MSc Research Project Reading Notes

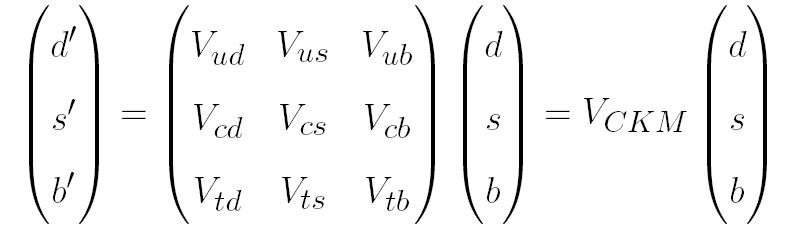
***Chapter 1: Background and Motivation***

**The Standard Model of Particle Physics #EMPHASISE WEAK DECAYS, AXIONS AND AXION LIKE PARTICLES (ALPS)**

* Gauge bosons (force mediators), and fermions (make up all matter)
* Fermions -> Quarks + Leptons
* Four fundamental forces: strong, weak, EM, and gravity, each of which are mediated by the bosons described above(except for gravity)

**Weak Interactions**

The weak interaction, unlike its strong and electromagnetic counterparts, does not possess an associated “charge” (where the strong and EM forces possess colour, and electric charge respectively). There are two types of interactions which are mediated by the charged W bosons, and the neutral Z boson, named charged, and neutral current interactions respectively. Flavour is not conserved in charged weak interactions involving quarks due to the principle of quark confinement (i.e. quarks are always found in bound states). Quarks are ‘skewed’ for weak interactions (i.e. the weak force couples the following pairs):



Here, $d’,s’ and b’$ are linear combinations of $d, s$, and $b$, and $V\_{CKM}$ represents the coupling strengths between the quarks ($V\_{ud}$ represents the coupling of $u$ to $d$ (i.e.$d\rightarrow u + W^{-}$). The elements of the CKM matrix have been experimentally measured and are given by:

**Electroweak Penguin Decays (Egede et al.)**

The most common decays of $b$ hadrons take place at the quark level through the decay of the $b$ quark via the emission of a virtual W boson. The $b$ quark is unable to decay directly to an $s$ quark as this would require a vertex with a neutral vector boson and a change of flavour. Such a process is known as a *Flavour Changing Neutral Current (FCNC)* process and is forbidden in the SM at tree level. However, at one-loop level, the FCNC quark level process like $b\rightarrow s\gamma$ is permitted. Examples of such decays include $B^{0}\rightarrow K^{\*0}\gamma$. Such decays which consist of either a lepton or a hard photon in the final state are referred to as **electroweak penguin decays.**

Electroweak penguin decays can act as a discovery mode for New Physics (NP). At either tree level or at loop level, there can be particles such as new vector bosons or leptoquarks that mediate the decays. The influence of these particles can be observed as differences with respect to the Standard Model for these decays. The theoretical calculation of the electroweak penguin decays employs an OPE (Operator Product Expansion). By analogy with the Fermi theory of weak decays, one exploits the fact that these decays are only sensitive to the spin, parity and CP properties of couplings involving particles at masses well below the b-hadron mass. For a radiative decay process, such as

Here, the operators $\mathcal{O}\_{i}$ encode the low energy behaviour and the complex valued Wilson coefficients $C\_{i}$ characterise how these different operators contribute to the overall process. Any new physics will manifest itself through Wilson coefficients that have different values form those expected in the SM or through Wilson coefficients that correspond to completely new operators such as scalar, pseudoscalar or tensor currents. The contributions to the Wilson coefficients from NP depend on both the coupling constants between the NP particles and the SM particles, as well as the masses of the NP particles. The study of electroweak penguin decays cannot therefore precisely determine the mass of any NP particles.

