



The University of Manchester

DOCTORAL THESIS

Searches for CP violation in $D^0 \rightarrow K_S^0 K \pi$ decays with the Energy test method, module assembly and commissioning for the LHCb VELO Upgrade

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THE UNIVERSITY OF MANCHESTER

Abstract

Faculty of Science and Engineering
Department of Physics and Astronomy

Doctor of Philosophy

Searches for CP violation in $D^0 \rightarrow K_S^0 K \pi$ decays with the Energy test method, module assembly and commissioning for the LHCb VELO Upgrade

by Gianluca Zunica

A search for Charge Parity (CP) violation is performed in $D^0 \rightarrow K_S^0 K \pi$ decays with the Energy Test (ET) method, an unbinned model independent statistical method pioneered by the University of Manchester. This decay channel is a golden candidate for further CP violation discovery in the charm sector with a maximum predicted asymmetry as large as 0.003. The selection criteria and ET robustness tests are described, as well as control channel studied that confirmed the reliability of the method and excluded the presence of significant sources of bias in the signal sample. A visualisation tool is illustrated, which would allow to locate the phase space region contributing the most to CP violation effects, if found. The results are compatible with CP symmetry. The VELO Upgrade is a brand new detector replacing the old VERtEX LOcator, which played a crucial role in the reconstruction of primary and secondary vertices of interaction contributing to the many outstanding results delivered by the LHCb detector. The VELO Upgrade characteristics and modules assembly procedure are explained, along with their validation setup and procedure, followed by a report on the grading criteria used to classify each module. As the glue attaching the sensors to the cooling structure is responsible for the heat management of the modules, the results of the R&D effort carried out on the choice and assessment of the ideal production glue are illustrated. The High Voltage project developed during detector commissioning at CERN is described, specifically the Current vs Voltage (IV) scan panels and the Storck database implementation. The information extracted from the IV scans taken during 2022 allowed to carry out the first radiation damage estimation on the sensors after a the first year of data-taking.

Declaration of Authorship

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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Preface

The work presented here focuses on the search for Charge Parity (CP) violation in $D^0 \rightarrow K_S^0 K \pi$ decays with the Energy Test (ET) method using data collected by the LHCb detector during 2016-8. Then, the assembly and R&D activity carried out during the construction of the new VELO detector is described. Finally, the commission of the newly built detector is summarised, with an in depth description of the Current vs Voltage scan panels which enabled to perform the first radiation damage estimation on the detector sensors after 2022.

The first chapter gives a brief summary of the work carried out by the author and described in this thesis.

The second chapter introduces the framework of the Standard Model of particle physics and gives an overview of the CP violation mechanism, focusing specifically on the challenges of CP violation searches in the charm sector.

The third chapter describes the LHC accelerator and its four main experiments. A more detailed description of the LHCb experiment and its sub-detectors is given as well as an insight on the Run3 upgrades.

The fourth chapter reports in detail the search for CP violation in $D^0 \rightarrow K_S^0 K \pi$ decays. A theoretical motivation is given and the analysis strategy outlined. The ET is introduced as experimental method able to determine whether the analysed sample contains any trace of CP violation. A visualisation tool that would allow to locate regions in phase space contributing the most to the asymmetry is described as well. The selection requirements are reported, along with background checks. The sensitivity of the ET to different CP violation scenarios is described. The sensitivity studies were not carried out by the author and are reported here for the sake of completeness. The credits for this portion of the work go to Yue Pan. Then, the method robustness checks presented. The latter consists in the analysis of decay channel with similar characteristics of the signal channel but no CP violation. Finally, the results are outlined. The analysis work has been carried out by the author in all its parts (selection, robustness studies, crosschecks) with the exception of the sensitivity studies, as stated above.

The fifth chapter gives a brief overview of the theory of semiconductor materials, with a focus on silicon and silicon detectors. The main features of these are outlined, with a review of the radiation damage effects on their performance. Specifically, the main contributions to bulk damage effects are broken down

and described.

The sixth chapter introduces the new VELO Upgrade detector with a detailed breakdown of its layout and key features. Both the detector structure and modules are described, highlighting the technologies employed for the sensors and cooling.

The seventh chapter presents the assembly, metrology and validation of VELO Upgrade modules. These were carried out by the author in cooperation with the members of the VELO group at The University of Manchester. The database allowing for automatic grading of all the tests and modules is also reported. The author did not develop any of the database components and grading criteria, but used these tools as part of the validation process.

The eighth chapter offers a summary of the R&D activity carried out to re-optimize the process of tile gluing to the micro-channel substrate. The pattern optimisation activity is described for a number of alternative adhesives, followed by the experience gained in the production of mock-up and fully functional modules. A shear test campaign to assess the elastic properties of the adhesives after reiterated mechanical stress and accelerated ageing is also reported. The author contributed together with other members of the VELO group to these activities.

The ninth chapter focuses on the commissioning effort of the VELO detector after installation, with the development of two IV scan panels. The instantiation of the Storck database interface with the High Voltage project is outlined. With the IV scans collected during 2022 it was possible to carry out the first studies on the radiation damage of the sensors, which are described in this chapter. The author made a strong contribution to the development of the IV scan panels and the Storck interface. The radiation studies results were also led by the author.

The tenth chapter summarises the studies described in the thesis and concludes the thesis.

As the achievements in a big collaborations are never fully the results of a single person effort, all the studies that will be described in the aforementioned chapters are the results of the interaction of multiple researchers, offering their experience, advice and guidance to each other, including of course the author. Thus, the credit of the results obtained in the analysis goes first of all to its proponents, while the successful completion of the construction, validation and commissioning of the VELO detector have been possible thanks to the efforts of the components of the VELO group, both from Manchester and the rest of participating bodies. For this same reason, it is important to cite, when possible, those whom with the author cooperated the most during the aforementioned

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Chapter 1

Introduction

LHC is the longest and most powerful particle accelerator on the planet, capable of achieving proton-proton (p-p) collisions at centre of mass energy of 13.6 TeV. After allowing for the discovery of the Higgs boson, the last particle predicted by the Standard Model (SM) left to discover, research efforts have been directed in searches for what is referred to as “Beyond Standard Model” (BSM) physics, which could shed light on the intrinsic inconsistencies of the SM. The most stark of these is the matter-antimatter asymmetry measured in the universe at present days. As known, at the very beginning of the universe matter and antimatter were created in equal quantities in the Big-Bang, yet only matter has survived, and the known physics phenomena responsible for matter-antimatter asymmetry predicted by the SM, as CP violation are not enough to justify the sole survival of matter. The LHCb [1] experiment proposes to shed light on the mechanisms behind CP violation. The experimental apparatus consists of a single arm spectrometer focusing on beauty and charm hadron decays, with the goal of precisely reconstructing their decays to measure their creation and decay position to infer any CP violating effects. In this scope, this thesis will focus on searches for Charge Parity Violation effects in $D^0 \rightarrow K_S^0 K \pi$ decays (Chapt. 4), a promising channel in the charm hadron decay sector with a sizeable predicted asymmetry [2]. The analysis has been carried out with the “Energy Test” (ET) method, a model-independent method pioneered by the University of Manchester. As mentioned above, the reconstruction of the vertices of interaction plays a crucial role in the LHCb physics programme, with the “Vertex Locator” (VELO) detector playing a crucial role within this respect. The VELO detector which collected the data used in the $D^0 \rightarrow K_S^0 K \pi$ analysis was a micro-strip silicon detector with 46 retractable modules which could go as close as 7.1 mm from the beam line, with a primary vertex resolution close to 10 μm . After delivering excellent performance for almost ten years, the VELO has been replaced by the VELO Upgrade [3], a completely new silicon pixel

detector comprising 52 modules divided in two retractable halves reaching this time 5.1 mm to the beam when fully closed. The second part of the thesis (Chapt.6) is devoted to the description of the new detector and the contribution of the author to its assembly and commissioning, as well as to a number of R&D activities carried out during the VELO Upgrade assembly campaign effort.

Chapter 2

Theory

The SM is the foundation of particle physics since the 1970s and regardless of the discoveries and advancement that have taken place till nowadays, its validity still holds. In 2012 the discovery of the Higgs boson, the last remaining predicted particle yet to discover, represented the final success of this theory.

This chapter will introduce the SM (Sec. 2.1) and the concepts of CP violation (Sec. 2.2), along with a more detailed description of its mechanism in relation to the decay channel under study in this thesis (Sec. 4.1).

2.1 Standard Model

The SM of particle physics is a gauge theory that describes the electroweak and strong interactions in terms of fundamental pointlike particles which interactions are mediated by bosons. Fermions, which have half-integer spin, obey the Pauli exclusion principle and are split into quarks and leptons. These can be classified into three flavor families, comprising two quarks (up and down-type), one charged lepton and one neutral lepton each. Bosons, whose spin is integer, are classified into scalar and gauge bosons: the former, with zero spin, generate gauge bosons masses via spontaneous symmetry breaking mechanism, the latter with non-zero spin, are force carriers.

The three flavour families of fermions are identical except for their masses, which increase progressively, with the notable exception of neutrinos which mass ordering is still not defined. Quarks within each family are divided into up-type and down-type quarks, carrying $+(2/3)e$ and $-(1/3)e$ charge, respectively. Leptons carry an electrical charge of one, whereas neutrinos are neutral. There are four gauge bosons: the photon, γ , carrying the electromagnetic force, the $W^\pm$ and Z , carrying the weak force and eight types of gluons g , carrying the strong force. The only scalar boson is the Higgs boson H^0 that as stated above

is not a force carrier but generates the other boson masses. All the fundamental fermions and bosons are shown in Table 2.1.

u	c	t	H^0	
d	s	b		
e^-	μ^-	τ^-	γ	Z^0
ν_e	ν_μ	ν_τ	g	$W^\pm$

TABLE 2.1: Fundamental fermions and bosons of the SM. In the left upper quadrant: the three up (first row) and down (second row) type quark families; in the lower left quadrant: the three lepton families, with charged leptons in the upper row and their neutral counterpart in the bottom row. In the upper right quadrant: the Higgs boson; in the lower left quadrant: the force carrying gauge bosons.

In terms of groups, the SM is a $U(1) \times SU(2) \times SU(3)$ gauge field theory. In this scope, quantum field theory and group theory provide a mathematical framework that allows to easily obtain the generators of the fields and automatically extract conservation and symmetry laws.

2.1.1 Electroweak theory

Electroweak interactions are generated within the SM by the $SU(2)_L \times U(1)_Y$ groups, where $SU(2)_L$, which is non-abelian, produces the weak isospin and only couple to fermions that are left (L) handed. The $U(1)_Y$ group is the generator of the weak hypercharge (Y_W), where $Y_W = 2(Q - T_3)$, with Q being the electric charge and T_3 the weak isospin. In Table 2.2 the charge and weak isospin of left and right handed fermions is summarised.

Particle	Q_f	$T_{3,L}^f$	$T_{3,R}^f$	Anti-Particle	$Q_{\bar{f}}$	$T_{3,L}^{\bar{f}}$	$T_{3,R}^{\bar{f}}$
u, c, t	+2/3	+1/2	0	$\bar{u}, \bar{c}, \bar{t}$	-2/3	0	-1/2
d, s, b	-2/3	-1/2	0	$\bar{d}, \bar{s}, \bar{b}$	+2/3	0	+1/2
e^-, μ^-, τ^-	-1	-1/2	0	$\bar{e}^-, \bar{\mu}^-, \bar{\tau}^-$	+1	0	+1/2
ν_e, ν_μ, ν_τ	0	+1/2	0	$\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$	0	0	-1/2

TABLE 2.2: Charge (Q) and weak isospin (T_3^L) of left (L) and right (R) handed fermions (f) with their anti-particles ($\bar{f}$).

The electroweak interaction is mediated by three bosons, $\gamma, W^\pm, Z$, although the actual fields generated by the gauge groups are W^0 and $W^\pm$ for $SU(2)_L$ and B for $U(1)_Y$. The B and W^0 fields mixing then produces the Z and γ boson as their mass eigenstates.

$$\begin{pmatrix} \gamma \\ Z \end{pmatrix} = \begin{pmatrix} \cos \theta_w & \sin \theta_w \\ -\sin \theta_w & \cos \theta_w \end{pmatrix} \begin{pmatrix} B \\ W^0 \end{pmatrix}, \quad (2.1)$$

with θ_W , the weak mixing angle, computed from the coupling g and g' of the $SU(2)_L$ and $U(1)_Y$ groups, respectively:

$$\cos \theta_W = \frac{g}{(g^2 + g'^2)^{1/2}}, \sin \theta_W = \frac{g'}{(g^2 + g'^2)^{1/2}}. \quad (2.2)$$

The mass of the Z boson is then deduced as

$$m_Z = \frac{m_W}{\cos \theta_W}. \quad (2.3)$$

Summarising, within the electroweak theory framework, the $W^\pm$ boson mediates the flavour-changing charged currents and acts exclusively on left-handed fermions, the γ boson mediates the electromagnetic interaction which is parity-conserving, the Z boson mediates the neutral currents.

2.1.2 Strong interactions

The strong interaction, described by quantum chromodynamics (QCD), is generated by the non-abelian $SU(3)_C$ gauge group, where C stands for *colour*, which is the strong charge carried by gluons and quarks. The $SU(3)_C$ group generates three of such charges, *green*, *red*, *blue*, such that QCD describes quark fields in terms of triplets:

$$\begin{pmatrix} q_{red} \\ q_{green} \\ q_{blue} \end{pmatrix}, \quad (2.4)$$

The interactions are mediated by *gluons* (g), the bosons carriers of the strong force. These carry a colour and an anti-colour charge and interact with quarks and other gluons, i.e. the carriers of strong charge. QCD is described by the $SU(3)_C$ invariant Lagrangian

$$L_{QCD} = \bar{\psi}_i (i(\gamma^\mu D_\mu)_{ij} - m\delta_{ij}) \psi_j - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}, \quad (2.5)$$

where $G_{\mu\nu}^a$ is the gauge invariant field strength tensor

$$G_{\mu\nu}^a(x) = \delta_\mu A_\nu^a(x) - \delta_\nu A_\mu^a(x) + gf_{abc} A_\mu^b(x) A_\nu^c(x), \quad (2.6)$$

and where $D^\mu = \delta^\mu - igA^\mu(x)$ is the covariant derivative. In eq. 2.6 the term $A_\mu^b A_\nu^c$ produces gluon self coupling via triple and quartic gluonic vertices, which in turn produces colour confinement and asymptotic freedom [4].

2.2 *CP* violation

The SM has had an extraordinary success during its decades long life, both in describing the experimental behaviour of particles and in predicting those not yet discovered. Still, some incongruities between SM predictions and experimental observations are left unexplained, the most notable of these being the asymmetry between matter and antimatter in the universe. At the beginning of the universe, matter and antimatter were created in equal quantities, while at present day only matter has survived. The fraction of excess baryonic matter which allowed for its survival is estimated to be $O(10^{-9})$ [4]. The source of this asymmetry, known as “Baryogenesis”, is regulated by the Sakharov conditions [5], which must be satisfied in order for baryogenesis to manifest:

- Baryon number violation.
- C and *CP* symmetry violation.
- Interactions out of thermal equilibrium.

While *CP* violation has been formalised within the SM (see the following subsections) after its discovery in the meson sector, to this date no evidence of baryon number violation has been observed in baryon decays, and no *CP* violation in baryon decays has been observed either (see e.g. [6]). Furthermore, *CP* violation, at the levels allowed by the SM, which is per mille, cannot explain such asymmetry, which must imply the presence of a further mechanism breaking it. Hence, investigating *CP* violation offers the opportunity to possibly uncover new physics.

2.2.1 Symmetries in the SM

Laws of conservation are a key element of the SM in particle physics [4], more specifically, as stated by E.Noether’s theorem [7], to each symmetry of a Lagrangian a conserved current is associated. In terms of operators O acting on the hamiltonian H of a system, this is invariant under the transformation operated by O if

$$H_O \equiv O^\dagger H O = H. \quad (2.7)$$

If this condition is satisfied, then H is symmetric under O and O is conserved.

Three discrete symmetries govern the matter-antimatter asymmetry: parity, charge conjugation, time reversal.

2.2.1.1 Parity

Parity is a unitary operator which transformation reverses the sign of space coordinates

$$\mathbb{P}|\psi(q, \vec{x}, t)\rangle = P|\psi(q, -\vec{x}, t)\rangle, \quad (2.8)$$

where q is the charge, $\vec{x}$ is the spatial vector and t is time. As P is unitary and satisfies $\mathbb{P}^2 = 1$, its eigenvalues are real with $P = \pm 1$: these define the intrinsic parity of a particle. Fermions have intrinsic parity $P = +1$ (even parity), anti-fermions $P = -1$ (odd parity). P is a multiplicative quantum number, such that in a many body system

$$\mathbb{P}\psi(\vec{x}_1, \vec{x}_2 \dots \vec{x}_n, t) = P_1 P_2 \dots P_n \psi(\vec{x}_1, \vec{x}_2 \dots \vec{x}_n, t). \quad (2.9)$$

As example, for a particle in an angular momentum state km we have

$$\mathbb{P}|\psi_{km}(\theta, \phi)\rangle = (-1)^k |\psi_{km}(\theta, \phi)\rangle, \quad (2.10)$$

i.e. angular momentum states are parity eigenstates. Thus, for a system of particles the total parity will be the product of the intrinsic parities multiplied by the parity of the total angular momentum

$$\mathbb{P}|\psi_{L_1 m}(\vec{x}_1, \theta, \phi), \psi_{L_2 m}(\vec{x}_2, \theta, \phi)\rangle = P_1 P_2 (-1)^{L_1 + L_2} |\psi_{L_1 m}(\vec{x}_1, \theta, \phi), \psi_{L_2 m}(\vec{x}_2, \theta, \phi)\rangle. \quad (2.11)$$

Strong and electromagnetic interactions are invariant under parity transformations, with $P_\gamma = P_g = -1$, while weak interactions are not as e.g. the charged W boson couples to left handed electrons but not to right handed ones. In 1956 Parity violation was observed for the first time in the prominent experiment by C.S. Wu [8] on beta decay of cobalt-60. Parity violation was measured more recently in baryon $\Lambda_b^0 \rightarrow p \pi^- \pi^+ \pi^-$ decays with the ET method by the LHCb collaboration [9], observing an effect exceeding 5 standard deviations.

2.2.1.2 Charge conjugation

The charge conjugation operator $\mathbb{C}$ changes a particle into its anti-particle, meaning it flips all the quantum numbers (e.g. barionic, charge, leptonic) without acting on the space-time coordinates (e.g. time, position, momentum, spin)

$$\mathbb{C}|p, \psi(\vec{x}, t)\rangle = C|\bar{p}, \psi(\vec{x}, t)\rangle. \quad (2.12)$$

As $\mathbb{P}$, the charge conjugation operator is unitary ($\mathbb{C}^2 = 1$) with eigenvalue $P = \pm 1$. Electromagnetism and strong interaction are both invariant under $\mathbb{C}$, with $C_\gamma = -1$, whereas weak interactions break $\mathbb{C}$ invariance as e.g. the W charged boson couples with left handed electrons but not with left handed positrons. $\mathbb{C}$ -symmetry violation was discovered by L.Lederman [10] shortly after P -violation in the study of charged pion decays into $\mu^+ \mu^-$. Only particles that are their own anti-particles can be eigenstates of the $\mathbb{C}$ operator, i.e. the photon, the neutral pion or the ω , with $C_\gamma = -1, C_{\pi^0} = +1, C_\omega = +1$, respectively. In this regard, fermions are not $\mathbb{C}$ eigenstates as $\mathbb{C}|q\rangle = \pm|\bar{q}\rangle$, yet bound fermion states with neutral total charge (e.g $J/\Psi = c\bar{c}$) can be

$$\mathbb{C}|f\bar{f}\rangle = (-)^{L+S}|f\bar{f}\rangle, \quad (2.13)$$

with L and S being the total orbital momentum and total spin, respectively.

2.2.1.3 Time reversal

The $\mathbb{T}$ operator reverses time and all time dependant observables. It is anti-unitary, with $\mathbb{T}^2 = -1$. Once again, strong interaction and electromagnetism are invariant under time reversal, with weak interactions violating $\mathbb{T}$. A prominent example is the K^0 oscillation as the probability of this particle oscillating into its antiparticle is time dependent and is not symmetric under time reversal.

2.2.1.4 CP transformation

Charge-Parity transformations are the result of the subsequent application of the $\mathbb{C}$ and $\mathbb{P}$ operators, changing a left handed fermion into a right handed anti-fermion. CP symmetry is conserved by electromagnetic and strong interactions, while small violations occur in weak interactions in the weak decay of neutral kaons, which prompted the discovery of CP violation in 1964 by Cronin and Fitch [11], and in more recent days B and D mesons. Specifically, CP violation in B hadrons has been discovered by the Belle and BaBar collaborations in 2001 [12, 13] and in B_s hadrons by the LHCb collaboration in 2013 [14]. Finally, evidence for CP violation in the charm sector was announced in 2019, once again, by the LHCb collaboration [15].

2.2.1.5 CPT theorem

The *CPT* theorem states that under the combined application of $\mathbb{C}$, $\mathbb{P}$ and $\mathbb{T}$, the dynamic of a system remains unchanged. For Lorentz invariant quantum field theories this mean for example that particles and anti-particles must have the same mass, charge and decay time. Although *CPT* symmetry has to be respected globally, violation under one or two the these transformations are allowed, provided they are compensated for by a violation under the remaining operation or operations. An example of a phenomena that violates *CP* and $\mathbb{T}$ separately but respects *CPT* is the K^0 weak decay.

2.2.2 CKM matrix and CP violation

As stated above, $\mathbb{CP}$ transformation combines the discrete transformations of charge conjugation $\mathbb{C}$ and parity $\mathbb{P}$. The application of the $\mathbb{C}$ operator conjugates each quantum number switching particles with their anti-particles, and anti-particles into particles. Under $\mathbb{P}$ transformation space handedness is reversed. Thus applying the combined transformation of $\mathbb{CP}$ a fermion which is left-handed is transformed into an anti-fermion which is right-handed. If any physics *CP* conjugated process was to have exactly the same dynamics under $\mathbb{CP}$ transformation, then this would prove to be an exact symmetry. *CP* violation is parameterised within the SM by means of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [4], a unitary three-dimensional matrix with three Euler angles (three real parameters) and one imaginary phase.

In this scope, up-type quarks weakly interacts with their down-counterparts rotated by the CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}, \quad (2.14)$$

with $V_{CKM}^\dagger V_{CKM} = 1$.

In the SM all *CP* violation is generated automatically by the imaginary phase of the matrix when this is non-zero.

The matrix expression in terms of Euler angles and *CP*-violating phase is

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}, \quad (2.15)$$

where $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$, with θ_{ij} being the Euler angles between the quark generations; δ is the imaginary phase. Experimentally the hierarchy between the angles has been found to be $s_{13} < s_{23} < s_{12} < 1$ [16]. Quark transition proportional to c_{ij} are referred to as “Cabibbo-Favoured” (CF), while those

proceeding via matrix elements proportional one or two s_{ij} terms are referred to as “Singly-Cabibbo-Suppressed” (SCS) and “Doubly-Cabibbo-Suppressed” (DCS), respectively. In this representation it is useful to introduce an expression accounting for total amount of CP violation contained in the CKM matrix. This expression, known as Jarlskog invariant [17], is defined as

$$J = \text{Im}(V_{11}V_{22}V_{12}^*V_{21}^*) = c_{12}c_{13}^2c_{23}s_{12}s_{13}s_{23}\sin\delta, \quad (2.16)$$

where V_{ij} correspond to the CKM matrix elements. J is invariant under phase transformations and vanishes for $\theta_{ij} = 0, \theta_{ij} = \pi/2, \delta = 0, \delta = \pi$, which are the conditions for no CP violation.

Experimentally, from the measurements of the matrix elements, it is found that the the mixing angles between the quark generation are small, with $\phi_{12} = 13^\circ$, $\phi_{23} = 2.3^\circ$ and $\phi_{13} = 0.2^\circ$ [4]; this implies that the off-diagonal elements are quite small while the diagonal ones are close to 1. In this regards, the CKM matrix assumes a nearly diagonal form which well summarises the suppression of weak interaction between quarks belonging to different flavor generation in respect to those belonging to the same generations (i.e. the diagonal elements of the matrix). In this scenario interactions between quarks from third and first generation are the most suppressed [4]. A commonly used parametrisation of the CKM matrix, which exploits its diagonal nature [4], is the Wolfenstein parametrisation, which allows to single out small contributions and visualise the main ones

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4), \quad (2.17)$$

where θ_C is the Cabibbo angle of the 2×2 Cabibbo mixing matrix, $\lambda \simeq s_{12} = \sin\theta_C \sim 0.22$, $A\lambda^2 \simeq s_{23}/s_{12}^2$, $\rho = s_{13} \cos(\delta/s_{12}s_{13})$, $\eta = s_{13} \sin(\delta/s_{12}s_{23})$ and $A\lambda^3(\rho + i\eta) \simeq s_{13}e^{i\delta}$ with $\delta \simeq \tan^{-1}(\eta/\rho)$. The CP violation is zero when $\eta = 0$ which results in $\delta = 0$ as in this configuration the CKM matrix is real. Each CKM matrix element can be measured studying the decay amplitude of an appropriate quark transition. Thus, the current best measurements, summarised in Eq. 2.18 [18], have been obtained combining a vast amount of measurements on a wide variety of decay channels

$$|V_{CKM}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{pmatrix}. \quad (2.18)$$

From these measurements the imaginary CP violating phase is extracted: $\delta = 1.144 \pm 0.027$, highlighting the smallness of CP violating effects within the SM.

2.2.2.1 Unitarity triangle

The unitarity of CKM matrix requires that [18]

$$\sum_i V_{ij} V_{ik}^* = \delta_{jk}, \quad \sum_j V_{ij} V_{ik}^* = \delta_{jk}, \quad (2.19)$$

with V_{ij} being the matrix elements. These relations, six in total, each allow for a visual representation of the CKM matrix as a triangle in the complex plane. Conventionally the most popular of these representations is

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0, \quad (2.20)$$

as shown in Fig. 2.1.

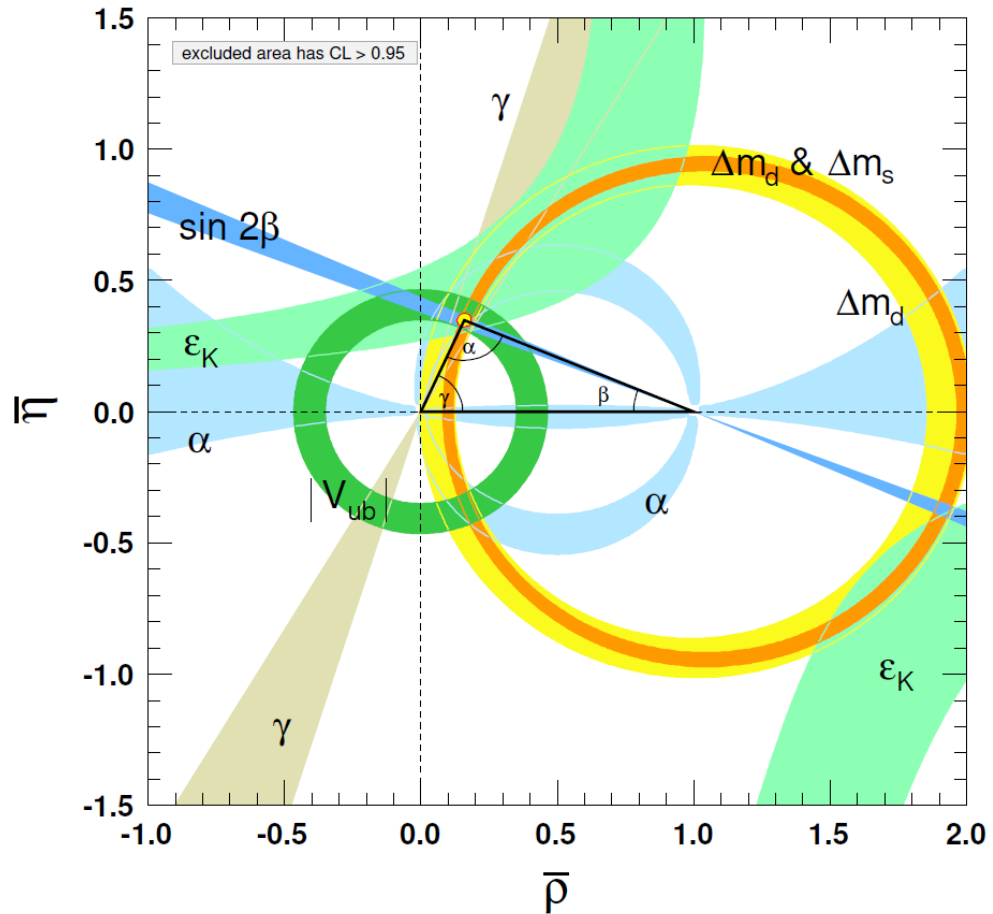


FIGURE 2.1: Unitarity triangle on the complex $\bar{\eta}$ vs $\bar{\rho}$ plane [18]. α, β and γ are related to the ratios between matrix elements, while $\bar{\eta}$ and $\bar{\rho}$ are the corresponding parameters described in Sec. 2.2.2 in the Wolfenstein parametrisation. Shaded regions correspond to a 95% CL.

The area of the unitarity triangle corresponds to half of the Jarlskog invariant. The unitarity condition expressed in Eq. 2.20 implies that the triangle is “closed”, thus great effort has been put into measuring every CKM element as a non-closed triangle would represent a clear hint of BSM physics. A further strategy to constrain CP violating parameters consists in measuring the triangle angles α, β and γ , which are related to the ratios between elements of different up-type quarks. The unitarity condition can be rewritten in terms of said angles as

$$\alpha + \beta + \gamma = 180^\circ, \quad (2.21)$$

thus measurements of the angles provide a further consistency test of the SM. Any discrepancy between measurements and predictions would constitute evidence for new physics. Figure 2.1 demonstrates how progressively constraining matrix elements and thus angles, in particular α and γ , is importance to confirm or reformulate the current interpretation of CP violation withing the SM. In this respect, decay modes involving loop diagrams are of particular interest as they may allow to probe BSM enhancements of the predicted CP violating SM effects.

2.2.3 Neutral meson mixing

As neutral mesons are strong interaction but not CP eigenstates, they transit to their CP conjugate in-flight in a process called “mixing”. Meson mixing is one of the most elegant examples of the principle of quantum superposition in nature, allowing to experimentally observe the fundamental principle of quantum mechanic at work. Mixing can occur via two main contributions, namely short and long range hadronic interactions. Short range interactions, i.e. exchange of intermediate quarks, are realised via box diagrams (Fig. 2.2, top). These are the main contributions in kaon and B neutral meson mixing, while being heavily suppressed in the charm sector. The second row of the CKM matrix contains the elements related to charm quarks: the main contribution for charm mixing in box diagrams is proportional to $V_{ci}^* V_{ui}$, with $i = d, s, b$. A first disadvantage is that the virtual quarks are all bottom type and thus have smaller masses than their up-type counterparts, specifically $m_b \sim m_t/40$. A second issue is represented by the small mass difference between s and d quarks, which means contributions via exchange of these quarks are suppressed as their contributions are similar in size but opposite in sign [19, 20]. Finally, the $V_{cb}^* V_{ub}$ contribution is minute, of the order of $O(\lambda^5)$. The second and main contribution to neutral meson mixing in charm are long range interactions (Fig. 2.2, bottom).

The D^0 mesons can decay in flight to CP eigenstates as K^+K^- or $\pi^+\pi^-$ that recombine into a $\bar{D}^0$ meson.

2.2.4 *CP* violation in neutral mesons

The mass eigenstates of neutral mesons can be written in terms of linear combination of flavour eigenstates with the relation

$$\begin{aligned} |P_1\rangle &= p|P^0\rangle + q|\bar{P}^0\rangle, \\ |P_2\rangle &= p|P^0\rangle - q|\bar{P}^0\rangle, \end{aligned}$$

with p and q being complex parameters satisfying $\|p\|^2 + \|q\|^2 = 1$.

Within this theoretical scheme, the sources of CP violation can originate from mixing, decay or interference between the mixing and decay. CP violation in decay is referred to as *direct*, whereas “indirect” CP violation is generated by mixing and interference between mixing and decay.

When the transition amplitude between initial and final states $P \rightarrow f$ differs from the one of the conjugate decay $\bar{P} \rightarrow \bar{f}$

$$\frac{\|A_f\|}{\|\bar{A}_{\bar{f}}\|} \neq 1, \quad (2.22)$$

where $\|A_f\|$ and $\|\bar{A}_{\bar{f}}\|$ are the decay amplitudes, then CP violation in decay manifests. For baryons and charged mesons decays this is the only possible type of CP violation to occur as mixing is not allowed by baryon number and electric charge conservation, respectively. Neutral mesons on the other hand can break CP symmetry also in mixing when

$$\left\| \frac{p}{q} \right\| \neq 1. \quad (2.23)$$

Mixing processes have two sources of contributions, namely long range (Fig. 2.2) and short range hadronic interactions, the latter mediated by intermediate quark exchange in “box” diagrams. As stated above, since the contributions via box diagram is small, the dominant contributor to D^0 mesons mixing are thus long range hadronic interactions, where a D^0 meson transitions via SCS decay to K^+K^- or $\pi^+\pi^-$ couple, which are eigenstates of the CP operator, and recombines in-flight into a $\bar{D}^0$ meson.

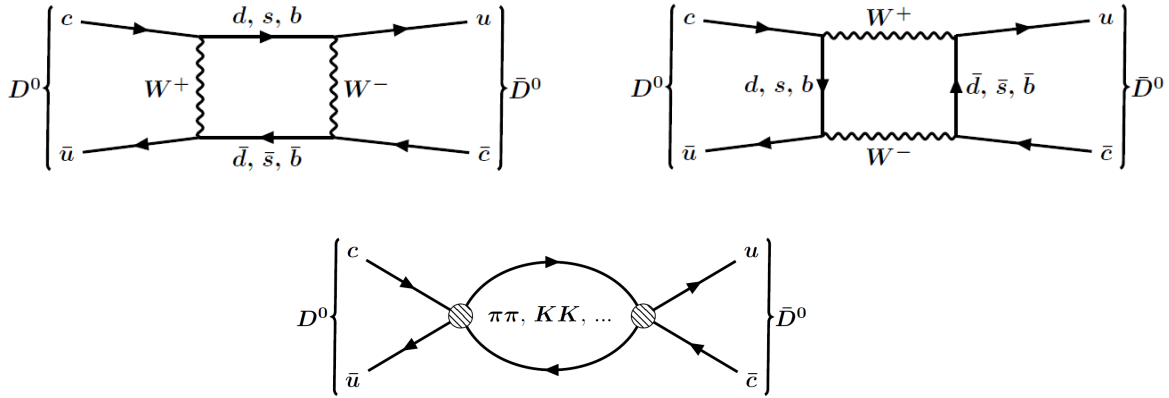


FIGURE 2.2: Contributions to neutral charmed meson mixing: short range box diagrams (top) and long range hadronic interactions (bottom) [20].

CP violation in interference can occur if a neutral meson and its anti-particle (P^0 and $\bar{P}^0$) decay both to the same CP eigenstates but with different amplitudes. In this scenario CP violation is generated by the interference between the decay with mixing $P \rightarrow \bar{P} \rightarrow f$ and the one without $P \rightarrow f$ if

$$\text{Im}(\lambda_f) \neq 0, \quad (2.24)$$

where

$$\lambda_f = \frac{q}{p} \frac{\bar{A}_{\bar{f}}}{A_f}, \quad (2.25)$$

with A_f is the decay amplitude without mixing and $\bar{A}_{\bar{f}}$ the amplitude of the decay with mixing.

Chapter 3

The LHC and LHCb detector

3.1 LHC

The Large Hadron Collider (LHC) [21] is a ~ 27 km accelerator complex near Geneva. It is the longest accelerator to present day, built to achieve p-p collisions up to 14 TeV of centre of mass energy with a peak luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The LHC has been built to explore BSM physics as well and test SM theories as CP violation, Supersymmetry, or the Higgs Mechanism.

The LHC is located in an underground tunnel under the Swiss-French border, stretching 26.7 km in length. The accelerator layout comprises two superconducting rings composed by more than 5000 superconducting magnets responsible for accelerating, bending and focusing the beam. The magnets use a NbTi alloy cooled to 1.5 K with superfluid helium to ensure superconductivity is reached. The coils can produce magnetic fields up to 8.4 T with a circulating current of around 11.7 kA. The rings intersect in 8 Interaction Points (IP), in 4 of which the main experiments are located. To reach the nominal energy, a chain of smaller accelerators (Fig. 3.1) gradually accelerates the protons before the injection in the main ring. The beams are generated by LINAC4 [22], which replaced the old LINAC2, where the protons are accelerated up to 160 MeV before being injected in the Proton Synchrotron Booster, where the energy is increased to 2 GeV. The protons are then injected in the Proton Synchrotron (PS), where the energy of 26 GeV is reached; from here the beams reach the Super Proton Synchrotron (SPS), where they are accelerated up to 450 GeV. Finally, the proton bunches are divided and injected in opposite directions in the LHC. The machine is capable of realising p-p collisions as well as heavy ion collisions (Pb-Pb or Xe-Xe).

As already mentioned, at the 4 IP the main experiments are located: ATLAS (A Toroidal LHC Apparatus), CMS (Compact Muon Solenoid), ALICE (A

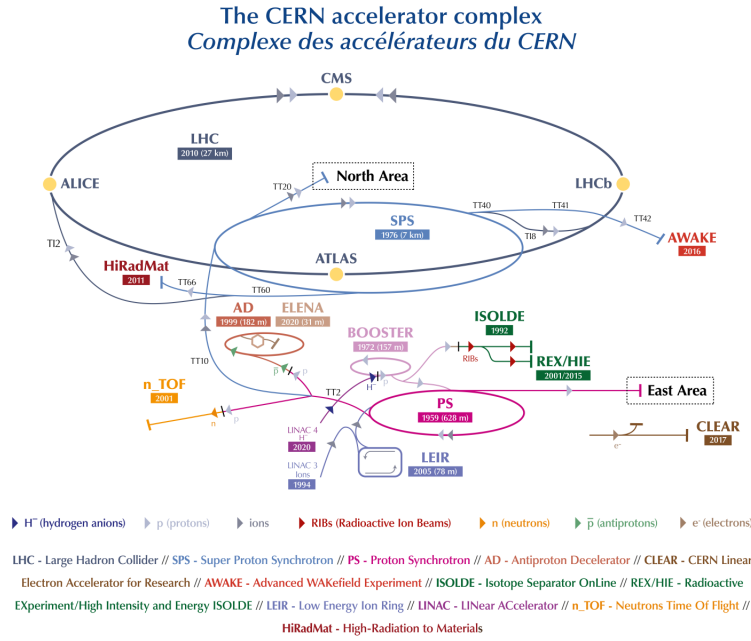


FIGURE 3.1: The LHC accelerator complex.

Large Ion Collider Experiment), LHCb (LHC beauty) (Fig. 3.2). ATLAS [23] and CMS [24] are positioned at point 1 and 5, respectively and are multi-purpose experiments complementary to each other. Their main purpose was the Higgs Boson discovery (reached the 4th July 2012) and the physics at the high energy frontier, comprising BSM theories like Supersymmetry, Dark Matter and test of the SM predictions. These experiments have been built to operate at peak luminosity ($L \simeq 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) with p-p collisions. ALICE [25] is located in the IP2 cavern, it is an experiment focused on the study of quark-gluon plasma produced in heavy-ion collision. This detector can operate both with Pb-Pb and Pb-p beams, and can operate at a luminosity up to $L = 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ with a center of mass energy of $\sqrt{s_{NN}} = 5.5 \text{ TeV}$. Quark-gluon plasma is a phase of matter where both quark and gluons are deconfined, creating the opportunity to understand the mechanisms underlying the first instants of the life of the Universe and other phenomena as such neutron stars. LHCb, at IP8, is a single arm forward Spectrometer [26], which studies are focused on flavour physics (e.g. b and c hadron oscillations, and all heavy quarks physics in general) and CP violation to investigate the matter-antimatter asymmetry in the universe. It consists of a 21 m long spectrometer for the identifications of particles produced in the p-p collisions, and it is meant to operate at "low" luminosity ($L \simeq 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$). Finally, the TOTEM (TOTal Elastic and Diffractive cross section Measurement) experiment is located at IP5 sharing the experimental hall with CMS. TOTEM measures the elastic scattering and total cross section

upgrade is outlined as well, including the VELO Upgrade that will be further described in Chapt. 6. All the subdetector upgrades been successfully installed in time for the start of 2023 datataking and will operate until the end of Run4 in 2032.

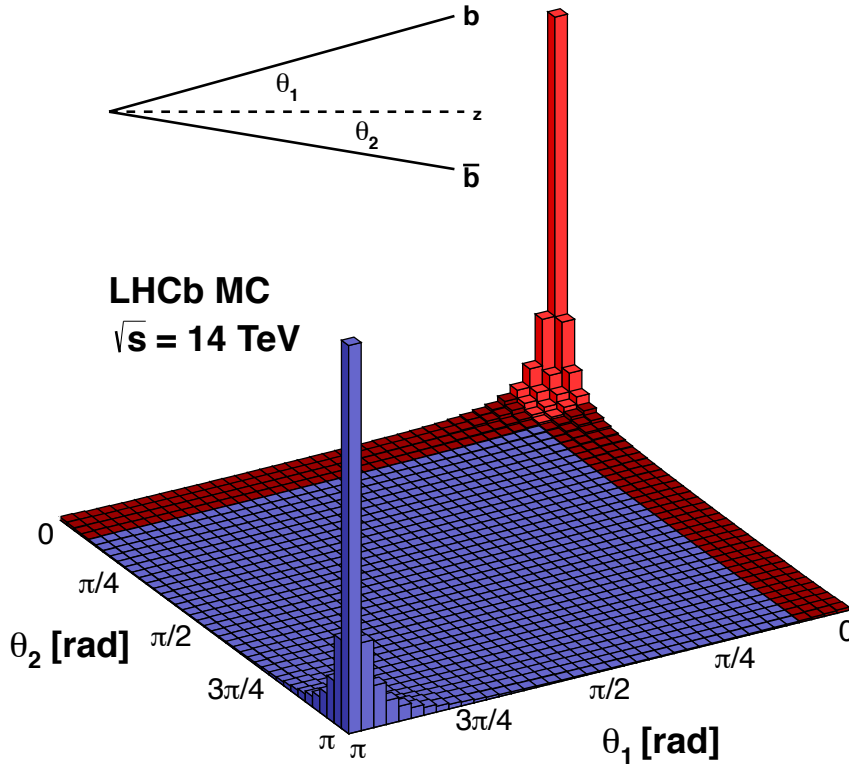


FIGURE 3.3: Angular distributions of b hadrons pairs at 14 TeV [30]. θ_1 and θ_2 represents the b hadron production angles along the z axis i.e. the beam line. The distribution is sharply peaked near $\theta = 0$ and π . The LHCb angular acceptance region is shown in red.

3.2.1 VELO detector

The VELO detector [31] (Fig. 3.4) is a silicon microstrip tracker, decommissioned at the end of Run2, consisting of 42 half-moon shaped modules divided in two retractable halves that can go as close as 8.1 mm to the interaction zone. Each module contains an r and ϕ plane used to measure radial and polar coordinate with a resolution of $13 \mu\text{m}$ on the x and y coordinate. Cooling is provided by evaporative CO_2 flowing through aluminium blocks attached at the edge of the Printed Circuit Board (PCB), allowing for an operation temperature of -5°C . Each half is enclosed in a thin aluminium box, the RadioFrequency (RF) foil, to

separate it from the beam vacuum and shield it from the beam induced-charge. The main purpose of the VELO detector, aside from identifying tracks, is to provide accurate discrimination between creation and decay vertices of beauty and charm hadrons [31], as well as precise measurements of their lifetimes and impact parameter.

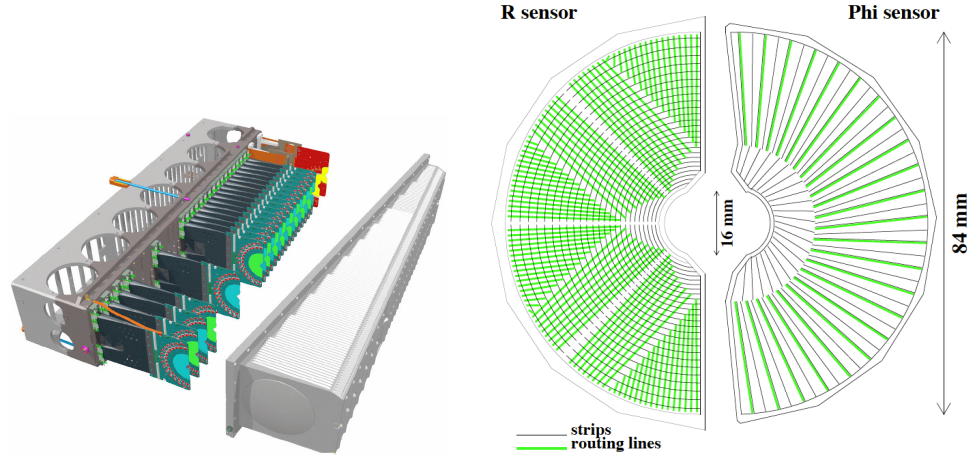


FIGURE 3.4: The old VELO detector. On the left the structure of one half with the RF foil [32]: the sensors are in green-blue, the support structure in grey. On the right the structure of each sensor [33]: R and Phi microstrips, installed back to back on each module, allow to measure both radial and polar coordinate.

3.2.1.1 VELO Upgrade

The VELO Upgrade detector (Fig. 3.5), replacing the old VELO (Fig. 3.4), is a pixel silicon tracker composed of 52 modules split in two retractable halves. When closed, they go as close as 5.1 mm from the beam line. Each of the modules comprises 4 sensors, two on each side, bump bonded to three ASICs each. The detector offers enhanced tracking with its 41 million readout channels and a 40 MHz readout rate. Each VELO module is cooled via evaporative CO₂ [34] flowing inside 19 micro-channels etched into a silicon substrate, which offers both structural support and cooling, onto which the ASICs are directly glued. This ensures low and even material budget, while providing excellent thermal efficiencies for the dissipation of the 30 W of energy produced by each modules during operation conditions.

3.2.2 Tracking stations

The tracking stations together with the VELO form the LHCb tracking system. There are four tracking stations: the TT, a single station silicon microstrip detector located before the magnet, and the IT-OT, comprising three stations

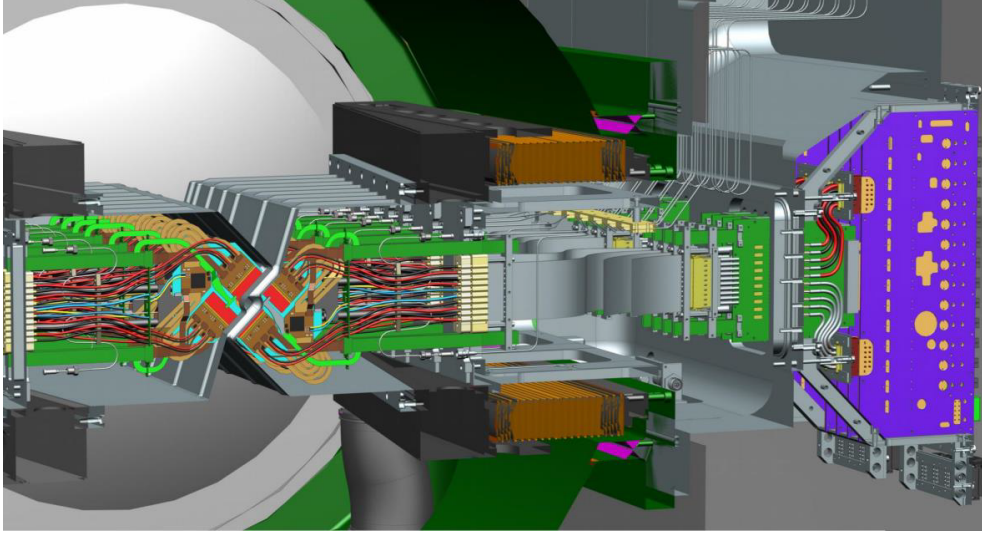


FIGURE 3.5: Schematics of the VELO Upgrade detector [35]. The modules and the RF foil on each half are shown on the left hand side, with sensors highlighted in red and micro-channel plates in azure. The Vacuum Feed-through Board (light green) and Opto-Power Board (purple) are shown on the right hand side of the diagram.

(T1, T2, T3) located after the magnet and using silicon microstrips and straw tubes technology, respectively. Each station comprises four detection layers with a vertical-stereo patterns for sensitive planes: the first and last layer are vertical, the second is rotated 5° clockwise, the third 5° anti-clockwise. This arrangement allows for precise measurement of the track coordinates in the bending plane of the magnet, sufficient resolution for pattern recognition of the non-bending plane and drastically reduces the amount of ghost tracks.

Tracker Turicensis The Tracker Turicensis [36] is a silicon detector approximately 150 cm wide and 180 cm high for around 8 m^2 of active area. It uses 512 silicon microstrips (n-doped substrate with p^+ implants) with a pitch of $183 \mu\text{m}$ and $500 \mu\text{m}$ of thickness. The TT comprised four layers for particle detection (Fig. 3.6): the first and last use vertical strips, the second and third stereo strips rotated by -5° and $+5^\circ$, respectively, to allow for reconstruction of the second coordinate.

Inner Tracker The IT [37] covers the region closest to the beam pipe in the last 3 tracking stations, where the fluence is highest. It uses the same microstrip technology as the TT with the same pitch, but with a thickness of $320 \mu\text{m}$. Each station has 4 detection layers, arranged in the same fashion as the TT: the first and last one have vertical strips, the second and third are rotated by $\pm 5^\circ$ respect to the former. The total active area is 4.2 m^2 .

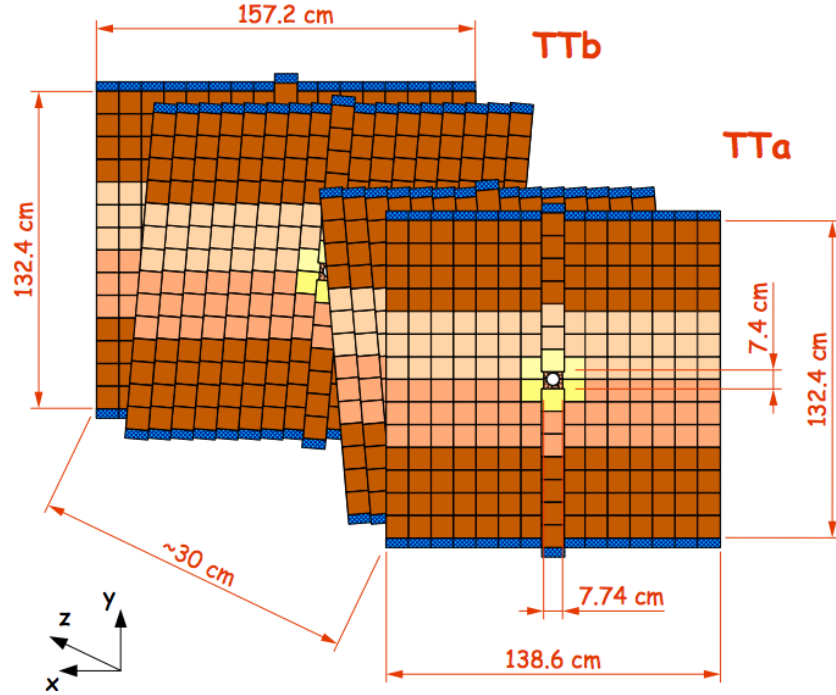


FIGURE 3.6: Tracker Turicensis layout: the second and third layers are tilted by $\pm 5^\circ$ to allow for track reconstruction on the non-bending plane and ghost tracks reduction [36]. Different colour shades represent different readout sections.

Outer Tracker The OT [38] is a drift-tube gas detector located in acceptance region not covered by the IT. It consists of 200 gas-tight, 4.9 mm thick, straw-tube modules with drift-time read-out with a spatial resolution of about 200 μm . These are filled with an Ar-CO₂-O₂ (70-28.5-1.5%) mixture and are arranged in 4 layers per stations as the TT and IT with the same vertical-stereo arrangement. The total covered area is 597 cm $\times$ 485 cm for a total of 55 000 tubes. Each particle crossing a straw tube produces around 35 electrons in the gas that rapidly drift (< 50 ns) towards the central anode wire where they are amplified and collected.

Magnet The LHCb magnet [39] is a warm (non-superconducting) dipole magnet with 4 Tm of integrated magnetic field over a 10 m length (typical length of a track crossing the tracking system). It is located between the TT and the T1 stations, and has a saddle shape that allows to cover the full LHCb acceptance. Its shape contributes to minimise the residual magnetic field outside its longitudinal extension which could affect the correct functioning of the RICH Hybrid PhotoDiodes (HPDs). The intensity of the magnetic field in respect to the tracking system layout is shown in Fig. 3.7. To minimise systematic effects due to any asymmetries in the detector the magnet polarity can be switched between data taking periods.

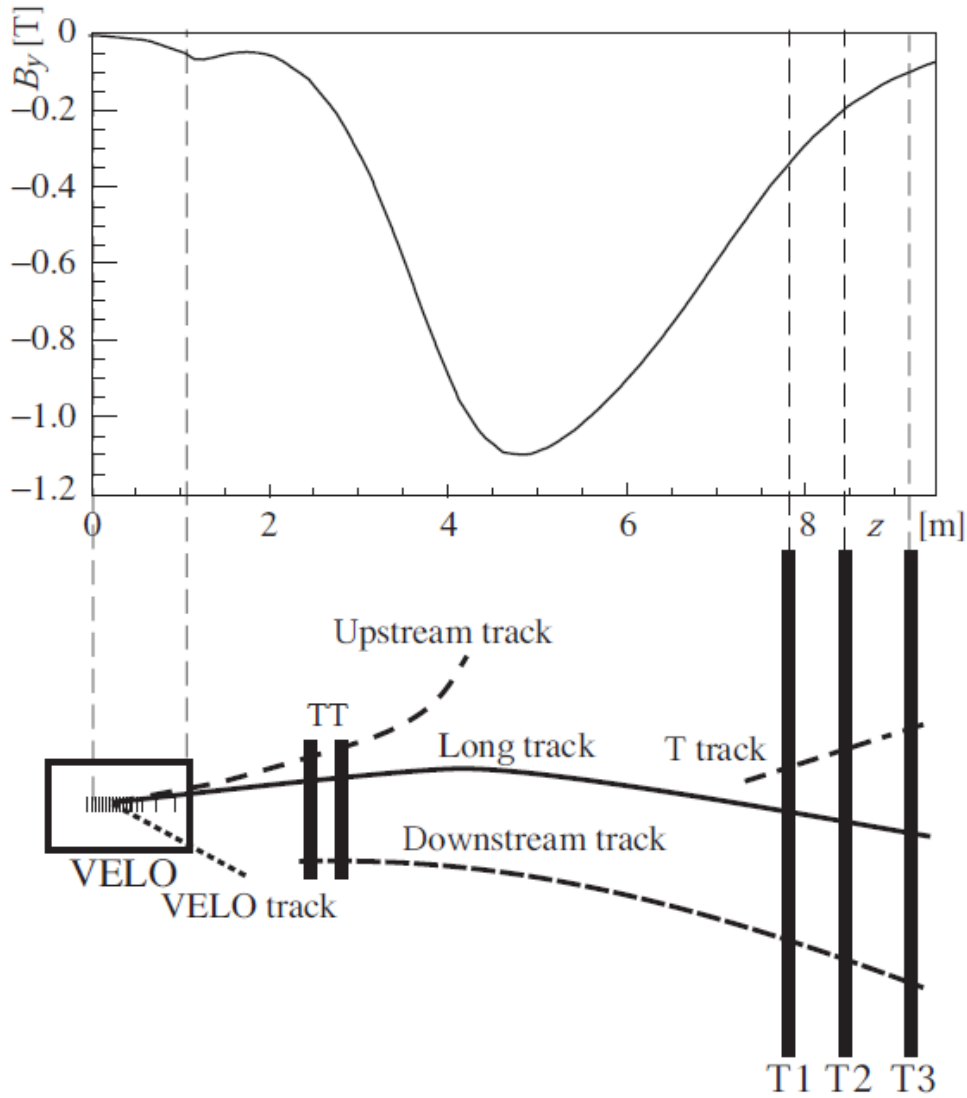


FIGURE 3.7: Magnetic field y component as function of z coordinate in respect to the tracking system [36]. The various track types are shown as well.

3.2.2.1 Tracking Update

Similarly to the VELO, the tracking stations have been upgraded for Run3 [40] to withstand more fluence and cope with the increased data rate of Run3 environment, both due to the increased pile up and the move to a full software trigger. For these reasons, the TT has been replaced by the Upstream Tracker (UT) and the IT-OT have been replaced by the Scintillating Fibre Tracker (SciFi). Both UT and SciFi keep the vertical-stereo arrangement of the detector they replace.

UT The UT uses the same microstrip technology as the TT, with the notable difference of a thinner silicon layer (250 μm against 500 μm) and a variable strip

pitch: 190 μm that halves to 95 μm near the beam region. A representation of the UT layers and strip pitch arrangement is shown in Fig. 3.8.

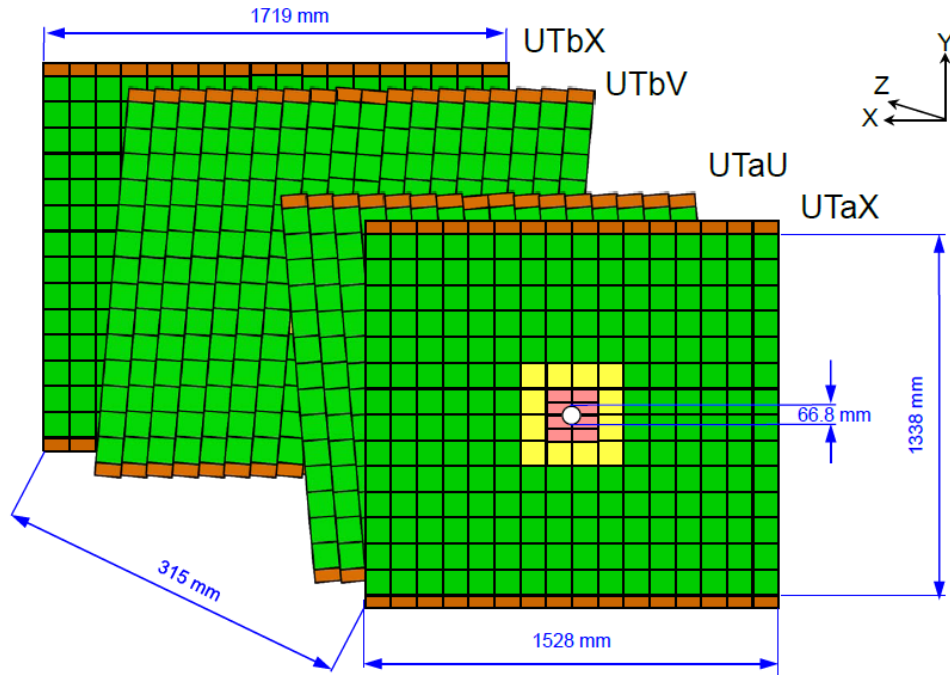


FIGURE 3.8: Layout of the UT detector planes looking downstream. The areas with different strip pitch are colour coded [40].

SciFi The SciFi detector replaces both the IT and OT although keeping the same 3-stations with 4-layers per station arrangement. It is composed entirely of 2 m long, 250 μm thick scintillating fibre layers with 270 μm pitch. These are read-out by Silicon PhotoMultipliers (SiPMs).

3.2.3 RICH

LHCb comprises two Ring Imaging CHerenkov RICH detectors [41] for the identification of charged particles: one is positioned between the VELO and the TT (upstream of the magnet) and one after the tracking stations (downstream of the magnet). Particle IDentification (PID) is crucial to make precise measurements of b and c hadron rare decays and CP violation. For example, neutral B hadrons decay to final states with overlapping invariant mass peaks as $\pi^+\pi^-$, $K^+\pi^-$ and K^+K^- that require PID to be clearly distinguished. RICH detectors use the Cherenkov radiation to determine the speed of charged particles. Cherenkov radiation is produced whenever a charged particle passes through a dielectric medium faster than light, causing the emission of photons in a cone around the particle path. Since the aperture angle of the cone depends on the

refractive index of the medium and on the speed of the particles, measuring the former allows to infer the latter, given that the refraction index is known. The speed measurement together with momentum information from the magnet allows to distinguish particles with different masses (Fig. 3.9).

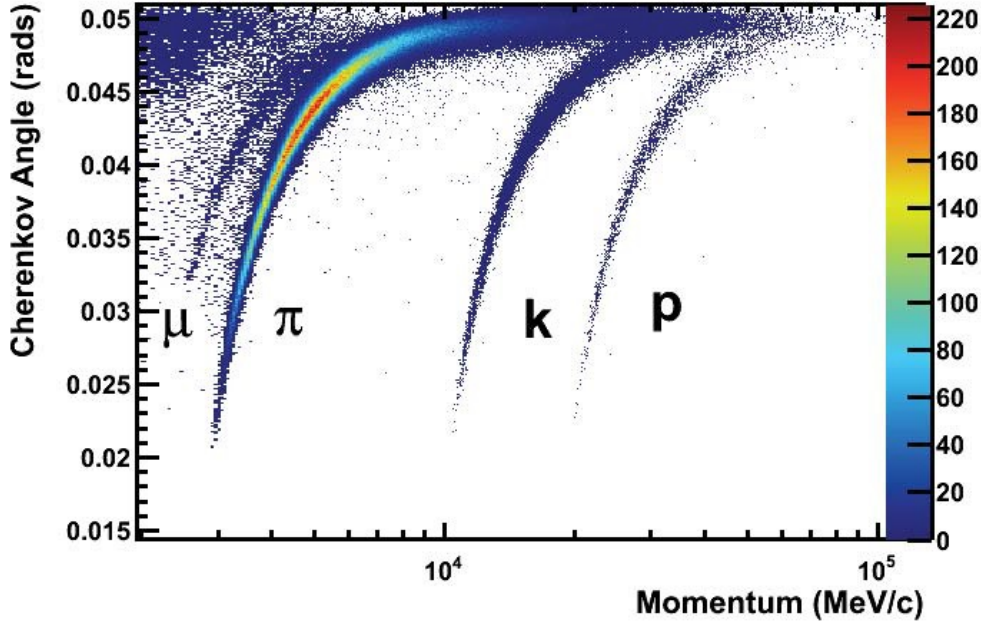


FIGURE 3.9: Reconstructed Cherenkov angle from isolated tracks as a function of the track momentum in the C_4F_{10} radiator [42]. Each particle produces a distinct band that is well separated from those produced by different particle species.

Both RICH share the same working principles, shown in Fig. 3.10, consisting of a radiator (i.e. the dielectric medium), flat and spherical mirror for light reflections and HPDs for light collection: the particles traversing the radiator produces a cone of radiation in the visible spectrum which is reflected by the spherical mirrors onto the flat mirror which reflects it to the HPDs. The photons hitting the photo-cathode of the HPDs produce emission of photo-electrons which are accelerated in a 20 kV electric field and detected by an array of 1024 silicon pixel detectors, each pixel measuring $0.5 \text{ mm} \times 0.5 \text{ mm}$. The HPDs are sensitive to photons between 200 nm and 600 nm of wavelength. Since the HPDs are extremely sensitive to magnetic fields, the whole RICH is shielded with Mu-Metal.

RICH1 The first RICH is optimised for discrimination of low momentum particles ranging from 2-60 GeV/c [42] and uses C_4F_{10} as radiator. It covers the full LHCb acceptance from $\pm 25 \text{ mrad}$ to $\pm 300 \text{ mrad}$ on the horizontal plane and $\pm 250 \text{ mrad}$ on the vertical plane.

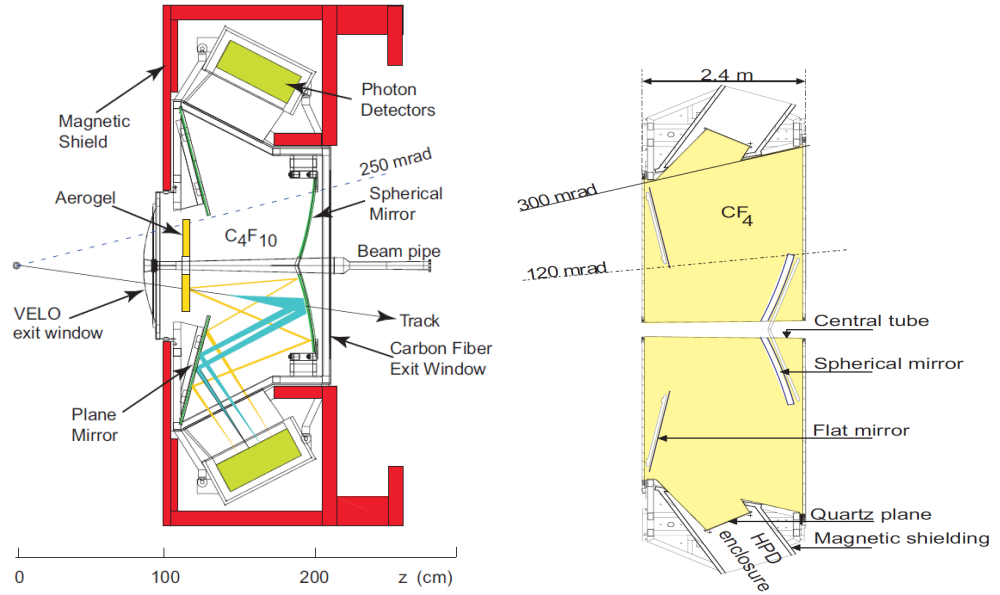


FIGURE 3.10: Structure of the RICH1 (on the left) and RICH2 (on the right) [43]. Note that aerogel was removed from RICH1 before Run2.

RICH2 RICH2 uses CF_4 as radiator and is optimised for tracks in the high momentum range from $15 \text{ GeV}/c$ to $100 \text{ GeV}/c$. Since high momentum tracks tend to be closer to the beam pipe and low momentum particles are swept away from the Magnet, this detector covers a smaller angle of acceptance from $\pm 15 \text{ mrad}$ to $\pm 120 \text{ mrad}$ (horizontal) and $\pm 100 \text{ mrad}$ (vertical).

3.2.3.1 RICH Upgrade

The general layout of the RICH detectors is unchanged [44], however the focal length of RICH1 has been increased; this results in a reduction of the occupancy in the central region of the detector even with the increase of luminosity planned for Run3. The photodetectors have been upgraded to Multi-anode Photo Multiplier Tubes (MaPMTs) with increased granularity and readout rate to match the 40 MHz bunch crossing rate.

3.2.4 Calorimeter

The electromagnetic and hadronic calorimeters [45] measure the energy of electron, photons and hadrons, respectively. A particle crossing a calorimeter produce a shower of secondary particles, which energy is absorbed and readout by the detector. Calorimeters provide PID of the aforementioned particles as well as measurements of their position. Furthermore, one of the main function of the calorimeter system is to select high transverse momentum candidates for

the first level trigger (L0) [42]. The calorimeter is composed of four sections: the Scintillating Pad Detector (SPD), the Pre-Shower (PS), the electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL).

SPD & PS The SPD and the PS [45] consist of around 6000 scintillator pads readout by wavelength-shifters connected to clear plastic fibres transporting the scintillation photons to multi-anode PMTs. The SPD allows to discriminate charged from neutral particles, while the PS allows for discrimination of electrons from pions and photons from hadrons. A 15 mm thick lead converter plate is positioned between the two detectors to improve electron/photon to hadron discrimination.

ECAL The electromagnetic calorimeter is a “shashlik” sampling calorimeter built with alternating lead-scintillator tiles [45]. The 2 mm lead tiles work as absorber, while the 4 mm scintillator is the active material; between these a 120 μm Tyvek layer, a thin reflective material, is found to increase the light collection. The lead/scintillator stacks have small holes to allow the passage of wavelength-shifter fibres that bring the light to PMTs. The detector has 6016 channels in total, with a 0.835 m thickness corresponding to 25 X_0 (radiation lengths) to allow for full containment of electromagnetic showers.

HCAL The hadronic calorimeter is a sampling detector alternating steel absorber to scintillating tiles [45], both 20 cm long. Differently to common design, this detector has its scintillating tiles oriented in parallel to the beam axis. The HCAL is segmented into cells with different dimensions, 131.3 mm in the inner part of the detector and 262.6 mm in the outer region. The scintillation light is collected by wavelength-shifter fibres running on the edge of the active material and readout by PMTs. The total thickness of the system is 1.65 m ($X_0=5.6$), which is not enough to contain the full hadronic shower: this is not an issue since the main function of this detector is triggering. Orthogonally to the beam axis the sections are 16 mm and 3 mm for the iron and scintillating tiles, respectively; these are interleaved by a 120 μm Tyvek sheet to improve light collection.

3.2.4.1 Upgrade

The Upgrade of the calorimeters [44] has foreseen the removal of the SPD and PS detectors and the replacement of all the front-end and back-end electronics of the ECAL and HCAL to adapt the to the new fully software online trigger and

reach 40 MHz readout rate. The structure of the two detectors has remained the same.

3.2.5 Muon system

The Muon system [46] comprises 5 stations (M1-M5) dedicated to muon identification and L0 triggering. The first chamber is located in front of the calorimeters and allows to improve transverse momentum (P_T) measurements, whereas the other chambers are positioned after the calorimeters. All the muon chambers are gaseous detectors, specifically M1 is composed by a 3 layer Gas Electron Multiplier (GEM) detector, while M2-M5 are Multi Wire Proportional Chambers (MWPC). The triple GEM technology was used for M1 to cope with the higher rate of that region. M2-M5 layers are interleaved by a 80 cm thick iron absorber to select only the most penetrating muons, with the minimum momentum cut-off operated by the absorbers being 6 GeV. The full system comprises 1380 chambers for an active area of 435 m², with each station divided into 4 regions with scaled linear dimensions that increases with the distance from the beam axis (1:2:4:8 ratio); this allows to keep the occupancy almost constant in all the regions.

3.2.5.1 Upgrade

Due to the higher occupancy expected for Run3 [44], the M1 station has been removed as it would be extremely hard to associate the M1 hits to any muon segment track, leaving this layer virtually useless. The M2-M5 stations have remained untouched, with only the electronics upgraded to 40 MHz readout. To help contain particle showers escaping the HCAL and reduce the hit rate on the innermost region of M2, an additional iron-tungsten 30 cm deep shield has been positioned along the beam pipe after the HCAL; this allowed to reduce the hit rate in the innermost M2 region by circa 26%.

3.3 Summary

The LHC is the longest and most powerful accelerator in the world, built to discover the Higgs boson (goal reached in 2012) and test the SM and BSM theories. Four main experiments ATLAS, ALICE, CMS and LHCb are located respectively at IP 1,4,5 and 8: ATLAS and CMS are multi-purpose experiments complementary to each other, designed to discover the Higgs boson and pursue a vast physics program after its discovery; ALICE is designed for heavy ion

studies to comprehend quark-gluon plasma dynamics, whereas LHCb is a spectrometer focusing on CP violation studies. Each of these experiments have been upgraded during LS 3 to cope with the higher instant luminosity that the LHC will deliver during Run3 and exploit the higher number of collisions at higher energy that will be delivered for the years to come. As this work focuses on the LHCb detector, an overview of the the upgrades installed for each subdetector has been described: for a number of detectors (Muon system, calorimeters, RICH) this equals to an upgrade of the electronics to cope with the higher radiation of Run 3 and minor updates, whereas for others (VELO, UT, Sci-fi) this equals to a major overhaul of the detector design, with the adoption in some cases of a new layout and detection technology.

Chapter 4

Searches for CP violation in the $D^0 \longrightarrow K_S^0 K \pi$ channel

4.1 Introduction

The search for CP violation in the charm system is motivated by the fact that several BSM physics theories predict sizeable enhancements above the very small effects expected in the SM [47, 48]. SCS decays provide a promising laboratory for direct CP violation searches because of the significant role loop diagrams play in these processes [49]. Direct CP violation arises from the interference of amplitudes with different strong and weak phases leading to the same final state. The first discovery of direct CP violation in charm mesons was observed in 2019 by measuring the difference of the asymmetries in two different SCS final states, $\Delta A_{CP} = A_{CP}(D^0 \rightarrow K^+ K^-) - A_{CP}(D^0 \rightarrow \pi^+ \pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$ ¹, with a significance of more than five standard deviations [50]. There is no unanimous agreement within the theory community on whether BSM physics is necessary to explain this result, or whether it originates in a mild non-perturbative enhancement due to rescattering effects or to the presence of a nearby 0^{++} resonance such as $f_0(1710)$ [51–55]. Since this is the only significant measurement of charm CP violation, it is of a crucial importance to explore as many additional SCS decay modes as possible. In this scenario, the $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ decay is of a particular interest to study the effects of CP violation in the charm sector. More specifically the channel follows the chain $D^{*+}(2010) \rightarrow (D^0 \rightarrow K_S^0 K^\pm \pi^\mp) \pi_{soft}^+$, where the “soft” pion from the $D^{*+}(2010)$ (hereafter referred to as D^{*+}) strong decay tags the flavour of the D^0 meson at production. Finally, the D^0 decays weakly through a rich resonance structure which could enhance any CP violation effects. In the following we will refer to final states where the D^0 child pion

¹The cited uncertainty includes both statistical and systematic contributions.

charge matches the soft pion charge (i.e. in the $D^{*+} \rightarrow \pi_S^+ D^0 \rightarrow K_S^0 K^- \pi^+$ and charge conjugate (c.c.) decay chain) as “Same Sign (SS)” final states whereas those where the D^0 child pion charge is opposite to the soft pion one (as in the $D^{*+} \rightarrow \pi_S^+ D^0 \rightarrow K_S^0 K^+ \pi^-$ and c.c. decay chain) will be referred to as “Opposite Sign (OS)” final states. Both decays are SCS, with the branching fraction (BF) of the SS decay is approximately a factor 1.5 larger than the one of the OS decay [16]. The main Feynman diagrams contributing to these decays are shown in Fig. 4.1.

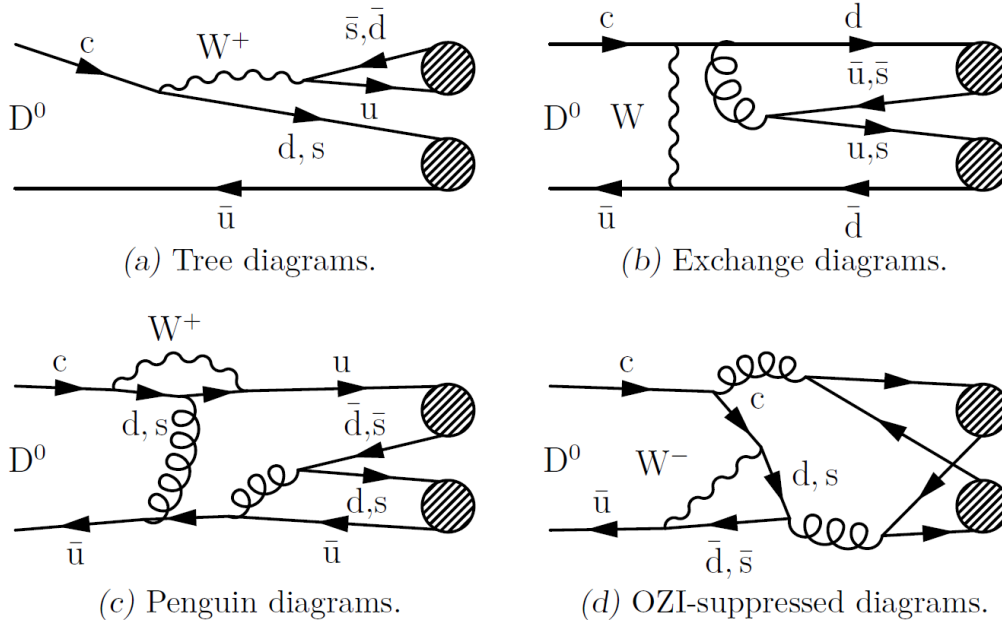


FIGURE 4.1: Diagrams for the SCS categories contributing to $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ decays. (a): tree colour-favoured diagrams contributing to $K_{0,1,2}^{*\pm} \rightarrow K_S^0 \pi^\pm$ and $(a_{0,2}, \rho)^\pm \rightarrow K_S^0 K^\pm$ channels. (b): exchange color-suppressed diagrams for $K_{0,1,2}^{*0} \rightarrow K^+ \pi^-$, $\bar{K}_{0,1,2}^{*0} \rightarrow K^+ \pi^-$ and $(a_{0,2}, \rho)^\pm \rightarrow K_S^0 K^\pm$ channels. (c): penguin diagram for second-order loop processes for $K_{0,1,2}^{*\pm} \rightarrow K_S^0 \pi^\pm$ and $(a_{0,2}, \rho)^\pm \rightarrow K_S^0 K^\pm$ decays. (d): penguin annihilation OZI-suppressed diagrams contributing to all channels. Figure reproduced from [56].

In this respect, theorists argue that one of the most promising CP violation discovery modes is $D^0 \rightarrow KK^*$ [2]. The K^* resonance decays instantly to a $K\pi$ pair with a BF close to 100% [16].

The $D^0 \rightarrow K_S^0 K^{*0}$ mode has a major advantage: the prompt decay $K^{*0} \rightarrow K^+ \pi^-$ produces charged tracks pointing directly to the D^0 decay vertex. Furthermore, near the K^{*0} resonance the maximum value of the tagged direct CP asymmetry is $a_{CP}^{dir, tag} \lesssim 0.003$ [2]. These effects are expected to be produced by SM contributions, specifically from exchange diagrams, which implies that the asymmetry does not vanish even in the limit of $SU(3)_F$ symmetry (i.e. the up, down and strange quarks having the same mass) and receive negligible

enhancements from penguin diagrams, whose contribution would equally vanish without BSM effects. Finally, the $D^0 \rightarrow K_S^0 K^{*0}$ allows for a more efficient reconstruction of signal candidates respect to similar channels with higher predicted CP asymmetry such as $D^0 \rightarrow K_S^0 K_S^0$ [57], where the displacement of both K_S^0 vertices to the parent D^0 hinder the reconstruction efficiency of the events. Here, a study of the $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ decays is reported, which includes $D^0 \rightarrow K_S^0 \bar{K}^{*0} (\rightarrow K^\pm \pi^\mp)$ decays as one of the intermediate processes. Studying the multibody SCS final state $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ also has the advantage that the interfering intermediate resonances can lead to enhanced CP violation in local regions of the phase space, such as the region around the K^{*0} resonance. CP violation effects will be investigated in the whole phase space and not only near the K^{*0} resonance. An amplitude analysis of the $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ decays has already been performed by the LHCb collaboration using LHC Run1 data corresponding to an integrated luminosity of 3.0 fb^{-1} [19, 56]. This has provided a good understanding of the resonant substructure in the decay, and has allowed us to optimise the sensitivity of our analysis to CP violation in the phase space. In addition, a model-dependent search for CP violation measured the asymmetries for all contributing amplitudes, however all results were consistent with CP conservation [19, 56].

The study reported here uses data collected during the 2016-2018 period at centre-of-mass energies of $\sqrt{s} = 13 \text{ TeV}$ corresponding to an integrated luminosity of about 5.4 fb^{-1} . A well established unbinned model-independent technique, the Energy Test (ET) [58], is employed to search for CP violation. The ET method sets out the calculation of a single test statistic, T , in order to search for local asymmetries in the phase space of the 3-body final state. The method is by construction only sensitive to local CP violating asymmetries, providing no sensitivity to global asymmetries, and has been previously applied at LHCb in the analysis of $D^0 \rightarrow \pi^- \pi^+ \pi^- \pi^+$ [59], $\Lambda_b^0 \rightarrow p \pi^- \pi^+ \pi^-$ [60], and $D^0 \rightarrow \pi^- \pi^+ \pi^0$ [61] decays. It has been shown that the ET can provide higher sensitivity to CP violation effects than model-independent binned methods [20, 58–60, 62–64].

4.1.1 Analysis strategy

This analysis is “blind”, meaning the results of the signal decay modes have not been checked until permission to unblind by the LHCb Review Committee had been granted. However, the analysis method has been validated in advance with calibration decay channels referred to as control channels 4.5. The ET method is then recapped in details in Sect. 4.2. The dataset analysed and the

selection of signal candidates are discussed in Sect. 4.3. The configuration of the ET contains one free parameter which is used to determine the distance scale within which local asymmetries in the phase space are investigated, similar to a binning in binned analyses. This parameter is optimised using a model of the signal process in order to maximise the sensitivity of the test to potential CP violation. This is discussed in Sect. 4.4. It is crucial to perform tests to confirm that any sample asymmetries that would induce a claim of CP violation in the analysis of the signal channel are not caused by detector effects or by second order effects due to the K_S^0 itself. For this reason control channels where no significant direct CP -violating effects are expected have been used: the CF decays $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ and the time integrated decays $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ [65]. The former has the same final state particles as the signal channel and allows to check for detector effects, the latter contains a K_S^0 that enables to check for effects due to the K_S^0 asymmetry. The ET has been run on these channels to confirm the validity of the ET method as a search for CP violation; these studies are reported in Sect. 4.5. In addition, the likelihood that the presence of background processes can not mimic CP violation in any way is cross-checked. These checks are described in detail in Sect. 4.6. Section 4.7 reports studies on possible “cross-feed” effects (i.e. contamination) produced by channels with similar final state particles which are misidentified by the LHCb reconstruction software and wrongly attributed to the signal channel. Specifically, the contamination from $D^0 \rightarrow K_S^0 KK$ decays, with a kaon misidentified as a pion, and $D^0 \rightarrow K_S^0 \pi \pi$ decays, where a pion is misidentified with a kaon, are discussed. Studies of the unblinded signal mode are reported in Sect. 4.8. Finally, a visualisation method has been developed for the ET [62]. This visualisation method allows regions of the phase space with the largest contribution to the test statistic to be determined, and the source of any CP violation to be localised. If a hint of CP violation is found then a complete amplitude analysis has to be performed to find the origin. In this context the visualisation tool here described can offer a hint of where in the Dalitz plot the effect is coming from, but this is no substitute for a complete amplitude analysis. This is discussed in Sect. 4.2.4.

4.2 Experimental method: Energy Test

The search for CP violation in the $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ channel is carried out with a model-independent statistical technique, the ET, which will be applied to the time-integrated phase space. This approach allows to probe agnostically any possible source of CP violating effects without sacrificing sensitivity in favour of a specific mechanism. Analysing the full time-integrated Dalitz plot enables to be sensitive to the full set of intermediate resonances that could produce localised effects in the phase space. Thus, the ET does not require careful parametrisation of the relevant CP violating and SM production mechanisms which are characteristic of Model-dependent approaches, and it is instead a “discovery tool” to rapidly assess whether any local asymmetry is found in the phase space of the Dalitz plot. The ET method produces a single P-value that expresses the statistical probability of two set of candidates to belong to the same underlying population. Thus, as the P-value does not express a measurement of any CP violating mechanism parameter it is not possible to place any constraint on any CP violation models, both in the case of a positive and negative results. The chosen phase space variables are described in Section 4.2.1. The ET is discussed in Section 4.2.2. In section 4.2.4 an ET-based visualisation tool is introduced allowing to identify regions of phase space which contribute the most to CP violation.

4.2.1 Phase space variables

In three-body decays, such as $D^0 \rightarrow K_S^0 K \pi$, two independent variables are sufficient to completely describe the phase space: the convention is to choose the sum of the invariant mass squared of two-body combinations. Nevertheless, for reasons that will be clarified in Sec. 4.2.1.1, in this specific case all three invariant mass squared two-body combinations are used

$$m^2(K, \pi), m^2(K_S^0, \pi), m^2(K_S^0, K). \quad (4.1)$$

4.2.1.1 Degrees of freedom and chosen variables

The decay of a pseudo-scalar particle P into n pseudo-scalar children particles $(1, 2, 3, \dots) P \rightarrow 123 \dots (n)$ is described by n four-vectors $p_1^\mu, p_2^\mu, p_3^\mu, \dots$, for a total of $4n$ parameters. n degrees of freedom (d.o.f.) are removed knowing the masses of the particles identified in the final state 1, 2, 3, Conservation of $E, \mathbf{p}$ allows

to remove four more d.o.f.. Finally invariance under rotation around the three spatial axes removes three additional d.o.f. bringing the total remaining to $3n - 7$ d.o.f. Hence three-body decays could be fully described using only two parameters. The aforementioned degrees of freedom can be described through a set of invariants, the choice of which influences the phase space distance between events. A commonly used set of invariants is $p_i p_j$ or analogously s_{ij} , the latter being a linear combination of the former

$$s_{ij} = (p_i + p_j)^2 = m_i^2 + m_j^2 + 2(p_i p_j). \quad (4.2)$$

For three-body decays the number of these two-body mass invariants are $\frac{1}{2}n(n-1) = 3$.

