Article

Tracking Charged *b*-Hadrons: Feasibility Study of the Use of Inner Trackers to Improve $B_{(c)}^+$ Reconstruction

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Abstract: A method to improve the reconstruction of charged *b*-hadron decays is proposed that uses energy deposits left by the hadron in tracking detectors close to the production point. Performances are shown for different detector configurations and different number of deposits reconstructed, as obtained in simulation, for *b*-hadrons produced in high energy proton-proton collisions. It is shown that up to few percent of the B^+ mesons could leave two deposits before decaying, depending on the detector configuration. The presented results can inform the design of future inner detectors. This method could increase significantly the physics reach of flavour physics at hadron colliders, opening it to decays with missing particles and vertex information that are otherwise unreconstructable.

Keywords: tracking; *b*-hadrons; flavour physics; hadron colliders; vertex detectors

1. Introduction

The physics of heavy flavours, particularly of *b*-hadrons, is a fantastic probe for our understanding of fundamental interactions, and particularly of the violation of Charge-Parity (CP) symmetry or searches for new phenomena in rare decays. The study of partially reconstructed *b*-hadron final states poses challenges that limit their sensitivity compared to fully reconstructed ones. This is particularly true at hadron colliders where there is no possibility of closing the kinematics with information from the initial state, or where reconstructing the second accompanying *b*-hadron would severely limit the statistics. In particular for charged *B* mesons, i.e. B^+ or B_c^+, some final states present minimal information reconstructible at experiments, such as only one charged track and one or no calorimetric deposit from neutral particles. Among these are rare decays such as $B^+ \to \ell^+ \nu$ where ℓ is a leptr'ron [1,2], sensitive to extensions of the Standard Model with charged heavy particles [3], or CP-violation sensitive decays such as $B^+ \to \pi^+ \pi^0$ [4,5]. Increasing the background suppression of these and other partially reconstructed decays can enhance the performances of several experiments as well as opening new ways of looking for new physics.

In this article a new method is proposed to search for partially reconstructed decays of charged *b*-hadrons, by tracking the hadron before its decay in detectors placed very close to the hadron-production vertex. Given the typical lifetime of *b*-hadrons [6], when produced in high energy collisions, e.g. at the LHC, their boost allows them to fly up to a few centimetres before decaying. A few of these hadrons can reach one or more tracking stations, depending on the detector geometry. Subsequently, the reconstructed track segment can be used to constrain the direction, and thus the momentum direction of the *b* hadron, constraining its kinematics in case of missing final state particles, particularly in the case in which no other vertex reconstruction is possible. The proposed method can

enable measurements that are typically considered infeasible at hadron colliders that are based on decay channels with limited possibilities of reconstruction of the final state.

This article stems from the experience of the authors with the LHCb experiment and as such takes this experiment, and in particular the Vertex Locator (VELO) as an example; however, the method is more general and not limited to this experiment and could be exploited for example in current and future inner trackers of the ATLAS and CMS experiments. The use of tracks of long-lived particles in the LHCb experiment, in the case of charged strange hadrons, was discussed in Refs. [7,8]. In that case, the hadron can fly up to 1 meter and traverse a significant portion of the VELO detector, traversing multiple sections. Standard tracking was exploited and the strange hadron track was connected to its origin vertex. Here it is proposed to exploit all information, starting from a single energy deposit (hit) in the tracking detectors, to improve the background rejection and kinematic reconstruction of charged B decays. Adding hits can improve the identification of the relevant primary vertex among many, the direction of the B^+ momentum, and the background rejection from neutral B decays. We therefore consider one to three or more hits, and evaluate the efficiency to reach those tracking detectors for different realistic geometry configurations. The results here presented can inform the design of future inner tracking devices.

A performance study for specific cases would require a full detector simulation and to take into account possible background, which is the subject of future work. In this article only the signal reconstruction feasibility is considered.

The proposed method relies on tracking detectors very close to the interaction point where the B hadrons are produced. Such subdetectors are present in current particle physics experiments at LHC [9–11], to identify and distinguish primary vertices, tracks and displaced particles. In this paper we take as benchmarks the VELO [12] detector of the LHCb experiment and its current and future upgrades. However, results can be applied to any detector with similar distance to the interaction point with minor changes. In the following we will consider a generic tracking detector with these configurations, measuring 2D coordinates of particles at fixed z distances regardless of the hardware technology that allows this.

The paper is organised as follows: in Section 2 we present the considered detector geometries, the B^+ simulation and tracking feasibility is presented in Section 3, while in Section 4 we discuss the results and draw our conclusions.

