELO with pixels
  - new silicon strip detector, new scintillating fibre detector
  - Particle ID: new optics, new photon detectors
  - calorimeters: reduce PMT gain and new electronics
  - muon detector: new electronics and increased granularity
  - upgraded trigger **all in software** (L0 removed)

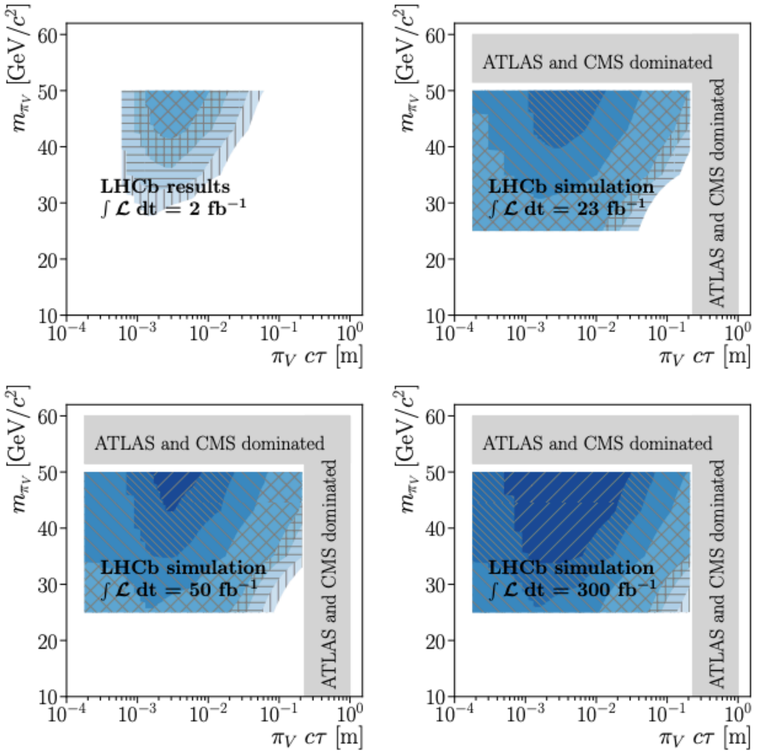


Prospects for LLPs searches at LHCb

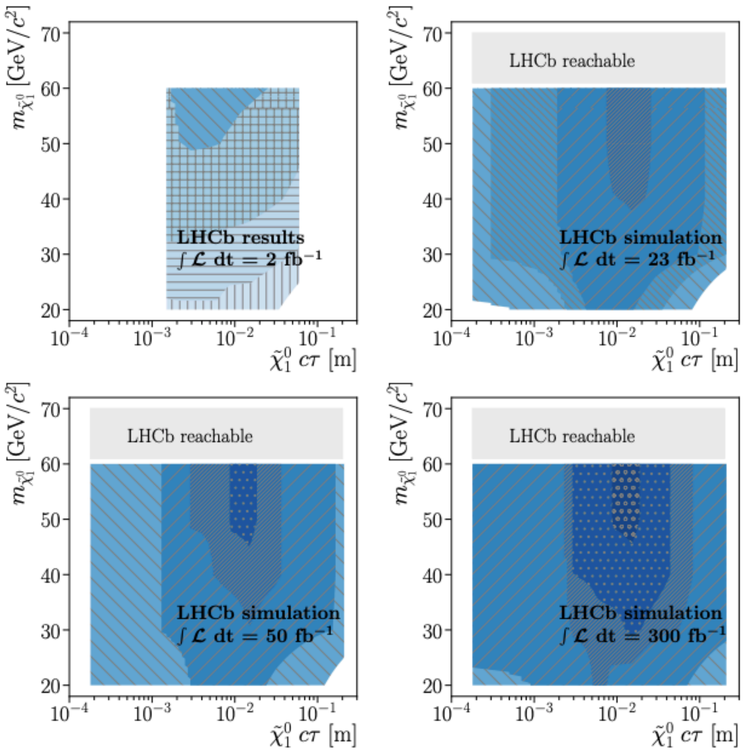
Rich program for LLPS searches

arXiv.2105.12668

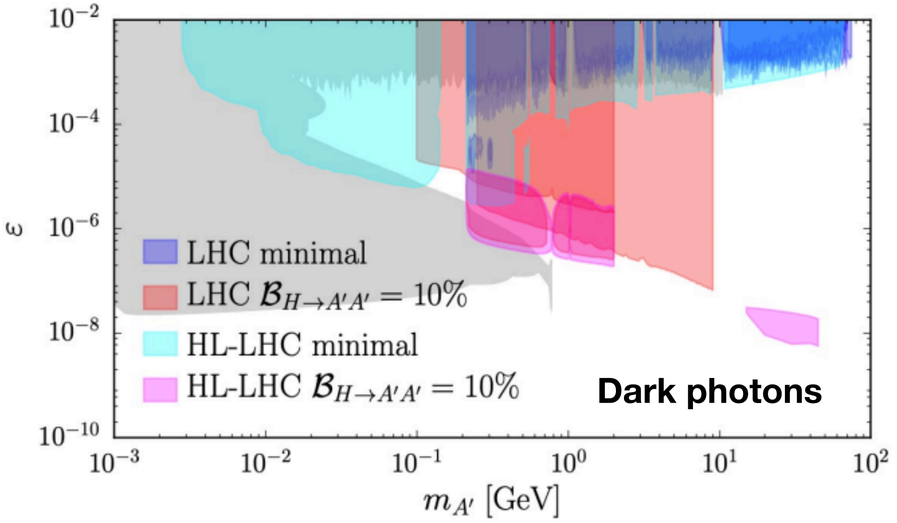
LLPs decaying to jets



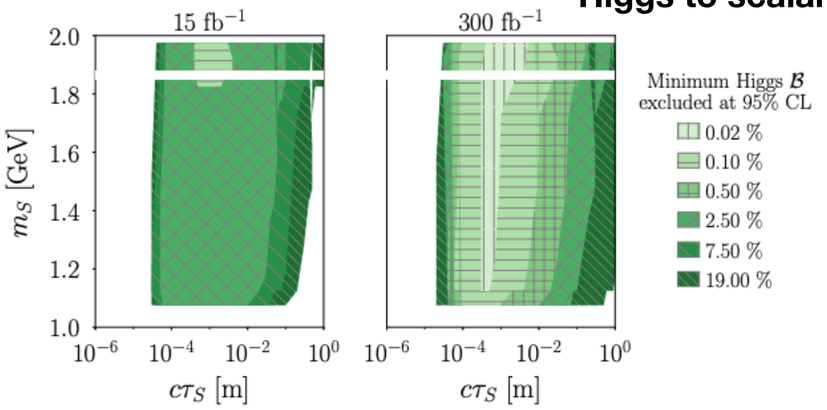
LLPs decaying semileptonically



Dark photons



Higgs to scalars



Conclusions
Wrap up

- LHCb is by all means a **general purpose forward detector**
- LHCb is a unique place to study LLPs:
  - Detection of low-mass particles and soft signatures
  - Studies on b- and c-decays
  - Phase space region complementary to ATLAS and CMS
- **Several analyses on Run I and Run II data:**
  - Dark photons and di-muon resonances
  - HNLs
  - LLPs decaying to jets and semileptonically
- Getting ready for next runs:
  - Whole new detector
  - Fully-software trigger