Thus, the phase space of a three-body decay is described by three two-body mass invariants s_{ij} . Nonetheless, since the phase space of a three-body decay is defined by $3 \times 3 - 7 = 2$ d.o.f., only two of s_{ij} are needed to fully define it. This choice is in principle valid for CP violation searches as they are the standard Dalitz plot variables choice. Furthermore, when s_{ij} are used as variables the resonances in the Dalitz plot manifest as bands. However, given that different choices correspond to different sensitivities of the analysis as they modify the phase space distance between pair of events, choosing only two s_{ij} would leave some ambiguity in the phase space distance, depending which combination of two two-body squared mass is used. Thus we decided to use all of the three s_{ij} variables so that the phase space distance is well defined.

4.2.2 Energy Test

The ET is a model-independent statistical method able to assess whether two distributions come from the same underlying population. This is done through the computation of a single test statistic called the T-value [66]. Traditionally, binned χ^2 -style approaches are employed in model-independent searches for CP violation effects where a decay and its CP conjugate are compared [67]. The ET differs from these approaches being unbinned and agnostic to the underlying source of the effect. The method was introduced in [62] and proved to deliver better sensitivities to CP violation effects over traditional binned methods when applied to multibody decays [58]. The method reliability and performance is testified by the number of CP violation searches carried out within the LHCb collaboration [60, 68, 69].

The test statistic T uses a distance function ψ_{ij} to compare the average distances between pair of events ij , belonging to two samples (particle and

anti-particle decays in this case), in the phase space. The definition of T is

$$T = \sum_{i,j>i}^n \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\bar{n}} \frac{\psi_{ij}}{\bar{n}(\bar{n}-1)} - \sum_{i,j}^{n,\bar{n}} \frac{\psi_{ij}}{n\bar{n}}, \quad (4.3)$$

where the first and second terms compute the weighted average distance among all the n events within the D^0 decays and the $\bar{n}$ events within the $\bar{D}^0$ decays, respectively. Finally, the third term defines the weighted average distance between events from one sample to the other. To remove global asymmetries between the two samples, each term is weighted with a normalisation constant at the denominator [63].

ψ_{ij} is the distance function defining the distance between events in the phase space and is in principle a squared Euclidean distance, namely

$$d_{ij}^2 = \sum_{k=1}^D (x_{k,i} - x_{k,j})^2, \quad (4.4)$$

with D being the number of the phase space dimensions and $x_{k,i}$ the phase space position of the i -th event along the k phase space axis. The number of relevant dimensions, as explained in Sec. 4.2.1.1, is $3n - 7$ with n representing the number of final state particles of the decay under study, being $n = 3$ in this case. Thus, for $D_0 \rightarrow K_S^0 K \pi$ decays we have $x_{k,i} = m_{k,i}^2$, with $m_{k,i}^2 = m_{K_S^0 \pi, i}^2, m_{K \pi, i}^2, m_{K_S^0 K, i}^2$. As stated above, ψ_{ij} can assume any form, still a distance function that falls when the distance between pair of events d_{ij} increases is better suited to maximise the sensitivity of the method to local asymmetries. The natural choice in this case is a Gaussian function [58, 70]

$$\psi_{ij} \equiv \psi(d_{ij}) = e^{-d_{ij}^2/2\delta^2}, \quad (4.5)$$

with δ , i.e. the width of the Gaussian function, defining the effective phase space radius where the local asymmetry is measured. The δ parameter plays a crucial role in the optimisation of sensitivity of the ET, thus its value must be carefully chosen: as the aim is to measure local asymmetries varying across the phase space, a small δ value should be selected to avoid dilution of such asymmetries. Nonetheless, by definition δ must be larger than the resolution of d_{ij} . The choice of δ parameter in the ET has comparatively the same role of the bin-width in a classical binned approach.

While the choice of a less-optimal value does not reduce the validity of the test, instead corresponding to a different test, a choice of δ that increases the sensitivity to CP violation is clearly desirable. The optimal δ is dependent on

the parent particle mass in a multibody decay.

A single reference T-value is computed from eq. 4.3 with real data, called T_0 . Then, as the aim of the ET is to test the null hypothesis, i.e. absence of CP violation, so called “permuted” T-values are computed using random flavour tagging to mimic the no-CP violation scenario. The permutation method consists in random relabelling of both D^0 and $\bar{D}^0$ events with the same or opposite flavour. After each permutation a so called “permuted” T-value is computed. By construction this technique should produce two samples whose events are identically distributed across the phase space. Thus repeating this process many times should return, by construction, a T-value distribution reproducing the null hypothesis. Finally, the reference T-value T_0 can be compared with these to compute the probability of obtaining such a result against the no-CP violation scenario. To avoid biases that might be produced in the relabelling procedure, a high number of permutations has to be run. Finally, the tested samples might contain different number of D^0 and $\bar{D}^0$ candidates. This constitutes a global asymmetry produced by e.g. acceptance or reconstruction asymmetries. As a safety measure, to ensure that such asymmetry cannot bias the ET result, the relabelling ratio in the permuted samples is the same as the one in the real data. As example, if the sample under study contains 1000 D^0 candidates and 2000 $\bar{D}^0$ candidates, the first will be permuted e.g. 1000 times, and the second 2000 times.

Furthermore, to eliminate a possible source of detector bias, all the tests will use equal number of events for each polarity.

4.2.3 P-value calculation

The computation of the P-value associated with T_0 is defined as the fraction of permuted T-values (thus calculated under the null hypothesis) that are larger than the one computed from the real data (T_0) [66].

As CP violating effects should increase only the distances between D^0 and $\bar{D}^0$ events in the phase space, the baseline T-value is expected to increase as a result ($T_{\text{permutations}} > T_{\text{data}}$), thus the upper tail of the permuted T-value distribution is used in the comparison. The formal definition of the P-value is:

$$P = \frac{\text{Permuted Tvalues} > T_0}{\text{Number of permutations}}. \quad (4.6)$$

Figure 4.2 shows a typical null hypothesis T values distribution.

If the samples are symmetric the distribution of events in phase space will be similar, whereas any difference will prompt an increase of the baseline T-value.

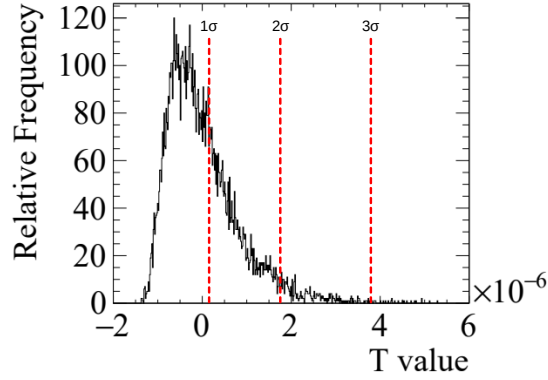


FIGURE 4.2: A typical distribution of T-values under the null hypothesis, found by randomly permuting the events in the samples. The T-values associated with particular significances are marked on. These correspond to T-values for which (roughly) 68%, 95% and 99.7% of T-values under the null hypothesis (in these case) are below. This plot uses pseudo experiment data

Repeatedly applying this procedure to multiple sub-samples allows to obtain a P-value distribution (see for example Sec. 4.5). Samples that are extracted from the same underlying population will return P-values with a random value between $[0,1]$, or else they will tend to accumulate around zero.

The P-value distribution can then be compared with a uniform distribution to extract the consistency with the null hypothesis by means of a Kolmogorov-Smirnov (KS) or a χ^2 test to extract an overall P-value [71,72].

To avoid biases, the number of permutations is kept to 10000 for each P-value calculation. This is specifically the procedure followed in the control channels testing (see Sec. 4.5). For the signal channel only one P-value will be computed. Furthermore, as the precision to which the P-value is computed is dependent on the total number of permutations used (i.e. with 1M permutations the smallest meaningful P-value which can be determined is 1×10^{-6}), we will use 50 million permutations to cover for a 5σ effect (or $p=3 \times 10^{-7}$). Due to the computationally intensive nature of the ET, the permutations are computed with the “Scaling Method” [66]: this allows to run the permutations with only a subset of the event in order to save CPU time. It has been found [66] that the T-values computed with 4.3 scale linearly with a factor k when the sample size is increased, provided that events are used only once in the computation of phase space distances.

More precisely the three factors composing T each scale with k , meaning that for large enough samples kT does not depend on the sample size. This property can be exploited to produce the permuted T-values distribution for the CP symmetric scenario with only a subsample of the total data and save CPU time. It has been proven that this approach works for subsamples with $n \geq 100$ events. Since as stated above the T scales with k , each permuted T-value is then unscaled by multiplying with the ratio $n_{full\ dataset}/n_{subsample}$ [9]. In this analysis it was chosen to use 500 events, although as few as 100 are needed to ensure reliable results.

4.2.4 Visualisation tool

The ET will be applied to the signal sample and return a single P-value. If any CP violating effect is found, i.e. a small P-value is returned, it would be important to trace back the origin of the effect to the region in phase space producing it. The golden standard in such instances is to carry out a full amplitude analysis, which requires a model-dependent approach. The visualisation tool hereafter described allows instead to locate the areas in the Dalitz plot where the asymmetry is larger, while retaining the model-independent approach.

This can be achieved by individually computing the contribution of each matter (D^0 decay) event T_i and anti-matter ($\bar{D}^0$ decay) event $\bar{T}_i$ to the final T value as follows

$$T_i = \frac{1}{2n(n-1)} \sum_{j \neq i}^n \psi(\Delta \vec{x}_{ij}) - \frac{1}{2n\bar{n}} \sum_j^{\bar{n}} \psi(\Delta \vec{x}_{ij}), \quad (4.7)$$

$$\bar{T}_i = \frac{1}{2\bar{n}(\bar{n}-1)} \sum_{j \neq i}^{\bar{n}} \psi(\Delta \vec{x}_{ij}) - \frac{1}{2n\bar{n}} \sum_j^n \psi(\Delta \vec{x}_{ij}), \quad (4.8)$$

where $T = \sum_i T_i + \sum_i \bar{T}_i$.

The values of T_i and $\bar{T}_i$ (these will be referred to as T_i values in the following) will then provide an indication of the areas of phase space providing the larger contribution to the total T-value.

Since a large positive T_i in one sample is always accompanied by a large negative $\bar{T}_i$ in the other sample, as an over-density in e.g. D^0 decays by definition is accompanied by an under-density in the e.g. $\bar{D}^0$ decays, the $|T_i|$ can then be used to localise, in both samples, the regions in phase space that contribute the most to the overall T-value. It is then possible to assign ‘pseudosignificances’ to these values:

- The first step consists in applying the test to the permuted samples. For each permutation, the maximum and minimum T_i values are recorded, the $|T_i^{min}|$ compared with $|T_i^{max}|$ and the larger value is kept to form a distribution from n_p of these extremal T_i values, with $n_p =$ number of permutations. This allows to obtain a distributions of the largest $|T_i|$ values related with the test performed under the null hypothesis (i.e. CP symmetry). A typical example of this distribution is given in Fig. 4.3.
- It is then possible to associate each $|T_i|$ value with each event in real (i.e. unpermuted) data.
- Each unpermuted $|T_i|$ values from data is compared against the distribution of absolute extremal values from permuted samples (thus obtained under the null hypothesis). Then, to each event a probability, or “pseudosignificance”, is assigned defined as the fraction of the larger $|T_i|$ values from permuted samples greater than the $|T_i|$ value for that event. Specifically, when each value in real data is compared with the extremal values from permuted samples the “pseudosignificance” has a rigorous interpretation. Under the null hypothesis the probability of an $n \sigma$ effect corresponds to the probability for an event to contain at least one $|T_i|$ value (i.e. the largest $|T_i|$ value in data) with $n \sigma$ “significance” when compared with the distribution of permuted extremal values.
- This approach is most useful as it illustrates the relative contribution to the total T-value of different phase space regions. If the result of the ET is a significant T-value, the $|T_i|$ values associated to events in phase space contributing the most to it will contribute with a large “pseudosignificance” as well.
- In the case any specific resonance is producing CP violating effects in the ET, a 2D plot with squared invariant masses of the 2-body combinations as axes (see Sec. 4.2.1.1) would allow to visualise the pseudosignificance of the events, which should manifest as localised structures in the plot. Figure 4.4 presents an instance of said plot. In this case the axes shows the dominant resonance structures of $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ decays which could be the source of any CP violating effects. In the instance of any CP violation observation claim this approach enables to complement it with an information regarding its potential source.

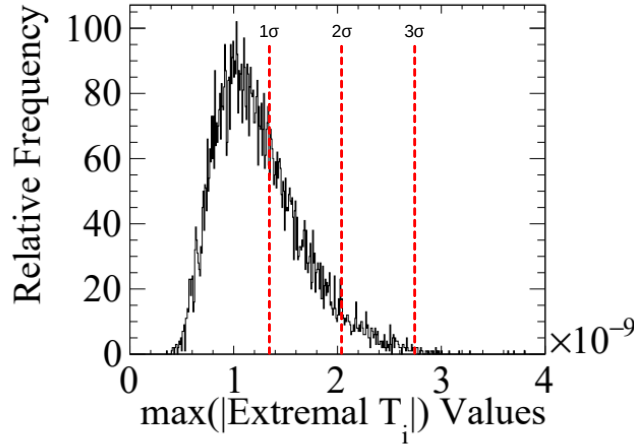


FIGURE 4.3: Distribution of maximum of extremal $|T_i|$ values from permuted samples (i.e. under null hypothesis). The $\max(|\text{extremal } T_i|)$ values corresponding to 1, 2, and 3σ significances are identified with dashed red lines. Specifically, the probability for a $\max(|\text{extremal } T_i|)$ values computed under the null hypothesis to be found beyond the 3σ band is 0.3%.

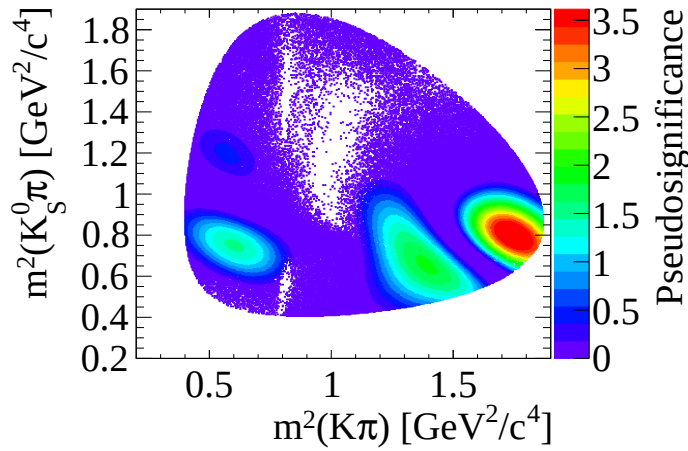


FIGURE 4.4: Pseudosignificance of $\max(|\text{extremal } T_i|)$ values in data computed comparing these to the permuted $\max$ extremal $|T_i|$ values in permuted samples (i.e. Fig 4.3). The plot reports pseudosignificances for D^0 decays (the $\bar{D}^0$ plot would be identical). The pseudosignificance, in sigmas, is shown on the z axis. This plot has been realised using a toy sample with a 3% injected CP asymmetry in the amplitude of the $K^*(892)^+$ resonance with 450 000 events, 10 thousand permutations and $\delta=0.2$. Note how the most significant $|T_i|$ values are grouped in the region corresponding to the invariant mass squared corresponding to the $K^*(892)^+$. This confirms that the visualisation tool is able to link the most significant contributions to asymmetry to a region in phase space in case any CP violating effects are detected by the ET.

4.3 Data samples and selection

The analysis uses the 2016-18 Run2 dataset corresponding to approximately 5.4 fb^{-1} of integrated luminosity. The 2015 sample is not available for this channel due to unstable beam conditions and low integrated luminosity. As already mentioned, candidates are reconstructed according to the decay chain $D^{*+}(2010) \rightarrow (D^0 \rightarrow K_S^0 K^\pm \pi^\mp) \pi_{soft}^+$, where the “soft” pion from the D^{*+} strong decay tags the D^0 meson flavour at production; the K_S^0 candidate is reconstructed in a decay to a pair of charged pions, and the D^{*+} particle must be consistent with originating at p-p collision point, henceforward called the Primary Vertex (PV). As the D^{*+} can decay both strongly (as in the decay just mentioned) or weakly (via production of a lepton in the final state), the specific dataset under analysis will be referred to as “prompt”, referring to the fast (hence prompt) decay time of the charged D^* parent after production. In this analysis, K_S^0 candidates are reconstructed from either tracks produced by particles inside the VELO, TT and tracking detectors after the magnet (so called long tracks) or particles interacting with only the TT and tracking stations (downstream tracks) 4.5.

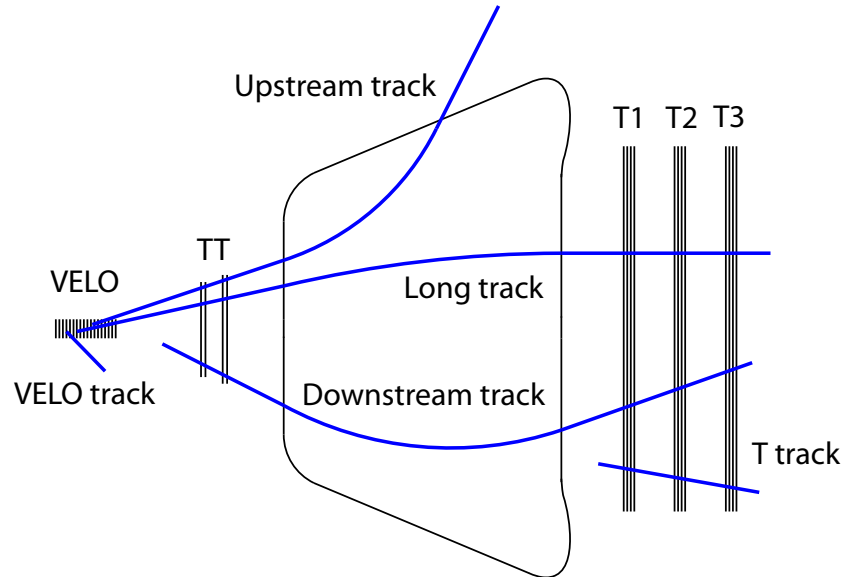


FIGURE 4.5: Types of tracks for the LHCb detector during Run1 and Run2 [73].

Each dataset contains both magnet polarities, meaning any asymmetry caused by the detector acceptance or temporary detector inefficiencies can be averaged out using the combined data sample. As an additional safety measure, the ET will be run using samples with equal number of candidates reconstructed with the magnet in both polarities; this results in an average loss of 4% of the events.

4.3.1 Trigger selection and event reconstruction

The LHC provides p-p interaction at a rate of 40 MHz, of these only ~ 10 kHz constitute events of interest for the LHCb experiment. Thus, a selection strategy, i.e. a trigger, to reduce the incoming data rate has been laid out to separate uninteresting data from actual physics processes. The LHCb trigger is structured on three levels:

- Level 0 (L0) trigger: fast hardware trigger based on FPGAs.
- High Level Trigger (HLT) 1 and 2: software based triggers.

The L0 trigger allows to reduce the data bandwidth from 40 MHz to 1 MHz [73] and bases its decisions on few inputs to decrease decision time: transverse energy deposit in the calorimeters, SPD hits and muon transverse momentum measured in the muon system. A first instance of track reconstruction is performed at this stage fitting straight lines to hits in the muon stations allowing for a first estimation of muon candidates. The HLT1 trigger further reduces data rate to 110 kHz [73] applying P_T requirements on tracks crossing the whole detector: at this stage primary vertex and tracks and P_T reconstruction is carried out. Specifically, the first step of track reconstruction is performed fitting hits in the VELO with straight lines, forming “VELO tracks”. A Kalman filter is used in the fitting procedure to improve fake tracks rejection. The primary vertex is reconstructed and tracks extrapolated to match hits in the TT, before the magnet. These form “upstream tracks”. These tracks allow to estimate the momentum of the reconstructed candidates. Finally, upstream tracks are further extrapolated to the T station downstream of the magnet using Kalman filtering to reduce fake tracks. To account for the deflection due to the magnetic field, a geometric window is opened to look for matching clusters or hits in the IT and OT. The window is defined by the trajectory of a charged particle with $p_T > 500$ MeV/c with maximum deflection [73]. If the extrapolation is successful, a “long track” is formed. Finally, at HLT2 level the full event is

reconstructed, including tracks from charged and neutral particles. The track reconstruction procedure performed at HLT1 stage is repeated with looser p_T requirements, this time extrapolating VELO hits directly to the T stations. In addition, track segments reconstructed solely in the T stations that are not associated to any VELO track are fitted back to the TT, accounting for the magnetic field, to form “downstream” tracks [73]. These are crucial for the reconstruction of candidates that decay outside of the VELO detector as neutral baryons, pions or K_S^0 . A Kalman filter is applied here as well to increase the final fitted track quality. Particle Identification (PID) is carried out at this stage as well using the combined information of RICH detectors (charged particles) and calorimeters (neutral particles). More precisely, the RICH detectors allow to distinguish protons, kaons, pions and electrons measuring the light cone aperture (i.e. the speed of the particle) and returning a mass hypothesis [73]. The HLT2 selection is tailored on the need of each decay channel, and brings down the final data rate to 12.5 kHz [73]. In Run2 “Turbo lines” were introduced as data format containing only information from the sub-detectors allowing to save disk space. Turbo lines contain tracks, decay and primary vertices, PID, neutral particles and information from calorimeters and tracking. As stated above, each HLT2 Turbo line contains a unique set of selection criteria to maximise the signal candidates yield for each specific decay channel. For the $D^0 \rightarrow K_S^0 K \pi$ channel, the description of the L0 and HLT1 trigger strategy is briefly explained in Sec. 4.3.1.1, whereas a thorough explanation of the HLT2 selection criteria is given in Sec. 4.3.1.2.

4.3.1.1 L0 and HLT1 selection

At L0 level, the candidates are required to pass the **Dst_L0Global_TIS** requirement, where TIS [74] stands for Trigger Independent of Signal, meaning that a positive trigger decision is generated taking into account the part of the event not associated with detector hits produced by the signal decay. More specifically, an event is registered as TIS if removing all of the signal decay hits from the detector the L0 decision is still triggered. If a charm and a beauty mesons arise both from the same underlying p-p interaction, the charm event is registered as TIS if the L0 decision is triggered by e.g. any of the beauty hadron decay products.

The possibility to use candidates that pass the **Dst_L0Global_TIS** or **D0_L0HadronDecision_TOS** (Tigger On Signal, i.e. events for which the trigger decision is generated by the presence of signal [74]) requirement have been investigated, however studies carried out with the

$K\pi\pi\pi$ control channel demonstrated a bias induced by the L0 trigger decision on the D^0 candidate. Thus, the **D0_L0HadronDecision_TOS** requirement was dropped and only **Dst_L0Global_TIS** is now required; this resulted in a loss of around 24% of the events compared to the **Dst_L0Global_TIS** or **D0_L0HadronDecision_TOS** requirement for both the $K\pi\pi\pi$ and the signal channel. A full description of the aforementioned studies can be found in Appendix A together with a more detailed description of the TIS and TOS trigger classes. Candidates are required to pass **D0_Hlt1TrackMVADecision_TOS** or **D0_Hlt1TwoTrackMVADecision_TOS** at the HLT1 level. These selects one good quality final state pion track or two such tracks that share a common vertex, respectively. The common vertex has to be sufficiently displaced from the p-p interaction point as well. Furthermore, these requirements apply a preliminary P and P_T threshold. A list of the trigger criteria is summarised in Appendix B.

4.3.1.2 HLT2 selection

Events satisfying the L0 and HLT1 requirements have to pass the last layer of the High Level Trigger: the HLT2. The HLT2 requirements used within this analysis are contained in specific trigger lines called “Turbo” lines, which are designed to contain a basic combination of mass, momentum and PID criteria that can be rapidly processed by the HLT2 trigger while maintaining appropriate background rejection qualities. In this analysis the following Turbo lines were used:

- **Hlt2CharmHadDstp2D0Pip_D02KS0KmKp_KS0DDTurbo** for a pair of downstream tracks (DD, tracks from a K_S^0 decay originating outside the VELO acceptance).
- **Hlt2CharmHadDstp2D0Pip_D02KS0KmKp_KS0LLTurbo**: for a pair of long tracks (LL, tracks from a K_S^0 decay originating inside the VELO acceptance).

In 2017, a number of trigger parameters have changed and some new criteria have been introduced to improve the sample purity and background rejection. The most noticeable differences are hereby listed:

- The requirement on the D^0 vertex quality, $D^0 \chi_{VT}^2 < 20$, was tightened to < 5 ;
- Added criteria on the χ^2 distance between K_S^0 and D^0 decay vertices: $\log([D^0 - K_S^0] \chi_{VS}^2) > 5$;

- Added criteria on the track ghost probability: **TRGHOSTPROB** < 0.4 of D^0 children π and K ;
- Added requirements on the π_S :
 - track χ^2 per degree of freedom (DOF) < 3
 - **TRGHOSTPROB** < 0.25
 - **P_T** > 200 MeV/c
 - **P** > 1000 MeV/c

A detailed explanation of all the trigger jargon that will be used next can be found in Appendix D. The complete set of requirements is presented in Table 4.1.

Particle	Parameter	DD	Common	LL
D^{*+}	VFASPF(VCHI2NDOF)		< 10	
D^0	CHI2VXNDOF PT D2DVVDCHI2(KS) BPVDIRA BPVLTIME BPVVDCHI2		< 5 (< 20) > 1800 MeV/c > e^5 (*) > cos 0.0346 > 0.0001 > 20	
K/π	TRCHI2NDOF TRGHOSTPROB PT P MIPCHI2DV(PRIMARY) PIDK		< 3 < 0.4 (*) > 200 MeV/c > 1000 MeV/c > 4 $K > 5 / \pi < 5$	
π_{soft}	TRCHI2DOF TRGHOSTPROB PT P		< 3(*) < 0.25 (*) MeV/c > 200 (*) MeV/c > 1000 (*) MeV/c	
K_S^0	ADAMASS ADMASS VFASPF(VCHI2PDOF) BPVLTIME BPVVDZ BPVLTIME VFASPF(VZ)	< 80 MeV/c ² < 64 MeV/c ² > 400 mm - > 300 mm, < 2275 mm	< 30 > 0.0005	< 50 < 35 - > 2.0 ps > -100 mm, < 500 mm
π from K_S^0	TRCHI2DOF P PT MIPCHI2DV(PRIMARY) TRGHOSTPROB	< 4 > 3000 MeV/c > 175 MeV/c -	< 0.4	< 3 - - > 36

TABLE 4.1: Full list of the HLT2 selection criteria for Run2 prompt data. In brackets are the requirements before the 2017 changes. An asterisk marks a selection criteria added for the 2017-8 lines. All the parameters definitions can be found in Appendix D.

All candidates are refitted with the Decay Tree Fitter (DTF) package [75]: the algorithm selects each candidates full decay chain and parametrises it using the momentum parameters, decay lengths and vertex positions. These are all fitted simultaneously fixing a number of constraints of interest, such as masses of parent/child particle, impact parameter, 4-momentum conservation. The

DTF uses a Kalman filter to increase fit efficiency. The $K_S^0 K \pi$ data comes with three different DTF flavors: in the first DTF version, the π_{soft} coming from the D^{*+} meson is constrained to point back to its primary vertex, the second version (**DTFKS**) adds the K_S^0 mass constraint to the PDG value [16], and the last version (**DTFD0KS**) also constraints the D^0 mass to its PDG value. This analysis will use the latter version, as it improves the resolution of the distribution of mass difference $\Delta M = M(D^{*+}) - M(D^0)$, where $M(D^{*+})$ is the D^{*+} mass and $M(D^0)$ is the D^0 mass.

4.3.2 Offline selection

A set of requirements is applied offline to further improve the purity of the data, remove detector acceptance asymmetries and hadronic interactions with the detector material. The requirements, listed in Table 4.2, are hereby summarised:

- The HLT2 Run2 requirements that have been modified or introduced since 2017 are applied offline on 2016 data to align the selection for all Run2 data samples (see Fig. 4.6). This has resulted in a 75% event rejection in the 2016 sample.
- Requirements on the D^0 creation and decay vertex are imposed to exclude interactions with the RF foil or detector material that could induce local asymmetries in the phase space. A requirement on the primary vertices position along the Z axis is applied as well. For a detailed description of these requirements see Appendix C.
- The D^0 candidate is required to have a displaced decay vertex from the best primary vertex, and be consistent with originating at the best primary vertex. This ensures that the D^0 has a good quality vertex and that the D^0 is correctly associated with the appropriate parent D^{*+} .
- To increase signal purity, PID requirements are placed on the D^0 final state particles K and π as well as on the π from the K_S^0 decay, and a looser one on the soft flavour-tagging pion, π_{soft} .
- Fiducial selection criteria are applied to the soft pion momenta to remove regions with detector asymmetries reaching 100% [76]. Such asymmetries arise when one charge of the soft pion candidates is bent out of the detector acceptance or in the beam pipe for one magnet polarity, and the other one is not. These criteria allow to remove acceptance asymmetries.

- The Decay Tree Fitter is required to converge, and a loose quality requirement is applied. This avoid selecting candidates where the kinematic fit of the D^{*+} decay products to the D^{*+} decay vertex is not of good quality or have not converged.

Finally, the signal region is selected with the criteria listed below, each corresponding to a 3σ mass window from the known value of the corresponding distribution:

- $|m(K_S^0) - 497.669| < 11.567 \text{ MeV}/c^2$,
- $|m(D^0) - 1865.65| < 22.111 \text{ MeV}/c^2$,
- $|m(D^{*+}) - m(D^0)| > 144.739 \text{ MeV}/c^2$ and $|m(D^{*+}) - m(D^0)| < 146.114 \text{ MeV}/c^2$.

Fiducial selection criteria are intended to remove detector acceptance asymmetries that are not averaged out when combining data samples with opposite magnet polarities. Specifically slow charged particles like π_{soft} can be bent out of the detector by the magnet. This results in areas of the detector that are reached by one charged type as the other is deflected out by the magnet in each polarity configuration. The effect is shown in Fig. 4.7 for the p vs p_x plane. A similar issue can manifest on the p_x and p_y plane, where two shadows of the beam pipe can be observed: pions can be deflected back into the beam pipe and leave hits in some tracking stations while missing others by crossing the beam pipe [20]. These candidates are not fully reconstructed and produce this artifact. As these candidates can potentially produce local asymmetries in the phase space, the kinematical regions of maximal asymmetry are removed to avoid any bias in the ET result. The fiducial requirements are taken from the Run1 analysis of $D^0 \rightarrow hhhh$ decays, where $h = K$ or π , which uses the ET method to search for CP violation [76]. They are applied on the soft pion momenta as described below:

$$\begin{aligned} |p_x| &\leq \alpha(p_z - p_0), \\ \alpha &= 0.317, \\ p_0 &= 2400 \text{ MeV}/c, \end{aligned} \tag{4.9}$$

and

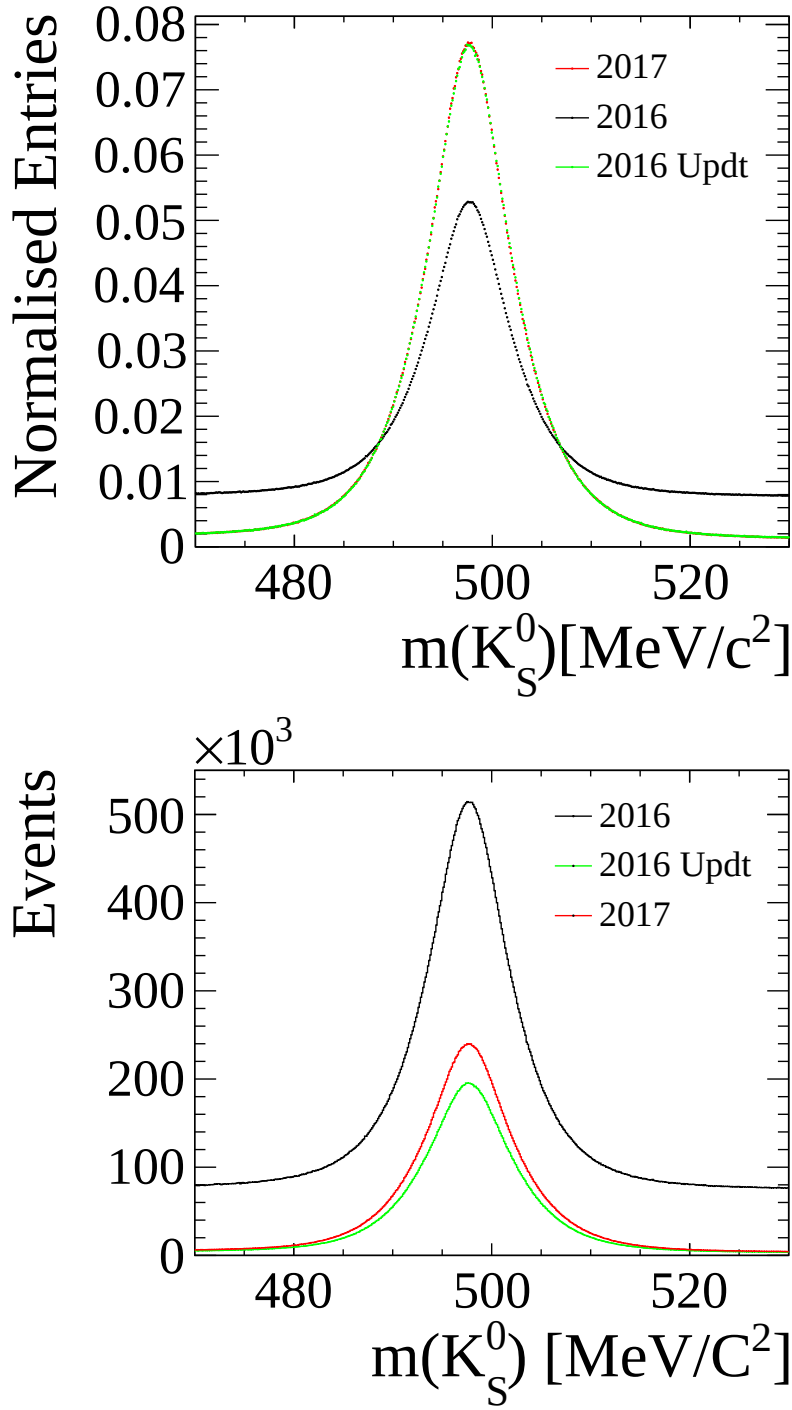


FIGURE 4.6: Top: Comparison of the normalised K_S^0 mass distributions in 2016 (black), 2016 with updated HLT2 criteria (green) and 2017 (red). Note how, after updating the HLT2 requirements, the green curve is overlapping with the red one, proving that the 2016 and 2017 samples are now aligned. Bottom: comparison of the same distributions without normalisation: here the magnitude of the event rejection in the 2016 sample with the updated criteria (circa 75%) is clearly visible.

$$\begin{aligned}
 p_1 - \beta_1 p_z &< |p_x| < p_2 + \beta_2 p_z, \\
 p_1 &= 418 \text{ MeV}/c, \\
 p_2 &= 497 \text{ MeV}/c, \\
 \beta_1 &= 0.01397, \\
 \beta_2 &= 0.01605,
 \end{aligned}
 \tag{4.10}$$

Run2 HLT2 selection criteria applied offline to the 2016 data sample

D^0 vertex χ^2 per DOF	< 5
K_S^0 vertex separation χ^2 to D^0 decay vertex	$> e^5$
K/π from D^0 ghost track probability	< 0.4
π_{soft} track χ^2 per DOF	< 3
π_{soft} ghost track probability	< 0.25
$\pi_{soft} P_T$	$> 200 \text{ MeV}/c$
$\pi_{soft} P$	$> 1000 \text{ MeV}/c$

 D^0 displacement and PID selection criteria

D^0 vertex separation χ^2 from the primary vertex	≥ 50
D^0 IP χ^2	≥ 0 and < 20
D^0 and K_S^0 final state particles ProbNN	$> 0.3 (\pi), > 0.6 (K)$
π_{soft} ProbNN π	≥ 0.1

Decay Tree Fitter selection criteria

All DTFs vertex χ^2 per DOF	> 0
DTF DOF	> 0
DTF χ^2	$< 15 \times \text{DTF DOF}$

 D^0 Decay, Origin and Primary vertices constraints

$$D_{EV}^0 R_{XY} < 4.7 \text{ mm and } |D_{EV}^0 Z - 10.48| < 83.42 \text{ mm}$$

$$\text{where } R_{XY} = \sqrt{(D_{EV}^0 X - PV_X)^2 + (D_{EV}^0 Y - PV_Y)^2}$$

$$D_{OV}^0 R_{XY} < 4.7 \text{ mm and } |D_{OV}^0 Z - 0.54697| < 86.3588 \text{ mm}$$

$$\text{where } R_{XY} = \sqrt{((D_{OV}^0 X - PV_X)^2 + (D_{OV}^0 Y - PV_Y)^2)}$$

$$|PV_Z + 1.48863| < 81.932 \text{ mm}$$

TABLE 4.2: Complete list of the offline requirements applied to the signal channel. Regarding the D^0 vertices constraints: D_{EV}^0 is the particle *EndVertex* i.e decay position; D_{OV}^0 is the particle *OriginVertex* i.e creation position; PV stands for *PrimaryVertex* i.e. the p-p collision position. R_{XY} is the radial distance of the particle vertex (EV or OV) from the primary vertex on the XY plane.

for the $|p_y/p_z| < 0.02$ regions only. The application of the fiducial criteria results in the removal of the regions with highest asymmetry, this accounts for about 15% of the events. The high-asymmetry regions and the effect of the fiducial criteria can be seen in Fig. 4.7.

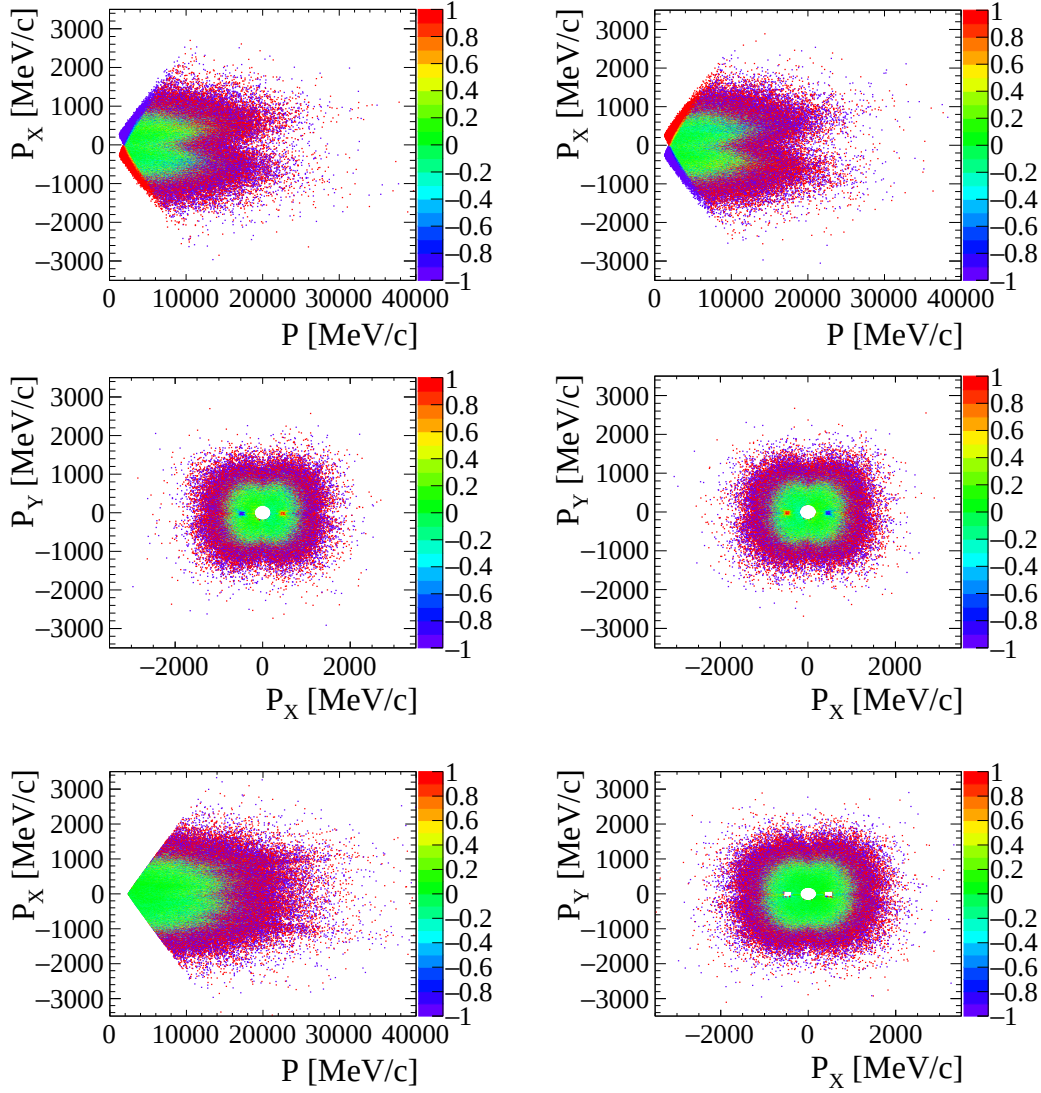


FIGURE 4.7: Plots for the fiducial selection criteria for the $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ channel. The amount of asymmetry is color coded on the z axis: in green areas reached by both charged pion, in blue and red areas reached only by one charged pion. $D^0 - \bar{D}^0$ candidates asymmetry as a function of soft pion momenta on the p vs p_x (top) and p_x vs p_y (centre) plane for magnet up (left) and magnet down (right) sample. The removal of the areas of maximal asymmetry after the application of fiducial criteria is shown at the bottom for the p vs p_x (left) and p_x vs p_y (right) plane.

4.3.2.1 Removal of multiple candidates

Multiple candidates are reconstructed events formed by “ghost” particles, i.e. produced from mis-reconstructed tracks, or by particles from other decays. In such instances it is not possible to unambiguously distinguish the *true* particle from the duplicate, thus the LHCb reconstruction software keeps both instances labelling them as two different events producing a multiple candidate. As only one of these is the real event and the removal of duplicates is performed

randomly, the process is performed at the very end of the offline selection. This helps maximising the chances of reducing the number of multiple candidates and selecting the only true event. The percentage of retained events in the SS and OS signal samples after the multiple candidates removal is 96.36% for the former and 96.01% for the latter, respectively.

4.3.2.2 Signal yields

The ET relies on using a pure data sample to be able to effectively detect asymmetries in the phase space and to minimise the chances of picking up those induced by background events within the signal region (e.g. cross-feed from channels with same final state particles). Thus, is necessary to estimate the purity of the signal sample resulting from the offline selection. The estimation is performed fitting the ΔM distribution with a binned maximum likelihood fit after applying the aforementioned offline requirements to the signal sample (apart from the selection criteria on the ΔM). The results are shown in Fig. 4.8. The fit uses a double-Gaussian function to model the signal component and a *RooDstD0BG* [77] Probability Density Function (PDF) to model the $D^{*+} - D^0$ mass background. The two Gaussian functions that model the signal PDF are constrained to have the same mean whereas the widths are left as free parameters.

The signal and background candidates, together with the fit parameters are given in Table 4.3 for OS and SS decays. The whole sample fit parameters are given in Table 4.4. The purity is computed as $p = [s/s + b]$, where p is the purity, s is the number of signal candidates and b the number of background candidates in the signal region. For the SS and OS samples is 90.9% and 91.4% respectively, and 91% for the whole sample.

4.3.3 Signal dataset

The final signal dataset, as already specified, is obtained after applying all the criteria illustrated in the previous sections. For the SS sample this results in 948 286 candidates in the signal window with an estimated purity of 90.9%, while for OS decays the final yield is 621 181 candidates with estimated 91.4% purity. We highlight that the yields are the results of the selection process, while the fits are used only to estimate the purity; this justifies the slight discrepancy between the estimated total candidates in table 4.3 and the actual yield. The

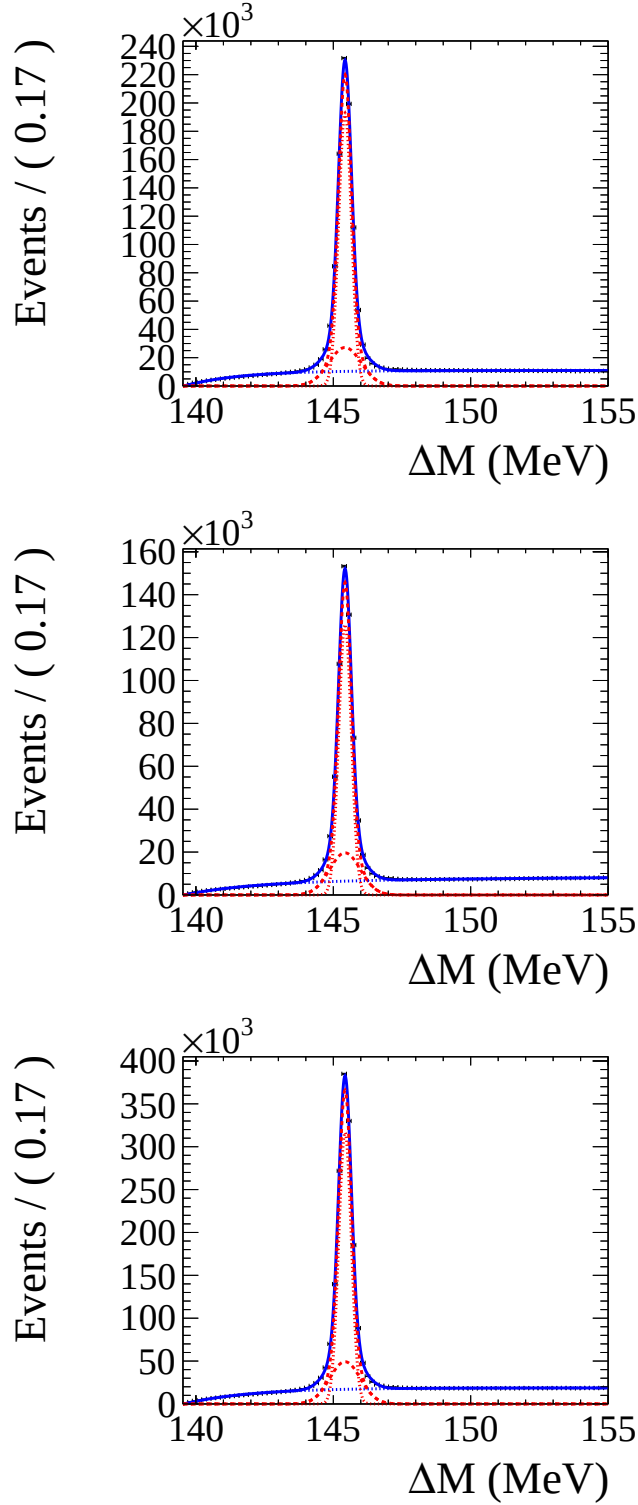


FIGURE 4.8: Fit to the ΔM distribution of $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ decays. At the top, SS decays; in the middle, OS decays. At the bottom: the combined mass fit. The red dotted and dashed lines correspond to the double-Gaussian function components, the blue dotted line shows the background component, the blue solid line is the total fit.

Dalitz plots for these datasets are shown in Fig. 4.9 along with their axis projections. These are the final samples that will be analysed with the ET in the CP

Parameter	$K_S^0 K^- \pi^+$	$K_S^0 K^+ \pi^-$
Total candidates	921 067	601 547
Signal candidates	$836\,848 \pm 1041$	$549\,680 \pm 887$
Mean [MeV/ c^2]	145.427 ± 0.001	145.426 ± 0.001
σ_1 [MeV/ c^2]	0.277 ± 0.001	0.229 ± 0.001
σ_2 [MeV/ c^2]	0.587 ± 0.005	0.557 ± 0.006
fraction	0.737 ± 0.004	0.725 ± 0.005
Background candidates	$84\,219 \pm 107$	$51\,867 \pm 86$
Purity [%]	90.9	91.4

TABLE 4.3: Signal and background candidates, and fit parameters for the SS and OS samples. Here, Mean is the shared mean value of both Gaussian functions, σ_1 and σ_2 are the widths of the double-Gaussian function; fraction is the signal fraction of the narrower Gaussian function. The signal and background candidates correspond to a 3σ mass window centred on the mean value. The purity is given by the fraction of signal candidates on signal+background candidates.

Parameter	$K_S^0 K^\pm \pi^\mp$
Total candidates	1 520 627
Signal candidates	$1\,383\,170 \pm 1\,335$
Mean [MeV/ c^2]	145.426 ± 0.001
σ_1 [MeV/ c^2]	0.229 ± 0.001
σ_2 [MeV/ c^2]	0.558 ± 0.004
fraction	0.725 ± 0.003
Background candidates	$137\,457 \pm 135$
Purity [%]	91

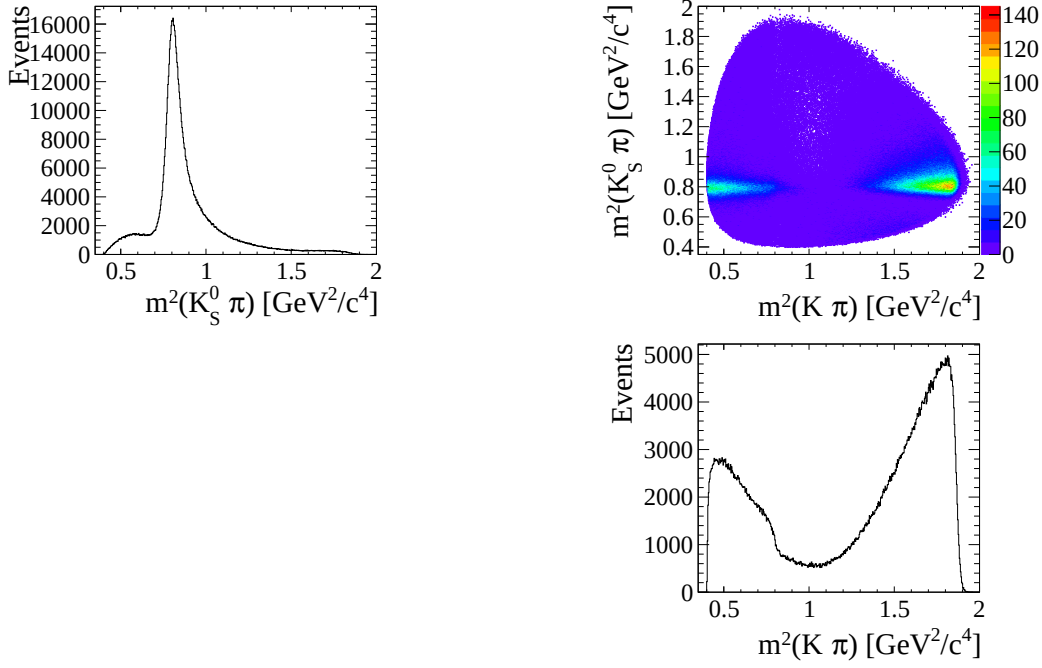
TABLE 4.4: Signal and background candidates, and fit parameters for the whole sample. Here, Mean is the shared mean value of both Gaussian functions, σ_1 and σ_2 are the width of the double-Gaussian function; fraction is the signal fraction of the narrower Gaussian function. The signal and background candidates correspond to a 3σ mass window centred on the mean value. The purity is the fraction of signal candidates on signal+background candidates.

violation search.

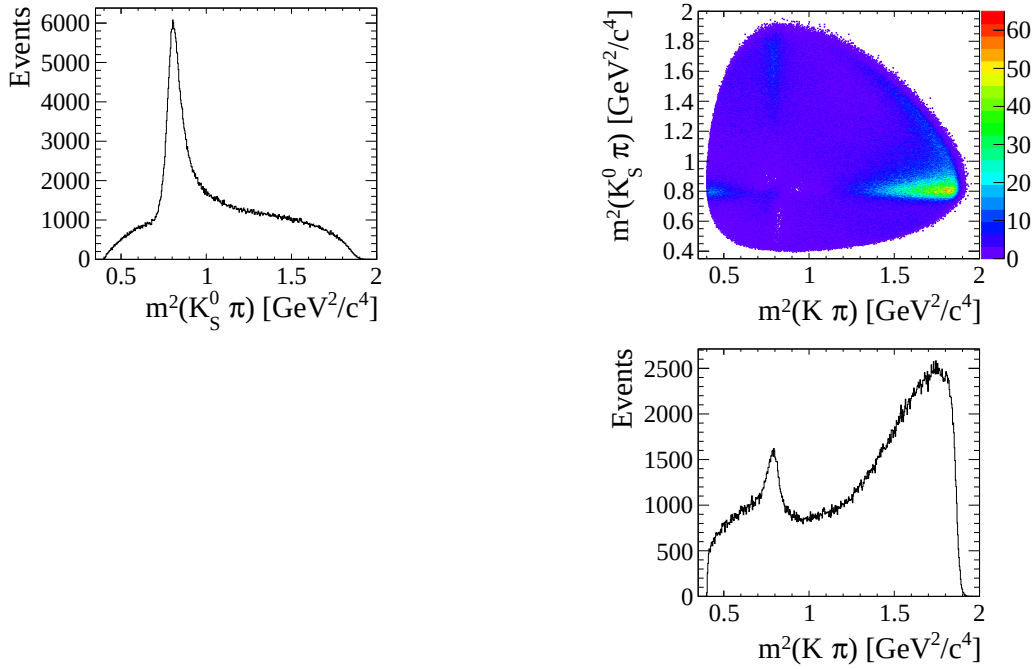
4.3.4 Background events

Background events are tested with the ET to ensure no asymmetry is being introduced. The background region is defined by the K_S^0 , D^0 and ΔM sidebands, starting 5σ away from their respective mass peak.

In total, the background candidates for the $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ decays amount to 116 852 for the SS sample, and 78 217 for the OS sample. From the fits applied to the ΔM distribution, we know that in the signal peak region there are around 84 219 and 51 867 background candidates in the SS and OS samples, respectively. Since the sidebands and background in the signal region statistics



(A) SS decays.



(B) OS decays.

FIGURE 4.9: Dalitz plot of the $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ signal candidates, with projections onto its X (bottom) and Y (left) axes for SS (a) and OS (b) decays. The population of each bin is colour coded in the z axis. The Dalitz plot X axis shows the $m^2(K\pi)$ distribution, while $m^2(K_S^0\pi)$ is reported on the Y axis. On the Y axis, the sharp peak in both SS and OS decays corresponds to the $K^*(892)^+$ resonance. On the X axis, the peaking structure in the OS decays corresponds to the $K^*(892)^0$ resonance, which is absent in the SS sample.

are comparable, this tests offer a realistic insight on the possible effects of background asymmetries on the ET. The test, described in Sec. 4.6, will be run with the maximum number of events available to increase the sensitivity.

4.4 Sensitivity studies

The studies and results described in this subsection have been carried out and obtained by Yue Pan and are reported here for completeness. To interpret the results and verify that the ET is sensitive to CP violation, a “sensitivity study” had been carried out. The sensitivity study employs pseudoevents simulating the signal sample, referred to as pseudo experiment data, to simulate different CP violation scenarios and test the capability of the ET to detect such effects. The procedure is the following:

- Simulate pseudo experiment samples with an amplitude model of comparable statistics to the data samples.
- Input different types of asymmetries in the magnitude or the phase (a, Φ) of the contributing amplitudes, run the ET, check the resulting P-values.
- Vary the distance parameter δ .
- Select the δ value which minimises the P-values i.e. ensures the best sensitivity.

4.4.1 Simulation samples

The pseudo experiment samples of $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ decays used in the sensitivity study are generated with the GOOFIT package [78] according to the results of the $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ amplitude analysis [56] by the LHCb collaboration. In the model, the amplitude is constructed based on the isobar formalism, the total amplitude is the sum of the corresponding partial waves

$$A_{K_S^0 K^\pm \pi^\mp} (m_{K_S^0 K}^2, m_{K_S^0 \pi}^2) \propto \epsilon (m_{K_S^0 K}^2, m_{K_S^0 \pi}^2) |\mathcal{M}_{K_S^0 K^\pm \pi^\mp} (m_{K_S^0 K}^2, m_{K_S^0 \pi}^2)|^2, \quad (4.11)$$

where $\mathcal{M}$ is described by the multiplication of the complex coefficients (a_R , which is determined by the fit) and the matrix elements $\mathcal{M}_R$, which is defined as

$$\mathcal{M}_R = B_L^D(p, p_0, d_D) \Omega_L T_R(m_{AB}) B_L^R(q, q_0, d_R). \quad (4.12)$$

Here, B_L is the barrier penetration factor, in which L represents the relative angular momentum of the decay products, Ω_L describes the angular distribution of the final state particles, and T_R is the lineshape of the resonances. The

detailed description of the amplitude construction could be found in the Run1 amplitude analysis [56].

The parameters of the resonances are listed in Table 4.5.

Resonance	Amplitude a_R	Phase ϕ_R [$^\circ$]	Fit fraction [%]
$D^0 \rightarrow K_S^0 K^- \pi^+$			
$K^*(892)^+$	1.0 (fixed)	0.0 (fixed)	$57.0 \pm 0.8 \pm 2.6$
$K^*(1410)^+$	$4.3 \pm 0.3 \pm 0.7$	$-160 \pm 6 \pm 24$	$5 \pm 1 \pm 4$
$(K_S^0 \pi)_S^+$	$0.62 \pm 0.05 \pm 0.18$	$-67 \pm 5 \pm 15$	$12 \pm 2 \pm 9$
$\bar{K}^*(892)^0$	$0.213 \pm 0.007 \pm 0.018$	$-108 \pm 2 \pm 4$	$2.5 \pm 0.2 \pm 0.4$
$\bar{K}^*(1410)^0$	$6.0 \pm 0.3 \pm 0.5$	$-179 \pm 4 \pm 17$	$9 \pm 1 \pm 4$
$\bar{K}_2^*(1430)^0$	$3.2 \pm 0.3 \pm 1.0$	$-172 \pm 5 \pm 23$	$3.4 \pm 0.6 \pm 2.7$
$(K\pi)_S^0$	$2.5 \pm 0.2 \pm 1.3$	$50 \pm 10 \pm 80$	$11 \pm 2 \pm 10$
$a_2(1320)^-$	$0.19 \pm 0.03 \pm 0.09$	$-129 \pm 8 \pm 17$	$0.20 \pm 0.06 \pm 0.21$
$a_0(1450)^-$	$0.52 \pm 0.04 \pm 0.15$	$-82 \pm 7 \pm 31$	$1.2 \pm 0.2 \pm 0.6$
$\rho(1450)^-$	$1.6 \pm 0.2 \pm 0.5$	$-177 \pm 7 \pm 32$	$1.3 \pm 0.3 \pm 0.7$
$\rho(1700)^-$	$0.38 \pm 0.08 \pm 0.15$	$-70 \pm 10 \pm 60$	$0.12 \pm 0.05 \pm 0.14$
$D^0 \rightarrow K_S^0 K^+ \pi^-$			
$K^*(892)^-$	1.0 (fixed)	0.0 (fixed)	$29.5 \pm 0.6 \pm 1.6$
$K^*(1410)^-$	$4.7 \pm 0.5 \pm 1.1$	$-106 \pm 6 \pm 25$	$3.1 \pm 0.6 \pm 1.6$
$(K_S^0 \pi)_S^-$	$0.58 \pm 0.05 \pm 0.11$	$-164 \pm 6 \pm 31$	$5.4 \pm 0.9 \pm 1.7$
$K^*(892)^0$	$0.410 \pm 0.010 \pm 0.021$	$176 \pm 2 \pm 9$	$4.82 \pm 0.23 \pm 0.35$
$K^*(1410)^0$	$6.2 \pm 0.5 \pm 1.4$	$175 \pm 4 \pm 14$	$5.2 \pm 0.7 \pm 1.6$
$K_2^*(1430)^0$	$6.3 \pm 0.5 \pm 1.7$	$-139 \pm 5 \pm 21$	$7 \pm 1 \pm 4$
$(K\pi)_S^0$	$3.7 \pm 0.3 \pm 1.8$	$100 \pm 10 \pm 70$	$12 \pm 1 \pm 8$
$a_0(980)^+$	$1.8 \pm 0.1 \pm 0.6$	$64 \pm 5 \pm 24$	$11 \pm 1 \pm 6$
$a_0(1450)^+$	$0.44 \pm 0.05 \pm 0.13$	$-140 \pm 9 \pm 35$	$0.40 \pm 0.09 \pm 0.34$
$\rho(1450)^+$	$2.3 \pm 0.4 \pm 0.8$	$-60 \pm 6 \pm 18$	$1.5 \pm 0.5 \pm 0.9$
$\rho(1700)^+$	$1.04 \pm 0.12 \pm 0.32$	$4 \pm 11 \pm 20$	$0.5 \pm 0.1 \pm 0.5$

TABLE 4.5: Isobar model fit results for $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ decays with the $(K\pi)_S$ -wave of the GLASS model [56].

As the detector efficiency is not uniform within its acceptance and the trigger performance is not constant across the whole range of P and P_T of incoming particles, this means that particles reconstruction efficiency varies across the phase space. Specifically, the inefficiencies depend on the two-body invariant masses as they are related to the four-momentum of the particles. For this reason the generated pseudo experiment samples include the reconstruction efficiency variation across the phase space. The efficiency histogram is extracted from the amplitude analysis [56] with Run1 data. The 6th order Polynomial defined below is the used to fit the 2D efficiency histogram

$$\epsilon(s_{K_S^0 K}, s_{K_S^0 \pi}) = \sum_{i=1}^6 a_i (s - s^0)^i, a_0 = 1, \quad (4.13)$$

where, $s_{K_S^0 K}^0$ and $s_{K_S^0 \pi}^0$ are two offsets lying approximately in the centre of the available phase space, and set to be $s_{K_S^0 K}^0 = 1.95 \text{ GeV}^2/c^4$ and $s_{K_S^0 \pi}^0 = 1.15 \text{ GeV}^2/c^4$, respectively. The fit results are shown in Fig. 4.10.

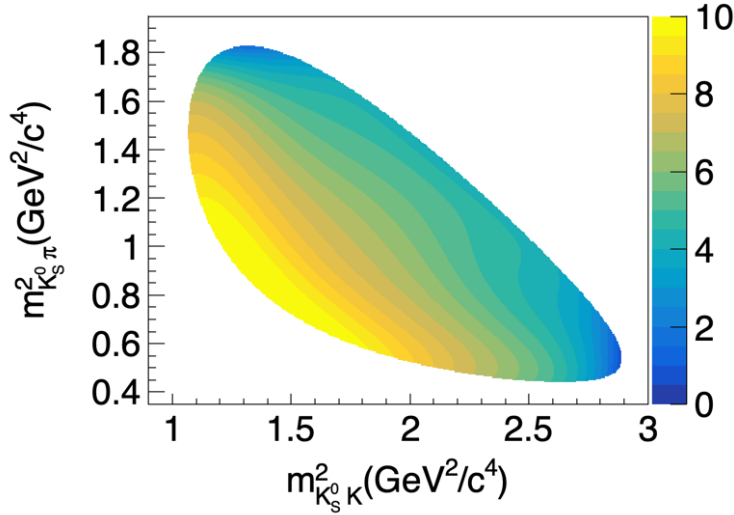


FIGURE 4.10: Fit result of the efficiency variation of the $D^0 \rightarrow K_S^0 K \pi$ decay across the phase space. The z-units, showing the efficiency, are arbitrary.

After taking into account the efficiency function, the projections of the generated pseudo experiment samples are illustrated in Fig. 4.11. To ensure the model used, borrowed for the Run1 analysis, is still relevant in the Run2 environment, a study was carried out to ensure to check for possible differences in acceptance. This study, described in Appendix H, confirmed the relevance of the Run1 model.

The different types of asymmetries are introduced by varying the resonance amplitude and phase in the amplitude model. If CP violation is introduced in the magnitude of one amplitude with a proportion of x , the magnitude of the amplitude is changed to $a_R(1 + x)$. If the asymmetry is introduced in the phase by changing x , the phase is altered as $(\Phi_R + x)$. When generating the pseudo experiment samples, one D^0 meson decays via the model with the parameters listed in Table. 4.5, and the other $\bar{D}^0$ meson decays via the modified amplitude model with the asymmetries introduced. For the sensitivity study, the sample size of the pseudo experiments is comparable to the data sample size (around 450 thousand events).

4.4.2 Variation of δ

The optimal δ value may vary with different CP violation scenarios such as the enhancement of the decay amplitude or the strong phase variation of a

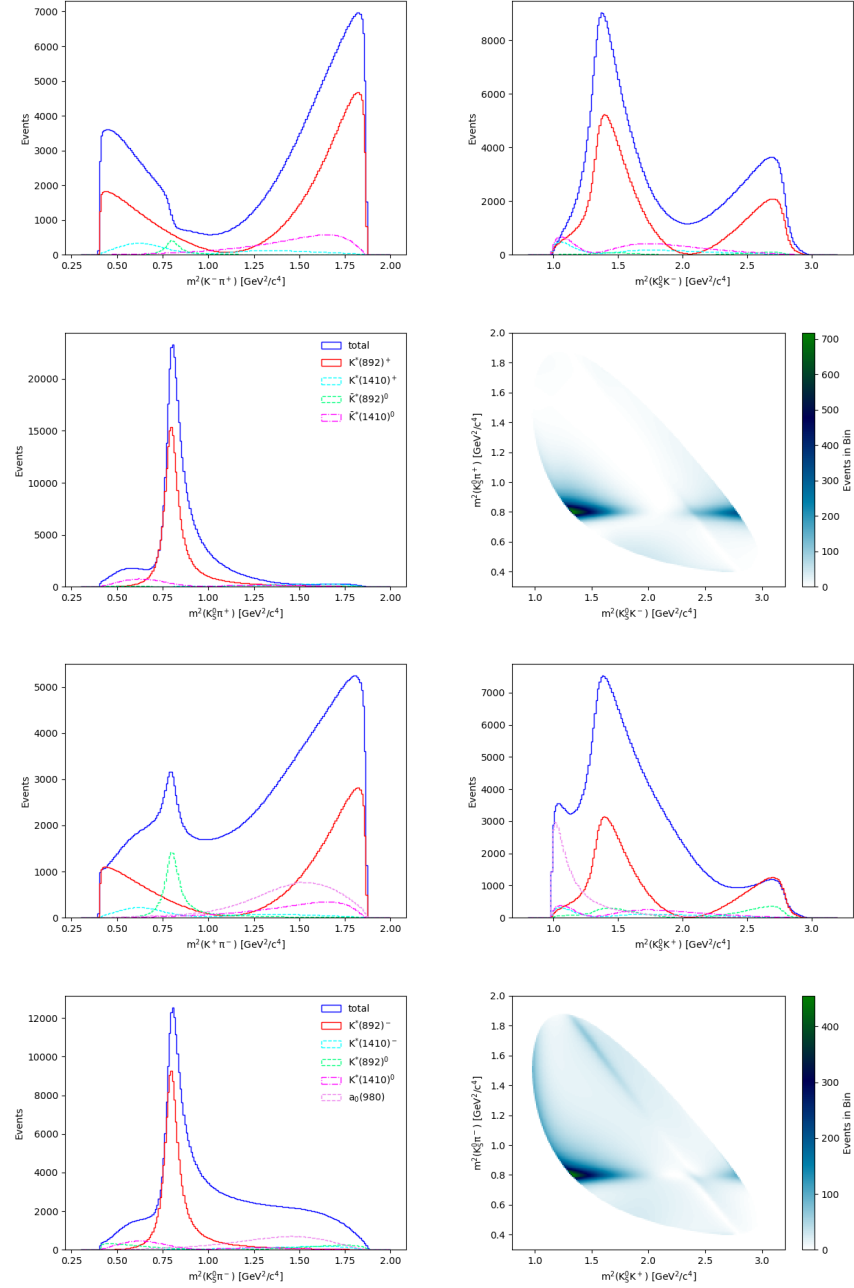


FIGURE 4.11: Projections for pseudo experiment samples where the efficiency variation across the Dalitz plot is taken into account. The upper four plots are for $D^0 \rightarrow K_S^0 K^- \pi^+$ decays, and the bottom four plots are for $D^0 \rightarrow K_S^0 K^+ \pi^-$ decays.

resonance respect to its established values. Different scenarios refer to different amounts of injected CP asymmetry, in the form of ΔAmp (in %, representing the percentage of asymmetry introduced in the amplitude of a resonance) and $\Delta\delta_D$ (in degrees, referring to the asymmetry introduced in the strong phase). The ranges of variation of ΔAmp and $\Delta\delta_D$ were chosen to cover the most plausible CP violating scenarios in steps of 1% and 0.5-1, respectively.

Therefore, a delta scan (here δ refers to the ET distance parameter, see 4.2.2) was performed for each of the investigated resonances and each of the amplitude and phase variations. Values from $\delta = 0.1$ to 0.5 were scanned with a 0.1 step, values from $\delta = 1$ to 5 were incremented with 0.5 steps. Only the scenarios which returned at least a significant P-value 0.1 were registered. The scans show minima at δ values ranging from 0.2 to 1. Since the minima for most of the resonances lie around $\delta = 0.2$ and the resonances of greater interest have a minima here, $\delta = 0.2$ will be used as main value for the signal sample P-value. The results of the δ parameter scans in ΔAmp and $\Delta\delta_D$ are reported in Fig. 4.12 and Fig. 4.13 for the SS sample; the results for the OS sample are shown in Fig. 4.14, 4.15 and Fig. 4.16.

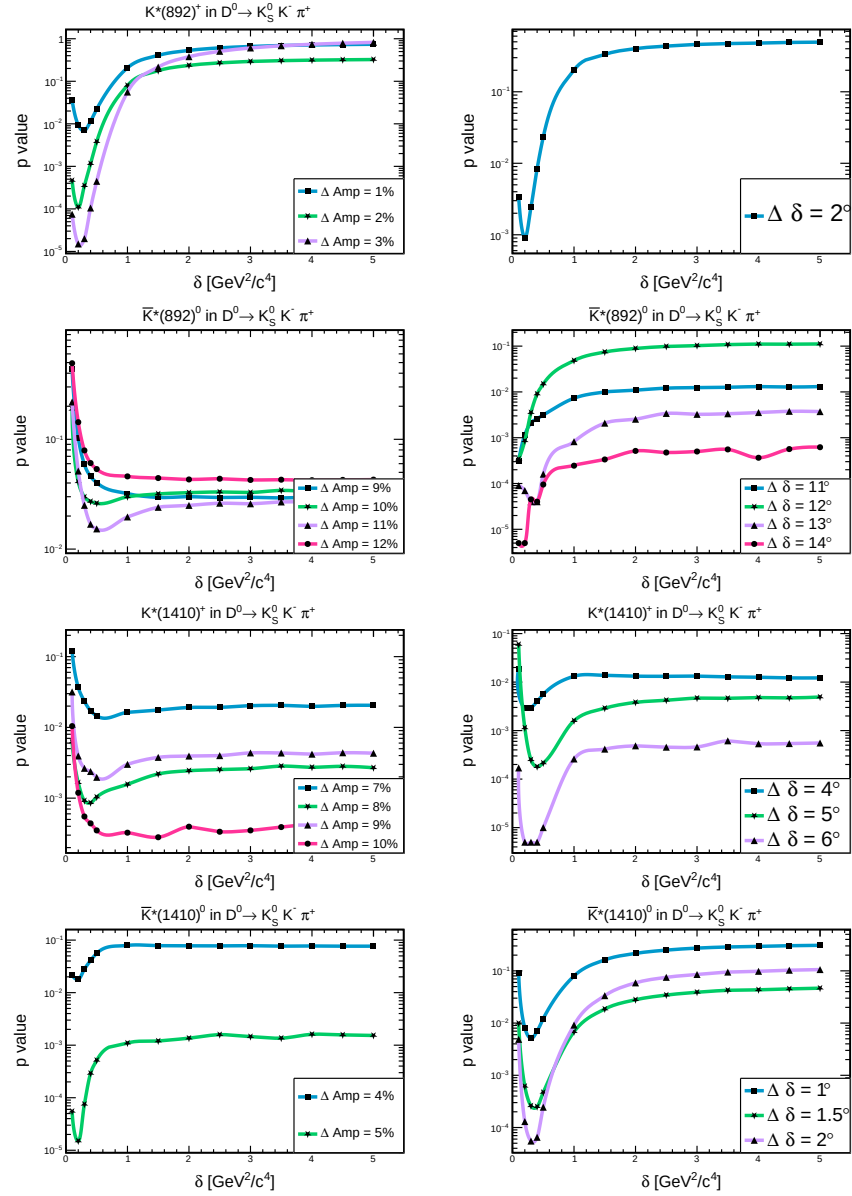


FIGURE 4.12: Scan of the δ parameter for the $D^0 \rightarrow K_S^0 K^- \pi^+$ mode for the $K^{*+}(892)$, $K^{*0}(892)$, $K^{*+}(1410)$ and $K^{*0}(1410)$ resonances with different asymmetries introduced. ΔAmp (in %) refers to an asymmetry introduced in the amplitude of the resonance, $\Delta \delta_D$ (in degrees) refers to an asymmetry introduced in the strong phase.

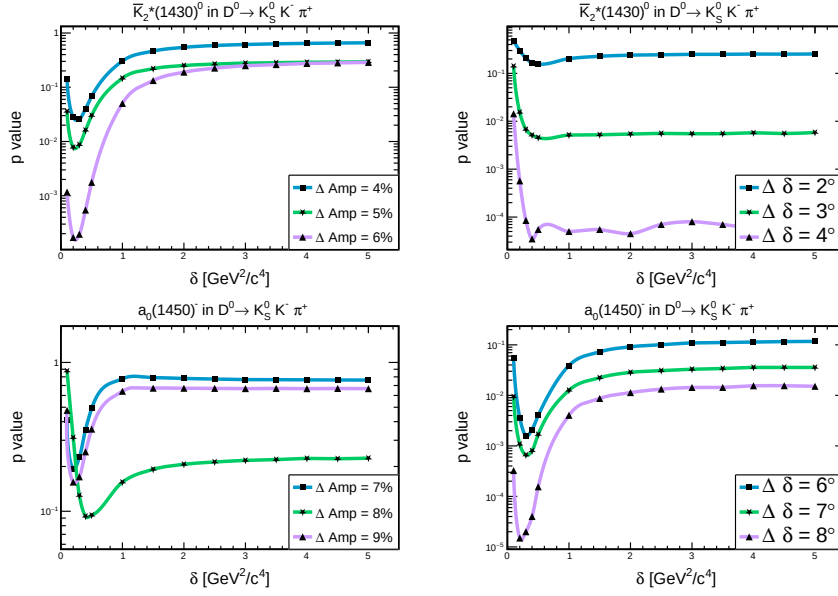


FIGURE 4.13: Scan of the δ parameter for the $D^0 \rightarrow K_S^0 K^- \pi^+$ mode for the $K_2^{*0}(1430)$ and $a_0(1450)$ resonances with different asymmetries introduced. ΔAmp (in %) refers to an asymmetry introduced in the amplitude of the resonance, $\Delta\delta_D$ (in degrees) refers to an asymmetry introduced in the strong phase.

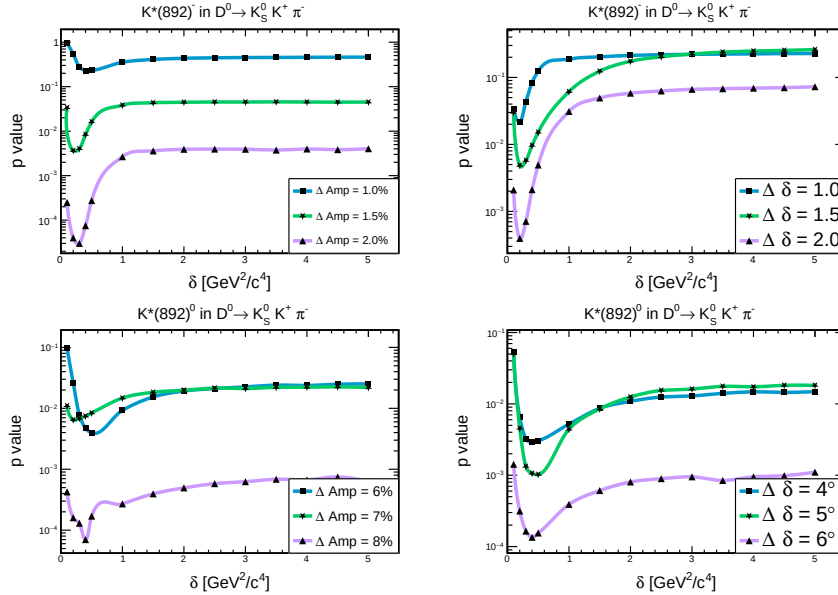


FIGURE 4.14: Scan of the δ parameter for the $D^0 \rightarrow K_S^0 K^+ \pi^-$ mode for the $K^{*-}(892)$ and $K^{*0}(892)$ resonances with different asymmetries introduced. ΔAmp (in %) refers to an asymmetry introduced in the amplitude of the resonance, $\Delta\delta_D$ (in degrees) refers to an asymmetry introduced in the strong phase.

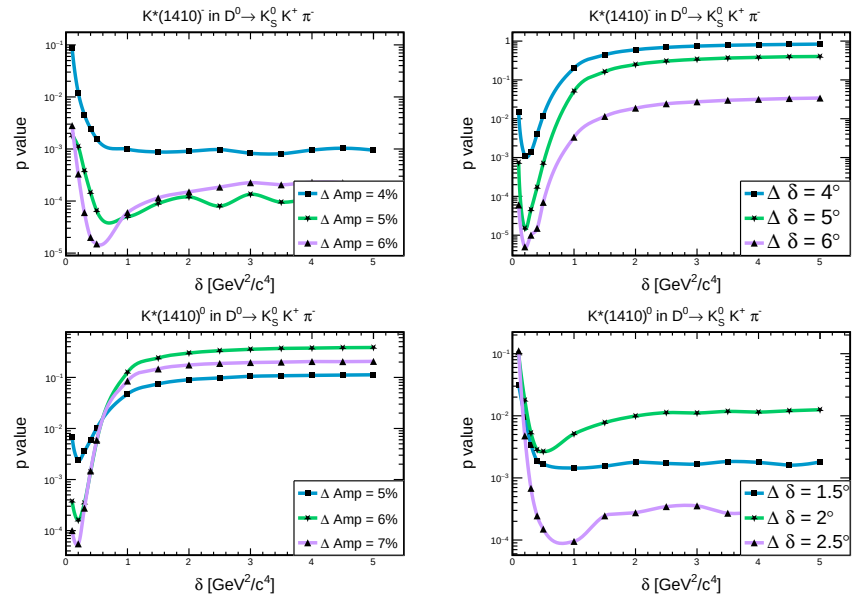


FIGURE 4.15: Scan of the δ parameter for the $D^0 \rightarrow K_S^0 K^+ \pi^-$ mode for the $K^{*-}(1410)$ and $K^{*0}(1410)$ resonances with different asymmetries introduced. ΔAmp (in %) refers to an asymmetry introduced in the amplitude of the resonance, $\Delta \delta_D$ (in degrees) refers to an asymmetry introduced in the strong phase.

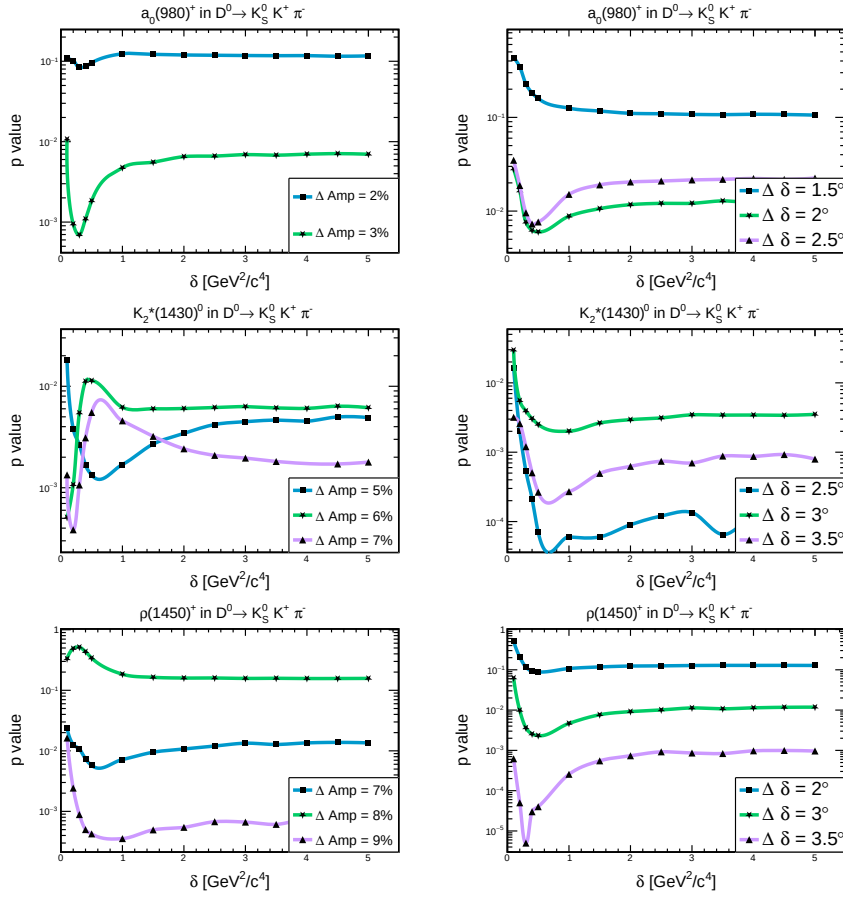


FIGURE 4.16: Scan of the δ parameter for the $D^0 \rightarrow K_S^0 K^+ \pi^-$ mode for the $a_0(980)$, $K_2^*(1430)$ and $\rho(1450)$ resonances with different asymmetries introduced. ΔAmp (in %) refers to an asymmetry introduced in the amplitude of the resonance, $\Delta \delta_D$ (in degrees) refers to an asymmetry introduced in the strong phase.

4.5 Control channels

To calibrate the ET, a control channel is needed to ensure the correct behaviour of the method when tested with CP symmetric data. Desirable features for a control channel are:

- high sample size;
- same final state particles;
- no or negligible CP violation e.g. a Cabibbo-Favoured (CF) mode.

Since the control channel is expected to be CP symmetric, the expected result of the ET with the control sample is a set of uniformly distributed P-values. Any deviation from symmetry points out an asymmetry which could be caused by the detector itself, by the trigger choice or by biasing offline requirements, etc.

The control channels chosen to validate the ET method for the $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ channel are $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ and $D^0 \rightarrow K_S^0 \pi^+ \pi^-$. The choice of these two channels will be motivated in the following sub-sections.

In Appendix F a direct comparison between the kinematics of selected D^0 children particles for the control and signal channel is shown. This allows to confirm that the choice of the aforementioned channels is pertinent.

Finally, both control channel samples were tested splitting by year and polarity to ensure no bias that could be masked or compensated for in the total sample. Furthermore, the DD and LL track samples for the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ channel have been tested separately. All these studies are reported in Appendix G.

4.5.1 The $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ control channel

The $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ channel is dominated by a CF $c \rightarrow s\bar{u}d$ diagram, with a small contribution of a Doubly-Cabibbo-Suppressed $c \rightarrow d\bar{u}s$ amplitude, thus the CP violation level is expected to be negligible. The final state particles are the same as those of the signal channel, so the final state kinematics are expected, and have been confirmed (see Appendix F), to be similar. This channel allows to investigate second order effects on the ET of the $K - \pi$ detection asymmetry. More specifically, the detection efficiency of the LHCb detector for charged kaons and pions depends on the particle momentum [79]. This could potentially

produce local asymmetries in the distribution of D^0 and $\bar{D}^0$ decays in phase space that could mimic CP violating effects.