2. Geometry of the Detectors

Six different geometries are considered in this paper. Two example geometries are shown in Figure 1. Each detector configuration is composed of several identical tracking stations. For the studied geometries, four types of tracking stations are considered. To simplify the geometries, the stations are simulated with an infinitesimal thickness, since the sensor thickness is negligible with respect to the typical B^+ flight distances, and multiple scattering is not considered in this work.

The detector configurations used as case studies are chosen based on different designs of the LHCb VELO detector, both past and future. The VELO is a silicon detector composed of a series of tracking sensors in the transverse plane positioned along the beam direction. This study covers the former VELO used in Run 1 and 2 between 2010 and 2018 which used silicon microstrips, the new VELO detector based on silicon pixel technology, installed for Run 3 and Run 4, and new scenarios which are being considered in view of future LHCb upgrades.

Because of the aforementioned technologies, during LHC Run 1 and 2, the VELO detector measured r and ϕ coordinates (in a cylindrical coordinate system where the z axis is the beam direction), while the current detector measures Cartesian coordinates in the transverse plane. The distance between two consecutive stations is 3 cm (2.5 cm) in Run 1/2 (Run 3/4); as shown in the following, this is a major parameter in the efficiency of this method. The distance of the sensors from the beam-line is 8 mm (5.1 mm) in Run 1/2 (Run 3/4). Thus, the typical radial distance of the first hit of a charged particle decreases from 10 mm to about 6 mm. The Run 1/2 geometry is composed of 42 tracking stations spaced out at 30 mm intervals. Each tracking station is a semi-circle with a radius of 42 mm. The inner 8.2 mm radius semi-circle is not sensitive. The Run 3/4 geometry has 52 equal tracking stations spaced 25 mm from each other. Each tracking station has an L shaped sensitive area consisting of two adjacent rectangles of $42.57 \, \text{mm} \times 28 \, \text{mm}$. The detector sensitive areas are placed at 5.1 mm from the beam line at the closest point.

Four more geometries are developed to test the method in different conditions. Two of them try to maximise performance during possible LHC Run 5 and 6 scenarios, and two are similar to the proposed detector in the LHCb Upgrade II FTDR [13]. The Closer geometry is equal to the Run 3/4 one but with a reduced distance from the beam line from 5.1 mm to 4 mm. This distance is chosen such that the radiation fluence to the innermost sensors is equal to $1 \cdot 10^{17} \, \text{n}_{\text{eq}} \, \text{cm}^{-2}$, a value for which 3D trench sensors, proposed as a candidate technology for the Phase II Upgrade of the LHCb VELO detector, have demonstrated full efficiency [14]. The B scenario and the X scenario are geometries presented in the LHCB FTDR for the Phase II Upgrade that are similar to the Run 3/4 VELO geometry

