1. Introduction

Tracking Detectors in Particle Physics:

Tracking detectors are crucial in particle physics experiments as they record the paths of charged particles. From these paths, conclusions about the particles' properties, such as momentum, can be drawn. In the LHCb experiment, tracking detectors are realized using scintillators in the form of 2.5-meter-long and 250-micrometer-thick fibres. When a charged particle passes through a scintillator, it deposits energy, exciting the material. The excited material then releases this energy as photons, which can be detected using silicon photomultipliers (SiPMs).

Objective of the Lab Course:

This lab course aims to investigate the properties of scintillating fibres in more detail and to adapt an existing simulation to reality by comparing measurement and simulation data.

2. The LHCb Experiment

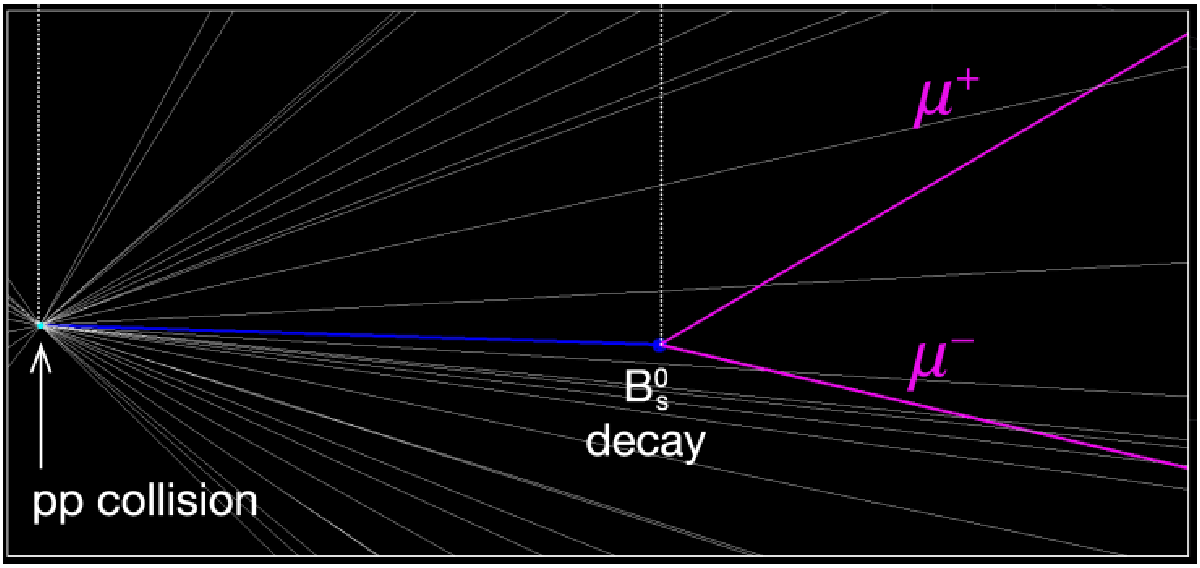
Overview: The Large Hadron Collider (LHC) is the world's largest particle accelerator, hosting numerous experiments to study high-energy physics using proton-proton collisions. One of the four major experiments at the LHC is the LHCb (Large Hadron Collider beauty) experiment, which focuses mainly on investigating CP violation by analysing rare b decay.

Objective: The LHCb experiment aims to test the Standard Model of particle physics and look for evidence of physics beyond it. It primarily seeks to explain the asymmetry between matter and antimatter in the universe.

2.1 Large Hadron Collider

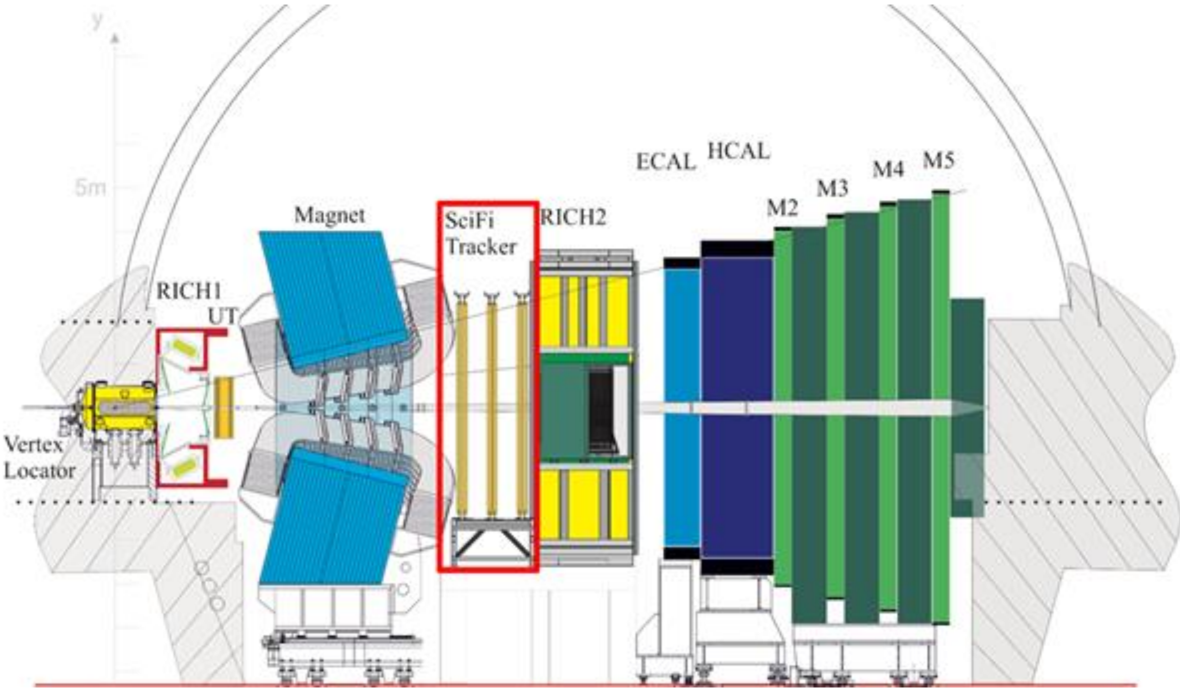
The Large Hadron Collider (LHC) at CERN, near Geneva, is a particle accelerator that collides proton beams at a centre-of-mass energy of 7 TeV. Each beam contains approximately 2000 bunches, each with about 1.1 × 10^11 protons, colliding at an average rate of 15 MHz, resulting in numerous inelastic interactions. The main goal of the LHC experiments is to test the Standard Model (SM) of particle physics and to search for physics beyond SM.