**Strong CP Problem**

To motivate the strong CP problem, one must understand the nature of transformations of systems under charge conjugation, C (which refers to the interchange of particles with their corresponding antiparticles), and parity, P, an inversion of spatial coordinates within a system. Parity is evidently violated in the weak theory is: the left-handed fields couple differently from the right-handed fields. It is manifest in nuclear $\beta$-decay which always produces left-handed electrons. It is also known that CP invariance (i.e. the invariance of a system under the combination of the aforementioned transformations) is violated by rare processes involving hadrons. This phenomenon is referred to as weak CP violation. There exists another form of CP violation known as **strong CP violation** which has been predicted by theory, but has not been experimentally observed. The absence of such an observation is known as the **strong CP problem.**

The QCD Lagrangian (subject to renormalisation) is given by:

Here, $q$ represents the quark fields, and F\_{\mu\nu} represents the QCD field strength. Here, $m$ represents the mass of the quarks involved, and $g$ represents the coupling strength of the strong interaction. At high energy, the short distance behaviour. On the other hand, long distance physics is hard for the strong force. For three light quarks (e.g. u, d, s), the aforementioned Lagrangian possesses a U(3) x U(3) symmetry at the classical level under which:

given that the masses of the quarks are neglected. The consideration of the mass would break this symmetry. SU(3) x SU(3) is spontaneously broken by

Here, the left hand side represents the **order parameter,** $c$ is a constant, $\Lambda$ represents a QCD scale and $\delta\_{ff’}$ is the Kronecker delta. The above relation leads to an unbroken symmetry in the case where $U = V$ (i.e. $SU(3)\_{V}$). This leads to 9 broken generators (and therefore 9 Goldstone bosons, namely the charged and neutral pions and kaons, the anti-kaon, and the eta. The ninth boson appears to be missing, the only candidate for which at this stage is the $\eta’$ (with a mass of 958 MeV). For a relativistic field theory for scalars, the relevant mass parameter is $m^{2}$ (i.e. the mass of the $\eta’$ is large).

Something that could account for this is that there is a current which does not associate itself with a Goldstone boson. Mathematically:

Classically:

This term vanishes in the limit that $m\rightarrow 0$ (i.e the current is conserved in the limit that the quark masses tend to 0). However, there exists an extra term in the current, known as the **anomaly** such that

Here, $F\_{\mu\nu}$ represents the QCD field strength and $\tilde{F} = \frac{1}{2}\epsilon\_{\mu\nu\rho\sigma}F^{\rho\sigma}$. F and its dual are related by an exchange of $\vec{E}$ and $\vec{B}$ (electric and magnetic fields).

An additional term containing depending on an angle $\theta$ can be added to the QCD Lagrangian, thereby leading to:

**Axions**

Axions were postulated by Peccei and Quinn in 1977 as a solution to the Strong CP problem of quantum chromodynamics. They obey a well-defined relation between their mass and coupling to SM particles. Dropping the mass-coupling relation, any scalar or pseudoscalar particle with similar couplings to the SM particles may be referred to as an axion-like particle (ALP).

**Axion Like Particles (ALPs)**

Unlike axions, which are expected to be within the sub-eV regime, and hence very light, the masses of ALPs are not as constrained, meaning that these can be arbitrarily heavy. ALPs will always couple to photons and can hence be produced in photon-photon collisions. They could also couple to gluons, Z bosons, and Higgs bosons, as well as fermions (i.e. leptons and quarks). The interactions of ALPs with these SM particles preserves a global shift symmetry $a\rightarrow a+c$, where $a$ represents the ALP field, and $c$ is a constant. In general, ALPs arise as pseudo Nambu-Goldstone bosons in various predictions associated with theories with spontaneously broken symmetries. ALPs could resolve several outstanding issues relating to the naturalness of SM parameters, such as the aforementioned strong CP problem, as well as the hierarchy problem, and can also serve as mediators to dark sector. As such, there is growing interest in the search and phenomenological study of these particles.

At colliders, pseudoscalars can be produced in rare meson decays. Meson decays via flavour changing neutral currents (FCNC) are suppressed in the Standard Model but can be strongly enhanced if the ALP is resonantly produced. Additionally, constraints on the ALP masses due to their couplings to W +- bosons have not been explored in significant detail. Such constraints on the masses of ALPs only arise due to previous experimental searches, and not theoretical impositions. As such, this coupling can be exploited to obtain a pathway to more powerful discovery modes.

