LHCb-PUB-2017-016
September 22, 2017

A study on Scintillating Fiber tracker optimisation for the LHCb upgrade

Alessio Piucci [1], Andrea Mogini [2], Sevda Esen [1], Thomas Nikodem [1]

[1] *Physikalisches Institute, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*

[2] *LPNHE, Paris, France*

Abstract

New tracking stations made from scintillating fibres are designed as a part of the LHCb Upgrade to provide the tracking capabilities in the data-taking environment foreseen after Run II. Due to the higher track multiplicity and higher total integrated radiation dose, larger inefficiencies are found in the simulation compared to the current tracker. This note presents the optimisation studies and proposals which would improve the reconstruction efficiency in the three stations of the scintillating fiber tracker.

Contents

1 Introduction

The LHCb detector [1,2] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. For the upgrade, several subdetectors will be modified, including the tracking stations which will be completely replaced [3]. A sketch of the LHCb upgraded detector is shown in Fig. 1.

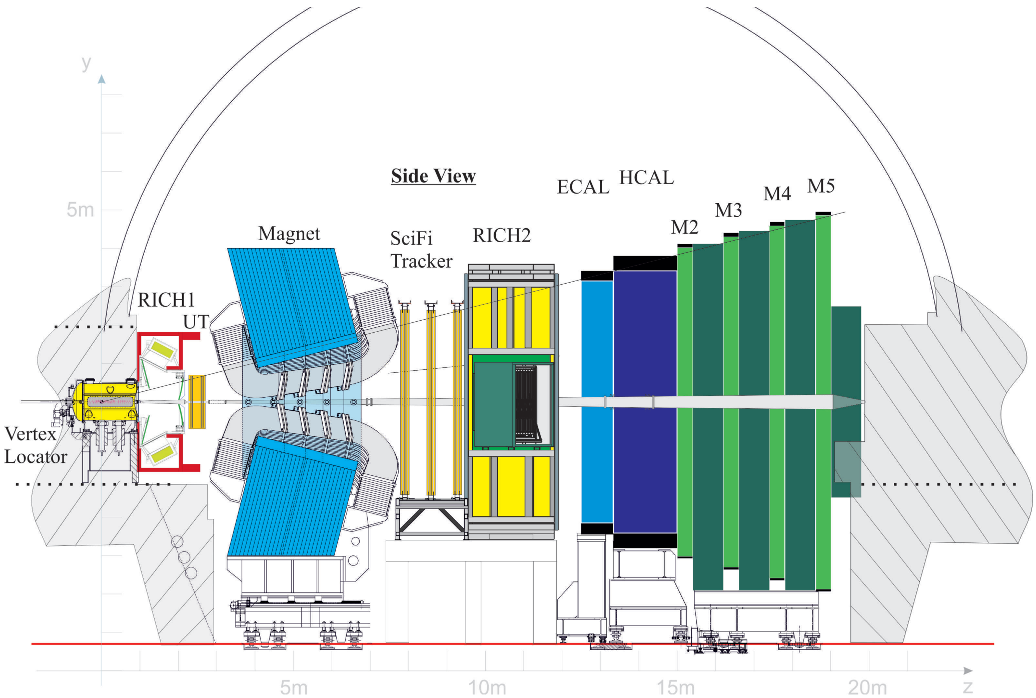


Figure 1: Schematic view of the upgraded LHCb detector.

The large tracking detector downstream of the magnet consists of three stations, T1, T2, T3, as shown in Fig. 2 with mats of scintillating fibres as active material. The detector geometry is described in detail in Ref. [4]. Each station is composed of four layers (x-u-v-x). In the first and fourth layer of each station, fibres are vertically oriented to give the x coordinate of the track at that position, while in the second and third layers the fibers have a $\pm 5°$ angle with the y axis of the laboratory frame, providing the u and v stereo coordinates as shown in Fig. 3. The effects of radiation damage corresponding to 50 fb^{-1} of data-taking are simulated in the events used to evaluate the performance of the scintillating-fibre (SciFi) detector. For these conditions, the expected efficiency to detect a single hit is $\approx 99\%$ [5]. Additional inefficiencies are caused by the dead regions of the detector and the clustering algorithm. Overall, the hit efficiency is $\approx 96\%$ in the simulation. The single hit resolution is $\sim 70\,\mu\mathrm{m}$ depending on the number of fibres combined in a cluster. The hit resolution is sufficiently small, as the limiting factor for the momentum resolution is multiple scattering. Nevertheless, the good spatial resolution is an advantage for pattern recognition algorithms for efficient track finding and reducing the number of wrong combinatorics.

Several proposals which are made to improve the tracking performance are studied. In order to reduce the amount of fake tracks reconstructed, we study the effect of additional y position information by placing two y-segmented layers in the high occupancy regions of the detector. A second option is to have two additional layers in the inner regions, which can provide better selection of high momentum tracks without reconstructing more fake tracks. Finally, the size and shape of the SciFi beam hole, as well the layer sizes, are studied to optimise the tracking performances accordingly with the mechanical constraints. This note will describe these optimisation studies and results from the current Forward and Seeding tracking algorithms.

2 Current tracking algorithms

Tracks are classified based on the different tracking subdetectors that they traverse as illustrated in Fig. 4. Several tracking algorithms are designed to find all track types effectively. The long tracks are mainly reconstructed by the forward algorithm while the seeding algorithm reconstructs the T tracks. T tracks can later be used to make long tracks by a matching algorithm or downstream tracks by a downstream-tracking algorithm.

2.1 Forward tracking

The forward algorithm [6] uses as input the reconstructed VELO tracks of the event, which provide additional information in the reconstruction process. The output tracks of the forward algorithm are long tracks. They include measurements from at least the VELO and the SciFi detector, and thus provide a precise measurement of the four-vector of the particle.

The main idea of the forward algorithm is that a single measurement of the SciFi detector, combined with a VELO track, is enough to determine the trajectory of the particle through the detector. Therefore, for each combination of VELO input track and SciFi measurement an intersection of the hypothetical particle with a plane at a fixed z value (the so-called *reference plane*) is calculated. Measurements belonging to the same particle as the VELO track cluster together on this plane. A sketch of this Hough-like clustering is shown in Fig. 5.

In the forward algorithm the clustering is done with all measurements from the x planes which pass a *preselection* stage. In this stage the x-measurement is projected to the nearest u/v plane and it is checked for a consistent measurement in this plane. In particular, a matching of the x hit with at least one hit on the stereo plane is required, within a window which depends on the slope of the VELO track. If the x hit does not match with any stereo hit, it is not used in the Hough-like clustering later. The preselection is important for removing wrong measurements, however, as now two measurements of the particle are required, the hit efficiency is effectively reduced. A missing measurement already in this early reconstruction stage is problematic for all following reconstruction stages; therefore

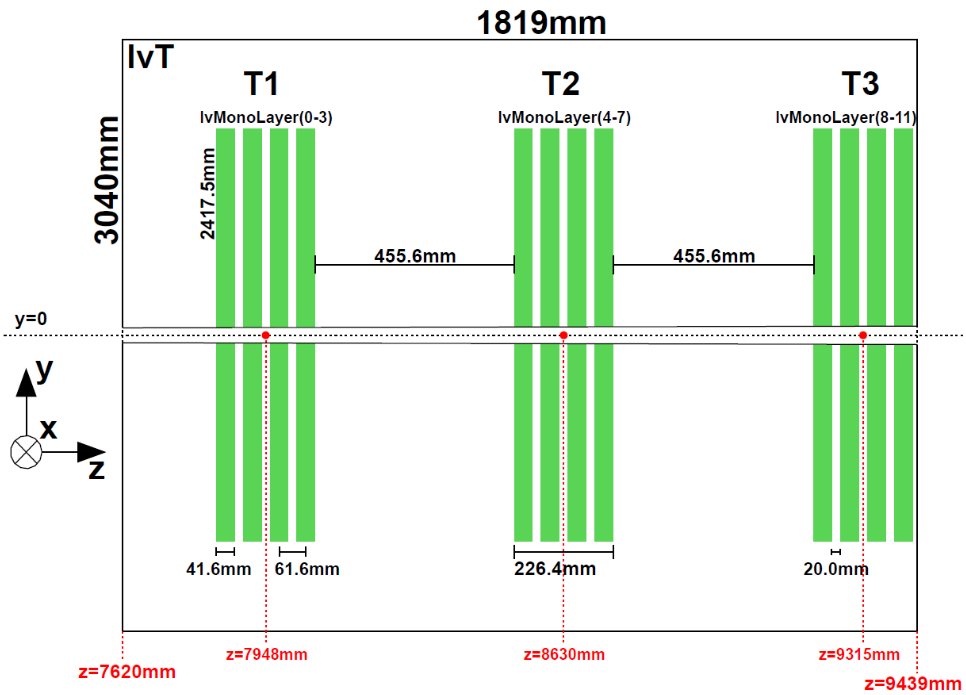


Figure 2: Schematic side view of the SciFi tracking stations.