Unleashing the full power of LHCb to probe Stealth New Physics

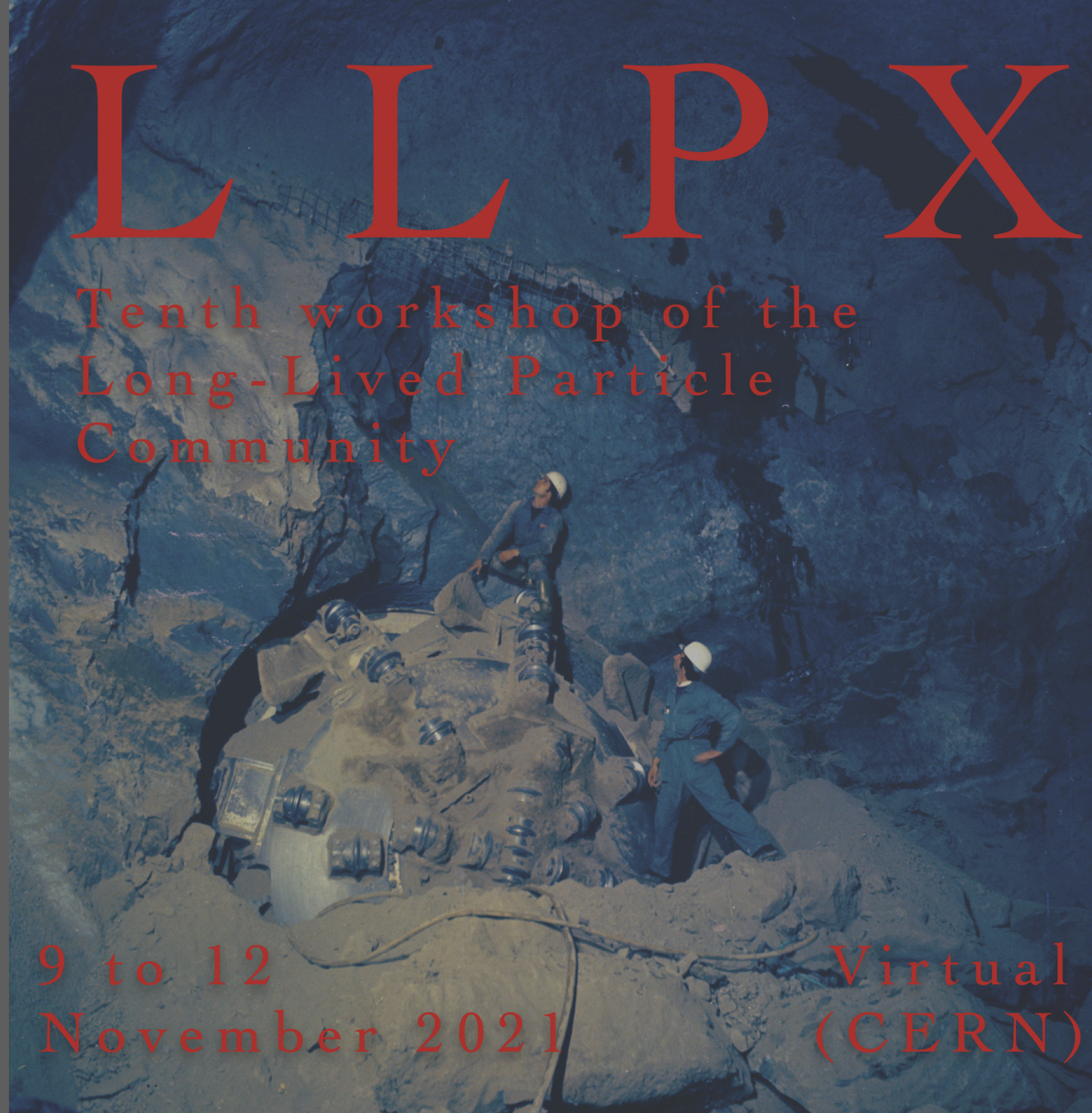
Editors: M. Borsato[1], X. Cid Vidal[2], Y. Tsai[3 4], C. Vázquez Sierra[5], J. Zurita[6]

Authors: G. Alonso-Álvarez[7], A. Brea Rodríguez[2], D. Buarque Franzosi[9,10], G. Cacciapaglia[11,12], A. Casais Vidal[2], M. Du[13], G. Elor[14], M. Escudero[15], G. Ferretti[9], T. Flacke [16], P. Foldenauer[17], J. Hajer[18,19], L. Henry[5], P. Ilten[20], J. Kamenik[21,22], B. Kishor Jashal[6], S. Knapen[5], F. L. Redi[23], M. Low[24], Z. Liu[13,25,26], A. Oyanguren Campos[6], E. Polycarpo[27], M. Ramos[28,29], M. Ramos Pernas[30], E. Salvioni[5], M. S. Rangel[27], R. Schäfer[8], L. Sestini[31], Y. Soreq [32], V. Q. Tran[13], I. Timiryasov[23], M. van Veghel[33], S. Westhoff[8], M. Williams[34], J. Zupan[20]

