CALORIMETERS AND MUON DETECTION

by Vincent Hedberg

Introduction

Measurements using calorimeters and muon detectors are essential parts of most particle physics experiments. In order to learn not only about detector methods but also about the underlying principles, a problem for problem based learning was designed in which an important process, Higgs production, was chosen. The main Higgs boson decays are to two photons or a pair of Z-particles that decay into electrons or muons. In order to study Higgs production it is therefore necessary for an experiment to have good electromagnetic calorimeters and muon detectors.

The two most important particle physics experiments in the coming decades will be the ATLAS and CMS experiments at the LHC accelerator at CERN. In the past there has been many particle physics experiments around the world studying different processes and these experiments have used different detector technologies. As the size and cost of competitive experiments has increased, the number of experiments around the world has sharply decreased. It is therefore valuable for the students to study in detail the detector technologies used by the two main experiments at the LHC since they will dominate particle physics in the future.

Taken all of this into account, a problem was made which used Higgs production and the ATLAS and CMS experiments to learn about measuring methods as well as measuring techniques as used by the two LHC experiments. The question in the problem is which experiment is the best in studying Higgs production. The answer to this question is not obvious and will therefore hopefully stimulate a debate among the students about why the two experiments have chosen different types of detectors. And this will in turn lead to a better understanding of the experiments themselves. In the next section the problem is given and the goal and evaluation of the problem is then presented in the following sections.

The Problem

The Fellowship

When Mary got the news that she had been awarded a CERN fellowship she knew that she had some serious decision making to do. She had done her Ph.D. work on the muon chambers in LHCb and the LHCb management had supported her fellowship application but she knew that with a research fellowship she was allowed to choose any experiment at CERN. The physics at LHCb was OK but the big thing was the Higgs. With the LHC starting up she had the chance of a lifetime to get involved in something that would for sure go down in physics history. It was time to change experiment.

She first went to see the ATLAS spokesman. Fellows were always welcome to ATLAS he said and he pointed out that ATLAS hade the largest and most impressive muon spectrometer the world had ever seen. No better place to look for Higgs to four muons. He described the different types of muon chambers and how to trigger on them.

The CMS spokesman did not agree: "Listen Mary, big is not necessarily better. We will measure muons as well or better than ATLAS. And with our calorimeter we will nail a Higgs to two photons before ATLAS knows what hit them. It will stick up over the background in our detector but not be seen in ATLAS. It is possible that the CMS calorimeter will be the most important detector at the LHC. "

Afterwards she realized that to decide which experiment was the best for discovering the Higgs she could not rely only on what the spokesmen had told her.

Learning goals

Since this is a detector course the details about the Higgs production mechanism is not part of the course. It is introduced in the problem as an illustration and should not become a major part of the studies. These should instead concentrate on calorimeter and muon measurements. Both these topics can be divided up into measurement techniques, detector methods and performace. The calorimeter part can in addition be divided up in a part about electromagnetic calorimeters and hadronic calorimeters. The exact knowledge about where different types of detectors are situated in the ATLAS and CMS experiments is useful but not essential.

Calorimeters – Basic principles and measurement techniques

The basic knowledge about calorimeters relate obviously to electromagnetic and hadronic showers. For graduate students this is presumably well-known facts. They should know already before the course the basics about shower development and the different size of electromagnetic and hadronic showers. What is perhaps not known so well is the difference between a crystal calorimeters such as the one used in CMS and the sampling calorimeters used in ATLAS. A detailed understanding of the standard calorimeter resolution formula with its sampling, constant and noise terms is therefore important. The students should understand how the terms depend on the calorimeter type. They should also understand how the position is measured and which factors limit the position resolution of a calorimeter.

