

Searches for Majorana Neutrinos and Direct Searches for Exotics at LHCb

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These proceedings present the LHCb results on Majorana neutrino searches and direct production of exotic particles using the data collected during Run I of LHC. For the former, Majorana neutrinos are searched for both on-shell and off-shell in B and D decays to final states with two same-sign muons. For the latter, different types of new particles are studied profiting the unique coverage of LHCb with respect to other detectors.

I. INTRODUCTION

LHCb is one of the four primary detectors of the Large Hadron Collider (LHC) project at CERN (Geneva, Switzerland). LHCb is a single-arm forward spectrometer with a unique coverage in terms of pseudorapidity, η (see FIG. 1), originally designed to study the production and decay of b - and c -hadrons but currently extending its physics programme to include also other areas such as electroweak or exotica searches. Exotica at LHCb includes both the direct production of particles beyond the Standard Model and Higgs physics. The strong points of LHCb are an excellent particle identification (including K/π separation), secondary vertex, lifetime, momentum and invariant mass resolution.

During Run I of LHC, LHCb recorded data at centre of mass energies of $\sqrt{s} = 7$ TeV (2010 and 2011) and 8 TeV (2012). To optimise the performance for b -physics, LHCb runs with lower instantaneous luminosity than ATLAS and CMS, with the advantage of having stable conditions in terms of the instantaneous luminosity during a fill (thanks to the luminosity levelling). LHCb took 37 pb^{-1} in 2010, 1 fb^{-1} in 2011 and 2 fb^{-1} in 2012, respectively.

These proceedings present LHCb results on the search for New Physics (NP) in Majorana neutrino and exotica related analyses. Searches at LHCb can be performed both through the indirect or direct approach. The indirect approach implies searching for new virtual particles that appear in the Feynman diagrams. This has the advantage of being potentially sensitive to higher mass scales than those accessible by direct searches, since the new particles are produced virtually, although very precise measurements are required in this case. The direct approach is somehow the more classical one, in which new particles are directly searched for in some final state. This is the strategy more typically followed by ATLAS or CMS. The indirect approach is the one followed partly for the Majorana neutrino searches, through decays of heavy mesons to final states with two same sign leptons. For the direct searches, LHCb has the advantage of its unique

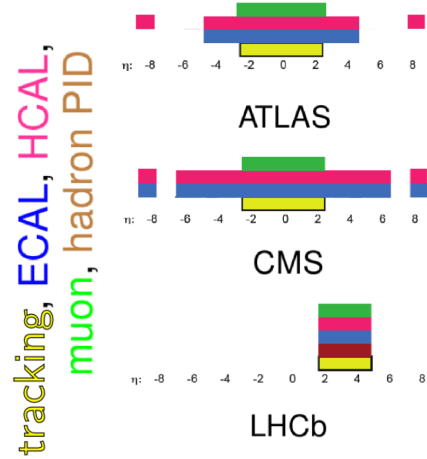
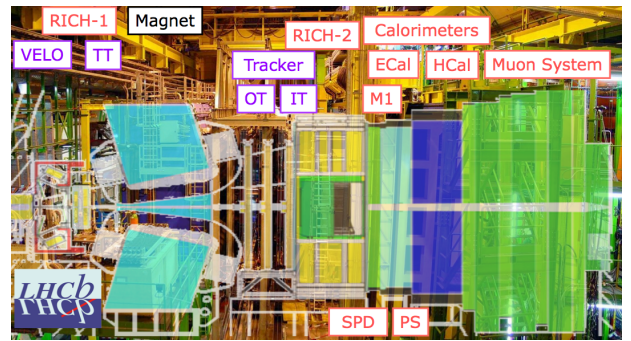


FIG. 1. Top: Photograph of the LHCb detector with its sub-detectors highlighted. Bottom: η coverage comparison between LHCb, ATLAS and CMS.

phase space coverage. The direct approach is the strategy followed for on-shell Majorana neutrinos and exotica searches. FIG. 2 shows examples of diagrams for both direct and indirect searches.

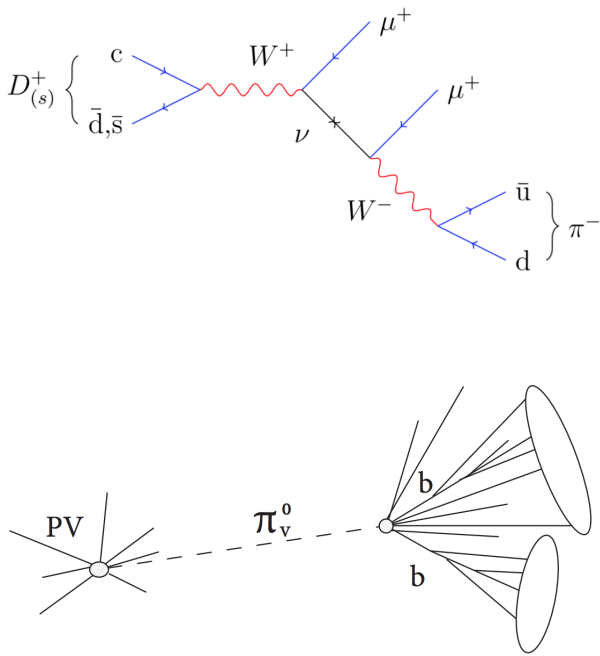


FIG. 2. Diagrams for the indirect (top) or direct (bottom) approach in searches. In the top diagram, a Majorana neutrino is produced off-shell in a $D_{(s)}^+$ decay to a final state with two same-sign muons (with the same diagram, the Majorana neutrino could be also produced on-shell). In the bottom one, a hidden valley pion is produced on-shell to later decay to a pair of jets.

