

**The  $\phi(1020)$ -meson production cross  
section measured with the ATLAS detector  
at  $\sqrt{s} = 7$  TeV**

Lucie de Nooij

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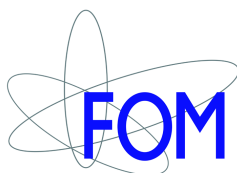
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# Introduction

"Whoooooooooooooooooohaaaaaaaaaaaaaa, the particles fly through the tunnel at enormous speed. When they collide they have so much energy they smash apart and make new particles!" The kids move forward in their chairs, they did not expect the "physicist" to actually tell an exciting story, but she does!

The start-up and the first three years of running of the Large Hadron Collider (LHC) at the CERN research complex in Geneva, Switzerland, have been exciting indeed. The LHC is the most powerful particle accelerator ever built and it has provided enough data already to announce the discovery of the Higgs boson on 4 July 2012. The Higgs boson interacts with the masses of the elementary particles of the Standard Model of particle physics, the theoretical model that describes these particles and the forces between them.

At four points along the LHC where the protons collide, detectors are recording the particles that emerge from the collisions. The ATLAS experiment is one of the two general-purpose experiments at the LHC and it is well-suited for searches for new physics. To operate a large and complex system like the ATLAS detector, a sophisticated framework of safety procedures and software packages is in place. To provide real time monitoring of the operational performance, the recorded data are processed online and the results are assessed by physicists who staff the control room.

When the LHC collides protons, the protons may break up and new particles are created, such that observed particle multiplicities at the LHC range up to a few hundred. With large energy transfers in the collision the interactions can be calculated by quantum chromodynamics (QCD), the part of the Standard Model that describes the interactions between the constituents (quarks and gluons) of the colliding protons. But if the energy transfer is low QCD is no longer calculable, because the strength of the coupling constant increases with decreasing energy transfer, impeding the use of perturbation theory. At this regime the theory needs to be complemented with data.

In this thesis, a measurement of the differential  $\phi$ -meson cross section is presented. The  $\phi$ -meson is produced in the hard scatter of a proton-proton collision, as well as in the softer hadronisation processes that take place simultaneously. This makes the  $\phi$ -meson cross section a suitable variable to calibrate the non-perturbative models. On the other hand, the  $\phi$ -meson is measured in a low-momentum regime, that is not probed with most measurements, and the selection of  $\phi$ -mesons uses particularities of the experiment that can only be exploited with excellent understanding of the detector.

**Thesis layout**

Chapter 1 of this thesis introduces QCD and the phenomenological models that are used to predict the physics of the non-perturbative regime. The implementation of these models in the Monte Carlo event generators PYTHIA, HERWIG++ and EPOS is discussed in detail.

In chapter 2 the LHC and the ATLAS experiment are introduced, chapter 3 discusses the inner tracker of ATLAS in more detail, because it is most important for the measurement of the  $\phi$ -meson cross section and because I was responsible for a part of the online operation of the inner detector during my PhD project.

The reconstruction of the trajectories of charged particles and the usage of energy loss in the inner tracker for particle identification are discussed in chapter 4. The discriminating power between the different particle species is assessed using simulated data.

Chapter 5 describes the selections and selection efficiencies of the  $\phi$ -meson reconstruction, while the  $\phi$ -meson production cross section is presented and compared to different theoretical predictions in chapter 6.

# Chapter 1

## Strangeness production

The main aim of the two general-purpose detectors at the Large Hadron Collider (LHC) is to study and explore physics in collisions around and above the electroweak symmetry-breaking scale. These processes typically take place at high energy transfers, which separates them from the prevalent processes: namely strong force interactions with low momentum transfers described by the phenomenological models of non-perturbative quantum chromodynamics (QCD). To examine rare processes the LHC needs to be run at high instantaneous luminosities, which results in up to 30 proton-proton interactions occurring simultaneously in 2011. Monte Carlo event generators are used to simulate these soft predominant processes, to allow for credible comparison between the data and theoretical predictions. For reliable development of the predictions the models need tuning to data.

In this chapter QCD and the phenomenological models are introduced. The focus will be on strangeness production and in particular the  $\phi$ -meson in order to provide a framework for the  $\phi$ -meson cross section measurement presented in this thesis. The models used for event generation and that are compared to the data are described.

### 1.1 Introduction to strangeness

In the 20th century, the number of known particles increased rapidly from a few particles in the 1930s to several dozens in the 1950s. Depending on whether particles decay strongly or weakly, the lifetimes are around  $10^{-23}$  s up to  $10^{-6}$  s. To explain the big differences in lifetime the new quantum number “strangeness” was postulated in 1953, which is conserved in strong interactions, but violated by weak interactions.

The first strange particle was discovered in 1946 when the  $K^0 \rightarrow \pi^+ \pi^-$  decay was observed in cosmic rays [1]. The  $\phi(1020)$ -meson was discovered in 1962 [2] in data obtained in an exposure of the BNL 20-in. hydrogen bubble chamber at the Brookhaven AGS as an “existence of marked departures from phase space in the effective-mass distributions of  $K\bar{K}$  states”, the corresponding invariant mass spectrum is shown in figure 1.1 a). The observed anomaly was assumed to be due to the decay of a resonant state  $K^*$  and was found to have a mass of  $M_{K^*} = 1020$  MeV and a full width of 20 MeV. The current mass and width of the  $\phi$  as quoted by the PDG [3] are  $m_\phi = 1019.455 \pm 0.020$  MeV and  $\Gamma_\phi = 4.26 \pm 0.04$  MeV, based on few dozens of

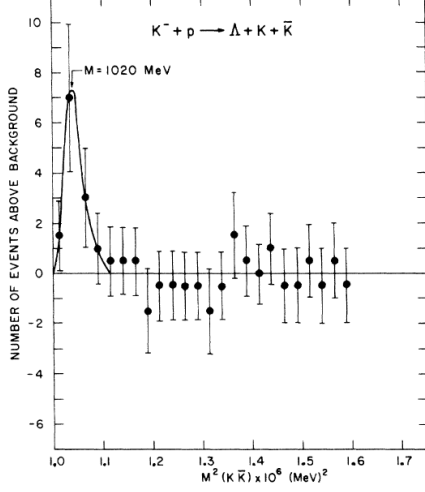


FIG. 4. The (effective mass)<sup>2</sup> distribution for  $K\bar{K}$  from the channel  $\Lambda K\bar{K}$  for those events above phase space.

(a)

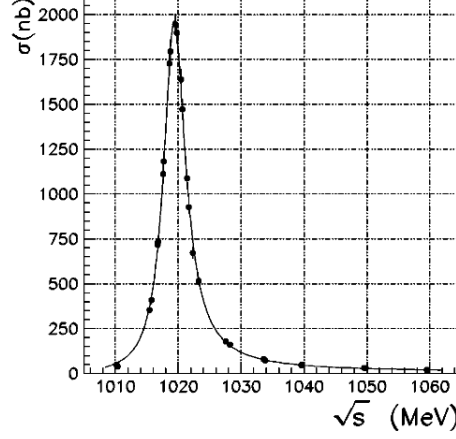


FIG. 14. The  $e^+e^- \rightarrow K^+K^-$  cross section. The dots are experimental data; the curve is the fit.

(b)

Figure 1.1: a) The first invariant mass peak showing the  $\phi(1020)$ -resonance in data of the BNL 20-in. hydrogen bubble chamber at the Brookhaven AGS in 1962 [2]. b) The  $\phi$ -meson mass peak in  $e^+e^-$  collision data from the SND detector at the VEPP-2M collider [4].

measurements. The largest contribution to the combined mass and width measurements is from  $e^+e^-$  collision data, an example of direct production in  $e^+e^- \rightarrow \phi \rightarrow K^+K^-$  using data from the SND detector at the VEPP-2M collider in Novosibirsk in Russia, is shown in figure 1.1 b).

The different production mechanisms of the  $\phi$  meson and motivations to study  $\phi$  production in  $pp$  collisions will be discussed in section 1.3 after introducing the different processes that take place in a  $pp$  interaction. First, the shape of a resonance with a short lifetime and the different decays channels of the  $\phi$  meson are discussed in the remainder of this section.

The  $\phi(1020)$ -meson decays strongly and therefore has a very short life time of  $\tau_\phi = 1.55 \pm 0.01 \cdot 10^{-22}$  s [3]. The invariant mass spectrum of a resonance has a typical shape, the Breit–Wigner form, clearly visible in the right panel of figure 1.1. This is an intrinsic consequence of the decaying quantum state,  $\psi(t)$ , with mean life  $\frac{1}{\Gamma}$  and central mass  $m_0$ :

$$\psi(t) \propto e^{i(m_0 - i\frac{\Gamma}{2})t}, \quad (1.1)$$

such that it will decay exponentially as

$$|\psi(t)|^2 \propto e^{-\Gamma t}. \quad (1.2)$$

To get the amplitude in energy space, we take the Fourier transform of equation 1.1:

$$\psi(m) \propto \int_0^\infty dt \psi(t) e^{imt}. \quad (1.3)$$



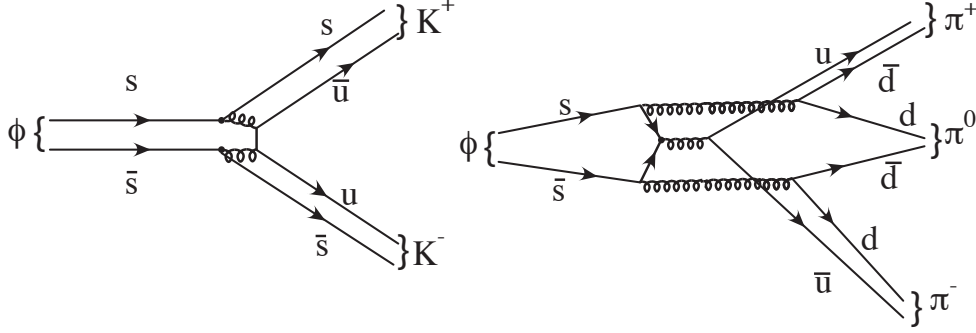


Figure 1.2: An illustration of the decays  $\phi \rightarrow K^+ K^-$  and  $\phi \rightarrow \pi^+ \pi^- \pi^0$ .

The integration yields:

$$\psi(m) \propto \frac{1}{(m - m_0) + i\frac{\Gamma}{2}}, \quad (1.4)$$

which becomes the Breit–Wigner when taking the absolute value squared:

$$|\psi(m)|^2 \propto \frac{1}{(m - m_0)^2 + \frac{\Gamma^2}{4}}. \quad (1.5)$$

The  $\phi(1020)$ -meson predominantly decays to  $K^+ K^-$ , with a branching ratio of  $(48.9 \pm 0.5)\%$ . The second and third preferred decays are to  $K_L^0 K_S^0$ ,  $(34.2 \pm 0.4)\%$ , and  $\pi^+ \pi^- \pi^0$ ,  $(15.32 \pm 0.32)\%$ . The decay to two kaons is preferred over the kinematically more attractive decay to three pions, because it does not include the production of three intermediate gluons, as illustrated in figure 1.2. The decays to an electron/positron or muon/anti-muon pair have similar branching ratios of  $\sim 3 \cdot 10^{-4}$  and proceed via an intermediate photon. The decay into two pions has a small branching fraction of  $(7.4 \pm 1.3) \cdot 10^{-5}$  since the two pions have to be in an angular state with  $L = 1$ . That is, the space part of the wave function is anti-symmetric. Since the initial state has isospin 0 the two pions have to carry isospin 0 as well. The isospin wave function of two isospin 1 particles with third component +1 and -1, respectively, forming an isospin 0 state is symmetric. As a consequence, the total wave function of the two identical bosons would be anti-symmetric.

## 1.2 The Quark Model

The quark model [5] offered a classification scheme for the large number of hadrons being discovered in the 1950s, when it was mentioned that “..the finder of a new elementary particle used to be awarded with a Nobel Prize, but such a discovery now ought to be punished by a \$10.000 fine.” [6].

In the quark model, each hadron is given a label derived from the quantum numbers of its constituent elementary quarks. For example, the quantum number *isospin* was introduced by

| Quark           | Charge [e] | Isospin $ I, I_z\rangle$            | Strangeness S |
|-----------------|------------|-------------------------------------|---------------|
| up ( $u$ )      | +2/3       | $ \frac{1}{2}, \frac{1}{2}\rangle$  | 0             |
| down ( $d$ )    | -1/3       | $ \frac{1}{2}, -\frac{1}{2}\rangle$ | 0             |
| strange ( $s$ ) | -1/3       | $ 0, 0\rangle$                      | -1            |

Table 1.1: The quark model for the three lightest quarks as it was proposed in 1964. By convention, the quark flavor has the same sign as the charge.

W. Heisenberg in 1932 to explain symmetries of the then newly discovered neutron [7]. The proton and the neutron are almost identical, except for their different electrical charge, yet the strength of their coupling to the strong force is the same. To explain this, the proton and the neutron were assumed to be two different states of the same particle in the context of the strong interaction. The proton and the neutron, and the different pions that were discovered later, are different states of the same isospin multiplet. The value of the third component of isospin is calculated from the number of  $u$  and  $d$  valence quarks in the hadron  $I_z = \frac{1}{2}(n_u - n_d + n_{\bar{d}} - n_{\bar{u}})$ . The quantum number isospin should not be confused with the *weak isospin*, which is conserved in weak interactions.

The quark model with three quark flavors  $u$ ,  $d$  and  $s$  was introduced in 1964 and is called The Eightfold Way. In table 1.1 the values of the quantum numbers charge, isospin and strangeness are given for the three quarks. The charge  $Q$  in units of elementary charge  $e$  of a quark is given by the Gell-Mann-Nishijima formula

$$Q = I_z + \frac{B + S}{2}, \quad (1.6)$$

with  $B$  the baryon number and  $S$  the strangeness. By convention the flavor of a quark has the same sign as the charge, resulting in the strangeness of the  $s$  quark being  $S = -1$ , and quarks and anti-quarks having opposite flavor signs.

Quarks and gluons are confined in hadrons with two or three quarks, called mesons and baryons, respectively. The different quantum numbers relevant for the light mesons are listed in table 1.2. The spin momentum  $s$  for mesons is either  $s = 0$  if the quark spins are antiparallel or  $s = 1$  if the quark spins are parallel. To understand the classification of the  $\phi$ -meson, which has orbital momentum  $l = 0$ , only mesons with  $l = 0$  are discussed here. The parity conjugation  $P$  is given by  $P = (-1)^{l+1}$  and the charge conjugation  $C = (-1)^{l+s}$ . The total angular momentum  $J$  depends on the quark and orbital spin as  $|l - s| \leq J \leq |l + s|$ .

Given these quantum numbers, mesons are classified in  $J^{PC}$  multiplets and all allowed combinations of quarks have been observed. The  $l = 0$  states are the pseudoscalar ( $0^{-+}$ ) and the vector ( $1^{--}$ ) mesons and the orbital excitations  $l = 1$  are the scalars, axial vectors and tensors. Table 1.3 lists the pseudoscalar and vector mesons containing the light quarks.

Having the same  $J^{PC}$  and isospin, the  $\phi(1020)$ -meson and the  $\omega(782)$ -meson can mix. The

| Quantum number     | Symbol | Expression                    | Allowed with $s = 0, 1$ and $l = 0$ |
|--------------------|--------|-------------------------------|-------------------------------------|
| Baryon number      | B      | $B = 0, 1$                    |                                     |
| Orbital momentum   | $l$    | $l = 0$                       |                                     |
| Spin momentum      | $s$    | $s = 0, 1$                    |                                     |
| Parity             | P      | $(-1)^{l+1}$                  | $P = -1, 1$                         |
| Meson spin         | J      | $ l - s  \leq J \leq  l + s $ | $J = 0, 1$                          |
| Charge conjugation | C      | $(-1)^{l+s}$                  | $C = -1, 1$                         |

Table 1.2: Some relevant quantum numbers used in the quark model.

| Isospin                         | $I = 1$                                                       | $I = \frac{1}{2}$                         | $I = 0$      | $I = 0$       |
|---------------------------------|---------------------------------------------------------------|-------------------------------------------|--------------|---------------|
| Content                         | $u\bar{d}, \bar{u}d, \frac{1}{\sqrt{2}}(d\bar{d} - u\bar{u})$ | $u\bar{s}, d\bar{s}, \bar{d}s, -\bar{u}s$ | $f'$         | $f$           |
| Pseudoscalar: $J^{PC} = 0^{+-}$ | $\pi$                                                         | $K$                                       | $\eta$       | $\eta'(958)$  |
| Vector: $J^{PC} = 1^{--}$       | $\rho(770)$                                                   | $K^*(892)$                                | $\phi(1020)$ | $\omega(782)$ |

Table 1.3: The pseudoscalar and vector mesons containing  $u$ ,  $d$  and  $s$  quarks. See text for definitions of  $f'$  and  $f$ .

quark contributions to the mesons are expressed as:

$$\begin{aligned}
 f' &= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\cos\alpha - s\bar{s}\sin\alpha, \\
 f &= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\cos\alpha + s\bar{s}\sin\alpha.
 \end{aligned} \tag{1.7}$$

For so-called “ideal mixing” with  $\alpha = 90^\circ$ , the  $f'$  (corresponding to  $\phi(1020)$ ) is pure  $s\bar{s}$  and the  $f$  (corresponding to  $\omega(782)$ ) is pure  $u\bar{u} + d\bar{d}$ . The physical mixing angle is found to be  $\alpha = 87.3^\circ$  [3] and thus the  $\phi(1020)$  is a nearly pure  $s\bar{s}$  state. The mixing between the two  $\eta$  pseudoscalar mesons is much larger, which is not further discussed here.

The allowed number of mesons containing light quarks can also be understood from a symmetry argument, which is explained in detail in ref. [8] and summarized here. If the masses of the light quarks are almost the same, the symmetry of the Lagrangian is increased from  $SU(3)$  and becomes  $U(3)$ . This can be decomposed as  $U(1) \otimes SU(3)$ , where  $U(1)$  corresponds to the conservation of quark number and the (new) approximate symmetry  $SU(3)$  is flavor symmetry, which becomes exact if the masses of the three quarks are degenerate. In this case  $SU(3)$  gives the classification of the meson and baryons into a flavor octet and decuplet, respectively. This octet in fact describes the lightest hadrons, so chiral  $SU(3)$  perturbation applies, which is illustrated in figure 1.3.

If the masses of the quarks are set to zero, the quark sector of the Lagrangian permits independent left and right handed rotations, called a *chiral* symmetry, hence chiral  $SU(3)$ . Chiral symmetry is not an observed feature of QCD. If it was, every hadron would be accompanied by a

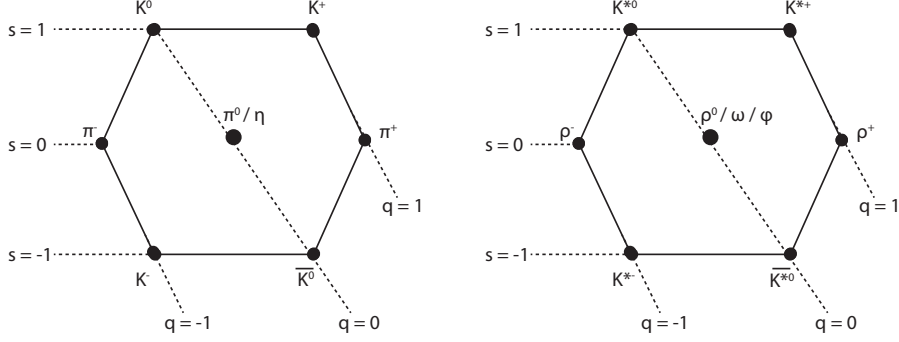


Figure 1.3: The meson octet for spin-zero and spin-1 particles. Particles along the same horizontal line share the same strangeness,  $s$ , while those on the same diagonals share the same charge,  $q$ .

partner of opposite parity and the same mass. This means that the chiral  $SU(3)$  is spontaneously broken.

### 1.3 Proton-proton collisions

In any hadron-hadron interaction, several parton-parton interactions may take place and different mechanisms play a role in the production of the particles that appear from the collision. To better understand the different processes that take place in a  $pp$  interaction, quantum chromodynamics (QCD), the model that describes the physics of the strong force [8], is introduced in this paragraph.

Interactions with a large four-momentum<sup>1</sup> transfer  $Q^2$  can be described with high precision using perturbative QCD calculations. Interactions with low(er) momentum transfers, the predominant ones in  $pp$  collisions, cannot be calculated exactly and are approximated with phenomenological models.

QCD is a non-Abelian gauge theory, which implies that the gluons also have colour charge themselves, making self-interactions between the gluons possible. The fundamental parameters describing the theory are the coupling constant  $g_s$ , or the usually more convenient  $\alpha_s = g_s^2/4\pi$ , and the masses of the quarks  $m_q$ . The features of QCD are most notably expressed in two experimental observations:

- **Confinement** The potential between quarks increases linearly at large distances between the quarks, resulting in the quarks being confined in hadrons. The colour potential be-

<sup>1</sup>In the remainder of this chapter, the four-momentum will be referred to as “momentum”.

has as  $V(r) \sim \lambda r$ , making it more favorable to create new colourless hadrons than having two partons separated.

- **Asymptotic freedom** When probed at high momentum transfers, the quarks and gluons can be treated as freely moving particles inside the hadrons, because the coupling constant of the strong force decreases. Thus part of the collisions between hadrons can be described perturbatively as interactions between the partons only.

Both these features are reflected by the running of the coupling constant  $\alpha_s$ .

The renormalization procedure in field theory consists in a redefinition of the unrenormalized constants that appear in the Lagrangian, in such a way that the observable quantities can be kept finite when the ultraviolet cut off  $\Lambda_{UV}$  is removed. In any renormalization, dimensional reasons require the introduction of a new parameter  $\mu$  with the dimension of mass. When  $\mu$  is close to the momentum transfer  $Q^2$  of a given process, the coupling constant evaluated at  $Q^2$  is a measure for the strength of the strong coupling for the process.

The physical parameters cannot depend on the scale  $\mu$ , and  $\alpha_s(Q^2)$  is given by the renormalization group equation

$$Q^2 \frac{\partial \alpha_s}{\partial Q^2} = \beta(\alpha_s). \quad (1.8)$$

The  $\beta$  function remains finite if  $\Lambda_{UV} \rightarrow \infty$  and in perturbative theory takes the form at first order

$$\beta(\alpha_s) = - \left( \frac{33 - n_f}{12\pi} \right) \alpha_s^2, \quad (1.9)$$

with  $n_f$  the number of active quark flavors. The decrease of  $\alpha_s^2$  with increasing momentum transfer in the  $\beta$  function reflects the increase of the coupling with decreasing momentum transfer  $Q^2$ . The world average of  $\alpha_s$  is usually expressed at the mass of the Z boson [3]:

$$\alpha_s(m_Z^2) = 0.1184 \pm 0.0007. \quad (1.10)$$

The expression for the running coupling constant can be simplified when we define the QCD scale parameter  $\Lambda_{QCD}$  as follows

$$\frac{1}{\alpha_s(Q^2)} = \frac{1}{\alpha_s(\mu_R^2)} + b \ln \left( \frac{Q^2}{\mu_R^2} \right) \equiv b \ln \left( \frac{Q^2}{\Lambda_{QCD}^2} \right). \quad (1.11)$$

The parameter  $\Lambda_{QCD}$  is thus equal to the scale where  $\alpha_s(\mu^2)$  becomes infinite. Now we may write

$$\alpha_s(Q^2) = \frac{1}{b \ln(Q^2/\Lambda_{QCD}^2)}. \quad (1.12)$$

At  $Q^2$  values close to  $\Lambda_{QCD} \sim 200$  MeV, the coupling constant becomes large and perturbative QCD breaks down. When momentum transfers are lower than  $\Lambda_{QCD}$  phenomenological models are introduced to describe the physical interactions.

In  $pp$  collisions strong interactions with various momentum transfers take place simultaneously. This is illustrated schematically in figure 1.4. The different processes are labelled:

1. The incoming hadrons are seen as incoming beams of quarks and gluons;
2. One parton (gluon or quark) of each incoming hadron participates in the hard scatter;
3. The hard scatter, the interaction with the largest momentum transfer in the event;
4. Before interacting, the partons may radiate gluons, that produce hadrons in what is called initial-state radiation;
5. The hard process may produce a set of short-lived resonances, like  $Z/W^\pm$  bosons, or a top-quark that decay to partons or stable particles;
6. If the outgoing partons of the hard scatter radiate gluons before decaying, the resulting particles are referred to as final-state radiation;
7. The produced partons after these decays may split into two, sharing the incoming momentum. This splitting occurs until the partons have an energy comparable to  $\Lambda_{\text{QCD}}$ , below this cutoff energy, hadronization of color-charged partons takes place, which is modelled in a non-perturbative approach called fragmentation.
8. In one  $pp$  collision, several interactions with considerable momentum transfer may take place. This is referred to as multiple parton interaction (MPI).

The description of the known physics processes that take place at high momentum transfers is reliable. Describing the fragmentation process is challenging, because there are no exact solutions. Measuring the strange quark production is interesting, because  $m_s$  is relatively low allowing for strangeness production in the fragmentation process. But  $m_s$  is not so low that the mass can be set to zero in the calculations, like is done for the  $u$  and  $d$  quarks. An important part of the study of strangeness production is the study of the  $\phi(1020)$ -meson, which is an almost pure  $s\bar{s}$  state.

Sources of  $\phi$ -mesons in  $pp$  collisions are production from strange sea quarks [10], from gluon fusion or from the fragmentation process. This makes them a probe of the phenomenology of the hadronization, in contrast to the production of third generation quarks, which is determined by perturbative calculations [11]. The investigation of  $\phi$ -meson production in both hadronic and electromagnetic processes are aimed to obtain the amount of strangeness in hadrons.

## 1.4 Monte Carlo simulation

To understand the manifestation of physics processes and the detector response we rely on computer simulations. With these computer simulations, the physics models can in turn be compared to experimental data. The simulated events are structured such that they can be analyzed as if they were data. The simulation of the ATLAS experiment consists of three steps. First collision events are generated like they are produced in the  $pp$  collisions at the LHC (event generation), then particle decays and their interactions in the detector are simulated and finally

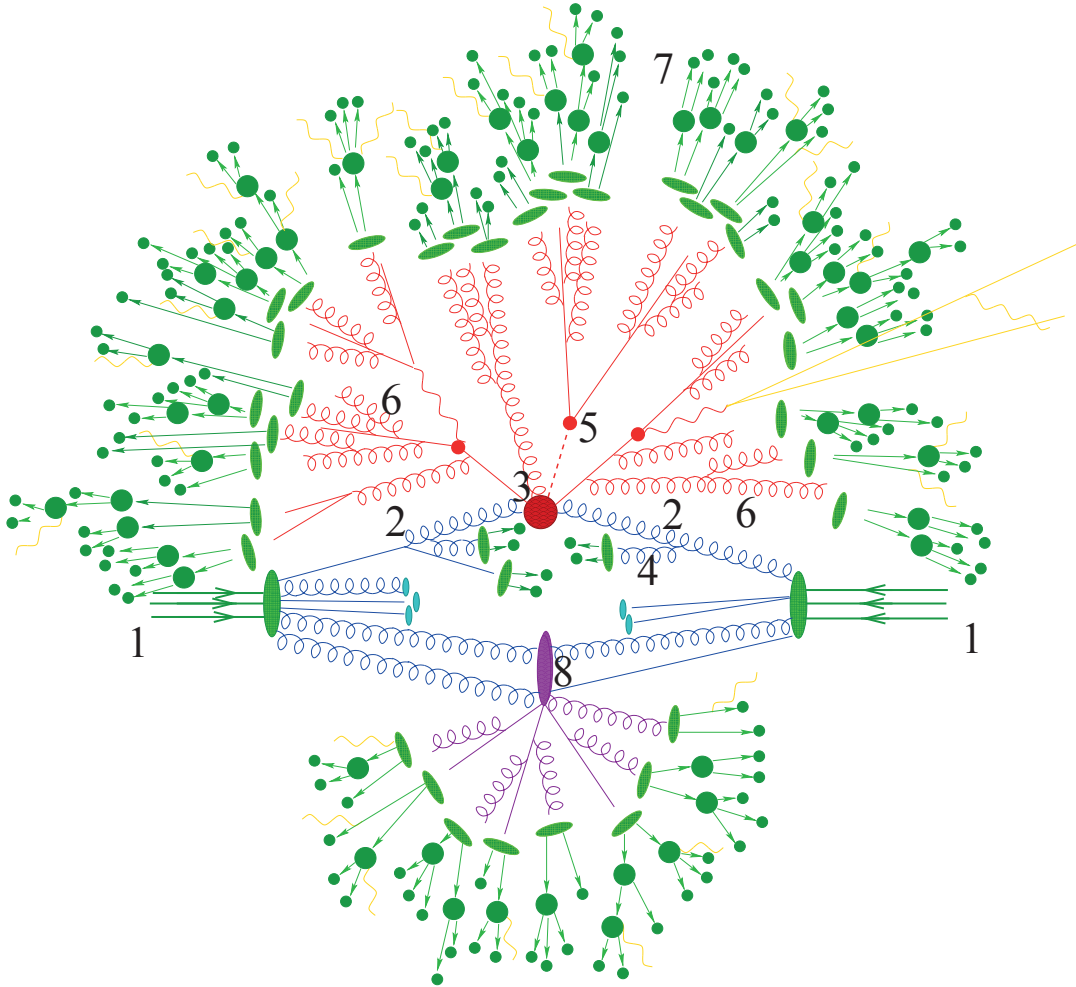


Figure 1.4: Artist impression of a  $pp$  collision. The labelled processes are discussed in the text. Adopted from [9].

the response of each of the sub-systems in terms of electronic signals is predicted (digitization). Each of these steps is discussed below.

Observed particle multiplicities at the LHC range up to a few hundred. Event generation is used to produce events with particles emerging from the  $pp$  collision, which includes particles that decay before they can interact with the detector. Like a real collision, the resulting stable particles are detected and used to reconstruct the physics in the collision. Because not all processes are calculable with the same precision, most event generators factorize the problem into steps that include the hard interaction, hadronization and simulation of the underlying event.

The hard scatter is the core of the collision and it describes the interaction between two incoming partons of the colliding protons and the outgoing particles. It is illustrated as step 3 in figure 1.4. The partons participating in the hard scatter are taken randomly from the parton density functions (PDFs), that define the substructure of the proton in terms of flavor composition and momentum distribution. In the hard scatter usually two outgoing partons are produced.

The partons (valence quarks, sea quarks and gluons) carry a fraction  $x$  of the momentum of the incoming hadron. The fraction carried by the partons of the incoming particles 1 and 2 is given by [12]:

$$x_1 = \frac{M}{\sqrt{s}} e^{+y} \quad \text{and} \quad x_2 = \frac{M}{\sqrt{s}} e^{-y}, \quad (1.13)$$

where  $M$  is the total invariant mass produced in the hard scatter,  $\sqrt{s}$  the center-of-mass energy and  $y$  the rapidity of  $M$  in the center-of-mass frame; its rapidity  $y$  is expressed as  $y = \frac{1}{2} \ln((E + p_z)/(E - p_z))$  with  $E$  being the energy of  $M$  and  $p_z$  the momentum component parallel to the beam-axis.

Figure 1.5 shows the leading order proton PDFs of the Martin-Stirling-Thorne-Watt (MSTW) group [13–25] as a function of the momentum fraction  $x$  for two energy scales  $Q^2 = 10 \text{ GeV}^2$  and  $Q^2 = 10^4 \text{ GeV}^2$ . The PDFs are determined by a fit to all available deep inelastic scattering (e.g. electron/positron on proton) and relevant hadron-hadron hard-scattering data. Although the PDFs have been evaluated including higher order contributions in the strong coupling constant as well, the leading order is sufficiently predictive for soft and semi-hard processes such as strangeness production. At these energy scales the contributions of the  $u$  and  $d$  valence quarks to the PDFs are largest from  $x \sim 0.2$  and the gluons dominate for low momentum fractions. Due to the high center-of-mass energies at the LHC, the prevalent interactions that take place with low momentum fractions are probed with the experiments.

