

Universität Bonn

Physikalisches Institut

Simulation of a silicon pixel tracker in a 400 GeV proton on thick target experiment to measure the charm production cross section

Matei Climescu

A charm cross section measurement test beam was conducted in July 2018 in preparation for the SHiP experiment. It combined emulsion, pixel, SciFi, drift tube and RPC detectors as well as a magnet to observe charm decays. The pixel detector, its spatial reconstruction, time reconstruction and energy reconstruction were simulated in FairShip using GEANT4. The simulation results were studied, compared to expectations, used to create tracks and compared to data.

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Preface

Physics has witnessed an unprecedented string of discoveries in recent years such as the discovery of a Higgs boson through proton collisions using the Large Hadron Collider (LHC) in 2012 [1, 2].

At the time it was theorized, the existence of a Higgs was suspected but not certain by any means. Investigating it was therefore highly desirable but not yet possible, leading to the eventual design and subsequent construction of several machines, notably the Large Electron-Positron collider (LEP), the Tevatron and eventually the LHC. The sheer effort put into building these colossal particle colliders highlights how crucial such measurements can be. When there is a measurement required to which those machines are not sensitive, it becomes necessary to build a new machine with different sensitivities.

The *Standard Model* (SM) is currently placed in a similar situation: it is a massively successful theory, which accurately predicted and describes particles and their interactions. It is now, however, also notable in what observations it is unable to explain, implying a need for either an extension or an overhaul of the theory. The LHC's role includes investigating certain such models, but it has so far been unsuccessful in that, a decade after its first collisions, leading some physicists to advocate for other solutions leading to new measurements.

There is a number of experiments proposed to investigate and measure anomalies in the SM as well as investigate physics that go beyond it. One such experiment is the Search for Hidden Particles (SHiP) which suggests a different approach to the one used by the large LHC experiments: instead of producing a relatively scarce number of particle collisions and maximizing the collision energy by crossing beams, it would utilize a single beam to be dumped onto a specially designed target so as to maximize the number of interactions thus ensuring interaction for nearly all particles of the beam and maximizing secondary particle production. SHiP in particular would study extremely rare decays of charmed particles and therefore requires an accurate estimation of the number of particles that would be produced in the experiment. Thus the measurement of the charm cross section associated with colliding protons on a thick target is crucial. Such experiments are largely reliant on software simulations of the setup and detector systems for testing and analysis comparison.

This thesis will highlight the simulation implementation and optimization studies performed for the pixel detector of the charm cross section test measurement performed in July 2018 as well as additional contributions made to the associated analysis and software.

Introduction to the Standard Model and Hidden Sectors

The Standard Model is amongst the most successful theories in physics and the most successful one in describing elementary particle physics. It has been developed in the 1960s and 1970s, been tested over the last 50 years and has accurately predicted and depicted the behaviours of three of the four interactions known to exist in nature: electromagnetism, the strong force and the weak force. It has been tested and verified in many experiments and been finally declared “complete” in 2012 when the Higgs boson was discovered at the LHC [1, 2]. It had become increasingly clear however that the SM has multiple shortcomings which create the need for studies of physics that go beyond it. This manner of investigation often takes the form of production and decay observation of the heavier SM particles. The Standard Model will thus be overviewed. However, since it isn’t perfect, some of its limits will be examined. These issues are not insurmountable, therefore some possible solutions coming from the so-called Hidden Sector will be highlighted.

2.1 The Standard Model

Today’s best understanding and description of the phenomenology of fundamental interactions is articulated by the Standard Model of Particle Physics. It is a self-consistent, locally gauge-invariant quantum field theory that appears like it could hold consistency until the *Planck Scale* [3], the energy scale at which gravity is no longer negligible for subatomic physics.

The SM was observed to hold six *leptons*: the electron e^- , the electron neutrino ν_e , the muon μ^- , the muon neutrino ν_μ , the tau τ^- and the tau neutrino ν_τ . All non-neutrino leptons have an electrical charge of (-1). The SM also has six *quarks*: the up quark u , the down quark d , the strange quark s , the charm quark c , the bottom or beauty quark b and the top quark t . u , c , t will sometimes be called up-type quarks and noted q_u as they share the same electric charge of ($\frac{2}{3}$) while d , s and b are sometimes called down-type quarks and noted q_d as they have an identical ($-\frac{1}{3}$) charge. For each of those particles there is also an associated antiparticle which has identical physical properties such as mass but opposite *internal quantum numbers* which intrinsically define the particle. *Electric charge* or *weak isospin* for example are internal quantum numbers. They are different from *relative quantum numbers* which relate to the reference the particle is observed in, such as helicity [4]. These particles and their antiparticles are regrouped under the name *fermions* which are particles that have their spin

quantum number $s = 1/2$. When a particle meets its antiparticle, they annihilate to a boson. A *vector* boson, that has its spin $s = 1$, is the *photon* (γ) which mediates the *electromagnetic interaction*, an infinite range force that governs our everyday lives, being notably responsible for macroscopic effects and maintaining atomic cohesion. It is the result of the $U(1)$ symmetry. There are also eight massless vector bosons known as *gluons* (g) which are the result of the $SU(3)$ symmetry and mediate the *strong interaction*. They are identical apart from their different strong charges (referred to as colour). The strong interaction allows nuclear cohesion and for quarks and gluons, *partons*, to assemble into composite objects such as the proton. This is done through *asymptotic freedom*: interactions between coloured objects get asymptotically weaker as the energy scale increases or, equivalently, as the distance between them decreases. It should thus be noted that quarks in particular cannot be isolated and are solely found inside those composite particles which are called *hadrons*. Hadrons composed of a quark and an anti-quark are named *mesons* while those made of three quarks are called *baryons*, the proton, for instance, is a baryon. Other hadron types have been observed [5] but are very uncommon. The physics describing the strong interaction is called *Quantum Chromodynamics* or *QCD*. Three massive vector bosons, the Z , W^+ , W^- arise from the broken $SU(2)$ symmetry and mediate the weak interaction which is in particular responsible for certain types of radioactivity. Finally a single massive scalar boson, which has spin $s = 0$, the Brout-Englert-Higgs-Guralnik-Hagen-Kibble boson, often abbreviated Higgs boson H , allows for particles to acquire mass and for the entire theory to be gauge invariant, that is to be remain unchanged under specific space-time symmetry transformations. These particles and their coupling can be found in Figure 2.1.

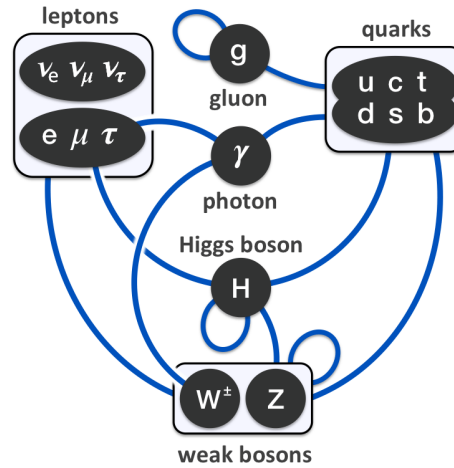


Figure 2.1: Illustration of the Standard Model of particle physics. Particles are represented by black ellipses and their interactions are shown through the connecting lines [6].

The Standard Model is described by a single Lagrangian from which are derived all of the equations of motions describing interactions. Said Lagrangian is itself the result of an $SU(3) \times SU(2) \times U(1)$ symmetry and is found in Equation 2.1.

$$\begin{aligned}
 \mathcal{L} = & -\frac{1}{4}\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} - \frac{1}{8}\text{Tr}(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}\text{Tr}(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) \\
 & \text{U(1), SU(2) and SU(3) gauge terms. } \mathbf{B}, \mathbf{W} \text{ and } \mathbf{G} \text{ are the associated vector potentials.} \\
 & + (\bar{\nu}_L, \bar{e}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \bar{\nu}_R + (\text{h.c.}) \\
 & \text{lepton dynamics term. (h.c.) is the hermitian conjugate of the previous expression} \\
 & - \frac{\sqrt{2}}{v} \left[\bar{e}_L \phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} e_L \right] \\
 & \text{charged leptons mass term} \\
 & + (\bar{u}_L, \bar{d}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.}) \\
 & \text{quark dynamics term.} \\
 & - \frac{\sqrt{2}}{v} \left[(\bar{u}_L, \bar{d}_L) \phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \right] \\
 & \text{down-type quarks mass term} \\
 & - \frac{\sqrt{2}}{v} \left[(-\bar{d}_L, \bar{u}_L) \phi^* M^u u_R + \bar{u}_R \bar{M}^u \bar{\phi}^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix} \right] \\
 & \text{up-type quarks mass term} \\
 & + (\overline{D_\mu \phi}) D^\mu \phi - \frac{m_h^2 \left[\bar{\phi} \phi - \frac{v^2}{2} \right]^2}{2v^2}. \\
 & \text{Higgs dynamics and mass term}
 \end{aligned} \tag{2.1}$$

The Lagrangian of Equation 2.1 gives rise to fields the excitations of which are interpreted as fermions: the quarks and leptons discussed earlier.

2.2 Standard Model limits

Despite its successes, the Standard Model has been unable to explain certain observed phenomena and is as such an incomplete theory. There is in particular the existence of neutrino oscillations, an observed difference in the amount of matter and antimatter in the Universe and a lack of mass in the Universe.

2.2.1 Neutrino oscillations and mass

Neutrinos are some of the most elusive particles in the Standard Model, they are very abundant in the Universe [7] yet scarcely interact with matter after creation. As such, neutrino detection experiments are generally some of the largest in High Energy Physics [8].

For a long time, they were thought to be massless until neutrino oscillations were observed [9, 10]. Neutrinos oscillating from one flavour to another meant that there exists a unitary transformation

linking neutrino mass and flavour eigenstate:

$$\begin{aligned}
 |\nu_k\rangle &= \sum_{\alpha} U_{\alpha k} |\nu_{\alpha}\rangle; & |\nu_{\alpha}\rangle &= \sum_k U_{\alpha k}^* |\nu_k\rangle; \\
 \begin{pmatrix} \nu_e \\ \nu_{\mu} \\ \nu_{\tau} \end{pmatrix} &= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}; & \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} &= \begin{bmatrix} U_{e1}^* & U_{e2}^* & U_{e3}^* \\ U_{\mu1}^* & U_{\mu2}^* & U_{\mu3}^* \\ U_{\tau1}^* & U_{\tau2}^* & U_{\tau3}^* \end{bmatrix} \begin{pmatrix} \nu_e \\ \nu_{\mu} \\ \nu_{\tau} \end{pmatrix}.
 \end{aligned} \tag{2.2}$$

This gives rise to $U_{\alpha k}$ which is known as the *Pontecorvo–Maki–Nakagawa–Sakata matrix* (PMNS) *matrix* [11], the neutrino flavour-mass mixing matrix.

Neutrinos have very low masses (< 1 eV) [12], scarcely interact and are produced with a minimum energy of $O(1$ MeV), they are thus always ultrarelativistic in practice, their mass can be neglected compared to their total energy. The probability of flavour change implied by the PMNS matrix is found in Equation 2.3 [13].

$$P_{\nu_{\alpha} \rightarrow \nu_{\beta}}(t) = |A_{\nu_{\alpha} \rightarrow \nu_{\beta}}(t)|^2 = \sum_{k,j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* \exp\left(-i \frac{\Delta m_{kj}^2 t}{2E}\right). \tag{2.3}$$

Here, P is the transition probability, A is the transition amplitude, $U_{\alpha i}$ are the PMNS matrix elements, Δm_{kj} is the mass difference between mass eigenstate k and j , E is the energy of the system and t is the time.

We notice here how the oscillations imply mass. Indeed if one fixes $\Delta m_{kj} = 0$ the transition probability would be constant which is observed not to be the case [13]. This means that out of three neutrino mass eigenstates, at least two are non-zero. How these neutrinos acquire mass is unknown since this isn't predicted by the SM as can be seen in Equation 2.1.

2.2.2 Baryonic asymmetry and CP violation

According to widely held cosmological studies [14, 15], the origin of the Universe is found in the Big Bang [16] where the Universe initially consisted of a single initial singularity which went on to inflate and produce massive matter through energy conversion. This initial singularity was nothing but energy, all quantum numbers were 0 and it would seem natural to assume that particles and antiparticles would then be produced in equal amounts. Current observations suggest otherwise however, especially in the baryon sector. Indeed antimatter is observed to be extremely rare compared to matter in the Universe leading to the conclusion that it was likely never produced [17]. This would imply a preference in nature for matter being produced over antimatter. This is called *Charge-Parity symmetry Violation* (CP violation or CPV), in other words the behaviour of particles is not identical if one looks at a particle within a spatial coordinate system and at its antiparticle according to the inverted coordinate system.

Many studies have been conducted on CPV, in the quark sector through observations such as particle decays [18, 19] and mixing [20, 21]. CPV is included in the SM as a complex phase of the weak interaction's quark mixing matrix [22]. This is seen in the so-called *Cabibbo–Kobayashi–Maskawa Matrix* or *CKM Matrix* which is analogous to the PMNS matrix for quarks.

The amount of CP violation observed in the hadron sector is however insufficient to explain the amount of matter (or equivalently lack of antimatter) observed in the Universe, implying the existence

of other sources of CPV. Since the strong interaction does not violate CP up to a very high limit, ruling it out as a source of sufficient CPV [23], the lepton sector CPV was and is also investigated. In such a scenario, there would be CPV in the lepton sector which would be transferred over to the quark sector through *sphaleron processes* [24]. This type of CPV is similar in its formulation as baryonic CPV in that it is created by either a single or three complex phases in the neutrino mixing matrix of the weak interaction shown in Equation 2.2 [11]. While it is identical in its principle to the CKM matrix, the weakness of neutrino interactions and the difficulty in observing them implies a lower degree of knowledge as to its components [25].

Lepton flavour violation is an actively investigated subject to this day and many experiments, current and proposed, are measuring or planning to measure neutrino mixing [26].

2.2.3 Dark Matter and gravity anomalies

Astronomy has made observations as to the amount of matter in the Universe which have motivated the existence of “invisible matter” as soon as 1933 [27]. However, research performed over the past few decades have confirmed that in many areas, the behaviour of gravity throughout the Universe, both for astrophysical and cosmological uses, could not be explained with current knowledge [28–30] suggesting the existence of a massive material invisible to current day telescopes: Dark Matter. This interpretation to this unexplained behaviour of gravity in the Universe is getting large attention although other explanations also exist [31–33].

There have been many Dark Matter candidates imagined by theory, be it through “fixing” the lack of CP violation in QCD [34], postulating new symmetries [35], new particles [36] such as *Weakly Interacting Massive Particles* (WIMPs) or new operators [37].

The nature of Dark Matter is actively researched by experiments across the world through creation [38], indirect detection [39] and direct detection [40]. Further experiments are proposed to improve the sensitivity to Dark Matter [41–43].

2.3 Extending the Standard Model through Hidden Sectors

Since the Standard Model cannot explain certain observations as shown in Section 2.2, an extension or a revamp of the theory raising physics *Beyond the Standard Model* (BSM) is called for. Since the SM has been very successful otherwise, extending it seems a natural way to proceed. The simplest way is to add terms to the SM Lagrangian shown in Equation 2.1 that cancel out in the SM derivation thus not appearing in SM equations of movement. The argument for new particles is that they are either too heavy to be produced in current-day experiments or interact too weakly with SM particles to have been observed as shown in Figure 2.2.

It is conceivable that some of these hypothetical particles would be massive and wouldn’t directly interact with the SM at all. These “*Hidden Sectors*” may however couple to the Standard Model via renormalizable interactions via higher-dimensional operators suppressed by the dimensionful couplings Λ^{-n} which correspond to the energy scale of the hidden sector or with small dimensionless coupling constants called “*portals*”. There are three such portal classes: *Vector*, *Scalar* and *Neutrino* that could interact with the SM, each with its own energy dimension. The following discussion on Hidden Sectors will closely follow the one found in [44].

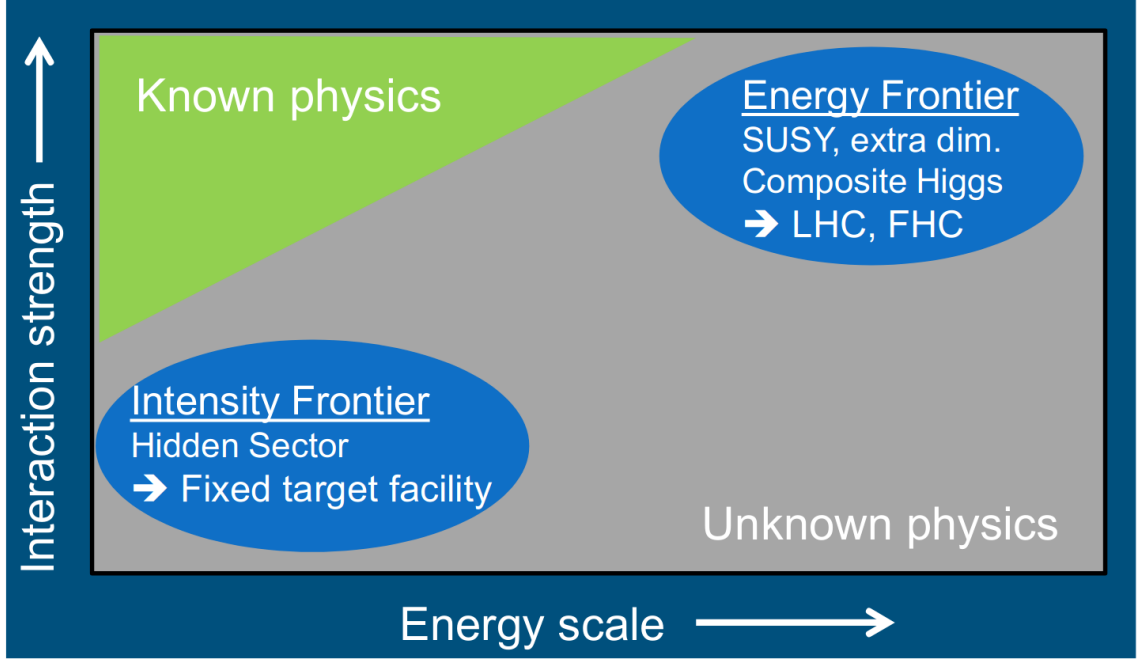


Figure 2.2: New physics is to be found either at higher energies or lower interaction strengths [44].

2.3.1 The Vector Portal

The Vector portal relies on adding an additional $U(1)$ symmetry to the SM which would transform it into a $SU(3) \times SU(2) \times [U(1)]^2$ symmetry [45]. This would result in a new interaction similar to electromagnetism with new particle fields A'_μ and an extra Lagrangian term

$$\mathcal{L}_{\text{Vector portal}} = \epsilon F'_{\mu\nu} F_Y^{\mu\nu}$$

with ϵ a dimensionless coupling characterising the mixing between the new vector field with the Z^0 and the γ , $F'_{\mu\nu}$ and $F_Y^{\mu\nu}$ the field strength and the hypercharge field respectively. This $U(1)$ symmetry could also be broken, inducing mass to its resulting particles either via a “hard” mass term on the induced particles V with a scale $\mathcal{L} = \frac{1}{2}m_V^2 V_\mu^2$ or through an additional broken gauge symmetry inducing a Higgs mechanism similar to the one present in the SM. Those would take the form

$$\mathcal{L}_\phi = |D_\mu \phi|^2 - \lambda |\phi|^4 + \mu^2 |\phi|^2 \quad (2.4)$$

which after spontaneous symmetry breaking would result in $\phi = \frac{(v+h')}{\sqrt{2}}$ and give rise to a dark Higgs sector extended with its own self interactions [44, 46]. It is perhaps notable that this model is compatible with a (broken) symmetry between SM bosons and fermions (often called *SUperSYmmetry* or *SUSY*) [47].

This Vector portal would induce the existence of new particles such as one or more *Dark Photons* γ' . These particles would mediate this “Dark Electromagnetism” and would allow a solution to the $g - 2$ anomaly if it is confirmed: the observed discrepancy between the theory-predicted muon magnetic moment and the experimental measurement [44, 48, 49] as shown in Figure 2.3. It would provide a

mediator for DM interaction with the SM mentioned in Section 2.2.3 and would also allow for the description of *Dark Matter self interactions* [44].

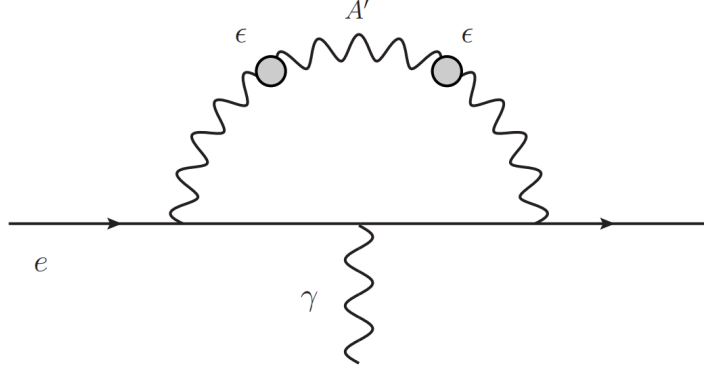


Figure 2.3: A first order loop that could correct the muon anomalous magnetic moment in ways unexplained by the SM due to the exchange of the dark photon [44].

Observation of the new field A' could notably be done through Kaon decays $K^+ \rightarrow \pi^+ + A' \rightarrow \pi^+ + \text{missing energy}$ as $K^+ \rightarrow \pi^+ + \nu\bar{\nu}$ is extremely suppressed.

2.3.2 The Scalar Portal

The discovery of the Higgs boson has shown that scalar particles do in fact exist in nature, motivating searches for other fundamental light scalar bosons. Such a field S would manifest itself in its most general form as the following Lagrangian:

$$\mathcal{L}_{\text{Scalar Portal}} = \frac{1}{2} \partial_\mu S \partial^\mu S + (\alpha_1 S + \alpha S^2)(H^\dagger H) + \lambda_2 S^2 + \lambda_3 S^3 + \lambda_4 S^4. \quad (2.5)$$

with $\lambda_2, \lambda_3, \lambda_4$ the scalar self-couplings, α, α_1 the portal couplings to the SM Higgs doublet H . The singlets introduced here are assumed to be CP-even. It should be noted that SM and Hidden Sector matter interactions can also be mediated through $|H|^2$ [50].

There are now two possibilities: either the linear coupling to the SM Higgs $\alpha_1 = 0$ or $\alpha_1 \neq 0$. This first case is quite diverse and appears in many scenarios such as any $\mathbb{Z}_2$ symmetry ($S \leftrightarrow -S$ and $H \leftrightarrow -H$) where the scalar S develops a vacuum expectation value $\alpha_1 = 4\alpha\langle S \rangle$ and $\lambda_3 = 0$, or in SUSY models where an extra singlet fermion and pseudoscalar enter the Lagrangian [51]. In this case, $\mathcal{T}$ and B could decay into the singlets if the latter are lighter than the former, said singlets may themselves decay further into SM particles and thus be observed. An example of this is shown in Figure 2.4(a).

If $\alpha_1 \neq 0$ the portal may mediate decays of the SM Higgs into any exotic particles that may exist [52]. Such scalars may be seen in flavour changing penguins as shown in Figure 2.4 or in direct decays. They also give rise to a popular string of models called Hidden Valley models which are quite diverse but share in common:

- A coupling between the valley and SM sector which is induced via particle exchange and/or loops;

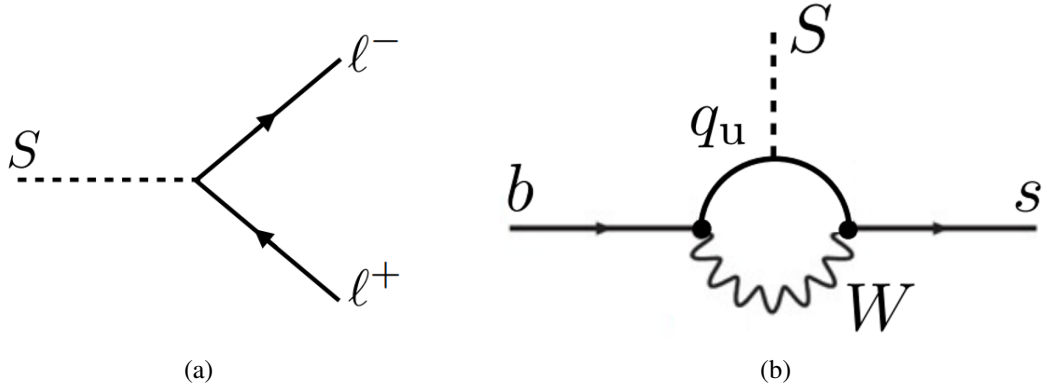


Figure 2.4: (a) Decay of the S singlet to a pair of SM fermions. (b) b - s - S flavour-changing penguin [44].

- Multiparticle production in the valley sector that are realized through decay cascades, QCD-like parton showers for instance;
- A difference in mass preventing certain valley particles from decaying into the same sector. This is done through SUSY breaking or confinement.

More information on Hidden Valleys can be found in [53, 54]. Many such models have a QCD-like dark sector with stable baryonic resonances as DM candidates which carry a conserved DM number. For such models the unstable resonances, similarly to QCD, could notably decay either to SM fermions or photon pairs.

2.3.3 The Neutrino Portal

The Neutrino Portal arises with the coupling of fermions that are neutral under SM gauge interaction N_I ($I = 1, 2, \dots, \mathcal{N}$), with $\mathcal{N}$ the number of neutrino generations, to the gauge invariant operator $(\bar{L}_\alpha \cdot \tilde{\Phi})$ which can be parametrized via the Lagrangian:

$$\mathcal{L}_{\text{Neutrino Portal}} = F_{\alpha I} (\bar{L}_\alpha \cdot \tilde{\Phi}) N_I + \text{h.c.} \quad (2.6)$$

where $F_{\alpha I}$ is a dimensionless, generally complex Yukawa coupling, L_α is the left lepton doublet ($\alpha \in \{e, \mu, \tau\}$ the flavour of the doublet); Φ is the SM Higgs doublet and $\tilde{\Phi}_a = \epsilon_{ab} \Phi_b$. It is considered that only right-chiral components of fermions N_I couple to the SM.

Replacing the Higgs phase by its vacuum expectation value $\tilde{\Phi} = \frac{1}{\sqrt{2}} \begin{pmatrix} v \\ 0 \end{pmatrix}$ means quadratic mixing of neutrinos with the fermions N_I . This would imply that N_I could be produced instead of neutrinos for all kinematically allowed configurations. This justifies their common denomination of *heavy (right-handed) neutrinos* or *sterile neutrinos* (since they have no SM charge). This would give rise to a new such neutrino for every currently known neutrino with mass M_I independent of $F_{\alpha I}$.

The acquisition of mass for these particles can be done by combining them with ν_α from the SM Lagrangian of Equation 2.1 to form a Dirac spinor and make Equation 2.6 a *Dirac mass term*, i.e. implying the neutrino to be a particle acquiring mass through the Higgs mechanism like every other SM fermion.

Since N_I does not carry SM gauge charges, they could also have a *Majorana Mass term*:

$$M_{\text{Majorana}} = M_I \bar{N}_I^C N_I + \text{h.c.}$$

where N_I^C is a charge-conjugated fermion. These explanations on their own do not suffice to explain the difference in mass scale between SM neutrinos and other fermions. It can be noticed however that for energies lower than the masses of the right-handed neutrinos, a dimension-5 Weinberg operator [55, 56] arises in the effective Lagrangian of the active neutrinos:

$$\Delta \mathcal{L}_{\text{osc}} = c_{\alpha\beta} \frac{(\bar{L}_\alpha^C \cdot \tilde{\Phi})(\tilde{\Phi} \cdot L_\beta)}{\Lambda} \quad (2.7)$$

where L_α^C is a charge-conjugation of the left lepton doublet L_α and Λ is a parameter with the dimension of mass defined by M_I and $F_{\alpha I}$ and $c_{\alpha\beta}$ is often taken as ~ 1 . This formula can be solved in several ways [56, 57] the simplest of which is via the neutrino portal of Equation 2.6. In this case the SM Lagrangian is extended with right-handed neutrinos:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + i \bar{N}_I \gamma_\mu \partial^\mu N_I - (F_{\alpha I} \bar{L}_\alpha N_I \tilde{\Phi} + \frac{M_I}{2} \bar{N}_I^C N_I + \text{h.c.}). \quad (2.8)$$

In the Higgs phase the neutrino portal interactions $(\bar{L}_\alpha \tilde{\Phi}) = \bar{\nu}_\alpha$ which leads to $\nu_\alpha - N_I$ mixing. There is therefore a difference between *charge* and *mass* eigenstates of Equation 2.8. The mass eigenstates are obtained by diagonalizing the mass matrix

$$\mathcal{M}_{\nu, N} = \begin{bmatrix} 0 & m_D \\ m_D^T & M_I \end{bmatrix}.$$

where, m_D is the $3 \times \mathcal{N}$ Dirac mass matrix and M_I the $\mathcal{N} \times \mathcal{N}$ Majorana mass matrix. If $m_D \ll M_I$, Equation 2.8 leads to the Weinberg operator in Equation 2.7 with

$$\frac{c_{\alpha\beta} v^2}{\Lambda} = \left(\mathcal{M}_\nu \right)_{\alpha\beta} = \sum_I (m_D)_{\alpha I} \frac{1}{M_I} (m_D)_{\beta I}.$$

Since $m_D \ll M_I$ it implies that the 3 eigenvalues of $(\mathcal{M}_\nu)_{\alpha\beta}$ corresponding to the active neutrino masses become much smaller. This operation is called the *seesaw mechanism* and provides an explanation for why SM neutrinos are so much lighter than other fermions. In this case, the fermions with mass corresponding to the heavy states are called *Heavy Neutral Leptons* or *HNLs*. They can arise in different ways as well [44].

HNLs if shown to exist could solve some of the SM's problems. They could provide an explanation for baryonic asymmetry, provide candidates for dark matter [58] and solve the problem of neutrino oscillations as shown previously.

They could especially be produced in charmed mesons $(c + \bar{q}_d)$ decays and observed as they decay to SM neutrinos $N \rightarrow \pi^\pm + \nu_{\ell^\mp}$ as shown in Figure 2.5.

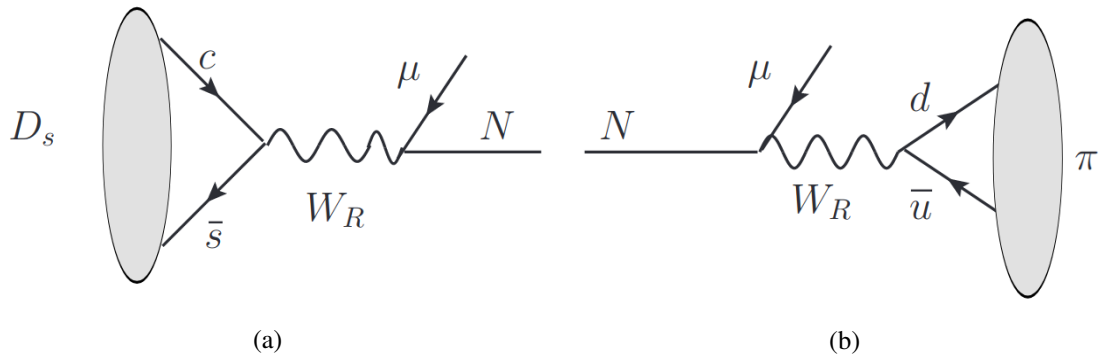


Figure 2.5: Production (a) and decay (b) of HNLs examples [44].

Experimental approaches to new physics and the Search for Hidden Particles

In light of the limits of the Standard Model and of the proposed solutions that exist it is necessary to design experiments that would investigate said limits and make discoveries that would clarify unexplained phenomena. A great deal of effort is devoted into these studies across multiple experiments. These searches will be overviewed before looking into an experiment aiming to comprehensively investigate the Hidden Sector: the *Search for Hidden Particles (SHiP)* which intends to study the result of energetic protons on a thick target collisions, particularly the decays of charmed particles. A review of said charmed particles will conclude this chapter.

3.1 Current experimental status

Experiments in high energy physics rely on their detectors and the measurement of cross sections thus, these concepts will first be overviewed. Amongst the best known experiments in present-day particle physics are those at the LHC. ATLAS and CMS in particular have been in the spotlight after their discovery of the Higgs Boson. These experiments and others are so-called *direct searches* for Beyond the Standard Model physics. The different types of direct searches will be looked into and their areas of sensitivity will be reviewed. Another LHC experiment *LHCb* looks for indirect signs of BSM physics. These experiments and the type of physics they are sensitive to will be discussed as well.

3.1.1 High energy physics experimental principles

3.1.2 Particle energy deposition in matter

Particle detectors, in their aim to detect particle traversing them, rely on energy deposition. This energy deposition is created when electromagnetically interacting particles pass through a material. This energy is recorded by the detector which creates a *hit*: the reconstructed coordinates of the interaction. Most detectors also provide extra information such as the reconstructed amount of deposited energy and the reconstructed time of the interaction.

By definition a material is an atomic construct which is roughly electrically neutral. The energy deposition of a charged particle is given by the *Bethe-Bloch Formula* [59, 60]:

$$-\left\langle \frac{dE}{dx} \right\rangle = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left(\ln \left(\frac{2m_e c^2 \gamma^2 \beta^2}{I} \right) - \beta^2 - \frac{\delta}{2} \right);$$

where c is the speed of light in vacuum, β is the ratio of the particle's speed and c , m_e and r_e are the electron rest mass and the classical electron radius ($r_e = \frac{e^2}{4\pi\epsilon_0 m_e c^2}$) with ϵ_0 the vacuum permittivity and e the elementary charge. Z is the material's atomic number, A its relative atomic mass and N_A the Avogadro Number. E is the energy, x is the distance the particle travels into the material and z is the charge of the incident particle in units of elementary charge while I is the absorber material's mean excitation energy which can be approximated by $I \sim 16 Z^{0.9}$ eV for $Z > 1$ (which is almost always the case). Finally, δ is a parameter which characterizes the extended transverse electric field of incident relativistic particles screened by the charge density of atomic electrons [61]. It can be approximated by $\delta \sim 2 \ln \gamma + \zeta$ with ζ a material dependent constant and $\gamma = \frac{1}{\sqrt{1-\beta^2}}$. At very high energies, Fermi's density correction should also be applied [62].