The LHCb experiment is one of the four main experiments at the LHC is specifically designed to study CP-violation and the rare decays of hadrons containing b and c quarks. The B meson is very unstable particle and decays quickly after only a few centimetres. The detector is a single-arm forward spectrometer & positioned at the LHC's interaction point 8 (IP8).. This design is optimized to capture particles produced in the forward direction, where b quarks are predominantly emitted following proton-proton collisions.



The B meson decays after travelling a few cm

2.2 Construction of LHcB



2.2.1 Vertex Locator (VELO)

The Vertex Locator (VELO) is crucial for reconstructing the primary vertex, where the initial proton-proton collisions occur, and secondary vertices, where short-lived particles decay. The VELO consists of pixels detectors arranged in close proximity to the interaction point. These detectors provide high-resolution measurements of particle trajectories, allowing precise determination of vertex positions.

2.2.2 Tracking System

The tracking system of LHCb includes a dipole magnet and several tracking stations. The dipole magnet creates a magnetic field that bends the paths of charged particles. By measuring the curvature of these tracks, the momenta of the particles can be calculated. The tracking stations, consist of silicon strip detectors positioned before magnet and the scintillation fibre tacker (SciFi) tracker placed after the magnet. This SciFi tracker is the main focus of this report. This SciFi Tracker uses scintillating fibres read out with silicon photomultipliers (SiPMs) to detect particles.

2.2.3 Calorimeter System

The calorimeter system of LHCb is designed to measure the energy of photons, electrons, and hadrons. It consists of Electromagnetic Calorimeter (ECAL), and the Hadronic Calorimeter (HCAL). The ECAL absorbs the electromagnetic particles while the HCAL absorbs the hadrons and hence, their energy is determined. The ECAL uses lead as the material while HCAL uses iron as the material.

2.3.4 Particle Identification Detectors (RICH1 & RICH2)

Two Ring-Imaging Cherenkov (RICH) detectors are used for particle identification. RICH1 is located upstream of the magnet, and RICH2 is downstream. These detectors exploit the Cherenkov effect, where charged particles traveling faster than the speed of light in a medium emit light at a characteristic angle. By measuring this angle, the velocity and, consequently, the mass and type of the particle can be determined.

2.3.5 Muon System

The muon system consists of alternating layers of iron and multi-wire proportional chambers. Muons, unlike most other particles, can penetrate the dense iron layers, allowing them to be identified and tracked. This system is essential for studying decays that produce muons in the final state.

2.3.6 Online and Offline Data Processing

The LHCb detector produces a vast amount of data, which is filtered and processed in real-time by an online trigger system. This system selects events of interest and reduces the data volume for further analysis. Selected events are then sent to an offline computing grid, where detailed analyses are performed.

2.3 Scintillating Fibre Tracker

The SciFi Tracker is a relatively new component in the LHCb which was integrated into the LHCb during the upgrade of 2019-20 and was put it into the place replacing the old detectors

The SciFi Tracker consists of scintillating fibres read out with silicon photomultipliers (SiPMs).

Advantages of Scintillating Fibres:

1. High Resolution: The fibres provide a high-resolution tracking capability.

2. Low Scattering: They scatter the penetrating particles less than other methods.

3. Cost-Effective: They are inexpensive to manufacture, allowing coverage of a large area.

Resolution: The resolution of the SciFi Tracker is said to be better than 100 µm, even though the fibres are 250 µm wide. This high resolution is achieved through the variance of a uniform distribution.

3. The Experimental setup

The experimental setup involves a computer-controlled measuring device that includes a spectrometer, scintillation fibres and an xy table, all managed by a central program. It aims to mimic to study the measurement of scintillating fibres used in the LHCb experiment. In the first experiment, we used spectrometer measurements for detecting the photons emitted or reflected by the sample. For this analysis, we first started the controlling PC and did the reference run to see if everything is working fine.

Key Components of the Setup:

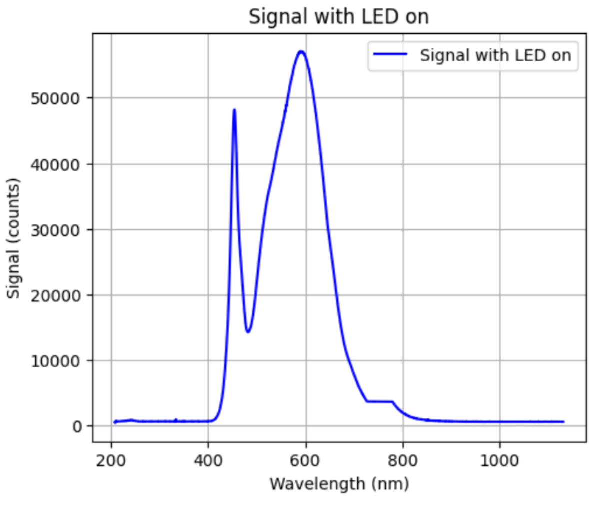
LED Box and xy-Table: The LED box is used to excite the fibre. It can be moved along the fibre's length using the xy-table.