The importance of the energy and angular resolution of an electromagnetic calorimeter can be studied by investigating how the resolution influences for example the measurement of the Higgs mass when this particle decays to two photons. The formula $m_H = 2E_{\gamma1}E_{\gamma2}(1\text{-}\cos(\theta_{\gamma\gamma}))$ is a good starting point for this study. While the ATLAS calorimeters have a sampling term of 9-10% the resolution of the CMS crystal calorimeter is about 3%. The angular resolution of the calorimeters in both experiments is about 50 mrad. The students should be able to find plots of the invariant mass distributions of a Higgs to $\gamma\gamma$ signal for the two experiments as well as plots of the signal significance. At a luminosity of 30 fb^{-1} and a Higgs mass of 120 GeV the expected signal significance of ATLAS is 4 while CMS has a predicted significance of 8.
A huge difference !

The hadronic calorimeters are much less important for the Higgs search. The students should understand that the purpose of these detectors is instead to measure jets and missing energy as well as provide particle identification. The resolution of the hadronic calorimeters in ATLAS and CMS can be compared (the resolution of the ATLAS detectors is somewhat better than those of CMS).

Calorimeters – Detector methods

The ATLAS and CMS experiments use crystal calorimeters as well as sampling calorimeters. The sampling calorimeters use not only liquid argon and scintillators as active mediums but also quartz fibres. A study of the calorimeters in these two experiments will therefore cover most modern calorimeter techniques.

The lead tungstate ($PbWO_4$) crystal calorimeter in CMS is one of the most impressive detectors ever made. It consists of some 77,000 crystals read out by avalanche photo diodes (APD) and photo triodes (VPT). A crystal calorimeter provides a superior energy resolution to sampling calorimeters but they also have disadvantages. The main one is the large cost and the time needed to grow all the crystals. Lead tungstate has a low light yield. It is also difficult to make a longitudinal segmentation with a crystal calorimeter. Radiation damage and temperature dependence are other considerations. Photomultipliers cannot be used in a large magnetic field. The APDs are used in the CMS barrel while VPTs are used in the forward calorimeters due to the larger radiation in the forward region.

Figure 1 shows what calorimeters are used in ATLAS. The electromagnetic liquid argon calorimeters are using lead absorbers with an unusual accordion shape while the hadronic liquid argon calorimeters are using flat copper plates as absorbers. The hadronic tile calorimeters are using flat iron absorbers and scintillator tiles that are more or less parallel to the direction of the hadronic showers. This makes it more easy to read out the light from the tiles with optical fibres and multi-anode photomultipliers.