but with an increased distance from the beam line up to 12.5 mm (7.1 mm) for the B scenario (X Scenario). The last simulated geometry is named Double, and consists of a Run 3/4 geometry but with twice the number of stations, so that the distance between the active planes is reduced from 25 mm to 12.5 mm. A summary of the considered geometries with their characteristics is shown in Table 1.
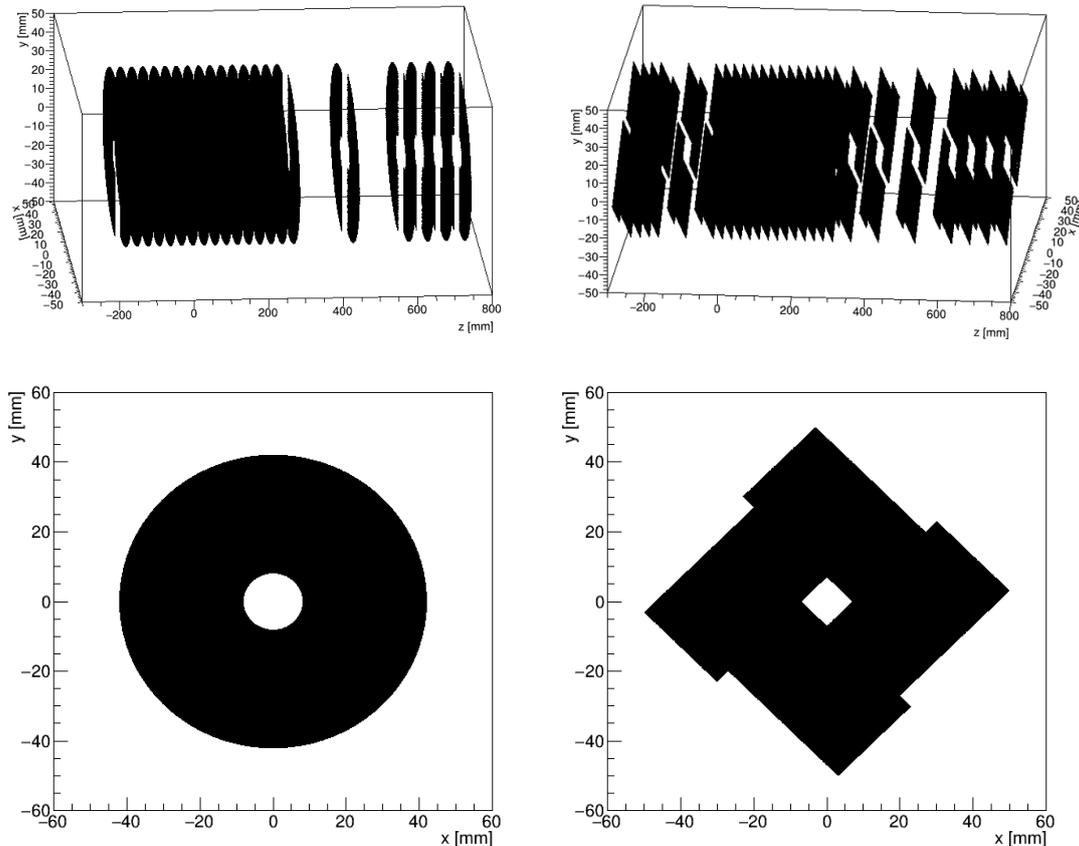

Figure 1. Examples of the simulated geometries. (**Left**) Run 1/2 VELO; (**Right**) Run 3/4 VELO. Only the sensitive area of the detectors is shown.

It has to be noted that a comprehensive evaluation of such variations in the design of a real detector will include additional aspects beyond the scope of this discussion, in particular multiple scattering, radiation lengths, and data rate considerations.

Table 1. Geometry configuration of the considered detectors.

Name	Geometry	Distance between Stations	Distance to Beam Line
Run 1/2	Semi-circular	30.0 mm	8.2 mm
Run 3/4	L shape	25.0 mm	5.1 mm
Run 5/6 Closer	L shape	25.0 mm	4.0 mm
Run 5/6 Double	L shape	12.5 mm	5.1 mm
Run 5/6 B Scenario	L shape	25.0 mm	12.5 mm
Run 5/6 X Scenario	L shape	25.0 mm	7.1 mm

3. Simulation of B^+ Decays and Tracking Feasibility

For this study, simulated B^+ decays produced in proton-proton (pp) collisions are employed. The generation of pp collisions is performed with Pythia [15], tuned to the configuration in Ref. [16], and decays of B mesons are generated with EvtGen [17]. A sample of 4 million pp collisions at 13 TeV is generated, in which B^+ mesons are produced and forced to decay to the $B^+ \to J/\psi K^+$ final state; note that the particular final state is mostly irrelevant for the performance of the B^+ tracking, as that happens before decay. Only events where the K^+ meson and the two muons produced in the decay of the J/ψ meson are inside the LHCb acceptance are considered in this work. Emulating the LHCb acceptance, these particles are required to be in a pseudorapidity range of $2 < \eta < 5$. The kinematic variables of the generated particles are reported in Figure A1 for reference.