4.5.1.1 Selection of prompt $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decays with Run2 data

The Run2 sample is selected with the **Dstp2D0Pip_D02KmPimPipPipTurbo** Turbo line. The prompt Turbo line criteria are listed in Table 4.6, and are mostly similar to those of the $D^0 \rightarrow K_S^0 \pi^\pm \pi^\mp$ TURBO line.

Particle	Parameter	Value
D^{*+}	VFASPF(VCHI2PDOF)	< 15
D^0	PT	$> 2000 \text{ MeV}/c$
	P	$> 30000 \text{ MeV}/c$
	CHI2VXNDOF	< 12
	BPVVDCHI2	> 25
	BVPDIRA	$> \cos(0.02) (> 0.99985)$
	BPVLTIME	> 0.0001
$K - \pi$	TRGHOSTPROB	$< 0.4(-)$
	TRCHI2DOF	< 3
	PT	$> 250 \text{ MeV}/c$
	P	$> 1000 \text{ MeV}/c$
	MIPCHI2DV(PRIMARY)	> 3
	PIDK	$K > 5$ $\pi < 5$
π_{soft}	TRCHI2DOF	< 3
	TRGHOSTPROB	$< 0.25 (< 0.4)$
	PT	$> 200 \text{ MeV}/c$
	P	$> 1000 \text{ MeV}/c$

TABLE 4.6: HLT2 requirements for the prompt $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ channel. In brackets are the values for 2015-6 data samples, a ‘-’ means the requirement was not yet implemented in the HLT2 but was applied offline. The definition for all the parameters can be found in Appendix D.

The signal mass window for the D^0 candidates and the mass difference ΔM are the same as for the signal channel (Sec. 4.3.2). The reconstructed data for this channel contains two versions of the DTF: **ReFit**, which constrains the D^{*+} vertex, and **D0Fit**, which additionally constrains the D^0 mass to the PDG value. The latter was chosen in our study being the most similar to the **DTFD0KS** conditions used in the signal channel selection. In Fig. 4.17 and 4.18, the fits to the D^0 mass distribution are shown for reference. In Table 4.7, the fit parameters for the ΔM distribution are summarised.

Since the $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ channel shares the same final state particles as the $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ channel, to avoid accidental unblinding a 5σ veto has been

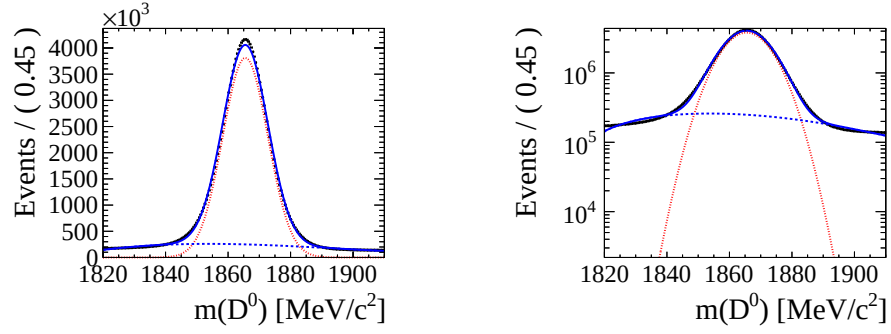


FIGURE 4.17: Fitted distribution (left) and with log y axis (right) for the D^0 invariant mass for $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decays. The red dotted line corresponds to the Gaussian function, used for the signal, the blue dotted line shows the background component, the blue solid line is the total fit.

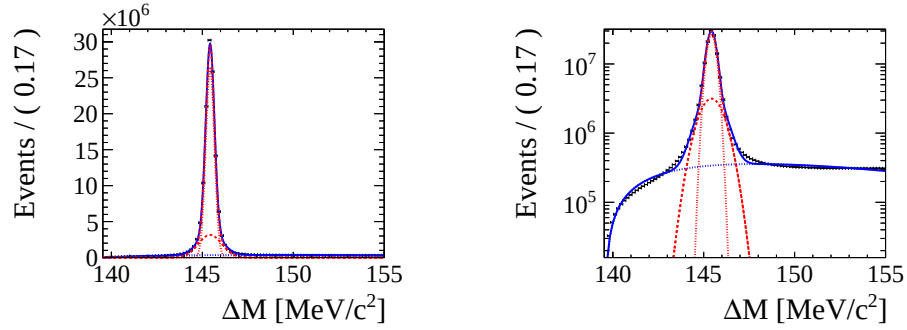


FIGURE 4.18: Fitted distribution (left) and with log Y axis (right) for **D0Fit** ΔM , for $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decays. The red dotted and dashed lines correspond to the double-Gaussian function components, the blue dotted line shows the background component, the blue solid line is the total fit.

Parameter	$K^- \pi^+ \pi^- \pi^+$
Total candidates [10^3]	116 770
Signal candidates [10^3]	$113\,918 \pm 11\,090$
Mean [MeV/c^2]	145.428 ± 0.001
σ_1 [MeV/c^2]	0.328 ± 0.001
σ_2 [MeV/c^2]	0.643 ± 0.004
fraction	0.755 ± 0.001
Background candidates [10^3]	$2\,852 \pm 728$
Purity [%]	97.6

TABLE 4.7: Signal and background yields, and fit parameters for the $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ sample. Here, Mean is the central value of both Gaussian functions, σ_1 and σ_2 are the width of the double-Gaussian function; fraction is the signal fraction of the narrower Gaussian. The signal and background yields correspond to a 3σ mass window centered on the mean value. The purity is the fraction of signal candidates on signal+background candidates.

put on any neutral combination of charged pions mass that could mimic a K_S^0 particle. This resulted in a loss of around $\sim 9.6\%$ of the sample candidates.

Furthermore, to check that there is no overlap between the $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ and signal channel, for each of these combination of pions the subvertices corresponding to opposite charged pion pairs are required to have sufficient separation from their parent D^0 decay vertex. This corresponds to requiring $\log(\text{FDCHI2}) > 5$, which is analogous to requesting $\text{DVDVVDCHI2(KS)} > e^5$ (see Sec. 4.3.2). Applying these criteria limits the number of neutral combination of charged pions from the $D^0 \rightarrow K^\pm \pi^\mp \pi^\pm \pi^\mp$ channel to 1, therefore this control sample and the signal channel sample are completely disjoint and there is no risk of accidental unblinding occurring.

The ET for the $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ control channel makes use of the same variables as the signal channel (see 4.2.1.1): this is achieved by randomly selecting, event by event, two opposite sign pions combining them together to mimic a K_S^0 . The remaining pion is then used to compute the s-variables exactly as for the $K_S^0 K \pi$ channel. This allows to treat $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decays as 3-body just like $K_S^0 K \pi$ decays for a one on one comparison.

ETs have been run with the optimised δ values ranging from 0.2 – 0.5 to take into account various amplitude and phase asymmetry scenarios (Sec. 4.4). Tests have been run with a sample size comparable to the signal channel: 500 thousand events per sample (i.e. for a total of 1 million events, slightly more than the sample size available for the $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ SS sample, see Sec. 4.3.3), 10 thousand permutations, 500 events per permutation.

This approach aims to test samples with a sample size comparable to the signal channel (Sec. 4.3.2.2) to verify that no asymmetry is detected in a one to one comparison. Further studies, carried out with double the sample size of the signal channel are summarised in Appendix E.

As explained in Sec. 4.2.3, the obtained P-value distributions are compared against a flat uniform distribution with a χ^2 and KS test. A perfectly uniform distribution would yield a $P(\chi^2) = 100\%$ and $\text{KS} = 1$.

The P-value distributions, obtained with 500 thousand events, 10 thousand permutations and 500 event per permutations, with $\delta = 0.2 - 0.5$, for a total of 100 P-values for the whole Run2 prompt sample, are shown in Fig. 4.19.

The χ^2 and KS results, summarised in Table 4.8, show no significant deviation from uniform distribution. This means that using a number of events comparable with the signal sample size of the $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ channel, the ET results for the control mode $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ are in agreement with the null-hypothesis as expected.

In conclusion, no deviation from the null-hypothesis is found by running the ET on the control channel with the same sample size as the one of the signal

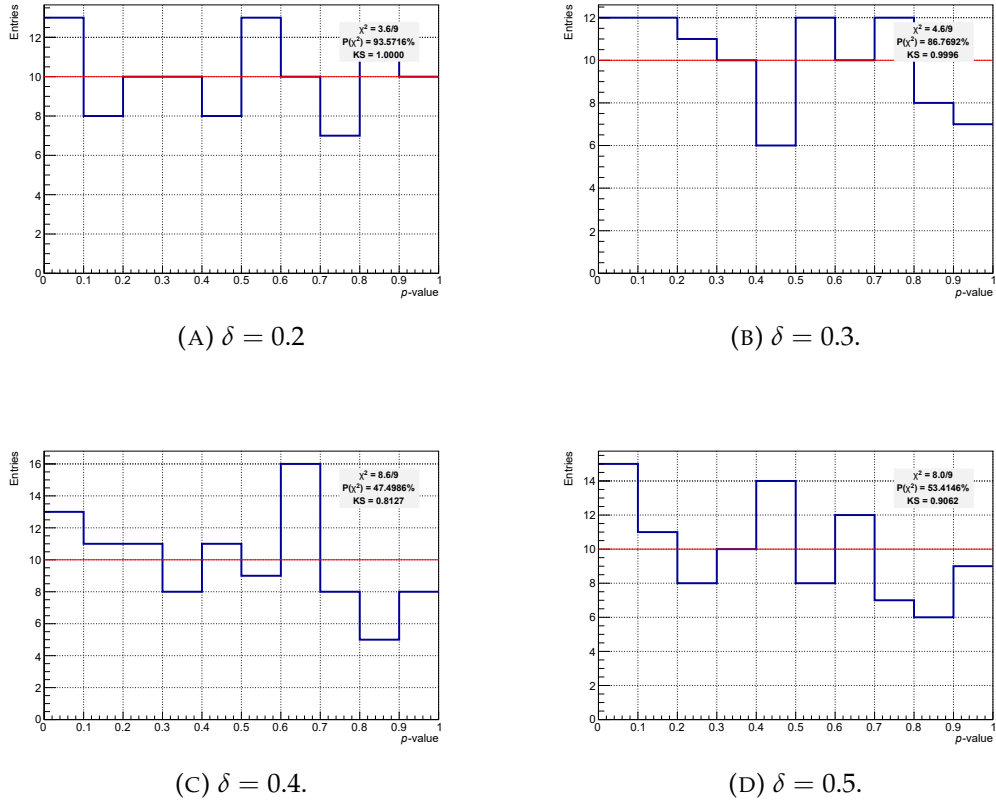


FIGURE 4.19: Results of ET runs on the $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ channel for 500 thousands events, 10 thousand permutations, 500 events per permutation, with the optimised delta values; each test allowed for 100 P-values with the available Run2 prompt sample size. Plot a), b), c) and d) shows the result with a value of $\delta = 0.2 - 0.3 - 0.4 - 0.5$, respectively. The χ^2 and KS test results show no deviation from a uniform distribution.

δ	$P(\chi^2)[\%]$	KS
0.2	93.5716	1.0000
0.3	86.7692	0.9996
0.4	47.4986	0.8127
0.5	53.4146	0.9062

TABLE 4.8: P-value and KS test results for P-value distributions obtained with the ET using $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decays with 500 thousand events sample size for a total of 100 P-values and $\delta = 0.2 - 0.5$. No significant deviation from uniform distribution is found.

mode: in this scenario the resulting P-value distributions are compatible with a uniform distribution.

4.5.2 The $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ control channel

To investigate the impact of the K_S^0 asymmetry on the ET, the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ channel has been chosen as second control channel. Although the final state particles differs from the signal channel for a charged π , the presence of the K_S^0 allows to investigate possible second order effects of the K_S^0 detection asymmetry on the ET. The time-integrated CP asymmetry in these decays is expected to be negligible [65], allowing this to be used as a control channel. The L0 and HLT1 trigger requirements are the same as the signal channel ones (see Sec. 4.3).

4.5.2.1 Selection of prompt $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays with Run2 data

Prompt decays from the **Hlt2CharmHadDstp2D0Pip_D02KS0PmPp_KS0DDTurbo** and **Hlt2CharmHadDstp2D0Pip_D02KS0PmPp_KS0LLTurbo** lines have been used as further control channel to cross-check for any effect that may be induced by the K_S^0 . The HLT2 selection criteria are for this channel are listed in Table 4.9.

Particle	Paramter	DD	Common	LL
D^{*+}	VFASPF(VCHI2NDOF)		< 10	
D^0	CHI2VXNDOF		< 5 (< 20)	
	PT		$> 1800 \text{ MeV}/c$	
	D2DVVDCHI2(KS)		$> e^5$ (*)	
	PVVDIRA		$> \cos 0.0346$	
	BPVLTIME		> 0.0001	
	BPVVDCHI2		> 20	
π	TRCHI2NDOF		< 3	
	TRGHOSTPROB		< 0.4 (*)	
	PT		$> 200 \text{ MeV}/c$	
	P		$> 1000 \text{ MeV}/c$	
	MIPCHI2DV(PRIMARY)		> 4	
	PIDK		< 5	
π_{soft}	TRCHI2DOF		< 3 (*)	
	TRGHOSTPROB		< 0.25 (*) MeV/c	
	PT		> 200 (*) MeV/c	
	P		> 1000 (*) MeV/c	
K_S^0	ADAMASS	$< 80 \text{ MeV}/c^2$		$< 50 \text{ MeV}/c^2$
	ADMASS	$< 64 \text{ MeV}/c^2$		$< 35 \text{ MeV}/c^2$
	VFASPF(VCHI2PDOF)		< 30	
	BPVLTIME		> 0.0005	
	BPVVDZ	$> 400 \text{ mm}$		-
	BPVLTIME	-		$> 2.0 \text{ ps}$
	VFASPF(VZ)	$> 300, < 2275 \text{ mm}$		$> -100 \text{ mm}, < 500 \text{ mm}$
π from K_S^0	TRCHI2DOF		< 4	
	P	$> 3000 \text{ MeV}/c$		-
	PT	$> 175 \text{ MeV}/c$		-
	MIPCHI2DV(PRIMARY)	-		> 36
	TRGHOSTPROB		< 0.4	

TABLE 4.9: Full list of the HLT2 parameters for the $D^0 \rightarrow K_S^0 \pi \pi$ channel prompt decays for Run2. Between brackets are the parameter values before the trigger changes introduced in 2017 (see 4.3.1.2) to increase the sample purity. Asterisk marks a parameter added for the 2017-8 lines. The meaning of all parameters is provided in Appendix D.

This channel shares the same Decay Tree Fitter modes (for the definition of the Decay Tree Fitter see 4.3.1.2) as the $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ channel, thus the **DTFD0KS** mode is chosen. The selection criteria applied to the mass distributions are the same used for the $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ channel (Sec. 4.3.2). For reference, the fits to the D^0 and ΔM distributions are shown in Fig. 4.20 and 4.21, respectively. The fit results are given in Table 4.10.

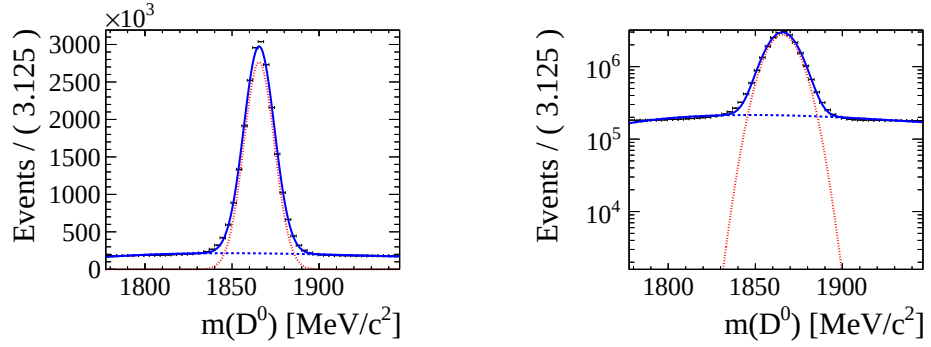


FIGURE 4.20: Fitted distributions of D^0 mass with linear y (left) and log y axis (right) for $K_S^0 \pi^+ \pi^-$ decays. The red dotted line corresponds to the Gaussian function used for the signal, the blue dotted line shows the background component, the blue solid line is the total fit.

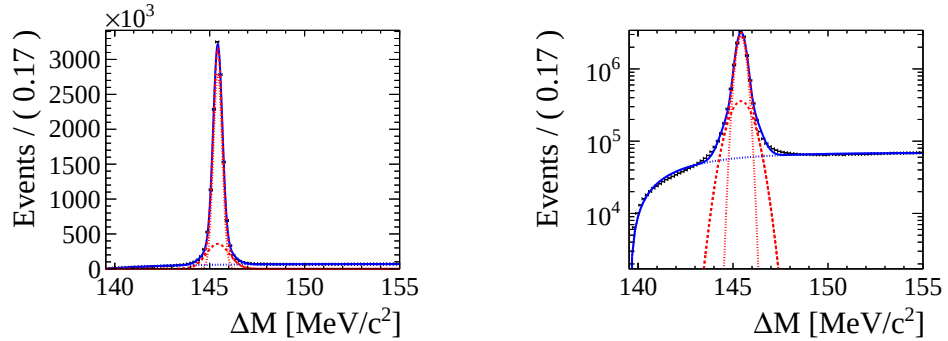


FIGURE 4.21: Distribution of DTFD0KS ΔM mass distribution for $K_S^0 \pi \pi$ decays overlaid with the fit described in the text with linear (left) and log (right) y axis scale. The red dotted and dashed lines correspond to the double-Gaussian function components, the blue dotted line shows the background component, the blue solid line is the total fit.

ETs have been run with the optimised δ values ranging from 0.2 – 0.5 to take into account various amplitude and phase asymmetry scenarios (Sec. 4.4). Similarly to Sec. 4.5.1, tests have been run with a sample size comparable to the signal channel (Sec. 4.3.2.2) to have a one to one comparison: 500 thousands events per sample, 10 thousands permutations, 500 events per permutation were used, for a total of 13 P-values for the whole run 2 sample. The P-value distributions, obtained for $\delta = 0.2 - 0.5$ are shown in Fig.4.22. In Table 4.11

Parameter	$K_S^0 \pi^+ \pi^-$
Total candidates	12 609 412
Signal candidates	$12\,121\,130 \pm 3\,676$
Mean [MeV/c]	145.427 ± 0.001
σ_1 [MeV/c]	0.236 ± 0.001
σ_2 [MeV/c]	0.600 ± 0.001
fraction	0.754 ± 0.001
Background candidates	$488\,828 \pm 265$
Purity [%]	96

TABLE 4.10: Signal and background yields, and fit parameters for the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ sample. Here, Mean is the central value of both Gaussian functions, σ_1 and σ_2 are the width of the double-Gaussian function; fraction is the signal fraction of the narrower Gaussian. The signal and background yields correspond to a 3σ mass window centred on the mean value. The purity is the fraction of signal candidates on signal+background candidates.

the χ^2 and KS test results are shown, proving that no deviation from uniform distribution is observed. Further studies, carried out with double the sample size of the signal channel are summarised in Appendix E.

In conclusion, no deviation from the null-hypothesis is observed in the tests carried out with $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays, confirming that the ET is not sensitive to second order effects induced by the K_S^0 , nor other detection asymmetries when tested with a comparable sample size to the signal channel. Thus, the ET will not pick up any effect induced by the short-lived neutral kaon when $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ is tested with the available sample size (Sec. 4.3.2.2).

δ	$P(\chi^2)[\%]$	KS
0.2	19.2485	0.8536
0.3	40.9370	0.9237
0.4	86.0264	0.9996
0.5	86.0264	0.9797

TABLE 4.11: P-value and KS test results for P-value distributions obtained with the ET using $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays with 500 thousand events samples size for a total of 13 P-values and $\delta = 0.2 - 0.5$. No significant deviation from uniform distribution is detected.

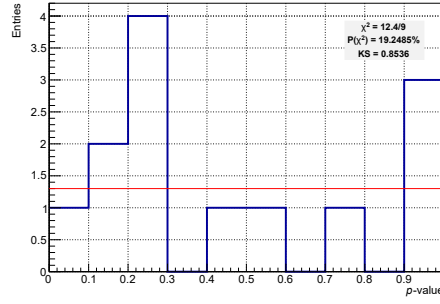
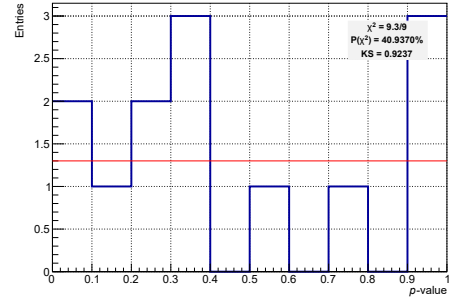
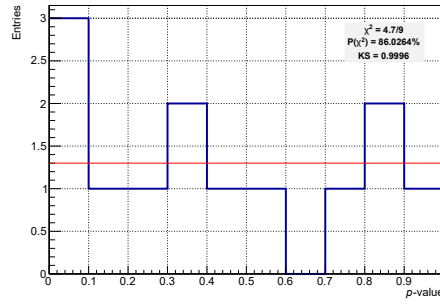
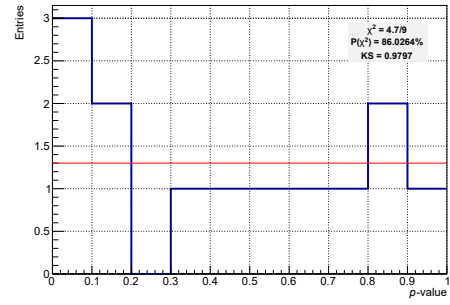
(A) $\delta = 0.2$ (B) $\delta = 0.3$ (C) $\delta = 0.4$ (D) $\delta = 0.5$

FIGURE 4.22: Results of ET runs on the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ channel for 500 thousands events, 10 thousand permutations, 500 events per permutation for a total of 13 P-values with the optimised δ values. Plot a), b), c) and d) shows the result with a value of $\delta = 0.2 - 0.3 - 0.4 - 0.5$, respectively. No deviation from uniform distributions is seen.

4.6 Background studies

In general, there are several sources of asymmetries that can affect the measurement presented here. As the method is only sensitive to local asymmetries in the phase space, rather than to global asymmetries, it is sufficient to focus on these local effects. Detection asymmetries of the final state particles can introduce local asymmetries if they depend on the particle kinematics. The impact of this can be estimated through the analysis of the $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ mode, as the kaon detection asymmetry is not cancelled and therefore contributes at first order. This has been discussed in Sec. 4.5 and results show no effects at the level of the sample size that will be used in the signal channel.

4.6.1 Background asymmetries

Although the $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ sample has high purity (91% circa) in the ΔM signal region, there can still be some asymmetries in a contributing background component which may affect the CP violation search. Any background asymmetry which is uniform across the phase space distribution has no impact on the ET method, however, local asymmetries can bias the measurement. The background selection uses the K_S^0 , D^0 and ΔM sidebands, as described in Sec. 4.3.4.

The test was carried out as follows: the SS decays test was ran with 54 000 D^0 and $\bar{D}^0$ events and 10 000 permutations, the OS decays test used 36 000 D^0 and $\bar{D}^0$ events and 10 000 permutations. These correspond to roughly the number of background events estimated in the ΔM signal region (see Sec. 4.3.4).

The tests have been carried out with $\delta = 0.2 - 0.5$. One P-value was computed due to the size of the available sample. The results are listed in Table 4.12. No deviation from the null-hypothesis is found.

δ	P-value	
	SS	OS
0.2	0.8871	0.6501
0.3	0.8947	0.5056
0.4	0.8808	0.3529
0.5	0.8889	0.2855

TABLE 4.12: ET results for $D^0 \rightarrow K_S^0 K^\pm \pi^\mp$ decays in the background region. The SS and OS tests have been carried out with 54 000 and 36 000 events per sample, respectively.

No deviation from the null-hypothesis is observed.

4.6.2 Combinatorial background with real D^0 and K_S^0

Further crosschecks have been performed on the ΔM sidebands (5σ away from the peak) including the D^0 and K_S^0 signal region. This allows to check the amount of real K_S^0 and D^0 in the background sample. The aforementioned distributions are shown in Fig. 4.23 and Fig. 4.24 for the SS and OS sample, respectively.

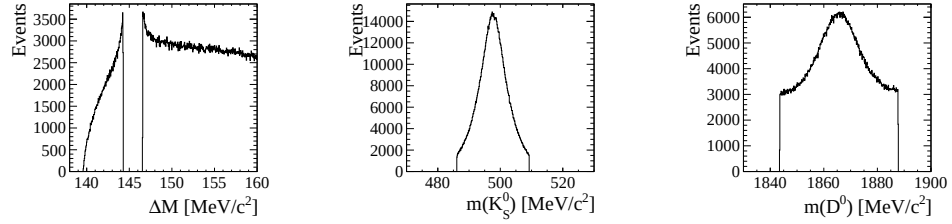


FIGURE 4.23: Mass distributions for the SS sample, selecting ΔM sidebands 5σ away from the peak (left), signal K_S^0 (centre) and D^0 mass (right). The plots show conspicuous amount of combinatorial background.

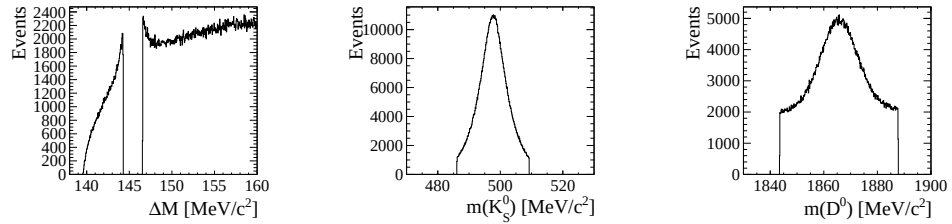


FIGURE 4.24: Mass distributions for the OS sample, selecting ΔM sidebands 5σ away from the peak (left), signal K_S^0 (centre) and D^0 mass (right). The plots show conspicuous amount of combinatorial background.

Since the amount of real K_S^0 and D^0 is not negligible, to ensure that this will not induce any bias when the ET is run on the signal sample, these sample have been tested with the ET. The test was done using 85 thousand and 52 thousand events per sample for the SS and OS samples, respectively, which is double the number of background candidates estimated to be under the signal region (see Sec. 4.3.4). The number of P-values computed with the size of the available sample were 7 and 9, for the SS and OS samples, respectively. The other test parameters were unchanged, and only $\delta = 0.2$ was used for this crosscheck. The resulting P-values distributions are shown in Fig. 4.25, while the χ^2 and KS test results are summarised in table 4.13. No evidence of bias was found.

4.6.3 SS sample background studies

The results obtained for the SS sample in the previous section show a low $P(\chi^2)$, caused by the accumulation of some P-values in two bins. No P-value is in the

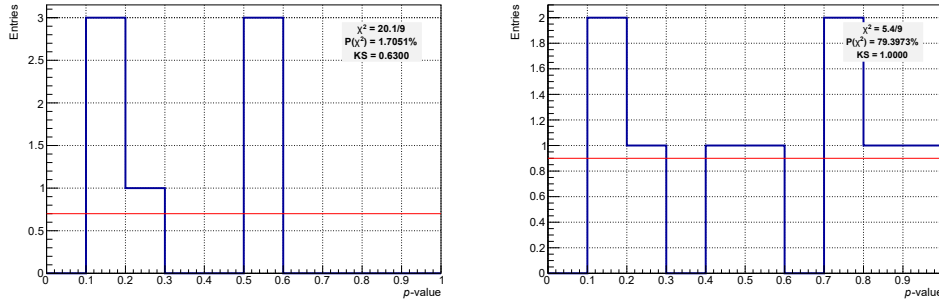


FIGURE 4.25: P-value distributions for the SS (left) and OS (right) sideband samples. No deviation from the null-hypothesis is detected, with no P-values in the first bin for both cases.

Sample	$P(\chi^2)$	KS
SS	1.7051	0.6300
OS	79.3973	1.0000

TABLE 4.13: ET results for SS and OS samples in the ΔM sidebands region, with real K_S^0 and D^0 candidates. The SS and OS tests have been carried out with 85 000 and 52 000 events per sample, respectively. No deviation from the null-hypothesis is observed.

first bin, meaning no asymmetry is present in this data sample. Nevertheless, to further check for possible asymmetries, additional studies have been carried out with ΔM sidebands (5σ away from the peak) and either D^0 in the signal region and K_S^0 sidebands (5σ away from the peak) or K_S^0 from the signal region and D^0 sidebands. All tests have been run with $\delta = 0.2$. For the real D^0 and combinatorial K_S^0 test only 45 000 events were available, thus the ET has been run using 20 000 events per sample allowing for 1 P-value, with a $P=0.137$. The test with real K_S^0 and combinatorial D^0 have been carried out with 85 000 events per sample, with the statistics allowing for 15 P-values. The P-value distribution is shown in Fig. 4.26, while the test results are summarised in Table 4.14. No deviation from the null hypothesis is found.

4.6.4 Combinatorial background in the K_S^0 mass sidebands

For the sake of completeness, the combinatorial background for the K_S^0 mass sidebands (5σ away from the peak) in the ΔM and D^0 mass distributions is

Sample	$P(\chi^2)$	KS
SS	63.7119	0.9993

TABLE 4.14: ET results for the SS sample in the ΔM and D^0 mass sidebands region, with real K_S^0 candidates. The SS test have been carried out with 85 000 events per sample. No deviation from the null-hypothesis is observed.

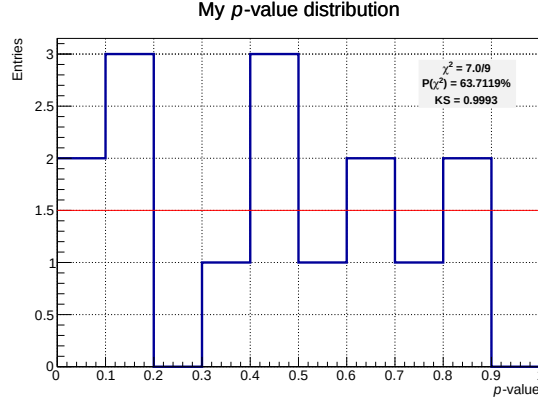


FIGURE 4.26: ET results for the SS sample in the ΔM and D^0 mass sidebands region, with real K_S^0 candidates. The test have been carried out with 85 000 events per sample. No deviation from the null-hypothesis is observed.

shown here for the SS (Fig. 4.27) and OS samples (Fig. 4.28), respectively.

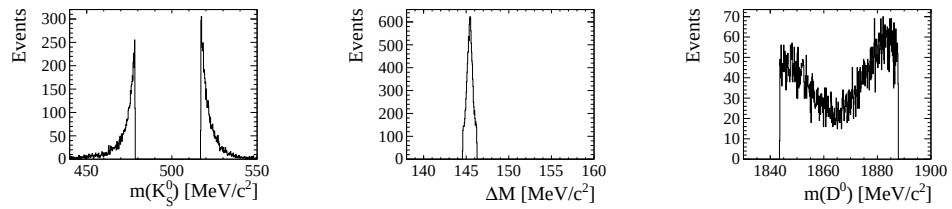


FIGURE 4.27: Mass distributions for the SS sample, selecting K_S^0 mass sidebands 5σ away from the peak (left), signal ΔM (centre) and D^0 mass (right).

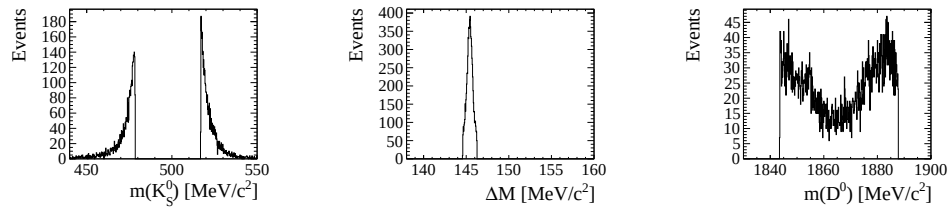


FIGURE 4.28: Mass distributions for the OS sample, selecting K_S^0 mass sidebands 5σ away from the peak (left), signal ΔM (centre) and D^0 mass (right).

A residual amount of peaking component can be observed in the ΔM signal window with this selection. This is caused by the tighter mass window which is applied to the $M(K_S^0)$: the mass distributions are modelled with a double Gaussian function, with same mean value and different width. It was chosen to use the width of the narrowest Gaussian function to define the signal window. This choice leaves some residual signal events in the $M(K_S^0)$ sidebands when the signal window for the ΔM and D^0 mass are selected.

4.6.5 Combinatorial background in the D^0 mass sidebands

Similarly to what is shown for the K_S^0 mass sidebands, in this section the combinatorial background for the D^0 mass sidebands (5σ away from the peak) in the ΔM and K_S^0 mass distributions for the SS (Fig. 4.29) and OS samples (Fig. 4.30) are shown, respectively. Some residual background of real K_S^0 is present in the this sample.

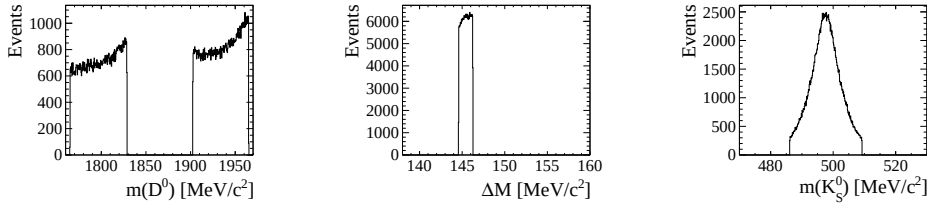


FIGURE 4.29: Mass distributions for the SS sample, selecting D^0 mass sidebands 5σ away from the peak (left), signal ΔM (centre) and K_S^0 mass (right).

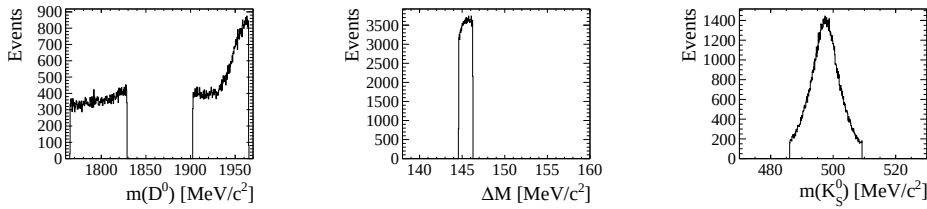


FIGURE 4.30: Mass distributions for the OS sample, D^0 mass sidebands 5σ away from the peak (left), signal ΔM (centre) and K_S^0 mass (right).

4.7 Peaking background studies

This section is dedicated to the investigation of the presence of peaking structures in the background candidates of the signal sample. All the PID variables used in the following subsections are explained in detail in Appendix D

4.7.1 Mis-ID cross-feed events

This subsection investigates the possibility of potential contamination of the signal sample with cross-feed events due to misidentified particles coming from other channels. Two cross-feed contributions are investigated:

- $K_S^0 \pi \pi$ events with π misidentified as K .
- $K_S^0 K K$ events with K misidentified as π .

To investigate the amount of cross-feed, 1 million pseudo experiments events were generated with the RapidSim [80] package using the appropriate alternative mass hypothesis, then the standard signal selection (see Sec. 4.3.2) was applied. The next subsections contain the details of the pseudo experiments generation and results after the application of the signal requirements. It should be noted that since RapidSim is not able to generate all the variables that are contained in regular MC or WG ntuples, only a subselection of the offline criteria was applied. Therefore, the results described in the following subsections are an overestimation of the actual amount of cross-feed events present in the signal channel. The applied criteria are listed in Table 4.15. The signal mass windows and fiducial cuts are the same as those listed in Sec. 4.3.

4.7.1.1 $K_S^0 \pi \pi$ events with a π misidentified as K

The $K_S^0 \pi \pi$ pseudo experiments were generated with RapidSim using the external generator EvtGen [81]. The following EvtGen decay models were used to generate the decays:

- $D^{*+} \rightarrow D^0$: VSS (vector to scalar scalar).
- $D^0 \rightarrow K_S^0 \pi \pi$: D_DALITZ (Dalitz amplitude for $D \rightarrow K \pi \pi$ decays).
- $K_S^0 \rightarrow \pi \pi$: PHSP (generic phase space to n-body).

From Run2 HLT2 selection criteria

$\pi_{soft} P_T$	$> 200 \text{ MeV}/c$
$\pi_{soft} P$	$> 1000 \text{ MeV}/c$

PID selection criteria

D^0 and K_S^0 final state particles ProbNN	$> 0.3 (\pi), > 0.6 (K)$
π_{soft} ProbNN π	≥ 0.1

 D^0 Decay, Origin and Primary vertices constrains

$$D_{EV}^0 R_{XY} < 4.7 \text{ mm and } |D_{EV}^0 Z - 10.48| < 83.42 \text{ mm}$$

$$\text{where } R_{XY} = \sqrt{(D_{EV}^0 X - PV_X)^2 + (D_{EV}^0 Y - PV_Y)^2}$$

$$D_{OV}^0 R_{XY} < 4.7 \text{ mm and } |D_{OV}^0 Z - 0.54697| < 86.3588 \text{ mm}$$

$$\text{where } R_{XY} = \sqrt{((D_{OV}^0 X - PV_X)^2 + (D_{OV}^0 Y - PV_Y)^2)}$$

$$|PV_Z + 1.48863| < 81.932 \text{ mm}$$

TABLE 4.15: List of the offline requirements applied to the RapidSim pseudo experiments. Regarding the D^0 vertices constrains: D_{EV}^0 is the particle *EndVertex* i.e decay position; D_{OV}^0 is the particle *OriginVertex* i.e creation position; PV stands for *PrimaryVertex* i.e. the p-p collision position, which in the pseudo experiments corresponds to the D^{*+} creation vertex. R_{XY} is the radial distance of the particle vertex (EV or OV) from the primary vertex on the XY plane.

The Charge Conjugate (C.C.) decay was generated with the same model, but with $D^{*-} \rightarrow \pi^- D^0 (\rightarrow K_S^0 \pi \pi)$. Furthermore, pseudo experiments were generated using the LHCb geometry for production and acceptance, and the final state particles were required to remain in the acceptance of the LHCb detector downstream of the dipole magnet.

One million events were generated, with HLT2 $K_S^0 K \pi$ requirements on the D^0 pion and soft pion momentum and transverse momentum, and D^0 transverse momentum:

- $P_T(D^0) > 1800 \text{ MeV}$.
- $P_T(\pi, \pi_{soft}) > 200 \text{ MeV}$.
- $P(\pi, \pi_{soft}) > 1000 \text{ MeV}$.

Out of the 1M generated events only 71 554 (72 058 for C.C. decay) were selected.

To have a 1-to-1 comparison with the SS sample ($D^{*+} \rightarrow \pi_{soft}^+ D^0 (\rightarrow K_S^0 K^- \pi^+)$) and C.C., the π^- (π^+) was generated with the K^- (K^+) wrong mass hypothesis.

It should be noted that the wrong mass hypothesis is only applied to the mass of the particle and does not affect the kinematic variables (P , P_T , η , ϕ etc.)

The effect of the wrong mass hypothesis on the D^0 mass distribution is shown in Fig. 4.31.

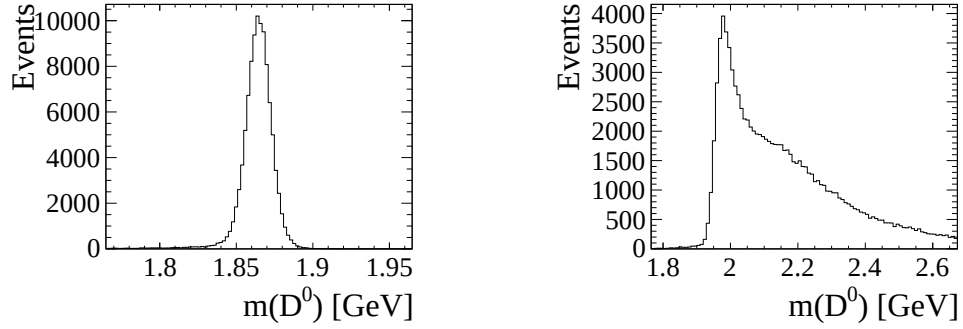


FIGURE 4.31: Mass distribution for the D^0 meson without (left) and with (right) the wrong mass hypothesis for the $\pi^- \rightarrow K^-$ swap.

After applying the applicable offline signal criteria only 9 events (0.013%) survived using the $\pi^- \rightarrow K^-$ mass hypothesis, whereas 11 survived for the C.C. pseudo experiments (0.015%). Thus, the overall offline efficiency on the pseudo experiments SS sample would be 0.014%. Then, taking into account the number of candidates in real data that passes the HLT2 trigger requirements, using the mis-ID efficiencies from the PIDCalib2 package, it is possible to get an estimation of the real cross-feed from one channel to the other. Specifically, the $K_S^0 \pi \pi$ WG ntuples (LL and DD tracks, 2016-2018 data, up and down polarities) contain 194.4 million candidates passing the 2017-8 HLT2 criteria (see Sec. 4.3.1.2).

As the $K_S^0 \rightarrow \pi \pi$ pions have to pass a $DLLk < 5$ requirement, we can use the $\pi \rightarrow \pi$ PID efficiency to estimate the total number of candidates before applying this criteria. Using the calibration samples, PIDCalib2 estimates a PID efficiency for a pion to pass a $DLLk < 5$ of 95.8%. We then can estimate the total number of candidates before applying the $DLLk < 5$ criteria to be:

$$194.4M / 0.958 = 203M \quad (4.14)$$

Let us now consider the PID efficiency for a mis-ID pion: the $K_S^0 K \pi$ channel HLT2 Turbo lines require the kaon from the D^0 decay to pass a $DLLk > 5$ criteria; for this cut the PID efficiency for a pion, considering the calibration samples taken in 2018 and averaging on the up and down polarity, is of the order of 5%. Thus, one can estimate approximately that 5% of the $K_S^0 \pi \pi$ events that are selected by the HLT2 lines to pass the $DLLk > 5$ criteria and spill into the $K_S^0 K \pi$

channel which translates into approximately

$$203 \text{ M} \times 0.05 = 10.2 \text{ M} \quad (4.15)$$

events. We then apply our offline cuts, which efficiency was estimated with the pseudo experiments to be 0.014%

$$10.2 \times 10^6 \times 0.00014 = 1\,428 \quad (4.16)$$

events. This is a very conservative estimation, as not all the offline requirements were applied for the reasons mentioned above. We then conclude that cross-feed events from the $K_S^0 \pi \pi$ channel are too few to constitute a significant source of bias.

4.7.1.2 $K_S^0 KK$ events with a K misidentified as π

The $K_S^0 KK$ pseudo experiments were generated with RapidSim using the external generator EvtGen [81]. The following EvtGen decay models (see [81]) were used to generate the decays:

- $D^{*+} \rightarrow D^0$: VSS (vector to scalar scalar).
- $D^0 \rightarrow K_S^0 KK$: D0MIXDALITZ (Dalitz amplitude with mixing for $D^0 \rightarrow K_S^0 KK$, with mixing turned off).
- $K_S^0 \rightarrow \pi \pi$: PHSP (generic phase space to n-body).

The C.C. decay was generated with the same model, but with $D^{*-} \rightarrow \pi^- D^0 (\rightarrow K_S^0 KK)$. As done in the study in Sec. 4.7.1.1, pseudo experiments were generated using the LHCb geometry for production and acceptance requesting, and the final state particles were required to stay in the acceptance of the LHCb detector downstream of the dipole magnet.

One million event were generated, with HLT2 $K_S^0 K \pi$ requirements on the D^0 and D^0 pion momentum and transverse momentum:

- $P_T(D^0) > 1\,800 \text{ MeV}$.
- $P_T(K) > 200 \text{ MeV}$.
- $P(K) > 1\,000 \text{ MeV}$.

Out of the 1 M generated events only 132 561 were selected.

To have a 1-to-1 comparison with the SS sample

($D^{*+} \rightarrow \pi_{soft}^+ D^0 (\rightarrow K_S^0 K^- \pi^+)$ and C.C., the K^+ (K^-) was generated with the

π^+ (π^-) mass hypothesis. It should be noted that the wrong mass hypothesis is only applied to the particles masses and does not affect the kinematic variables (P, P_T, η, ϕ etc.)

The effect of the wrong mass hypothesis on the D^0 mass distribution is shown in Fig. 4.32.

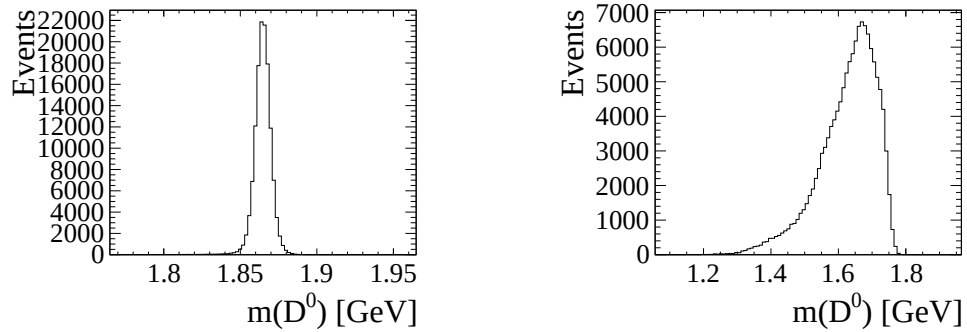


FIGURE 4.32: Mass distribution for the D^0 meson without (left) and with (right) wrong mass hypothesis for $K^+ \rightarrow \pi^+$ swap.

After applying the applicable offline signal criteria no event survived: in this case the wrong mass hypothesis moves the D^0 mass distribution out of our signal window. Thus, cross-feed events from this channels due to kaon misidentification are not a concern.

4.8 Results

The signal selection has been applied to the $D^0 \rightarrow K_S^0 K \pi$ Run2 sample and the SS and OS samples tested separately for CP violation with the ET. In both instances the ET has been run with $\delta = 0.2$, which is the optimised value found through the sensitivity studies. The ET has been run on the full signal sample yield with 50 million permutations to allow to detect effects up to 5σ , while the permutation used 500 event from each sample. The results are, for SS sample $P=0.696278$ and $P=0.658292$ for the OS sample. Both results are compatible with a CP symmetry within 1σ using the data samples available. A paper summarising the analysis and its results is in preparation.

4.9 Conclusions

A search for CP violation in $D^0 \rightarrow K_S^0 K \pi$ decays using the full Run2 data collected by the LHCb detector between 2016-8, for a total of 5.4 fb^{-1} , has been

carried out with the ET method, an unbinned method pioneered by the University of Manchester. A visualisation tool, able to trace the region in phase space giving the most contribution to the overall T-value was proposed. A selection for SS and OS samples has been developed to minimise background and isolate the signal, obtaining an estimated purity of about 91% in both subsamples. The sensitivity studies allowed to select $\delta = 0.2$ as optimal value for the distance parameter to run the ET with. The robustness and reliability of the method has been tested with the control channels, allowing to rule out possible spurious contributions from $K - \pi$ detection asymmetry nor K_S^0 induced effects that could induce a false CP violation claim. This has been proved for the full Run2 dataset and single polarity, year and track type samples alike. Furthermore, crosschecks on the signal channel sidebands proved that background events cannot induce small P-value, again leading to erroneous CP violation claims. To ensure that the control channel studies were relevant the kinematics of the final state particles and K_S^0 from all the channels were compared and confirmed the validity of the tests done. The relevance of the Run1 efficiency model, here used to model the pseudo experiment data used in the sensitivity studies, to the Run2 environment were checked and confirmed. Finally, investigation of cross-feed effects from misidentified particles from the $D^0 \rightarrow K_S^0 \pi \pi$ and $D^0 \rightarrow K_S^0 K K$ channels were investigated and ruled out. After applying the ET to the signal channel, the results are $P=0.696278$ and $P=0.658292$ for the SS and OS samples, respectively. These are compatible with the CP symmetry scenario. As previously mentioned the ET does not provide a measurement of a CP violating parameter, yet the obtained result bears two implications, which are correlated to the available sample size (and thus statistical power) and chosen δ value: none of the simulated CP violating scenarios to which the ET proved sensitive to seem to be realised in nature, and the pseudo-experiments model used could be further refined to match the observed outcome. Nevertheless, the obtained P-values might have been caused by an unfavourable strong phase in the Dalitz plot, notwithstanding that this cannot be simultaneously true for all the investigated resonances. A future search for CP violation in this channel would greatly benefit from the increased candidate yield that will be insured by Run3, which has already started, and future runs. Increased statistic will allow to expand the sensitivity of the ET to a wider range of CP violating scenarios, including the K^{*0} resonance that theorists has predicted to be a good candidate to further expand the CP violation landscape in the charm sector. Moreover, sensitivity to new CP violating scenarios and intermediate resonances will prompt a new optimisation of the δ value to extract the maximum potential available

from the ET. The increase in statistics will also increase background candidates yield, which might augment the impact of background asymmetries on the ET. Thus, developing a selection capable to achieve even higher purity will be of paramount importance. Similarly, larger control samples will have to be analysed to ensure the ET will not be sensitive to any detector induced asymmetries.

Chapter 5

Semiconductors Theory

The VELO Upgrade detector has adopted silicon pixel sensors in place of the silicon micro-strips previously fitted to the Run1-2 detector. Thus, it is useful to introduce the principles of semiconductor theory before further describing in detail the VELO Upgrade detector and the characteristics of its sensors in the next chapters. Discussing the signal collection mechanism and interplay between leakage current, temperature and radiation will allow to highlight the importance of the innovative cooling choices implemented for the VELO Upgrade (Chapts. 6, 7 and 8) as well as the importance of monitoring the behaviour of the detector with irradiation (Chapt. 9).

Semiconductor detectors have been widely utilised in particle physics since the early 60's for their low atomic number and fast response. These characteristics have made them the detector of choice for tracking purposes, where low material budget and fast signal collection is crucial for efficient tracking and vertexing. Semiconductors can be highly segmented as well, allowing for high resolutions to be achieved. This chapter will introduce the fundamental principles of semiconductor (Sec. 5.1) and specifically silicon detectors (Sec. 5.2), with a section describing the essential notion of radiation damage (Sec. 5.3). The information hereby reported have been summarised from reference sources [82–92].

5.1 Semiconductors

Materials can be distinguished on the basis of their ability to conduct electricity into three categories: conductors, insulators, semiconductors. The different behaviour when exposed to an electric field lies in the orientation of atoms and molecules within the material structure, as well as the nature of the molecular

bond. Specifically, in crystalline solids, atoms bond via covalent bonding, which requires sharing a valence electron with consequent overlap of their respective orbitals. As the energy of valence electrons can assume a continuous number of values within a maximum and a minimum (Bloch theorem), the electrons are effectively in an energy band. The energy band where the electrons are tightly bound to their atoms is the “valence band”. Between these bands the “Fermi level” is located, defined as the energy of the state that has 50% probability of being occupied. If energy is supplied to the material, for example applying an electric field, the electron can gain enough energy to transition to a band where it can freely move between orbitals belonging to other atoms in the lattice: this is the conduction band. What distinguishes various solids is the distance between the valence and conduction band, called energy gap E_g : in insulators it is high ($O(5)$ eV), so that a lot of energy, or a high electric field, is needed to promote electron to the conduction band; in metals or conductors in general the bands are overlapped, so that valence electrons are free to move in the crystal structure, being shared effectively between all orbitals. A semiconductor is a crystalline solid which exhibits intermediate properties: in normal conditions it behaves like an insulator, but as E_g is low ($O(1)$ eV), a small amount of energy (an electric field or even thermal energy) is enough to promote electrons to the conduction band. An example of the distance between energy bands in the three types of material is shown in Fig. 5.1.

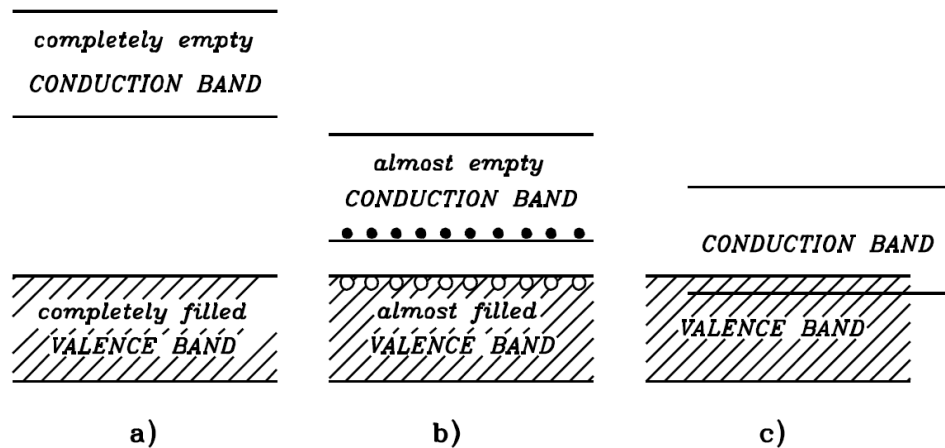


FIGURE 5.1: Representation of the energy gap between valence and conduction bands in insulators (a), semiconductors (b) and conductors (c) [86].

In semiconductors, when an electron is promoted to the conduction band, a hole is left in its place: this behaves effectively as a free positive charge that contributes to the overall conductivity of the material. A few elements in nature behave as semiconductors, such as silicon, germanium, carbon, tellurium. When

pure, these constitute intrinsic semiconductors for which at room temperature electron can jump to the conduction band via thermal excitation leaving a hole behind them. As intrinsic lattice structures are meant to contain no impurities, the number of holes is always equal to the number of electrons. To enhance the characteristics of conduction and number of charge carriers available, impurities are purposely introduced in the crystal lattice of intrinsic semiconductors: this practise is called doping, and results in an extrinsic semiconductor. Extrinsic semiconductors are of two types: p-type and n-type. N-type (Fig. 5.2) refers to introducing a so called donor atom in the lattice, i.e. an atom with a electron in excess in the valence band. P-type (Fig. 5.3) refers to doping with an acceptor atom, i.e. an atom with an electron less than the doped material in the outermost valence orbital. In the first case, the material will have an excess of negative charges that will create an energy band close to the conduction band, so that they can be easily excited into it. In the second case the holes will create a band close to the valence band that can be easily filled with valence electrons, leaving mobile holes inside the valence band to act as charge carriers. In both cases the results is an increase in charge carriers.

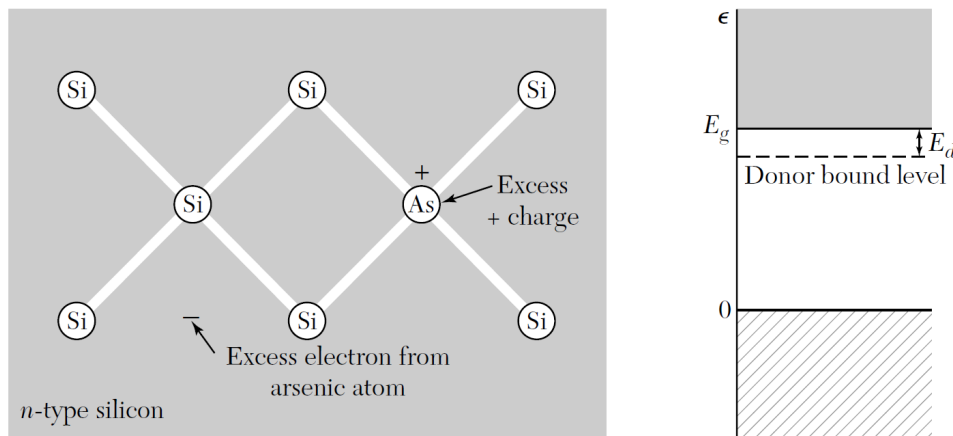


FIGURE 5.2: Example of n-type doping by an arsenic donor in a silicon crystal. The energy bands configuration of the doped material is shown on the right [85].

5.1.1 p-n junction

The junction between a p-doped and n-doped extrinsic semiconductor allows to exploit the free charge carriers to realise a device, the p-n junction, with new properties respect to its components. When a p-n junction is created, free electrons in the n-doped region will migrate to fill the holes in the p-doped region. This results in the formation of negative ions in the former and positive ions in the latter. This transient current will continue until the built-in coulomb

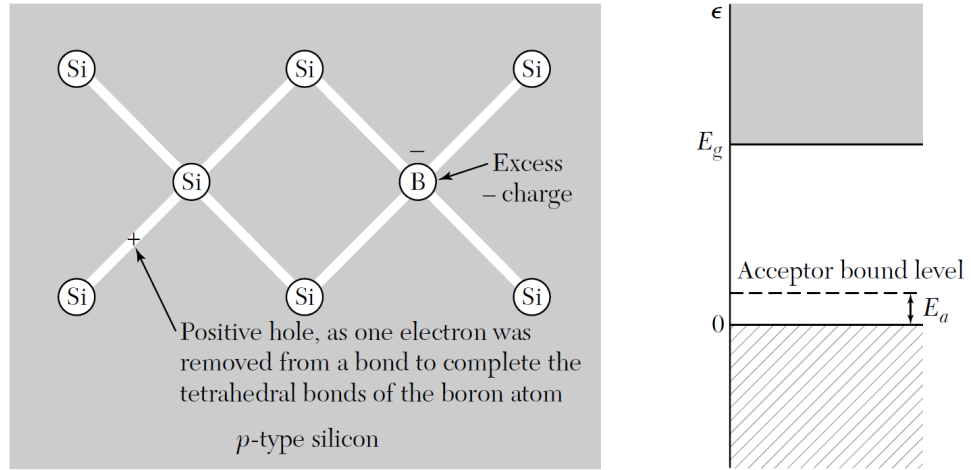


FIGURE 5.3: Example of p-type doping by a boron acceptor in a silicon crystal. The energy bands configuration of the doped material is shown on the right [85].

potential V_{bi} produced by the ions reaches the Fermi level and prevents further charge flow, resulting in the formation of a depletion zone at equilibrium (Fig. 5.4).

P-n junctions can be biased applying an external potential V_{bias} to either enhance the effect of the V_{bi} potential and further extend the depletion region or instead nullify it to allow the charge carriers to flow freely from one end to the other of the junction. The former case is referred to as “reverse bias”, the latter as “forward bias”. Thus, as the p-n junction can prevent or allow current flow, it represents the most basic implementation of a diode.

5.1.1.1 Reverse-biased p-n junction

In a reverse bias configuration a voltage is applied in the same direction of the V_{bi} potential, applying a positive polarity to the n-doped region and a negative polarity to the p-doped one: this way the natural flow of the charge carriers is prevented as electron will migrate toward the positive potential and holes towards the negative pole. Charge migration results in the expansion of the depletion region until $V_{bi} = V_{bias}$, after which the current ceases except for a small dark (also called leakage) current caused mostly by thermal excitation of electrons, with a component of diffusion of charge carriers from underdepleted regions. The dark current, from the whole volume of the junction, is thus a function of temperature and is proportional to [84]

$$I(T) \propto T^2 e^{-\frac{E_g}{2k_B T}}, \quad (5.1)$$

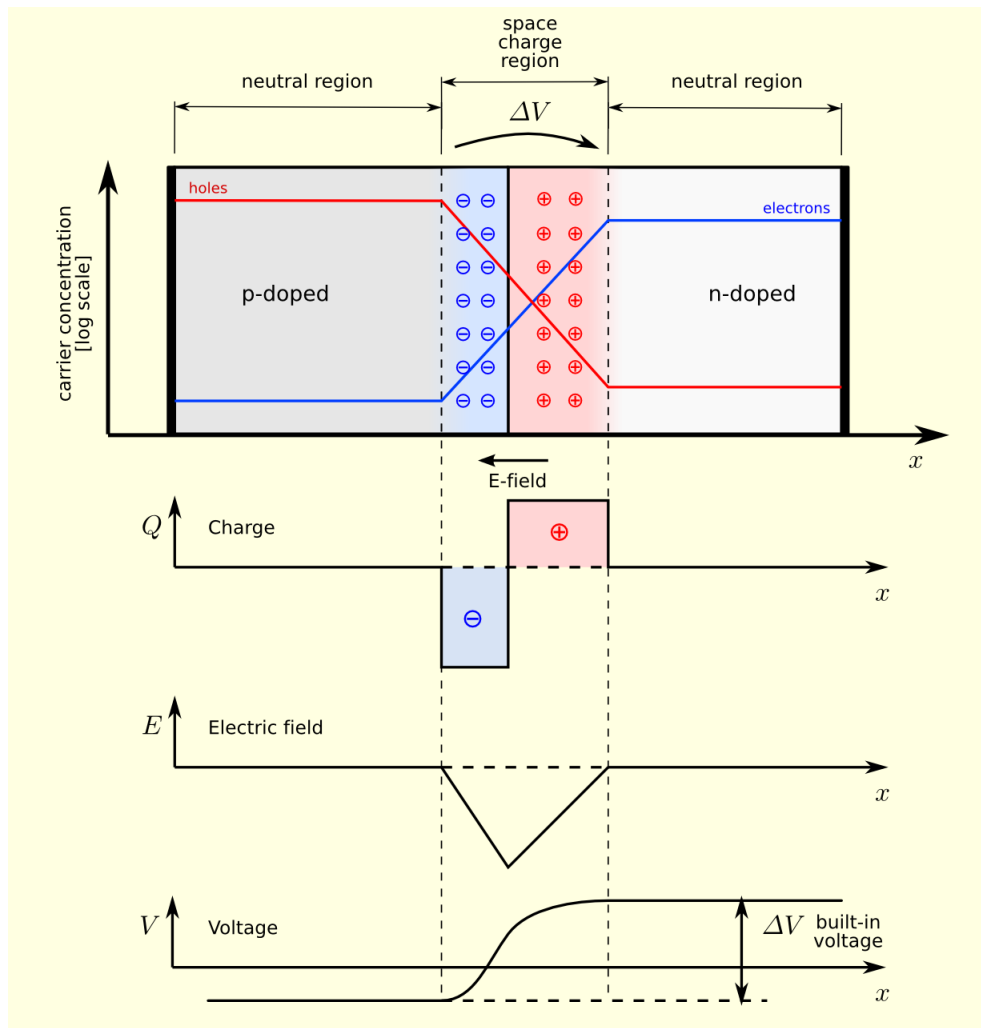


FIGURE 5.4: Representation of a p-n junction at thermal equilibrium with the depletion region highlighted (top). A representation of the charge (Q), electric field (E) and built in potential (V) as function of the position in the junction are reported as well [93]

where k_B is the Boltzmann constant and E_g is the energy gap, with $I(T)$ doubling approximately every 8 K. This is the reason why reverse biased junction are usually operated at low temperature.

5.1.1.2 Forward-biased p-n junction

In a forward biased p-n junction the external potential is applied in the opposite direction of V_{bi} , with positive and negative potential applied to the p-doped and n-doped region, respectively. This in practice nullifies the built in potential allowing electrons to flow towards the depletion zone, which is as result shrunk, and recombine with holes. If $V > V_{bi}$ the electron will be able to traverse the depletion zone, which in this case disappears, and moves towards the positive pole. Holes will migrate towards the negative potential in a similar fashion. In this configuration the junction will freely conduce current.

5.2 Silicon detectors

One of the most popular materials used in semiconductor devices and particle detectors, partially thanks to its abundance in nature, is silicon. It has atomic number $Z=14$ with four valence electrons, with a gap energy of 1.12 eV and an excitation energy of an electron-hole pair of 3.6 eV [86]. Silicon is an intrinsic semiconductor which is used in combination with both p and n doping agents to increase the number of carriers. In p-type configuration acceptor atoms from the 13th group as boron, aluminium, gallium are introduced as impurities in the lattice: these have 3 valence electrons, therefore a hole in the valence band is introduced which acts as positive free charge. Doping elements of the 15th group are used as donors in n-type configurations: these have 5 electrons in the valence band so that the excess one acts as negative charge carrier in the conduction band. Atoms commonly used in this configuration are phosphorous, arsenic or antimony. Extrinsic silicon is widely used in many electronic application, spanning from diodes (as p-n junction) to microprocessors transistors with the size of the order of few nanometers to particle detectors. In particle detectors silicon is widely used in reverse bias p-n configuration for tracking and vertexing purposes as its low Z allow to minimise energy losses and multiple scattering while the low excitation energy allows to produce high numbers of charge carriers allowing to keep the amount of material low. Reverse bias is applied as it allows to expand the depletion zone and thus the active area. Structurally, silicon based particle detectors are based on bulk volume of lightly doped volume and a combination of n-and p-type implants on its opposite sides

(Fig. 5.5), covered with a thin metal layer that act as electrodes. Everything is then encapsulated in a layer of SiO_2 which provides electrical insulation [86]. The working principle of a silicon detector is the following: when a charged particle crosses the lightly doped bulk volume, which acts as depletion area, it releases hole-electron pairs which move under the action of the external potential provided by the metalisation towards the highly doped implants where they are collected and the signal read out. As mentioned above, one of the key features of silicon sensors is that they have a factor ten lower energy gap when compared to other tracking technologies like gas detector, which ionisation energy is 30 eV; this means that for one ionised gas molecule 10 charge pairs can be produced in a silicon sensor [89]. Moreover, taking into account silicon high density, for a Minimum Ionising Particle (MIP) the average energy loss is around $390 \text{ eV}/\mu\text{m}$, which means around 108 electron-hole pairs for μm , giving silicon sensors an excellent energy resolution [89].

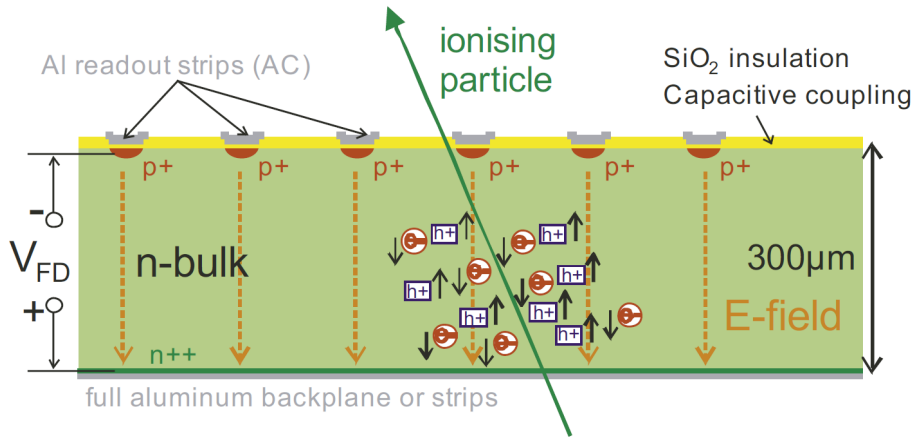


FIGURE 5.5: Representation of a strip detector with n-type bulk sensor and p+ strips implant. V_{FD} is the voltage where full depletion of the sensor volume is reached. As a MIP travels through the bulk material electron-hole pairs are produced and start to drift toward the n++ and p+ doped implants, respectively, under the effect of V_{FD} which is applied through the metal electrode. In this specific example the holes are collected via the strips [89].

The signal in semiconductor particle detectors is given by the current induced by the charge movement (Shockley-Ramo theorem [94, 95]) and not by the charge collection as in e.g. gas detectors. The induced current i is given by

$$i = eE_v v, \quad (5.2)$$

where e is the charge of the electron, v is the carrier velocity and E_v is the component of the electric field in the direction of v . E_v is defined as the field that would exist at the instantaneous position of the electron under these

constraints: the electron is removed, all the electrodes are set to zero potential and the electrode under observation is set unit potential [94]. The integral of the current induced by the carrier motion gives the total collected charge. The signal has then to be amplified with low noise electronics and digitised for further utilisation. This is done usually with an Application Specific Integrated Circuit (ASIC) which measures the charge collected with one of the following modalities [90]:

- ADC (Analog Digital Converter) counts mode: counts constituting the signal amplitude are sampled from the currents or voltage curves. Flexibility on sample rate adjustments allows to register only peak values, e.g. to sustain high data rate, or to have more details about the signal real shape.
- ToT (Time over Threshold) mode: this method measures the amount of time the signal stays over a predefined threshold; it offers some information on the signal shape and allows to indirectly measure the deposited charge.
- Binary mode: the information of particle hit is recorded if the collected signal is higher than a set threshold; this mode offers high signal throughput at the cost of no information on the deposited charge and thus on the energy of the interacting particle.

5.2.1 Segmentation

An important feature of silicon detectors is the possibility to produce a wide variety of shapes and designs to achieve high spatial resolutions [86]. As mentioned above, semiconductor particle detectors are realised depositing highly doped implants on a lightly doped bulk volume. Therefore the size, pattern, shape and pitch of said implants can be adapted to the desired application and to achieve specific tracking performances or energy resolutions. Figure 5.5 shows the typical layout of a strip detector, which can be imagined as a series of long and thin p-n junctions, while Figure 5.6 shows the typical configuration of a pixel detector. Pixel structures can be imagined as a matrix of small p-n junctions.

Strip configurations offer a cost effective way to cover large areas but only provide information on one coordinate, while pixels are ideal for accessing positional information on both axis. With the former configuration the second coordinate can be recovered using a second layer of strips slightly tilted with a stereo angle respect to the first layer. This configuration also allows

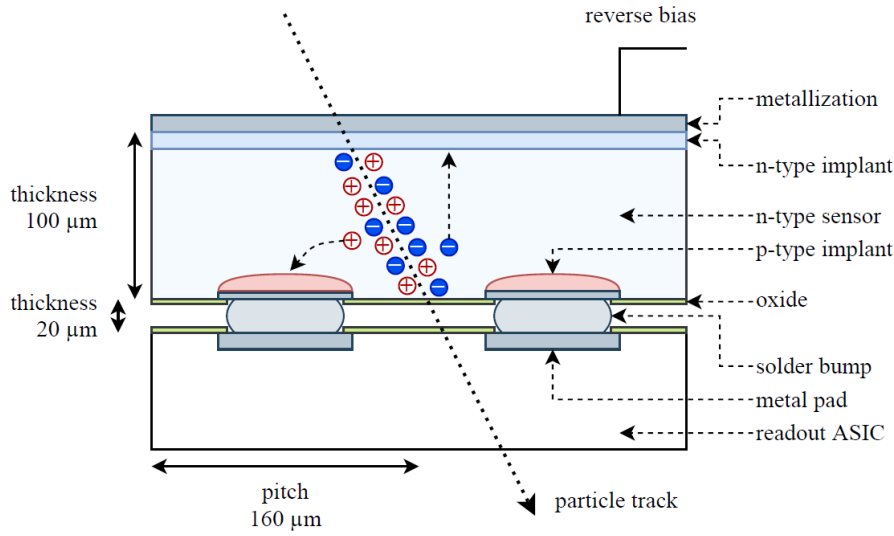


FIGURE 5.6: Typical configuration of a silicon pixel detector bump-bonded to its read-out ASIC [90].

to reduce ghost hits (see Sec. 3.2.2). Signal is usually readout via wire-bonds (preferred solution for strips) or bump-bonds, which allow to directly connect each sensor pixel to a pixel of the ASIC (this solution is referred to as “hybrid pixel” detector). Another common solution for pixels are MAPS (Monolithic Active Pixel Sensors), where the read-out electronics is implemented directly on the silicon substrate [96]. As an improved spatial resolution is the main advantage of segmentation, the reduced area demanded to charge collection intrinsically reduces the signal yield that can be collected on the electrodes, as part of the charges will migrate towards the neighbouring strips or pixels while others will diffuse into the bulk material and recombine. Another result of the segmentation is the spread of charge carriers due to the Gaussian diffusion motion, resulting in charge sharing between neighbouring pixels or strips. This effect is most noticeable when the track is angled, and in case of binary readout can reduce the position resolution. For this reason, when information regarding charge distribution or signal shape is available, the particle hit position is computed using the signal “centroid” [89]. Finally, the spatial resolution achievable with segmentation is directly linked to the pitch of the charge collecting doped implants, where for strips with analogue readout the spatial resolution is proportional to [89]

$$\sigma_x \propto \frac{\text{strippitch}}{\text{signal/noise}}, \quad (5.3)$$

while for binary readout one has [89]

$$\sigma_x \approx \frac{pitch}{\sqrt{12}}. \quad (5.4)$$

5.3 Radiation damage

As particles traverse silicon sensors ionising the atoms and producing electron-holes pairs, when interaction with Si nuclei occurs a damage in the crystal lattice can be induced: this effect is commonly referred to as “Radiation damage”. Radiation damage has multiple fallout on the detector performance, depending on the kind and entity of the defect induced on the crystalline structure of silicon. When damage occurs to the bulk of the lattice it is referred to as “bulk damage”, which results in the increase in leakage current, change of doping concentration and charge trapping effects. Radiation damage can also occur in the dielectric oxide on the surface of the detector, creating “surface damage” which can generate undesired space-charge effects.

5.3.1 Surface damage

Surface damage occurs in the layer of silicon oxide (or any other insulator) which encapsulates the detector. In this specific type of radiation damage the displacement of atoms is not the source of any sizeable effect as the lattice structure of the dielectric is already highly irregular; the source lies instead in the ionisation process and consequent charge trapping mechanism [84]. As particles ionise the oxide layer, electrons will quickly migrate towards the nearest electrode thanks to their high mobility ($\mu_{e,oxide} \simeq 20 \text{ cm}^2(\text{Vs})$), whereas charge collection of holes is much slower due to their low mobility in the lattice ($\mu_{h,oxide} \simeq 2 \cdot 10^{-5} \text{ cm}^2(\text{Vs})$). If holes reach the interface region between bulk silicon and the oxide they can be permanently captured by interstitial oxygen atoms; as this process increases with the increase in absorbed radiation, a space charge eventually build up at the interface region. A further source of positive charges in oxide are trivalent silicon atoms where one valence electron is not involved in a bond. The atom can be easily ionised and the electron ejected from the material, leaving behind a positive ion. The build-up of positive spatial charges near the silicon-oxide interface causes the accumulation of a layer of electrons at the bulk volume surface if the implant is n-type, or a depletion layer as holes are pushed away if the implant is p-type [84]. The net effect is in both instances the creation of a counterbalancing layer of negative charges. As surface damage only affects electron, it can be reversed with annealing at 150° C or higher temperatures, which causes electrons in the silicon lattice to

tunnel through the interface to the oxide. Since the net effect of surface damage is a modification of the field near the transition area it poses no danger to the performance of the detector.

5.3.2 Bulk damage

Bulk damage occurs when a silicon atom is removed from its position in the crystal lattice as result of scattering of the incident particle with the atom nucleus [84]. The recoil energy needed to break the Si covalent bonds is 25 eV, meaning the threshold energy for an incident proton or neutron to produce such recoil is around 190 eV, while an electron being lighter needs at least 260 eV. If sufficient energy is provided by the incoming particle to the atom, this will further interact with neighbouring atoms and produce more defects. If the energy of the recoiling atom is higher than 2 keV it will interact depositing energy in a very small area to create a cluster of defects [84]. If recoil energy is higher than 12 keV more point like-defects and clusters will be created [86]. Defects can be distinguished in four main categories:

- Vacancies: an atom removed from its lattice position leaves a vacancy (i.e. an empty position) in its place; a di-vacancy is formed if two contiguous atoms in the lattice are displaced.
- Interstitial atoms: a displaced atom in the lattice which is inside the crystalline structure.
- Frenkel pairs: the combination of a vacancy next to an interstitial atom.
- Schottky defect: the combination of a vacancy next to an interstitial atom which have migrated to the crystal surface.

A visual sketch of these is shown in Fig. 5.7.

Point-like defects as vacancies and interstitial atoms are not stable and can move within the lattice, eventually annealing one another with a probability up to 95%, whereas more complex structures like Frenkel pairs have around 60% probability to anneal in their migration in the crystal [92]. Defects can also recombine with other impurities creating a stable structure, introducing new levels in the preexisting energy bands leading to trapping phenomena which hinder the charge collection efficiency of the detector slowing down charge carriers. Stable defects can be charged too modifying the space-charge configuration of the depletion zone and again worsening the detector performance. Contrary to surface damage, ionisation does not have impact on bulk damage as

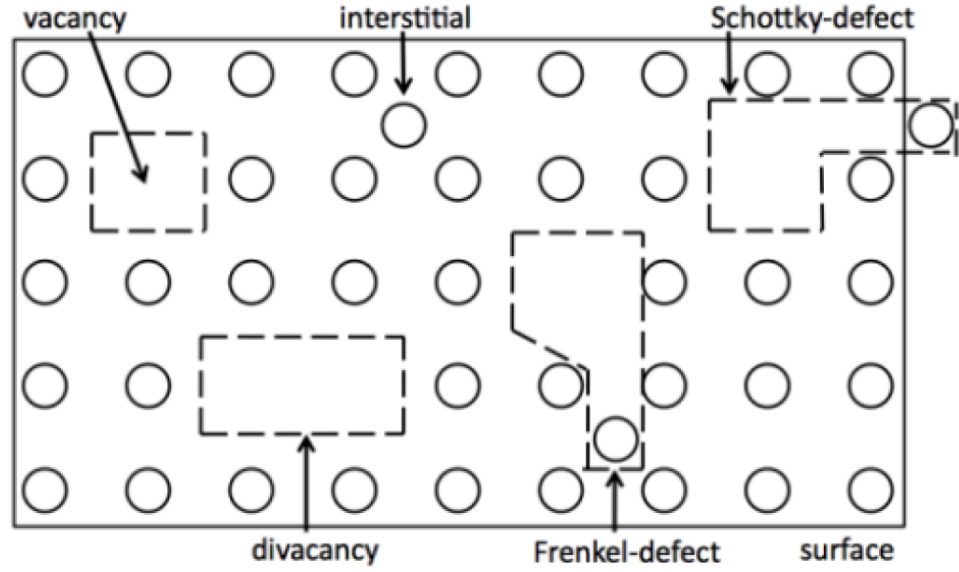


FIGURE 5.7: Visual representation of the defects in bulk damage in silicon [92].

charge carriers have high mobility and can recombine easily within the regular lattice structure. As the amount of bulk damage depends on the irradiation and on the type of incident particle, the NonIonising Energy Loss (NIEL) is introduced as quantity which allows to standardise the damage generated by different particles at different energies [84]. NIEL describes the amount of energy, not involved in any ionisation process, that is deposited in the crystal lattice. The particle used as reference to standardise the radiation damage are 1 MeV neutrons. NIEL is defined as the cross section of displacement damage, integrating over all possible recoil energies E_R [97]

$$D(E) = \sum_{\nu} \sigma_{\nu}(E) \cdot \int_0^{E_R^{max}} f_{\nu}(E, E_R) P(E_R) dE_R, \quad (5.5)$$

where ν represents all possible interactions of an incident particle with energy E with atoms in the bulk volume which results in a displacement in the crystalline structure, σ_{ν} is the cross section of the ν reaction, $f_{\nu}(E, E_R)$ is the probability of a particle with energy E interacting as ν to produce a recoil energy E_R . In Eq. 5.5, $P(E_R)$, referred to as Lindhard function [97], describes the fraction of recoil energy required to displace an atom; it is defined as zero for all energies lower than the recoil threshold: $P(E_R < E_d) = 0$. For 1 MeV neutrons $D_n(1 \text{ MeV}) = 95 \text{ MeV mb}$. It is then possible to express the fluence Φ (particle flux per unit area) of any particle as

$$\Phi_{eq} = \kappa \Phi, \quad (5.6)$$

with Φ_{eq} as the equivalent fluence of 1 MeV neutrons (or 1 MeV n_{eq} cm^{-2}); κ is the *hardness factor*, which depends on the particle energy and type.

5.3.2.1 Leakage current

As mentioned above defects introduce further energy levels in the crystal energy band which act at generation and recombination centers, which in turn lengthen the generation time, increase the number of carriers and thus the leakage current. More leakage current results in increased power absorption with consequent rise in temperature that in turn increases the leakage current (see Eq. 5.1), triggering a positive feedback loop which can lead to the thermal runaway of the sensor. Thus, highly irradiated detectors have to be constantly cooled to avoid critical damage [90]. The current increase per volume can be expressed as

$$\frac{I_{vol}}{V} = \frac{I_{vol,\Phi_0}}{V} + \alpha\Phi_{eq}, \quad (5.7)$$

where α is the “current related damage rate” and Φ_{eq} the NIEL equivalent fluence. The last term can be rewritten as

$$\alpha\Phi_{eq} = \frac{\Delta I_{vol}}{V} \quad (5.8)$$

where α is a proportionality factor mentioned above and is experimentally measured; it does not depend on the doping type nor the resistivity nor the silicon process (Fig. 5.8) [97].

Summarising, the leakage current (and thus the radiation damage) linearly increases with the fluence.

5.3.2.2 Depletion voltage

Radiation damage can effectively change the doping implant properties, producing defects that can behave as neutral (e.g. a vacancy-phosphorus [86]), acceptor or donor atoms. As the doping concentration is modified with increasing fluence, the depletion voltage is modified as a result. Moreover, complex defects can modify the space charge distribution in the bulk volume, leading to an increase of the operation voltage. The evolution of the effective doping concentration and depletion voltage as function of fluence is shown in Fig. 5.9.

For an n-type implant the doping profile decreases to effectively neutral space charge at $\Phi = (2 - 5) \times 10^{12} \text{ cm}^{-2}$, to then increase again with a p-type like behaviour. This phenomenon is referred to as “type inversion”, although at

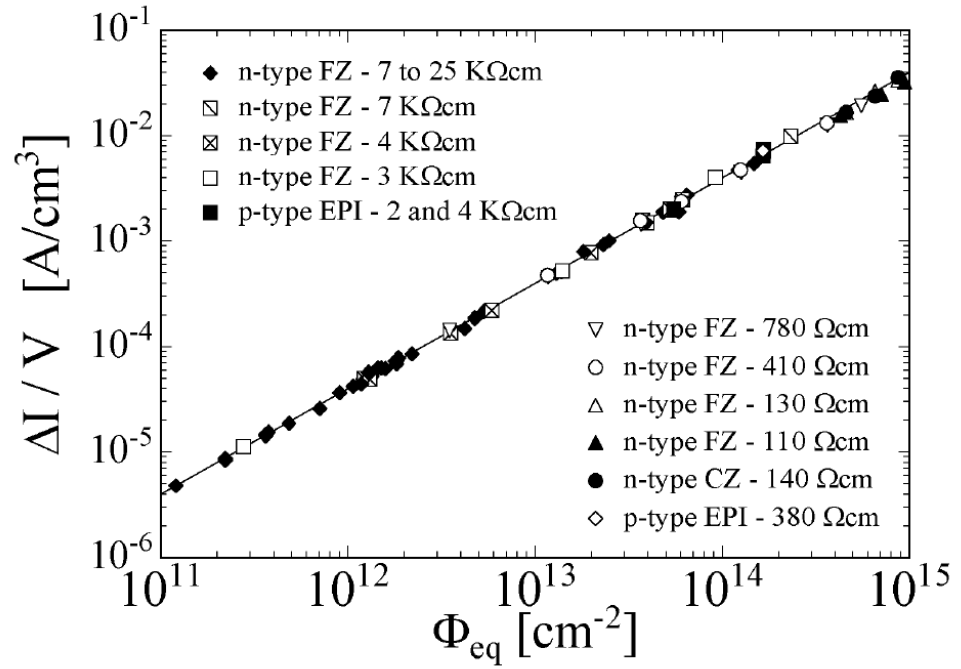


FIGURE 5.8: Leakage current increase per volume as function of equivalent fluence for different doping profiles, resistivity and silicon processes [97].