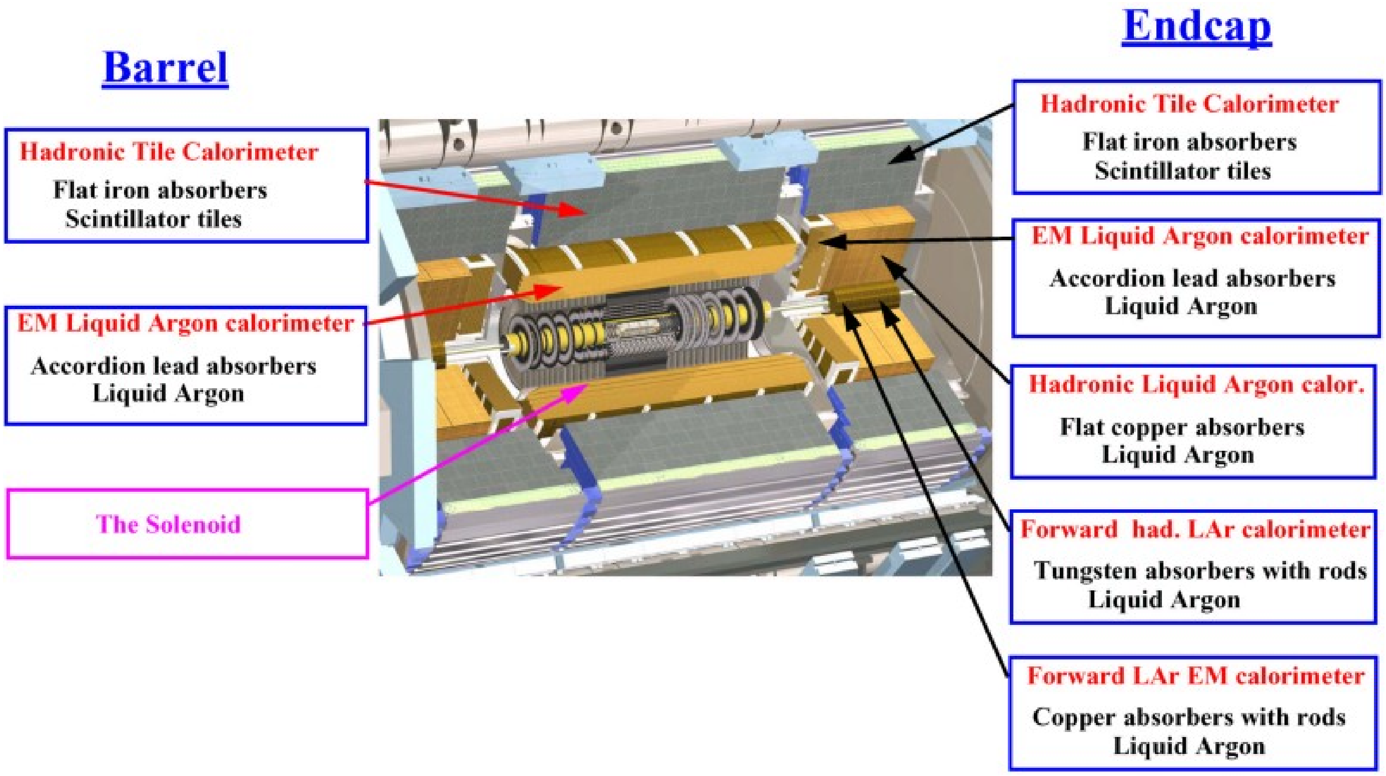

Figure 1. The location of the different types of calorimeters in ATLAS.

Muon spectrometers – Basic principles and measurement techniques

There are three main parameters that determines the resolution of a muon momentum measurement: (1) The size of the magnetic field; (2) The length of the muon trajectory in the magnetic field; (3) The resolution of the muon chambers. These parameters are in turn depending on additional factors such as the alignment of the chambers, how well the magnetic field is known, the distance between the muon chambers, energy loss and multiple scattering.

While the CMS experiment is using a strong solenoid magnet for its muon measurements, the ATLAS experiment is using both a solenoid and three large toroidial magnets. The toroid magnets in ATLAS make it possible to do muon measurements without the central tracker and still have a very impressive momentum resolution of around 2% at 100 GeV. The CMS experiment relies on finding the muon tracks in the inner silicon tracker. If this can be done efficiently then CMS will measure muons with a momentum resolution that is comparable or even better to that of ATLAS. The large background rate at the LHC, where the interesting events are in coincidence with many minimum bias events, means that the muon track finding efficiency will be an important performance issue and this should be recognised by the students.

The process of Higgs decay to two Z^0 that then decays two four muons can be used as a bench-mark process to evaluate the muon spectrometers. It is now expected from electroweak measurements that the Higgs boson has a relatively low mass. Simulated invariant mass distributions for a luminosity of 30 fb^{-1} and Higgs masses less than 200 GeV show that the significance for a Higgs to four muons is only 2-4. It is only after it is combined with the Higgs to four electron channel that there is a discovery potential after the first 3-4 years of running.

