

**Strange particle production rates for the K_s^0 and Λ at
 $\sqrt{s} = 13 \text{ TeV}$ with ATLAS**

by

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December 2016

A thesis submitted to McGill University
in partial fulfillment of the requirements of the degree of
Master of Science

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Abstract

After a long shutdown, the Large Hadron Collider (LHC) restarted activities in 2015 at center-of-mass energy $\sqrt{s} = 13$ TeV, up from $\sqrt{s} = 8$ TeV before its stop in 2012, producing new data at energies never before reached. At the end of this run, another long shutdown will take place in preparation for the LHC higher luminosity. During that time, the ATLAS experiment, like others, will be undergoing repairs and upgrades. A laboratory at McGill University will be testing the new small Thin Gap Chambers (sTGCs) for the replacement of the small muon detector wheels. First, the development of a reliable and robust control system for this facility is discussed. The core analysis follows, which is the measurement of the production rates of K_s^0 and Λ particles at the new center-of-mass energy $\sqrt{s} = 13$ TeV using data from ATLAS. It is the first time these measurements are done for this energy at the LHC. Mass measurements of $497.8 \pm 0.3(stat)$ MeV for the K_s^0 and $1115.71 \pm 0.02(stat)$ MeV for the Λ are obtained and kinematic distributions are shown.

Résumé

Après un long arrêt, le Grand Collisionneur Hadronique (LHC) est redevenu actif en 2015 à une énergie de centre de masse de $\sqrt{s} = 13 \text{ TeV}$, comparée à $\sqrt{s} = 7 \text{ TeV}$ avant son arrêt, produisant de nouvelles données à une énergie plus haute que jamais. En mi-2018 un deuxième long arrêt suivra pour préparer pour le LHC à plus haute luminosité. Durant cette période, l'expérience ATLAS, comme les autres expériences du LHC, va procéder à des réparations et améliorations. Le remplacement des petites roues de détection de muon du détecteur ATLAS est l'une de ces améliorations. En premier, le développement d'un système de contrôle robuste et fiable pour le laboratoire d'essai des nouvelles chambres à petits écarts en construction pour les nouvelles petites roues de détection de muon est discuté. Ensuite, les taux de productions des particules étranges K_s^0 et Λ sont étudiés pour la première fois à la nouvelle énergie de centre de masse de $\sqrt{s} = 13 \text{ TeV}$. Des valeurs de $497.8 \pm 0.3(stat) \text{ MeV}$ pour la masse du K_s^0 et de $1115.71 \pm 0.02(stat) \text{ MeV}$ pour la masse du Λ sont mesurées et des distributions cinématiques sont présentées.

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Acknowledgments

I give big thanks to those who supported me throughout my journey as part of the McGill ATLAS group. They made this journey not only memorable but fun and exciting.

It goes without saying, my first thanks are to my supervisor François Corriveau, who guided and supported me throughout, giving me good advice and getting me on my feet when I was struggling. Also very well appreciated was all the help from others in the ATLAS group who helped me a lot and kept me on the right track, especially Andr  e Robichaud-V  ronneau, S  bastien Prince and Robert Keyes.

More thanks go to people from ATLAS at CERN and more particularly to the vertexing and SM Soft QCD group. Especially Tim Martin, whose help and work on the reconstruction of the corrupted MC simulations elements was of great help.

Finally, big hugs to my family who supported me with all their hearts and would keep a dinner plate for me even when I would come home very late. A very special thanks to year old nephew Caleb, who gave me something to smile about by visiting me every now and then during the writing of this thesis.

Chapter 1

Introduction

Answering fundamental questions of particle physics means looking at how the constituents of matter interact. Due to the very small size of these constituents, experiments are consistently reaching for higher energies. This also means that particle accelerators and detectors require the latest technologies available. The Large Hadron Collider (LHC) [2] at CERN is the highest energy particle accelerator in the world. The ATLAS experiment [3] is its largest detector, studying particles at center of mass energies up to $\sqrt{s} = 13 \text{ TeV}$. Following the end of the current active period of the LHC, a long stop for upgrade and repairs is scheduled for July 2018, which includes changes to the ATLAS detector [4].

This thesis contains two sections: the first part discusses a contribution to the upgrade of the ATLAS detector and in the second part of this thesis, the production rates of the K_s^0 and Λ particles are measured.

sTGC Testing Facility

One of the ATLAS detector upgrades during the next shutdown will be the replacement of two of the detector components which detect muons, the two muon small wheels. The detector modules that will form the new wheels are known as small Thin Gap Chambers (sTGCs) [5]. These will be produced with the collaboration of multiple countries around the world, including Canada. The sTGCs built in Canada will have their quality and performance tested at McGill University. The hazardous presence of flammable pentane gas and high voltages, necessary for the operation of these detectors, means that the operation and testing

of these detectors must occur in a safe environment for the integrity of the sTGCs and the facility as well as the safety of the operators. Risks include leaks of pentane in the laboratory, damages to sTGC components or lab equipment due to pentane condensation, electric shocks to operators and high voltage damage to electronic components of the sTGCs or testing equipment. To address this, a system that minimizes such situations from occurring is required.

The first part of this thesis therefore discusses the resulting development at the McGill sTGC testing laboratory of a Slow Control system and its associated state machine. Its purpose is to allow for system control while monitoring activity and providing automated safety actions if necessary. The triggers for automated safety actions are the detection of a risk of damage to operators, lab equipment or sTGCs as well as undesirable environmental conditions for safe operation.

Strangeness Production

During proton-proton collisions at the LHC, new particles are created through fundamental interactions, among which is the strong interaction described by Quantum Chromodynamics (QCD) theory, one of the components of the Standard Model. To reliably model high energy events studied at the LHC, which produce complex interactions with a very large numbers of particles involved, it is necessary to understand a wide range of energy transfer. While QCD can calculate interactions with high energy transfers, complications in the low energy regime are less well understood. Hence data is needed to complement the theory. Measurements of the production rate of strange low mass particles provides data for this. These particles contain the strange quark, the third-lightest of all quarks, and have a clear signature (or detection pattern), allowing for a high efficiency analysis. New data collected from p-p collisions at 13 TeV energy using the ATLAS detector might provide new insights at low energies while addressing a new range of energy transfers. For this purpose, the two lowest mass strange particles, the K_s^0 and Λ , have their production rates measured in this work.

Part I

The Slow Control System of the sTGC Testing Facility at McGill

Chapter 2 introduces the testing environment for the sTGCs at McGill University. Following that, the steps of developing a Slow Control system are described in Chapter 3. Chapter 4 shows details on the operation of this system.

Chapter 2

The sTGC testing facility at McGill University

The small Thin Gap Chambers (sTGCs) are ionization detectors whose purpose here is to detect muon particles, a type of charged particle. As shown in Figure 2-1, they are composed of four thin ionization chambers (with gas gaps) with high voltage cathode plates on each side. Anode wires in the middle of the gas gaps provide readings in one direction, while detection strips provide readings in the other (shown in Figure 2-2). Detection pads on top of the cathodes are used for fast coincidence as well as helping to choose which strips should be utilized. Before being shipped from Canada to Geneva for installation in the ATLAS detector (see Chapter 6), the sTGCs built in Canada are to be tested for quality assurance at the McGill University sTGC testing facility. During testing, the sTGCs are placed on horizontal shelves inside a hodoscope array, whose scintillators cover the top and bottom section (see Figure 2-3). Multiple shelves permit multiple sTGCs to be tested concurrently. For the muon source, cosmic rays are used. These are high energy radiation which form particle showers when they hit the atmosphere, producing muons. They are a readily available and reliable source of muons and thus ideal for the testing facility. A data acquisition system reads and interprets the data from the sTGCs and the hodoscope array, comparing them to check for problems or abnormalities in the operation of the sTGCs.

As both the hodoscope and the sTGCs require high voltages of approximately 2.5 kV and 3 kV [5], respectively, a high voltage power supply is located inside the lab. CO₂ and

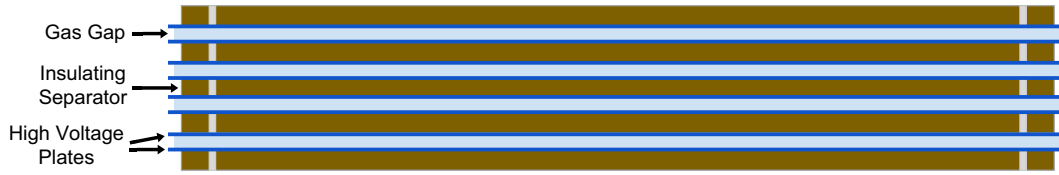


Figure 2-1: Schematics (not to scale) of a sTGC is shown, with four gas gaps between high voltage cathode plates.

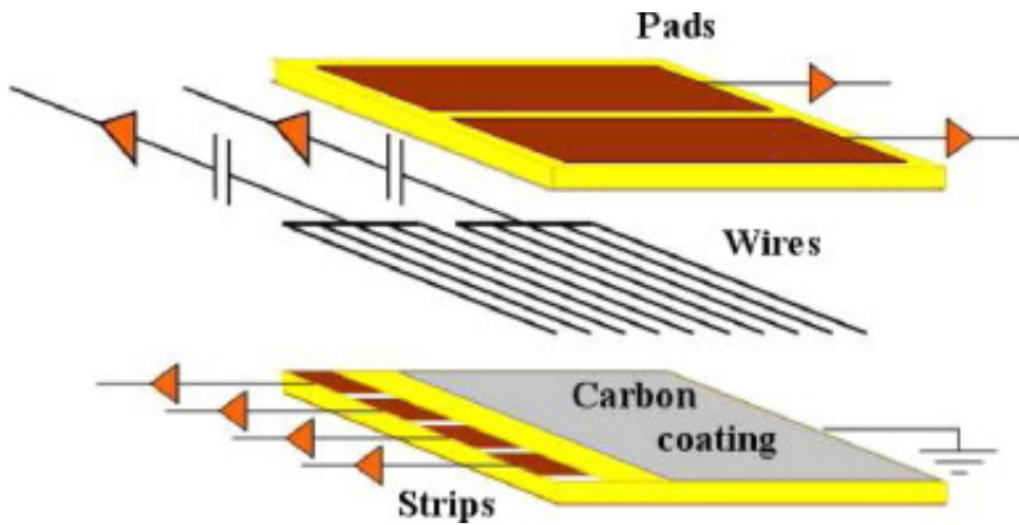


Figure 2-2: Schematic diagram of an sTGC gap structure [6].

pentane gas mixtures are the gases used for the sTGCs. This is provided through a gas system specifically designed for the facility [7] and which was built on site. The system is fitted with sources of pentane and CO_2 . The amount of CO_2 flowing into the system is controlled by two Mass Flow Controllers (MFCs). One provides pure CO_2 while the other MFC feeds a pentane mixing system which controls the gas mixture, keeping it at a required 45% pentane and 55% CO_2 during normal operation. The mixture is then sent through individual gas lines, each of which can feed the gas gaps of one sTGC. The lines must be manually operated to switch between pure CO_2 flow and the pentane mixture. After exiting the sTGCs, the gas mixture is fed into a pentane recovery fridge. This then recuperates most of the pentane through condensation, with the remaining gas mixture, mostly CO_2 ,

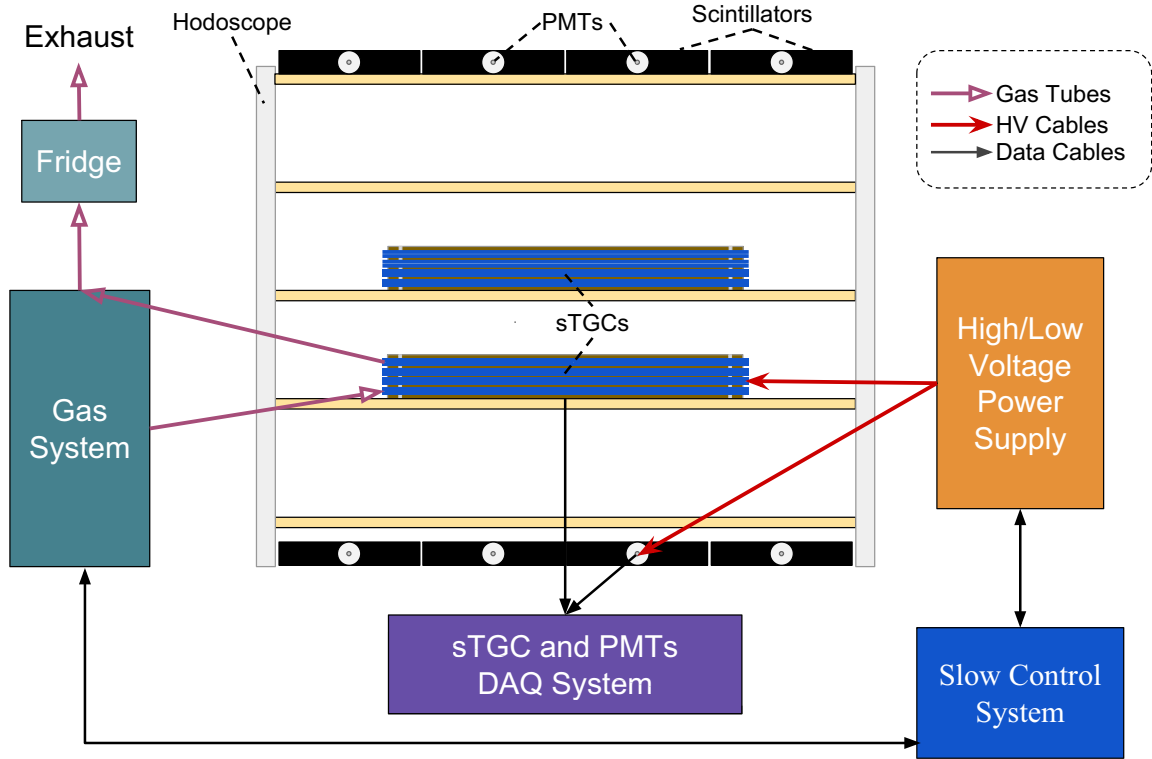


Figure 2-3: The layout of the sTGC testing facility is shown. The hodoscope array can support the simultaneous testing of up to four sTGCs, one per each of the shelves.

being exhausted thereafter. The pentane being a flammable gas, solenoid shutoff valves are placed at strategic locations in the system so as to isolate all pentane reserves if necessary. To determine if such a situation has arisen is left to the Slow Control system, introduced in Section 3, through the use of multiple sensors included in the gas system.

Chapter 3

Design of a Slow Control system

The original template of the Slow Control system is a gas and HV monitoring system which allows the operator to control the gas flow through Mass Flow Controllers (MFCs) by specifying how much is needed for each gas line and turning on the appropriate valves. The template also has a state machine, which comes from a concept in process automation. The implementation here has sets of testing conditions which are given predefined states that indicate the current status of operation. However, that template lacks automatic functions, such as prevention of hazardous conditions, and has unreliable data acquisition and fault-prone code. This chapter discusses the development of the current Slow Control system, which seeks to fix these problems and further improve the system as a whole.

The current Slow Control system is composed of a hardware part and a software part. The hardware includes sensors to acquire information about the status of the system, with components to control the operations and react to problematic conditions (activate the solenoid shutoff valves in the case of a leak for example). The software part monitors the data from the sensors and uses it to perform some automatic actions as well as informing operators through graphical interfaces. It also allows said operators to control independently multiple sTGC tests by using an individual state machine for each one. A list of hardware components follows:

- CO₂ tank pressure sensor: an electronic pressure sensor reading the CO₂ tank pressure before the regulator.

- CO₂ input line pressure sensor: an electronic pressure sensor reading the output pressure of the tank after the regulator.
- Mass Flow Controllers (2): CO₂ calibrated flow controllers that regulate and monitor the amount of CO₂ flowing from the source into the gas system.
- Peltier System: custom built system that takes CO₂ as input and outputs a controllable pentane mixture to the system.
- Differential pressure sensors (6): sensors reading the pressure difference between the room and an individual gas line.
- Solenoid valves (6): gas valves that control the flow of gas to and from Peltier sources and can switch the system to pure CO₂ flow.
- Solenoid valves temperature sensors (6): sensors reading the temperature of the solenoid valves.
- Exhaust flow sensor: a flow sensor verifying that the exhaust vacuum is functional.
- Explosive gas detectors (2): detect the presence of explosive gas such as pentane.
- Room temperature sensor: sensor reading the temperature of the testing facility.
- Recovery fridge sensor: sensor reading the temperature of the fridge used for pentane recovery.
- Humidity sensor: sensor reading the current humidity in the testing facility.

The software part was built using LabVIEW block programming software [8]. It is composed of three main Virtual Interfaces (VIs): the Data Acquisition (DAQ) panel, the High/Low Voltage HV/LV panel and the Slow Control State Machine.