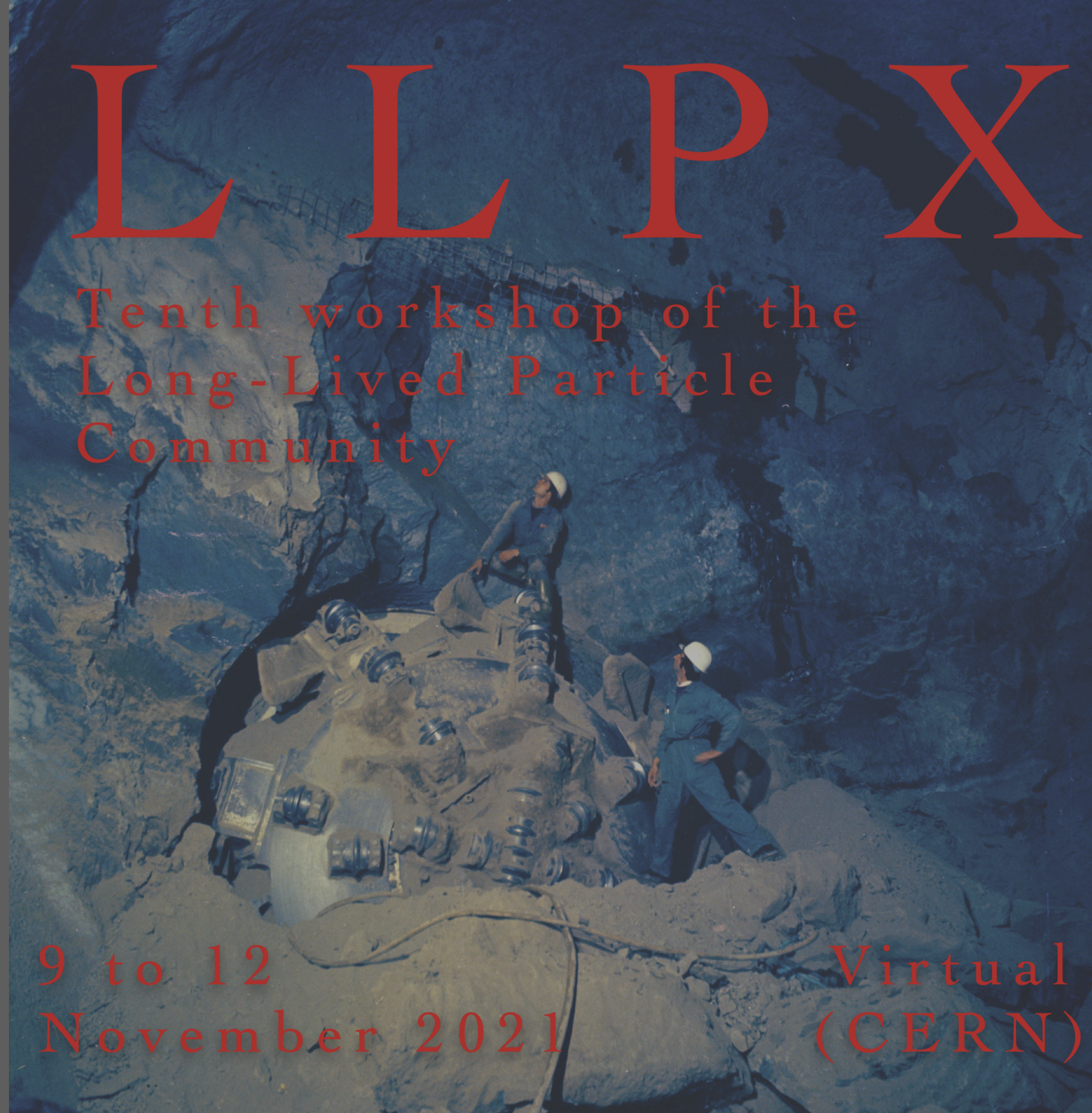
Abstract

In this paper we describe the past, present and future potential of LHCb to find Stealth physics. This refers to Beyond the Standard Model signatures with excellent theory motivation and not falling in the category of "flavor physics". Examples of these signatures include Long-Lived particles, light resonances or hadronic final states where particle identification can play an important role. We will describe why LHCb is very well equipped to discover this kind of physics at the Large Hadron Collider, and provide good examples of well motivated theoretical models that can be probed with great detail at the experiment.