The Bethe-Bloch formula has a characteristic shape shown in Figure 3.1 which varies from material to material but conserves a similar shape for all heavy particles. Particles with $\beta\gamma \sim 3$ are seen to display the absolute minimum average energy deposition. Particles which have a $\beta\gamma \approx 3$ are thus called Minimum Ionizing Particles (MIP).

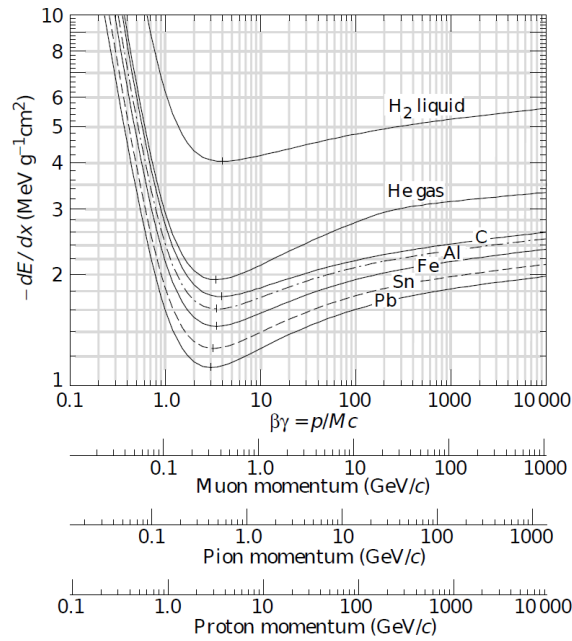


Figure 3.1: Energy loss in different materials for different particles according to the Bethe-Bloch formula [25].

Electrons Electrons, being very light and common in materials, display a somewhat different behaviour. Since energy deposition in matter is done through ionization, the breaking of nucleus-electron bonds, and since electrons have very weak (electromagnetic) bonds relatively to other (strong) bonds present in the material, they are easily knocked off. This implies that all electromagnetically

interacting particles free multiple electrons in their passage through matter. This gives rise to so-called *knock-off electrons* or δ -electrons. They deposit energy in the material in addition to that deposited by the incident particle itself. δ -electrons have very low momentum relative to the incident particle and as shown in Figure 3.1 thus deposit much more energy than high energy particles.

Those factors and others [61] lead to a smearing of the Gaussian shape of the energy distribution which becomes what is called a *Landau distribution* shown in Figure 3.2.

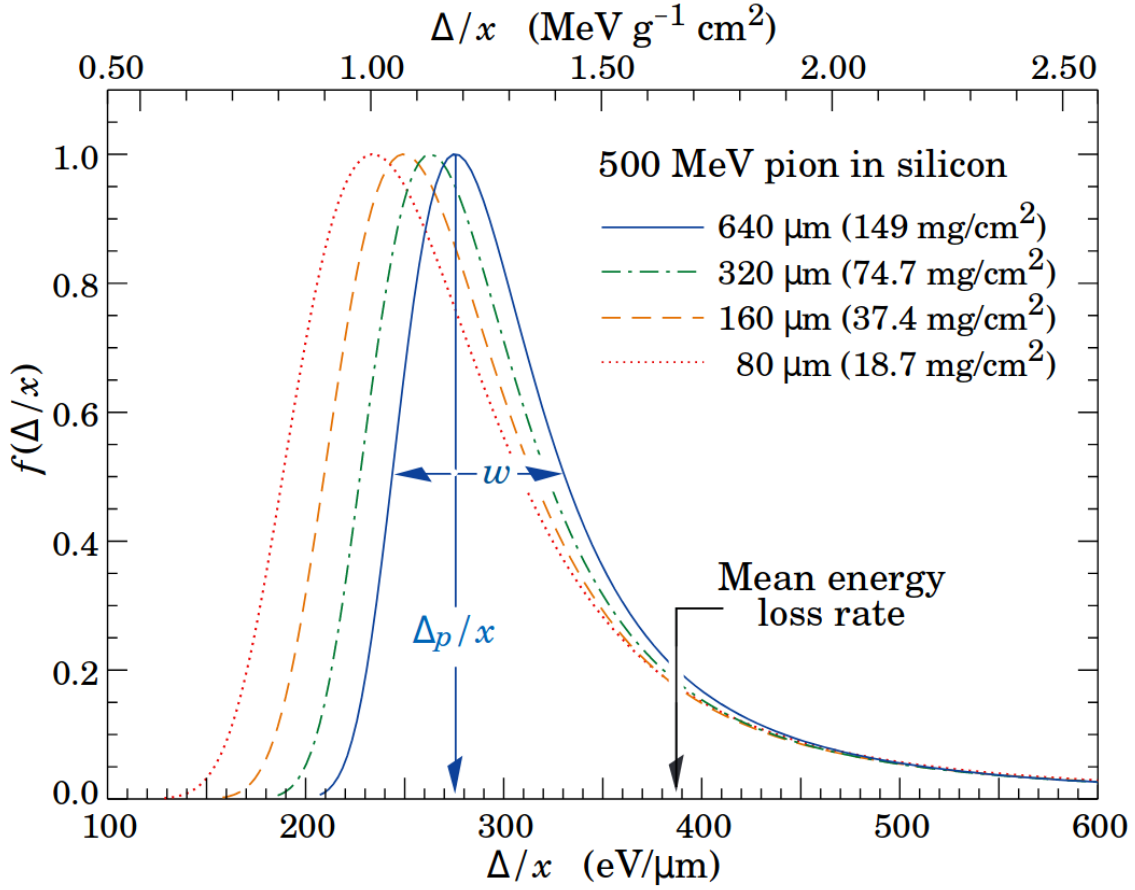


Figure 3.2: Energy loss in silicon for 500 MeV pions, normalized to unity at the most probable value Δ_p/x . The width w is the full width at half maximum [25].

Incoming electrons and positrons of high energy predominantly lose energy in matter via *bremsstrahlung*, i.e. photon emission induced by deceleration of the electron due to the presence of another charged particle such as another electron.

Photons Photons in turn also behave differently. Their energy deposition is not described by the Bethe Bloch formula as they are uncharged and massless. There are mainly three mechanisms for photon energy loss: the photoelectric effect, Compton scattering and pair creation [61].

The Photoelectric effect is an atomic phenomenon which takes place when a photon is absorbed by an atom which then goes on to emit one or several electrons. This process takes place when the

photon possesses sufficient energy to break electron-nucleon bonds ($O(\text{eV})$) meaning it dominates for low energy photons.

Compton scattering is the inelastic scattering of a photon on a charged particle, generally an electron. The photon loses energy which is imparted to the recoiling electron. This phenomenon is common for mid-range ($O(\text{keV})$) energies.

Pair creation takes place and is dominant in matter when the photon has an energy exceeding twice the rest mass energy of an electron of 511 keV. As its name suggests, it's the creation of an electron-positron pair using the field of another charged particle, either the nucleus or an electron.

The full photon energy loss spectrum can be found in Figure 3.3.

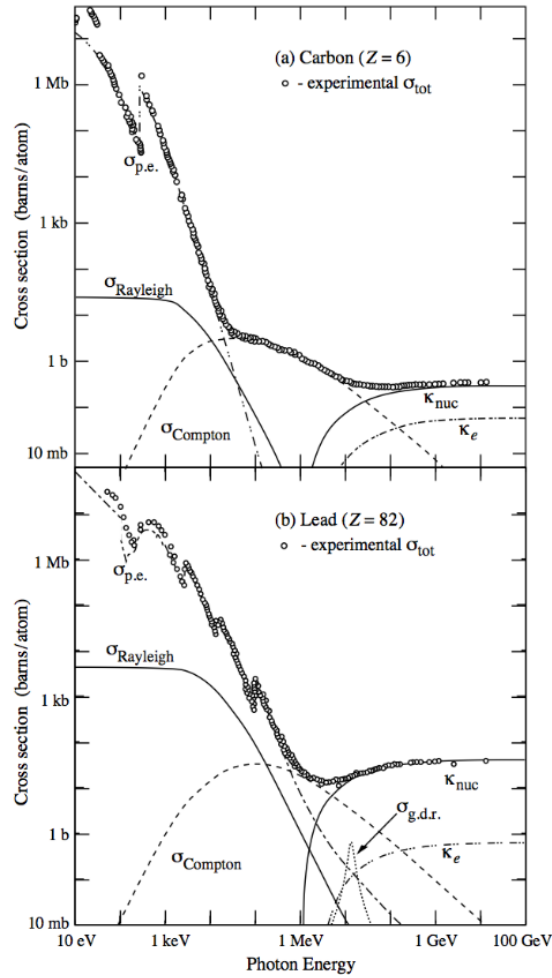


Figure 3.3: Photon energy loss spectrum. $\sigma_{\text{p.e.}}$ is the photoelectric effect cross section. σ_{Compton} is the Compton effect cross section and κ_{nuc} and κ_e are the pair creation cross sections for nuclear and electron field respectively [25].

Cross sections in high energy physics

Cross sections are an integral part of high energy physics and become relevant whenever one performs scattering experiments. They can be seen, in an analogy with classical physics, as the surface exposed by the target to the beam in a scattering experiment as shown in Figure 3.4. It is thus a measure of the probability for a certain process to occur in a collision.

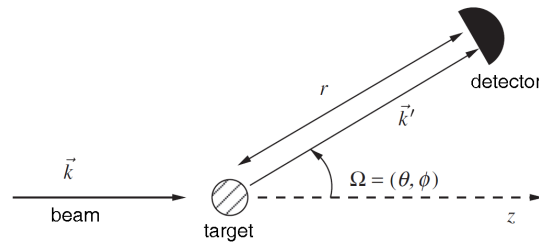


Figure 3.4: Sketch of a scattering experiment [63]. $\vec{k}$ is the momentum of the incoming beam, $\vec{k}'$ is that of the outgoing particles, r is the distance between the target and the detector, θ and ϕ are the polar and azimuthal angle of $\vec{k}'$ with respect to the initial beam direction.

Many experiments aim at observing the way cross sections behave as a function of certain variables, such as energy or angle. The measured quantity is then the *differential cross section*, the cross section within a certain set of parameters, which is physically a more sensitive measurement. For example, in the famous Rutherford experiment [64], the differential cross section of an α particle being deflected at certain angles by an atomic nucleus was measured. Integrating the differential cross section over every variable yields the total cross section. Cross sections are denoted σ and measured in units of area, commonly *barns* (b) with $1 \text{ b} = 10^{-24} \text{ cm}^2$. A complete explanation of cross sections can be found in Reference [63].

Luminosity or *Instantaneous Luminosity* L is the number of collisions that can be produced in the experiment per unit of area and per unit of time. Instantaneous luminosity is integrated over the time during which collisions occur t_{exp} in $\int_0^{t_{\text{exp}}} L dt$ to produce the experiment's *Integrated Luminosity* $\mathcal{L}$ which has units of b^{-1} . Both, cross section and luminosity are related by Equation 3.1:

$$\sigma = \frac{N}{\mathcal{L}} \quad (3.1)$$

where N is the number of produced events. The cross section of a phenomenon is thus measured by counting the number of events which take place and knowing the experiment's luminosity accounting for the detector's efficiency, defined by $\epsilon = \frac{N_{\text{observed}}}{N_{\text{expected}}}$, and acceptance, defined by the physical regions where the detector is sensitive.

3.1.3 Direct searches

Direct searches for new physics can largely be divided in two categories: production and observation at colliders and observation of new physics produced elsewhere in the universe.

Production at Colliders

Colliders such as the LHC use particle beams, accelerated to very high energies, and collide them at interaction points, creating new particles through the mechanism mathematically described by the relation

$$E^2 = m^2 + p^2 \quad (3.2)$$

where E is the energy of the system, m is its mass and p its momentum and where natural units $c = \hbar \equiv 1$ are used. This universal relationship implies the possibility to create massive particles from energy and vice-versa. This can be done through existing massive particles decaying into lighter particles or, as done in colliders, creating massive particles from kinetic energy as seen in Figure 3.5.

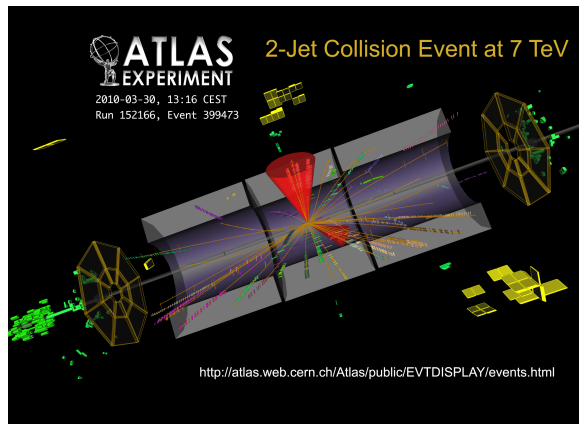


Figure 3.5: A proton-proton collision event visualisation observed at the ATLAS experiment. The red cones are collections of colored particles called *jets*, the orange lines are tracks of charged particles, the colored blocks indicate subdetector responses. These new particles are created from the energy of the collision [65].

Sectors of relatively low mass and high interaction rate having been investigated thoroughly in past experiments, modern colliders experiments such as ATLAS and CMS at the LHC specialize in investigating high energy scales for new physics as shown in Figure 2.2. They are looking for new, heavier particles that can only be produced at higher energies, these particles would then have their decay products be observed via the intricate detector systems that constitute the large detectors characterizing such searches [66, 67].

Observation of Dark Matter

Producing new physics at colliders has many advantages as they are the only ones able to probe the high energy sector in a controlled setting. They may however miss new physics: either because they didn't produce the particles to begin with or were unable to disentangle the decay products produced by the new physics, the *signal*, from other particles produced alongside it, called *background*. The cosmos has natural accelerators much more powerful than the LHC [68] which enables them to produce particles beyond its reach if said particles exist.

As such, basing themselves on the observation that there is new physics in the universe, many other experiments have been built. They are often based on extremely sensitive detectors highly shielded

from external background sources and wait to observe an unknown particle produced beyond the Solar System. This particle type would interact with the detector and produce an event that would have an unexpected energy signature or perhaps produce exotic particles. Dark matter searches using such apparatuses are especially common [69, 70] such as in the example given in Figure 3.6. Common Dark Matter candidates in those searches are the WIMPs mentioned in Section 2.2.3.

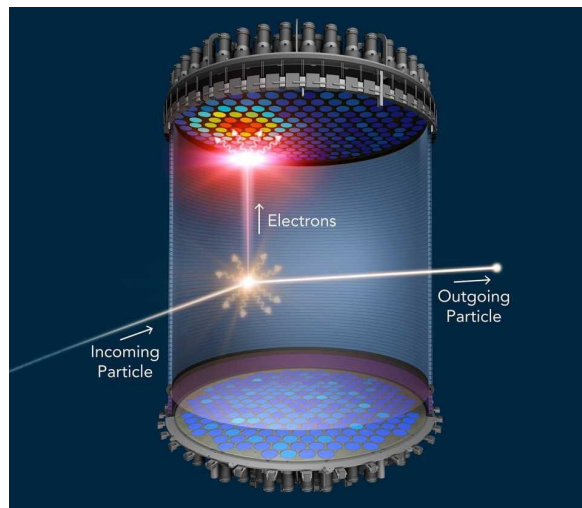


Figure 3.6: An example event observed by the LUX-ZEPLIN experiment, a detector searching for WIMP interactions [71].

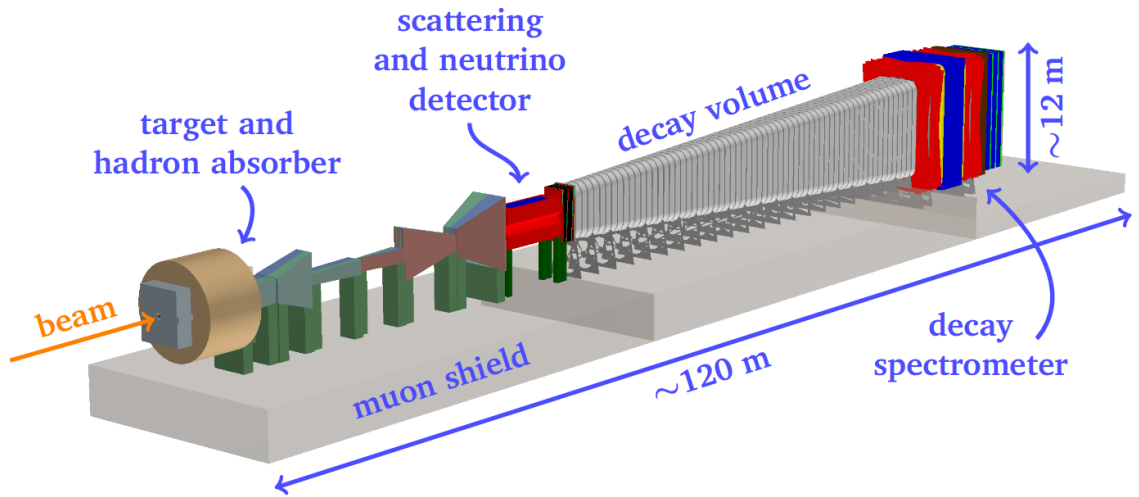
3.1.4 Indirect searches

Indirect searches rely on precision measurements of known phenomena in order to try to observe signs of BSM physics. This involves very accurate measurements of observables well defined by theory and otherwise well verified by experiments, for example the $g-2$ of the muon [42], or very difficult measurements of hard-to-access parameters, such as the PMNS matrix elements [72].

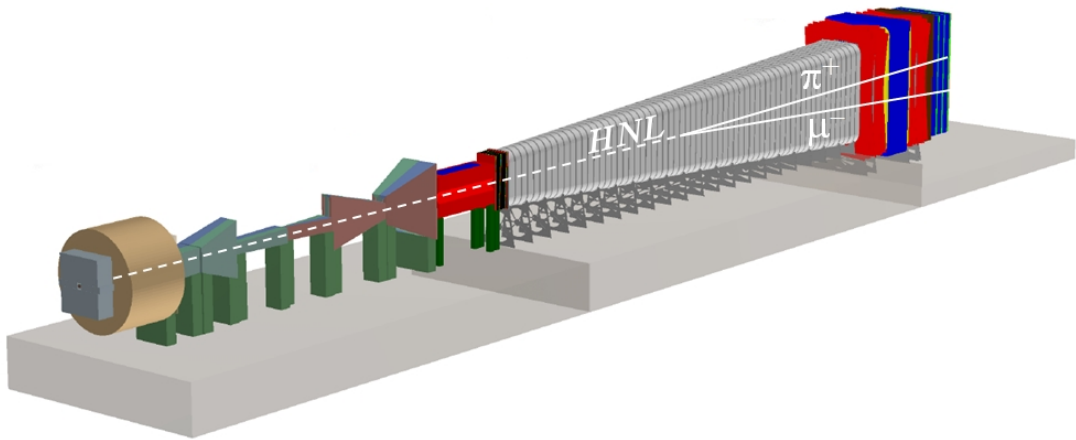
Those searches are also common at accelerators, especially in beauty-quark physics (B-physics) where large amounts of b quarks are produced and their behaviour and decays are observed. The current B-physics experiments are the LHCb experiment at CERN [73] and the Belle-2 experiment at KEK [74].

3.2 The Search for Hidden Particles

Probing new physics, both directly via the production of Hidden Sector Particles described in Chapter 2 and via precision measurements of known, and in certain cases some of the most difficult to observe phenomena in the Standard Model involving in particular ν_τ interactions, is especially important to complement current day searches described earlier. The ideal ground for such searches is realized in the *Search for Hidden Particles* (SHiP) Experiment [75], a new general purpose fixed target experiment proposed at the CERN Super Proton Synchrotron. the current day design of SHiP is shown in Figure 3.7.



(a)



(b)

Figure 3.7: (a) The SHiP experiment design [76], (b) example of Hidden Sector particle (here a Heavy Neutral Lepton) production and decay [76].

3.2.1 SPS and the Beam Dump Facility

The *Super Proton Synchrotron* or *SPS* is currently the world's second largest particle accelerator surpassed in that capacity by only the LHC. Its building was finished in 1976, it is a synchrotron-type and therefore circular accelerator located at CERN in a 6.9 km tunnel crossing the French-Swiss border. It accelerates protons and ions, including lead, to high energies of up to 450 GeV using electromagnets to bend the beams around the ring. It feeds the LHC with particles that will then be accelerated further and provides 400 GeV protons to a variety of fixed target experiments [77, 78]. The SPS has its protons extracted by *spills*. Each spill is a collection of protons extracted over 4.8 s from the main beam [79].

In order to accommodate further developments in high-intensity beam-dump physics, while maintaining existing and meeting the needs of future facilities, the building of a large *Beam Dump Facility* (BDF) is foreseen in the North Area. It will deliver 4×10^{19} protons per year [78] and would house the SHiP experiment.

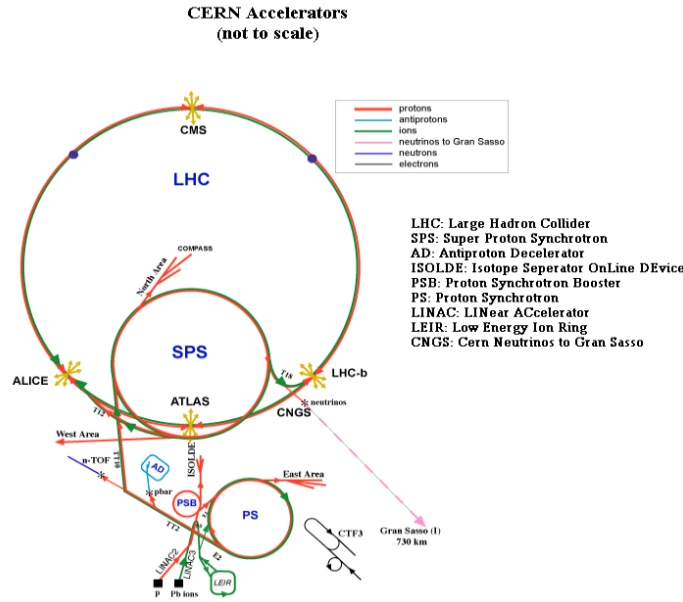


Figure 3.8: Schematic illustration of the CERN accelerator complex [80].

3.2.2 SHiP concept and detectors

SHiP is an experiment based around overcoming the Intensity Frontier shown in Figure 2.2 and seeing signs of the Hidden Sector through heavy hadron decays, especially D mesons. These hadrons may decay into Hidden Sector particles which themselves may produce an observable signal. Due to the theorized scarcity of Hidden Sector events, the experiment must maximize hadron production, reduce background to near-zero levels and therefore filter out as many background sources right after production.

This gives rise to the setup shown in Figure 3.7 which is designed to maximize the number of produced secondary particles. This is done by utilizing large numbers of 400 GeV protons which,

through their hadronic nature can interact in many ways and create numerous hadronic secondary particles. Additionally, there already exists a facility accelerating large amounts of protons to high energies in the aforementioned SPS which has vacant time and is scheduled to be maintained for the decade to come at least in its capacity to feed the LHC [81]. SHiP plans to have 2×10^{20} 400 GeV Protons on Target (PoT) after 5 years of operation. This is expected to produce $O(10^{18})$ D mesons, $O(10^{14})$ B mesons and $O(10^{16})$ τ - leptons. SHiP has undergone extensive studies to ensure its maximal effectiveness. Its new physics detection process is shown in Appendix A.1 while its signal particles and sensitivities are shown in Appendix A.

As shown in Figure 3.7, there are essentially five parts to the SHiP detector system: the target and hadron absorber, the muon shield, the scattering and neutrino detector, the decay volume and the decay spectrometer. These will be overviewed in order.

Target and hadron absorber

The proton target is the first element and is where the charm production takes place. It is thus designed so as to maximize heavy meson production and minimize that of neutrinos and muons. This implies that the target must have the shortest possible nuclear interaction length: that is hadrons should interact as soon as possible after entering the material. A challenging aspect stems from the very high beam power (~ 350 kW) required by the experiment. This requires widening the beam spot so as to rely on energy dilution: having the beam energy being deposited on a larger surface. This performance is achieved through a 58 cm thick titanium-zirconium doped molybdenum (TZM) alloy block followed by a 58 cm thick pure tungsten block. In order to preserve the target from the very high energy intensity, each block is interleaved with sixteen 5 mm slits for water cooling as shown in Figure 3.9.

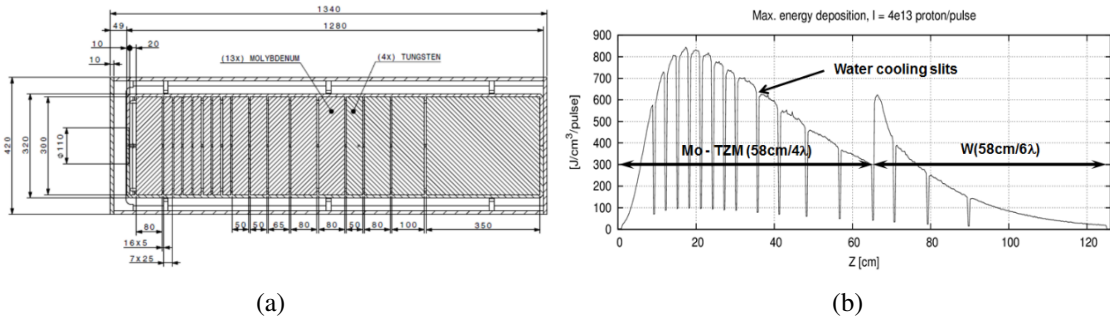


Figure 3.9: (a) Target configuration schematic [82]. (b) Peak energy deposition during a spill and water cooling slit effects [82].

Muon shield

The muon shield is an essential part of the experiment as it is the dominant source of background filtering. Muons are an important signal, produced in Hidden Particle decays as shown in Figure 2.5. This means no initial muons can be allowed to reach the latter detector units. The currently considered design relies on a six-section joined apparatus built from square frames shown in Figure 3.10.

Each visible “bump” in the apparatus is in fact a square steel frame covered by a copper coil which is used for magnetic field induction. The total field reached is 1.7 T and is designed such as to remove

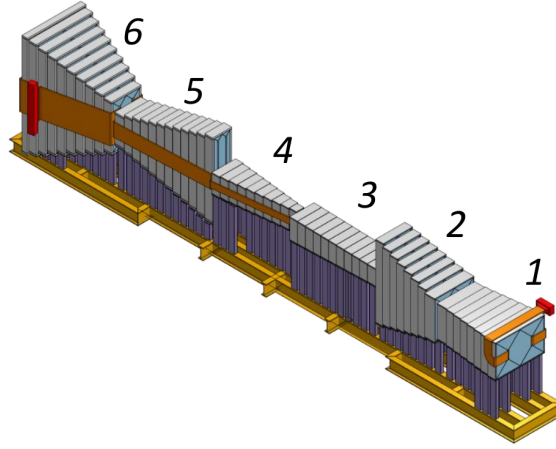


Figure 3.10: SHiP muon shield design. Each number represents a section of the shield, designed to maximally filter out initial muons [83].

even the highest energy muons from acceptance. The segmentation of the shield is done so as to iteratively remove muons of all momenta from the experiment.

Scattering and neutrino detector

Investigating ν_τ physics is also one of the aims of SHiP as they would be produced in large quantities in the SHiP setup and are the least observed particle in the Standard Model, having only been observed directly by the DONUT [84] and OPERA [85] experiments. Better understanding of these particles would provide tighter constraints on SM parameters and may also provide indirect evidence of new physics through measurements of the PMNS matrix mentioned in Section 2.2.1 for instance.

Since neutrinos scarcely interact with matter, their detection requires a very dense volume. Thus SHiP makes use of a lead target interleaved with an emulsion plate spectrometer placed in a magnetic field followed by a Scintillating Fiber (SciFi) detector and a Resistive Plate Chamber (RPC) detector. The latter two serve both as veto and muon identification tools as illustrated by Figure 3.11. Emulsion detectors rely on nuclear emulsion to track charged particles. They are the highest point resolution detectors currently available, providing a spatial resolution of under $1\ \mu\text{m}$ [86] which would be used in observing ν_τ interaction and especially τ decays: $\nu_\tau \rightarrow \tau^- + W^+ \rightarrow \nu_\tau + \tau^-_{\text{products}} + W^+_{\text{products}}$. Since τ -leptons have a very short decay length ($c\tau \sim 90\ \mu\text{m}$), emulsions are the ideal choice in that regard. The τ -leptons would be produced in the brick walls and observed along with its decay in the emulsion.

Decay volume

The SHiP decay volume is essential as it is there that Hidden Sector particles would decay. All particles incoming from upstream are accounted for and as such all decays that happen within this detector can be observed, creating good conditions for BSM discoveries. The decay volume is filled with vacuum. It is a 50 m long steel frame veined with outer cavities filled with liquid scintillator. The scintillator is readout with *Wavelength shifting Optical Modules* (WOMs) [88] and Silicon PhotoMultipliers (SiPM) forming the Surround Background Tagger (SBT), its definitive geometry and the exact scintillator

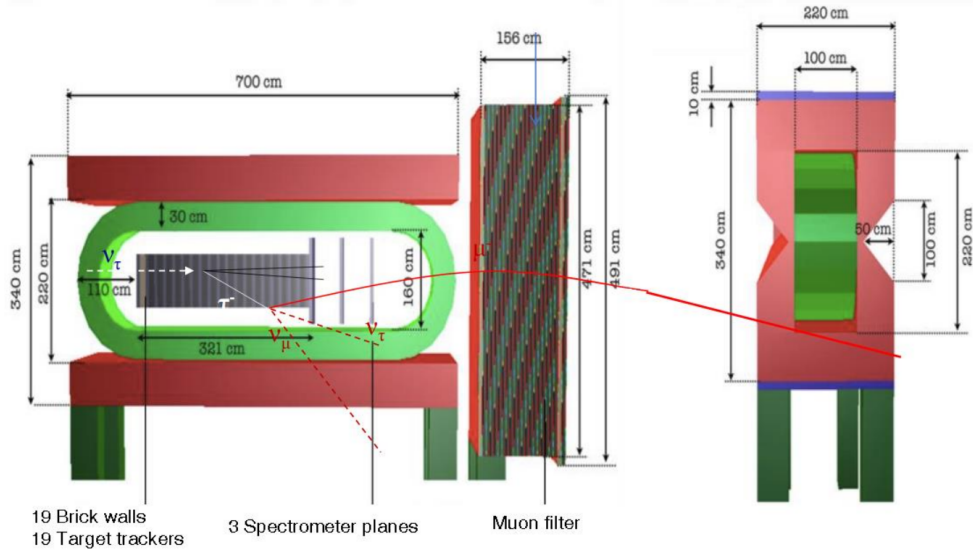


Figure 3.11: Scattering and neutrino detector design. (Left) side view in the [yz] plane, the beam travels left to right. (Right) front view in the [xy] plane, the beam travels inward [87].

remain to be determined. If a particle enters or exits the volume otherwise with an open angle compared to the beam, such as cosmic rays or natural radioactivity, it will be spotted, thus insuring that the no-background condition remains fulfilled. The system is shown in Figure 3.12.

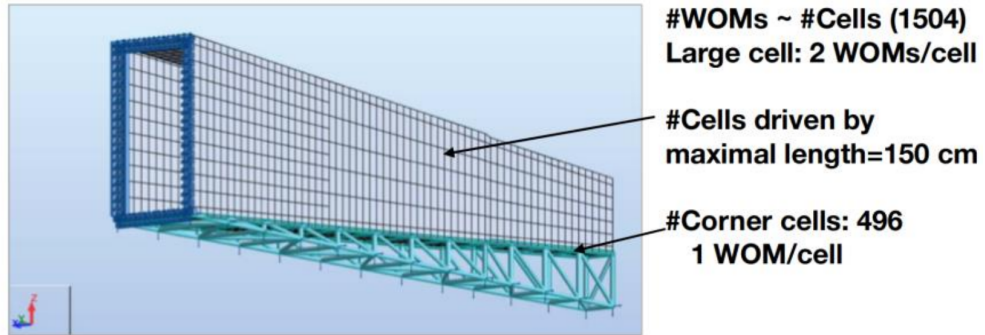


Figure 3.12: Illustration of the SHiP decay volume design [89].

Decay spectrometer

The final element of the SHiP experiment is a detector system aiming to reconstruct particle position, time, energy and identity. It is composed of a straw tracker, a timing detector, a two-detector electromagnetic calorimeter and a muon detector.

SHiP Straw Tracker The SHiP Straw Tracker (SST) is the first detector in the decay spectrometer. It is made of cylinders (straws) filled with gas, traversed by wires and plunged into a dipole's magnetic

field. The straws are 10 m long and are arranged in four stations. The achieved spatial resolution will be $120\ \mu\text{m}$.

Timing detector The next component is a timing detector made from scintillating bars readout by large SiPMs that offer a timing resolution $\leq 80\ \text{ps}$.

SplitCal An electromagnetic calorimeter, the SplitCal, will be based around interleaving absorber planes with 40-50 scintillating planes corresponding to 20-25 interaction lengths readout via wavelength shifting fibres [90] and Silicon Photomultipliers (SiPMs) [91]. Two to three high precision layers will allow for measurements of the shower development and direction. The entire calorimeter will be one to two meters long and have a $6 \times 12\ \text{m}$ cross section as shown in Figure 3.13.

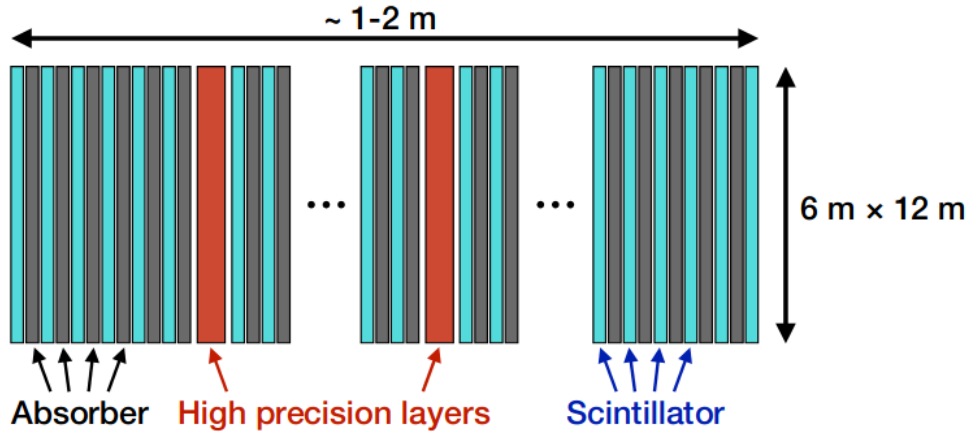


Figure 3.13: SHiP SplitCal design as seen in the $[yz]$ plane [92].