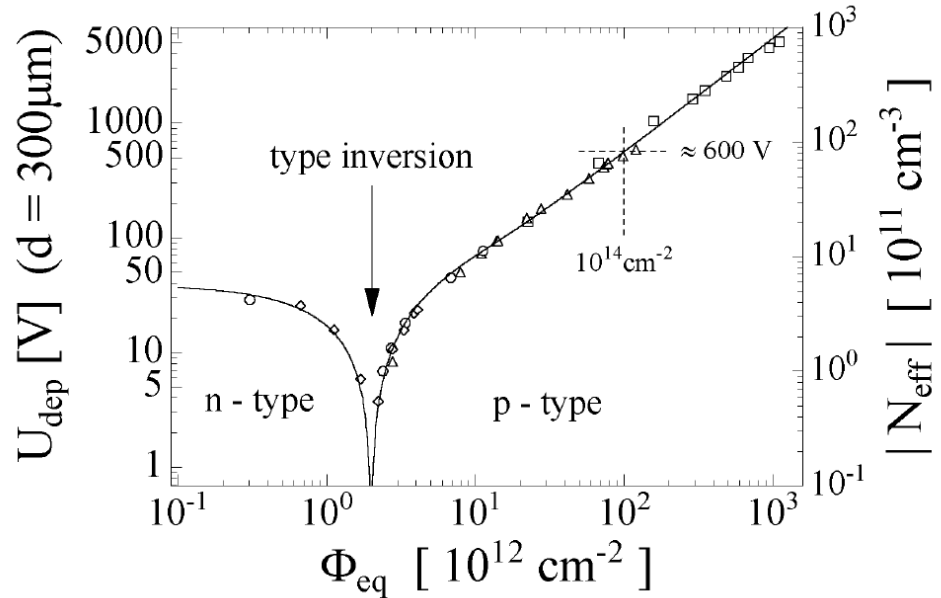


FIGURE 5.9: Evolution of the depletion voltage and effective doping concentration as function of neutron equivalent fluence. Measurements have been taken after irradiation [88].

this fluence level the space charge is dominated by defects acting as acceptors with negative space charge, which behave as p-type material. For this reason the type inversion is technically a “space charge sign inversion” [84]. This causes the p-n junction depletion zone to switch from the p^+ region to the n^+ region of the sensor, and the space charge extending from there [84]. For a p-type bulk the net effect of the concentration variation is in increase of the depletion voltage. The evolution of the doping concentration with fluence is modelled by the *Hamburg model* [97] and can be described as

$$N_{eff} = N_{eff, \Phi_{eq}=0} - \Delta N_{eff}(\Phi_{eq} T_a, t), \quad (5.9)$$

where

$$\Delta N_{eff}(\Phi_{eq} T_a, t) = N_C(\Phi_{eq}) + N_a(\Phi_{eq}, T_a, t) + N_Y(\Phi_{eq}, T_a, t). \quad (5.10)$$

$N_C(\Phi_{eq})$ represents the stable damage contribution coming from displaced atoms fixed in the lattice, it is the only contribution that describes the effective doping in relation to the fluence. It is parameterised as

$$N_C(\Phi_{eq}) = N_{C,0}(1 - e^{-c\Phi_{eq}}) + g_c\Phi, \quad (5.11)$$

where the first term models the partial removal of initial donor atoms, which increase with fluence, and the second term represents the creation of defects behaving as acceptors. It should be noticed that although initial donors are progressively removed, even after delivering high fluences a fraction of these remain electrically active. $N_a(\Phi_{eq}, T_a, t)$ and $N_Y(\Phi_{eq}, T_a, t)$ are the “short term” annealing, also described as “beneficial” annealing, and reverse annealing terms, respectively, which model the doping concentration variation as function of time and silicon temperature (T_a) after the irradiation. Contribution by $N_a(\Phi_{eq}, T_a, t)$ decrease in times of the order of hours (hence “short term”) and thus does not influence the operation of the detector. $N_Y(\Phi_{eq}, T_a, t)$ models the depletion voltage increase after times of the order of weeks at room temperature [84]; it is the most relevant contribution to ΔN_{eff} together with $N_C(\Phi_{eq})$. Summarising, the effect of the reduction of the doping concentration N_{eff} is the creation of deep carrier traps near the electrodes [98].

5.3.2.3 Annealing

As mentioned above, annealing processes contribute significantly to the evolution of effective doping concentration over time, and thus influencing the depletion voltage. It has been observed that after irradiation radiation damage changes with the post-irradiation time and temperature, first decreasing and, for highly irradiated sensors, successively increasing. The process of partial disappearance of defects in the crystal lattice is referred to as “annealing”, although this consists mostly in the conversion of meta-stable complex defects into more stable defects with different properties. This process can be triggered reaching appropriate “annealing temperatures” [86]. As annealing permanently removes part of the radiation induced defects, it decreases the current related damage rate α (see Sec. 5.3.2.1) thus reducing the leakage current. This reduction depends both on time and temperature of annealing (Fig. 5.10).

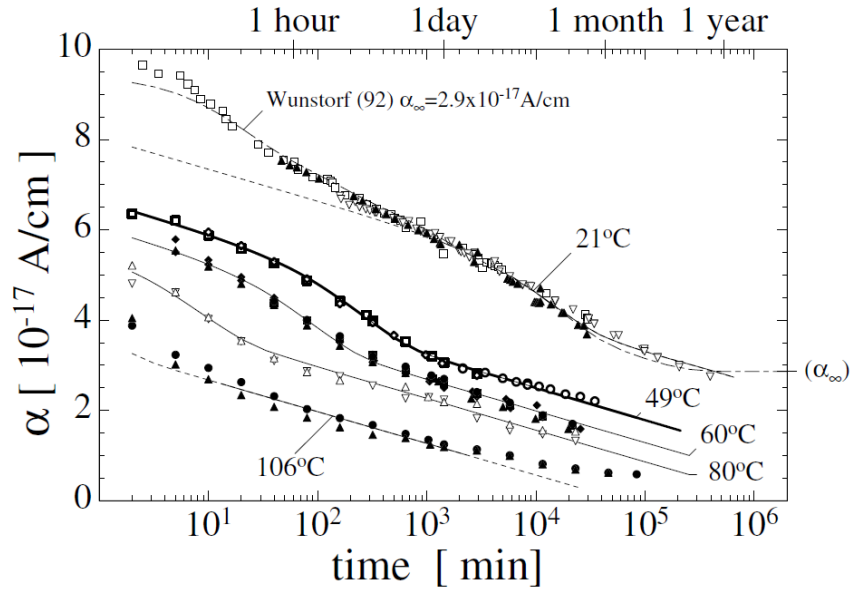


FIGURE 5.10: Current-related radiation damage rate as a function of annealing time for various sample temperatures. Note how after decreasing the radiation damage does not increase for longer annealing times [87].

Short term annealing Short term or beneficial annealing is parameterised as

$$N_a(\Phi_{eq}, T_a, t) = \Phi_{eq} \sum_i g_{a,i} e^{-t/\tau_{a,i}(T_a)} \approx \Phi_{eq} g_a e^{-t/\tau_a(T_a)}, \quad (5.12)$$

where T_a is the annealing temperature, i is the type of defect, and $\tau_{a,i}$ is the annealing constant of each type, it varies from minutes to weeks [86]. This transient phase is triggered when the thermal energy is high enough to break

meta-stable defects (e.g. vacancies filled by interstitial silicon atoms), although some annealing occurs even at room temperature.

Reverse annealing Reverse or long term annealing is the process causing the increase of the variation in effective doping after the first phase of beneficial annealing. This phenomenon occurs in the span of weeks or months, and leads to the increase of depletion voltage, and it is caused by the decay of inactive complex defects into charged ones [86]. The reverse anneal contribution is parameterised as

$$N_Y(\Phi_{eq}, T_a, t) = N_{Y,\infty} \left(1 - \frac{1}{1 + t/\tau_Y} \right), \quad (5.13)$$

with $N_{Y,\infty} = g_Y \Phi_{eq}$ (where g_Y is an experimentally determined proportionality constant) and τ_Y a time dependent time constant. Reverse annealing can be significantly slowed down and even stopped (around 0° C) with appropriate cooling of the sensors, which is why in highly irradiated environments as the LHC the sensors are kept at low temperature for their whole lifetime [84].

The evolution of the effective doping concentration as function of time is shown in Fig. 5.11, where the relative contribution of N_a and N_Y are highlighted.

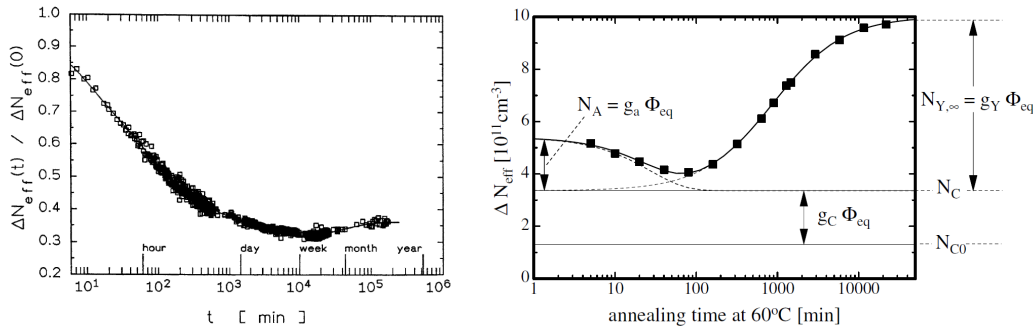


FIGURE 5.11: Left: evolution of the effective doping concentration with time; a rise is observed for longer time-scales (reverse annealing) after an initial decrease (beneficial annealing) [88]. Right: annealing behaviour of doping concentration as function of time at 60° C after irradiation with $\Phi_{eq} = 1.4 \times 10^{13} \text{ cm}^{-2}$; single contributions from N_a and N_Y are shown in Sec. 5.

5.3.2.4 Charge trapping

Point-like and cluster defects induced by radiation act both as generation and recombination centres, as previously noted, which cause the increase of leakage current thus lowering the depletion voltage, and act as traps for charged carriers. The result of charge trapping is an increased charge collection time at the

electrodes, as carriers are held or trapped in trapping centres (which are mostly empty in the depletion zone) before being re-emitted, thus impacting the signal height at readout [84]. The trapping time constant as function of fluence is modelled as

$$\frac{1}{\tau_{t,c}(\Phi_{eq})} = \frac{1}{\tau_{t0,c} + \gamma_c \Phi_{eq}}, \quad (5.14)$$

where c is the charge carrier, electron or hole, and $\tau_{t,c}$ is the average trapping time for the carrier, which is different for electron and hole due to their different mobility; $\tau_{t0,c}$ is the average time before irradiation, and γ_c an experimentally measured constant [86].

5.4 Summary

Semiconductors offer a high performance option for tracking detectors due to their fast signal collection time, low ionisation energy and charge carriers creation efficiency compare to other traditional detectors. All semiconductor detectors are based on the diode working principle, where a highly doped p-n junction is reverse-biased to create a depletion region; when a ionising particle crosses it electron-hole pairs are created and start to migrate towards the p-n implants where they are collected. The signal is given by the electric field generated by the carrier in motion under the external bias. Silicon abundance on earth and the possibility to segment the electrodes in various shapes makes Si detectors a preferred choice for applications where high spatial resolution is required. The bulk volume of these sensors is composed by crystalline silicon, which lattice can be damaged as the material is irradiated. The formation of defects inside the lattice has a number of undesired effects which decrease the performance of the detector as the radiation fluence increases. Imperfection in the crystalline structure cause longer charge collection times, a change of the effective doping concentration and increase of leakage current, plus issues related to these as increased depletion voltage and increase in power consumption. Thus, when designing and operating silicon sensors (and readout electronics) these factors have to be accounted for to ensure the working parameters of the detector can be adjusted to extract consistently high performance during its whole lifespan.

Chapter 6

VELO Upgrade

As mentioned in 3.2.1.1, the VELO has been upgraded to a completely new detector, the VELO Upgrade [3]. The VELO Upgrade (Fig. 3.5) is a silicon vertex detector with a 40 MHz readout (against the 1 MHz of the old VELO) to operate at an instant luminosity of $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, five times more than the one of the previous Runs. The new detector can reach 5.1 mm to the beam, and is equipped with 41 million $55\mu\text{m} \times 55\mu\text{m}$ pixels (against 0.2 M strips for the old detector), arranged in rectangular sensors read out by three VeloPix ASICs. Each VELO Upgrade module has 4 sensors attached, with a total of 52 modules split in two halves. To avoid loss of angled tracks, the sensors on opposing sides of the substrate are overlapped by $100 \mu\text{m}$. The sensors are cooled via evaporative CO_2 circulating inside 19 micro-channels embedded in the silicon substrate, allowing for reliable dissipation of the 30 W of heat produced by each module at operation conditions, while keeping the material budget low (Fig. 6.1).

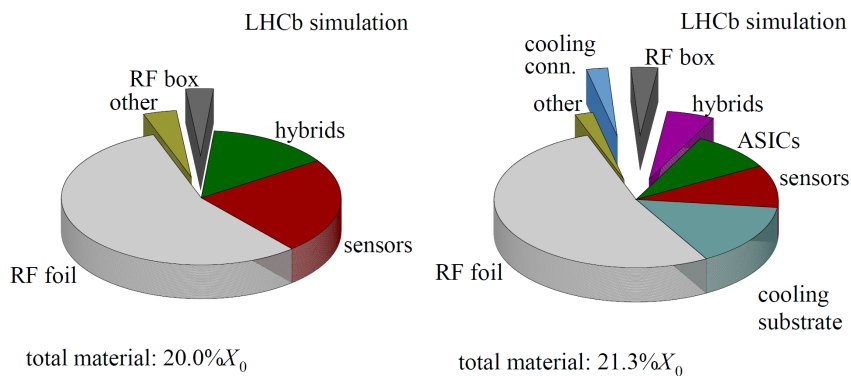


FIGURE 6.1: Material budget in % of radiation length for the old VELO (left) and VELO Upgrade (right) [3].

The sensors are able to withstand an integrated fluence up to

$\phi = 8 \times 10^{15} \text{ 1 MeV } n_{eq}/\text{cm}^2$ compared to the $4 \times 10^{14} \text{ 1 MeV } n_{eq}/\text{cm}^2$ for the old VELO. The detector is enclosed in a $250 \text{ }\mu\text{m}$ RF aluminium alloy box which separates it from the LHC vacuum and shields it from beam-induced charge effects. The new VELO has been designed to provide fast pattern recognition, enhanced tracking, superb IP resolution and to reliably identify primary and secondary vertices (Fig. 6.2).

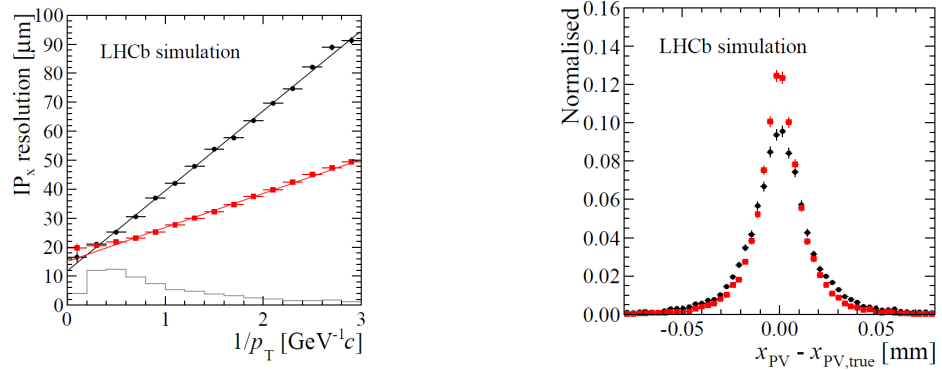


FIGURE 6.2: On the left: resolution on the IP x coordinate as a function of the inverse of the transverse momentum. On the right: difference between true and reconstructed primary vertex position on the x axis. The distribution for the old VELO is shown in black dots, the VELO Upgrade in red squares. [3].

6.1 Detector layout

The VELO Upgrade keeps the same acceptance (full LHCb pseudorapidity coverage, $2 < \eta < 5$) and tracking requirements of the old detector (see [31]). The new detector has 52 L-shaped modules instead of 42 moon-shaped ones, separated in two retractable halves, disposed perpendicularly to the beam axis and spaced in such a way that a decaying particle will leave a hit in at least 4 chips. A schematic representation of the layout is shown in Fig. 6.3.

In the central region of the detector, the spacing between modules is 25 mm; the two halves are displaced by 12.5 mm with respect to each other to allow for overlap when the detector is closed, allowing for full coverage on the azimuthal angle. The detector is separated from the proton beams by the “Radio Frequency” (RF) foil, one for each half, which protects the electronics from beam induced charge effects and provides wake-field suppression as well. The foil separates the VELO from the LHCb vacuum and it has to have a minimal thickness not to degrade the IP resolution. The surface of the foil is corrugated following the shape of the modules allowing them to overlap when the detector is fully closed. The RF foils are anchored on two “bases” that

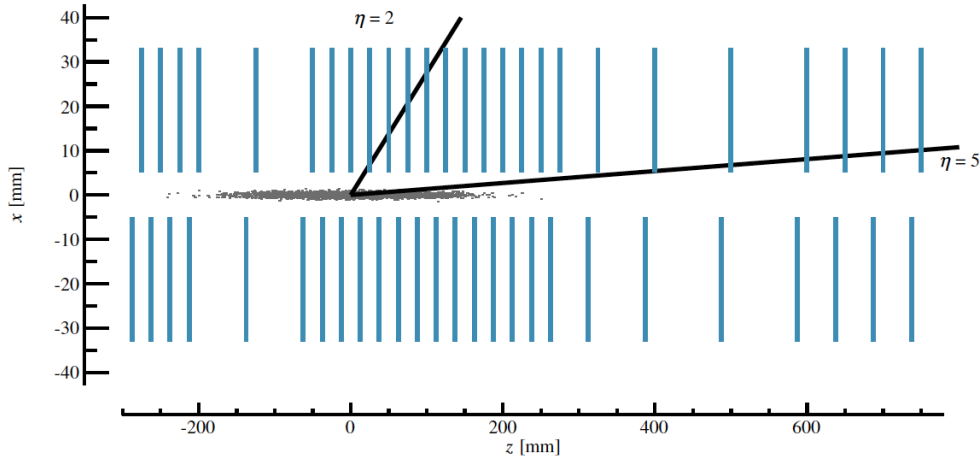


FIGURE 6.3: Layout of modules positioning on the z axis at $y = 0$, with an illustration of main interaction zone with tracks emerging at the nominal LHCb acceptance [3].

allow for the movements of the halves in both horizontal (to close and open the detector depending on the beam conditions) and vertical direction (to adjust for small changes in the beam position). More precisely, as the beam can be offset on the x axis and its transverse section can vary during operation, the two halves can move independently on the x coordinate to finely adjust their position around the beam. This level of flexibility is not necessary on the y axis therefore the halves can only move together of the vertical axis. Everything is enclosed into a 1.4 m long and 1.1 m diameter cylindrical vacuum tank (Fig. 6.4), along with the bellows system for the halves movement and wake-fields suppressors. The passage of cables for data signal transfer, control signals, low and bias voltage supply is ensured by Vacuum Feed-through Boards (VFB), which are inserted in two hoods used to seal the detector halves. The VFB have soldered connectors on either side of the hood, allowing the communications between the modules on the vacuum side and the Opto-Power Boards (OPB) on the cavern side. The OPB is an electronic board that works as interface between the Front-End (FE) and off-detector electronics, performing electrical to optical data and control signal conversion as well as DC/DC conversion of the supply voltages powering the FE hybrids.

6.1.1 RF foil

The VELO Upgrade is meant to operate at 5.1 mm from the beam, a distance not reachable with the standard LHC beam pipe. Yet, due to e.g. beam induced charges, it is not possible to operate the detector in direct contact with the proton beams either. The solution is thus to use the RF foil itself as substitute for the beam pipe, as it allows to shield the sensors from the induces charges and

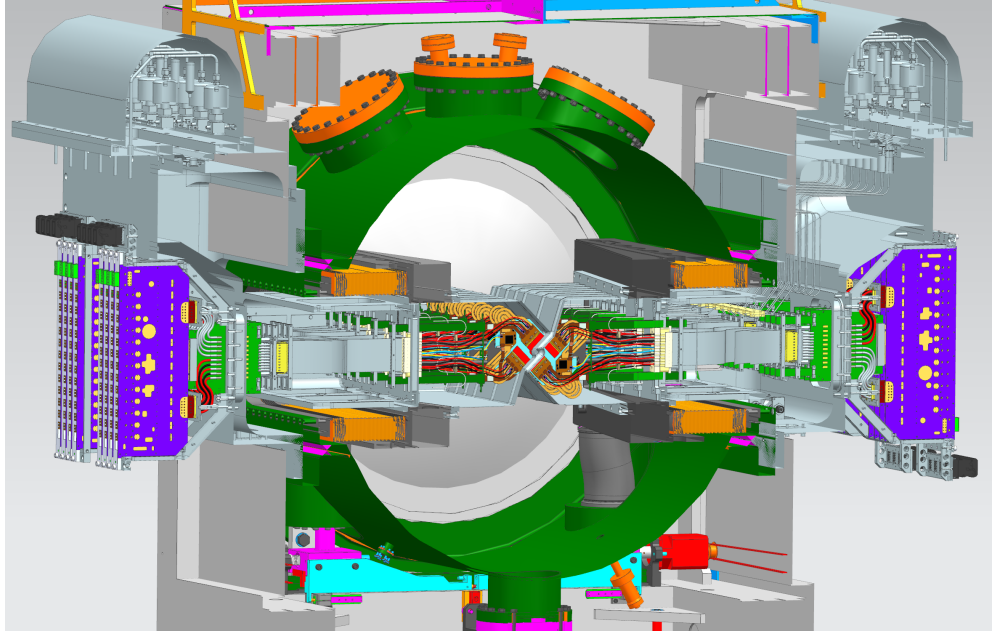


FIGURE 6.4: Schematic of the VELO Upgrade layout inside the vacuum tank, with the main components highlighted: in the centre and surrounding the modules, in grey, the RF foil; in light green, the Vacuum Feed-through Boards; in purple, the Opto-Power Boards; in green, the Vacuum tank [35].

protect the LHC vacuum from potential outgassing of CO_2 from the detector. To ensure protection from the beam, vacuum tightness and minimal material budget, while withstanding the Run3 luminosity, the RF foil has to meet the following requirements:

- 250 μm thickness.
- radiation hardness up to 1000 MRad.
- pressure resistant up to 10 mbar (pressure difference between the LHC and ELO vacua).
- uniform thickness better than 200 μm over ~ 1 m length.
- withstand temperature gradients up to 10°C .

The RF is made of an aluminium alloy (AlMg_3) and it has been obtained milling down a metal block down to 500 μm of thickness at the Nikhef laboratories. To reach the required 250 μm thickness, the foil was chemically etched in the region close to the beam and then further etched to 150 μm in the innermost part. The stages of the foil production are shown in Fig. 6.5.



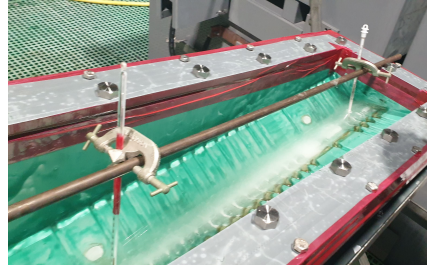
(A) Aluminium block.



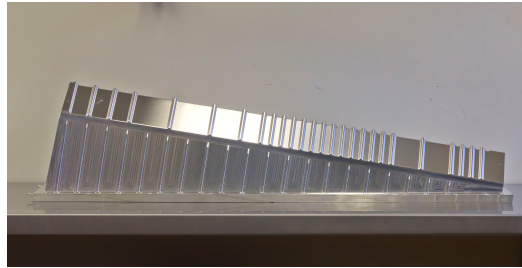
(B) Milling process of the foil (inner portion).



(C) Support mold for the milling of the outer portion.



(D) Chemical etching of the inner portion of the foil.



(E) Completed RF foil.

FIGURE 6.5: The main steps of the RF foil production at Nikhef [35].

6.1.2 VFB

The Vacuum Feed-through Board (VFB), as mentioned in section 6.1, carries the data signals, LV and HV from the detector to the outside of the vacuum tank. It is a custom-made 12-layer 2 mm thick PBC, with soldered connectors on either sides, inserted in an aluminium flange (Fig. 6.6). The PCB is glued to the flange with Araldite 2011 and then the assembly is potted with Araldite 2020 for leak tightness.

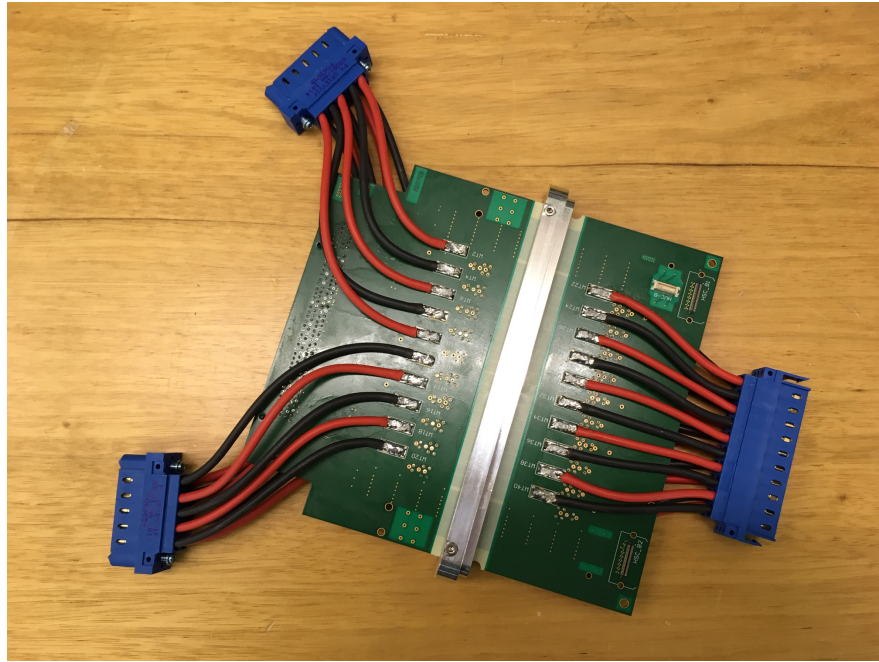


FIGURE 6.6: Vacuum Feed-through Board with the aluminium flange. The vacuum side is on the right [99].

6.2 Module layout

Each VELO Upgrade module has 2 tiles on each side arranged in a L-shape fashion (Fig. 6.7). These are attached to micro-channel silicon plate which serves as structural and cooling device. Each tile consists of a silicon sensor with three bump-bonded VeloPix ASICs. The micro-channel plate is connected to a support structure comprising an aluminium foot, that provides connection to the VELO base, and two carbon fibre legs and a midplate, connecting the aluminium foot to the micro-channel. An Invar (Fe-Ni alloy) connector, equipped with two cooling pipes, is soldered to the micro-channel plate to allow for the circulation of the coolant. The tiles are glued to the substrate and wire-bonded to the FE hybrids, which in turn are linked to the GBTx hybrid with an interconnect cable. The FE hybrid is a passive element that works as a bridge between the VeloPix ASICs and the GBTx chip. This chip is in charge of configuring and controlling the ASICs, as well as providing synchronisation and decodification of the LHCb clock. Data is transported from the FE hybrids to the OPB via thin PCB tapes, one for each tile, with up to 7 links per tile for a total of 20 links for each module. The chips are powered through 20 copper wires with silicone coating and a PCB *bridge*: this allows to both reduce the section of the cables to minimise the material budget close to the beam and function as support for the cables, data and HV tapes. Finally, the sensors are biased using PCB tapes, which are glued

to the micro-channel plate and wire-bonded directly to the top surface of the sensors.

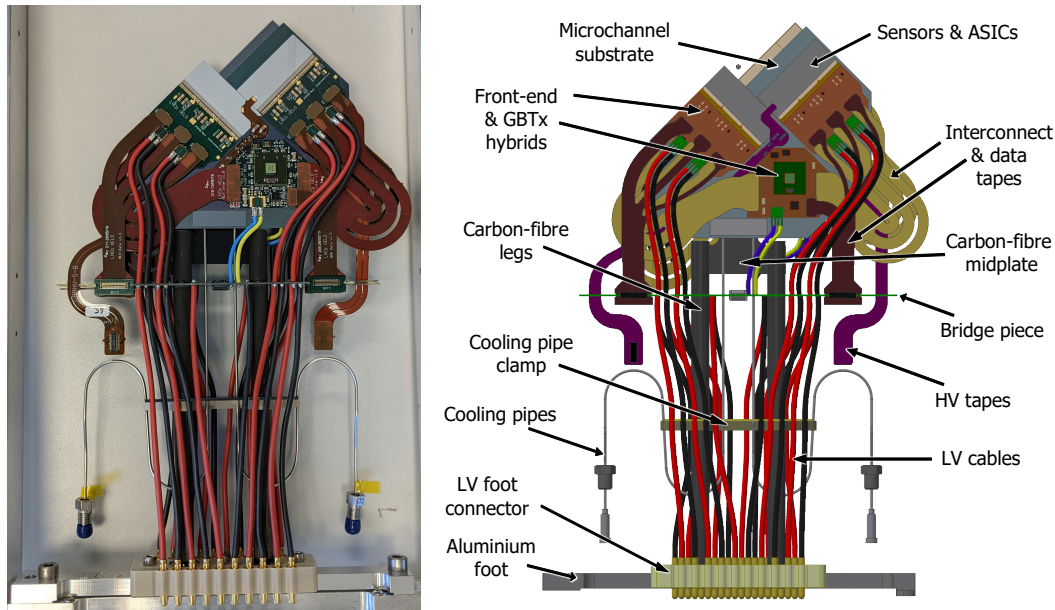


FIGURE 6.7: Left: picture of a complete VELO Upgrade module. Right: schematics of a VELO Upgrade module with all the components highlighted.

6.2.1 Micro-channel substrate

The silicon micro-channel substrate (Fig. 6.8) is a crucial component of a module, providing both structural support and cooling. It is a 500 μm thick silicon plate with an area of approximately $11.6\text{ cm} \times 11.4\text{ cm}$, carrying the tiles, FE and GBTx hybrids. Moreover, as the VELO operates in vacuum to allow for efficient dissipation of the heat generated during operation condition 19 micro-channels circulating evaporative CO_2 are embedded in the substrate (hence micro-channel substrate).

6.2.1.1 Cooling technology

The VELO Upgrade is the first detector to employ the silicon micro-channel technology with evaporative CO_2 (Fig. 6.9). Evaporative cooling exploits the phase-transition, which is an isothermal process, to efficiently remove the heat from the electronics without increasing the temperature of the circulating CO_2 ; the heat is instead spent to make the liquid CO_2 evaporate, so that the net effect of the process is an increase in gas percentage in the mixture [34].

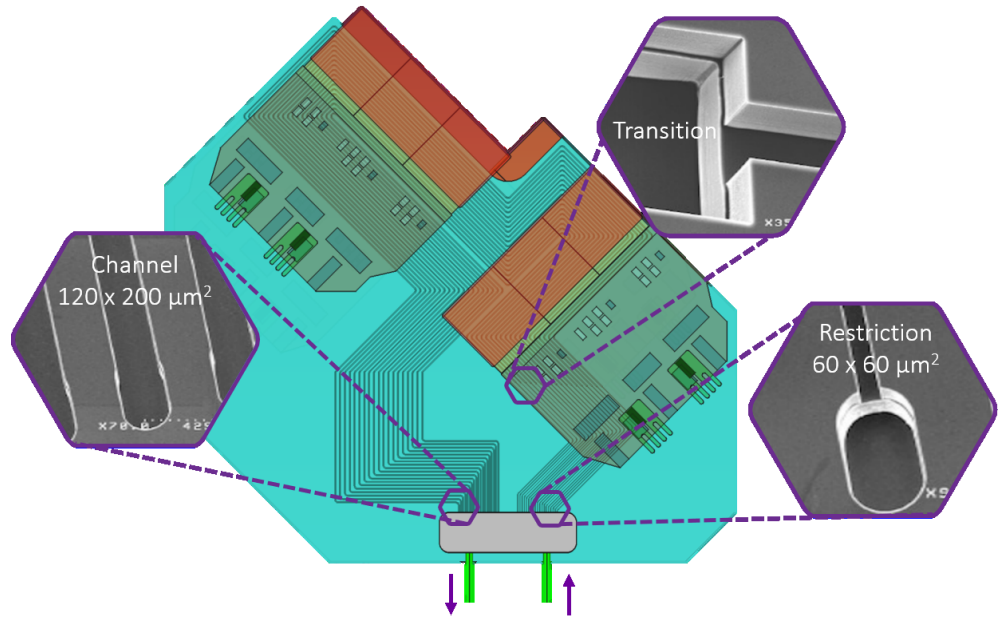


FIGURE 6.8: Micro-channel substrate with its 19 micro-channels highlighted; the sensors, FE hybrids and cooling connector are shown as well [90]. In the hexagons: electron microscope scanning (courtesy of ©CEA) of the inlet, outlet and transition zone, respectively; the latter helps to trigger the boiling of incoming CO₂ and even out the flow in the 19 channels.

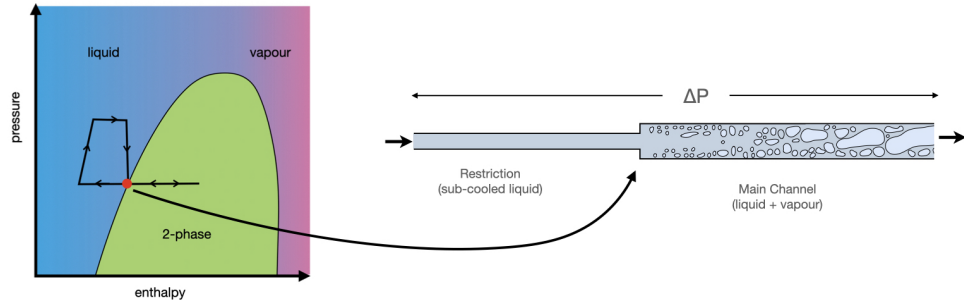


FIGURE 6.9: Evaporative CO₂ cooling principle [34]. Sub-cooled liquid flows into a restricted channel first, the micro-channel then expands causing a pressure drop that helps triggering the boiling. The boiling is triggered in the region corresponding to the electronic components to be cooled.

The silicon micro-channel with circulating CO₂ allows to fulfil the cooling criteria dictated by the heat dissipation of the electronics, higher particle rate and smaller distance to the beam [3] with respect to the original VELO:

- Reliable dissipation 30 W per module in operation condition (1.9 W per ASIC, 1 W per tile after irradiation for 50 fb⁻¹, 1.6 W per GBTx).
- Maintain the whole detector below $< -20^{\circ}\text{C}$ to keep a safe margin against thermal runaway. The requirement is most challenging in the

region nearest to the beam, where the radiation damage and leakage current is larger [3]; this is accomplished by requiring $\Delta T < 8^\circ \text{C}$ between the sensor and the coolant.

- Keep the material budget as low as possible to preserve the IP resolution performance.
- No leaks tolerated, with a maximum 10 mbar tolerance across the RF foil if a blowout occurs.
- Minimise mismatches between the coefficient of thermal expansion (CTE) of the components to avoid mechanical distortions.

In this scope, the high thermal conductivity of the silicon allows to efficiently transfer heat from the electronics to the circulating coolant, while the micro-channel technology keeps the material budget low avoiding any pipe in the active region. Furthermore, silicon and CO_2 are radiation hard making it suitable for high particles flux applications. The choice of silicon substrate matched with silicon sensors and electronics minimises any CTE mismatch across the module.

6.2.1.2 Performance

The isothermal nature of evaporation process allows to keep the temperature between the sensors almost constant regardless of the heat, except in the event of a “dry-out”, where all the liquid is evaporated into gas before it reaches the micro-channel outlet. To avoid this, the modules have been designed for a 0.4 g/s CO_2 flow, which gives a 25 % final vapour quality [34] for 30 W heat dissipation; this allows both for good thermal efficiency and safe margin from “dry-out” events. The flow can also be adjusted by regulating the pressure. The cold modules operate at a 12 bar pressure at -30°C , increasing to 60 bar at 22°C in case of failure of the cooling system. The substrates have been validated to safely withstand 186 bar for safety reasons [34].

A number of prototypes and simulations have been produced to evaluate the micro-channel substrate performance. Pressure tests were carried out to test the rupture point of both the micro-channels and the connector; the soldering process has been extensively tested as well as the heat transfer performance using simulations of the final micro-channel size and spacing together with simulated electronics with the heat dissipation levels expected during operation conditions [3, 34]. Concentric heat sources were used to replicate the beam condition [3]. Given that the VELO cooling plant can cool the CO_2 down

to -30°C , the micro-channels are able to comfortably dissipate 30 W with an expected $\Delta T < 7^{\circ}\text{C}$ between the coolant and the hottest tip of the chip, located on the overhanging region of the sensors, thus keeping the whole detector below -20°C and reducing reverse currents and reverse annealing.

6.2.1.3 Production

Silicon substrates have a thickness of 500 μm with 19 embedded micro-channels running under the electronic components generating heat (namely ASICs, FE and GBTx hybrids) during operation. The micro-channels have two portions, a so called “restriction” zone with a cross section of 60 $\mu\text{m} \times 60 \mu\text{m}$, where the coolant is pumped in a subcooled state, and an expansion zone where the volume increase generates a pressure drop that helps trigger the boiling and equalise the flow between the channels: here the cross section is 200 $\mu\text{m} \times 120 \mu\text{m}$. The channels after the restriction have similar length to ensure uniform cooling across the channels: the length of the longest channel is 292 mm, the shortest is 231 mm [34]. The substrates are produced via a series of steps involving both lithography and etching as follows (Fig. 6.10):

- A 550 μm silicon substrate is etched via Deep Reactive Ion Etching (DRIE) to produce 200 μm and 60 μm trenches (main channels and restrictions, respectively).
- The wafer is covered and bonded with another 550 μm wafer via hydrophilic bonding.
- The assembly is thinned down to 500 μm .
- The surface of the etched wafer is metalised with layers of Titanium, Nickel and Gold to allow soldering of the connector.
- The inlets and outlets are plasma etched.

Finally, the connector and the micro-channel are aligned and soldered together using a 100 μm *Sn-Pb-Ag* alloy foil.

6.2.1.4 Cooling system safety

Since the VELO modules are located in a secondary vacuum inside the RF foil, any leak in the micro-channel substrates can pose a risk to the foil integrity and potentially spoil the LHC primary vacuum [3]. The principal potential sources of risk are the rupture of the micro-channel substrate or of the cooling

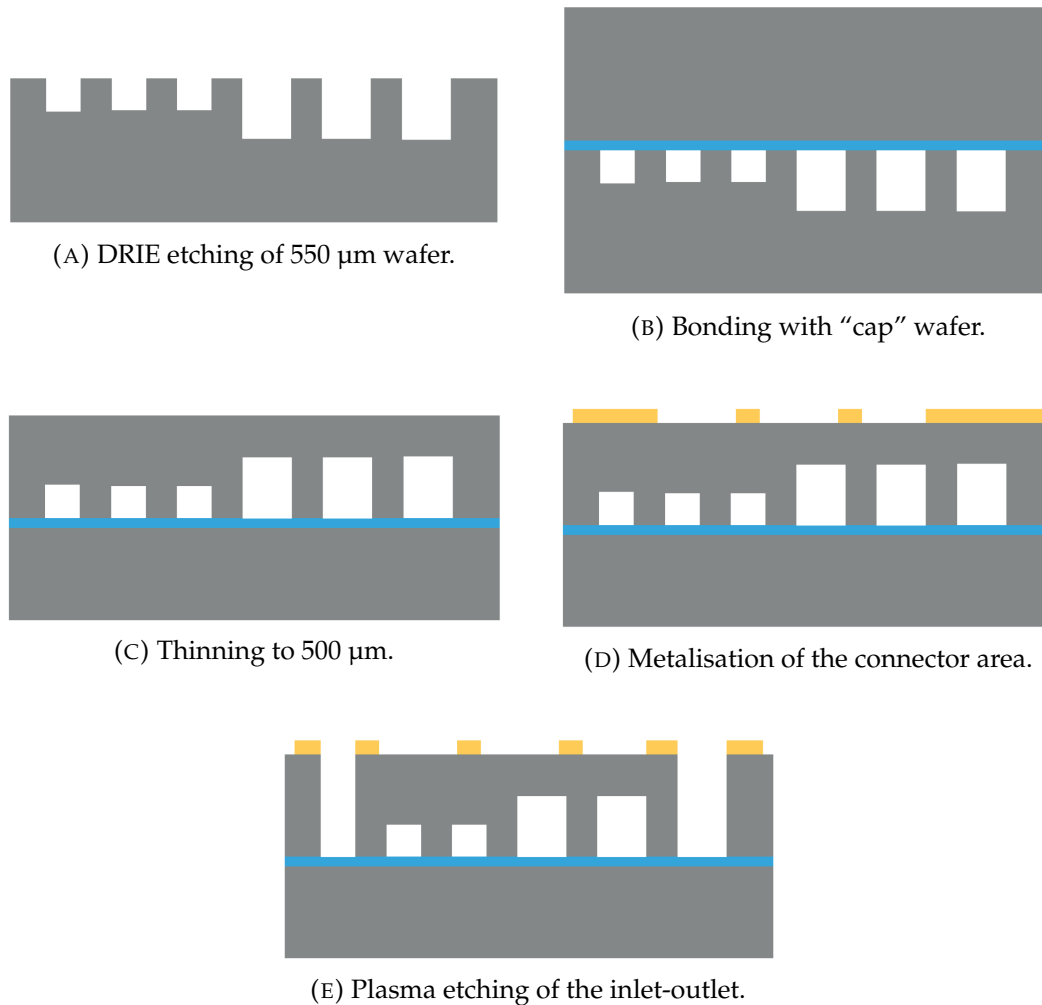


FIGURE 6.10: The main steps of the micro-channel production [100].

connector soldering. The nominal pressure at operation conditions is 12 bar for the micro-channels at -30°C , which can increase to 60 bar at 22°C in the case of a cooling plant failure. Thus, the cooling system had to be validated at 186 bar as regulated by the European Pressure Directive in order to ensure a safety margin of 2.5 times the room temperature pressure [35, 101]. To ensure they satisfy these requirements all components have been pressure tested, showing results well above the required safety ratings: the micro-channels could withstand up to 400 bar of pressure, while the soldered connector were validated for 186 bars. Furthermore, the soldered joint was tested with thousands of temperature (from -40°C to $+60^{\circ}\text{C}$) and pressure (from atmospheric pressure to 186 bar) cycles to simulate the stress provoked by powering procedures corresponding to the LHC fills. No fatigue effects were observed [34]. A further danger to the system integrity is represented by the clogging of one or more micro-channels, especially at the restrictions, where impurities might slowly deposit over time:

this risk is mitigated by filtering the CO₂ with filters able to remove particles down to the micron level. As the restrictions have a 60 $\mu\text{m} \times 60 \mu\text{m}$ section, the filters should be enough to avoid any blockage [34]; pressure monitoring is also used to detect if any of said blockages occur.

6.2.2 Electronics

To fully exploit the higher luminosity of Run3 and the decreased distance from the beam the new VELO has been upgraded with completely new electronics, starting with a change from the microstrip to pixel technology. As result, the new tracker has ~ 41 M readout channels (0.2 M strips for the Run1-2 VELO [31]), higher readout rate (40 MHz against 1 MHz) and higher radiation hardness, being able to withstand 8×10^{15} 1 MeV $n_{\text{eq}} \text{ cm}^{-2}$ compared to 4×10^{14} 1 MeV $n_{\text{eq}} \text{ cm}^{-2}$ of the old detector.

The four tiles in a VELO module are uniquely identified by three letters, referring to the side of the module, the edge of the micro-channel plate and their distance to the beam. The side is identified with the letter C for the cooling connector side, or the letter N for the non-connector side. The micro-channel edge is either Long (L) or Short (S). The distance to the beam is referred to as Outside (O) or Inside (I) for the tile furthest or closest to the beam, respectively. The tiles identifiers are thus CLI, CSO, NSI, NLO (Fig. 6.11).

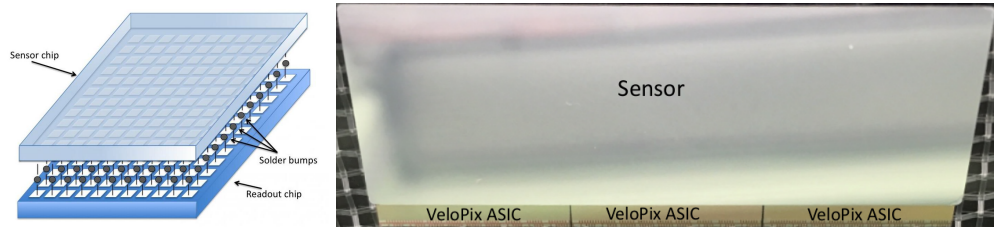


FIGURE 6.11: On the left: Bump bonding of the ASIC to the sensor. On the right: tile structure, with the sensor of top of the three ASICs (visible on the bottom where the wire-bonding pads are located) [102].

6.2.2.1 Sensors

The upgraded VELO uses planar silicon sensors made by Hamamatsu. These are 200 μm thick and use a n implants in p bulk. The pixel size is 55 $\mu\text{m} \times 55 \mu\text{m}$ to match the pixel size of the ASICs; on the inner edges the pixels are elongated (55 $\mu\text{m} \times 137 \mu\text{m}$) to avoid dead areas in the gaps between the ASICs. The sensors use e^- collection to avoid “time-walk” effect, i.e. to disentangle the signal rise time (dependent from the deposited charge) to the triggering

time. Since the sensors will withstand the whole fluence of the Run3 and 4 of the LHC (around $8 \times 10^{15} \text{ 1 MeV } n_{eq} \text{ cm}^{-2}$, Fig. 6.12), the depletion voltage will have to be progressively increased over time. The chosen sensors can operate from 140 V, the initial nominal depletion voltage, to 1000 V towards the end of the detector, while maintaining a detection efficiency $> 99 \%$ [102].

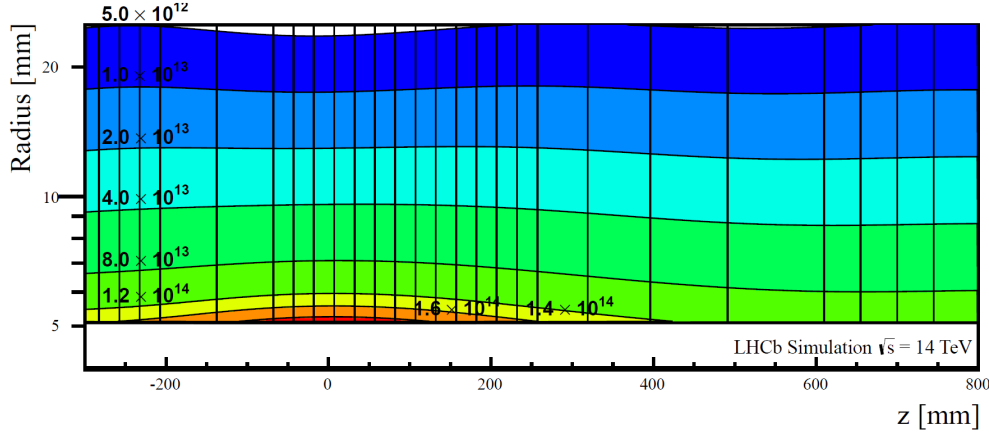


FIGURE 6.12: VELO estimated radiation damage (in $1 \text{ MeV } n_{eq} \text{ cm}^{-2}$) per fb^{-1} at upgrade conditions on the $R - z$ plane. The contours show the radiation damage; the vertical axis is in logarithmic units [3].

6.2.2.2 ASICs

The VELO Upgrade detector uses VeloPix3 ASICs (each with 256×256 pixels), which are based on the TimePix3 chips; the main differences are listed in Table 6.1. The VeloPix chip has less time resolution in exchange of higher throughput, which is a desired property with the triggerless readout of the LHCb experiment for Run3. The high throughput is achieved using “zero-suppressed” readout, meaning only the signal from pixels that registered an interaction is used. Furthermore, the pixel matrix is read out as a Super Pixel Packet (SPP). The concept of reading “superpixels”, a 4×2 pixel array, is used to further improve the bandwidth: each time one or more pixels detect a particle, a data packet is read out along with the bunch crossing ID (BxID), the column and row of the SPP and an 8-bit map of the location of the hit pixel within the array. The array size has been optimised to minimise the number of packets sent out for each hit, based on the expected cluster size for the VELO [91].

The functioning scheme of each pixel is shown in Fig. 6.13.

Each SPP is transferred to the End of Column block (EoC, a dedicated region of the ASIC where data is collected and distributed to outgoing data links) forming packets of 30 bit that are then sent out from the ASIC [90]. Four SPP, along with header and parity bits for a total of 128 bits are sent out of the VeloPix

ASIC	Timepix3	VeloPix
Technology	130 nm CMOS	130 nm CMOS
Power consumption	<1 W/cm ²	<1.5 W/cm ²
Charge collection	e ⁻	h ⁺ e ⁻
Pixels	256 × 256	256 × 256
Pixel size	55 μm · 55 μm	55 μm · 55 μm
Timing resolution	1.5625 ns	25 ns
Readout	Triggerless, ToT	Triggerless, binary
Peak hit rate ASIC	80 Mhits/s	900 Mhits/s
Peak hit rate pixel	1.2 khits/s	50 khits/s
Total bit rate	5.12 Gbit/s	20.48 Gbit/s

TABLE 6.1: Comparison between the key parameters of Timepix3 and Velpix ASICs [103].

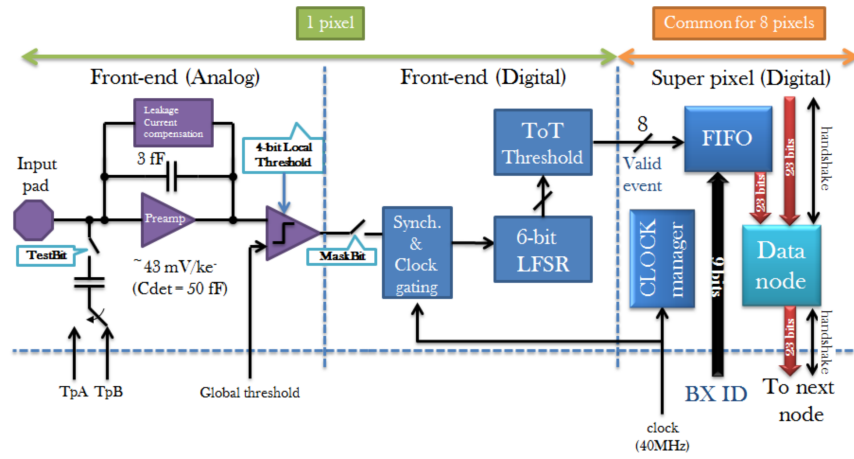


FIGURE 6.13: Schematics of the architecture of the VeloPix pixels [103].

at the 40 MHz rate. To optimise the data transmission a custom designed GigaBit Wireline Transmitter (GWT) capable of transmitting data at 5.12 Gb/s [91] was adopted instead of a standard GigaBit Transceiver (GBT) [90].

The ASICs are connected as well to the Experiment Control System (ECS) slow control interface for monitoring and configuration.

6.2.2.3 FE electronics

On each side of the VELO Upgrade modules are glued 2 FE and one GBTx hybrid. The former are glued in the near vicinity of the tiles and are wire-bonded to the ASICs, the latter is glued towards the centre of the micro-channel substrate. Both are 390 μm thick flexible four-layered printed circuit. The FE hybrids distribute low voltage to the ASICs and provide connection between them and the ECS through the GBTx. They are equipped with two MOLEX slimstack connectors to distribute ground and positive voltage to the digital and

analogue power line of the ASICs; three more connectors allows for data transfer and communication with the control chip via interconnect cables. FE hybrids are equipped with one Negative Temperature Coefficient (NTC) thermistor each to monitor the temperature of the substrate.

The GBTx hybrid is composed by the GBTx control chip and a Laser Driver (GBLD). The GBLD allows for the good ECS signal quality along the 60 cm flex tapes connecting the hybrid to the ECS. The GBTx chip allows to distribute ECS communications, clock, TFC (Timing and Fast Control) and reset signals to the six ASICs on the same side through the FE hybrids (via a GBT Slow Control Adapter (GBT-SCA)) [91]. Furthermore, it allows to monitor their bias voltages. The GBTx hybrids are equipped with a MOLEX slimstack connector to carry the voltages for the control chip and the GBLD (1.2 V and 2.5 V, respectively) and three more connectors [91]: two of these allows communication with the FE hybrids, the third one connects the GBTx to the flex tapes via data tapes (see next paragraph) and brings the ECS commands to the GBTx chip.

6.2.2.4 Tapes and cables

A combination of flexible PCB tapes and cables is used in the modules to connect the off-detector electronics with the control and FE hybrids. Power is brought to the chips via Low Voltage cables, whereas interconnect tapes connects the GBTx to the FE hybrids. Finally, data tapes bring data from the ASICs to the OPB. Data tapes are made of Pyralux AP-Plus, a dielectric, radiation hard material with low dissipation of high frequency signals [3, 104]. Two interconnect tapes and two data tapes are accommodated on each side of the modules, the former transmitting control signals (TFC, ECS slow control, clock, reset) from the GBTx to the FE hybrid. Data tapes connects to the FE hybrids and route signal from the ASICs to the off-detector electronics. The CLI and NSI tiles comprise 7 GWT links 4 of which are assigned to the ASIC closer to the beam (which will face the highest data rate), two to the middle one and one for the ASIC further away from the beam. This arrangement has been decided to divide the data rate in such a way that each link doesn't have to transmit more than 5 Gbits/s of data. For the outer tiles only one link is per ASIC allocated. The expected data rate per ASIC is shown in Fig. 6.14. Data tapes connects to the FE hybrid and to the OPB via MOLEX Slimstack connectors.

Finally, HV tapes are glued to the micro-channel substrate and wire-bonded directly onto the sensors to provide bias voltage. Their highest operation voltage is 1000 V.

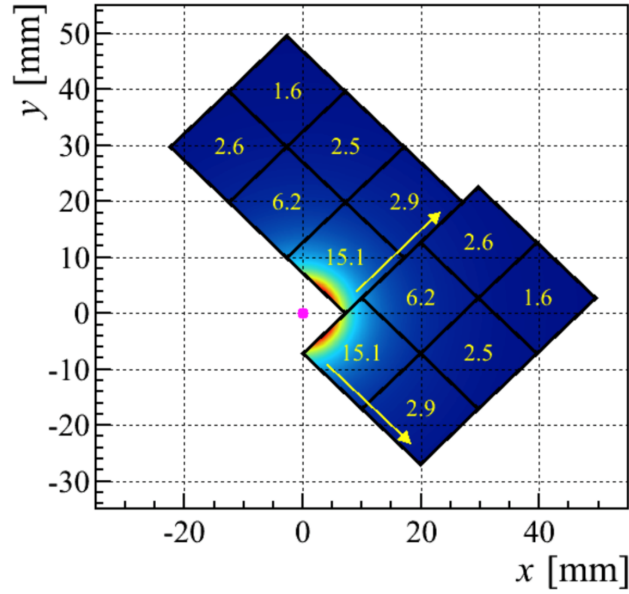


FIGURE 6.14: Expected data rate simulation in each VeloPix ASIC, in Gbit/s: the inner-most chips face the highest rate, requiring the most data links to avoid overload [102].

6.2.2.5 OPB

The OPB is a PCB located after the VFB and responsible for converting and monitoring the signals incoming from the module to deliver them to the off-detector electronics. It carries out electrical-optical signal conversion, power delivery and monitoring of temperatures voltages and currents. It possesses its own GBTx hybrid with a GBT-SCA (Slow Control Adapter). The electrical-optical conversion is carried out by 10 Versatile Twin Transmitter (VTTx) modules and 3 Versatile Transceiver (VRTx) modules: the former convert the signal coming from the VeloPixes, the latter convert the GBTx data; the data from the VTTx is then sent via optical fibres to the off-detector electronics, the VRTx allows for both data conversion and communication both ways. The GBLD is, similarly to what happens in the module, used to transmit data from the OPB to the module via the long flex tapes. Finally, fourteen radiation hard DC/DC converters are used to deliver the LV: ten are 1.3 V converters to power the modules, four are 2.5 V converters and are used by the board itself [90].

6.2.2.6 Off-detector

The VELO Upgrade modules' data is transported from the OPBs to the data centre on the LHC point 8 surface via 300 m optical fibre cables, where the electronics responsible for timing, control and readout is located [102]. Here, the zero-suppressed data coming from the modules is processed by the SOL40,

TELL40 and S-ODIN boards, which works as interface, readout and supervisor boards, respectively; the S-ODIN manages the SOL40 and TELL40 boards, providing an interface for TFC synchronisation as well [90]. The SOL40 distributes the ECS and TFC signals to the FE electronics as well as slow control signals, while the TELL40 is responsible for the DAQ and reads the FE data to pre-process it before combining it in the event builder network [90, 102]. The interface and readout boards are based on the Intel Arria 10 Field Programmable Gate Array (FPGA), a PCIe40 board with 4 transceiver and 4 receiver Multi-fibre Push On (MPO) connectors, each with 12 links, for a total of 48 links going both directions. Each MPO is equipped with a “MiniPoD”, responsible for optical-electrical conversion of the data coming from the fibres [102]; these are connected to a FPGA high speed input/output.

6.3 Summary

The LHCb experiment has undergone an extensive upgrade of a number of subdetectors as the VELO, the UT and Sci-fi. The VELO specifically, has been replaced with a completely new detector, the VELO Upgrade, currently installed and commissioned in the LHCb cavern. The VELO Upgrade consists of 52 double sided modules divided into two retractable halves, with each module being equipped with 4 pixel sensors read out by 3 VeloPix ASICs each. Both the technology of the sensors (pixels in lieu of microstrips) and the modules positioning has been changed to re-optimize the detector to the new, harsher environment of Run 3. Each module comprises a novel micro-channel silicon substrate which offers both cooling and mechanical support for the sensors and FE electronics. Micro-channel technology has been chosen for its outstanding cooling capabilities while allowing to keep the material budget low; it offers an extremely high safety margin as well, being able to withstand pressures up to 400 bar. The FE hybrids are composed of flexible PCB and two different kinds are positioned on each side of each module: the FE hybrids, wire-bonded to the ASICs, route the data to the OPB and provide a connection to the GBTx hybrid for the monitoring and configuration of the ASICs. All the control and data signals are managed by the OPB, which acts as link between the detector and the off detector-electronics.

Chapter 7

VELO Upgrade module production

Production of the VELO Upgrade modules (52 for the full detector plus 6 spare modules) has been divided between two assembly sites: The University of Manchester in Manchester, UK, and Nikhef in Amsterdam, Netherlands; here the modules were built and validated for installation in the detector. The assembled modules have then been transported to The University of Liverpool in Liverpool, UK, where they were mounted onto the two VELO bases and tested again individually and in parallel. Specifically, 26 modules (a full half) were simultaneously cooled during the tests and up to 4 modules could be powered and tested in parallel. The completed halves were then shipped to CERN in Geneva, Switzerland, for the final testing of the whole system and installation into the experiment. The production of the 52nd detector grade module, the last to complete the whole VELO, was successfully completed on November 2021, while the production campaign ended with the production of the 63th module in July 2022. The whole campaign produced a total of 63 modules, 5 of which with either faulty components or sub-standard performance which did not allow for installation. As already mentioned, the production sites carried out both the assembly and the testing of each module, performing metrology and validation of electrical and thermal performance in experiment-like conditions. A grade was assigned after each test, and an overall mark assigned to each module at the end of testing. Both the assembly and the validation were carried out in a clean room (CR): the former in a ISO 1 000 CR to guarantee minimal risk of dust deposits on the sensors and adhesives used during the critical steps of the assembly, the latter was carried out in a ISO 10 000 CR. Checklists were developed to standardise and control each step of the construction and validation of the modules. In this chapter the assembly procedure (Sec. 7.1)

will be described, followed by the description of the metrology (Sec. 7.2) and the validation procedure (Sec. 7.3). Finally, the grading criteria and the overall quality output of the production procedure for Manchester built modules will be analysed (Sec. 7.4).

7.1 Module assembly

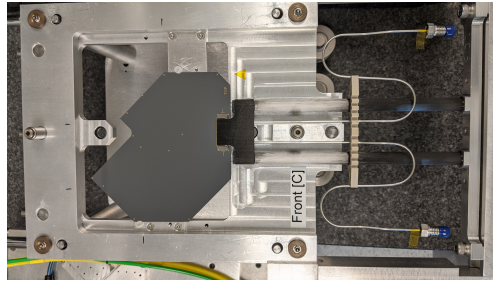
The assembly procedure consists of five major steps (Fig. 7.1):

- Bare module assembly.
- Tile gluing.
- Hybrid Gluing.
- Wire-bonding.
- Cabling.

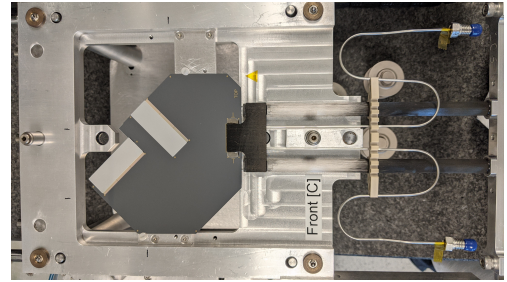
Each step is followed by careful metrology and grading as it will be illustrated in detail in section 7.2. As already mentioned, each phase of these steps is guided by a checklist specifically developed to allow the operators to perform each action in a predetermined order to maximise consistency throughout the whole module production campaign and minimise chances of human error. The steps are similar between the Manchester and Nikhef sites, although due to a slight difference in approach and equipment the tile gluing, hybrid gluing and cabling are performed in different order. This thesis will focus on the approach followed by the Manchester site while mentioning the key features of the procedure followed in Nikhef.

7.1.1 Bare module assembly

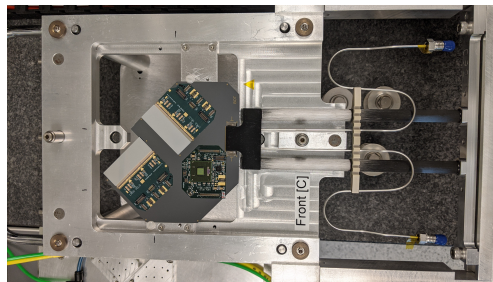
The first step consists in the assembly of the support structure of the module: the micro-channel substrate (with cooling pipes already brazed on the fluidic connector) is assembled with the carbon fibre midplate, the carbon fibre legs, cooling pipe clamp and aluminium foot. The latter constitutes the base of each module and has a dowel hole on one side which is used for precise alignment during installation in the VELO base via a corresponding dowel pin. The dowel hole/pin system provides an accurate mechanism for the positioning of the modules and has been used to define a reference system during the assembly of each module. The carbon fibre legs are glued to the foot and the assembly



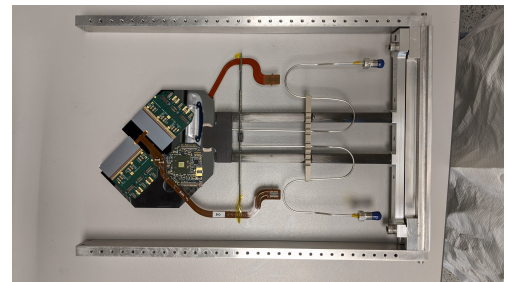
(A) Bare module assembly stage.



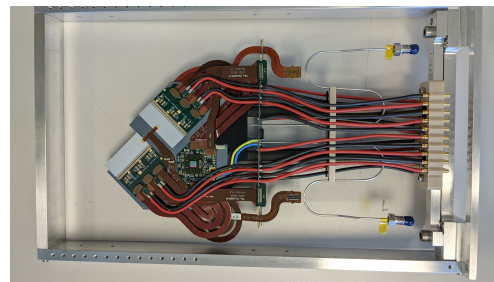
(B) Tile attachment stage.



(C) Hybrids gluing stage.



(D) Wirebonding phase.



(E) Cabling phase.

FIGURE 7.1: The five stages of the VELO Upgrade modules assembly procedure [35].

mounted in a custom-made jig. The clamp is glued to the cooling pipes to fix them in place minimising the propagation of mechanical stress due to the thermal expansion of the cooling system components to the substrate itself. At this stage the micro-channel plate is mounted into the frame and aligned with the legs using three small pillars; the midplate is now glued to both the micro-channel and the legs, providing mechanical connection. The glue is left to cure for one day and afterwards the bare module is moved into a “turn-plate”, a second custom-made frame with two glass windows with engraved fiducial markers, which are used to define a local reference system for the dowel hole in the module aluminium foot. This provides a reference between the turn-plate and the LHCb reference systems. A completed bare module on its turn-plate is shown in Fig. 7.1.

7.1.2 Tiles gluing

The tile gluing stage consists in the attachment of the silicon sensors with the three bump bonded ASICs to the micro-channel substrate with a bi-component glue which is automatically deposited via a robot dispenser. This step is one of the most crucial of the whole assembly procedure: a careful positioning of the tile and glue layer evenness, to avoid tilting the tile on the z axis, are required to ensure high tracking performance and IP resolution, while the glue layer thickness is crucial for a correct heat dissipation so to keep the thermal noise at minimum. More precisely, as the detector is operated in vacuum, the glue layer is the only medium available for heat dissipation, making the glue deposition a critical step. The glue layer has also to be thick enough to absorb thermal expansion of the components, but at the same time thin enough to minimise its contribution to the thermal gradient between the ASICs and the coolant. The gluing procedure is slightly different for the two construction sites:

- Manchester: all four tiles are attached at the same time using assembly stages (for the alignment of the tiles) and “transfer-plates” (for the glue deposition and attachment to the substrate); both are shown in Fig. 7.2.
- Nikhef: a “pick and place” machine (Fig. 7.3) is employed for alignment and attachment and two tiles are attached at a time.

All the other phases of this step are the same. This section will illustrate the gluing procedure, while the choice of the glue and the relevant studies will be described in detail in Sec. 8.

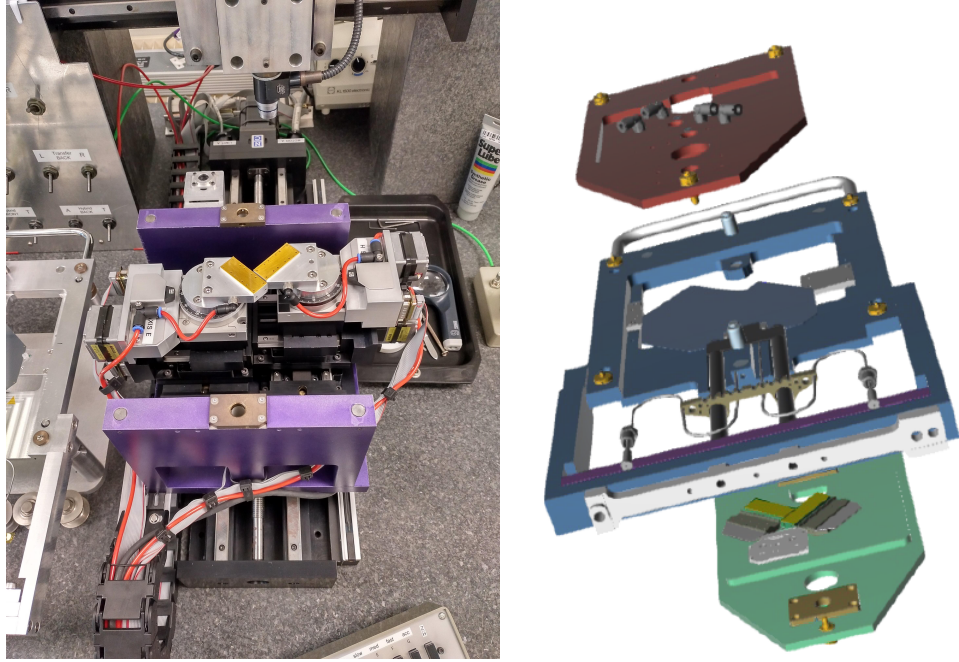


FIGURE 7.2: Left: assembly stages for the tiles alignment. Right: transfer-plates and turn plate schematics for the attachment of the tiles [35].

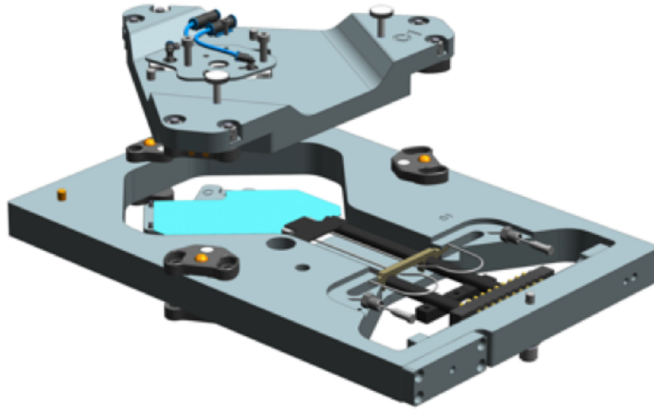


FIGURE 7.3: Schematics of Nikhef pick and place machine [35].

Even though all 4 tiles are glued at the same time, the adhesive is dispensed on one side (i.e. two tiles) at a time: first C side and then N side. The tile gluing stage is structured as follows:

- Two tiles are aligned on the assembly stages with a precision of less than $30\text{ }\mu\text{m}$. This system consists of two “stages” with two translational (planar) and one rotational (around the axis orthogonal to the plane) degrees of freedom, one per tile, and a camera with pattern recognition capabilities [90]. The tiles are held in place by a vacuum chuck. The alignment is automatised, and employs the camera to locate markers etched on each VeloPix ASIC and individually rotate and move each

stage.

- The two tiles are transferred to a transfer-plate, which is laid on top of the assembly stages: the vacuum is turned on on the former and only after that switched off on the latter, allowing for a precise and fast transfer of the tiles. The successful outcome of the procedure is assessed inspecting the pin-holes on the transfer-plate in proximity of the fiducial markers on the ASICs. This procedure is then followed again for the second set of tiles.
- The glue, Stycast 2850 FT [105], is mixed with a liquid catalyst (Catalyst 23LV) with a 7.5% ratio by weight. The mixing is performed with a planetary mixer for 5 minutes at 1000 RPM.
- The glue is transferred into a syringe with a metal needle (23 gauge) which is placed into a robotised glue dispenser (FISNAR F5200N [106], Fig. 7.4). Since the glue is dispensed in patterns on each ASIC, the speed at which the robot moves when dispensing the glue has to be tuned to dispense the same amount on each tile. This is paramount to keep the glue layer consistent throughout the whole assembly campaign. To decide the speed, the glue viscosity is monitored for around ten minutes and a table used to decide the correct speed value (Table 7.1); alternatively the empirical relation $speed = 0.125 \cdot observed\ viscosity$ can be used. The viscosity is assessed by measuring the weight of glue deposited in 1 minute and used to set the robot speed. The robot uses pressurised air at 1.5 bar to dispense the glue, which can be adjusted to meet the viscosity requirement.
- Once the parameters are set, the glue is dispensed in a double hourglass shaped patterns on each ASIC for the C side tiles. The development of this specific pattern and its advantages are described in detail in section 8. The glue is dispensed on two tiles (Fig. 7.5).
- The freshly dispensed patterns are heat treated with a heat gun (Fig.7.6) to remove any moisture that could have deposited on them. Both tiles are heated at the same time for one minute at a temperature of 60° C. Dedicated 3D printed nozzles (Fig. 7.6) for the C and N side are used to achieve a uniform air flow and heating across the whole area of each tile.
- The transfer-plate is picked up and placed over the turn-plate and pressed down onto the micro-channel. Three micro-metric screws on the former allow to precisely control the desired distance between the tiles and the

silicon substrate, while the alignment is ensured by two dowel pins on the turn-plate that match two corresponding holes on the transfer-plate. The plates are fixed together with two retention springs, one fitted on each dowel.

- The viscosity is measured again two or three times and the speed adjusted accordingly.
- The dispensing, heat treatment and press-down procedures are repeated for the N-side.
- The glue is left to cure for one day.

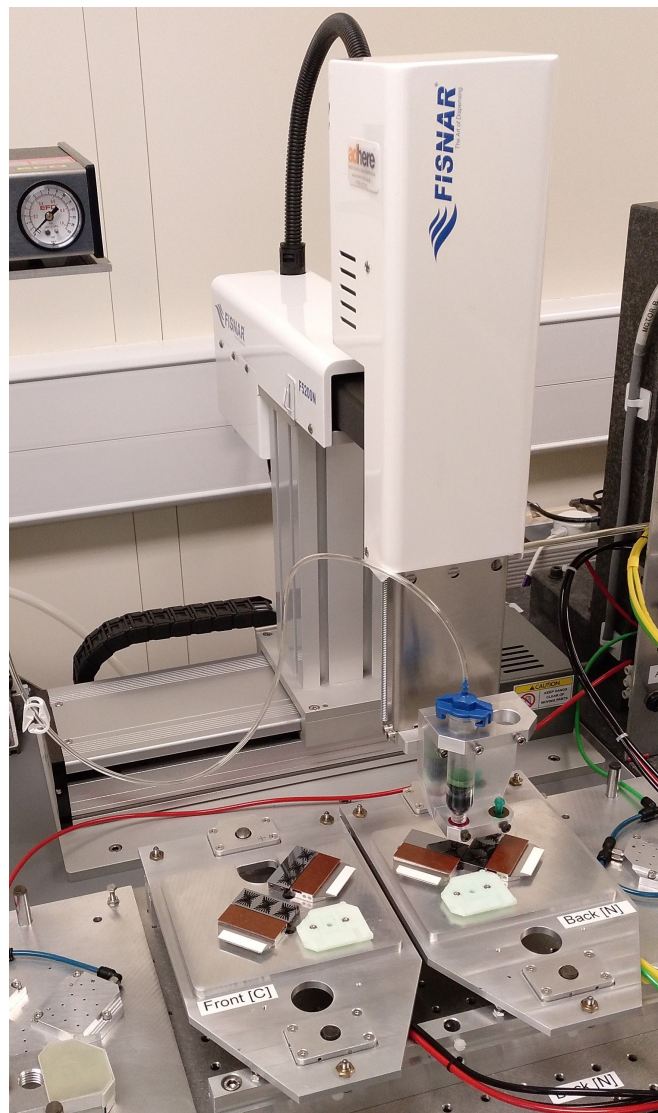


FIGURE 7.4: FISNAR 5200N glue dispenser robot.

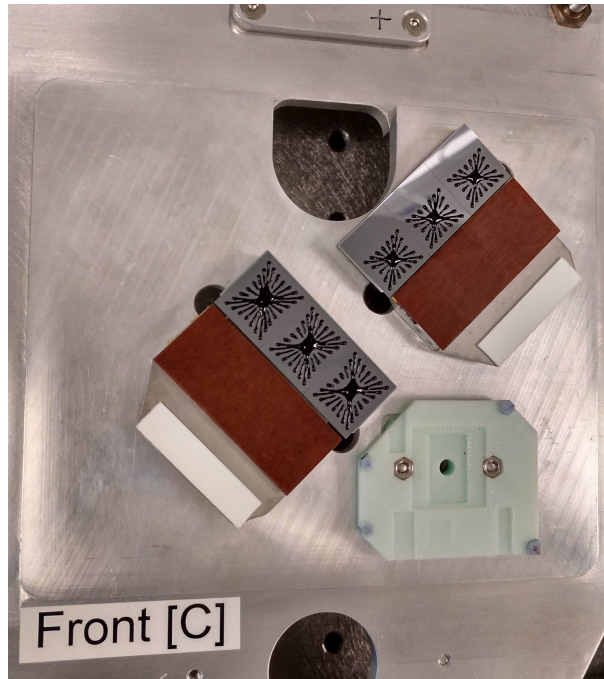


FIGURE 7.5: Glue patterns deposited on the C-side tiles. Note the double-hourglass star pattern.

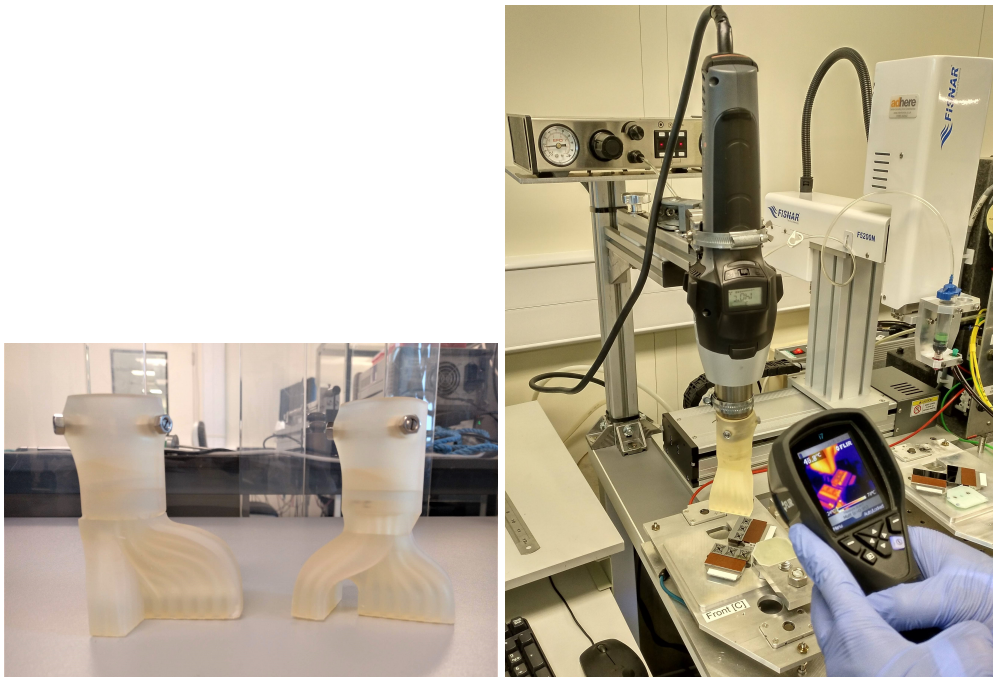


FIGURE 7.6: Left: 3D printed nozzles for the heat treatment. Right: heat treatment process performed by operator on freshly deposited patterns. Note the thermal camera to monitor the glue temperature.

7.1.3 Hybrid gluing

The hybrids are glued to the substrate in a similar fashion as the tiles, although the precision required for the components alignment is now less critical (less

Viscosity (mg in 1 min)	Speed (mm/s)
95 - 100	12.1
90 - 95	11.5
85 - 90	11.0
80 - 85	10.3
75 - 80	9.7
70 - 75	9.0
65 - 70	8.4
60 - 65	7.8

TABLE 7.1: Glue viscosity intervals and dispensing speed of the FISNAR robot used during the tile gluing stage.

than 100 μm). Furthermore, as hybrids dissipate less heat, instead of an epoxy adhesive a silicone glue was used. Specifically, the main requirements for the hybrids adhesive were flexibility, to absorb mechanical stress due to the CTE mismatch between the silicon substrate and the copper in the hybrid PCB, and radiation hardness: Loctite 5145 silicone adhesive was thus chosen.

In Manchester, the hybrids for both sides, 4 FE and 2 GBTx, are attached at a time; in Nikhef one side is attached at a time. The hybrids are mechanically aligned using pins, then transferred on the transfer-plates on bespoke plastic holders (Fig. 7.7) using vacuum. The vacuum also allows to fix the hybrid in place during the gluing procedure.

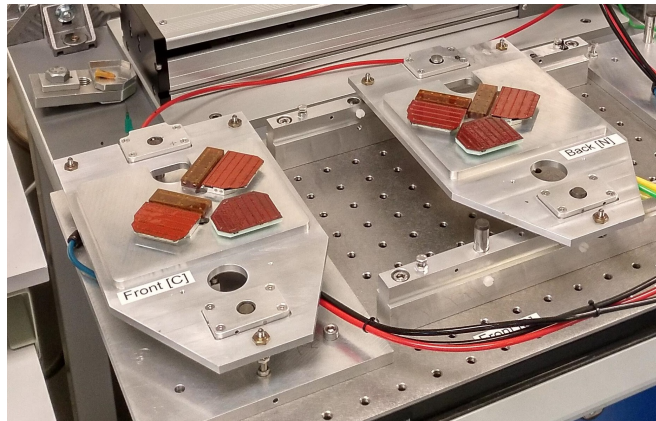


FIGURE 7.7: Hybrid positioned on the supports on the transfer-plates during the hybrid gluing phase.

The glue is dispensed in straight lines on the back of the hybrids using the same Fisnar F5200N glue robot, using a bigger syringe with wider gauge needle. Five lines with even spacing are deposited on the FE hybrids, with one of those placed in correspondence of the bond pads to ensure the PCB is mechanically

constrained during the wire-bonding; nine tighter evenly spaced lines are deposited under the GBTx hybrid to allow for increased cooling efficiency. The glue is dispensed on the C-side hybrids first, then on the N-side hybrids. The patterns for the FE and GBTx hybrids are shown in Fig. 7.8.

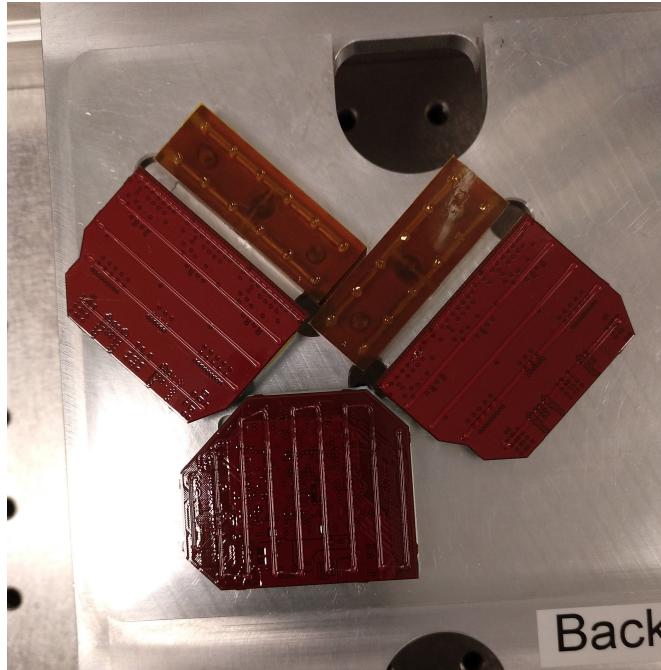


FIGURE 7.8: Glue patterns used for the hybrids gluing. The semi-transparent silicone glue is deposited in straight lines on the hybrids back side (in dark red).

Once the glue has been deposited, the transfer-plates are positioned over the turn-plate following the gluing order: first C-side hybrids, then N-side. The assembly is left to cure for one day before proceeding with the next phase. At the Nikhef site the hybrid gluing phase follows the same steps, but the interconnect and data cables are mounted before the gluing step. Cables attachment is performed as last step in Manchester.

7.1.4 Wire-bonding

At this stage the ASICs are wire-bonded to the FE hybrids to allow the transfer of signals from the tiles to the hybrids and off-detector electronics. The wire-bonds run from the ASICs to the FE hybrid bond pads which are organised in two rows of 240 pads each (Fig. 7.9), with one row of bonds being under the second row of longer wires. During the wire-bonding step the HV cable is also attached, one per each side.

The module is mounted in a dedicated holder frame and Araldite 2012, a fast curing bi-component epoxy, is used to glue in place the HV cable. Once

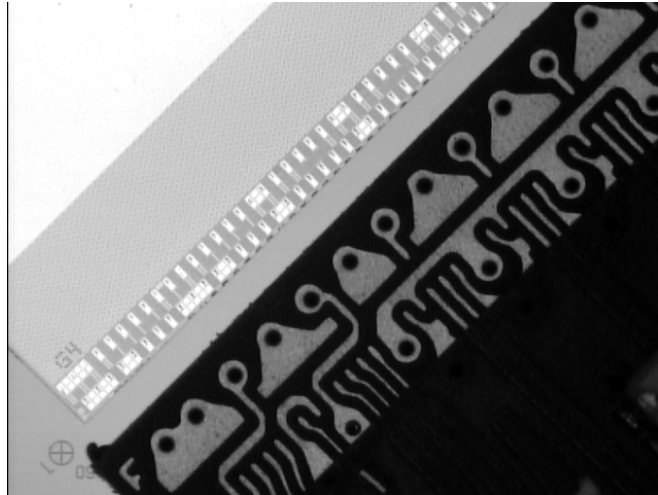


FIGURE 7.9: A picture of the bond pads on both ASIC (bright pads on the centre left-hand side of the picture) and FE hybrid (light grey areas on the centre right-hand side of the picture) [35].

the adhesive is cured the module is positioned into the wire-bonding machine (Fig. 7.10) and held in place by two vacuum chucks; the wire-bonder uses image recognition technology to locate the pads and automatically wire-bond the tiles to the FE hybrids.