II. SEARCHES FOR MAJORANA NEUTRINOS

Majorana neutrinos at LHCb

The LHC collisions produce ~ 15 kHz $b\bar{b}$ pairs and ~ 300 kHz $c\bar{c}$ pairs in the LHCb detector [1], which allows to set very stringent limits on rare B and D decays. In particular, this makes possible the search for off-shell and on-shell Majorana neutrinos, with final states in which two same-sign muons are present. The searches profit from the aforementioned excellent mass and lifetime resolutions of LHCb.

Searches in B and D decays are complementary to other searches, such as those looking for neutrino-less double β decay [2]. In this case, LHCb searches are useful to study the coupling of Majorana neutrinos to muons. There exist specific NP models with Majorana neutrinos that can be constrained by LHCb results. An example can be found in reference [3], where a type-I seesaw model with three right-handed neutrinos is presented. FIG. 3 shows the fraction of phase space constrained by LHCb results.

The main results of LHCb in the search for Majorana neutrinos are summarized below.

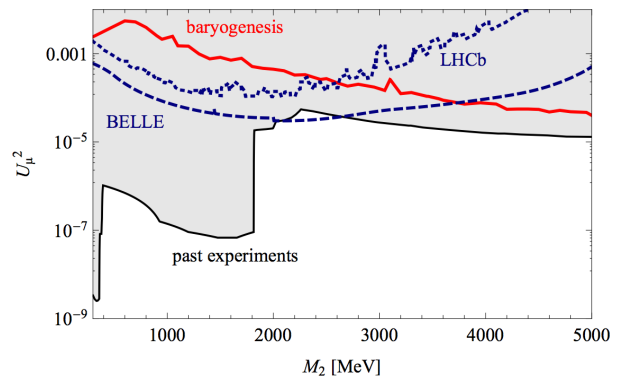


FIG. 3. Allowed parameter space for the model presented in reference [3]. The x-axis shows the mass of the Majorana neutrino and the y-axis the coupling of the neutrino to muons squared. Constraints by the different experiments are also shown. The Belle search can be found in reference [4], although the theoretical reference used to obtain the limit on the coupling is different to that of LHCb. The red line shows the constraint from the observed baryon asymmetry of the Universe.

$$B^\pm \rightarrow h^\mp \mu^\pm \mu^\pm$$

LHCb results in B^\pm decays probe a wide range of Majorana neutrino masses and lifetimes. The searches are of the type $B^\pm \rightarrow h^\mp \mu^\pm \mu^\pm$ and the results are gathered in three different papers, with different final states and LHCb datasets. FIG. 4 shows examples of the Feynman diagrams for these decays. The final states and associated papers are:

- $h^\mp = K^\mp$ or π^\mp , with $\sim 36 \text{ pb}^{-1}$ ($\sqrt{s} = 7 \text{ TeV}$) [5]
- $h^\mp = D^\mp, D^{*\mp}, D_s^\mp$ and $D^0 \pi^\mp$, with $\sim 40 \text{ pb}^{-1}$ ($\sqrt{s} = 7 \text{ TeV}$) [6]
- $h^\mp = \pi^\mp$, with 3.0 fb^{-1} ($\sqrt{s} = 7 \text{ TeV} + \sqrt{s} = 8 \text{ TeV}$) [7]

For these searches, the Majorana neutrino is generally assumed to be short-lived, i.e., not detached from the B^+ decay vertex. However, in reference [7], the possibility of a long-lived Majorana neutrino is also considered. In order to convert the yield into a branching fraction, a normalization channel, with a well-known branching fraction, is chosen. $B^+ \rightarrow J/\Psi K^+$ (with $J/\Psi \rightarrow \mu^+ \mu^-$) is the normalization channel chosen for the 3-body final state channels and $B^+ \rightarrow \Psi(2S) K^+$ (with $\Psi(2S) \rightarrow J/\Psi \pi^+ \pi^-$ and $J/\Psi \rightarrow \mu^+ \mu^-$) for the 5-body final state channels. The dominant background for this analysis is that of charmonium decays, in which one of the final state particles is misidentified. The expected contribution from this background is estimated from data. As an example, FIG. 5 shows the relevant mass spectra for the searches performed in reference [7].

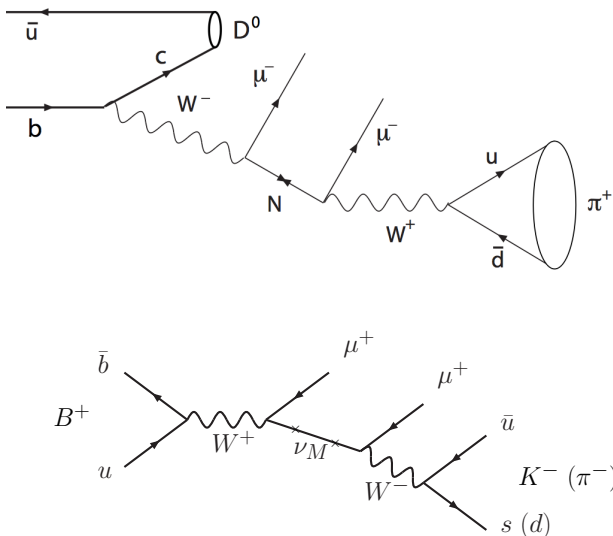


FIG. 4. Examples of Feynman diagrams for the search for Majorana neutrinos in B^+ decays.

Channel	BR _{UL} 95% CL
$B^\pm \rightarrow K^\mp \mu^\pm \mu^\pm$	5.4×10^{-8}
$B^\pm \rightarrow D^\mp \mu^\pm \mu^\pm$	6.9×10^{-7}
$B^\pm \rightarrow D^{*\mp} \mu^\pm \mu^\pm$	2.4×10^{-6}
$B^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$	4.0×10^{-9}
$B^\pm \rightarrow D_s^\mp \mu^\pm \mu^\pm$	5.8×10^{-7}
$B^\pm \rightarrow D^0 \pi^\mp \mu^\pm \mu^\pm$	1.5×10^{-6}

TABLE I. Summary of upper limits on the branching fraction of different channels in Majorana neutrino searches in references [5–7].