In the hard scatter,  $\phi$ -mesons are predominantly produced from strange sea quarks or from gluon fusion. In addition, neutral mesons may be produced via  $q\bar{q}$  fusion into a virtual photon that then fluctuates into a neutral meson. A clear way to observe this process is the observation of the conversion into  $\mu^+\mu^-$ -pairs as shown in figure 1.6 from reference [27]. The number of dimuon events is of the order of 8000 in  $1.5 \text{ pb}^{-1}$  of collision data. This yields a cross section of  $\sigma_{\gamma^* \rightarrow \mu^+\mu^-} \sim 5.3 \text{ nb}$ . Let's assume that the photons can only decay to  $u$ ,  $d$  and  $s$  quarks in this energy range, that each come in three colors, and that the virtual photon can also decay to an electron-positron pair all with equal branching fractions [8]. This yields a total virtual photon cross section of about  $\sigma_{\gamma^*} \sim 60 \text{ nb}$ . Given that the total cross section for the  $\phi(1020)$ -meson is of the order of mb,  $\phi$ -mesons are predominantly produced in the fragmentation process.

The incoming and outgoing partons of the hard scatter have color charge, thus they radiate gluons that in turn may produce other colored objects. This whole process is referred to as



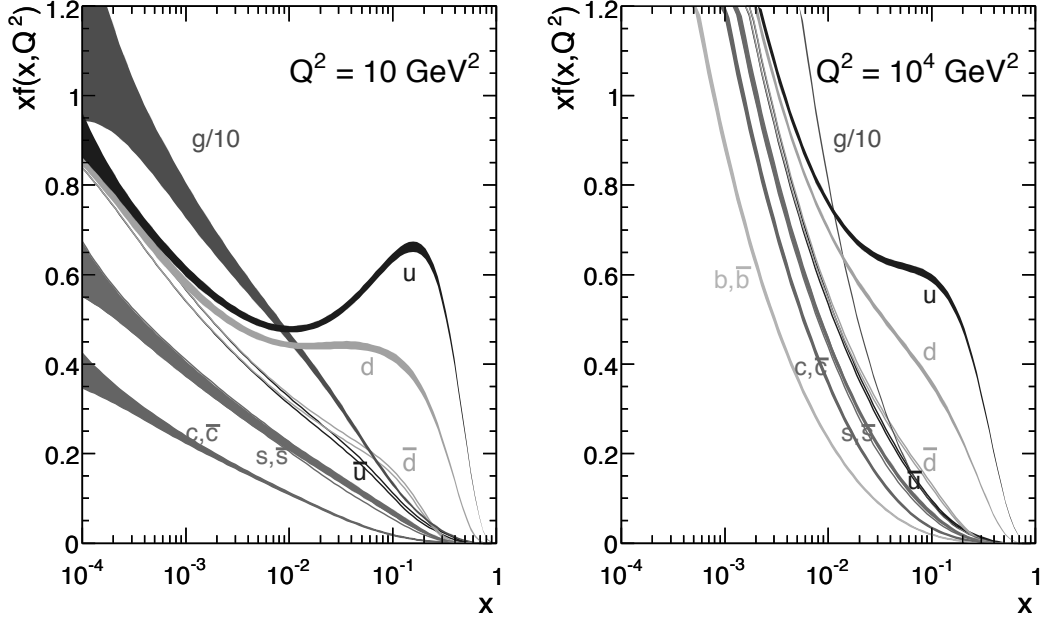


Figure 1.5: MSTW leading order parton distribution functions for the energy scales  $Q^2 = 10 \text{ GeV}^2$  and  $Q^2 = 10^4 \text{ GeV}^2$  as a function of the momentum fraction  $x$  of the partons. [26]

*parton showering*. The behavior of the shower is expressed as a function of  $Q^2$  by the DGLAP evolution equations [28–31] that express the probability that a ‘mother’ parton will branch into two daughters [32]. Depending on whether the branching is before or after the hard scatter, the branch contributes to an initial- or final-state shower

If the energy of the parton reaches some cut-off, the colored objects from the parton shower are combined to colorless hadrons in a process called *hadronization* or *fragmentation*. Of course, an absolute factorization of initial and final state radiation is unphysical, but the non-factorisable parts are incorporated in the hadronization modelling. The simplest approach to model the fragmentation process is an “independent fragmentation” of each of the produced partons [33]. In the fragmentation, one starts with the original quark of flavor  $a$ . A quark-antiquark pair is generated from the vacuum and they form a “primary meson” with energy fraction  $z$  of the original parton. The process continues with the leftover quark that now has energy fraction  $1 - z$ . It stops when the energy fraction carried by the produced quarks come below some tunable threshold.

The two models that are used by the event generators discussed in this thesis to model the fragmentation are string fragmentation and cluster fragmentation, which both are more sophisticated models that incorporate correlations between different initial partons. During the

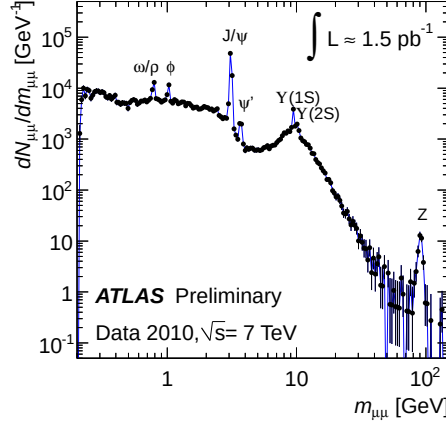


Figure 1.6: Di-muon invariant mass spectrum at  $\sqrt{s} = 7$  TeV as measured using the ATLAS experiment. [27]

fragmentation both unstable and stable hadrons are formed and the unstable hadrons decay to stable particles. The resulting particles are photons, leptons, mesons and baryons that can be detected.

In addition to the hard process considered above, further semihard interactions may occur between the other partons of two incoming hadrons. When a shower initiator is taken out of a beam particle, a beam remnant is left behind. In  $pp$  collisions, the “underlying event” (UE) is defined as the hadronic activity apart from particles originating from the hard scatter. UE activity thus includes activity from multiple-parton interactions (MPIs) and from hadronization of the beam remnants other than initial- and final-state showers. (Sometimes, the initial- and final-state radiation is also included in the UE.) These soft and semihard interactions cannot be completely described by perturbative QCD and require a phenomenological description involving parameters that must be tuned with the help of data. Study of the underlying event and the possibly higher  $p_T$  interactions that are part of it, probes some of the physics that is hardest to solve and model theoretically. Higher  $p_T$  MPIs are an important background for new physics searches, for example same-sign  $W$  boson production from MPIs is a possible background to the same-sign SUSY searches [34]. Better understanding of the UE can reduce the Jet Energy Scale uncertainties.

After particles have been created by the event generator, their propagation in the ATLAS detector is simulated. For this the detector structure needs to be modelled as precisely as possible as well as the particle interactions with various sub-systems, the deflections in the magnetic fields and the recording of the energy depositions in the detectors. In ATLAS, the detector simulation is done using the GEANT4 [35] simulation toolkit. The geometry of the ATLAS detector is constructed in great detail with more than 316 thousand different types of shapes [36] that describe basic properties of the materials. In total the full detector description consists of nearly 5 million detector elements. During the simulation, the geometry layout can be modi-

fied to account for real detector conditions, such as any mis-calibrations, mis-alignments, dead channels and more.

When particles propagate through the detector, various processes, e.g. photo-electric effect, ionization, pair production, Compton scattering and hadronic interactions can take place due to interactions with detector materials, creating more (secondary) particles in the detector. Also the decays of long-lived particles take place during the simulation step. Modelling those processes and calculating the deflections in the magnetic fields makes the detector simulation time-consuming.

Particles passing through sensitive regions of the detector produce “hits”; records of energy deposition with information of position and time. They serve as input to the next step of the simulation, the digitization, where the response of the ATLAS detector is reconstructed. The hits from the detector simulation are converted into the detector response, which is typically a signal produced when the voltage or current on a particular readout channel rises above a configured threshold within a particular time-window. The responses are stored in a format compatible with the data recorded by the real detector.

Activity from for instance MPIs, multiple  $pp$  interactions occurring simultaneously or the cavern background, can influence the detector response. Such types of events are treated separately at the event generation and detector simulation stages; but their hits and energy depositions are incorporated before the digitization takes place, to make sure the detector response is simulated as realistically as possible.

## 1.5 Generators

$\phi(1020)$ -mesons may originate from the hard scatter, but are predominantly produced in the fragmentation process and the underlying event. They can also appear as a decay product, e.g. in  $B_s^0 \rightarrow J/\psi\phi$ , but these are not separately considered, as they are not identified as such. The  $\phi$ -meson production cross section at  $\sqrt{s} = 7$  TeV is compared to several Monte Carlo event generators discussed below.

### 1.5.1 PYTHIA

The PYTHIA [37] program is frequently used for event generation in high-energy physics. A set of models describes a range of physics processes including the hard scatter, MPIs, initial- and final-state parton showers, the possible decays of the beam remnants, the fragmentation and the particle decays. To model the soft interactions PYTHIA makes use of sets of adjustable parameters, so-called *tunes*. The majority of the physics is determined by a few important parameters, such as the value of the strong coupling in the perturbative domain and the form of the fragmentation function for massless partons in the non-perturbative energy region.

As an aside, the neutral meson production via an intermediate photon is simulated using the photon parton distributions for the mesons that have been obtained using known distributions for the proton and the pions. For example the  $\rho^0$  parton distribution is assumed to be

$$f_i^{\rho^0} = f_i^{\pi^0} = \frac{1}{2}(f_i^{\pi^+} + f_i^{\pi^-}), \quad (1.14)$$

where the distributions for  $f_i^{\pi^+}$  and  $f_i^{\pi^-}$  were taken from data. The  $\omega$ -meson distribution function is assumed to be the same, while  $\phi$  and  $J/\psi$  functions are assumed to obey:

$$f_{s,\text{val}}^\phi = f_{u,\text{val}}^{\pi^+} \quad f_{s,\text{sea}}^\phi = f_{u,\text{sea}}^{\pi^+} \quad (1.15)$$

and are thus estimated in a rather crude way.

After the hard process,  $qq$ ,  $qg$  or  $gg$  scattering, and parton showering when the virtuality of the partons falls below a predefined cut-off, the formation of hadrons is described by the fragmentation. PYTHIA makes use of the Lund String Fragmentation model [38], where the color field between partons is represented by strings, such that the end of each string represents a quark or an antiquark. The model is most easily described for  $e^+e^-$  annihilation and most of the parameters have been determined in this process. The produced quark and antiquark move out in opposite directions, losing energy to the color field, which is a stringlike configuration. The string has a uniform energy per unit length, corresponding to a linear quark confining potential. The string breaks up into hadron-sized ( $\sim 1$  fm) pieces through spontaneous  $q\bar{q}$  production in the intense color field.

The string model resembles the independent fragmentation model discussed above. The string may be broken starting at the quark or the antiquark or at both places in the same time and the fragmentation proceeds iteratively. By using the string model, the fragmentation function (a dimensionless function that describes single particle distributions in the final state) is more constrained and it ensures independence from whether the fragmentation is started from a quark or an antiquark. In the independent fragmentation model, gluons do not have a real role, but in the string model, they produce kinks on the string, each initially carrying localized energy and momentum, equal to that of its parent gluon. The fragmentation of the kinked string leads to an angular distribution of hadrons in  $e^+e^- \rightarrow$  three jets final states that is in better agreement with experiment.

A schematic picture of the production of a busy final state in  $e^+e^-$  annihilation using the string model is shown in figure 1.7 on the left. Whenever a gluon splits perturbatively into a quark-antiquark pair, an additional string segment is produced. In the end to produce stable hadrons, the fragmentation process needs to know the relative fractions of  $u\bar{u}$ ,  $d\bar{d}$ ,  $s\bar{s}$  etc and the relative probabilities to form a specific meson, e.g. a  $u\bar{d}$  can form a  $\pi^+$ , a  $\rho^+$ , or some higher state.

To decide the quark flavor, a suppression of heavy quark production is assumed  $u : d : s : c \sim 1 : 1 : 0.3 : 10^{-11}$ . Charm and heavier quarks are hence not expected to be produced in the soft fragmentation. Once the quark flavor is selected, a choice is made between the possible meson states. The relative composition of different spins can not be derived from first principles and depends on the details of the fragmentation process. By default it is assumed that only pseudoscalar and vector mesons, thus with  $L = 0$ , are produced. The mixing between the physical mesons containing  $u\bar{u}$ ,  $d\bar{d}$  and  $s\bar{s}$  is accounted for using the mixing angles from the Particle Data Group (PDG) [3]. The default choices are:

$$\begin{aligned} \eta/\eta' &= \frac{1}{2}(u\bar{u} + d\bar{d}) - / + \frac{1}{\sqrt{2}}s\bar{s} \\ \omega &= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) \quad \text{and} \quad \phi = s\bar{s}, \end{aligned} \quad (1.16)$$

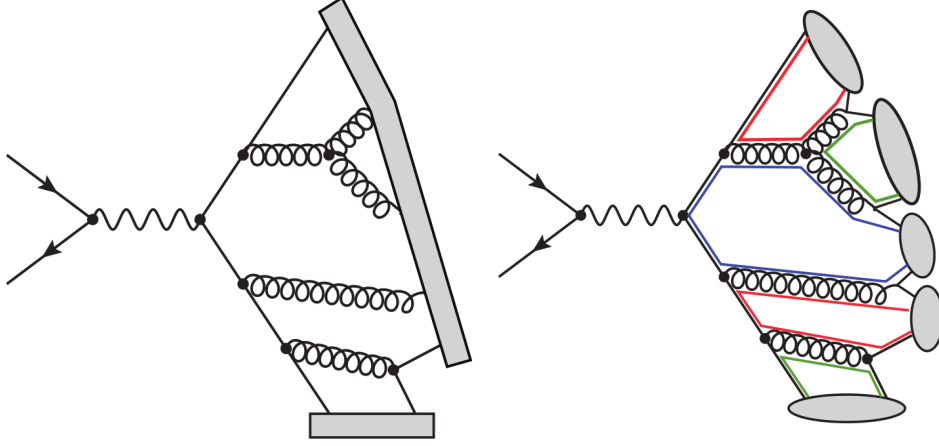


Figure 1.7: Parton shower with string (left) and cluster (right) hadronization model for  $e^+e^- \rightarrow$  hadrons. Both from ref. [8].

which implies ideal (no) mixing in the  $\omega - \phi$  system.

Assuming fragmentation universality, meaning that the hadronization process after  $e^+e^-$  annihilation is the same as in a  $pp$  interaction, most of the parameters in the string model can be fixed to  $e^+e^-$  data.

In this thesis two PYTHIA tunes are compared to data; PYTHIA 6 [37] version 6.4.21, using the MC09 [39] tune and PYTHIA 8 [40] version 8.153, using the A2:MSTW 2008LO [41] tune. The difference between PYTHIA 6 and PYTHIA 8 is the fully re-written code using the object-oriented programming language C++ in PYTHIA 8 and it includes a new algorithm for parton showering. The MC09 tune was created in preparation for the LHC collision data. It is derived from data of the Tevatron Runs I and II. With the introduction of PYTHIA 8.140 the default tune was 2C that uses the CTEQ6L1 [42] parton density function, and is intended to give good agreement with much of the published CDF data. The subsequent tune 4C, based on 2C, shows better agreement with some early key LHC data numbers, such as the particle multiplicity and the activity in the underlying event. The A2:MSTW 2008LO tune compared to data in this thesis uses the 4C tune, but is based on the MSTW 2008 LO [13] PDF.

## 1.5.2 HERWIG

HERWIG++ (Hadron Emission Reaction With Interfering Gluons) [43] is another Monte Carlo event generator used for the simulation of hard lepton-lepton, lepton-hadron and hadron-hadron collisions. The basis of the HERWIG project is to provide a good description for perturbative QCD, with less emphasis on the modelling of non-perturbative physics. The model includes an angular ordered parton shower algorithm using Sudakov form factors, a cluster hadronization model and a multiple scattering model for the underlying event.

The main features of a high momentum transfer process can be divided into the hard scat-

ter, the initial- and final-state parton showers, the heavy object decays and the subsequent hadronization, which is most important for  $\phi$ -meson production. The hadronization model adopted in HERWIG++ is meant to disrupt as little as possible the event structure established in the parton showering phase. Showering is terminated at a low scale,  $Q_0 < 1$  GeV, and the preconfinement property of perturbative QCD [44] is used to form colour-neutral clusters [45] which decay into the observed hadrons. Preconfinement implies that the pairs of color-connected neighboring parton have an asymptotic mass distribution that falls rapidly at high masses and is asymptotically  $Q^2$ -independent and universal. In cluster hadronization, color-singlet clusters form after the jet development [8]. The remnants of incoming hadron undergo a soft underlying event interaction modelled on minimum bias hadron-hadron collisions.

The cluster hadronization is independent of hard process and the energy. An important property of the parton branching process is the preconfinement of color [44]. The simplest way for color singlet clusters to form is through splitting of gluons in  $q\bar{q}$  pairs. Neighboring quarks and antiquarks can then combine into singlets. The resulting cluster mass spectrum peaks at low masses. Its precise form is determined by  $\Lambda_{\text{QCD}}$  and the scale where parton branching changes into fragmentation. Most clusters have masses of a few GeV and they are treated as superpositions of mesons. Each such cluster is assumed to decay to a pair of hadrons, with the branching ratios determined by the density of states. The reduced phase space for cluster decay into heavy mesons and baryons is enough to account for the observed relative multiplicities in  $e^+e^- \rightarrow$  hadron final states. The hadronic energy and  $p_T$  distributions agree quite well with experiment, without the introduction of tunable fragmentation functions. The angular distribution of  $e^+e^-$  to three jets is successfully described.

The cluster hadronization in figure 1.7 on the right is the same as that defined on the left for the string model. The gluons that remain after the parton shower are split non-perturbatively into  $q\bar{q}$  pairs, neighboring pairs (not from the same gluon) can form color singlet mesonic clusters, which can decay into the observed hadrons. In HERWIG++ the default choice for the mixing between the  $\omega$  and  $\phi$  mesons is ideal mixing.

Using these models, the higher  $p_T$  physics from the Tevatron data is especially well described. But the description of the charged particle multiplicity in ATLAS [46] at  $\sqrt{s} = 900$  GeV was rather poor. It was assumed that this problem originated from the cluster fragmentation model [47]. The model was extended with the implementation of “colour reconnection” that allows for the reformation of clusters mimicing the exchange of soft gluons during the non-perturbative hadronization. Using this extended model, the description of the underlying event at  $\sqrt{s} = 900$  GeV improved significantly.

In this thesis data are compared to the UE7-2 [48] tune, that uses a different PDF for the low and higher  $p_T$  regime and that provides a reasonable description for the underlying event [49] and thus the soft and semi-hard processes.

### 1.5.3 EPOS

The relatively new event generator EPOS [51] simulates soft and hard processes in the same formalism. EPOS stands for **E**nergy conserving quantum mechanical approach, based on **P**artons, parton ladders, strings, **O**ff-shell remnants, and **S**plitting of parton ladders.

The motivation to model complete events is the observation that in  $p\bar{p}$  collision at the Teva-

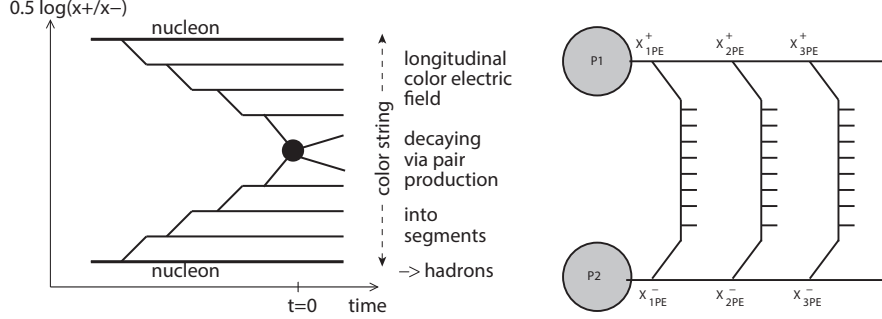


Figure 1.8: The elementary interaction in EPOS (left) is generated simultaneously with the multiple parton interactions (right), where energy is shared between the ladders. From ref. [50].

tron the number of multiple parton interactions (MPIs) increases with increasing leading jet  $p_T$  in an event [52]. The parton model hides multiple scatterings, which apparently also occur in  $pp$  interactions. It was observed that the usual event generators did not model this behavior correctly. EPOS generates hard scatterings in the context of MPIs, which provides more control over the underlying event [53]. The collective approach proved useful to describe strange particle production in  $pp$  collisions [54] and also characteristics of  $d + \text{Au}$  collisions [55] measured with the RHIC detector.

The elementary interaction in EPOS is represented as a parton “ladder”, see figure 1.8, which could be seen as a longitudinal color field that decays via pair productions into hadrons [56].

Particle production follows the Lund String Model. In the initial stage of  $pp$  collisions (or heavy ion collisions), MPIs interactions occur in parallel, which is represented in EPOS as an exchange of a parton ladder in parallel. The allowed energy exchange via the ladder covers the whole allowed range, but the total energy is shared between the ladders, limiting the total number of possible interactions. The obvious down-side of generating the whole event in one go, is that (like in a real experiment) many events need to be generated in order to produce rare processes. This is not a problem when studying the relatively large  $\phi(1020)$ -meson cross section.

EPOS uses a different method to handle the way color charge behaves during the fragmentation. The approach has proved successful to describe minimum bias data and to describe strangeness production in  $pp$  interactions [57]. In this thesis data are compared to the EPOS LHC [58] tune, which is tuned to minimum bias data from the LHC at  $\sqrt{s} = 0.9$  and 7 TeV.

#### 1.5.4 Comparing to recent data

When a Monte Carlo data set has been tuned to a limited set of data, the simulation can be used to model detector effects and reconstruction acceptances, to estimate sources of background processes and to fit the shape of a background. If some feature of the data is over- or underestimated, adjusting a specific parameter and comparing the effect can yield extra understanding of what physics may cause the disagreement.

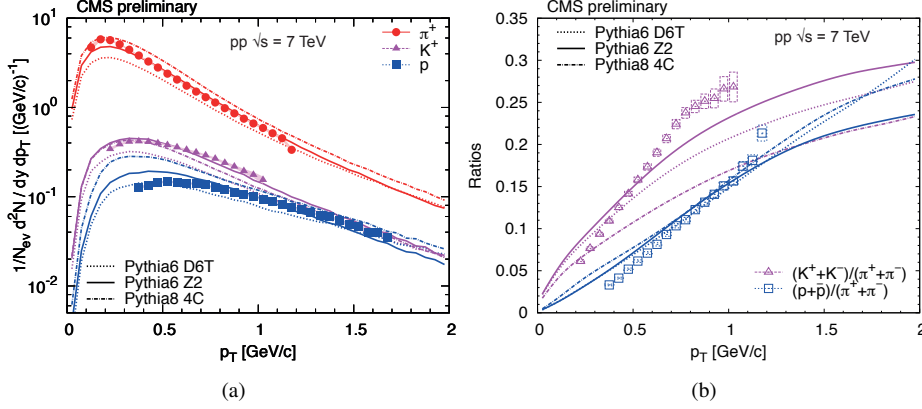


Figure 1.9: Left: Transverse momentum distributions of charged pions, kaons and protons in the range  $|y| < 1$ , for positive particles, at  $\sqrt{s} = 7$  TeV. Right: Ratios of particle yields as a function of transverse momentum. Curves indicate predictions from PYTHIA 6 (D6T and Z2 tunes) and the 4C tune of PYTHIA 8. Data measured by CMS [59].

To study strangeness production in hadron hadron interactions, both the total yields of particles containing one or more strange quarks and the ratio of the kaon/ $\pi$  yield is of interest, because of the smaller systematic uncertainties on such a ratio.

The description of strangeness production in  $pp$  collisions at a center-of-mass energy of  $\sqrt{s} = 7$  TeV is compared to a measurement conducted by the CMS experiment at the LHC (see next chapter). Figure 1.9 shows the total yield of identified pions, kaons and protons and the ratios of kaons and protons to pions [59]. The total yield of identified particles as a function of transverse momentum in the low  $p_T$  regime ( $p_T < 2$  GeV) is typically between the model predictions, indicating that strangeness production is not described perfectly. The total yield of the  $\phi$ -meson, which has two strange quarks and thus probes the suppression parameter for the strange quark with respect to the up and down quark quadratically, can be used to tune the models more effectively.

Going to higher  $p_T$ , the normalized  $K_s^0$  meson and  $\Lambda$  baryon yields as a function of  $p_T$  are shown in figure 1.10 [60]. Data are compared to PYTHIA6 AMBT2BT (using ATLAS minimum bias data), Z1 (CMS minimum bias data) and Perugia2011 (mixture) tunes, to the PYTHIA 8 4C tune and to HERWIG++. The  $K_s^0$  yield is well-described by all these generators, only the HERWIG++  $p_T$  is too soft. In the very low  $p_T$  domain,  $p_T < 500$  MeV, the models overestimate the yields. This overestimation is not seen when models are compared to kaon yields in  $e^+e^-$  interactions [61]. In  $e^+e^-$  interactions there is no underlying event, so the modelling of the underlying event may cause the overestimation at low  $p_T$ . Interestingly, all generators significantly overestimate the  $\Lambda$  yield from  $p_T > 6$  GeV, which is an unsolved issue at time of writing [62]. The effect is also seen in  $e^+e^-$  comparisons, so it most likely arises from a problem in the tuning of one of the fragmentation parameters.



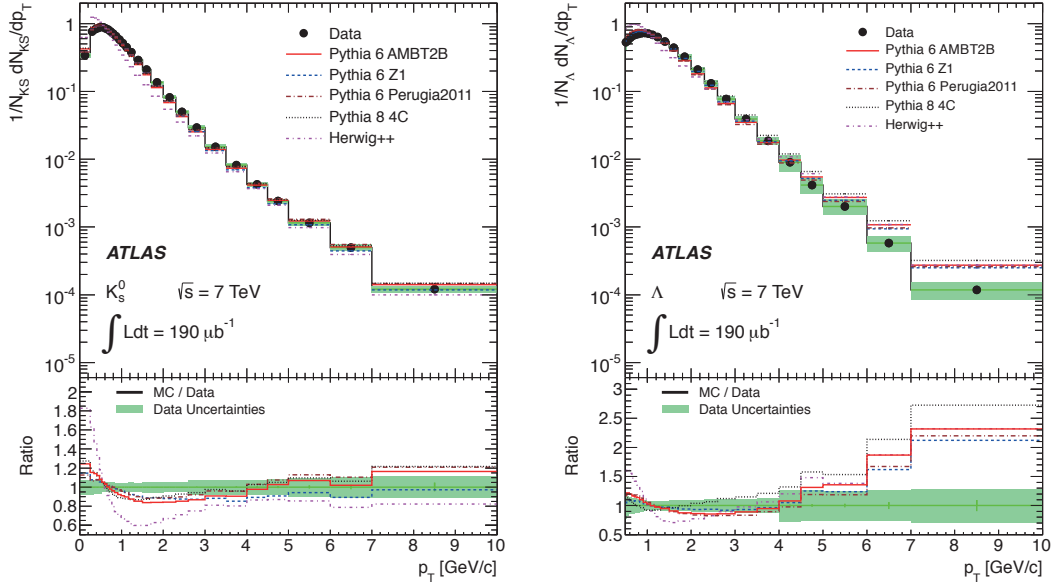


Figure 1.10: The  $p_T$  distribution of  $K_s^0$  mesons (left) and  $\Lambda$  baryons in 7 TeV data compared with the hadron-level distributions from several Monte Carlo generators and tunes. [60]

## 1.6 Summary

In  $pp$  interactions the  $\phi(1020)$ -meson is predominantly produced in processes with low momentum transfer. The physics of these processes cannot be described exactly using perturbative calculations, but are approximated using phenomenology. Three Monte Carlo event generators, PYTHIA, HERWIG++ and EPOS that have different approaches to simulate collision events are described. While PYTHIA and HERWIG++ both factorize the task and start the event generation from the hard scatter, EPOS simulates the whole event in one step. Strangeness production, important to describe  $\phi$  meson production, is described in the hadronization step of the event generation. PYTHIA and EPOS use a string fragmentation model while HERWIG++ uses a model based on the formation of color-neutral clusters.

The  $\phi(1020)$ -meson production cross section measured with the ATLAS detector at  $\sqrt{s} = 7$  TeV presented in chapter 6 will be compared to predictions from two tunes of PYTHIA and to HERWIG++ and EPOS. PYTHIA is also used to simulate the detector acceptance.



## Chapter 2

# The ATLAS experiment at the LHC

The  $\phi(1020)$ -meson production cross section is measured using collision data at a center-of-mass energy of  $\sqrt{s} = 7$  TeV produced at the LHC and recorded with the ATLAS detector. In the first paragraph of this chapter the LHC is introduced and in the remainder of the chapter an overview of the detector and its performance in 2010 and 2011 is given. The discussion of the ATLAS inner tracking system is left to the next chapter.

## 2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [65] is a particle accelerator located underground at CERN in Geneva, designed to collide proton beams with a center-of-mass energy of  $\sqrt{s} = 14$  TeV and lead ions with an energy of  $\sqrt{s_{NN}} = 5.5$  TeV per nucleon. A schematic picture of the current accelerator complex at CERN is shown in figure 2.1. The LHC is a 26.6 km long ring filled with superconducting magnets to control the trajectories of two particle beams circulating in opposite directions. The particles are accelerated up to an energy of 450 GeV by a chain of pre-accelerators before being injected in the LHC, where they are further accelerated to the collision energy. Ultimately, the beam energy is limited by the maximal magnetic field available to keep the protons in their orbit. If the LHC is completely filled, it runs with 2808 bunches of  $10^{11}$  protons each, with the 10 cm long bunches 25 ns or  $\sim 8$  m apart. At design luminosity (further discussed below) of  $\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  there are on average 23 interactions per bunch crossing at the interaction point. The key parameters of the LHC performance in 2010 and 2011 are listed and compared to design values in table 2.1.

The bunches are collided at four points along the LHC, where the experiments are located. They are:

- **ATLAS** [67] and **CMS** [68], the two general purpose experiments.
- **ALICE** [69] investigates the lead-lead collisions provided by the LHC.
- **LHCb** [70] a single arm spectrometer designed to study  $B$ -physics.

The first bunches were accelerated in the LHC in September 2008, but shortly after this, during the ramping-up of current in the main dipole circuit at the nominal rate of 10 A/s, a

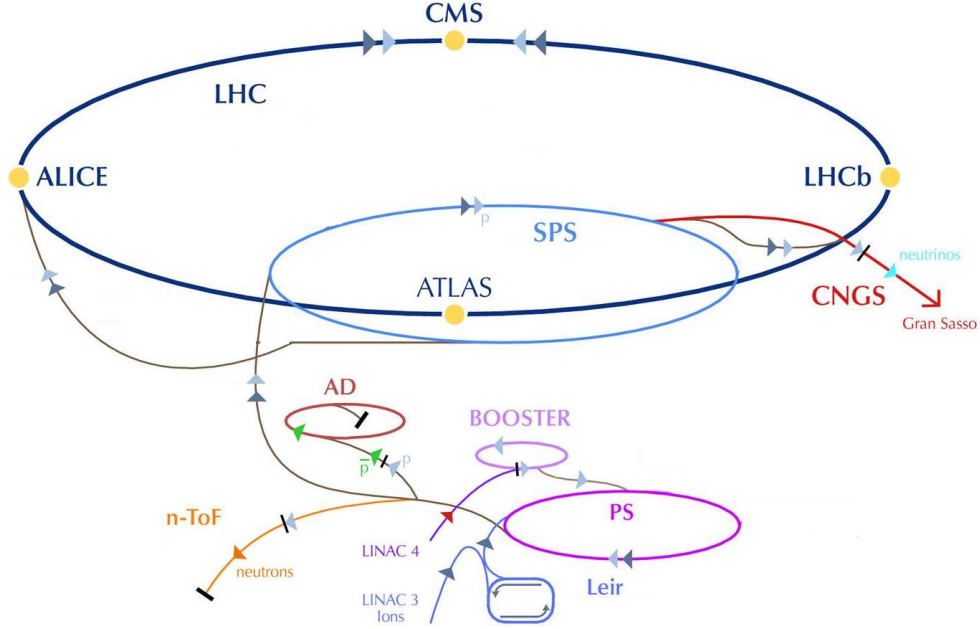


Figure 2.1: Schematic overview of the CERN accelerator complex showing the LHC and its chain of pre-accelerators. The locations of the experiments are also shown. From [63].

resistive zone developed. The power supply tripped off and the energy discharge switch opened. Dump resistors were inserted into the circuit to produce a fast current decrease, the so-called quench detection. During the discharge, many magnet quenches were triggered automatically in the part of the LHC where the incident occurred and the helium was recovered through the self actuated relief valves. The helium release caused a pressure increase which lifted several of the superconducting magnets off their supports, breaking the interconnections between them. The replacement of 53 superconducting magnets, over fifty electrical interconnections and the partial repairs to another 150 interconnections took 14 months. During the repairs engineers discovered the collider has hundreds to thousands of flawed electrical splices between magnets. These did not need urgent repair, but they limited the amount of current which can be safely run through the machine [71]. The first  $pp$  collisions were delivered in December 2009 by colliding protons at the injection energy of 450 GeV. From March 2010 onwards, the LHC was operated at center-of-mass energy of 7 TeV, which was increased to 8 TeV in 2012. The LHC and ATLAS performance in 2010 and 2011 are relevant for this thesis.