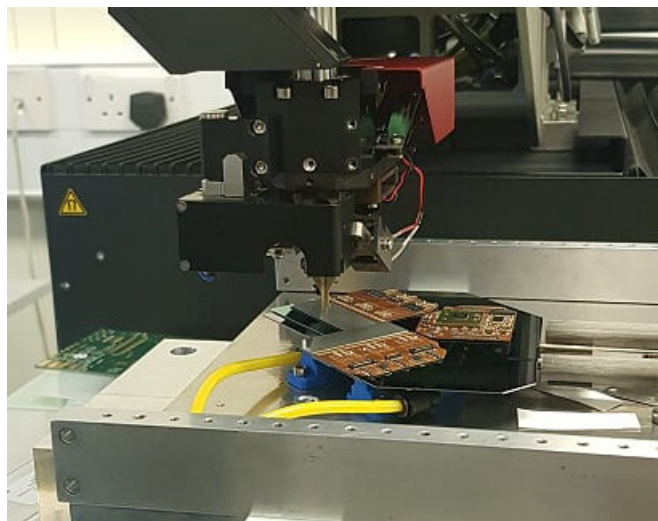


FIGURE 7.10: Wire-bonder machine with module on the holder [91].

Once the process is complete, a visual inspection of the bonds is carried out. If any wire-bond is found to be not properly attached, it is manually removed and a new wire bonded. The HV tape is bonded manually with 4 to 6 bonds to the surface of the silicon sensors. The procedure is then repeated for the other side. An image of finished wire-bonds is shown in Fig. 7.11.

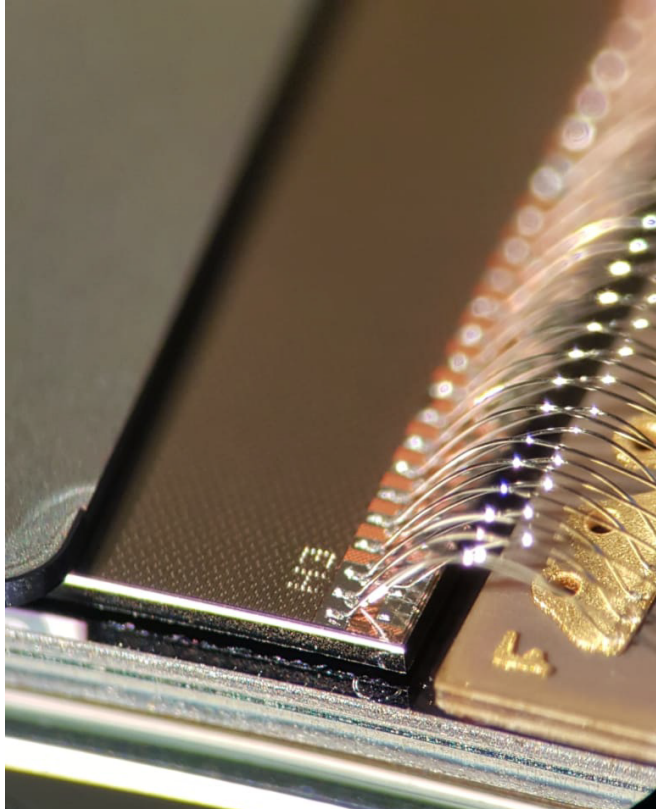


FIGURE 7.11: Close-up picture of the wire-bonds [35].

7.1.5 Cabling

Data and interconnect cables are mounted at the final step of the assembly procedure, together with LV cables (Manchester site only). The interconnect cables, two per side, allow two way communication between the chips (via the FE hybrids) and the GBTx hybrid (and thus the OPB); the data tapes, again 2 per side, allow to bring data from the sensors to the OPB and the off-detector electronics. The LV cables allow to distribute low voltage and power all the active module components.

7.1.5.1 Hybrid cables

Data and interconnect tapes are flat thin kapton flex circuits with connectors on both ends to be plugged into the FE and GBTx hybrids; data tapes have a further connector to transfer the data to the OPB via PCB tapes. As these (Fig. 7.12) are long and fragile, special care has to be put when plugging them to avoid damaging the metal pins.

Tapes are plasma cleaned before installation to remove any residual impurities from their production or accumulated during storage time. First, the interconnect tapes on C-side are attached, followed by those on the N-side;



FIGURE 7.12: Left: interconnect tapes; centre: data tapes; Right: HV tapes [35].

successively the N-side data tape is connected and finally the C-side one. To allow pressing the connectors into place without damaging the wire-bonds, the module is placed into the cabling jig (Fig. 7.13) which allowed to place the module vertically and rotate it around the vertical axis such that it could be placed in the most convenient orientation to easily mount each cable.

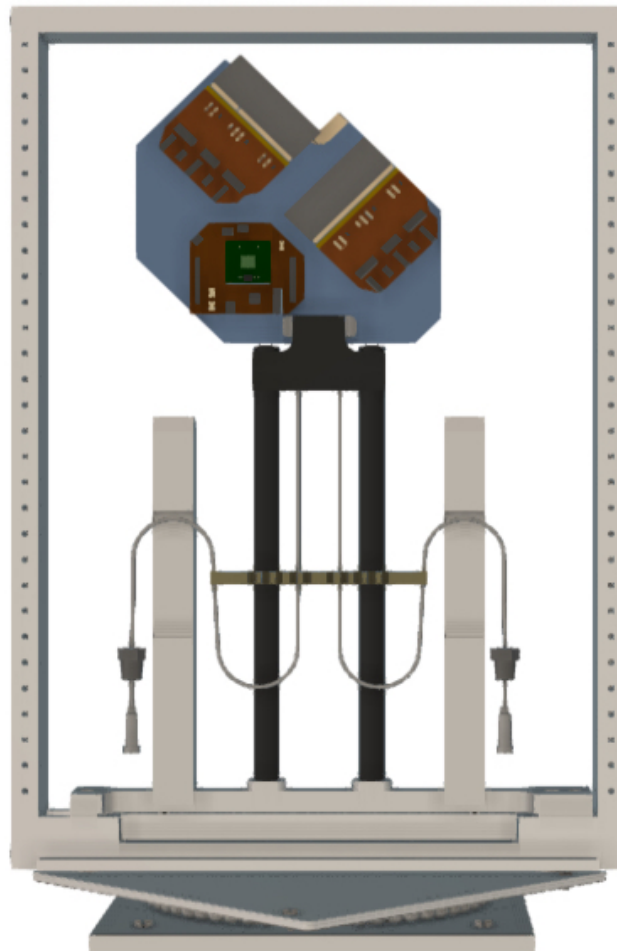


FIGURE 7.13: Schematic of the cabling jig [35].

7.1.5.2 LV cables

The low voltage cables are copper cables coated with silicone, they come in a pre-assembled LV harness (Fig. 7.14) containing the bridge piece, the LV cables with connectors for the FE and GBTx hybrids (north of the bridge piece) and pins (south of the bridge piece) for both sides of the module. Black and red cables are dedicated to powering the tiles, whereas the blue and yellow are dedicated to power up the GBTx. The bridge piece itself is made of PCB and is composed of two halves that clips around the carbon fibre legs and are electrically connected through a connector in the centre; it serves as a transition to thin the gauge of the cables near the detector to minimise the amount of material near the active area of the module and detector. It also contains slots to fit the data and HV tapes connector.

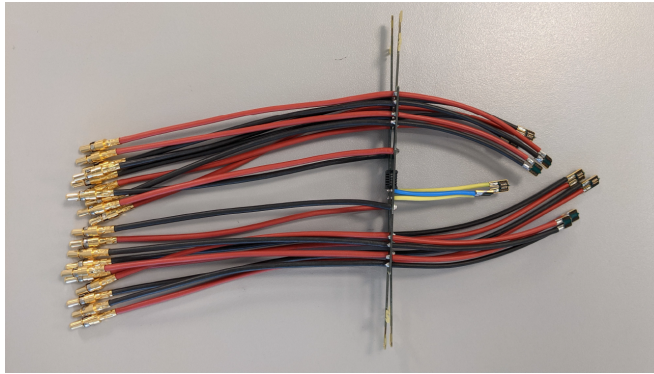


FIGURE 7.14: Low voltage harness [91].

First, the bridge piece is glued to the carbon fibre legs, then the LV pins are inserted in the LV foot connector, a machined plastic connector fixed to the aluminium foot. Then, the LV connectors are pushed in place on the hybrids. The assembly procedure is then complete.

7.2 Metrology

After each assembly step, careful metrology and grading is carried out to ensure all the quality parameters are within specification and to spot possible defects before proceeding with the following assembly step. Quality assurance is thus paramount to avoid wasting components in the assembly of a defective module. The metrology is run on the following:

- Substrate flatness (after bare modules assembly).

- Tile position, glue layer thickness, tile flatness (after tile gluing).
- Hybrid positioning (after hybrid gluing).
- Wire-bond pull test (after wire-bonding).
- Photo inspection (after module completion).

After each test, a grade is assigned to evaluate the quality of the build. To keep track of the results, a database is used to register all the modules test results and elaborate a final grade. The database and the grading system will be discussed in detail in Sec. 7.4.

The first metrology steps are performed using a “Smart-scope”, i.e. an optical coordinate measuring machine able to run autonomously based on a user-provided scripts. The smart-scope [107] (Fig. 7.15) used at the Manchester site is equipped with a laser and telescopic lenses to precisely scan surfaces and allow pattern recognition. The machine then saves the x , y and z coordinate to a text file for further analysing. The tool has a precision of $2\text{ }\mu\text{m}$ and $5\text{ }\mu\text{m}$ on the xy plane and z coordinate, respectively.

7.2.1 Substrate flatness

After the bare module assembly, the surface of the micro-channels is scanned to measure its flatness and compare it with measurements previously carried out at CERN, where the silicon substrate is soldered to the fluidic connectors. The bare module is positioned on the smart-scope scanning area and fixed to a metal holder which is directly screwed onto the tool frame (Fig. 7.16). Then an automatic routine is set up to recognise markers on the edges of the micro-channel and set the proper z plane for the laser scanning. The optics also recognises the edges of the substrate, allowing to identify its boundaries and compute the area to be laser-scanned. After the edges are defined, the surface is scanned and the measurements stored in a file to be uploaded to the database for further analysing. Any distortion of the substrate is likely to come from the added stress of the mid-plate and attachment of the cooling pipes to the clamp. Only the C-side is scanned in this test.

7.2.2 Tile position

The tile position is determined after the tile gluing step. Again, the module, is fixed in the metal holder and to the smart-scope. A script is run to identify the edges of each tile and compute their position. Then, fiducial markers on

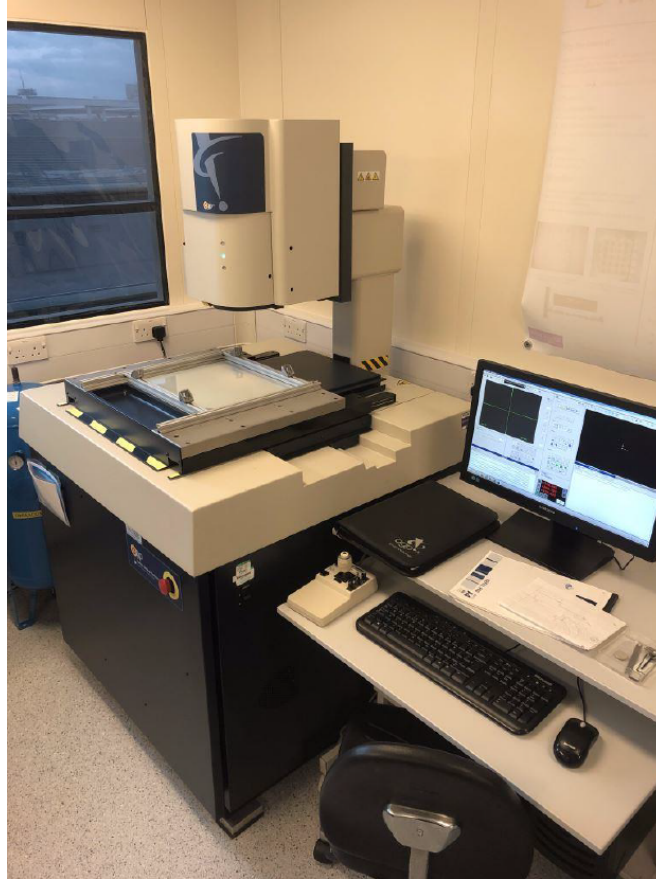


FIGURE 7.15: The smart-scope OGP model Flash 300: on the bottom right the operator location, on the left the smart-scope; The laser and optical camera are housed in the robotised white arm, the module is fixed on the white glass plane. The plane can move freely on the x - y coordinates, while the arm moves on the z axis [35].

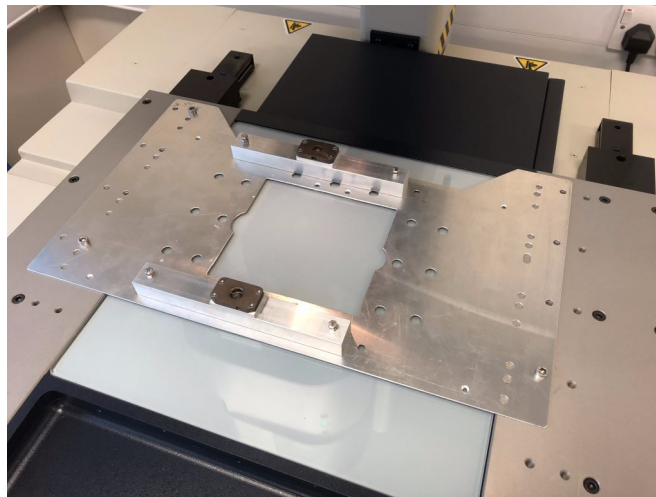


FIGURE 7.16: Turn-plate holder fixed on the smart-scope scanning area.

the corner of the sensors and ASICs (Fig. 7.17) are located and their position registered. The ASIC markers will be used to compute the distance and the angle of the tile respect to its nominal position. Sensors fiducial are instead

etched on the back of the tile, so that the only visible ones are those on the other side of the module, and only for the overhanging tile. Thus, tile markers are only used to cross-reference front and back position measurements.

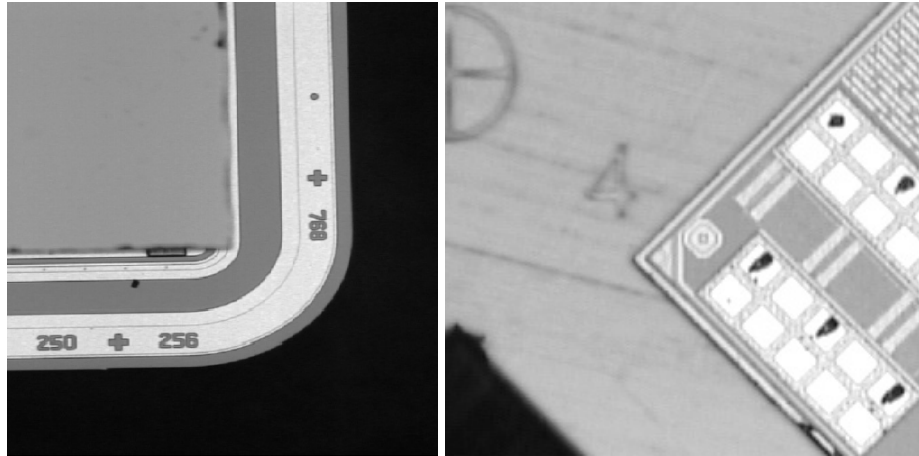


FIGURE 7.17: Left: fiducial marker on the back of the sensor. Right: fiducial marker in the ASIC [35].

The results of the tile position metrology are also fed back to the tile attachment step, such that the target position of the tiles on the assembly stages can be updated to more accurate values.

7.2.3 Glue thickness

Glue layer thickness is crucial to ensure a uniform heat transfer across each tile, thus after the gluing procedure the thickness of the adhesive under each ASIC is measured.

The smart-scope first scans the surface in the near vicinity of the perimeter of the tile and fits a reference plane upon to measure the layer width. Then the surface of the tile is scanned and its distance from the plane computed and saved (Fig. 7.18). The database will subtract the tile thickness and return the adhesive one. During the R&D phase, this information has been used to calibrate the amount of dispensed glue and adjust the micrometric screws that set the distance between the transfer-plate and the turn-plate (i.e. the tiles and the micro-channel substrate) to the required target of 80-100 μm . It should be noted that there is an intrinsic uncertainty in the glue thickness measurement, as it is not possible to account for any bending of the substrate surface under the glued tile; similarly any distortion of the bottom surface of the tile is not detectable.

7.2.4 Tile flatness

Tile flatness is directly related to both the uniformity of the glue layer beneath the sensors and the substrate flatness. It is measured in a similar fashion respect to the glue thickness, but this time a reference plane is fitted to the tile surface measurements and the residuals computed to map the flatness (Fig. 7.18). Once again, this measurement is used to correct the amount of deposited glue and the tile to micro-channel distance.

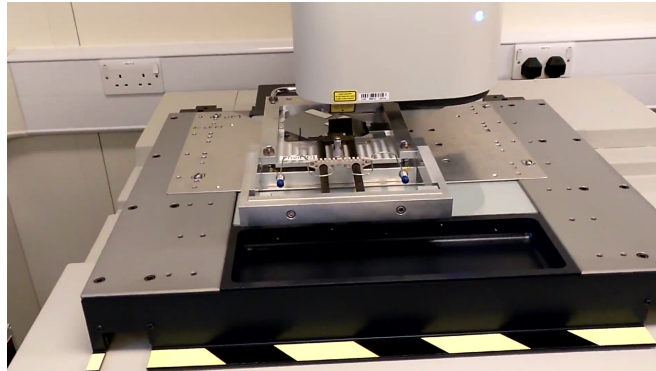


FIGURE 7.18: Tile flatness and glue thickness scan. The module is fixed on the metal holder screwed to the smart-scope scanning area. Here the pattern recognition camera is identifying the tile edges. This step has to be carefully overseen by the operator as the camera is in the close vicinity of the sensors.

7.2.5 Hybrid positioning

After the hybrids gluing step, the position of the hybrids is checked taking zoomed-in images of the FE (Fig.7.19) to check the distance between these and the tiles to ensure they are not critically close and that there are no glue spillages (both from the FE hybrid and the tile). These information are used during the wire-bonding phase to calibrate the machine parameters during the automatic procedure.

7.2.6 Wire-bonds pull testing

The quality of the wire-bonds is assessed measuring their strength. This step is carried out after the wire-bonding procedure is completed, by means of a “pull-tester”, a dedicated device with a needle terminating in a hook able to register the maximal pull force needed to break the wires. Each ASIC is equipped with 4 “sacrificial” bonds (Fig.7.20), for a total of 48 per module, specifically meant to be pulled off to infer the overall quality of the bonds, where this includes the wire strength and the wire-pad adhesion quality. The break strength is

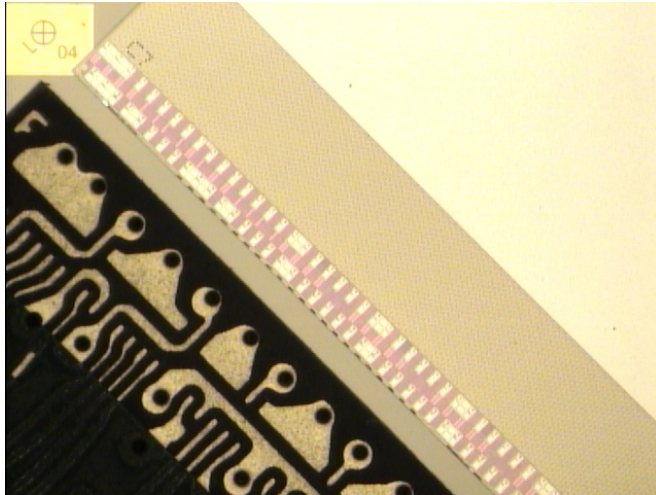


FIGURE 7.19: Picture of the FE alignment metrology: the tile and FE hybrids are uniformly spaced.

registered and used to assign a grading to the wire-bonds. Strong enough bonds are vital to ensure their survival through the manipulations the module has to face during the validation, halves assembly and full detector installation.

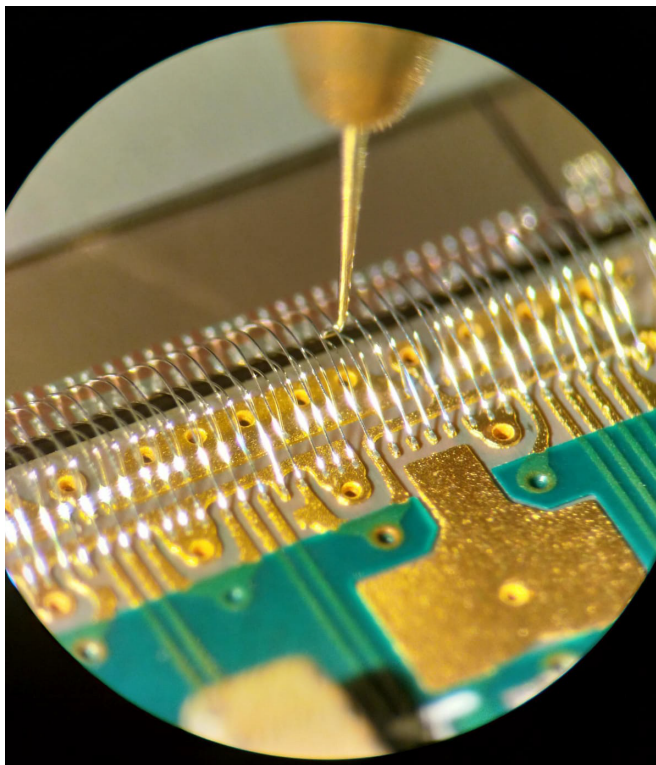


FIGURE 7.20: Sacrificial bonds about to be pulled [35].

7.2.7 Photo inspection

Once the module is fully assembled, a careful photo inspection follows to check the overall build integrity and for future reference. This phase helps to spot missed failures as well, e.g. broken wire-bonds, unplugged cables or bad connectors. The pictures are saved to database, although no grading is assigned at this stage.

7.3 Module validation

Completed modules have to be validated in operation-like conditions to evaluate their mechanical and electrical soundness as well as assess their thermal and electrical performance. Thus, a validation setup (Fig.7.21) has been commissioned at the University of Manchester consisting of a vacuum tank, to mimic the detector vacuum; a cooling machine, which provides circulating CO₂ for the micro-channel substrate and keeps the modules at the nominal operation temperature of -30° C; a vacuum feed-through board to bring electrical signals in and out of the tank; a cooling feed-through for bringing the coolant inside the tank; an electrical feed-through for any additional device or probes installed in the tank; an Opto-and-Power Board for the electrical to optical signal conversion; a DAQ system for the processing of the data coming from the module as well as providing the services; LV power supplies; HV power supplies; an interlock box.

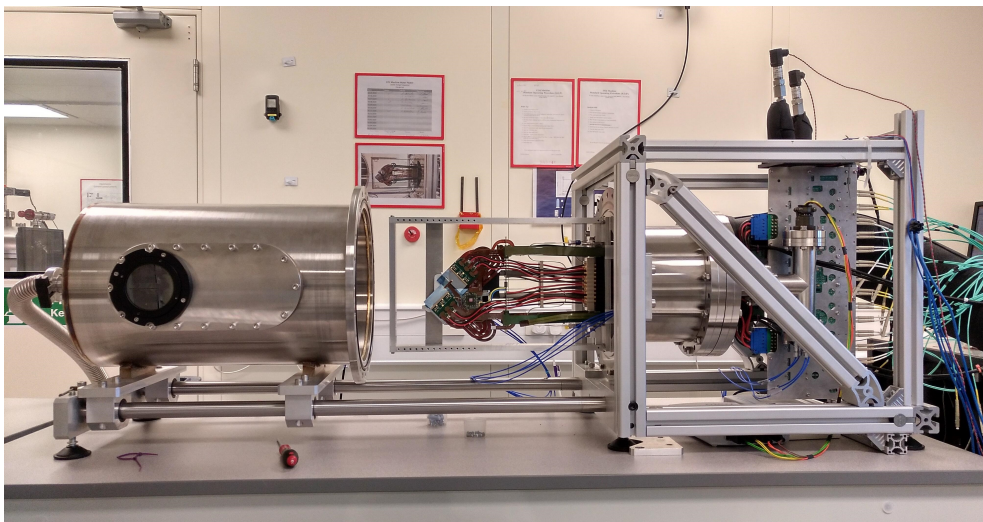


FIGURE 7.21: Validation setup at UoM in the open position: on the right the OPB, VFB and the module under test mounted; on the left the vacuum tank with the small window to allow inspection with a thermal camera.

Modules are installed while mounted on the frame used during the cabling step. Two plexiglass screen are installed on either side of the frame to avoid making contact with the most fragile parts of the module, i.e. the wire-bonds. The frame is attached to the flange in the vacuum tank aligning the LV connector to a LV plug mounted on the vacuum side of the VFB. Once in place, the frame is screwed to the flange and the plexiglass windows removed. Data and HV tapes coming from the VFB are clamped to the side of the flange to allow mating with the corresponding tapes on the module side. As the data tape connectors are fragile, a special tool made of two plastic blocks with two alignment screws is used to evenly press the connectors together; these are then tightened with nuts and bolts to secure them in place. Finally, the vacuum-side cooling pipes are hand tightened (they will be fully tightened only at the testing stage) to the modules cooling pipes via Swagelok Vacuum Coupling Radiation (VCR) fittings. After the module installation in the tank, two displacement sensors (Micro-Epsilon CSH1-CAM1,4 [108] capacitive displacement sensor with sub-micron precision) are mounted on the module holding frame, facing the N-side tiles. The displacement sensors are used to measure the deformation of the module during a number of stages, namely the tightening of the VCR connectors, the evacuation of the tank and the cooling down from room temperature to operational temperature. They are readout by a LabView program showing the trending of the module position over time.

A picture of the installed module within its frame, with a detail of the displacement sensors holder is shown in Fig. 7.22.

7.3.1 Electrical setup

To test the whole FE and DAQ detector chain, the setup is equipped with a VFB to allow connection with an OPB and a PCi40 MiniDAQ server (Fig. 7.23) to verify the full FE-DAQ chain from configuration of the chips to the reading of the optical fibres. The MiniDAQ server provides both slow control and TFC timing to the module, allowing to control the GBTx hybrid and configure the ASICs. The server also reads the information back from the module (temperature and internal voltages) and communicates with the OPB (again temperatures). It has 6 “minipods” (optic fibres bundle connectors), 4 of which are used to read, in bundles, the 20 optical fibres carrying the data from the sensors.

Furthermore, the modules and OPB temperature sensors are read out by a PC and constantly monitored during the testing via a LabView interface. The module is also connected to the HV via a power supply. The LV is provided by

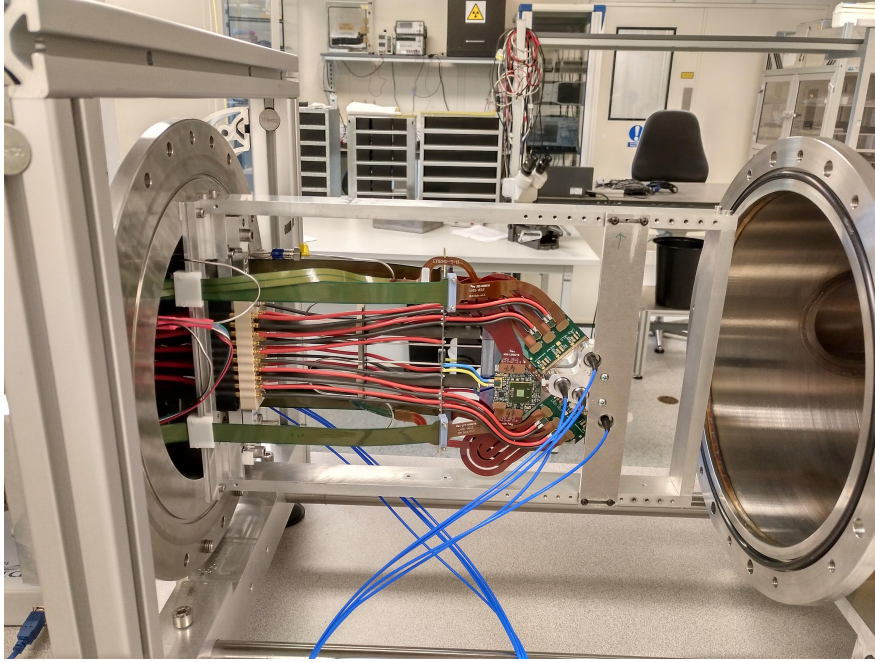


FIGURE 7.22: Module in its frame attached to the vacuum tank flange. On the right side the displacement sensors can be seen.



FIGURE 7.23: Left: the Manchester MiniDAQ. Right: detail of the minipods with 4 optic fibre bundles attached.

a power supply via a custom-made interlock box, which automatically powers off the module if the temperature rises above 40° C.

7.3.2 Vacuum

The tank is connected to a Pfeiffer Vacuum D-35614 Asslar Turbo Pump (Fig.7.24) which provides vacuum levels down to $< 1 \cdot 10^{-5}$ mbar. The tank is split in two section: one is fixed and hosts the VFB, the other, connected to the pump, can slide on rails and allows for the space needed for the module installation. The interface between the two section is sealed with an O-ring and fixed with 6 bolts.

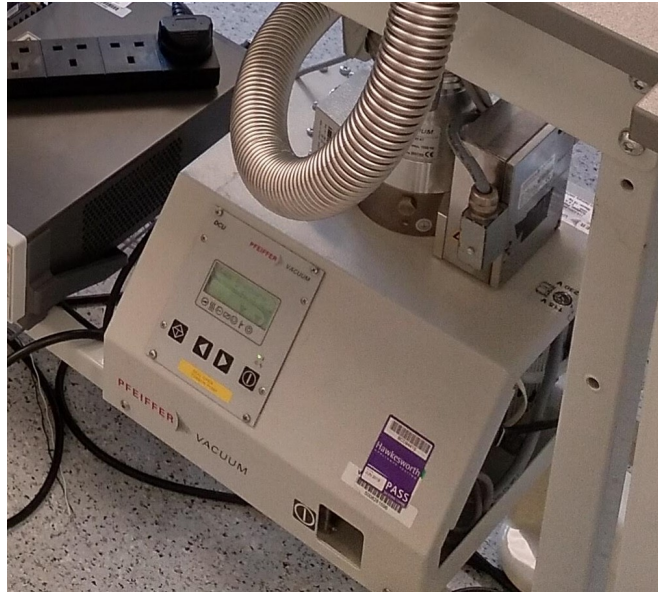


FIGURE 7.24: Manchester Pfeiffer Vacuum D-35614 Asslar Turbo Pump.

7.3.3 Cooling

The cooling is provided by a cooling machine based on a blow system designed at Nikhef [109] (Fig. 7.25) that connects a CO₂ bottle to the module.

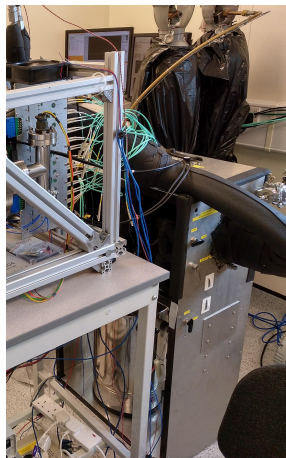


FIGURE 7.25: UoM cooling machine: the CO₂ bottles on the back, the cooling machine is inside the metal box; the insulated CO₂ tube feeding the module under test is on the forefront.

It has a heat exchanger, a needle valve to regulate the flow, back-pressure valve for setting the pressure drop across the module, and a flow-meter. All the pressure and flow parameters are monitored via a LabView project, showing the precise value of the pressure gauges and a trending plot of the flow. The cooling machine is connected to a second vacuum pump connected to the outlet of the module and it is used to evacuate the system (including the micro-channels) in the case of presence of air (i.e. water) in the channels or in the rest of the system.

7.3.3.1 Starting procedure

The cooling machine has to be started carefully following a number of steps to avoid releasing the full pressure of the CO₂ bottle (circa 60 bar) into the module. First, a small vacuum pump is used to evacuate the system (machine plus module) from any residual air. Specifically, any moisture contained in the air inside the system could freeze when in contact with sub-zero CO₂, potentially leading to blockages of the micro-channels. At this stage, without any residual gas in the system, the gas bottles are slowly opened, followed by the main CO₂ valve. As back-pressure builds up, the back-pressure regulator is slowly opened at the 20 bar mark and the gas is let into the system. The flow-meter on the outlet of the machine should confirm that gas is flowing, otherwise a blockage must be occurring in the machine or worse in the module, requiring the immediate closure of the gas bottle. If gas is flowing, the back-pressure should be regulated around 12 bar to reach -30° C. After the system reaches this temperature the flow is reduced to 0.4 g/s and the system let stabilise. The module is then ready for testing.

7.3.4 Tests

Assembled modules are put through a series of tests to assess their mechanical robustness, electrical and thermal performance; starting from the tightening of the VCRs to the thermal degradation of the glue layer. A grading is assigned to each test to allow for a thorough evaluation of each aspect of a module; these will be discussed in the database section 7.4, while each test procedure will be discussed in the following subsections. All the electrical tests are carried out using a WinCC/OA [110] Finite State Machine (FSM) software, which allows the operator to control and communicate with the hardware. The user interface comprises a number of panels with buttons to access the various module functionalities and test interfaces. An example of the main module panel is shown in Fig. 7.26.

WinCC/OA The WinCC/OA software is a SCADA (Supervisory Control And Data Acquisition) system used to control hardware components which is employed by all the big experiments at the LHC. Specifically, LHCb employs WinCC for both the ECS and DAQ implementation. Hardware control is performed via a User Interface (UI), in the form of panels which can be created via a UI editor, called *gedi*, that allows to structure the controls using “widgets”.

Widgets are graphical objects acting on *Data Points Elements* (DPE). These represents actual parameters on the hardware side, e.g. the voltage settings of a power supply. Thus, acting on the widgets the operator is able to read and modify setting and parameters of the actual hardware. DPE are grouped within Data Points (DPs), which represents the software instances of real hardware components (e.g. a HV module, a FE board, a temperature sensor). Panels can be nested for greater flexibility, and *widgets* can act on other UI elements as well. Both panels and *widgets* are fully programmable with scripts (the language used is similar to C) and can be set to react to specific events as the change of a DPE value (e.g. a change in temperature), or a user input (e.g. mouse or keyboard click). WinCC/OA is equipped with an Oracle Database that allows to archive all the values of a DPE. As result, the software can produce “trending” plots of any of these, which are crucial to monitor the current hardware behaviour and check what it was at any point in time. Each DPE is associated with an alarm, which can be configured to trigger a warning signal or an error depending on the value of the DPE; thresholds with lower and upper limit can be configured as well for greater flexibility.

WinCC is associated with the JCOP (Joint Control Project) framework allowing for the implementation of FSMs, enabling for the control of multi-layered systems, as those needed to control a detector or an experiment, from a single control panel. FSMs are tree-like structures, with a “Top” panel (e.g. the ECS) which governs directly all its sub-layers (e.g. single detector parts). These allow to access finer granularity information about the single detectors, sub-detectors, single modules and so on and so forth. Commands from the top layer are propagated to the bottom layers, while states and alarms are propagated on the opposite direction to inform the top layer. This effectively enables to control complex systems through just a few commands from the top level and be informed immediately if any component from any of the lower layers goes into an undesired state.

The module panel features direct control of single chips, FE and GBTx hybrids, as well as the possibility to change the power mode in which the module (i.e. all ASICs and hybrids) will be configured. Five power modes are available, each allowing to set up the module for different tests [35]:

- Low power: reduces the analog current minimising the DAC (Digital-Analog Converter) settings.
- Minimal/QA: standard mode for module operation, nominal voltages and currents to access the basic configuration and monitoring features.

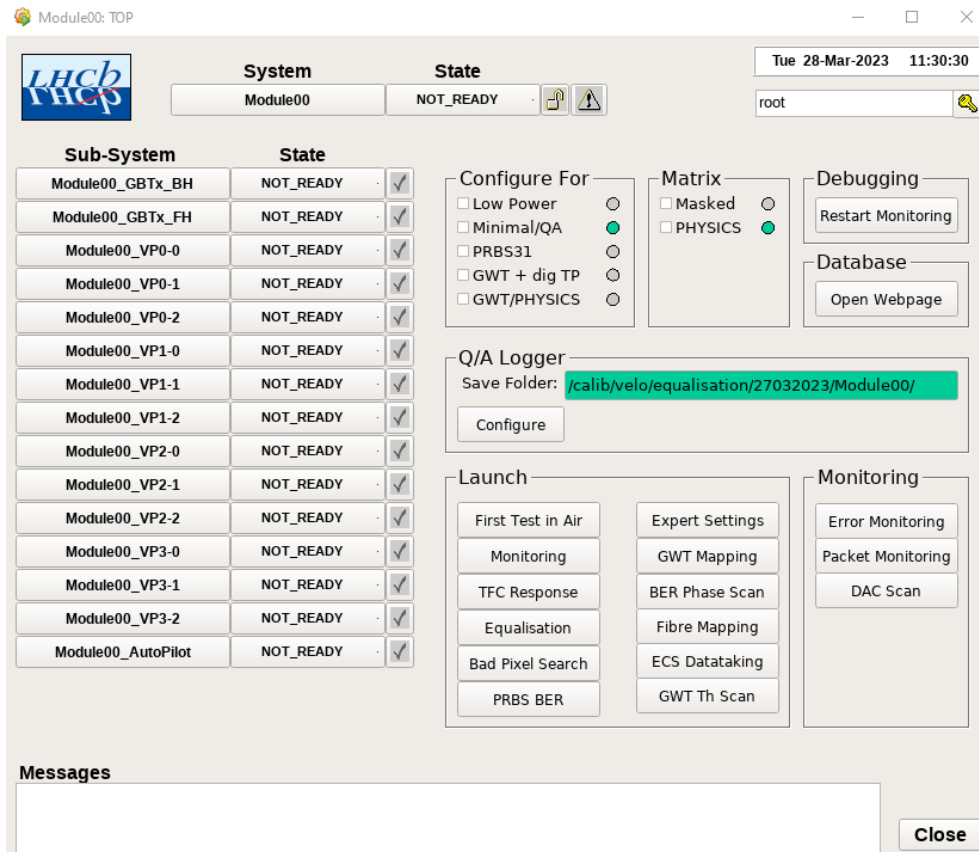


FIGURE 7.26: Main WinCC panel used to operate the electrical tests.

- PRBS: increases power consumption of the ASICs allowing to power open the “shutter”, which is the signal that enables transmission down the data links [102] and produce Pseudo Random Bit Sequence (PRBS) strings. In this respect, PRBS mode is the minimum power mode which enables data transmission.
- GWT/dig TP: configure the pixel matrix and the ASICs to transmit SPPs. It allows to generate Test-Pulses in the chips.
- GWT/Physics: maximum power mode, used for physics data taking. It is the nominal power mode that will be used during operation.

7.3.4.1 Mechanical tests

The mechanical tests take place immediately after the installation of the displacement sensors on the module frame. These are capacitive Micro-Epsilon displacement sensors, positioned in front of the outermost side of tile NSI and of the innermost side of tile NLO. Modules will be subject to distortions after installation in the VELO base caused by CTE mismatch of the various components when cold, and due to the mechanical stress of the cooling pipes

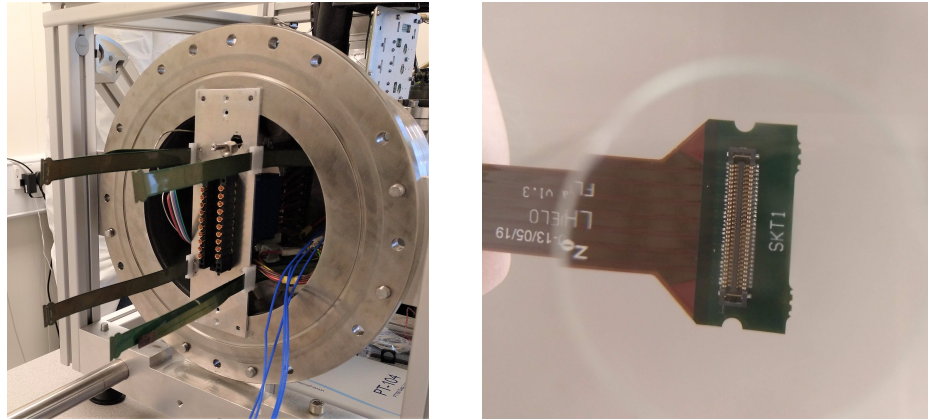


FIGURE 7.27: Left: detail of the data and HV tapes coming from the tank side of the validation setup. Right: detail of the data tape connector; note the slots on the edges. These are used to fix the tapes to the transition piece and to align the data tapes connection harness.

and tapes from the off-module side. Thus, keeping track of the position of the extreme edges of the tiles allow to evaluate the expected distortion on the z axis. This will benefit the standard alignment procedure, which is extremely accurate on the x - y plane but less effective on the z axis, when the full detector is installed. There are three mechanical test:

- Data and HV tapes connection.
- VCRs tightening.
- Pump-down and cooling down.

Technically speaking a fourth mechanical test is carried out: the thermal cycling; this procedure will be described later on as it is carried out after the first set of electrical tests.

Tapes connection The HV and Data tapes on the module side are connected to those coming from the VFB. The connection is carried out by hand for the HV tapes, pushing together the connectors, while for the long and thin Data tapes (Fig. 7.27) a special harness is used to evenly distribute the pressure without breaking the metal pins. The harness is made of two plastic rectangular blocks with two aligned holes for fitting a screw and a nut. The holes are aligned with small slots on the connector edges. During the process, the position sensors register the position of the module, which is saved at upon termination and send to database for grading.

VCRs tightening The two VCRs, one per cooling pipe, which are pre-tightened by hand, are tightened using two wrenches to avoid putting torque on the cooling pipes on the module side, which would distort the module or worse damage or break the cooling connectors or the pipes themselves. The position of the module is recorded during the whole operation and data sent to database for grading.

Pumping and cooling down The vacuum tank is closed after the leak test and fixed in place with 6 bolts. Vacuum tightness is guaranteed by an O-ring. The tank is then pumped down to a few 10^{-5} mbar. This takes some hours. Reaching a satisfactory level of vacuum is needed before starting the cooling machine, in order to avoid condensation of water vapour on the cold components. The cooling machine is then started and the module cooled down to -30° C. The displacement is recorded through both phases and sent to database for further analysis.

7.3.4.2 First communication in air

The first electrical test are carried out before the closure of the tank to ensure communications to and from the module are possible. This allows to spot any macroscopic failure along the readout chain: broken ASICs or wire-bonds, malfunctioning tapes. Since the module will still produce heat when configured, a fan is used to cool down the ASICs during the test ($O(10\text{ s})$). To run the test, the module is configured in Minimal/QA and the “monitoring” panel (Fig. 7.28) is opened to check that all the information of each ASIC (ID, temperatures, analogue, digital and bandgap voltages) can be read out. Specifically, all analogue and digital voltages should be higher than 1.2 V. The operator will then record the values taking some snapshots. As only ECS information is used in this test, only the data path to the tiles through the GBTx is checked. If any failure is spotted at this stage the module can be quickly inspected and if necessary removed from the tank, and connection of the tapes can be checked without having to pump down and cool (or warm) the module.

7.3.4.3 TFC

The TFC test allows to check the fast control and synchronisation of the module with the LHC clock, which is crucial to align the time response of each module in the full detector and the latter with the whole experiment. To run the test the module is configured in Minimal/QA and the SODIN (command distribution

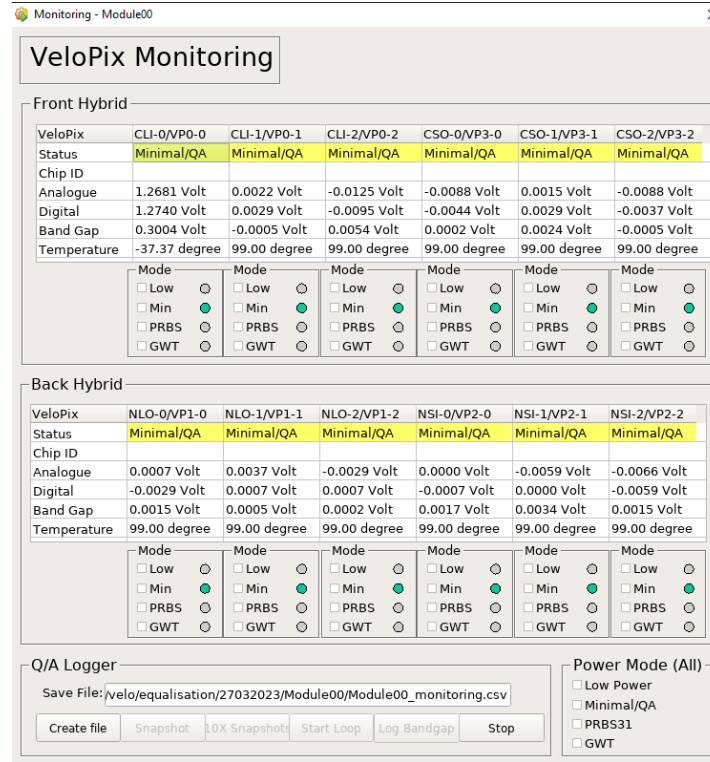


FIGURE 7.28: Panel used for the quick communication (and later thermal performance) test.

and timing readout supervisor) is configured as well. TFC signals are sent from the MiniDAQ through the SOL40 (the interface board, see Sec. 6.2.2.6) to the OPB, and from there they are sent to the GBTx chip which distributes them to the ASICs [91]. Counters are increased as TFC signals are received. These are then read out by the ECS and snapshots of the values taken with the WinCC panel (Fig. 7.29). Several signals are sent and the response recorded [90,91]:

- BXID reset: the bunch ID counter is reset when the signal is sent, which is once every $86 \mu\text{s}$ (one LHC orbit) during operation. The reset counter is expected to increase in the ECS panel each time a reset signal is received.
- FE reset: the ASICs reset is triggered.
- Calibration A: triggers a test-pulse injection by the VeloPixes with a defined pattern.
- Snapshot: the TFC counters status is saved into dedicated registers allowing for ECS readout. It is automatically sent by the panel.

- Synchronisation: inserts a predefined pattern into the outgoing data stream. The packet reception confirms that the VeloPixes are synchronised with each other and the Front-End is properly synchronised with the Back-End. 10 sync signals are sent by the panel, triggered by the user.

The BXID reset and snapshot are expected to increase over time after activating the “run X orbits” button, while the others have to be triggered by the user. The test is successful if the counters match the number of TFC signals sent.

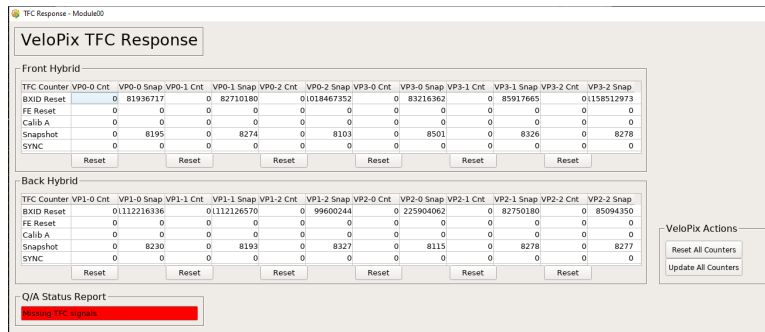


FIGURE 7.29: Panel used for the TFC test.

7.3.4.4 PRBS

The Pseudo Random Bit Stream (PRBS) test aims to check the integrity of data sent to from the ASICs down to the optical fibres to the MiniDAQ, verifying the data transmission from the modules to the off detector electronics. During the test the module is configured in PRBS mode and the BER panel is used (Fig. 7.30). First, the GBT server is started, then from the panel the test is launched: a number of 31 bit strings of pseudo-random numbers are sent from the ASICs to the MiniDAQ through the 20 data links and the consistency between the sent and received word checked. If errors are found, a counter is increased. Ideally, if the full chain FE+DAQ is intact, no errors should be registered. The strings are generated in the periphery of the ASIC, specifically in the EoC blocks. As the “pseudo” prefix suggests, the strings are pre-defined once the clock is set, so that the MiniDAQ knows exactly which 31 bit string is being sent from the ASIC and thus can check its integrity along the data links.

7.3.4.5 Noise and Equalisation

To check the noise levels of the sensors and equalise their response, the gain and amplification of each pixel is changed and its response registered. Since pixels provide only binary information (active, non active) the amplification levels are

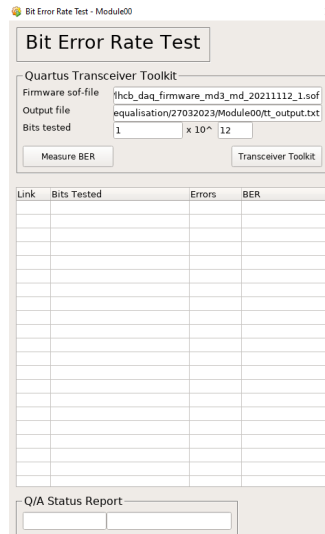


FIGURE 7.30: Panel for the PRBS test.

scanned to measure the noise level of each pixels and their activation threshold. This allow to equalise them such that each pixel respond in the same way to the same signal. This test is carried out in Minimal/QA and with the HV set to -140 V, the full depletion voltage. Pixels are scanned varying the global pixel threshold from the base level, Trim0, to TrimF i.e. the highest value available, corresponding to 15 DAC steps, each corresponding to 12.5 DAC counts. The scan ranges are specified by the operator in the equalisation panel (Fig. 7.31), while the chip will try to uniform the pixel response across the ASIC. The target range of the equalisation is also user specified. Once all the data is collected, noise maps are drawn along with 1D histograms of the pixels noise distribution. Dead and masked pixels (pixel are masked if they are always active meaning their noise level is too high) are registered as well. The collected data is then sent to database for grading.

7.3.4.6 Bandgap and thermal performance

The bandgap measurement allows to measure the energy gap between the valence and conduction band at different temperatures. The thermal performance instead aims to test the cooling of the whole micro-channel, glue and tile assembly to extrapolate the delta temperature of the chip at 26 W, the nominal expected power dissipation before irradiation. During this test the module is progressively powered at higher and higher power consumption modes, varying the absorbed current and thus the produced heat. This test requires an extremely steady flow of CO₂ to allow a pertinent comparison of the heat dissipation capabilities of the module under different loads. The cooling machine is

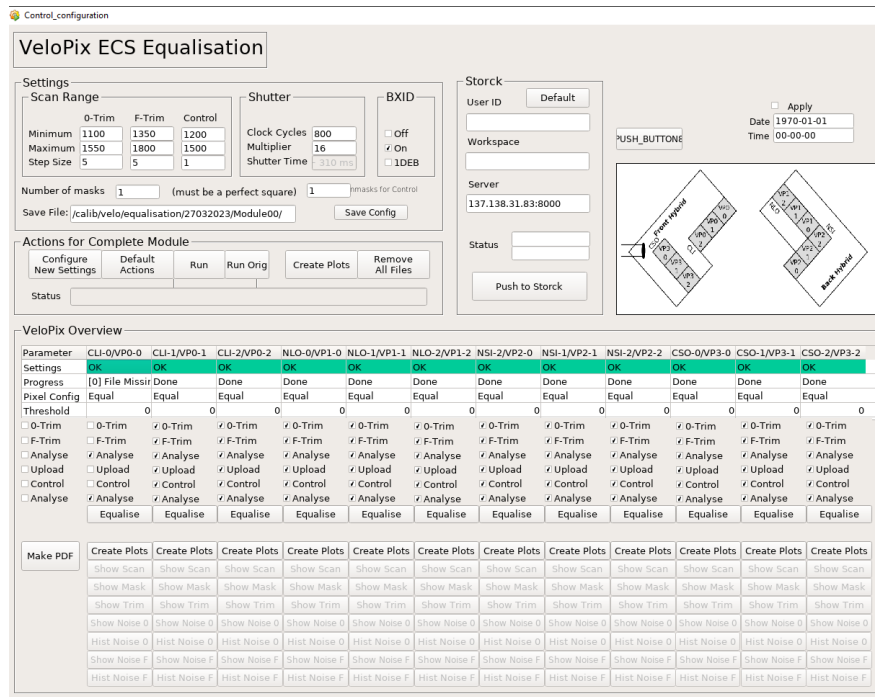


FIGURE 7.31: Panel for the pixel response equalisation and noise scan.

then preliminary set to achieve a flow of 0.3 g/s with 12 bar of pressure. The test begins by configuring the module in “low power” mode, then in Minimal/QA and finally in GWT/Physics, the higher power consumption mode: upon each configuration a minute is allowed for the module to reach thermal stability, then for three minutes the temperature of each ASIC is recorded and only then the power mode is changed. The time vs temperature vs power mode is sent to the database for further analysing.

7.3.4.7 IV scans

The current drawn by each sensors as a function of the bias voltage is recorded and compared to measurements previously taken at CERN with a probe station. This test allow to measure the breakdown voltage of the sensors and detect possible anomalies, as short circuits or early breakdowns. The test is carried out at 0° C, ramping up the Voltage from 0 to -1000 V, with ramping step of 1 V/s. Each time the voltage is increased some seconds are allowed to let the current stabilise. The scan is taken autonomously with a dedicated interface connected to the HV power supply (Fig. 7.32). The I vs V data is then sent to database.

Ramp-up As final check, and only after Thermal cycling (see next subsection), after each IV scan the temperature was lowered from 0 to -30 C and the voltage

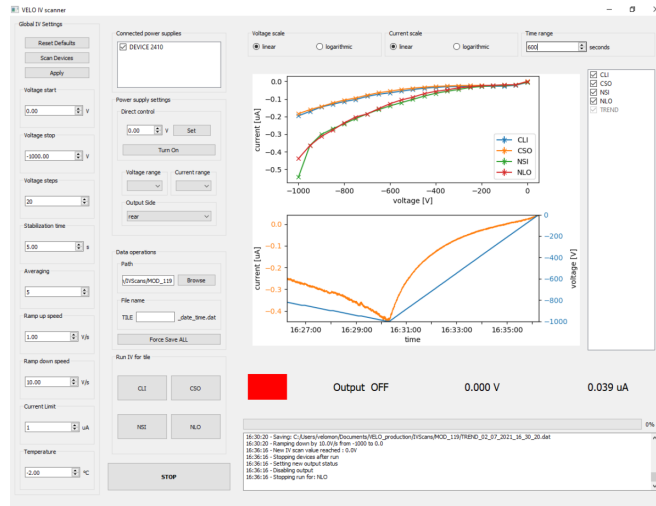


FIGURE 7.32: Interface for the IV scan of the module under test [90].

ramped above the depletion voltage (140 V) to ensure that the leakage current did not show anomalous behaviour.

7.3.4.8 Thermal cycles

Once the first batch of tests is completed, the module is thermally cycled to simulate the cooling and warm up cycles it will be subject to during operation, due to technical interventions on the detector during the technical stops of the accelerator or interventions to the cooling system. Thus, each module is thermal cycled 10 times, where a thermal cycle consists in reaching -30°C from room temperature and slowly warming up again stopping the CO_2 flow to the module. Thermal cycling put the mechanical integrity of the module to the test, in particular the adhesive interface between the tiles and the silicon substrate. Any failure (i.e. partial or total detachment of the tile from the substrate) would result in a abrupt worsening of the thermal performance and increase in electrical noise in the chips due to the lack of proper cooling. The glue layer is aged as well as result of the cycling, offering a first insight on the evolution of the cooling performance later in the life of the detector. During the test the temperature is monitored via the NTCs (Fig. 7.33).

7.3.5 Rinse and repeat

The electrical test described above are repeated in the same order after thermal cycling to compare its impact on the performance of the module. Each test data and results are recorded and sent to database for analysis and comparison with the pre-cycling results.

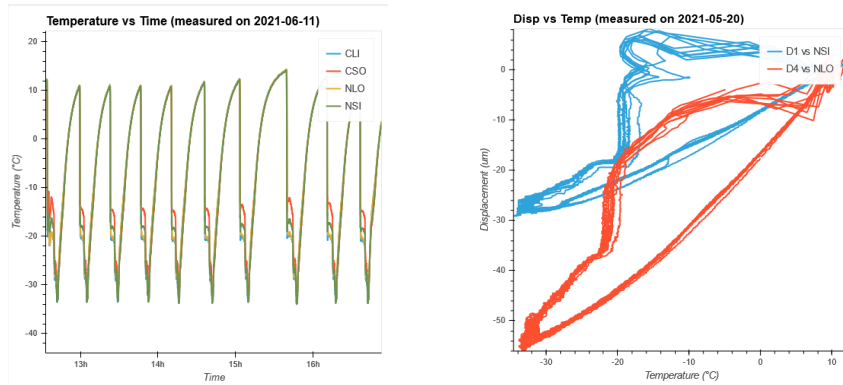


FIGURE 7.33: Left: Typical temperature versus time plot of the thermal cycling procedure. The procedure takes about 5 hours. Right: displacement versus temperature plot for the 10 thermal cycles.

7.3.6 Thermal degradation

Thermal degradation uses data from the bandgap measurement to detect any defects in the glue adhesion, which would be worsened by the mechanical stress induced by the thermal cycling. It compares the thermal performance before and after the 10 cycles and measures the net temperature increase between each ASIC at each power level. Then, it extrapolates this to the nominal 26 W that are expected during operation. The analysis of the before-after thermal cycles is performed in the database, and grading is assigned accordingly.

7.3.7 Summary

The module production campaign has been successfully carried out in the assembly sites of Manchester and Nikhef, with a total production, at the time of the writing, of 64 VELO Upgrade Modules, 59 of which of detector quality. The assembly steps required great precision in the positioning of the sensors not to hinder the detector performance, whereas extreme care was put in the glue layer quality to ensure proper thermal (and thus electrical) performance during its lifetime. Each assembly step has been followed by metrology and grading (discussed in the next section 7.4). After the assembly procedure is completed, modules passing the metrology checks are installed in the validation setup, consisting of a vacuum tank connected to a vacuum pump and a cooling machine to simulate the LHCb environment; a VFB allows to connect the module under test with all the off detector electronics from the OPB to optical fibre cables to a MiniDAQ, reproducing the whole FE and DAQ chain. The validation procedure consists in a series of mechanical and electrical test, which are repeated after 10 consecutive thermal cycles to assess the integrity

and thermal performance of the module. Moreover, the validation procedure ensures the sensors are configurable and able to stream data to the off-detector electronics, which serves as a crosscheck of the full functionality of the FE and GBTx hybrids. Data from each of these tests is uploaded to the VELO Upgrade production database and grading is assigned accordingly.

7.4 Database and grading

The database, a python based PostgreSQL accessed via the Django framework [90], is used to store information regarding each components involved in the assembly of the whole VELO Upgrade detector. A number of sub-projects, listed below, allow to organise and share data efficiently [90]:

- Common: shared objects accessible from the other projects (i.e. institutes, operators, issues etc.).
- Pixel tiles: information regarding VeloPix ASICs bump-bonding, measurements at the probe-station and testing.
- Cooling: data tracking the micro-channel substrate manufacture and testing.
- Electronic components: information regarding cables, VFBs, OPBs, tapes, any electronic parts made and tested before use in the detector assembly or commissioning.
- Modules: here each assembly and testing step and their outcome, as well as possible uncategorised issues of each module is recorded and automatic grading is performed.
- Installation: data regarding the installation of the modules on the VELO bases and the relative performed tests.

This thesis will focus on the Modules portion of the database, specifically on the grading criteria for each of the tests listed in Sec. 7.2 and Sec. 7.3.

7.4.1 Modules project and grading criteria

The modules project collects all the information of all the components used in the assembly campaign, as well as information on the status or grade of each performed stage of the assembly and testing stage; the information is organised

in columns, with a row for each module (Fig. 7.34). The database also allows for the upload of multiple test instances for the same qualification process if this is repeated more than once in time (e.g. multiple IV scans).

The screenshot shows a web interface for a 'Modules' database. At the top, there's a navigation bar with 'Home', 'Modules', and 'Modules'. Below this, a 'Modules' section contains a table with columns for module ID, location, and various test results (A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z). The table lists modules like BMO_120, BMO_119, BMO_118, BMO_117, BMO_116, BMO_115, BMO_114, BMO_113, BMO_112, and BMO_111. Each row shows the status of different tests, with grades (A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z) and a 'Grade' column. The interface also includes a search bar, a filter dropdown, and a 'Show all' link.

FIGURE 7.34: Overview of the Modules project database user interface.

Columns contain the status of the specific test or stage or the corresponding grading with the following convention:

- Letters A-F define the grades.
- Letter P defines “Pending”, e.g. a test yet to be completed.
- Letter M stands for “Multiple” QA tagged test uploaded [90].
- Letter Z stands for not graded.

More precisely, as only one test instance can be tagged as QA, if more than one “QA” tagged instances are uploaded the database alerts the user by assigning the letter M.

Most of the test are automatically graded when the relevant data is uploaded, whereas others, mostly related to the assembly phase and the visual inspections, are graded manually by the operator. The definition of the grades can be summarised as follows:

- A: excellent.
- B: very good.
- C: good.
- D: one missing functionality.
- F: more than one missing functionality.

Test graded from A to C are considered passed, and corresponding modules have full functionality and are suited for installation in the detector. A “D” grade signal a missing functionality generally recoverable (a broken wire-bond that escaped previous checks, a bad tape connector); F grade is assigned to tests with more than one missing functionality. Modules with a test graded D are functioning but their installation is not recommended unless necessary (i.e. a module failing catastrophically that needs replacement) as their operation is not completely under control. Modules with test graded F are not safely operable and are not fit for installation. Finally, the operator can manually override the grade (a module with a failed ASIC can be installed in a low occupancy region); manual grading must always be followed by a comment specifying the reason for the override and the detailed nature of the issue. The grading criteria between the assembly sites is consistent, although the technique used to measure the same quantities are slightly different in some cases because of the different tools available. This thesis will focus on the University of Manchester (UoM) testing techniques and will report only the results for the modules produced in the Manchester assembly campaign.

7.4.1.1 Substrate flatness

The grading is assigned by measuring the flatness of the silicon substrates after the bare module assembly. The flatness is measured at each stage of the micro-channel life, the first one being after the fluidic connector soldering at CERN: here the surface of the micro-channel is optically scanned and a map is obtained. At UoM, the surface is instead laser scanned with the smart-scope. The data is uploaded to the database which automatically fits a plane to the z coordinates with a least-square method; the flatness is then computed at $\Delta Z = z - z_{plane}$ for each x, y value. Outlier measurements corresponding to the 5% of the most distant points are excluded to minimise their effects: these are often caused by scattered or unfocused laser. The result is a map with a violin plot on the side showing the ΔZ , median and quartiles distribution. The plot allows for a fast recognition of cracks, bumps or anomalies on the substrate, which can also be compared with the CERN measurement. Any critical difference can signal a damage incurred during assembly or shipping. Identifying criticalities is crucial to stop the assembly procedure at early stages to save healthy components and avoid failures later in the assembly or worse during the module operation. A direct comparison of CERN and UoM measurements for Module 93 is shown in Fig. 7.35: the flatness difference is due to the stress induced by the carbon fibre midplate anchoring the substrate to the legs and by the holders fixing the bare

module to the the turn-plate; the CERN measurement is done with the micro-channel directly lying on a flat surface, free from any constraints. This amount of distortion is expected and the module does not present any defect. The grading criteria are listed in Table 7.2, they are assigned based on the Q_2 and Q_3 quartile distributions. These have been chosen over the mean and standard deviation due to the biasing effects of the outliers, which are difficult to remove in an automatic process [90]. For the same reason Q_4 is not used as it is influenced by the outliers given by the farthest measured points. The distribution of the ΔZ quartiles across the whole Manchester module production is shown in Fig. 7.36, where inconsistencies due to Q_4 can be spotted, while Q_2 and Q_3 stay consistent. The mean value of ΔZ is around zero.

Grade	Absolute value of Q_2 and Q_3
A	$< 50 \mu\text{m}$
B	$< 75 \mu\text{m}$
C	$< 100 \mu\text{m}$
D	$> 100 \mu\text{m}$
F	-

TABLE 7.2: Micro-channel flatness grading criteria.

7.4.1.2 Tile position

Tile positioning is evaluated by comparing the actual position of the tiles after attachment to their target position. More specifically, the database automatically locates a middle point between the fiducial markers on the corners of the leftmost and rightmost ASICs in a tile, and compares it to a target value to compute the offset (x_{off}, y_{off}) . Then, an angle θ is computed as the angle between the line passing for the target fiducial position and the one for the measured fiducial position (Fig.7.37).

Another variable to keep under control is the distance between the NLO and NSI tiles, being very close together. The grading is then based on the position (given by the offset) and angle of each tile and the distance between the N-side tiles. The grading criteria is described in Table 7.3, with the trend of the position of the offset, angles and N-side tiles distance in Fig. 7.38. As mentioned earlier, the results of the tests were fed back to the positioning step in order to correct for any small offset.

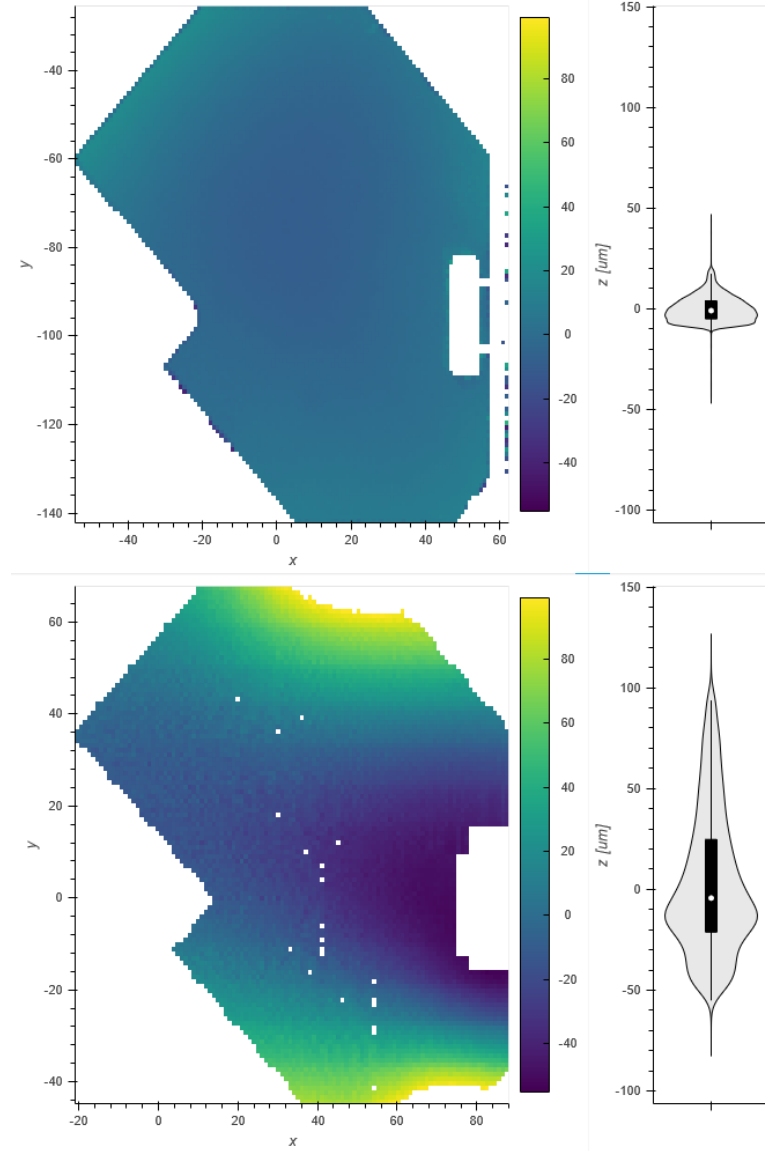


FIGURE 7.35: Comparison of the flatness of the substrates measured at CERN (top) and UoM (bottom) with their violin plots. The distribution of the ΔZ measurements is shown in the violin plot together with the median (white dot) and quartiles (black rectangle for the Q_1 – Q_3 range, black line for Q_0 – Q_1 and Q_3 – Q_4 ranges). The missing part on the substrate on the bottom plot is due to the carbon fibre midplate, which was not present on the micro-channel in the CERN measurement. Other small missing dots are due to laser scattering or mis-focusing of the smart-scope. These outliers points fall in the first and fourth quartile and are excluded from the grading process.

7.4.1.3 Glue thickness

The glue thickness is a crucial parameter that influences the thermal efficiency of the module, thus keeping it under control is paramount to maintain the module quality high. The layer thickness is measured by scanning the micro-channel substrate in the vicinity of the tiles and then scanning the surface of the tiles themselves. A peak finding algorithm uses the overall tile thickness

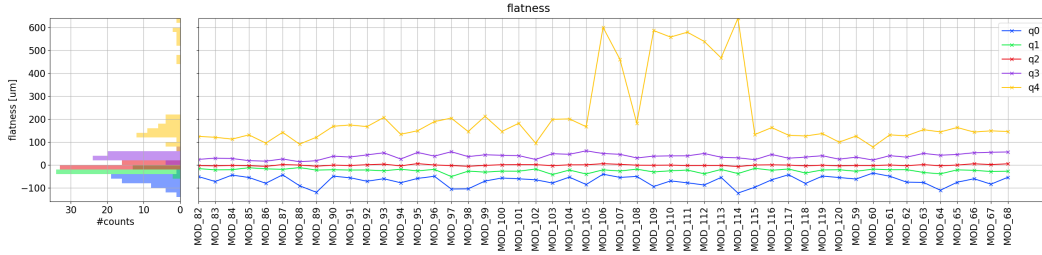


FIGURE 7.36: Distribution of the measured flatness quartiles for the whole Manchester assembly campaign.

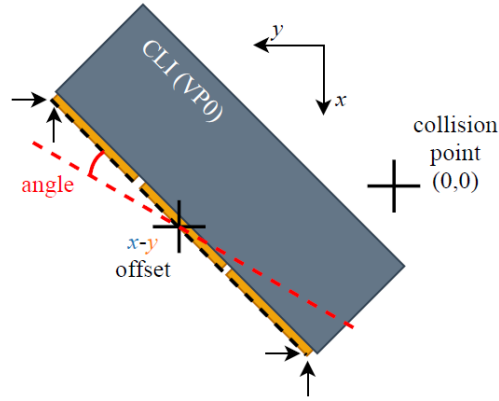


FIGURE 7.37: Visualisation of the computed x_{off}, y_{off} from the target value and θ angle [90].

Grade	Position	Angle	Distance
A	$< 55 \mu\text{m}$	$< 1 \text{ mrad}$	$> 130 \mu\text{m}$
B	$< 110 \mu\text{m}$	$< 2 \text{ mrad}$	$> 100 \mu\text{m}$
C	$> 110 \mu\text{m}$	$> 2 \text{ mrad}$	$> 50 \mu\text{m}$
D	-	-	$< 50 \mu\text{m}$
F	-	-	$< 10 \mu\text{m}$

TABLE 7.3: Tile position grading criteria.

$d = 420 \mu\text{m}$ (sensor + ASIC + bump-bonds) to localise the top surface of each tile, and distinguish it from the substrate. A plane is then fitted with a least-chi squared algorithm to the z values of the substrate (z_s) and tile (z_t). Then the difference between the measured and fitted z coordinate is computed as:

$$\Delta z = z_{meas} - z_t - z_s - d \quad (7.1)$$

The database then produces a x, y map of the Δz values, with a violin plot with mean and σ (Fig. 7.39). The target thickness is between 60 and 100 μm (grading criteria in Table 7.4); lower values are dangerous from a mechanical point of view as the glue layer could not be able to absorb the

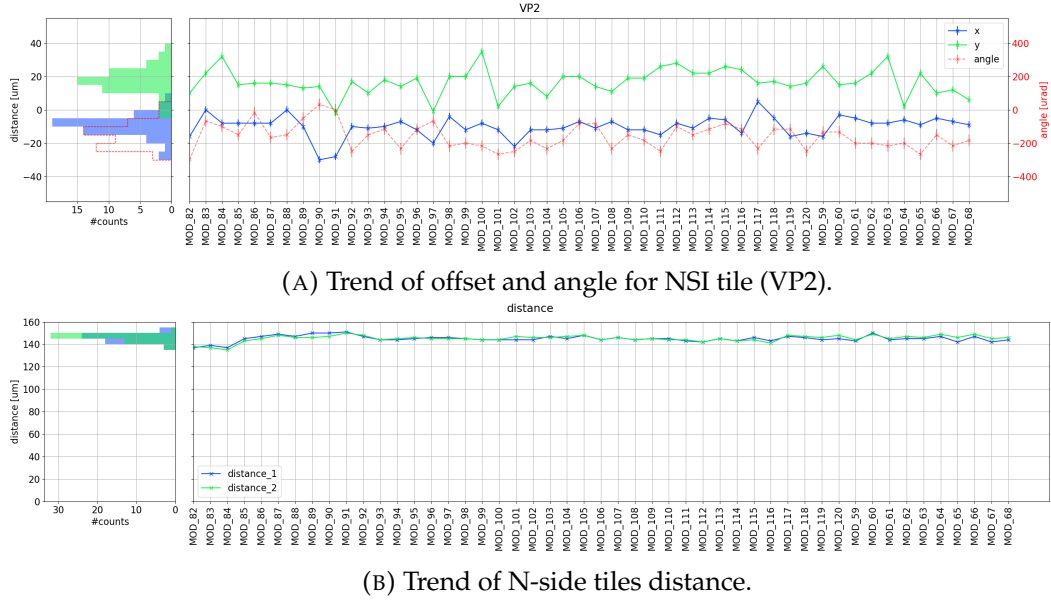


FIGURE 7.38: Trending of the position, angle and N-side tiles distance for the whole Manchester module assembly campaign.

thermal distortion of the components, whereas higher values can impair the heat dissipation capabilities of the module. The slope of the layer is also an important indicator of possible issues: a relatively steep slope can hint to the presence of a contaminant (metal shedding, foreign object or debris) embedded in the adhesive, and thus possibly dangerous for the electronics or the tile and micro-channel integrity. Keeping track of the adhesive layer thickness below each ASIC (automatically recognised by the database from the x, y coordinates transposed in the LHCb system, Fig. 7.41) allows to detect anomalies in the gluing procedure (air bubbles within the glue, needle clogging, glue curing prematurely) that can be accounted and corrected for in the construction of the next module.

Grade	Mean $\pm 2 \sigma$
A	(50 μm , 120 μm)
B	(20 μm , 160 μm)
C	(0 μm , 200 μm)
D	outside
F	-

TABLE 7.4: Glue layer thickness grading criteria.

7.4.1.4 Tile flatness

The tile flatness is computed with the same procedure just discussed, with the exception that this time the Δz is computed as the difference between the

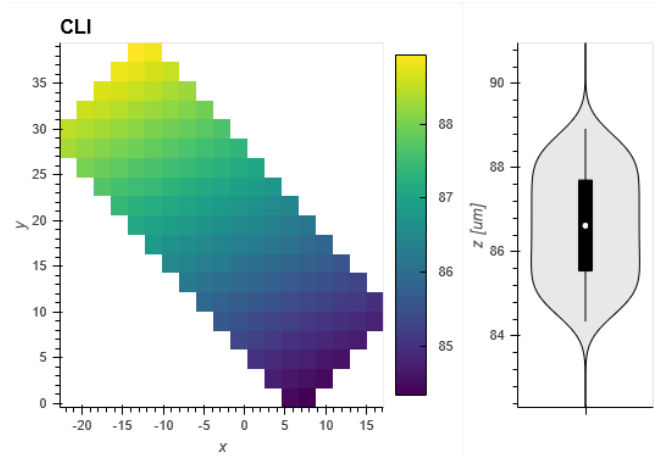


FIGURE 7.39: Glue layer thickness map with violin plot for the CLI tile from Module 117. The distribution of the Z measurements is shown in the violin plot together with the median (white dot) and quartiles (black rectangle for the Q_1 – Q_3 range, black line for Q_0 – Q_1 and Q_3 – Q_4 ranges).

measured (z_{meas}) and the fitted tile plane (z_t) coordinate:

$$\Delta z = z_{meas} - z_t \quad (7.2)$$

A 2D plot is generated accordingly, together with a violin plot with mean and standard deviation (Fig. 7.40). This measurement allows to identify defects or damage on the tile surface, resulting in compromised performance. Figure 7.41 shows the mean tile flatness trend (along with the glue thickness under each ASIC) for the whole Manchester assembly campaign. The flatness grading are reported in Table 7.5.

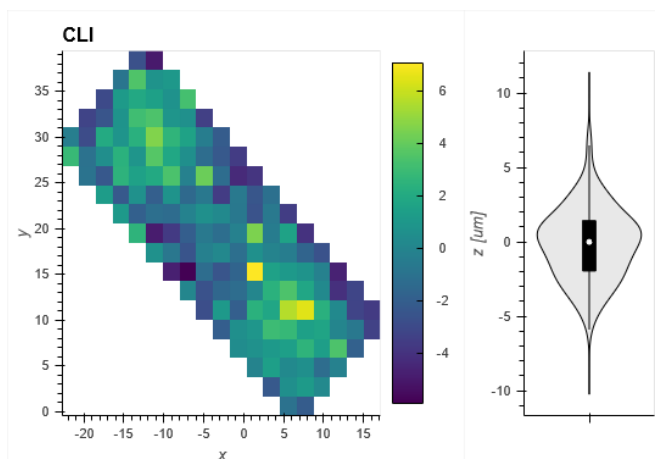
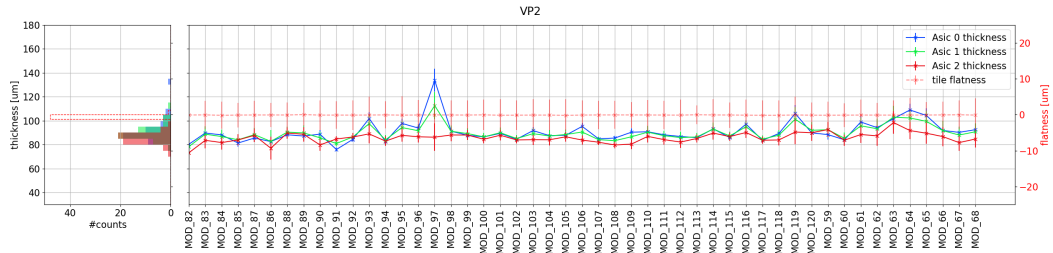


FIGURE 7.40: Tile flatness 2D map with violin plot for the CLI tile from Module 117. The distribution of the Z measurements is shown in the violin plot together with the median (white dot) and quartiles (black rectangle for the Q_1 – Q_3 range, black line for Q_0 – Q_1 and Q_3 – Q_4 ranges)

Grade	Mean $\pm 2\sigma$
A	$< 30\ \mu\text{m}$
B	$< 65\ \mu\text{m}$
C	$< 120\ \mu\text{m}$
D	$> 120\ \mu\text{m}$
F	-

TABLE 7.5: Tile flatness grading criteria.

FIGURE 7.41: Glue layer thickness for for each ASIC for NSI (VP2), with the mean tile flatness shown as well (right side y axis), for the whole Manchester production campaign.

7.4.1.5 Hybrid positioning

Hybrid positioning is manually rated, and pictures of the FE positioning are uploaded anyway as reference. The aim of this check is to make sure there is no spillage of glue between the ASICs and the FE edge, both with Stycast and Loctite, to avoid problems during the wire-bonding e.g. if the glue covers a bond pad. Furthermore, this allow to verify that the tile-FE distance is within the wire-bonding procedure range.

7.4.1.6 Pull testing

Sacrificial bonds (4 per ASIC) are pulled to measure the quality of the bond achieved during the automated procedure. The wire-bonds are individually pulled and the breakage strength recorded. All the wires are pulled before the thermal cycling as it was observed that it had no impact on the recorded strength. Furthermore, as the pull test is performed on the pull tester, pulling the bonds after thermal cycling would have meant an additional transfer of the module to a different frame, putting unnecessary stress on the delicate components. The grading criteria are listed in Table 7.6: ideally the breakage strength for all the bonds should be higher than 5 g.

The trend (Fig. 7.42) of the recorded breakage force is used to monitor the quality of the bond and check for possible failures during the bonding procedure if the tested module had a sub-standard performance.

Grade	Pull force weight
A	> 5 g or at most 2 between 4 g and 5 g
B	< 4 g or more than 2 lower than 5 g
C	-
D	< 2 g
F	-

TABLE 7.6: Pull test grading criteria.

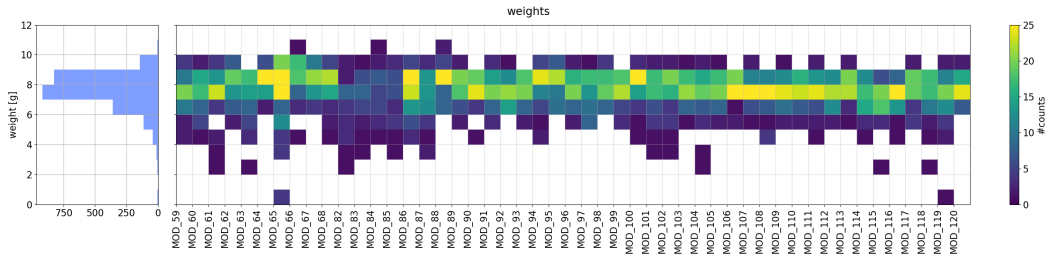


FIGURE 7.42: Trend of the pull force needed to break each sacrificial wirebond for each ASIC throughout the Manchester assembly campaign.

7.4.1.7 Photo inspection

The photo inspection is manually graded. Usually a A grade is assigned if everything is in order.

7.4.1.8 Mechanical tests

The VCR tightening, pump down and cool down displacement are graded to check the module z position variation; the data contains the tile distance from the capacitive sensors, time and NTC values for all the tiles. The VCR tightening test is graded based on the position of the module before and after the pipes connection, which is an indicator of the pull force exerted on the module. The pump and cool down maximum displacement values are used instead to grade these tests, as they will give an indication of how the module will move on the z coordinate, which is difficult to access through the standard alignment procedure, once installed in the full detector. The grading criteria for all the three tests are reported in Tables 7.7, 7.8 and 7.9, whereas the trend of the maximal displacement measured by the sensors during cool-down for the whole assembly campaign is shown in Fig. 7.43.

7.4.1.9 Communication test

The first communication test, performed warm and in air, is aimed to check that all the key information of the chips are correctly shown (ID, temperature, internal voltages, bandgap voltage). The grading is based on internal analogue

Grade	Displacement
A	< 50 μm
B	< 80 μm
C	< 100 μm
D	> 100 μm
F	-

TABLE 7.7: Grading criteria for VCR-tightening displacement.

Grade	Maximum displacement
A	< 50 μm
B	< 80 μm
C	< 100 μm
D	> 100 μm
F	-

TABLE 7.8: Grading criteria for pump down displacement.

Grade	Maximum displacement
A	< 50 μm
B	< 80 μm
C	< 100 μm
D	> 100 μm
F	-

TABLE 7.9: Cool down displacement criteria.