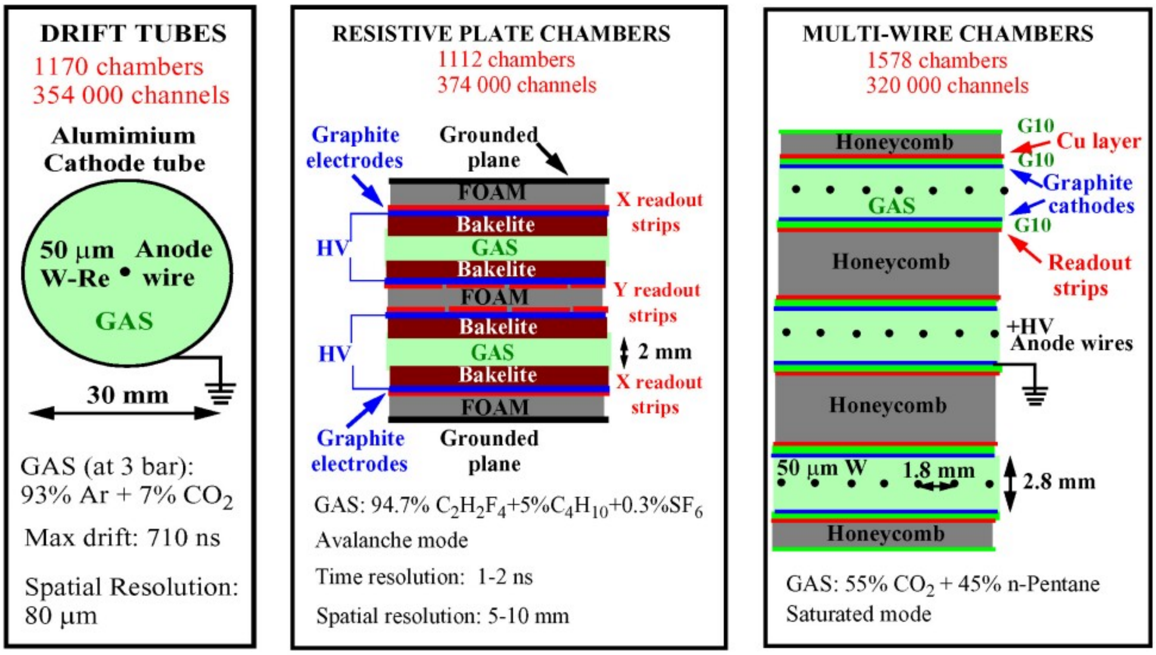

Figure 2. The structure of the three main types of muon chambers in ATLAS. From left to right: Monitored Drift Tubes, Resistive Plate Chambers and Thin Gas Chambers.

Muon chamber techniques

The muon chambers can be divided up into two classes. One set of chambers is based on drift chamber technique and provide precision measurements of the muon trajectory. Another set of chambers provides fast signals for triggering purpose.

Figure 2 two shows the basic structure of the three main detector types in ATLAS. The drift tubes consist of aluminium tubes with an anode wire in the centre. CMS is also using drift tubes for precision measurements, but they have a rectangular shape. It is important that the students understand how the time measurement is done and how the resolution of a chamber is obtained from the resolution of the individual tubes. A precise alignment is important for these chambers and the alignment methods used by ATLAS and CMS should be discussed.

Resistive Plate Chambers are used by both ATLAS and CMS to trigger on muons in the barrel region. The principle of the RPC is shown in Figure 2. In the forward region both ATLAS and CMS are using fast multi-wire chambers for triggering. ATLAS is mostly using the type of detector called Thin Gap Chamber that is shown in Figure 2 while CMS are using multi-wire proportional chambers called Cathode Strip Chambers. This type of chambers is used also by ATLAS but only in a small part of the forward region. In order for the students to understand the differences between the different types of chambers it is vital that they understand how the gas amplification differs for different operational modes such as ionization mode, proportional mode, limited proportional mode and streamer mode.

Literature

The literature for this problem can mostly be found on the web. Neither ATLAS nor CMS have published many detector papers but the technical design reports of both experiments are available on the web. These reports are to some extend outdated but both collaborations also have a large list of experimental notes that are available from their home pages and the CERN library web pages. A simple google search will also reveal a very long list of slides from talks that address the questions presented by the problem.

Evaluation of the problem

The problem was presented to a group of graduate students at CERN and the students were given one week to study it. Three meetings were made with the supervisor. In the first the problem was analysed, in the second a plan for the work was made and in a final meeting at the end of the week, the result of the work by the students was presented in a set of presentations.

The students divided themselves up in two teams. One studying calorimeters and the other studying muon measurements. The calorimeter team fulfilled all the goals mentioned above. The muon team had not studied in detail the factors that influence the momentum resolution. They also had quite a shallow description of the different types of muon chambers. Overall the presentations made by the students were, however, very impressive.