Muon detector The muon detector, built around scintillating tiles read out by SiPMs will complete the spectrometer. It will allow the experiment to detect muons traversing the calorimeter and enabling the observation of $N \rightarrow \pi^- \mu^+$, $N \rightarrow \mu^- \mu^+ \nu_\mu$, $V \rightarrow \mu^- \mu^+$, $S \rightarrow \mu^- \mu^+$ from neutrino, vector and scalar portals respectively by separating the final state particles from those created by the neutrino background. The scintillator stations will be interleaved with iron slabs in the same way as OPERA to filter out excess particle [93]. The system is shown in Figure 3.14.

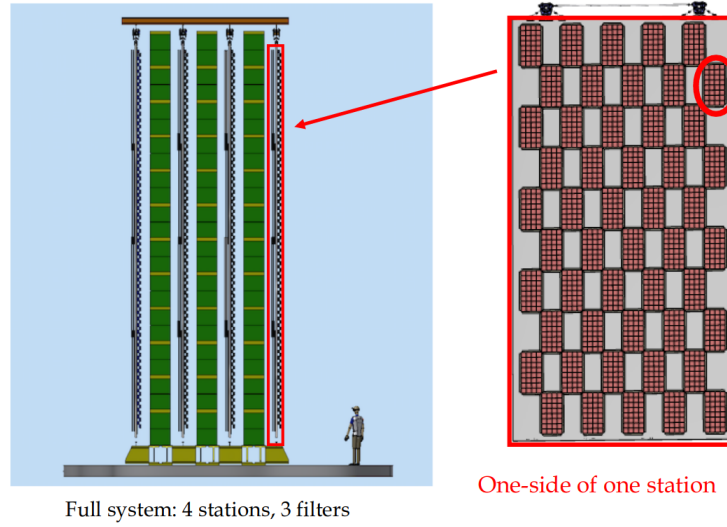


Figure 3.14: The SHiP Hidden sector muon system. It is composed of 4 scintillator stations and 3 filter stations. The stations are composed of scintillator modules each made of 32 scintillating tiles [94].

3.3 Charm production

Charmed hadrons are an important possible source of new physics. Events are characterized by having one or more charm quarks. An overview of hadronic structure will first be given. Then, proton-on-fixed-target induced charm production will be described followed by a practical explanation of the physics of charm decays.

3.3.1 Hadron structure

As explained in Chapter 2.1, hadrons are characterized by their partons, the SM particles sensitive to the strong interaction. There are mainly two classes of hadrons: baryons, composed of three quarks and mesons, composed of a quark and an antiquark. This however is a simplified view of a hadron. In reality a hadron is composed of many quarks and antiquarks in what is known as the *quark sea*. The quark sea is dynamic and constantly changes in size and composition while remaining constrained inside the hadron through asymptotic freedom. The quarks that were referred to earlier are the *valence quarks* which are defined as follows: for N_q the total number of quarks for a certain quark species (u , d , s , c , b or t) and $N_{\bar{q}}$ the total number of antiquarks, $N_q^{\text{valence}} = N_q - N_{\bar{q}}$ with N_q^{valence} the number of valence quarks. The t is not produced in any measurable capacity at relevant energies inside of a hadron because of its large mass (and the fact that it decays before hadronizing) [25]. The dynamics of the sea of quarks are explained by quark-antiquark annihilation and creation mediated by QCD. In other words, quark and antiquarks are constantly annihilating, creating and radiating gluons that will both interact with other gluons and create new (and perhaps different) quarks and antiquarks. An illustration of this is given in Figure 3.15.

In a fixed target experiment using protons, events are parton-on-parton interactions, either quark on quark, quark on gluon or gluon on gluon. The function describing the probability of finding a parton at a certain fraction of the total longitudinal hadron momentum typically named x at a certain energy

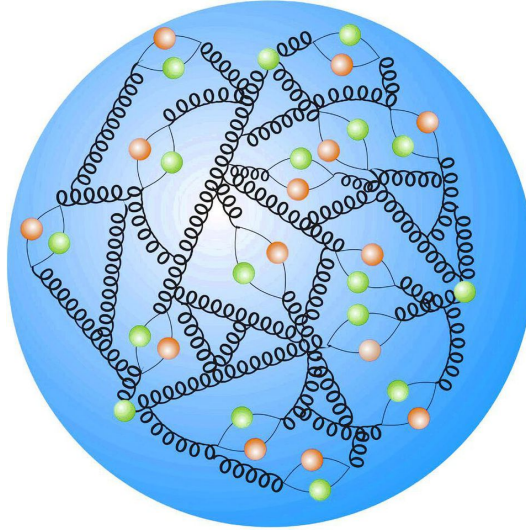


Figure 3.15: An illustration of a hadron: in green are the quarks of which 3 are valence quarks, in red are the antiquarks. The spring-like connectors are gluons [95].

scale Q^2 inside of the hadron is called the *Parton Distribution Function (PDF)*. At low Q^2 the three valence quarks are very dominant inside the nucleon. The higher the Q^2 , the more quark-antiquark pairs become important. At very high Q^2 , gluons dominate the distribution. PDFs were precisely measured up to high Q^2 notably at HERA [96].

3.3.2 Producing charm at fixed target experiments

In proton-beam dump experiments such as SHiP, the base principle of particle production is proton-nucleon interactions. The partons of the proton will interact with those of the nucleon. Since there are no charm quarks in the initial state, they must be produced either through interactions with quarks or gluon-gluon fusion as shown in Figure 3.16.

Single charm quark production, as shown for instance in Figure 3.17, is heavily suppressed as it relies on $O(\lambda)$ weak currents, with $\lambda \sim 0.22$ the Wolfenstein parameter scaling the amplitude of the interaction [97], in an environment where QCD is dominant. Thus charm quarks are in their overwhelming majority produced in pairs, not necessarily as bound states such as J/ψ , and may involve isolated charm quarks to immediately hadronize and form relatively long lived open charm particles such as D mesons [98].

3.3.3 Charmed particle decays

Charmed particles are unstable, they decay rapidly into lighter, longer-lived particles with a $c\tau \sim O(100\mu\text{m})$. The reconstruction of these decays is crucial for SHiP and similar experiments. Since charmed hadrons have small decay lengths, reconstructing them is quite challenging as it requires detectors with a spatial resolution of $O(10\mu\text{m})$ or better, meaning that only the highest point-resolution pixel detectors or emulsion detectors are reasonable choices for this kind of decay search.

An added difficulty are the many decay modes of charmed particles: because of their high mass, charmed particles have a large variety of decay modes. As a simple example, if looking only at

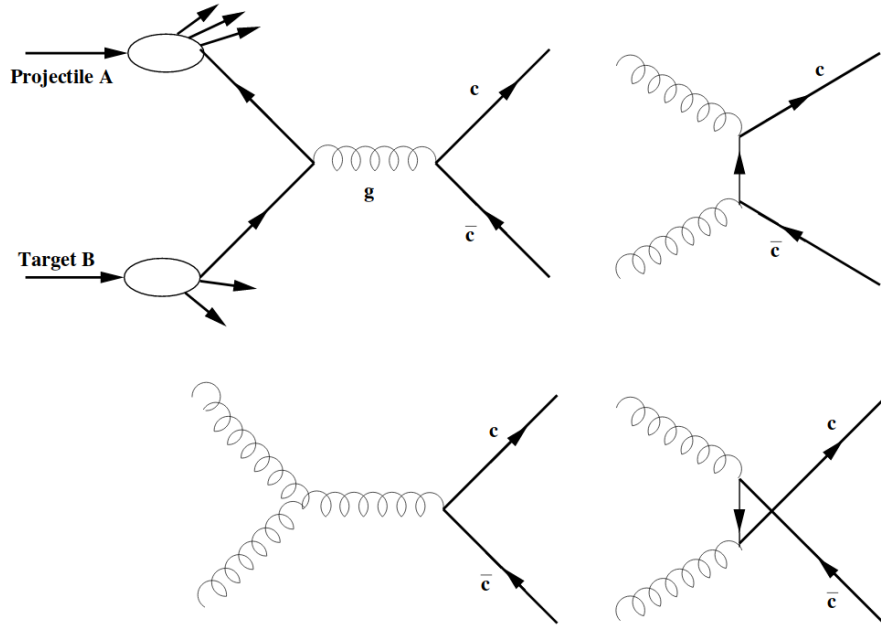


Figure 3.16: Typical leading-order charm production in a fixed target setup via quark-antiquark annihilation and via gluon fusion [98].

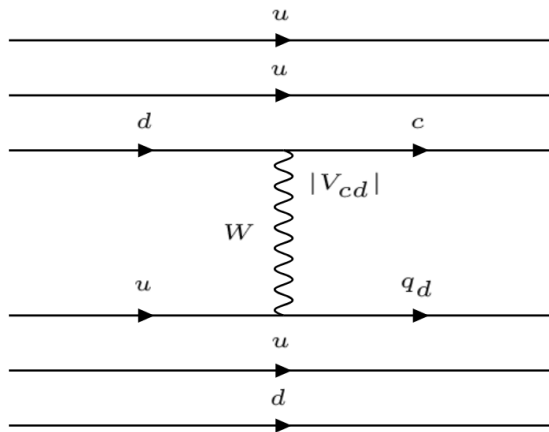


Figure 3.17: Example of single charm quark production. It requires a weak interaction as well a $\propto |V_{cd}|$ current and is thus suppressed.

decay modes including a lepton in the final state, *semileptonic*, decay channels of the D^0 , which account only for $\sim 15\%$ of total D^0 decays, the highest branching fraction among these corresponding to $D^0 \rightarrow K^- + e^+ + \nu_e$ is of only $\sim 3.54\%$. This high multiplicity of channels means that properly reconstructing every decay mode, each with its own backgrounds, is quite challenging, especially as final states may contain unseen particles such as neutrinos.

There are many different charmed particles produced in a proton beam dump setup, some of the most common produced ones are overviewed in Table 3.1. More information on charm physics can be found in [99].

Particle	Content	Mass [MeV/c ²]	$c\tau$ [μm]	Most common inclusive decay	BF [%]
$D^\pm$	$c\bar{d}/\bar{c}d$	1869.00 ± 0.09	311.8	$K^0/\bar{K}^0 + \text{anything}$	61 ± 5
$D^0/\bar{D}^0$	$c\bar{u}/\bar{c}u$	1864.83 ± 0.05	122.9	$K^-/K^+ + \text{anything}$	54.7 ± 2.8
$D_s^\pm$	$c\bar{s}/\bar{c}s$	1968.27 ± 0.10	149.9	$\pi^0 + \text{anything}$	123 ± 7
Λ_c^+	udc	2286.46 ± 0.14	59.9	p or n + anything	50 ± 16
Ξ_c^+	usc	$2467.98^{+0.28}_{-0.40}$	132	$\Xi^- + 2\pi^+$	$2.3^{+0.7}_{-0.8}$ ^a

Table 3.1: Most commonly produced charmed hadrons, excited states are not shown. BF stands for Branching Fraction.

^a Relative to $\Xi^- + 2\pi^+$

Charm cross section measurement and pixel detectors

The SHiP experiment, as a high-intensity experiment looking to produce large amounts of charmed particles is sensitive to the exact charm production cross section for a centre of mass energy around 28 GeV, relevant for 400 GeV protons on a fixed target. In order to properly determine this sensitivity a measurement of the charm yield, and therefore the charm cross section must be performed. The SHiP collaboration has performed a test measurement in July 2018 at CERN and plans to carry out the actual measurement in 2022. The 2018 test will be detailed, followed by an overview of the pixel detector that was used during the measurement.

4.1 The July 2018 charm test beam

4.1.1 Motivation for a charm cross section measurement

Charm production in a fixed-target experiment can occur in two ways: either through direct nuclear interaction of primary beam protons with the target, mediated by the diagrams shown in Figure 3.16 or from subsequent interactions of the particles produced in the hadronic cascade. Simulations predict that said secondary interactions increase the charm yield by a factor exceeding two [100]. However, the actual cross section in a thick target and the effects of charm cascades have not yet been measured.

On the theoretical side, perturbative QCD can be used to compute hadroproduction of heavy quarks (c , b , t) [101] with a mass greatly exceeding the QCD scale Λ_{QCD} . The total cross section for heavy quark production can be written as the convolution of the PDFs of the colliding hadrons, the partonic hard scattering cross section and the fragmentation function which models the non-perturbative transition of a heavy quark to a specific hadron with heavy flavour.

A number of calculations for hadron production are available at next-to-leading order (NLO) [102]. Charmed hadrons require a fragmentation function and computing their production cross section theoretically is difficult due to the large uncertainties that arise because of large corrections at next-to-next-to-leading order (NNLO) [103], implying the need for experimental checks. Measurements compared to theoretical predictions at NLO can be seen in Figure 4.1.

In light of the issues with theoretical predictions, numerical simulation methods relying on random number generation called Monte Carlo simulations are interfaced to the results of the LO and NLO

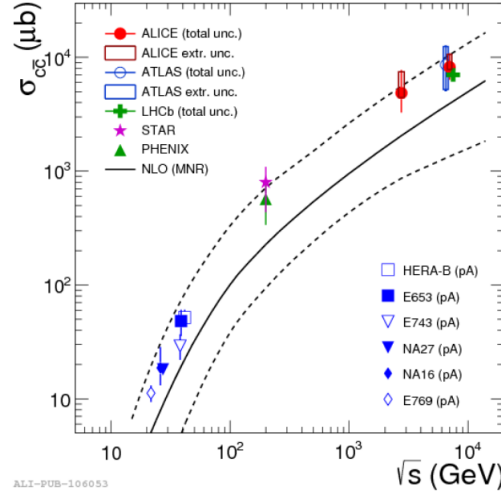


Figure 4.1: Inclusive charm cross-section measurements (coloured points) and NLO perturbative QCD prediction (solid line) [102]. QCD prediction uncertainties are shown in dashed lines [104, 105].

truncated theoretical calculations. These methods, especially Monte Carlo Parton Shower (MCPS) programs such as Pythia [106] have attained a high level of maturity and accuracy and thus are a common way to simulate such events. Those simulations have many adjustable parameters so as to allow tuning of the simulation to data.

The SHiP collaboration has performed a study based on simulation in order to predict the charm cross section [105] and has found that charm cascades lead to a charm yield 2.3 times larger than the primary protons on target contribution for 400 GeV protons. This study however relies on a set of charm quark fragmentation parameters, the corresponding Pythia parameters of which have been tuned according to available parameters that were measured in electron-positron annihilations at LEP [107] which exceeds 90 GeV. At centre of mass energies of around 28 GeV relevant for SHiP, those parameters imply a very different hadronization model and thus parameters compared to those corresponding to LEP data. The set of parameters thus needs to be adjusted. They can be determined from a detailed measurement of charm fragmentation at low energies in order to establish the reliability of the hadronization models used.

4.1.2 Experiment layout

The SHiP charm test beam was performed at CERN in July 2018 using 400 GeV protons. It utilized a detector system composed of emulsion plates interleaved with passive material, a pixel detector, a 1.5 T magnet used to bend particle trajectories and momentum reconstruction, a SciFi detector, a drift tube tracker and an RPC-based muon tagger. The system in its entirety can be seen in Figure 4.2.

The experiment was divided in setups and runs. Each setup had varying quantities of passive material and differing numbers or manufacturers of emulsion plates and spills. They are identified by a number ranging from 0 to 6 and had a number of runs which each have their own ID. Additional runs were performed without emulsion and/or with magnetic field switched off for alignment. The information on relevant runs is compiled in Table 4.1. For the purpose of the experiment, an event is defined as one Proton on Target (PoT).

Setup Name	Setup description	Run name	Run ID	Spill number	PoT number
Charm 1	No PM, 29 e.p. interleaved with 28 1 mm plates of Pb	Run 1	2886	10	136 270
		Run 2	2787	10	110 352
		Run 3	2788	10	107 442
		Run 4	2789	10	76 307
		Run 5	2790	10	73 575
	No PM, 29 e.p. interleaved with 28 0.9 mm W	Run 6	2793	5	38 892
Charm 2	28 mm Pb PM, 29 e.p. interleaved with 28 1 mm Pb	Run 1	2781	10	132 415
		Run 2	2794	5	35 763
		Run 3	2795	5	38 853
		Run 4	2796	5	43 131
		Run 5	2782	10	143 988
		Run 6	2783	10	123 288
Charm 3	56 mm Pb PM, 57 e.p. interleaved with 56 1 mm Pb	Run 1	2797	5	29 586
		Run 2	2798	5	38 839
		Run 3	2799	5	34 027
Charm 4	112 mm Pb PM, 57 e.p. interleaved with 56 1 mm Pb	Run 1	2800	5	24 578
		Run 2	2805	5	26 661
		Run 3	2806	5	26 160
Charm 5	168 mm Pb PM, 57 e.p. interleaved with 56 1 mm Pb	Run 1	2807	5	25 593
		Run 2	2811	5	34 030
		Run 3	2784	10	98 436
Charm 6	224 mm Pb PM, 57 e.p. interleaved with 56 1 mm Pb	Run 1	2812	5	20 443
		Run 2	2814	5	17 123
		Run 3	2785	10	119 894
	No PM nor emulsion		2815	73	~ 292 000

Table 4.1: Description of the charm test beam setup: e.p. stands for the number of emulsion plates, PM stands for the amount of passive material in front of the emulsion. Emulsion plates were interleaved with plates of either lead (Pb) or tungsten (W).

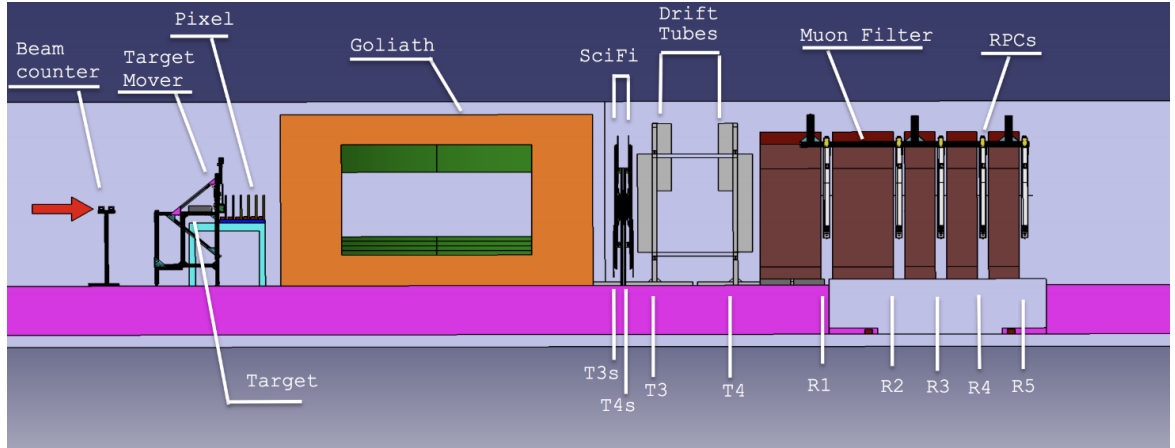


Figure 4.2: Illustration of the July 2018 SHiP charm test beam detector layout. The entire setup is 10 m long and not to scale here [108]. The beam arrives on the beam counter, then hits the emulsion target, it then passes through the pixel tracker, is bended by the magnet before traversing the scintillating fibre detector, the drift tube tracker before ending in the muon detector.

Charm1-Run6 is used as a reference run around which all subdetectors have performed early studies and optimization.

4.1.3 Subdetectors

Emulsion detector

The emulsion detector is the first detector in the beam line. It functions with the Emulsion Cloud Chamber technique which consists of alternating slabs of passive material with nuclear emulsion films. Those nuclear emulsion films are photographic glass plates containing a silver halide compound with a thick emulsion layer and a uniform grain size. The crucial element of emulsion detectors are the $0.2\mu\text{m}$ AgBr crystals which are the sensitive element of the detector. They are immersed in a gelatine binder to allow them to move and are sensitive to ionization. The passage of a charged particle displaces and sensitizes these crystals, creating a trace of so-called *latent image centres*. A chemical process called *development* can then be used to increase the size of the latent image centres, forming silver clusters with a diameter of $0.6\mu\text{m}$ that can then be observed with an optical microscope. These clusters are called grains and their reconstruction allows particle tracking. A Minimum Ionizing Particle typically leaves ~ 36 grains every $100\mu\text{m}$ which defines the emulsion sensitivity [109].

The trace reconstruction is done after the measurement is completed, meaning that there is no way to acquire the emulsion data “online” as there is no electronic readout system. The reconstruction process has a mean hit reconstruction efficiency which ranges from 76% to 95% [110, 111] depending on the quality of the emulsion plate. The emulsion grains can however be reconstructed to very high spatial resolution (below $1\mu\text{m}$) exceeding that of every other current day detector [86]. This allows the emulsion to observe events with the highest accuracy and thus motivates their use.

The emulsion detector used in the charm testbeam has the crucial role of observing the production and decay of charmed particles by reconstructing their decay locations. Charm particles are produced in both primary proton interactions and secondary interactions and decays. Those take place in the

layers of passive material and are then observed by the emulsion plates. The decay topologies and their relative contributions in simulation are shown in Figure 4.3.

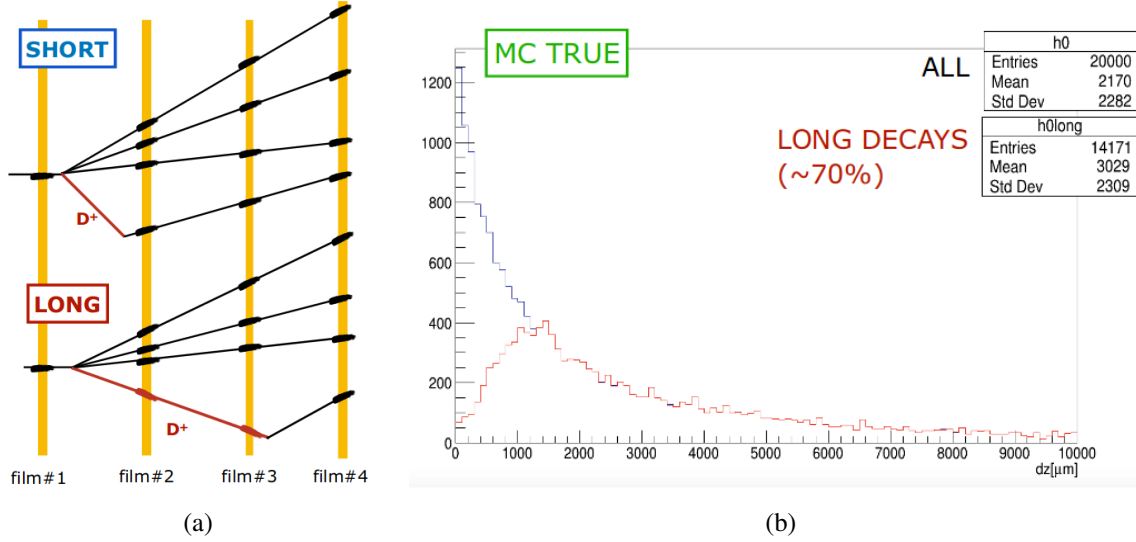


Figure 4.3: (a) Decay topologies, the short decay topology is characterized by the charmed particle decaying without traversing an emulsion film while the long decay one is defined as one where the charm particle traverses emulsion films before decaying. (b) Topology distribution according to simulation for Charm1-Run6. In blue all decays and in red, long decays. The x-axis shows the distance traversed by the particle in the material. [112].

Beyond that, the emulsion detector allows for tracking and vertexing to be performed. A track is a linear fit performed on hits in order to try to reconstruct the particle trajectories while a vertex is the position from which multiple tracks originate. Tracks and vertices examples in emulsion are shown in Figure 4.4.

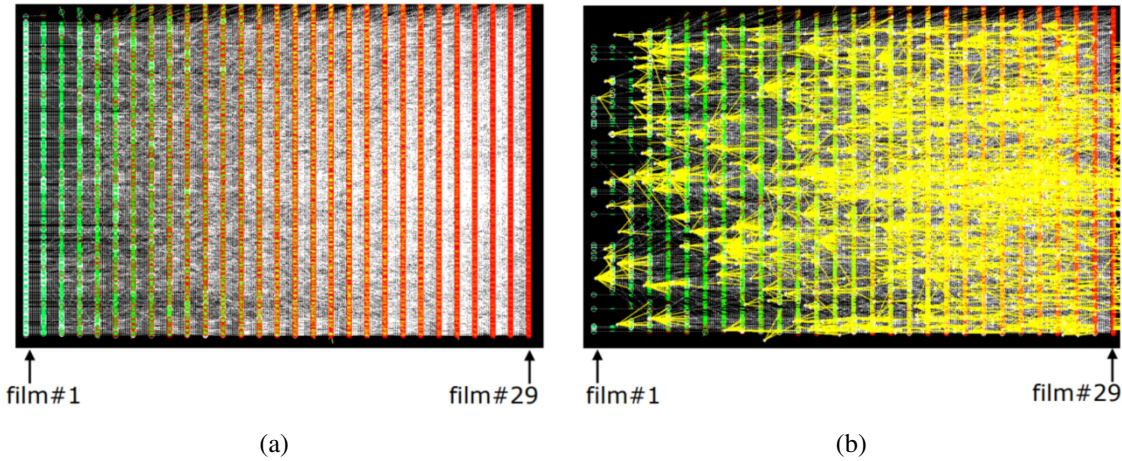


Figure 4.4: (a) Emulsion tracks for Charm1-Run6. (b) Emulsion vertices for Charm1-Run6. [113].

The emulsion's recording capacity is limited because all depositions are permanent. This implies that the emulsion quickly gets saturated which leads to a drop in reconstruction efficiency. In order to

counteract this, the emulsion target was moved at a speed of 26 mm s^{-1} in a pattern shown in Figure 4.5.

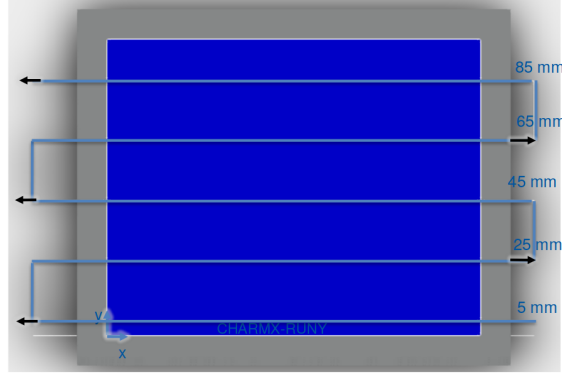


Figure 4.5: Emulsion movement pattern relative to the beam axis for a 5 spill run. Indicated right are the y-axis coordinates of the beam spot in the brick's coordinate system [114].

SciFi Detector

Scintillating Fibre detectors rely on cylindrical fibres of plastic scintillator arranged in parallel. This material emits photons of a given wavelength when traversed by a charged particle. The detector functions by arranging the fibres in parallel and reading out the produced photons via photon detectors, generally Photo-Multiplier Tubes (PMTs) or Silicon Photomultipliers (SiPMs) [115]. The fact that the signal particle is a photon and thus travels at the speed of light implies excellent time resolution and the low achievable thickness of the fibres allows for good position measurements [116].

The charm test beam used $250 \mu\text{m}$ diameter Kuraray plastic double cladding scintillating fibres (SCSF-78MJ [117]) arranged on $3 \times 12 \text{ cm}$ wide mats made of six staggered fibre layers with a horizontal pitch of $270 \mu\text{m}$ and a length of 40 cm , this is shown in Figure 4.6(b). The fibres are covered in a thin epoxy and titanium dioxide so as to reduce channel cross-talk. Three mats form a plane. Two planes create a module shown in Figure 4.6(a). Two modules form a station and there are two stations in the experiment.

The main responsibility of the SciFi detector is providing post-magnet time stamps and tracking to the experiment. It is therefore necessary to achieve a good timing resolution which is here about 650 ps .

Drift Tube Tracker

Drift tube technology is widely used in high energy physics experiments as they provide a low-cost, relatively easy to manufacture, high-resolution option for tracking. They are analogous to straw tube trackers. The drift tube detector used in the charm test beam is a prototype from the OPERA experiment [118]. It's built with 38 mm outer diameter aluminium tubes with a wall thickness of 0.85 mm and a length of 1.6 m or 1.1 m , with a $45 \mu\text{m}$ diameter gold-plated wire as anode [119]. The tubes are filled with Argon and CO_2 with a mixing ratio of 80:20, creating a maximum drift time of $1.3 \mu\text{s}$ and providing a spatial resolution of $250 \mu\text{m}$. The detector is used to reconstruct tracks by measuring a set of drift circles created in the tubes and finding the common tangent lines to these

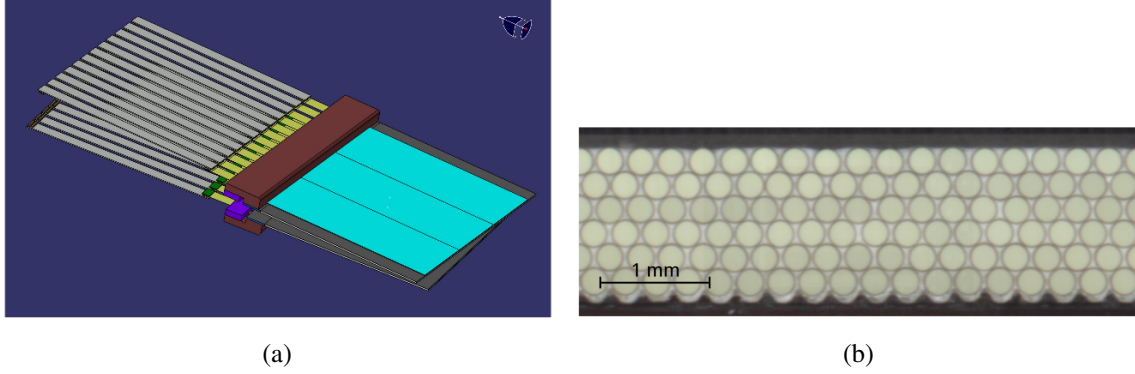


Figure 4.6: (a) Layout of a SciFi module. In light blue are three fibre mats per plane, which are assembled on a dark grey support structure. The fastening pieces in brown and purple fix twelve SiPMs on each fibre plane. The SiPMs are assembled on flexible Polychlorinated biphenyl in yellow [105]. (b) Cross section of a SciFi mat. The vertical pitch is $270\text{ }\mu\text{m}$ [116].

circles. The drift tube detector is however unable to distinguish hits if two charged particles pass the same tube at the same time which leads to a drop in resolution in this case. The layout of the detector with an example of the aforementioned process and the layout of a module are shown in Figures 4.7(a) and 4.7(b) respectively.

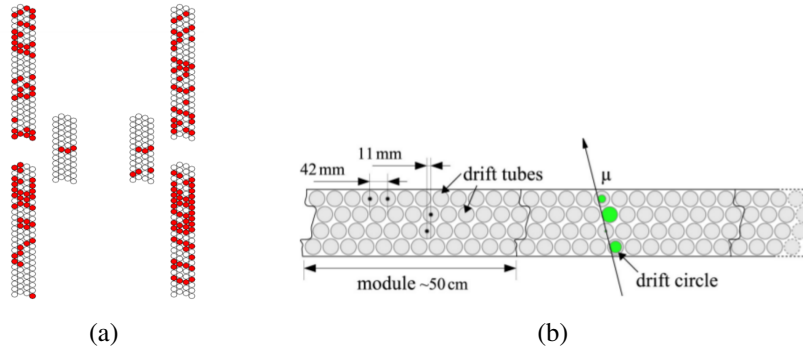


Figure 4.7: (a) Layout of the drift tube tracker in the charm testbeam with an example event as seen from above [120]. The tubes highlighted in red have registered a hit. It can be seen that too many hits are registered to effectively reconstruct a track in some stations, especially the bottom-right one. (b) Drift tube tracker module and working principle sketch [105].

Muon Tagger

The muon tagger is the most downstream detector in the setup. It has, as its name suggests, the role of identifying and tracking muons so as to reconstruct muon momentum thus allowing the tagging of leptonic decays of charmed particles.

The detector is based around five slabs of iron acting as hadron absorbers which are interleaved with five Resistive Plate Chambers (RPCs) as shown in Figure 4.8. RPCs are fast gaseous detectors commonly used to provide a muon trigger [121]. They function by having two plates, one being a

positively charged anode and one being a negatively charged cathode, separated by a gas volume.

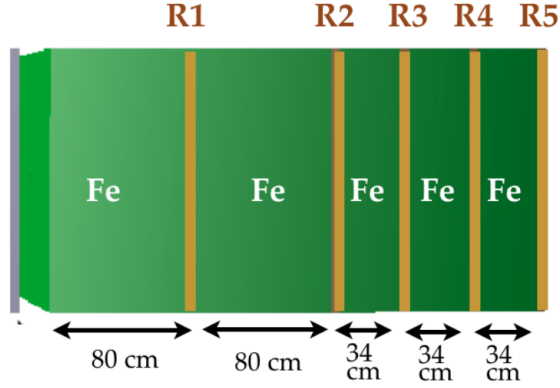


Figure 4.8: Layout of the muon tagger of the charm test beam [105].

The RPCs used in the charm testbeam had five plates measuring $195 \times 125 \text{ cm}^2$. Since there isn't enough material in front of the tagger to stop all primary protons, a sizeable portion of them is expected to reach the muon tagger. They would interact with the iron and produce large amounts of hadronic showers outside of the target. In order to avoid said proton interactions the iron slabs were arranged such as to obtain a 5 cm sided square hole in the beam spot location [122].