Considering each of the detector geometries, the stations crossed by the B^+ meson between its production and decay vertices are counted. The detection efficiency of a station in its active area is assumed to be 100%, which is very similar to the efficiency in real operating conditions [18]. A sub-sample of generated events obtained with the Run 3/4 geometry is shown in Figure 2, showing only the B^+ tracks for each event. This shows that a significant portion of the B^+ mesons crosses at least two stations before decaying.
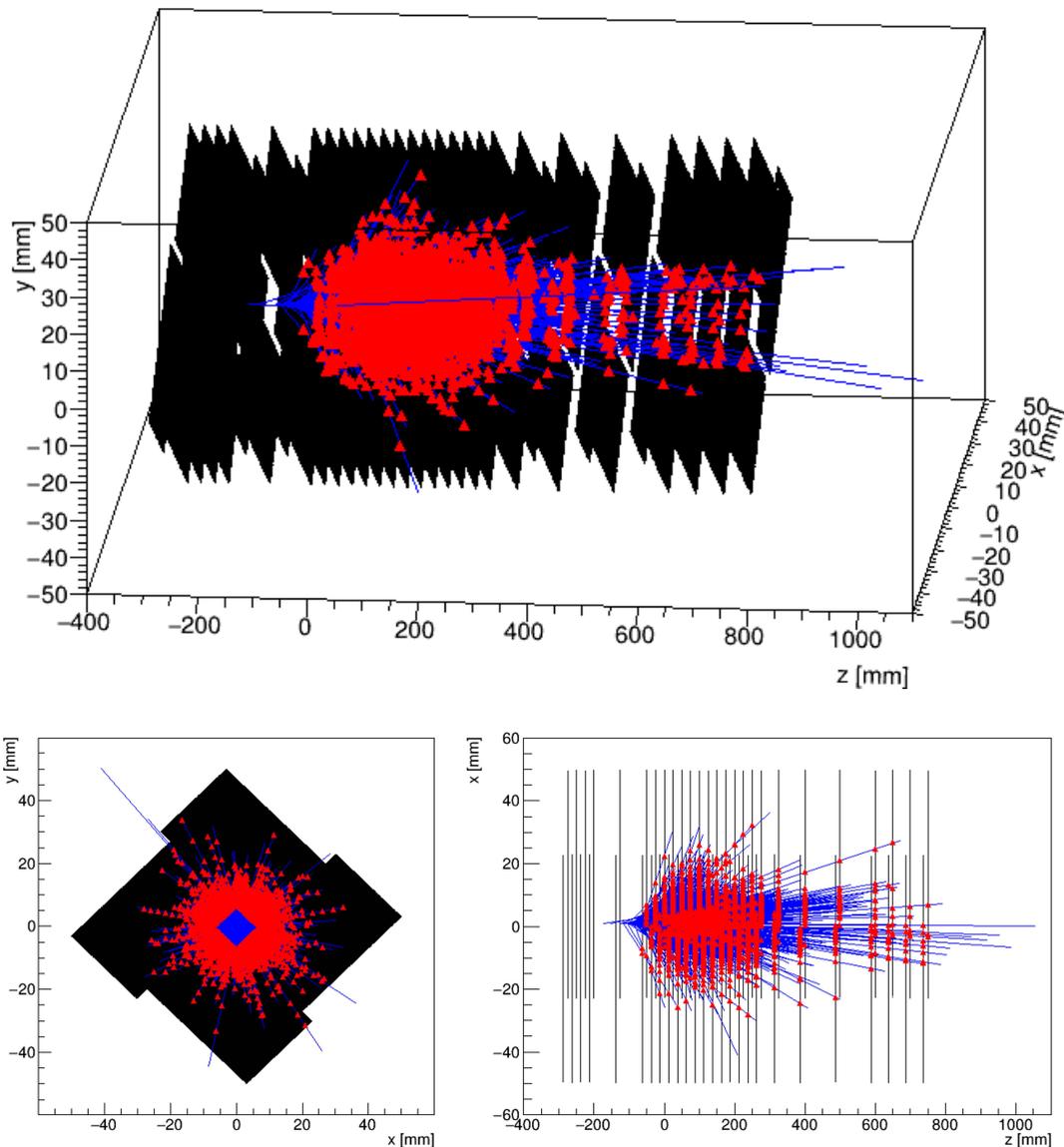

Figure 2. Sample of simulated B^+ mesons in proton-proton collisions at 13 TeV traversing at least two detecting stations in the Run 3/4 geometry. Blue lines represent the paths of the mesons before decaying, red dots represent energy deposits.

From the number of deposits left by the B^+ mesons in the tracking stations, it is possible to estimate the fraction of B^+ that can be tracked and reconstructed according to thresholds defined below.

A B^+ meson is considered tracked if it intercepts at least 2 tracking stations, even if a stand-alone track is typically obtained by at least three hits. Even a single hit, together with the position of the primary vertex and in certain cases on subsequent decay vertices, can be used to enhance the reconstruction of decays with missing particles.

It has to be noted at this point that tracking algorithms efficiencies are typically high, in excess of 80–90% depending on the number of required hits, while "fake" tracks can be kept as low as 5–15% depending on the kinematics [19]. For the LHCb experiment this includes track segments reconstructed in the VELO and matched to the wrong track segment in the rest of the detector. This implies that for the purpose of this work we can ignore, at first instance, background from wrongly assigned tracks for the B^+ meson. The details of this and an optimisation of purity versus efficiency will depend on the characteristics of the experiment implementing the presented method.