No signal is observed in any of the searches, so upper limits on the branching fraction are set. For the searches of reference [7], upper limits are set by scanning across in $5 \text{ MeV}/c^2$ steps of neutrino mass from 250 to 5000 MeV/c^2 with varying mass resolution. For long lived neutrinos, the scan is done both in terms of the mass and lifetime of the neutrino. FIG. 6 shows these upper limits and also the interpretation of the limit as bounds on the couplings of a fourth generation lepton to muons. The explanation of how this coupling is calculated is given in reference [7]. The upper limits on the branching fraction for short-lived neutrinos are calculated from the average detection efficiency using the CL_S method. The limits for all the decay modes under scrutiny are shown in TABLE I. All these limits are world's best, and improve the previous limits by as much as factor of ~ 100 .

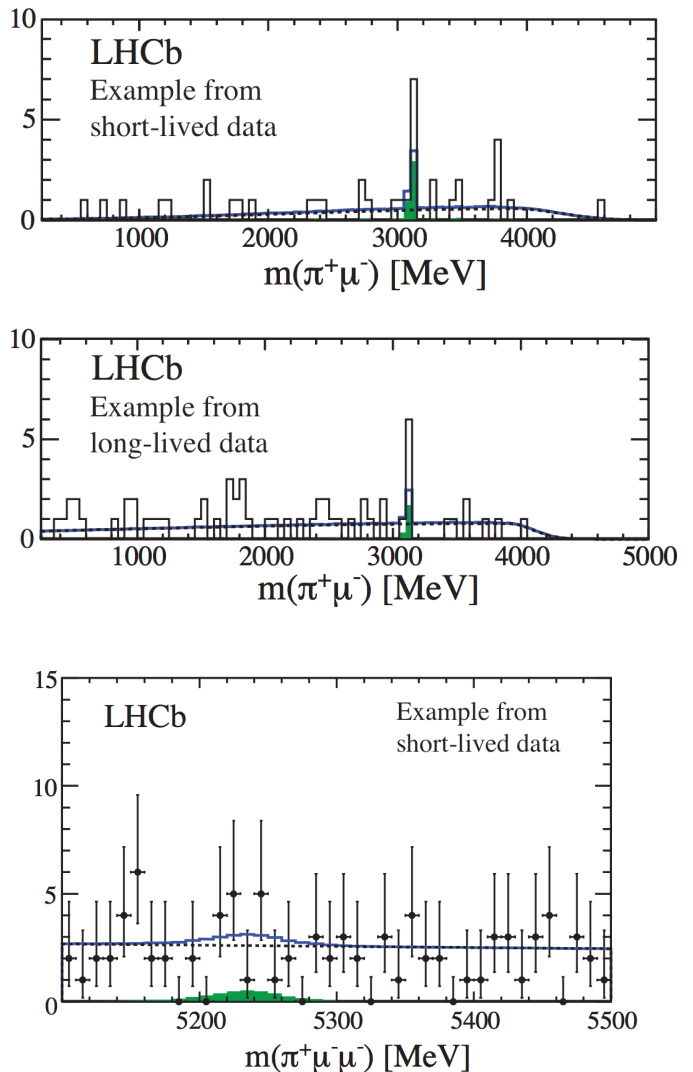


FIG. 5. Mass spectra in data for Majorana neutrino searches in reference [7]. Top and medium, $\pi^+\mu^-$ for a 2σ window around the B^+ mass (σ being the mass resolution); bottom, $\pi^+\mu^-\mu^-$. The expected contribution from charmonium backgrounds is shown in green. For the $\pi^+\mu^-$ mass spectra, top plot shows the case in which the Majorana neutrino is short-lived and medium plot the case in which it is long-lived. The $\pi^+\mu^-\mu^-$ mass spectra is only shown for the short-lived case. For the long-lived (short-lived) case, the Majorana neutrino decay vertex is (not) detached from the B^+ decay vertex.

$$D_{(s)}^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$$

The physics case for this analysis is similar to the one presented for the B decays. An example process was previously given in the top diagram of FIG. 2. This search is performed using the the LHCb 2011 data sample, i.e., 1 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$ [8]. The Majorana neutrino is considered to be short-lived.

For this analysis, the normalization is done to the $D_{(s)}^+ \rightarrow \phi(\mu^+\mu^-)\pi^+$ decay. Furthermore, the candi-

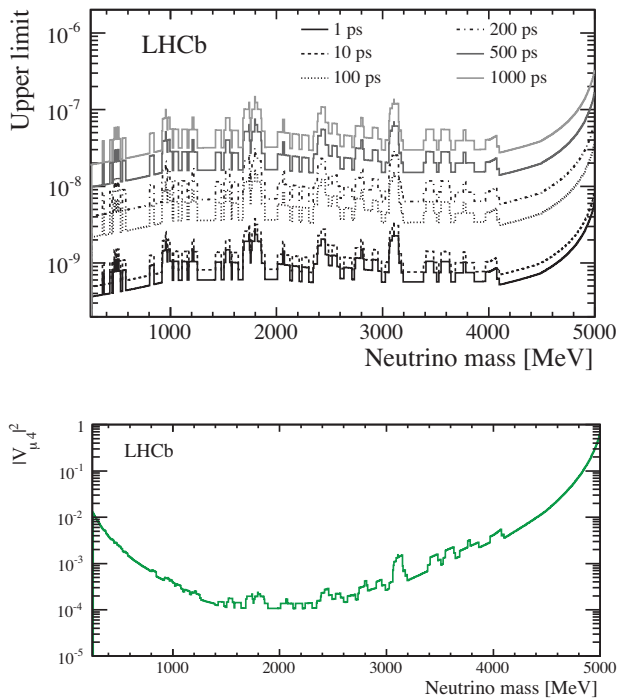


FIG. 6. Main results from the Majorana neutrino search in reference [7]. Top, upper limit on the branching fraction as a function of mass and lifetime of the neutrino. Bottom, limits on fourth generation couplings, $|V_{\mu 4}|^2$, as a function of neutrino mass. The limits in both cases are at 95% CL.