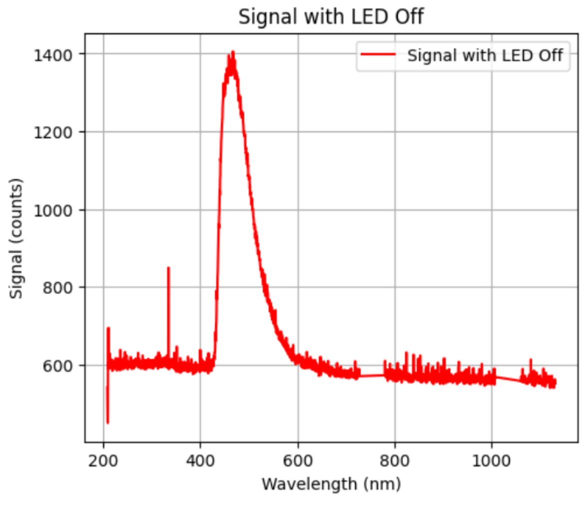
Spectrometer Movement: The spectrometer can be moved horizontally and vertically to measure light at different angles relative to the fibre. However, due to potential collisions with the fibre, its movement is restricted to specific angular intervals: horizontally between -20° to 90° and vertically between -6° to 90°.

In the first experiment, we studied this spectroscopic measurement.

3.1 Spectroscopic Measurement

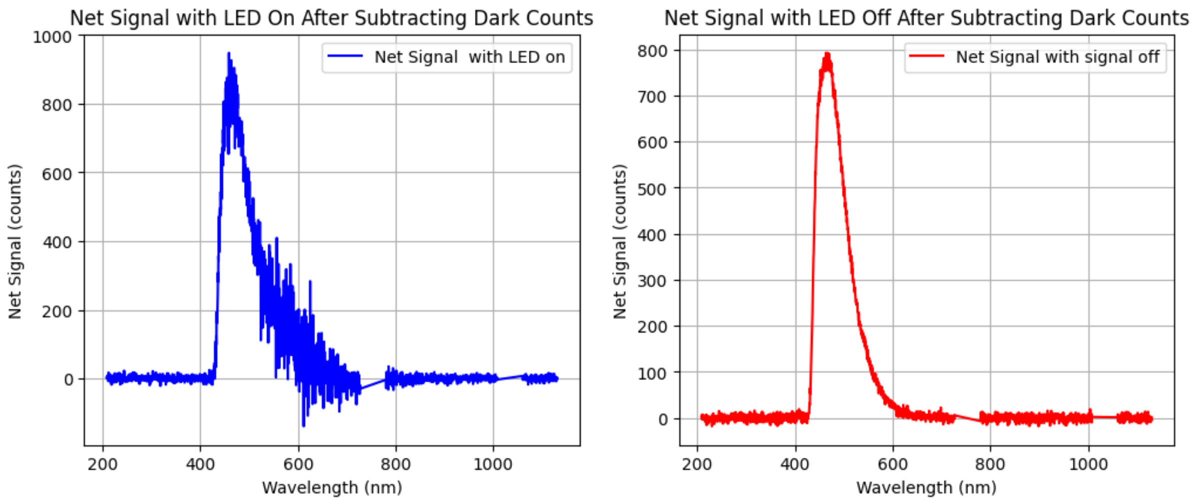
The spectrometer measures the intensity of light (photon count) as a function of wavelength. In this experiment, scintillation fibres emit light when excited by room light. Further, measurements are conducted with room light both switched on and off to differentiate between the actual signal and off light interference.





Signal with roomlight On (Left Plot): The plot shows two distinct peaks around 450 nm and 550 nm, indicating significant photon emission at these wavelengths when the fibre is excited by the LED. This suggests the emission spectrum of the scintillating fibres includes these wavelengths prominently. The signal counts are much higher in this case as expected (due to LED).