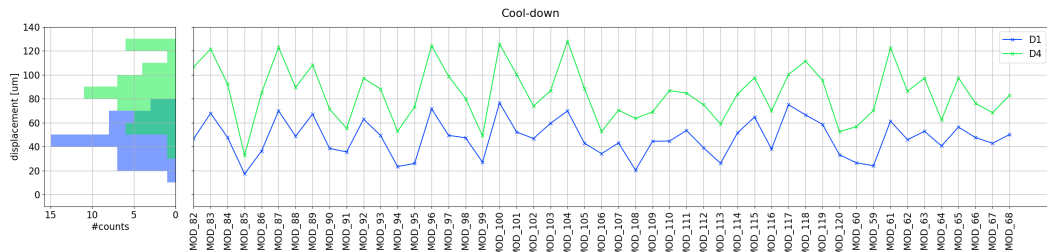


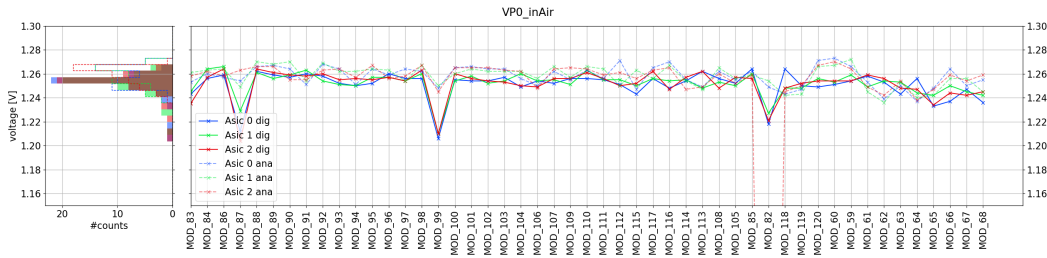
FIGURE 7.43: Trend of the displacement as registered by the capacitive sensors during the cool down procedure. The plot includes all modules built during the Manchester assembly campaign.

and digital voltage read-back from the ASICs. The snapshotted values are uploaded to database and the mean value for each ASIC computed. Since this test can be carried out both cold and warm and before and after thermal cycling, it offers precious information regarding the impact of temperature on the modules performance. Ideally, all the voltages should be over 1.20 V, although the minimum working voltage for the chips is 1.18 V; a higher voltage offers a safety margin during operation. The detailed grading is shown in Table 7.10; the operation voltages of CLI as a function of module number are shown in Fig. 7.44: an improvement of the performance with lower temperatures can

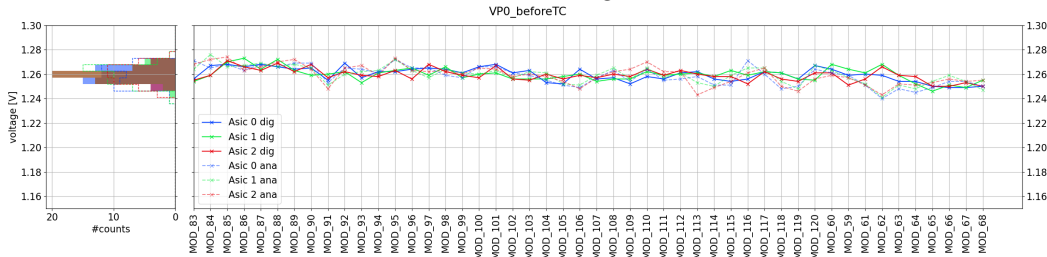
be observed, as well as no noticeable degradation after thermal cycling. Only on Module 101 the internal voltages were lost after the cycles, causing the loss of information regarding the tile NTC as well: since no information regarding the tile temperature is available, if the module was to be used (it has not been installed in the final VELO Upgrade detector), it would be advisable to position it in a low fluence region to avoid unmonitored temperature rises.

Grade	Analog and digital voltages
A	> 1.20 V
B	> 1.18 V
C	< 1.18 V
D	One missing
F	Multiple missing

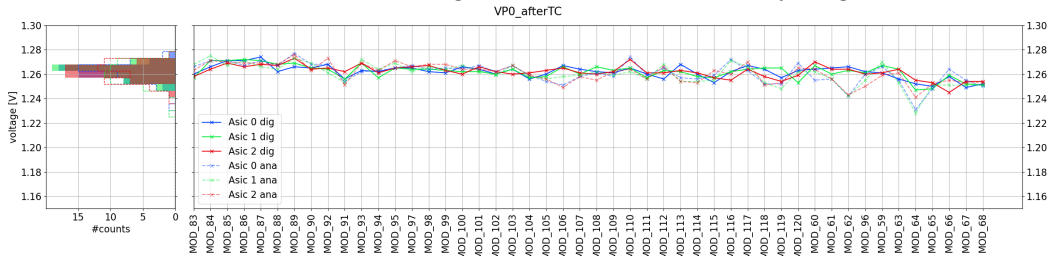
TABLE 7.10: Grading criteria for communication in air.



(A) Internal voltages in air.



(B) Internal voltages, -30° C, before thermal cycling.



(C) Internal voltages, -30° C, after thermal cycling.

FIGURE 7.44: Internal voltages (analogue and digital) of the CLI tile of Manchester built modules. On top: voltages read during the quick communication in air. In the middle: voltages when cold, under vacuum, before thermal cycling. On the bottom: voltages when cold, under vacuum, after thermal cycling.

7.4.1.10 TFC

The TFC test is a pass/non pass test, where the operator checks that all the signals sent were received. If any of these is missing, it means that communication with the chips is not fully functional, thus synchronisation and control is partially or completely impossible. An unresponsive ASIC cannot be used in the experiment, yet the rest of the module can still operate normally even with one chip turned off, albeit with lower performance. The grading is shown in Table 7.11, with the trend of all the tests done during the assembly campaign shown in Fig. 7.45. Only one ASIC had suffered TFC issues across the 57 modules shown in this picture.

Grade	Result
A	All ok
B	-
C	-
D	one missing
F	multiple missing

TABLE 7.11: TFC test grading criteria.

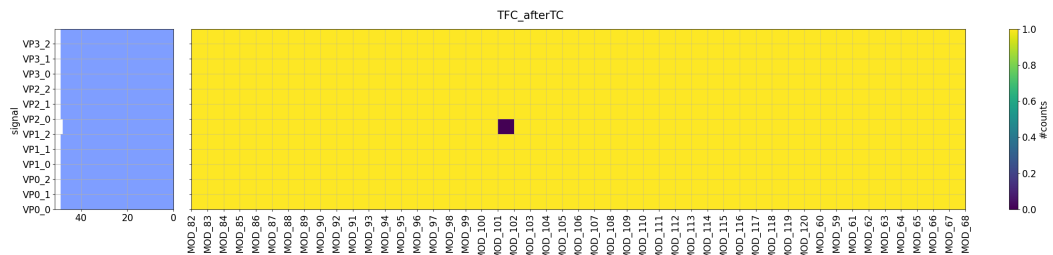


FIGURE 7.45: TFC response after thermal cycling trend for Manchester assembled modules. Note that one ASIC (NLO, ASIC 2) is missing due to lack of communications after cooling down the module.

7.4.1.11 PRBS

As the PRBS test is meant to evaluate the quality of the data transmission, the grading is based on the number of errors in the strings that are sent to the MiniDAQ from the chips. A stream of 1×10^{12} bits are sent through each link, the number of errors registered and uploaded to database, which computes the Bit Error rate (BER, Fig. 7.46). During the production campaign some links have shown to be more noisy, specifically 4, 6 and 13, regardless of the module under test; on the other hand most of the links did not show any error (Fig. 7.47). Generally speaking, the results of the PRBS test have been influenced

by environmental factors as relative humidity and temperature in the clean room, which are thought to have influenced the behaviour of the VTRx and VTTx on the OPB. Furthermore, the GBT server on the MiniDAQ has proven to be prone to instability, leading to high number of errors ($O(10^{10})$) distributed on several links. This issue has been partially solved by always restarting the server before executing the test. To take all these factors into account, the grading (Table 7.12) is based on both the worst single and worse half of the links.

Grade	BER of links	BER of more than half links
A	$< 1 \cdot 10^{-11}$	$< 1 \cdot 10^{-12}$
B	$< 1 \cdot 10^{-10}$	$< 1 \cdot 10^{-11}$
C	$> 1 \cdot 10^{-10}$	$> 1 \cdot 10^{-11}$
D	one missing	
F	multiple missing	

TABLE 7.12: Grading criteria for the PRBS test.

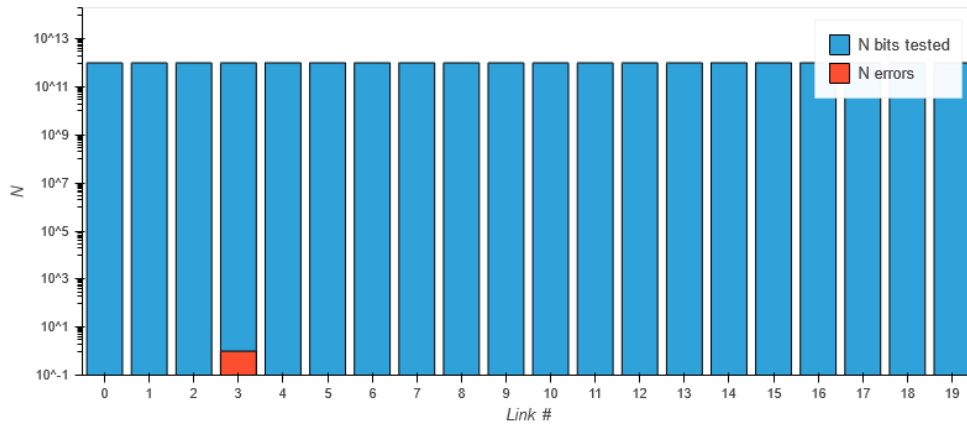


FIGURE 7.46: PRBS BER test result for Module 117 before thermal cycling. Only one error is recorded on link 3.

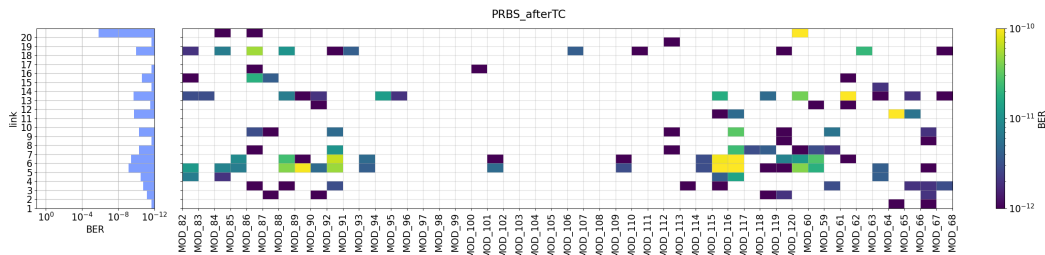


FIGURE 7.47: PRBS test BER after thermal cycling for Manchester built modules.

7.4.1.12 Noise and equalisation

The equalisation test is graded considering both the noise of the pixels and the amount of masked pixels. During the test, the DAC threshold of each pixel is changed and the number of pixel firing recorded at each step. This is done for two DAC offsets: Trim0 and TrimF. This data is uploaded to the database which creates a histogram with the two aforementioned distributions (Fig. 7.48), along with the target DAC settings for each pixels. These are computed taking into account a linear dependency between the various trim levels (16, from 0 to F, with 12.5 DAC counts between each trim level). At the end of the equalisation process, all pixels should be equalised in such a way that their DAC threshold lies in a narrow region between the Trim0 and TrimF curves.

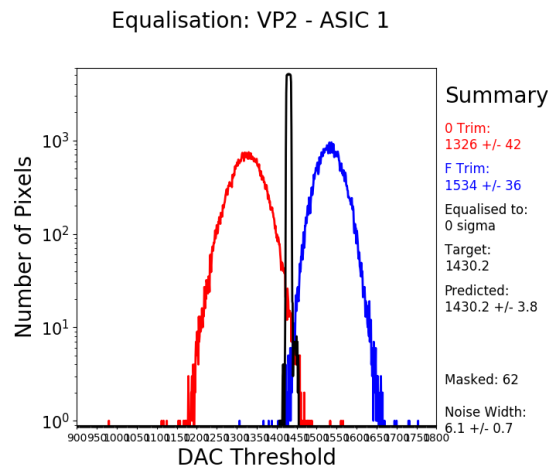


FIGURE 7.48: Equalisation of the pixel response of the NSI VP2 chip in module 84, before thermal cycling. In red the Trim0 curve, in blue the TrimF curve, in black the equalised pixel response.

A 2D noise map is produced as well (Fig. 7.49) which should not contain any visible pattern. Pixels that are too noisy, unresponsive, or not possible to equalise are automatically masked. The number and category of the masked pixels are displayed in a dedicated report with the following categorisation:

- A: dead pixel.
- B: unresponsive to Trim-0.
- C: unresponsive to Trim-F.
- D: could no be equalised.
- E: noise too large.

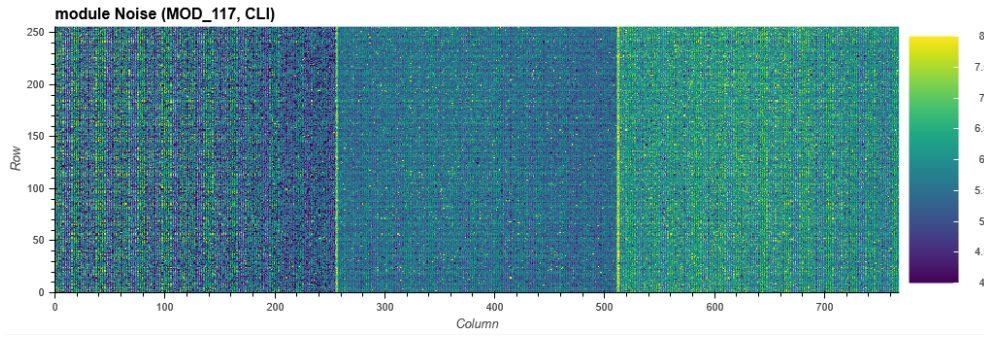


FIGURE 7.49: 2D noise maps for the CLI tile in module 117, before thermal cycling.

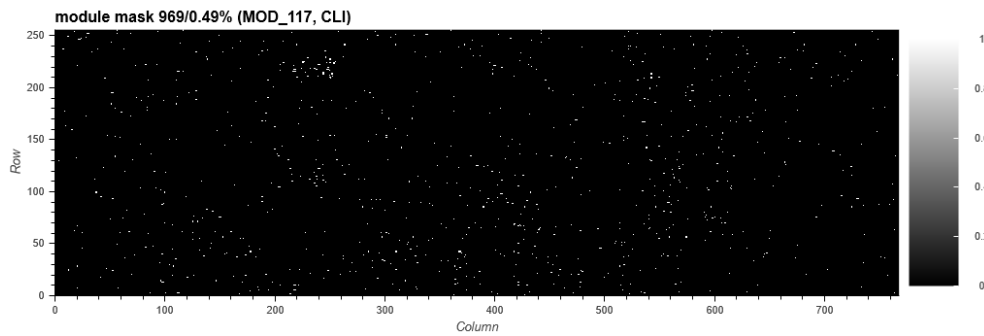


FIGURE 7.50: Map of the masked pixels for the CLI tile of module 117. In black the non-masked pixels, in white the masked ones.

A mask map (Fig. 7.50) is then generated showing the number, percentage and position of the masked pixels.

To compare the results with the noise scan taken during probe-testing the wafer and the tile, a histogram with the noise distribution of the pixel is created, showing the average value and standard deviation (Fig. 7.51). Noise is a key parameter in defining pixels response to signal, as to ensure correct functioning of the detector the thermal noise should be greatly lower than the typical MIP signal. Specifically, for a VeloPix chip:

$$1DAC \simeq 15e - h\text{pairs}, \quad (7.3)$$

meaning an average value of 6 DAC equates to 90 e-h pairs. A MIP creates an average of 16,000 pairs in a $200\mu\text{m}$ thick silicon sensor, creating a broad safety margin even with the buildup of radiation damage. The trends of the average noise and masked pixels for NSI are shown in Fig. 7.52, whereas the grading criteria are listed in Table 7.13. It was observed during the assembly campaign that keeping the BXID (bunch crossing) counter on during the equalisation led to increased noise in the tiles: the equalisation and noise test are thus repeated twice, one with BXID on and one with the counter off; this is done both before

Grade	% of tile masked	% of ASIC masked	noise	noise σ
A	< 1 %	< 5 %	-	-
B	< 5 %	-	-	-
C	> 5 %	-	-	-
D	-	-	>8	>2
F	-	-	-	-

TABLE 7.13: Noise and equalisation grading criteria.

and after thermal cycling.

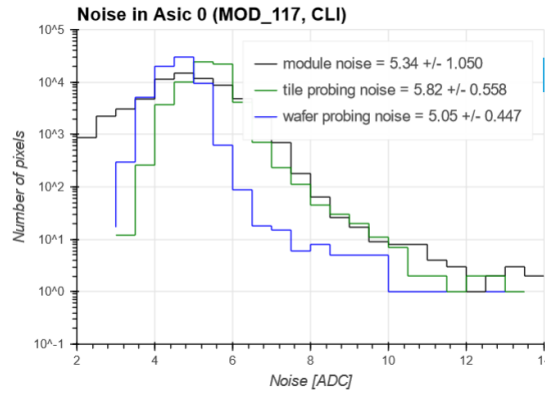


FIGURE 7.51: Pixel noise distribution for CLI ASIC 0 in module 117, along the same distribution from the wafer and tile probing stages.

7.4.1.13 Bandgap

The bandgap measurements are meant to check the cooling efficiency of the heat dissipation, related to the thickness and quality of the glue layer, at different power configuration of the modules. During the test the NTC temperatures of the tiles are recorded, as well as the LV power supply current output with time stamp. In addition, the WinCC panel logs the FE hybrids voltages, the bandgap temperatures, and a power-mode identifier. These data is uploaded to the database, which automatically locates the correct times when each power mode was engaged and produces the following plots (Fig. 7.53):

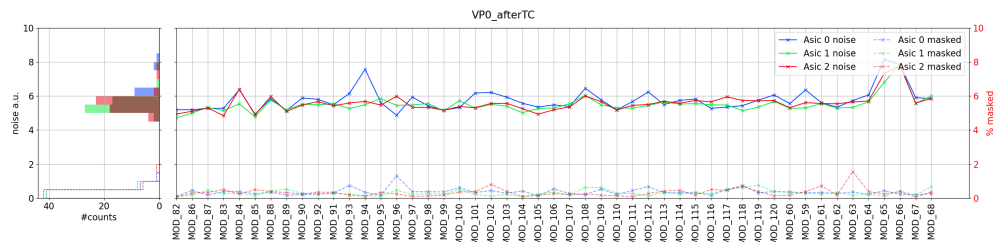


FIGURE 7.52: Noise trend for CLI (VP0) after thermal cycling. On the right-hand y axis the percentage of masked pixels is shown.

- NTC temperature trend, one for each tile.
- Bandgap measurement trend, one for each ASIC.
- Low voltage currents, both analog and digital.

These, which are generated with vertical bars to identify the time period of each power-mode measurement (red for the start, black for the end), are used to produce a delta temperature vs power consumption plot (Fig. 7.54), with a point corresponding to each power mode, with a fitted straight line for each ASIC plus the NTC. The temperature difference is computed subtracting the offset found with the linear fit from the NTC and chips data. The ΔT is used instead of the absolute temperature as the test is aimed at the evaluation of the thermal performance, i.e. the heat removal efficiency as function of power dissipation. The linear fit is extrapolated then at 26 W to evaluate the cooling efficiency at the maximum power consumption expected in non-irradiated sensors. A single plot is generated for each tile.

The first three plots can be used to identify macroscopic problems as temperature or current instabilities. The value of the NTC temperature closest to each chip is subtracted from each ASIC (Fig. 7.55) as follows [90]:

$$\Delta < T'_{VP_{0,1}} = VP_{0,1} - NTC_0, \quad (7.4)$$

$$\Delta T'_{VP_{2,3}} = VP_{2,3} - NTC_2. \quad (7.5)$$

This value, computed at 26 W, is used to determine (Table 7.14) the grading of the module. The trend of the cooling performance for NLO before thermal cycling is shown in Fig. 7.56.

Grade	ΔT at 26 W
A	$< 8^\circ \text{C}$
B	$< 10^\circ \text{C}$
C	$> 10^\circ \text{C}$
D	Missing data
F	-

TABLE 7.14: Grading criteria for the bandgap measurement.

7.4.1.14 Thermal degradation

The thermal degradation test measures the worsening of thermal performance after the thermal cycling of the module. The database compares two bandgap

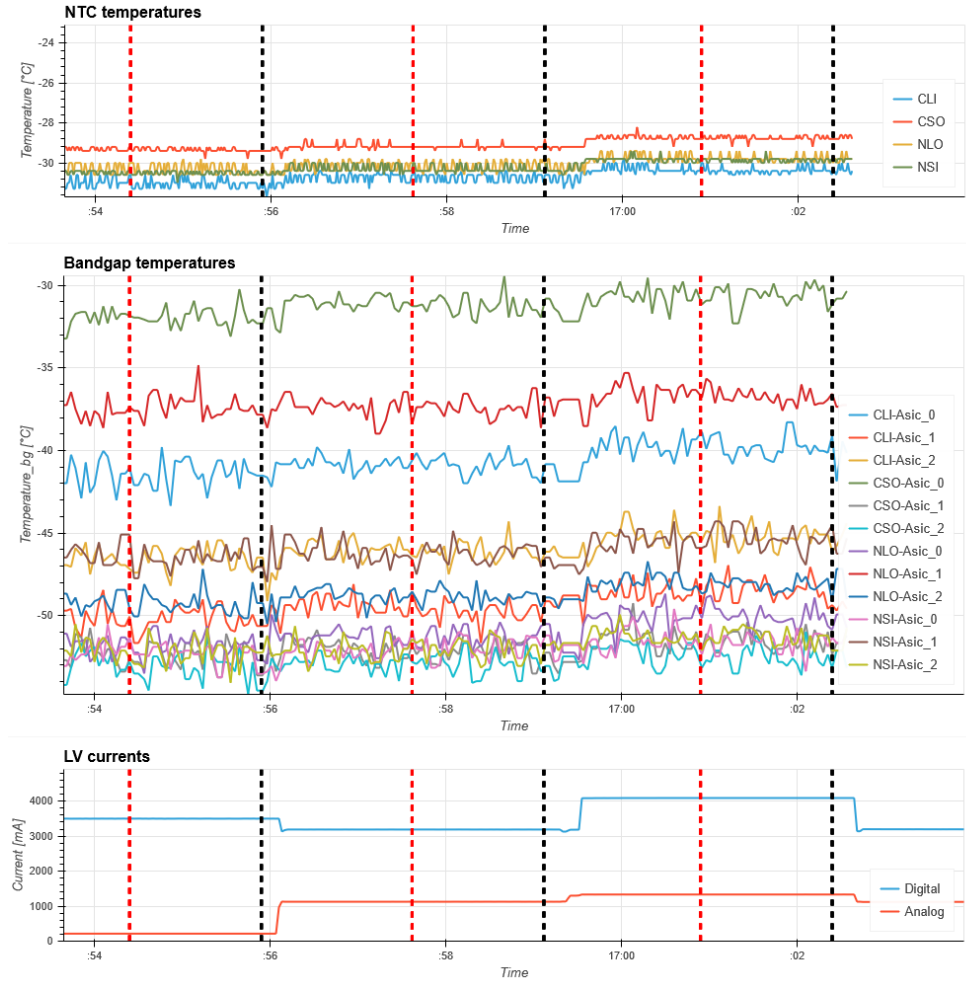


FIGURE 7.53: NTC temperatures (top), Bandgap temperatures (middle) and LV currents (bottom) as function of time during the cooling performance test for Module 117. Test performed after thermal cycling.

measurements, with the optional parameter of the glue thickness, to produce a “ $\Delta\Delta T$ ” vs glue thickness plot (Fig. 7.57), showing the variation of cooling performance (thermal degradation) as function of the glue layer thickness under each ASIC of the module. No detectable performance degradation due to the thermal cycling can be assessed, nor is any glue related effect. This is more clear in Fig. 7.58, which contains all the data from each module: the Gaussian distributions on the left side of the plot is centred on zero, with $\Delta\Delta T$ s ranging from negative to positive values. Since, as just mentioned, the thermal degradation ranges from negative to positive values, the mean and maximum absolute values are used to assign a grade. The grading scheme is shown in Table 7.15.

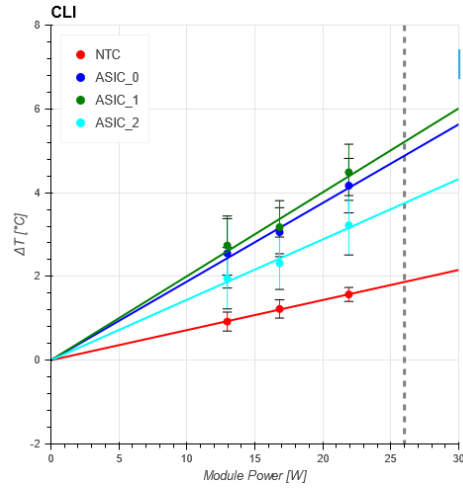


FIGURE 7.54: ΔT as function of power consumption for the CLI tile for Module 117, after thermal cycling. The colour coding for the NTC and single chips are specified on the plot. The dotted line represents the 26 W power consumption mark.

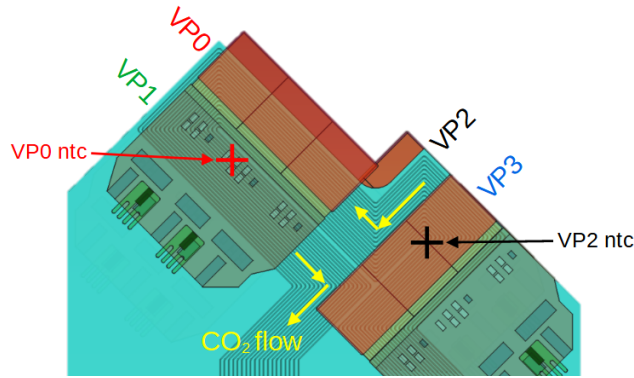


FIGURE 7.55: Schematic representation of the NTCs position on the tiles.

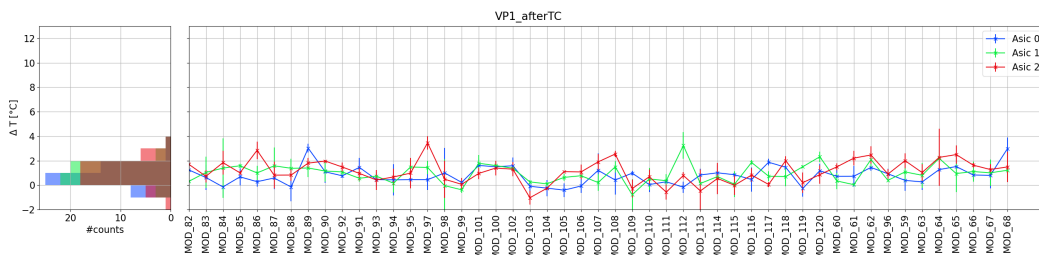


FIGURE 7.56: Cooling performance trend for NLO after thermal cycling for the whole Manchester assembly campaign.

7.4.1.15 IV curves

The IV curves are used to determine how the silicon sensors would respond to bias voltage after installation. The current vs voltage data stored by the HV python script [90] are uploaded to the database, which compares them to previous measurements taken at CERN with the probe-station. Ideally, the curves should be similar to those taken at CERN, yet some discrepancies are

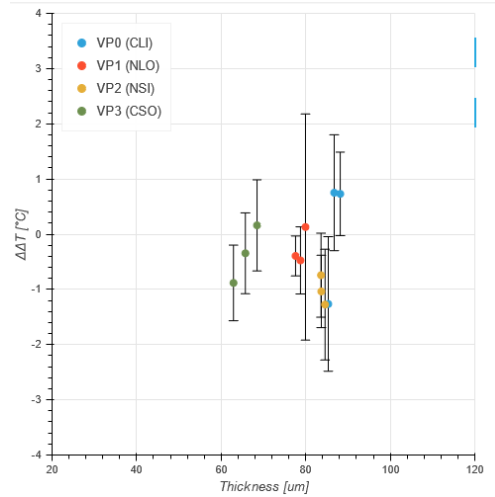


FIGURE 7.57: Thermal degradation ($\Delta\Delta T$) of the CLI tile cooling performance for Module 117 as function of glue thickness. Each dot represents a chip within the tile. No performance degradation is observed.

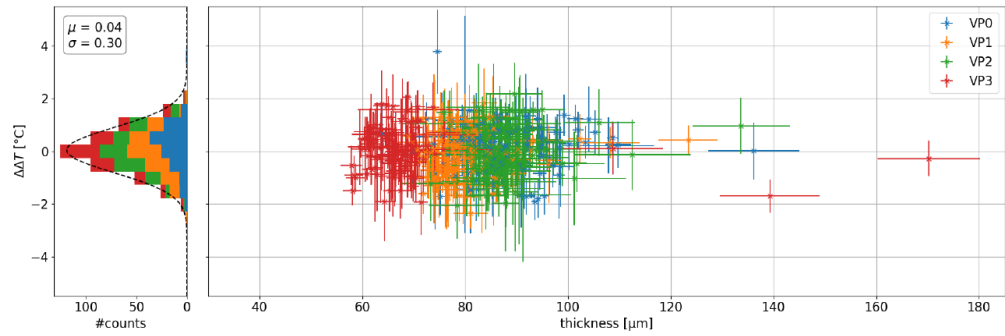


FIGURE 7.58: Thermal degradation ($\Delta\Delta T$) as function of glue thickness. Each dot represents a chip within a the tile. No performance degradation is observed. Plot reproduced from [90].

Grade	Mean	Maximum
A	$< 1^\circ \text{C}$	-
B	$> 1^\circ \text{C}$	-
C	-	-
D	-	$> 5^\circ \text{C}$
F	$> 5^\circ \text{C}$	-

TABLE 7.15: Thermal degradation test grading criteria.

to be expected due to the different setup. Specifically, measurements at CERN are taken at 20°C whereas at UoM at 0°C , which is the highest temperature the cooling machine can achieve in a stable configuration. The tiles are affected by the module and validation setup wiring and connections: the HV tape contains a capacitor and is attached to a further connector at the VFB; none of this is present on the probe station. To assign a grade (Table 7.16) the curves

are compared to the probe station measurements performed at CERN, both before and after Thermal cycling, and if a worsening has taken place after the module assembly the behaviour of the current for voltages higher than 140 V (full depletion voltage) is taken into account to assign a grade.

The IV curves for the NSI tile are shown as an example in Fig. 7.59: most of the curves (in green) are in line with the probe station measurements, whereas few others (black and orange) show a slightly degraded behaviour. In one case the tile is not usable (in red) as result of damage.

Grade	Curve
A	< high quality
B	< good quality
C	< good quality below 140 V
D	> good quality below 140 V
F	-

TABLE 7.16: IV curve grading criteria.

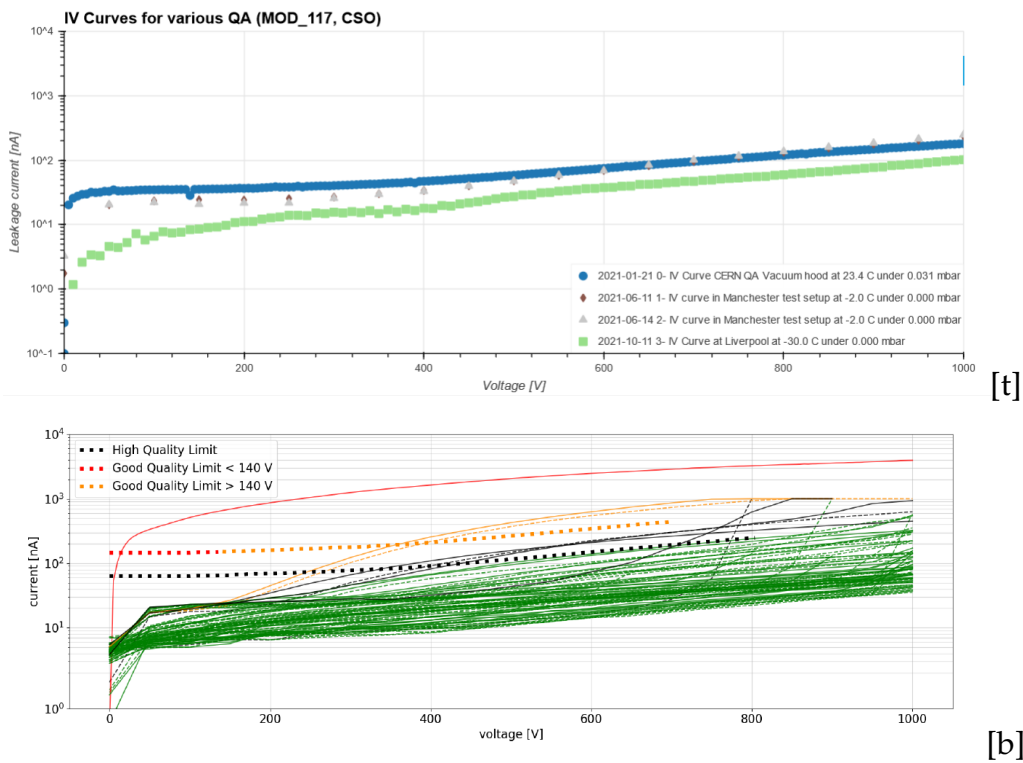


FIGURE 7.59: Top: IV curves for the NSI tile in Module 117 after thermal cycling. Bottom: NSI IV curves for the Manchester produced modules [90]; the straight lines represent the quality limits of the curves used to assign a grading [35].

Finally, in some occasion an improvement of the IV performance has been observed after thermal cycling, after being in vacuum for a prolonged time thus suggesting a humidity related effect.

Ramp-up The ramp-up test serves as a quick crosscheck that the tile can be safely biased at high voltages at the operation temperature of -30°C . Thus, the grade is assigned based on the voltage for which the tile hits the $1\text{ }\mu\text{A}$ leakage current. The test requires the same data as the IV scans. The grading criteria for this test are summed up in Table 7.17.

Grade	Lowest voltage before $1\text{ }\mu\text{A}$
A	$> 700\text{ V}$
B	$< 700\text{ V}$
C	-
D	-
F	$< 250\text{ V}$

TABLE 7.17: Grading criteria for the ramp-up test.

The trend of all the test results for the CSO tile are shown in Fig. 7.60.

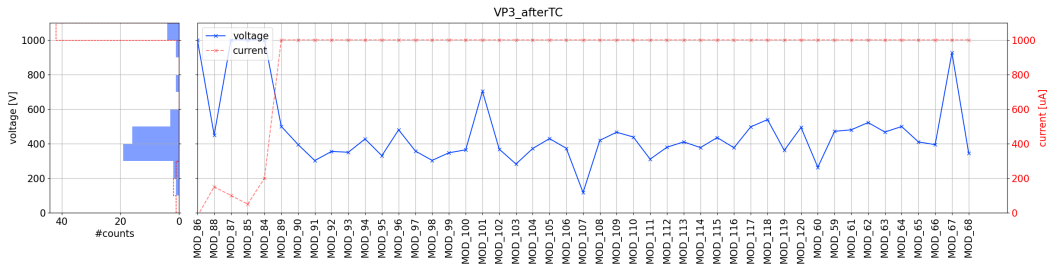


FIGURE 7.60: CSO ramp test results for the Manchester assembled modules.

7.4.2 Complete module grading criteria

The Modules are assigned an overall grading and quality number at the end of the validation process. Two metrics are used to give a better insight on the overall build quality and performance, and to make an informed choice when deciding the position of each module in the full detector: the best modules will be positioned near the interaction zone.

7.4.2.1 Grading

The lowest grade obtained during the assembly and validation tests is used to grade the modules. If a D or F grade has been obtained in any of the tests, the module will automatically be graded accordingly: this indicates either 1 missing functionality (1 missing link, a faulty ASIC, etc.) for grade D or more than one missing functionality for grade F. Modules which tests have not registered any D or F are graded B or C if they have obtained such grades more than two times,

else they are marked one grade higher. The only exceptions to this rule are the PRBS test and the IV test; the PRBS and IV tests were significantly impacted by environmental conditions (e.g. ambient humidity, not controllable in the testing clean rooms) and the specific test setup, therefore looser limits were imposed. The modules grading system offers a quick way to assess the quality of the modules and mostly allows to distinguish non detector grade modules from those that can be safely installed, yet its low granularity does not allow to distinguish perfectly functioning modules from high quality ones. The final number of yield for each grade for both assembly sites is shown in Table 7.18.

Grade	A	B	C	D	F
Modules	24	29	6	3	2

TABLE 7.18: Overall grades for all modules produced and tested in Manchester and Nikhef.

7.4.2.2 Quality number

To complement the grading described above with a finer granularity information, the quality number has been introduced as a weighted criteria ranging from 0 to 100 taking into account the results from all the testing steps from assembly to validation. The weighting is summarised in Table 7.19.

Grade	A	B	C	D	F
Weight	25	15	0	-50	-250

TABLE 7.19: Weighting criteria for the quality number calculation.

To account for the relative importance of the various assembly and validation procedures that take place during the construction of a module, different ratios are used for different stages of the building process [90]:

- Processes, i.e. assembly steps: ratio 20.
- Metrology, i.e. metrology, thermal cycling and degradation tests: ratio 30.
- Electrical, i.e. electrical tests before and after thermal cycling: ratio 50.

The final quality number is then defined combining the weighted sum of the grades and the aforementioned ratios.

The trends for each category and the total quality number is shown in Fig. 7.61, while the grading combined with the quality information is shown in Fig. 7.62.

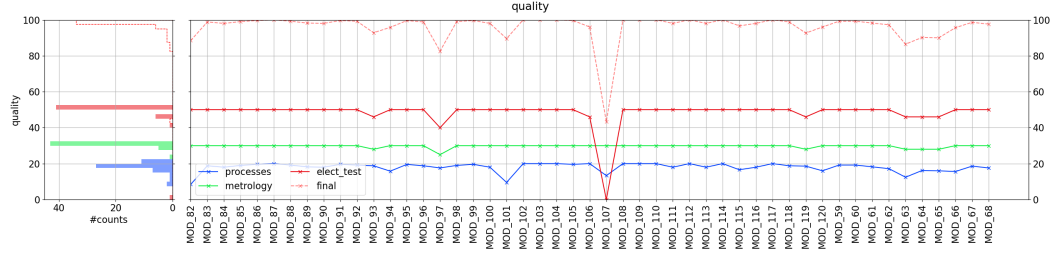
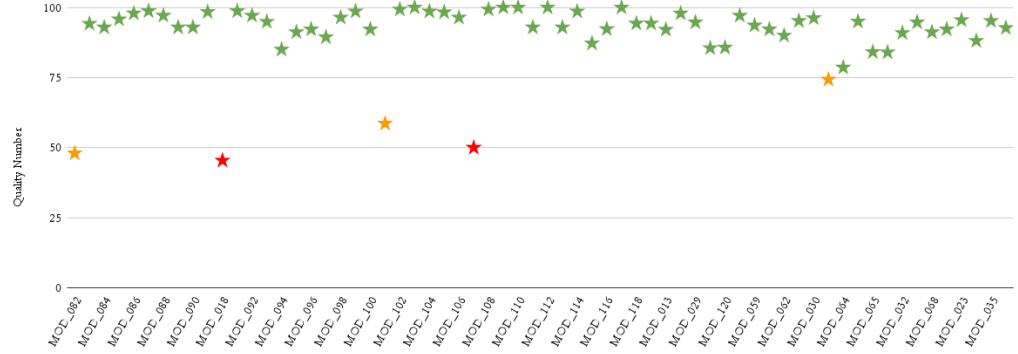


FIGURE 7.61: Quality number trend for the Manchester assembly campaign.

FIGURE 7.62: Final grading for the assembly campaign. A, B and C grade modules are shown in green and represent detector grade modules. D grade modules are in yellow, F grade modules in red. On the x axis only half of the labels are reported.

7.4.3 Summary

The database is a fundamental tool that allows to register and keep track of the outcome of each test performed during the construction of each module. A set of criteria has been developed to assess the performance of the outcome of each assembly and validation step, while a twofold strategy has been used to uniquely identify the quality of finished modules. The total yield of the assembly campaign is 59 (46 at UoM) detector grade modules (A-B-C grade), out of 64 built (49 at UoM), for a yield $> 93\%$, at the end of the VELO Upgrade module production campaign.

7.5 Summary

The module assembly campaign has been successfully completed in August 2022 with 64 completed modules by the two construction sites, with 59 of these to be detector grade. Each modules has been built following optimised checklists to ensure high consistency of each assembly step, each of these being followed by careful metrology and real time grading of the results to swiftly individuate possible mistakes or biases in the procedures. The validation setup

has been a crucial element in the assessment of the quality of build modules, allowing to check the modules behaviour with vacuum, cooling, and power consumption conditions similar to operation conditions. All modules have been thus tested before and after being thermally cycled to ensure their electrical, thermal and communication performance are up to the required standards. In this scope, the availability of a database has been crucial to monitor the outcome of every test and produce a grading capable of summarising the performance of all built modules. All these elements contributed to the successful production of more than the 52 required VELO Upgrade modules, with a yield greater than 93%.

Chapter 8

Glue Studies

8.1 Introduction

The VELO Upgrade modules are expected to receive, during the lifetime of the detector, an estimated fluence of $10^{16} \text{ 1 MeV n}_{\text{eq}} \text{ cm}^{-2}$ [3] (around 400 MRad [111]) in the the innermost sensors, which will result in leakage currents at 1000 V of around $200 \mu\text{A}/\text{cm}^2$. As explained in Sec. 6 each VeloPix ASIC is expected to produce around 2 W of heat, with an additional 1 W produced in the innermost sensors, for a total of up to 7 W for each tile. As VELO modules operate in vacuum, the only interface available for heat dissipation is the adhesive layer attaching the VeloPix chips to the silicon substrate. Thus, the glue layer plays a crucial role in keeping the tile temperature under control and avoid thermal runaway. Specifically, it has to ensure the sensor and ASICs assembly is consistently below -20°C at operation conditions, with a $\Delta T < 8^\circ \text{C}$ between the hottest tip of the sensor and the coolant flowing underneath.

To ensure adequate cooling performance the adhesive must then satisfy a number of key parameters:

- excellent thermal conductivity.
- CTE close to silicon to minimise stress due to temperature variations.
- Radiation hardness to withstand fluence of the order of $10^{16} \text{ 1 MeV n}_{\text{eq}} \text{ cm}^{-2}$.
- Good ageing properties to retain mechanical properties during the whole life of the detector.

The glue layer has to be optimised as well to achieve the best compromise between adhesive strength, mechanical soundness and heat dissipation. A thin glue layer may be desirable to improve thermal efficiency, with the drawback

of less thermal dilatation absorption capacity, which in extreme cases may lead to the detachment of the tile after reiterated tensile stress induced by the many power cycles of the ASICs during operation. On the other hand, the glue interface cannot be too thick not to hinder the cooling of the tile. Evenness of the glue layer is also a paramount parameter to ensure even heat dissipation; for this same reason the glue should also cover at least 70% of each ASIC.

The optimisation studies reported in the following describe the R&D campaign launched in 2019 after a failure with the assembly glue (Stycast 2850 FT with catalyst 9) was detected in one of modules built in the early stages of the production campaign. Efforts were thus redirected into both tracing the origin of the failure to solve it (this effort was carried out at Nikhef) and finding a suitable alternative adhesive (these studies were led by the University of Manchester). It should be noted that the priority was the solution of the production glue issues due to the amount of experience already developed with this adhesive.

To optimise the glue layer parameters and assess the evolution of its mechanical properties, an intense R&D effort (described in Sec. 8.2.2), followed by a shear force test campaign (explained in Sec. 8.3), has been carried out. The pattern shape has been optimised after trying different shapes to alleviate a number of issues emerged during the first instances of R&D. Specifically, any air trapping inside the glue patterns is undesirable, as trapped air would significantly expand under vacuum and heat, subjecting the tiles to additional stress. Furthermore, it was observed during the prototyping phase that any glue between the ASICs increases the capacitance of the system increasing the electronic noise, so any glue spillage filling the space between the ASICs must be avoided.

The glue originally selected for the VELO Upgrade module assembly campaign was Stycast 2850 FT with catalyst 9, which was later matched with a different catalyst in the early stages of the production because of the partial detachment of a tile from the cooling substrate. To highlight the importance of the modules validation procedure (Sec. 7.3), the detachment was detected thanks to an anomalous result during the cooling performance test (specifically a recorded $\Delta T > 80^\circ \text{C}$). After a thorough investigation, the cause was found to lie in the hygroscopic nature of the chosen catalyst, causing the accumulation of a layer of humidity on the deposited patterns that hinders the bonding properties of the glue. The moisture layer becomes visible only after thermal cycling (Fig. 8.1) and worsen over time, progressively weakening the adhesive strength and shortening the lifetime of the modules. Thus, a number of different

solutions were investigated as possible alternatives to Stycast 2850 FT catalyst 9.

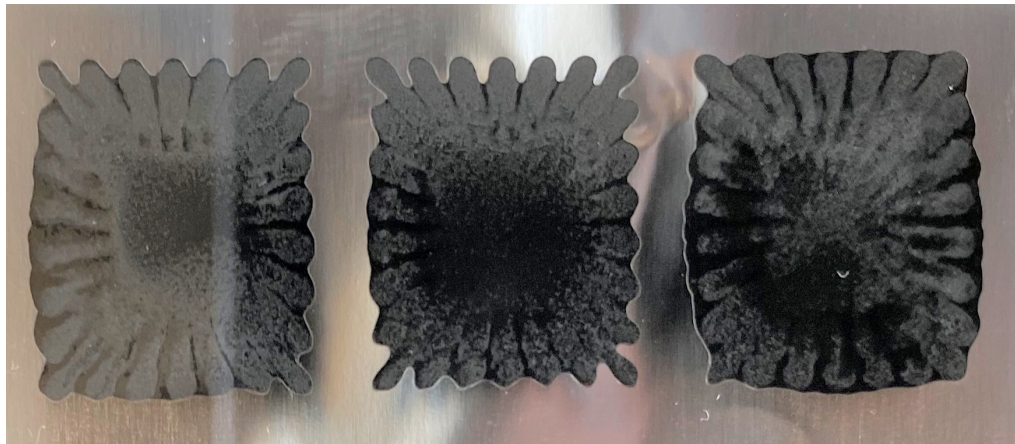


FIGURE 8.1: Stycast with catalyst 9 patterns after pressing down and ageing: the white halo is produced by humidity deposited on the glue surface [35].

8.2 Glue layer R&D campaign

Several glue patterns have been developed since the attachment procedure R&D phase. As already mentioned, glue patterns target parameters have been optimised to ensure appropriate module performance:

- 80 μm thickness to ensure good heat transfer and absorb thermal dilatation of the components.
- $\pm 40 \mu\text{m}$ evenness for uniform heat dissipation.
- 70% ASIC minimum coverage for efficient heat transfer from the chip to the micro-channel.
- No air bubbles trapping when pressing down the tile onto the substrate.
- Avoid spillages in-between the ASICs as it causes electronic noise.

While the thickness and evenness requirements are reached tuning the amount of deposited glue, the coverage, trapping and spillage targets are mostly governed by the shape of the deposited patterns. The first pattern to be employed in R&D modules has been the “snake” pattern (Fig. 8.2a): this ensured a good coverage of the ASIC and ease of deposition but was prone to air trapping between the “coils” of the snake. Thus it was discarded before the start of the assembly campaign. The “star” pattern (Fig. 8.2b) was the second to be deployed and the first to be used at the beginning of the assembly campaign;

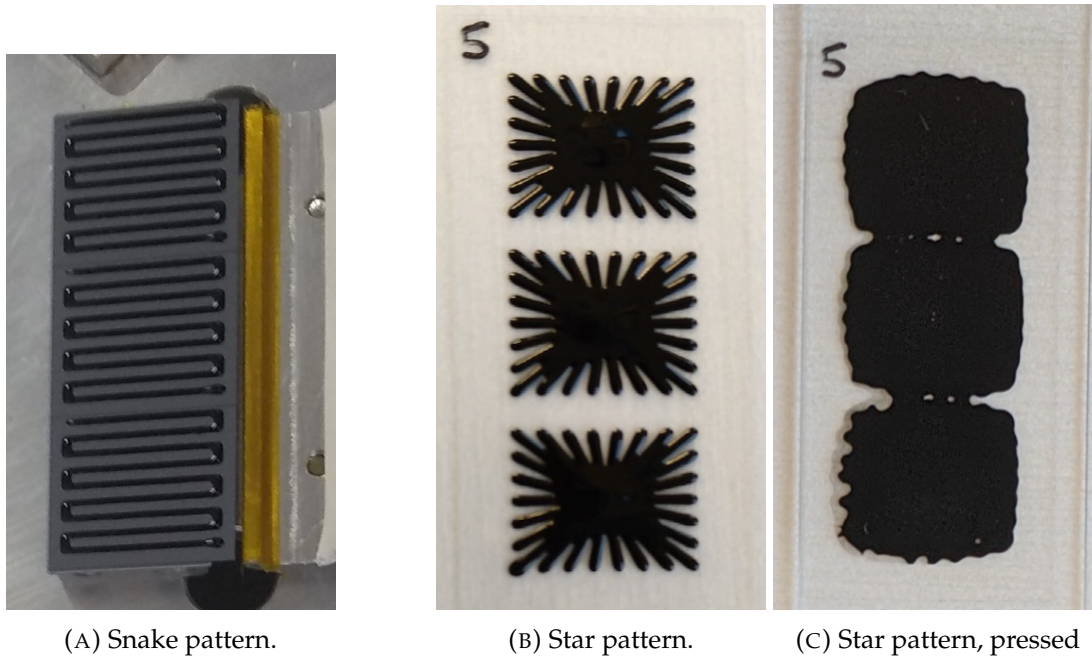


FIGURE 8.2: The initial patterns developed for tiles attachment. Note how the star pattern is prone to spillages after pressing down [35].

it comprised a variable number of glue “fingers” from each side extending from the centre of the ASIC to the edges of a rectangle, covering around 80% of the chip area. When pressed down the glue flows from the centre to the outside filling the space between the fingers avoiding the formation of air pockets. Nine fingers were used on the long side of the rectangle, 8 on the short side, 7 on the short side of the overhanging ASICs. This shape was optimised for Stycast 2850 FT with catalyst 9 and had to be re-optimised to suit the viscosity of the other glues to avoid spillages between the ASICs, to which the pattern revealed to be prone to (Fig. 8.2c). More specifically, the number of fingers and their width, the deposition speed and pressure, the vertical needle clearance and even the shape of the stars had to be fine tuned for each tested adhesive.

8.2.1 Tested adhesives

The adhesives proposed as possible alternative to Stycast 2850FT-catalyst 9 were: Araldite 2011 [112], Stycast 2850FT-catalyst 23LV [105] and Epo-Tek T7109-19 [113], with Table 8.1 showing their key features. Each of these is a low-viscosity glue suited for robotised dispensing. More specifically, Araldite 2011 is low viscosity bi-component, epoxy-based solution; Epo-Tek T7109-19 is a bi-component elastic epoxy paste suited for low stress applications where high heat dissipation is required; Stycast 2850FT is a bi-component potting compound, it has a base resin-filler (Aluminium Oxide) mixture which can be

combined with a number of liquid catalysts that define its mechanical properties, heat transfer rate and curing time.

Adhesive	Mixing ratio	Curing schedule	Pot life	Shelf life	Thermal conductivity
Stycast 2850FT (cat 9)	100:37.5 by mass	24 h @ 25° C	45 mins	12 months	1.25 W/mK
Araldite 2011	100:100 by volume	10 h @ 23° C	100 mins	36 months	0.22 W/mK
Stycast 2850FT (cat 23LV)	100:7.5 by mass	24 h @ 25° C	60 mins	12 months	1.1 W/mK
Epo-Tek T7109-19	100:15 by mass	24 h @ 25° C	120 mins	12 months	1.3 W/mK

TABLE 8.1: Main properties of the adhesives under study accompanied by handling and preparation information.

8.2.1.1 Glue preparation

Bi-component epoxies demand specific procedures to obtain nominal bonding strength, yet these must not introduce air pockets into the mix. For these reason the SpeedMixer DAC 150.1 FVZ-K, an orbital centrifuge mixer, was employed to ensure consistent and repeatable results for each of the glues. As each adhesive comes with distinct properties and chemical composition, appropriate mixing parameters have been chosen for each glue (Table 8.2).

Glue	Mixing speed (RPM)	Mixing time (min)
Araldite 2011	2600	4
Epo-Tek T7109-19	2000	5
Stycast 2850FT (cat 23 LV)	1000	5

TABLE 8.2: Time and speed settings used for each glue.

8.2.1.2 Glue deposition

Evenness of the glue layer is a crucial property to ensure appropriate thermal performance, thus to deliver consistent adhesive deposition across the whole assembly campaign a robotised dispenser was selected: the Fisnar F5200N automatic fully programmable robot. Patterns of any shape can be dispensed with the robot, with machine instructions generated via a python script. To allow for complete flexibility, the head dispenser speed can be customised, as well as its vertical clearance from the tiles surface and the waiting time at each stopping point. The pressure is instead independently operated through a EFD 1500XL unit [114]. A Stycast 2850 FT pattern is shown in Fig. 8.3 for reference.

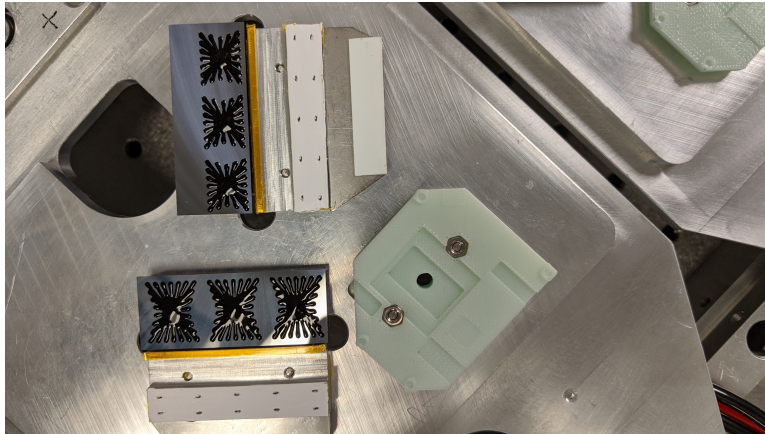


FIGURE 8.3: Stycast 2850 FT with catalyst 23LV pattern deposited on ASIC.

8.2.2 Pattern optimisation

Intensive R&D effort has been put into the pattern optimisation process, investigating different shapes and deposition settings to obtain a high quality layer which would meet evenness standards and would be air free. Prior to the production campaign, the “star” pattern was chosen as the ideal candidate to cover 80 – 90 % of the ASIC while avoiding air-pockets. Ideally, the same pattern would be adopted also for the alternative adhesives, and therefore dedicated optimisation studies had to be carried out in order to assess the best settings for each candidate. The following parameters were reviewed:

- line number;
- line thickness:
 - needle gauge;
 - line speed;
 - air pressure;
 - glue viscosity;
 - needle vertical clearance.

Special care have to be put in depositing the correct amount of adhesive, since an excessively thin layer would hamper the mechanical soundness of the module, while a glue excess could spill between the ASICs, joining the patterns and increasing electronic noise.

8.2.2.1 Araldite 2011

A variety of samples were utilised to direct the refinement of the dispensing settings: plastic samples glued on silicon were used with Araldite 2011 at the

very beginning when no other material was available (Fig. 8.4). A number of combination of pressures, lines and needle gauges were used to narrow down the optimal settings. As Araldite has low viscosity, spacers were used in the form of kapton tape strings in the attempt to constrain the height of the final patterns.

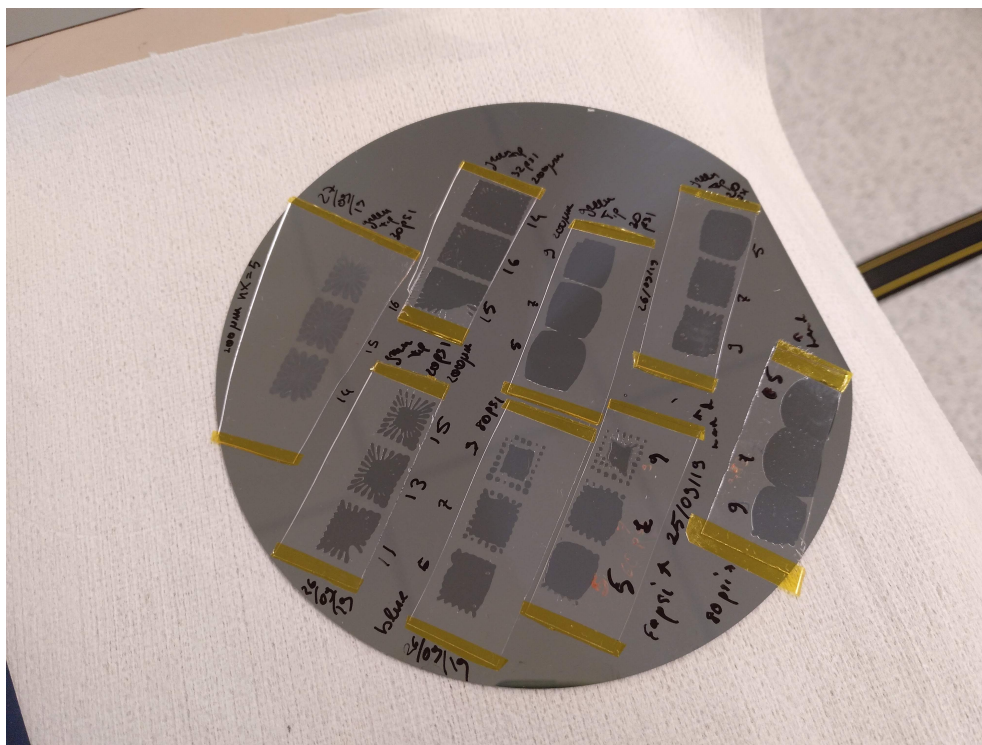


FIGURE 8.4: Araldite 2011 plastic-silicon samples. Note the number of different combinations used to assess the best combination of spacers, pressure, lines and gauge.

Glass on glass tiles were employed for a more realistic simulation of the adhesive behaviour after pressing down, together with glass-silicon pieces. The stiffness of the glass slides proved to be crucial to perform thickness studies in combination with spacers of different thicknesses; samples were pressed down with a 1 kg weight. These studies helped to narrow down and calibrate the final shape and deposition settings (Fig. 8.5). The optimal number of lines per side resulted to be 6 as it allowed to have enough glue to fill the gaps between the lines while avoiding to deposit too much adhesive resulting in circular shapes, rather than rectangular, after pressing down. The final optimised parameters are summarised in Table 8.3.

8.2.2.2 Epo-Tek T7109-19

Epo-Tek has been tested solely on glass-glass samples. A number of different parameter combinations were tested. The glue proved to be easy to handle

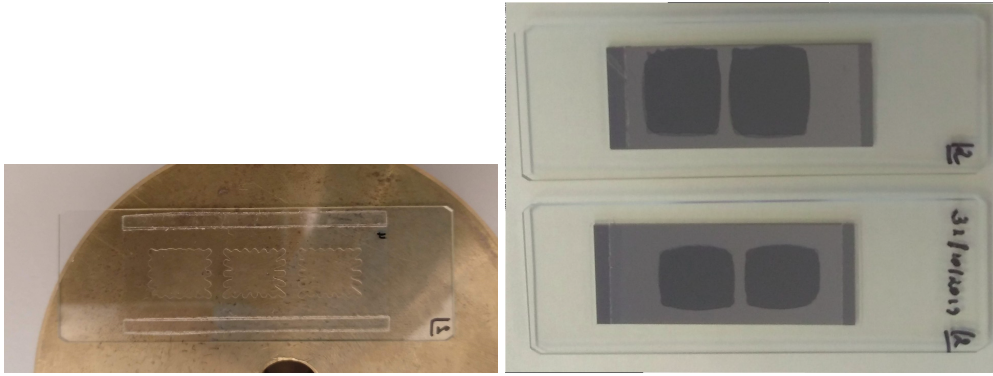


FIGURE 8.5: Araldite 2011 glass-glass (left) and silicon-glass (right) samples.

and deposit, but height and final shape after curing turned out to be difficult to control. The glue, although viscous, would thin out under the 1 kg weight used to press down the patterns, which would result in merged patterns and unsatisfactory thicknesses, as shown in Fig. 8.6.

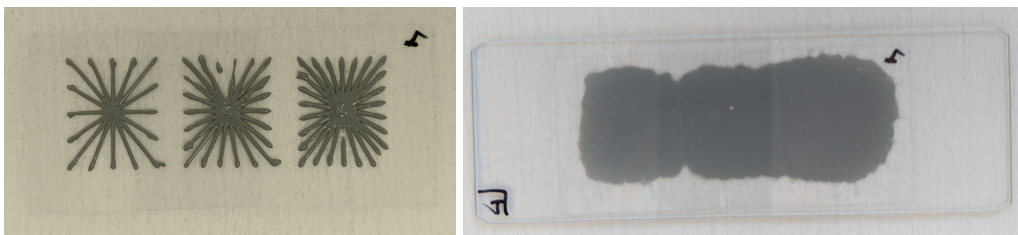


FIGURE 8.6: Epo-Tek glass-glass sample with a variable number of lines: 20, 24, 28 respectively, going from left to right. On the left: fresh patterns; on the right cured patterns after pressing down. All patterns have merged.

The solution proved to be a pattern with 7 line per side with a thin needle gauge to limit the glue quantity on the patterns (Fig. 8.7); this combination worked both with and without 80-90 μm spacers. Nevertheless, some resin-filler separation issues emerged after curing (Fig. 8.8), regardless of the mixing technique adopted. This undesired phenomenon could potentially be harmful for the detector operation as the resin seemed to spread well beyond the perimeter of the patterns (Fig. 8.9).

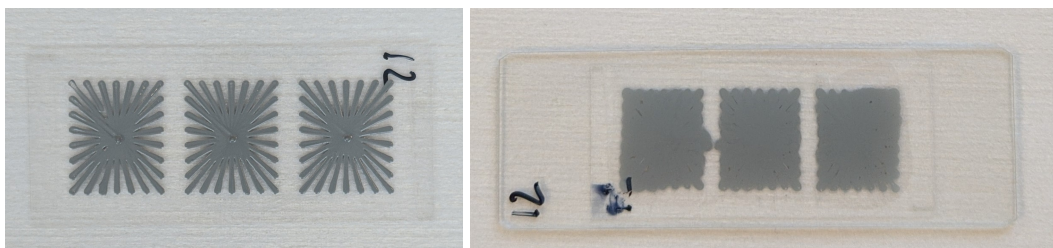


FIGURE 8.7: Glass on glass Epo-Tek patterns before (left) and after (right) curing. 80-90 μm spacers were used to set the thickness. The patterns have not merged.

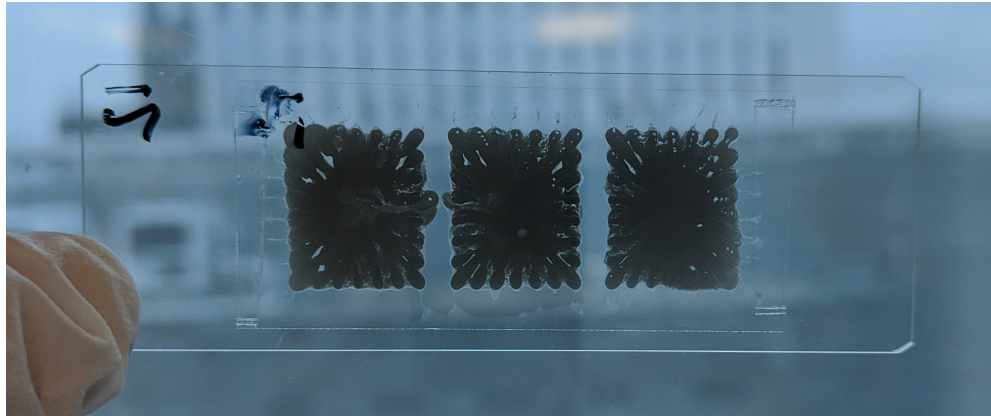


FIGURE 8.8: Example of resin-filler separation phenomenon on Epo-Tek patterns after curing.

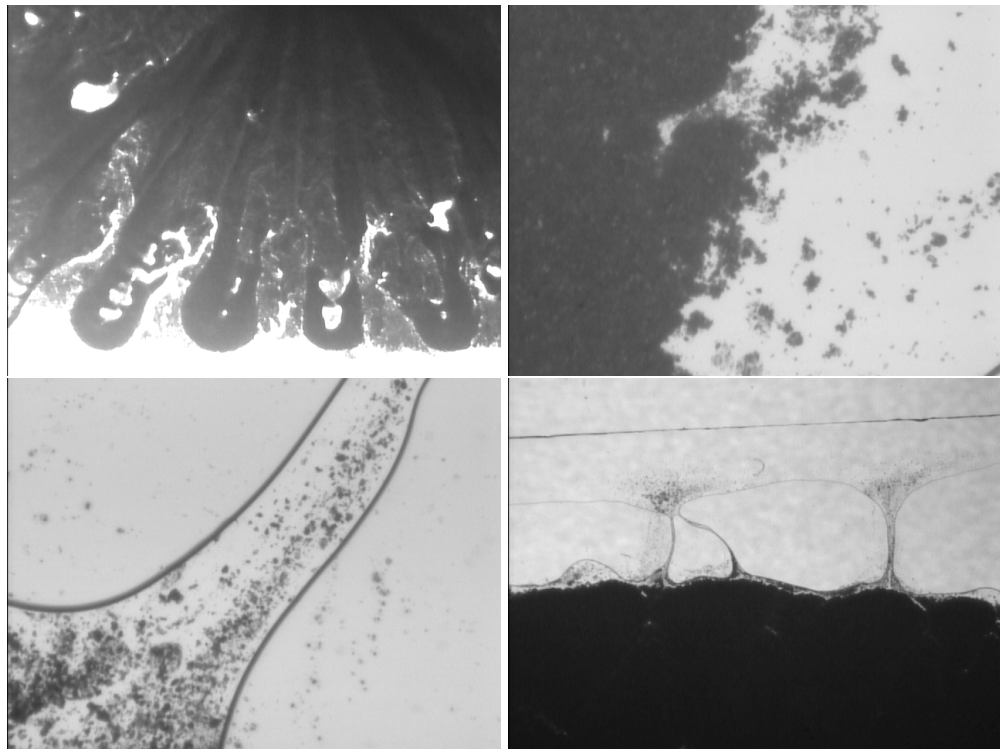


FIGURE 8.9: Microscope magnified images of the resin-filler separation areas on various patterns. Observe how the resin extends way beyond the perimeter of the pattern [35].

To improve the control over the final shape of the glue patterns, a bowing on the long sides was added to the star shape. The resulting pressed patterns, shown in Fig. 8.10, returned satisfactory results, although not completely resolutive of the spillage issues. The final optimised parameters are summarised in Table 8.3.

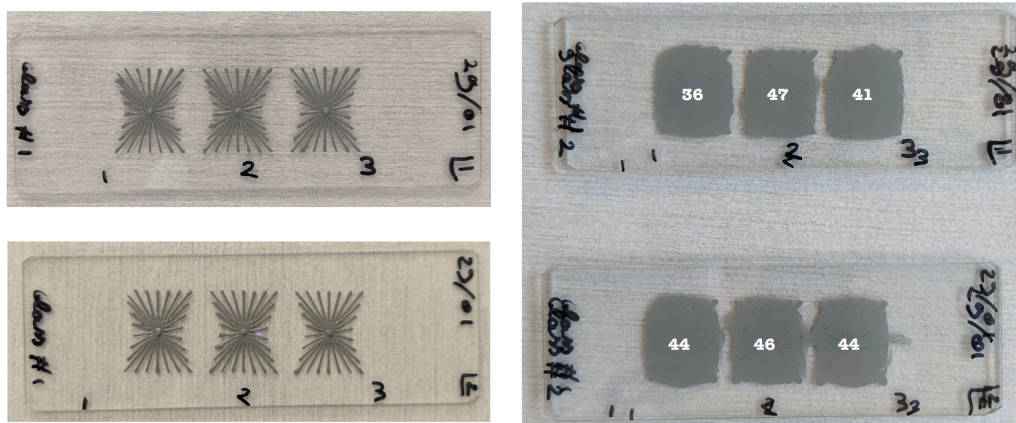


FIGURE 8.10: Example of “hourglass star” pattern on Epo-Tek samples. The patterns (with overlaid thickness) did not merge even without spacers.

8.2.2.3 Stycast 2850 FT catalyst 23 LV

The experience gained with the previous production glue allowed to quickly progress through the optimisation process of Stycast 2850 FT catalyst 23 LV patterns. Only glass-glass samples were produced, and all patterns were pressed down with a 1 kg weight. Target thickness was achieved with most of the samples without using spacers, as the resin-filler mix is viscous enough not to flatten under the pressure of the weight while curing. A few samples were produced resulting in non rectangular shapes (Fig. 8.11), although no merge between the patterns was observed.

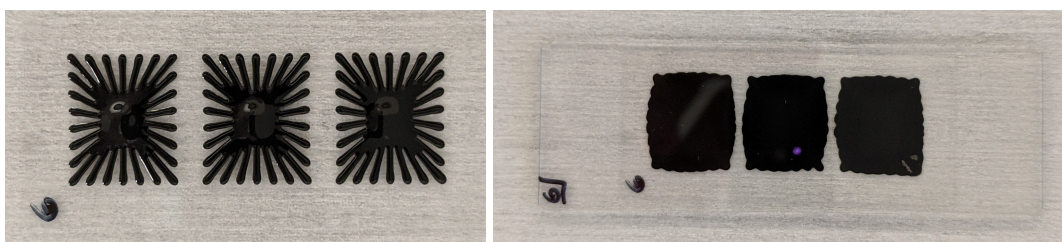


FIGURE 8.11: Stycast patterns before (left) and after (right) curing. Note the stars close to merging.

To better control the glue flow on the long sides, a bowing was added; this strategy allowed to achieve almost perfectly squared patters (Fig. 8.12). Finally, to further constrain spillages on the short sides a second bowing was added to the patterns, achieving the final “double hourglass star” optimised pattern (Fig. 8.14). The complete list of optimised settings is given in Table 8.3.

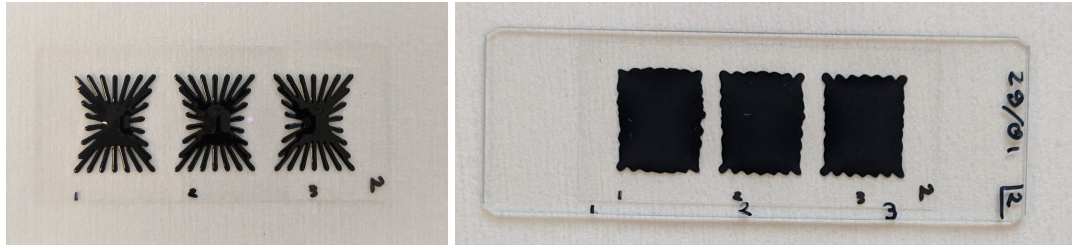


FIGURE 8.12: Stycast “hourglass” patterns before (left) and after (right) curing. Note the stars are almost perfectly square.

8.2.2.4 Summary

The pattern optimisation process provided a wealth of information on the properties and ease of use of each adhesive. Target thickness was hard to achieve with Araldite 2011 due to its high viscosity that rendered the use of spaces obligatory. Epo-Tek allowed to achieve target thickness more easily, yet the glue is prone to flattening and starts to merge if too much epoxy is deposited; furthermore separation phenomena of resin-filler separation emerged while curing under a weight. Stycast proved to be the easier to control to meet target parameters, offering a good resistance against flattening while curing. Table 8.3 recapitulate the outcome of these trials. Figure 8.13 illustrates the final optimised patterns. Note that a bowing has been added to the Stycast pattern sides to control spillages between the ASICs. The result is a “hourglass” star shape.

Glue	lines	Needle gauge	line speed (mm/s)	pressure (bar)	viscosity (mg/min)	aimed thickness (μm)
Araldite 2011	26	20	9	2.4	50	80
Stycast (cat 23 LV)	26	23	9-12	1.4	70-100	70-90
Epo-Tek T7109-19	24	21	9	3.5	25-35	50

TABLE 8.3: Optimised dispense settings for the epoxies under study. Clearance on the z coordinate is $200\mu\text{m}$ for all the adhesives.

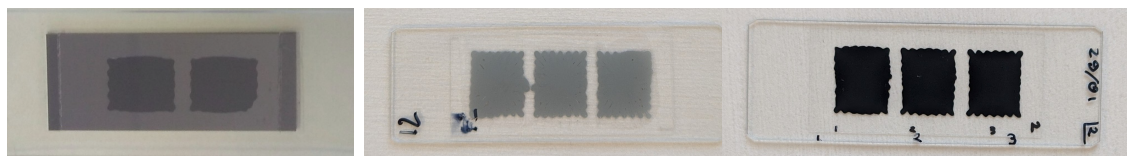


FIGURE 8.13: Final optimised patterns. Left: Araldite 2011; centre: Epo-Tek; right: Stycast.

Settings in Table 8.3 were applied to the production of *dummy* substrates (see next section 8.2.3) and full modules.

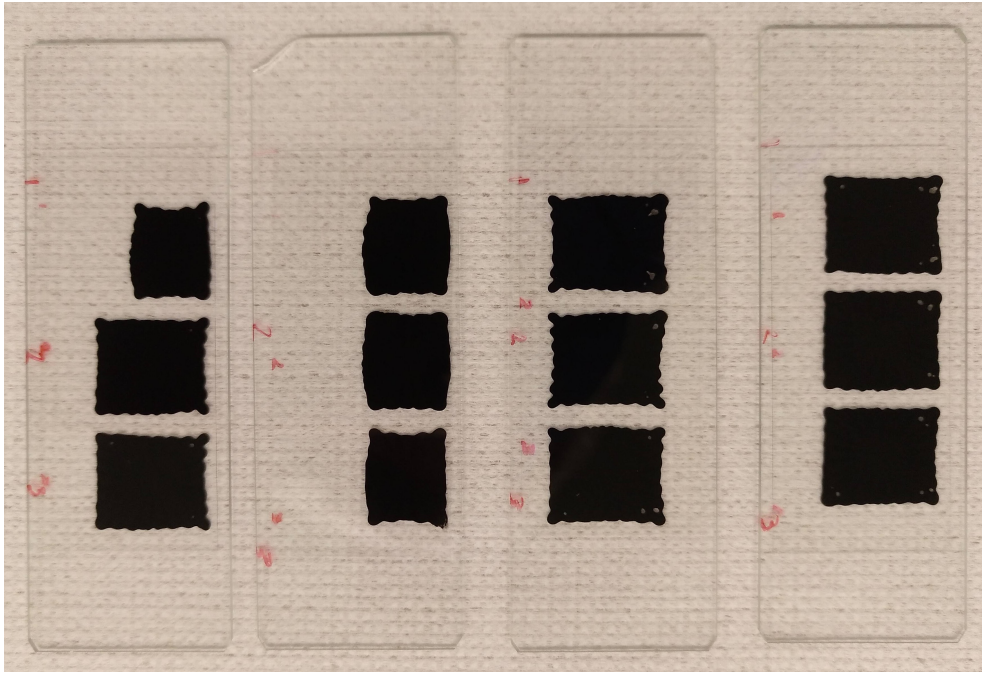


FIGURE 8.14: Final “double hourglass star” shape reproducing the patterns for each tile. No merging is observed with only some patterns extending beyond the ideal square shape.

Finally, as mentioned above, to further control spillages in all directions, a second bowing was added to the patterns (Fig. 8.14). This shape was tested before the restart of the assembly campaign and allowed to consistently achieve squared shapes and prevent glue spillage.

8.2.3 Dummy substrates

The parameters defined at the end of the R&D effort have been employed to assemble a number of mock-ups to further review the settings prior the production of a complete module. Mock-ups were built using 500 μm thick silicon wafers and 420 μm thick dummy tiles pre-cut in the shape and dimensions of a real tile. This intermediate step was carried out with the same jigs used for the assembly procedure and proved essential to finely adjust the micro-metric screws on the transfer-plate to achieve the desired glue thickness and tile flatness respect to the micro-channel. No other components are attached in the realisation of such mock-ups.

To verify the status of the patterns after curing time, the wafers are inspected under a thermal camera, then the glue layer width is measured with a smart-scope as explained in Sec. 7.2.

Requirements for a successful result are: satisfactory area coverage, non-joint patterns under each tile and adequate adhesive layer thickness. The adopted

adhesive settings are those reported in Sec. 8.2.2. Table 8.4 summarises the final results.

Glue	# of trials	Issues	Final results
Araldite 2011	8	Low viscosity. Merged patterns. Uneven glue layer.	Even glue layer thickness. CLI patterns partially merged Optimised thickness met.
Epo-Tek T7109-19	1	Insufficient ASICs coverage. Patterns not correctly pressed. Defective glue amount deposited.	Bow-star pattern used. Even thickness.
Stycast 23LV	6	Uneven layers. Insufficient coverage.	Even glue layers. Non-merged patterns. Thickness within specifications.

TABLE 8.4: Overview of the results obtained with mock-up wafers.

The best results accomplished with the wafer are shown in Fig. 8.15, along with the measured adhesive layer width under each chip.

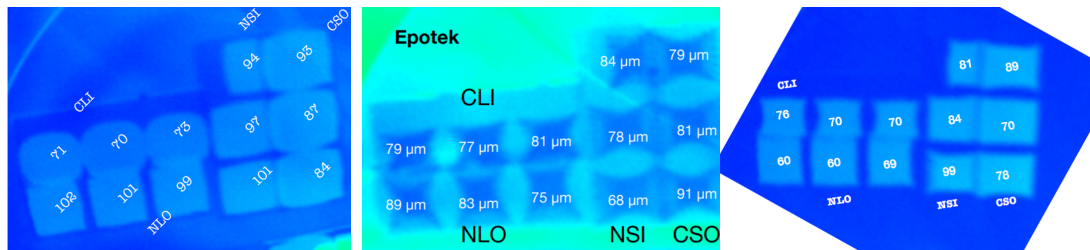


FIGURE 8.15: Infrared images captured with thermal camera showing the shape of the patterns after curing for the best mock-up wafer for each glue. A small temperature gradient is applied between the wafer and the glue to make the patterns underneath the silicon visible. Each ASIC has the measured glue layer width superimposed. On the left the Araldite 2011 8th wafer; in the middle the only realised Epo-Tek wafer; on the right the 6th Stycast 2850 FT-catalyst 23LV wafer [35].

The Stycast wafer was realised heat treating the patterns at 60° C before pressing down to remove any absorbed water; tiles were lowered on the wafer once the temperature had reached 40° C.

The final optimised criteria have been applied in the assembly of two further R&D modules, one built with Araldite 2011, the other with Stycast 2850 FT with catalyst 23LV. The dummies built with these adhesives were in fact the most promising ones, while a more extensive R&D with Epo-Tek was deemed necessary in order to achieve a satisfactory procedure, which was thus abandoned because of schedule constraints.

8.2.4 R&D modules

To assess the adhesive performance within the module construction procedure and under operation-like conditions, one electric (Module 80) and one

mechanical (Module 81) modules were assembled with Araldite 2011 and Stycast 2850 FT-catalyst 23LV, respectively. Both were built with D or F grade components as the main focus of these modules was to assess the thermal performance of the new glue and glue layer quality.

Specifically, Module 80 was assembled to establish target glue parameters and tile positioning could be met notwithstanding the Araldite 2011 very low viscosity, while the impact of its lower thermal conductivity (see 8.1) on the cooling performance had to be assessed as well. Module 81 is a purely mechanical module and was built to review the tile attachment procedure and the quality of its outcome using Stycast 2850 FT-catalyst 23LV.

8.2.4.1 Module 80 (Araldite 2011)

Module 80 has been build with a Grade C micro/channel substrate (solder residuals in the fluidic connector) and faulty sensors (early breakdown voltage, shorted pixels, excessively high currents). The standard *star* pattern was used (Fig. 8.16), as at the time of the assembly the *hourglass* and *double hourglass* shapes where yet to be proposed and tested.



FIGURE 8.16: Module 80 glue patterns. On the left: C-side; on the right: N-side.

Although the assembly procedure and tile positioning proved successful, the glue thickness measurements revealed a severely sloped layer under each tile. This is clearly shown in the adhesive thickness metrology results in Fig. 8.17 and summarised in Table 8.5. This issue can be traced back to the usage of a micro-channel substrate, which behaves differently from a silicon wafer under the mechanical pressure of the attachment procedure. Furthermore, glue patterns under CLI and NSI merged, with even some glue spilling outside the tiles, with CLI being the worse affected by this problem.

To grade its electric and thermal performance the module was installed in the validation setup 7.3 and the PRBS and bandgap tests were run before and after 100 thermal cycles, equivalent to running the standard thermal cycle test 10 times, to check the impact of ageing on the glue performance and monitor

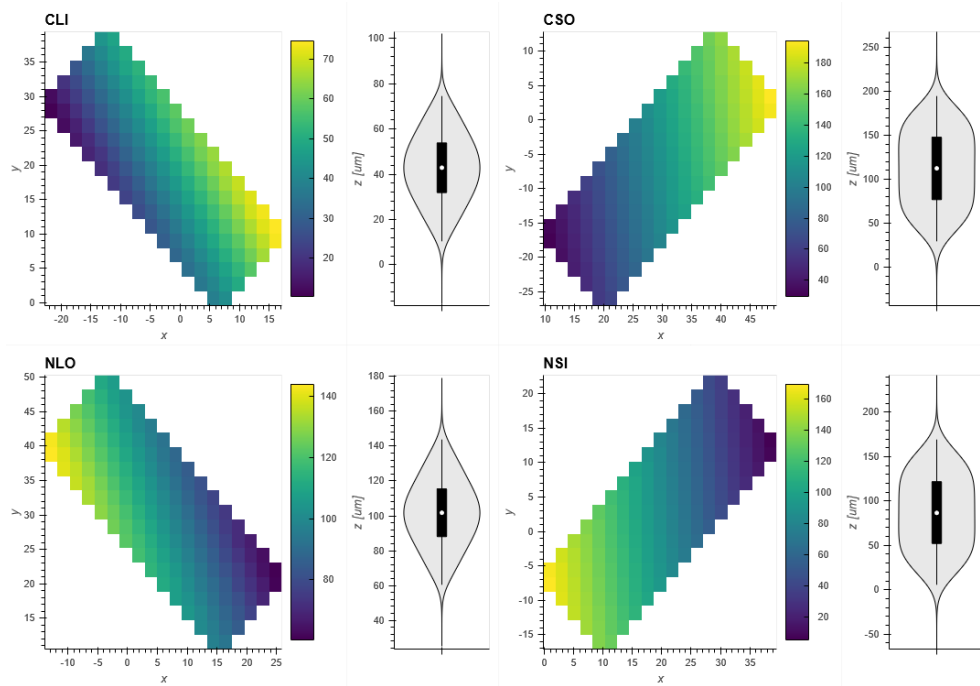


FIGURE 8.17: Glue layer thickness results for Module 80 [35].

TILE	ASIC-0	ASIC-1	ASIC-2
CLI	41 μm	51 μm	61 μm
CSO	160 μm	112 μm	66 μm
NLO	83 μm	100 μm	118 μm
NSI	125 μm	85 μm	40 μm

TABLE 8.5: Glue thickness under each VeloPix chip for Module 80 tiles.

the adhesion strength on the very thin 40 μm Araldite layer under the thermal expansion forces. The PRBS (Fig. 8.18) test result showed no sign of worsened performance after thermal cycling.

Bandgap measurements were Graded C before and after thermal cycling, with some thermal performance degradation quantifiable in a temperature increase of around 2° C between the cycles. To confirm this outcome, the module was thermally cycled two more times (with standard cycles) and tested for thermal performance after each time. The outcome was mixed, as the performance of some ASICs degraded slightly after each additional cycle, whereas other stabilised and other even appeared to perform slightly better. The thermal performance test result before and after all the thermal cycles is shown in Fig. 8.19.

Overall Module 80 delivered satisfactory electrical performance and was graded C for the thermal efficiency test before and after thermal cycling. Despite the sufficient results, Araldite 2011 low viscosity rendered hard to control the

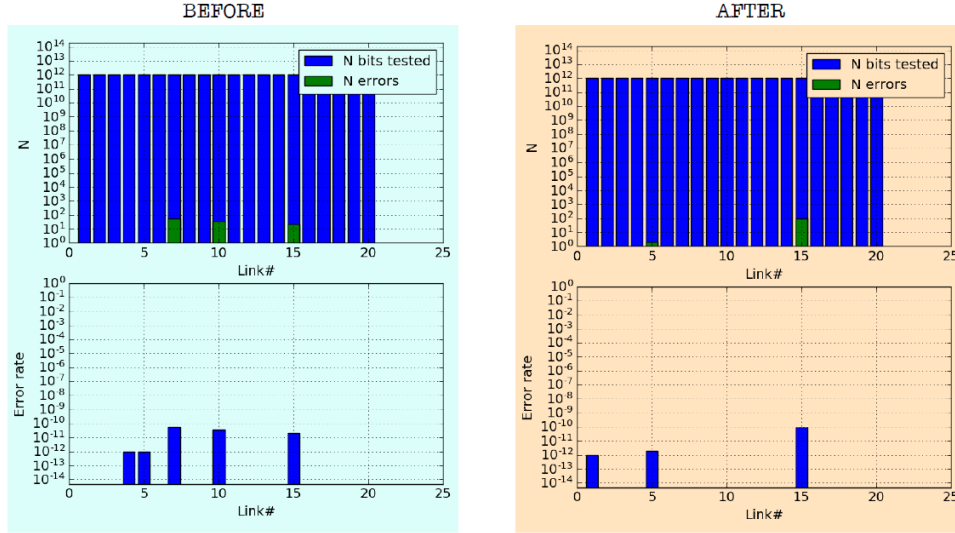


FIGURE 8.18: Outcome of the PRBS test on Module 80. Left: BER before thermal cycling. Right: BER after thermal cycling [35].