Thank you for your attention!



Backup slides

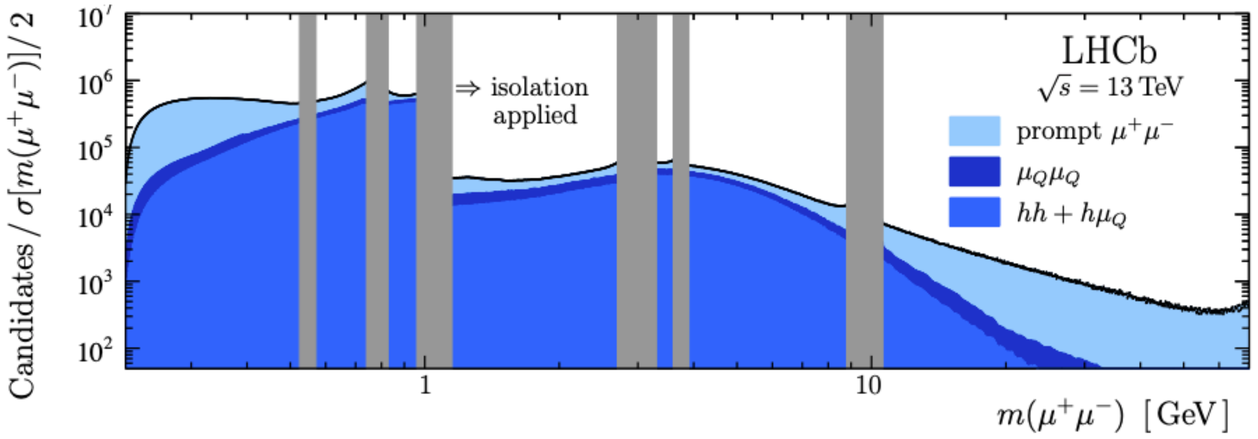


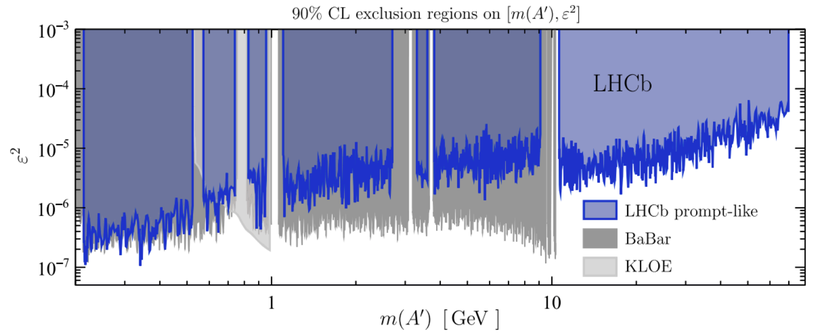
LLPs searches at LHCb

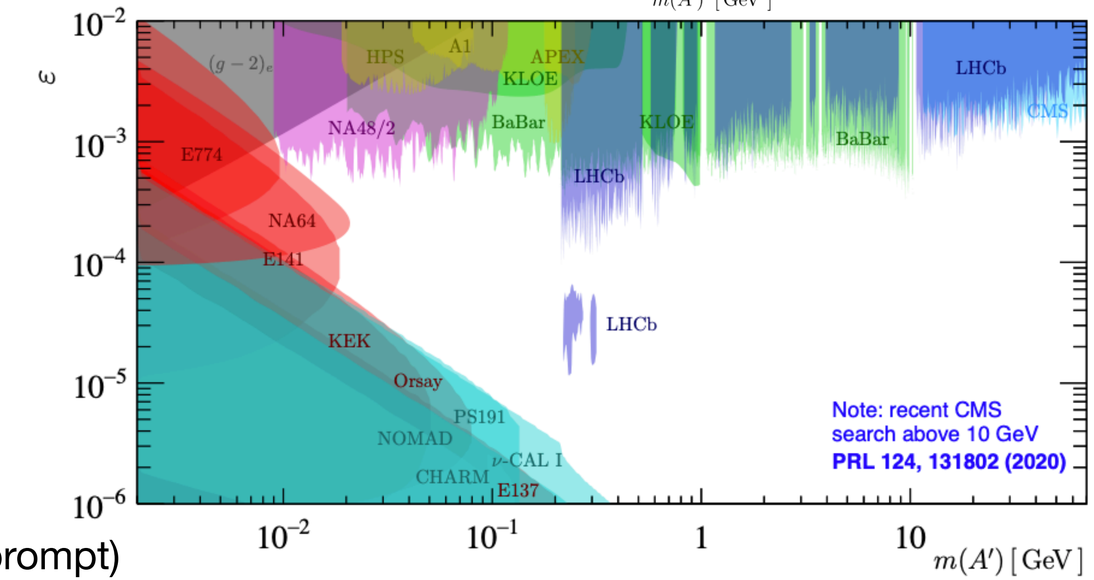
PRL 124(2020) 041801

Search for dark photons produced in 13 TeV pp collisions

- Search for massive long-lived particles (LLP) decaying into a muon and two quarks
- Light dark photons can appear in mixing with an off-shell photon
  - Large fraction in the forward region with low p_T