In about 120 days with stable collisions during the years 2010 and 2011, the LHC delivered  $\mathcal{L} = 5.6 \text{ fb}^{-1}$  of collision data at  $\sqrt{s} = 7 \text{ TeV}$  to ATLAS and CMS. If two bunches containing  $n_1$  and  $n_2$  particles collide head-on, the instantaneous luminosity  $\mathcal{L}$  is given by  $\mathcal{L} = f_r(n_1 n_2) / (4\pi\sigma_x\sigma_y)$  [3], with  $f_r$  the revolution frequency and  $\sigma_x$  and  $\sigma_y$  the rms transverse beam sizes in the horizontal and vertical directions. The LHC's instantaneous luminosity has steadily improved by the continuous effort of the CERN accelerator division. For example the

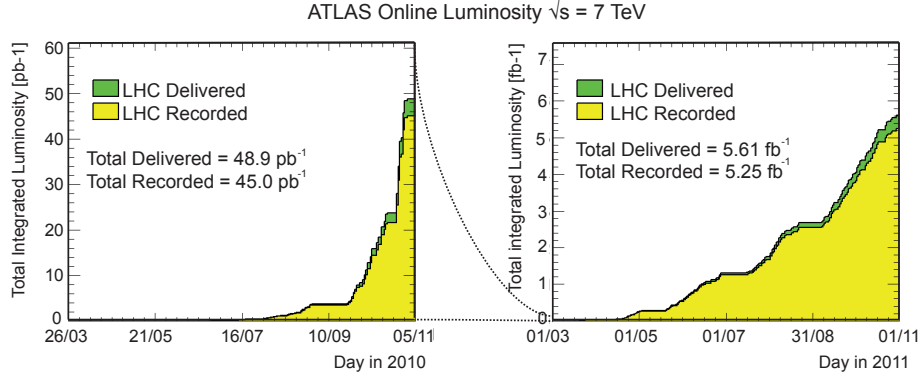


Figure 2.2: The integrated luminosity of proton-proton collisions at  $\sqrt{s} = 7$  TeV delivered by the LHC and recorded by ATLAS in 2010 (left) and in 2011 (right). The total luminosity recorded in 2011 is almost a factor 120 more than in 2010. Modified from [64].

| Parameter                                                    | 2010                   | 2011                  | Design |
|--------------------------------------------------------------|------------------------|-----------------------|--------|
| Beam energy (TeV)                                            | 3.5                    | 3.5                   | 7      |
| Number of proton bunches                                     | 356                    | 1331                  | 2808   |
| Bunch spacing (ns)                                           | 50                     | 50                    | 25     |
| Protons per bunch ( $10^{11}$ )                              | 0.6                    | 1.2                   | 1.0    |
| Peak luminosity ( $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ ) | 0.2                    | 3.6                   | 10     |
| Integrated luminosity                                        | $48.9 \text{ pb}^{-1}$ | $5.6 \text{ fb}^{-1}$ | -      |

Table 2.1: The LHC operation performance in 2010 and 2011 compared to the design specifications. [66]

number of interactions per bunch crossing increased from  $\langle \mu \rangle = 3.5$  in 2010 to an average of  $\langle \mu \rangle = 11.6$  in 2011.

The integrated luminosity of proton-proton collisions at  $\sqrt{s} = 7$  TeV delivered by the LHC and recorded by ATLAS as a function of time in the years 2010 and 2011 is shown in figure 2.2. Major improvements are made by increasing the number of protons per beam and by improving the focus of the beams at the interaction points. During the technical stops in between data taking periods, seen in figure 2.2 as the periods where the integrated luminosity does not increase, the machine has been prepared to improve the instantaneous luminosity. This results in the integrated luminosity increasing faster after each technical stop. The luminosity in 2010 is given in  $\text{pb}^{-1}$  and in 2011 in  $\text{fb}^{-1}$ , as the total integrated luminosity in 2011 almost 120 times larger than in 2010. The difference between the delivered and the recorded luminosity indicates the amount of time ATLAS was in the process of switching on or fixing operational problems while the LHC delivered collisions to the experiments.

For the  $\phi(1020)$ -meson production cross section measurement presented in this thesis a data sample with an integrated luminosity of  $383 \mu\text{b}^{-1}$  recorded in April 2010 is used. This cross-section is expected to be of the order of mb, so that this small dataset provides enough statistics

for the statistic uncertainty to become smaller than the systematic uncertainty. Data Quality and detector performance of the ATLAS experiment in general, but of the silicon strip tracking detector (SCT) in particular, are assessed during the whole data-taking periods of 2010 and 2011, and will be presented in chapter 3.

## 2.2 The ATLAS experiment

The ATLAS (A Toroidal LHC ApparatuS) detector [67] is a particle detector built to explore a wide range of different physics processes produced at the LHC, from detailed measurements of the Standard Model predictions to searches for new physics processes, which may appear with signatures that involve high  $p_T$  jets,  $b$ -quarks and missing transverse energy.

In combination with the high interaction rate resulting in high multiplicity and radiation dose, the detector necessarily provides:

- Good reconstruction efficiency and accurate momentum measurements for leptons in the inner detector, also with large *pile-up*, i.e. multiple interactions per beam crossing;
- Precise determination of secondary vertices to identify decays of  $\tau$ -leptons and jets from  $b$ -quarks;
- Good electromagnetic calorimetry for electron and photon identification and measurements, and full-coverage hadronic calorimetry for accurate measurements of jet and missing transverse energy;
- High-precision muon momentum measurements;
- Large acceptance in  $\eta$  with almost full  $\phi$  coverage;
- Efficient triggering to reject background events while keeping as many interesting physics events as possible;
- Fast, radiation hard electronics that can operate for several years;
- High detector granularity to cope with the expected multiplicities.

Figure 2.3 shows a cut-away view of the ATLAS detector with length of 44 meters, a diameter of 25 meters, yet a total weight of only 7000 tons. The installation of the experiment at Point 1 of the LHC was started in 2003 and completed in 2008. The LHC beam direction defines the  $z$ -direction and the  $x - y$  plane is the plane transverse to the beam. The design performance of the sub-systems is summarized in table 2.2, quantifying parts of the list above.

The sub-detectors of ATLAS are arranged in cylindrical layers around the beam-pipe in the central *barrel* and mostly as wheels perpendicular to the beam-pipe in the forward regions, the *end-caps*. From the outside-in, ATLAS consists of the muon spectrometer, the calorimeters and the inner detector. An air-core toroid and a solenoidal magnet provide a magnetic field in the muon system and the inner detector, respectively.

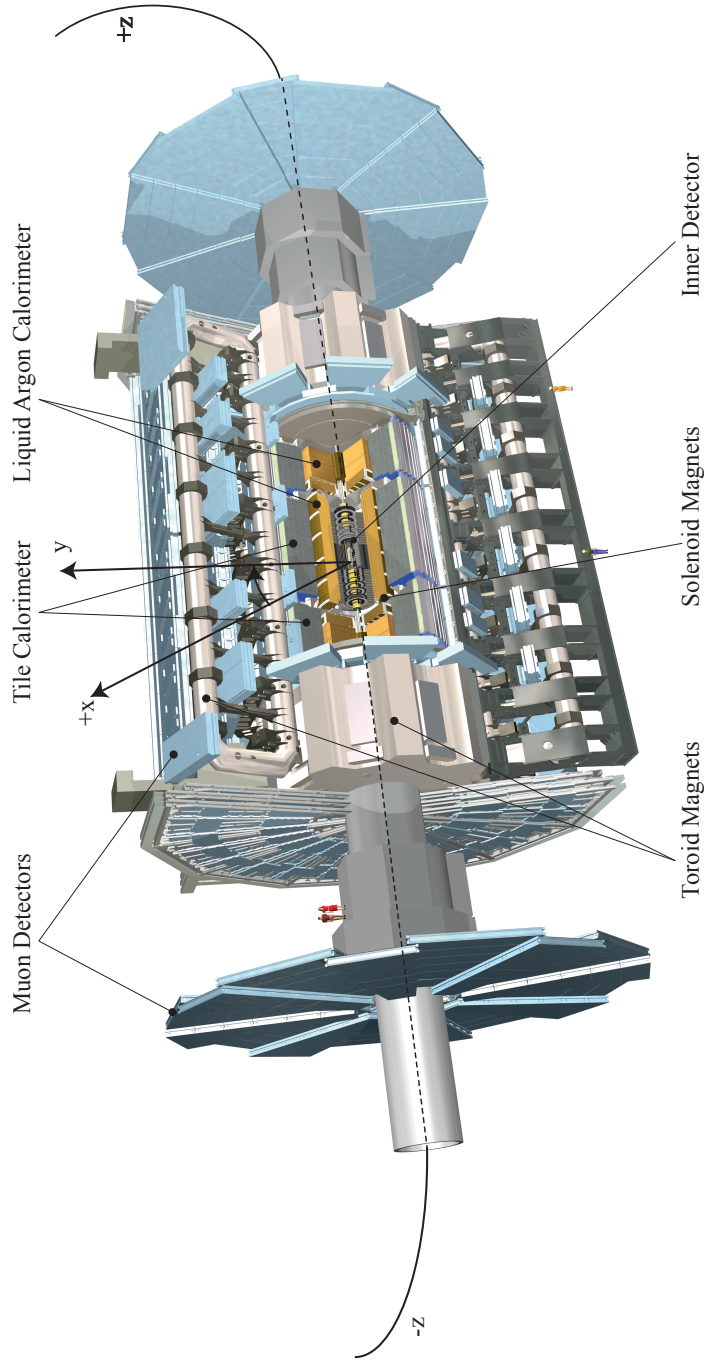


Figure 2.3: Cut-away view of the ATLAS detector, with from the inside-out pixel, SCT and TRT sub-detectors, the electromagnetic and hadronic calorimeters and the muon spectrometer. The inner detector is housed in the superconducting solenoid magnet and the toroid magnets surround the calorimeters. A right-handed coordinate system is used: The positive  $x$ -axis points towards the center of the LHC ring, the positive  $y$ -axis points upwards. Modified from [67].

| Sub-detector         | Required resolution                            | $\eta$ coverage      |                      |
|----------------------|------------------------------------------------|----------------------|----------------------|
|                      |                                                | measurement          | trigger              |
| Inner tracker        | $\sigma_{p_T}/p_T = 0.05\% p_T \oplus 1\%$     | $\pm 2.5$            | $\pm 2.5$            |
| EM calorimeter       | $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$      | $\pm 3.2$            | $\pm 2.5$            |
| Hadronic calorimeter |                                                |                      |                      |
| barrel and end-cap   | $\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$        | $\pm 3.2$            | $\pm 3.2$            |
| forward              | $\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$      | $3.1 <  \eta  < 4.9$ | $3.1 <  \eta  < 4.9$ |
| Muon spectrometer    | $\sigma_{p_T}/p_T = 10\% p_T$ at $p_T = 1$ TeV | $\pm 2.7$            | $\pm 2.4$            |

Table 2.2: Summary of the required resolution of energy or momentum measurements and the  $\eta$  range in which particles are measured. [67]

### 2.2.1 Muon Spectrometer

The muon spectrometer is the outermost sub-detector of ATLAS. Its three barrel layers are positioned at radii of 5, 7.5 and 10 meters from the beam-axis and the end-caps are placed at  $z$  equals  $\pm 7.4$ ,  $\pm 14$  and  $\pm 21.5$  meters and the coverage ranges up to  $|\eta| < 2.7$ . The muon momentum can be determined by measuring the curvature of the muon tracks in the toroidal magnetic field. The approximate field strength is 0.5 T in the barrel and 1 T in the end-caps, providing 2 to 7.5 Tm of bending power for  $|\eta| < 1.3$ .

The muon system is used to measure the muon trajectories as well as for triggering. The four different detector types used to do this are listed in table 2.3. The system provides an uniform  $p_T$  resolution within the  $|\eta|$  coverage and smaller detecting elements account for the higher particle multiplicities in the forward regions.

The  $p_T$  resolution for muons measured using cosmic ray muons is  $\sigma(p_T)/p_T = 8\%$  for muons with momenta up to 1 TeV [72]. The muon reconstruction efficiency has been extensively tested using the decays of the Z boson and the  $J/\psi$  particle in collision data and is close to 95%, which is in agreement with expectations from Monte Carlo simulation as shown for the decay of Z bosons in reference [73].

| Type                           | Goal                          | Coverage                                               | Readout channels |
|--------------------------------|-------------------------------|--------------------------------------------------------|------------------|
| Muon Drift Tubes (MDT)         | Tracking                      | $ \eta  < 2.7$                                         | 354k             |
| Cathode Strip Chambers (CSC)   | Tacking                       | $2.0 <  \eta  < 2.7$                                   | 30,7k            |
| Resistive Plate Chambers (RPC) | Triggering and 2nd coordinate | $ \eta  < 1.05$                                        | 373k             |
| Thin Gap Chambers (TGC)        | Triggering and 2nd coordinate | $1.05 <  \eta  < 2.7$<br>( $ \eta  < 2.4$ for trigger) | 318k             |

Table 2.3: Parameters of the four sub-systems of the muon spectrometer.



### 2.2.2 Calorimeters

The calorimeters measure the energy from particles by stopping them and are situated outside the solenoidal magnet that surrounds the inner detector. There are two calorimeter systems: an electromagnetic calorimeter and a hadronic calorimeter. Both are sampling calorimeters; they absorb energy in high-density metal and sample the size of the resulting particle shower, inferring the energy of the original particle from this measurement.

#### Electromagnetic calorimeter

The electromagnetic calorimeter measures the energy and direction of electromagnetic showers of incident electrons and photons. The energy-absorbing material is lead with liquid argon as the sampling or active material. The  $\Delta\eta \times \Delta\phi$  granularity is  $0.025 \times 0.025$  in the barrel which covers up to  $|\eta| < 1.5$ , while the end-caps provide coverage for  $1.375 < |\eta| < 3.2$ . The absorbing plates and active material are placed in a zig-zag like geometry, providing complete azimuthal coverage. The total amount of material in the electromagnetic calorimeter reaches 25 to 35 radiation lengths and two to four nuclear interaction lengths.

The electron energy resolution is determined using test beam data and the  $W \rightarrow e\nu$ ,  $Z \rightarrow ee$  and  $J/\psi \rightarrow ee$  decays in 2010 collision data. The energy resolution is  $\sigma(E)/E = 10\%/\sqrt{E} \oplus c$ , the constant factor  $c = 1\text{--}3\%$  depending on pseudorapidity. The electron energy scale is known up to a precision of 0.3–1.6% in the central regions and 2–3% in the forward region [74]. The uniformity of electromagnetic calorimetry response to photons has been examined using the  $\pi^0 \rightarrow \gamma\gamma$  decay in  $\sqrt{s} = 900$  GeV collision data and found to be better than  $\pm 2\%$  for these low momentum photons. [75].

#### Hadronic calorimeter

Strongly-interacting particles deposit a small fraction of their energy in the electromagnetic calorimeter. The hadronic calorimeters surrounding the electromagnetic calorimeter are used to measure the energy and direction of hadrons through their strong and electromagnetic interactions. The longitudinal development of hadronic showers scales with the nuclear interaction length and in general hadrons have a larger penetration depth. Hadronic showers are less uniform than electromagnetic showers, so the hadronic calorimeters allow for coarser granularity.

The hadronic calorimeter has three parts; the tile calorimeter, the Hadronic End-cap Calorimeter and the Forward Calorimeter. The tile calorimeter covers the pseudorapidity region  $|\eta| < 1.7$  and uses steel as an absorber and scintillating tiles as an active material. Its pseudorapidity coverage is extended up to  $|\eta| = 3.2$  by the Hadronic End-cap Calorimeter which uses copper as an absorber and liquid argon as the active material. The Forward Calorimeters have been installed to improve the measurement of missing transverse energy, they extend to  $|\eta| < 4.9$  and consist of two end-caps using liquid argon as an active medium and copper as the absorber in the first layer and tungsten in the other two layers to optimize for electromagnetic and hadronic interactions respectively. The material in the hadronic calorimeter amounts to 10 to 18 nuclear interaction lengths as a function of pseudorapidity.

The tile calorimeter energy response has been investigated using isolated charged hadrons, with isolated tracks having energy deposits compatible with minimum ionizing particles in the electromagnetic calorimeter. Their energy,  $E$ , measured in the tile calorimeter is compared with

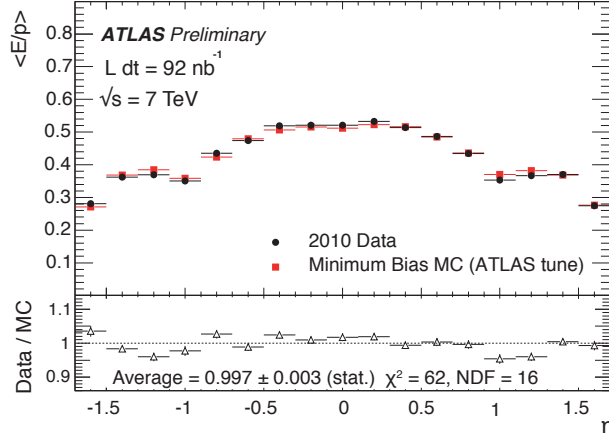


Figure 2.4: Mean value of the  $E/p$  as a function of  $\eta$  for 2010 collision data and Monte Carlo simulation. Bottom plot shows ratio of data to Monte Carlo of the mean value of the  $E/p$ . [76]

their momentum,  $p$ , measured in the inner detector, giving  $E/p$ . Figure 2.4 shows the mean values of  $E/p$  as a function of  $\eta$  for  $\sqrt{s} = 7$  TeV  $pp$  collision data and Monte Carlo simulation. The data is described by Monte Carlo within  $\pm 5\%$ . Using the decay of short-lived  $K_s$  and  $\Lambda$  particles, the calorimeter response to specific types of particles is measured and compared to the Monte Carlo predictions [76]. The energy resolution is within the design performance and depends on pseudorapidity and particle type. Finally, the jet energy scale uncertainty is determined by propagating the response uncertainty for single charged and neutral particles to jets. The scale uncertainty is 2–5% for central isolated hadrons and 1–3% for the final calorimeter jet energy scale, while the resolution for hadronic jets is found to be within design requirements [77].

### 2.2.3 Trigger system

The maximum bunch crossing rate of the LHC is 40 MHz, while the ATLAS trigger system [78] allows to record approximately 200–400 Hz. This rate would correspond to a data rate of  $\sim 300$  MB/s, a limit determined by the computing resources for offline storage and processing of the data. The trigger system selects events by identifying signatures of muon, electron, photon,  $\tau$ -lepton, jet, and  $B$ -meson candidates, as well as using total event signatures, such as the missing transverse energy. The trigger system has three levels; the first level (L1) is hardware-based, using unprocessed information from the calorimeters and muon spectrometer. The second (L2) and third (Event Filter, EF) levels are software-based, using information from all sub-detectors. Together, L2 and EF are called the High Level Trigger (HLT).

The relevant detector signals are stored in front-end electronics pending a decision from the

L1 trigger system. The L1 trigger is designed to reduce the rate to a maximum of 100 kHz and to identify *Regions of Interest* (RoIs) within the detector to be investigated by the HLT. The L2 triggers reduce the rate to  $\sim 3$  kHz with an average processing time of  $\sim 40$  ms/event. The EF decreases the rate to  $\sim 200$  Hz in  $\sim 4$  s/event. Data for events selected by the trigger system are written to data *streams* based on the trigger type. In 2010 and 2011 about 10% of all events accepted by the EFs are written to an *express* stream where prompt offline reconstruction provides calibration and Data Quality (DQ) information before the reconstruction of the physics streams.

### Minimum Bias Trigger

The minimum bias trigger is used to record events with as little as possible bias in the event selection. These events can be used to measure the efficiency of the more complex triggers. The first datasets of proton-proton collisions at  $\sqrt{s} = 7$  TeV recorded by the ATLAS experiment have been used to perform measurements such as the charged particle multiplicity [46]. In this section the minimum bias trigger used for the analysis presented in chapter 5 is discussed.

Minimum bias events are triggered with two wheels of in total 32 minimum bias trigger scintillators (MBTS) installed at a distance of  $z = \pm 3560$  mm from the interaction point, such that their disk surface is perpendicular to the beam direction. The disks span a radius of 153 to 890 mm, corresponding to the forward region at  $2.09 < |\eta| < 3.84$  [79]. Light emitted by each scintillator due to a traversing charged particle is collected by optical fibers and led via a photomultiplier tube to the electronic readout. The MBTS fires if the signal of one the scintillators exceeds a calibrated threshold.

The single particle response of the MBTS counters was probed using tracks that pass through both the inner detector and the MBTS wheels. The two systems overlap in the pseudorapidity range  $2.09 < |\eta| < 2.5$ . All inner tracker tracks with transverse momentum greater than 200 MeV are extrapolated to the MBTS and the deposited energy in a MBTS counter is examined if the extrapolated trajectory passes through the counter. To probe the single particle response, it is required that no other track is extrapolated to the same counter. The single particle efficiency is about 96% for  $2.09 < |\eta| < 2.25$  and  $> 98\%$  for  $2.25 < |\eta| < 2.5$ . The trigger efficiency of the minimum bias trigger for collision events is discussed in chapter 5.



## Chapter 3

# ATLAS Inner Detector

The inner detector [80] consists of three separate detectors: the pixel detector, a semiconductor tracker (SCT) and the Transition Radiation Tracker (TRT). The design of the detector is such that a particle originating from the interaction point crosses three pixel layers, eight SCT strip layers and around 36 TRT straws, giving on average 43 position measurements on a track. A layout of the inner detector is schematically shown for four tracks with different pseudorapidities in figure 3.1. The inner pixel layer is at 5.05 cm from the beam and the TRT extends to a radius 1.05 m from the beam line. In this chapter the inner detector is discussed from the inside out and the last section is devoted to the monitoring of the data quality of the SCT in 2010 and 2011.

The inner detector provides track and vertex reconstruction, with an efficiency for reconstructing an isolated track with  $p_T = 5$  GeV of  $\geq 95\%$  [67]. The achieved resolution is measured with cosmic rays and is  $(4.83 \pm 0.16) \cdot 10^{-4}$  GeV $^{-1}$  for the measurement of the ratio of the charge over the momentum and  $22.1 \pm 0.9$   $\mu\text{m}$  for the transverse impact parameter [81]. Its acceptance covers the full azimuthal angle in the region  $|\eta| \leq 2.5$  for precision measurements. The inner detector is housed in a superconducting solenoid magnet that generates a homogeneous magnetic field in the positive  $z$ -direction along the beam line with a field strength of about 2 T at  $z = 0$ . In this magnetic field, particles are deflected in the  $x - y$  plane, so the inner detector is built to have the highest precision in the transverse direction. The detector can measure charged particles with momenta  $p_T \gtrsim 100$  MeV.

### 3.1 Pixel detector

The pixel detector [82] is the sub-detector closest to the beam line. When running at high luminosity every  $\text{cm}^2$  of the pixel detector is hit by millions of particles per second. This close to the interaction point, the design is constrained by the occupancy and radiation damage. Reducing the size of the active elements brings occupancy to a manageable level and it tempers some effects of radiation damage of the sensors. The fine granularity allows the reconstruction of the individual tracks of charged particles with a high efficiency and it enables the identification of primary and secondary vertices.

The pixel detector consists of 1744 modules grouped in three cylindrical layers in the bar-

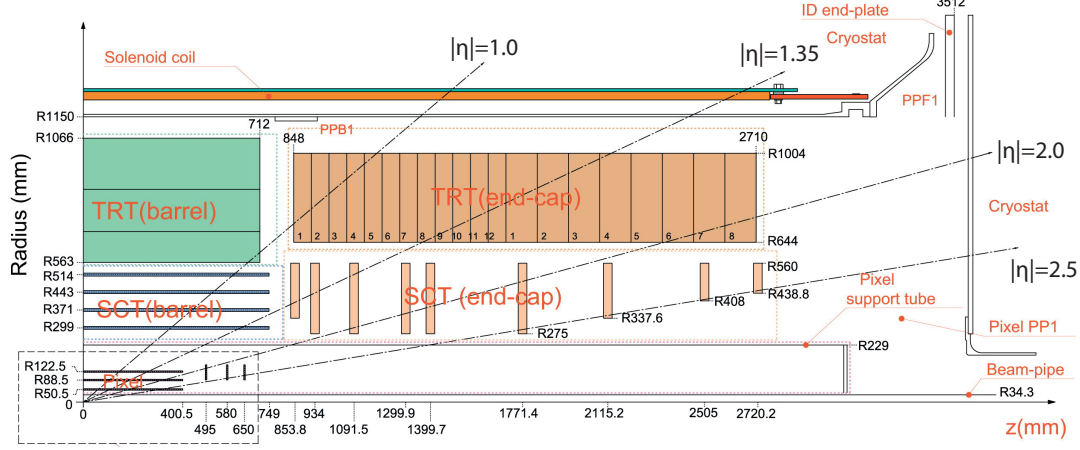


Figure 3.1: A drawing showing the sensors and structure of the inner detector, being traversed by four charged tracks with  $p_T = 10$  GeV with  $\eta = 1.0, 1.35, 2.0$  and  $2.5$ . [67]

rel and three disks in each forward region. It has 80M readout channels and a total active area of silicon of about  $1.7 \text{ m}^2$ . The sensors consist of  $256 \pm 3 \text{ } \mu\text{m}$  thick n-bulk silicon with  $\text{n}^+$  implants on the read-out side and each module is 62.4 mm long and 21.4 mm wide. The size of an individual pixel is  $50 \times 400 \text{ } \mu\text{m}^2$  in the local  $x$  and  $y$  direction. As the collected charge is assigned to the center of a pixel, the hit resolution of a single pixel is expected to be  $(\text{pixelsize})/\sqrt{12} = 14 \times 173 \text{ } \mu\text{m}^2$  and as illustrated in figure 3.2 a) the resolution is  $\sim 20 \text{ } \mu\text{m}$  if measured using 7 TeV collision data as the RMS of the residuals in the local  $x$ -direction [83].

There are 16 front-end chips in each pixel module that are read out by one module control chip. Each module is then connected to the off-detector Read-out Drivers (RODs) through optical-fiber links. One optical-fiber link is used to transmit clock, trigger, commands and configuration data from the RODs to the chips, while one or two links are used for event readout. The conversion of the electronic to optical signal needed for the communication between the modules and the RODs is done with laser diodes (VCSELs<sup>1</sup> [84, 85]). The same VCSEL design has been used for the diodes located close to the modules (on-detector) and in the data acquisition racks (off-detector). From May 2010, the VCSELs started failing, resulting in parts of the pixel detector not being readout until replacement of the diode. This was a common problem to the pixel and SCT detectors and will be discussed further in the next section.

In the pixel readout cells, the signal is amplified and compared to a discriminator threshold. When the signal is above threshold, the pixel address, a hit time stamp and the recorded time over thresholds are transferred to the module control chip. The time over threshold information is proportional to the collected charge and used for energy loss measurements as detailed in chapter 4. The time over threshold recording also allows for a better hit resolution compared to a binary readout, because the center of gravity of each cluster of hits can be used.

The hit efficiency, the noise occupancy and the resolution are important measures of detector

<sup>1</sup>VCSEL = Vertical Cavity Surface Emitting Laser

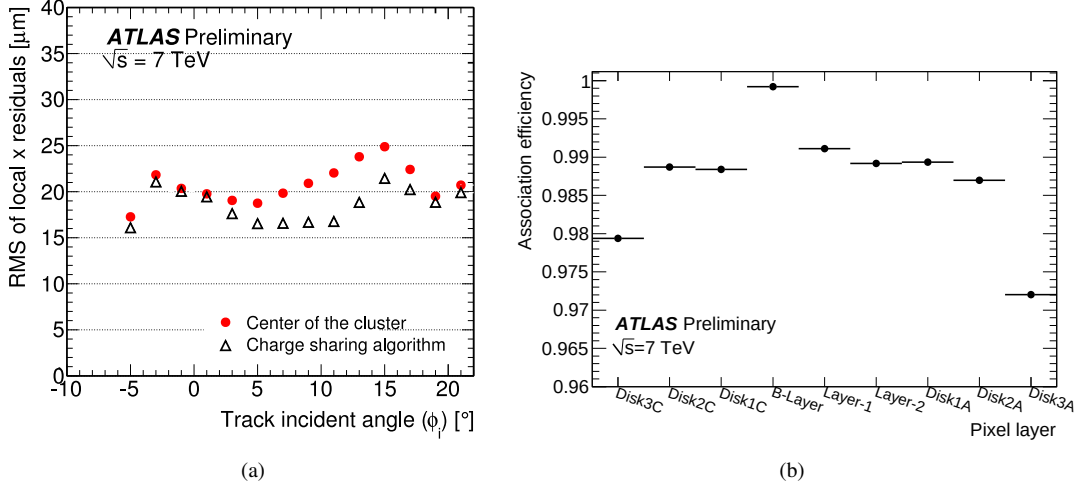


Figure 3.2: a) The RMS of residuals along the precise pixel direction for collision data, as a function of the track incident angle, corrected for the Lorentz angle. b) Hit to track association efficiency per pixel barrel layer or end-cap disk. Dead modules are excluded from the association efficiency computation, but otherwise dead regions contribute to the inefficiency. Both from [83].

performance. The hit efficiency is shown in figure 3.2 b) and is defined as the probability for a track to have a hit associated to it when crossing a pixel detector layer. When the efficiency is corrected for known dead modules, it is approximately 99% for all layers, except the outer disks, where the efficiency is slightly lower. The occupancy was measured in randomly triggered events with empty bunches in April and May 2010. The noise rate is dominated by few pixels (300-1500 out of 80M) which are detected for each data-taking period of a few hours by offline prompt calibration and masked during processing before data are made available for physics. The remaining noise occupancy is  $< 10^{-7}$  hit/pixel/(bunch crossing) as shown in figure 3.3 a).

The expected total fluence the pixel detector is designed to withstand is approximately  $1 \cdot 10^{15}$  neutron equivalent  $\text{cm}^{-2}$  [86]. Aside from the increase in leakage current, radiation damage will invert the sensor bulk and then the depletion voltage gradually increases. As shown in figure 3.3 b), the evolution of the leakage current is proportional to the total integrated luminosity and all measurements of the current are in good agreement with each other and with the model predictions [87]. The current decreases at a time scale of weeks due to *beneficial annealing* (see section 3.2.4) and this annealing is more effective when the detector is not actively cooled. This is seen as the drop of the current in Winter 2011-2012 in figure 3.3 b). Type-inversion of the n-bulk has occurred in the two innermost layers in the last quarter of 2012 [88]. Oxygen impurities have been introduced in the bulk to increase the tolerance of the silicon against bulk damage caused by charged hadrons [89]. To further mitigate the effects of radiation damage, the detector is kept at  $-7^\circ \text{C}$ .

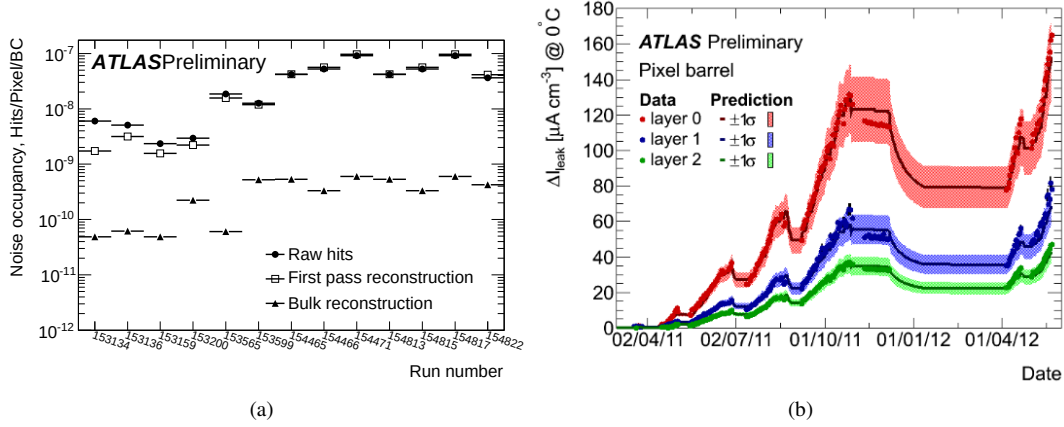


Figure 3.3: a) Pixel detector occupancy for different steps in event reconstruction. The *bulk processing* is the last re-processing step before data are made available for physics analysis, in which noisy readout channels have been excluded. b) The leakage currents of the three pixel barrel layers as a function of time in 2011 and 2012. Both from [83].