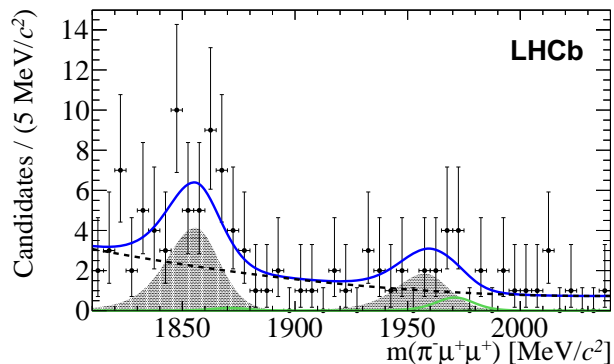


FIG. 7. $\pi^- \mu^+ \mu^+$ mass spectra for the search in reference [8]. The expected peaking background from $D_{(s)}^+ \rightarrow \pi^+ \pi^+ \pi^-$ is represented by the filled grey histograms.

dates are classified using PID cuts and a BDT that included kinematic and geometrical variables. The important peaking background from $D_{(s)}^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays is also taken into account, with the expected yield also measured from data. FIG. 7 shows the invariant mass spectra obtained in data, with the relevant peaking background expected.

No significant signal is found in this search, so upper limits on the corresponding branching fractions are set. For this, a fit in bins of $m(\pi^- \mu^+)$ is performed in order to

Channel	BR _{UL} 95% CL
$D^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$	2.5×10^{-8}
$D_s^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$	1.4×10^{-7}

TABLE II. Upper limit on the branching fractions of the decays searched for in reference [8].

improve the statistical significance. The results, shown in TABLE II, correspond to an improvement by a factor of 50 with respect to previous limits.

III. DIRECT SEARCHES FOR EXOTICS

Limits on $H^0 \rightarrow \tau^+ \tau^-$ production

This is the first LHCb paper concerning a search for the Higgs boson [9]. No excess is found in the 2011 dataset, so upper limits on the production are set using the CL_S method. This is done both in a model independent way (as a function of the Higgs boson mass, m_H) and in one particular realization of the Minimal Supersymmetrical Standard Model (MSSM). FIG. 8 shows the main results of this search.

Higgs decays to long-lived particles

LHCb carries out a search for long-lived massive particles decaying from a Standard Model-like Higgs boson. The search is performed using using 0.62 fb^{-1} of the 2011 LHCb dataset [18]. In this case, the full 2011 dataset is not used since the most efficient triggers were only operated from summer 2011 on. Several NP models predict this kind of particles. Examples are:

- SUSY models with Baryon number Violation (BV), $h^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$, with $\tilde{\chi}_1^0$ being a long-lived neutralino and $\tilde{\chi}_1^0 \rightarrow 3$ quarks [19].
- Some Hidden Valley (HV) models, $h^0 \rightarrow \pi_V^0 \pi_V^0$, and π_V^0 decays to a pair of displaced b -quarks [20].

The experimental signature for this search is a displaced vertex with two associated jets. This signature specifically profits the LHCb advantage on aspects such as vertexing. Furthermore, it should be noted that, concerning the parameter space coverage, the contribution from LHCb is particularly interesting and complementary to that of other experiments. FIG. 9 shows a diagram of the experimental signature and a plot of the LHCb complementarity in the specific case of HV models.

This search finds no excess above background, which was mainly composed of $b\bar{b}$ pairs. Because of this, upper limits on the production are set in different regions of

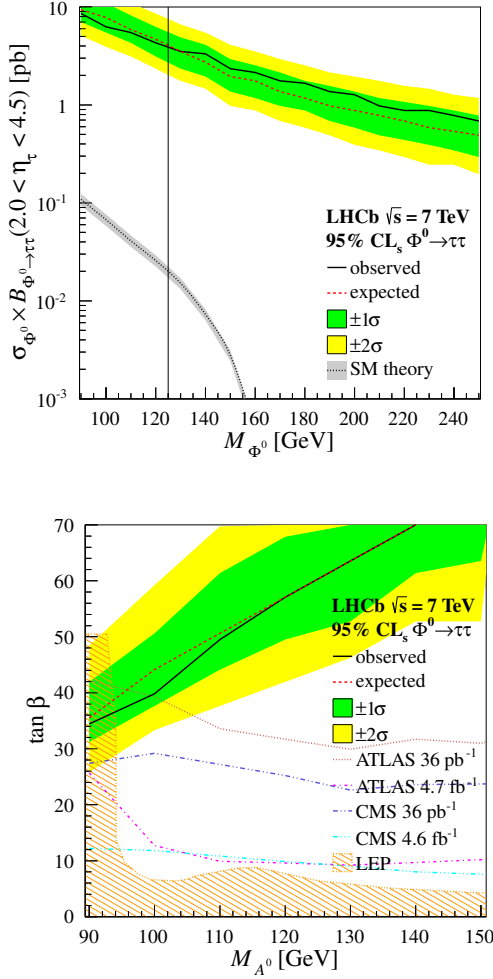


FIG. 8. Results on the $H^0 \rightarrow \tau^+\tau^-$ search at LHCb [9]. All limits are at 95% CL, set using the CL_s method. Top, model independent limit in terms of $\sigma_H \times BR(H^0 \rightarrow \tau^+\tau^-)$ (for the SM prediction, see [10, 11]). Bottom, limit compared to ATLAS [12, 13], CMS [14, 15] and LEP [16] in the $m(h^0)_{max}$ scenario [17].

the NP models parameter space. For this, fits are performed for different radial distances of the long-lived particles. The radial distance works here as a proxy for the long-lived particles lifetime. FIG. 10 shows one of these fits and the limits as a function of the long-lived particles mass and lifetime. For reference, the complementary CMS and ATLAS results can be found in references [21, 22], although they cover a different phase-space, so they are not directly comparable.