- Search for $A' \to \mu^+\mu^-$ at 13 TeV ($\mathscr{L} \sim 1.6\text{fb}^{-1}$) using Run II data
- Both prompt and displaced signatures are studied







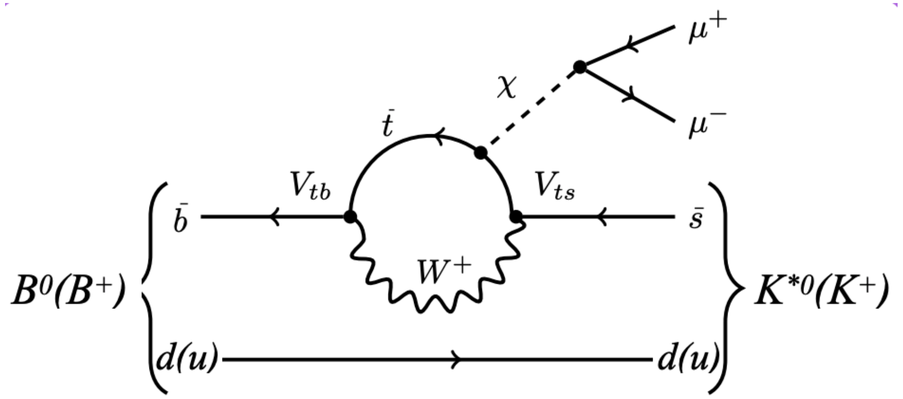
- World's best upper limits for invariant mass range of ~200-700 MeV (prompt)
- Can be extended with di-electron search at very low masses in $D^* \to Dee$

LLPs searches at LHCb

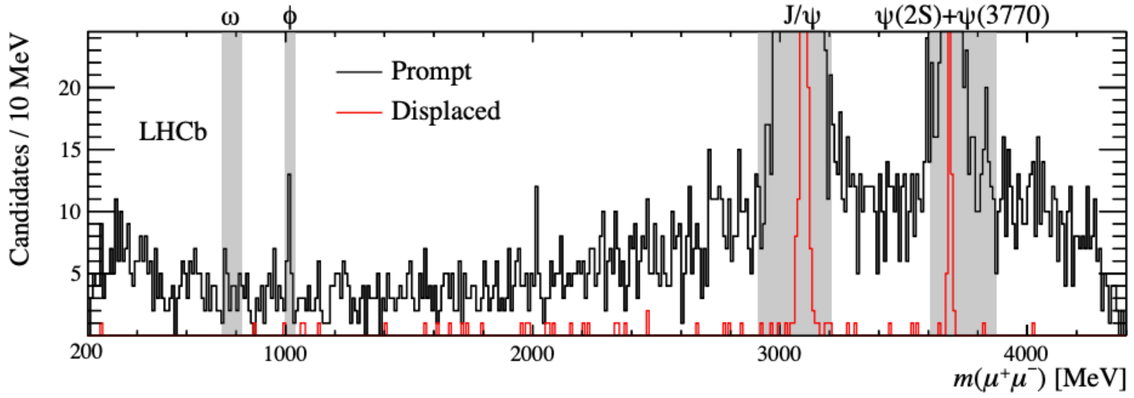
Search for massive long-lived particles in $B^+ \to K^+\chi(\mu^+\mu^-)$ decays