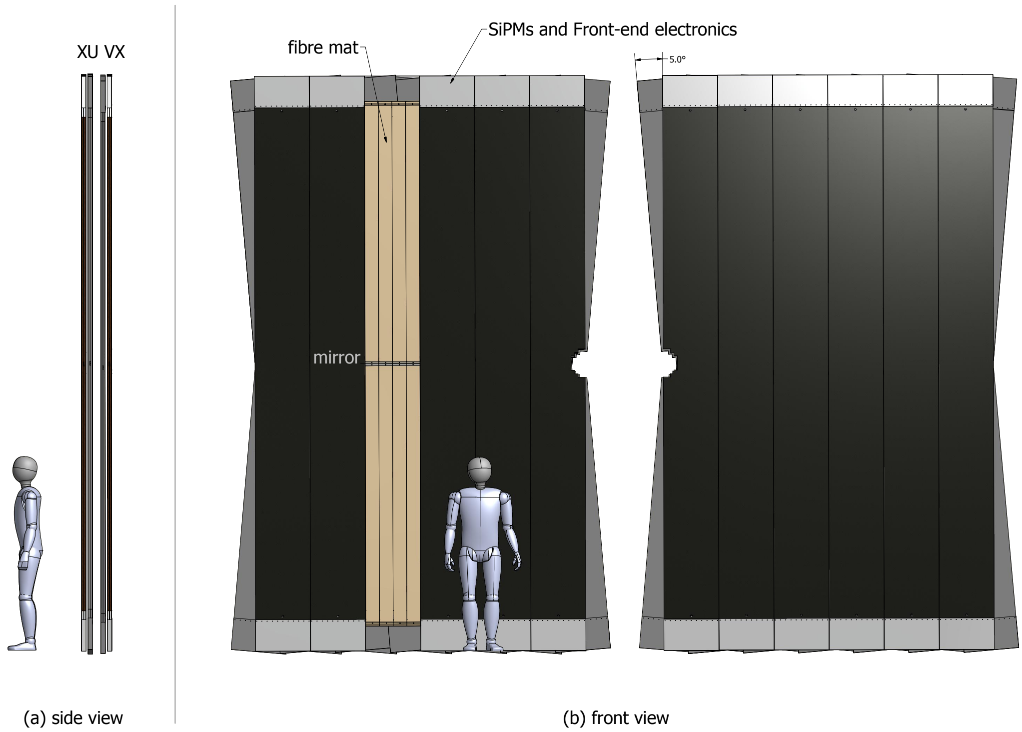


Figure 3: Schematic view of a SciFi station.

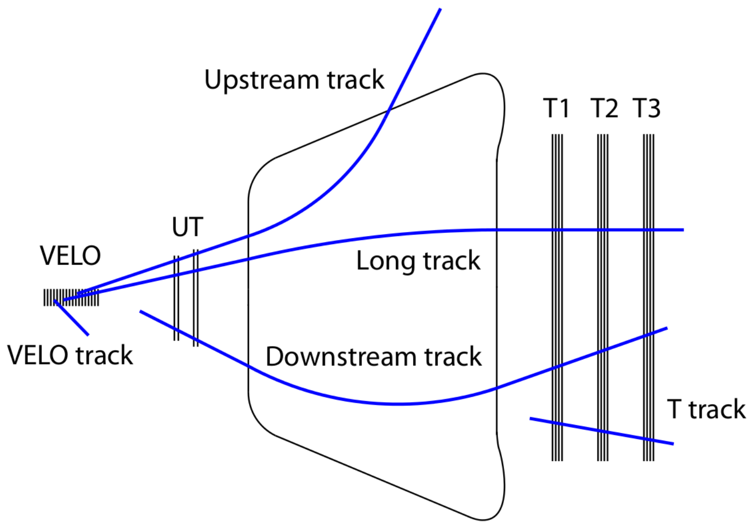


Figure 4: Track types at LHCb.

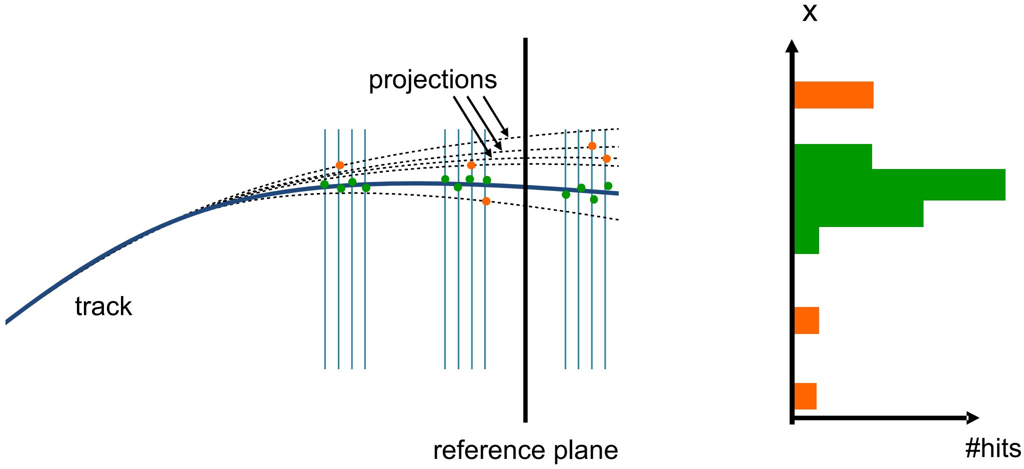


Figure 5: A sketch of the projection of x hits on a reference plane. The green dots are hits which belong to the particle intersecting the detector, represented as a thick blue line. The orange dots are hits from other particles, or from noise sources. The black dotted lines represent projections of single hits to the reference plane. Only hits which belong to the same particle cluster together on the reference plane, on the right [6].

this step shows great potential to benefit from an improved detector design.

In the further processing, several χ^2 fits are performed to select the measurements which match the trajectory best. Afterwards, measurements from u/v planes which are compatible with the x candidate are searched, and a final χ^2 fit including all measurements is done. The last stage of the algorithm is a cleanup, which attempts to remove fake tracks and tracks that are multiply reconstructed.

2.2 Seeding algorithm

The seeding algorithm reconstructs tracks using only hits in the SciFi tracking stations. The algorithm is crucial for the reconstruction of the long lived particles as well as a good indicator of the detector performance since it performs independently from the other sub detectors.

The current seeding algorithm is called hybrid seeding and described in detail in Ref. [7]. The algorithm needs to find the tracks without any prior information which requires many hit combinations to be tested. The current algorithm is designed to reach a good compromise between tracking efficiencies, amount of fake tracks reconstructed and timing. The main idea behind the hybrid seeding is to progressively clean the tracking environment by finding the tracks which are easier to reconstruct first and then looking for the rest using the leftover hits. For each event, using hits in six x-layers, all possible track candidates passing the minimum hit and fit quality requirements are reconstructed. These candidates are later combined with hits in the stereo layers to obtain the full tracks.

In the following, all results pertaining to the seeding algorithm are obtained using the most recent version of the algorithm at the time of each study.

2.3 Performances

The reconstruction efficiency is defined as the ratio between the number of reconstructed tracks which are matched to a *reconstructible* simulated particle, and the total number of simulated reconstructible particles. Particles are considered to be reconstructible if they leave enough hits in the tracking layers as to meet a specific requirement.