By the time of writing this thesis, the pixel detector has been operated for more than four years in the ATLAS cavern taking data from cosmic rays, from  $pp$  collisions and from the lead lead collisions. In the years 2010, 2011 and 2012 the detector was operated with a focus on stable detector operation. During data taking, approximately 95.0% of the 80M channels were operational [90]. During  $pp$  collisions in 2012, there were on average 88 (5%) disabled modules and an average failure rate of 12 modules per year has been observed. The failures were found to be highly correlated with the temporarily stops of the cooling of the detector and therefore the operations team tried to reduce thermal cycling to the minimum. Most common failures are in the optical communication boards (failures in the cold soldering, broken wire bonds and VCSELs), less common were module failures. In general, the pixel detector has been operated reliably in 2010, 2011 and 2012.

## 3.2 Semiconductor Tracker

The SCT is a silicon strip detector and it consists of four layers in the central barrel and has nine end-cap disks on each side. The SCT inner barrel layer is located at a radius of 30 cm from the beam line. Here the charged particle density is low enough to use silicon strips instead of pixels, which reduces the number of readout-channels. The design ensures that particles pass through at least eight silicon detectors (making four space points) in the acceptance region. The SCT is the most crucial part of the inner detector for track finding in the plane perpendicular to the beam. In this section the SCT lay-out and operational performance are explained in detail.



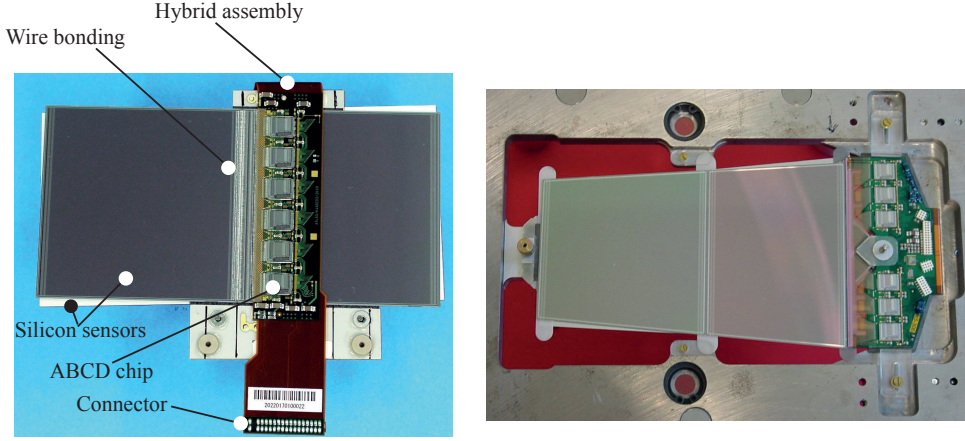


Figure 3.4: Photographs of an SCT barrel (left) and end-cap module.

### 3.2.1 SCT lay-out

The SCT comprises  $61 \text{ m}^2$  of silicon sensors with in total 6.3M readout channels. The modules are mounted in four cylindrical barrel layers at radii 30–51 cm and  $|\eta| < 1.1$ –1.4 and nine end-cap disks on each side that cover  $1.1 < |\eta| < 2.5$  and radii extending to 56 cm. The SCT silicon sensors [91] consist of a  $285 \text{ }\mu\text{m}$  thick n-type bulk material with 786 p-type strips each. The 8448 barrel sensors have sizes of  $64.0 \times 63.6 \text{ mm}^2$  and  $80 \text{ }\mu\text{m}$  strip pitch. The 6944 sensors used in the end-caps are wedge-shaped, with the strip pitch ranging from  $54 \text{ }\mu\text{m}$  up to  $90 \text{ }\mu\text{m}$ . An SCT barrel module consists of two pairs of sensors, wire-bonded together in the middle and glued back-to-back under a small stereo angle of 40 mrad to provide a measurement along the strip length, now in total 12 cm. See figure 3.4 for a photo of the barrel and end-cap modules.

Figure 3.5 shows a schematic cross section of a p-in-n sensor. The  $\text{p}^+$ -type is implanted in strips on an n-type substrate. To achieve the reverse bias, the backplane is put at a positive voltage with respect to the strips. The strips are surrounded by a guard ring structure at the edges that is connected to the same potential as the backplane. This avoids a potential difference along the edges of the sensor, which could lead to high leakage currents. An  $\text{n}^+$ -type layer is implanted on the backside, because the metal-semiconductor contact forms a Schottky barrier, a charge barrier similar to a pn-junction. Adding a highly-doped region of silicon to make the contact, reduces the width of the potential barrier, making the characteristic resistance of the formed junction very small.

A charged particle passing a silicon sensor will transfer energy, eventually creating electron-hole pairs in the material. The electrons can move in the conduction band, while the corresponding vacant spots in the valence band can be occupied by other electrons, causing the holes to also “move”. Under the influence of the reverse bias, the electrons are drawn to the n-side and the holes to the  $\text{p}^+$ -side, but they have differently velocity. The time required for a charge carrier to cross the detector volume is called the collection time and is up to ten ns for a sensor of

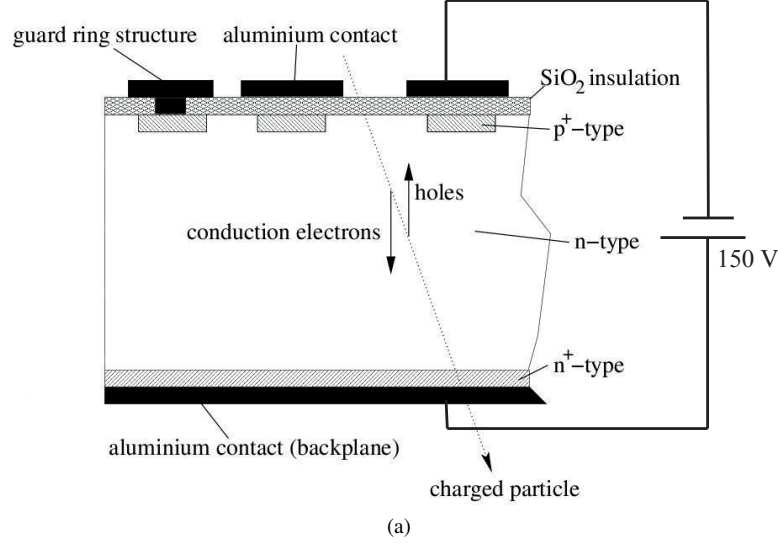


Figure 3.5: A (schematic) cross-section of a practical implementation of a silicon strip-sensor. The picture is not to scale; the vertical dimensions of the structures in the silicon are  $1\ \mu\text{m}$ .

| Selection criterion | Hit pattern | Usage                                              |
|---------------------|-------------|----------------------------------------------------|
| hit                 | 1XX,X1X,XX1 | Detector alignment                                 |
| level               | X1X         | Normal data taking with LHC bunch spacing of 50 ns |
| edge                | 01X         | Normal data taking with LHC bunch spacing of 25 ns |
| test                | XXX         | Test mode                                          |

Table 3.1: The four selection for the three time bins readout. At each trigger three bins are readout. “1” indicates a hit, “0” indicates no hit and “X” indicates no requirement.

$\sim 300\ \mu\text{m}$  thick, if fully depleted. To speed up the charge collection to about 8 ns for electrons and three times that for holes, the SCT is operated with a reverse bias of 150 V, while it is already fully depleted at  $\sim 70\ \text{V}$ .

Each side of a module is readout by six ABCD chips [92]. The chips have a binary readout with a programmable threshold, nominally set to 1.0 fC. A minimum ionizing particle causes a charge deposit of about 3 fC in  $285\ \mu\text{m}$  silicon. The output of the comparison of the signal to the threshold is stored on the chip every 25 ns, awaiting the ATLAS trigger. If a trigger signal is received, the contents of the storage of three clock cycles are collected. This is referred to as *three time bins* readout. The timing of the readout is optimized at a module-by-module basis, such that a hit from a collision track results in a 01X occupancy pattern in the sampled time bins (no hit in first bin, hit in second bin, no requirement for the third bin). The readout can be tuned for optimal efficiency during different types of data-taking, the different selection modes are listed in table 3.1.

Communication between modules and the off-detector electronics occurs via optical links

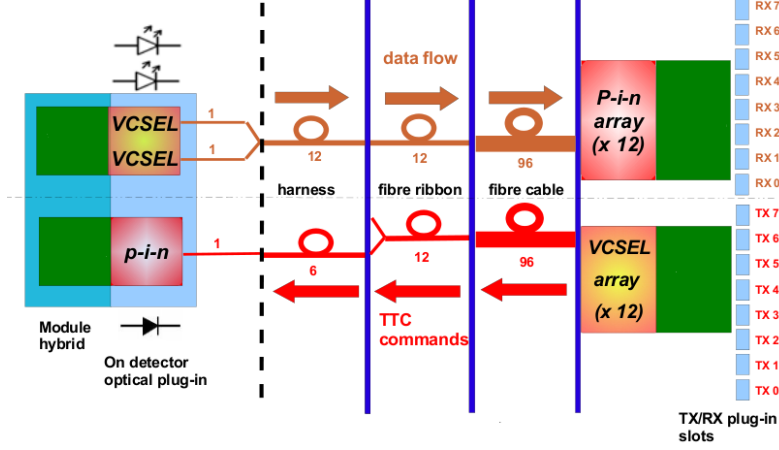


Figure 3.6: An overview of the SCT optical link architecture. Modified, from [94].

[93]. An overview of the SCT optical link architecture is given in figure 3.6. The usage of optical fibers minimizes the material and the signals in the fibers do not suffer from nor give electro-magnetic interference. For each module two data receiving (RX) links and one Timing, Trigger and Control (TX) link are in place. VCSEL arrays are used as light sources, and silicon *p-i-n* diodes for the detection of light signals.

Redundancy options for the optical links are available in case a fiber breaks, a VCSEL is lost or *p-i-n* diode problems. If a module loses its Timing, Trigger and Control (TTC) signal for some reason, the neighboring module can share its signal, without impact on data taking. For the data receiving links, one side of the module can be configured to use the link of the other side. Using the redundancy option to receive data results in reduced readout bandwidth, but no data have to be lost. The use of this redundancy has been relatively stable at about 2.5% of the links. Most of these links broke even before the installation of the SCT. The use of redundancy of the TTC links to send commands to the modules has varied due to losses of the VCSELs in the readout creates, as discussed in more detail in section 3.2.2.

The SCT is operated in a near zero humidity nitrogen environment and is cooled by a bi-phase evaporate cooling system [95], which runs with  $C_3F_8$  fluid at  $-25^\circ\text{C}$ . The target temperature for the SCT silicon sensors after irradiation was  $-7^\circ\text{C}$  to suppress the effects of radiation damage as discussed in more detail in section 3.2.4.

### 3.2.2 Operations

More than 99% of the SCT strips were functional and available for data-taking at all times during 2010 and 2011 [96]. The SCT delivered tracking data for 99.9% and 99.6% of the delivered *pp* luminosity in these years. The evaporative cooling for the SCT kept the modules of the inner three barrel layers at a temperature of approximately  $2^\circ\text{C}$ , while the modules of the outermost barrel layer and the end-caps were maintained at about  $7^\circ\text{C}$ . The mean temperatures

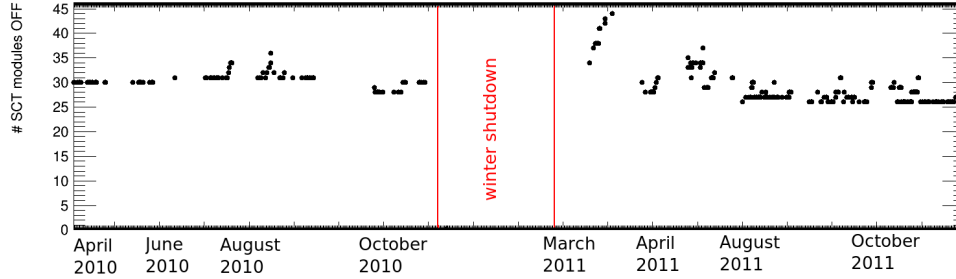


Figure 3.7: The number of SCT modules switched OFF as function of time.

of each layer or disk were stable within about one degree during running.

Although individual strips can be masked, the largest contribution to missing strips for data-taking is due to (temporarily) disabled modules. The fraction of disabled modules as a function of time is shown as a function of time in figure 3.7. About 15 modules are permanently out of configuration due to low-voltage, high-voltage and readout problems, and 13 modules are disabled for data taking due to one cooling loop that is closed as a result of an inaccessible leak in that loop. Although the sensors could be operated at a higher temperature, the ABCD chips would become too hot if not cooled. This might not only damage the chips, but may also effect the glue holding the module together.

Shortly after the start of data-taking, the VCSELs of the TX transmitters started failing, at a typical rate of three or four deaths per day, explaining the rises in the fraction of disabled modules in figure 3.7, for example in the end of July 2010. These VCSELs are located in one of the counting rooms ( $\sim 100$  m from the detector) and can be exchanged during access. Operationally, the impact of TX deaths was minimized by using redundancy until no longer possible. During short shutdowns between data taking periods, dead VCSELs were replaced and the fraction of disabled modules drops. After thorough investigation, the cause of the VCSEL failure was traced back to exposure to humidity in the off-detector areas where the TXs are installed. The on-detector VCSELs can not be re-placed, but as the detector is operated in a very dry environment, this did not cause extra VCSEL losses.

Before merging the SCT data with the data from other detectors to do physics data analysis the quality of the SCT data is carefully checked. For example errors in the DAQ system may compromise the integrity of a data set. DAQ unavailability happened on very rare occasions, mostly due to two reasons. Firstly, chips may become disfunctional after a Single Event Upset (SEU). During such an SEU one of the thresholds of a chip may be changed, resulting in non-reliable data. The occurrence of SEUs became apparent in 2011 (see section 3.4) and it was resolved by implementing an automatic re-configuration of all chips every half hour during collision runs. Secondly, a Readout Driver Board (ROD), which reads out and controls up to 48 modules, may exert a BUSY signal, obstructing the total ATLAS data flow until resolved. The RODs went BUSY more often than expected in the first half of 2011 due to the TX problems, because a death results in time-out errors until the transmitter is configured to use redundancy or is replaced. At the higher trigger rates, a ROD will go busy if more than eight links throw

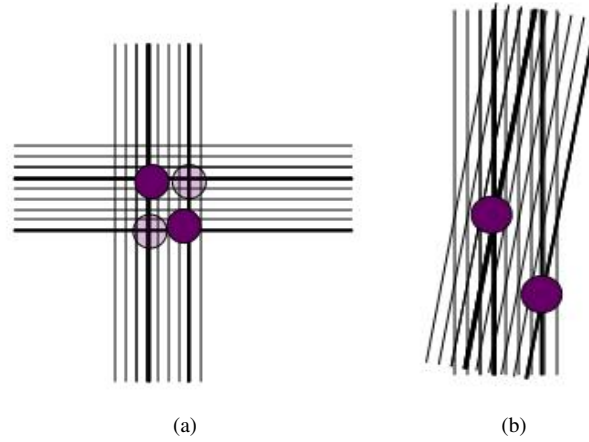


Figure 3.8: If the strips of the two sides of an SCT module would be under a  $90^\circ$  angle, two traversing charged particles would create four possible hits a), when the strips are under a smaller angle ( $10^\circ$  for illustration in b), the two particles leave two hits.

time-out errors. This may happen if during running a VCSEL that already supplies redundant TX signal for a neighbor fails, increasing the number of timed-out links with four after one TX death. The short-term solution was to make sure a BUSY ROD was recovered without having to stop ATLAS running within a few minutes, and in the longer term the RODs were reprogrammed to handle time-out errors differently.

### 3.2.3 Tracking performance

The SCT was designed to operate with a noise occupancy of less than  $5 \cdot 10^{-4}$  at a hit efficiency of 99% [80]. Several parameters, like the noise occupancy, hit efficiency and cluster widths, are monitored online and offline to ensure the detector is in the expected condition and is efficiently operated.

The position resolution is determined in the first place by the strip “pitch”  $p$  and is expected to be  $16 \mu\text{m}$  in the  $R - \phi$  plane. The SCT strip length is 12 cm, limited by the electronic noise and the expected hit rate per strip. To acquire a position measurement along the strip length, two sets of strips with a mutual angle are used. The mutual stereo angle between the sensors of the SCT is 40 mrad, resulting in an expected hit resolution of 5.8 mm in the direction of the strips. The most accurate two dimensional position resolution is obtained when the strips are mutually perpendicular, but this leads to a higher rate of ghost hits, as illustrated in figure 3.8, which would impede the pattern recognition.

The SCT alignment can be measured using the hit residuals, that are defined as the measured hit position minus the expected position from the track extrapolation in the local  $x$ - and  $y$ -direction [97]. Figure 3.9 shows the unbiased residual distribution in local  $x$ , the direction

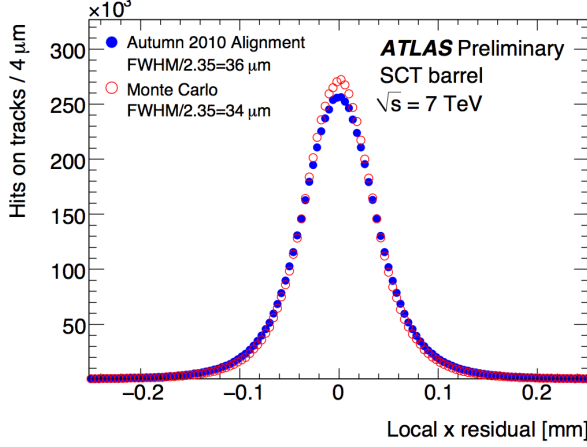


Figure 3.9: SCT hit residual distribution for the barrel layers in the local  $x$  direction, which is across the micro-strip direction, integrated over all hits-on-tracks in the SCT barrel for perfect alignment (red, open circles) and the autumn 2010 alignment with  $\sqrt{s} = 7$  TeV collision data taken in 2010 (blue, closed circles). [97]

perpendicular to the strips, for all hits-on-tracks in the SCT barrel layers for simulated data with design geometry and after the autumn 2010 alignment with collision data (run 153565) taken in April 2010. Tracks are selected to have  $p_T > 2$  GeV and  $> 5$  silicon hits. The residual is defined as  $\sigma = \text{FWHM}/2.35 = 36 \mu\text{m}$ , which approaches the simulated value of  $34 \mu\text{m}$ , that is achieved with perfect alignment [98]. The mechanical stability of the SCT is continuously monitored to ensure stable residuals [99].

The noise occupancy can be measured by counting the fraction of triggers which result in a hit when there is no particle activity in the detector. Figure 3.10 a) shows the noise occupancy, which is significantly below  $5 \cdot 10^{-4}$  [81].

The SCT hit efficiency is shown in figure 3.10 b) and is measured as the probability to record a hit at the passage of a charged particle. Particles are required to have  $p_T > 1$  GeV and at least seven SCT hits, excluding the hit under test. The track is again reconstructed without the hit in the detector under test, unless the hit under test is at the extremes of the track. If the track is still reconstructed without this hit, it is checked if there indeed was a hit in the SCT layer that the track traversed. The efficiencies in the innermost and outermost layer ('0 inner' and '3 outer' for the barrel) are undefined by definition for the SCT stand-alone tracks as they are on the extremes of the track. The measured efficiencies are well above the required design efficiency of 99% [98].

The drift of charge carriers through the silicon bulk material under the influence of an electric field  $\mathbf{E}$  may be deflected in the presence of a magnetic field  $\mathbf{B}$ . In the SCT barrel modules,  $\mathbf{E}$  and  $\mathbf{B}$  are mutually perpendicular. The charge carriers drift along the Lorentz angle  $\theta_L$  with respect to the normal of the sensor plane. If  $\mathbf{E}$  and  $\mathbf{B}$  are mutually perpendicular, the Lorentz angle is given by:

$$\tan \theta_L = \mu_H B = \gamma_H \mu_d B, \quad (3.1)$$

where  $\mu_H$  is the Hall mobility, the product of the charge carrier mobility  $\mu_d$  and the Hall factor  $\gamma_H$ , which is of the order of unity. The charge carrier mobility depends on the bias voltage and the sensor temperature [100]. For fully-depleted modules, the average expected shift of the collected charge is approximately  $10 \mu\text{m}$ .

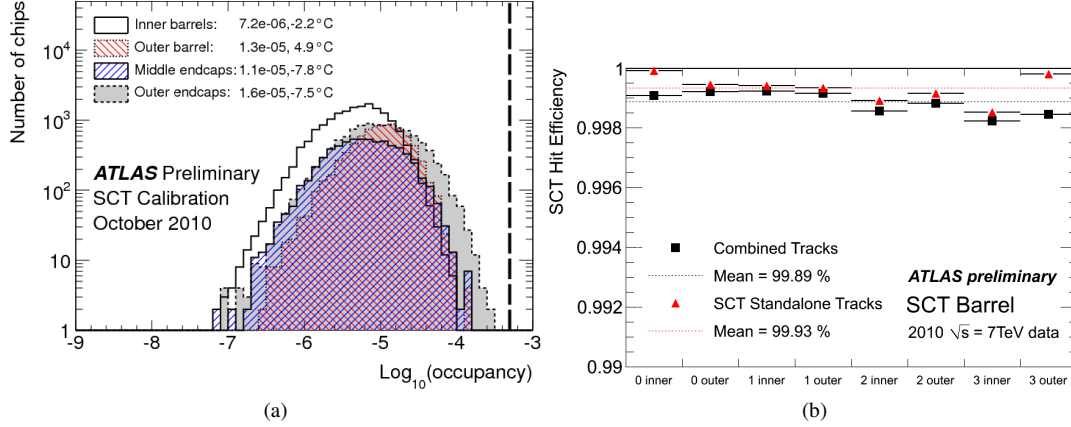


Figure 3.10: a) The SCT noise occupancy for each chip averaged for the different parts of the detector is measured at 150V and is found to be below the TDR specification of  $5 \cdot 10^{-4}$  (dashed line). b) The intrinsic module efficiency for tracks measured in the SCT barrel. This hit efficiency is the number of hits per crossing of a charged particle, where dead modules and chips are excluded from the measurement. [98]

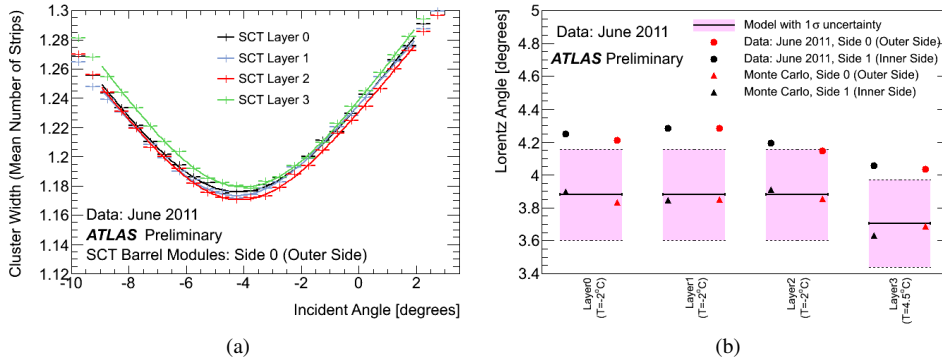


Figure 3.11: a) Cluster width size in strips as a function of track incident angle for the SCT barrel layers. b) Measured Lorentz angle for each barrel layer from a 2011 collision run with Monte Carlo predictions overlaid. [98]

The Lorentz angle is measured from the dependence of the cluster size on the incident angle of the charged particle. When the incident angle equals the Lorentz angle, all charge carriers drift along the particle direction and are collected on the same point (apart from diffusion) on the sensor surface, giving a minimum cluster size. The value of the Lorentz angle depends on the magnetic and electric fields within the silicon, the temperature and the amount of accumulated radiation damage, so analysis of the Lorentz angle and its development with time is used to understand the detector. Figure 3.11 a) shows the cluster widths for the barrel sensors facing the beam line, indicating the Lorentz angle, panel b) shows the measured Lorentz angles for each barrel layer compared with model predictions. As seen in figure 3.11 b) the Lorentz angle in barrel layer 3 is lower than in the other layers, because this layer is operated at a higher temperature [98]. The TRT that is closest to this outermost layer can not be operated at 2°C and the heater pads that were installed to ensure running with the SCT colder than the TRT are not functioning.

### 3.2.4 Radiation damage

The SCT was designed to withstand a particle fluence of  $2 \times 10^{14}$  1 MeV neutron equivalent  $\text{cm}^{-2}$  and a  $1 \times 10^5$  Gy ionizing dose. This corresponds to the fluence after an integrated luminosity of 700  $\text{fb}^{-1}$ . Until December 2012 an integrated luminosity of  $\sim 29 \text{ fb}^{-1}$  has been delivered to the ATLAS experiment and as a result of radiation damage an increase of the leakage current has been observed. Radiation damage to silicon detectors occurs in two ways; bulk damage and surface damage. In this section the possible radiation effects and the impact of radiation damage on the SCT performance are discussed.

Bulk damage is caused by the non-ionizing energy loss interactions of an incident particle with sufficient energy ( $\sim 25$  MeV) with the silicon atoms that can displace the silicon atom from its position in the lattice. The atom is then called a primary knock-on atom (PKA). The recoil energy of the PKAs can be up to 130 keV and therefore they can remove other atoms from the crystal lattice, giving rise to a PKA cascade. Most of the displacements repair and only 2% of all generated defects form electrically active states. Such disordered regions are referred to as defect clusters. Defect clusters have high local defect density and can be tens of nanometers wide. At temperatures above 150 K these primary defects diffuse within the silicon bulk. These defects can generate higher leakage currents and change the effective doping concentration which leads to a modification of the depletion voltage.

The increase of depletion voltage is due to an increase in the effective doping concentration  $N_{eff}$ , the difference between the number of ionized donor and acceptors in the depletion region of the sensors. The depletion voltage is given by:

$$V_{dep} \approx \frac{q_0}{2\epsilon_0\epsilon_r} |N_{eff}| d^2, \quad (3.2)$$

where  $q_0$  is the electron charge,  $d$  the detector thickness and  $\epsilon_0\epsilon_r$  the permittivity of silicon. Unirradiated, the SCT bulk material is n-doped. Defects in the silicon become charged by capturing charge carriers and the silicon bulk changes from being effectively n-doped to p-doped, which is referred to as type inversion and this has already occurred in the two innermost pixel barrel layers. After three years of running, the depletion voltage in the SCT is still well below the initial operational setting of 150 V.



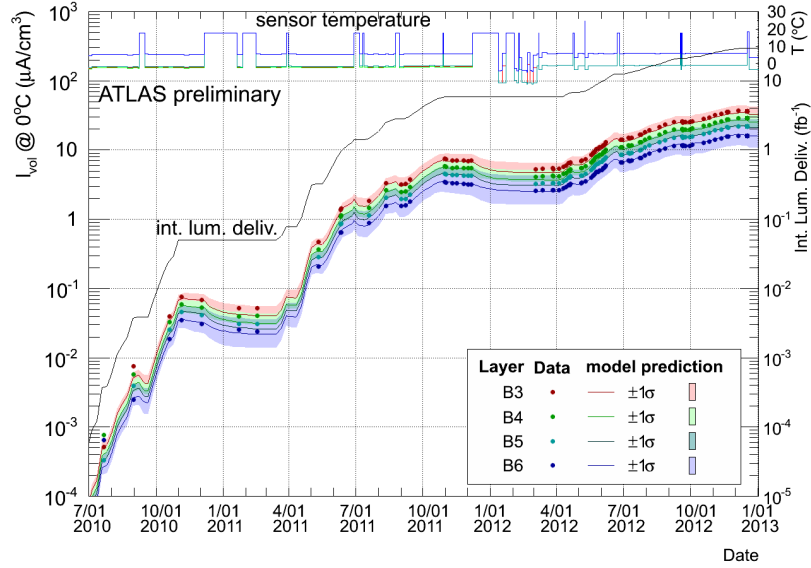


Figure 3.12: The average leakage current for the barrel modules of the SCT as a function of time. [98]

The increase in leakage current is a measure for the amount of damage due to non-ionizing radiation to the bulk material. It correlates strongly with the luminosity delivered by the LHC and the temperature of the sensors. The leakage current is monitored over time and compared to simulation with the FLUKA transport code [101, 102]. As illustrated in figure 3.12, the leakage current has increased from  $\sim 4 \cdot 10^{-3} \mu\text{A}$  in July 2010 to  $\sim 4 \mu\text{A}$  in August 2011, which is in excellent agreement with expectations from simulation [98]. The limit for a module to trip was set to  $5 \mu\text{A}$  in 2010 and increased to  $50 \mu\text{A}$  to be well above the initial and evolved leakage current.

Dislocated atoms thermally move back into the lattice, which is referred to as *beneficial annealing*. This results in a decrease in leakage current. Beneficial annealing happens at relatively short time scales of weeks and does not occur if the detector is cold. In figure 3.12, the reductions of the leakage current due to beneficial annealing during the winter stops when the cooling plant of the inner detector was shut down is clearly visible.

Reverse annealing on the other hand increases the leakage current at a longer time scale ( $\approx 500$  days), such that simultaneously an initial improvement due to the beneficial annealing is observed, while the leakage current increases again after more than a few weeks. It is possibly due to the diffusion of dislocations. To mitigate the effect of reversed annealing, the SCT was designed to be kept at  $-7^\circ\text{C}$  after irradiation and eventually operated at  $2^\circ\text{C}$ .

The charge collection efficiency and the amount of collected charge are also lowered, since the electrons and holes, created by the traversing particle, may become temporarily trapped by a defect. Both electrons and holes can be trapped for a short period of time, resulting in a

reduced number of carriers  $N_{e,h}$  measured. There is an exponential decrease in the number of  $e, h$ , described by:

$$N_{e,h}(t_c) = N_{e,h}(0)e^{-\frac{t_c}{\tau_{eff}}}, \quad (3.3)$$

where  $N_{e,h}(0)$  is the initial number of charge carriers,  $t_c$  the charge collection time and  $\frac{1}{\tau_{eff}}$  the effective trapping probability. This effect is small after three years of running.

Surface damage is determined mostly by the design of the detector and is caused by trapped charges in the oxide layers. The incident particle traversing the surface can create  $eh$ -pairs in the  $\text{SiO}_2$  layer. The pairs do not recombine and represent an additional contribution to the total oxide charge to which electrons are attracted that form an accumulating layer. This leads to an increase of the capacitive coupling between pixels or strips. Direct consequences are the larger charge sharing between strips and an increased noise due to the rise of the capacitive load seen by the electronic readout.

### 3.3 Transition Radiation Tracker

The TRT, the outermost component of the inner detector, is a transition radiation tracking detector. Drift tubes (straws), each four millimeters in diameter and up to 144 cm long in the barrel and 37 cm in the end-caps, are used to detect charged particles. All straws are filled with a gas mixture<sup>2</sup> and contain a 30  $\mu\text{m}$  thick anode wire. When a charged particle passes through, some of the gaseous atoms become ionized and the free electrons in the gas are multiplied after they drift closer to the wire. The positive ions drift to the tube wall and the resulting current is measured. The TRT barrel is divided into three layers of 32 sectors each and has a maximal number of 73 straws layers covering  $|\eta| < 1$ . In each end-cap the straws are oriented perpendicular to the beam axis and extend up to  $|\eta| < 2$ .

The TRT measures at least 30 hits per track to improve the pattern recognition and to enhance the separation between electrons and charged pions. To achieve the best hit resolution the distance from the straw at which the charged particle traversed is determined from the drift time of the electrons. Figure 3.13 a) shows the track-to-wire distance as a function of the measured drift time fitted with a third order polynomial. The intrinsic accuracy per hit expected from the drift-time measurement is 108  $\mu\text{m}$  in the barrel and 135  $\mu\text{m}$  in the end-caps. To measure the hit resolution, the width of the distribution of the distance from the predicted track position to the measured hit position in the module is used. The TRT position resolution is 142  $\mu\text{m}$  in the barrel, see figure 3.13 b), and 161  $\mu\text{m}$  in the end-caps. The intrinsic hit resolution and the track parameter errors contribute to the width of this hit residuals distribution, which is therefore larger than the intrinsic hit accuracy only.