4. Results and Discussion

The fractions of the B^+ mesons that intercept one or more detector stations are shown in Table 2. More than 1 per mil of the mesons have at least 1 hit in the Run 3/4 configuration, and $2.4 \cdot 10^{-4}$ have 3 or more deposits.

Table 2. Fraction of B^+ that produce one or more hits for the studied VELO geometries. Uncertainties are statistical from the sample size.

Geometry	B^+ Fraction ≥ 1 Hit	≥ 2 Hit	≥ 3 Hit
Run 1/2	$(4.5 \pm 0.1) \cdot 10^{-4}$	$(1.28 \pm 0.06) \cdot 10^{-4}$	$(5.0 \pm 0.4) \cdot 10^{-5}$
Run 3/4	$(1.80 \pm 0.02) \cdot 10^{-3}$	$(5.3 \pm 0.1) \cdot 10^{-4}$	$(2.36 \pm 0.08) \cdot 10^{-4}$
Run 5/6 Closer	$(3.77 \pm 0.03) \cdot 10^{-3}$	$(1.11 \pm 0.02) \cdot 10^{-3}$	$(4.8 \pm 0.1) \cdot 10^{-4}$
Run 5/6 Double	$(2.41 \pm 0.02) \cdot 10^{-3}$	$(1.15 \pm 0.02) \cdot 10^{-3}$	$(6.4 \pm 0.2) \cdot 10^{-4}$
Run 5/6 B Scenario	$(7.1 \pm 0.4) \cdot 10^{-5}$	$(2.6 \pm 0.3) \cdot 10^{-5}$	$(1.1 \pm 0.2) \cdot 10^{-5}$
Run 5/6 X Scenario	$(6.0 \pm 0.1) \cdot 10^{-4}$	$(1.8 \pm 0.07) \cdot 10^{-4}$	$(8.3 \pm 0.4) \cdot 10^{-5}$

Other geometry configurations show that moving closer to the beam line and decreasing the distance between planes increases the efficiency as expected by meson decay length. The two Run 5/6 Closer and Double geometries allow to increase the fraction of B^+ that can be tracked by a factor two. Reducing the spacing between tracking stations significantly increases the number of events in which B^+ mesons produce more than two hits, as shown in Figure 3. The B scenario, having a larger distance, appears to be instead disadvantaged.
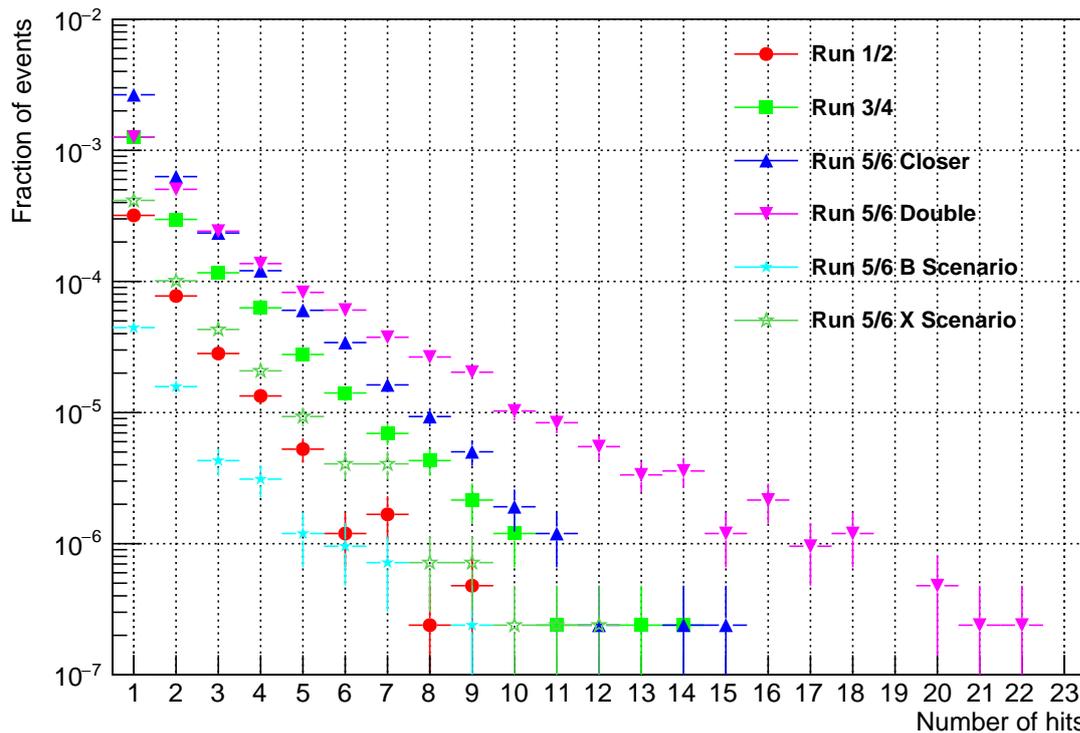

Figure 3. Fraction of B^+ mesons as a function of the number of hits produced for the different geometry configurations.