Slow Control DAQ

STOP

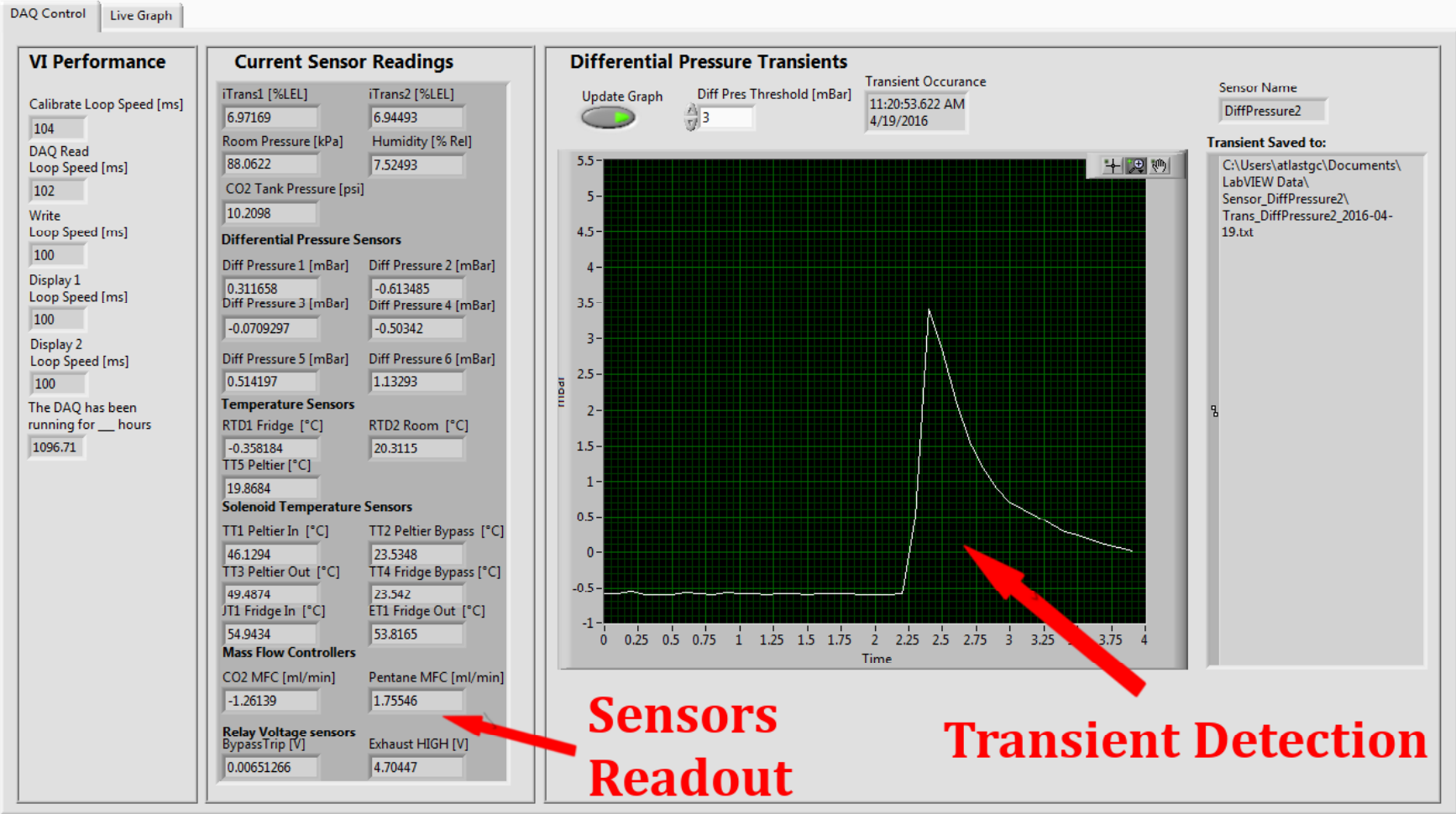


Figure 3-1: The DAQ panel, showing the calibrated readings from the sensors. A graph shows the latest transient data peak detected.

3.1 Data Acquisition

The data is acquired through multiple individual sensors and controllers in the gas system. It is then sent to the computer where the DAQ panel first calibrates the data, transforming voltage and current readings into readable unit representations (e.g. °C for temperature). The DAQ then logs the results and is meant to communicate them to other VIs for interpretation. This VI is insulated from the operations of the other two main VIs, to reduce the possibility of being affected by any problem that would arise in them. The original Slow Control data acquisition system was initially logging information once every minute, whatever the behavior of the data was. The need to record transient peaks, that is rapid changes to the data that return to normal in less than one minute (see Figure 3-1), arose over time for certain sensors and events. The system was thus changed to also record any relevant change at the highest possible rate, which is limited by the individual sensors response times. Per sensor configurable thresholds determine when to start acquisition, recording events each time the data has shifted by a the threshold amount. Information on transient events is thus recorded by the system. Since most sensors have a response time of a few milliseconds or less and the testing setup is only sensitive to changes that last at least a few seconds, adapting the logging rate to the sensor response time makes the system more efficient. This was a major improvement to the usefulness of the logged data.

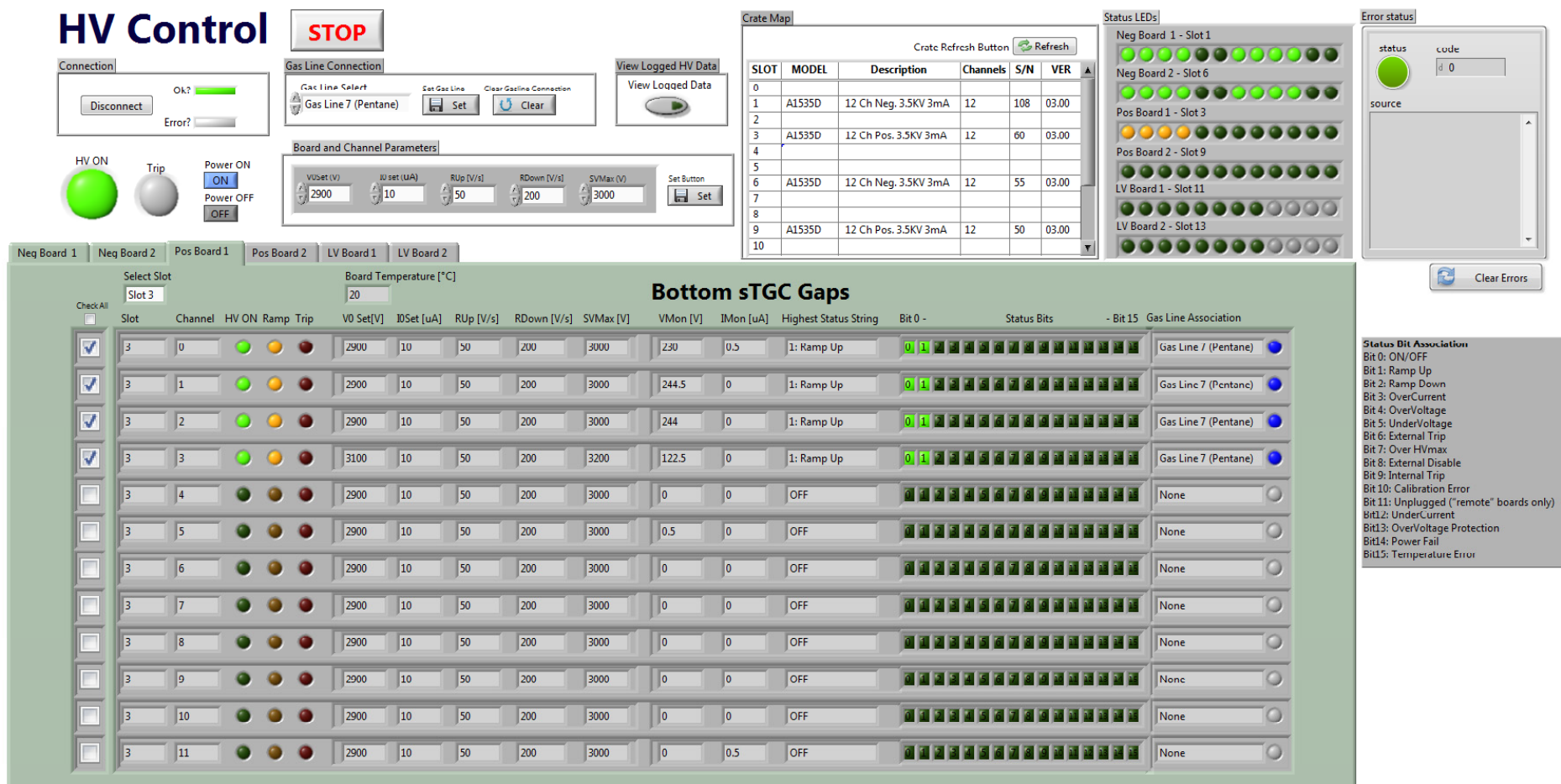


Figure 3-2: The HV/LV panel VI, with each channel on a single line. Global status information is shown on top left. Gas line association is made on the left of the channels. Tabs separate the PMT, sTGC gap and low voltage channels.

3.2 HV/LV Panel

The power supply of the testing facility provides high and low voltages to different components of the sTGCs and hodoscope through channels. Each channel can be set to a different voltage and is individually monitored. It is controlled remotely by the Slow Control through the HV/LV panel (see Figure 3-2). This panel reads the information about the channels from the power supply and logs any observable changes to the voltage or status. The panel allows an operator to set the voltage as well as to power on and off channels. For channels that are meant to be connected to sTGCs, they must first be associated with a gas line. When a power on command is sent, the panel first verifies that the channel is associated with a gas line. If this is the case, it then asks the Slow Control State Machine VI if the sTGC with this gas line is ready for high voltage. If either of these tests fails, a warning is sent to the operator and the channel is not powered. When a channel is powered, that status is made available for the Slow Control State Machine.

State Machine Control

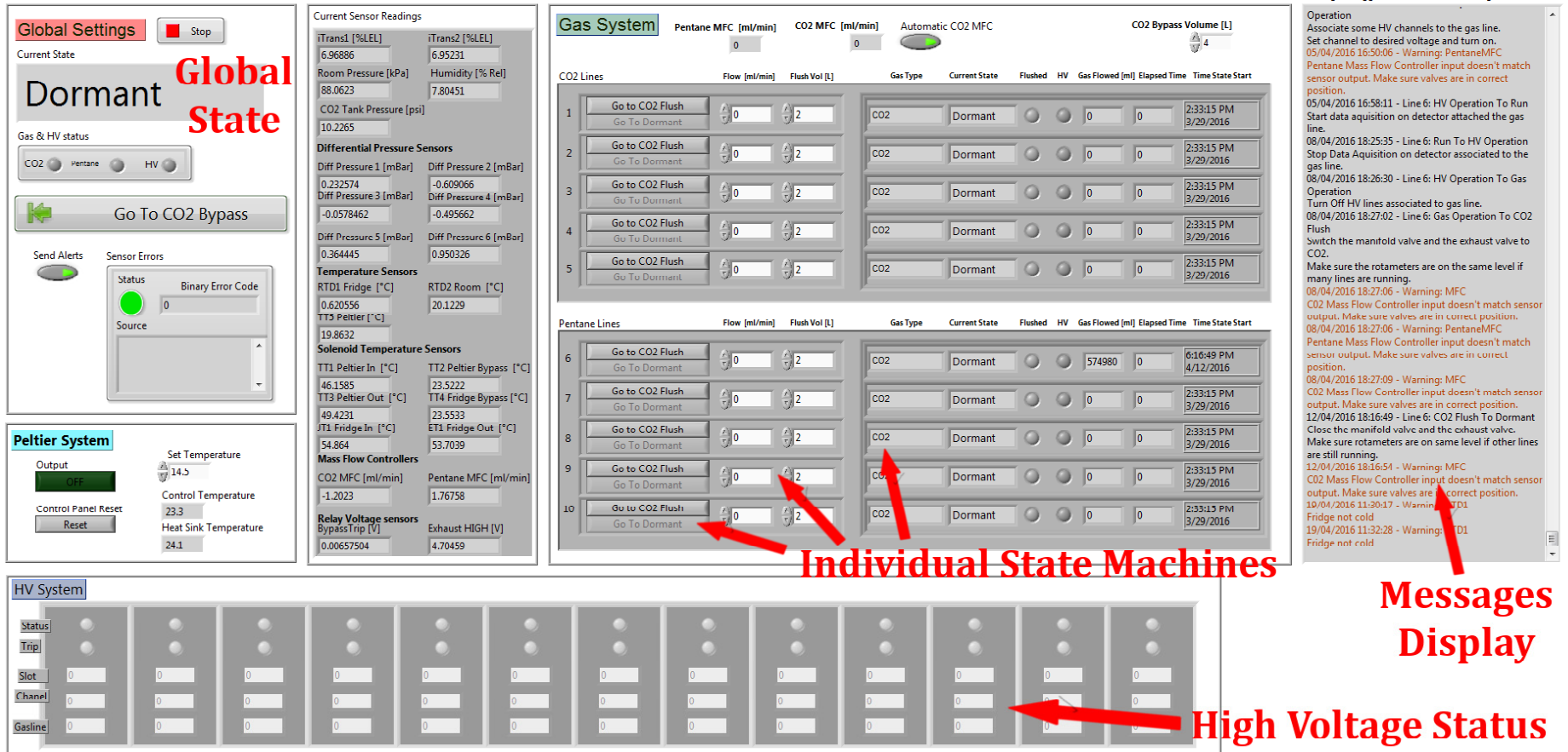


Figure 3-3: The Slow Control State Machine VI, with the top right box showing information on the system status and displaying the global state. The center parts contain individual state machine control and monitoring. Messages and alerts are shown on the right.

3.3 The Slow Control State Machine

The Slow Control software is required to run multiple tests simultaneously. However, a single state machine for the whole system proved to be inefficient. Therefore, the system is split into two parts. One part is multiple state machines, one per gas line and each gas line can feed one sTGC, that operate independently of each other under normal conditions. Hence, simultaneous yet independent testing of multiple sTGCs can occur. The five possible states are listed in in Table 3.1. Note that the last two states in the table are special states that affect all gas lines. The flow of operation is shown in Figure 3-4(a), where higher states in the hierarchy are closer to fully operational testing. A global Slow Control state exists (see Figure 3-3). It is either at the highest normal state in operation or at one of the two special states. This global state is displayed in large text in the status section of the panel. Thus operators can easily be aware of the current operation level of the testing facility. This is supplemented by the individual indicators for pentane flow and high voltage activity to provide more information on the testing status of sTGCs.

State	HV	Gas	Description
Dormant	Off	Stopped	Inactive state.
CO ₂ Flush	Off	CO ₂	CO ₂ gas flow at high rate in gas line.
Gas Operation	Off	CO ₂ or mixed	Gas changed to CO ₂ -pentane mixture if necessary. Gas flow at normal rate.
HV Operation	On	CO ₂ or mixed	High voltage is turned on.
Run	On	CO ₂ or mixed	Data acquisition state.
CO ₂ Bypass	Off	CO ₂	Error state. Pentane systems isolated, high voltage turned off with CO ₂ flow at high rate for active lines.
Pause	On or Off	Stopped	Operator intervention state. Stops gas flow on all active lines for at most ten minutes while keeping high voltage on if present.

Table 3.1: Description of the possible states for the state machine. The high voltage status and type of gas mixture flowing is shown for each state. The states from Dormant to Run are individually controlled for each gas line. The last two states affect all gas lines at the same time.

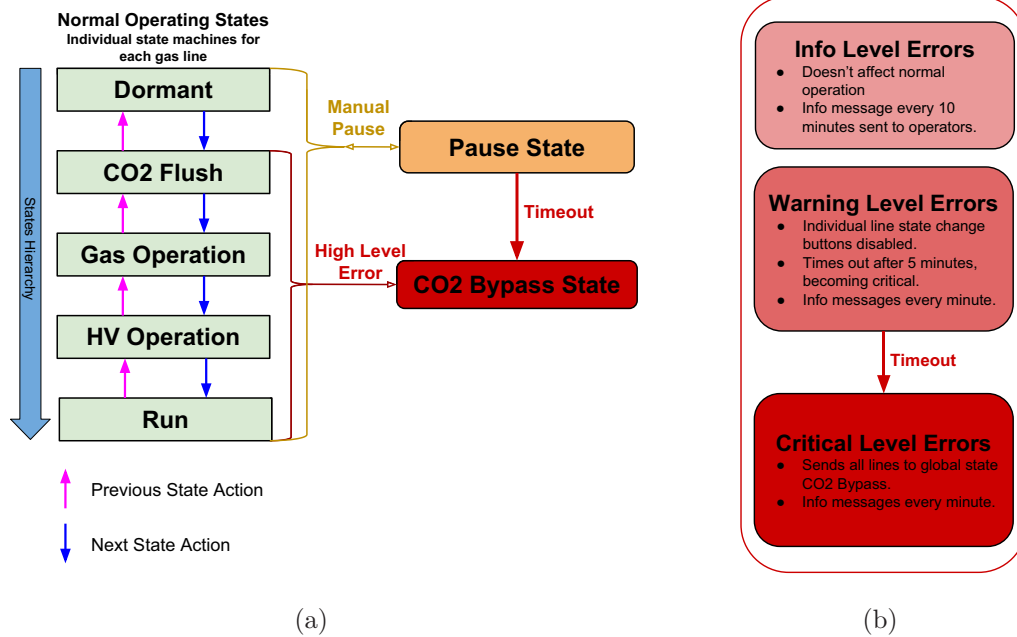


Figure 3-4: State machine description. (a) State machine transition diagram. The vertical arrow indicates the state hierarchy. The *Timeout* illustrated here is the time allowed for the system to be in the Pause state, after which the system transitions to the CO₂ Bypass state. (b) State machine errors. The *Timeout* illustrated here is the time allowed for a Warning level error to be active before it becomes a Critical level error.

Chapter 4

Operation of the State Machine

The data acquisition from sTGCs can only begin once the state machine has reached the *Run* state. To prepare a sTGC for a run, the operator must first connect it to a gas line and four high voltage channels, one per detector gap. This gas line is then shifted to the *CO₂ Flush* state. In this state, the sTGCs are ventilated at a high rate of 100 mL/min with a pure CO₂ gas until impurities have all been removed from the detector. The time this takes depends on the volume of the sTGC being tested. When the gas volume has been flushed, the operator prepares the system for CO₂-pentane mixture input. At this point the state machine allows the operator to initiate to the next state, in this case, *Gas Operation*. Here the system is again being flushed, though at a lower 80 mL/min rate and this time with the CO₂-pentane mixture. The operator then waits until the mixture has reached an equilibrium inside the detector, determined again by the gas volume that has flowed. The *HV Operation* state follows, permitting the operator to turn on the high voltage channels associated with the detector gas line using the HV/LC panel. High voltage channels for sTGC gaps cannot be turned on until a gas line has been associated with it on the HV/LV panel, which then waits for the Slow Control State Machine VI for confirmation. This is given when the line is in the *HV Operation* state. When the nominal voltage is reached, the HV/LV panel notifies the state machine. The operator can then switch to the *Run* state and start sTGC and hodoscope data acquisition (done by a separate system, not to be confused with the DAQ Panel acquisition for the Slow Control).