4.2 Pixel detector

The pixel detector used in the charm testbeam will be reviewed. Object-building for analyses using the pixel detector will then be described.

4.2.1 Pixel detector principles

PN junctions, doping and charge cloud

Pixel detectors are solid-state semiconductor detectors that are generally made of silicon. Silicon is an intrinsic semiconductor, yet, in order to allow for it to be used in a detector, its properties are enhanced and modulated by the use of *doping*: the introduction of impurity atoms with a different electronic structure to the original material lattice as shown in Figure 4.9.

These impurities can come in two variants: those with more electrons on their valence band than the base material, which allow for negative-doping or n-doping: an extra electron is added to the system. Those with a valence band with fewer electrons than that of the base material enable positive-doping or p-doping: one less electron which can be interpreted as an extra positive "hole". Both dopings add new energy states inside of the material's band gap, either lowering the conduction band (n-doping) or raising the valence band (p-doping). This is shown in Figure 4.10.

Both dopings are used in semiconductor detectors [61] as they rely on a pn-junction: a common interface between a p-doped semiconductor and an n-doped semiconductor which allows the extra charges to recombine and create an electric field induced by the differences in charge on both sides of

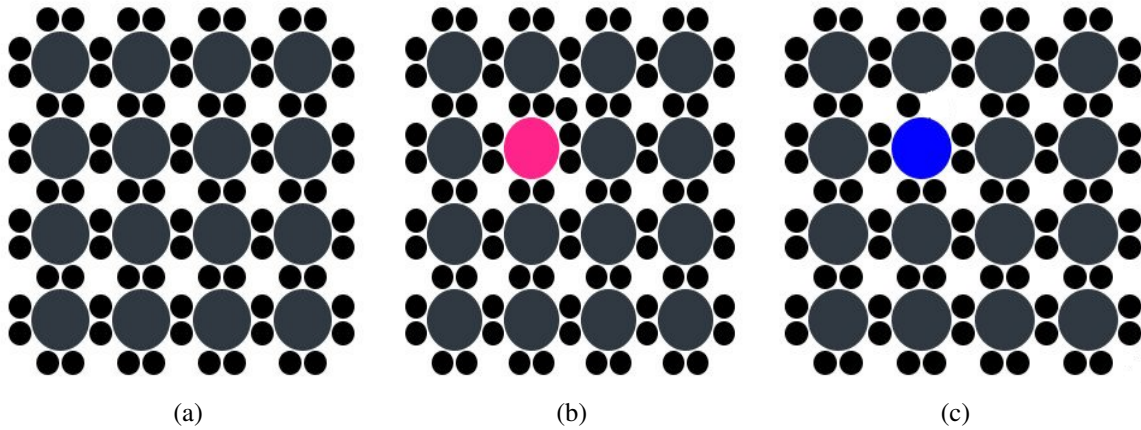


Figure 4.9: (a) Non-doped semiconductor (here silicon) lattice structure sketch. Grey circles correspond to the silicon nucleus while black circles correspond to valence electrons. (b) n-type doped silicon: the pink nucleus is Phosphorus, an atom bringing an extra electron to the lattice. (c) p-doped silicon. the blue nucleus is Boron, an atom which brings one fewer electron to the lattice [123].

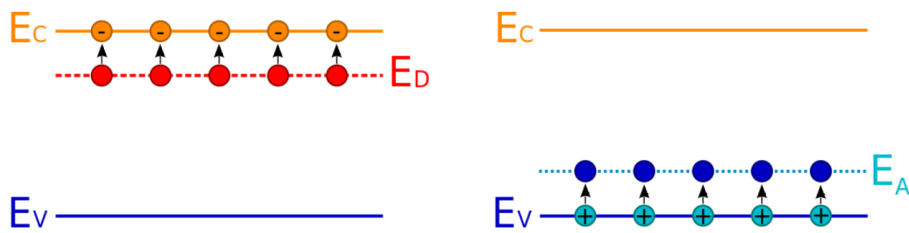


Figure 4.10: (Left) Effects of n-doping on the material's band structure [124]. (Right) Effects of p-doping on the band structure [125].

the pn-junction [126]. The area surrounding the contact between the n and p regions, being deprived of free charge is called the depletion region and forms a potential barrier. This is shown in Figure 4.11.

In order to use pn-junctions as detectors, the sensitive region of the detector, the sensor, must have a depletion region: there must be no free charges left in an area of the junction. It is common for semiconductor detectors to be fully depleted at least at the start of their operation. Radiation damage can progressively reduce the size of the depletion region [128]. The full depletion of the sensor is done by widening the pn-junction in order to have any newly created electrons (in the p-type area) or holes (in the n-type area) from particles passing through the sensor carry the current. A bias is applied in the reverse direction to achieve this as shown in Figure 4.11.

Pixel detector working principle

Pixel detectors are based on fully depleted semiconductors and provide high spatial resolution as well as good time resolution. A semiconductor doped bulk is equipped with opposite-doped implants to form the sensitive sensor, allowing for one charge type (electron or hole) to carry most of the current. The implants are generally located at the back of the sensor where they serve as electrodes which sense the voltage created by the free charges created by the passage of a particle in the material and collect

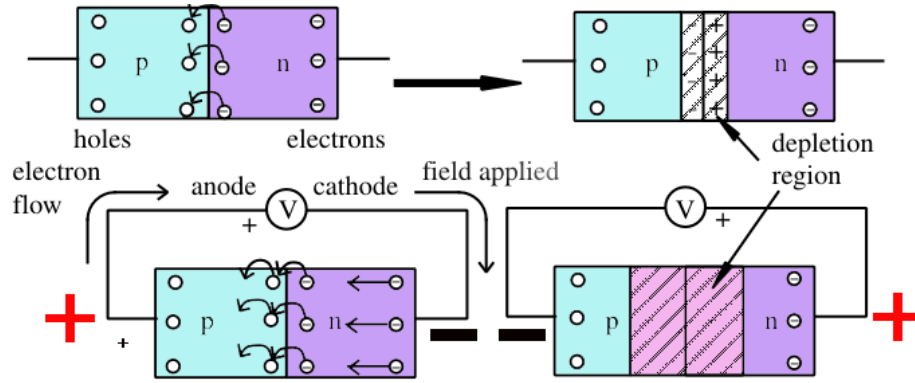


Figure 4.11: (Top left) Migration of electrons and holes towards each other. (Top right) Resulting depletion region and potential barrier. (Bottom left) Effects of a forward external bias: closing of the potential barrier resulting in current flowing in one direction. (Bottom right) Effects of reverse external bias: increase of the potential barrier and depletion region preventing current flowing in the reverse direction [127].

them. These electrodes form a regular grid which in turn determine the pixel detector's 2D spatial resolution. The build of a pixel is shown in Figure 4.12(a). When enough charges are created near an electrode at a given time, the induced signal is electronically processed by the front-end electronics and stored for analysis.

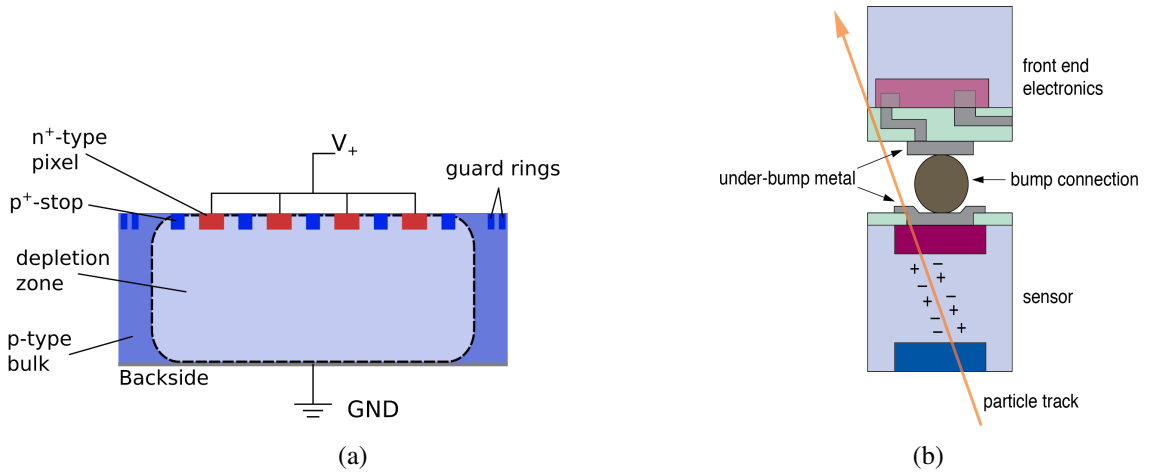


Figure 4.12: (a) Illustration of a pixel sensor. n^+ implants (red) form electrodes for charge collection in a p-type bulk (light blue). p^+ -type implants (blue) isolate pixels from each other. At the edge of the sensor in blue are guard rings which protect the read out chip by allowing a controlled reduction of the sensor bias-voltage [129] [130]. (b) Illustration of the working principle of a pixel [131].

Hybrid pixel detectors are assembled in modules. Those are sensitive areas, *sensors*, described above which are bump-bonded to front-end chips and read-out electronics using a conductive bump. This is shown in Figure 4.12(b).

Charge Cloud When a charged particle passes through a material, it deposits energy by creating electron-hole pairs. The charge is created as a cloud which is Gaussian distributed along:

$$A \cdot \exp\left(-\left(\frac{(x - x_0)^2}{2\sigma_X^2} + \frac{(y - y_0)^2}{2\sigma_Y^2}\right)\right); \quad (4.1)$$

where A is the amplitude given by the total energy deposition, x_0 and y_0 the coordinates of the Gaussian mean, σ_X and σ_Y being the widths. If the bulk of the sensor is p-doped, the n-doped substrate can be neglected which leads to [132]

$$\sigma_X(z) = \sigma_Y(z) = d \sqrt{\frac{k_B T}{e V_{\text{dep}}}} \sqrt{-\ln\left(1 - \frac{2V_{\text{dep}}}{dV + V_{\text{dep}}} z\right)}; \quad (4.2)$$

d being the sensor thickness, k_B is the Boltzmann constant, T is the temperature, e is the elementary charge, V_{dep} is the minimum voltage required to fully deplete the sensor, the depletion voltage. V is the bias voltage applied to the sensor, finally z is the space coordinate along the sensor of the energy deposition, with $z = 0$ being defined at the entry point of the particle into the silicon.

4.2.2 The ATLAS IBL pixel detector

Pixel characteristics and geometry

The pixel detectors used in the charm test beam are essential in that they provide a high-resolution tracking to the experiment and a timestamp to the data recorded by the emulsion detector. The time resolution provided by the emulsion detector, being reliant on its position at the time of interaction is too rough to be utilizable on its own. The ATLAS FE-I4 [133] pixel chips were used to build the ATLAS IBL pixel detector. Those detectors are used to great success in the ATLAS Inner Detector, allowing for precise reconstruction of long lived particles in the ATLAS experiment such as beauty particles [134]. 12 modules, each having a 160×336 pixel grid, were used. For each sensor, pixels are numbered in order for columns and rows from 0 to 159 and 0 to 335 respectively. Each pixel detector has a rowpitch of $50 \mu\text{m}$ but pixels in columns 0 and 159 have a length of $500 \mu\text{m}$ on the x-axis while columns-pixels 79 and 80 have a size of $450 \mu\text{m}$, all other pixels have a column-size of $250 \mu\text{m}$ [135]. Pixel modules are setup perpendicularly to the beam along 6 module pairs. In order to compensate for the non-even pixel sizes, modules 0, 1, 4, 5, 8, 9 are rotated by 90° on the z-axis. The full module layout of the detector is shown in Figure 4.13.

The sensor thickness is $245 \pm 10 \mu\text{m}$ for all modules apart from modules 2 and 11 which have a thickness of $200 \pm 10 \mu\text{m}$. The pixel module's time resolution is 25 ns as provided by the integrated FE-I4B front end chips [137] readout electronics. The FE-I4B is $150 \mu\text{m}$ thick silicon. The pixel is connected to a flex circuit board which is $50 \mu\text{m}$ kapton and $100 \mu\text{m}$ copper and is mechanically held by 6 mm thick aluminium frames located outside of the detector acceptance. The entire detector is contained in a box equipped with a $110 \mu\text{m}$ kapton entrance window. The box and the modules are shown in Figure 4.14.

Data acquisition

The most obvious information collected by the pixel detector is the pixel position which reports an energy deposition. Whenever a sensor sends enough charge to the front-end, it produces a unique ID

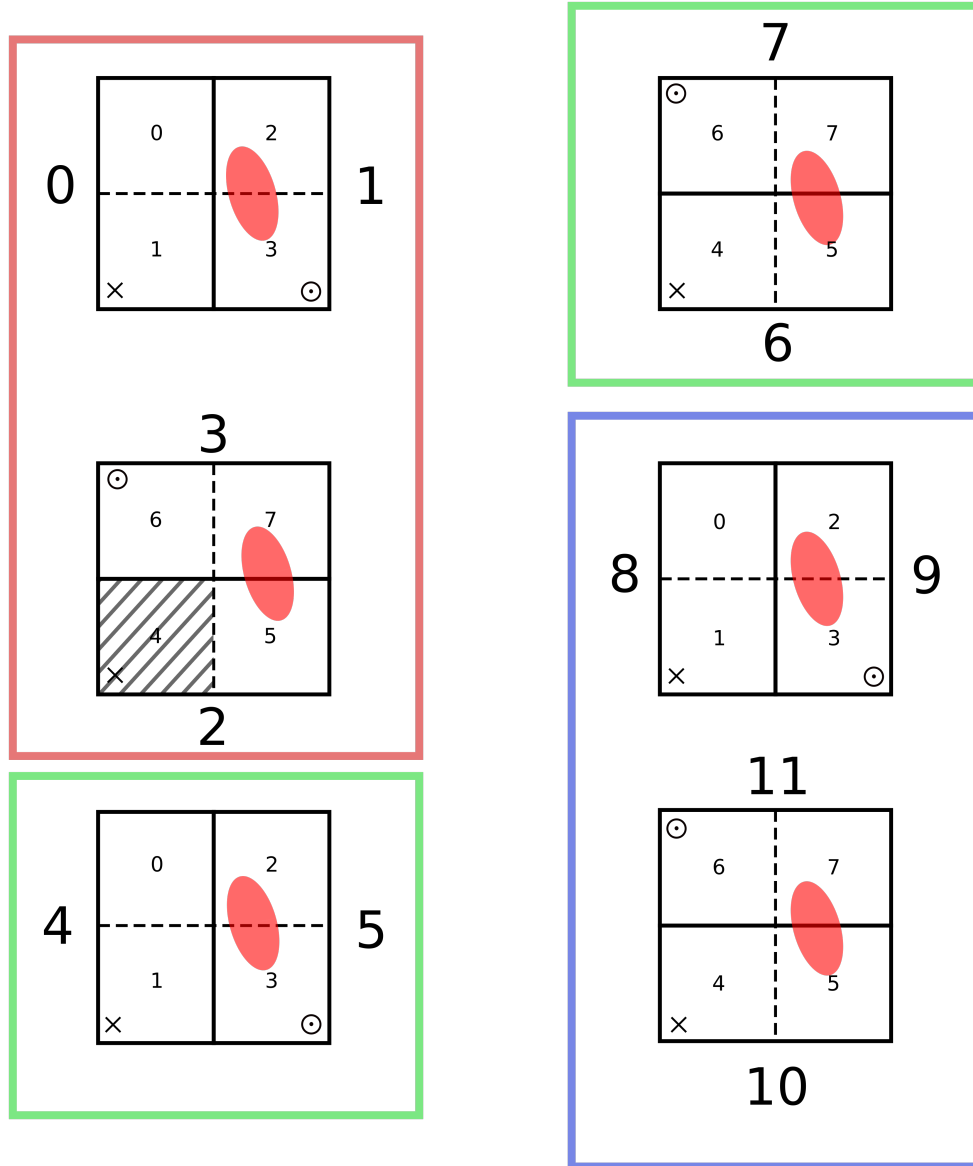


Figure 4.13: Pixel module pairs and orientations. The beam area is indicated in red and the module numbers are given in bold, on the side of each module. Module orientation is given on the side of each module. Numbers bordering the modules indicate the order of the modules in the z direction with 0 being the module closest to the emulsion detector and 11 being the furthest away. One of the chips from module 2 did not function during the test and is therefore shaded [136].

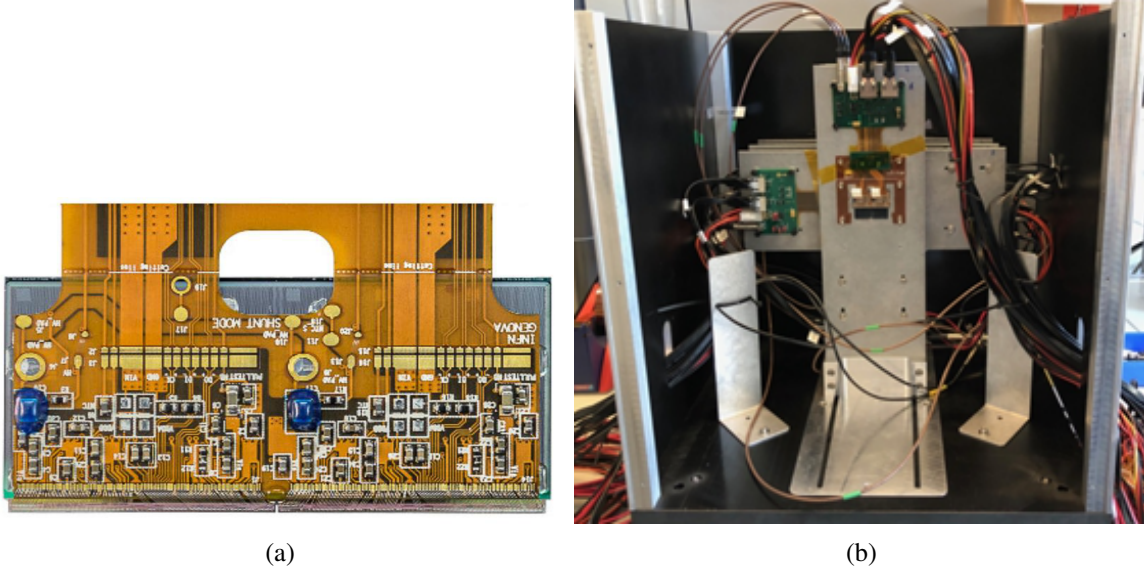


Figure 4.14: (a) Photograph of an IBL module. The flex is the orange material. [138]. (b) Pixel box and modules as seen from the beam [136].

encoding the pixel row, its column and a timestamp. It then becomes possible to trace back exactly which pixel was hit and map its position.

Pixel time resolution is of major importance for the experiment. This information is stored by the front-end at the same time as the location ID. Time is recorded in the form of a timestamp by counting increments of 25 ns. Said timestamp starts at 0 with the time of Start-of-Spill (SoS). The SoS signal is given 75 ms before the first protons hit the target. Each 25 ns will see the timestamp increment by 1 over the duration of the 4.8 s spill. Each pixel location that reports an energy deposition is associated with a timestamp and all locations with identical timestamps are associated to an event.

Not all energy depositions will be recorded by the detector: they must first pass a threshold of 2800 electrons collected by the electrode to be considered. Energy depositions that create fewer electrons are not recorded. This, in association with the time counting of the detector, gives rise to the energy resolution of the pixel detector: the Time over Threshold (ToT). ToT is a measure of the time spent over the 2800 electron threshold for a given energy deposition. The more energy deposited in a hit, the more electrons are created. The analog signal produced by the front-end is directly proportional to the number of collected electrons. This implies that the signal spends some time over the threshold if enough electrons were initially created. This time is measured in units of 25 ns as shown in Figure 4.15 and is then recorded as a ToT over 4 bits. In practice, however, the 14 and 15 ToT values are unused, giving rise to a ToT ranging from 0 (no interaction recorded) to 13 (maximum ToT).

Data processing

The raw hits produced by the pixel detector are a starting point for physics analysis. There are steps taken in order to produce better usable objects. Most notable amongst these objects are *hits* which are used to produce *clusters*, they are used to construct *tracks* which in turn allow the mapping of *vertices*.

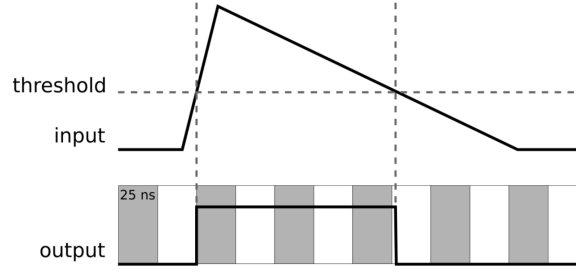


Figure 4.15: Time-over-Threshold sketch. In this case the ToT would be 5 [136].

Hits Hits are the most primitive information that can be used for analysis, they correspond to the position, the ToT and the time of a pixel that passed the threshold on the grid. This involves mapping the position of each pixel and transferring it into a global coordinate system. The local coordinate system used for a pixel module has its origin in the gap between pixels 79 and 80 in row 0. This information is then transferred into the experiment's coordinate system whose origin is located at the start of the pixel box. The hit mapping for module 1 is shown in Figure 4.16

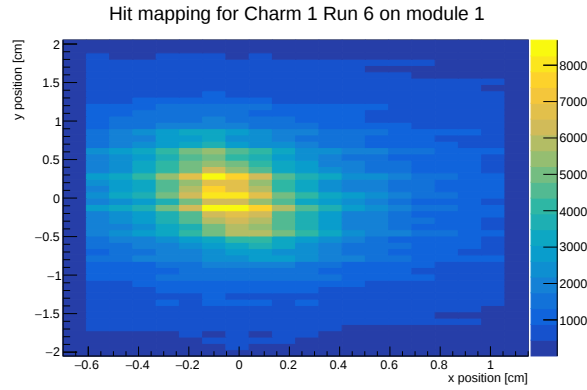


Figure 4.16: Hit map for module 1 in Charm1-Run6. The colours are in arbitrary units.

Clusters A cluster is a group of adjacent hits which have had a larger than 0 ToT with the same timestamp. Said clusters notably have a size, corresponding to the number of pixels which constitute them. Clusters also have a total charge which is the sum of all ToTs of pixels in the cluster. This, along with the cluster size distribution and cluster number distribution, is shown in Figure 4.17.

The collection of adjacent hits created through the charge clouds described in Section 4.2.1 will allow the creation of clusters if enough charge is collected by multiple adjacent electrodes for them to pass their threshold in a single hit. This process is illustrated in Figure 4.18(a) and was performed with pyBAR [132, 139] a charge and cluster reconstruction software designed for the FE-I4. The operating temperature was not recorded but estimated to be around 300 K. The depletion voltage $V_{\text{dep}} = 57.6$ V for the thicker modules and $V_{\text{dep}} = 47$ V for the thinner ones. The applied bias voltage was $V = 80$ V. Using these values we can compute the theoretical maximal Gaussian width which is around $5 \mu\text{m}$ for particles of normal incidence.

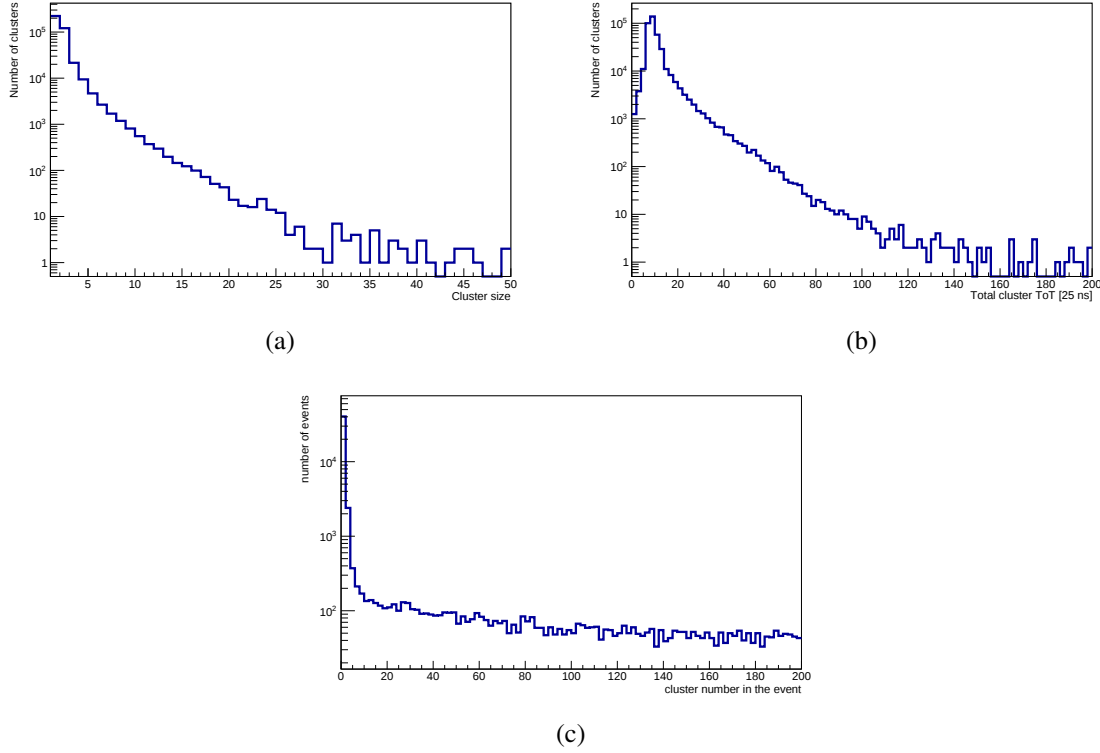


Figure 4.17: (a) Cluster size distribution for Charm1-Run6. (b) Cluster charge distribution for Charm1-Run6. (c) Number of clusters distribution for Charm1-Run6. All histograms are shown for module 10. Distributions for other modules can be found in Annex B.

Another essential information given is the cluster barycentre. It is not uncommon, as shown in Figure 4.17(a), to see clusters larger than a single pixel, meaning that multiple adjacent pixels fire for a single energy deposition.

As such, if an energy deposition takes place close enough to the border between pixels, they may collect more than the 2800 electrons needed to pass the threshold, thus creating a cluster of size larger than 1. It then becomes possible to compute the cluster centre using the positions of all hits as well as their ToTs. This is done by computing the cluster barycentre. This allows for a more precise measurement of the energy deposition's position and implies a better reconstruction of the particles' trajectory.

Tracks Tracks are the result of particle trajectory reconstruction in the detector, which is an essential task of the pixel tracker. This is done by taking all clusters and performing a χ^2 fit, minimizing the residuals for each cluster. The base principle is picking two clusters in an event on two planes to seed the track, then for each hit pair in the seed plane, a volume is built linking both clusters. The closest cluster centres to the track projection are taken as fitting points and a cut is made on the fit quality. All possibilities are tested until all possible tracks falling under the chosen χ^2 are reconstructed [140].

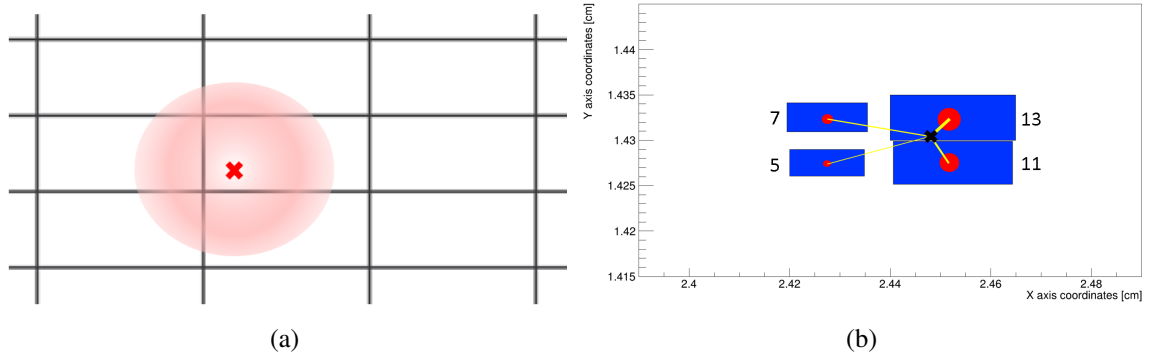


Figure 4.18: (a) Pixel grid and Gaussian distribution for a particle arriving perpendicularly to the pixel plane (schematic, not to scale). The particle position is given by the red cross while the red circle highlights the electron cloud. (b) Illustration of the corresponding cluster reconstruction. Each number indicates the ToT of their adjacent pixel. The total energy deposition in each pixel is represented by the size of their respective blue box. Each ToT is a weight in the weighted position average of the barycentre. The black cross represents the computed barycentre.

Vertexing Apart from primary protons, other particles observed in the detector may produce decay vertices. A vertex is the point in space from which multiple tracks originate. It is build around tracks by deducing whether they are compatible with a common origin point within the setup. For the charm test beam, the vertices are expected to mostly be located in the emulsion detector or the preceeding passive material. An image of a vertex reconstruction is shown in Figure 4.19 [138, 140].

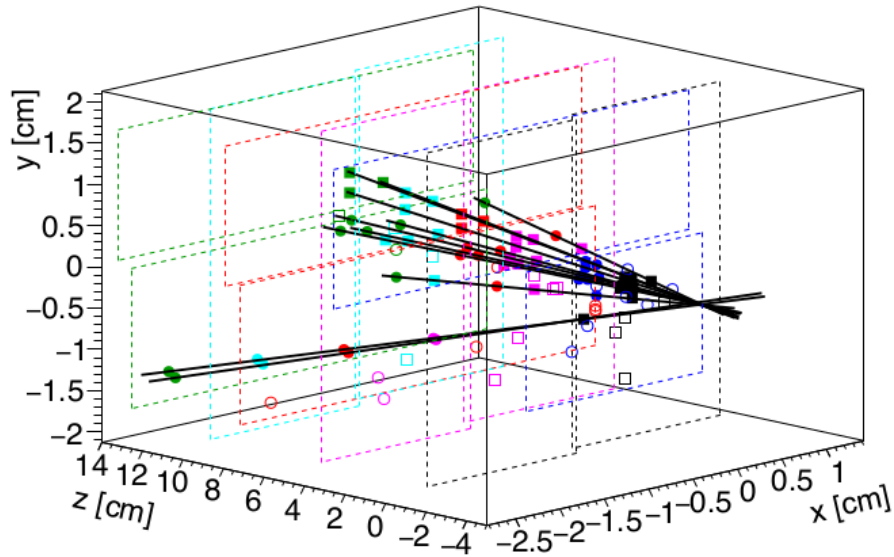


Figure 4.19: Event display with 89 hits represented by the square points, 11 tracks shown by the lines pointing to one vertex [138].

High energy physics simulation and FairShip

5.1 Monte Carlo simulation

Particle physics heavily relies on the production and observation of intricate processes. Producing those processes and observing them however is highly difficult, and expensive to run with any degree of effectiveness.

In order to counteract this, it is highly common for high energy physics experiments to utilize simulations. Simulations reproduce the behaviour of natural phenomena and allow for experiments to set discovery expectations using random number generation.

5.1.1 Random number generation

The production of “random” numbers brings the question of what randomness truly is. Randomness can be seen as unpredictable, something over which one has no control and cannot guess. As such the decay of a radioactive nucleus is random because, while the *probability* of said decay may be known, whether the nucleus will actually decay after a given time is not. In comparison, the weather is not random, it is a complicated behaviour which is difficult to foresee, yet, if all of the information is available, the weather can be predicted as shown by the existence and success of weather models based on inputs from the current weather.

Simulations have 3 constraints: they must be effective, fast and substantially cheaper than the measurement of the actual event. The effectiveness requires a random number generation which is “random enough” to allow for accurate predictions to be made, yet the number generation should be well distributed and not repetitive. A simple example of effective random generation could come from generating binary integers: the generation should produce amounts of each number which should be roughly equal over large series. The speed requires for said random sample to be accessed at a moment’s notice, and the cost excludes overcomplicated apparatuses such as the use of vast amounts of radioactive samples being used as random number generators.

The obvious candidates for producing random numbers fulfilling those last two constraints are numerical methods: they run on relatively cheap computers and can easily be optimized. They also have the advantage of being easily adaptable. This however creates the issue of how to use a computer to produce random numbers. A computer is a deterministic machine designed to *eliminate* randomness. As such, producing “true random” numbers isn’t possible without physical input. A common source

of randomness in computers is the specific time keys are pressed, as it makes the assumption that the user is not predictable. This allows the computer to gather entropy and use it in random number generation. Unfortunately this is limited in time as there is only so much “randomness” available to the computer implying that the computer eventually “runs out” of entropy, making it again predictable. Therefore this method is not suited to large scale random number generation.

An alternative to “truly random” numbers are pseudorandom numbers. They function around a seed value and an algorithm to produce numbers that may appear random but are in fact predictable. In this case, the computer doesn’t gather data from its environment. Although one may be able to predict the number series, the algorithm insures limited repetitiveness and a change of seed will fundamentally change the generated series. By far, the most used pseudorandom number generator used is the *Mersenne Twister* [141], a highly evolved, patent-free algorithm. It passes many tests for statistical randomness [142], has a very long period of $2^{19937} - 1$ and is quite fast. This random number generator is the one used for most Monte Carlo simulations.

5.1.2 Simulating high energy physics

There are mainly two requirements in adequately simulating physics: first the law of large numbers must be fulfilled by the simulation:

$$\lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=0}^N f(u_i) = \frac{1}{b-a} \int_a^b f(u) du; \quad (5.1)$$

with N the number of attempts, u_i is the generated random variable with $[a, b]$ the limits to its probability density and f the evaluated function. The Monte Carlo estimate should converge to the true value. The second requirement is the fulfilment of the Central Limit theorem:

$$\sigma = \frac{\sqrt{V[f]}}{\sqrt{N}} \sim \frac{1}{\sqrt{N}}; \quad (5.2)$$

with σ the standard deviation, V the variance. The observed distribution should converge to a Gaussian distribution for a large number of random variables. Moreover the effective variance $V[f]$ must be reduced, or the number of attempts N must be increased to decrease σ .

High energy physics requires simulation for all processes which do not have a fixed final outcome such as the simulation of detector response, the response of a particle detector, the behaviour of an interaction or the hadronization process. One example would be the interaction $e^+ e^- \rightarrow \mu^+ \mu^-$ shown in Figure 5.1.