Electron/pion separation is achieved with layers of materials with different dielectric constants between the straws. When a high energetic particle crosses the boundaries between the layers transition radiation photons with energies between 5 keV and 10 keV are produced. The amount of transition radiation depends on the Lorentz factor  $\gamma = E/m$  of the incoming particle. Pions are more than 250 times heavier than electrons, so over the entire energy range, electrons produce much more transition radiation photons since they are ultra-relativistic. These photons

<sup>2</sup>The TRT is filled with a gas mixture of 70% Xe, 27%  $\text{CO}_2$  and 3%  $\text{O}_2$

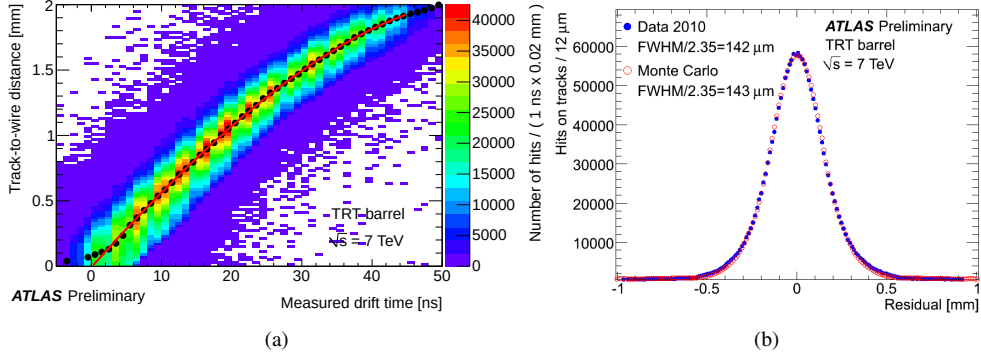


Figure 3.13: a) The distance as a function of drift-time for the TRT barrel. The points show the peak position of the fit to the track-to-wire distance distribution in slices of measured drift time. The line shows the third order polynomial that is used to determine drift distance based on the measured drift time [103]. b) Comparison of TRT hit residuals for the barrel modules [97].

are absorbed by the xenon gas mixture and thus produce extra electrons in the gas. To detect this extra signal, the TRT is readout with a high and low threshold. The high threshold probability as a function of the  $\gamma$  factor is shown in figure 3.14 a). The pion misidentification probability is of the order of 10% for high threshold hits that give 90% electron efficiency, see figure 3.14 b).

The TRT hit efficiency calculated as the ratio of the number of hits associated to track and the number of straws crossed by the charged particle is about 95% [104]. The efficiencies measured in data agree very well with simulation. The hit efficiency in the TRT is lower than in the silicon detectors, but with  $\sim 36$  TRT hits on track, compared to three and eight hits in the pixel and SCT detectors, this is not a problem. The TRT has been reliably operated since 2008. During the years 2010 and 2011 97.3% of the 350k read out channels were operational [90] and data quality is constant.

### 3.4 Data Quality Monitoring

Each of the sub-detectors of ATLAS have dedicated services like power, cooling and gas supply. A Detector Safety System (DSS) has been built to detect possible operational problems and abnormal and potentially dangerous situations at an early stage and, if needed, to bring the relevant part of ATLAS automatically into a safe state [106]. To ensure the data taken are of good enough quality for physics analysis and to provide fast feedback to the operating teams, a fraction of the events that passed the Event Filter are written to the *express stream*. Events from the express stream are processed at the CERN computing center and histograms are produced for Data Quality Monitoring (DQM). The DQM histogram production is done by dedicated modules in the ATLAS software framework ATHENA [107]. The DQM differs from the DSS as notifications by the DQM do not always require immediate follow-up. If the detector becomes too warm, measures will need to be taken before something breaks down, but data that do not

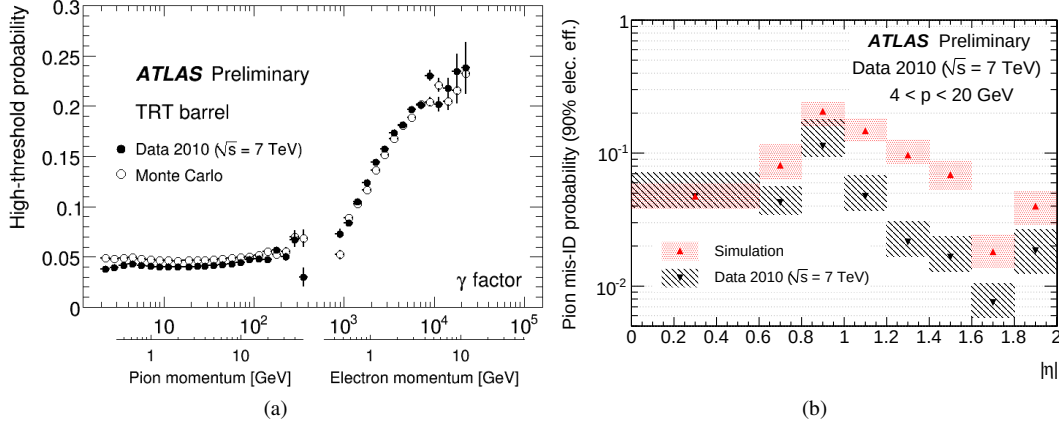


Figure 3.14: a) The probability of a TRT high-threshold (HT) hit as a function of the Lorentz factor,  $\gamma = E/m$ , for the TRT barrel obtained from 2010 collision data compared to expectation [104]. b) Pion misidentification probability for HT fraction cuts that give 90% electron efficiency in bins of pseudorapidity. [105]

fulfill all the data quality requirements may still be useful for all physics analysis.

The DQM is for example used to detect possible small detector movements, resulting in detector misalignment. Misalignment of the detector results in a bias of the hit residuals and thus an increase of the average  $\chi^2$  of reconstructed tracks. To detect detector movements early on, the  $\chi^2$  of all tracks is monitored. To enable DQM, automated checks are run and the outcome of these checks is considered online by a shifter on duty in the control room and made available offline on the web after a full run is processed. The online DQM is mainly focused on efficient running and focuses on noise, hit efficiency and detector status. The offline DQM checks are performed before the data are re-processed for physics and provide the opportunity to mask dead detector parts or exclude parts of the data run if for example the detector was not fully functional.

The data quality depends both on the status of the sub-systems and on the performance of the tracking and trigger. The data are flagged as “good” if they pass all checks and may be flagged differently otherwise. The flagging procedure changed in 2011, when specific “defects” were introduced that can be assigned to (parts of) a data run. The defect “more than forty noisy modules” sometimes used by the SCT operations team was considered “tolerable”, while a number of 120 noisy modules is considered “intolerable”.

Each sub-system may have different requirements for variables to be checked and specific monitoring may even use a specific trigger. For example empty events are triggered for noise monitoring. The operating team need feedback on the state of the detector before the actual physics data taking has started, which is achieved by monitoring the noise and for example the number of dead modules directly from randomly picked (empty) L2 accepted events at all times during ATLAS running. Tracks from events passing the High Level Trigger are reconstructed

and used for the data quality assessment. The monitoring is run in separate tasks, or jobs, and specific trigger selection can only be applied per job. The final variables shown in the control room to the shifter are selected from these different jobs.

Online, the shifter will receive a visual warning if one of the DQM checks is not passed and he or she will need to decide if action is needed. The data are available to the shifter in the control room via two presentation tools:

- The Data Quality Monitoring Display (DQMD) [108], that graphically presents the different detector regions. The regions are colored and the color indicated if the histograms in that region passed the DQ checks implemented.
- The Online Histogram Presenter (OHP) [109], a simple GUI that directly shows the histograms, meant to serve as backup for the DQMD, but in practice used as the main tool by most shifters because of its easy usage.

If the online DQM software reports that the data taken are useless, the problem can hopefully be resolved before the LHC stops a run. Reoccurring problems are “taken offline” and preventive measures can be taken. In 2010 and 2011 85% of all delivered luminosity by the LHC was good for physics analyses [110].

The following two examples of operational problems with the SCT were first noticed with the online DQM. Firstly, in June 2011 the shifter reported the occurrence of SCT modules that were extremely noisy; having three orders of magnitude more hits than the surrounding modules. These so-called “hot modules” started appearing every run, so further investigation was needed. A correlation between the appearance of clusters (groups of adjacent strips hit) with a width of 128 strips and the hot modules was spotted shortly after. As one chip reads out 128 strips, it was suggested that the hot modules are caused by a single event upset (SEU) [111], where the threshold of a chip is changed due to passage of a charged particle. Whether or not the hot modules were really caused by SEUs, a re-configuration of the SCT was installed to happen every half hour and the hot modules were not seen anymore after. A verification of the SEU hypothesis is provided by studying the correlation between SEU rate and module fluence. The average number of SEUs / module / number L1 triggers depends linearly on the cluster occupancy /  $\text{mm}^2$ , which supports the SEU hypothesis [112].

Secondly, when time between bunches in the LHC was for the first time lowered from 100 ns to 50 ns in April 2011, the SCT hit efficiency appeared to have dropped from  $> 99\%$  to  $\sim 98\%$ . This was a feature of the combination of the three time bin readout and the hits accepted by the tracking. As mentioned above, the SCT is readout three times 25 ns at trigger. When the bunch spacing in the LHC was reduced to 50 ns, tracks from a previous bunch crossing can contribute to the current event if the SCT is readout long enough. If a track is found, but there is no hit in a module anymore, the reconstructed hit efficiency is artificially low. The problem was solved by changing the readout to record only ‘X1X’ hits.



# Chapter 4

## Low $p_T$ tracking

Charged particles may emerge from the interaction point, or from a secondary vertex if produced as decay products of long lived particles. In this chapter the reconstruction of low  $p_T$  tracks is examined, which is crucial for the  $\phi$ -meson reconstruction. The  $\phi \rightarrow K^+ K^-$  decay results in kaons with momenta of  $\lesssim 1$  GeV compared to the multi-GeV particles from hard processes. The different track parameters and their physical interpretation are discussed. Next, energy loss by charged particles is assessed in detail and later used for particle identification. In the last section, the performance of particle identification using  $dE/dx$  is discussed.

### 4.1 Tracks

In the presence of a homogeneous magnetic field, charged particles follow a helical trajectory. The helix is defined by five track parameters [113], as illustrated in figure 4.1. The track parameters are usually expressed at the point of closest approach to the beam axis, the *perigee point*, as follows:

- The charged-signed inverse momentum,  $q/p$ , with  $q$  the charge in units of elementary charge  $e$ . The inverse momentum is related to the curvature  $\kappa$  or radius  $\rho$  of the track in the  $x-y$  plane and the magnetic field  $B$  by

$$\kappa \equiv \frac{1}{\rho[\text{m}]} = \frac{0.3 \cdot B[\text{T}]}{p[\text{GeV}]} \quad (4.1)$$

The uncertainties of the curvatures of the tracks are Gaussian distributed, whereas using  $q \cdot p$  as track parameter would yield a non-Gaussian distribution for the uncertainties, biasing the reconstruction. In the physics analyses often transverse momentum  $p_T$ , the projection of the momentum onto the  $x-y$  plane, is used.

- The polar angle,  $\theta$ , the angle with respect to the  $z$ -axis in  $R-z$  plane. Most analyses use the pseudorapidity  $\eta = -\ln(\tan(\theta/2))$ , as track multiplicity is to first order constant in  $\eta$ .
- The azimuthal angle,  $\phi_0$ , the angle to the  $x$ -axis at the perigee in the  $x-y$  plane.

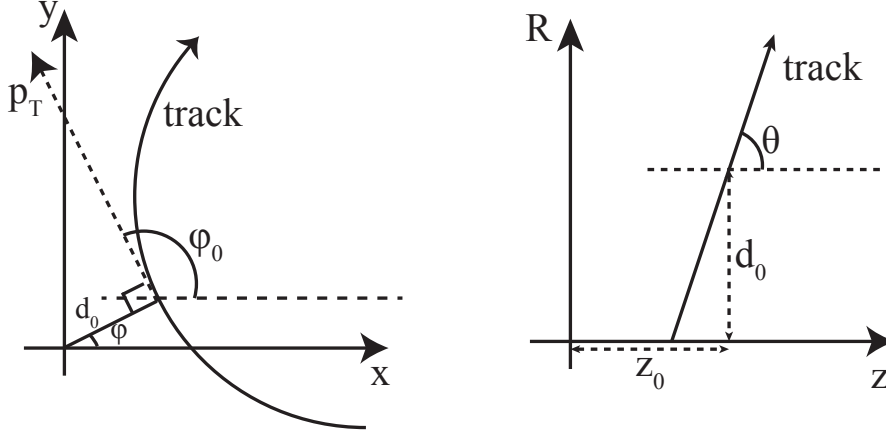


Figure 4.1: Schematic view of the five track parameters of a helical track projected onto the  $x - y$  (left) and the  $R - z$  plane (right). For this track  $d_0$  is negative.

- $z_0$  is the  $z$ -coordinate at the point of closest approach to the  $z$ -axis and is referred to as the longitudinal impact parameter.
- $d_0$  is the transverse impact parameter, the point of closest approach to the  $z$ -axis in the  $x - y$  plane. The sign of  $d_0$  is determined as:

$$\text{sign}(d_0) = \text{sign} \left( (\vec{p} \times \hat{z}) \cdot \vec{d} \right), \quad (4.2)$$

where  $\vec{p}$  is the momentum vector,  $\hat{z}$ , the unit vector pointing in the direction of  $z$ -axis and  $\vec{d}$  points to the perigee point from the origin.

Using these parameters, the location of any point on the track can be expressed with respect to any point in the detector. The impact parameters get a physical interpretation when expressed with respect to the primary vertex of the collision, as they are then related to the decay length, which is in turn associated to the lifetime of the particle decaying to charged particles.

The track finding and fitting procedure is performed in roughly three steps:

1. *Pattern recognition* [114] aims to resolve tracks using hits from charged particles. Usually three hits in the pixel detector or spacepoints in the SCT are used to form a seed. Track candidates are formed from the seeds by extrapolating a track through the detector and assigning more hits within a defined window. Each seed can become at most one track candidate.
2. *Ambiguity solving* [115] to remove ambiguities arising from track candidates that share hits or are composed from a random combination of hits. If a track from the pattern recognition passes the first selections from the ambiguity solver, the track is fitted. After track



fitting, each track is assigned a weight, based on the number of hits and holes assigned to the track, and tracks may be disregarded according to their weights. A hole is a layer that the track passed through, but did not leave a hit in. Basic requirements are applied, including the requirement that  $p_T > 100$  MeV, a maximum transverse impact parameter of 10 mm and a minimum number of five hits in the silicon detectors. These cuts ensure a basic track quality and remove hit combinations that formed a track unlikely to originate from a particle.

3. *Track fitting* aims at obtaining the best estimates for the track parameters, taking into account the traversed detector material and uncertainties in hit position. Charged particles are deflected in the magnetic field and may be scattered through Coulomb interactions in the detector material. Energy loss effects arise from nuclear and electromagnetic interactions in the material and are accounted for in the track fitting procedure by reducing the momentum according to the thickness of the transversed material. Energy loss is examined in detail in the next section of this chapter.

The quality of the track description depends on the number of hits correctly assigned to a track and the resolution of those hits. It is limited by the understanding of inhomogeneities in the magnetic field and the amount of material a particle traverses. If a charged particle traverses the detector, it can have a hadronic interaction with a nucleus in the detector where typically many new particles are produced. These new particles may be reconstructed and the hadronic interaction identified, but the original particle is lost. Moreover, multiple Coulomb scattering and the energy loss effects lead to uncertainties in track extrapolation and therefore influence the precision of the description of the trajectory. The fitting procedure used for the analysis presented in this thesis is based on a global least squares approach [116], which includes the minimization of a  $\chi^2$  function

$$\chi^2 = \sum_{meas} \frac{r_{meas}^2}{\sigma_{meas}^2} + \sum_{scat} \left( \frac{(\theta_{scat}^{proj})^2}{\sigma_{scat}^2} + \frac{\sin^2(\theta_{loc})(\phi_{scat}^{proj})^2}{\sigma_{scat}^2} \right), \quad (4.3)$$

The first part of this formula describes the sum over the hit residuals  $r_{meas}$  divided by their uncertainties. The second term refers to multiple Coulomb scattering and is a sum over the scattering angles  $\theta_{scat}^{proj}$  and  $\phi_{scat}^{proj}$  in individual detector components divided by their uncertainties. The track is described in term of its track parameters and the values for the track parameters for which equation 4.3 is minimized are chosen. If the scattering angles are small, they are described by a Gaussian distribution when they are projected on the  $x-y$  plane or  $R-z$  plane. The width of this Gaussian is given by the Highland scattering formula [117] :

$$\sigma_{MS} = \frac{13.6 \text{ MeV}}{\beta c p} Z \sqrt{s/X_0} (1 + 0.038 \ln(s/X_0)), \quad (4.4)$$

where  $\beta c$ ,  $p$  and  $Z$  represent the velocity, momentum and charge of the particle traversing a material.  $X_0$  is the radiation length, defined as the amount of matter high energy electrons traverse such that they lose  $1/e$  of their energy due to bremsstrahlung.  $s/X_0$  is the thickness of the material normalized to  $X_0$ . From equation 4.4 it is clear that the uncertainty on the scattering angles decreases with increasing momentum.

A charged particle flying through ATLAS traverses the active detector materials where it is detected, but also traverses cables, cooling systems and support structures. Because the total amount of material in a large detector like ATLAS is difficult to characterize precisely from drawings, data-driven methods are used to validate the material model in simulations. The  $K_S^0$  mass is known to high precision and by using its decay to two charged pions [118], it is inferred that the total amount of material is understood with an uncertainty smaller than 10%.

In figure 4.2 comparisons for the  $p_T$ ,  $\eta$  and the number of pixel clusters per track are shown for data and Monte Carlo. Events are selected with the event selection as described in chapter 5. Here tracks are required to be within  $|\eta| < 2.0$ , with  $p_T > 230$  MeV and with track momentum smaller than 800 MeV, please note that the  $p < 800$  MeV requirement causes the decreasing behavior as a function of  $\eta$ . Reasonable agreement is shown, which illustrates good understanding of the detector, the numbers of dead or otherwise lost pixel modules, and track finding and fitting procedures.

The expected number of clusters of pixel hits on track differs for positively and negatively particles in the low momentum regime up to  $p_T < 800$  MeV. A negative track may pass between two pixel modules, due to the fan-like geometry of the detector. This is illustrated using the Atlantis event display [119] in figure 4.3 a) and b). The average number of pixel hits on track in data and simulation is compared for positive and negative tracks in figure 4.3 c) and d) and is  $2.96 \pm 0.01$  per positive track and  $2.79 \pm 0.01$  per negative track.

## 4.2 Energy loss

In this section energy loss and its use for particle identification is discussed.

### 4.2.1 Bethe–Bloch

Charged particles passing through a medium will lose energy due to Coulomb interactions with atomic electrons, leading to ionization or excitation. The amount of energy lost can be estimated in the following rough derivation, which provides insight in the relevant parameters. To do so it is assumed that:

- the mass of the incoming particle,  $M$ , is much larger than the electron mass  $m_e$ , so that the incoming particle follows a straight path. This assumption is obviously not valid if the incoming particle is an electron;
- the velocity of the incoming particle,  $v_M = \beta c$ , is constant and its charge is  $ze$ ;
- the atomic electron is free and at rest during the collision,  $v_M \gg v_e$ , which is valid because the velocity of the electron in the atomic orbit is  $\sim 0.02c$ .

The goal is to find the energy transfer from the incoming particle to the atomic electron in the medium. The energy transfer to one free electron that is originally at rest with mass  $m_e$  is

$$\Delta E = \frac{\Delta p^2}{2m_e}. \quad (4.5)$$

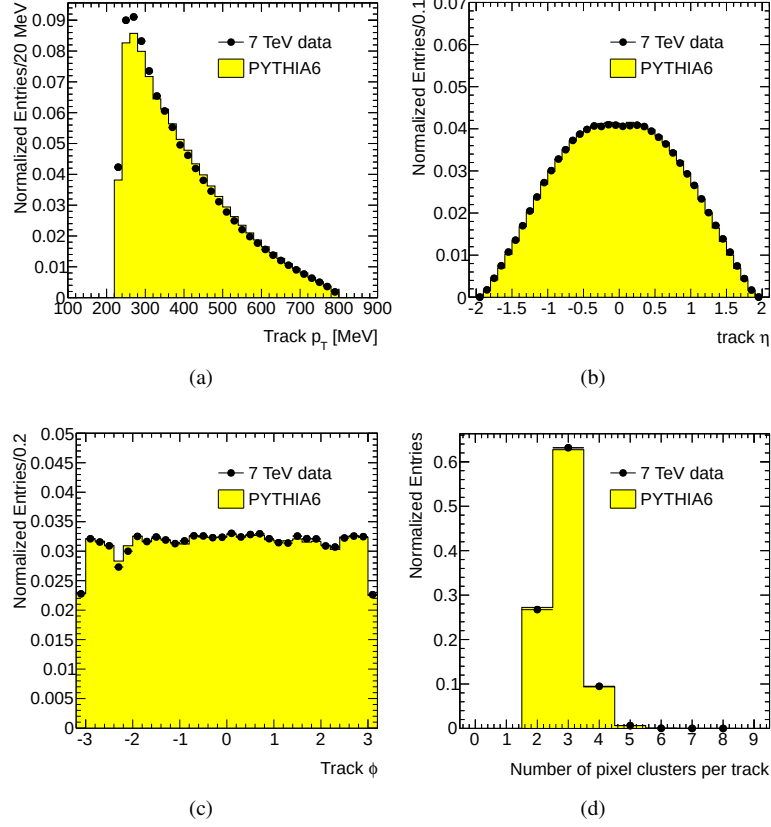


Figure 4.2: Track parameters as reconstructed from data and Monte Carlo. See text for discussion.

The total momentum transfer can be found by integrating the force over time

$$\Delta\vec{p} = \int_{-\infty}^{\infty} \vec{F}_C dt, \quad \vec{F}_C = \frac{1}{4\pi\epsilon_0} \frac{ze^2}{r^2} \hat{r}, \quad (4.6)$$

where  $F_C$  is the Coulomb force and  $r$  is the distance between the atomic electron and the incoming particle. See figure 4.4 for illustration of the parameters. From a symmetry argument it is clear that the longitudinal components ( $x$ -components) cancel, so that only the transverse component ( $y$ -component) of the Coulomb force  $F_{C,t}$  has an effect

$$|F_{C,t}| = |\vec{F}_C| \frac{b}{|\vec{r}|} = F_C \cos\theta, \quad (4.7)$$

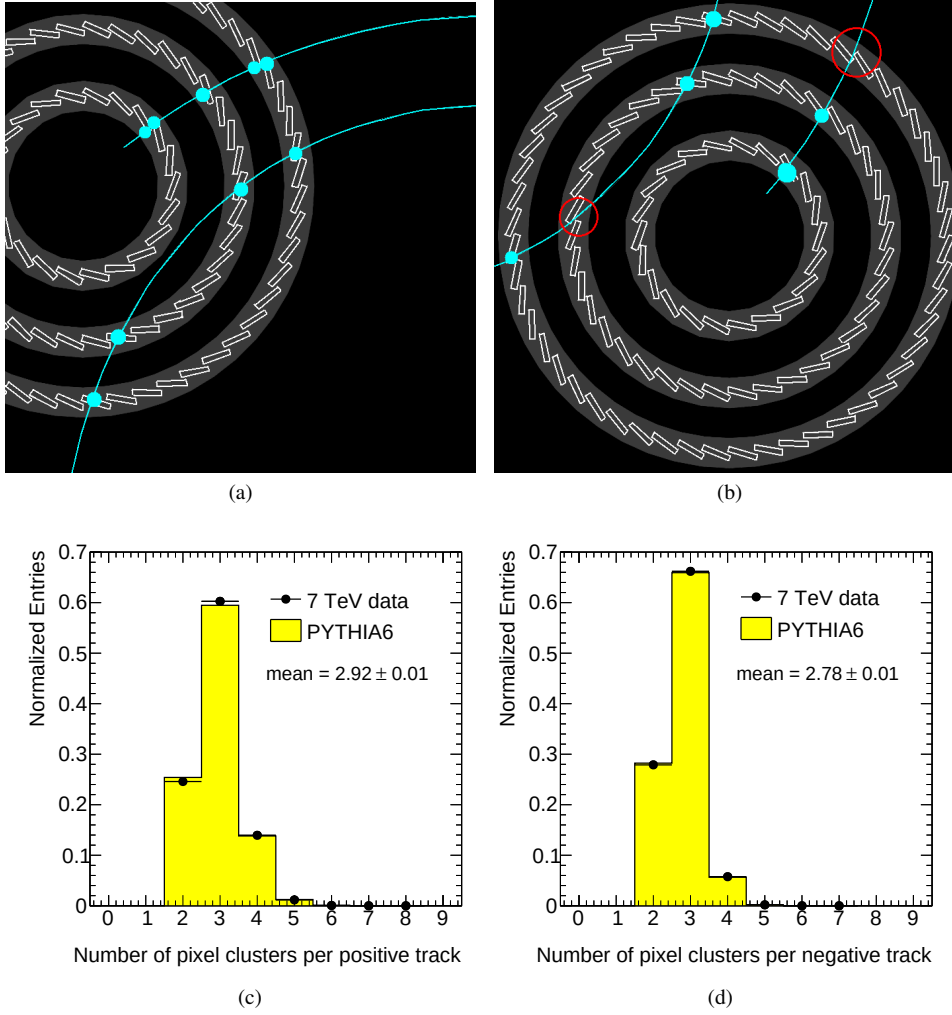


Figure 4.3: A positive a) and negative b) pion track in the pixel detector as simulated by Atlantis. The negative track may pass between pixel modules, not leaving a hit. The number of clusters of pixel hits per track for c) positive and d) negative tracks.

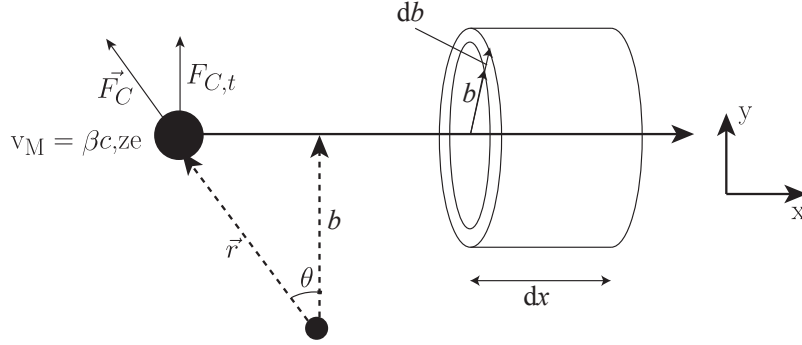


Figure 4.4: The parameters used to calculate energy loss.

where  $b$  is the impact parameter, the distance of closest approach to the electron, and  $\theta$  the angle between  $b$  and  $\vec{r}$ . When taking  $r = b/\cos\theta$ , the transverse force on the electron becomes

$$|F_{C,t}| = \frac{1}{4\pi\epsilon_0} \frac{ze^2}{b^2} \cos^3\theta. \quad (4.8)$$

And the momentum transfer can then be expressed as

$$\Delta p_t(b) = \int_{-\infty}^{\infty} |F_{C,t}| dt = \int_{-\infty}^{\infty} |F_{C,t}| \frac{dx}{v} = \frac{1}{4\pi\epsilon_0} \frac{ze^2}{b^2} \int_{-\infty}^{\infty} \cos^3\theta \frac{dx}{v}, \quad (4.9)$$

with  $dx = b d\theta / \cos^2\theta$ :

$$\Delta p_y(b) = \frac{1}{4\pi\epsilon_0} \frac{ze^2}{bv} \int_{-\pi/2}^{\pi/2} \cos\theta d\theta = \frac{1}{4\pi\epsilon_0} \frac{2ze^2}{bv}. \quad (4.10)$$

So that the energy transfer becomes

$$\Delta E(b) = \frac{1}{(4\pi\epsilon_0)^2} \frac{2z^2e^4}{m_e c^2 \beta^2 b^2}. \quad (4.11)$$

In a material the incoming particle can interact with all atomic electrons. If the electrons are on a cylinder with length  $dx$ , thickness  $db$  at radius  $b$  the incoming particle will interact with

$$N_e = 2\pi b db dx N_A \frac{Z}{A} \rho \quad (4.12)$$

electrons, where  $N_A$  is Avogadro's constant,  $Z$  is the atomic number,  $A$  the atomic mass and  $\rho$  the density of the medium.

Integrating equation 4.11 over the impact parameter  $b$  and including  $N_e$  as found in equation 4.12, the expected mean energy loss per unit length becomes

$$-\frac{dE(b)}{dx} = \frac{1}{(4\pi\epsilon_0)^2} \frac{4\pi z^2 e^4}{m_e c^2 \beta^2} N_A \frac{Z}{A} \rho \ln \frac{b_{\max}}{b_{\min}}. \quad (4.13)$$

To find  $b_{\min}$  and  $b_{\max}$  the maximum and minimum energy transfer are considered respectively. The maximum energy transfer occurs when  $b$  is smallest and thus the collision is head-on. The electron, originally at rest, acquires velocity  $2v$  of the incoming particle. The energy transfer equals the energy of the electron after collision:  $\Delta E(b_{\min}) = 2m_e\beta^2c^2\gamma^2$ . The minimum energy transfer corresponds to  $b_{\max}$  and in this case the electron is only excited, such that the energy transfer equals the average excitation potential of the medium,  $I$ .

Combining this and equation 4.13 leads to a description for the energy loss per unit length  $-dE/dx$ :

$$-\frac{dE}{dx} = \frac{1}{4\pi\epsilon_0^2} \frac{z^2e^4}{m_e c^2} \frac{N_A Z \rho}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e\beta^2c^2\gamma^2}{I} \right] \quad (4.14)$$

in units of MeV/cm.

A fully quantum mechanical derivation leads to the well-known Bethe–Bloch formula [120]:

$$-\frac{dE}{dx} = \frac{1}{4\pi\epsilon_0^2} \frac{z^2e^4}{m_e c^2} \frac{N_A Z \rho}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta)}{2} \right], \quad (4.15)$$

where  $T_{\max}$  is the maximal kinetic energy that can be transferred, the factor  $-\beta^2$  accounts for screening of the Coulomb field by the surrounding matter when interactions take place over longer distances,  $\delta(\beta)$  is a density correction due to polarization for the medium, which only becomes important if  $\beta\gamma > 30$ .  $T_{\max}$  introduces a small dependence on  $M$  at the highest energies.

Equations 4.14 and 4.15 are similar up to  $\beta\gamma < 20$  apart from the factor  $I^2$  and  $-\beta^2$  in the Bethe–Bloch. The deposited energy falls rapidly as the velocity increases explained as above by the particle having less time to transfer momentum through the Coulomb force to the atomic electron. Figure 4.5 a) shows the mean energy loss in silicon as a function of  $\beta\gamma$ , using the semi-classical derivation and the Bethe–Bloch formula. The energy loss predicted by the Bethe–Bloch is larger predominantly because of the factor  $I^2$ . The relativistic rise in the semi-classical derivation arises from the implementation of  $\Delta E(b_{\min}) = 2m_e\beta^2c^2\gamma^2$ . At even larger  $\beta\gamma$ , the polarization effect would suppress the relativistic rise in the Bethe–Bloch, which is not accounted for in the classical derivation.

If the velocity approaches the speed of light, increasing energy leads to slower increase in velocity and thus a smaller decrease in energy loss. For  $\beta\gamma \sim 3 - 4$ ,  $dE/dx$  reaches a minimum where the particle is dubbed a minimum ionizing particle (MIP). For example, a muon with  $p \sim 600$  MeV is a MIP. Beyond this,  $\beta$  tends to unity and the logarithmic factor in the Bethe equation gives the relativistic rise in  $-dE/dx$ . This is due to Lorentz contraction of the electric field in the material, making interactions with electrons further away from the track more efficient. Figure 4.5 b) shows the energy loss from the classical derivation for pions, kaons and protons with momenta up to 2.5 GeV to illustrate the effect of particles having different masses.