Search for long-lived heavy charged particles

Using an innovative approach, a search for charged massive stable particles (CMSP) is performed using the

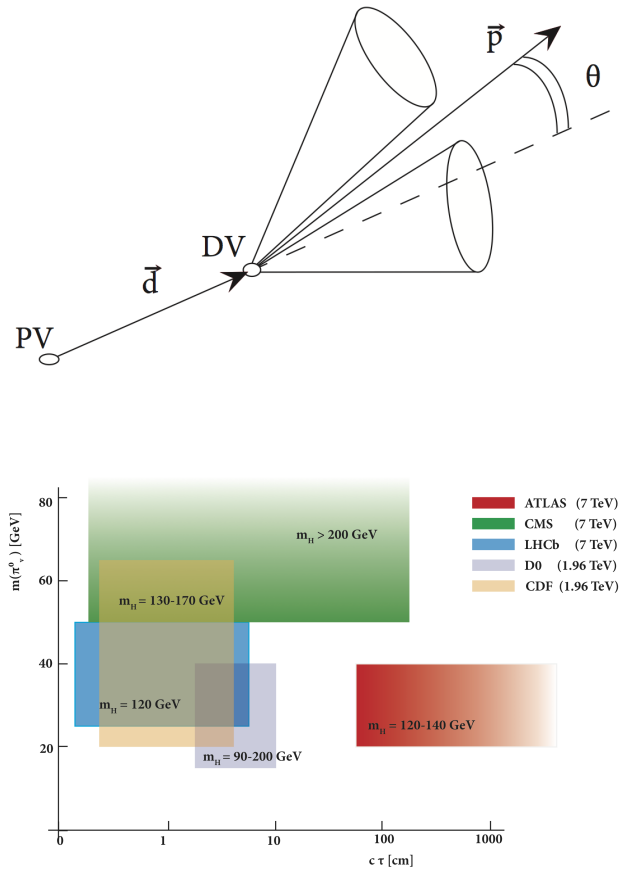


FIG. 9. LHCb on H^0 decays to long-lived particles. Top, experimental signature. Bottom, LHCb parameter space coverage in HV models compared to other experiments: x-axis corresponds to the long-lived particle lifetime and y-axis to its mass.

LHCb detector and the 2011 and 2012 datasets [23].

For the analysis, the $\tilde{\tau}$ from the mGMSB model [24–26] is used as a benchmark.

When performed at other experiments, these kinds of analyses are typically based on dE/dx and time-of-flight measurements. However, LHCb developed a novel technique that is based on the Ring Imaging Cherenkov (RICH) detector [27]. Using the information from the RICH, a Delta Log Likelihood is built to distinguish CMSPs (with lower β) from other standard stable particles. In particular, since CMSPs are slow, the absence of corresponding light rings in the RICH is looked for. The main background for this search is Drell-Yan pair-production of $\mu^+\mu^-$.

No signal is found in this search, so upper limits are set on its production using the Feldman-Cousins technique. FIG. 11 shows an example of the Delta Log Likelihood built as a discriminant between CMSPs and other particles and also upper limits on the production of these particles as a function of their mass. Searches for CMSPs at ATLAS and CMS can be found in references [28, 29].

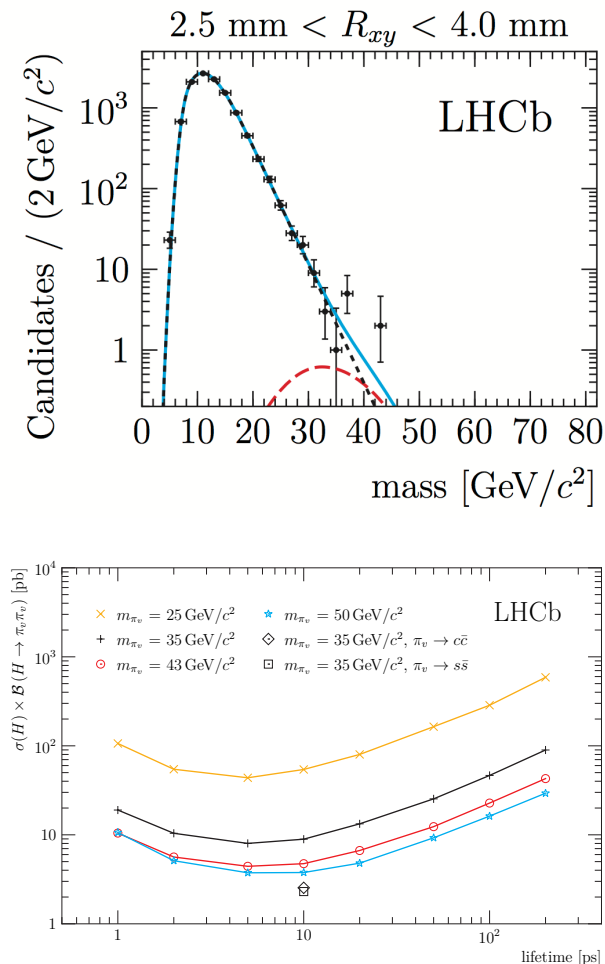


FIG. 10. Main results from reference [18]. Top, example from one of the fits to different radial distances. Bottom, 95% CL upper limits on the production depending on the lifetime and mass of the long-lived particle.

Searches for low mass dark bosons

Several theoretical models predict the existence of new particles that couple to SM particles by mixing with the Higgs. In particular inflaton, axion-like and dark matter mediator models also predict these particles to be light. LHCb performs a search for such particles [31], referred to as χ , as di-muon decaying resonances in a B meson decay: $B^0 \rightarrow K^* \chi (\mu^+ \mu^-)$. The diagram for this decay can be found in FIG. 12.

The features of χ depend on the theoretical model considered, and in particular a wide variety of lifetimes of χ could be possible. Two benchmark models are considered in this search: inflaton models [32] and axion portal models [33].