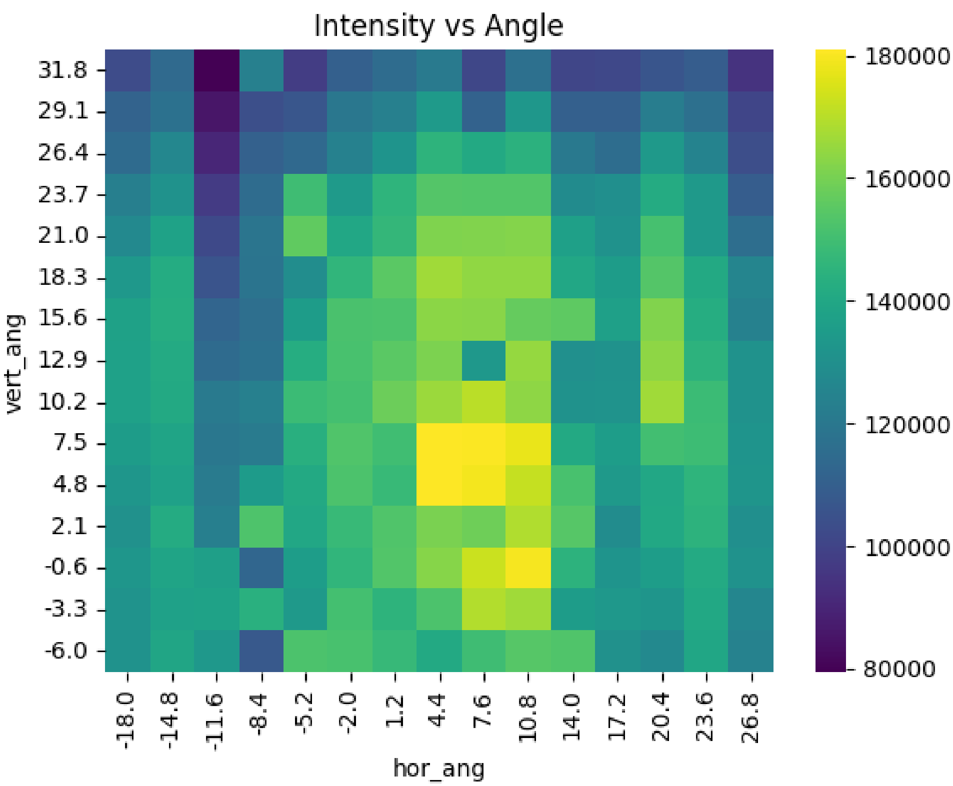
Signal with roomlight Off (Right Plot): The plot shows a lower with a noticeable peak around 450 nm, representing background light interference. This serves as the baseline measurement to account for dark counts and background noise.



Intensity vs wavelenth after subtracting the dark counts are plotted above.

3.2 Radial Symmetry

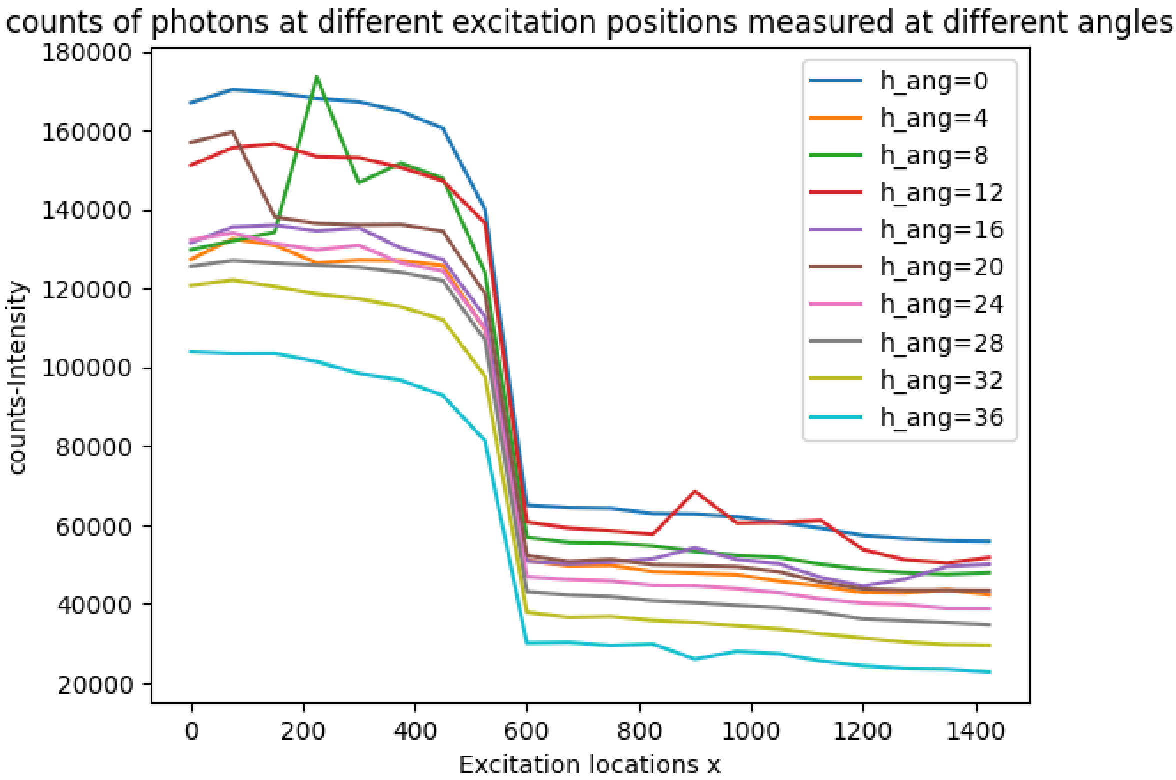
The objective of this measurement is to verify the radial symmetry of the light intensity emitted by the scintillating fibres. To achieve this, the light intensity is recorded at horizontal angles ranging from -18 to 26.8 and vertical angles ranging from -6 to 31.8. The collected data is displayed in two-dimensional histograms representing the net intensity of light as a function of horizontal and vertical angles. Radial symmetry cant be observed that well due to the broken movements of the spectrometer.