In Figure 4, the flight distance, meson lifetime, and meson momentum are shown before and after requiring that the B meson left two hits in the tracking stations, in the different geometries. As expected, most of the reconstructed B^+ mesons have long lifetime and/or high boost due to momentum. These are however also characteristics that improve the trigger and selection efficiencies of a B^+ decay analysis, hence the total efficiency for analyses using B-tracks will be higher than naively expected from multiplying the usual efficiencies with the additional requirement of a reconstructed B-track. This effect will increase the efficiency of this method at high transverse momentum, making it viable for the typical B^+ mesons analysed by multi-purpose experiments such as ATLAS and CMS. While the B^+ mesons considered here come from inclusive $pp \to b\bar{b}$ production, highly boosted B^+ from electroweak or beyond the Standard Model high mass particles could benefit even more from B^+ tracking. Future higher energy

experiments, could also have higher efficiencies due to an even higher boost, provided they could keep detectors at the same distance from the primary interaction, and possibly extend the method to $D^+_{(s)}$ mesons.
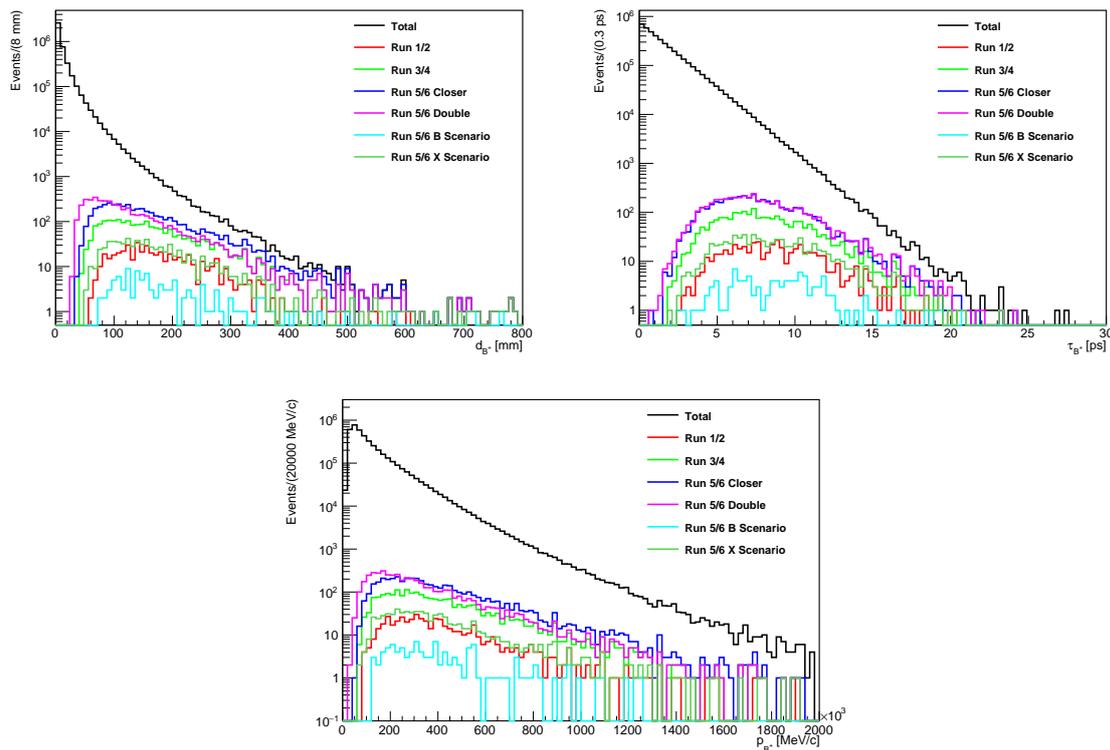

Figure 4. Characteristics of B^+ mesons that produce at least two hits in the detector stations for the different geometry configurations: (**top left**) flight distance from the primary vertex, (**top right**) B^+ meson lifetime and (bottom) momentum.