The state machine also sometimes requires the operator to perform manual operations

when going from one state to another, such as switching valves from CO₂ flow to pentane flow and adjusting rotameters to equalize gas flow between lines. The system communicates this through prompts and then awaits operator confirmation before proceeding to the next state. The array of sensors is continuously monitored, making sure no anomalies are occurring, such as could be caused if the operator didn't correctly carry out the manual operations. A dedicated log window shows color-coded messages about state changes as well as any alert caused by detected errors. The possible errors are separated into three classes, shown in Figure 3-4(b). The lowest level, *Info level*, refers to system information and abnormal environmental conditions (such as very high humidity in the facility) messages. Normal operation can still occur while these messages are present. *Warning level* errors are more serious errors that require operator intervention. They prevent state changes and prompt the operator to fix the issue. Failure to address the issue within a specified time will result in the error being promoted to critical. *Critical level* errors include these elevated errors as well as critically dangerous operating condition errors, such as the detection of a pentane leak. They automatically send all the state machines to the global *CO₂ Bypass* state. This stops all pentane mixture flows and turns high voltages off. The sTGCs are then flushed at a high rate with pure CO₂. A button on the state machine panel allows this state to be activated manually by the operator if deemed necessary.

A simulation of a blockage in the gas line causing a *CO₂ Bypass* state was done. The cooling of the four shut-off valves in Figure 4-1(a) confirms the isolation of the system from the pentane source and the fridge, with bypass valves opening to start pure CO₂ flushing. Figure 4-1(b) shows the MFC raising the flow to 100 mL/min and the high voltage turning off in reaction to the state change.

If any error is present for more than one minute (ten minutes for *Info level* errors) without being fixed, the state machine starts sending emails and SMS periodically (the time between messages doubles each time to prevent spamming) to operators until actions are taken. If an operator needs to perform some intervention that requires all gas flow to be temporarily stopped, such as changing the CO₂ tank feeding the system, the operators can activate the *Pause* state. This temporary halt to gas flow gives a prompt to the operator with a ten-minute countdown counter to resume operation. If the timer elapses before the operator

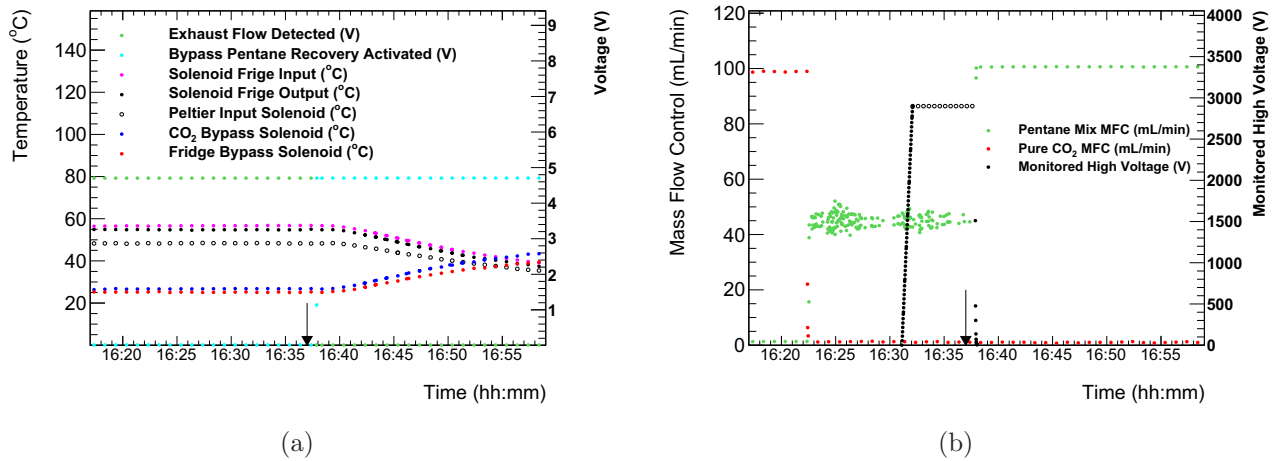


Figure 4-1: Response of the gas system to a simulated exhaust blockage (indicated by an arrow). (a) Bypass solenoid valve system response to a blockage event. Solenoid valves are normally closed, so their temperatures increase when they stay open. (b) High Voltage and MFC response to a blockage event. Note that after the blockage event, the gas flowing in the system is pure CO₂.

allows the resuming of operations, the *CO₂ Bypass* state is activated. This is necessary to protect the sTGC from prolonged pentane exposure with no flow present, which can potentially cause damage to the sTGC gaps, especially if pentane condensation happens.

Part II

K_s^0 and Λ production rates measured by the ATLAS detector at $\sqrt{s} = 13$ TeV

The first chapter in this part will introduce the concept of production of strange particles. Then, the LHC collider and ATLAS detector, which were used to produce and collect the data used here are detailed. The analysis of that data is then discussed in Chapter 7 and the results presented in Chapter 8. Chapter 9 will conclude both parts of this thesis.

Chapter 5

Strangeness production

5.1 The Standard Model of particle physics

The Standard Model (SM) is by far the most well-known model of elementary particles and their interactions [9, 10, 11, 12]. Every measurement to date has been in agreement with it. Hence, it is a good model for particle physics experiments. It describes matter as being composed of spin- $\frac{1}{2}$ fermions of two types, quarks and leptons. Each type and flavour constitution has both a particle and anti-particle fermion. The fermions compose the fermionic family, shown in Table 5.1, with a total of six leptons and six quarks flavours. They are separated into three generations, which have similar properties except for mass, which rises with higher generations.

There are four known forces: the strong, weak, electromagnetic and gravitational forces. The gravitational force is much weaker than the other forces at the scale of particle interactions, and as such is not included in the Standard Model. The strong force is mediated by eight gluons, the weak force by three vector bosons ($W^\pm$ and Z^0) while the photon (γ) mediates the electromagnetic force. Finally, there is the recently discovered Higgs boson [13], confirming the existence of the Higgs field, which gives the other bosons their masses. The bosons are their own antiparticle, except for the $W^\pm$, which are each other's anti-particle.

The interactions formed by the electromagnetic and the weak force are described by the SM field theory Quantum Flavour Dynamics (QFD). This sector of SM successfully predicted the existence of the $W^\pm$ and Z^0 bosons. According to the theory, these bosons

Quarks				
Generation	flavour (symbol)	electric charge	flavour (symbol)	electric charge
I	up (u)	$+2/3$	down (d)	$-1/3$
II	charm (c)	$+2/3$	strange (s)	$-1/3$
III	top (t)	$+2/3$	bottom (b)	$-1/3$
Leptons				
I	electron (e)	-1	electron neutrino (ν_e)	0
II	muon (μ)	-1	muon neutrino (ν_μ)	0
III	tau (τ)	-1	tau neutrino (ν_τ)	0

Table 5.1: The fermions.

are involved in the weak interactions between quarks or lepton generations, with the Z^0 mediating in a neutral interaction and the $W^\pm$ in a charged transfer one. QFD also describes quark-lepton interactions of electromagnetic nature and the two forces are combined into the electroweak force. The SM field theory that covers strong interactions is known as Quantum Chromodynamics (QCD). The *chromo* refers to the quarks carrying a *colour* charge: *red*, *green* and *blue*. This *colour* charge makes quarks combine to form “colourless” hadrons, which are divided into two types: mesons if it is a pair made by a “colour” quark combining with its “anti-colour” quark or baryons if formed by a “colourless” triplet of different coloured quarks. This leads to the concepts of confinement as no free quark or gluon has ever been directly observed.

5.2 Introduction to strangeness

The first observation in cosmic ray experiments of strange particle interactions was the discovery of the $K^0 \rightarrow \pi^+\pi^-$ decay in 1946 [14]. The Λ was first observed in an other cosmic rays experiment one year later. It was expected to have a mean lifetime of about 1×10^{-23} s, but instead results a much longer lifetime, at $\sim 1 \times 10^{-10}$ s. This led to the postulation in 1953 of a new quantum number, dubbed ”strangeness”.

The currently accepted masses as reported by the Particle Data Group (PDG) [15] are 497.611 ± 0.013 MeV for the K^0 and 1115.683 ± 0.006 MeV for the Λ . The K^0 is a superposition of two weak eigenstates which decays through weak interactions at two vastly different lifetimes, though both are relatively long compared to strong decays. The longer-

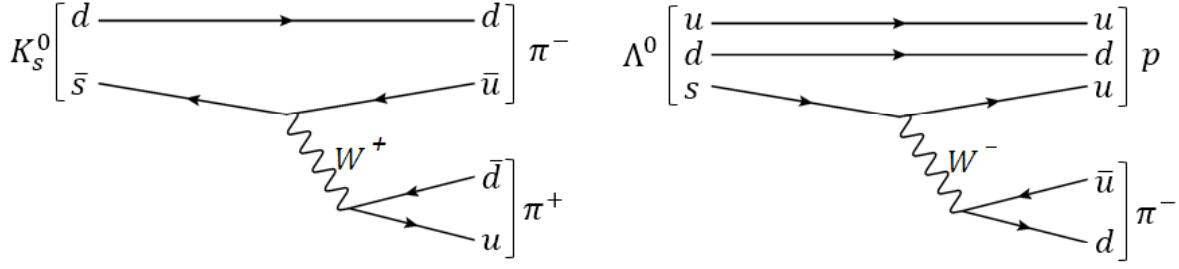


Figure 5-1: Feynman diagrams of the main decay modes of the K_s^0 meson and Λ baryon.

lived K_L^0 decays to three pions, one positive, one negative and one neutral, with a lifetime of $(5.116 \pm 0.021) \times 10^{-11}$ s. The K_s^0 has a shorter lifetime of $(8.954 \pm 0.004) \times 10^{-11}$ s. Its main decay mode, $K_s^0 \rightarrow \pi^+\pi^-$, has a large branching ratio of $69.20 \pm 0.05\%$ and an easily identifiable symmetry, and hence was chosen for this study. The mean lifetime of the Λ baryon is $(2.632 \pm 0.020) \times 10^{-10}$ s. The main decay mode is $\Lambda \rightarrow p\pi^-$ (or $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ for its antiparticle), with a branching ratio of $63.9 \pm 0.5\%$. Figure 5-1 shows the Feynman diagrams of these decays. The K_s^0 has a quark content of the form $\frac{d\bar{s}-s\bar{d}}{\sqrt{2}}$, a superposition of the K^0 and its antiparticle. The Λ contains an up, a down and a strange quark, with its antiparticle containing the corresponding antiquarks. For the rest of this thesis, Λ shall be used to refer to both its particle and antiparticle unless otherwise specified.

5.3 Previous Experiments

Previous experiments have measured the production cross section of K_s^0 and Λ . This includes lower energy runs at the LHC and experiments at the HERA collider.

The ZEUS experiment at the HERA collider had a neutral strangeness production study at a center-of-mass energy of $\sqrt{s} = 300$ GeV [16] which found the number of K_s^0 mesons per event to be $0.038 \pm 0.006(stat) \pm 0.002(syst)$. The number of Λ baryons per hadronic event was found to be $0.289 \pm 0.015(stat) \pm 0.014(syst)$. It was found to agree with previous results at lower energies [17, 18, 19, 20]. The ATLAS experiment at the LHC had previous runs at lower energies, 900 GeV and 7 TeV, that were also studied for strangeness production (see [21] for detailed results).

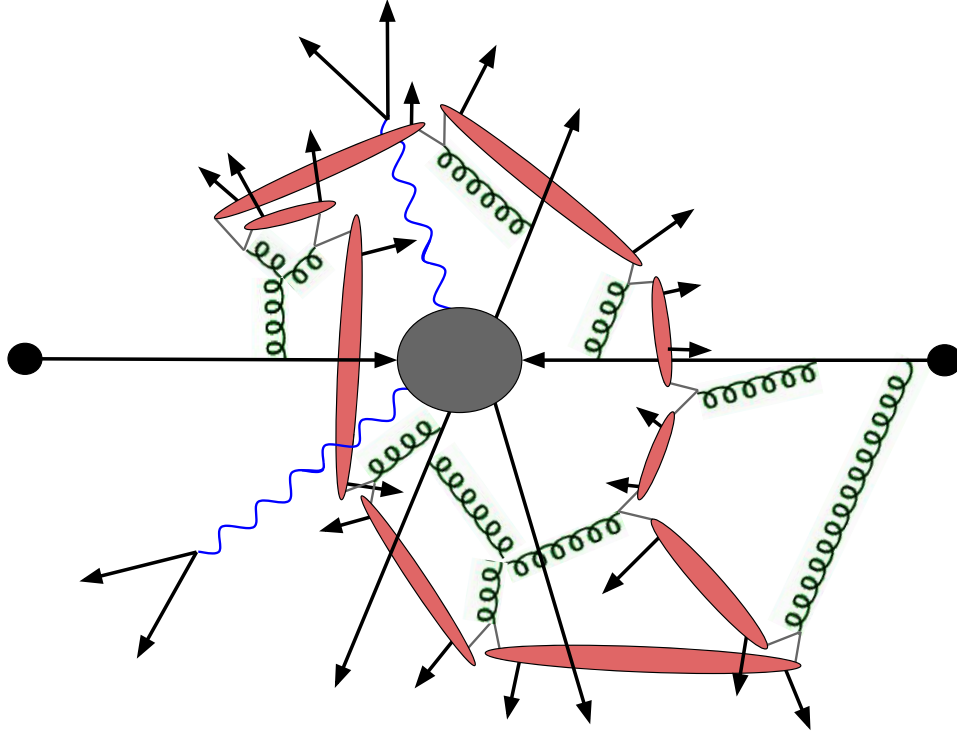


Figure 5-2: Simplified schematics of a proton-proton collision, depicting the outgoing objects and the parton showers produced by a Monte Carlo event generator (see text).

5.4 Monte Carlo simulation

Monte Carlo (MC) simulations are precise calculation tools that reproduce experimental measurements using all known physics processes between particles so as to model the results as accurately as possible. They are crucial tools in modern high energy physics experiments and necessary in data analysis to correct for detector effects as well as to evaluate possible systematic uncertainties. The first part of a MC simulation is the physics generator [22]. In the case of the ATLAS detector, this means simulating $p - p$ collisions and their final state particles, shown in Figure 5-2. Hard sub-processes, shown as a grey circle in the figure, are where high momentum interaction produce a few outgoing fundamental SM particles, as well as sometimes including hypothetical particles from a new theory. The interactions produce partons (quarks and gluons) that will radiate virtual gluons. These virtual gluons can produce more partons, forming parton showers (green spirals in figure). The next step in the generator simulation is the hadronization (red ovals in figure), where quarks and gluons

in the particle showers are bound into observable “colourless” hadrons by strong interactions. The formed hadrons are mostly unstable, and thus the final generation step is the simulation of hadron decays. The information produced is then fed into another type of simulator. This type simulates the detector itself and how particle showers interact with its sub-detectors. For ATLAS, this final step is done using the GEANT4 [23] simulation toolkit.

The first step in producing a simulation is choosing an event generator, which is a simulation program which produces four-vectors of particles after p-p collisions. In the case of this thesis, the need arises for accurate production of the low mass strange particle and decay products. Two generators which fit this criterion were used:

- PYTHIA [24]: A program often used for high energy physics simulation is the PYTHIA program. It simulates physics processes such as hard scatters, initial and final state parton showers, as well as the fragmentation processes and particle decays. It uses the Lund string model [25] for hadronization, a precise and reliable model that replicates many of the observed features of hadronic showers. The different PYTHIA configurations of its simulation parameters are called *tunes*. This thesis uses the non-diffractive PYTHIA 8 A2:MSTW 2008LO tune [26].
- EPOS [27]: A more recent event generator is EPOS. It simulates both soft and hard processes in the same formalism as PYTHIA. This event generator uses a special simulation where every event in EPOS is equivalent to one in the LHC, with every particle typically produced generated. An EPOS LHC [28] tune, which has minimal constraints on event selection, is used in this thesis.

The tunes had missing information such as the links between mother and daughter particles in the simulation which are needed in the event reconstruction. This prevented a full analysis of being done without redoing part of the reconstruction. The long processing time of a new analysis and time constraints for this thesis highly limited the amount of MC tunes and simulated events that were available, thus resulting in a sufficient but limited analysis.

Chapter 6

Experimental Setup

6.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [2] is an underground particle accelerator located at the CERN research center in Geneva, Switzerland. It is designed for proton-proton collisions with center-of-mass energies of up to $\sqrt{s} = 14 \text{ TeV}$ and lead-ion collisions with an energy of up to $\sqrt{s_{\text{NN}}} = 5.5 \text{ TeV}$ per nucleon. An aerial view of the site is shown in Figure 6-1 and schematics of the present CERN accelerator complex in Figure 6-2. To reach the LHC, protons must first undergo a series of pre-accelerators [29]. The proton source is a simple bottle of compressed hydrogen gas, whose hydrogen atoms are stripped of their electrons by an electric field, forming a beam. This beam of newly ionized protons is then fed through the first accelerator in the chain, the Linac 2. The beam comes out at 50 MeV and is then further accelerated to 1.4 GeV by the Proton Synchrotron Booster (PBS). It is then injected into the Proton Synchrotron (PS), which further accelerate the proton beam to 25 GeV, followed by the Super Proton Synchrotron (SPS), pushing the beam to 450 GeV and injecting it into the LHC. The LHC is a 26.6 km long ring containing two particle beams that are kept circulating in opposite directions by superconducting magnets. The two beams are inside the same cold mass, a unique feature and engineering feat to the LHC, necessary due to the lack of tunnel space and the high cost of a second separate ring. The particles are injected as ten centimeters long bunches of 10^{11} protons. At maximum capacity, where each bunch is only 25 ns (approx. 8 m) apart from the next, up to 2808 bunches can be fit into each of



Figure 6-1: Aerial view of the LHC ring (located underground). The locations of the four collision experiments are also shown, with CMS on the left side , ALICE and the right side, LHCb at the top of the ring with ATLAS not far to its right.

the beam pipes [30].

There are currently four collision points, where the major experiments are located:

- ATLAS [3] The largest of the two general purpose detectors.
- ALICE [31] A heavy ion collision detector (lead-lead or lead-proton).
- CMS [32] The heaviest general purpose detector.
- LHCb [33] A spectrometer designed to study B-physics.