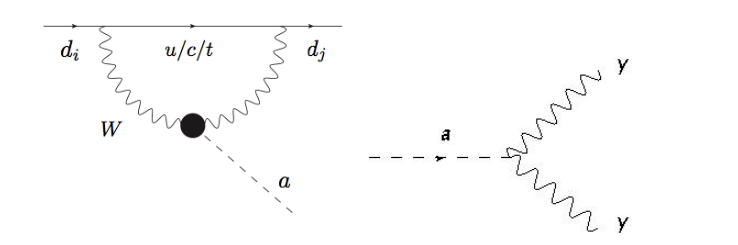
One can consider a minimal ALP (a) model with coupling $g\_{aW}$ to the SU(2)\_{W} gauge-boson field strengths, $W^{b}\_{\mu\nu}$, and Lagrangian:

$\tilde{W}^{b\mu\nu}$ is the dual field-strength tensor. This coupling leads to the production of ALPs at one-loop level in the process $B\rightarrow K^{\*}a$, where the ALP is emitted from an internal $W^{\pm}$ boson. Electroweak symmetry breaking and the resulting gauge boson mixing generates an ALP coupling to a pair of photons, and the branching fraction for $a\rightarrow\gamma\gamma$ is almost 100% in this model for $m\_{a} < m\_{W}$. The same ALP production and decay modes also occur in models with axion coupling to gluons.

**$B\rightarrow K\*A, A\rightarrow\gamma\gamma$ Decay Process**

For the purposes of this decay, one can consider the model described in **(Tongyan, Lin, Shuve paper)**, and thereby exploit the coupling of ALPs to W+- bosons, which can give rise to observable signatures. This ALP model possesses a zero coupling with gluons. The effective Lagrangian can be written as:

Here, the $g\_{aW}$ represents the coupling between the ALP field $a$ and the electroweak gauge boson field W ($\tilde{W}^{\mu\nu} = \epsilon^{\mu\nu\alpha\beta}W\_{\alpha\beta}/2$)



The above diagram represents a Flavour Changing Neutral Current (FCNC) process. Such a process is forbidden at tree level, but is permitted at loop level (as illustrated in the diagram on the left).

Considering the nature of the coupling of the ALPs to pairs of gauge bosons (specifically photons), the following decay channels were deemed to be promising for the detection of ALPs at the LHCb:

***Chapter 2: The LHCb Detector***

The LHCb experiment is dedicated to heavy-flavour physics at the LHC. It seeks indirect evidence of new physics in CP violation and rare decays of beauty and charm hadrons.

The extent of CP violation in the Standard Model weak interaction cannot explain the amount of matter in the universe. As a result, a new source of CP violation beyond the Standard Model is needed to solve the puzzle. The effect of such a source may be evident in heavy flavour physics. The LHCb intends to study the phenomenon of CP violation by analysing the higher statistics and various decay modes of the $B\_{d}$, $B\_{s}$ and $D$ mesons

The LHCb has a $b\bar{b}$ production cross-section of approximately 500 microbarn at an energy of 13 TeV, and is therefore the most abundant source of B mesons in the world. It must therefore be able to exploit the large number of $b$ hadrons. As a result, its trigger must be sensitive to a variety of final states. Displaced vertex and high transverse momentum signatures are exploited in order to separate the decays of interest from the background. The momentum and invariant mass resolution of the detector is also required to be high in order to mitigate effects from the combinatorial background. Additionally, the identification of charged particles is essential in flavour physics experiments, in order to, for instance, isolate suppressed decays and for b-quark flavour tagging. The ability to detect photons and charged particles permits the reconstruction of radiative decays, as well as more common ones such as those containing $\pi^{0}$ and $\eta$ mesons in the final state.