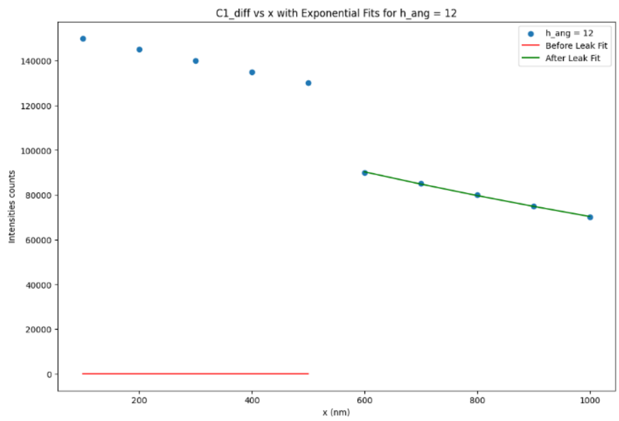
3.3 Intensity Measurement

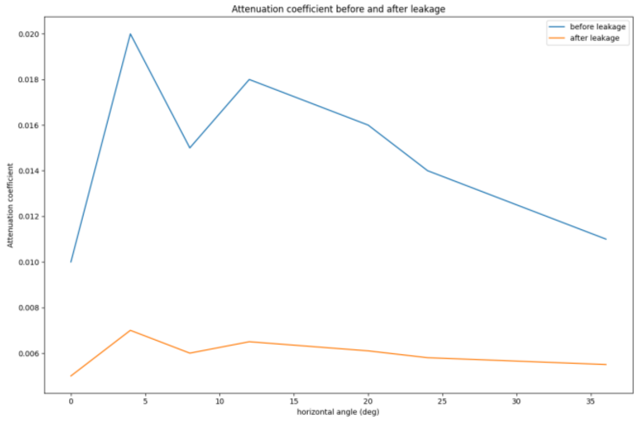
The objective of this part is to measure the x-dependent intensity of light emitted by the scintillating fibres at various angles. This will help in understanding how the intensity varies along the length of the fibre along with different excitation angles. This distribution can be seen in the graph below.

It can be seen that the intensity of light decays exponentially as the signal passes through the fibre., indicating absorption of the photon along its path. Furthermore, it can be seen that this absorption of signal is dependent on the angle of excitation of the fibre.



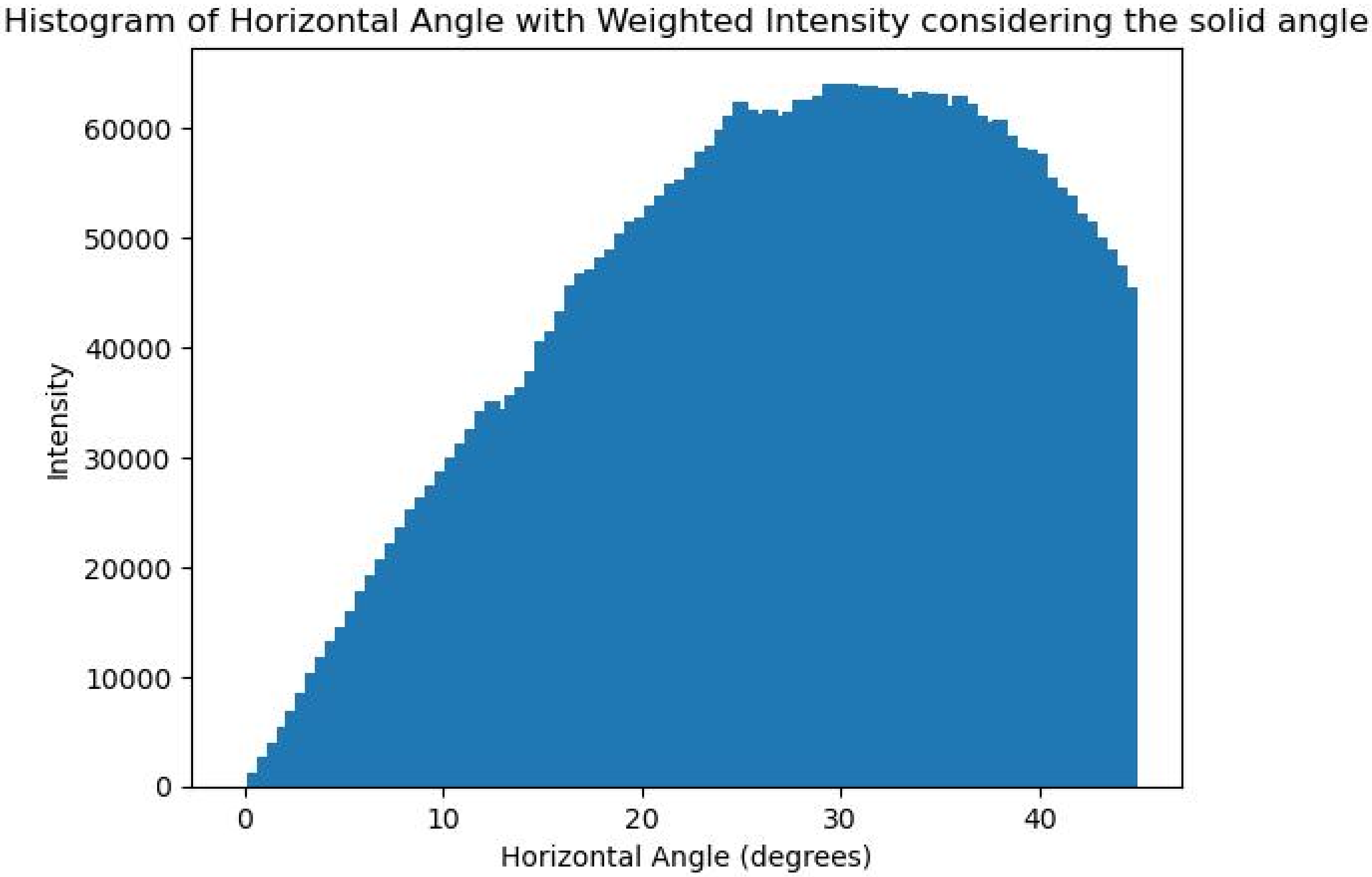
The plot displays the intensity of light (counts) as a function of the excitation position (x in nm) along the fibre for different horizontal measurement angles. A sharp decrease of intensity can be seen very clearly between 550 to 600 nm, due to the broken part the fibre.. By these measurements attenuation coefficient of the material can be determined as shown the graph.