The LHC first accelerated proton bunches in September 2008, but the first collisions occurred much later, in December 2009, and only at a center-of-mass energy of 450 GeV, the injection energy. This was due to an electrical fault in the superconducting cables, causing

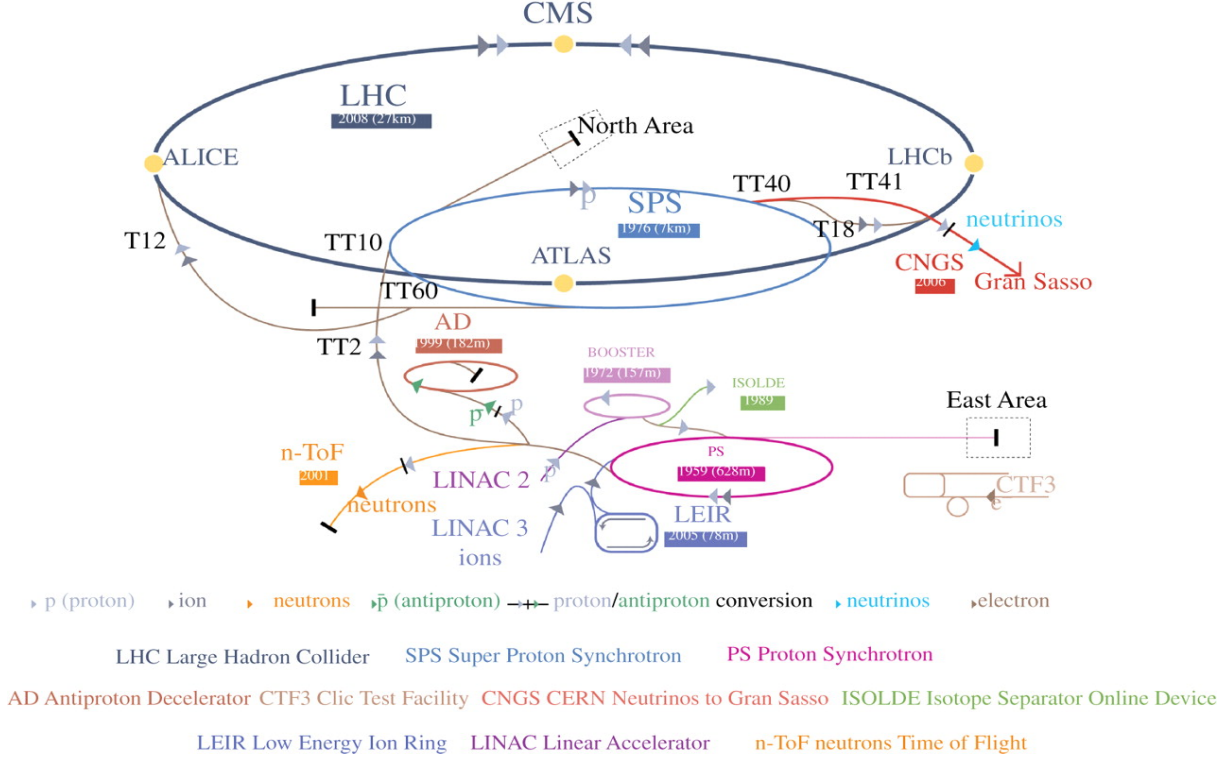


Figure 6-2: The CERN accelerator complex. Schematics of the pre-accelerator rings and location of the detectors are shown (see text for details).

heavy damage to part of the accelerator shortly after the initial startup. The ensuing repairs ended up creating around 14 months of delay. This meant the LHC could not immediately operate at its nominal center-of-mass energy of 14 TeV. Proton collisions at an energy of 7 TeV started in March 2010, followed by a slightly higher energy run at 8 TeV in 2012. The three years formed the active phase of the LHC known as Run-1. The accelerator was then shut down for upgrades and repairs to restore its original potential. Run-2 started at 13 TeV in 2015. In this thesis, the data from runs at 13 TeV will be used, and they will be compared to data from similar runs done at 7 TeV.

The total data delivered by the LHC at 7 TeV during 2010 and 2011 produced 5.6 fb^{-1} of data in terms of integrated luminosity [34]. In 2015, the first year of Run-2, about 4.2 fb^{-1} were delivered by the LHC. The current year of 2016 has already delivered nine times more data, with an integrated luminosity of 38.9 fb^{-1} . This is due to CERN accelerator division continuous work at increasing the instantaneous luminosity of the LHC, which went from a peak luminosity of $2.1 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ in 2010 [34] to the current average luminosity of

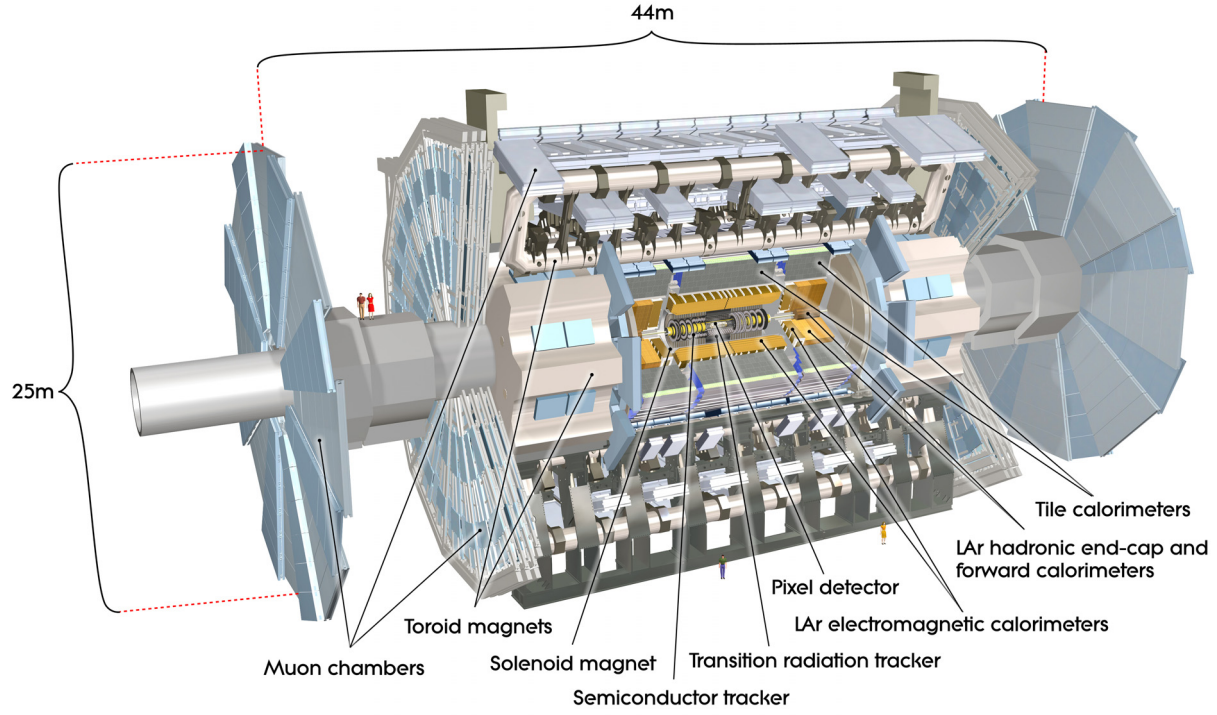


Figure 6-3: A cut view illustration of the ATLAS Detector, showing the main components. Starting from the interaction point is the inner detector, which contains the pixel detectors, SCT and TRT, surrounded by the solenoid magnet. Following this, the electromagnetic liquid argon calorimeter is found, surrounded by the tile calorimeters. On the outer is the muon spectrometer and toroid magnets.

$$13.7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}.$$

6.2 The ATLAS experiment

ATLAS (A Toroidal LHC ApparatuS) [3] at CERN is a particle physics detector built for multiple purposes, such as b-physics searches, testing the SM, finding the Higgs and looking for physics beyond the SM [35], which is made possible by the high energies produced by the LHC.

Assembly of the ATLAS detector at the CERN site started in 2003 and ended in 2008. The detector has the shape of a rough cylinder of 44 meters long and 25 meters in diameter. A cut-view of the detector is illustrated in Figure 6-3. Detection elements are either in the end-cap or barrel regions of the cylinder. In the ATLAS coordinate system, the z-axis follows

the LHC beam direction, leaving the x-y plane perpendicular to the beam, with y pointing up and x pointing towards the center of the LHC ring, forming a right-handed coordinate system. The polar angle θ is the angle with respect to the z-axis (beam). The azimuthal angle ϕ refers to the angle in the x-y plane with respect to the positive x-axis. A commonly used variable in this experiment is the Lorentz invariant pseudorapidity, which is defined as:

$$\eta = -\ln \left(\tan \left[\frac{\theta}{2} \right] \right) \quad (6.1)$$

The three main detection sections are, from outside in:

- The muon spectrometer does measurements covering the $|\eta| < 2.7$ region. It is composed of a barrel region with three layers of muon detectors as well as two end-cap regions with each having one small inner wheel and two larger outer wheels. It contains the large toroid magnets, whom the namesake of ATLAS is attributed to.
- The calorimeters are divided into two parts, the electromagnetic and the hadronic calorimeters. The electromagnetic calorimeter is a liquid-argon detector covering a detection region of $|\eta| < 3.2$. A large part of the hadronic calorimeter is a tile calorimeter which has only $|\eta| < 1.7$ coverage, though smaller detectors allow it to cover up to ± 4.9 in pseudorapidity. This is possible due to the Hadronic End-Cap (HEC) and the Forward Calorimeter (FCal), which are copper and copper-tungsten/liquid argon detectors who cover the high pseudorapidity (and high radiation) regions of $1.5 < |\eta| < 3.2$ and $3.1 < |\eta| < 4.9$ respectively.
- The inner detector covers the smallest rapidity region, with a $|\eta| < 2.5$ coverage at maximum. Encased inside a superconducting solenoid magnet, it contains the transition radiation tracker (TRT), the semiconductor tracker (SCT) and the Pixel detector. It is the primary source of data used here as it provides most of the tracking information necessary for finding the particles of interest.

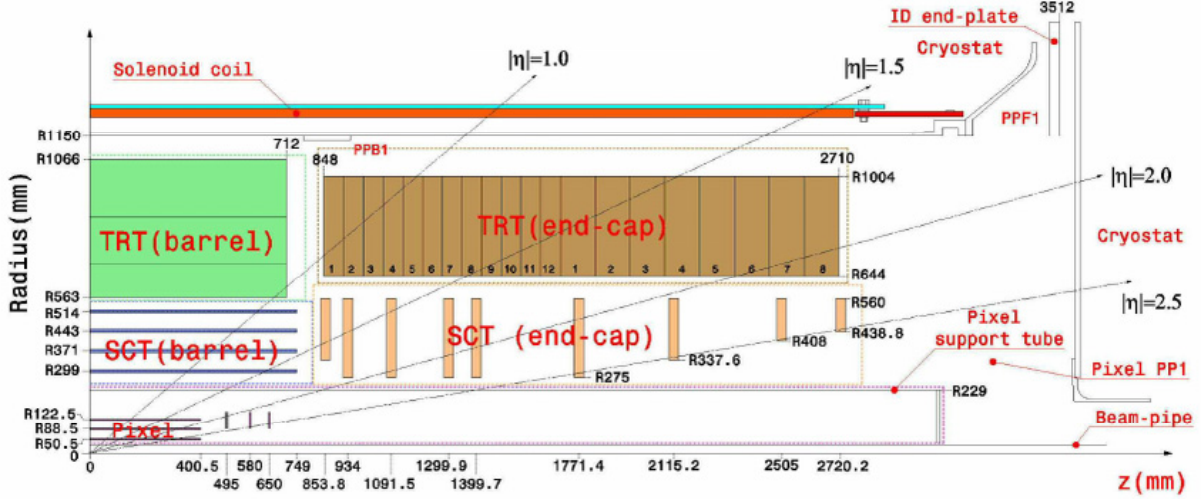


Figure 6-4: Layout of a quarter-section of the ATLAS inner detector showing the three sub-detectors and the solenoid magnet. The four tracks shown have momenta of 10 GeV at pseudorapidity $|\eta| = 1.0, 1.35, 2.0$ and 2.5 [3].

6.2.1 Inner Detector

The Inner Detector (ID) is a three-part tracking detector that is designed with an excellent position resolution of up to $10\mu\text{m}$ in the x-y plane ($R\phi$) and $115\mu\text{m}$ in z [36], and with a robust pattern recognition to detect particle tracks. The nominal threshold momentum of 0.5 GeV is used for most measurements but can go as low as 0.1 GeV if low momentum particles need to be studied, such as those analysed in this thesis. The ID has coverage of the pseudorapidity range of $|\eta| < 2.5$ and a broad energy spectrum, from 0.1 GeV to 150 GeV . A schematics layout of the ID is shown with four tracks at different pseudorapidities in Figure 6-4. The pixel detector starts at 5.05 cm from the beam, and the TRT goes to a radius of 1.05 m from the z-axis. The total cylindrical envelope is 1.150 m in radius and 7.024 m long. The ID can register track hits with an efficiency of up to 95% for an isolated track of $p_T = 5\text{ GeV}$.

A relative momentum resolution of $\frac{\sigma_p}{p} = (4.83 \pm 0.16) \cdot 10^{-4} \text{ GeV}^{-1} \times p_T$ was measured using cosmic ray testing (where p_T is the transverse momentum) [37]. The superconducting solenoid magnet located around the ID produces a 2 T homogenous magnetic field in the positive z-direction. This allows the detector to fully use its high precision in the transverse direction, as particle will be deflected in the x-y plane.

The high-radiation environment due to the close proximity to the beamline and interaction point means stringent conditions had to be imposed on the design of the ID. For instance, to keep the noise performance due to radiation damage at reasonable levels, the Pixel detector and SCT must be maintained at cold temperatures ranging from -5 to -10 °C. In comparison, the TRT which is located further away from the beamline operates at room temperature.

6.2.1.1 Pixel Detector

The Pixel detector is the detector closest to the interaction point in ATLAS. It is subjected to the highest amount of radiation, which highly constrains the design, with a requirement to still be operational after 500 kGy of lifetime dosage [38]. This high particle density also means an occupancy of at least 10 hits per pixel channel has to be satisfied. It is further required to have a fine granularity to resolve ambiguities in tracking, as most tracks are still very close to one another. Thus a transverse impact parameter resolution of at least $15\text{ }\mu\text{m}$ is needed as well as resolution in the z -coordinate that would permit primary vertex reconstruction with a standard deviation in z of less than 1 mm. To satisfy these highly constraining specifications on radiation hardness, resolution and occupancy, building it required leading-edge technologies.

The Pixel detector is composed of 1744 identical $19 \times 63\text{ mm}^2$ pixel sensors grouped in three layers (three cylinders for the barrel region and three disks in the forward region). Each sensor is $256 \pm 3\text{ }\mu\text{m}$ thick with n-bulk silicon wafers with the readout pixels on n^+ implants. A sensor module has 47232 pixels divided into 144 columns and 328 rows. The nominal individual pixel size is $50 \times 400\text{ }\mu\text{m}^2$ except for the front-end region of a module, where it is $50 \times 600\text{ }\mu\text{m}^2$. The spatial resolution of a single pixel is estimated at normal incidence angles to be $12\text{ }\mu\text{m}$ according to test beam results [39, 40].

6.2.1.2 Semiconductor Tracker

The SCT is a silicon strip detector made of 4088 modules with AC-coupled readout strips. Strip silicon detectors can be used here over pixels due to the lower radiation and lower charged particle density, allowing for cost and reliability improvements as well as ease of

production. The SCT central barrel region has four layers with rectangular modules having a strip pitch of $80\,\mu\text{m}$ and being composed of two sets of sensors glued back to back with a stereo angle of $40\,\text{mrad}$. The angle between the sensors allows for a measurement to have a precise z position using the crossing points of strips hit. The trapezoidal end-cap modules have nine radial strip sensors forming three rings around the beamline. As strips are rectangular, the pitch of these radial strips becomes greater as radial distance grows, with an average pitch of approximately $80\,\mu\text{m}$. With this design, particles in the acceptance region will pass through at least four modules, giving the minimum requirement specified of four space points. The strips have a position resolution of $17\,\mu\text{m}$ in $R\phi$, $580\,\mu\text{m}$ in z and an intrinsic hit efficiency of $99.74 \pm 0.04\%$ [41].

6.2.1.3 Transition Radiation Tracker

The TRT is composed of polyimide drift straw tubes $4\,\text{mm}$ in diameter and up to $144\,\text{cm}$ long (at most $37\,\text{cm}$ in end-caps). These straws are filled with a gas mixture of 70% Xe, 27% CO_2 and 3% O_2 with a $31\,\mu\text{m}$ diameter anode wire in the center. The straws detect charged particle by ionization of gaseous atoms followed by the multiplication of free electrons that drift close to the wire. That drift is what is measured and allows for position determination. When highly relativistic charged particles pass through the TRT, they may produce transition radiation by interacting with the TRT. This is especially true for the electron, meaning the TRT can also be used for particle identification. Transition radiation can then react with the gas, producing elevated signals and thus stronger readout signals. For each track going through the inner detector, at least 40 hits will be recorded in the TRT, which is used for better pattern recognition (e.g. by differentiation of charged pions from electrons). The TRT barrel is composed of straws parallel to the beamline that cover the pseudorapidity region $|\eta| < 1$. It has a position resolution in $R\phi$ of $142\,\mu\text{m}$ [42]. The end caps straws are perpendicular to the z -axis and cover the region up to $|\eta| = 2$, with a position resolution of $161\,\mu\text{m}$ in z . The TRT complements the SCT by having higher hits per track and higher sampling frequency, though with a lower position resolution.

6.2.2 Calorimeters

The Calorimeters are positioned around the inner detector between the muon spectrometer and the solenoid magnet. They measure the energy of particles by fully absorbing them. Energy is sampled by layers of detection (active) material separated by layers of absorbing material (passive), which are then combined with precise calibration [43] to get the total energy of the particles. The passive material is used to degrade the energy of the particles, while the active material is an excellent detector, thus allowing for reasonable energy resolution with good spatial resolution. The system is divided into two sampling calorimeter systems, the electromagnetic and the hadronic calorimeters, to enhance electromagnetic and strongly interacting particle detection, respectively.