This search at LHCb relies on muon triggers, and includes the application of a multivariate selection not dependent on the χ mass or lifetime. Furthermore, in order to maximize the phase space coverage, the lifetime was

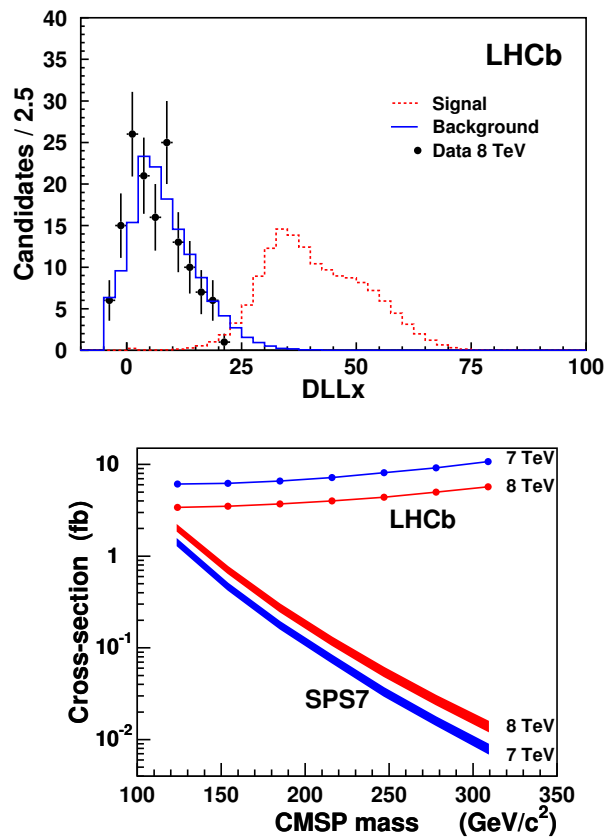


FIG. 11. Results from reference [23]. Top, RICH likelihood discrimination between Drell-Yan $\mu^+ \mu^-$ and a $124 \text{ GeV}/c^2$ long-lived particle. Bottom, 95% CL upper limits on the production of the charged massive stable particle obtained with the Feldman-Cousins method. Theoretical cross sections in SPS7 [30] (one of the scenarios of mGMSB) are also shown.

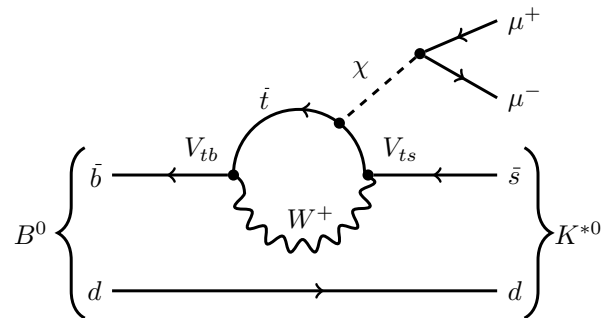


FIG. 12. Feynman diagram for the resonant production of a low mass dark boson in a $B^0 \rightarrow K^* \mu^+ \mu^-$ decay.

factorized into prompt and detached.

The search for the χ resonance is carried out by doing a scan in steps of the di-muon mass (with the B^0 mass constrained) and computing a test statistic, according to reference [34]. Following this procedure, the search does not find any excess and upper limits on the the production of χ are set as a function of its lifetime and

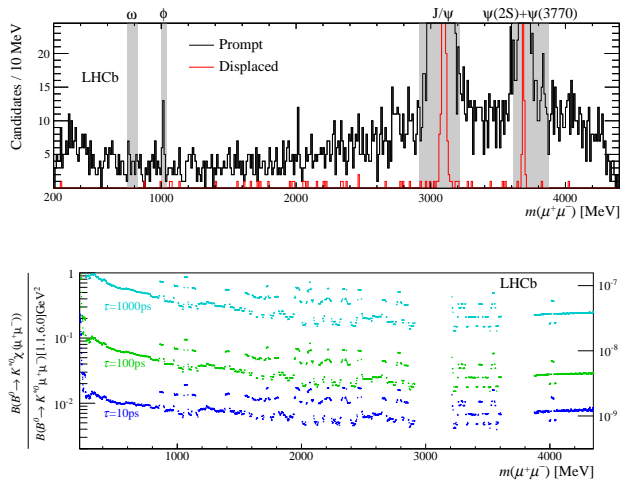


FIG. 13. Results of references [31]. Top, $\mu^+\mu^-$ mass spectra whenever the di-muon pair is detached or not. Bottom, 95% CL upper limits on the production as a function of the lifetime and mass of the χ resonance.

mass. FIG. 13 shows the di-muon invariant mass spectra in this search and the resulting upper limits. Finally, FIG. 14 shows the parameter space constrained by this result in two specific theoretical models that predict the production of inflatons and axions [32, 33].

Towards $H^0 \rightarrow b\bar{b}$

$H^0 \rightarrow b\bar{b}$ is interesting to study the coupling of the Higgs boson to quarks. The probability to have both b quarks decaying from H^0 in the LHCb acceptance is estimated to be $\sim 5\%$ at $\sqrt{s} = 7/8$ TeV, with an expected improvement at 13 TeV.

As a proof of the possibility of this search, LHCb has already successfully tested its jet reconstruction capacities, and also has achieved substantial progress on in b -jet tagging [36]. Several related analysis have been performed and are published. Some important examples are the top analysis [37], the measurements of W and Z + jets or b/c jets [38–40], and the measurement of the charge $b\bar{b}$ asymmetry [41].

IV. CONCLUSIONS

In these proceedings, LHCb has been shown to be competitive for NP searches following both direct and indirect approaches. LHCb can offer a unique coverage and complement other experiments.

Several LHCb Majorana neutrino searches have been presented. Even if these searches found no evidence, important constraints are set using both B and D decays to same sign muons.