PRL 115 (2015) 161802
PRD 95 (2017) 071101

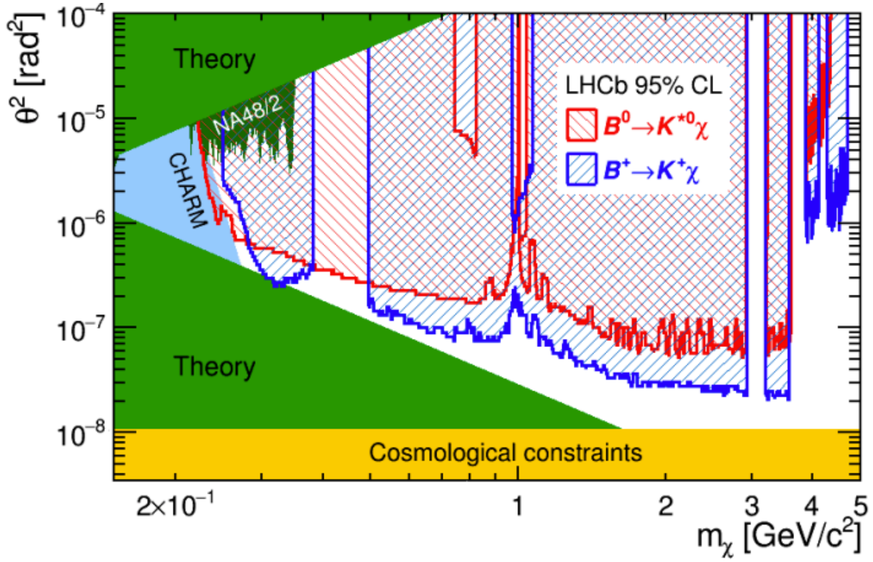
- A hidden sector boson χ can contribute to $b \to s\mu\mu$ decays



- Run I data ($\mathscr{L} \sim 3\text{fb}^{-1}$)
- Scan of the di-muon mass distribution



- Two analyses:
  - $B^0 \to K^{0*}\chi$ with $K^{0*} \to K^+\pi^+$ and $\chi \to \mu^+\mu^-$
  - $B^+ \to K^+\chi$ and $\chi \to \mu^+\mu^-$
- Similar analysis strategies:
  - $\chi \to \mu^+\mu^-$ allowed to be displaced
  - BDT classifier to reduce background



World's best upper limits below $2m_\tau$

LLPs searches at LHCb

Updated search for long-lived particles decaying to jet pairs

EPJC 77 (2017) 812
PRD 92 (2015) 073008
PRD 92 (2015) 012010

- A Higgs boson could decay to a pair of Hidden Valley (HV) pions, which in turn decay to $q\bar{q}$ pairs
- Search for a "displaced di-jet vertex" $\Longrightarrow$ good resolution of primary (PV) and secondary vertices (SV) is needed
- LHCb can access low lifetimes and small HV pion masses
- Run I data ($\mathscr{L} \sim 2$ fb^{-1}) are analyzed
- Different distances from PV are considered (R_{xy})
- Upper limits are set on $\sigma(gg \to H^0) \times \mathscr{B}(H^0 \to \pi_V \pi_V)$
- LHCb results are compared with ATLAS/CMS
- LHCb could explore exotic Higgs decay processes ($H^0 \to SS$) followed by a displaced decay of the scalar S