Data taking at the LHCb detector is divided into fills and runs. A fill is a single period of collisions delimited by the announcement of stable beam conditions and the dumping of the beam by the LHCb; a phase which typically lasts approximately 12 hours. A fill is further divided into runs, each of hich lasts a maximum of one hour.In order to benefit from the high event rate at the LHCb, a high-bandwidth data acquisition system and a robust, and selective trigger system are essential. This chapter describes the key components of the experimental setup, as well as the processes relating to the acquisition and analysis of data from this experiment.

**Structure of the LHCb Detector**

The LHCb is a single arm spectrometer with a forward angular coverage from approximately 10 mrad to 300 mrad in the bending (non-bending) plane and covering the pseudorapidity range between 2 and 5. The detector is designed such that the b and $\bar{b}$ hadrons are produced in the same forward or backward cone at high energies, and consists of a high-precision tracking system consisting of the following components:

* **Silicon-strip vertex detector (VELO)**
* **Silicon strip detector (TT) detector**
* **Dipole magnet with a bending power of 4 Tm, located downstream from TT detectors**
* **Straw drift tubes**

These components are collectively referred to as T-stations. The tracking system provides a measurement of the momentum of charged particles with a relative uncertainty ranging between 0.5% to 1.0% at 200 GeV/c. The other key components that are responsible for measuring the properties of the particles that traverse the detector include the two ring imaging Cherenkov (RICH) detectors, and a calorimeter system comprising of a scintillating-pad (SPD) and preshower detectors (PS), as well as electromagnetic and hadronic calorimeters (ECAL and HCAL respectively). A system responsible for detecting muons is also present as part of the experimental setup. Each of the components are described in further detail below

**Vertex Locator (VELO)**

The VELO is a silicon microstrip detector that surrounds the proton-proton interaction region in the LHCb experiment. It provides measurements of track coordinates that enable the identification of the primary interaction and secondary vertices, which are characteristic of b and c-hadron decays. The VELO was designed to optimise the following aspects of the LHCb experiment:

* **Angular coverage:** The VELO is designed to cover the forward region such that all tracks inside the nominal LHCb acceptance of 15-300 mrad cross at least three VELO stations. In this way, the detector fully reconstructs roughly 27% of $b\bar{b}$ production for 7 TeV proton-proton centre of mass collisions, while covering just 1.8% of the solid angle. The VELO also reconstructs tracks in the forward and backward directions hich do not have momentum information, but are useful to improve the primary vertex reconstruction
* **Triggering:** The reconstruction of the primary vertex and displaced secondary decay vertex of a heavy flavour hadron in the VELO is a key ingredient of the high level trigger which reduces the event rate from a 1 MHz event rate to a few kHz
* **Efficient reconstruction:** LHCb has studied decay modes with up to six charged tracks in the final state. This relies on the highly efficient cluster reconstruction in the VELO since the track reconstruction efficiency losses are transmitted as the sixth power. The cluster reconstruction efficiency in the VELO is paramount, both for the selection of those tracks, as six measurements per track are required, and for efficient pattern recognition and fake track rejection.
* **Displaced tracks and vertices:** Excellent vertex resolution is essential to the LHCb physics programme. Most analyses rely heavily on selection cuts on the distance with which tracks approach the primary vertex (i.e. the impact parameter). The impact parameter resolution was optimised by positioning the VELO sensors as close to the LHC beam as permitted by safety consideration, having a small inter-strip pitch at the inside of the sensors, and minimising the amount of material traversed by a particle before the first measured hits in the VELO
* **Decay time:** The decay time of a particle is obtained from the measurement of its flight distance in the VELO. This is necessary for lifetime requirements and, critically, for time-dependent measurements in the rapidly oscillating $B\_{s}^{0}-B\_{s}^{0}$ bar meson system

**RICH Detectors**

The two Ring Image Cherenkov (RICH) detectors, named RICH1 and RICH2 are responsible for the identification of charged hadrons (e.g. pions, kaons, and protons). RICH1 covers the low and intermediate momentum region (i.e. 2-40 GeV/c) over the full spectrometer angular acceptance of 25-300 mrad, while RICH2 covers the high-momentum region 15-100 GeV/c over the angular range 15-120 mrad.