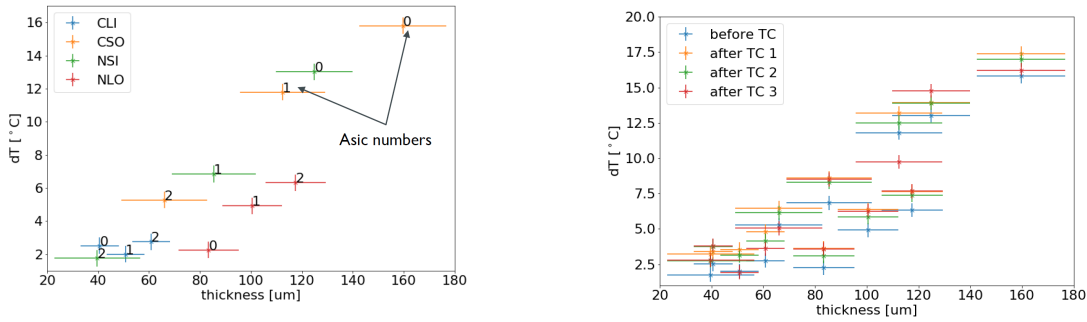


FIGURE 8.19: Results for Module 80 thermal performance test before (left) and after (right) thermal cycling. The plots show the δT (defined as temperature difference between full and minimal power mode for the ASIC) as a function of the adhesive layer thickness under each VeloPix ASIC for each tile. Three thermal cycles were performed and thermal performance test run after each one. The result do not allow to define a clear trend other than a general worsening of the performance [35].

thickness of the glue layer.

8.2.4.2 Stycast module (M81)

Module 81 has been assembled with only mechanical components to confirm the positive results obtained with mock-up wafers. A pierced micro-channel (Grade D) was employed and non-production tiles with bad sensors to replicate the attachment procedure of real components. Low quality hybrids were added as well to reassess the wire-bonding procedure with the new adhesive. The tiles were aligned following the standard procedure and the patterns deposited

(Fig. 8.20). The patterns were heat treated up to 50° C after being deposited and pressed down at around 40° C.

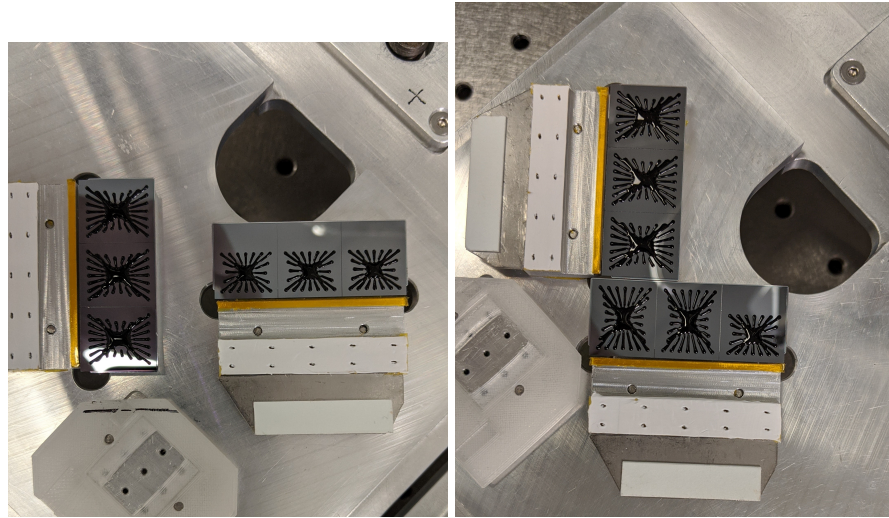


FIGURE 8.20: Freshly deposited patterns for C-side (left) and N-side (right) tiles of Module 81. Note the hourglass shape.

The patterns were let cure and examined with a thermal camera (Fig. 8.21), showing squared patterns without spillages between the ASICs and outside of the tile. Metrology was run to check the thickness of the glue layer, which results are shown in Fig. 8.22: a uniform glue layer for CLI and NLO tiles, whereas some degree of tilt is recorded for NSI and CSO. Tile positioning was graded A.

In summary, the Stycast 2850 FT-catalyst 23LV mechanical module confirmed that the glue can be reliably used in module assembly thanks to a more viscous consistency which helps control the pattern shape and width after pressing down. The high thermal conductivity also contributed to choose this glue over the other epoxies under study.

8.3 Shear test

Araldite 2011 was deemed too complicated to manipulate to be a realistic replacement of the previous production glue after the construction of Module 80, thus the interest shifted on Stycast 2650 FT-catalyst 23LV and Epo-Tek T7109-19. The chosen adhesive should possess elasticity amidst its key properties to tolerate the tensions on the glue interface generated by the components thermal expansion and contraction during the detector power cycles. Elasticity should be retained during the whole lifespan of the VELO, around 10 years, as well as nominal adhesion strength.

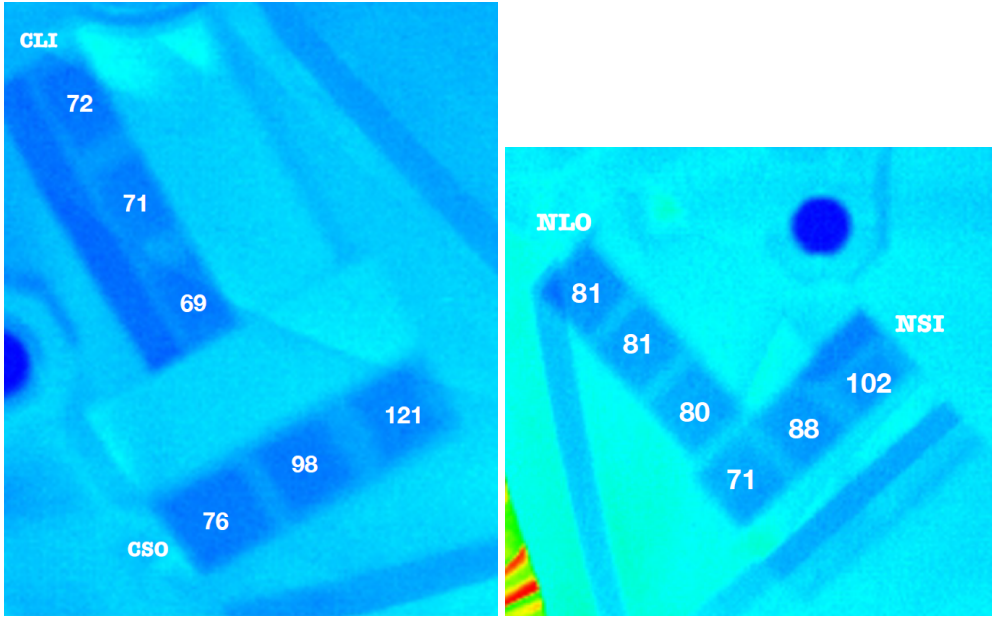


FIGURE 8.21: Thermal camera image of Stycast M81 glue patterns shape with the layer thickness for each ASIC (in μm) superimposed [35]. A small temperature gradient is applied between the micro-channel plate and the adhesive layer to make the patterns underneath the silicon visible.

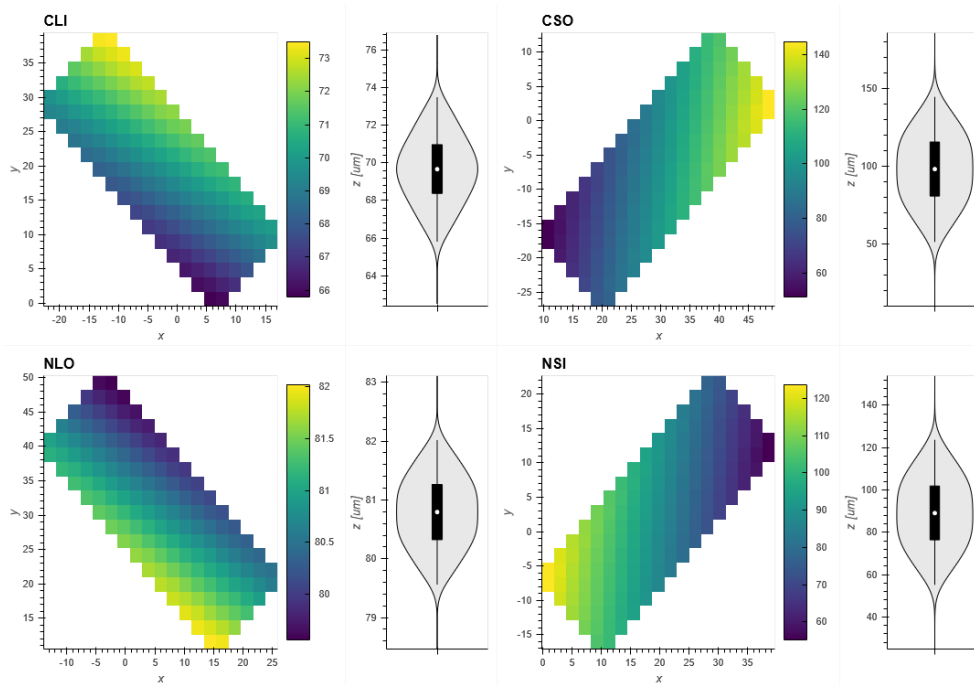


FIGURE 8.22: Glue layer thickness results for Module 81. Note how CLI and NLO have a perfectly even layer and meet target thickness, while CSO and NSI are slightly thicker with a more pronounced slope [35].

Thus, to test the evolution of their elastic properties (specifically the Young's modulus) when exposed to reiterated mechanical stress and ageing, a test device was assembled to apply a shearing force to a glue layer sample while

recording the displacement as function of the force applied to two “carriers” plates attached together by the glue. The samples were also aged in the oven to test their properties in the late life of the detector. The adhesives underwent multiple shear test instances at increasing ageing stages to assess the evolution of their properties. Then, Young’s modulus is extracted fitting the displacement vs load curves with a straight line and extracting its slope.

The following section will describe the experimental apparatus with which the tests were carried out (Sec. 8.3.1), as well as the test procedure (Sec. 8.3.5) and results (Sec. 8.3.6), along with details about the sample preparation and ageing procedure.

8.3.1 Apparatus

The experimental apparatus assembled to shear test the glue samples is equipped with a load cell for force measurements and a transducer to record displacement. The load cell is a Single Point Aluminium Load Cell Model 1022 by Tedeo-Huntleigh [115], which exploits the piezo-electric characteristics of its internal components to modify its electrical resistance when the cell is deformed. The load cell used had a maximum load of 100 N, and was readout via a digital amplifier (SY043) connected and powered via USB to a computer [111]. The displacement transducer, more precisely a Linear Variable Differential Transducer (LVDT) Solartron Metrology Analogue Sensors [116], uses a needle with a ferromagnetic core to induce currents in a coil; the resulting voltage output is proportional to the position of the needle tip from the equilibrium position, which in turn can be translated in a distance measurement [111]. The LVDT is connected to a 10 V power supply and read out by a Keithley 2000 multimeter, this is connected via RS-232 port to a PC. Figure 8.23 illustrates the structure of the shear force device alongside the load cell and displacement sensor position. The samples under test are positioned in the sample compartment which allows to apply shear force tangentially to the adhesive surface. As the test samples, two small silicon tiles glued together, are too small to be directly tested with the apparatus, they are glued to two aluminium carrier plates which tightly fit into the sample compartment and allow to distribute the force uniformly. The carriers are fixed to the top and bottom compartment plate with screws. The bottom plate is mechanically connected to the lower portion of the compartment plate, which is joint to the load cell and thus locked in place. The top carrier is free to move under the pulling force of a load spring or weights suspended over the pulley via a rope. If the former method is used, the far end of the load spring is put in tension with a micrometer for a precise control of the

extension. All the tests reported in the following sections have been carried out using the micrometer. The displacement is monitored with the LVDT which is connected to the top carrier. Both sensors had been previously calibrated, more information can be found in Ref. [111].

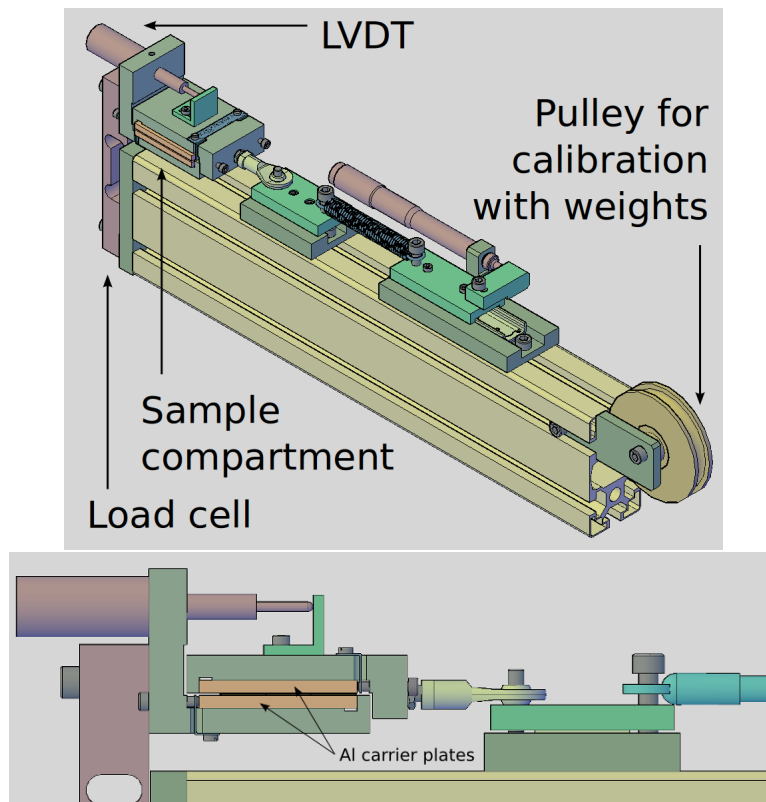


FIGURE 8.23: Top: schematic of the test apparatus. Bottom: side view. The apparatus is composed by an aluminium beam where the main components are anchored. The carrier plates, to which the glue sample is glued onto, are highlighted in orange. These are fixed with screws into the sample compartment, with its lower part connected to the load cell and the upper part to a trolley. Shear force is applied to the trolley via weight suspended over a pulley or with a load spring extended with a micrometer. The displacement of the upper carrier compartment is recorded by the LVDT [111].

8.3.2 Sample preparation

Shear test samples were prepared gluing together two small silicon tiles with a small amount of adhesive. 13 Epo-Tek samples were prepared, 11 of these with $20 \times 10 \text{ mm}^2$ and 2 with $27 \times 10 \text{ mm}^2$ rectangular tiles, respectively. These were collected from a $500 \text{ }\mu\text{m}$ pre-cut silicon wafer (Fig. 8.24). 10 Stycast samples were assembled, using leftover silicon from the pre-cut wafer. These were cut with a diamond pen in $20 \times 10 \text{ mm}^2$ size.

The samples gluing procedure will be explained in detail on the following paragraph.

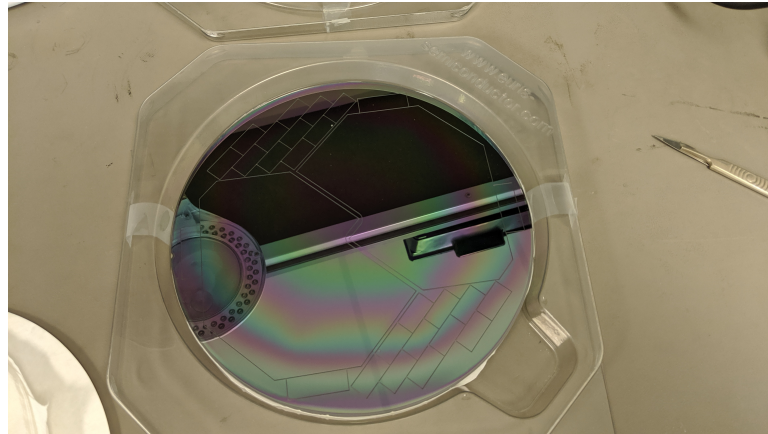


FIGURE 8.24: Silicon wafer with pre-cut tiles used for the shear test tile assembly [35].

Gluing procedure The adhesives were mixed using the ratios and procedure listed in Table 8.1 and 8.2. The glue was deposited with the same Fisnar glue robot used for the module assembly, dispensing 3 mm long lines for the $20 \times 10 \text{ mm}^2$ tiles and 7 mm for the $27 \times 10 \text{ mm}^2$ ones. Line width is defined by the needle gauge: 21 gauge for Epo-Tek, while for Stycast 23 gauge needle was used.

The tiles are carefully laid on the gluing support by hand and are kept in place with vacuum. The gluing support is a kapton coated aluminium plate 8.25 with pin-holes for vacuum, following the same principle adopted to securely fix the sensors during the tile attachment procedure. Reference marks are drawn on the kapton to guide the tile alignment. The glue robot is programmed to deposit the adhesive in the middle of the markings. Prior to starting the dispensing procedure a cross-check is run to ensure the Fisnar robot has been correctly set-up: the procedure is started and interrupted as soon as the first glue line is laid on the first tile. A glass slide is pressed on the glue to assess the glue position and approximate coverage (Fig. 8.25). If the test is passed the tile is cleaned and the procedure started. The top tiles are once again carefully positioned by hand.

To press the patterns a thick plexiglass sheet is positioned on top of the samples and a 975 g brass disk placed on the sheet. The plexiglass ensures that the weight is evenly distributed on all the tiles. One (Stycast) or two (Epo-Tek) days are allowed for curing.

The resulting gluing area after curing is roughly a 10 mm circle and a $15 \times 10 \text{ mm}$ ellipse for the smaller and longer Epo-Tek tiles, respectively. Stycast adhesion area was slightly smaller due to the higher viscosity of the glue which spread less under the brass weight, resulting in a 7 mm disk.

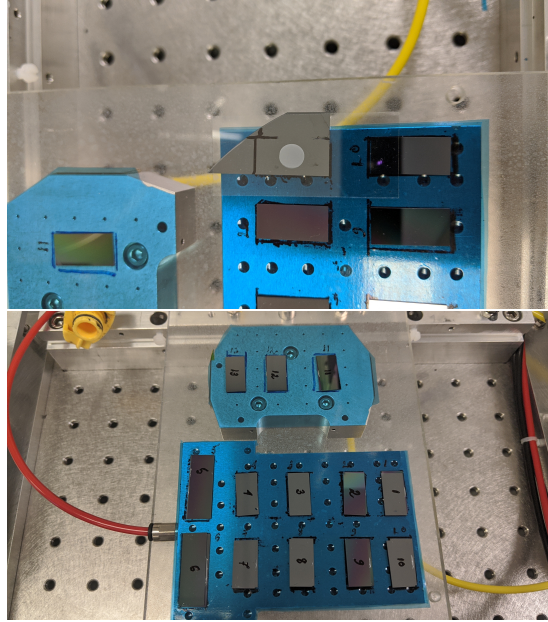


FIGURE 8.25: Top: cross-check procedure to ensure the proper alignment of the robot and target glue quantity is deposited. Bottom: test tiles gluing support with complete samples. The guidelines are clearly visible in both pictures [35].

Carrier plates attachment The cured tiles, which will be referred to as samples in the following, are glued to the aluminium carrier plates using Araldite 2012 [117], a fast curing bi-component epoxy requiring 60 min at 25° C to fully cure. Due to the extremely short working time of the adhesive, mixing was performed by hand mixing roughly 0.5 cm³ of each component on a plate and mixing with a swab until a uniform mixture is obtained. A thin layer of the mixture is then deposited on one surface of the sample which is positioned by the operator in the centre of the plate. The process is repeated again for the other sample surface (the top tile) and the top plate laid over it. A 200 g weight is positioned on it to reach nominal adhesion strength after curing, for which one day is waited. During this procedure the operator has to be extremely conservative with the amount of Araldite deposited on the sample to prevent any glue spillages that could bond together the silicon tiles.

8.3.3 Prepared samples

Thirteen Epo-Tek samples have been prepared, named S1-13, were prepared according to the following specifications:

- 20 × 10 mm² and 27 × 10 mm² rectangular tiles from pre-cut dummy wafer.
- Glue mixing: 100:15 by mass, 5 minutes at 2000 RPM.

- Glue dispensed with Fisnar robot, two days curing time allowed.
- Carrier glued with Araldite 2012.

The first Epo-tek created sample was sacrificed to tune the testing routine, the remaining 12 were shear tested.

Ten Stycast samples, named S1-10, were prepared according to the following specifications:

- $20 \times 10 \text{ mm}^2$ rectangular tiles from dummy wafer left-overs.
- Glue mixing: 100:7.5 by mass, 5 minutes a 1000 RPM.
- Glue dispensed with Fisnar robot, one day curing time allowed.
- Carriers glued with Araldite 2012.

8.3.4 Ageing

Samples were aged using an oven at 70°C , which allowed to reproduce nearly two years of operation time in the span of three weeks. This was achievable thanks to the law governing the glue ageing

$$F = 2^{(T-20)/10}, \quad (8.1)$$

with T being the ageing temperature and F the ageing factor. Using $T = 70^\circ \text{C}$ the ageing factor is $F = 32$, resulting in 32 h equivalent of ageing at 20°C for each hour at 70°C .

Samples were split by sample number into even and odd, and tested in batches. Odd and even batches were thus alternated from testing to ageing, being switched each half year equivalent of ageing, approximately, i.e. a week. This setup helped maximise the number of tests carried out on each sample for each ageing stage, which proved crucial due to the incoming COVID 19 lockdown.

8.3.5 Test procedure

A test routine was formulated to characterise the response of the glue to the shearing force:

- Force raised to 20 N over 1 minute.
- 3 minutes settle time under 20 N load.

- Force reduced to 0 N (spring in rest position) over 1 minute.

Displacement, force and time are registered during the entire routine, which takes five minutes. The routine, which will be referred to as “trial”, is performed 5 times in a row for each ageing stage and each sample. Any shock-induced failure is averted slowly increasing the applied stress, then 3 minutes are allowed for the adhesive to settle under the 20 N tension. Similarly, gradually reducing the tension with the same pace as it was raised allows to verify that the sample returns to its starting position.

8.3.6 Results

Force, time and displacement are outputted in a text file in three columns. Displacement as function of the force data corresponding to 5 trials is extracted (Fig. 8.26), while time information is not used as only the behaviour under shear stress is under study. It should be noted that during the first trial a significant displacement is recorded at the beginning of the testing procedure. This is caused by small gaps between the apparatus components which become looser after one sample is removed and a new one tightened in the sample compartment. The effect is shown in Fig. 8.26. Thus, for further analysis the first trial is removed from data.

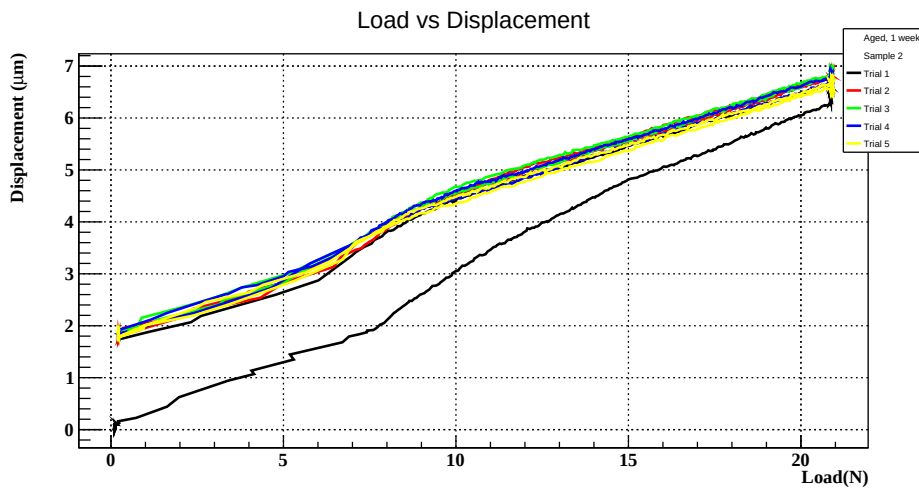


FIGURE 8.26: Displacement as function of shear load for Sample 2 after 1 week of oven ageing. Multiple colours are used to distinguish the five trials. Note the sizeable displacement in the first trial after which the system is “set”.

The initial offset of each trial is removed subtracting the initial displacement during data analysis, which allow to assess the presence of any residual displacement after the load is removed.

Data is fitted with a straight line and the slope, i.e. the Young's Modulus, extracted.

The slopes are thus extracted using 4 trials for each sample and are averaged to minimise the impact of external factors as carriers initial settling in the compartment or slight inconsistencies during the application of the shear stress. The performance is evaluated on the basis of the average slope. Data from each ageing step is analysed in this fashion.

The results are summarised in Fig. 8.27, each dot representing the averaged fit slope over 4 trials. Data for all the 12 Epo-Tek and 10 Stycast samples is shown, including all ageing steps from "fresh" samples to 1, 2 and 3 weeks of oven ageing, i.e. half, one year and almost two year of equivalent time, respectively. No clear evolution of the coefficients as function of ageing is found.

Figure 8.28 illustrates the straight lines (on the Displacement vs Load plane) obtained using the slope coefficient in Fig. 8.27, allowing to visually observe the final results: once again no clear trend emerges, with position of the curves and the displacement at 20 N unrelated to the ageing level and the number of trials.

Figure 8.27 shows how for both glues the slope variation is minimal, both within different ageing steps for the same sample and among all the tested samples. Summarising, the shear test results (Fig. 8.27, Fig. 8.28) show no relation between the elasticity of the glue and the ageing level, at least within 2 years of simulated time. Furthermore no degradation with repeated stress is traceable in the elasticity coefficient, even after a total of 15 trials performed over the span of 2 equivalent years.

To assess the affinity of the adhesives with silicon the samples were broken down after completing the tests. The desired outcome is a breakage originating in the glue interface which would leave glue residuals on both silicon surfaces. A clean silicon tile would instead suggest a failure in the glue-silicon interface testifying low adhesive affinity to silicon.

All 12 Epo-Tek samples were broken apart (Fig. 8.29) and 10 exhibited adhesive traces on both tiles. In two cases the failure happened in the Araldite 2012-carrier plate interface, proving the excellent bond strength of the glue.

Only four Stycast samples were broke apart and documented (Fig. 8.30), the remaining were kept for further studies. The samples showed an extreme bonding strength and outstanding silicon affinity, with one breakage in the glue layer, one in the silicon itself and two in the Araldite 2012 layer in the tile-aluminium interface.

As final observation, Epo-Tek glue samples appeared to be thinner and

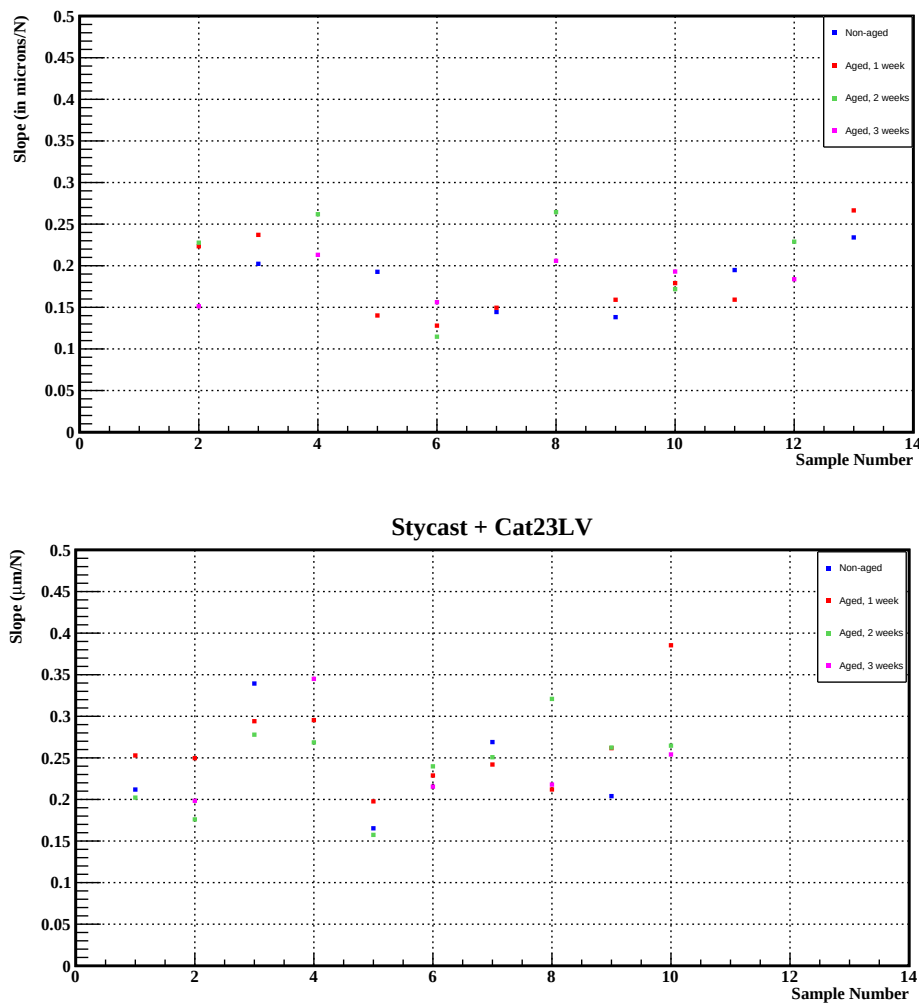


FIGURE 8.27: Results for the Epo-Tek (top) and Stycast (bottom) shear test campaign. Each dot represents the 4-trials average slope coefficient. On x axis the sample number, the slope (in $\mu\text{m}/\text{N}$) is on the y axis; the oven age stage and corresponding colour coding is shown in the legend. No detectable trend in the variation of the slope as function of ageing is observed.

more spread out with respect to the Stycast counterpart, with some traces of resin-filler separation occurring. Stycast on the contrary offers more resistance to pressure when pushed with a weight due to its higher viscosity.

8.3.7 Conclusions

Epo-Tek T7109-19 and Stycast 2850 FT-catalyst 23LV showed excellent resistance to reiterated elastic stress keeping their elasticity intact even with two years of equivalent ageing. The shear test campaign outcome excluded any worsening (nor any dependency) of the elastic properties with progressive ageing for both tested adhesives: both for the slope coefficient (Fig. 8.27) and the displacement

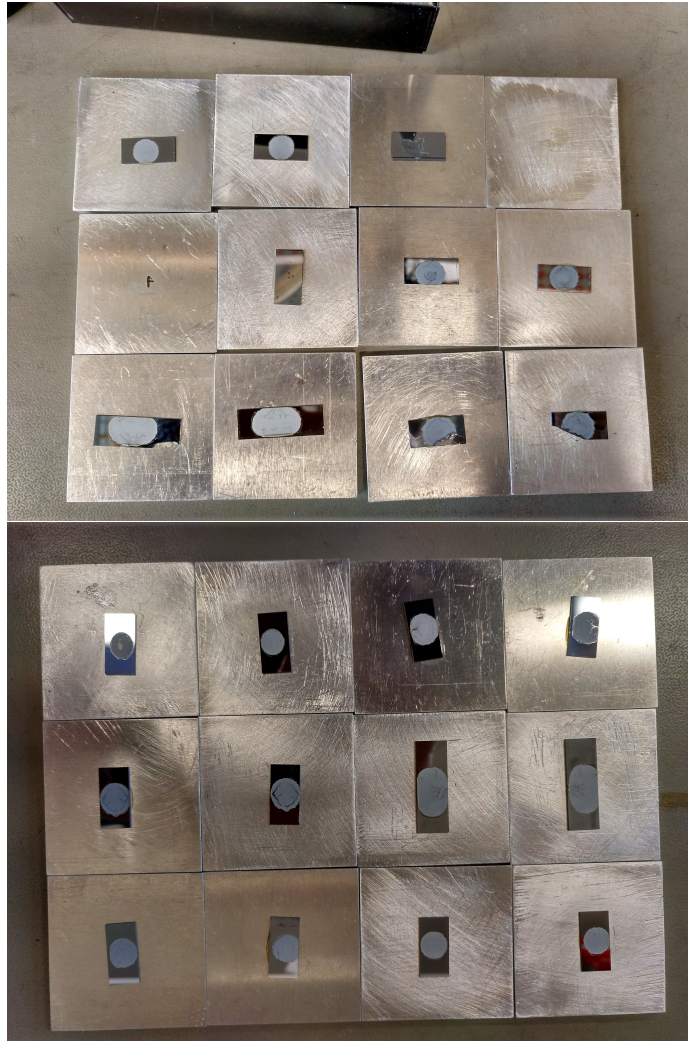


FIGURE 8.29: Split shear test Epo-Tek samples. The samples were broken apart after the end of the testing campaign to assess the adhesive affinity with silicon. On the left even numbered samples; on the right odd numbered samples, with two samples with failure in the Araldite 2012-aluminium interface (top image, empty aluminium plates). Note the glue residues on all tiles surfaces.

8.3.8 Heat treatment

The catalyst chosen for production glue, Stycast 2850 FT-catalyst 23LV, shares a number of properties with the first glue employed in the early modules, Stycast 2850 FT-catalyst 9, among which the hygroscopicity of the catalyst, although to a lesser amount. Thus, on the basis of the experience previously gained with catalyst 9, a procedure was developed to prevent any humidity deposition on the glue surface before pressing down the tiles on the micro-channel substrate. The procedure, known as “heat treatment” (Fig. 7.6) consists in blowing hot air with a heat gun on freshly deposited patterns to remove any trace of moisture; the glue has to be pressed down within 1 minute from the treatment to prevent humidity reabsorption. To uniformly distribute the air flow

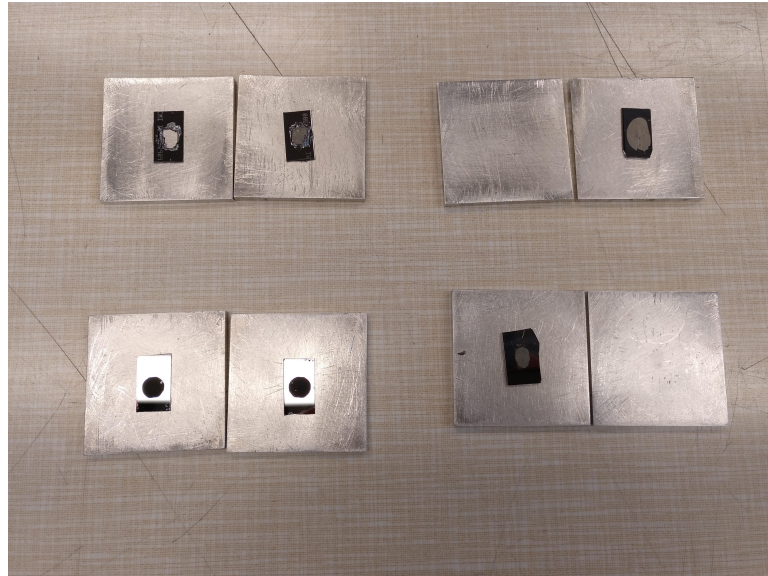


FIGURE 8.30: Stycast samples 1,2,3 and four after being split. In two samples failure in the Araldite 2012-aluminium interface is observed; in the top left sample the silicon is torn apart, adhesive traces can be observed on both tiles surface of the remaining sample.

bespoke nozzles were 3D-printed at Nikhef (Fig. 8.31), designed specifically to reflect the position for the tiles on each side.



FIGURE 8.31: Bespoke nozzles developed for the heat treatment. On the left the N-side nozzle, on the right the C-side one.

8.4 Summary

The choice of the correct adhesive to be employed in the VELO Upgrade module assembly campaign has been one of the most fundamental steps in the whole VELO Upgrade project after the shortcomings of the previously chosen glue. The glue layer that binds the tiles to the micro-channel substrate is the only medium available for heat exchange in the vacuum environment where the modules are operated. The layer needed to enable efficient cooling while retaining mechanical strength and elasticity in a 10 year lifespan while coping with the thermal deformations of the components. An intense R&D campaign has been launched to find a suitable substitute for Stycast 2850 FT-catalyst 9, which comprises pattern optimisation studies and the realisation of a number of mock-up wafer, one electrical module and a mechanic one. A shear testing campaign have been carried out at the University of Manchester to test the glue refractoriness to ageing and reiterated shear stress. Three glue were evaluated as Stycast 2850 FT-catalyst 9 alternatives: Araldite 2011, Epo-Tek T7109-19 and Stycast 2850 FT-catalyst 23LV. Araldite 2011 was discarded due to its low viscosity that rendered challenging to set and reach the target pattern thickness. Epo-Tek T7109-19 and Stycast 2850 FT-catalyst 23LV were shear tested, showing both excellent adhesion and elastic properties with no detectable degradation of their mechanical properties with ageing up to 2 years nor under reiterated mechanical stress. Epo-Tek T7109-19 was finally discarded because of schedule constraints as a more extensive R&D proved to be necessary in order to achieve a satisfactory attachment procedure outcome. Stycast 2850 FT-catalyst 23LV was finally chosen due to its overall excellent performance, ease of deposition and previous expertise available.

Chapter 9

VELO Upgrade commissioning

The VELO Upgrade detector installation was completed on 12 May 2022, when the A-side was successfully installed in the LHCb experiment after C-side installation in March the 2nd. After this moment the commissioning phase begun. The detector was tested once more for electrical performance to ensure all the components were properly powered and the Experiment Slow Control (ECS) and Data Acquisition (DAQ) chain were intact. Cooling was also checked to ensure the detector could be fully powered for physics datataking while keeping temperatures under 20° C and proper CO₂ boiling could be triggered correctly in all modules. Care was taken to ensure all the ASICs and FE hybrids could be appropriately controlled and configured via the GBTx chips. Equalisation of the pixel response was as well performed for each ASIC to uniform the response of the whole detector to interacting particles. Finally, the motion system was tested, proceeding with gradual steps until the full closure, which happened in 21 October 2022. The VELO, commissioned and able to fully close, was then ready to deliver its full performance.

9.1 The VELO Upgrade project

The whole detector is controlled and monitored via a number of WinCC/OA (see Par. 7.3.4) projects, each of those dedicated to control specific functions and portions of the VELO Upgrade. The safety system of the detector is controlled by the VELO Safety System (VSS) projects. This is in charge of monitoring the temperatures and voltages of the VELO modules, as well as the pressures in the primary and secondary vacua. The VSS can trigger alarms if any of the surveyed parameters is outside the safety ranges. Furthermore, it monitors the distance of the modules from the beam and can trigger a “beam dump” (i.e. the proton beam is deflected out of the accelerator before reaching the

LHCb experiment) if beam instabilities threaten the integrity of the sensors when the halves are fully closed. A summary panel allows to control the full CO₂ circuit and visualise all the temperatures for each module and tile, while monitoring the foil and base temperatures as well. All the NTCs and PT100 readings are visible, with colour coding to quickly assess an anomalous reading. Each reading is clickable and opens a trending page where the trend history can be accessed. This allowed for example to identify a dry-out problem (i.e. total evaporation of CO₂ in the micro-channels) in Module 35, caused by the loss of the boiling point of the coolant that resulted in an undesired increase in temperature during the night. This Module was found to have a restriction in one of the CO₂ pipes which prevented it to reach stable cooling conditions. It was since deactivated waiting for the 2022 YETS (Year End Technical Stop) and has now been repaired. In addition to this, two NTCs are malfunctioning (readings are not consistent in time) and are greyed out to signal the operator not to rely on their information. For the same reason they are excluded from the VSS as well. These are also excluded from the safy. The configuration of each module is demanded to 4 FE projects, 2 for each side, each comprising odd and even modules. These allow to configure 13 modules each and recover errors that may arise during the datataking. DAQ has a dedicated project as well, which allows to monitor the behaviour of each data link and disable them if any malfunctioning or frequent errors are detected; this is most crucial when physics data is being collected as it might compromise data quality. The motion system has a dedicated project as well which can permit the close of the halves towards the beam line, reaching 5.1 mm from the p-p interaction point. High Voltage (HV) and Low Voltage (LV) have their own projects to bias the sensors and power the Opto Power Board (OPB), hybrids and chips, respectively. LV and HV projects are closely interlinked as LV must be provided to the modules before HV can be turned on: HV is in fact connected to the LV lines of the ASICs so if no low voltage is passed to the chips the ground is floating. This is dangerous as it could generate sparks that can irreparably damage the sensors, ASICs and wirebonds. The FE project allow to configure the GBTx, FE hybrids and ASICs of each module into various power modes (see Par. 7.3.4), similarly to the panel used during modules validation (see Sec. 7.3). From here all the chip functionalities such as internal voltages and temperatures are accessible. The FE project allows as well to open the equalisation panel for each ASIC. Finally, the “Top” panel allows to control the full detector and gives access to the sub-projects of the VELO sub-components (e.g. DAQ, LV, HV).

9.2 High Voltage project

The High Voltage project is demanded to bias the sensors (in the following “tile” will be used in lieu of “sensor” for convenience) and monitor their currents and voltages. It communicates with the HV boards (Iseg EHS Series [118], 16 channels with 2 nA current resolution) that deliver voltage to the tiles via the HV tapes mounted on each module. The project is divided in two FSMs, one per half, each accessible from the Top VELO panel which opens a global operation panel (Fig. 9.1) with two buttons, one to check the OPB status and another to open the HV crates (Iseg ECH 54A [119]) view.

As multiple VELO modules are connected to a single HV board, and up to 7 boards to a single HV crate, it is useful to specify the channel mapping of the HV hardware to each VELO tile. An HV crate is assigned to each VELO half, namely **C00** for C-side and **C01** for A-side. Within each crate are allocated 7 HV boards, **M##** where **##**=00-16 is the number of the board. Each board can power up to 16 channels, going from **ch00** to **ch15**, corresponding to a VELO tile each. As 16 channels can power up to 4 modules, a naming convention allow to map each HV channel to a VELO tile. Thus, each **ch##** is associated to **VX##_VPK**, where X=C,A indicates the VELO half, **##**=00-52 is the VELO module number and K=0-3 identifies the tile on the module. Thus, taking Fig. 9.3 as reference, **VELO_HV_C00M12 ch04** corresponds to **VC22_VP3**, that is tile VP3 for Module 22 on the C-side.

From the “Manual Operations” box the interested portion of the detector can be selected, ranging from a single HV board i.e. 4 VELO modules up to a full half up to the entire detector. From here the operator can power off, set a global voltage value or open the “low granularity” IV scan panel for the selected portion of the VELO (Fig. 9.2). In this panel a number of settings for the scan can be specified (maximum voltage, step, ramp, number of measures to average) and a bar trend is used to visualise the monitored currents of all the tiles together to enable the operator to spot anomalous high currents and promptly stop the scan. The scan time is defined by the ramp speed, number of measures, maximum voltage and step value and does not depend on the number of channels selected. A scan from 0 to 300 V with ramp speed 2 V/s, step voltage of 10 V and 10 measures per point takes around 20 minutes.

The “VELO_HV_ISEG” button opens a summary view of the HV crates (Fig. 9.3) displaying the status of the HV boards connected to it. A box is dedicated to each board displaying the tiles connected to it in the form of a small rectangle. This reports the channel-tile mapping, applied voltage and

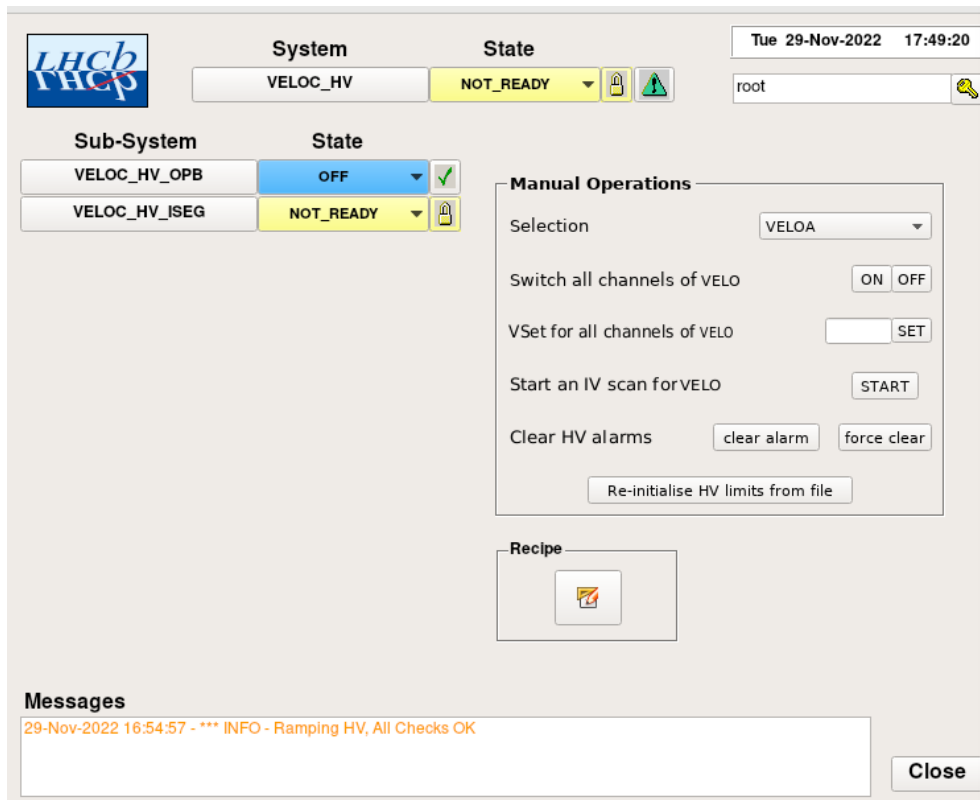


FIGURE 9.1: The main HV project panel.

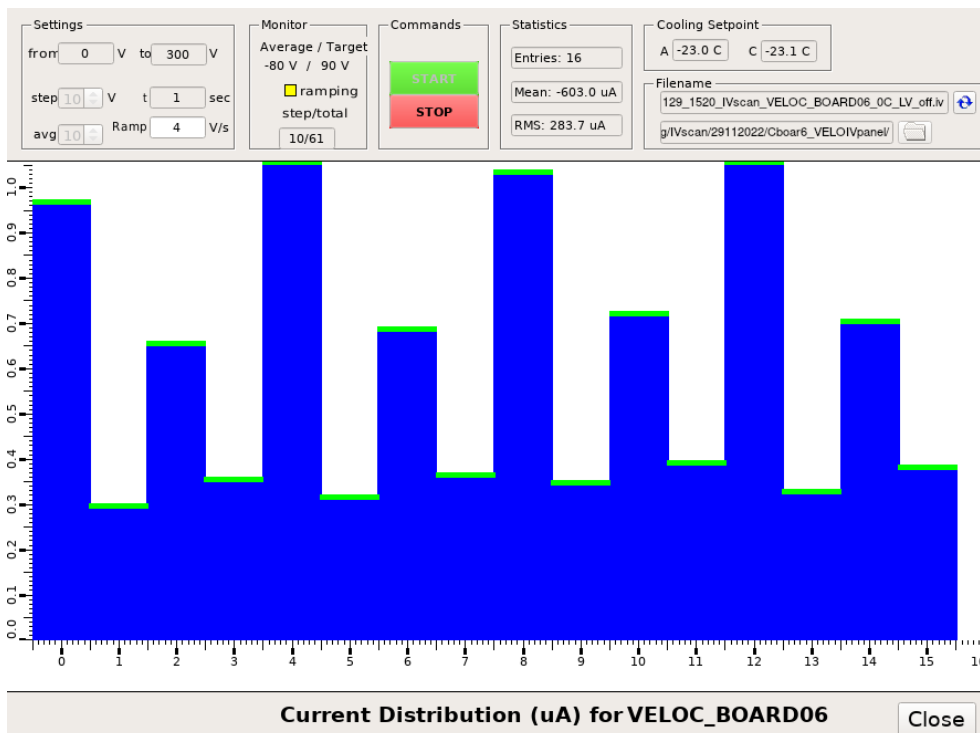


FIGURE 9.2: The “low granularity” IV scan panel.

current reading. The status of each tile is colour coded: blue stand of “off”, orange for “standby” or “ramping”, green for “ready”, red for “trip” or “error”.

Clicking on the tile box an advanced settings window is opened where values of Itrip (maximum trip current), Vset (set voltage), Vramp (voltage ramp speed) can be set.

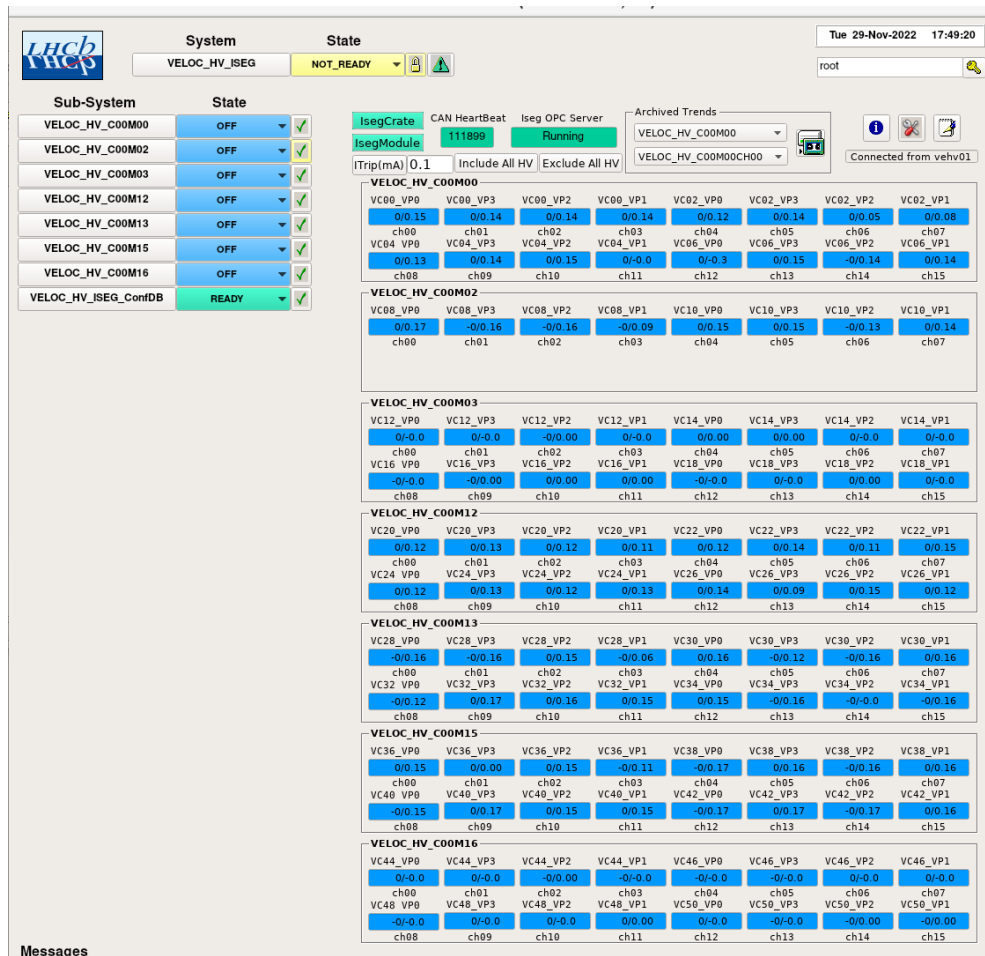


FIGURE 9.3: Summary view of the HV crates.

Clicking on the button related to each board, e.g. **VELOC_HV_C00M00**, opens its detailed view panel in Fig. 9.4, with explicit information regarding the monitored current and voltage of each tile. Clicking the **Settings** button (or the **chxx** button on the left, with xx=00-15) enables to access advanced settings as Itrip, Vset, and ramp speed and clear alarms. The channel status is highlighted by three colour coded LEDs with the same blue-orange-green-red coding mentioned above.

This panel allows to access the trending page for the 16 monitored channels and the IV scan panel (Fig. 9.5) for a specific HV board. From here it is possible to select and scan from one to the whole 16 connected tiles, for a total of 4 modules at the time. The parameters of the scan are user-entered and comprise maximum voltage to reach, step value, ramp speed, number of measures to take at each voltage step (can be one). A trending plot shows in real time the

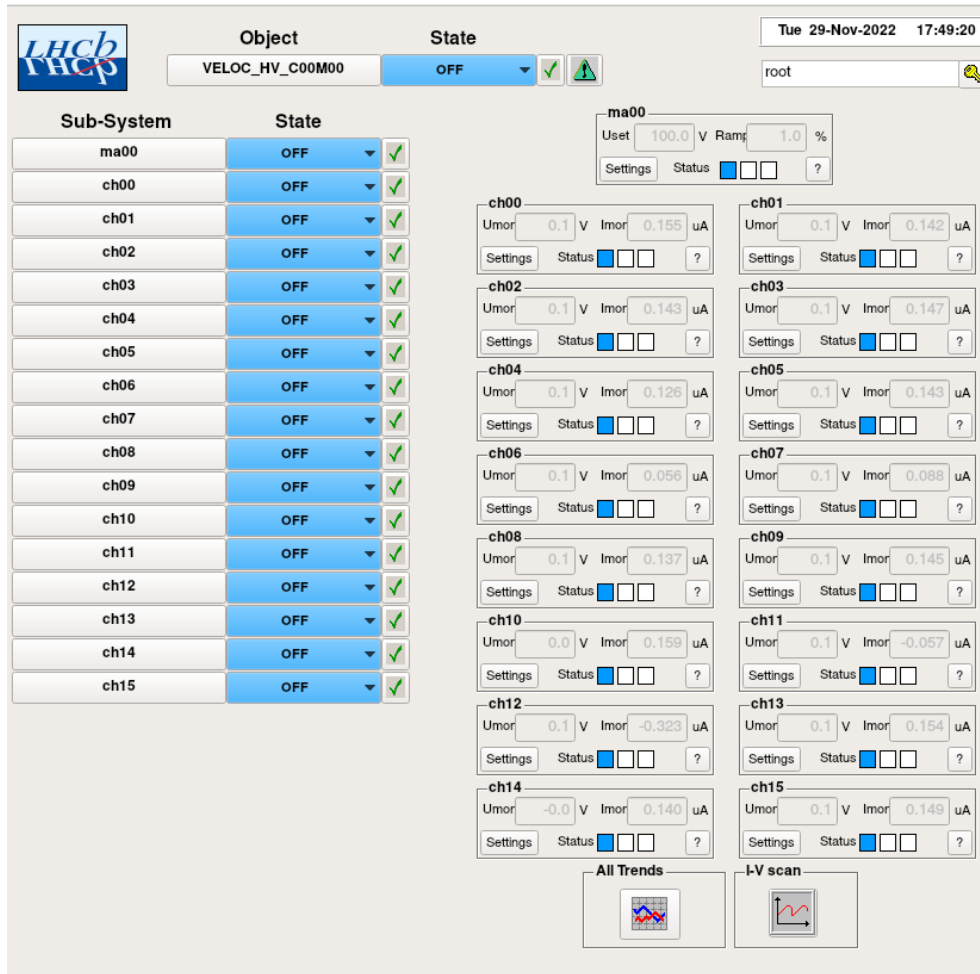


FIGURE 9.4: Detailed view of one ISEG Module.

current read at each step, or the mean of the selected number of measurements. An option to show a previous scan from the same channel is available too that prints a point in sync with the current scan. The cooling set-point can be specified as well to provide information regarding the cooling conditions at the moment of the scan and enable proper leakage current comparisons with future or older IV curves. This IV panel has Storck (the official LHCb database, see Sec. 9.2.1 below) functionalities embedded to communicate with the LHCb database. The scan time depends on the same parameters mentioned above, namely ramp speed, number of measures, maximum voltage and step value and not on the number of selected tiles to scan. As for the other panel, a scan from 0 to 300 V with ramp speed 2 V/s, 10 as step voltage and 10 measures per point take around 20 minutes.

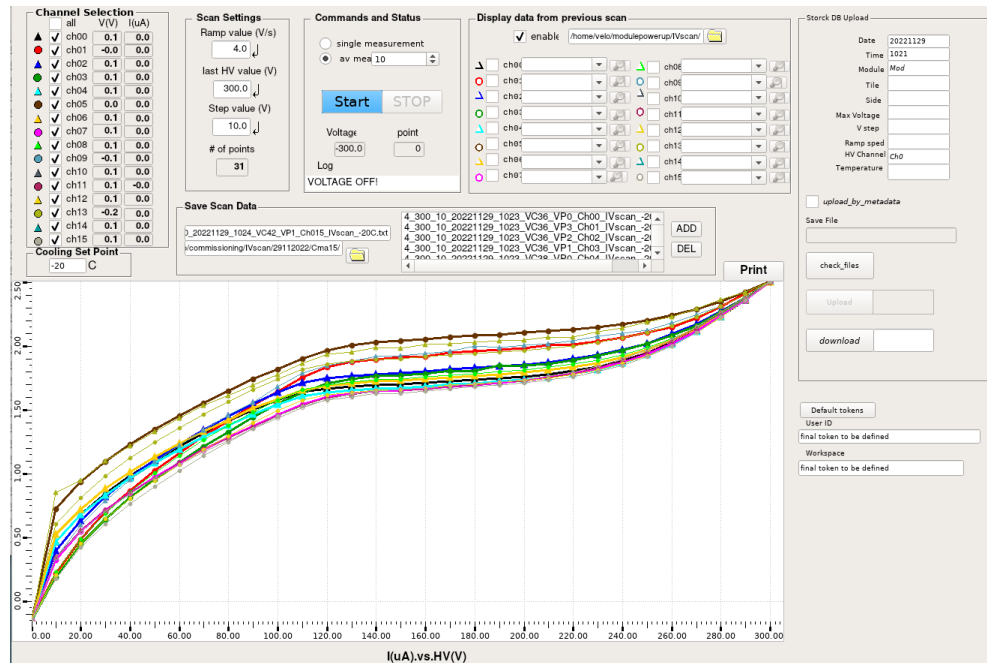


FIGURE 9.5: “High granularity” IV scan panel with embedded database functionalities.

9.2.1 Storck database

Storck is a database based on kubernetes [120] designed to host the LHCb data for Run 3. It has a web user interface from which data can be visualised and accessed. The interaction of the HV project with the database is based on a Py-DIM [121] server which communicates with the HV machine via the Distributed Information Management (DIM) system [122] protocol and with the database via Storck client (python). The communication is realised via client commands and services, writing and reading datapoints (DPs) on the WinCC/OA HV project: when the HV panel writes DPs it triggers a corresponding function in the server. The server then performs a defined task (e.g. data integrity check, search, download) and writes DPs back into the project to signal that action has been completed. As an example, the upload of IV scans that have been just taken proceeds as follows: the operator clicks the **check_files** button, which writes the file names to be checked into a DPs array. This action triggers the “check file” function on the server side that verifies that the files have been written. After the check is complete the server writes a DP to the project, enabling the **Upload** button. Upon click, the process repeats, but this time the server uploads the scans to the database using the upload function embedded in the Storck client. The scan parameters entered by the user in the HV panel are used as metadata for the database, so that data can be easily retrieved with queries. Up to the moment when this document has been written, the server is able to upload the scans just taken, to upload using metadata query and perform

simple sanity checks on data, as “the file exists” and “the file is not empty”.

9.3 Radiation damage estimation

The VELO Upgrade detector is expected to receive a total dose up to 8×10^{15} 1 MeV n_{eq} cm^{-2} in its lifetime [3]. This corresponds to a maximal current, for the most irradiated tiles, of approximately 200 μA at $-20^\circ C$ and 1000 V (expected depletion voltage at end of life of the detector), equating to ~ 7 nA in the most irradiated pixels [3]. The irradiation profile is strongly dependent on the distance from the interaction point, with fluence curves to follow approximately a $A \times R^{-k}$ profile, with R being in mm and A a proportionality constant. An example of the simulated fluence curves for VP0, the tile closest to the beam, are shown in Fig. 9.6 for two modules. The irradiation profile strongly depends on the distance, on the z axis, with the exponent varying from 2.1 to 1.9 across the length of the detector (Fig. 9.6(a)). Modules near the interaction zone ($z=0$) are thus expected to receive a higher dose and accumulate more radiation damage compared to the downstream ones, leading to higher leakage currents. IV (Current versus Voltage) scans offer a fundamental tool to monitor the evolution of the radiation damage with fluence by monitoring the increase of leakage current with time.

Few scans have been taken during the 2022 year of datataking, accounting for both VELO open and closed configurations. The number of scans taken has been limited by a number of factors: beam time, priority of other operations (e.g. equalisation of the ASIC pixel response) and availability of high precision ISEG modules [118] able to read currents of the level of the nano ampere. Thus, only 3 high precision IV scans are available for a selection of modules, while all the others have two. The scans were taken at three levels of delivered luminosity (i.e. the number of p-p interactions produced by the LHC at the LHCb interaction point), one at the very early life of the detector, one just before the VELO was fully closed for the first time, and the last one at the end of the operations in 2022. The dates with VELO delivered luminosity are listed in Table 9.1. In the following results for Module 44 ($z=587.50$ mm), Module 36 ($z=262.50$ mm) and Module 15 ($z=0$ mm) will be shown. All the scans were taken averaging 10 measurements at each voltage step to mitigate the impact of possible current fluctuations occurring when increasing the voltage.

The three scans for Module-44 are shown in Fig. 9.7: before drawing any conclusion on the evolution of the leakage current, it must be noted that the

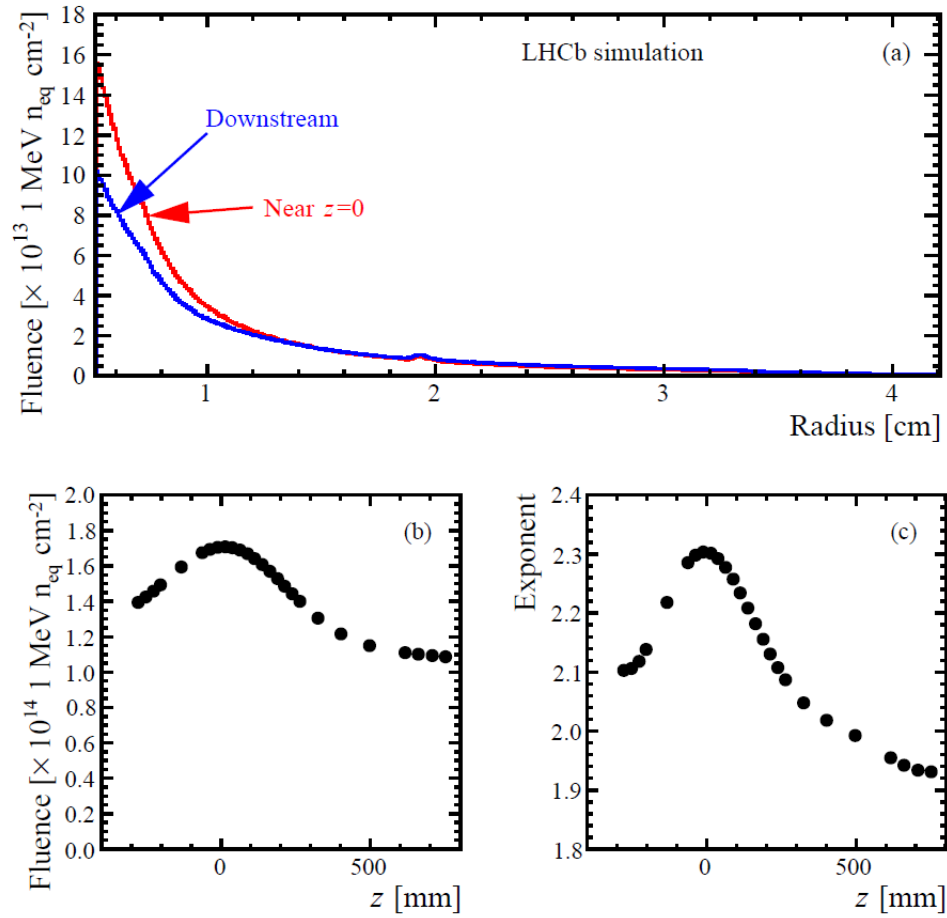


FIGURE 9.6: On top: simulation of the expected fluence per fb^{-1} profile as function of R for the most irradiated sensors in a downstream module (blue) and a module above the interaction zone (red); both curves are fitted with $A \times R^{-k}$ where A and k are fit constants and R is the radius. Down left: fluence at the closest tip to the beam as function of z coordinate of the module. Down right: exponent as function of the z coordinate. Images from [3].

Date	Total delivered luminosity	Delivered luminosity, VELO out	Delivered luminosity, VELO in	Temperature
03/08/22	0.093 fb^{-1}	0.093 fb^{-1}	0	-29° C
28/09/22	0.321 fb^{-1}	0.321 fb^{-1}	0	-30° C
29/11/22	1.059 fb^{-1}	0.793 fb^{-1}	0.264 fb^{-1}	-22° C

TABLE 9.1: Delivered luminosity at the time of the three IV scans with related temperature. The VELO position with correspondent delivered luminosity is specified as well.

scans were taken in different cooling conditions thus at slightly different temperatures. Thus, unless stated otherwise, all the data shown in the following has been re-scaled to -30° C to allow for a pertinent comparison of the currents. The currents have been re-scaled using

$$I(T) = I(T_{ref}) \left(\frac{T}{T_{ref}} \right)^2 \exp \frac{-E_g^{eff}}{2K_B} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right), \quad (9.1)$$

where $E_g^{eff} = 1.21$ eV is the effective energy gap, $K_B = 8.617 \cdot 10^5$ eV/K is the Boltzmann constant, $I(T)$ and $I(T_{ref})$ the current at the re-scaled temperature and reference temperature in Kelvin, respectively. Approximately the current halves every 8 K. The temperature corrected scans are shown in Fig. 9.8, and a noticeable decrease in leakage current is observed comparing the last luminosity step curve with the non-corrected one.

It can be observed that the leakage current is higher on VP0 and VP2, which are the tiles closest to the beam line, as expected, with VP0 having consistently more leakage current at all irradiation stages. This can be due to temperature effects, as VP0 has larger overhanging area not directly cooled by micro-channels. This translates in a temperature gradient which is likely responsible for the current difference. This trend is confirmed looking at Module 36 and 15 IV curves (Fig. 9.9 and 9.10), for which only the two last luminosity steps were available.

The leakage current increase with delivered luminosity from the first to the second step is twofold, while a sixfold increase is observed from the second to the third step, which corresponds with datataking with VELO fully closed. The increase in current is most evident when comparing Module 44 VP0 leakage current for the three scans together (Fig. 9.11). The comparison between VP0 returns a similar result for the other two modules, with a sixfold increase in leakage current between the scans taken in 28/09/22 and 29/11/22 (Fig. 9.11).

To evaluate whether the increase in current is within expectations it is necessary to convert the delivered luminosity into a fluence. The fluence, which expresses radiation dose received by the sensors, can then be plotted against the current measurements performed at each luminosity stage. Fluence curves have been extracted using the simulation data available in the VELO Upgrade Technical Report (TDR) [3]. Specifically, the exponent k and the maximum fluence per fb^{-1} for $z = 0, 262.50, 587.50$ (see Fig. 9.6(b) and (c), respectively) were used to work out the proportionality factor A and reconstruct the corresponding fluence curves (Fig. 9.12).

Accounting for both VELO opened and closed positions, 0.52 cm (in 2022 1 mm safety shims were installed to prevent the sensors to inadvertently touch the RF-foil) and 3.3 cm from the beam line, respectively, the fluences per fb^{-1} were extracted for the three aforementioned modules (see Table 9.2).

These values can be then multiplied by the delivered luminosity to obtain the fluence values at each luminosity step (Table 9.3).

The Hamburg model [87] states that the increase in leakage current is linear with the fluence following the relation

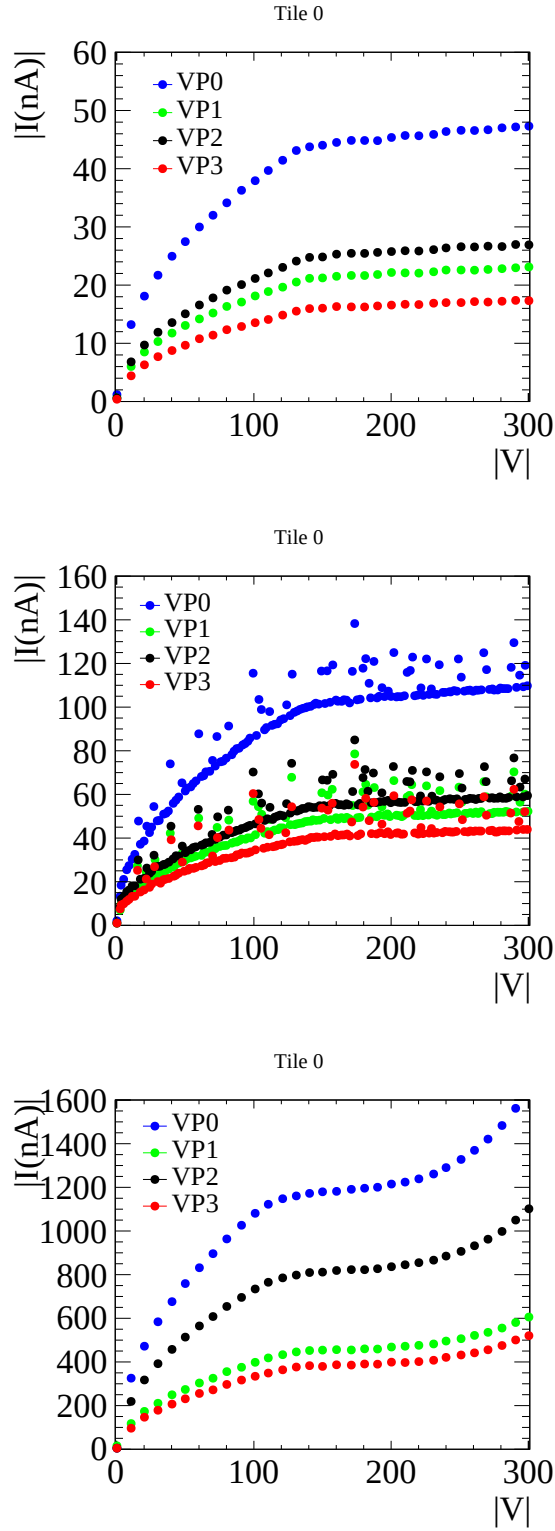


FIGURE 9.7: Module 44 IV scans taken during 03/08/22 at -29°C (top), 28/09/22 at -30°C (centre), 29/11/22 at -22°C (bottom). A 10 V step was used for the top (August) and bottom (November) scans, a 2 V step was used for scan the middle (September). The fluctuations observed in the latter are caused by current over-fluctuation induces by the voltage increase in the HV modules. These values were recorded instead of the averaged values. The curves corresponding to each tile are colour coded (see legend): VP0 in blue, VP1 in green, VP2 in black, VP3 in red.

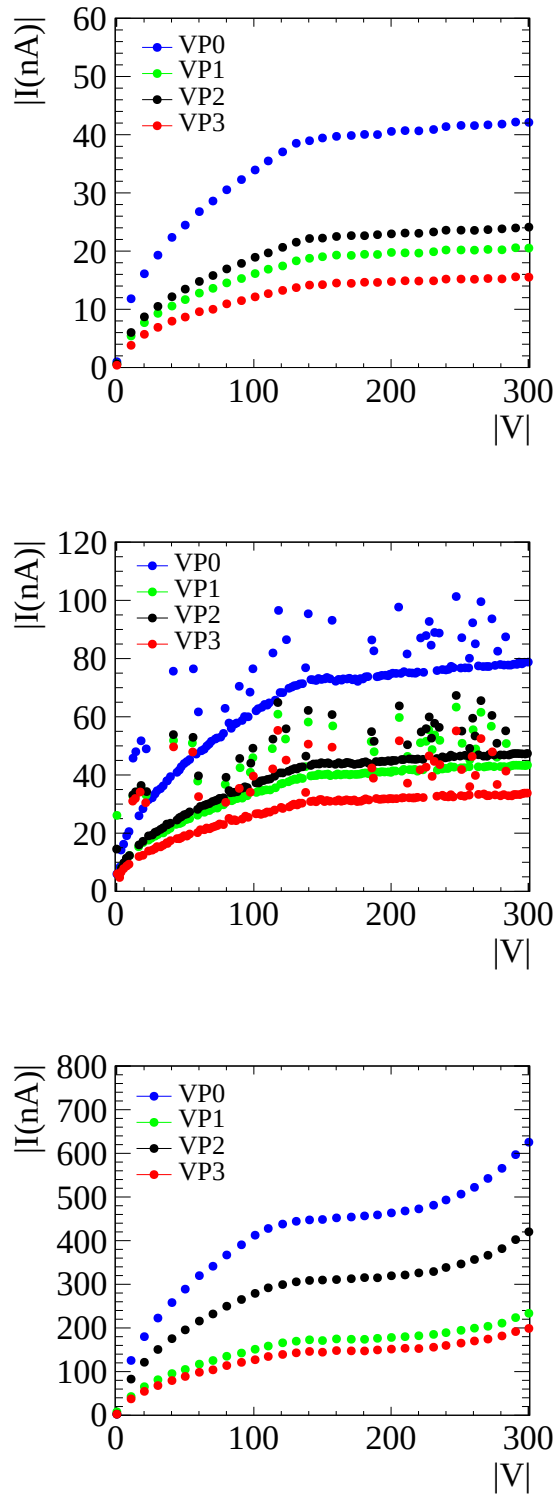


FIGURE 9.8: Module 44 IV scans, re-scaled to -30°C , taken during 03/08/22 (top), 28/09/22 (centre), 29/11/22 (bottom). A 10 V step was used for the top (August) and bottom (November) scans, a 2 V step was used for scan the middle (September). The fluctuations observed in the latter are caused by current over-fluctuation induces by the voltage increase in the HV modules. These values were recorded instead of the averaged values. The curves corresponding to each tile are colour coded as specified in the legend.

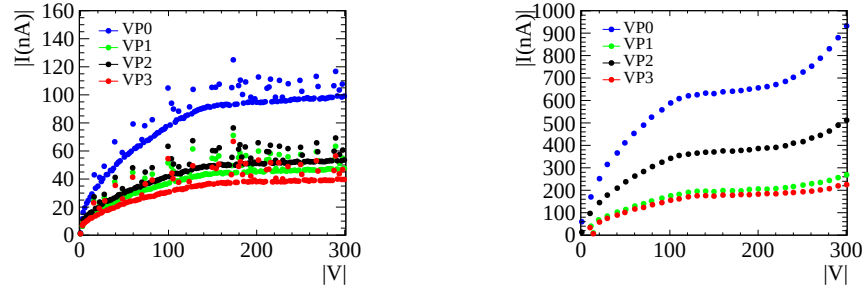


FIGURE 9.9: Module 36 IV scans taken during 28/09/22 (left), 29/11/22 (right). The colour coding for each tile is specified in the legend.

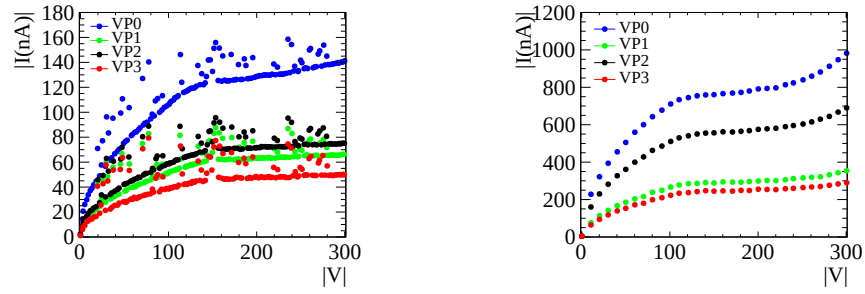


FIGURE 9.10: Module 15 IV scans taken during 28/09/22 (left), 29/11/22 (right). The curves corresponding to each tile are colour coded (see legend).

	VELO position	Module 15	Module 36	Module 44
Φ per fb ⁻¹	Open	0.23×10^{13} n _{eq} /cm ²	0.29×10^{13} n _{eq} /cm ²	0.28×10^{13} n _{eq} /cm ²
Φ per fb ⁻¹	Closed	16.2×10^{13} n _{eq} /cm ²	13.5×10^{13} n _{eq} /cm ²	10.6×10^{13} n _{eq} /cm ²

TABLE 9.2: Estimated fluence (Φ) per fb⁻¹ at the position of the pixel closest to the beam for Modules 15, 36, 44 for VELO opened and closed positions.

Date	Delivered Luminosity	Φ Module 15	Φ Module 36	Φ Module 44
03/08/22	0.093 fb ⁻¹	//	//	0.26×10^{12} n _{eq} /cm ²
28/09/22	0.321 fb ⁻¹	0.73×10^{12} n _{eq} /cm ²	0.92×10^{12} n _{eq} /cm ²	0.89×10^{12} n _{eq} /cm ²
29/11/22	1.059 fb ⁻¹	44.7×10^{12} n _{eq} /cm ²	37.8×10^{12} n _{eq} /cm ²	30.2×10^{12} n _{eq} /cm ²

TABLE 9.3: Estimated fluence at the position of the pixel closest to the beam for Module 44 extracted for each delivered luminosity, taking into account both VELO open and closed position.

$$\frac{\Delta I}{V} = \alpha \Phi_{eq}, \quad (9.2)$$

where ΔI is the variation in leakage current, V is the sensor volume, α is a fitted constant and Φ is the fluence (see 5.3).

Knowing that the increase in current should be linear with the fluence, the currents at depletion voltage (140 V) can be plotted as function of Φ and fitted with a straight line. The fit result for Module 44 is shown in Fig. 9.13, proving that at first order the increase is linear although more points would be needed to

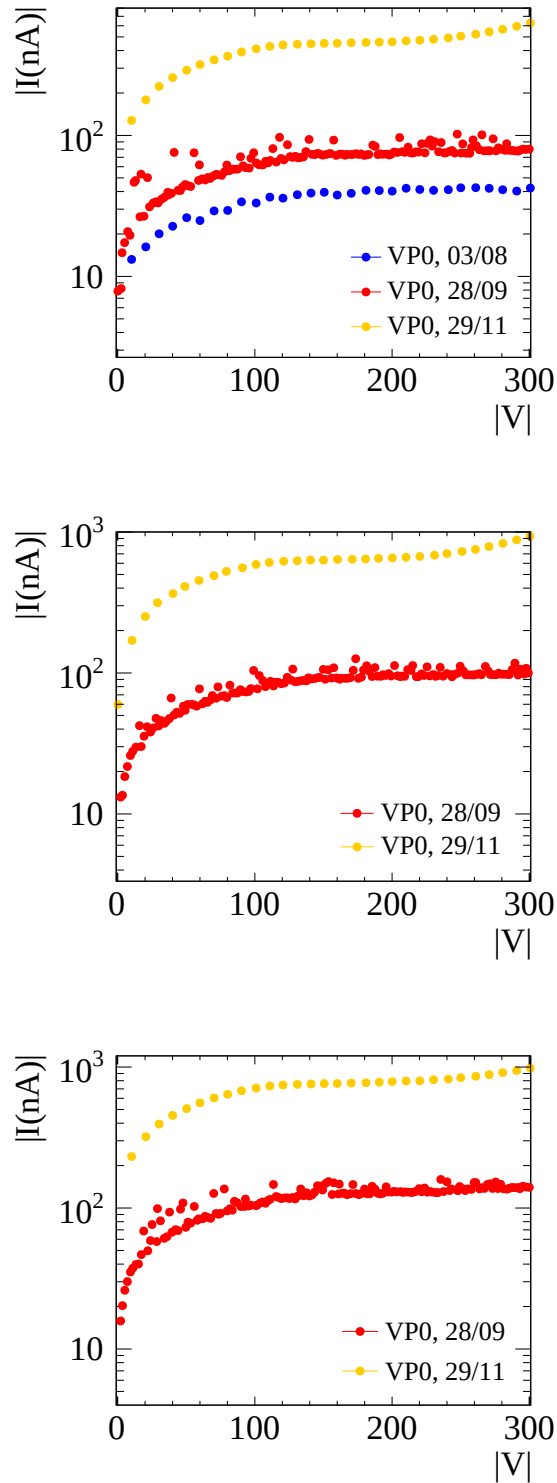


FIGURE 9.11: Leakage current for VP0 at different delivered luminosities for Module 44 (top), Module 36 (centre), Module 15 (bottom). The colour coding of the curves is specified in the legend for each figure.

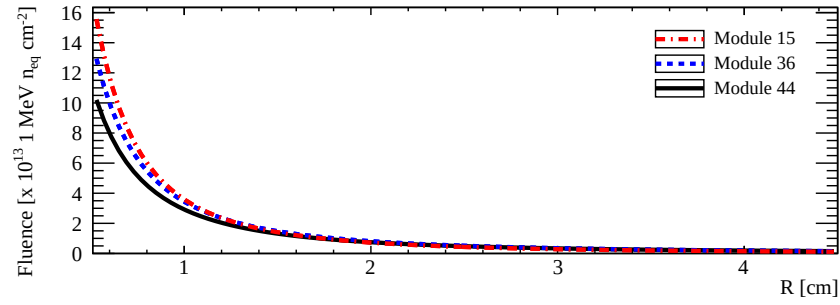


FIGURE 9.12: Reconstructed fluence curves per fb^{-1} for Module 44, 36 and 15. The curve for VP0 is show in blue, the one for VP1 in green, VP2 in black and VP3 in red.

better constrain the fit results. The same process can be repeated for Module 36 and Module 15 (Fig. 9.14): in both cases only two points are available, so the only meaningful information is provided by the slope of the fitted straight line. In all three instances the slope values (Table 9.4) are compatible with each other. This suggests that the increase in leakage current after 2022 data-taking is compatible with scaling linearly with the fluence and uniformly across the whole detector. Furthermore, the compatibility of fit results assures that no anomalous increase in current is occurring.

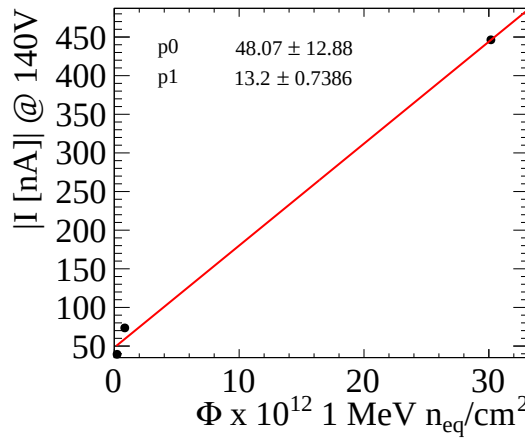


FIGURE 9.13: Fitted current as function of fluence at depletion voltage.

	Module 15	Module 36	Module 44
Slope $[\text{nA} \times 10^{-12} \text{ cm}^2 / \text{MeV } n_{eq}]$	14.45 ± 0.03	14.65 ± 0.04	13.2 ± 0.74

TABLE 9.4: Slope values from the I vs Φ fits for Module 15, 36, 44.

Further information can be obtained observing the leakage current at 140 V as function of the z axis, i.e. module position. The results, shown in Fig. 9.15

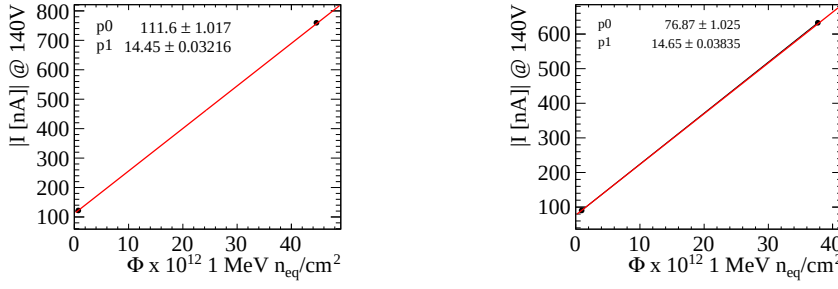


FIGURE 9.14: Fitted current as function of fluence at depletion voltage for Module 15 (left) and Module 36 (right).

at the original temperature of -22°C , testify an increase of the leakage current in modules, going from negative z (upstream module) toward the interaction point, situated around $z=0$ mm, which decreases again going towards the downstream modules (high z). Once again the leakage trends among the tiles are confirmed, with VP0 having consistently higher currents than VP2, followed by VP1 and VP3. A further crosscheck is the increase in current as a function of the multiplicity (μ) of p-p interactions for each bunch crossing. As more charged particles are generated by the increased number of collision per bunch, the current is expected to scale linearly with it. The effect is shown in Fig. 9.16a for Module 18 ($z=262.5$ mm) at 140 V, confirming a linear increase of the current at depletion voltage with the mean number of collision per bunch. The linear increase is even clearer looking at the ratios between the measured current at each μ step and the current recorded at $\mu = 1.1$ versus $(\mu/\mu = 1.1)$ (Fig. 9.16b). The following expression is used for the current ratios for each tile

$$\frac{I_{\mu} - I_{\mu=0}}{I_{\mu=1.1} - I_{\mu=0}}, \quad (9.3)$$

where $I_{\mu=0}$ is the current when no p-p interactions are occurring. This allows to remove the offset in each tile due to the radiation damage contribution to leakage current.