Considering specific B^+ decays, while a penalty of $10^{-3} - 10^{-4}$ in efficiency could seem large, single event sensitivities of $10^{-11} - 10^{-12}$ are already attainable with current datasets at LHC [20]. Therefore, branching fractions of the order of $10^{-7} - 10^{-9}$ could be reachable with this method. Considering rare decays such as $B^+ \to \ell\nu$ or CP violating ones such as $B^+ \to \pi^+\pi^0$, where a decay vertex is not reconstructible, this would be the only available method at hadron colliders: connecting the daughters reconstructed track(s) with the primary interaction through the B^+ track would allow to identify the B^+ momentum direction and the missing p_T, and thus mass, in the decay. For other decays, where a secondary vertex is available this would improve the background rejection increasing the sensitivity by allowing looser selections.

While it is clear that the optimisation details will depend on the specifics of the considered experiment, this method could open up the possibility of reconstructing previously unreconstructible decays at hadron colliders in a healthy competition with B-factory experiments, and inform the decision on the design of future vertex detectors.

Author Contributions

All authors have contributed to the publication, being variously involved in the conceptualisation, simulation, data analysis and paper writing and editing.

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Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.
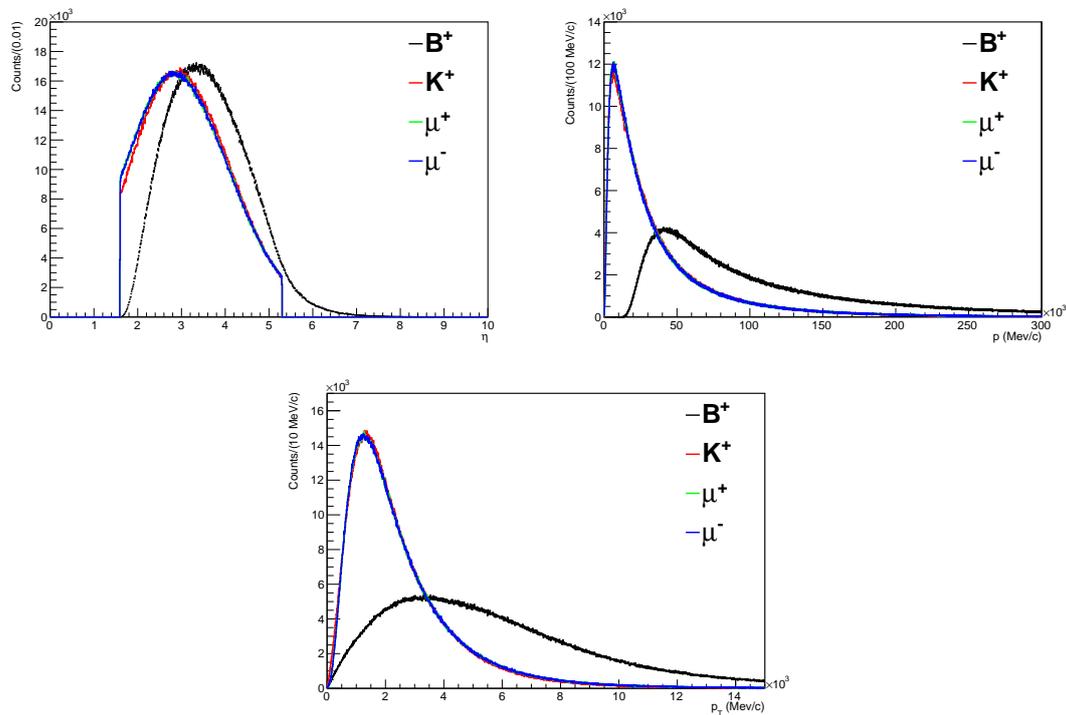
Appendix A. Kinematics of the B^+ Decays

Figure A1. Kinematic variables of all the generated particles: pseudorapidity (**top left**), momentum (**top right**), and transverse momentum (**bottom**).

References

1. Lees, J.P.; Poireau, V.; Tisser, V.; et al. Evidence of $B^+ \to \tau^+ \nu$ decays with hadronic B tags. *Phys. Rev. D* **2013**, *88*, 031102. https://doi.org/10.1103/PhysRevD.88.031102.

2. Kronenbitter, B.; Heck, M.; Goldenzweig, P.; et al. Measurement of the branching fraction of $B^+ \to \tau^+ \nu_\tau$ decays with the semileptonic tagging method. *Phys. Rev. D* **2015**, *92*, 051102. https://doi.org/10.1103/PhysRevD.92.051102.