Reconstructed track candidates which do not correspond to any simulated particle are called ghosts. T-track ghosts, reconstructed using SciFi measurements, are referred to as *T-ghosts*. Long candidates which are ghosts can be further classified as T-ghost if the reconstructed part in the T stations is a T-ghost, or as *matching ghost* if the VELO and T parts are not ghosts, but they do not correspond to the same simulated particle. Finally, the ghost rate is defined as the ratio of ghost tracks over all reconstructed tracks.

Tracking performances of the forward and hybrid seeding algorithms are summarised in Table 1.

3 Optimization studies

The track reconstruction performances can be improved by increasing the signal-over-background ratio of hits produced in the detector, where signal hits are referred to be the ones produced by particles intersecting the tracking layers, and the background ones come from noise sources of the detector or from spillover events. This can be accomplished by decreasing the detector noise, which is difficult without resulting in lower hit efficiency and consequently in a smaller portion of signal tracks. Another approach is to increase the number of good hits available for the reconstruction, for instance using more tracking

	Forward	Seeding
long	83.8%	90.5%
long, $p > 5\,\mathrm{GeV}/c$	92.1%	94.0%
long, $p > 5\,\mathrm{GeV}/c$, from B	94.5%	
total ghost rate	35.9%	18.3%
T-ghost rate	17.5%	18.3%
matching ghost rate	18.4%	

Table 1: Tracking performances for forward and seeding algorithms. Reconstruction efficiency for long particles and ghost rates are shown. The results are computed over a sample of 5000 simulated $B_s \to \phi\phi$ events.

layers. Following this idea, tracking studies are performed with additional layers to the baseline configuration of the SciFi detector.

A different approach is to give more hit information to the tracking algorithms in order to better discriminate between real and fake tracks. In particular, y information of hits can be retrieved by segmenting the fibres along the y coordinate. This solution, referred in the following as *y segmentation*, and its impact on the tracking performances, is investigated.

3.1 y Segmentation

The high occupancy in the inner regions of the detector causes higher ghost rates compared to the outer regions, due to more combinations of hits that the tracking algorithms have to handle. The critical dependence of the ghost rate on the occupancy can be shown by characterising its variation with the number of primary vertexes of the event, as presented in Fig. 6 for the forward algorithm. In particular, T-ghosts are exponentially increasing with the occupancy of the detector.

In order to mitigate this effect, it might be useful to segment the inner modules of the x-layers along the y direction to reduce the hit ambiguity and the ghost rate. Lower ghost rate will allow to relax the quality requirements used by the tracking algorithms to gain in reconstruction efficiency. However, the y segmentation can only reduce T-ghosts, since it cannot change the effectiveness of the matching procedure with VELO tracks to build long tracks.

Due to the high radiation field and increased probability of creating secondary particles, it is not possible to place photodetectors and their supporting infrastructure in the middle of the detector layer, but only on the top and bottom part of the modules. The y segmentation of the SciFi detector can be realised by having double-layered modules where one of the layers has shorter fibres as sketched in Fig. 7. Both layers of the module are readout at the same time, which allows to discriminate the y segment of a hit, as shown in Fig. 8. If a particle intersects the outer part of the module, both full-sized and short fibres would produce a signal which is referred as an *outer hit*. In case of passage of the

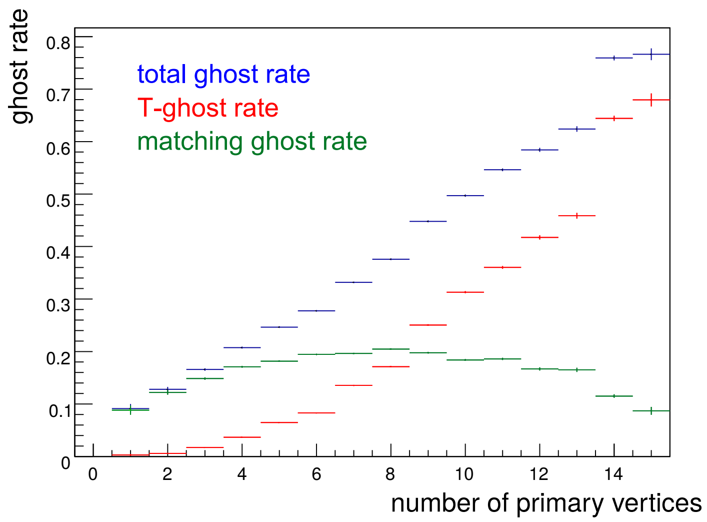


Figure 6: Forward ghost rate dependence versus the number of primary vertices of the event, for matching ghosts (green), T-ghosts (red) and sum of the two contributions (blue).

track in the inner part of the module, only the full-sized layer would see a signal, which corresponds to an *inner hit*. However, when two particles intersect at the same fibre both inner and outer parts of a segmented module, the signal recorded by the detector is similar to a single particle intersecting only the outer region. In this case, only the outer hit is created, reducing the hit efficiency. Furthermore, the addition of extra segmented modules enhances the multiple scattering due to the increased detector material. In the most realistic design only two inner modules of two x layers can be segmented in order to minimize the negative impact of the extra material and hit inefficiency.

3.1.1 Simulation

The y segmentation of the SciFi layers is simulated by a toy model implemented in the cluster decoding algorithm, at reconstruction level. For each cluster of the y-segmented modules, the simulated particles from which it is created are retrieved. If at least one particle crosses the outer region, the cluster is set to be an outer one. If all the contributing particles cross the inner region, the cluster is flagged as inner one. If the cluster has no contributions from hits belonging to simulated particles of the event, for instance in case of spillover or noise cluster, the region is randomly assigned ignoring any correlation between occupancy level and noise.

3.1.2 Optimization of the tracking algorithms

The forward algorithm first uses the y hit information in the preselection step, where hits from x layers are required to match with hits from stereo planes. The y segmentation improves the effectiveness of this preselection. A further optimisation is added to the fit

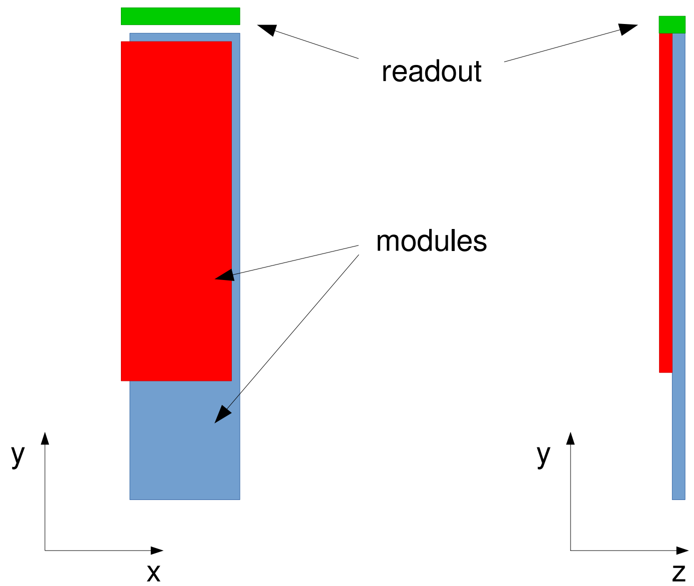


Figure 7: Sketch of SciFi y segmentation, realised by adding modules constituted by shorter fibres in the outer part of the layer.

method of track candidates, checking if the hits have y coordinates compatible with the y projection of the fitted candidate to the segmented layers.

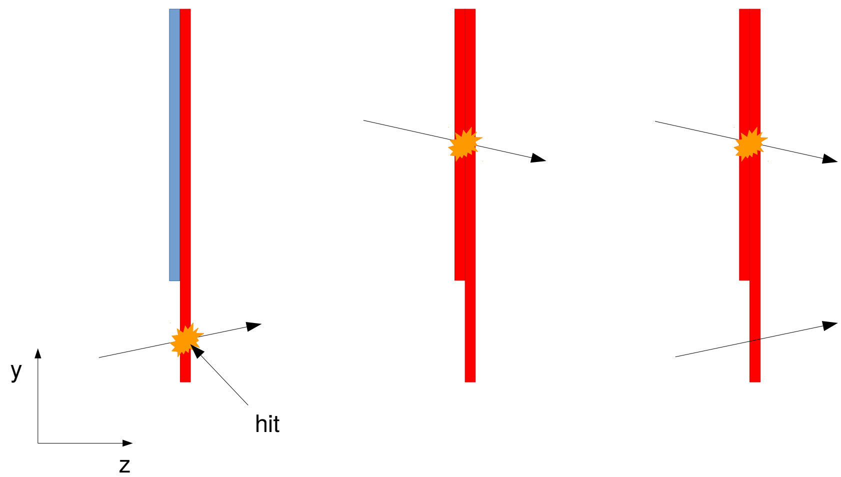


Figure 8: Sketch of SciFi y segmentation readout scheme. When a particle intersects the inner, not segmented part of the module (left), this corresponds to an inner hit. In case of intersection with the outer part of the module (middle), an outer hit is created. When two particles intersect at the same fibre both inner and outer parts of the module, the outer hit only is created.