9.3.1 Beneficial annealing studies

The VELO Upgrade detector spent 35 days at the temperature of around 23°C (from 12th January 2023 to 17th February 2023) due to a failure in the Detector Safety System which stopped the cooling. As mentioned in Sec. 5.3, silicon sensors have to be permanently cooled during and after irradiation to “freeze” the crystal lattice damage in place and avoid increase in leakage current and

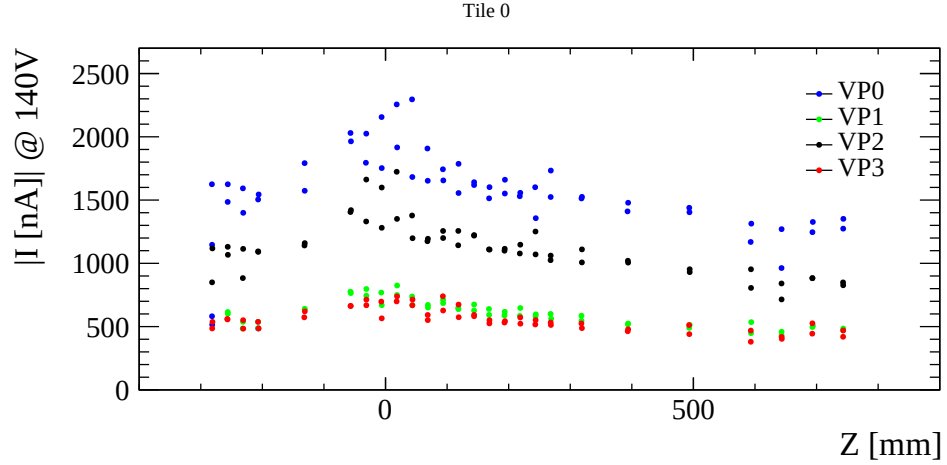


FIGURE 9.15: Currents at 140 V for each module at -22°C . Odd and even module are displayed at the same averaged z . The curves corresponding to each tile are colour coded (see legend): VP0 in blue, VP1 in green, VP2 in black, VP3 in red.

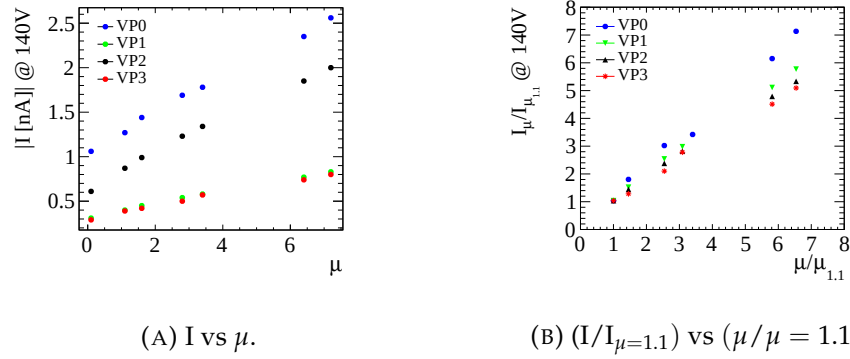


FIGURE 9.16: Left: I vs μ at 140 V. Right: $I/I_{\mu=1.1}$ as function of $\mu/\mu = 1.1$. Both plots are referred to Module 18. The increase in current for each tile is linear as expected. The curves corresponding to each tile are colour coded (see legend): VP0 in blue, VP1 in green, VP2 in black, VP3 in red.

eventually thermal runaway. If active cooling is not applied after irradiation, the thermal energy of the atoms trigger the annealing of point-like defects, causing at first a reversal of radiation damage followed by a non-reversible increase. The former, known as *beneficial annealing*, happens in time scales spanning from days to few months, while the latter, known as *reverse annealing*, dominates at larger time scales. Both beneficial and reverse annealing modify the effective doping of the silicon, decreasing and raising the sensors depletion voltage, respectively, whereas the leakage current is expected to decrease with annealing as consequence of the partial removal of lattice defects. Thus, after 35 days at room temperature, it was possible to investigate the impact of annealing on the sensors by measuring the leakage currents at 140 V across the detector. Specifically, the impact of annealing on the leakage current of Module 15, 36

and 44 was assessed. In Fig 9.17 the leakage current at 140 V is shown for each module as function of the time the measurement was taken. A clear decrease in current is observed for all tiles, ranging from ~ 500 nA for the most irradiated tiles to ~ 60 nA for the least irradiated ones. The beneficial effects of the removal of lattice defects increases with the delivered dose (Fig. 9.18), meaning the current difference before and after annealing is higher for the VP0 and VP2 tiles and for the innermost modules. Interestingly, the innermost tiles of Module 44 benefited of a higher current decrease than VP1-3 from the modules closer to the interaction point, suggesting the Φ depends more strongly on the radius than on the z distance from the interaction point.

The current increase with the fluence was then cross-checked after the annealing period to confirm the linear proportionality regime is still valid, at least at first order. Thus, the fluence for a number of modules from $z = -300$ mm to $z = 800$ mm (namely Module 0, 6, 10, 15, 16, 18, 22, 26, 30, 34, 38, 44, 50; see [123] for the precise z position) was computed. The current at depletion voltage of the VP0 tiles for these modules was then plotted as a function of the estimated fluence and fitted with a straight line. The results, shown in Fig. 9.19, demonstrate that at first order the current still scales linearly with the fluence, despite some outliers. Furthermore, the slope value is lower than those registered at the end of 2022 data-taking, confirming the increased beneficial effects of damage removal for the most irradiated sensors. This will prove crucial for the operation of the VELO Upgrade detector at progressively higher irradiation, when short beneficial annealing phases will allow to mitigate the rise in leakage current and depletion voltage of the sensors.

9.4 Summary

The VELO Upgrade detector has been successfully installed in the LHCb experiment on the 12th May 2022. At this very moment the commissioning effort had begun and culminated with the first full closure of the VELO halves in October 2022. A number of WinCC/OA projects, spanning from an overarching control system, the VSS, to temperature (Summary panel) and voltage monitoring (LV and HV projects) have been laid down to monitor and control every functionality of the detector allowing to deliver its full performance. The High Voltage project is demanded to bias the silicon sensors to fully deplete them during p-p collisions, monitor the leakage currents and signal the operator when a channel trips due to anomalously high values. Within the HV project two IV scan panels have been developed as an essential tool to monitor the impact of the radiation

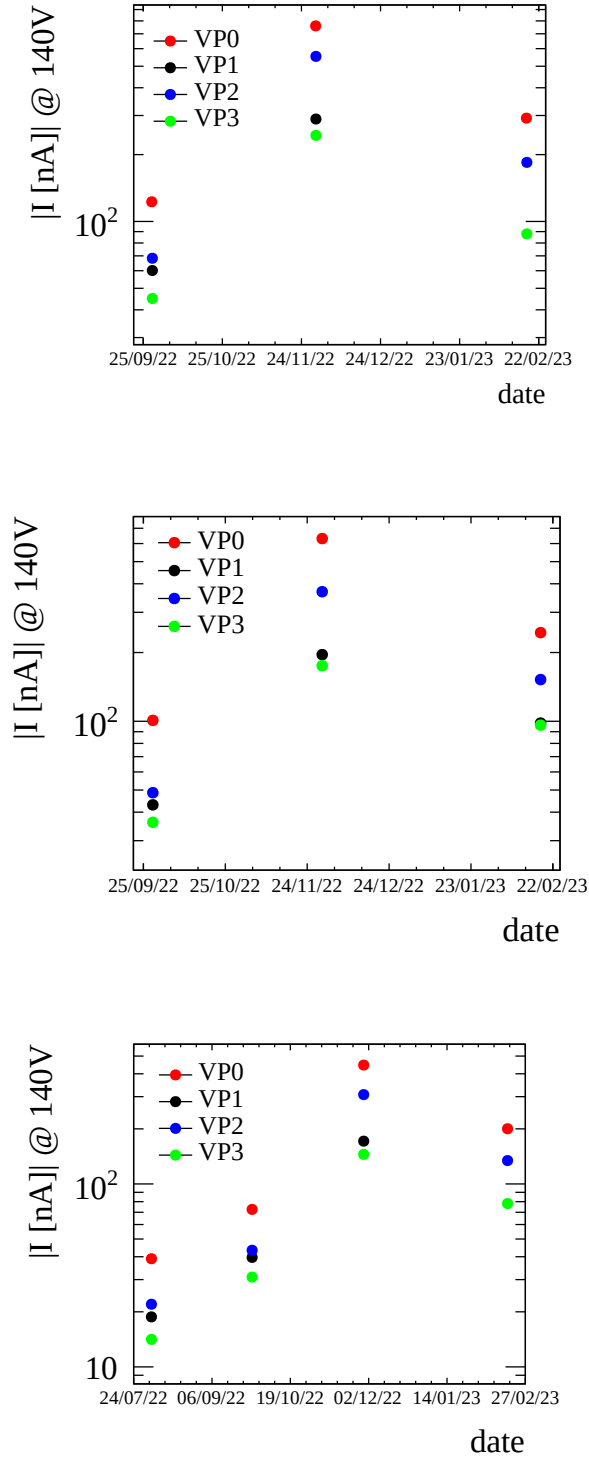


FIGURE 9.17: Current measured at 140 V as function of time for Module 15 (top), 36 (centre), 44 (bottom). The colour coding for each tile is specified in the legend.

damage build-up on the leakage currents of the sensors. The panels allow to scan from a single VELO tile up to the full detector in around 20 minutes. The “high granularity” panel allow to communicate with the Storck database and

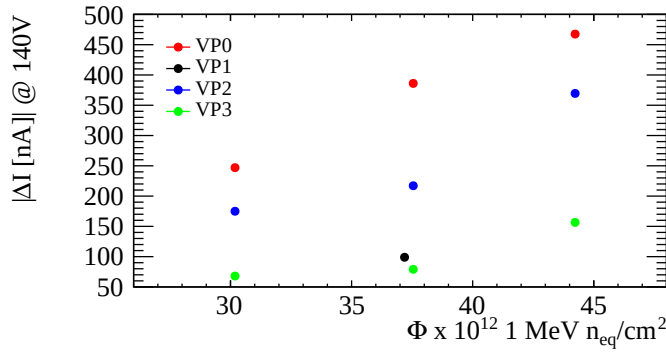


FIGURE 9.18: Absolute value of current variation before (ba) and after annealing (aa) defined as $|\Delta I| = |I_{aa} - I_{ba}|$ as function of total received dose from VP0 for modules 15, 36 and 44. The colour coding for each tile is specified in the legend.

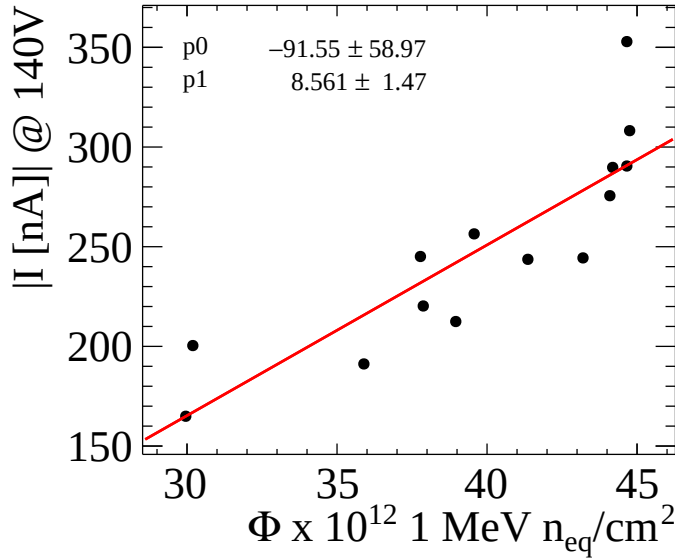


FIGURE 9.19: Current as function of fluence for VP0, fitted with a straight line. The increase in current is at first order linear. Data for Modules 0, 6, 10, 15, 16, 18, 22, 26, 30, 34, 38, 44, 50 is used to account for modules upstream, near the interaction zone and downstream.

upload the scans just taken or previous data, which can be selected using the scan parameters for metadata based queries. Up to three IV scans were taken during 2022 datataking, with an additional current measurement performed after 35 days of annealing of the detector at room temperature. With the collected data it was possible to carry out a first estimation of the impact of radiation damage on the sensors. The registered increase in leakage current has proved to scale linearly with the fluence, in line with prediction from the Hamburg model. Furthermore, the tiles closest to the beam (VP0 and VP2) were observed to have

consistently higher leakage currents than the farthest away (VP1 and VP3), confirming the radial dependence of the fluence profiles. The dependence on the distance from the interaction point of the radiation damage was confirmed observing the increase of currents registered in the central modules, which progressively decreases distancing from the interaction point. A multiplicity scan was performed progressively increasing the number of p-p interactions per bunch crossing while keeping the voltage at 140 V, resulting in a proportional increase of secondary particles crossing the sensors of the detector. This allowed to test the linearity of the response of the sensors as function of the number of tracks crossing them. The impact of the annealing was measured to be in line with expectations as well, with the beneficial effects of the removal of lattice defects increasing with the delivered dose. Finally, a linear fit was performed using a number of modules distributed across the detector proved that the current linearly scales with the fluence after annealing as well.

Chapter 10

Summary and conclusions

The LHCb detector has started in 2022 data-taking for the Run3 of the LHC. While the heart of the experiment, the VELO, has been upgraded to a whole new detector, a lot is left to discover with the available Run1 and Run2 data. This thesis has reported the search for CP violation in the $D^0 \rightarrow K_S^0 K \pi$ channel with the ET method with Run2 data, with final P-value of $P=0.696278$ and $P=0.658292$ for the SS and OS samples, respectively. These are compatible with CP symmetry scenario in the analysed samples. The assembly, R&D and commissioning of the VELO Upgrade has been discussed as well. The new detector is expected to face a fluence two order of magnitude higher than the old one: in this highly irradiated environment it must keep intact its efficiency and excellent track and impact parameter resolutions, to allow for the reconstruction of primary and secondary vertices of interaction. These are essential to carry out the b and c hadron physics programme of the LHCb collaboration. The new detector now comprises pixel sensors in lieu of microstrips, reaching 5.1 mm to the beam line. To keep the sensors cool a micro-channel silicon plate is employed to circulate evaporative CO_2 directly beneath the tiles, allowing for the dissipation of 30 W of heat produced by each module at operation conditions. As the glue attaching the tiles to the micro-channel is the only medium available for heat dissipation, the adhesive selection and layer optimisation underwent thorough R&D and properties assessment campaign to finally choose the most reliable, consistent and easy to use epoxy available: Stycast 2850 FT with catalyst 23LV. The University of Manchester carried out part of the VELO Upgrade module assembly campaign, building 46 detector grade modules currently installed in the VELO detector. During the assembly of each module careful metrology was carried out after each assembly step to ensure the quality of the build and spot defects in the components or procedures as soon as they manifest. After the assembly each module has been validated in a vacuum

tank reproducing operation conditions for electrical and cooling performance; tests spanned from displacement of the module under the strain of cooling pipes to the integrity of data transmission to thermal degradation of the glue layer. Each test data has been uploaded to the VeloPix database for automatic grading of the test results. After the completion of all the tests, modules are assigned a overall grade and quality number; only modules with overall A, B or C (efficiency > 99%) score are accepted for detector installation. As sensors are operated in a high radiation environment, the monitoring of the leakage current is a crucial tool to monitor the radiation damage evolution with the delivered dose. In this respect, two IV scan panels were developed, allowing to scan from a single tile up to the whole detector. A database interface was implemented as well, allowing for easy upload of the data directly from the scan panel. Three scans, at best, were taken during 2022 data-taking, with a further current measurement at depletion voltage taken after 35 days of annealing time. The picture extracted from this data is in line with expectations: modules closer to the interaction point have higher leakage current, while upstream and downstream modules are less affected by radiation damage. Furthermore, the innermost tiles consistently have higher leakage current than the farthest one from the beam line. Beneficial annealing has also had a sizeable impact on the leakage current, removing part of the crystal lattice damage. Finally, the leakage current before and after annealing scales linearly with the fluence as expected. The LHC will start a new year of data-taking in May 2023, opening a new exciting page for particle physics. New data will be stored at unprecedented pace for the LHCb detector, strengthening the statistical power of established analysis and paving the way to new investigations which might shed light on some of the intrinsic contradictions of the SM. All of this will pass through the pixels of the new VELO Upgrade and the rest of the ambitious LHCb Upgrade, the results of a incredible cooperative effort that will ensure a prosperous future for the physics programme of the whole collaboration.

Appendix A

L0 trigger choice

As stated in Sec. 4.3.1.1, at L0 level, only the **Dst_L0Global_TIS** (TIS) trigger is used in this search, whereas the use of **D0_L0HadronDecision_TOS** (TOS) (within the '**Dst_L0Global_TIS || D0_L0HadronDecision_TOS**' request) was investigated and discarded. Before discussing the studies carried out it is useful to describe the definitions of TIS and TOS trigger categories:

- TIS stands for Triggered Independent of Signal: an event is registered as TIS if removing all of the signal decay hits from the detector the L0 decision is still triggered. This can happen if the trigger is produced by a particle generated in the same p-p interaction as the signal decay but belonging to a different decay chain, e.g a muon with sufficiently high transverse momentum.
- TOS stands for Triggered On Signal: an event is registered as TOS if the signal is sufficient to trigger a positive decision, e.g. a child pion from a signal D^0 leaving enough energy in the calorimeter.

Thus, the **Dst_L0Global_TIS** request generates a positive decision if the triggering event contained also a D^* hadron, whereas a **D0_L0HadronDecision_TOS** positive decision is taken if the event is triggered by the signal D^0 . Specifically, the impact of the L0 trigger parameters on the ET was tested using the $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ control channel. The tests involved three combinations of L0 trigger queries:

- '**Dst_L0Global_TIS || D0_L0HadronDecision_TOS**';
- '**D0_L0HadronDecision_TOS**';
- '**Dst_L0Global_TIS**'.

These samples were tested with the ET using 4 million events, 10 thousand permutations, 500 event per permutation; all tests were carried out with $\delta = 0.5$. The results, shown in Fig. A.1, suggest that the TOS requirement introduces a bias in the data: the TIS || TOS sample shows a preference for low P-values, whereas the TOS ones are predominantly concentrated in the first bin. Only the TIS sample shows a flat distribution, meaning the explicit request of TOS events is introducing a bias. Thus, we require only TIS events for further analysis. This results in a loss of around 24% of events compared to requiring TIS || TOS. The χ^2 and KS test results confirm this observation and are shown in Table A.1.

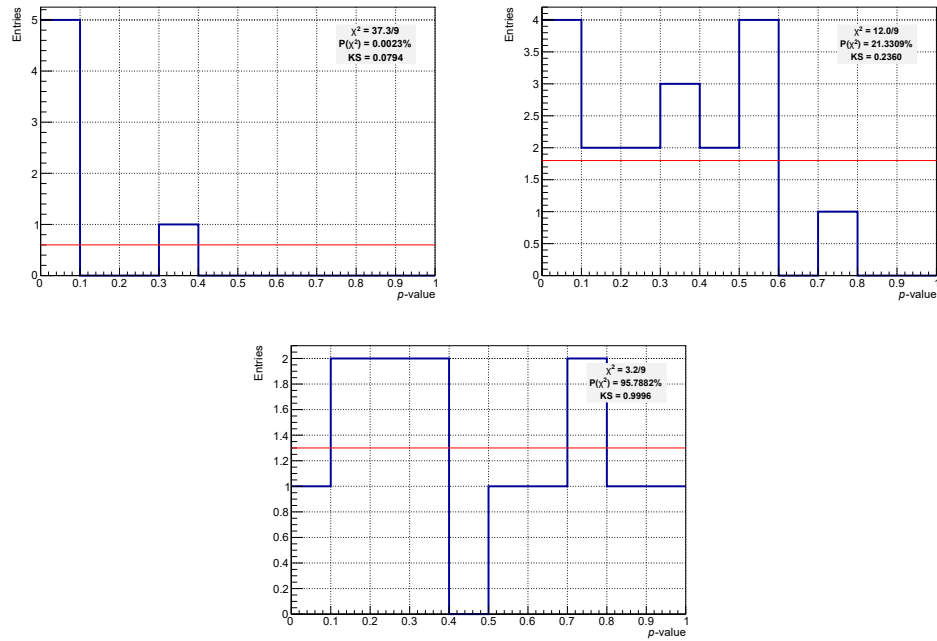


FIGURE A.1: P-value distributions for ET L0 trigger test carried out with 4M event samples, 10 thousand permutation, 500 permutation per sample with $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decays. Top left: ET results requiring TOS: there is a clear preference for the lower bins. Top right: ET results form the TIS || TOS sample: the results are slightly biased towards the low P-value bin. Bottom: ET results requiring TIS: the distribution is flat, proving the absence of bias. The visual observation is supported by the χ^2 and KS test results shown in the legend boxes.

L0 trigger	$P(\chi^2)$ [%]	KS
TOS	0.0023	0.0794
TIS TOS	21.3309	0.2360
TIS	95.7882	0.9996

TABLE A.1: P-values and KS test results for the distributions from the ET carried out on the TOS, TIS || TOS, and TIS samples. Values for the TOS sample represent a clear deviation from a uniform distribution. Requesting TIS || TOS results in a lower deviation, whereas only the TIS sample is in agreement with a uniform distribution.

A.1 D^0 TOS children particle studies

Since requesting only TIS at L0 trigger level results in a loss of roughly 24% of the events, further studies have been carried out to test the TOS requirement on the D^0 daughter particles to check if any (or all) of those was driving the bias. Thus, the following L0 TOS requests were investigated:

- **D0_P0_L0HadronDecision_TOS**, for the Kaon;
- **D0_P1_L0HadronDecision_TOS**, for the first pion;
- **D0_P2_L0HadronDecision_TOS**, for the second pion;
- **D0_P3_L0HadronDecision_TOS**, for the third pion.

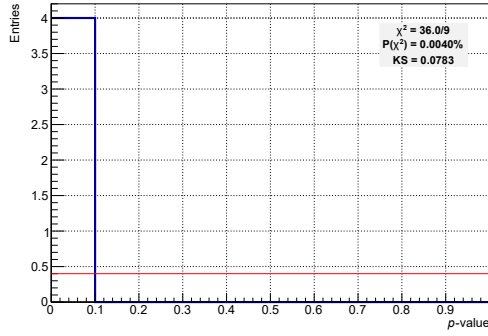
The corresponding samples were tested with the ET using the same statistics and parameters were used for these tests, apart from the δ parameter, set to $\delta = 0.2$. The results are shown in Fig A.2. All the results were asymmetric, meaning that all these L0 trigger induce a bias in the corresponding samples. No events can be thus recovered from any of these samples. The test results for each sample are listed in Tab A.2.

D^0 child particle	$P(\chi^2)$ [%]	KS
P0, Kaon	0.0040	0.0783
P1, Pion	53.4146	0.5441
P2, Pion	3.5174	0.3927
P3, Pion	53.4146	0.5441

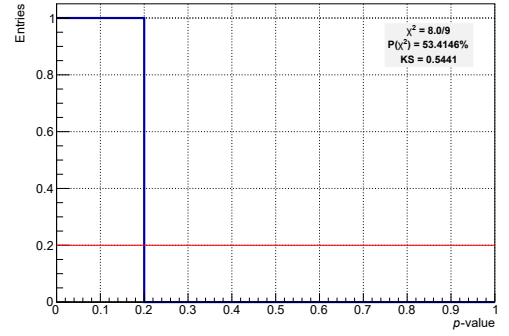
TABLE A.2: P-values and KS test results for the distributions from the ET carried out on the the D^0 children particle TOS samples. All the values testify the presence of a bias. It should be noted that for the P2 sample, both P-values were 0; the P1 and P3 result are due the limited number of P-values available (2).

A.2 KS TOS studies

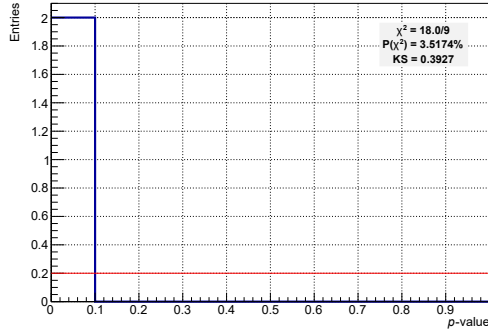
The KS_L0HasdronDecision_TOS trigger option has been tested for the $K_S^0 K \pi \pi$ channel. The test have been carried out with the following parameters: 500 thousand events per sample, 10 thousands permutations, 500 max permutation events, $\delta = 0.2$. The KS_TOS total size of 2.6 million events allowed for two P-value to be computed with this parameters. The resulting P-value distribution (Fig. A.3) and test results (table A.3) are compatible with a uniform distribution. It should be noted though that the available statistics for this trigger request



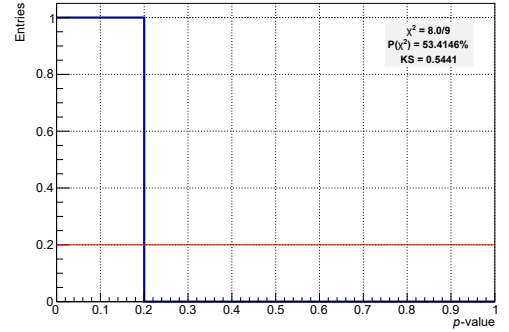
(A) D0_P0_L0HadronDecision_TOS



(B) D0_P1_L0HadronDecision_TOS



(C) D0_P2_L0HadronDecision_TOS



(D) D0_P3_L0HadronDecision_TOS

FIGURE A.2: Energy Test results for each of the samples where TOS was requested on the D^0 children particles. All of the results show a bias.

(500 thousand events per sample versus 4 million events) is too low to draw any conclusion.

L0 trigger	$P(\chi^2)$ [%]	KS
KS_TOS	53.4146	1.0000

TABLE A.3: P-values and KS test results for the distribution from the ET carried out on the KS_TOS sample. The results are in agreement with a uniform distribution.

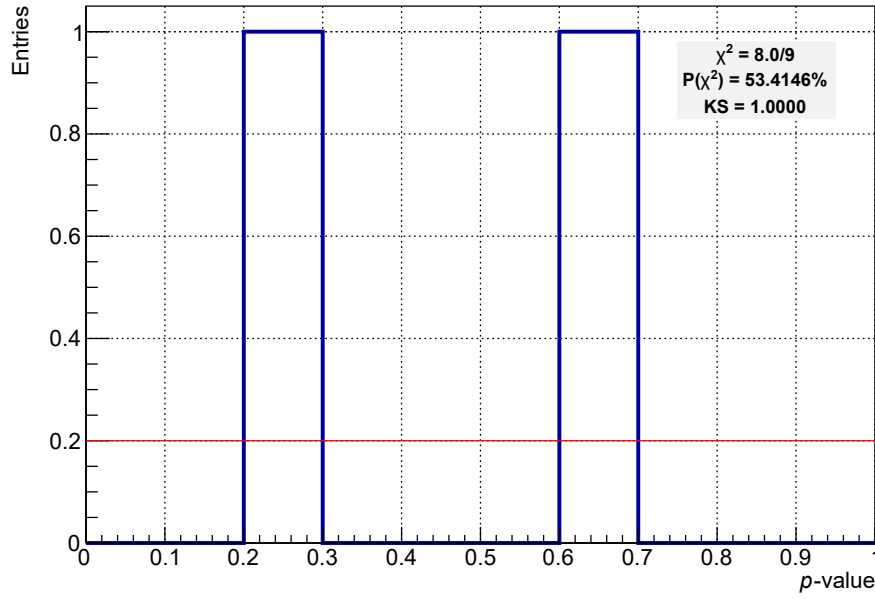


FIGURE A.3: Energy Test results for the KS_TOS trigger request. The distribution is in agreement with a uniform distribution.

Appendix B

Hlt1 trigger parameters

This appendix summarises the Hlt1 trigger requirement for the **D0_Hlt1TrackMVADecision_TOS** or **D0_Hlt1TwoTrackMVADecision_TOS** lines for the $K_S^0 K^\pm \pi^\mp$ channel. The criteria are applied to the final state pions in both cases. For the **TrackMVADecision** the following criteria are applied:

- $\text{TRCHI2DOF} < 2.5$;
- $\text{TRGHOSTPROB} < 0.2$;
- $((\text{PT} > 25000.0 \text{ MeV}/c \ \& \ \text{BPVIPCHI2} > 7.4)) \mid \mid$
 $(1000 \text{ MeV}/c < \text{PT} < 25000.0 \text{ MeV}/c) \ \& \$
 $(\log(\text{BPVIPCHI2}) > (1.0 / ((\text{PT} / \text{GeV} - 1.0)^2) +$
 $(1.1 / 25000.0) \times (25000.0 - \text{PT}) + \text{math.log}(7.4))))).$

These criteria select one good quality final state pion track which is detached from the primary vertex i.e. the p-p interaction vertex.

For the **TwoTrackMVADecision** the requirements applied are:

- $((\text{PT} > 600.0 \text{ MeV}/c) \ \& \ (\text{P} > 5000.0 \text{ MeV}/c) \ \& \$
 $(\text{TRCHI2DOF} < 2.5) \ \& \ (\text{TRGHOSTPROB} < 0.2) \ \& \ (\text{BPVIPCHI2} > 4.0))));$
- $(\text{HASVERTEX} \ \& \ (\text{VFASPF}(\text{VCHI2}) < 10.0) \ \& \ ((2.0 < \text{BPVETA} < 5.0)) \ \& \$
 $((1000.0 \text{ MeV}/c^2 < \text{BPVCORRM} < 1000000000.0 \text{ MeV}/c^2)) \ \& \$
 $(\text{BPVDIRA} > 0.0)).$

These criteria select two good quality final state pion tracks that share a common vertex. The tracks are required to be detached from the primary vertex as well.

The explanation of all the trigger jargon can be found in Appendix D.

Appendix C

Vertices constraints

The aim of the constraints on the decay, origin and primary vertices of the D^0 particle, shown in Table 4.2, summarised for convenience in Table C.1, is to consider only particles arising and decaying within the main interaction zone and away from the RF foil. Excluding mesons interacting with the foil is crucial as the D^0 interactions with the material might follow different dynamics from the one under study, thus introducing undesired asymmetries. The distribution of the D^0 decay vertices shown in Fig. C.1 allows to visualise the silhouette of the RF foil and the detector material, confirming that a number of reconstructed decays originates from meson interactions with the detector. Specifically, the RD foil extends up to 4.7 mm from the beam axis on the XY plane: the radial selection requirements on the decay vertex position thus excludes all decays with a radius $R(D_{EV}^0)_{XY} > 4.7$ mm, where EV stands for *EndVertex* i.e. the decay vertex position. For a similar reason an analogous selection requirements is applied to the meson origin vertex (i.e the parent D^* decay position) as shown in Fig. C.2. These plots show as well how a number of interaction are displaced from the main interaction zone on the Z axis (Figs. C.1,C.2,C.3). As further safety measure, the decay, origin and primary vertex position on the Z axis are constrained to exclude displaced events. An example is shown in Fig. C.4: the main interaction zone is defined by the decay vertex distribution of D^0 along the Z axis; the selection requirements is computed excluding events outside a 2σ window from the mean value of the distribution.

All these requirements have been studied and tuned using the $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ sample, due to the large available statistics that allowed to highlight the interactions with the detector material. The application of the aforementioned constraints has been inspired by previous studies [124, 125].

D^0 Decay, Origin and Primary vertices constraints

$$D_{EV}^0 R_{XY} < 4.7 \text{ mm and } |D_{EV}^0 Z - 10.48| < 83.42 \text{ mm}$$

$$\text{where } R_{XY} = \sqrt{(D_{EV}^0 X - PV_X)^2 + (D_{EV}^0 Y - PV_Y)^2}$$

$$D_{OV}^0 R_{XY} < 4.7 \text{ mm and } |D_{OV}^0 Z - 0.54697| < 86.3588 \text{ mm}$$

$$\text{where } R_{XY} = \sqrt{((D_{OV}^0 X - PV_X)^2 + (D_{OV}^0 Y - PV_Y)^2)}$$

$$|PV_Z + 1.48863| < 81.932 \text{ mm}$$

TABLE C.1: List of the offline vertices requirements applied to the signal channel. D_{EV}^0 is the particle *EndVertex* i.e decay position; D_{OV}^0 is the particle *OriginVertex* i.e creation position; PV stands for *PrimaryVertex* i.e. the p-p collision position. R_{XY} is the radial distance of the particle vertex (EV or OV) from the primary vertex on the XY plane.

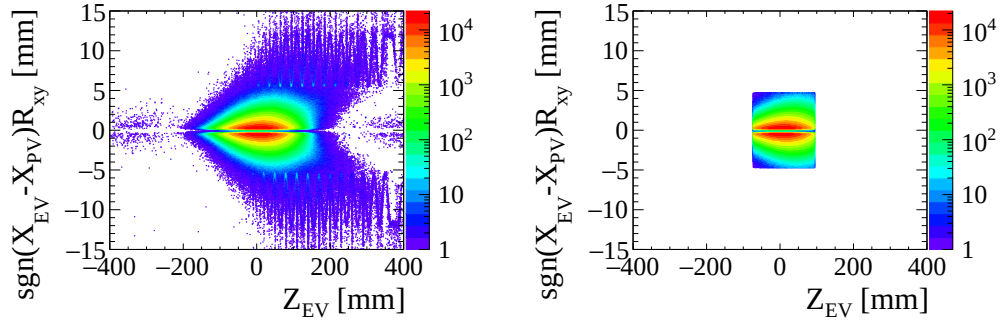


FIGURE C.1: Map of the D^0 vertices distribution, with Z decay coordinate on the x axis and signed radial coordinate on the y axis. The bin population is colour coded on the z axis. Here EV stands for End Vertex (i.e. decay vertex), PV for Primary Vertex. Left: raw vertices distribution. Right: vertices distribution after applying the selection requirements.

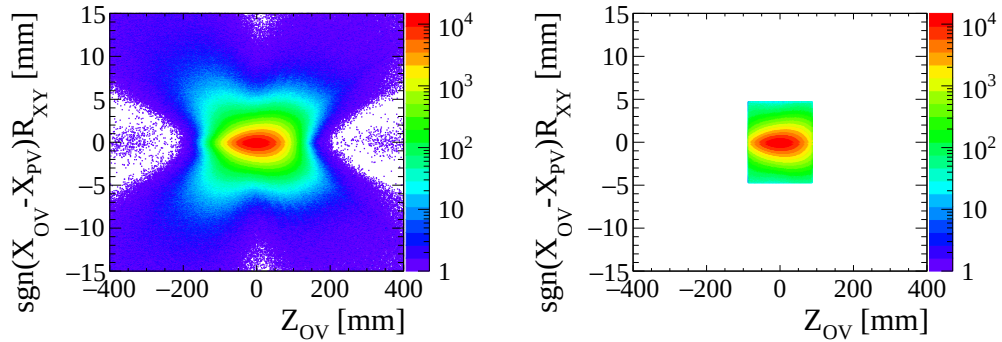


FIGURE C.2: Map of the D^0 vertices distribution, with Z origin coordinate on the x axis and signed radial coordinate on the y axis. The bin population is colour coded on the z axis. Here OV stands for Origin Vertex, PV for Primary Vertex. Left: raw vertices distribution. Right: vertices distribution after applying the selection requirements.

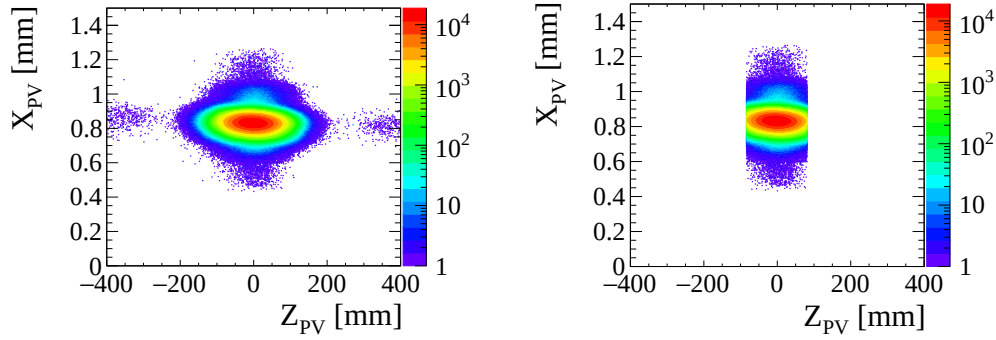


FIGURE C.3: Map of the D^0 vertices distribution, with Z primary coordinate on the X axis and Y primary vertex coordinate on the Y axis. Here PV stands for Primary Vertex. Left: raw vertices distribution. Right: vertices distribution after applying the selection requirements.

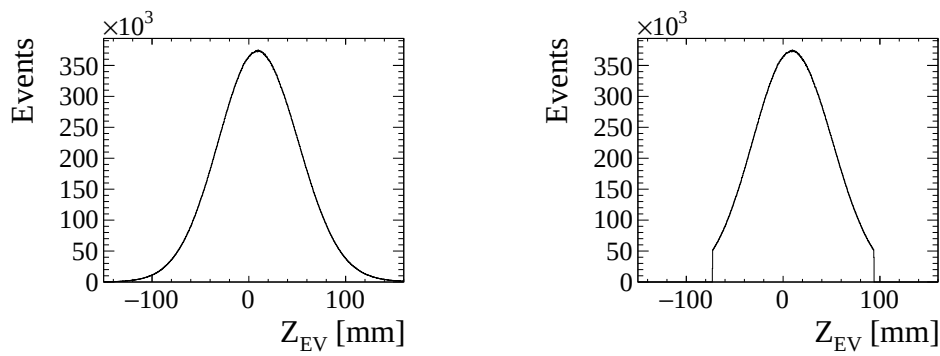


FIGURE C.4: Distribution of the D^0 decay vertices on the Z axis. Here EV stands for *EndVertex* i.e decay vertex. Left: raw distribution. Right: distribution after selection a 2σ window from the mean value.

Appendix D

Trigger parameter definitions

In this appendix a complete explanation of all the trigger jargon is given.

- **CHI2VXNDOF**: vertex reduced χ^2 per degree of freedom.
- **BPVDIRA**: cosine of the angle between the particle momentum and flight direction from the best primary vertex to the decay vertex.
- **BPVVDCHI2**: χ^2 distance between decay and related best primary vertex.
- **BPVLTIME**: particle proper time measured in nanoseconds.
- **VFASPF**: Vertex Function as Particle Function, applies a vertex function to the particle “Endvertex”. Vertex Function and Particle Function are objects of the reconstruction software. The former is the reconstructed vertex, the second is the reconstructed particle. These can be combined to create more complex entities such as the one described here, where the vertex of a particle is defined. The “Endvertex” is defined as the decay vertex of a particle.
- **VCHI2PDOF**: evaluator of the vertex χ^2 per degree of freedom.
- **VFASPF(VCHI2PDOF)**: evaluator of the vertex χ^2 per degree of freedom applied to the particle vertex.
- **D2DVVDCHI2**: signed χ^2 vertex-vertex distance for child particles in a decay chain.
- **TRCHI2DOF**: track fit χ^2 per degree of freedom.
- **TRGHOSTPROB**: probability of the track to be a ghost track. A ghost track is defined as a track which has less than 70% of hits matching the hits of any final state particle [126]. More specifically, ghost tracks are

the result of multiple detector hits produced by a number of different particles that are sufficiently aligned to mimic a real track produced by a single final state particle.

- **DLLX**: Delta Log Likelihood for X mass hypothesis. Is defined as $\Delta \log L(X - \pi)$, where $X = K, \pi$ is the mass hypothesis under test.
- **PIDX**: combined identification for particle X (Kaon or pion) hypothesis. Analogous to DLLX.
- **ProbNNx**: probability for a particle hypothesis ($x = K, \pi$). The information is obtained from a Neural Network combining multiple PID and tracking inputs.
- **MIPCHI2DV**: minimum impact parameter χ^2 , returns the χ^2 distance of a particle trajectory from a set of vertices.
- **MIPCHI2DV(PRIMARY)**: χ^2 distance of a particle trajectory from primary vertex.
- **VZ**: vertex Z-axis position.
- **VFASPF(VZ)**: applies a selection requirement or condition to the decay vertex z-axis coordinate.
- **ADAMASS**: array function, compute the absolute value of the difference between the measured mass of a set of particles (the “array”) and the PDG reference value.
- **ADMASS**: compute the absolute value of the difference between the measured mass of a single particle the PDG reference value.

Appendix E

High statistics control channel studies

As further safety crosscheck, the control channels tests were run again with double the statistics to ensure that, even with two times the expected statistics for the signal sample, the ET would not pick up any detection ($D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ channel) or K_S^0 ($D^0 \rightarrow K_S^0 \pi \pi$ channel) asymmetry. The ET was run with $\delta = 0.2 - 0.5$ with the following parameters: 1 million events per sample, 10 thousand permutations, 500 events per permutation; 50 P-values were produced for the $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ channel, 6 P-values for the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ channel.

E.1 Test for $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ channel

The test results (Fig. E.1) show for each δ value a P-value distribution compatible with the null hypothesis, as confirmed by the χ^2 and KS test results (Table E.1).

δ	$P(\chi^2)[\%]$	KS
0.2	1.5598	0.5441
0.3	17.1867	0.8643
0.4	61.6305	0.9639
0.5	12.2325	0.7112

TABLE E.1: P-value and KS test results for P-value distributions obtained with the ET using $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decays with 1 million events samples size for a total of 50 P-values and $\delta = 0.2 - 0.5$. No significant deviation from uniform distribution is detected.

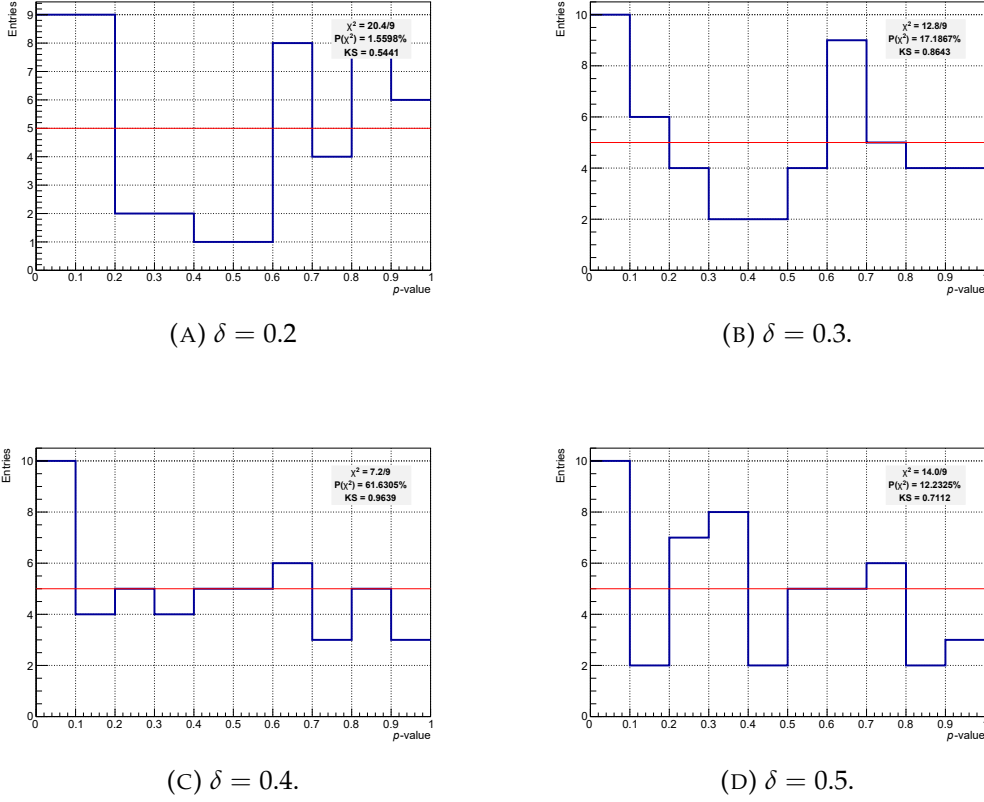


FIGURE E.1: Results of ET runs on the $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ channel for 1 million events, 10 thousand permutations, 500 events per permutation, with the optimised delta values; each test allowed for 50 P-values with the available Run2 prompt statistic. Plot a), b), c) and d) shows the result with a value of $\delta = 0.2 - 0.3 - 0.4 - 0.5$, respectively. The χ^2 and KS test results show no deviation from uniform distribution.

E.2 Test for $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ channel

The test results (Fig. E.2) show for each δ value a P-value distribution compatible with the null hypothesis, as confirmed by the χ^2 and KS test results (Table E.2).

δ	$P(\chi^2)[\%]$	KS
0.2	39.2456	0.9972
0.3	4.8716	0.9972
0.4	63.7119	1.0000
0.5	39.2456	1.0000

TABLE E.2: P-value and KS test results for P-value distributions obtained with the ET using $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays with 500 thousand events samples size for a total of 13 P-values and $\delta = 0.2 - 0.5$. No significant deviation from uniform distribution is detected.

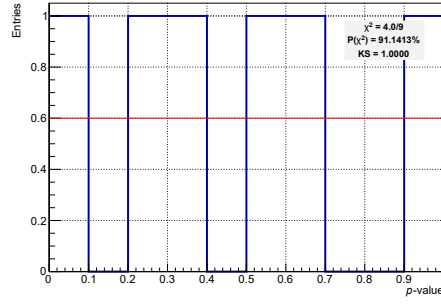
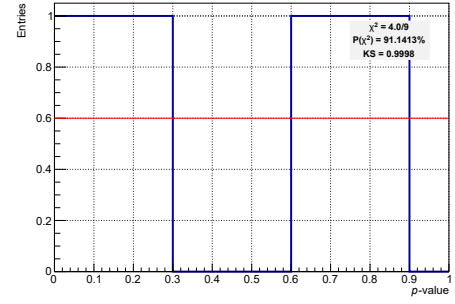
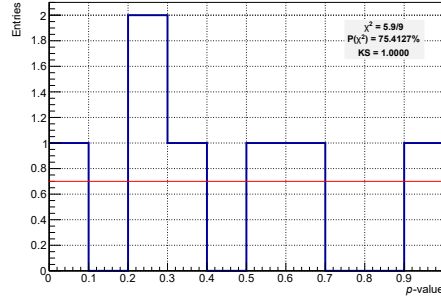
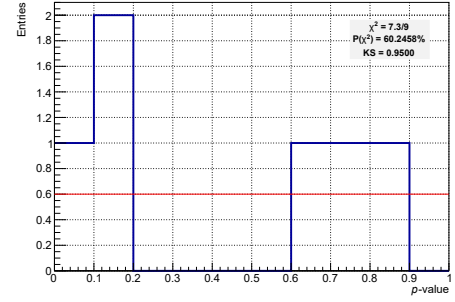
(A) $\delta = 0.2$ (B) $\delta = 0.3$.(C) $\delta = 0.4$.(D) $\delta = 0.5$.

FIGURE E.2: Results of ET runs on the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ channel for 1 million events, 10 thousand permutations, 500 events per permutation, for a total of 13 P-values with the optimised δ values. Plot a), b), c) and d) shows the result with a value of $\delta = 0.2 - 0.3 - 0.4 - 0.5$, respectively. No noticeable deviation from uniform distributions is detected.

Appendix F

Kinematics studies

To ensure that the control channel studies are relevant we compare the kinematic distributions between the control and signal channels. The variables taken into account are: P , P_T , ϕ , η . We focus on comparing the K_S^0 distributions between the $K_S^0 K\pi$ and $K_S^0 \pi\pi$ channels, the K from the $K\pi\pi\pi$ and $K_S^0 K\pi$ channels and the π from the same channels. It should be noted that we are considering only the right-sign sample in the $K\pi\pi\pi$ channel, whereas we are using both SS and OS samples in the $K_S^0 K\pi$ channel. Thus to avoid any ambiguity we compare the distributions of the pions with opposite charge to the kaon in one case, and separately those with same charge. We also include a comparison between the distributions of the pions from the K_S^0 , although these distribution are not used in the ET.

Specifically, we compare the normalised distributions kinematics of both K_S^0 from the $K_S^0 K\pi$ and $K_S^0 \pi\pi$ (Fig. F.1) and both kaons from $K\pi\pi\pi$ and $K_S^0 K\pi$ (Fig. F.2). Regarding the pions, we will compare those of the $K\pi\pi\pi$ and $K_S^0 K\pi$ channels using the following notation:

- Pions from the $K\pi\pi\pi$ channel:
 - π_1 and π_2 have opposite charge to the K .
 - π_3 has same charge to the K .
- Pions from the K_S^0 from $K_S^0 K\pi$ channel:
 - π_1 has opposite charge to the K .
 - π_2 has same charge to the K .
- Non- K_S^0 pion from $K_S^0 K\pi$ channel:
 - π has opposite charge to the K .

We compare the pions with opposite charge to the K from the $K\pi\pi\pi$ channel with the K_S^0 pion with opposite charge to the K from the $K_S^0 K\pi$ channel (Fig. F.3). We then show the same with the pions and kaon with same charge (Fig. F.4). We report the distributions for all the non- K_S^0 pions from both channels, thus including same and opposite charge pions (Fig. F.5). For completeness, we also report the distributions of all pions (same and opposite charge to the kaon for both $K\pi\pi\pi$ and $K_S^0 K\pi$ channel) including the pions from the K_S^0 decay (Fig. F.6).

To summarise, the distributions from the kaons and K_S^0 are almost identical between the $K\pi\pi\pi$ and $K_S^0 K\pi$ channel, and $K_S^0 \pi\pi$ and $K_S^0 K\pi$ channel, respectively. The non- K_S^0 pions have similar distributions as well between the $K\pi\pi\pi$ and $K_S^0 K\pi$ channel; the K_S^0 pions have similar η and ϕ distributions, whereas the momentum and transverse momentum are steeper for the K_S^0 pions respect to the pions from the $K\pi\pi\pi$ channel, with a heavier tail for the latter; this is true regardless of the charge relative to the kaon. This is a phase space effect.

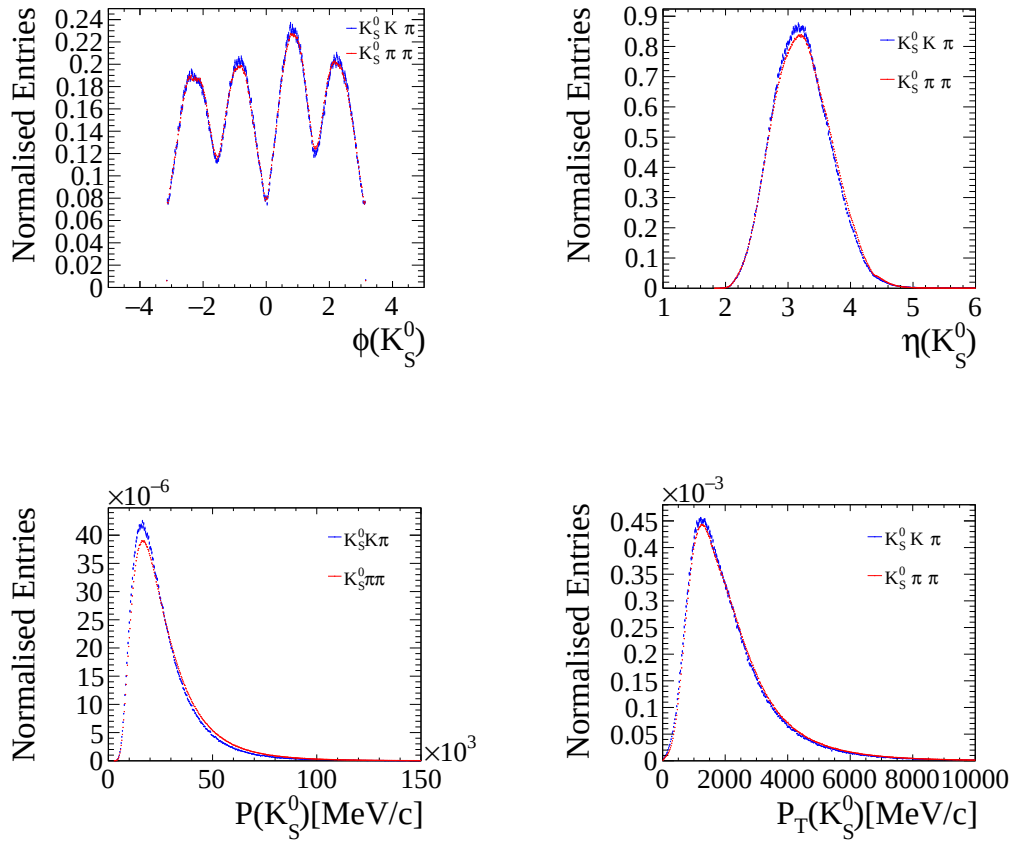


FIGURE F.1: Normalised K_S^0 distributions between the $K_S^0 K \pi$ and $K_S^0 \pi \pi$ channels. In blue the Ks from $K_S^0 K \pi$; in black the Ks from $K_S^0 \pi \pi$. All the distributions are similar.

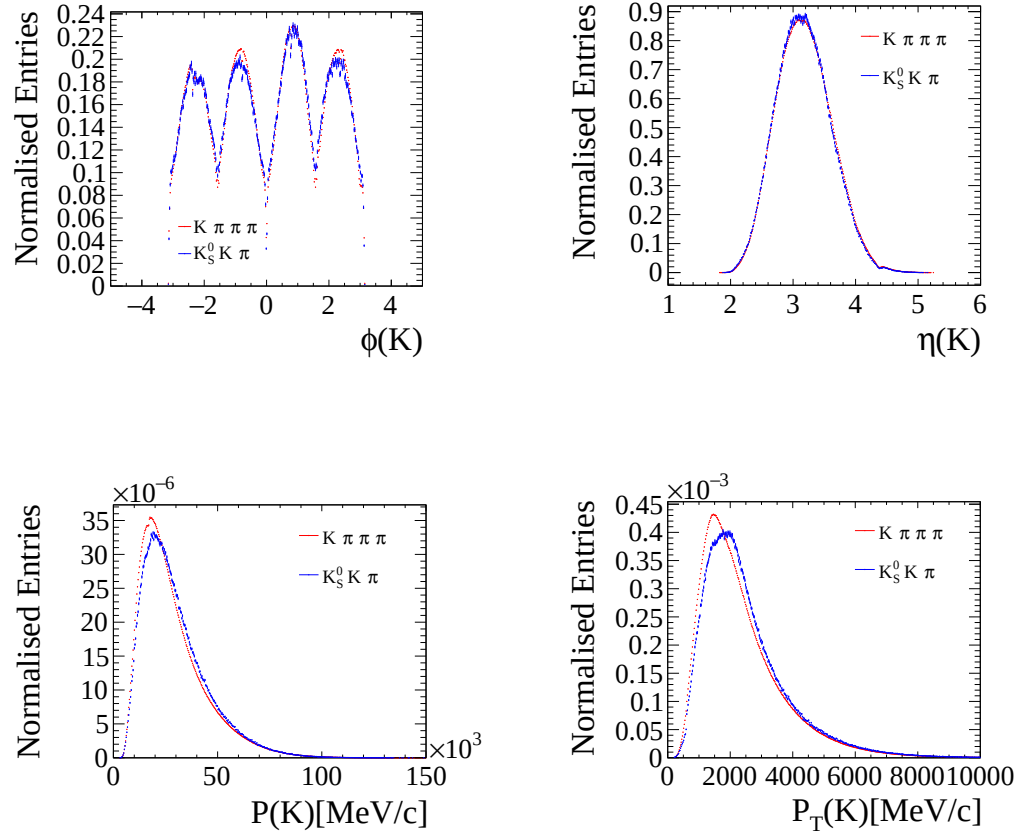


FIGURE F.2: Normalised kaon distributions between the $K_S^0 K\pi$ and $K\pi\pi\pi$ channels. In blue the K from $K_S^0 K\pi$; in black the K from $K\pi\pi\pi$. All the distributions are similar.

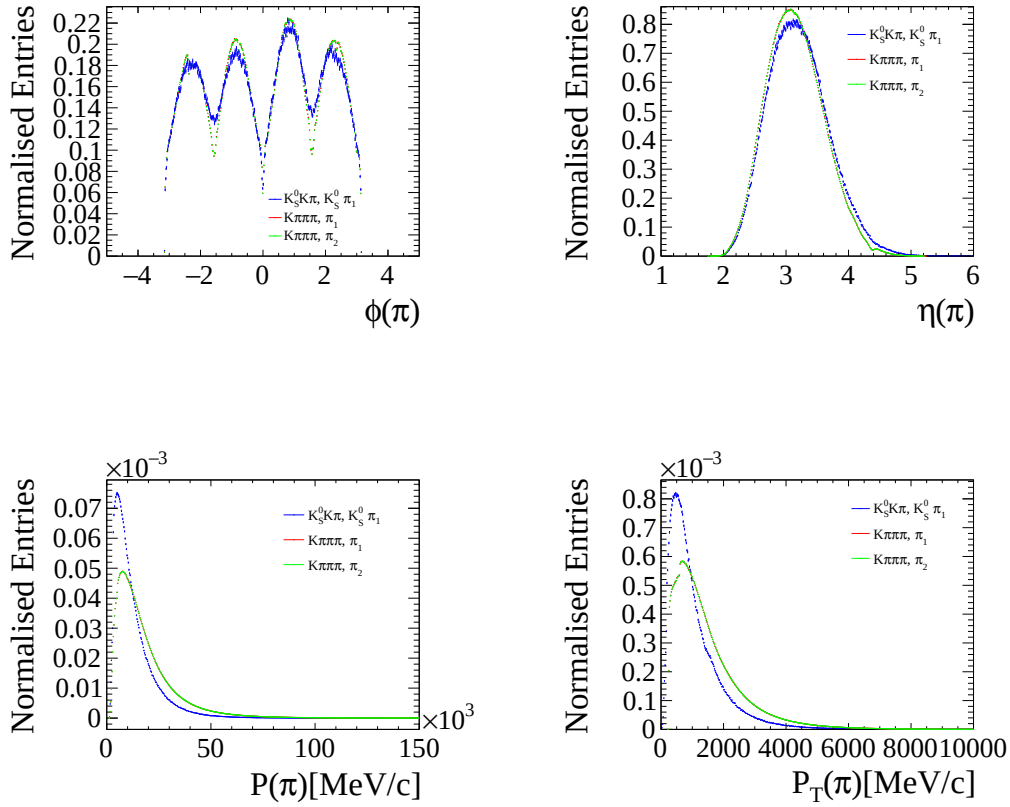


FIGURE F.3: Normalised distributions of pions with opposite charge to the kaon (π_1 and π_2 from $K\pi\pi\pi$ and $K_S^0 \pi_1$ from $K_S^0 K\pi$). In blue π_1 from the K_S^0 from $K_S^0 K\pi$; in red π_1 and in green π_2 from $K\pi\pi\pi$. The distributions are quite similar, whereas the P and P_T distributions of the pion from the K_S^0 are steeper than those of the $K\pi\pi\pi$ pions.

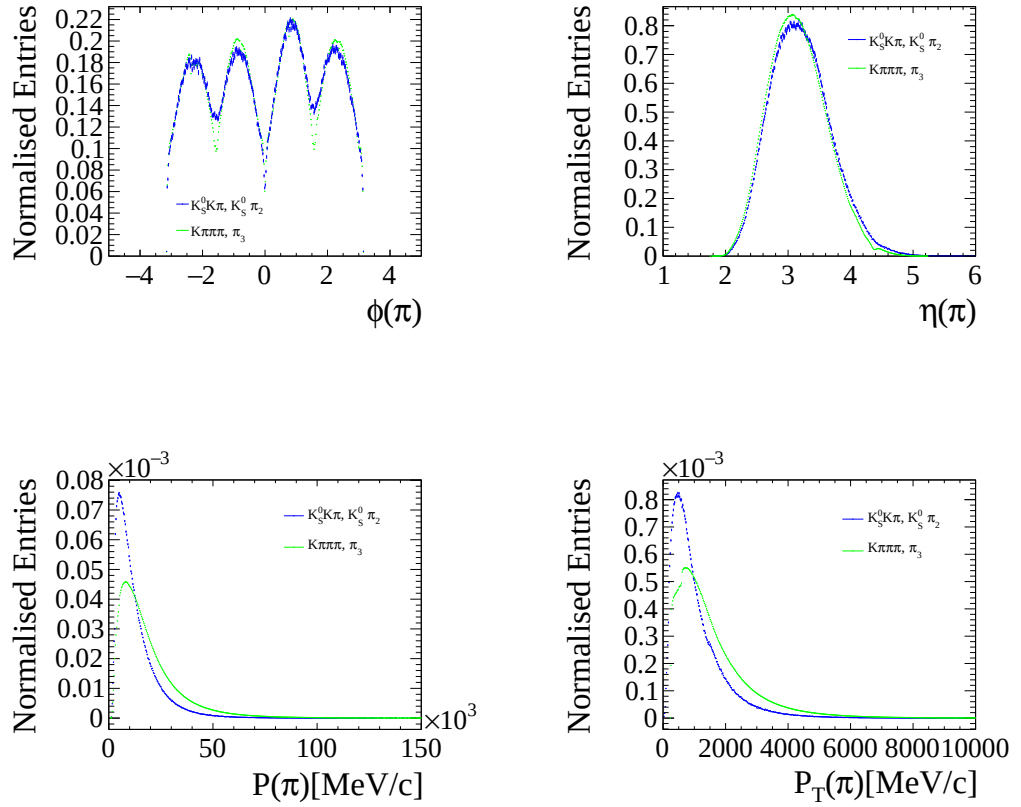


FIGURE F.4: Normalised distribution of pions with same charge of the kaon (π_3 from $K \pi \pi \pi$ and $K_S^0 \pi_2$ from $K_S^0 K \pi$). In blue π_2 from the K_S^0 from $K_S^0 K \pi$; in green π_3 from $K \pi \pi \pi$. The η and ϕ distributions are quite similar, whereas the P and P_T distributions of the pion from the K_S^0 are steeper than those of the $K \pi \pi \pi$ pion.

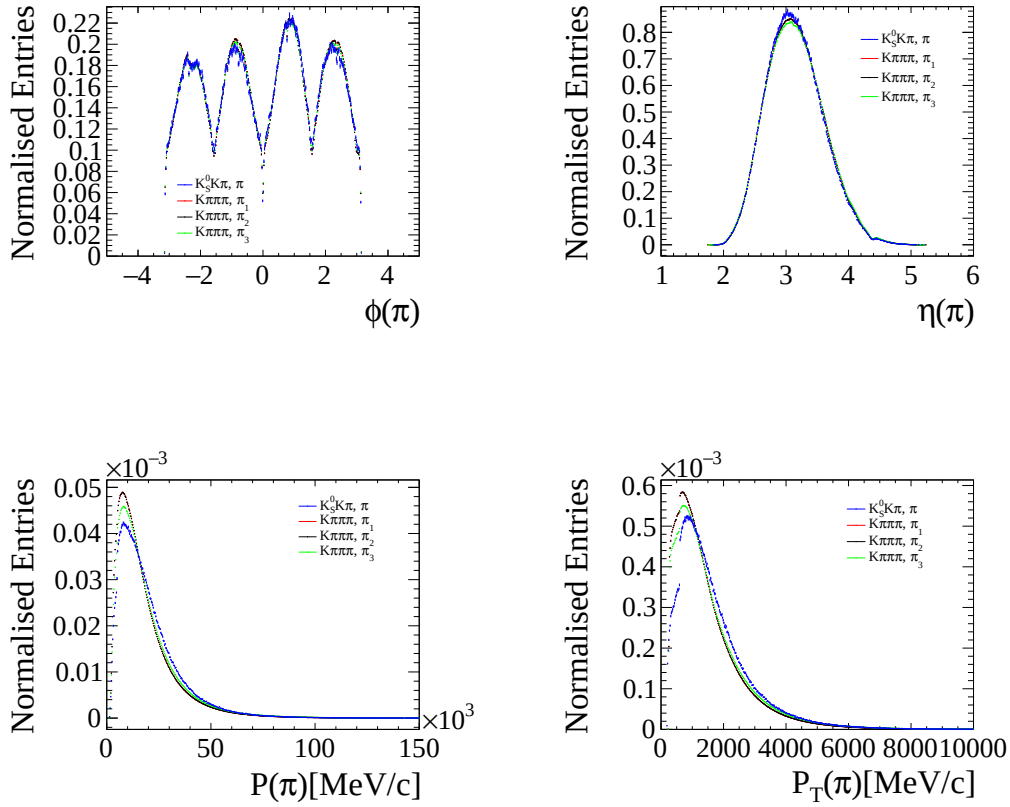


FIGURE F.5: Normalised distributions for the pion from the the $K_S^0 K \pi$ and all three pions from the $K \pi \pi \pi$ channels. In blue the π from $K_S^0 K \pi$. In red (π_1) and black (π_2) the $K \pi \pi \pi$ pions with opposite charge to the K ; in green (π_3) the $K \pi \pi \pi$ pion with same charge of the K . All the distributions are similar.

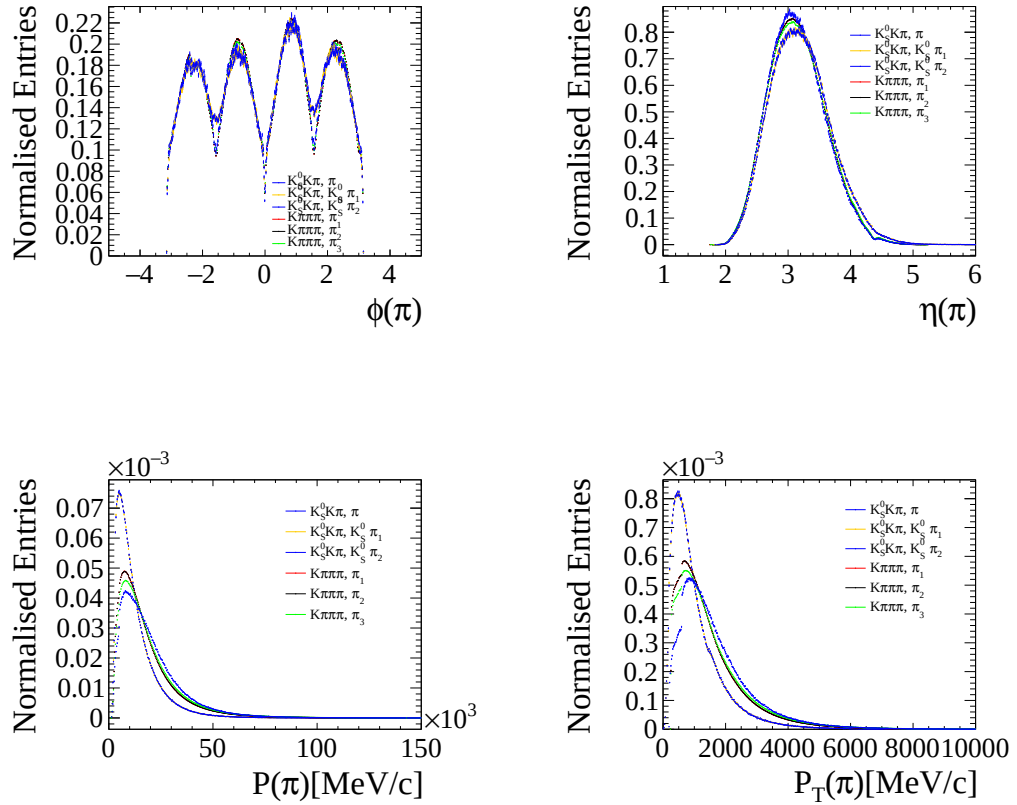


FIGURE F.6: Normalised distributions for all the pions from the $K_S^0 K \pi$ (including pions from K_S^0 decay) and $K \pi \pi \pi$ channels. In blue the π from $K_S^0 K \pi$; in azul (π_1) the $K_S^0 \pi$ with opposite charge to the K ; in orange (π_2) the $K_S^0 \pi$ with same charge of the K . In red (π_1) and black (π_2) the $K \pi \pi \pi$ pions with opposite charge to the K ; in green (π_3) the $K \pi \pi \pi$ pion with same charge of the K . All the distributions are similar, apart from the P and P_T of the pions arising from the K_S^0 which are steeper.

Appendix G

Split sample studies

To ensure that the control channels did not contain any bias that could be hidden or compensated for in the whole sample, this was split by year and magnet polarity and each subsample tested with the ET using $\delta = 0.2$. Furthermore, each track type (DD, LL) was tested for the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ channel. All of the ET were carried out with 500 thousands events to reproduce a statistics similar to the signal sample one, 10 thousand permutations and 500 event per permutation. No bias was detected in any of the tests.

G.1 $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ channel

The $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ sample was split by year and polarity and each subsample tested separately with the ET to ensure none of these contained any hidden bias.

G.1.1 Single year samples

The test results for the 2015-18 year samples (Fig. G.1) show a P-value distribution compatible with the null hypothesis, as confirmed by the χ^2 and KS test results (Table G.1).

Year	$P(\chi^2)$ [%]	KS
2015	73.9918	0.9671
2016	91.1413	1.0000
2017	38.9906	0.7056
2018	25.0662	0.9018

TABLE G.1: P-value and KS test results for P-value distributions obtained with the ET using $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decays with 500 thousand events samples size for each year. No significant deviation from uniform distribution is detected.

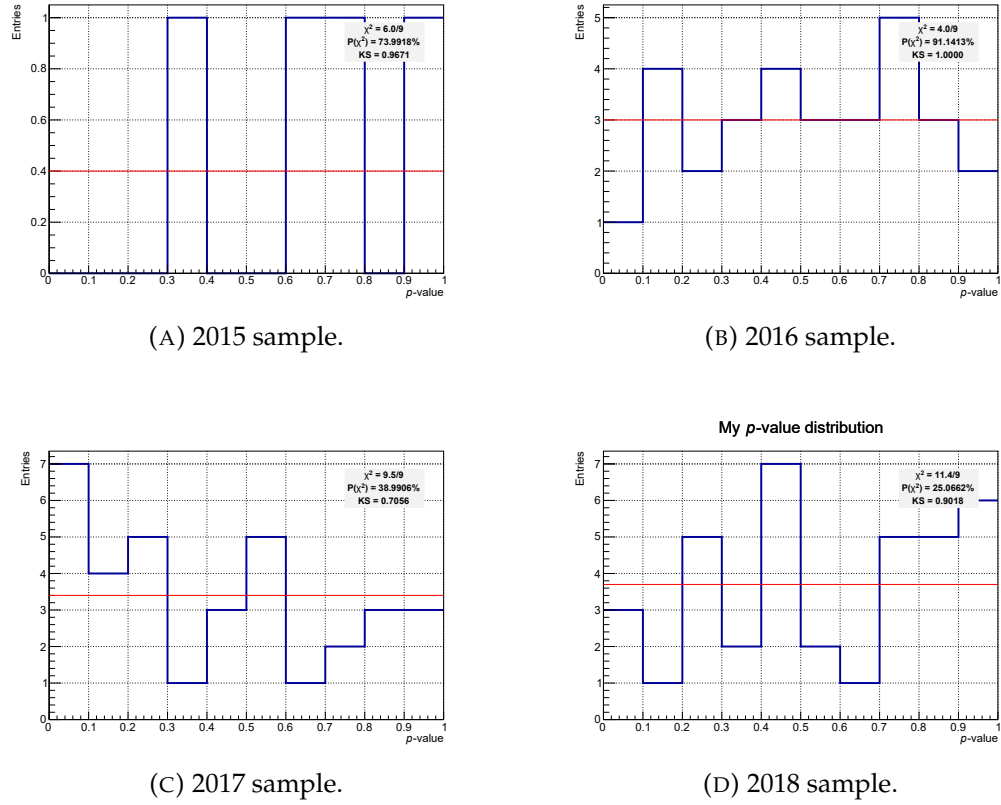


FIGURE G.1: Results of ET runs on the $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ channel for 500 thousand events, 10 thousand permutations, 500 events per permutation. Plot a), b), c) and d) shows the result for the 2015-6-7-8 sample, each containing 4, 30, 34 and 37 P-values, respectively. No noticeable deviation from uniform distributions is detected.

G.1.2 Magnet polarity samples

The test results for the magnet up and down year samples are shown in Fig. G.2. The χ^2 and KS test results are summarised in Table G.2. No bias was detected.

Polarity	$P(\chi^2)[\%]$	KS
Magnet down	38.8519	0.9986
Magnet up	13.7282	0.3927

TABLE G.2: P-value and KS test results for P-value distributions obtained with the ET using $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decays with 500 thousand events samples size for each magnet polarity. No significant deviation from uniform distribution is detected.

G.2 $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ channel

The $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ sample was split by year, polarity and track type (DD and LL). Each subsample was tested separately with the ET to ensure none of these

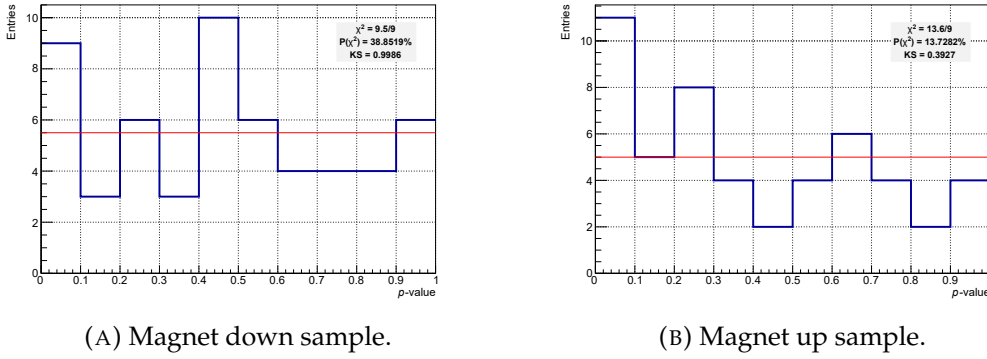


FIGURE G.2: Results of ET runs on the $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ channel for 500 thousand events, 10 thousand permutations, 500 events per permutation for the single magnet polarity samples. On the left: Magnet polarity down, 55 P-values; on the right: magnet polarity up, 50 P-values. No noticeable deviation from uniform distributions is detected.

contained any hidden bias.

G.2.1 Single year samples

The test results for the 2016-18 year samples (Fig. G.3) show a P-value distribution compatible with the null hypothesis, as confirmed by the χ^2 and KS test results (Table G.3).

Year	$P(\chi^2)$ [%]	KS
2016	63.7119	0.9700
2017	73.9918	1.0000
2018	27.5709	0.8127

TABLE G.3: P-value and KS test results for P-value distributions obtained with the ET using $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays with 500 thousand events samples size for each year. No significant deviation from uniform distribution is detected.

G.2.2 Magnet polarity samples

The test results for the magnet up and down year samples are shown in Fig. G.4. The results are summarised in Table G.4. No bias was detected.

Polarity	$P(\chi^2)$ [%]	KS
Magnet down	60.2458	0.9998
Magnet up	60.2458	0.9833

TABLE G.4: P-value and KS test results for P-value distributions obtained with the ET using $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays with 500 thousand events samples size for each magnet polarity. No significant deviation from uniform distribution is detected.

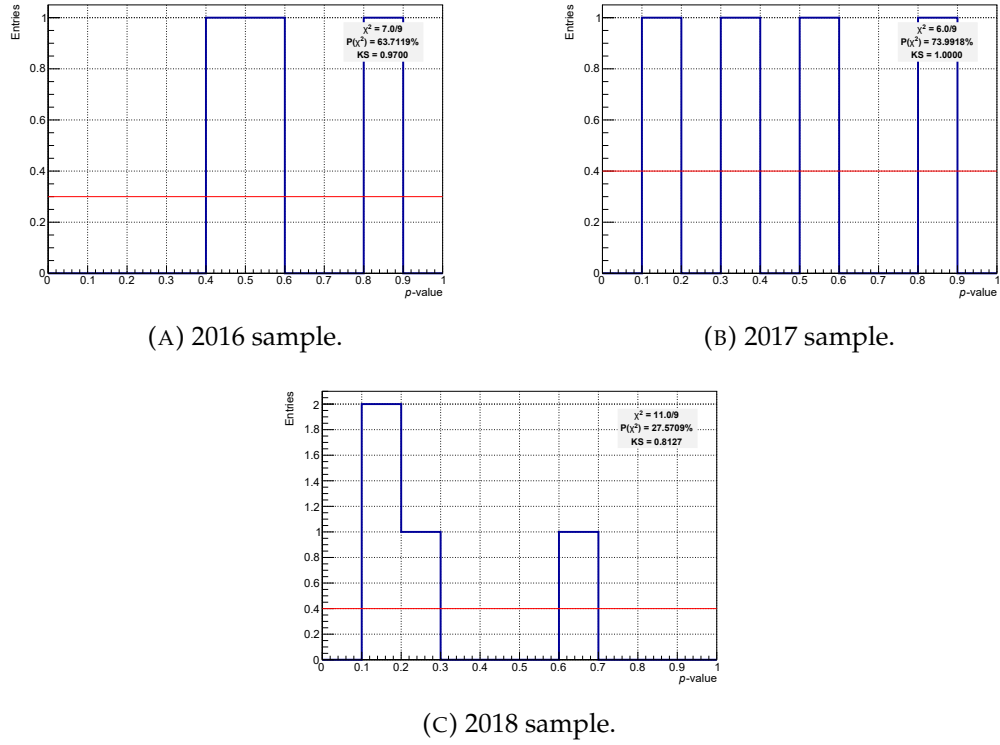


FIGURE G.3: Results of ET runs on the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ channel for 500 thousand events, 10 thousand permutations, 500 events per permutation. Plot a), b) and c) shows the result for the 2016-7-8 sample, each containing 3, 4 and 4 P-values, respectively. No noticeable deviation from uniform distributions is detected.

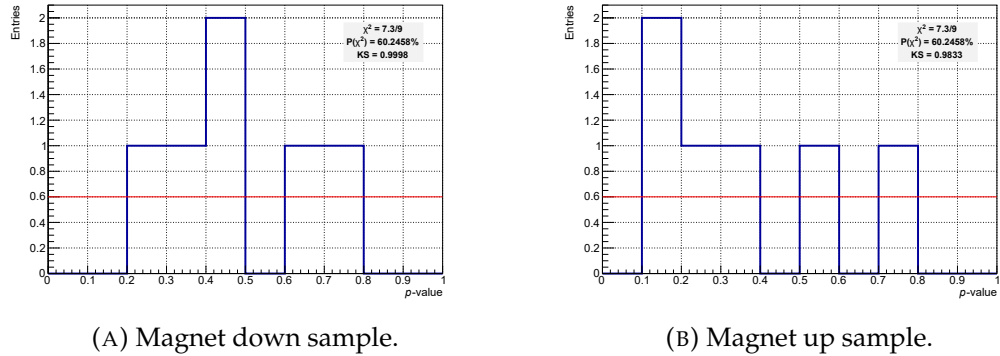
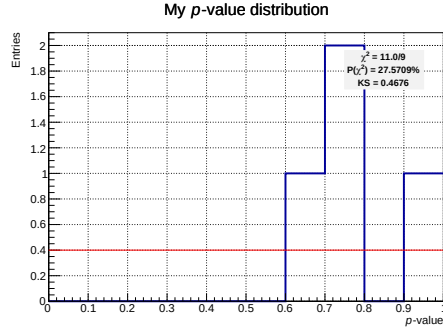


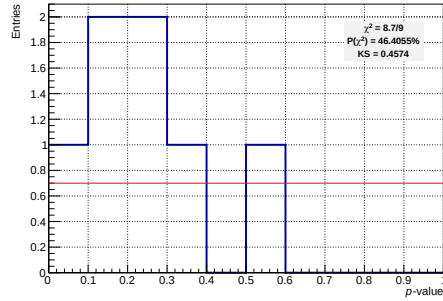
FIGURE G.4: Results of ET runs on the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ channel for 500 thousand events, 10 thousand permutations, 500 events per permutation for the single magnet polarity samples. On the left: Magnet polarity down, 6 P-values; on the right: magnet polarity up, 6 P-values. No noticeable deviation from uniform distributions is detected.

G.2.3 Track type samples

The P-value distributions for the LL and DD track samples are shown in Fig. G.5, with the χ^2 and KS results summarised in Table G.5. Both the distribution and the test results are compatible with the null hypothesis.



(A) LL tracks sample.



(B) DD tracks sample.

FIGURE G.5: Results of ET runs on the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ channel for 500 thousand events, 10 thousand permutations, 500 events per permutation for the single magnet polarity samples. On the left: LL tracks, 4 P-values; on the right: DD tracks, 7 P-values. No noticeable deviation from uniform distributions is detected.

Track type	$P(\chi^2)[\%]$	KS
LL tracks	27.5709	0.4676
DD tracks	46.4055	0.4574

TABLE G.5: P-value and KS test results for P-value distributions obtained with the ET using $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays with 500 thousand events samples size for each track type. No significant deviation from uniform distribution is detected.

Appendix H

Toy-Data checks

The Sensitivity studies, as explained in Sect .4.4, have been carried out using a Run1 amplitude model with Run1 efficiencies (see [19]). These have been used to generate all the GooFit toys used for the optimisation of the delta parameter. To ensure that the Run1 model still holds with the higher statistics of Run2 and check for possible differences in acceptance, the Toys and Run2 invariant mass distributions used as input for the ET have been compared. The normalised distributions in Fig. H.1 compare the SS sample $K\pi$, $K_S^0 K$ and $K_S^0 \pi$ invariant mass distributions generated with GooFit with those obtained from the Run2 data signal sample. The distributions are all similar, proving the Run1 model still hold for Run2.

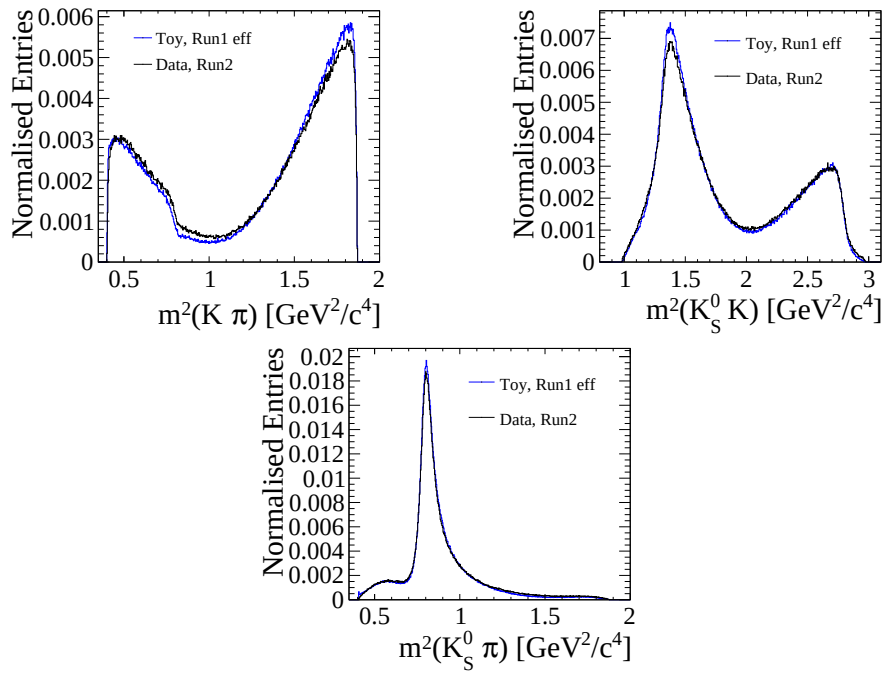


FIGURE H.1: Normalised distributions for the invariant masses of the toys produced with Run1 efficiencies (blue line) and Run2 signal data for the SS sample (black line). The $m^2(K\pi)$ (top left), $m^2(K_S^0 K)$ (top right) and $m^2(K_S^0 \pi)$ (bottom) distributions are all similar.

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