In order to limit its overall volume, RICH 1 is placed as close as possible to the interaction region, and is located immediately downstream of the VELO described above. RICH 2 on the other hand, is placed downstream of the magnet, since the high momentum tracks that it measures are less influenced by the magnetic field. Both detectors consist of entrance and exit windows that serve as links to the VELO and magnet respectively. These windows form a foam sandwich construction, and are skinned with carbon fibre and aluminium respectively. (LINK TO RICH PAPER FOR MORE INFORMATION)

**Calorimeters**

The calorimeters are assembled in to two halves (A and C sides) which can be moved out horizontally for assembly and maintenance purposes, as well as to provide access to the beam pipe. The SPD, PS, ECAL and HCAL are segmented in the plane perpendicular to the beam axis into square cells.

At the LHC, the density of the particles incident on the calorimeters varies by two orders of magnitude over the calorimeter surface, the inner part being subject to the highest density. The calorimeters are divided into regions with cells of different sizes in accordance with these variations. There are three regions for the SPD, PS, and ECAL, and two regions for the HCAL

All four sub-detectors (SPD, PS, ECAL and HCAL) consist of successions of lead, or iron absorbers, and scintillator plates. The scintillation light resulting from the showers of the particles going through the detector is collected by the wavelength-shifting (WLS) fibres. The fibres transport the light to photomultiplier tubes (PMT) or multi-anode photomultiplier tubes (MA-PMT) that convert the light into electrical signals, which are readout by electronic Front-End-Boards (FEB).

Each cell of the ECAL and HCAL is equipped with a PMT and the corresponding FEB converts the signal to an energy value E, in order to obtain a constant dynamic range in transverse energy over the calorimeter plane. The transverse energy, $E\_{T}$ is defined as $E\_{T} = E\sin(\theta)$ where $\theta$ is the angle between the beam axis and a line from the interaction point to the centre of the cell.

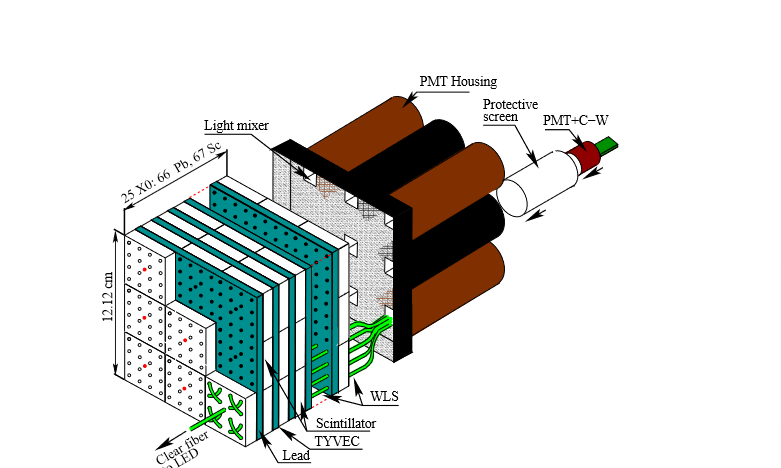
The SPD and PS provide information for particle identification of electrons and photons, which are used by the L0 trigger. The PS information is used to separate electrons, photons, and pions, while the SPD measurements contribute to the separation of neutral particles from charged ones. Additionally, the overall SPD hit multiplicity provides an estimation of the charged particles multiplicity in each beam crossing. This information can be used to veto complex events that would be difficult to analyse offline

The ECAL measures the transverse energy of electrons, photons and neutral pions for the L0 trigger, which is relevant to select B decays with an electron or photon in the final state The offline reconstruction and energy computation of neutral pions, electrons and photons also make use of the information from the PS detector. The HCAL provides a measurement of the transverse energy of hadrons for the L0 trigger in order to select a large variety of D and B decays with a charged hadron (e.g. a kaon, pion, or proton) in the final state. The SPD, PS, ECAL and HCAL are all used for offline particle identification