3. Baek, S.; Kim, Y.G. Constraints on the R-parity violating couplings from $B^\pm \to \ell^\pm \nu$ decays. *Phys. Rev. D* **1999**, *60*, 077701. https://doi.org/10.1103/PhysRevD.60.077701.

4. Aubert, B.; Bona, M.; Boutigny, D.; et al. Study of $B^0 \to \pi^0\pi^0$, $B^\pm \to \pi^\pm\pi^0$, and $B^\pm \to K^\pm\pi^0$ Decays, and Isospin Analysis of $B \to \pi\pi$ Decays. *Phys. Rev. D* **2007**, *76*, 091102. https://doi.org/10.1103/PhysRevD.76.091102.

5. Adachi, I.; Aggarwal, L.; Ahmed, H.; et al. Measurement of branching fractions and direct CP asymmetries for B→Kπ and B→ππ decays at Belle II. *Phys. Rev. D* **2024**, *109*, 012001. https://doi.org/10.1103/PhysRevD.109.012001.

6. Navas, S.; Amsler, C.; Gutsche, T.; et al. Review of particle physics. *Phys. Rev.* **2024**, *D110*, 030001. https://doi.org/10.1103/PhysRevD.110.030001.

7. Contu, A. *A Method to Study Long Lived Charged Particles at LHCb*; Technical Report LHCb-PUB-2014-032, CERN-LHCb-PUB-2014-032; CERN: Geneva, Switzerland, 2014.

8. LHCb Collaboration; Aaij, R.; Abdelmotteleb, A.S.W.; et al. Tracking of charged particles with nanosecond lifetimes at LHCb. *Eur. Phys. J. C* **2024**, *84*, 761. https://doi.org/10.1140/epjc/s10052-024-12993-2.

9. The LHCb Collaboration. *LHCb VELO Upgrade Technical Design Report*; Technical Report CERN-LHCC-2013-021, LHCB-TDR-013; CERN: Geneva, Switzerland, 2013.

10. Tracker Group of the CMS Collaboration. *The CMS Phase-1 Pixel Detector Upgrade*; Technical Report; CERN: Geneva, Switzerland, 2020.

11. *Technical Design Report for the ATLAS Inner Tracker Strip Detector*; Technical Report; CERN: Geneva, Switzerland, 2017.

12. LHCb; Aaij, R.; Affolder, A.; et al. Performance of the LHCb Vertex Locator. *JINST* **2014**, *9*, 09007. https://doi.org/10.1088/1748-0221/9/09/P09007.

13. CERN. *Framework TDR for the LHCb Upgrade II : Opportunities in Flavour Physics, and beyond, in the HL-LHC Era*; Technical Report; CERN: Geneva, Switzerland, 2021.

14. Addison, M.; Bellora, A.; Borgato, F.; et al. Characterisation of 3D trench silicon pixel sensors irradiated at $1 \cdot 10^{17} 1 \mathrm{MeVn_{eq}cm^{-2}}$. *Front. Phys.* **2024**, *12*. https://doi.org/10.3389/fphy.2024.1497267.

15. Sjöstrand, T.; Mrenna, S.; Skands, P. A brief introduction to PYTHIA 8.1. *Comput. Phys. Commun.* **2008**, *178*, 852–867, https://doi.org/10.1016/j.cpc.2008.01.036.

16. Beiyaev, I.; Brambach, T.; Brooke, N.H.; et al. Handling of the generation of primary events in Gauss, the LHCb simulation framework. *J. Phys. Conf. Ser.* **2011**, *331*, 032047. https://doi.org/10.1088/1742-6596/331/3/032047.

17. Lange, D.J. The EvtGen particle decay simulation package. *Nucl. Instrum. Meth.* **2001**, *A462*, 152–155.

18. LHCb; Aaij, R.; Affolder, A.; et al. Performance of the LHCb Vertex Locator. *JINST* **2014**, *9*, P09007. https://doi.org/10.1088/1748-0221/9/09/P09007.

19. Aaij, R.; Abdelmotteleb, A.S.W.; Beteta, C.A.; et al. The LHCb Upgrade I. *JINST* **2024**, *19*, P05065. https://doi.org/10.1088/1748-0221/19/05/P05065.

20. Aaij, R.; Beteta, C.A.; Ackernley, T.; et al. Analysis of neutral B-meson decays into two muons. *Phys. Rev. Lett.* **2022**, *128*, 041801. https://doi.org/10.1103/PhysRevLett.128.041801.