The seeding algorithm determines the full track trajectory from a cubic fit to all hits. Once the trajectory is known, the consistency between the expected y coordinate of the hits and the boundaries of the segmented modules is checked. The x hits that are in the wrong region of the module are removed from the track, and the track is only kept if there are enough hits remaining in it.

3.1.3 Results

The optimal y segmentation of modules is defined as the absolute value of the y coordinate of the shorter modules for which the tracking efficiency is largest and the ghost rate smallest.

Figure 9 shows the results obtained for the forward algorithm with the two inner modules segmented. With higher values of y segmentation, the total ghost rate is first suppressed by about $\approx 10\%$, and then it reaches a plateau where the information of the y coordinate of the hits is no more useful to further decrease ghosts. Over the full y segmentation range, the number of matching ghosts per event is about constant, and only the number of T-ghosts is decreasing, due to the suppression of hit combinatorics caused by the detector segmentation. The tracking efficiency is also decreasing by up to 4% for values of the y segmentation of 200 mm, because of the decreasing detector hit efficiency, before finally reaching a plateau. The y segmentation value which assures the best compromise between loss of efficiency and decreasing of ghost rate is chosen to be 150 mm, also accordingly to the seeding studies shown in the next paragraphs.

In Table 2 the forward results with baseline SciFi detector, and with y segmentation equal to 150 mm, are summarised. The total ghost rate is decreasing by 8%, mainly due to the strong reduction of T-ghosts. However, the tracking efficiency significantly decreases for all types of tracks, due to the missing hits in the inner parts of the y segmented modules coming from particles crossing the same fibres in the outer region. To recover the efficiency, the hit requirements in the forward algorithm are then relaxed: the reconstruction efficiencies for long tracks and long tracks of high momentum from B mesons are now almost recovered, but with higher ghost rate with respect to the not segmented SciFi detector. Concluding, the implementation of the SciFi y segmentation currently studied is not giving any benefits to the forward reconstruction in terms of tracking efficiency and ghost rate, with respect to the baseline SciFi detector.

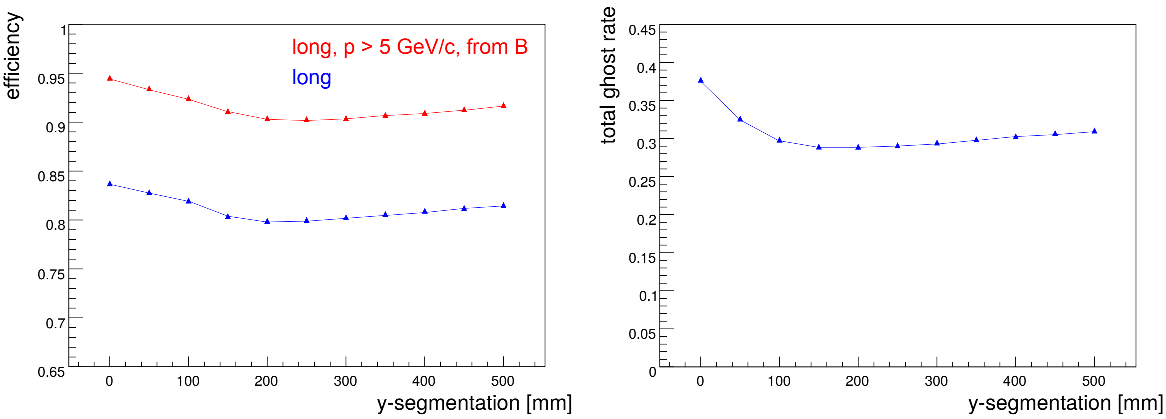
Table 3 lists the performance of the seeding algorithm for long and high momentum long tracks. Only a small gain in efficiency is seen due to the hit inefficiency introduced by y segmentation. Depending on the number of layers segmented, 2% to 9% reduction in ghost rate is seen.

3.2 Additional x layers

As already mentioned in section 3.1, it is crucial to add extra detector material only where this can improve the reconstruction performances on particles of physics interest, because of the increasing multiple scattering effects due to the material. In particular,

hit requirements	no y segmentation default	y seg $= 150\,\mathrm{mm}$ default	y seg $= 150\,\mathrm{mm}$ reduced
long	83.8%	80.4%	83.4%
long $p > 5\,\mathrm{GeV}/c$	92.1%	86.5%	88.9%
long $p > 5\,\mathrm{GeV}/c$, from B	94.5%	91.1%	93.2%
total ghost rate	35.9%	27.9%	36.3%
matching ghosts/event	23.1%	23.7%	26.7%

Table 2: Forward performances with baseline SciFi detector and default hit requirements (minimal number of x hits equals 4 and minimal total number of hits equals 10) used in the reconstruction, and y segmentation equal to 150 mm with reduced hit requirements (minimal number of x hits equals 3 and minimal total number of hits equals 9). The results are computed over a sample of 5000 simulated $B_s \to \phi\phi$ events.



(a) (b)

Figure 9: Forward performances with two inner modules segmented. a) Reconstruction efficiency for long tracks (blue) and long tracks with momentum greater than $p > 5\ GeV/c$ coming from B meson decays, depending of the y segmentation value. b) Total ghost rate versus y segmentation.

the inner region of the SciFi, nearest to the beam pipe, is intersected by the majority of B meson daughters, and has the highest particle occupancy of the detector, where the availability of more hits can improve the track reconstruction. This is why the most preferable configuration of extra layers considers the addition of two inner modules only.

3.2.1 Simulation

A full-detailed simulation is realised creating custom geometries which include the extra layers, starting from the geometry databases describing the SciFi detector in the LHCb simulation framework. Both generation and digitisation simulations have to be modified

	long	long, $p > 5\,\mathrm{GeV}/c$	ghost rate
no y segmentation	90.5%	94.0%	18.3%
2 segmented x layers			
100 mm	+0.70%	+0.60%	+0.60%
150 mm	+0.70%	+0.50%	−0.80%
200 mm	+0.70%	+0.60%	−1.50%
250 mm	+0.80%	+0.60%	−1.90%
300 mm	+0.80%	+0.60%	−2.00%
3 segmented x layers			
100 mm	+0.70%	+0.50%	−1.40%
150 mm	+0.70%	+0.40%	−3.40%
200 mm	+0.70%	+0.40%	−4.40%
250 mm	+0.70%	+0.50%	−4.70%
300 mm	+0.80%	+0.50%	−4.60%
6 segmented x layers			
100 mm	+0.60%	+0.30%	−5.10%
150 mm	+0.50%	+0.10%	−8.00%
200 mm	+0.50%	+0.00%	−9.10%
250 mm	+0.60%	+0.20%	−9.20%
300 mm	+0.60%	+0.20%	−8.60%

Table 3: The performance of the seeding algorithm for different scenarios of y-segmented modules.

according to the modified number of SciFi layers. In this detailed simulation, all digitisation effects are simulated for extra layers such as for standard planes.

Several geometries were tested in order to find, within the given engineering and infrastructural constraints, the optimal configuration of the extra layers for which the maximum improvement in tracking performances can be obtained. The optimal configuration found is characterised by two extra layers with inner modules only, positioned right behind the first station and the second one, as shown in Fig. 10. This geometry will be referred in the following as UFT 5x5, to discriminate it from the baseline SciFi geometry, called UFT 5x. For cross check purposes, a geometry version with full-sized additional layers is studied too, named UFT 5x6.