6.2.2.1 Electromagnetic calorimeters

The electromagnetic calorimeters measure the energy and direction of electromagnetic showers due to photons and electrons. An accordion geometry (see Figure 6-5) is used to provide continuous coverage in ϕ . The high-density material used for energy absorption is lead while liquid argon fills the gaps as the sampling material. The barrel region covers up to $|\eta| = 1.5$ with the end-caps covering the $1.375 < |\eta| < 3.2$ region. Depending on the pseudorapidity, the materials in the electronic calorimeter have between 25 to 40 radiation lengths, whereas radiation lengths are the distance in g cm^{-2} over which an electromagnetic particle loses all but $\frac{1}{e}$ of its energy.

6.2.2.2 Hadronic Calorimeters

Wrapped around the electronic calorimeter is the hadronic calorimeter. Covering the region of up to $|\eta| = 4.9$, it is separated into three parts: The barrel-shaped tile calorimeter, the Hadronic End-cap Calorimeter (HEC), and the Forward Calorimeter (FCal). They measure the energy and direction of hadrons through both their strong and electromagnetic interactions. Hadrons being strongly interacting particles, they only lose a small fraction of their energy when they interact, meaning that on average they have a much longer penetration depth. This depth scales with nuclear interaction length. The tile calorimeter has steel as

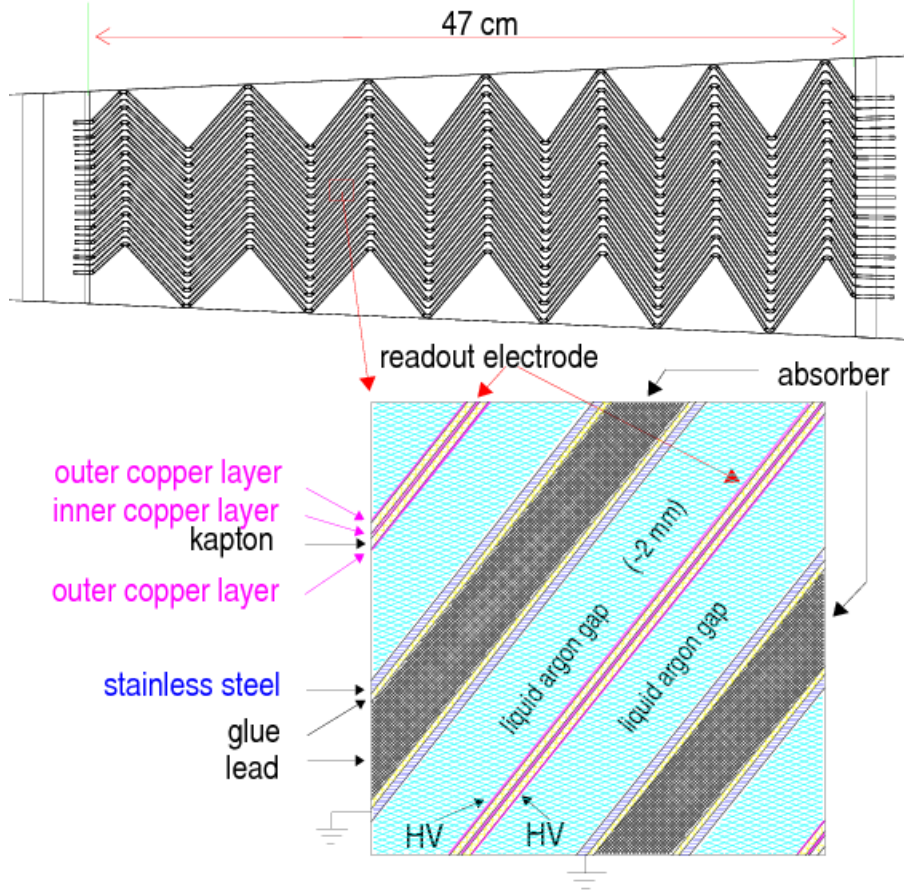


Figure 6-5: Schematics showing the accordion structure of the liquid argon calorimeter barrel region. The top figure is a view of a small sector of the barrel calorimeter in a plane transverse to the LHC beams [1].

the absorber material with scintillating tiles as the active material. It covers the low pseudorapidity region below $|\eta| = 1.7$. The next section is covered up to $|\eta| = 3.2$ by the HEC. The HEC has copper as an absorber and liquid argon as an active material. The FCal is installed very close to the beam, at high η and approximately 4.7 m from the interaction point. It covers the region $3.1 < |\eta| < 4.9$ but is also exposed to very high particle fluxes. Special small liquid argon gaps therefore had to be designed to resist radiation dosages of about 2300 kGy per year [44] while keeping a fast signal collection time to prevent build up. Two types of absorber materials are used, with copper for the first layer and tungsten for the second and third, optimizing electromagnetic and hadronic particle detection respectively. Altogether the hadronic calorimeter components have between 10 to 18 interaction lengths, depending on the pseudorapidity.

6.2.3 Muon Spectrometer

The muon spectrometer is the outermost sub-detector of the ATLAS experiment. A toroidal magnetic field of 0.5 T in the barrel region and 1 T in the end-cap regions bends the muon tracks to allow measurements of their momentum. The barrel toroid provides bending power of 1.5 to 5.5 Tm in the pseudorapidity range $0 < |\eta| < 1.4$. The end-cap toroids provide 1 to 7.5 Tm in the region $1.6 < |\eta| < 2.7$. The bending power is at its lowest in the overlap region of the two magnets. The track curvature is measured by acquiring three space points measurements along its path. This is provided by having three detection layers in the barrel region and three per end-cap regions. The barrel layers are located at radii of 5, 7.5 and 10 meters from the z-axis, while the 6 detector wheels are positioned at $z = \pm 7.4, \pm 14$ and ± 21.5 meters respectively. This allows a coverage of $|\eta| < 2.7$. It is also used for triggering at up to $|\eta| < 1.4$.

The muon spectrometer measures muon trajectories. The region used for triggering covers a pseudorapidity range of $|\eta| < 1.4$. Four detector types and their function are listed in table 6.1. The muon reconstruction has an efficiency of approximately 95%, as was shown by extensive testing and comparison with MC [45]. It has a momentum resolution better than 4% over a wide p_T range [46] and a multi-layer position resolution of about 50 μm depending on the background rate [47].

Detector Type	Function	Coverage
Muon Drift Tubes (MDT)	Precision Tracking	$ \eta < 2.7$ (Innermost layer: $ \eta < 2.0$)
Cathode Strip Chambers (CSC)	Precision Tracking	$2.0 < \eta < 2.7$
Resistive Plate Chambers (RPC)	Triggering	$ \eta < 1.05$
Thin Gap Chambers (TGC)	Triggering	$1.05 < \eta < 2.7$ ($ \eta < 2.4$ for triggering)

Table 6.1: The four detector types of the muon spectrometer, with their function and coverage.

6.2.4 Trigger System

Proton-proton collisions in ATLAS happen at a bunch crossing rate of 40 MHz [48], with an average interaction rate per bunch crossing of 13.7 in 2015. If all the data at every interaction

were recorded, over 1 PB/sec of data would be produced. As such data rate cannot possibly be stored for offline analysis, for which the transfer rate is limited to about 300 Hz, event filtering must occur. As rare events such as the Higgs boson happen at a rate of 10^{-5} Hz, the filtering must be very selective and have a very high efficiency when selecting events or rejecting background. The trigger system uses different detectors as well as combinations of hardware components and software algorithms to identify possible signatures of particles of interest, such as electrons, muons, photons and τ -leptons, jets and B -meson candidates. Total event signatures (e.g. missing transverse energy) can also be identified. The trigger system is divided into three levels:

- L1: The first level of trigger uses hardware only with direct information from the calorimeters and the muon spectrometer. It reduces the data rate from 1 GHz to an average of 75 MHz, identifying the objects the next trigger levels will process.
- L2: The second level of trigger is software based and can use processed information pertaining to the identified objects to further bring down the data rate to less than 10 kHz. It has an average execution time of approximately 40 ms per event.
- Event Filter (EF): The third level of trigger uses software to further process the data and identifies objects and classifies them into aforementioned particle and total event signatures. Together with the L2, it forms the High Level Trigger (HLT). Information from one event takes an average of four seconds to be processed.

During the 2010 and 2011 runs, the data rate out of the EF was approximately 200 Hz. Upgrades and improvements to the trigger system continuously improve this, with the 2015 $\sqrt{s} = 13$ TeV runs operating at up to 4 kHz.

6.2.4.1 Minimum Bias Trigger

During event selection using the main trigger system, selection of specific events will introduce biases in the measured production rate of a particle. The minimum bias trigger is a special trigger used to record events that have the smallest possible biasing in the event selection, which is useful when looking at production rates of commonly occurring particles.

A few runs at $\sqrt{s} = 7 \text{ TeV}$ in 2010 and $\sqrt{s} = 13 \text{ TeV}$ in 2015 were taken using this trigger, of which some of the later are used for this thesis.

The detector used for triggering is composed of two wheels which contain 32 Minimum Bias Trigger Scintillators (MBTS) [49]. These wheels are positioned at $z = \pm 3560 \text{ mm}$ and centered on the beam axis, with an inner radius of 153 mm and outer radius of 890 mm. Thus, a pseudorapidity coverage of $2.08 < |\eta| < 3.86$ [50] is achieved. A minimum bias event occurs if a particle passes through both the inner detector and the MBTS counters. This can take place in the range $2.08 < |\eta| < 2.5$, limited by the ID.

Chapter 7

Analysis

In this chapter, the analysis of the neutral K_s^0 and Λ production is presented. The masses and rates of these two particles are determined. First, the strange particles chosen (Section 7.1), as well as the data samples and reconstructions (Section 7.2) used for the analysis are introduced. In Section 7.3, the process of finding vertices that are K_s^0/Λ candidates is explained. The results are presented in Chapter 8.

7.1 Low Mass Neutral Strange Hadrons

The neutral strange hadrons considered in this analysis, K_s^0 and Λ , are chosen here for strange particle production rate studies in ATLAS as they have clear and direct analysis steps. The K_s^0 is the lightest of the strange mesons and similarly, the Λ is the lightest of the strange baryons. This means that many more of these hadrons are produced at the LHC than other heavier strange hadrons. The two particles have simple two-body decay modes with large branching ratios. These decays produce two oppositely charged particles. Particle reconstruction and identification in the inner detector can be done using preexisting available algorithms [51]. The K_s^0 is reconstructed using the decay channel $K_s^0 \rightarrow \pi^+\pi^-$ and the Λ baryon reconstruction is done using the $\Lambda \rightarrow p^\pm \pi^\mp$ decay channels. All of them are weak decays, corresponding to a long decay time which allows for the hadrons to decay a measurable distance away from the measured primary interaction point.

The primary vertex is the position of the particle that has the largest measured transverse

momentum (p_T) associated with it, which is assumed to be the primary interaction point. Other interaction points are defined as pile-up vertices, identified as particles with high momentum and at least four tracks, other than the primary vertex particle. All these vertices must be near the z-axis to be valid. The vertices reconstructed from the tracks of interest from strange particle decays are called secondary vertices. A secondary vertex (V0) is defined as a neutral vertex that is not on the z-axis, differentiable from a primary vertex and associated to two oppositely charged tracks. Other possible vertices are discarded (e.g., three tracks or not opposite charges) as they cannot belong to the particle decays of interest.

7.2 Data samples and V0 reconstruction

Following the end of the upgrades [52] leading to the Run-2 data taking period of the LHC, a few data sets were produced using the minimum bias triggers. The data sample used in this analysis was collected in April 2015 at $\sqrt{s} = 13 \text{ TeV}$. The sample corresponds to an integrated luminosity of $101 \pm 9 \mu\text{b}^{-1}$. The data is processed by V0 reconstruction algorithms with the inclusion of low momentum tracks ($< 1 \text{ GeV}$). These algorithm output sets of V0 candidates, which are vertices with two oppositely charged tracks associated with them. Tracks contain information on a particle trajectory, charge and momentum. The algorithm also saves information on a primary vertex and on pile-up vertices if present.

The invariant mass is the Lorentz invariant measure of a particle's total energy and momentum. To calculate the invariant mass of a decayed particle, the following formula can be used:

$$M^2 = \left(\sum E \right)^2 - \left\| \sum \mathbf{p} \right\|^2 \quad (7.1)$$

Where M is the decayed particle's mass, $\sum E$ is the sum of the energies and $\sum \mathbf{p}$ is the vector sum of the momenta of each decay product. Three possible values of the invariant mass for each V0 candidate have to be calculated, depending on the assumption on the identity of the original particle. For the K_s^0 particle, both decay products are assumed to be pions, thus giving the first value. For the Λ particle, the positively charged decay product is

instead assumed to be a proton and the negatively charged decay product, a negative pion (in the $\bar{\Lambda}$ case the argument is reversed). To reduce background from the start, the V0 candidates then have very basic cuts applied to them:

- Have two and only two tracks of opposite charge.
- Have a track momentum > 100 MeV.
- Have a loose cut on the resulting reduced χ^2 of the two-track vertex fit with $\chi_\nu^2 < 15$.

The χ_ν^2 is calculated using the following formula [53]:

$$\chi_\nu^2 = \frac{1}{N_{df}} \sum_i \left(\frac{r_i}{\sigma_i} \right)^2 \quad (7.2)$$

Where N_{df} is the number of degrees of freedom of the fit, r_i is the distance between a point in the fit and the fitted model (approximation of the two track curvatures), and σ_i the uncertainty on the position measurement of the point.

7.3 Event and vertex Selection

Event selection cuts, shown in Table 7.1, are performed on the data and simulations to reduce the number of background events before vertex candidates are selected. Events must be in the Good Runs Lists (GRLs), which checks that the event was collected during stable LHC and ATLAS running conditions (e.g. during stable beams). Events must have a primary vertex and at least one secondary vertex but no pile-up vertices. In other words, events must contain one and only one proton-proton collision, and at least one K_s^0/Λ candidate. The latter are rejected as they produce a high amount of background since our data assumes that the strange hadrons produced come from the primary vertex direction and are a rare occurrence in minimum bias events. The resulting data has a little over three million events, with almost always multiple V0 candidates per event, with ~ 33 on average.

The secondary vertices remaining after the event cuts are then processed to determine if they are good candidates for K_s^0 or Λ decays. These cuts are partly based on the lower center-of-mass energy analysis done in [54].

Cut Description	Number of Events
Total events before the cuts below are applied.	8 665 704
Events are in Good Runs Lists.	7 272 839
Events have a primary vertex.	3 985 207
Events do not contain pile-up vertices.	3 958 451
Events contain at least one secondary vertex.	3 323 517

Table 7.1: List of cuts applied for event selection.

First, a check is done that verifies if the decay occurred at least 4 mm away from the primary vertex. Figure 7-1 shows this cut for the K_s^0 and Figure 7-2 shows it for the Λ . As the decays of both these particles happen through weak interaction, they have relatively much longer lifetimes when compared to strong decays, which allows this cut to be done. Hence, the background near the primary vertex, stemming mostly from strong decays, is removed.

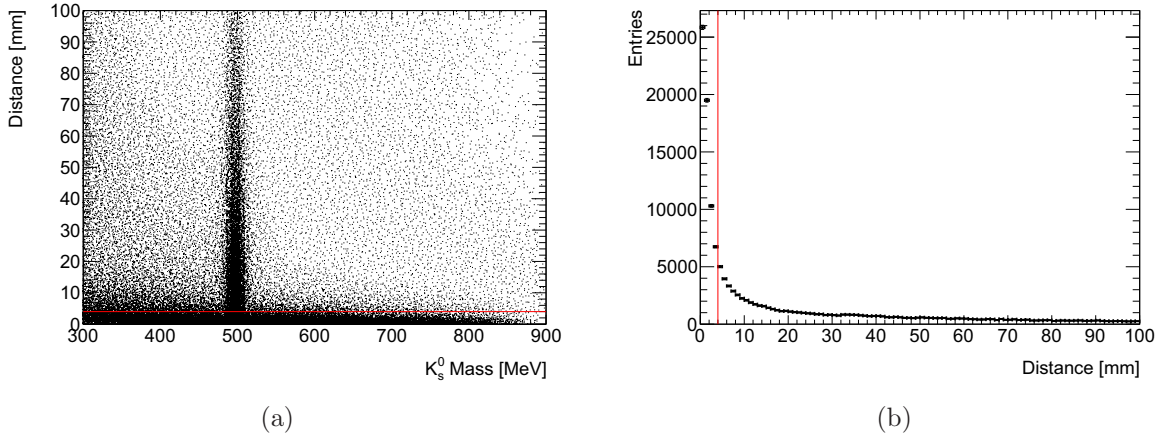


Figure 7-1: The distance from primary vertex as a function of the K_s^0 invariant mass is shown on the left (a). The K_s^0 invariant mass spectrum can be seen as a black peak at around 500 MeV. The right plot (b) shows the projection of the left plot on the distance, resulting in a histogram of the number of candidates as a function of distance. The red lines in both plots corresponds to the minimum 4 mm distance requirement.