3.4 Angle Intensity Measurement

For this analysis, only, the horizontal angle is varied from 0 degrees to 36 degrees while, the excitation location and the vertical angle are kept constant. This can be used to study the angle at which maximum photons left the surface. For this the counts were subtracted from the dark counts.



The angle at which most photons leave the fiber is: 8.5° with a weighted intensity difference of 170417.20

4. Stimulation

The stimulation aims to assess the performance of the scintillating fibre tracker before its construction. In our simulation, we stimulated the behaviour of scintillating fibres when excited by photons. The simulation considers various physical processes such as Rayleigh scattering, attenuation, and reflections at the fibre interfaces. The simulated data has 11807972 rows and 15 columns which also includes information about the position, angle, and intensity of the photons as they travel through the fibre. A glimpse of some of the columns can be seen in the following figure.

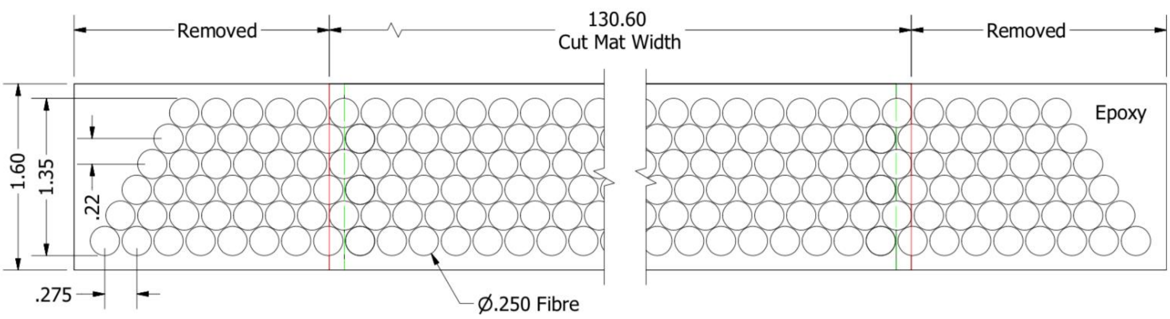
	y_exit	z_exit	x_start	y_start	z_start	px_start	py_start	pz_start	reflCoCl	reflClCl
0	-0.026978	-0.061619	2400.019897	-0.051878	0.096635	0.948434	0.162628	-0.272077	3649.0	0.0
1	-0.055254	0.050902	2400.000732	0.085666	0.015889	0.977825	-0.139056	-0.156593	2674.0	0.0
2	0.049212	0.065583	2399.990967	0.006511	-0.025208	0.917937	-0.225034	0.326729	0.0	3894.0
3	-0.018177	-0.106197	2400.062012	-0.043234	-0.098842	0.885576	0.074564	-0.458470	0.0	5517.0
4	0.050591	0.043467	2400.000977	-0.004035	-0.069628	0.971248	-0.103995	-0.214154	2757.0	0.0

4.1 Simulation Components

1. Rayleigh Scattering
Rayleigh scattering involves the scattering of photons by particles much smaller than the wavelength of light, causing the photons to change direction. This process is significant because it can lead to the loss of photons from the intended path, affecting the overall light transmission efficiency of the fiber.

2. Attenuation
Attenuation refers to the reduction in the intensity of the photon beam as it passes through the material, due to both absorption and scattering. This parameter is vital for understanding how far photons can travel within the fiber before their intensity diminishes significantly.

3. Reflections at Fiber Interfaces
Photons undergo reflections at the interfaces within the fiber, specifically at the core-cladding and cladding-cladding interfaces. These reflections are governed by the difference in refractive indices between the core and cladding, leading to total internal reflection that keeps photons confined within the core, facilitating their transport along the fiber's length. The figure belows show how the fibre structures looks.



4.2 Structure of fibres

Scintillation fibres have cladding. cladding refers to a layer of material surrounding the core of the fibre. This layer has a lower refractive index than the core, allowing total internal reflection to occur at the core-cladding interface and hence, guidess the photons along the length of the fibre with minimal loss.

4.3 Stimulated data analysis

4.3.1 Removing un-physical stimulations

This is the very first step carried out in the analysis. It includes removing the instances which can arise only from some stimulation errors. E.g. the Maximum Distance from the Exit Point to the Center of the Fiber cannot be greater than the radius of the fiber. Given the fiber has a core radius of 220 µm and two cladding layers of 7.5 µm each, the total radius which is 250/2 µm. Any photon written beyond that is not physically possible and is hence, removed.

4.3.2 Removing photons with Rayleigh scattering and then dividing them into core and cladding photons

After that, the photons that have undergone Rayleigh scattering have been removed and the remaining data is categorized on whether they are in the core or cladding. Then, the distance of each photon from the center of the fiber at the exit point using the Pythagorean theorem.

In the next step, the photons are classified into core and cladding based on the fact if the photon has travelled any distance in the cladding given by the column of ‘length_clad > 0.

4.3.3 Angle Calculation (θ) Relative to the X-Axis

To analyze the directionality of the photons, we calculated the angle θ of each photon relative to the x-axis based on their momentum components. The angle θ was derived from the cosine inverse of the x-component of the photon's momentum.