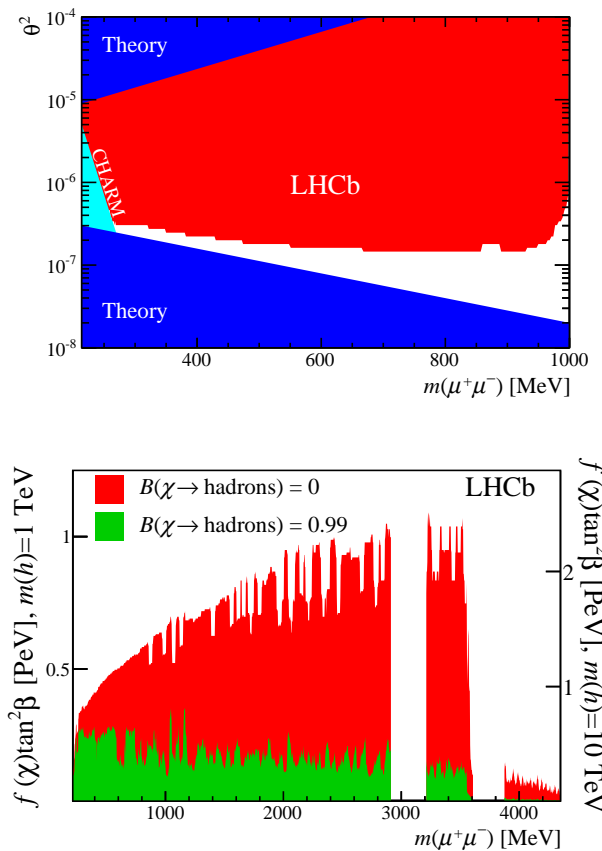


FIG. 14. Exclusion regions at 95% CL in two dark matter mediator theoretical models. Top, inflaton model [32]. Bottom, axion model [33]. For the former, the regions excluded by the theory and by the CHARM experiment [35] are also shown.

Finally, several searches for exotica have been carried out at LHCb using the 2011 and 2012 datasets. Examples are the first LHCb paper on the Higgs boson: $H^0 \rightarrow \tau^+\tau^-$, the searches for long-lived particles decaying to jets and heavy long-lived stable particles as well as the study of low mass dark bosons in B decays.

- [1] T. T. Brambach, *Measurement of the $B\bar{B}$ mixing frequency Δm_a and tagging calibration measurements with data from the LHCb Experiment*, Master's thesis, Technische Universitat Dortmund, 2013.
- [2] H. Ps and W. Rodejohann, *Neutrinoless Double Beta Decay*, [arXiv:1507.0170](https://arxiv.org/abs/1507.0170).
- [3] L. Canetti, M. Drewes, and B. Garbrecht, *Probing leptogenesis with GeV-scale sterile neutrinos at LHCb and Belle II*, *Phys. Rev.* **D90** (2014), no. 12 125005, [[arXiv:1404.7114](https://arxiv.org/abs/1404.7114)].
- [4] **Belle** Collaboration, D. Liventsev *et. al.*, *Search for heavy neutrinos at Belle*, *Phys. Rev.* **D87** (2013), no. 7 071102, [[arXiv:1301.1105](https://arxiv.org/abs/1301.1105)].