The goal of such a simulation is to generate the 4-momenta of the outgoing muons. The cross section of this process is well known at tree-level

$$\frac{d\sigma}{d \cos \theta d\phi} = \frac{\alpha_{em}^2}{4s} (1 + \cos^2 \theta); \quad (5.3)$$

with θ and ϕ the polar and azimuthal angles respectively, s being the square of the centre of mass energy and α_{em} the electromagnetic fine-structure constant.

For a known s there must therefore be two random numbers which take values between 0 and 1 generated: R_1 and R_2 which simulate the azimuthal angle $\phi = 2\pi R_1$ and the cosine of the longitudinal

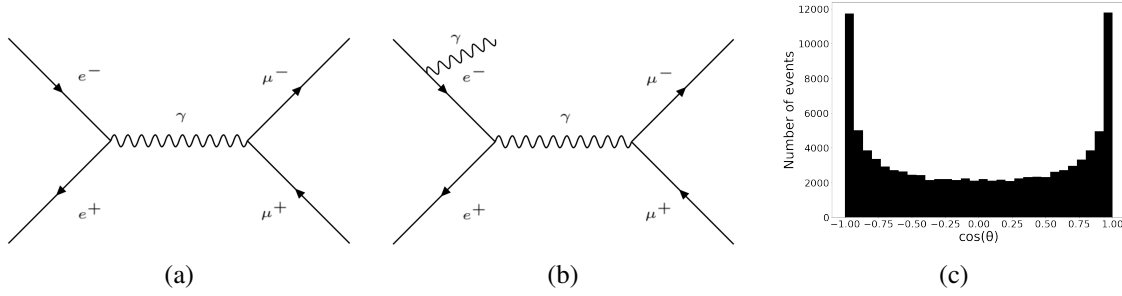


Figure 5.1: (a) Electron-positron annihilation into a muon antimuon pair with initial state radiation at LO in Quantum Electrodynamics. (b) Electron-positron annihilation into a muon antimuon pair with initial state radiation at Leading Order (LO) in Quantum Electrodynamics. (c) Tree level $e^-e^+ \rightarrow \mu^-\mu^+$ angular distribution for 100 000 events.

angle $\cos \theta = -1 + 2R_2$. A large number of events is simulated and the distribution is then reweighted with the resulting $\frac{d\sigma}{d\cos\theta d\phi}$. This gives rise to the distribution shown in Figure 5.1(c). It should be noted that Monte Carlo simulation is often processed after the initial production. The produced data points are called Truth, while the processed data will produce so-called hits when performing detector simulation (4.2.2).

An issue may arise when all possible processes have to be simulated that can take place in such an event. In fact, initial state radiation or other high-than-tree-level processes, may have a large effect on the cross section. It then becomes necessary to incorporate higher-level generators to describe the matrix elements of higher-order processes. Two such generators are especially relevant here: Pythia and EvtGen.

Pythia Pythia is a general-purpose event generator. It was originally written in Fortran 77 and has been maintained up until Pythia 6.4 but has seen rewriting to C++ in 2004 until the most recent version Pythia 8.2. Its focus is on hadron-hadron and lepton-lepton collisions at centre-of-mass energies greater than 10 GeV and lower than 100 TeV.

Pythia generates events according to matrix elements and PDFs where necessary. Pythia, as of version 8.2, is able to produce processes encompassing much of high energy physics but also softer processes [143]. PDFs are implemented at LO.

Parton showers are also simulated based on Initial-State-Radiation (ISR) and Final-State-Radiation (FSR) algorithms [144]. This allows for probing Hidden Valley models [53] and other BSM physics. MultiParton Interactions (MPI) and hadronization are implemented as well, allowing for effective simulation of hadronic showers [145, 146].

String parton fragmentation models are an integral part of Pythia. They are used to simulate inelastic interactions of primary hadrons with nuclei at high energies. They function around creating color forces in between, for example, $q\bar{q}$ pairs. Said color forces are then concentrated in a narrow tube or string which connects q and $\bar{q}$. As q and $\bar{q}$ are moving apart in their rest frame, they are decelerated by the string tension, thus effectively creating a hadron. When the energy is large enough, the string is broken into more $q\bar{q}$ pairs which form more hadrons [147].

EvtGen EvtGen is a generator specialized in simulating heavy quark flavour physics [148]. It contains models for scalar, vector and tensor decays [149]. It is particularly flexible as decays can be added as modules and thus the simulation is better controlled. EvtGen also utilizes decay amplitudes instead of probabilities for the simulation of decays. It is especially popular for simulating heavy flavour decays.

5.2 GEANT4

GEometry ANd Tracking, or GEANT, is CERN’s standard tool for simulating the passage of particles through matter. It is an object-oriented environment coded in C++ which saw its first release in 1998 and the current version of which is now GEANT4 [150], succeeding the widely-used FORTRAN 77-based GEANT3. GEANT4 utilizes well-established physics routines and dictionaries to model the physics of interactions and is therefore heavily employed by high energy physics experiments [151–153] to simulate their detector structure or planned upgrade performance. It also sees use by fields outside of particle physics such as medical physics and space science [154, 155].

GEANT4 isn’t specialized in high energy physics event generation the same way Pythia or EvtGen are. It does however make use of similar, albeit often less extensive models.

A GEANT4 simulation is divided into runs encompassing the geometry, primary particles, energy and setup utilized. Each run goes through initialization shown in Figure 5.2 and processing shown in Figure 5.3. Each interaction is given a unique code which allows the traceback to the original process [150].

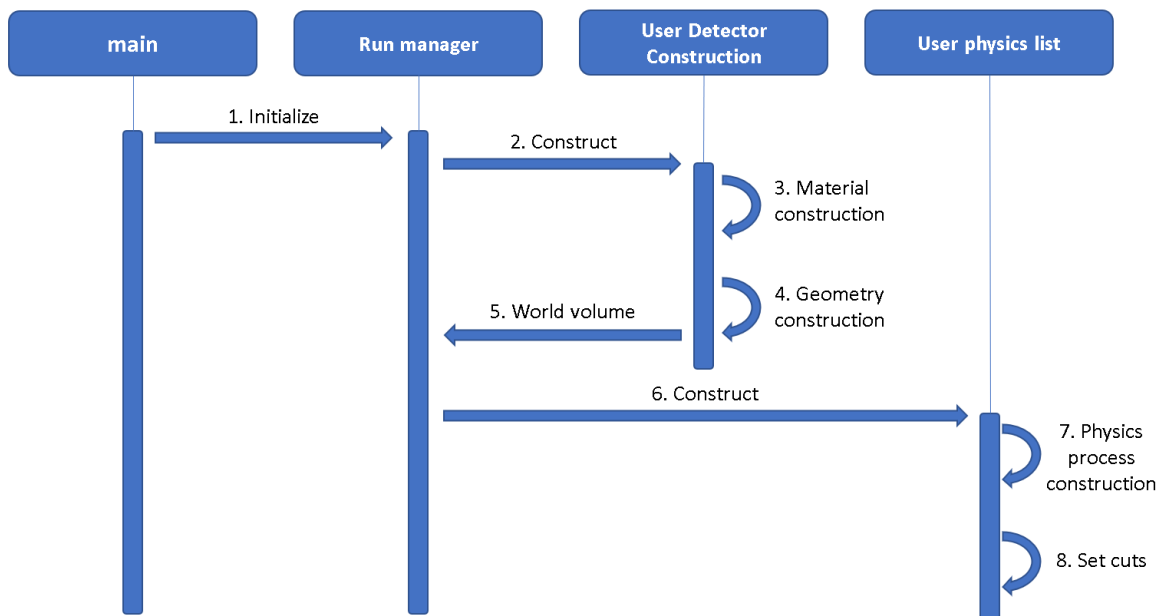


Figure 5.2: Illustration of GEANT4’s simulation run initialization.

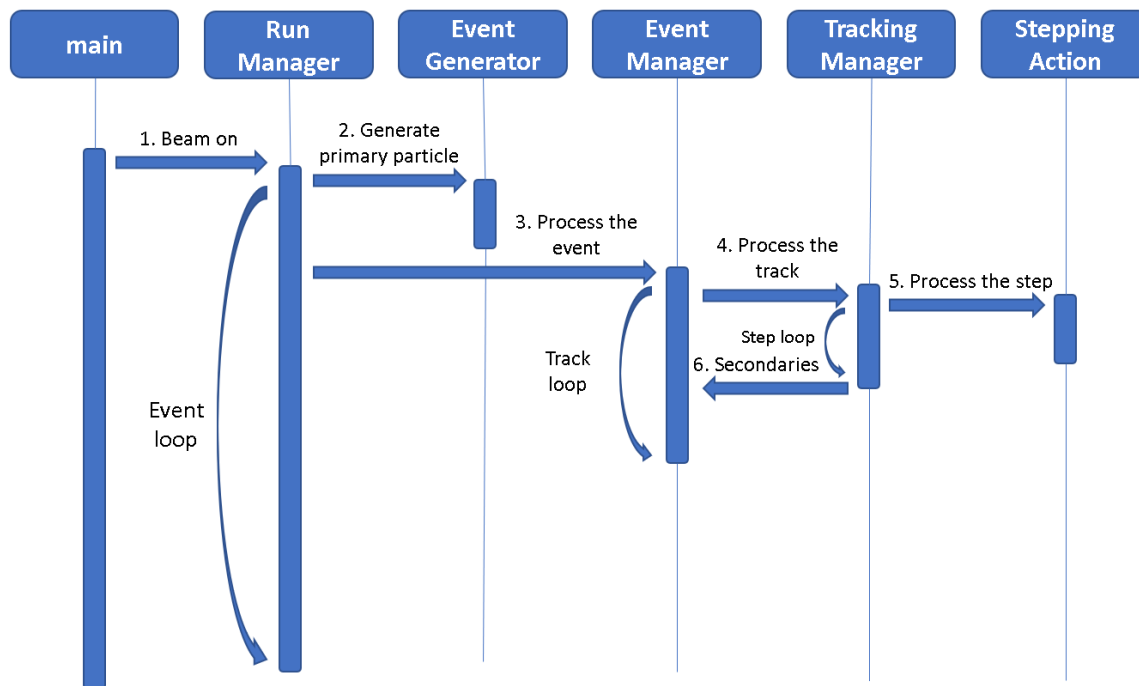


Figure 5.3: Illustration of GEANT4's simulation run processing.

5.2.1 Run initialization

A GEANT4 run initialization defines the elements of the run and is called in a function (generally the main function) of a program. The first step is the initialization of used materials and physics processes. Each material and process to be used in the run is specified. Then comes the initialization of the geometry. The geometry is initialized by specifying the volumes of space which will be filled with material. This is done via two landmarks: the “World” volume and the internal reference frame of the simulation. The “World” volume is the area in 3D space which needs to be considered by the simulation. The internal reference frame is a Cartesian system with origin at the center of the World. Each system component is defined as a geometrical volume with its centre placed in the reference frame of another volume. For example, an initial volume will be placed with respect to the internal reference frame. A subsequent volume can be placed either with respect to the internal reference frame or with respect to the first volume.

Once all volumes are placed, they are assigned materials. A material in GEANT4 is either a pure element or a compound. Compounds are defined through their atomic composition according to either their chemical formula or weight fractions, their mean excitation energy, as well as their density at a given temperature and pressure. Certain volumes can be defined as “sensitive” that being detector materials of which the response should be stored for analysis. Each such volume is given an identifier by the user.

After having defined and constructed the geometry and materials, the physics processes and models to be used in the simulation are loaded from the list specified by the user. Possible restrictions or cuts are then placed on the physics to be simulated.

5.2.2 Run process

After the run has been initialized, the simulation can begin. A “Beam on” signal is given and primary particles are generated, each corresponding to an event. This is done as many times as specified by the user, creating an event loop. The particle passes through the volumes and creates a track; every particle, depending on the chosen setup, may interact and give rise to more tracks. Each track may deposit energy in any traversed material.

Since simulating the interaction of each track with each atom in the material would require excessive processing time, GEANT4 uses steps. A step is a unit of distance representing a fraction of the material thickness. GEANT4 computes the interaction probability and energy deposition based on a random number generator, the chosen physics models and known physics of energy deposition such as the Bethe-Bloch formula 3.1.2 and records it for every step in the material.

Once this process is complete, GEANT4 records the energy depositions in volumes defined as sensitive into a container. The written information encompasses the event number, coordinates of the interaction, 3-momentum, particle type, amount of energy deposited by the particle and identifier of the traversed sensitive material, in particular. It should be noted that the interaction coordinates are given at the end of the step.

This means that if a 10 μm thick material is entered by a perpendicular particle travelling in the positive direction in coordinates [0,0,0], the energy deposition will be recorded in [0,0,10]. By default, GEANT4 records are written into histograms but it is possible to set the information writing into other containers such as NTuples.

5.3 FairShip

FairShip is the official software of the SHiP collaboration. It is being developed by 30 contributors since 2015 [119]. It is used both for SHiP simulation and analysis.

FairShip is based on FairRoot [156] and it is based on C++ for all computing heavy tasks. It is however operated via Python for flexibility and ease of use.

5.3.1 FairShip simulation

The FairShip simulation was designed for the SHiP detector and corresponding test beam experiments such as a muon flux measurement [157] and the charm test beam. The simulation in FairShip makes use of specific configurations which are described here.

5.3.2 SHiP FixedTargetGenerator and simulation configurations

FairShip’s FixedTargetGenerator serves three purposes.

- Providing muons leaving the hadron absorber for further processing with different setups of the active muon shield;
- Providing neutrinos for background studies in the SHiP experiment and signal reconstruction in the τ -neutrino detector;

- Providing any other particles leaving the hadron absorber for studying other potential backgrounds.

The events can be simulated by using GEANT4 directly, shooting 400 GeV protons on the target and letting GEANT4 handle every step of the process. The simulation can also take place through either proton-proton or proton-neutron interaction generation via Pythia8 and/or EvtGen and transporting the produced particles with GEANT4. The simulation also accommodates the reading of an external file with prefabricated charm (and bottom) hadrons produced by the SHiP Pythia6 cascade event generator [100]. In order to speed up the simulation, only particles above a certain threshold are transported by GEANT4 [158].

FairSHiP utilizes a standard set of units such as seconds for time, giga-electron-volts for energy, Tesla for magnetic field and centimetres for distance. The simulation's GEANT4 transport requires GEANT4 geometry C++ classes which contain the type and shape of the detector. Those classes are by convention named after the detector they represent (a SciFi detector is therefore called `SciFi.cxx` (h)). Those classes contain constructors which notably take the detector coordinates as parameters such that the Python-operated simulation doesn't require recompiling.

The Geometry classes also contain GEANT4 initialization and geometry constructor functions which handle the GEANT4 initialization process. Each detector also has a `ProcessHits` method which, after checking whether a GEANT4 track is entering a sensitive volume and has deposited energy, writes information into a `Point` class. These classes are the standard FairShip Truth container and contain the `TrackID`, the ID of the sensitive volume, the position 3-vector, the 3-momentum, the event number, the length of the track, the energy deposition of the particle and the particle type. `Point` classes typically specify the detector name in front of it, as such the Pixel detector's Points are called `PixelModulesPoints`. The simulation is launched by specifying which target is used (the SHiP target or a test beam target), the number of events, the event generator or file to be used. All `Point` classes are written into NTuples, here a ROOT TTree [159, 160] which can then be accessed. The history of all particles and the ID of the Geant4 process which produced the particle, are also stored.

5.3.3 Pixel implementation in FairShip

The Pixel detector, described in Subsection 4.2.2 has been implemented into the FairShip simulation in the course of this work inside the classes `PixelModules` and `PixelModulesPoint`. Both its FairShip GEANT4 classes and its geometry coordinates, including the silicon sensitive sensor, the silicon front-end, the copper and kapton module frame, and the kapton window in front of the pixel box. The implementation of the sensor geometry can be seen in Figure 5.4.

Once the pixel modules were implemented, the next step was to ensure that the geometry in the simulation matched the one from the experiment. This was done by checking the FairShip point distributions and comparing them to data. Using the pure GEANT4 variant of the simulation made this possible as it is the only one to conserve primary protons after interaction. This is shown in Figure 5.5. The geometry was found to acceptably match the one found in data.

The energy deposition distribution in the silicon was then investigated, this is shown in Figure 5.6. It results in the expected behaviour. Charged particles display a Landau-shaped energy-loss spectrum. The γ spectrum described in Section 3.1.2 is well visible. Muons, essential signal particles, are observed to be very rare and thus are not visible in the Figure, while electrons, despite being numerous

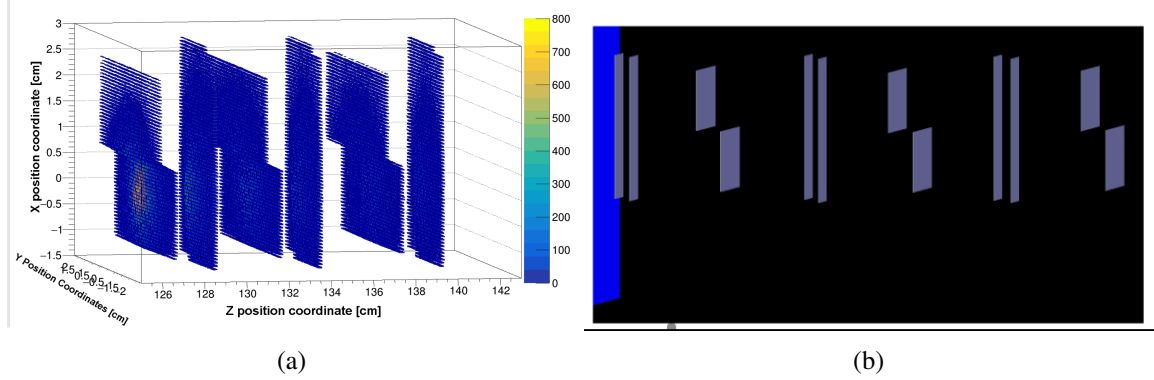


Figure 5.4: (a) The twelve pixel module sensors in FairShip, seen by the number of particles passing in a 10 000 event run with the Charm1-Run6 setup. (b) The twelve pixel module sensors in FairShip as seen in the FairShip geometry display.

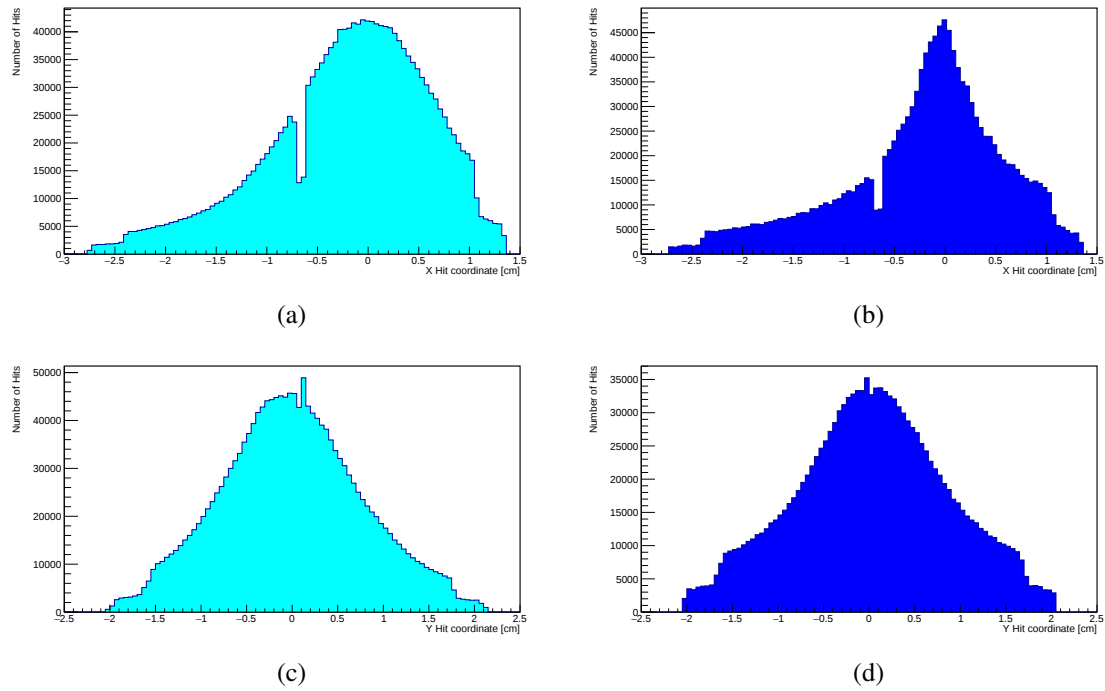


Figure 5.5: (a, b) x and (c, d) y hit coordinates distributions for all planes combined. Plane-by-plane distributions can be found in Annex C. Simulation results are shown in cyan while data results are shown in blue. The effect of variable pixel size is visible in data. It should be noted that the beam in the FairShip simulation is wider than that used in reality as seen especially in the x coordinate distributions. This discrepancy is documented in Section C.

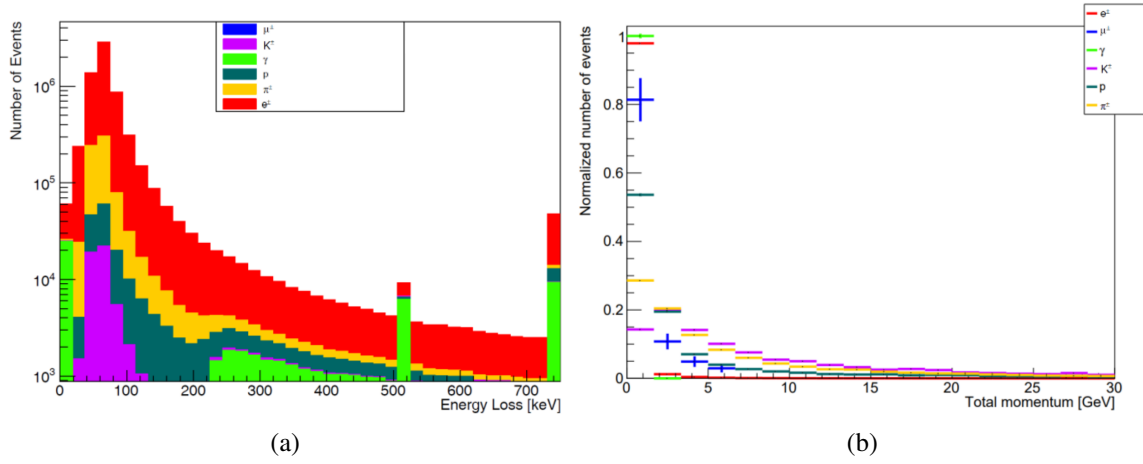


Figure 5.6: (a) Energy loss of particles in the silicon sensor for a simulated 10 000 event Charm1-Run6 run. Other particles represent a small fraction of the energy loss and are thus not shown. (b) Particle momentum as seen in the simulated pixel detector where each distribution is normalized to unit area under the curve.

at low energies, dominate the energy loss spectrum, especially in those regions. The expected most probable energy loss for a MIP in 245 μm of silicon is ~ 67 keV, which matches the simulation.

The spectrum of particle momenta matched expectations as well. The overwhelming majority of photons and electrons are produced at low momentum through atomic effects. The other particles display a soft spectrum.

The final check made at this stage was that of particle composition. Knowing which particles to expect from this kind of setup is crucial for the experiment and ensures that the event generator functions properly. The particle composition is shown in Figure 5.7. Muons are seen to be quite rare while electrons are prevalent, partly due to knock-off electrons. Other particles which deposit energy represent a small fraction of the total and are mostly α particles, ^3He nuclei and deuterons. Figure 5.8 shows a display of 100 overlaid events.

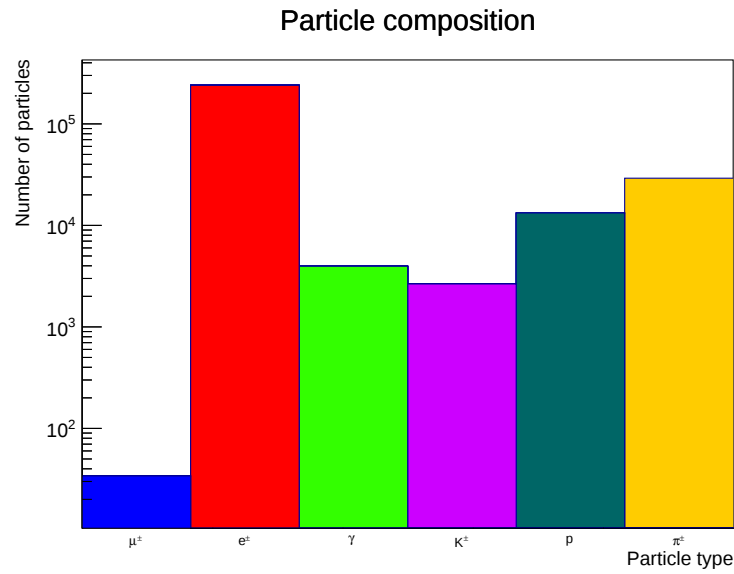


Figure 5.7: Particle composition in 10 000 simulated events using the Charm1-Run6 setup.

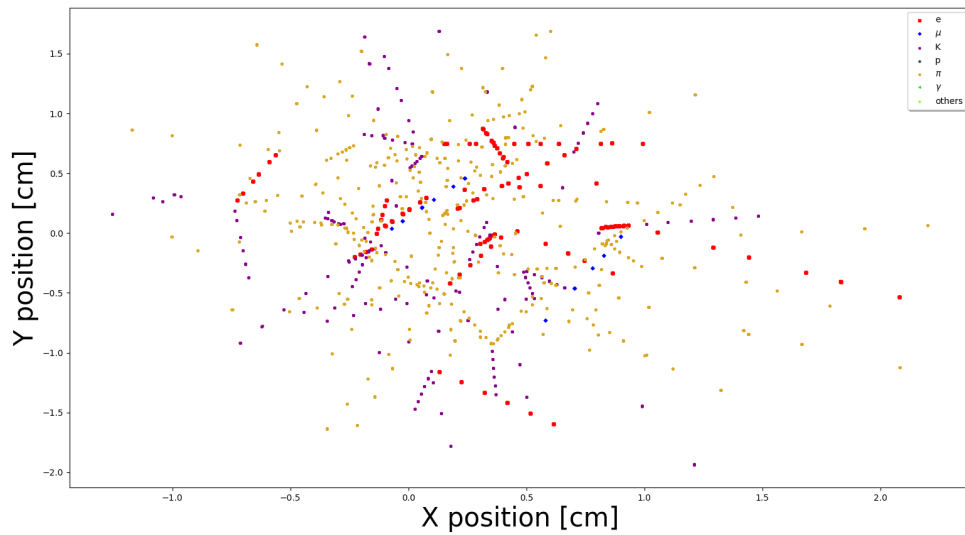


Figure 5.8: View of 100 events projected onto the $x - y$ plane. Particles with forward momentum $p_z < 1$ GeV are not shown to remove low energy electrons which dominate otherwise. Several vertices can be seen. The same 100 events including particles with less than 1 GeV forward momentum can be found in Figure C.6.

Pixel modules digitization

Once the FairShip simulation is in place it is possible to perform analysis on the simulated data. The pixel detector need to be implemented and thus it is possible to create higher-level objects as described in 4.2.2. In order for this to be done, further processing of the data was done. The Time-over-Threshold, the timestamp and a realistic energy deposition and response were simulated. The process of simulating the detector response is called the *digitization* of the detector.

6.1 Time-over-threshold simulation

As described in 4.2.2, the pixel detector's energy resolution depends on the ToT. An example of the ToT distribution can be seen in Figure 6.1. The dependence of ToT on the energy deposition is not a priori known. It is expected to behave roughly linearly with energy loss but ideally, a pixel-by-pixel calibration is needed. This was not possible in this case and thus a simplified procedure had to be developed.

The ToT distribution can be seen to peak sharply around 9 in Figure 6.1, which corresponds to the most common energy deposition it registers. If linear dependence between energy deposition and ToT is assumed, knowing both the threshold value starting from which a ToT is registered (corresponding to $\text{ToT}=1$) and the most probable energy deposition allows to build an energy conversion.

The energy required to create an electron-hole pair in silicon is 3.6 eV. Basing on the information given by Figure 5.6, it can be seen that the energy loss peaks at 67 keV which corresponds to $18805.94 \pm 0.82 e^-$ [161]. The pixel threshold has been set to $2800 e^-$ ¹. The ToT conversion equation system to solve is then:

$$\begin{cases} 2800 a + b = 1 \\ 18805.94 a + b = 9 \end{cases} \quad (6.1)$$

which yields constants ($a = 500 \pm 2$) $\times 10^{-6}$ and $b = -0.40 \pm 0.01$ ². Since ToTs above 13 are not used in practice, the distribution is made to saturate at 13. This gives rise to the distribution seen

¹ The threshold dispersion, that being the standard deviation of the real threshold compared to the set one, has been evaluated to be of $30e^-$ [162] for a $1400 e^-$ threshold but has not been measured for the used $2800 e^-$ threshold. It is assumed to scale linearly with the threshold and thus be of $60 e^-$.

² Errors for the threshold and the silicon response are assumed to be entirely uncorrelated.

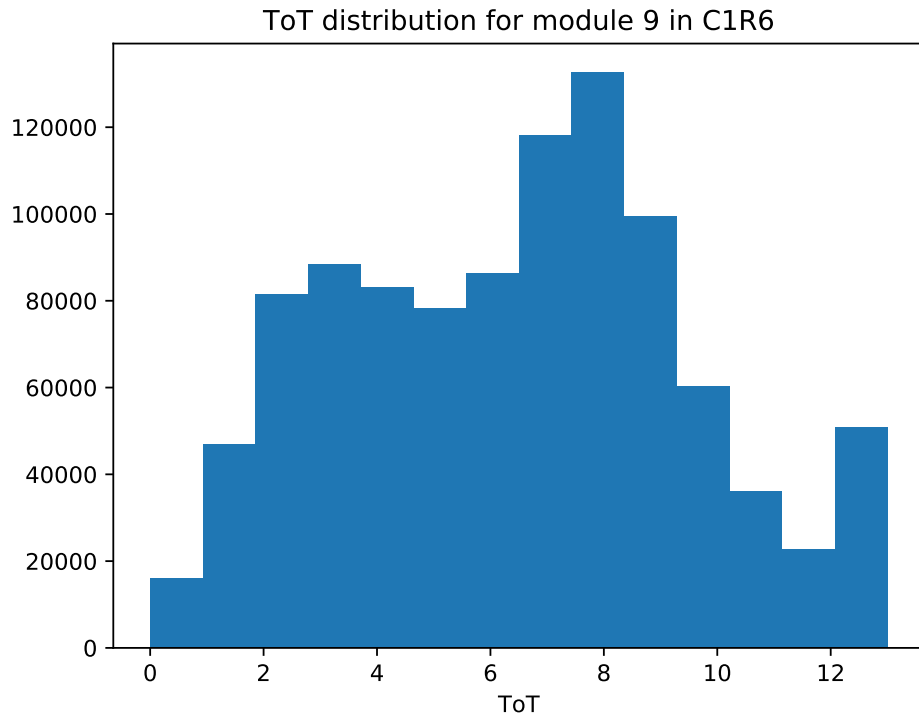


Figure 6.1: ToT distribution of module 9 in Charm1-Run6 [136].

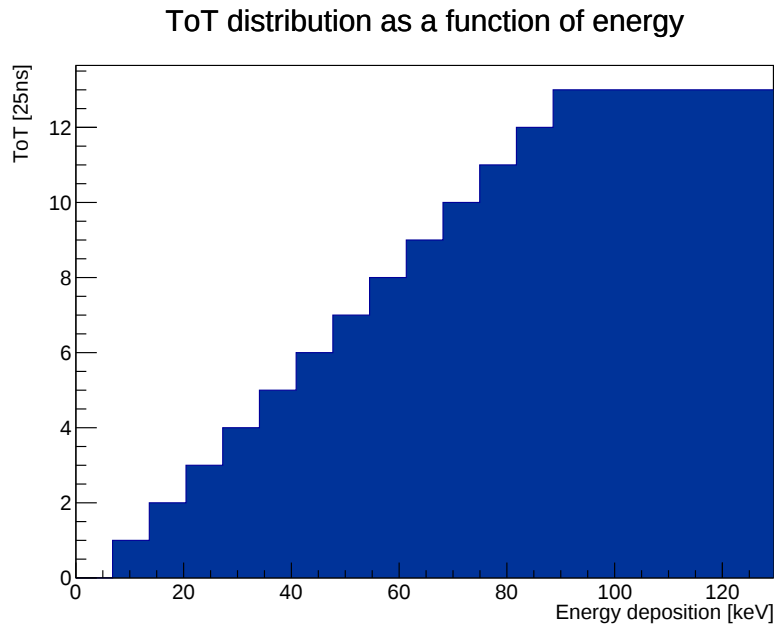


Figure 6.2: Conversion of energy deposition to ToT in the pixel simulation.

in Figure 6.2. This result allows for the energy resolution to be considered in the simulation, but only accounts for the average pixel response as individual pixels can have significantly different ToT behaviours.

6.2 Emulsion-pixel matching and pixel hit conversion

One of the main difficulties of the charm test beam described in Section 4 is the matching between emulsion and pixel data. This is necessary as the moving emulsion detector carries no timing information while the pixel detector provides 25 ns time resolution. If the matching is complete, timestamps can be assigned to emulsion events. Both the pixel detector and the emulsion detector have a set of tracks on an event-per-event basis with the distance between the last emulsion layer and the first pixel layer being about 1.8 cm.

A matching procedure is performed by looking at tracks which have at least 6 hits in the pixel detector, extrapolating the pixel track to the emulsion detector and attempting to match the two by finding a matching track among emulsion tracks after selecting the correct spill in emulsion by cutting on the tracks' y coordinates. The offsets x_0 and y_0 in the x and y direction between emulsion and pixels are then evaluated along with z_0 , the exact distance between the last emulsion layer and the first pixel layer. $\Delta\theta_{xz}$ and $\Delta\theta_{yz}$, the angles between the emulsion and pixel reference frames in the xz and yz planes, respectively, as well as θ_{xy} , the angle in the xy plane between the pixel and emulsion reference frames.