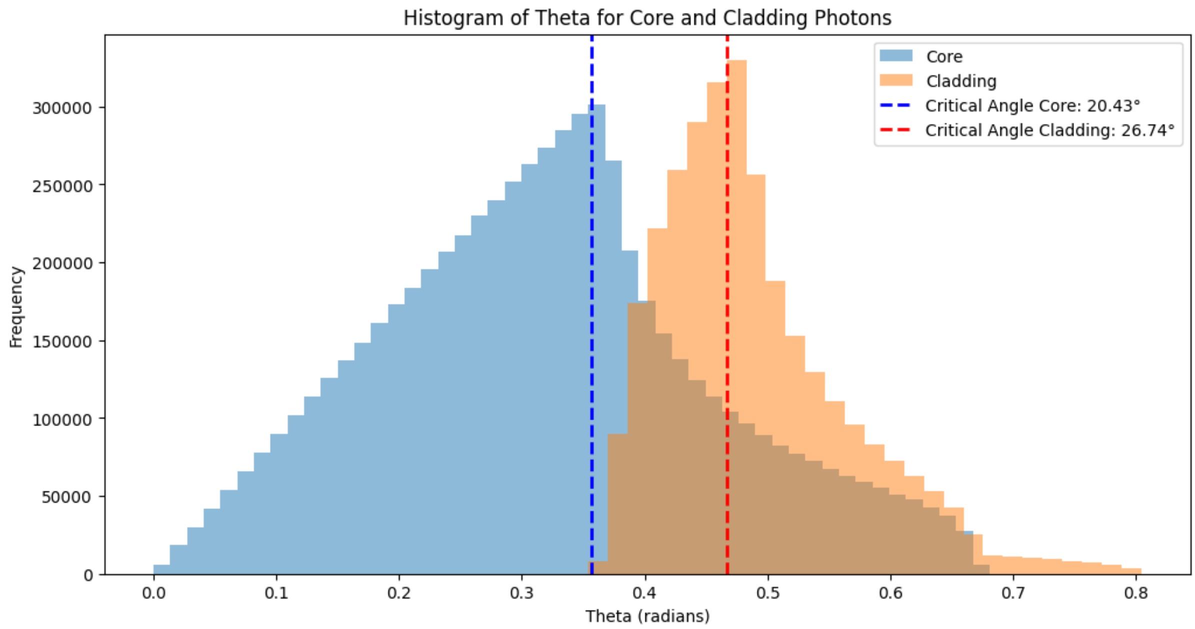
4.3.4 Analysis of critical angle

After classifying the data into core and cladding, the maximum angle for total internal reflection at the core-cladding interface is calculated using the Snell's law.

“Total internal reflection happens when the angle of incidence exceeds a certain critical angle while travelling from a denser to a lighter medium.”

This density of medium is explained on the basis of their refractive indices of the mediums.

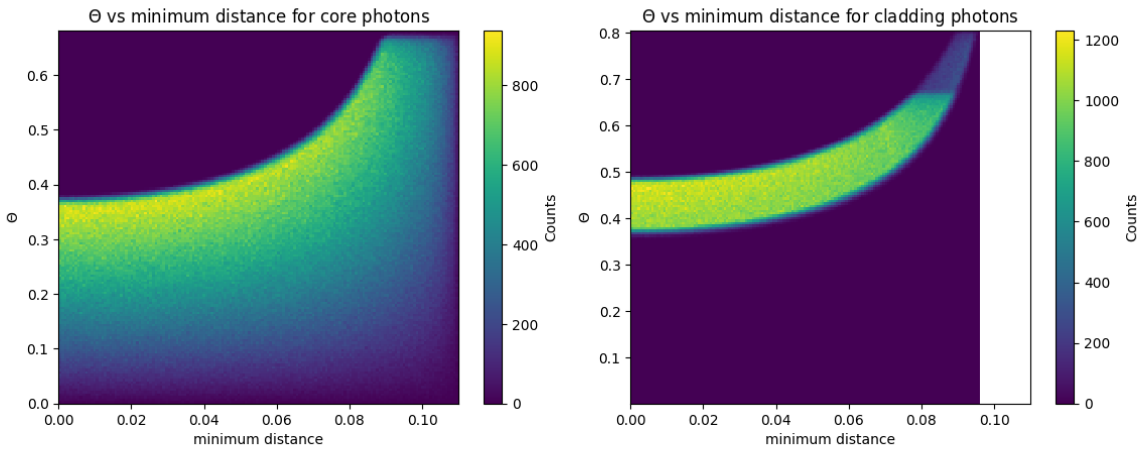
$$\theta_{\text{crit}} = \arccos\left(\frac{n_{\text{cladding}}}{n_{\text{core}}}\right)$$



To visualize the angular distribution of photons within the fiber, we plotted histograms of the angle θ for both core and cladding photons. The histograms provide insights into how photons are distributed angularly. Additionally, we marked the critical angles for total internal reflection to indicate the thresholds beyond which photons will not be confined within the core or cladding and it can be seen that the photon counts are maximum at the critical angle but decreases afterwards.