3.2.2 Forward algorithm optimisation and performances

The structure of the forward algorithm is based on the idea of track reconstruction using a homogeneous detector; one of the most important consequences is the expectation for

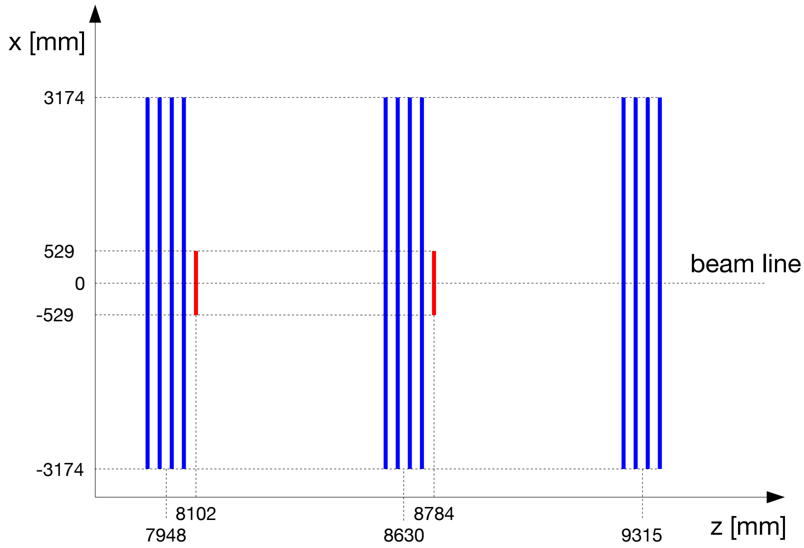


Figure 10: Sketch of the UFT 5x5 geometry, characterised by two extra layers (in red) with inner modules only. Standard layers are blue coloured. Only layer dimensions along the x coordinate are drawn to scale.

track candidates having the same number of hits. This idea is widely used in the algorithm, mainly for comparing multiple candidates of a single VELO track projection.

This geometrical assumption is no longer valid when adding extra layers consisting of inner modules only. In this case, the reconstruction algorithm has to distinguish between candidates which are expected to intersect or not the additional layers. In fact, to fairly compare tracks which are expected to geometrically intersect different number of planes, threshold values used for the reconstruction have to been differentiated. In particular, higher thresholds must be used for candidates which intersect the extra layers.

In the Hough-like clustering of hits, the extra layer boundaries are projected to the reference plane, according to the transformation defined by the extrapolated VELO track. Clusters of hits with an x projection compatible with included in the projected area of the additional layers, are flagged as expected to intersect extra layers. A more precise evaluation is performed after a fit of the full track. Finally, a quality factor is computed for each of the fitted track candidates, based on the number of expected intersected layers. This factor is then used at the final stage of the event reconstruction, to filter ghost tracks.

To improve the rejection of noise or combinatorial hits in the preselection step, x hits already matched with stereo ones can be additionally matched to x hits from extra layers. This matching uses a search window tighter than the one used for stereo hits. For each hit of an x layer within the x window search, a matching with both the nearest stereo and extra layer is required. This will be referred in the following as *triplet hit matching*, to be distinguished from the *doublet* case where a matching with hits from extra layers is not required.

To correctly implement *triplet* hit matching in the forward preselection stage, the working point of this method is determined by computing the discrimination power for *good hits* with respect to the others. In particular, a hit efficiency is defined by counting how many of the available x hits, which belong to the generated particle, passed the preselection; all other hits are defined as background. Values of preselection efficiency versus background rejection are computed varying the search windows for both triplet and doublet hit matching, as shown in Fig. 11. An x tolerance of 2 mm is chosen as working point for the *triplet* matching. This value is used for the results which follow.

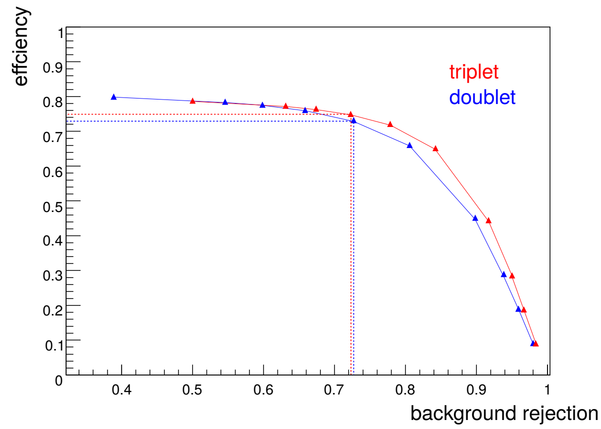


Figure 11: Forward preselection efficiency on hits selected by *doublet* (blue) or *triplet* (red) hit matching, versus hit background rejection. The blue dashed lines indicate the default working point for *doublet* matching, the red dashed the working point chosen for *triplet* matching.

It is also required to determine the new working point of the reconstruction algorithm on a geometry different than the baseline one. The four main parameters related to the number of hits required in the different stages of the forward algorithm are investigated:

- *MinTotalHits*: minimum number of hits required for a candidate track;
- *MinXHits*: minimum number of x hits required for a single Hough cluster;
- *MinXPlanes*: minimum number of x planes which have to be intersected, in a single Hough cluster;
- *MinXSinglePlanes*: minimum number of x planes which have to be intersected by a single hit, in a single Hough cluster.

Figure 12 shows the forward performances obtained for the UFT 5x6 geometry with full-sized extra layers, compared to the baseline UFT 5x geometry, for different sets of hit requirements. Exploiting the full-sized extra layers, with nominal SciFi hit efficiency it is possible to gain about 2% of tracking efficiency on long tracks, and about 1% on long tracks of high momentum which come from B meson decays, with a total ghost rate lower by about 1% with respect to the baseline SciFi geometry. Furthermore, it is useful to explore the performance, which can be obtained simulating additional hit inefficiency of the SciFi detector. A spatially uniform hit inefficiency is added, randomly removing a certain amount of SciFi clusters during the hit decoding phase of the reconstruction algorithm. In Fig. 12 the Forward performances are reported, simulating an extra 3% and 5% hit inefficiency. In both cases, assuming to keep the same total ghost rate of the scenario with nominal SciFi hit efficiency, the UFT 5x6 geometry assures a gain of about 3-4% on tracking efficiency for long tracks, and of about 1% for long tracks from B mesons with $p > 5\,\mathrm{GeV}/c$.

In Fig. 12 the forward performances of the baseline UFT 5x geometry is compared to the UFT 5x5 geometry with extra layers consisting of inner modules only. In this scenario, the addition of inner modules does not improve the performances of the forward algorithm. Further studies show that, for the current algorithm, the extra information coming from layers with inner modules only is not fully exploited to increase the signal-over-background hit ratio, that indeed remains almost constant for this detector region. All the optimisations studied to take advantage of the extra inner modules are not enough to better discriminate signal hits from background ones, especially for the inner detector region where the particle rate and density, and consequently the noise and spillover hit rates, are the highest. This is also related to the fact that the forward algorithm was originally designed to reconstruct particles intersecting a tracker consisting of identical and uniform detector layers. This design is not optimal to profit from the addition of non-full-sized layers.

3.2.3 Seeding algorithm adaptation and performances

The addition of two extra x-layers makes necessary to re-evaluate how to set the parameters of the seeding algorithm as well. On one hand, all the parameters related to the number of hits that a track candidate should contain must be adjusted. This includes both the number of x-hits and the number of the stereo-hits. Those parameters are *MinXPlanes* and *MaxNHits*, which govern the number of hits for the track candidates, as well as all the *MinUV* parameters, which relate the size of the xz-projection to the minimum number of required stereo-hits. Overall, there are 17 such parameters, since the seeding algorithm has 3 independent iterations for different momentum ranges sequentially.

On the other hand, the performance of the algorithm could improve by tweaking the other parameters sensibly. For this reason, a step-by-step profiling of the performance of the seeding algorithm is carried out in order to identify potential bottlenecks and to show which parameters may need adjusting. This shows, notably, that the additional layers help in keeping the ghost rate under control. So, it is possible to relax the conditions under which a hit belonging to a reconstructed track is removed from the pool of available hits for the following iterations of the algorithm. This removal procedure, called *flagging*, has a great impact on both ghost rate and timing. The relevant parameter that needs tuning in this context is the *SizeToFlag* parameter, which controls the number of hits that a reconstructed track must contain in order for its hits to be *flagged*.