Two requirements are then made: the cluster formed by those hits must be within an ellipse defined by a significance level of the extrapolated pixel tracks around it and the pixel track must then be compatible with all hits in an emulsion track. The quantity $\frac{1}{N_{\text{df}}} \sum \left(\frac{\Delta x^2}{\sigma_x^2} + \frac{\Delta y^2}{\sigma_y^2} \right)$ is then computed as reduced χ^2 with $N_{\text{df}} = N_{\text{hits}} - 5$, the number of degrees of freedom, as 6 hits minimum are required for the track. Finally, if more than one track is compatible, the one with the smallest reduced χ^2 is chosen [163].

In order to help refine this approach, the simulation, where all information is known beforehand, provided tracks for emulsion and pixels thus allowing the matching procedure to be validated.

A code based on the tracking algorithm from Section 4.2.2 was available beforehand [140], but the FairShip output files are incompatible with it and more information than that available in the raw simulation output had to be provided. Thus, the output FairShip information was converted to a format compatible with the tracking code. Since pixel-mapping and clustering was not yet available for the simulation Points, the following assumptions had to be made:

1. All hits are assumed to produce single pixel clusters. This is a reasonable approximation as can be seen from Figure 4.17(a), where a majority of clusters is single-pixel.
2. ToT is assumed to be accurate.

6.2.1 Pixel smearing

Emulsion-pixel matching can benefit from simulated tracks. In the simulation of the pixel modules, the truth information needs to be smeared according to the detector's spatial resolution. A uniform, pseudorandom pixel-sized smearing was applied to simulation during the data conversion from FairShip

Points to the tracking-compatible TTree for all x and y coordinates matching module orientation. This allows for more realistic tracks to be used for the matching.

Timestamp simulation

FairShip provides an event number, as shown in Section 5.3.2, and the way timestamp creation functions was described in Section 4.2.2. The delay between the SoS and the first incoming particles in the pixel detector is not particularly relevant for the matching and thus was arbitrarily set to $t_0 = 10^6 [\times 25 \text{ ns}]$ which is a reasonable approximation as seen in Figure 6.3. The δt corresponding to the time difference between two consecutive events was surveyed and fitted by an exponential function $A e^{Bt}$ with A and B being the fit parameters and t being the timestamp values. This is shown in Figure 6.4(a).

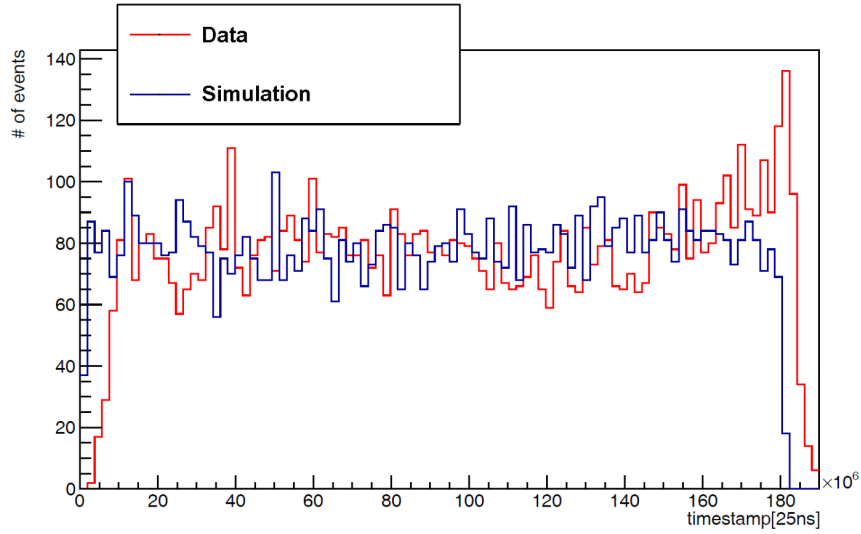


Figure 6.3: Timestamp profile for data and simulation for Charm1-Run6.

The subsequent fitted function from data was then sampled using a random number generator as described in Section 5.1.1 and the corresponding δt were added to the initial t_0 thus producing a similar distribution shown in Figure 6.4(b). The timestamp profile can be seen in Figure 6.3. The profiles exhibit some difference, there is more structure in data which is probably due to the beam structure not being completely homogenous.

Timestamps are expected to be similar for all runs as the fundamental dynamics of protons on target does not change. This was investigated for Charm1-Run5 and the result can be found in Figure D.1 and Table D.1.

6.2.2 Track angles

In order to compare simulated tracks and those from data, a comparison between track angles was made. This can be found in Figure 6.5.

The angle distributions were found to be comparable but an excess of 9% tracks was found in simulation. Since the beam was not centred in the data taking setup, more particles end up outside of

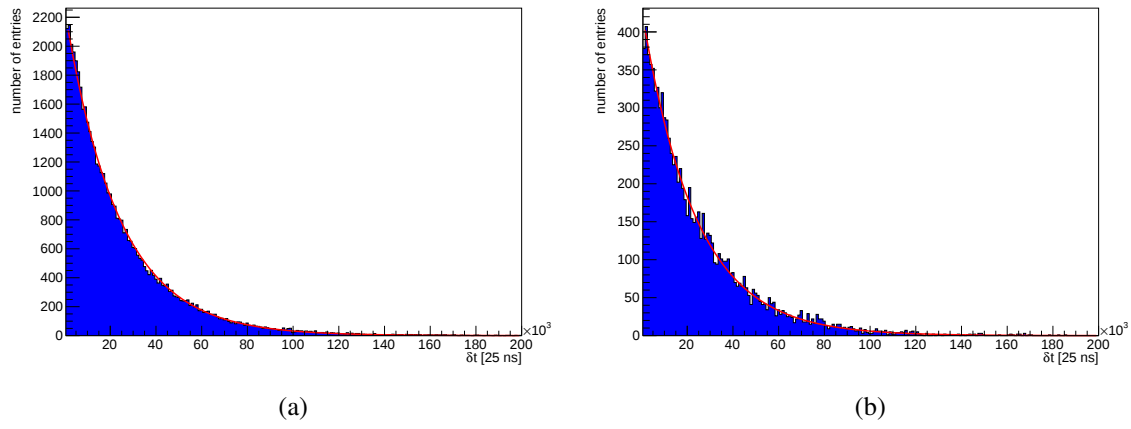


Figure 6.4: (a) δt distribution and fit of timestamps for Charm1-Run6 data. (b) Simulated δt distribution and fit of timestamps using the Charm1-Run6 setup.

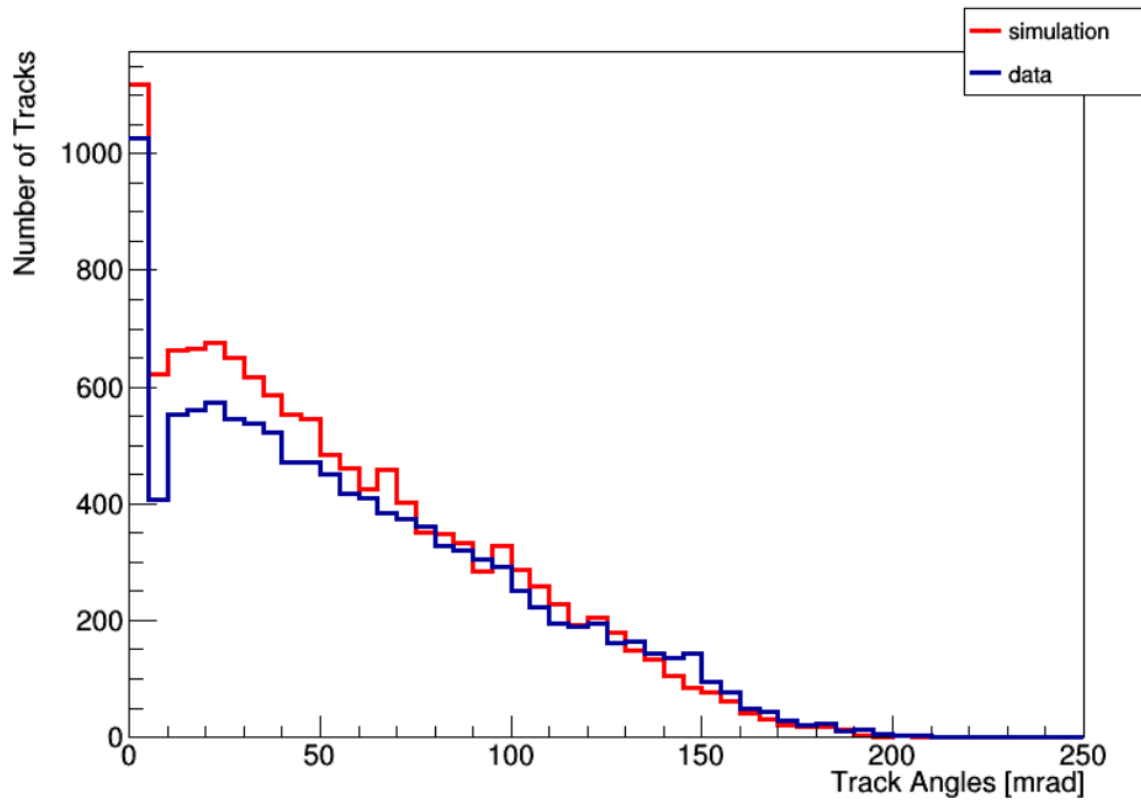


Figure 6.5: Track angle distribution for 1000 events of simulation and data tracks in the Charm1-Run6 setup.

acceptance compared to simulation which contributes to a lower number of hits and thus tracks found in data.

6.3 Energy deposition simulation

In order to have good quality hits in simulation it is necessary to accurately simulate the detector's response. The silicon and pixel behaviour was described in Section 4.2.1 and 4.2.2. Since all parameters of Equation 4.1 are known it is possible to simulate the charge cloud, charge sharing effects and the subsequent clustering. This simulation was written in C++ inside a single class `Hit` to allow for easier future merging into FairShip and is described below.

6.3.1 Charge sharing for particles of perpendicular incidence

The two orientations of the pixel modules will be referred to in the following as: “vertical” (modules 0,1,4,5,8,9) and “horizontal” (modules 2,3,6,7,10,11). The pixel orientation can be seen in Figure 5.4. A neighbouring pixel is defined as a pixel adjacent to another. Each pixel has 4, 6 or 9 neighbouring pixels including itself, depending on whether it is on the edge of the sensor.

Since particles parallel to the z-axis deposit energy for a single (x, y) coordinate through the full thickness of the sensor, it is easier to simulate the behaviour in those cases and thus this was the first step to simulating charge sharing. This was done by using FairShip Points converted to a ROOT TTree.

Prior to simulation, the pixel mapping was performed. This mapping is done by storing the pixel centre positions on the x, y and z-axis inside a triplet of static arrays which serve as map-arrays. Arrays for x and y contain the positions of the pixel edges with the lower left corner of a horizontal module's sensor facing the beam as coordinate origin. In order to accommodate the clustering algorithm, x and y map-arrays contains two extra positions, one for each side of the module which go outside of the detector's acceptance.

Array z contains the position of the plane of the module sensor facing the beam. This has been chosen because FairShip's GEANT4 options imply a single recording of energy deposition at the particle's exit point in each sensitive volume as described in Section 5.2.2. The module thickness however cannot be neglected.

Arrays x and y are then moved to match the setup geometry and, for vertical module pairs, inverted $x \rightarrow y$ and $y \rightarrow -x$. Each converted Point is then processed in the following way:

1. The x and y positions of the deposition are compared to their respective position arrays to find the corresponding hit pixel. This is done through the STL binary search algorithm `lower_bound` [164]. The next pixel edge is added to the found pixel edge in both directions and divided by 2 so as to obtain the pixel centre.
2. The energy deposition is converted to the number of electrons by dividing it by 3.6 eV.
3. The charge deposition in each neighbouring pixel is computed using the error function approximation for the integral of the Gaussian from Equation 4.1 in both x and y coordinates $1/2 \times \text{erf}\left(\frac{b-\mu_x}{\sqrt{2}\sigma}\right) - \text{erf}\left(\frac{a-\mu_x}{\sqrt{2}\sigma}\right)$, where b is the coordinate of the furthest neighbouring pixel edge and a is the coordinate of the closest neighbouring pixel edge. The product of both

approximations is multiplied by the number of electrons to get the total charge on the considered pixel.

4. The ToT of the neighbouring pixels is computed through the conversion described in Equation 6.1. ToTs of 0 and pixels outside the edges of the sensor are ignored.
5. The barycentre of the distribution is computed.
6. The resulting cluster centre is stored in a 2D histogram.

This algorithm was first tested on a horizontal module sensor using uniformly pseudorandomly generated x and y coordinates and an energy deposition distributed along a Landau according to that observed in 5.6. Those pseudorandom numbers were generated using ROOT's integrated TRandom3 class [159] which utilizes the Mersenne Twister described in Subsection 5.1.1. This was then extended to a vertical module sensor. The clustering in the two cases is shown in Figure A.5.

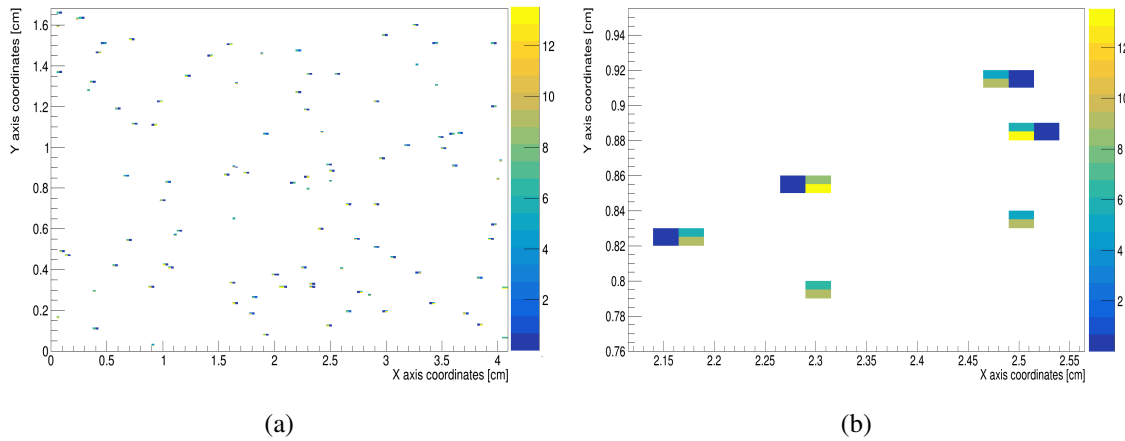


Figure 6.6: (a) Simulated horizontal pixel module sensor clustering while illuminated by 100 randomly distributed particles impinging perpendicularly. The colours correspond to the ToT. (b) Zoom highlighting some of the clusters from (a). The cloud width was exaggerated to 50 μm to highlight the clustering.

Examples of single clusters can be found in Figure E.3. The algorithm was then used with one million incoming particles. The result can be found in Figure E.4.

The cluster resolution was also studied. This can be found in Figure 6.7. In this case, since the cloud size is small in comparison to the size of the pixels, the clustering does not significantly improve the resolution. The uncertainty is dominated by the width and length of the pixels. This is particularly visible in Figure 6.7(a): the x-axis resolution can be seen to have features in three areas: a higher resolution area (0-125 μm) which corresponds to the reconstruction made in all pixels, the slight excess in the first bin compared to the other bins in this area represents the resolution improvement brought on by the clustering. This area has its border at half of the most common pixel length $250/2 = 125 \mu\text{m}$, as the values used for the barycentre calculation are the pixel centres. The edges of the pixel, located at 125 μm from the centre, are the furthest from the pixel centre that a particle could traverse the sensor while remaining inside of a pixel. The second area (125 - 225 μm) corresponds to the contributions made by the 450 μm and 500 μm long pixels at the centre and on the edges of the modules as explained

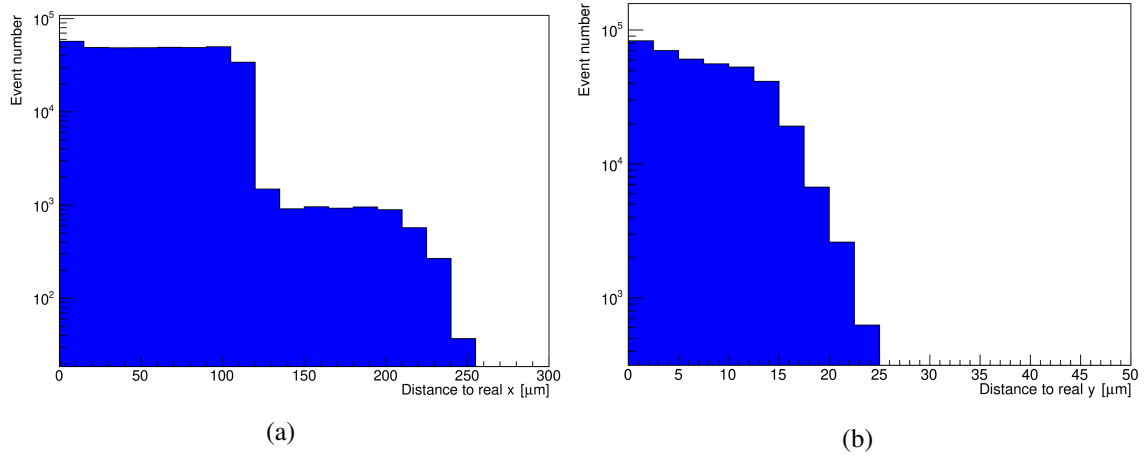


Figure 6.7: Distance of cluster centre to real energy deposition (a) in x-coordinates and (b) in y-coordinates for a realistic $\sigma = 5 \mu\text{m}$. The resolution for larger cloud widths is shown in Figure E.2.

in Section 4.2.2. This area ends at $450/2 = 225 \mu\text{m}$. The final section is the exclusive contribution of the longest, $500 \mu\text{m}$, pixels, thus extending to $250 \mu\text{m}$. The y-distribution in Figure 6.7(b) consists of only one area ending at $25 \mu\text{m}$ because all pixels have the same row pitch in the y-direction. The distribution decreases faster than the x-residuals distribution because the pixels are smaller in this direction relative to the cloud size compared to the x-coordinate case implying a better reconstruction of the cluster centre.

Once the conversion to hits had been implemented for normal particles, the next step was to implement processing of FairShip simulated data. This was done in two steps: first the relevant FairShip information was extracted from the `PixelModulesPoints` objects into a regular ROOT TTree, then normal particles (with an angle smaller than 0.1 mrad) were selected and processed. Those tracks are almost exclusively primary protons that have elastically interacted with the target. Results for modules 5 and 7 are shown in Figure 6.10.

Clustering for normal incidence particles was thus completed and the generalization to all particles is discussed in the next section.

6.3.2 Clustering for all particles

In order to produce clustering for all particles, their angles had to be reconstructed from the information of the pixel detector. It is convenient to decrease the GEANT4 step size described in Subsection 5.2.2 in order to require multiple steps inside of a single volume. In GEANT4 the sensors were segmented into 10 subsensors, referred as slices, of equal thickness. This allows for the simulation to produce 10 energy depositions of different z coordinate and thus to allow for charge sharing for angled particles. Each slice has its own unique GEANT4 detector ID. The process and its implementation into FairShip are shown in Figure 6.9.

The Hit conversion algorithm was updated as well, in order to support this new aspect of simulation. Two classes, `SliceHit` and `Hit`, were written, the former containing the mapping of energy depositions for x and y indices for a single slice, the latter containing a dynamic array of `SliceHits`. The `Hit` class also merges the energy deposition of the `SliceHits` and computes the corresponding cluster

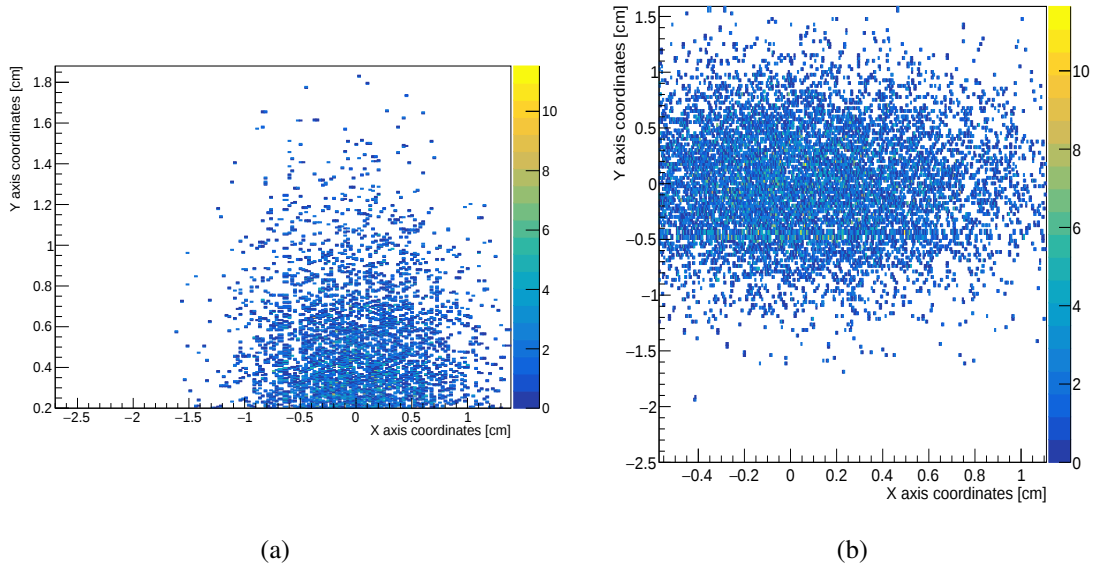


Figure 6.8: (a) Simulated response of module 7 for 10 000 Charm1-Run6 events. (b) Simulated response of module 5 for 10 000 Charm1-Run6 events. Colours are weighted for number of hits.

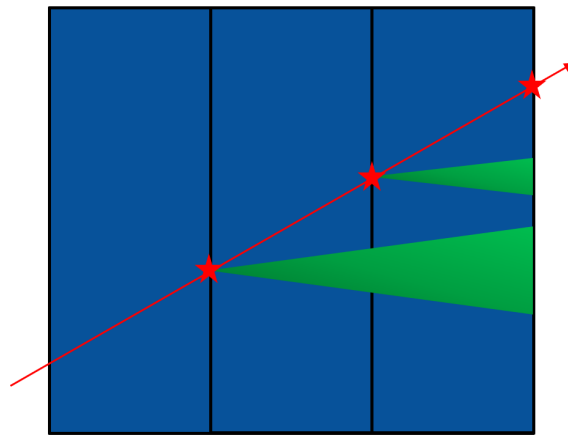
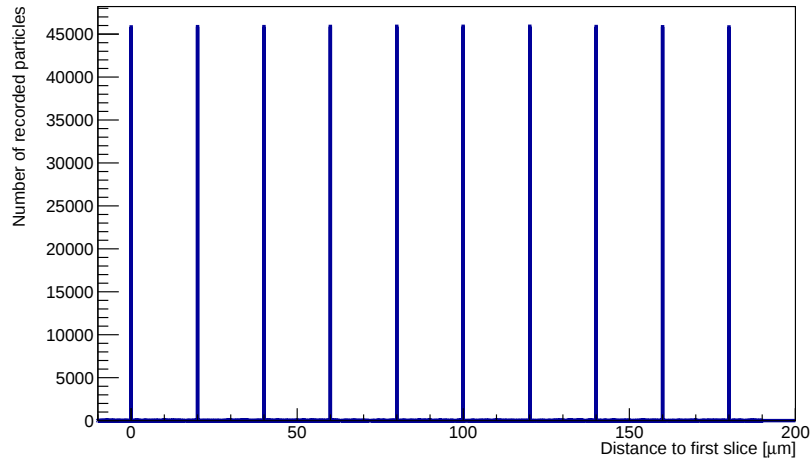
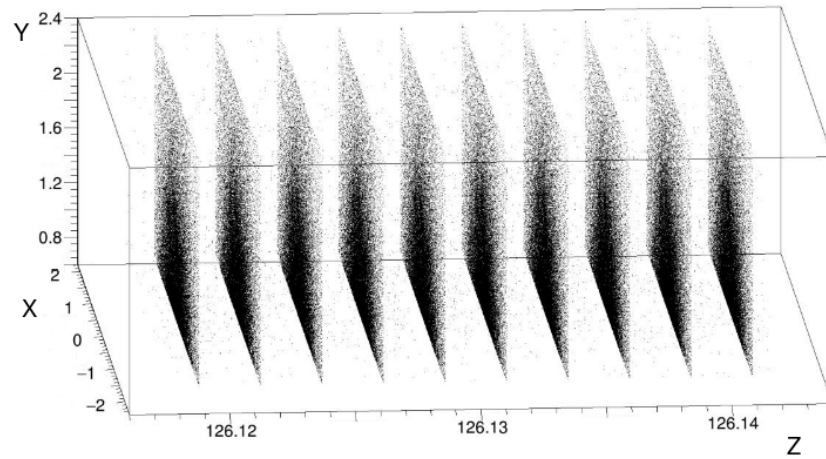


Figure 6.9: Slicing principle shown for 3 slices.



(a)



(b)

Figure 6.10: (a) Histogram of energy depositions in 10 000 events using the Charm1-Run6 setup in a pixel module after segmentation. A small binning was chosen to highlight the slicing. (b) 2D view of a sensor after segmentation. Hits outside of acceptance are due to a bug in FairShip's ProcessHits method.

centre for an energy deposition. A dynamic array [164] is used instead of a static one to account for the few occasions when GEANT4 does not deposit energy into the slice. Each `SliceHit` and `Hit` has access to the mapping information as the `Hit` class of Section 6.3.1. The algorithm is similar to the one used in Section 6.3.1, thus similar steps will not be detailed to the same extent. The algorithm is as follows:

1. A `Hit` is initialized.
2. An energy deposition from the 1st slice is chosen and a `SliceHit` is initialized with the deposition coordinates, its energy loss and its detector ID.
3. The x and y positions of the depositions are compared to their respective position in the x and y array-maps to find the corresponding pixel.
4. The energy deposition is converted to the number of electrons.
5. The charge deposition in each neighbouring pixel is computed.
6. The charge for each pixel is stored together with the centre index.
7. The `SliceHit` is added into the `Hit`'s dynamic array.
8. These steps are repeated until the next deposition is found to belong to another module.
9. The total charge of each pixel index is computed using $\sum_{k=1}^n N_e^k$ with N_e^k being the number of electrons in a pixel for the k^{th} deposition and n the total number of depositions in the sensor (10 in a majority of cases).
10. The ToT of the neighbouring pixels is computed through the conversion described in Section 6.1. ToTs of 0 and energy depositions outside the edges of the sensor are ignored.
11. The barycentre of the distribution is computed.
12. The resulting cluster centre is stored in a 2D histogram.
13. The process is repeated for all pixel modules in an event and for all events.

This algorithm has been implemented for modules 0-3. A mapping example can be found in Figure E.3. Timestamps, as described in Section 6.2.1, were also added to the stored data.

Conclusion

The implementation of the pixel detector's GEANT4-based FairShip simulation for the charm test beam of July 2018 was described showcased in this thesis. It consists of the implementation of the pixel modules and geometry including passive elements of the detector. Discrepancies between data and simulation were also found and corrected.

A full and realistic response of the pixel detector was implemented. This includes Time over Threshold, timestamp, charge sharing and clustering simulation. The conversion from GEANT4 truth to hits, emulating the detector's response, was done, first for perpendicular particles and then for all angles. The clustering and resolution were confronted with measurements which it matched.

Data conversion for FairShip's simulation pixel data into a format compatible with the available tracking code was made and the necessary hits were treated so as to match the data. The next step is the matching procedure between the static pixel detector comprising good time-resolution and the moving emulsion detector.

This work can be built upon by extending the full hit conversion to all modules, implementing the Hit conversion code to provide NTuples in a format compatible with the tracking code and porting the code to FairShip. The FairShip simulation can be improved by displacing all detectors including the pixel detector to positions and angles matching the real ones used in data, as well as by improving the passive material composition. Better ToT simulation can also be done if pixel-by-pixel calibration of the pixel modules is performed which would also allow to determine and thus implement in simulation the pixels which aren't responsive (so-called "dead pixels"). Once simulated Hit NTuples are ready, one can use them to produce tracks that better match the data.

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SHiP detection principles and sensitivity

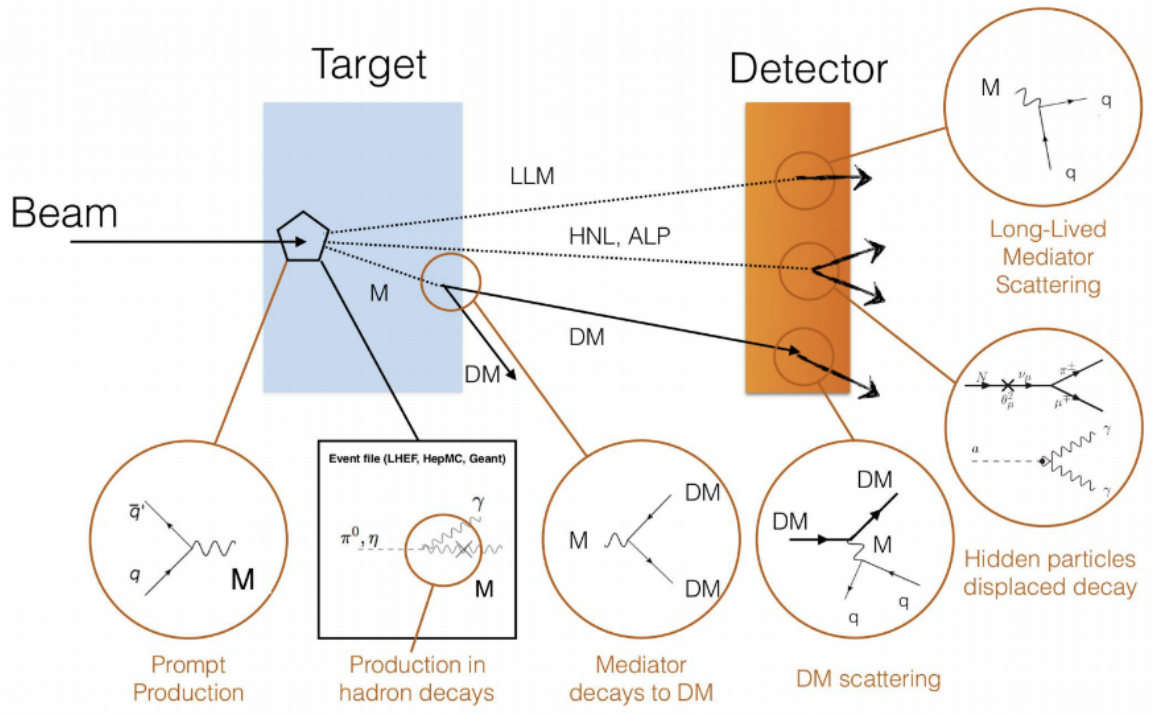


Figure A.1: Representation of SHiP new physics production and detection processes [165]. M stands for mediator, DM stands for Dark Matter, LLM stands for Long Lived Mediator, HNL stands for Heavy Neutral Lepton, ALP stands for Axion-Like-Particle.

Signature	Physics	Backgrounds
$\pi^- \mu^+, K^- \mu^-$	HNL, NEU	RDM, $K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$
$\pi^- \pi^0 \mu^+$	HNL($\rightarrow \rho^- \mu^+$)	$K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu (+\pi^0)$, $K_L^0 \rightarrow \pi^- \pi^+ \pi^0$
$\pi^- e^+, K^- e^+$	HNL, NEU	$K_L^0 \rightarrow \pi^- e^+ \nu_e$
$\pi^- \pi^0 e^+$	HNL($\rightarrow \rho^- \mu^+$)	$K_L^0 \rightarrow \pi^- e^+ \nu_e$, $K_L^0 \rightarrow \pi^- \pi^+ \pi^0$
$\mu^- e^+ + p^{\text{miss}}$	HNL, HP ($\rightarrow \tau\tau$)	$K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$, $K_L^0 \rightarrow \pi^- e^+ \nu_e$
$\mu^- \mu^+ + p^{\text{miss}}$	HNL, HP ($\rightarrow \tau\tau$)	RNDM, $K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$
$\mu^- \mu^+$	DP, PNGB, HP	RNDM, $K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$
$\mu^- \mu^+ \gamma$	Cherns-Simons	$K_L^0 \rightarrow \pi^- \pi^+ \pi^0$, $K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu (+\pi^0)$
$e^- e^+ + p^{\text{miss}}$	HNL, HP	$K_L^0 \rightarrow \pi^- e^+ \nu_e$
$e^- e^+$	DP, PNGB, HP	$K_L^0 \rightarrow \pi^- e^+ \nu_e$
$\pi^+ \pi^-$	DP, PNGB, HP	$K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$, $K_L^0 \rightarrow \pi^- e^+ \nu_e$, $K_L^0 \rightarrow \pi^- \pi^+ \pi^0$, $K_L^0 \rightarrow \pi^- \pi^+$
$\pi^+ \pi^- + p^{\text{miss}}$	DP, PNGB, HP ($\rightarrow \tau\tau$), HSU, HNL($\rightarrow \rho^0 \nu$)	$K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$, $K_L^0 \rightarrow \pi^- e^+ \nu_e$, $K_L^0 \rightarrow \pi^- \pi^+ \pi^0$, $K_L^0 \rightarrow \pi^- \pi^+$, $K_S^0 \rightarrow \pi^- \pi^+$, $\Lambda \rightarrow p\pi$
$K^+ K^-$	DP, PNGB, HP	$K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$, $K_L^0 \rightarrow \pi^- e^+ \nu_e$, $K_L^0 \rightarrow \pi^- \pi^+ \pi^0$, $K_L^0 \rightarrow \pi^- \pi^+$, $K_S^0 \rightarrow \pi^- \pi^+$, $\Lambda \rightarrow p\pi$
$\pi^- \pi^+ \pi^0$	DP, PNGB, HP, HNL ($\eta\nu$)	$K_L^0 \rightarrow \pi^- \pi^+ \pi^0$
$\pi^- \pi^+ \pi^0 \pi^0$	DP, PNGB, HP	$K_L^0 \rightarrow \pi^- \pi^+ \pi^0 (+\pi^0)$
$\pi^- \pi^+ \pi^0 \pi^0 \pi^0$	PNGB ($\rightarrow \pi\pi\eta$)	—
$\pi^- \pi^+ \gamma\gamma$	PNGB ($\rightarrow \pi\pi\eta$)	$K_L^0 \rightarrow \pi^- \pi^+ \pi^0$
$\pi^- \pi^+ \pi^- \pi^+$	DP, PNGB, HP	—
$\pi^- \pi^+ \mu^- \mu^+$	HSU	—
$\pi^- \pi^+ e^- e^+$	HSU	—
$\mu^- \mu^+ \mu^- \mu^+$	HSU	—
$e^- e^+ \mu^- \mu^+$	HSU	—

Table A.1: Physics signals targeted by the SHiP experiment. HNL stands for Heavy Neutral Lepton. NEU stands for Neutralino. DP stands for Dark Photon. PNGB stands for Pseudo-Nambu Goldstone Boson. HP stands for [Scalar] Higgs Portal, HSU stands for Hidden Supersymmetry, RNDM stands for random di-muon from the target [82]. An overview of the Cherns-Simons theory can be found in [166].