To differentiate Λ decays from its antiparticle decay, the assumption that for a high transverse momentum decay ($p_T > 1$ GeV), the higher momentum track is the proton holds true in over 99.8% of cases [21]. This is due to the heavier mass of the proton with respect to the pion taking a greater part of the Λ momentum at higher momenta. At lower momenta it is hard to tell a proton from a pion, resulting in a high background at these levels from

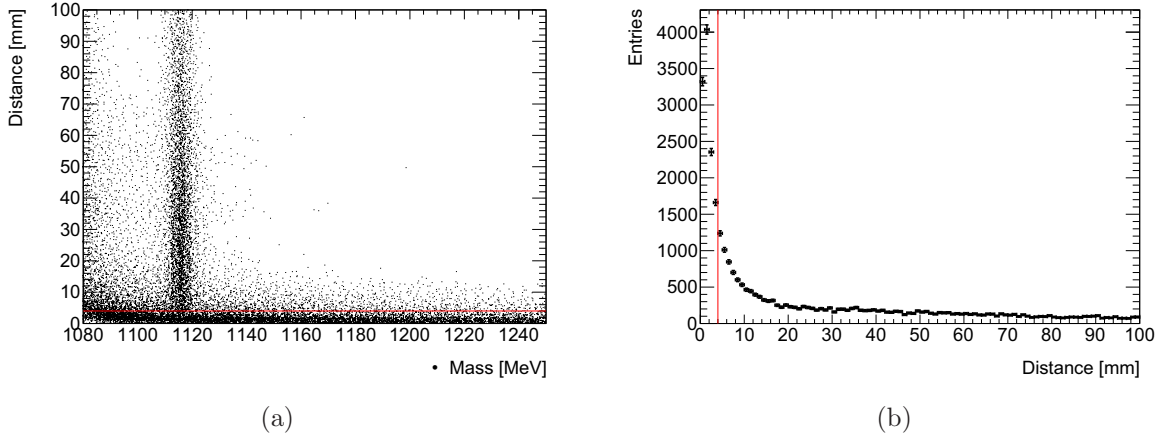


Figure 7-2: The distance from primary vertex as a function of the Λ invariant mass is shown on the left (a). The Λ invariant mass spectrum can be seen as a black peak at around 1115 MeV. The right plot (b) shows the projection of the left plot on the distance, resulting in a histogram of the number of candidates as a function of distance. The red lines in both plots corresponds to the minimum 4 mm distance requirement.

particle misidentification. A special cut shown later in Figure 7-4 is applied to Λ candidates to remove vertices associated to particles with a p_T below 800 MeV. Such a cut is not necessary for the K_s^0 since the decay is symmetric, with its decay products, two pions, having the same mass. This is made clear by Figure 7-3, which shows no significant background at low momenta around the K_s^0 mass region.

At this point, the current vertex selection applies to both K_s^0 and Λ candidates. The two can be separated by comparing the calculated the invariant masses for each. Wrong particle identification can lead to false assumptions on the invariant mass of the particles. If a candidate is a K_s^0 , assuming it is a Λ decay means a pion is incorrectly identified as a proton. These misidentified Λ will thus have very high values for the invariant mass on average, contributing to the background of the spectrum. Similarly, an underestimation of the K_s^0 mass can be caused by misidentified Λ candidates. Figure 7-5 shows this effect, where the crossing point of the two invariant mass spectra can be observed. Only a small fraction of candidates are close to this crossing point compared to the whole spectrum of each particle. Thus, cuts can be applied with slight losses to efficiency (rejecting few good candidates) to separate the two particles. For a K_s^0 candidate, if assuming it is a Λ gives an invariant mass value below 1125 MeV, it is rejected. For the Λ , candidates are rejected if the calculated

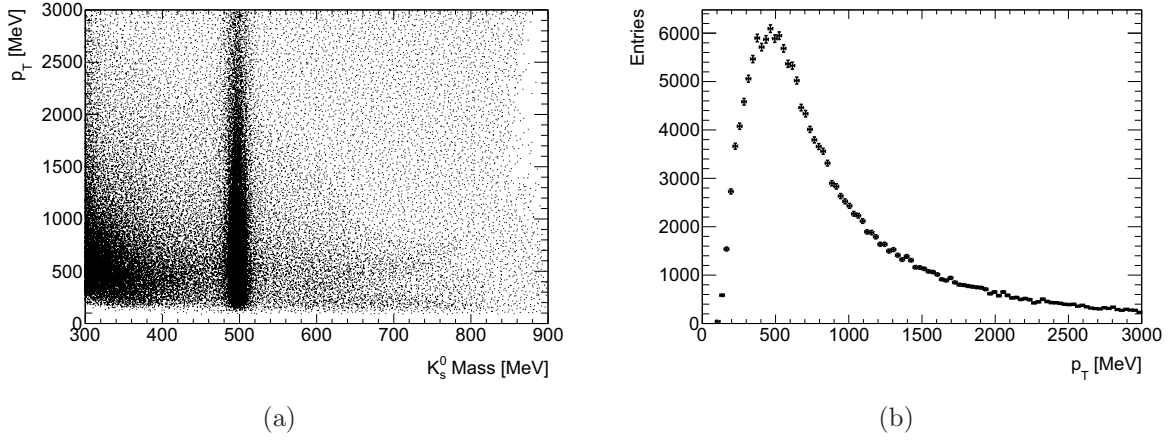


Figure 7-3: A plot of the reconstructed transverse momentum (p_T) as a function of the invariant mass for K_s^0 is shown on the right (a), which reveals no significant background correlation with momentum. The K_s^0 invariant mass spectrum can be seen as a black peak at around 500 MeV. The right plot (b) shows the projection of the left plot on, resulting in a histogram of the number of candidates as a function of momentum.

invariant mass under the assumption that they are K_s^0 candidates is below 475 MeV. The figure also shows the background resulting from photon conversions into electron pairs as a curved line in the bottom left.

Artifacts of the detection lower limit of 100 MeV on the momentum of a decay product, which affects the invariant mass calculation, can be observed in the top corners of the figure. The Λ invariant mass is thus being limited to between 1075 MeV and 1300 MeV. Similarly, the K_s^0 candidates have values for the invariant mass if between 350 MeV and 650 MeV.

To check for a proper secondary vertex, the reconstructed momentum vector must be coming from the primary vertex. The selection is made by measuring the angle θ between the momentum vector and a line crossing the primary vertex and the calculated decay position, as shown in Figure 7-6. A cut at $\cos\theta > 0.9998$ ($\theta \lesssim 1.15^\circ$) is chosen to lose as little efficiency as possible while having a high background reduction. This cut is shown in Figures 7-7 and 7-8 for K_s^0 and Λ respectively. The effect of the cut on the background can be seen in Figure 7-9, where the background of the K_s^0 invariant mass spectrum is heavily reduced and becomes approximately linear while keeping a similar signal peak size. The steep drop at about 650 MeV is caused by the lower limit on a decay product's momentum being reached for the calculations of the invariant mass.

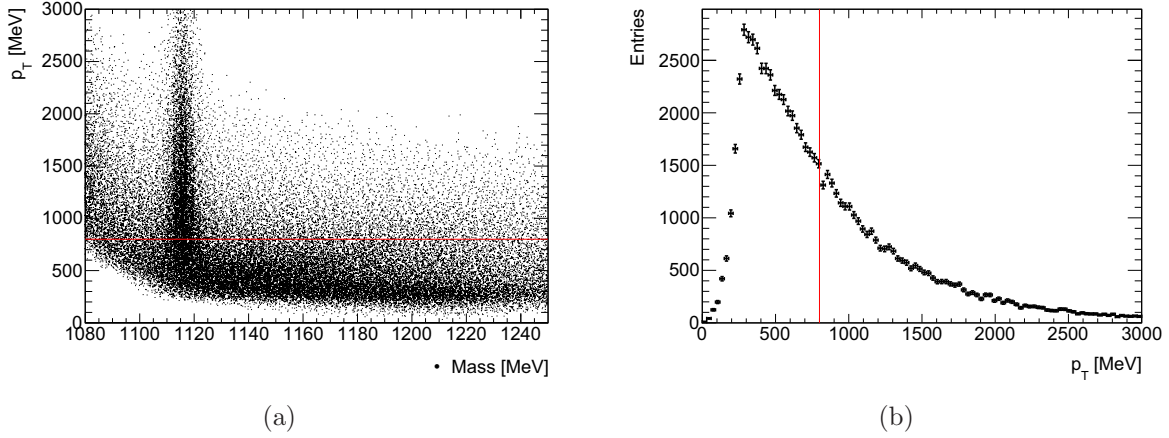


Figure 7-4: A plot of the reconstructed transverse momentum (p_T) as a function of the invariant mass for Λ is shown on the right (a). The Λ invariant mass spectrum can be seen as a black peak at around 1115 MeV. The right plot (b) shows the projection of the left plot on, resulting in a histogram of the number of candidates as a function of momentum. Candidates below the cut at 800 MeV, shown by the red lines, will be excluded.

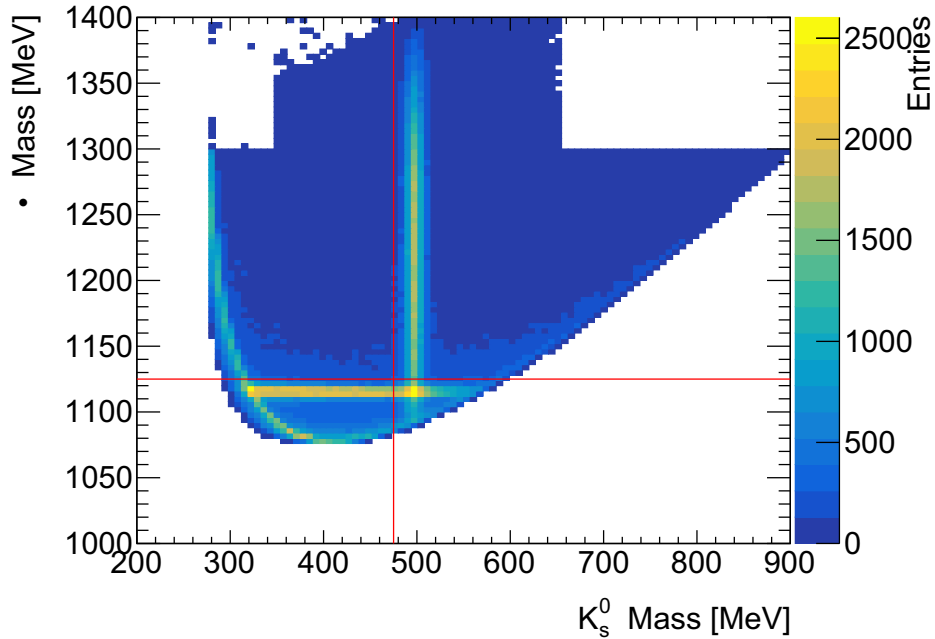


Figure 7-5: Plot of the K_s^0 invariant mass as a function of the Λ invariant mass. The horizontal red line is the cut on the K_s^0 candidates, when the calculated Λ mass is above 1125 MeV. The vertical line cuts on Λ candidates, if the K_s^0 invariant mass value is less than 475 MeV.

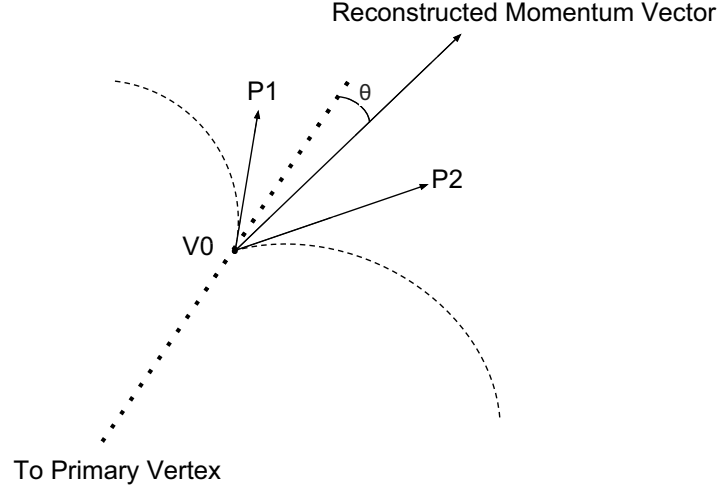


Figure 7-6: 2D view of the angle between the momentum vector of a secondary vertex and a line from that vertex to the primary vertex.

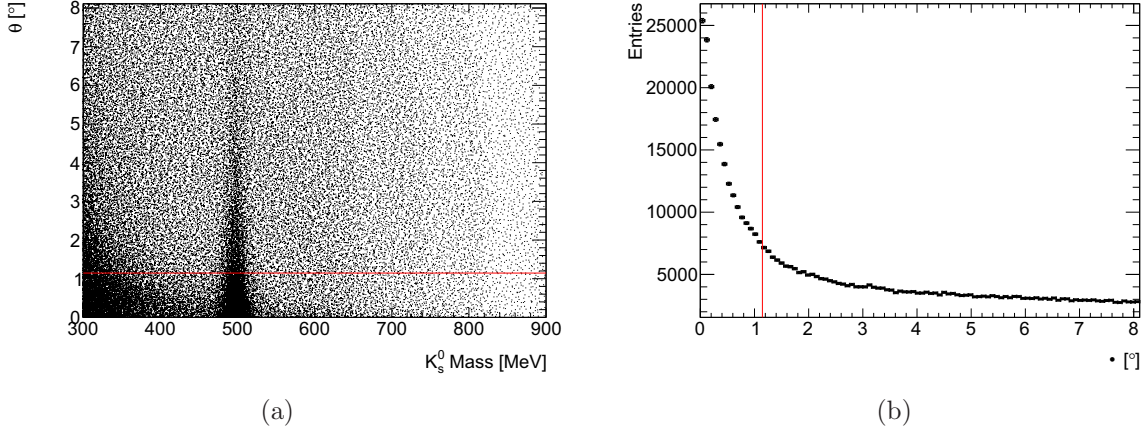


Figure 7-7: The angle θ as a function of the K_s^0 invariant mass is shown on the left (a). The K_s^0 invariant mass spectrum can be seen as a black peak at around 500 MeV. The right plot (b) shows the projection of the left plot on θ , resulting in a histogram of the number of candidates as a function of the angle. The red lines in both plots represent the $\cos \theta > 0.9998$ minimum requirement (below approx. 1.15°).

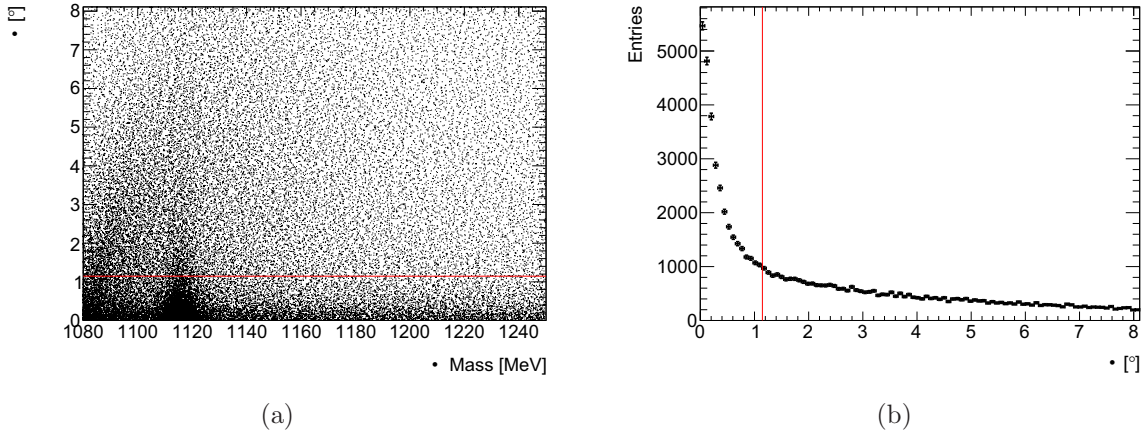


Figure 7-8: The angle θ as a function of the Λ invariant mass is shown on the right (a). The Λ invariant mass spectrum can be seen as a small black peak at around 1115 MeV. The right plot (b) shows the projection of the left plot on θ , resulting in a histogram of the number of candidates as a function of the angle. The red lines in both plots represent the $\cos \theta > 0.9998$ minimum requirement (below approx. 1.15°).

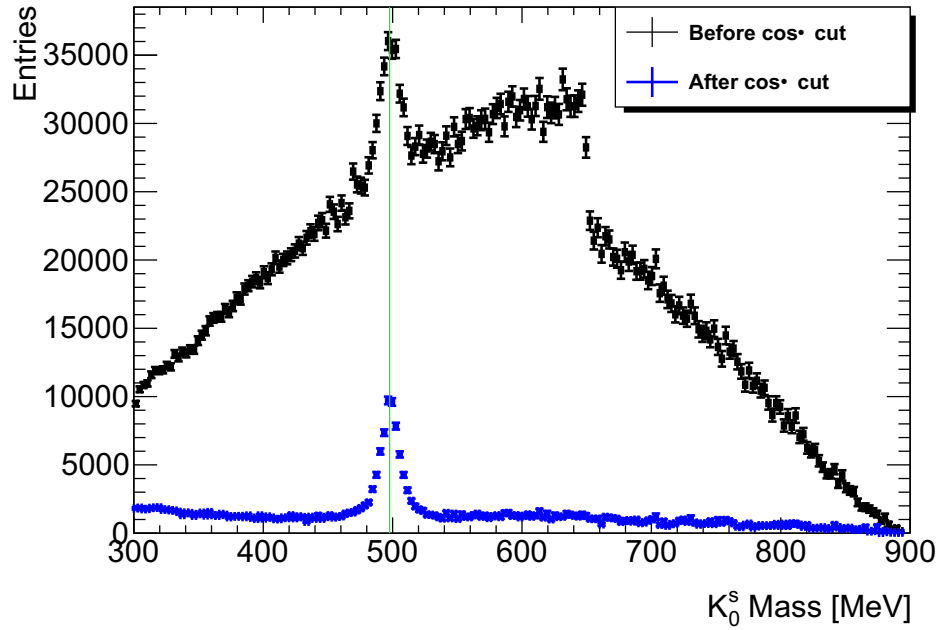


Figure 7-9: K_s^0 invariant mass histogram showing the effect of the cut on the angle between the momentum vector of the secondary vertex and the line from the primary vertex to the V0 candidate. It was plotted using a partial data sample.

Cut Description	Number of Candidates	
	K_s^0	Λ
Total K_s^0 and Λ candidates before vertex cuts are applied.	110 414 387	110 414 387
A distance of at least 4 mm between the measured primary vertex and V0 positions	33 810 109	33 810 109
The momentum of the V0 must be of at least 800 MeV for Λ candidates.	33 810 109	11 306 431
K_s^0 candidates are rejected if the invariant mass for the $\Lambda > 1125$ MeV.	29 449 796	11 306 431
Λ candidates are rejected if the invariant mass for the $K_s^0 < 475$ MeV.	29 449 796	4 730 129
A calculated $\cos \theta$ of more than 0.9998, where θ is the angle between the momentum vector of the candidate and a line from the primary vertex to the V0 position.	2 184 095	788 272

Table 7.2: List of cuts applied on individual V0 candidates. The two resulting sets represent our K_s^0 and Λ candidates.