Specifically for the UFT 5x5 geometry, it is necessary to include a check on the number

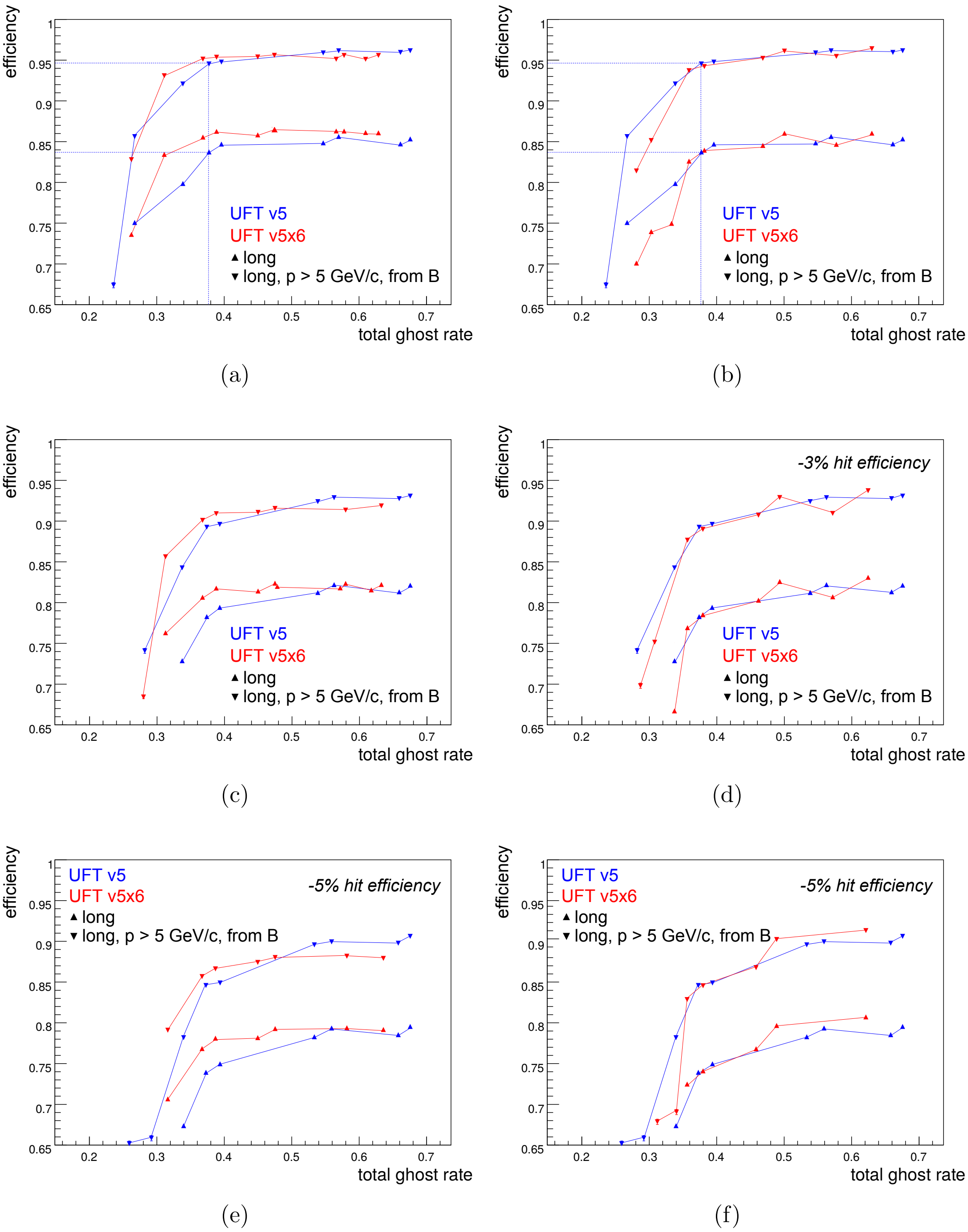


Figure 12: Comparison of forward reconstruction efficiency for long tracks and long tracks from B mesons with $p > 5\,\mathrm{GeV}/c$, on standard (blue) and geometries with extra layers (red). In left column, additional layers are full sized while for right column they only contain two inner modules. Each point corresponds to a set of hit requirements used in the reconstruction corresponding to the ghost rate in the x-axis. Results are for standard hit efficiency of the SciFi detector (top), and with additional hit inefficiency of 3% (middle) and 5% (bottom). The dashed blue lines indicate the performances for the standard reconstruction on the UFT 5x geometry.

of x-layers effectively crossed by the track candidate. This check is made during the xz-projection search as soon as the trajectory for the candidate is determined by using a cubic model and a triplet of hits. Depending on the result of this check, the algorithm adjusts all its parameters to one of the 3 possible configurations (corresponding to 6, 7 or 8 x-layers crossed).

In both alternative geometries, we also investigate the performance of the seeding when only the additional x-layer in the first station is active.

Unsurprisingly, the additional information given by the 2 extra x-layers allows for an improvement on the quality of the xz-projection candidates. A consequence of this improvement is that the other steps of the seeding algorithm are now less CPU-intensive, which brings down the overall run time of the seeding algorithm by a factor ~ 2 for the UFT 5x6 geometry and ~ 1.6 for the UFT 5x5 geometry. This reduction of the execution time is valuable since the algorithm will be run online at the trigger level.

The performance of the reconstruction improves for both alternative geometries: the ghost rate decreases when the number of active additional layers increases, while the efficiency improves or stays the same for every track category when compared to the 12 layers baseline.

It is interesting to note that, due to the discrete nature of the handle on the parameters of the algorithm, the optimal configurations for 13 active layers exhibit overall efficiencies on the same level and a slightly worse ghost rate if compared to the 14 active layer ones. The detailed performance for both geometries is shown in Table 4.

3.3 Beam hole and layer size

The beam hole shape and dimension, such as the layer size, are of crucial relevance to both SciFi engineering and tracking performances. The beam hole region is characterised by the highest particle density, with the maximum located on the beam itself, progressively decreasing towards the outer region of the SciFi layers. A wider beam hole, cutting away portions of the central region of the detector, can in principle assure a lower ghost rate and less critical degradation of the detector due to the particle irradiation. On other hand, fewer particles will intersect the detector, resulting in a smaller yield of particles. Vice versa, with a smaller beam hole the ghost rate is expected to get worse, but the particles that potentially can be reconstructed increase. The exact shape of the beam hole is important for engineering, as it defines how easy it is to build the inner modules. A circular hole would be ideal as that would allow to cover the full acceptance, however, this is considered not feasible to construct. Three different beam holes are studied, sketched in Fig. 13:

- *symmetric rectangle*: gives the highest acceptance of the detector, which requires two modules per layer which have a cutout. This cutout has different dimensions for x layers and for stereo layers;

- *asymmetric rectangle*: also has two central modules per layer, but the dimensions of the cutout are the same for x layers and stereo layers. This option has the drawback

	12 active layers	13 layers, UFT 5x6	14 layers, UFT 5x6	13 layers, UFT 5x5	14 layers, UFT 5x5
ghost rate	**18.4%**	**16.4%**	**15.1%**	**16.2%**	**15.1%**
long	89.9%	91.1%	91.3%	90.2%	89.9%
long, $p > 5\,\mathrm{GeV}/c$	94.5%	95.1%	95.0%	94.8%	94.6%
long from B, $p > 5\,\mathrm{GeV}/c$	94.9%	95.7%	95.6%	95.3%	94.9%
noVelo	87.6%	90.3%	90.7%	88.0%	87.7%
noVelo, $p > 5\,\mathrm{GeV}/c$	94.2%	95.9%	95.7%	94.4%	94.3%
noVelo from DB, $p > 5\,\mathrm{GeV}/c$	93.1%	98.1%	96.9%	94.4%	93.8%

Table 4: The performance of the seeding algorithm for the geometries UFT 5x6 (2 full additional x-layers) and UFT 5x5 (2 partial additional x-layers) over 1000 $B_s \to \Phi\Phi$ simulated events. The efficiencies are shown for long tracks and tracks not having a VELO component (these tracks can not be reconstructed with the forward algorithm). The gain in performance is clear already with only 1 active additional layer. The activation of the second additional layer mostly allows for an improvement in the ghost rate while the efficiencies slightly degrade.

of a smaller acceptance compared to the symmetric case;

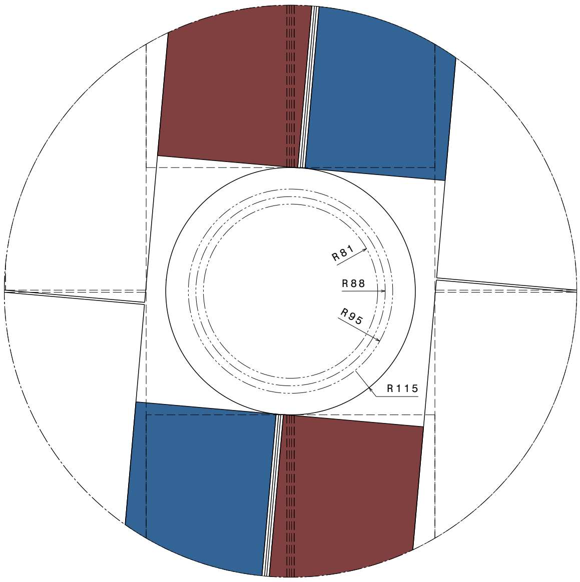
- *large symmetric rectangle*: has only one special module per layer, which has the same dimensions for x layers and stereo layers. This option has the worst acceptance.