## 4.2.2 Distribution of energy loss

The most probable value for energy loss,  $\Delta_p$  is lower than the mean of the expected energy loss as described by the Bethe–Bloch formula. This can be explained by the fact that the Bethe–Bloch derivation assumes that the incoming particle interacts with a large number of electrons. In practice this number is limited, unless the traversed material is very thick or dense, in which

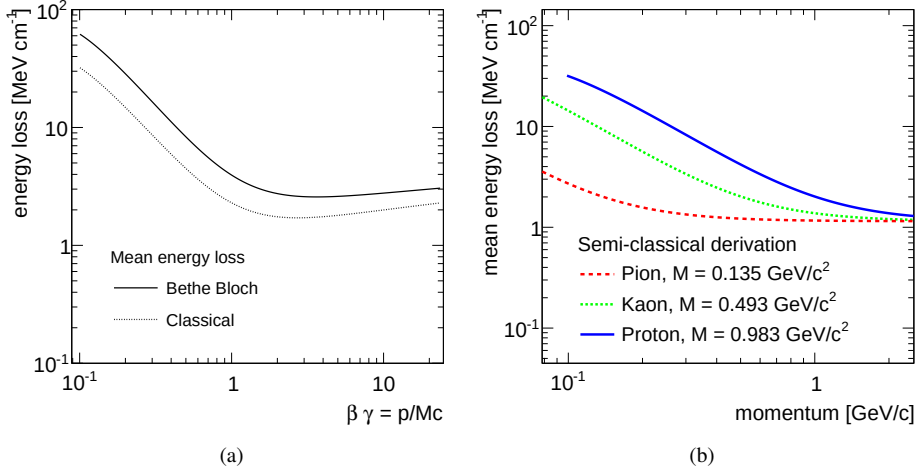


Figure 4.5: a) Comparison between the mean energy loss as calculated in a semi classical way (equation 4.14, dashed line) and with a full quantum mechanical calculation (equation 4.15, solid line). b) Mean energy loss in silicon for pions, kaons and protons with momenta up to 2.5 GeV, using equation 4.14.

case the probability density function for the energy loss approaches a Gaussian distribution around the mean energy loss as predicted by the Bethe–Bloch. If the number of collisions is limited, the fact that there are more combinations that yield a higher  $dE/dx$  will skew the mean energy loss to be higher than the most probable value. Moreover, each individual collision has a small probability to free a  $\delta$ -electron: an electron that has enough energy to cause more ionizations. This asymmetry in the  $dE/dx$  distribution is described by the Landau distribution, which is characterized by a narrow peak with a long tail towards higher values. The difference between the mean energy loss and the  $\Delta_p$  is illustrated in figure 4.6.

The most probable energy loss as a function of  $\beta\gamma$  is described by [121]:

$$\Delta_p(\beta\gamma) = \xi(x) \left[ \ln \frac{2mc^2\beta^2\gamma^2}{I} + \ln \frac{\xi(x)}{I} + 0.2 - \beta^2 \right], \quad (4.16)$$

where  $\xi(x) = (4\pi N_A r_e^2 \rho z^2)/(m_e c^2) \langle Z/A \rangle (x/\beta^2)$  MeV for a detector with thickness  $x$  in g cm<sup>-2</sup>. While  $dE/dx$  is independent of thickness,  $\Delta_p/x$  scales as  $a \ln x + b$ .

The silicon sensors in the ATLAS pixel detector are 250  $\mu\text{m}$  thick. From figure 4.6 it is inferred that for a 500 MeV pion passing such a sensor,  $\Delta_p \approx (6.3^{+1.2}_{-0.6}) \cdot 10^4$  eV per sensor. A pion with momentum 150 MeV, which corresponds to approximately the smallest momentum for which a track can be reconstructed, most probably loses  $< 0.05\%$  of its energy in the sensors when traversing the three pixel sensors perpendicularly. The total energy lost is larger due to interactions with the support structures and cooling system.

The material distribution for the inner detector is expressed in radiation lengths,  $X_0$ , and interaction lengths,  $\lambda$ , and is shown in figure 4.7. The design goal was to keep the amount of

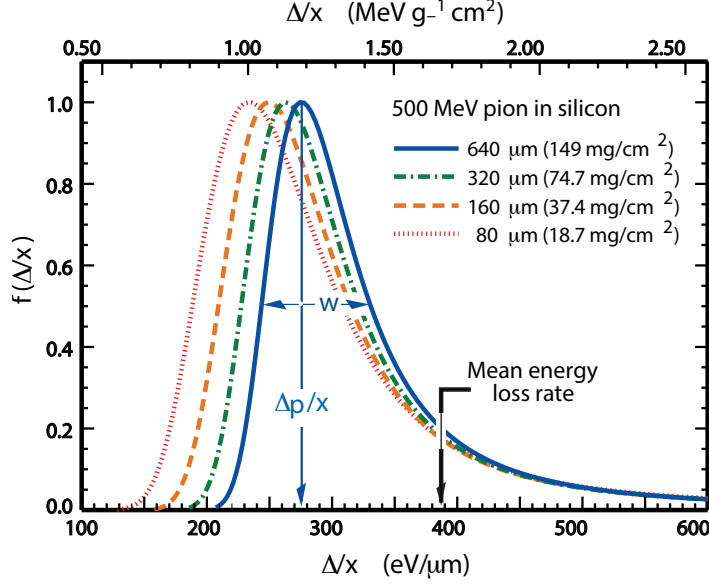


Figure 4.6: Energy loss probability density functions for a pion with energy 500 MeV ( $p = 480$  MeV) in silicon, normalized to unity at  $\Delta_p/x$ , from [3].

material as limited as possible, with the least material in the central part of the detector. The larger amount of material at  $|\eta| \sim 1.5$ , the transition region between the barrel and the end-caps, can be explained by the cables and support structures located between the TRT barrel and end-caps. After traversing the inner detector a charged particle has traversed approximately  $0.5 X_0$  at  $|\eta| = 0.5$  and  $1.5 X_0$  at  $|\eta| = 1.5$ .

### 4.2.3 $dE/dx$ and resulting signal in the pixel detector

In this section the assessment of the most probable energy loss,  $\Delta_p$  and the resulting signal for charged particles with momenta  $0.2 < p \lesssim 1$  GeV in the ATLAS pixel detector is examined in detail. The measured energy loss will be used for particle identification.

So far, the energy loss by a fast particle that interacts with the individual atoms in a material has been examined. When confined in a lattice, silicon atoms are ordered in a face-centered cubic lattice, such that the wavefunctions of their four valence electrons make covalent bonds and fill up the outer electron shell. The discrete energy states of the atomic shell broaden to form bands. The number of bonding states equals the number of electrons, so in the absence of excitation, e.g. if the lattice is at 0 K, all the electrons are in the lower energy valence band and the material is an insulator. With increasing temperature, electrons may cross the energy band into the conduction band until thermal equilibrium is reached. If a charged particle passes a silicon sensor it will lose energy, causing electrons to be excited across the band gap into the conduction band, creating electron-hole pairs. Although the size of the bandgap  $E_g$  for silicon



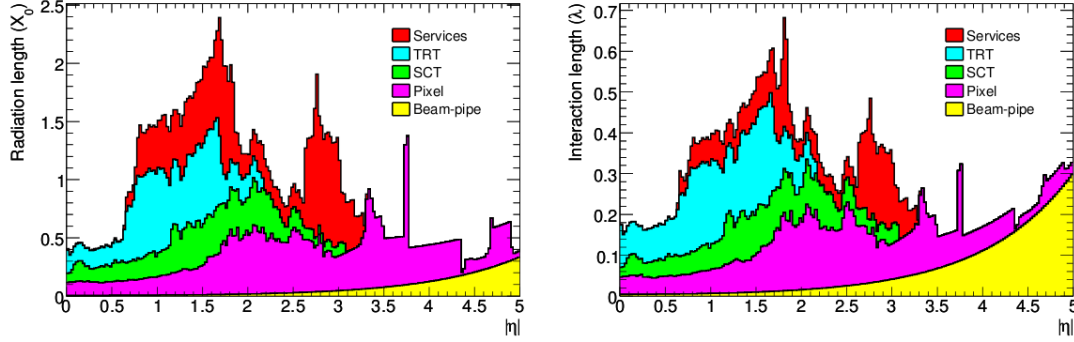


Figure 4.7: Material distribution expressed in radiation lengths,  $X_0$ , and interaction lengths,  $\lambda$ , at the exit of the inner detector envelope indicating the contribution of the individual sub-detectors, the beam-pipe and the support services [67].

is 1.12 eV [100], the average energy lost per ionization is  $W = 3.68 \pm 0.02$  eV/pair [122]. This is because an excitation across the bandgap in silicon also requires a simultaneous transfer of momentum, absorbed as lattice vibrations.

The amplitude of the signal is directly proportional to energy deposited. Because signals have the same shape, the width of the signal is proportional to the amplitude and thus the energy deposition. This width can be expressed as the duration of the signal, the *Time over Threshold* (ToT), and is measured by subtracting the leading edge timestamp from the trailing edge timestamp [123]. For any hit generated in the pixel detector information on the L1 trigger that accepted the event, pixel row, pixel column and ToT are stored. The ToT is converted to amount of charge through conversion functions derived by calibration scans in which a known charge is injected in a pixel. Each pixel diode is calibrated to measure a ToT count of 30 for a MIP, while the overflow is at 255.

Charge released by a track crossing the pixel detector is rarely contained in just one pixel. Neighboring pixels are joined together if the signal exceeds the threshold to form clusters and the charge of the cluster is calculated as the sum of the charges of all pixels after calibration correction. In order to ensure only good quality clusters are used, a cluster is excluded if:

- The local position of the cluster is at the edge of the module, because the cluster may then extend beyond the sensor, so charge can be lost over the edge and go underestimated;
- $\cos(\alpha) < 0.16$ , with  $\alpha$  the track spatial incident angle, because the most probable value of expected cluster charge sharply drops for smaller values of  $\cos(\alpha)$ ;
- The ToT count exceeds the overflow of 225 counts.

Clusters unaffected by these cuts are referred to as *good clusters* and represent 91% of all clusters. All tracks with two or more good clusters are accepted for analysis, thereby rejecting 3% of the tracks.

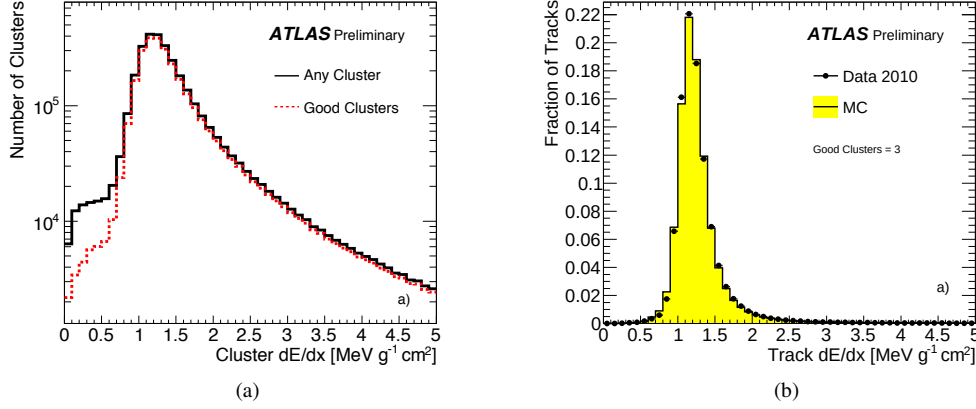


Figure 4.8: a) The cluster  $dE/dx$  distribution before (full line) and after (dashed) applying the good cluster requirements. b) The track  $dE/dx$  for data and Monte Carlo simulation. Both from [124].

The specific cluster energy loss,  $dE/dx$  in units of  $\text{MeV g}^{-1} \text{cm}^2$ , is derived from the charge contained in a cluster,  $Q$ , the average energy needed to create an electron-hole pair  $W$ , the path length in the silicon  $x = d/\cos \alpha$  and the silicon density  $\rho$ :

$$\frac{dE}{dx} = \frac{QW \cos \alpha}{epd}. \quad (4.17)$$

Figure 4.8 shows how the tails at low charge (mostly caused by charge being lost over the edge of the pixel) are effectively reduced using good clusters only and the agreement between data and Monte Carlo for good cluster  $dE/dx$ .

Track  $dE/dx$  is defined as an average of the individual cluster  $dE/dx$  measurements (charge collected in the cluster, corrected for the track length in the sensors), for all the good clusters associated to a track. The average is calculated using the truncated mean to reduce the effect of Landau tails for the expected energy loss; the average is evaluated after having removed the cluster(s) with the highest charge: one cluster is removed for tracks with 2, 3 or 4 good clusters and two clusters for tracks with 5 or more good clusters. A track  $dE/dx$  resolution of  $\sim 12\%$  is measured using particles with  $p_T > 3 \text{ GeV}$ . This is measured as the RMS of a Gaussian fit to the distribution of  $dE/dx$ .

For figure 4.9 the energy loss in the clusters on a track is simulated as a set of four random numbers generated from a Landau distribution with most probable value  $MPV = 240$  and width  $w = 50$ . The choice for the input parameters reflects the expected energy loss and width in  $\text{eV}/\mu\text{m}$  for a 500 MeV pion in a  $250 \mu\text{m}$  thick sensor, see figure 4.6. From the four generated numbers the average is plotted before (left) and after (right) having removed the highest numbers. The measured  $MPV$  and  $w$  are found by fitting a Landau to the distributions of these (truncated) means. The mean of the resulting distribution is taken as the average of all means. The input  $MPV$  is overestimated by a factor of 1.24 if using the normal means. The input

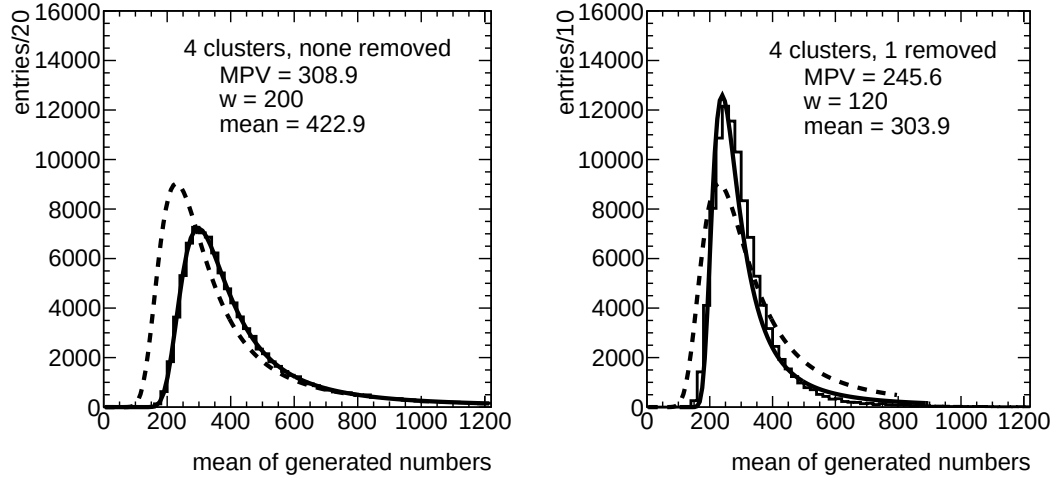


Figure 4.9: A test using simulated data to estimate the resolution improvement of using the truncated mean for the energy loss measurement (see text). The dashed lines show the input p.d.f. with  $MPV = 240$ , and the solid lines are the fit result of a Landau to the distribution of the (truncated) means.

$MPV$  is estimated within 2% when using the truncated means and the resolution improves from  $w = 200$  to  $w = 120$ .

#### 4.2.4 Very low momentum particles

For kaons and protons in the very low momentum regime, i.e. momenta up to 200 MeV, the energy loss in the active and support materials of the inner tracker is so large the particles are stopped. This is illustrated in figure 4.10. Kaons are not reconstructed in the central  $\eta$  regime, where  $|p_T| \sim |p|$ . In this region of phase space all energy is lost before reaching the SCT.

### 4.3 Particle identification

#### 4.3.1 Energy loss fit

To use energy loss for particle identification, the most probable value of the specific energy loss,  $\Delta_p$ , and the charged particle  $\beta\gamma$  are parametrized with a probability density function (p.d.f.). This p.d.f. can be factorized into:

1. A function that describes how  $\Delta_p$  depends on  $\beta\gamma$  described by a function with five free parameters that are obtained as a result of a fitting procedure to data;

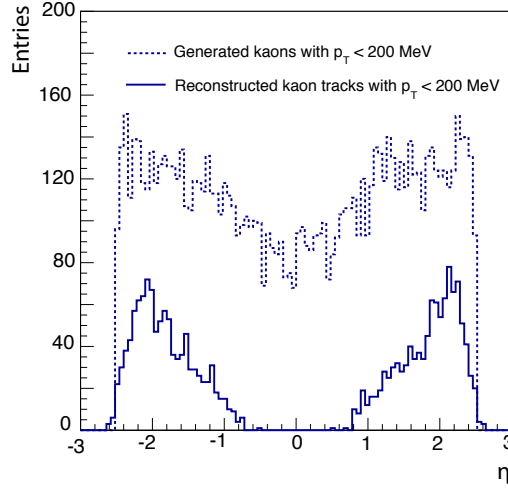


Figure 4.10: Although kaons with  $p_T < 200$  MeV and central  $\eta$  are produced at Monte Carlo generator level (dashed line), these particles lose all their energy before reaching the SCT detector and are therefore not reconstructed (solid line).

2. A Crystal Ball [125] function peaked at  $\Delta_p(\beta\gamma)$  that describes how the measured  $dE/dx$  fluctuates around  $\Delta_p(\beta\gamma)$  for a given charged particle  $\beta\gamma$ .

The Crystal Ball was chosen because it has a numerical advantage over the more common Landau-Gaussian fit and is therefore quicker in the computations, while the performance is comparable. From a sample of simulated tracks with  $\beta\gamma$  ranging between 0.3 and 10, a suitable parametrization is found for  $\Delta_p(\beta\gamma)$  [124]:

$$\Delta_p(\beta\gamma) = \frac{p_1}{\beta^{p_3}} \ln(1 + (|p_2|\beta\gamma)^{p_5}) - p_4, \quad (4.18)$$

Figure 4.11 shows a two-dimensional distribution of  $dE/dx$  as a function of the signed momentum. The pronounced bands resulting from pions, kaons and protons are indicated. Positively and negatively charged tracks each divided in groups of tracks with two, three and four or more clusters are fitted separately in slices of momentum. In figure 4.12 projections on the momentum axis (and thus the  $dE/dx$  distribution in bins of momentum) for positively charged tracks having three good clusters in data is shown, as well as the result of the global fit. The value found for  $p_3$  is always between 1.8 and 2.2.

The likelihood that the particle is a pion, kaon or proton is calculated with the measured number of good pixel clusters on the track, the momentum of the particle and the energy loss in the pixel detector. To do so, the result of global fit is used, given that the fluctuations of the energy loss are described by the Crystal Ball. The energy resolution is not good enough to distinguish between muons, electrons and pions, the “light particles”. The absolute probability

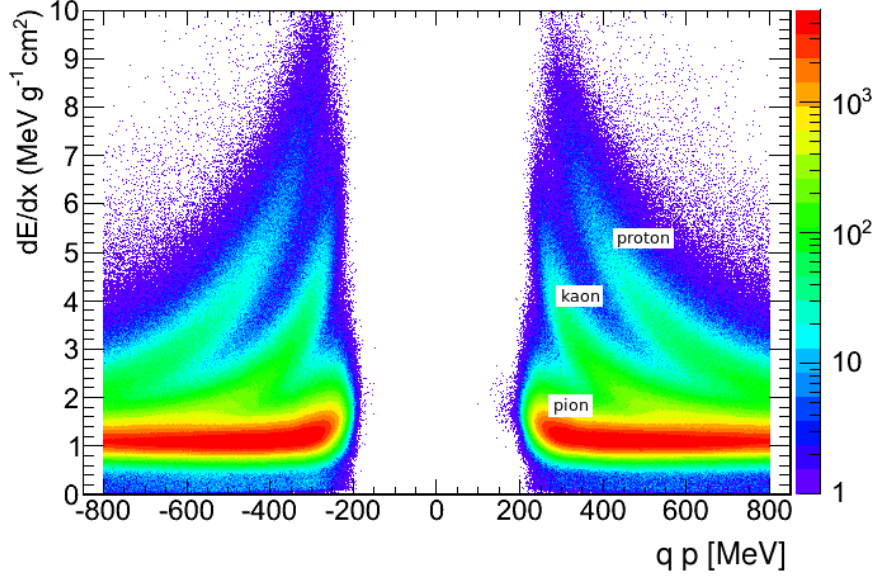


Figure 4.11: Two-dimensional distribution of  $dE/dx$  and charge signed momentum for data.

a track originates from a proton, kaon or light particle depends on the likelihoods ( $L_P$ ,  $L_K$ ,  $L_l$ ) and is defined as:

$$P_P = \frac{L_P}{L_P + L_K + L_l}, P_K = \frac{L_K}{L_P + L_K + L_l}, P_l = \frac{L_l}{L_P + L_K + L_l}. \quad (4.19)$$

### 4.3.2 Particle ID performance

The majority of charged hadrons produced at the interaction point are pions, that are tagged as light particles. Ignoring the contribution of electrons and muons in the set of particles tagged as a light particle, the likelihood probabilities become  $P_{\pi^\pm}$ ,  $P_K$  and  $P_l$ . These probabilities are used for identifying pions, kaons and protons with an efficiency,  $\epsilon_{\text{pid}}^{\pi^\pm}$ ,  $\epsilon_{\text{pid}}^K$ ,  $\epsilon_{\text{pid}}^P$ , measured using a Monte Carlo based method by defining

$$\epsilon_{\text{pid}}^{\text{particle}} = \frac{N_{\text{truth,pass}}^{\text{particle}}}{N_{\text{truth}}^{\text{particle}}}, \quad (4.20)$$

where  $N_{\text{truth}}^{\text{particle}}$  is the number of selected tracks having at least two good clusters associated with a specific particle type at generator level and  $N_{\text{truth,pass}}^{\text{particle}}$  is the subset of  $N_{\text{truth}}^{\text{particle}}$  passing a given requirement on  $P_{\text{particle}}$ . This efficiency is shown in figure 4.13 a) for kaons in three slices of momentum and ten slices in the kaon likelihood probability  $P_K$ . The efficiency is of the order

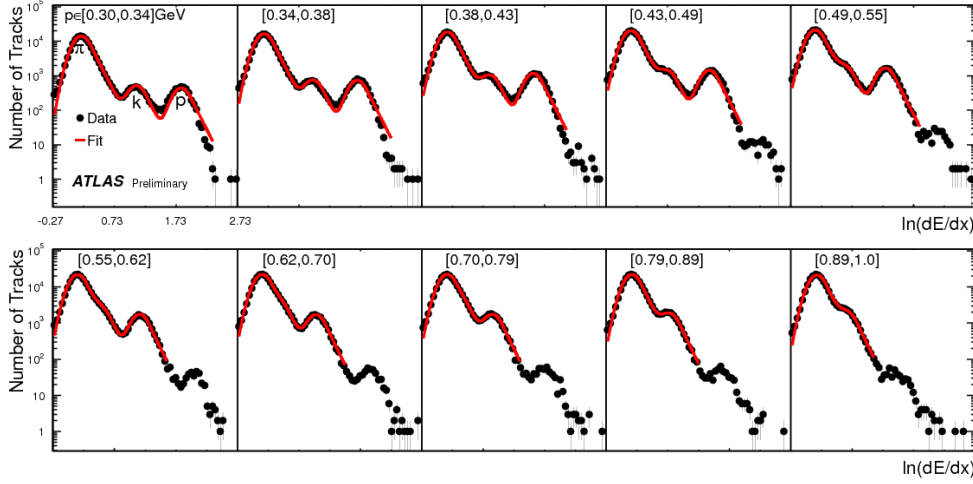


Figure 4.12:  $dE/dx$  distribution in ten momentum intervals, equally spaced in  $\ln(p)$ , compared with the fitted function accounting for pions, kaons and protons. The deuteron peak, visible for  $p > 0.4$  GeV, is not used in the fit. [124]

of 90% for kaons with momenta up to 600 MeV, this can be understood from figure 4.11, where the separation between the different energy bands is still clearly visible at 600 MeV. The energy bands start to overlap from  $\sim 600$  MeV and the expected tagging efficiency is therefore lower in the momentum slice  $600 < p < 800$  MeV. The efficiency decreases with more stringent requirements on  $P_K$ , because kaons will be less likely to pass the requirements.

When selecting kaons through a cut on  $P_K$ , the sample will be contaminated with other charged particles depending on the requirement on  $P_K$ . This contamination consists of mostly pions and is estimated using simulation defining the mistag rate for pions:

$$r_K^{\pi\pm} = \frac{N_{\text{truth,pass}}^{\pi\pm}}{N_{\text{truth}}^{\pi\pm}}, \quad (4.21)$$

where  $N_{\text{truth}}^{\pi\pm}$  is the number of truth pions and  $N_{\text{truth,pass}}^{\pi\pm}$  is the subset of truth pions passing the requirement on  $P_K$ .  $r_K^{\pi\pm}$  is shown in figure 4.13 b) and is about 10% for momenta up to 600 MeV and as large as 56% for pions with  $600 < p < 800$  MeV and  $P_K > 0.1$ . The mistag rate also decreases with more stringent requirements on  $P_K$  to less than 2% when requiring  $P_K > 0.9$ .

In figure 4.14  $\epsilon_{\text{pid}}^{\text{kaon}}$  is shown as a function of the mistag rates for pions and protons. As expected, the tagging efficiency decreases with increasing momentum and increasingly stringent cuts on the probabilities. The mistag rates increase with increasing momentum and are about 1–10%.

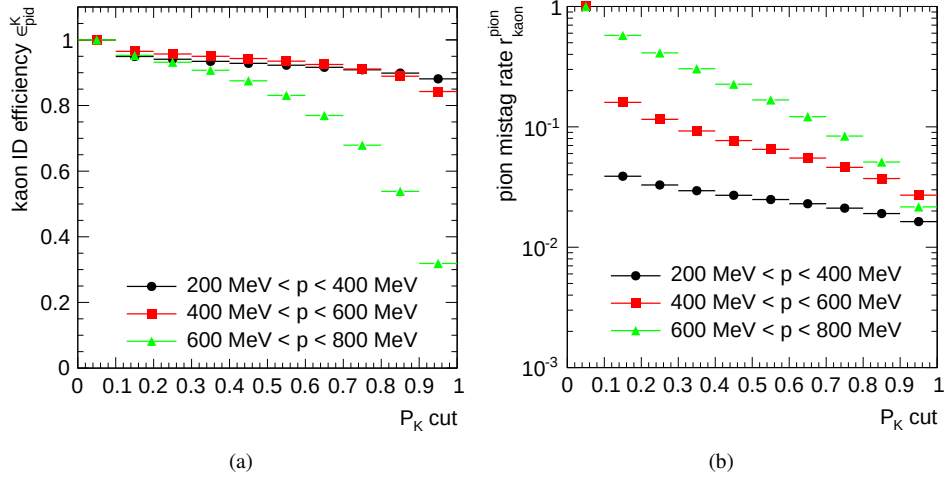


Figure 4.13: The particle identification efficiency a) and mistag rate b) for kaons in three slices of momentum for different requirements on  $P_K$ .

## 4.4 Summary

Track finding and fitting is an important part of the analysis of  $pp$  interactions. Energy loss in the pixel detector is used to select kaons with an efficiency of about 90% for momenta up to 600 MeV. The method loses discriminating power for kaons with momenta of  $p_K > 800$  MeV, or  $\beta\gamma \sim 2$ . Kaons with momenta lower than  $|p| \sim 200$  MeV lose all their energy before the first SCT barrel and will be excluded from the analysis. A data-driven way to determine the efficiency for kaon identification is explained in chapter 5.

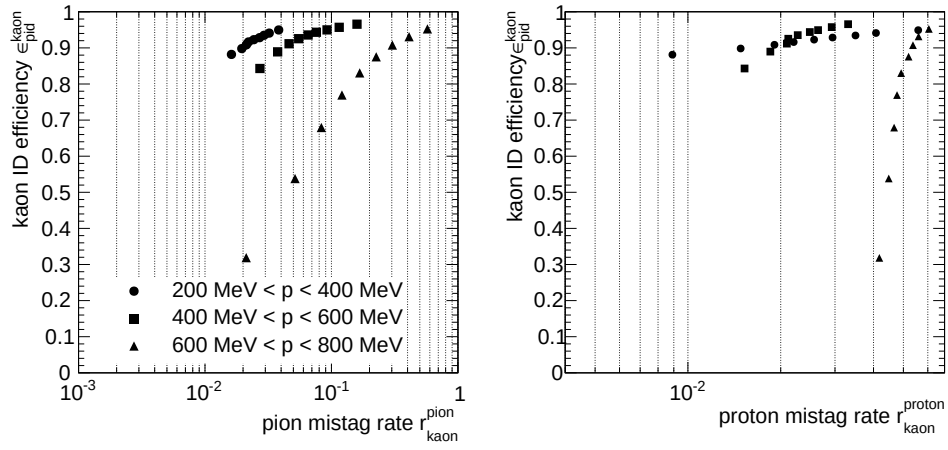


Figure 4.14: The pion and proton mistag rates as a function of the tagging efficiency for kaons. The datapoint with the highest efficiency and mistag rate is for  $P_{particle} > 0.1$  and with the lowest efficiency and mistag rate for  $P_{particle} > 0.9$ .



# Chapter 5

## Event and track selection

In this chapter the analysis for the measurement of the  $\phi(1020)$ -meson production cross section using the  $K^+K^-$  decay mode is presented in detail. In section 5.1 the analysis is introduced, in section 5.2 the data and Monte Carlo samples and event selection are explained, in section 5.3 the definition of the cross section is given and the efficiency of the track selection procedure is explained in the following sections. The cross section result is presented in the next chapter.

### 5.1 Kinematic acceptance

The identification of  $\phi(1020)$ -meson candidates is based on the reconstruction of an invariant mass peak using two oppositely charged kaons. Although the  $\phi$  meson also decays into two muons, this decay has a much lower branching fraction and it is therefore not used here. To account for the short lifetime, the tracks are required to originate from the primary vertex. The selection of  $\phi(1020)$ -meson candidates requires kaon identification to distinguish the kaons of  $\phi \rightarrow K^+K^-$  decays from the many charged particles, mostly pions, that emerge from a  $pp$  collision. For this selection, energy loss in the pixel detector is used, giving discriminating power up to  $\sim 1$  GeV (see section 4.2.3 for details). To avoid accepting tracks in the analysis that can not be identified as kaons the momentum range for tracks is limited to  $p_K < 800$  MeV.

Kaons with very low momenta,  $p_K < 230$  MeV, do not have enough energy to pass through the detector any further than the pixel detector or the first SCT layer. This was explained in detail in section 4.2.4. In this analysis a requirement on the minimum number of SCT hits is used for tracking. To avoid a too strong pseudorapidity dependence, tracks are accepted if the kaon transverse momentum  $p_{T,K} > 230$  MeV.

To understand the impact of these requirements driven by the instrumentation, figure 5.1 shows the expected two-dimensional distributions of  $\phi$ -meson transverse momentum,  $p_{T,\phi}$ , and  $\phi$ -meson rapidity,  $|y_\phi|$ , before and after the implementation of the cuts on kaon momentum. These distributions are from the event generator PYTHIA 6 without further detector simulation. The number of expected decays is roughly constant as a function of rapidity and decreases as a function of  $p_{T,\phi}$  from  $p_{T,\phi} \sim 600$  MeV. The requirement of  $p_{T,K} > 230$  MeV excludes decays with  $p_{T,\phi} < 400$  MeV and no decays are left with  $|y_\phi| > 1.0$  due to the  $p_K < 800$  MeV requirement. The impact of the cut on kaon momentum of  $p_K < 800$  MeV with increasing  $p_{T,\phi}$

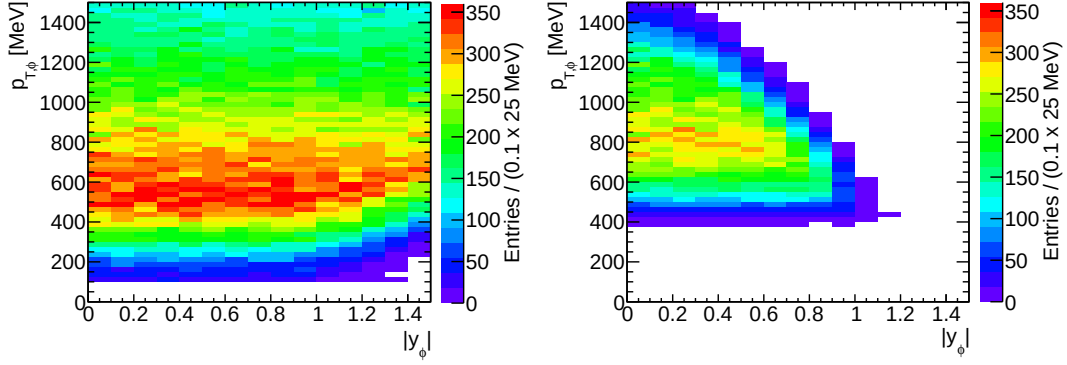


Figure 5.1: The two-dimensional distribution of expected  $p_{T,\phi}$  and  $|y_\phi|$  from generated  $\phi \rightarrow K^+K^-$  decays before (left) and after implementing the cuts on kaon transverse momentum  $p_{T,K} > 230$  MeV and kaon momentum  $p_K < 800$  MeV.