All of these cuts and number of vertices remaining for the K_s^0 and Λ after each cut is shown in Table 7.2.

7.3.1 Fitting mass distributions

To properly fit the invariant mass distribution, the remaining background needs to be accounted for. For the K_s^0 invariant mass, a first-degree polynomial for the background is combined with a Voigt signal function [55] and fitted to the distribution (Figure 7-10). The choice of a Voigt function (Breit-Wigner and Gaussian convolution) stems from detectors momentum resolution being on the same order of magnitude the momentum of most of the decayed K_s^0 . The fit equation used follows [56]:

$$f(m_{\text{inv}}) = p_0 + p_1 \cdot m_{\text{inv}} + \text{Constant} \cdot \text{Voigt}(\mu - m_{\text{inv}}, \sigma, \Gamma) \quad (7.3)$$

Where μ is the mean of the fit, σ is the standard deviation of the Gaussian and Γ is the full width at half maximum (FWHM) of the Breit-Wigner. The FWHM of the Voigt can be approximated by [56]:

$$f_v \approx 0.5346\Gamma + \sqrt{0.2166\Gamma^2 + f_G^2} \quad (7.4)$$

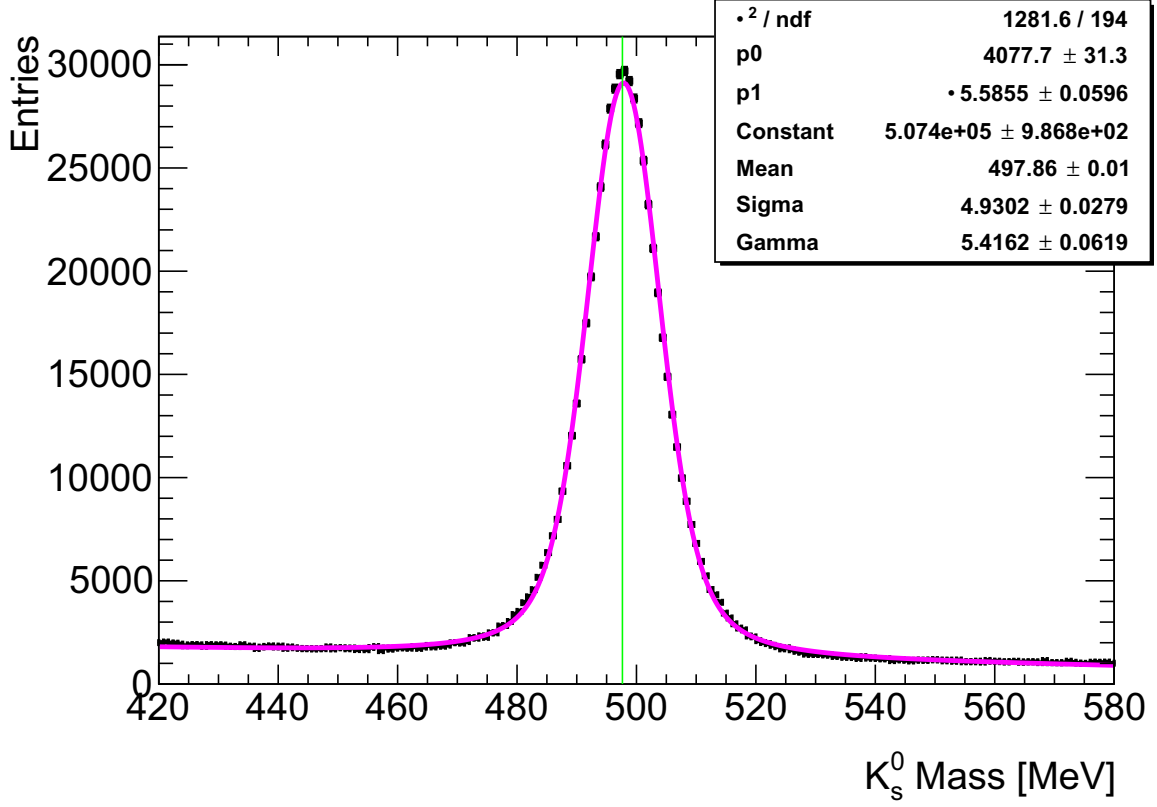


Figure 7-10: Invariant mass distribution of the K_s^0 invariant mass, fitted with a Voigt function superimposed on a linear polynomial shaped background. The green line is the PDG average mass of 497.611 ± 0.013 MeV [15].

Where $f_G = 2\sigma\sqrt{2\ln(2)}$ is the FWHM of the Gaussian. The resulting Voigt function is then integrated over 4σ on each side of the peak to find the number of reconstructed K_s^0 , where σ is the standard deviation from the Gaussian part of the convolution. A second fit is then achieved using an added constant instead of a first-degree polynomial, whose deviation from the previous result is used to estimate the systematic uncertainty of the fits.

The Λ invariant mass distribution has an exponentially decaying background remaining after the cut. A Voigt function is not necessary here as the vertices with low momentums have been removed by a cut. Thus, it is fitted with a combination of an exponential and relativistic Breit-Wigner distribution line. Figure 7-11 shows the resulting fit, which uses the following equation:

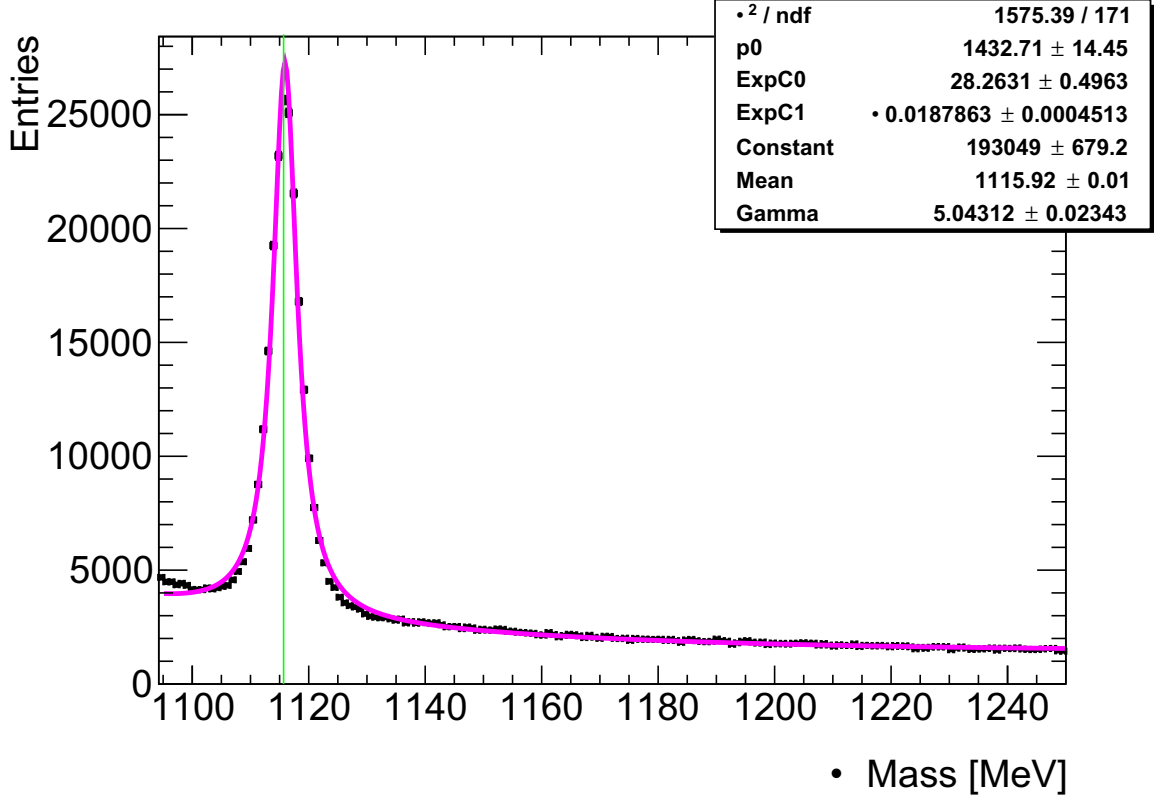


Figure 7-11: Invariant mass distribution of the Λ . A Breit-Wigner function superimposed on an exponentially decaying background is fit to the data. The green line is the PDG average mass of 1115.683 ± 0.006 MeV [15].

$$f(m_{\text{inv}}) = p_0 + e^{\text{ExpC0} + \text{ExpC1} \cdot m_{\text{inv}}} + \text{Constant} \cdot \text{BreitWigner}(m_{\text{inv}}, \mu, \Gamma) \quad (7.5)$$

Where p_0 is a constant 0th-degree term, ExpC0 and ExpC1 are respectively the constant and the coefficient of the exponential, μ is the mean of the Breit-Wigner and Γ its FWHM. The Breit-Wigner function is integrated until it goes to zero (below the background), as the standard deviation is not defined for Breit-Wigner distributions. A portion of the curve is excluded due to the close cut on the left side of the fit, to remove the peak in the conversion background appearing below 1080 MeV (as was seen in Figure 7-5). This remaining cumulative probability (5.3%) is included in the systematic uncertainties. A first-degree polynomial replaces the exponential function in the fit to estimate other systematic uncertainties.

Chapter 8

Results

In this chapter, the results from the invariant mass fitting for the K_s^0 meson and Λ baryon, mean lifetimes and production rates results are presented.

8.1 Strange particle masses

The mass of the K_s^0 was measured at $497.86 \pm 0.01(stat) \pm 0.29(syst)$ MeV and the Λ mass at $1115.92 \pm 0.02(stat) \pm 0.57(syst)$ MeV. They are within two and one standard deviations from the PDG average mass [15] of 497.611 ± 0.013 MeV and 1115.683 ± 0.006 MeV, respectively. The K_s^0 full width at half max (FWHM) was found to be $5.42 \pm 0.06(stat) \pm 0.01(syst)$ MeV, and the Λ FWHM was measured at $5.04 \pm 0.02(stat) \pm 0.03(syst)$ MeV. The systematic uncertainties are derived from fits using different background functions, with a first-degree polynomial or a constant for the K_s^0 invariant mass spectrum and either an exponential or a first-degree polynomial for the Λ invariant mass spectrum. A more accurate estimation of the systematic errors could be achieved with proper MC simulations. These widths are much greater than the natural widths of $(7.351 \pm 0.003) \times 10^{-12}$ MeV and $(2.50 \pm 0.02) \times 10^{-12}$ MeV of for the Λ [15]. The natural widths of these two hadrons are much below the detectors momentum resolution of about 4.8% with $p_T \sim 1$ GeV[37]. A fraction of the systematic error can be attributed to the contributions of photon conversions to the backgrounds of each spectra, reducing the quality of the fits in the low mass region.

8.2 K_s^0 and Λ mean lifetimes

To further confirm that the observed particles are the K_s^0 and Λ , the mean lifetime of each is measured using the distance a decay occurred from the primary interaction point. This is combined with the momentum of each particle to determine the velocity and hence the decay time. This is shown for the K_s^0 candidates in Figure 8-1(a) and for the Λ candidates in Figure 8-2(a). The time ranges are determined using logarithmic plots for each, as shown in Figure 8-1(b) and 8-2(b). The lower bound on the time range is determined as the point where the cut on the distance starts to affect the shape of the curve, seen as a peak that drops off quickly at the lower end of the time scale. For the K_s^0 , the higher bound is determined using a point where the background is visibly dominating the signal, which happens at high time scales. For the Λ , as seen in the logarithmic figure, the higher bound is the point where the data rate starts dropping off sharply. The nature of the background was determined using the distance of the secondary vertices from the primary vertex (Figure 8-3). This reveals a decaying exponential shape for the background. Thus, a double exponential fit is employed to determine the particle decays. The first exponential rate shown in the two decay time figures should correspond to the same source of background. They are scaled differently due to the assumption of whether a secondary vertex corresponds to a K_s^0 or a Λ candidate when calculating the decay times from the distance and momentum. Hence the rates shown in the fit are not the same. The secondary rates in the fit are those of interest, showing the rates of the exponential fits on the decay times.

For the K_s^0 , a mean lifetime of $(9.4 \pm 1.6(stat) \pm 0.9(syst)) \times 10^{-11}$ s is observed, which is in agreement within error from the $(8.954 \pm 0.004) \times 10^{-11}$ s value given by the PDG [15]. A mean lifetime of $(2.6 \pm 0.4(stat) \pm 0.1(syst)) \times 10^{-11}$ s is observed for the Λ , within one standard deviation from the PDG value of $(2.632 \pm 0.020) \times 10^{-10}$ s. The statistical uncertainties were estimated by not including the constant factor (C0 in the fit equation) in the background fit. This caused small fluctuations to the decay rates, reflected in the statistical uncertainty.

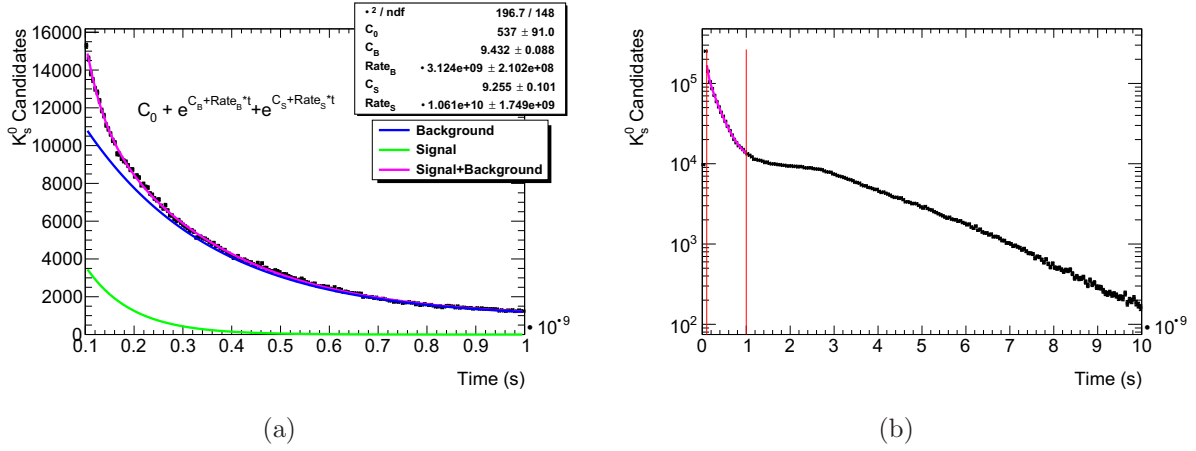


Figure 8-1: The decay time is calculated for each of the K_s^0 candidates. On the left plot (a), the first exponential rate correspond to the background and the second rate corresponds to fit on the decay times of the K_s^0 candidates. The time range selected can be seen (inside red lines) in the logarithmic plot on the right (b).

8.3 K_s^0 and Λ production rates

A production rate is usually measured in order to calculate the total cross section and is given as the number of a particle or group of particles produced per collision event. To calculate the cross section, one needs two components. First, the total number of reconstructed vertices from the invariant mass fit is divided by the total number of collision events (events with a primary vertex). The values observed are $0.768 \pm 0.001(\text{stat}) \pm 0.047(\text{syst})$ K_s^0 mesons per event and $0.1149 \pm 0.0004(\text{stat}) \pm 0.0092(\text{stat})$ Λ baryons per event, respectively. Systematic uncertainties are calculated using different mass distribution fits. The production rate is then normally scaled using the efficiency and acceptance of the reconstruction used, which is estimated using the MC simulations. However, as mentioned above, the MC simulations available was missing information after the reconstruction. At the time of this thesis, the simulation is still incomplete, and so efficiency calculations aren't accurate enough to calculate the total cross sections of the two strange hadrons. These initial values suggest a combined efficiency and acceptance of approximately 0.03% per event for the K_s^0 , though the accuracy of this value has yet to be determined. The distribution of the production rate of K_s^0 as a function of the rapidity and the transverse momentum are shown Figure 8-4 and Figure 8-5, respectively. The momentum distributions behave normally with a reduction in

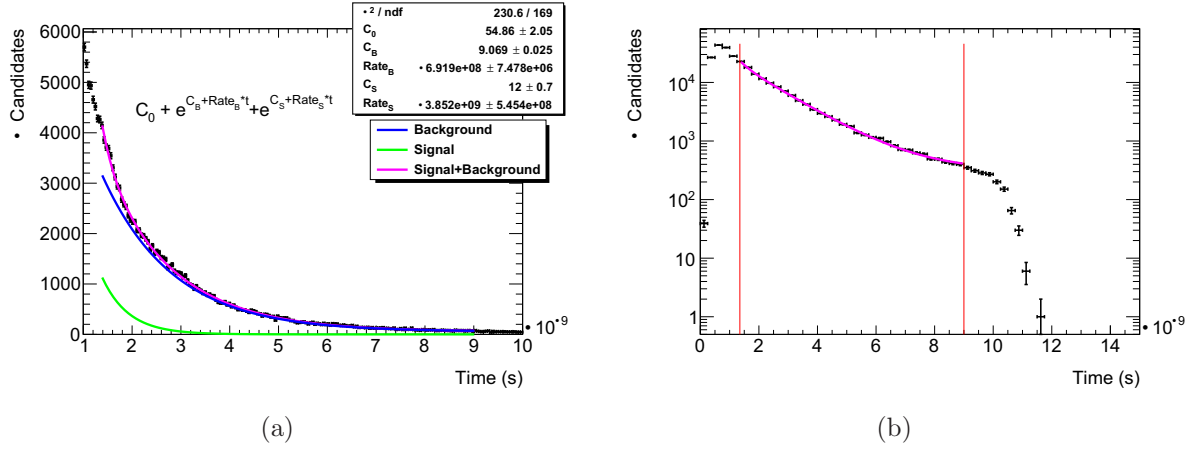


Figure 8-2: The decay time is calculated for each of the Λ candidates. On the left plot (a), the first exponential rate correspond to the background and the second rate corresponds to fit on the decay times of the K_s^0 candidates. The time range selected can be seen (inside red lines) in the logarithmic plot on the right (b).