For all configurations, the beam hole has same dimensions for each of the three SciFi stations. The minimum clearance to the beam pipe is 20 mm for the last station.

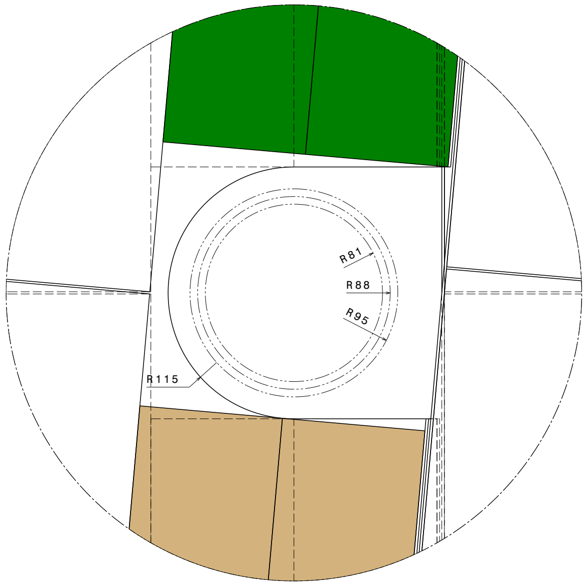
Finally, the layer size defines the SciFi geometrical acceptance, and must fulfill the geometrical constraints of the detector infrastructures. The baseline geometry in the simulation consists of 12 modules for all SciFi layers, and an alternative geometry with 10 modules only for the first two stations (T1, T2) and 12 modules for the last one (T3). The alternative geometry is sketched in Fig. 14. It correctly fits within the infrastructure design, remaining within the nominal geometrical acceptance of the LHCb detector of 300 mrad on the bending plane.

3.3.1 Simulation

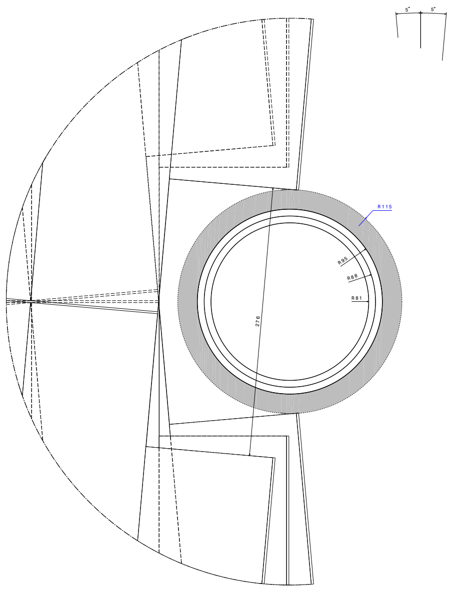
The studies on optimised beam hole and layer geometry are first performed by removing hits from the baseline geometry. During the hit decoding stage of the tracking algorithms,



(a)



(b)



(c)

Figure 13: Sketches of the symmetric rectangular (a), asymmetric rectangular (b) and symmetric, large rectangular (c) beam holes.

the new beam hole region is defined, and all hits falling in that region are deleted. The standard reconstruction follows, such as the redefinition of reconstructible particles basing on the new hit contents of the event, and the matching of reconstructed tracks with the simulated particles.

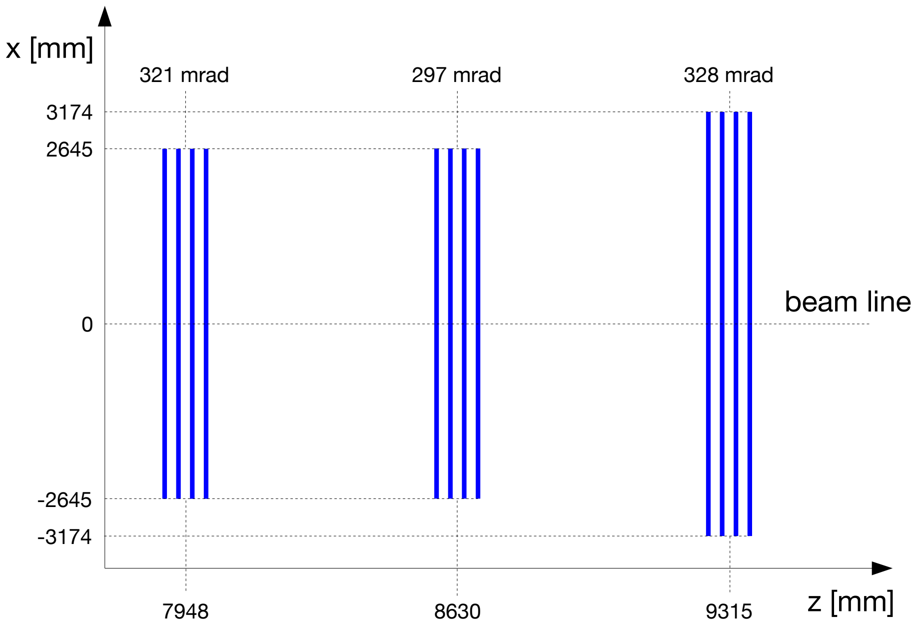


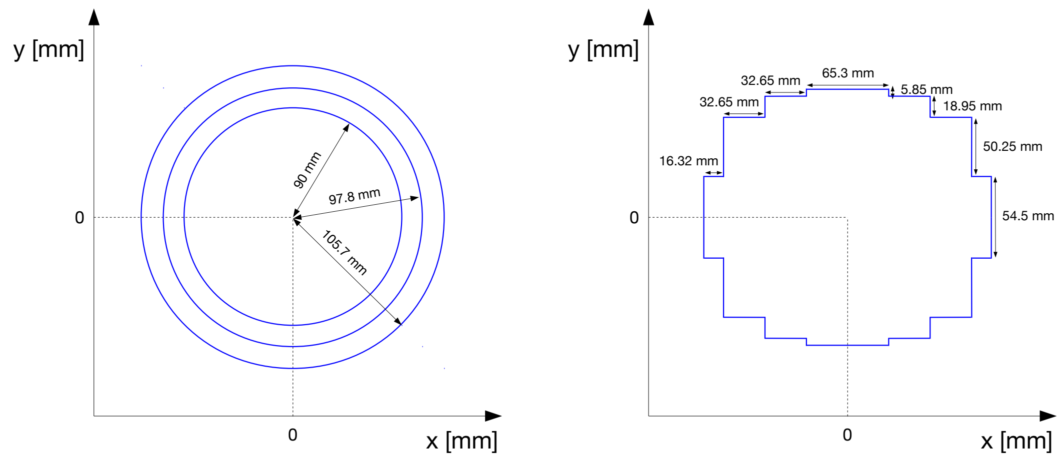
Figure 14: Sketch of the SciFi geometry having T1 and T2 stations constituted by 10 modules, and T3 by 12 modules. The values of the maximum angular acceptance along the xz plane are reported for the three stations. Only layer dimensions along the x coordinate are drawn in scale.