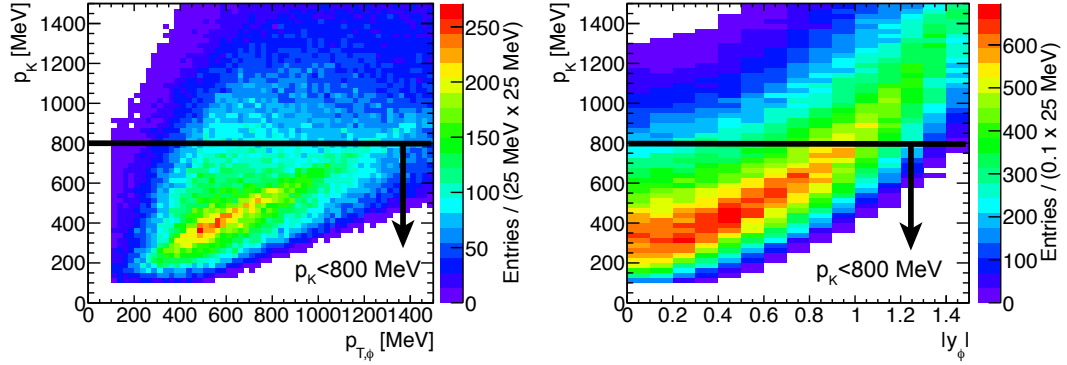


Figure 5.2: The two-dimensional distribution of expected  $p_{T,\phi}$  and  $|y_\phi|$  as a function of kaon momentum  $p_K$  from generated  $\phi \rightarrow K^+K^-$  decays before implementing the cuts on kaon transverse momentum  $p_{T,K} > 230$  MeV and kaon momentum  $p_K < 800$  MeV.

and  $|y_\phi|$  can be understood from figure 5.2, where the positive correlation between  $p_K$  and  $|y_\phi|$  is illustrated.

Figure 5.3 shows  $p_{T,\phi}$  distributions from PYTHIA6 before and after applying the cuts on kaon momentum. The *fiducial* range is limited to the region where enough  $\phi$  candidates are expected for efficiency determination:

- $500 < p_{T,\phi} < 1200$  MeV,
- $|y_\phi| < 0.8$ ,
- $p_{T,K} > 230$  MeV,
- $|p_K| < 800$  MeV.

Figure 5.4 shows an event display for an event that produced a pair of tracks that passed all the above requirements and for which both tracks were identified as kaons and the invariant mass of the reconstructed  $\phi$  candidate is  $1018.7 \pm 0.3$  MeV.

The cross section is measured as the number of efficiency-corrected decays, measured with a fit to the invariant mass spectrum of the two kaons, divided by the luminosity in the data sample. In the remainder of this chapter the selections and their efficiencies are explained in detail:

1. Event and track selections, section 5.2;
2. Pairing the remaining tracks in oppositely charged pairs gives  $\phi(1020)$ -meson candidates, that are examined in section 5.2.4;
3. Each pair is given a weight for trigger, vertex, tracking and kaon identification efficiencies. These corrections are explained in sections 5.3 and 5.4.

The invariant mass distributions from (3) are created and fitted to determine the number of efficiency-corrected  $\phi \rightarrow K^+ K^-$  decays,  $N_{\text{reco}}^{\text{weighted}}$ , and the cross section  $\sigma_{\phi \rightarrow K^+ K^-}$  is calculated as the ratio of  $N_{\text{reco}}^{\text{weighted}}$  and the integrated luminosity  $\mathcal{L}$ :  $\sigma_{\phi \rightarrow K^+ K^-} = N_{\text{reco}}^{\text{weighted}} / \mathcal{L}$ . The yield extraction and the cross section result are presented in the next chapter.

## 5.2 Data samples and $\phi$ -meson selection

### 5.2.1 Data samples

After a successful commissioning period of the LHC, minimum bias triggers were activated to collect the first LHC data sets. A data sample collected in April 2010 at  $\sqrt{s} = 7$  TeV with an integrated luminosity of  $383 \pm 13 \mu\text{b}^{-1}$  is used [126]. Table 5.1 lists the run numbers, trigger prescales, visible cross section and luminosity per run. The visible cross section,  $\sigma_{\text{visible}}$ , does not account for pile-up in these low luminosity runs and would be constant in the limit where there is absolutely no pile-up.

The data are collected with the minimum bias trigger EF\_L1ItemStreamer\_L1\_MBTS\_1, explained in section 2.2.3. To suppress the amount of data, this trigger is prescaled, i.e. triggered

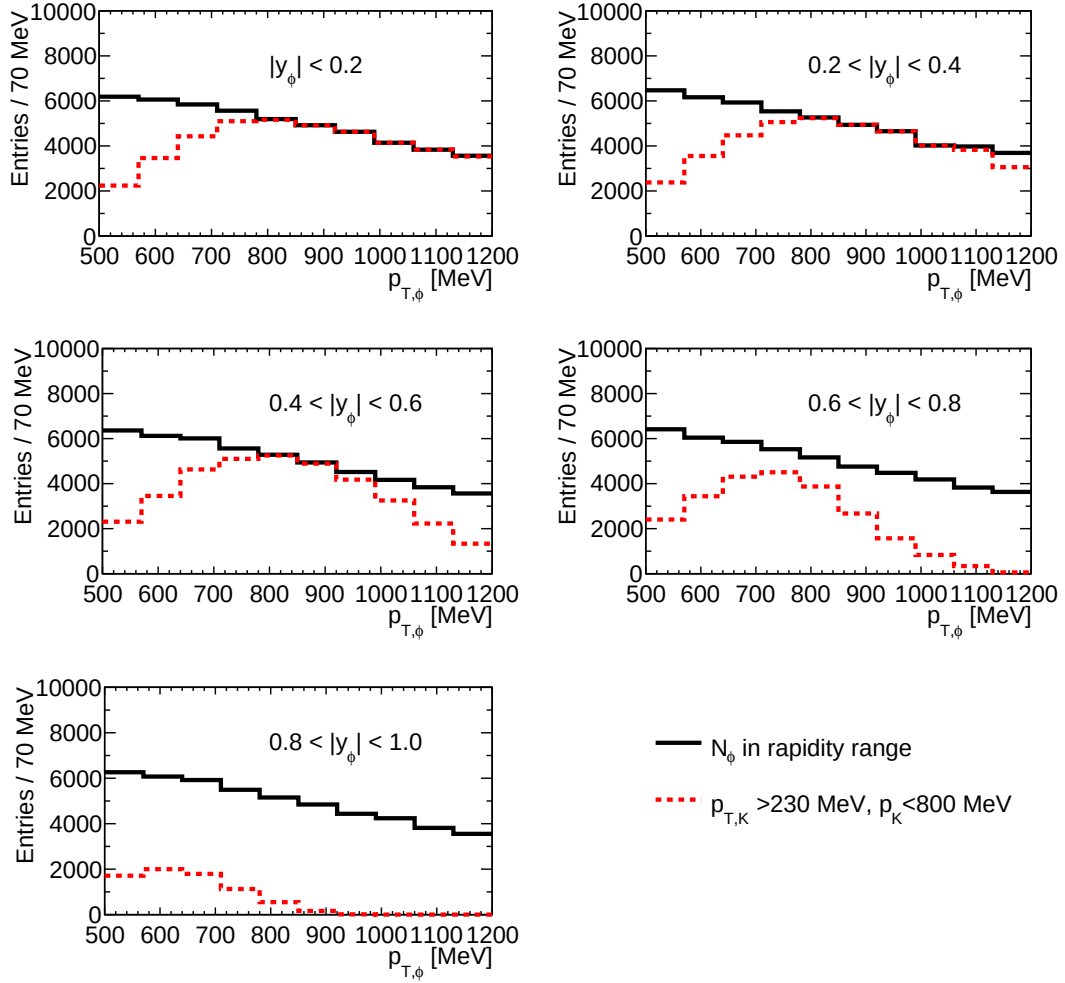
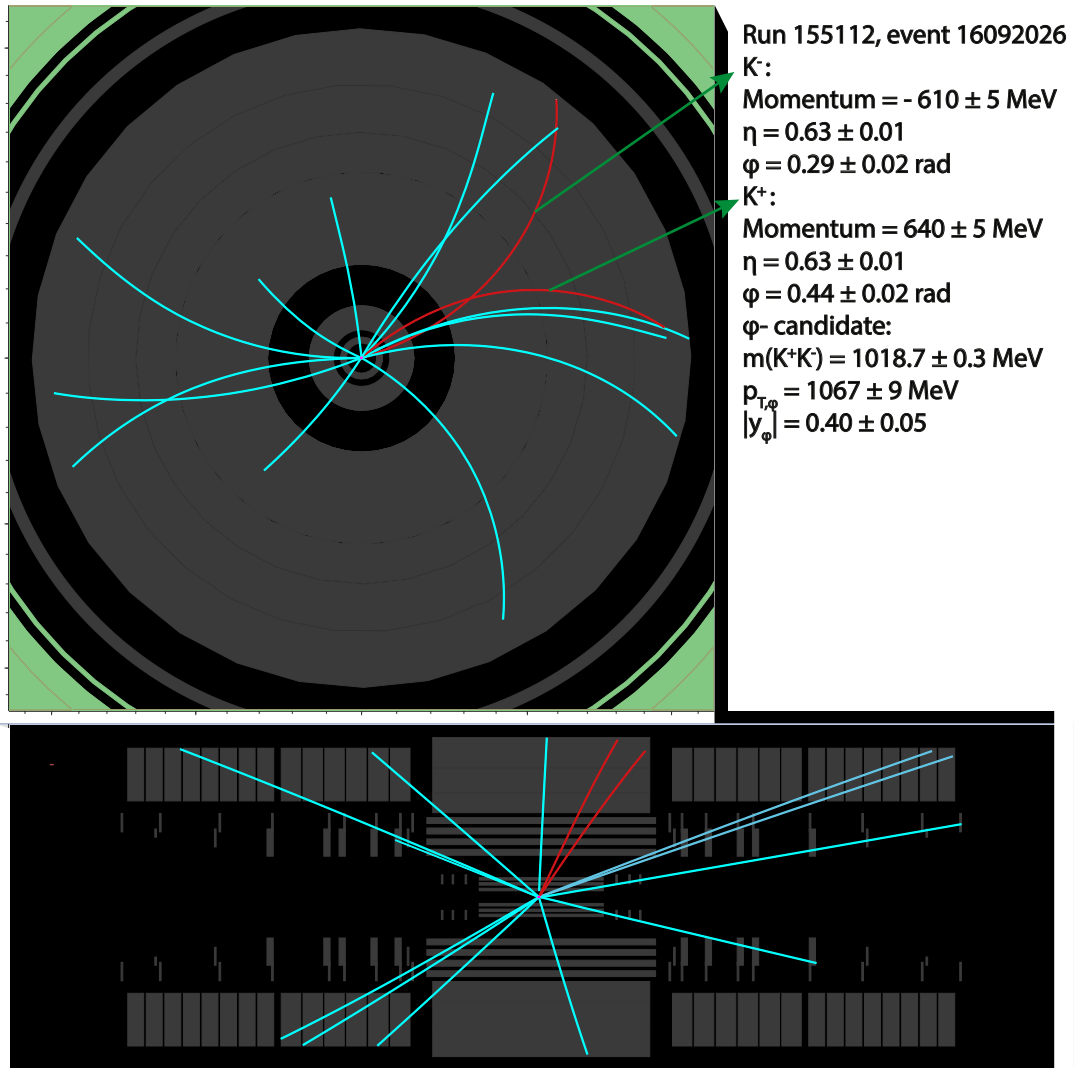


Figure 5.3: The expected  $p_{T,\phi}$  distributions from generated  $\phi \rightarrow K^+K^-$  decays in regions of  $|y_\phi|$  before (solid lines) and after (dashed lines) implementation of the cuts on kaon (transverse) momentum. The impact of the  $p_{T,K} > 230$  MeV cut on the number of expected decays is clearly visible in the low  $p_{T,\phi}$  region. The impact of the  $p_K < 800$  MeV requirement becomes more pronounced with increasing  $\phi$  rapidity and  $p_{T,\phi}$ .

Figure 5.4: Event display of an event with a  $\phi$ -meson candidate.

| Run    | $\mathcal{L}_{\text{del}}$<br>( $\mu\text{b}^{-1}$ ) | Pre-<br>scale | $\mathcal{L}_{\text{used}}$<br>( $\mu\text{b}^{-1}$ ) | $N_{\text{evts}}$<br>all | $N_{\text{evts}}$<br>good | $\sigma_{\text{visible}}$<br>(mb) | $N_{\phi} \cdot 10^3$ | $N_{\phi} / \mathcal{L}$<br>( $\mu\text{b}$ ) |
|--------|------------------------------------------------------|---------------|-------------------------------------------------------|--------------------------|---------------------------|-----------------------------------|-----------------------|-----------------------------------------------|
| 152409 | 66                                                   | 1             | 56                                                    | 3.7M                     | 3.5M                      | 62.92                             | $6.4 \pm 0.2$         | $113 \pm 4$                                   |
| 152441 | 63                                                   | 1             | 63                                                    | 4.3M                     | 3.9M                      | 62.78                             | $7.5 \pm 0.2$         | $120 \pm 3$                                   |
| 152777 | 40                                                   | 1             | 40                                                    | 3.2M                     | 2.5M                      | 62.78                             | $4.7 \pm 0.2$         | $117 \pm 5$                                   |
| 153565 | 619                                                  | 2-8           | 123                                                   | 12M                      | 7.8M                      | 62.80                             | $14 \pm 0.3$          | $120 \pm 2$                                   |
| 155073 | 1120                                                 | 12-30         | 54                                                    | 3.2M                     | 3.2M                      | 59.49                             | $6.2 \pm 0.2$         | $115 \pm 4$                                   |
| 155112 | 3280                                                 | 25-100        | 47                                                    | 3.0M                     | 2.8M                      | 59.77                             | $5.3 \pm 0.2$         | $112 \pm 3$                                   |

Table 5.1: Details of the data sample: Run number, the delivered luminosity ( $\mathcal{L}_{\text{del}}$ ), the inverse fraction of events accepted (prescale) for the L1\_MBTS.1 trigger, the prescale corrected luminosity ( $\mathcal{L}_{\text{used}}$ ), the number of triggered events, the number of triggered events after data quality requirements, total visible cross section ( $\sigma_{\text{visible}} = \frac{N_{\text{evts,good}}}{\mathcal{L}_{\text{used}}}$ ), the number of  $\phi(1020)$ -mesons and the fraction  $\frac{N_{\phi}}{\mathcal{L}_{\text{used}}}$ . The determination of the number of  $\phi(1020)$ -meson candidates is explained in section 6.1.

events are not processed, by at least a factor of two hundred since April 2010. This means that adding the data from extra runs adds little statistics to the analysis.

### 5.2.2 Simulation samples

Collision data are compared directly to two  $\sqrt{s} = 7$  TeV minimum bias Monte Carlo samples and the  $\phi$ -meson yield of two other generators is examined in section 6.5. The simulation samples are listed in table 5.2. For the PYTHIA 6 sample the non diffractive (ND), single diffractive (SD) and double diffractive (DD) samples and their cross sections are listed separately. The total inelastic cross section for the PYTHIA 6 sample is 71.3 mb and comparable to the total cross sections quoted for the other generators. A combined PYTHIA 6 sample with contributions of the three diffractive samples is created by weighting the non diffractive, single diffractive and double diffractive components according to their production cross sections. This sample is referred to as the PYTHIA 6 sample.

Events from PYTHIA 6 and HERWIG++ were processed using a simulation of the ATLAS detector with the simulation toolkit GEANT4 [35] and analyzed using the same algorithms as used for data. The reconstruction of  $K^{\pm}$  tracks from  $\phi \rightarrow K^+ K^-$  decays generated by PYTHIA 6 is used for the calculation of the tracking efficiency, to derive model dependencies of the reconstructed quantities and for the calculation of systematic effects. The consistency test of the full  $\phi(1020)$ -meson reconstruction was performed with both PYTHIA 6 and HERWIG++.

Data are also compared to the EPOS and PYTHIA 8 generators to examine different tunes and event generation models as explained in more detail in chapter 1.

| Generator      | $N_{ev}$ | $\sigma_{inel}$ (mb) | Tune               |
|----------------|----------|----------------------|--------------------|
| PYTHIA 6.4.21  | 20M      | 48.4 (ND)            | MC09 [39]          |
| PYTHIA 6.4.21  | 2M       | 13.7 (SD)            | MC09               |
| PYTHIA 6.4.21  | 2.5M     | 9.2 (DD)             | MC09               |
| PYTHIA 8.153   | 2M       | 71.14                | A2:MSTW2008LO [41] |
| HERWIG++ 2.5.1 | 2M       | 71.13                | UE7-2 [42]         |
| EPOS           | 3M       | 71.73                | EPOS LHC [58]      |

Table 5.2: Data are compared to four Monte Carlo datasets, the three PYTHIA 6 datasets are combined to one.  $N_{ev}$  is the number of generated events in each dataset and  $\sigma_{inel}$  is the inelastic cross section.

### 5.2.3 Event selection

Before starting the  $\phi$  reconstruction a selection of events is prepared. Data events must have a valid primary vertex (PV) [127] reconstructed using the beam spot information [128] and that contain at least two tracks with  $p_T > 150$  MeV. Generated events are required to contain at least two stable, charged particles. To obtain a realistic distribution for the  $z$ -position of the vertex in Monte Carlo, it was re-weighted to data.

To ensure that all tracks used in the analysis originate from the primary vertex, a vertex re-fit is performed. Furthermore, tracks are required to have at least two clusters of pixel hits (see section 4.2.3) and two SCT hits assigned to them.

The standard ATLAS track-fit assumes that all tracks come from pions. This mass assumption affects the fitted momentum in case of the energy loss in the detector. Fitting a low-momentum kaon track with a pion-mass assumption biases the reconstructed momentum, because the energy loss would be underestimated and thus the momentum overestimated. At low momenta a small error in the reconstructed momentum may lead to a large error on the momentum correction, since the Bethe–Bloch function is very steep ( $\propto 1/\beta^2$ ) in this region. It was already discussed in section 4.2.4 that kaon with momenta below  $\sim 230$  MeV are lost in the track reconstruction. Pions with such low momentum can be reconstructed normally. For a kaon track with generated momentum  $p_{truth,K} \sim 300$  MeV or 700 MeV, the pion-mass assumption will overestimate the momentum on average with 40 MeV and 20 MeV, respectively.

For this analysis, all accepted tracks are fitted with a kaon-mass assumption. As shown in ref. [129] there is a remaining momentum bias as a function of the kaon momentum after fitting in this way. This bias is  $\sim 5\%$  at  $p_{truth,K} = 200$  MeV and  $\sim 0.5\%$  at  $p_{truth,K} = 600$  MeV. This is due to a residual imperfection of the modelling of the energy loss and multiple scattering for kaons in the track fit. This effect has no consequence for the  $\phi$ -meson cross section, because the measured location of the invariant mass peak does not influence the measured signal yield.

### 5.2.4 $\phi(1020)$ -meson candidate selection

For each selected event, all tracks with opposite charge are paired. In each pair both tracks are required to pass the kaon identification cuts of  $P_{kaon} > 0.84$  and  $P_\pi < 0.1$ , as explained in section

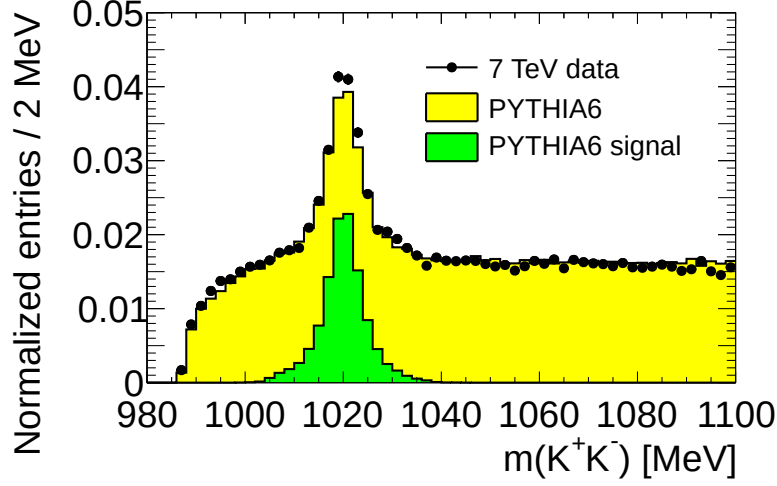


Figure 5.5: The  $K^+K^-$  invariant mass distributions after event and track selections of data and PYTHIA6.

4.3. Pairs of tracks that pass all these selections are considered a  $\phi(1020)$ -meson candidate.

Figures 5.5 to 5.9 show comparisons between data and PYTHIA 6 of several kinematic distributions from  $\phi(1020)$ -meson candidates that will be described later. Data are compared to PYTHIA 6 only, because this sample was used for the calculation of the tracking efficiency and to test systematic effects. Disagreements between data and simulation in any of these distributions should give rise to the inclusion of a systematic uncertainty, extra cross checks or the implementation of a data-driven derivation, to ensure a model-independent result. By construction, no entries are expected below values of  $m(K^+K^-) = 987$  MeV, twice the kaon rest-mass. The FWHM of the peak is about 6 MeV, while the natural width of the  $\phi(1020)$ -meson peak is 4.26 MeV, the difference is caused by the limited detector resolution.

In figure 5.5 the  $\phi$ -mass peak that emerges after the selections is clearly visible. The background contains pairs of tracks from wrong combinations and of pairs originating from the decays of other resonances. It was checked using simulation that for example pairs of tracks originating from the  $K^* \rightarrow K^\pm \pi^\mp$  decay make up about 20% of the background. The shape of this background is the same as the combinatorial background in the region  $1000 < m(K^+K^-) < 1060$  MeV. A background with peak-like shape would have made yield extraction assuming a uniform background contribution less reliable.

From the  $m(K^+K^-)$  distribution the normalization of the PYTHIA 6 signal with respect to the background is derived. Monte Carlo background is scaled to the tail of the spectrum,  $1030 < m(K^+K^-) < 1060$  MeV, and Monte Carlo signal to the signal region,  $1009 < m(K^+K^-) < 1029$  MeV. This separate scaling is needed, because the (relative) cross sections for background and signal used to produce the Monte Carlo are not correct. The histograms are filled giving generated pairs of tracks a weight:

$$MC = 0.45 \cdot MC_{\text{sig}} + MC_{\text{bkg}}, \quad (5.1)$$



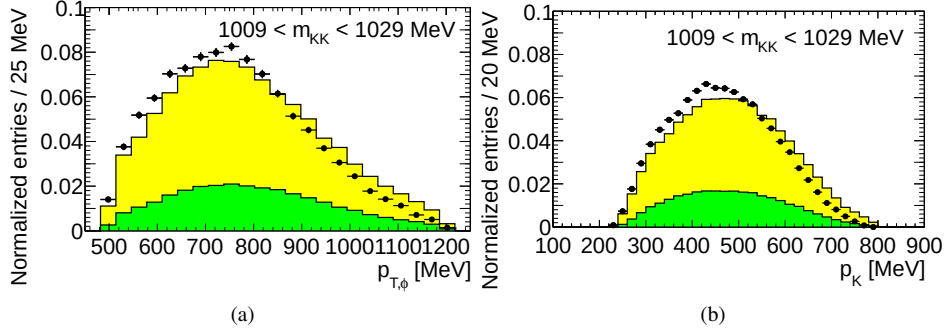


Figure 5.6: The distributions of a)  $\phi(1020)$ -meson transverse momentum,  $p_{T,\phi}$ , and b) the momenta of the kaons  $p_K$ , of data and PYTHIA 6.

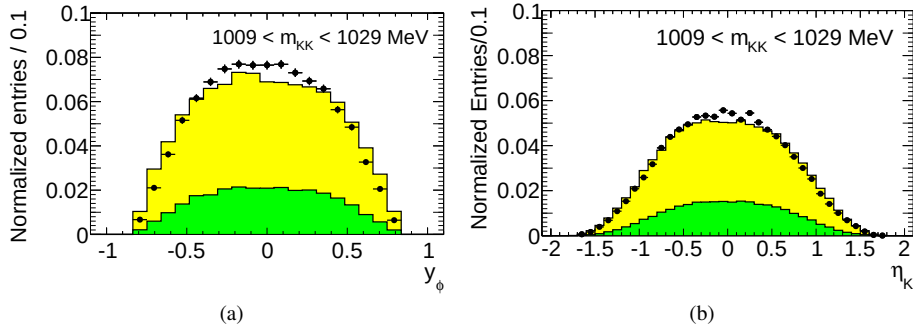


Figure 5.7: The distributions of a)  $\phi(1020)$ -meson rapidity,  $y_\phi$ , and b) pseudorapidity of the kaons,  $\eta_K$ , of data and PYTHIA 6.

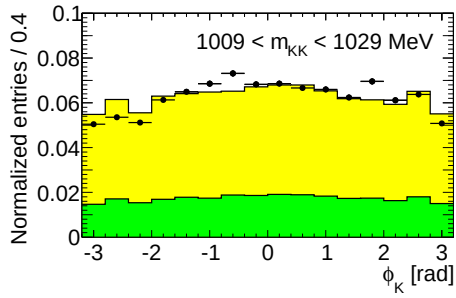


Figure 5.8: The distributions of the azimuthal angle of tracks of the kaons from  $\phi \rightarrow K^+ K^-$  decay candidates,  $\phi_K$ , of data and PYTHIA 6.

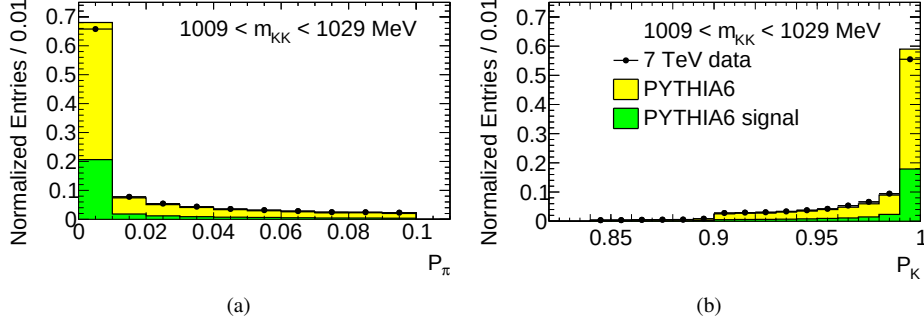


Figure 5.9: Probability distributions of a)  $P_{\text{pion}}$  and b)  $P_{\text{kaon}}$  of tracks from  $\phi \rightarrow K^+K^-$  decay candidates of data and PYTHIA6.

where “MC” is the relative contribution to each invariant mass bin,  $\text{MC}_{\text{sig}}$  is the relative contribution of pairs of generated pairs of tracks from  $\phi(1020)$ -mesons and  $\text{MC}_{\text{bkg}}$  the contribution of Monte Carlo background. In figures 5.6 to 5.9 this separate scaling is used and the plots show pairs of tracks with  $1009 < m(K^+K^-) < 1029$  MeV.

Figure 5.6 assesses the momenta of the  $\phi(1020)$ -meson candidates and of the kaons. The distributions in data are slightly more peaked and steeper than in PYTHIA6. Due to these disagreements and the momentum dependence of the kaon identification efficiency, this efficiency is necessarily measured using a data-driven way, as explained in section 5.4.2.

Figure 5.7 shows the (pseudo)rapidity of the  $\phi(1020)$ -meson candidates and of the kaons, which is modelled with reasonable accuracy. The disagreement between data and simulation for  $|\eta_K|$  shows that the relative abundance of different particle species in Monte Carlo is not modelled correct. The relative number of expected  $\phi(1020)$ -meson candidates is highest around  $|y_\phi| = 0$  and decreases with increasing  $|y_\phi|$  due to the  $p_K < 800$  MeV requirement having a larger impact at more forward rapidity.

Both the distributions of (kaon) momentum and (pseudo)rapidity rely on the underlying physics modelling or on the relative production cross sections of different particles. The azimuthal angle distribution of the kaons,  $\phi_K$ , is assumed constant and possible disagreement between data and simulation points to the description or performance of the detector or of the reconstruction of tracks not being correct. The  $\phi_K$  distributions are shown in figure 5.8 and a disagreement between data and simulation is visible. The data distribution shows a bump at around  $\phi_K \sim -0.5$  rad and  $\phi_K \sim 2$  rad. These bumps are not seen in figure 4.2 c), the corresponding figure before the requirements on  $P_\pi$  and  $P_K$ . The requirements on  $P_\pi$  and  $P_K$  are an implicit requirement on the number of clusters of pixel hits. The disagreement between the  $\phi_K$  distributions can be understood as a wrong number of dead pixel modules in the simulation (16 dead modules in data, 19 in simulation) in this  $\phi_K$  region.

The cuts used for kaon identification are illustrated in figure 5.9. Although the general Monte Carlo behavior matches the data, the probability for a track to originate from a kaon is overestimated in PYTHIA6. This correlates with the momentum being underestimated, because

for lower momenta the energy bands in figure 4.11 are more separated. In this low-momentum regime, a small error in the momentum reconstruction leads to a large error on the energy loss, due to the steep Bethe–Bloch behavior ( $\propto 1/\beta^2$ ). It has to be noted here that  $P_\pi$  and  $P_K$  are to high degree dependent on the energy loss modelling in GEANT4, which is also not perfect.

### 5.3 Event selection efficiencies

The fiducial cross section is determined in ten bins in  $p_{T,\phi}$  with a width of 70 MeV and in eight bins in  $|y_\phi|$  with a width of 0.1. Unless specifically stated, the cross section is not corrected for the branching fraction of the  $\phi(1020)$ -meson decaying to kaons within the fiducial region.

Candidate  $\phi(1020)$  decays are given a weight on an event-by-event basis to allow for several factors. Firstly a weight is given for trigger and vertex reconstruction efficiencies [46]. Secondly a weight is given for track reconstruction and kaon identification efficiencies. These efficiencies are calculated separately for tracks from positively and negatively charged particles, because significantly fewer clusters of pixel hits are expected on low momentum negatively charged particles, which may pass in between two pixel modules due to the tiling and tilt of the modules (see section 4.1). Finally, a weight is given to allow for the fraction of selected tracks passing the fiducial selection for which the corresponding primary particle is outside the fiducial range. Following the determination of the weight of each of the candidate  $\phi(1020)$  decays, the efficiency-corrected number of reconstructed candidate  $\phi(1020)$  decays is determined with a fit to the invariant mass distributions.

The cross section  $\sigma_{\phi \rightarrow K^+ K^-}$  in a bin  $i$  of  $p_{T,\phi}$  or  $|y_\phi|$  is defined as:

$$\sigma_{\phi \rightarrow K^+ K^-}^i = \frac{N_{\text{reco}}^{i, \text{weighted}}}{\mathcal{L}}, \quad (5.2)$$

where  $N_{\text{reco}}^{i, \text{weighted}}$  is the number of efficiency-corrected reconstructed candidate  $\phi(1020)$  decays and  $\mathcal{L}$  is the integrated luminosity in the data sample.

The two event selection efficiencies (trigger and vertex reconstruction) are discussed below. The track selection efficiencies (track reconstruction and kaon identification) are discussed in the next section.

#### 5.3.1 Minimum bias trigger

Events were triggered by Minimum Bias Trigger Scintillators (MBTS), explained in section 2.2.3. The trigger criterion requires a beam crossing and at least one hit in the MBTS counters. This trigger was applied with low prescale and no further HLT requirements for the whole dataset used in this analysis.