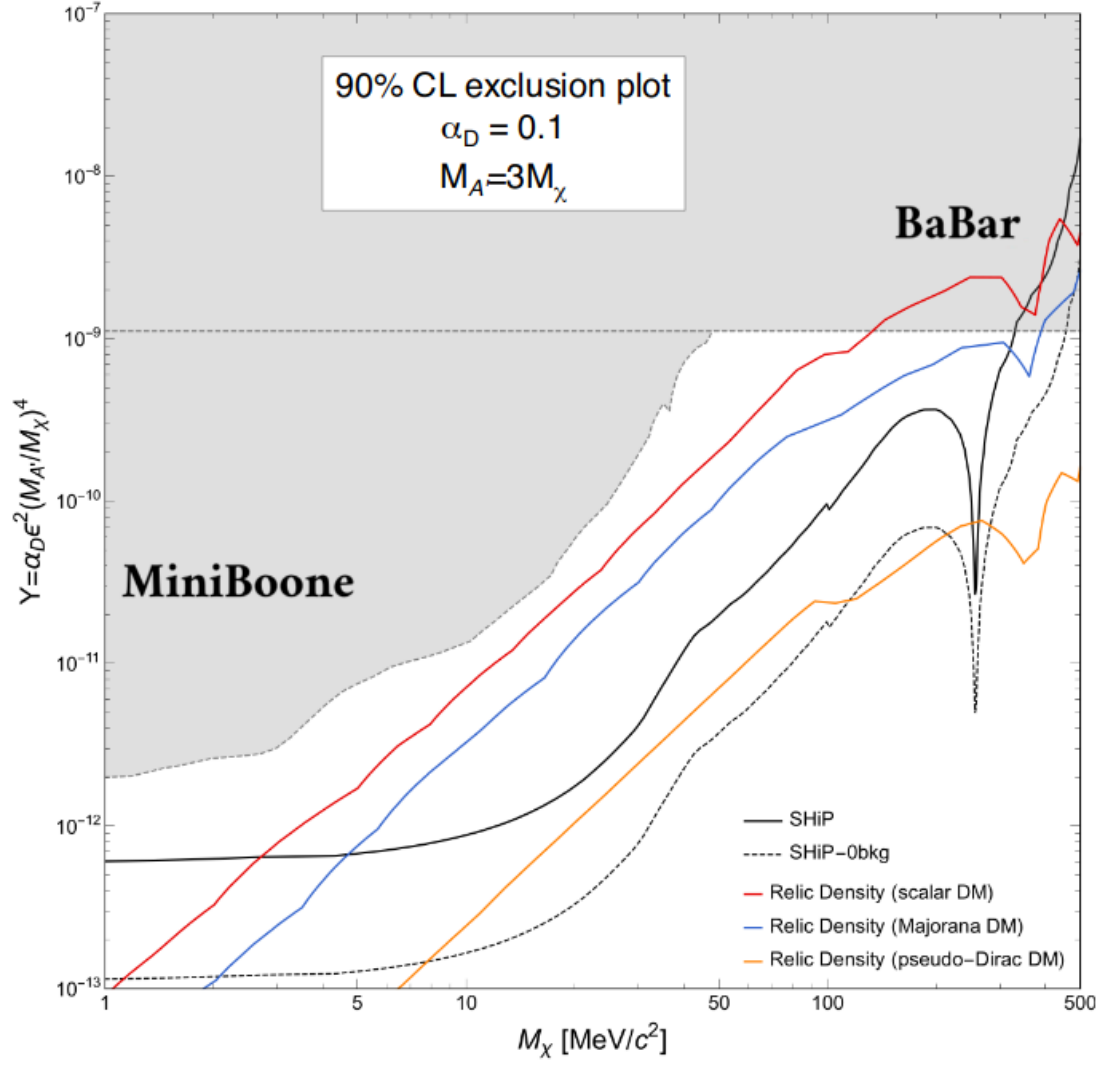


Figure A.2: SHiP sensitivity to model-independent Dark matter. The dotted line represents SHiP under the zero-background hypothesis [167].

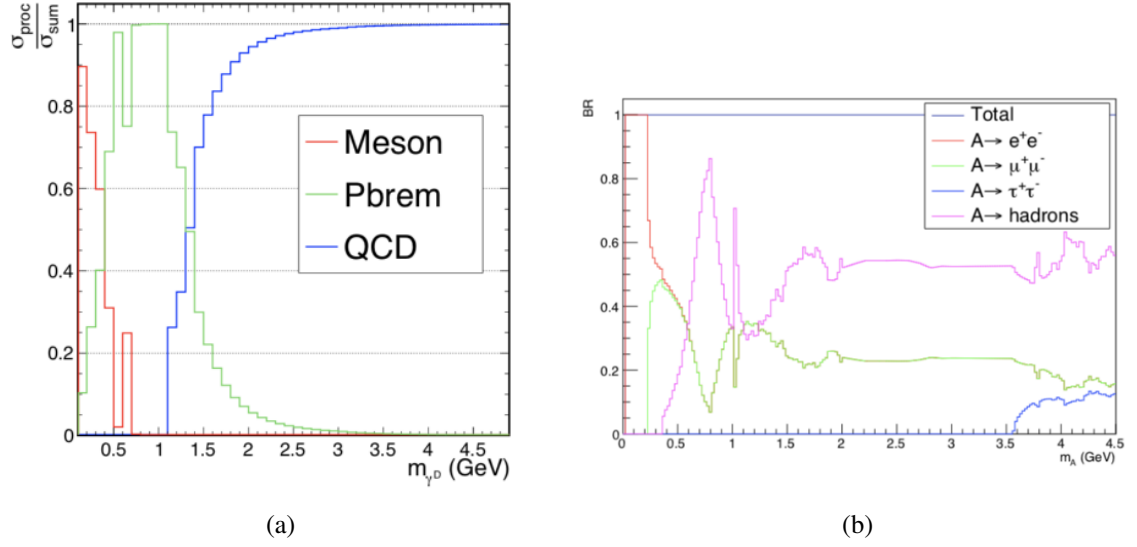


Figure A.3: (a) Dark Photon production cross section normalized by the total cross section as a function of Dark Photon mass for different production modes (through meson decays, photon bremsstrahlung and QCD). (b) Dark Photon branching fractions as a function of its mass for different channels. More information on Dark Photon production mechanisms can be found in [165, 168].

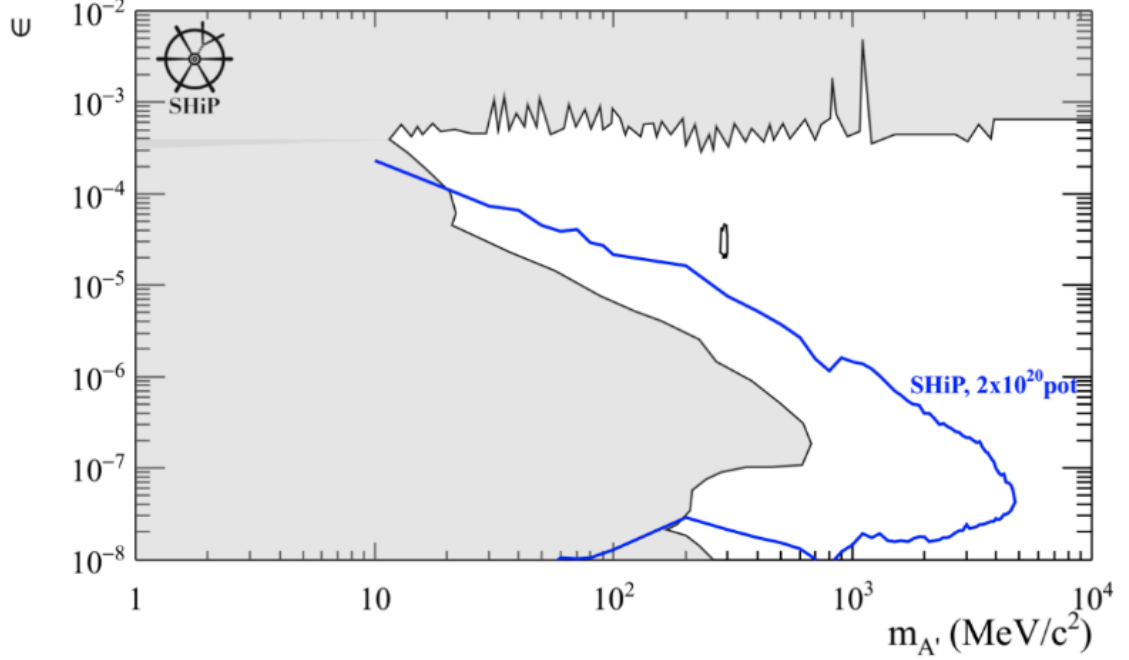
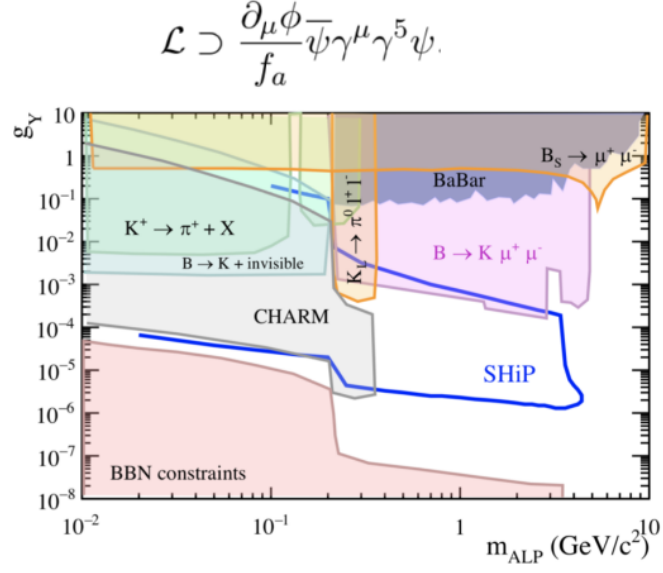
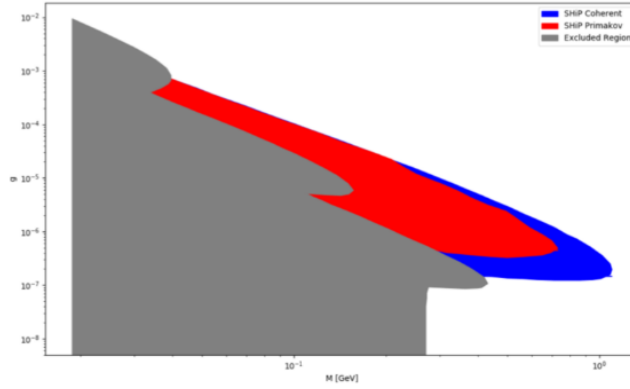


Figure A.4: SHiP sensitivity to Dark Photons. $m_{A'}$ is the mass of the Dark Photon, ϵ is related to the coupling to the SM [165].



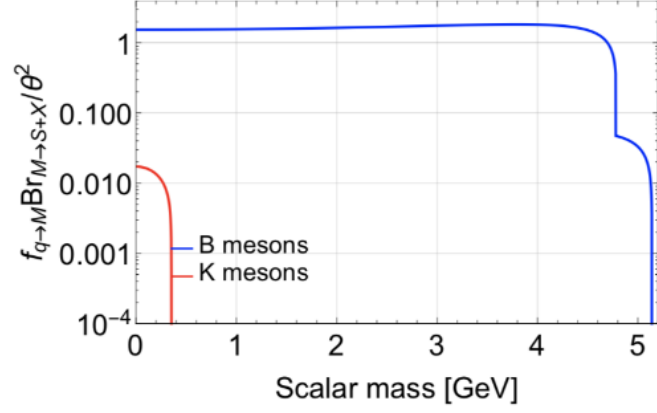
(a)

$$\mathcal{L} \supset \frac{\alpha}{4\pi f_a} \phi F^{\mu\nu} F_{\mu\nu}.$$

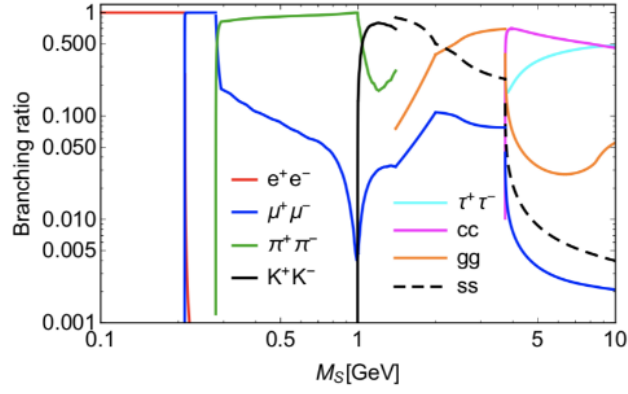


(b)

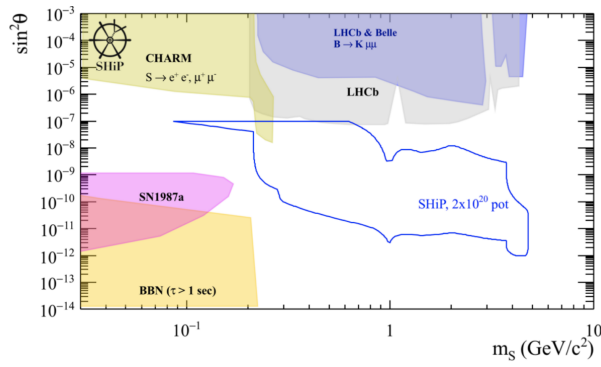
Figure A.5: (a) SHiP sensitivity to Axion-Like-Particles (ALPs) decaying to fermions for the given Lagrangian. On the x-axis is the mass of the ALP, on the y-axis is the coupling of the ALP to fermions. (b) SHiP sensitivity to Axion-Like-Particles decaying to photons for the given Lagrangian. On the x-axis is the mass of the ALP, on the y-axis is the coupling of the ALP to photons. In red is the SHiP $\text{ALP} \rightarrow \gamma\gamma$ production that takes place when $\gamma \rightarrow \text{ALP}$ scatters off the Coulomb field of a charged particle, called Primakov production [169–171], in blue is the SHiP coherent production [172] obtained through oscillations of ALPs into photons [165].



(a)



(b)



(c)

Figure A.6: (a) Production of Dark Scalar particles in SHiP. The y-axis is the production fraction. (b) Decay rates of Dark Scalars for charged lepton pairs ($e^+ e^-$, $\mu^+ \mu^-$ and $\tau^+ \tau^-$), pion pairs ($\pi^+ \pi^-$), kaon pairs ($K^+ K^-$), charm pairs (cc), gluon pairs (gg) and scalar pairs (ss). (c) SHiP sensitivity to Dark Scalars, m_S is the Dark Scalar mass, θ is the Dark Scalar mixing angle to the SM [165]. More on this mixing angle can be found in [173].

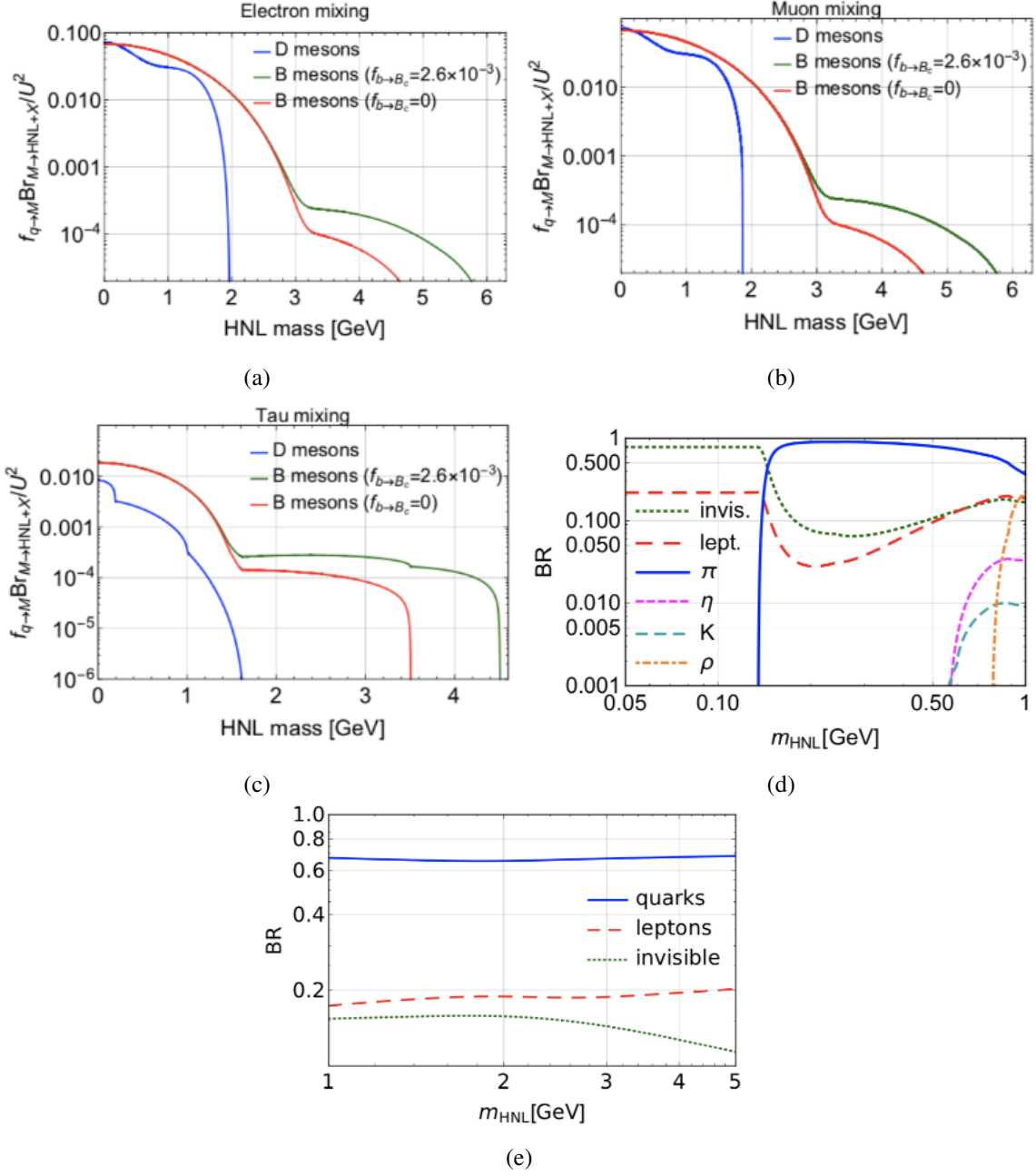


Figure A.7: (a) HNL mixing to electrons for different production through D mesons and B mesons with $f_{b \rightarrow B_c}$ being the production fraction of B_c . (b) HNL mixing to muons for different production through D mesons and B mesons. (c) HNL mixing to tau for different production through D mesons and B mesons. (d) Branching fraction of HNL as a function of their mass for decays to invisible particles (including neutrinos), leptons, pions, η meons, Kaons and ρ mesons. (e) Branching fraction of HNL as a function of their mass for decays to quarks, leptons and invisible particles (including neutrinos) [165].

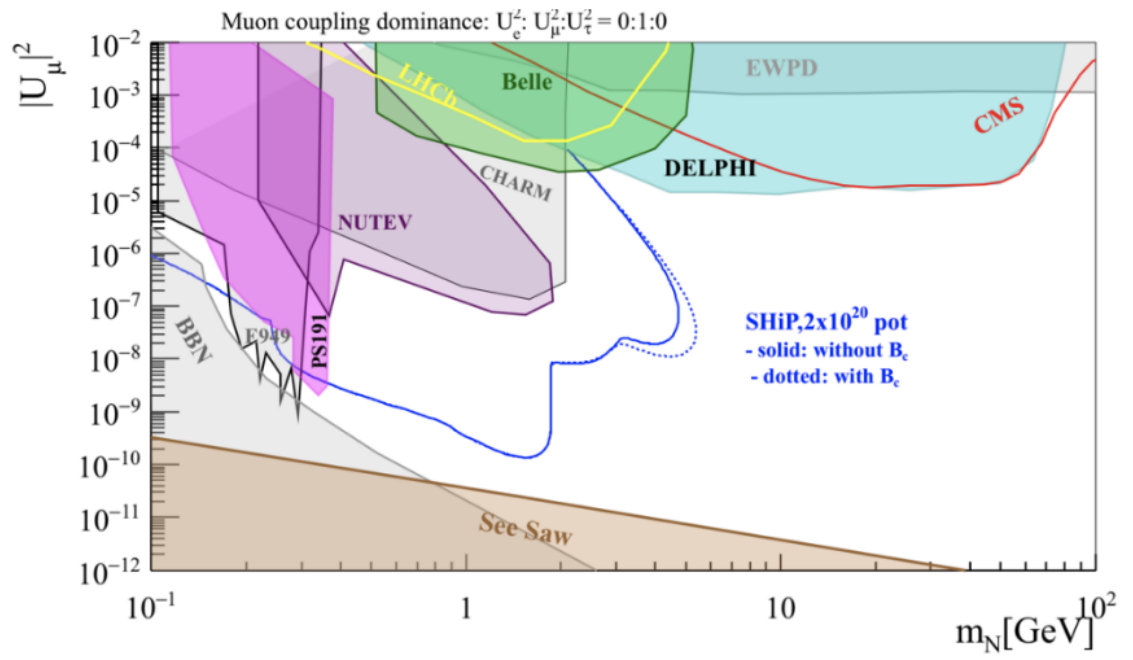
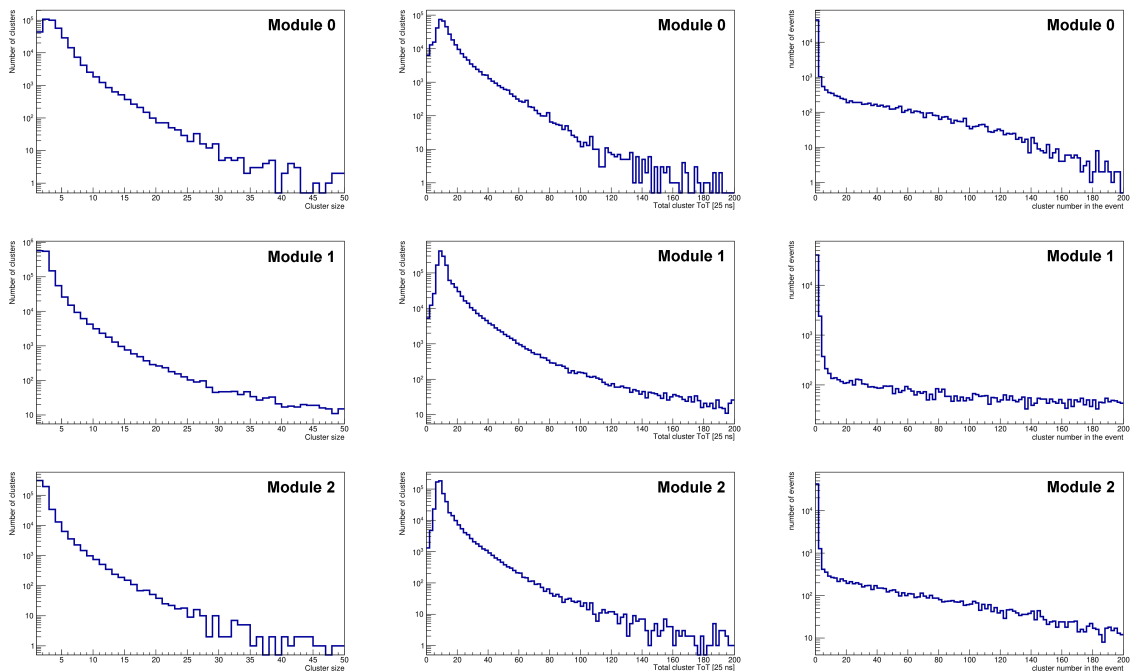
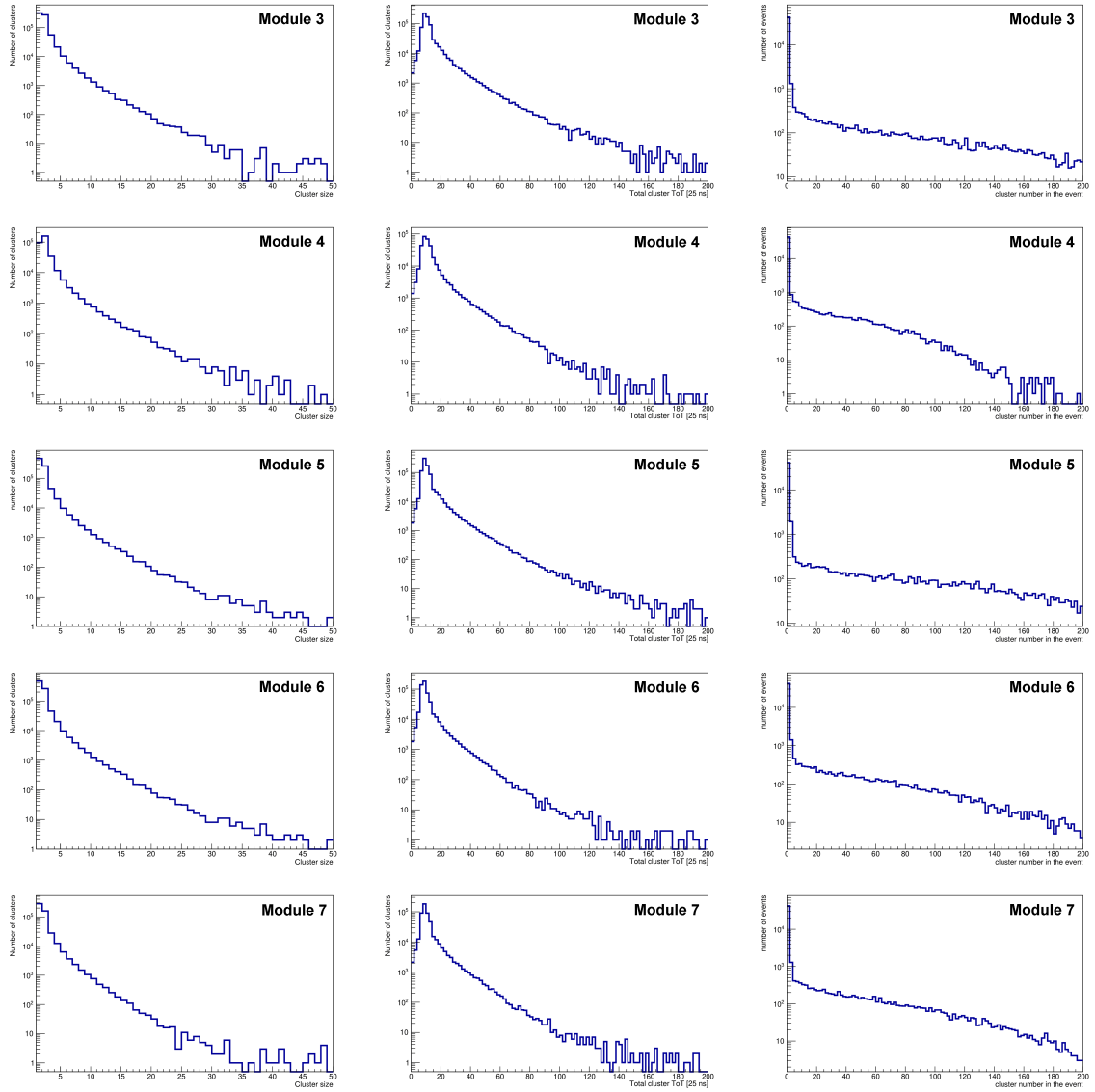


Figure A.8: SHiP sensitivity to HNLs. m_N is the mass of the HNL, U_μ is the coupling to the SM neutrino ν_μ [165].

Cluster information



Appendix B Cluster information



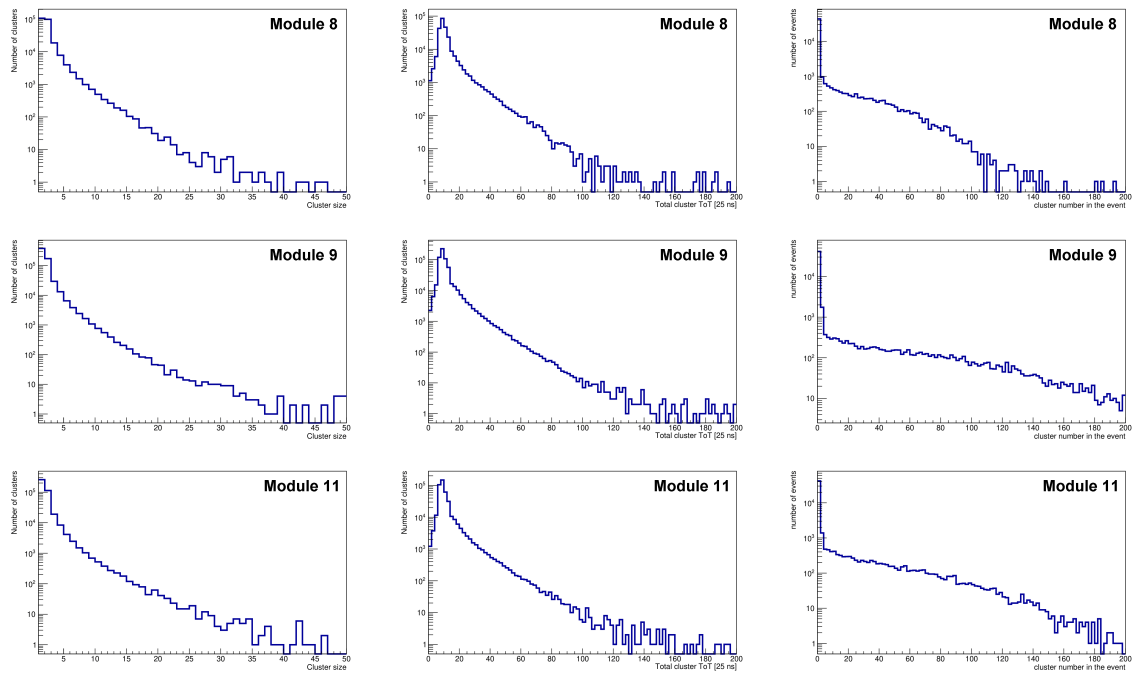


Figure B.1: (Left) Cluster size distribution. (Center) Cluster Charge distribution. (Right) Cluster number distribution. All data is given for Charm 1 Run 6. The modules are given in ascending order, excluding module 10 which is shown in Figure 4.17.

Beam width

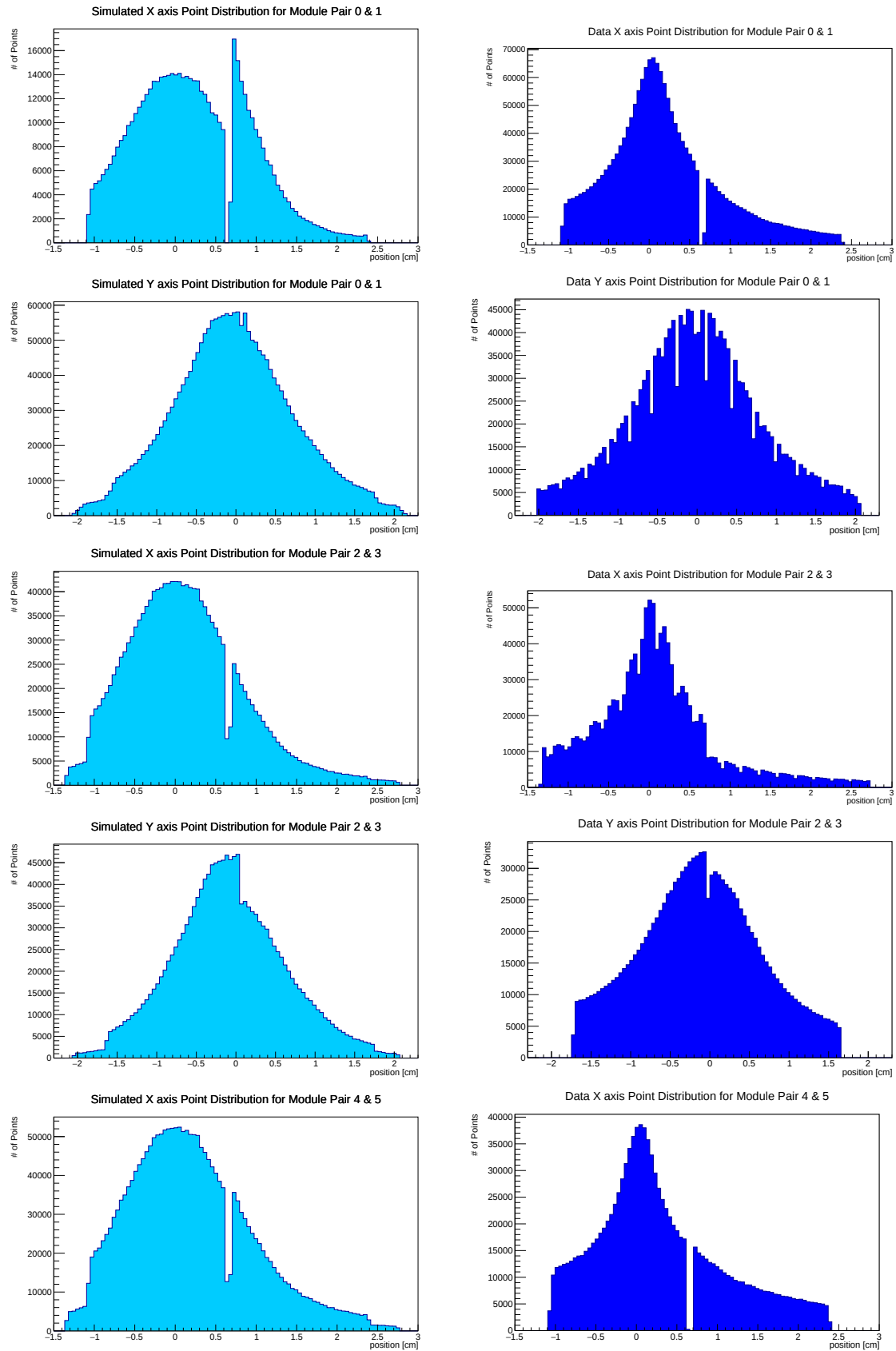
The beam width in simulation and data are compared. Figure C.2 shows the non-interacting primary protons ($\sim 70\%$ of initial primary protons for the Charm1-Run6 setup). The selection made for data are protons in spills with no passive material nor target in front of the pixel detector. The one made for simulation protons are those with momentum larger than 399 GeV. Hits in simulation are chosen before any clustering or smearing is applied. There is a clear distinction in the hits distribution. A difference can also be seen in the distribution excluding primary protons, selected from tracks with an angle in data and everything excluding the previous sample in simulation, as shown in Figure C.3.