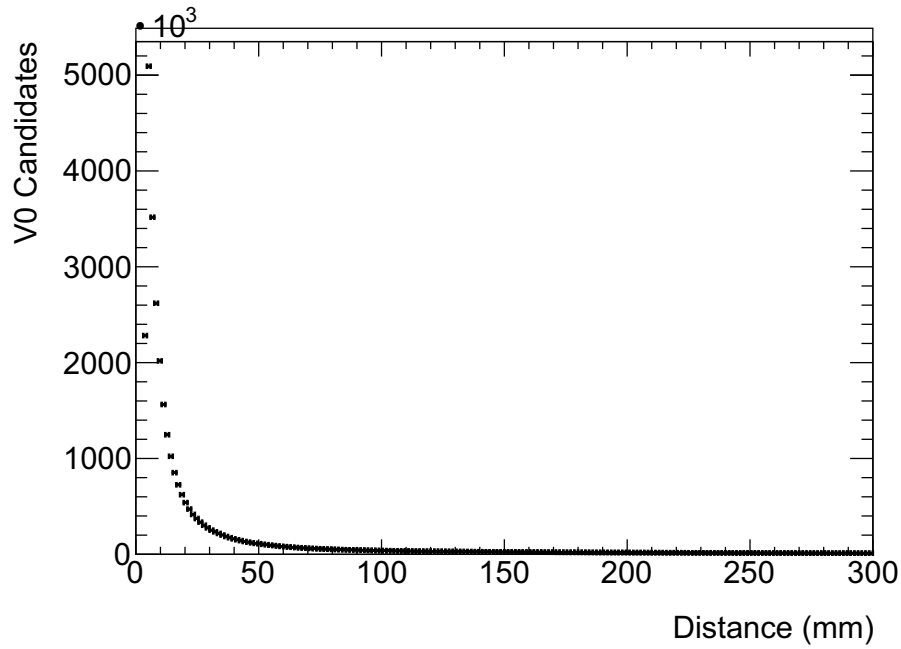


Figure 8-3: The secondary vertex distance from the primary vertex of all events is shown.

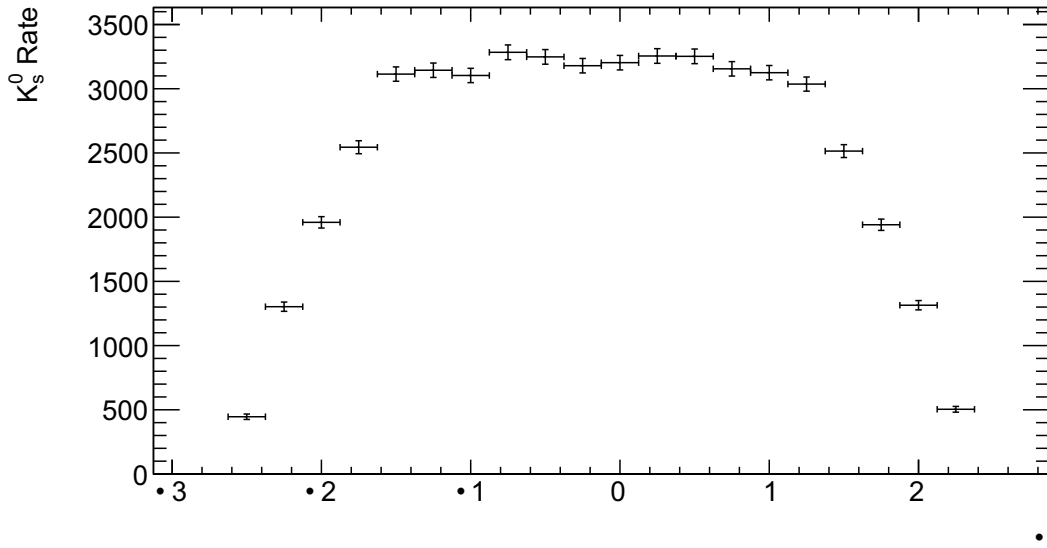


Figure 8-4: K_s^0 production rate with respect to η at $\sqrt{s} = 13$ TeV.

the production rate as the momentum rises, as did previous ATLAS results at a center-of-mass energy of $\sqrt{s} = 7$ TeV, shown in Figure 8-6(b). The η distributions follow the expected curve, as seen by a comparison with the 7 TeV results in Figure 8-6(a). The Λ production rate as a function of η (Figure 8-7) behaves similarly to the K_s^0 , with a slight reduction at low η caused by the cut on the momentum vectors of the vertices, since high momentum particles tend to be at higher η . The Λ production rate as a function of its momentum shown in Figure 8-8, like the K_s^0 , decays exponentially with rising momentum. Comparison with Figure 8-9(a) and 8-9(b) confirms these are the expected distribution shapes for the production rates as a function of η and p_T , respectively.

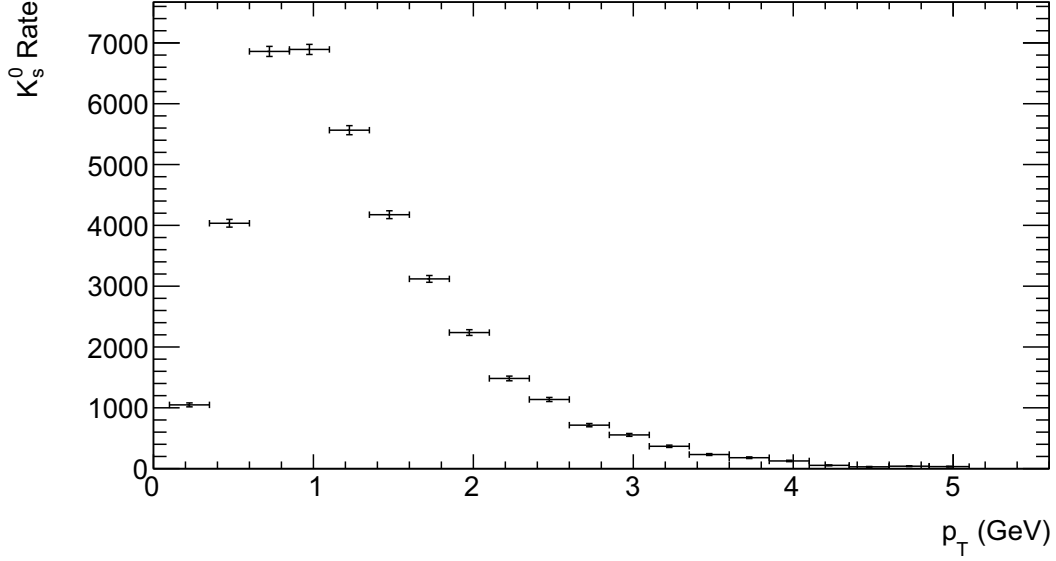


Figure 8-5: K_s^0 production rate with respect to transverse momentum (p_T).

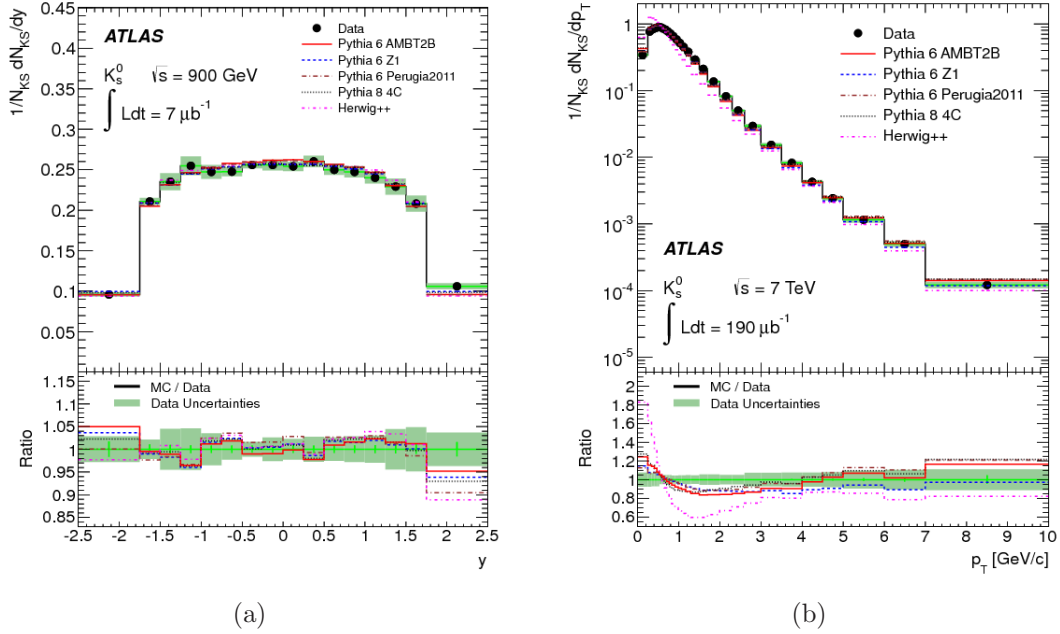


Figure 8-6: The corrected η (a) and p_T (b) distributions of K_s^0 mesons at center-of-mass of $\sqrt{s} = 7$ TeV in ATLAS, compared with the hadron-level distributions in MC samples for a variety of tunes, normalized to unity [21].

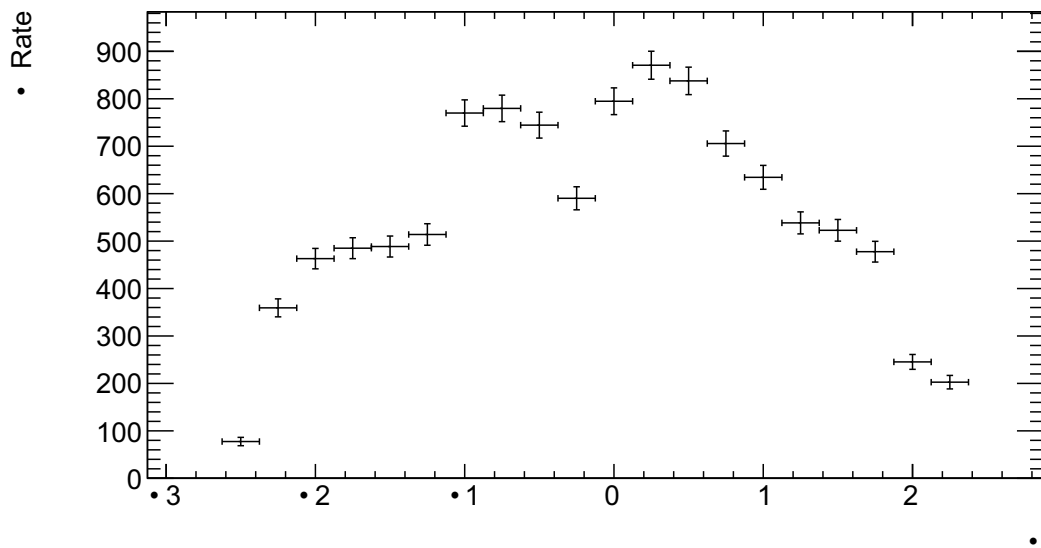


Figure 8-7: Λ production rate with respect to η .

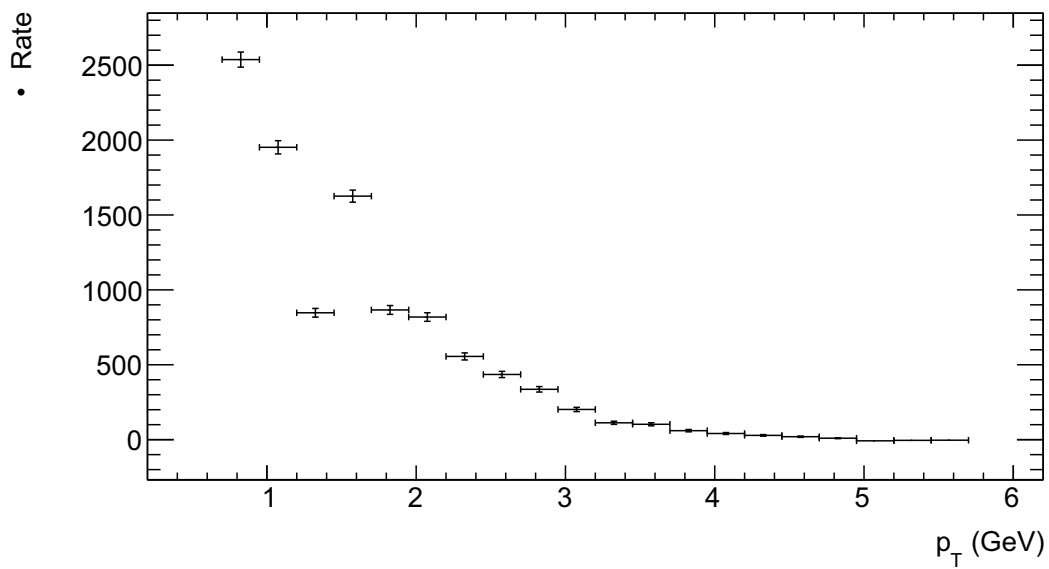
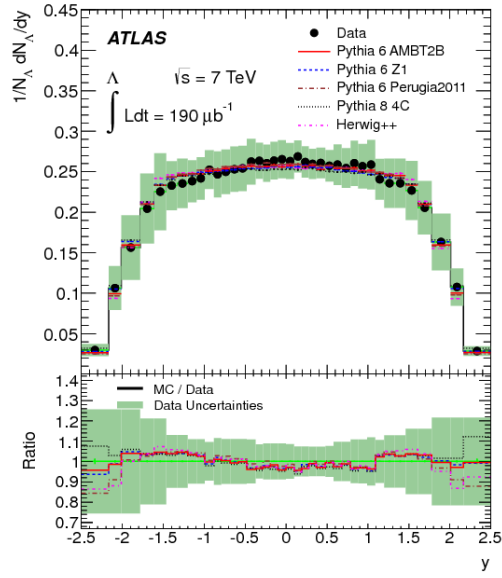
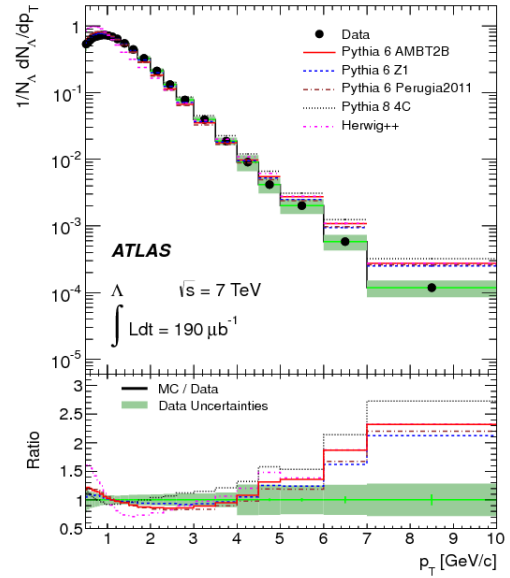


Figure 8-8: Λ production rate with respect to transverse momentum (p_T).



(a)



(b)

Figure 8-9: The corrected η (a) and p_T (b) distributions of Λ baryons at center-of-mass of $\sqrt{s} = 7$ TeV in ATLAS, compared with the hadron-level distributions in MC samples for a variety of tunes, normalized to unity [21].

Chapter 9

Conclusion

Part one: sTGC testing facility

To fulfill the need of a complete and reliable control and monitoring system for the sTGC testing facility at McGill, a dedicated Slow Control system was developed. It has undergone thorough testing in the last two years of development of the facility. Problems were uncovered, fixed, and many features deemed necessary or useful were added. The system eventually reached its current state, where it is using the full capabilities of a LabVIEW developed software. After months of operation with an sTGC prototype and no serious errors having occurred in the latter parts, the system is considered ready to for operation on the testing of the full sTGC modules. The system makes sure that testing operations are safe at all times for the operators, the equipment and the sTGCs. Constant monitoring of the testing equipment combined with a remote notification system is used to maintain stable operation without requiring operators to be present at all times. An efficient data acquisition system permits the Slow Control system to be operated reliably as well as giving the ability for operators to diagnose future situations with ease.

Part two: Strangeness Production

The original goal of this analysis was to measure the masses and production rates of the K_s^0 meson and Λ baryon in the new LHC energy regime, which could be used in improving

current simulation models at low energy regimes. The K_s^0 had a measured mass of $498.0 \pm 0.01(stat) \pm 0.3(syst)$ MeV and a production rate of $0.768 \pm 0.001(stat) \pm 0.05(syst)$ mesons per event. The Λ mass was measured to be $1116.1 \pm 0.02(stat) \pm 0.9(syst)$ MeV and had a production rate of $0.1149 \pm 0.0004(stat) \pm 0.009(stat)$ baryons per event. However, the lack of MC simulation data did not allow for reliable efficiency calculations. Thus, total cross-section measurements were not available. The masses of these hadrons were measured and agree with previous world averages. The production rates as a function of angle and momentum were shown to approximate the results obtained at $\sqrt{s} = 7$ TeV [21]. The mean lifetimes of the particles were also observed, with $(9.4 \pm 1.6(stat) \pm 0.9(syst)) \times 10^{-11}$ s for the K_s^0 and $(2.6 \pm 0.4(stat) \pm 0.1(syst)) \times 10^{-11}$ s for the Λ . As this matched relatively well the known values for the lifetimes of these particles, it improves the confidence that the particles observed are the those expected. Initial MC simulation analysis also shows a perhaps poor acceptance and efficiency of only 0.03% for the K_s^0 , much below the previous results in ATLAS at a center-of-mass energy of 7 TeV [21]. This could be an effect of the higher center-of-mass energy of the collisions, causing a reduction in detection efficiency, thus reducing the acceptance. The greater amount of particles in collisions at this energy partially compensates for the statistical effect compared to previous experiments. A more in-depth study looking at efficiencies and total cross section results is certainly needed to help properly tune future full detector MC simulations. A better understanding of the systematic uncertainties is also necessary. Further research needs to be done, with scenarios including new fully working MC simulations.

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