Note that with this toy implementation, custom beam holes can only be compared with a smaller hole, since hits can only be removed. For this reason, all toy studies are performed starting from samples generated with the UFT 2x geometry, which has a circular beam hole of minimal dimensions as sketched in Fig. 15. As reference, the beam hole implemented in the baseline UFT 5x geometry is used.

Two new geometries are created for the full simulation, based on the UFT 5x geometry, to validate the toy results. The so-called UFT 5x8 geometry implements the small symmetric rectangular hole previously described. The UFT 5x9 geometry also includes the reduced layer size, in addition to this rectangular hole.

3.3.2 Results

The resulting number of reconstructible particles obtained for the previously described beam holes are summarised in Table 5, and for the case of 10 modules in station T3. The results are compared with the ideal circular hole having constant radius 105 mm for all the stations, to assure a clearance of 20 mm to the beam pipe for the third station. For reference, the UFT 2x and UFT 5x beam holes are also simulated and added to the comparison. For wider beam holes, high-momentum particles show a more pronounced drop in reconstructability with respect to low momentum ones. This is expected, because of the increasing co-linearity of particles with the beam line, as the momentum increases. Removing the two outer modules from the first and second stations, about 0.7% of long-



(a) (b)

Figure 15: a) Sketch of the circular beam hole implemented in the UFT 2x geometry, with radius increasing from $r_1 = 90\ mm$ of the first station to $r_3 = 105.7\ mm$ of the third one. b) Sketch of the step beam hole implemented in the UFT 5x geometry for the first station. The hole dimensions gradually increase for the second and third stations.

reconstructible particles are lost, and about 0.3% of long-reconstructible particles having $p > 5\,\mathrm{GeV}/c$ and coming from B meson decays. This is because low momentum particles are more bent by the LHCb magnetic field, and consequently they have more hits on the outer layer modules with respect to high-momentum particles.

Table 6 shows the forward tracking performances for all the beam hole scenarios. The tracking efficiency is slightly reducing for wider holes for a maximum factor of 0.4%, and the total ghost rate is decreasing of about 3.5% because of the removal of hits in the most busy detector region, around the beam pipe. However, these represent conservative results, since the radiation damage is overestimated for wider holes when the attenuation maps to simulate irradiation resulting from the UFT v2 circular hole are used. This results in higher attenuation of the reflected photons, thus decreasing the effective hit efficiency of the detector which has a direct impact on the reconstruction efficiency.

Table 7 shows the variation of number of reconstructible particles for the full geometries UFT 5x8 and UFT 5x9, compared to the baseline UFT 5x. These results show the same trends as summarised in Table 5 for the toy model. In particular, the loss of reconstructible particles due to the removal of the outer modules from the first two stations, obtained as difference of the UFT 5x8 and UFT 5x9 results, confirms the toy results. However, a discrepancy of $0.4 - 0.5\%$ is observed for the variation on the number of reconstructible particles with the symmetric hole simulated by the full geometries, and the results of the toy model. This difference can be related to the large per-event fluctuations on the number of reconstructible particles observed by simulating independent samples, or to some effect not taken in account by the toy study. Anyhow, it is expected that this behaviour affects

	long	long, $p > 5\,\mathrm{GeV}/c$	long, $p > 5\,\mathrm{GeV}/c$, from B
	full-sized layers		
UFT 2x circle	+1.05%	+1.54%	+1.03%
symmetric	−0.68%	−1.81%	−1.48%
asymmetric	−1.03%	−2.38%	−1.71%
large symmetric	−1.92%	−3.38%	−2.41%
UFT 5x step	+0.16%	+0.09%	+0.11%
	T1-T2: 10 modules, T3: 12 modules		
UFT 2x circle	+0.35%	+1.42%	+0.78%
circular $r = 115$ mm	−0.70%	−0.32%	−0.34%
symmetric	−1.39%	−2.30%	−1.81%
asymmetric	−1.68%	−2.69%	−2.07%
large symmetric	−2.60%	−3.80%	−2.77%

Table 5: Percentage variation of the number of reconstructible particles for different beam hole shapes and layer sizes simulated by the toy model, with respect to the ideal circular beam hole having radius $r = 115$ mm and all layers 12 modules sized. The results are computed over a MC sample of 17000 simulated $B_s \to \phi\phi$ events.

T1-T2: 10 modules, T3: 12 modules			
	long	long, $p > 5\,\mathrm{GeV}/c$, from B	total ghost rate
circular $r = 115$ mm	81.0%	91.8%	38.9%
symmetric	80.8%	91.7%	35.6%
asymmetric	80.6%	91.6%	35.2%
large symmetric	80.6%	91.5%	35.1%

Table 6: Forward tracking efficiency and ghost rate for different beam hole shapes simulated by the toy model, compared to the ideal circular beam hole having radius $r = 115$ mm. The results are computed over a sample of 17000 simulated $B_s \to \phi\phi$ events.

almost equally the other geometries too, not affecting the overall conclusions of the studies.

The performances for the UFT 5x8 and 5x9 geometries are summarised in Table 8. With respect to the baseline UFT 5x geometry, the tracking efficiency remains almost constant, and a drop of $\approx 3\%$ for the total ghost rate is observed, confirming the toy results.

	long	long, $p > 5\,\mathrm{GeV}/c$	long, $p > 5\,\mathrm{GeV}/c$, from B
toy 5x step hole $\rightarrow$ toy symmetric hole	-0.84%	-1.90%	-1.59%
UFT 5x $\rightarrow$ UFT 5x8	-1.39%	-2.37%	-1.98%
UFT 5x $\rightarrow$ UFT 5x9	-2.17%	-2.86%	-2.34%

Table 7: Percentage variation of the number of reconstructible particles for UFT 5x8 and UFT 5x9 geometries compared to the baseline UFT 5x obtained with the full simulation, and for the symmetric hole compared to the UFT 5x one simulated by the toy model. The results are computed over samples of 5000 simulated $B_s \rightarrow \phi\phi$ events.

	long	long, $p > 5\,\mathrm{GeV}/c$, from B	total ghost rate
UFT 5x	83.5%	94.2%	36.2%
UFT 5x8	83.6%	94.6%	32.9%
UFT 5x9	83.5%	94.4%	33.1%

Table 8: Forward tracking efficiency and ghost rate for UFT 5x8 and UFT 5x9 geometries, compared to the baseline UFT 5x. The results are computed over MC samples of 5000 simulated $B_s \rightarrow \phi\phi$ events.

4 Conclusions

Studies have been performed to optimize the SciFi detector layout, in order to improve the performances of the tracking algorithms. Two possibilities are investigated: a y segmentation and the addition of more layers in the high occupancy regions of the detector. In both cases only a minor performance boost is observed in the seeding algorithm while the forward algorithm performs either the same or worse. Considering additional material and complexity introduced without significant gain, we do not recommend either of the two options.

Additional studies have been performed to estimate the acceptance loss due to changes in the beam hole shape and layer size. A rectangular beam hole and reduced layer size in the first and second stations is accepted as default with minimal loss in acceptance while allowing easier hardware installation and development.

References

[1] LHCb collaboration, A. A. Alves Jr. *et al.*, *The LHCb detector at the LHC*, JINST **3** (2008) S08005.

[2] LHCb collaboration, R. Aaij *et al.*, *LHCb detector performance*, Int. J. Mod. Phys. **A30** (2015) 1530022, `arXiv:1412.6352`.

[3] LHCb collaboration, R. Aaij *et al.*, *Framework TDR for the LHCb Upgrade: Technical Design Report*, CERN-LHCC-2012-007. LHCb-TDR-012.

[4] L. Del Buono, O. Gruenberg, and D. Milanés, *Geometry of the Scintillating Fiber detector*, LHCb-PUB-2014-005. This note describes the planned dimensions of the detector at the time of the optimization study.

[5] LHCb collaboration, R. Aaij *et al.*, *LHCb Tracker Upgrade Technical Design Report*, CERN-LHCC-2014-001. LHCb-TDR-015.

[6] Y. Amhis, O. Callot, M. De Cian, and T. Nikodem, *Description and performance studies of the Forward Tracking algorithm for a scintillating fibre detector at LHCb*, LHCb-PUB-2014-001.

[7] Y. Amhis, P. Billoir, F. Polci, and R. Quagliani, *The Hybrid Seeding algorithm for a scintillating fibre detector at LHCb: description and performances*, LHCb-PUB-2017-018.