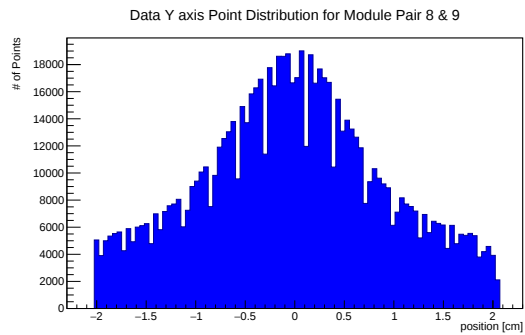
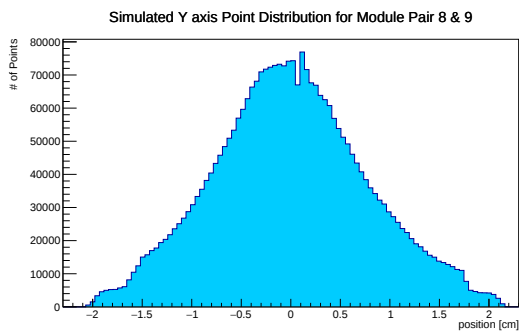
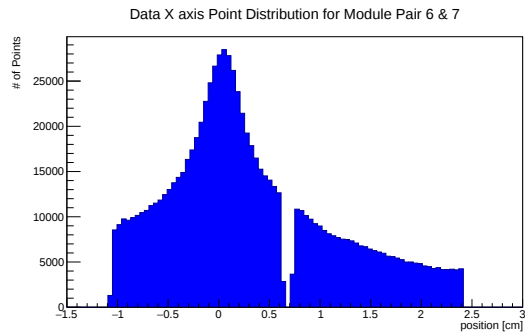
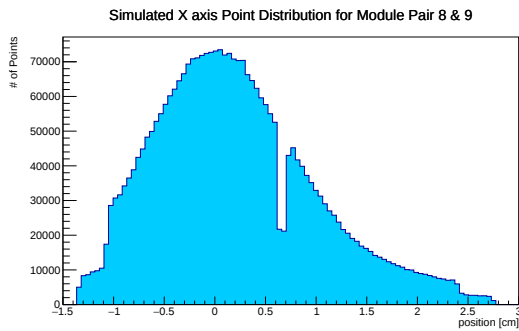
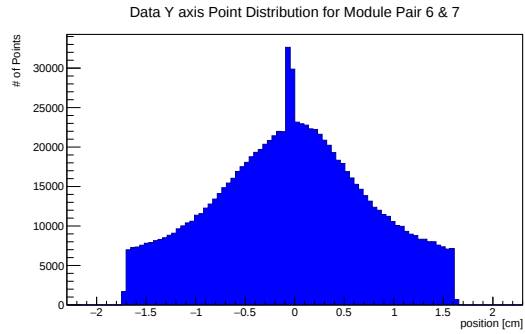
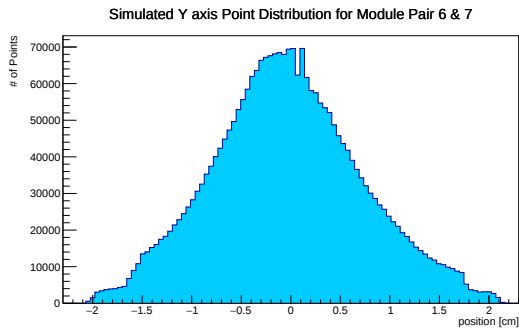
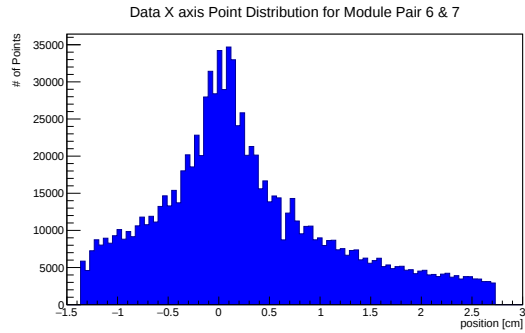
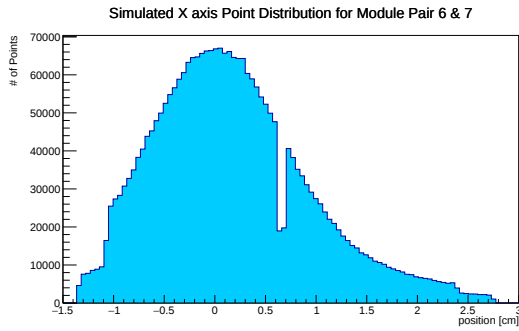
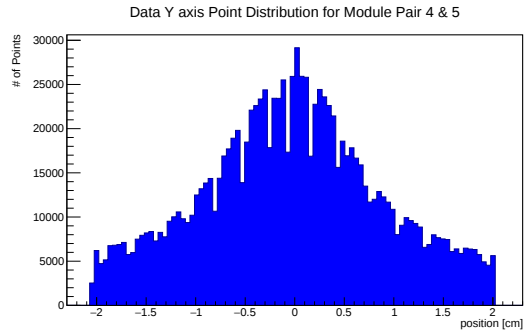
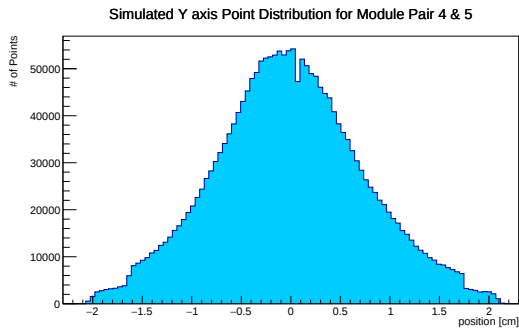
The quantization of this behaviour was desirable, thus the distributions were fitted in x and y as shown in Figure C.4 and Table C.2. A sizeable difference was found in the x coordinates and beam width. The emulsion simulation output was also investigated and found to be consistent with the pixel simulation. There was thus a difference in the incoming primary proton beam width distribution. A displacement of the FairShip detector coordinates is considered in order to adjust the beam to its true coordinates and insure that the detector acceptance is identical to the one used in data.

Module number	angle [rad]
0	0.0005
1	0
2	0.005
3	0.003
4	0
5	0.0023
6	0.0035
7	-0.005
8	0
9	0.0005
10	0.0045
11	0

Table C.1: Surveyed module angles [140].

Appendix C Beam width





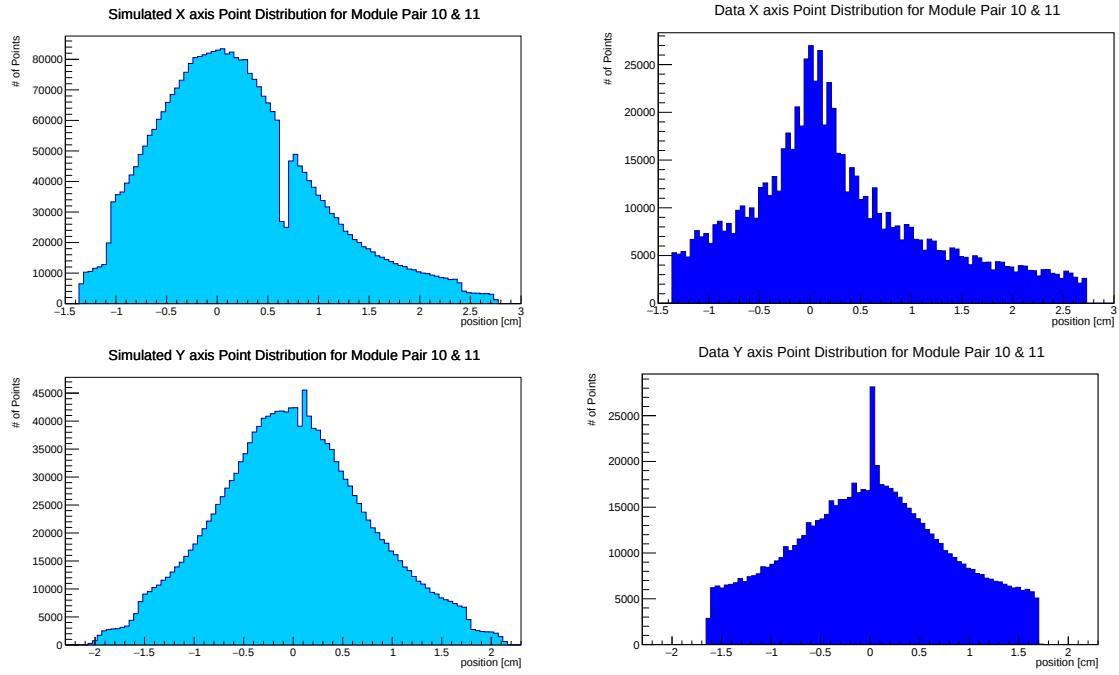


Figure C.1: x and y hit distribution for simulation (left) and data (right). Differences are caused by the different beam widths, the non-functioning chip on module 2 shown in Figure 4.13, the different beam positions, the absence of movement of the target in simulation and the absence of angles in simulation. This last effect is very weak as module angles are very small as shown in Table C.1.

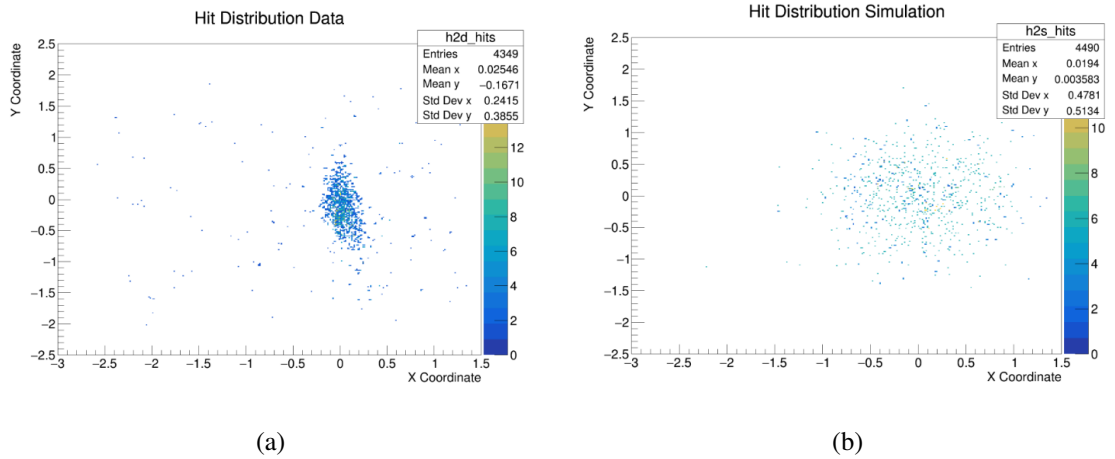


Figure C.2: (a) 2D histogram of primary protons hits in Charm1-Run6 data and (b) 10 000 events in the Charm1-Run6 setup simulation.

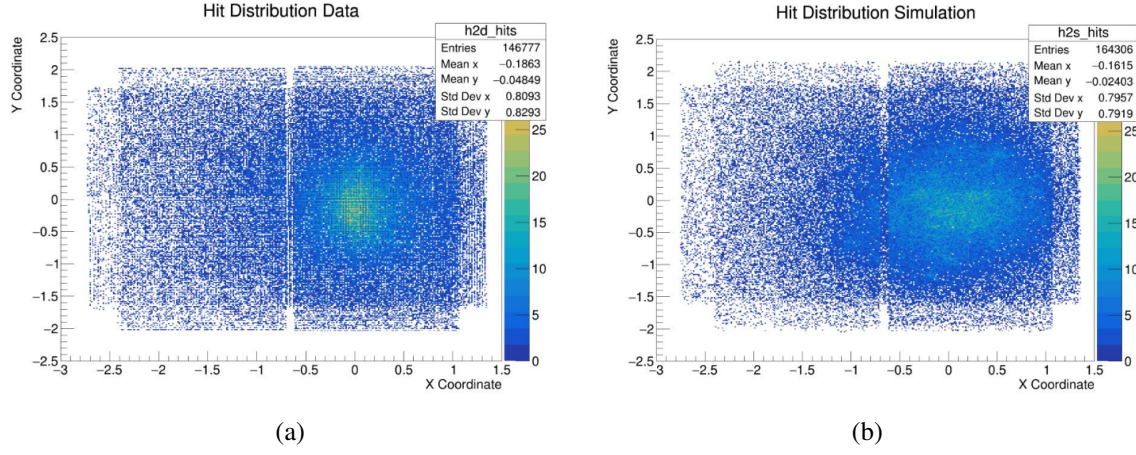


Figure C.3: (a) 2D histogram of all particles except for primary protons data plotted for hits belonging to tracks with no angle and (b) for simulation with all particles except for protons with forward momentum > 399 GeV is plotted. A clear discrepancy can be noted in the shape. Hits in simulation have not been subjected to clustering and are thus not smeared.

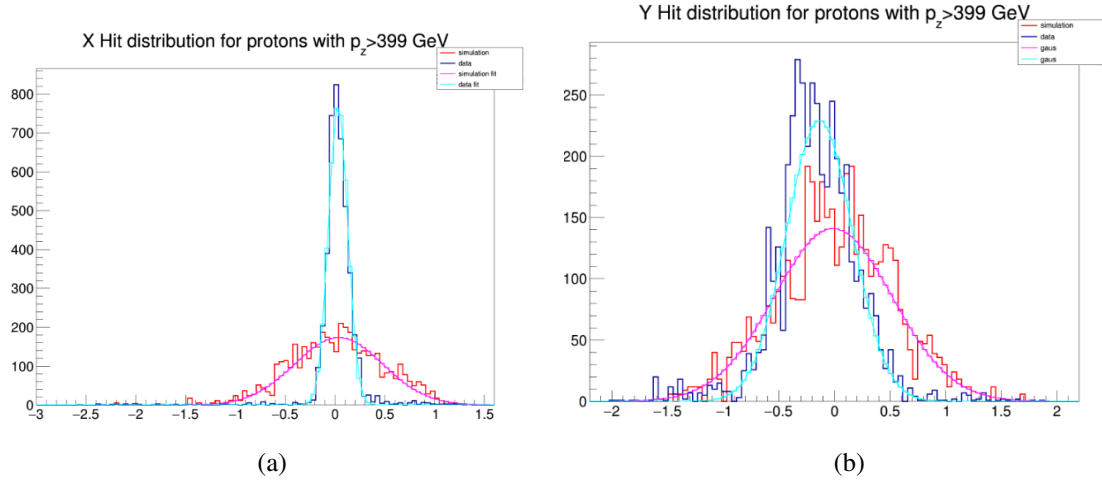


Figure C.4: Distribution and Gaussian fits of the x hits (a) and y hits (b) distribution for primary protons in data and simulation. The results of the fits can be found in Table C.2.

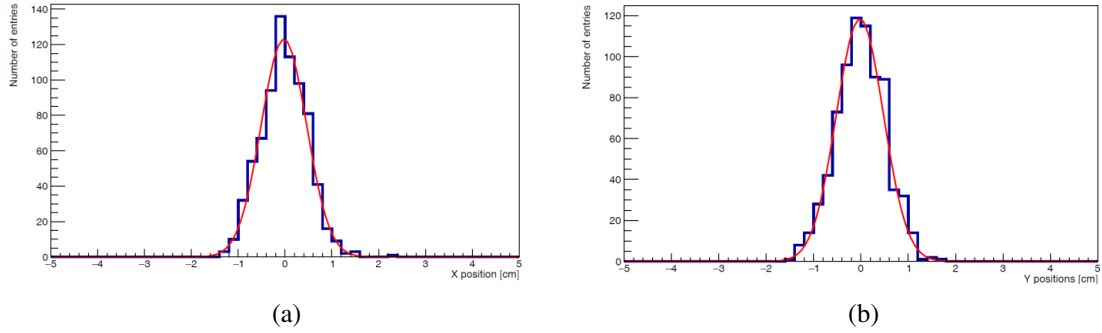


Figure C.5: Distribution and fit of points on the x-axis (a) and y-axis (b) of the last emulsion layer for the Charm1-Run6 setup simulation. The results of the fits can be found in Table C.2.

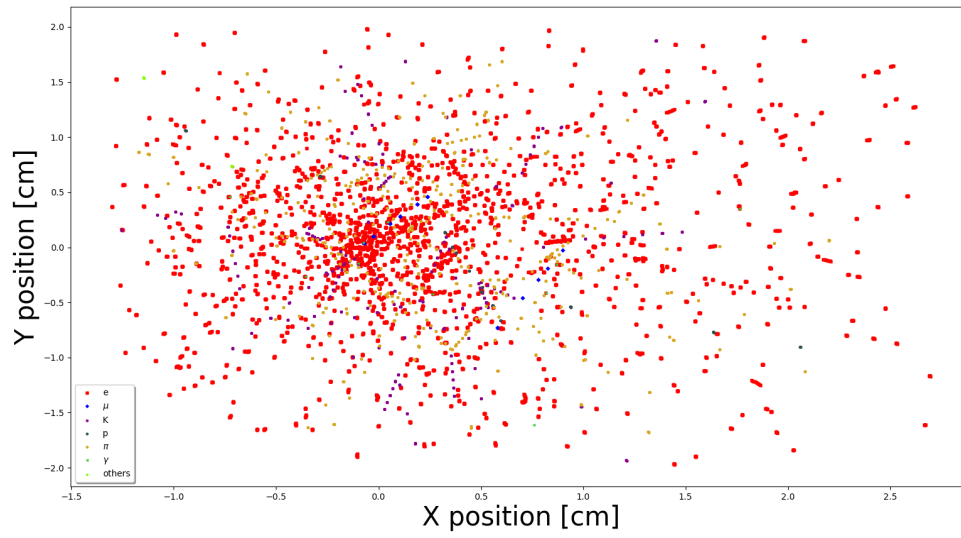


Figure C.6: 100 events from Figure 5.8 without electron cut. The large number of electrons makes it difficult to distinguish vertices.

Fit	A	μ	σ
Data x-axis beam profile fit (Subfigure C.4(a))	776.5 ± 15.5	0.03 ± 0.00	0.096 ± 0.001
Simulation x-axis beam profile fit (Figure C.4(a))	173.4 ± 3.3	0.04 ± 0.01	0.442 ± 0.005
Data y-axis beam profile fit (Figure C.4(b))	229.3 ± 4.6	-0.13 ± 0.01	0.297 ± 0.004
Simulation y-axis beam profile fit (Figure C.4(b))	141.0 ± 2.9	-0.01 ± 0.01	0.530 ± 0.008
Emulsion simulation x-axis beam profile fit (Figure C.5(a))	123.0 ± 5.5	-0.02 ± 0.02	0.485 ± 0.013
Emulsion simulation y-axis beam profile fit (Figure C.5(b))	118.5 ± 5.3	-0.02 ± 0.02	0.496 ± 0.127

Table C.2: Fit results for beam profiles found in Figure C.4.

Charm1-Run5 timestamps

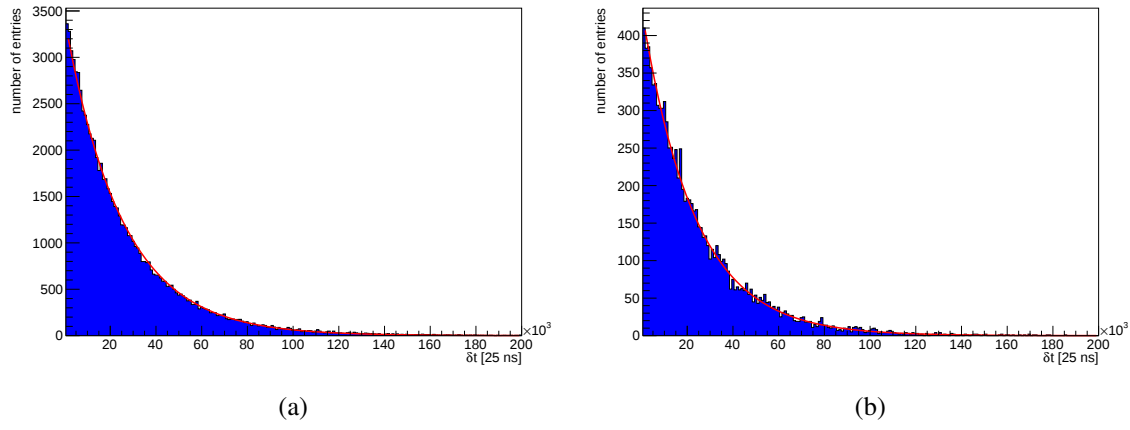


Figure D.1: (a) Distribution and fit of timestamps in Charm1-Run5. (b) Distribution and fit of 10 000 simulated timestamps using the Charm1-Run5 setup. The results of the fits can be found in Table D.1.

Fit	Constant	Slope
Charm1-Run6 data fit	7.72 ± 0.01	$(-4.26 \pm 0.02) \times 10^{-5}$
Charm1-Run6 simulation fit	6.06 ± 0.01	$(-4.28 \pm 0.04) \times 10^{-5}$
Charm1-Run5 data fit	8.14 ± 0.01	$(-4.00 \pm 0.01) \times 10^{-5}$
Charm1-Run5 simulation fit	6.08 ± 0.01	$(-4.32 \pm 0.05) \times 10^{-5}$

Table D.1: Fit results from Figures 6.4 and D.1.

Clustering

The effects of widening the charge cloud width have been investigated. This is shown in Figure E.1(c). The larger cloud size leads to an improvement in the cluster reconstruction resolution, as the cloud covers more pixels and thus allows for multiple pixels to contribute in the barycentre equation. This is seen in the first bin of each panel in Figure E.2. Since the cloud is larger relative to the pixel size, this leads to the pixel size losing in importance when computing the barycentre. When increasing the size to the point that the cloud starts to become prevalent, beyond the closest neighbouring pixels, a drop in resolution is seen. This can be observed in Figure E.2(d), where the cloud has twice the size of pixel width. This effect is shown in Figure E.1.

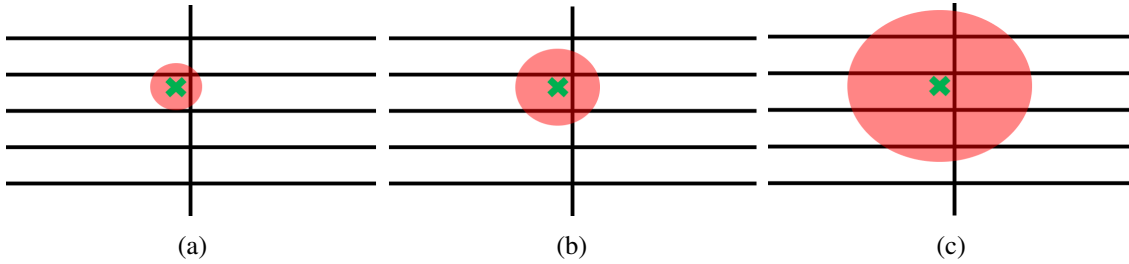


Figure E.1: Illustration of energy deposition in a pixel grid analogous to the one found in the ATLAS IBL for different cloud widths. (a) Small ($\sim 30 \mu\text{m}$), (b) medium ($\sim 50 \mu\text{m}$), and (c) large ($\sim 100 \mu\text{m}$). As the cloud gets larger, it covers more pixels, implying a better reconstruction, until the cloud goes beyond the closest neighbouring pixels into pixels not considered by the algorithm.

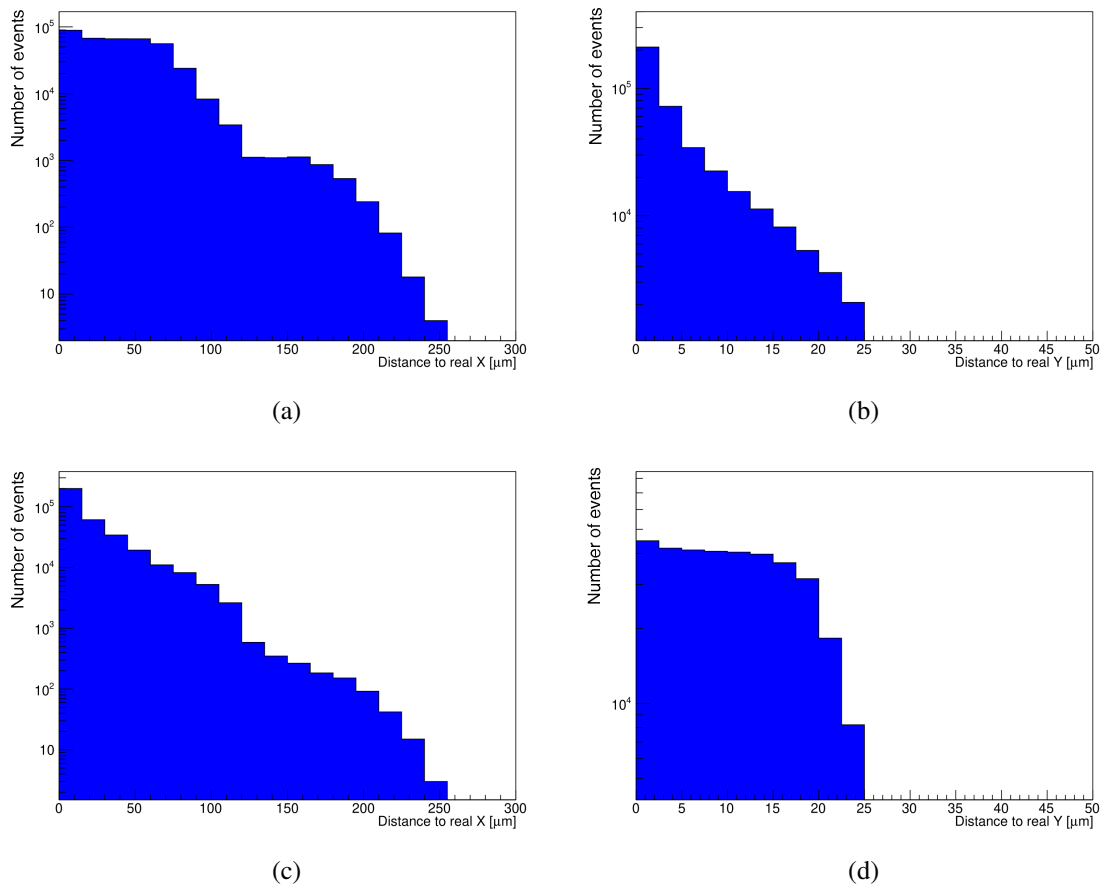


Figure E.2: Cluster centre distance to real energy deposition coordinates in the x-direction (a, c) and in the y-direction (b, d) for a 30 μm cloud width and a 100 μm cloud width, respectively.

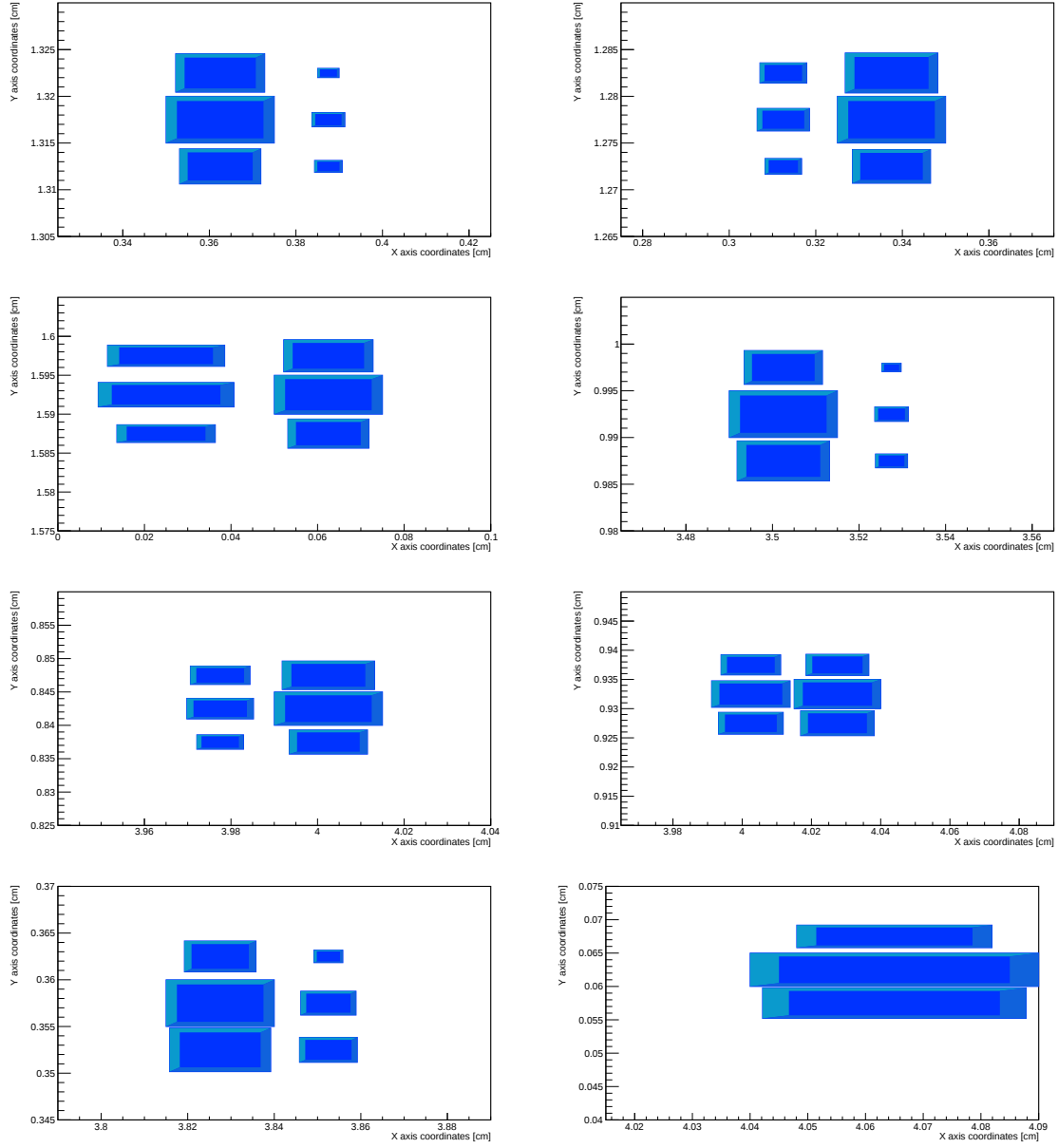


Figure E.3: Examples of multi-hits clusters obtained from FairShip simulation across modules. The size of the cluster is proportional to its ToT.

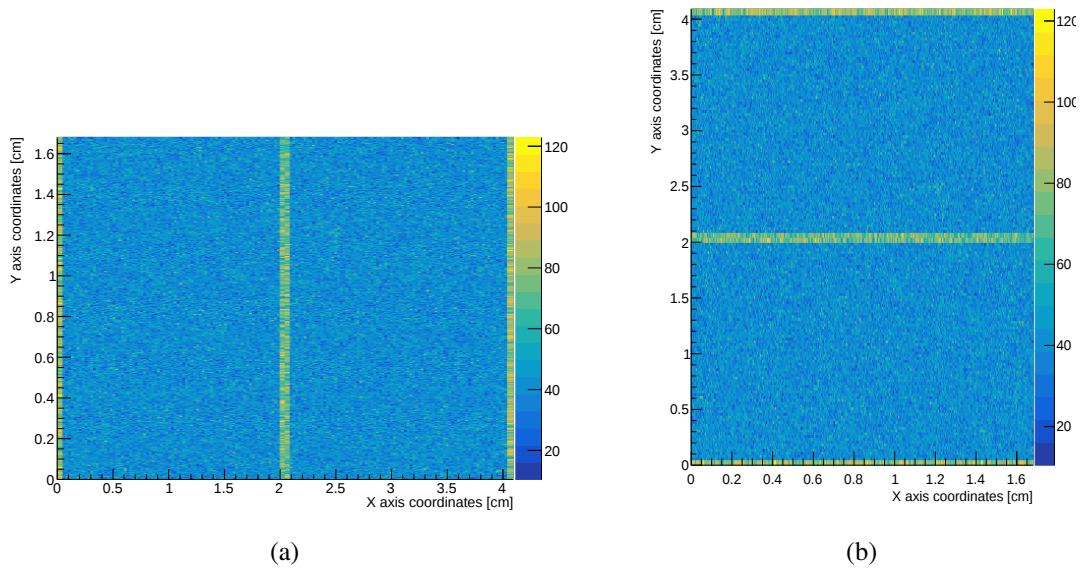


Figure E.4: Simulated (a) horizontal and (b) vertical pixel module illuminated by one million randomly distributed particles including clustering. The colors are scaled to the number of hits.