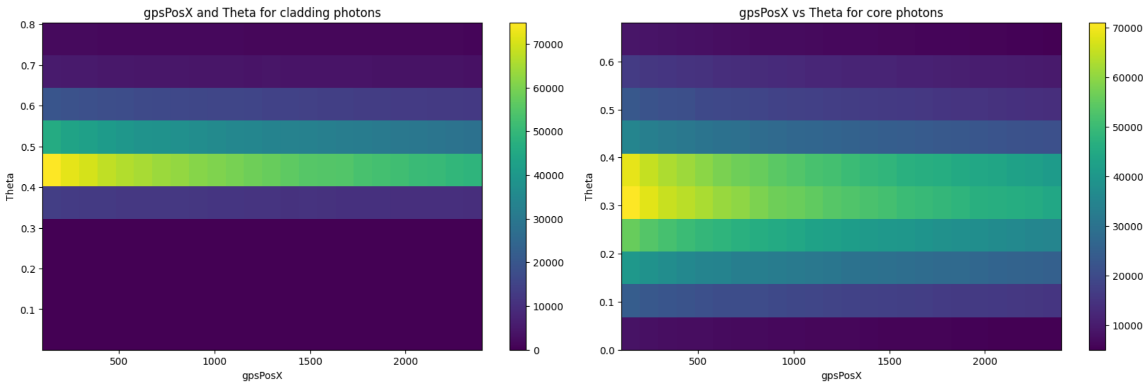
4.3.5 Photon distribution with varying distance and angle

In the next step the minimal distance of the photon is calculated. Using the information about the starting position and impulse of the photon the closest distance of the photon track to the fibre center can be easily determined. The resulting distance rmin can be histogrammed against the angle for both cladding and core photons. The resulting plots clearly show, that the maximum angle, at which photons still occur increases with the minimal distance for both core and cladding photons. This can be explained by the fact, that photons who travel further away from the fibre centre move in a helix like shape along the side of the fibre allowing them to surpass the theoretical critical angle.

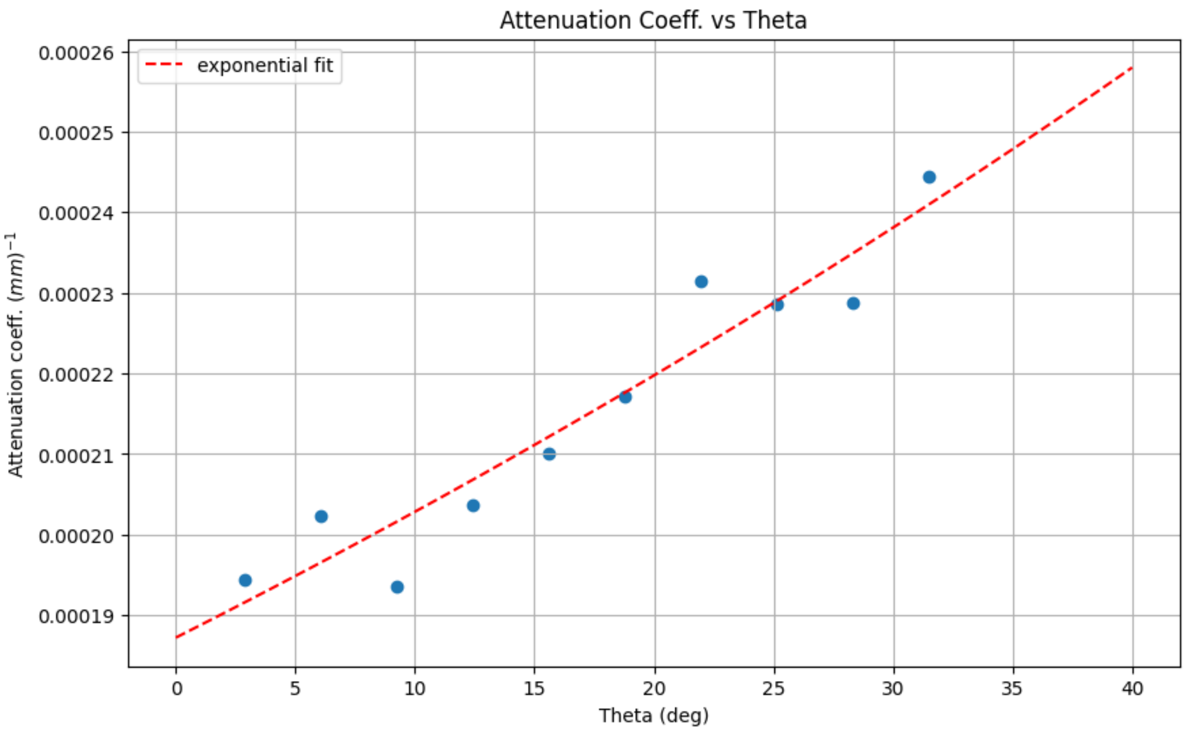


4.3.6 Intensity as a function of different angles excitation location

In a last step the impact of the excitation location on the intensity is investigated by histogramming it against the angle.



The resulting histograms show the decrease in intensity for higher excitation distances. The resulting histograms show the decrease in intensity for higher excitation distances. Using this, the attenuation coefficient can be determined by fitting an exponential function describing the intensity depending on the excitation location as seen in the plot.



Literature

1. LHCb full-detector real-time alignment and calibration: latest developments and perspectives, September 2018, https://www.researchgate.net/publication/329862057_LHCb_full-detector_real-time_alignment_and_calibration_latest_developments_and_perspectives
2. LHCb Scintillating Fibre Collaboration. ”LHCb Scintillating Fibre Tracker Engineering Design Review Report: Fibres, Mats and Modules”. Techn. Ber. LHCb-PUB-2015-008. CERN-LHCb PUB-2015-008. Geneva: CERN, März 2015. url: https://cds.cern.ch/record/2004811
3. https://home.cern/resources/faqs/facts-and-figures-about-lhc