- [5] **LHCb** Collaboration, R. Aaij *et. al.*, *Search for the lepton number violating decays $B^+ \rightarrow \pi^- \mu^+ \mu^+$ and $B^+ \rightarrow K^- \mu^+ \mu^+$* , *Phys. Rev. Lett.* **108** (2012) 101601, [arXiv:1110.0730].
- [6] **LHCb** Collaboration, R. Aaij *et. al.*, *Searches for Majorana neutrinos in B^- decays*, *Phys. Rev.* **D85** (2012) 112004, [arXiv:1201.5600].
- [7] **LHCb** Collaboration, R. Aaij *et. al.*, *Search for Majorana neutrinos in $B^- \rightarrow \pi^+ \mu^- \mu^-$ decays*, *Phys. Rev. Lett.* **112** (2014), no. 13 131802, [arXiv:1401.5361].
- [8] **LHCb** Collaboration, R. Aaij *et. al.*, *Search for $D_{(s)}^+ \rightarrow \pi^+ \mu^+ \mu^-$ and $D_{(s)}^+ \rightarrow \pi^- \mu^+ \mu^+$ decays*, *Phys.Lett.* **B724** (2013) 203–212, [arXiv:1304.6365].
- [9] **LHCb** Collaboration, R. Aaij *et. al.*, *Limits on neutral Higgs boson production in the forward region in pp collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **1305** (2013) 132, [arXiv:1304.2591].
- [10] M. Spira, *HIGLU: A program for the calculation of the total Higgs production cross-section at hadron colliders via gluon fusion including QCD corrections*, hep-ph/9510347.
- [11] S. Heinemeyer, W. Hollik, and G. Weiglein, *FeynHiggs: A Program for the calculation of the masses of the neutral CP even Higgs bosons in the MSSM*, *Comput.Phys.Commun.* **124** (2000) 76–89, [hep-ph/9812320].
- [12] **ATLAS** Collaboration, G. Aad *et. al.*, *Search for neutral MSSM Higgs bosons decaying to $\tau^+ \tau^-$ pairs in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *Phys.Lett.* **B705** (2011) 174–192, [arXiv:1107.5003].
- [13] **ATLAS** Collaboration, G. Aad *et. al.*, *Search for the neutral Higgs bosons of the Minimal Supersymmetric Standard Model in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *JHEP* **1302** (2013) 095, [arXiv:1211.6956].
- [14] **CMS** Collaboration, S. Chatrchyan *et. al.*, *Search for Neutral MSSM Higgs Bosons Decaying to Tau Pairs in pp Collisions at $\sqrt{s} = 7$ TeV*, *Phys.Rev.Lett.* **106** (2011) 231801, [arXiv:1104.1619].
- [15] **CMS** Collaboration, S. Chatrchyan *et. al.*, *Search for neutral Higgs bosons decaying to τ pairs in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys.Lett.* **B713** (2012) 68–90, [arXiv:1202.4083].
- [16] **DELPHI, OPAL, ALEPH, LEP Working Group for Higgs Boson Searches, L3** Collaboration, S. Schael *et. al.*, *Search for neutral MSSM Higgs bosons at LEP*, *Eur.Phys.J.* **C47** (2006) 547–587, [hep-ex/0602042].
- [17] M. Carena, S. Heinemeyer, C. E. M. Wagner, and G. Weiglein, *Suggestions for benchmark scenarios for MSSM Higgs boson searches at hadron colliders*, *Eur.Phys.J.* **C26** (2003) 601–607, [hep-ph/0202167].
- [18] **LHCb** Collaboration, R. Aaij *et. al.*, *Search for long-lived particles decaying to jet pairs*, *Eur. Phys. J.* **C75** (2015), no. 4 152, [arXiv:1412.3021].
- [19] L. M. Carpenter, D. E. Kaplan, and E.-J. Rhee, *Reduced fine-tuning in supersymmetry with R-parity violation*, *Phys.Rev.Lett.* **99** (2007) 211801, [hep-ph/0607204].
- [20] M. J. Strassler and K. M. Zurek, *Echoes of a hidden valley at hadron colliders*, *Phys.Lett.* **B651** (2007) 374–379, [hep-ph/0604261].
- [21] **CMS** Collaboration, *Search for long-lived neutral particles decaying to dijets*, Tech. Rep. CMS-PAS-EXO-12-038, CERN, Geneva, 2013.
- [22] **ATLAS** Collaboration, G. Aad *et. al.*, *Search for a light Higgs boson decaying to long-lived weakly-interacting particles in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *Phys.Rev.Lett.* **108** (2012) 251801, [arXiv:1203.1303].
- [23] **LHCb** Collaboration, R. Aaij *et. al.*, *Search for long-lived heavy charged particles using a ring imaging Cherenkov technique at LHCb*, arXiv:1506.9173.
- [24] S. Dimopoulos, S. D. Thomas, and J. D. Wells, *Sparticle spectroscopy and electroweak symmetry breaking with gauge mediated supersymmetry breaking*, *Nucl. Phys.* **B488** (1997) 39–91, [hep-ph/9609434].
- [25] G. F. Giudice and R. Rattazzi, *Theories with gauge mediated supersymmetry breaking*, *Phys. Rept.* **322** (1999) 419–499, [hep-ph/9801271].
- [26] S. P. Martin, *A Supersymmetry primer*, hep-ph/9709356. [Adv. Ser. Direct. High Energy Phys.18,1(1998)].
- [27] **LHCb RICH Group** Collaboration, M. Adinolfi *et. al.*, *Performance of the LHCb RICH detector at the LHC*, *Eur. Phys. J.* **C73** (2013) 2431, [arXiv:1211.6759].
- [28] **ATLAS** Collaboration, G. Aad *et. al.*, *Searches for heavy long-lived sleptons and R-Hadrons with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys. Lett.* **B720** (2013) 277–308, [arXiv:1211.1597].
- [29] **CMS** Collaboration, S. Chatrchyan *et. al.*, *Searches for long-lived charged particles in pp collisions at $\sqrt{s}=7$ and 8 TeV*, *JHEP* **1307** (2013) 122, [arXiv:1305.0491].
- [30] B. C. Allanach *et. al.*, *The Snowmass points and slopes: Benchmarks for SUSY searches*, *Eur. Phys. J.* **C25** (2002) 113–123, [hep-ph/0202233].
- [31] **LHCb** Collaboration, R. Aaij *et. al.*, *Search for hidden-sector bosons in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays*, arXiv:1508.4094.
- [32] F. Bezrukov *et. al.*, *Relic Gravity Waves and 7 keV Dark Matter from a GeV scale inflaton*, *Phys. Lett.* **B736** (2014) 494–498, [arXiv:1403.4638].
- [33] M. Freytsis *et. al.*, *Constraining the Axion Portal with $B \rightarrow Kl^+ l^-$* , *Phys. Rev.* **D81** (2010) 034001, [arXiv:0911.5355].
- [34] M. Williams, *Searching for a particle of unknown mass and lifetime in the presence of an unknown non-monotonic background*, *JINST* **10** (2015), no. 06 P06002, [arXiv:1503.0476].
- [35] **CHARM** Collaboration, F. Bergsma *et. al.*, *Search for Axion Like Particle Production in 400-GeV Proton - Copper Interactions*, *Phys. Lett.* **B157** (1985) 458.
- [36] **LHCb** Collaboration, R. Aaij *et. al.*, *Identification of beauty and charm quark jets at LHCb*, *JINST* **10** (2015), no. 06 P06013, [arXiv:1504.7670].
- [37] **LHCb** Collaboration, R. Aaij *et. al.*, *First observation of top quark production in the forward region*, *Phys. Rev. Lett.* **115** (2015), no. 11 112001, [arXiv:1506.0903].
- [38] **LHCb** Collaboration, R. Aaij *et. al.*, *Study of W boson production in association with beauty and charm*, *Phys. Rev.* **D92** (2015), no. 5 052001, [arXiv:1505.4051].
- [39] **LHCb** Collaboration, R. Aaij *et. al.*, *Study of forward Z + jet production in pp collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **1401** (2014) 033, [arXiv:1310.8197].

- [40] **LHCb** Collaboration, R. Aaij *et. al.*, *Measurement of the $Z+b$ -jet cross-section in pp collisions at $\sqrt{s} = 7$ TeV in the forward region*, *JHEP* **1501** (2015) 064, [[arXiv:1411.1264](#)].
- [41] **LHCb** Collaboration, R. Aaij *et. al.*, *First measurement of the charge asymmetry in beauty-quark pair production*, *Phys.Rev.Lett.* **113** (2014), no. 8 082003, [[arXiv:1406.4789](#)].