**Calorimeter L0 Trigger**

The calorimeter part of the L0-trigger computes the transverse energy deposited in clusters of 2 x 2 cells of the same size (or equivalently of the same region). Three different types of clusters or “trigger candidates” are built up by the L0-Calorimeter. The information from the different calorimeter sub-detectors allows to build through a trigger validation system. The first type is a “hadron” candidate, which is a HCAL cluster, with the transverse energy equal to:

The second type is the “photon candidate” which is an ECAL cluster with 1 or 2 PS cells hit in front of the ECAL cluster with no hit in the SPD cells corresponding to the PS ones. In the central zone of the ECAL, due to the higher multiplicity, an ECAL cluster with 3 or 4 PS cells hit in front of it is also defined as a photon, to increase the trigger efficiency.

The third type of candidate is the “electron candidate” which is built with the same requirements concerning the PS hits as the photon candidate requiring in addition at least one SPD cell hit in front of the PS ones. The transverse energy of the photon and electron candidates is the transverse energy of the ECAL cluster. The transverse energy of these candidates is compared to a fixed threshold (3.5 GeV for hadrons, and 2.5 GeV for electrons and photons, in Run 1). Only events containing at least one candidate above these thresholds are sent to the software trigger for further processing. 

**SPD and PS**

The SPD and PS are walls of scintillator pads (cells) with a WLS fibre coil grooved inside for better light collection. The two walls are separated by a lead curtain with a thickness corresponding to 2.5 radiation lengths. The SPD and PS have in total 6016 cells each. Their readout is multi-anode photomultipliers (MA-PMT) of type “Hamamatsu 5900 M64”.

The SPD delivers a binary information per cell, depending on the comparison of the energy deposited in the cell with a threshold. This is used to distinguish charged particles from neutral ones and, in association with the energy measured in the corresponding PS cells, helps photon and electron identification

**ECAL**

The ECAL thickness is of 25 radiation lengths to ensure the full containment of the high energy electromagnetic showers and to get an optimal energy resolution. The ECAL cells have a ‘shashlik’ structure, with scintillator (4 mm), and lead (2 mm) layers. The scintillation light readout is performed by Hamamatsu R7899-20 photomultipliers. The total number of cells is 6016

Three regions have been labelled in the diagram below (inner, middle and outer), depending on the distance of the cells to the beam-pipe. The cell size is such that the SPD-PS-ECAL system is projective, as seen from the interaction point. In addition, the outer dimensions of the ECAL match projectively with those of the tracking system $\theta\_{x} < 300 mrad$ and $\theta\_{y} < 250 mrad$ while the inner angular acceptance of ECAL is limited to $\theta\_{x,y} > 25 mrad$ around the beam pipe, where $\theta\_{x}$ and $\theta\_{y}$ are the polar angles in the LHCb frame in which (x,y) is the plane perpendicular to the beam axis. The ECAL front surface is located approximately 12.5 m from the interaction point.  The energy resolution of the ECAL for a given cell, measured with test-beam electrons is parameterised as:

Here, $E$ is the particle energy in GeV, $\theta$ is the angle between the beam axis and a line from the LHCb interaction point and the centre of the ECAL cell. The second contribution is the constant term (corresponding to mis-calibration, non-linearities, leakage, etc.) while the third one is due to the noise of the electronics, which is evaluated on average to 1.2 **ADC counts**

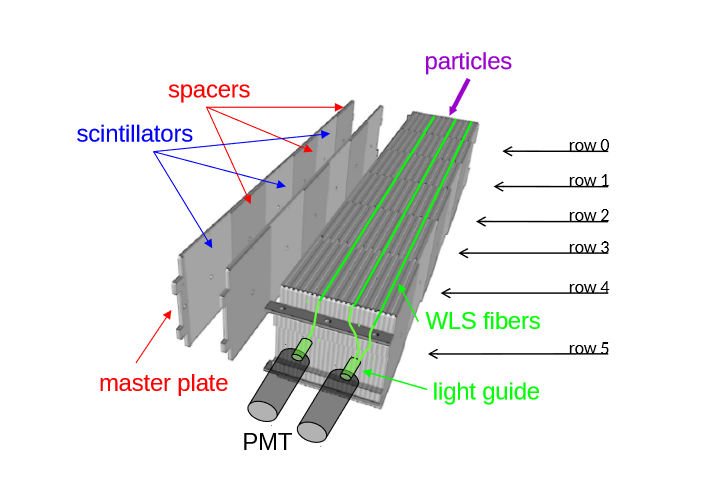
**HCAL**

The HCAL thickness is 5.6 interaction lengths due to space limitations. A sampling structure was chosen, made from iron and scintillating tiles, as absorber and active material, respectively. The special feature of this sampling structure is the orientation of the scintillating tiles that are placed parallel to the beam axis, thereby enhancing the light collection compared to a perpendicular orientation of the scintillating tiles. The same photomultiplier type as in ECAL (Hamamatsu R7899-20) is used for the readout. The HCAL has in total 1488 cells all of the same dimension located in two regions (inner and outer), depending on the distance to the beam pipe.

The energy resolution, measured in test beams, with pions is:

EE=675%E92%

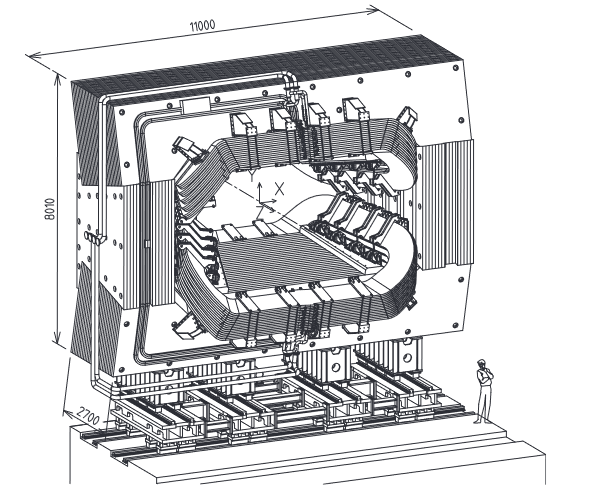
Here, $E$ is the deposited energy in GeV



**Magnet**

The LHCb dipole magnet is a **warm magnet** (i.e. it does not require cryogenic cooling) that consists of two trapezoidal coils bent at 45 degrees on the two transverse sides, arranged inside an iron yoke of window-frame configuration. It is responsible for the production of magnetic fields for momentum measurements of charged particles. The measurements cover the forward acceptance of $\pm 250$ mrad vertically and of $\pm 300 $ mrad horizontally. The magnet consists of saddle-shaped coils in a window-frame yoke with sloping poles in order to match the required detector acceptance, and has an integrated field of 4 Tm for tracks of 10 m length. This choice has been made to accommodate for the contrasting needs for a field level inside the RICHs envelope less than 2mT and a field as high as possible in the regions between the vertex locator and the Trigger Tracker tracking station. The external (top and bottom) parts of the magnet yoke were made up of laminated low carbon steel plates, of thickness 100 mm, and a maximum weight of 25 tons The magnet yoke weighs 1500 tons and contains two identical coils of conical saddle shape, weighing 54 tons, that are placed symmetrically to each other. Each coil consists of 15 pancakes arranged in five triplets and produced of pure Al-99.7 hollow conductor in an annealed state with a central cooling tunnel of 25 mm diameter. Cast aluminium clamps are used to hold together the triplets making up the coils, and to support and centre the coils with respect to the measured mechanical axis of the iron poles with tolerances of several millimeters.

The magnet is operated via the Magnet Control System, which controls the power supply and monitors a number of operational parameters (e.g. temperatures, voltages, water flow, mechanical movements, etc.). A second, fully independent system, the Magnet Safety System (MSS) ensures the safe operation and acts autonomously by enforcing a discharge of the magnet if critical parameters are outside the operating range



***“Chapter 3”: Experimental Methods***

**References**

* <https://www.youtube.com/watch?v=UlyGazWkeuA>