The efficiency of the MBTS trigger is measured using data by defining a control sample of events triggered by an alternative trigger, which requires a bunch crossing plus a total number of seven pixel and seven SCT spacepoints. An event that causes this much activity in the inner detector should always be triggered by the MBTS. The efficiency of the MBTS trigger,  $\epsilon_{\text{MBTS}}$ , is determined as:

$$\epsilon_{\text{MBTS}} = \frac{N_{\text{ev}}(\text{SpacePoints AND MBTS})}{N_{\text{ev}}(\text{SpacePoints})}, \quad (5.3)$$

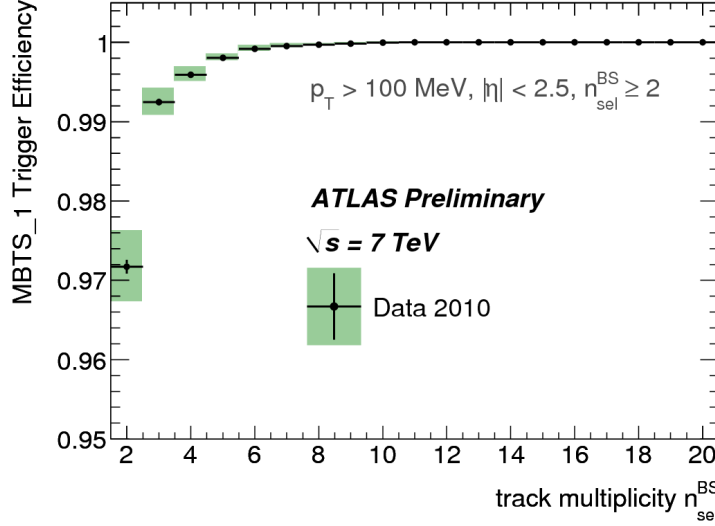


Figure 5.10: Efficiency of the L1.MBTS\_1 trigger as a function of track multiplicity in data. [130]

where  $N_{ev}(\text{SpacePoints AND MBTS})$  is the number of events that triggered both the triggers and  $N_{ev}(\text{SpacePoints})$  the number of events that triggered the alternative trigger.

The efficiency is 97.2% for events with two tracks, 99.2% for three tracks and then reaches 100% for events with more tracks [130] as shown in figure 5.10. The uncertainty on the trigger efficiency is  $\sim 0.1\%$  and neglected for the  $\phi$  meson cross section measurement.

### 5.3.2 Vertex reconstruction

The vertex reconstruction efficiency,  $\epsilon_{\text{vtx}}$ , is taken from [46] and determined from data by taking the ratio of triggered events with a reconstructed vertex to the total number of triggered events, after removing the expected contribution from beam background events. The efficiency is measured to be  $(90.0 \pm 0.1)\%$  and  $(92.3 \pm 0.1)\%$  for events with two and three tracks; it rapidly rises to 100% at higher track multiplicities. The vertex reconstruction efficiency is calculated for tracks with  $|\eta| < 2.5$  and  $p_T > 100$  MeV and constant in the kinematic range of this analysis. The uncertainty on the vertex reconstruction efficiency is of the order of 0.1% and neglected.

## 5.4 Track selection efficiencies

In the following sections the track reconstruction and kaon identification efficiencies and the related systematic uncertainties are examined.

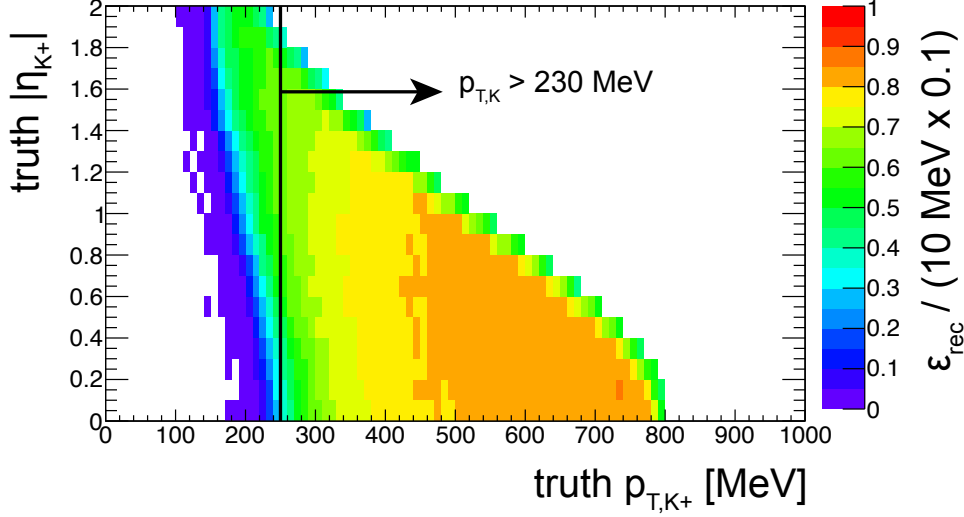


Figure 5.11: The track reconstruction efficiency for positive kaons as a function of  $p_{T,K}$  and pseudorapidity is estimated from PYTHIA 6.

#### 5.4.1 Track reconstruction

The track reconstruction efficiency,  $\epsilon_{\text{rec}}$ , is estimated using PYTHIA 6 simulated data as a function of both  $p_{T,K}$  and  $|\eta_K|$ . Figure 5.11 shows the tracking efficiency, calculated as the ratio of the number of generated particles with a track “matched” to them ( $N_{\text{gen,match}}$ ) to the total number of generated particles ( $N_{\text{gen}}$ ):

$$\epsilon_{\text{rec}}(p_{T,K}, |\eta_K|) = \frac{N_{\text{gen,match}}(p_{T,K}, |\eta_K|)}{N_{\text{gen}}(p_{T,K}, |\eta_K|)}. \quad (5.4)$$

Although  $\epsilon_{\text{rec}}$  is calculated for kaons generated down to  $p_{T,K} = 150$  MeV, tracks are accepted from  $p_{T,K} > 230$  MeV, because no or very few tracks are reconstructed at central pseudorapidity and such low  $p_T$ . This requirement is illustrated in figure 5.11: the tracking efficiency for kaons increases rapidly with increasing  $p_{T,K}$  and is roughly constant as a function of  $|\eta_K|$ . The  $p_K < 800$  MeV cut is clearly visible in figure 5.11 as the sharp drop of the efficiency to zero on the right. The reconstructed  $p_{T,K}$  and  $|\eta_K|$  may differ from the generated  $p_{T,K}$  and  $|\eta_K|$  due to the finite resolution and this leads to migration between different  $p_{T,K}$  and  $|\eta_K|$  bins.

In most bins the ratio of the number of accepted tracks in the fiducial volume ( $N_{\text{trk}}$ ) to the tracking efficiency yields the number of generated particles. But at the edges of the fiducial volume this ratio overestimates the number of generated particles:

$$\frac{N_{\text{trk}}(p_{T,K}, |\eta_K|)}{\epsilon_{\text{rec}}(p_{T,K}, |\eta_K|)} \geq N_{\text{gen}}(p_{T,K}, |\eta_K|). \quad (5.5)$$

This overestimation is caused by migration of tracks into the fiducial volume, while their generated particle is outside this volume. Thus these tracks falsely increase the tracking efficiency in

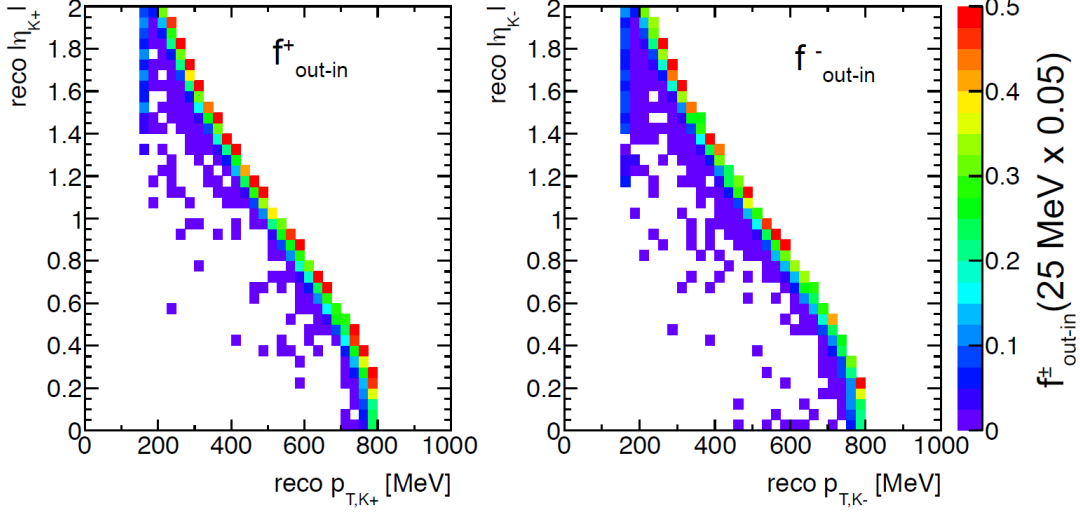


Figure 5.12: The fraction of accepted positive (left) and negative (right) tracks that are reconstructed inside the fiducial volume, while their associated truth particle is outside this volume is estimated from PYTHIA 6.

equation 5.5, while their generated particle is not considered in equation 5.4. To correct for this so-called *migration* effect, a correction factor  $f_{\text{out-in}}^{\pm}$  is estimated from PYTHIA 6 as the ratio of the number of accepted tracks with their generated particle outside the fiducial volume to the total number of accepted tracks. This migration is non-negligible especially for tracks with higher momenta.

Figure 5.12 shows  $f_{\text{out-in}}^{\pm}(p_{T,K}, |\eta_K|)$ . The largest corrections are expected at the edges of the acceptance region of  $N_{\text{gen}}$  in figure 5.11, because this is where tracks may migrate into the fiducial volume. The migration correction is small at low  $p_{T,K}$ . It is very unlikely that a track with  $p_{T,K} > 230$  MeV originates from a generated particle with  $p_{T,K} < 150$  MeV (the  $p_{T,K}$  resolution is of the order of MeV). The largest migration results from the  $p_K > 800$  MeV requirement and can reach about 50% in some bins.

To use the tracking efficiency correction to estimate the number of accepted  $\phi(1020)$ -mesons,  $\epsilon_{\text{rec}}$  and  $f_{\text{out-in}}$  are accounted for per positive or negative track in a track pair as a weight  $w_{\text{rec}}$  for the invariant mass:

$$w_{\text{rec}} = \frac{1 - f_{\text{out-in}}^+}{\epsilon_{\text{rec}}^+} \cdot \frac{1 - f_{\text{out-in}}^-}{\epsilon_{\text{rec}}^-}. \quad (5.6)$$

The effectiveness of the correction  $w_{\text{rec}}$  as a function of  $p_{T,\phi}$  and  $|y_\phi|$  is tested using a sample with generated  $\phi \rightarrow K^+K^-$  decays and illustrated in figure 5.13. The tracking efficiency improves with increasing  $p_{T,\phi}$  and is approximately stable as a function of  $|y_\phi|$ . The agreement between the efficiency-corrected number of decays and the generated data demonstrates the validity of the procedure to within 2%.

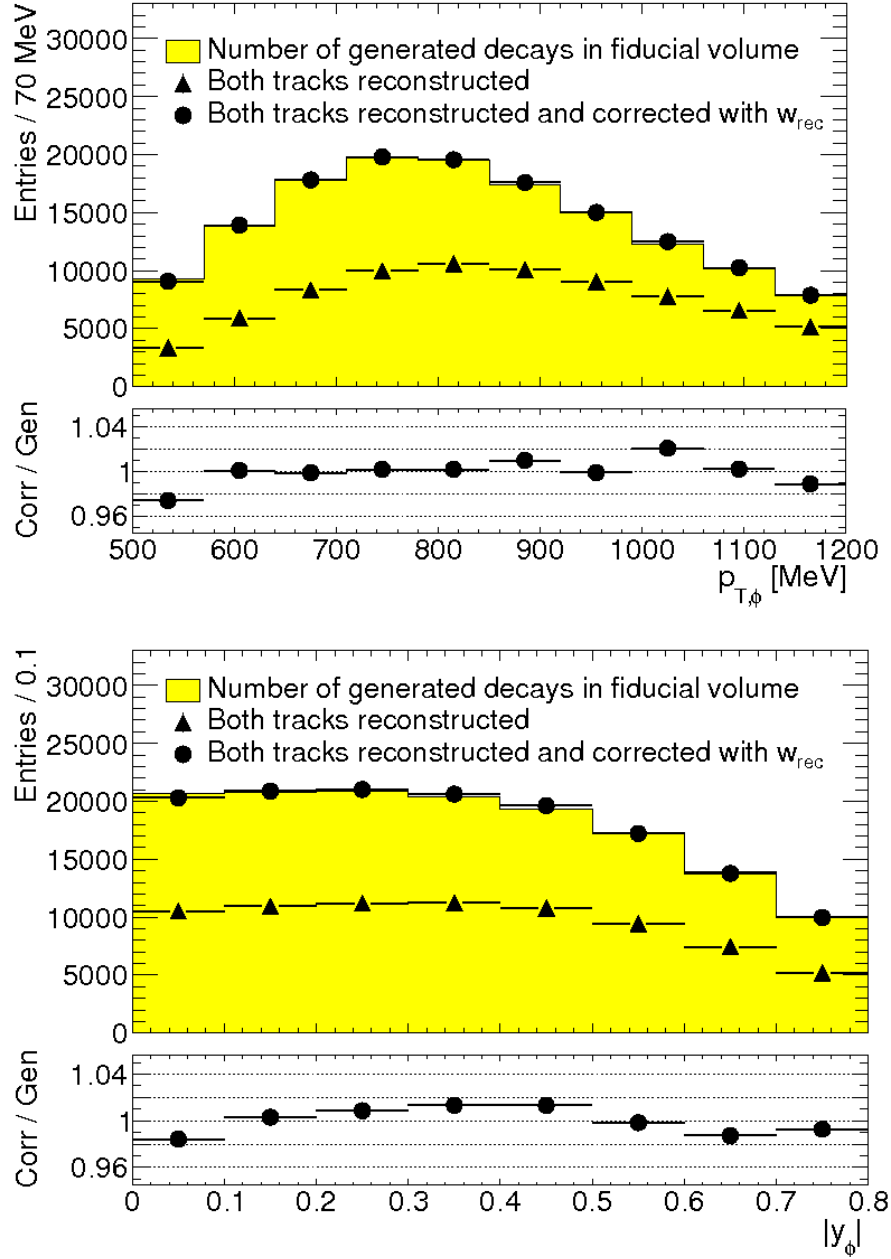


Figure 5.13: Reconstructed distributions of  $p_{T,\phi}$  and  $|y_\phi|$  for a generated sample of  $\phi(1020)$ -mesons. The solid histogram shows all  $\phi \rightarrow K^+K^-$  decays generated in the fiducial volume, the lower set of points with error bars shows the number of candidates for which both tracks are reconstructed and the upper set of points shows the reconstructed candidates after applying the efficiency corrections in equation 5.6. The agreement between the efficiency-corrected points and the generated data, also shown in the ratio plot at the bottom, demonstrates the validity of these correction factors to within 2%.

### Systematic uncertainty in the tracking efficiency determination

Several systematic effects add to the determination of the tracking efficiency correction. The largest contribution arises from uncertainties in the description of the amount and the location of detector and support materials.

#### Monte Carlo material description

It is difficult to get an exact description of the amount and the location of detector and support materials for a large and complex system as ATLAS. The tracking efficiency systematics due to uncertainties in the Monte Carlo material description are calculated in [131] and included here. The uncertainties range from 2 to 7% and are relative to the corresponding tracking efficiency.

To evaluate the effect of the material description on the tracking efficiency, two tests are conducted on a test sample. Firstly, the yield is extracted three times with three different methods in each bin. For the first fit the nominal tracking efficiency is used, for the second and third fit the fitting parameters are fixed and the nominal tracking efficiency plus or minus the relative uncertainty is used. Secondly, a percentage of tracks are removed according to the expected uncertainty on the tracking efficiency. Track pairs are found as usual and the yield in each bin is extracted. The variation on the yield, in this case only a downwards fluctuation, is compared to the yield with the nominal tracking efficiency and the difference is interpreted as the uncertainty on the cross section. The measured fluctuations on the extracted yield agree within statistical uncertainty for these two tests. The measured variation on the yield,  $\epsilon_{\text{rec}}(\text{material})$ , is interpreted as the systematic uncertainty on the cross section due to the material description and summarized in table 5.3.

#### Relative efficiency

The tracking efficiency is measured using the number of generated particles in simulation. The true number of particles produced in a  $pp$  collision is of course unknown. To estimate the quality of the Monte Carlo description for  $\epsilon_{\text{rec}}$  in data, the relative efficiency  $\epsilon_{\text{rel}}$ , a quantity independent of the number of generated particles is used. The relative efficiency is calculated as the fraction of the number of tracks passing all cuts in bins of pseudorapidity by the number of tracks passing the cuts, with one cut relaxed:

$$\epsilon_{\text{rel}} = \frac{\epsilon_{\text{cuts}}}{\epsilon_{\text{cuts}-1}} = \frac{N_{\text{rec}}(\text{cuts})/N_{\text{gen}}}{N_{\text{rec}}(\text{cuts}-1)/N_{\text{gen}}} = \frac{N_{\text{rec}}(\text{cuts})}{N_{\text{rec}}(\text{cuts}-1)}. \quad (5.7)$$

The cut on track  $p_T$  is raised from  $p_T > 150$  MeV to  $p_T > 170$  MeV, because relaxing the cut added very little tracks.

The behavior of  $\epsilon_{\text{rel}}$  with one fewer pixel cluster, one fewer SCT hit per track and a 10 MeV higher momentum cut is compared between two Monte Carlo samples and data and found to be consistent up to the one percent level, see figure 5.14. The systematic uncertainty on the tracking efficiency inferred is 0.5% per track and thus 0.7% per track pair.

#### Migration

The systematic uncertainty due to the migration into the fiducial volume is estimated by recalculating the migration matrices as depicted in figure 5.12 after re-weighting the truth  $p_K$



| Bin                       | $\epsilon_{\text{rec}}(\text{material})$ | Migration | Bin [MeV]                     | $\epsilon_{\text{rec}}(\text{material})$ | Migration |
|---------------------------|------------------------------------------|-----------|-------------------------------|------------------------------------------|-----------|
| $0.0 <  y_\phi  \leq 0.1$ | 4%                                       | <0.1%     | $500 < p_{T,\phi} \leq 570$   | 6%                                       | <0.1%     |
| $0.1 <  y_\phi  \leq 0.2$ | 4%                                       | <0.1%     | $570 < p_{T,\phi} \leq 640$   | 6%                                       | <0.1%     |
| $0.2 <  y_\phi  \leq 0.3$ | 4%                                       | <0.1%     | $640 < p_{T,\phi} \leq 710$   | 6%                                       | <0.1%     |
| $0.3 <  y_\phi  \leq 0.4$ | 4%                                       | <0.1%     | $710 < p_{T,\phi} \leq 780$   | 6%                                       | <0.1%     |
| $0.4 <  y_\phi  \leq 0.5$ | 5%                                       | <0.1%     | $780 < p_{T,\phi} \leq 850$   | 5%                                       | <0.1%     |
| $0.5 <  y_\phi  \leq 0.6$ | 5%                                       | <0.1%     | $850 < p_{T,\phi} \leq 920$   | 5%                                       | <0.1%     |
| $0.6 <  y_\phi  \leq 0.7$ | 5%                                       | <0.2%     | $920 < p_{T,\phi} \leq 990$   | 4%                                       | <0.2%     |
| $0.7 <  y_\phi  \leq 0.8$ | 5%                                       | 1%        | $990 < p_{T,\phi} \leq 1060$  | 4%                                       | 1%        |
|                           |                                          |           | $1060 < p_{T,\phi} \leq 1130$ | 4%                                       | 1%        |
|                           |                                          |           | $1130 < p_{T,\phi} \leq 1200$ | 4%                                       | 2%        |

Table 5.3: The systematic uncertainty on the cross section as a result of uncertainties on the track reconstruction efficiency, due to the Monte Carlo material description and as a result of migration into the fiducial volume.

spectrum to data. Using these re-weighted migration matrices, the number of efficiency-corrected decays in figure 5.13 is calculated again. The relative difference between the number of efficiency-corrected decays with and without the re-weighting is interpreted as the systematic uncertainty on cross section due to the migration correction. The effect is about 2% for the highest  $p_{T,\phi}$  bin and 1% for the second and third and highest  $p_{T,\phi}$  bin and negligible for the other bins as summarized in table 5.3.

#### Statistical uncertainty of tracking efficiency

The average tracking efficiency for the two tracks of a  $\phi \rightarrow K^+ K^-$  candidate in a bin is calculated as

$$\epsilon_{\text{rec},\phi} = \frac{N_i}{\sum_i N_i w_{\text{rec}}}, \quad (5.8)$$

where  $N_i$  is the number of extracted decays. It is clear that the nominator and denominator are completely correlated. Therefore, binomial error propagation is used for the calculation of the statistic uncertainty on  $\epsilon_{\text{rec},\phi}$ . For details, see the explanation on the kaon identification efficiency uncertainty in section 5.4.2. The statistical uncertainty on  $\epsilon_{\text{rec},\phi}$  is 2% maximal and included on the cross section as a systematic uncertainty.

#### Total systematic uncertainty in the tracking efficiency determination

To arrive at the total systematic uncertainty in the tracking efficiency determination, the uncertainties in the Monte Carlo material description (maximum of 6%), from the statistical uncertainty on  $\epsilon_{\text{rec}}$  (maximum of 2%), from the migration correction (maximum of 2%) and from the comparison of the relative efficiency in data and simulation (0.7%) are added in quadrature, under the assumption that they are uncorrelated.

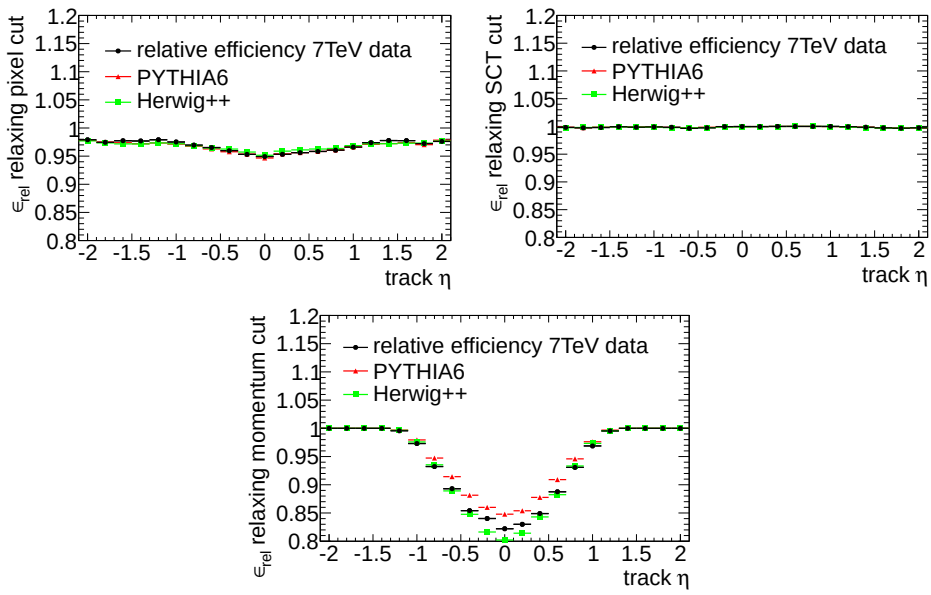


Figure 5.14: The division for the number of tracks passing all cuts by the number of tracks with one less pixelcluster (left), one less SCT hit (right) and for a somewhat looser cut on track momentum (lower) for data (bots) PYTHIA 6 (squares) and HERWIG++ (triangles).

### Monte Carlo truth matching

For some cross checks the Monte Carlo truth distributions without detector simulation are used. To compare generated and reconstructed variables, one can match a simulated and reconstructed particle with a generated particle. This “matching” is not completely straight forward and a pragmatic approach is needed. The matching is done at digitization level using the ratio of the number of inner detector hits which are common to a given track and the generated particles in the event and the number of hits on the track. The probability that a track originates from a generated particle is calculated giving (common) hits from the different sub-detectors different weights:

$$P_{\text{match}} = \frac{10 \cdot N_{\text{pix}}^{\text{common}} + 5 \cdot N_{\text{SCT}}^{\text{common}} + 1 \cdot N_{\text{TRT}}^{\text{common}}}{10 \cdot N_{\text{pix}}^{\text{track}} + 5 \cdot N_{\text{SCT}}^{\text{track}} + 1 \cdot N_{\text{TRT}}^{\text{track}}}. \quad (5.9)$$

The weights reflect the average number of hits in the tracking detector.

If  $P_{\text{match}} > 0.55$  the track is assumed to originate from the generated particle and the generated variables for the particle are used as the “truth” information for the corresponding track. It was checked that less than 0.01% of the tracks passing the tracking cuts are not matched to any generated particle.

### 5.4.2 Kaon identification

The particle identification (PID) efficiency is determined separately for positive and negative kaons as a function of both  $p_K$  and  $|\eta_K|$ . Figure 5.15 shows distributions of  $p_{T,\phi}$  and  $|y_\phi|$  in simulated events, compared to the true distributions, where the event-by-event PID efficiency has been corrected using two different techniques. In one case, the PID efficiency is calculated only as a function of the kaon momentum, averaging over the observed  $|\eta_K|$  distribution. This approach captures the behavior of the true distributions but does not describe the details particularly well. The second method treats the PID efficiency as a function of both  $p_K$  and  $|\eta_K|$  and, as expected, does a better job describing the true distributions.

For the data, we use a hybrid approach. The  $|\eta_K|$  dependence of  $\epsilon_{\text{pid}}$  is taken from simulation, while the  $p_K$  dependence of  $\epsilon_{\text{pid}}$  is measured using a data-driven method. The size of the available data sample limits this method to five bins in  $p_K$  and prevents extracting the  $|\eta_K|$  dependence from data as well. Figure 5.16 shows the  $p_K, |\eta_K|$  dependence of  $\epsilon_{\text{pid}}^+$  as measured in simulated events. Since most of the observed structure in this figure is along the  $p_K$  direction, our hybrid approach where the  $|\eta_K|$  dependence is taken from simulation yields stable results by construction.

The kaon identification efficiency is measured in data with a tag-and-probe method. In general one needs a mass resonance in order to calculate an efficiency this way. The method is based on a possibility to count the number of “tag” instances, of which the number of “probe” instances is an independent subset. The tag-and-probe efficiency is then defined as:

$$\epsilon_{\text{TnP}} = \frac{N_{\text{probe}}}{N_{\text{tag}}}. \quad (5.10)$$

To use tag-and-probe to measure the kaon identification efficiency for positive kaons the  $\phi$ -meson yield is extracted with the fitting procedure as will be explained in section 6.1. To

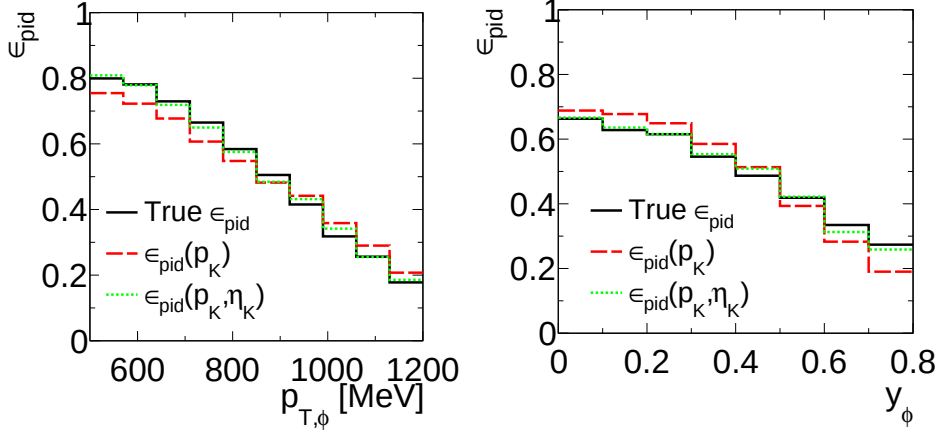


Figure 5.15: Distributions of  $p_{T,\phi}$  and  $|y_\phi|$  in simulated events for two PID efficiency methods compared to the true distributions. The dashed curve shows the distributions if PID efficiencies are calculated as a function of  $p_K$  only, and is seen to provide an approximate description of the true distributions, shown as the solid curve. The dotted curve, however, where PID efficiencies are calculated as a function of both  $p_K$  and  $|\eta_K|$ , is seen to provide a much better description.

obtain  $N_{\text{tag}}^-$ , only the negative kaons are required to pass the PID cuts. Because the  $\phi$  meson decays through  $\phi \rightarrow K^+ K^-$ , we know that this procedure also yields  $N_{\text{tag}}^-$  positive kaons. In the next step both kaons are to pass the PID requirements and the number of extracted  $\phi$ -mesons corresponds to  $N_{\text{probe}}$  and  $\epsilon_{\text{pid,TnP}}$  for positive kaons is measured as

$$\epsilon_{\text{pid,TnP}}^+ = \frac{N_{\text{probe}}}{N_{\text{tag}}^-}. \quad (5.11)$$

The signal yields  $N_{\text{tag}}^-$  and  $N_{\text{probe}}$  for  $400 < p_K < 500$  MeV are illustrated in figure 5.17. The relative error on  $N_{\text{tag}}^-$  is larger, because the signal over background ratio in the tag sample is lower, which leads to the background fit having a larger weight. Using equation 5.11 and binomial error propagation  $\epsilon_{\text{pid,TnP}} = 0.872 \pm 0.005$ .

Applying standard error propagation the uncertainty on  $\epsilon_{\text{pid,TnP}}$  would yield:

$$\sigma_\epsilon^2 = \left( \frac{\partial \epsilon}{\partial N_{\text{probe}}} \right)^2 \sigma_{N_{\text{probe}}}^2 + \left( \frac{\partial \epsilon}{\partial N_{\text{tag}}} \right)^2 \sigma_{N_{\text{tag}}}^2 = \left( \frac{N_{\text{probe}}}{N_{\text{tag}}} \right)^2 \left[ \frac{1}{N_{\text{probe}}} + \frac{1}{N_{\text{tag}}} \right], \quad (5.12)$$

but equation 5.12 assumes  $N_{\text{tag}}$  and  $N_{\text{probe}}$  to be uncorrelated, which they are not, since  $N_{\text{probe}}$  is a subset of  $N_{\text{tag}}$ . The uncorrelated variables are  $N_{\text{probe}}$  and  $N_{\text{rest}} = N_{\text{tag}} - N_{\text{probe}}$ . Using the uncorrelated variables [132]:

$$\begin{aligned} \sigma_\epsilon^2 &= \left( \frac{\partial \epsilon}{\partial N_{\text{probe}}} \right)^2 \sigma_{N_{\text{probe}}}^2 + \left( \frac{\partial \epsilon}{\partial N_{\text{rest}}} \right)^2 \sigma_{N_{\text{rest}}}^2 \\ &= \left( \frac{1}{N_{\text{tag}}} \right) \left( \frac{N_{\text{probe}}}{N_{\text{tag}}} \right) \left( \frac{N_{\text{rest}}}{N_{\text{tag}}} \right) = \frac{\epsilon(1-\epsilon)}{N_{\text{tag}}}, \end{aligned} \quad (5.13)$$

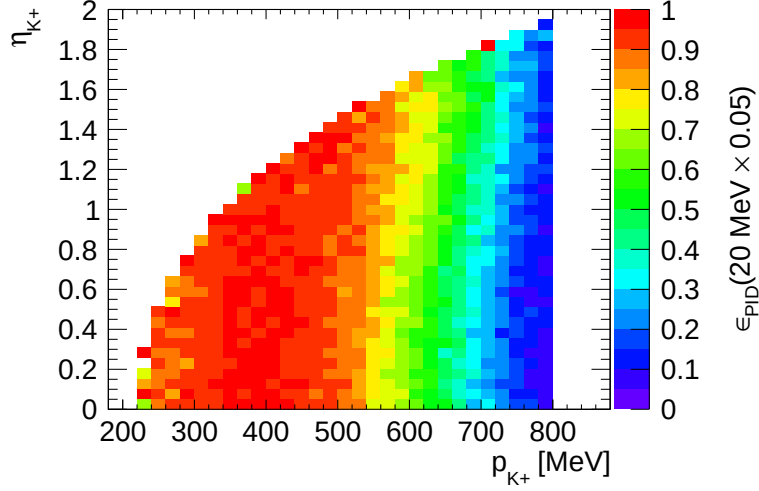


Figure 5.16: The kaon identification efficiency measured using simulation for positive kaons.

| Bin [MeV]            | Data                      |                           | PYTHIA 6                  |                           |
|----------------------|---------------------------|---------------------------|---------------------------|---------------------------|
|                      | $\epsilon_{\text{pid}}^+$ | $\epsilon_{\text{pid}}^-$ | $\epsilon_{\text{pid}}^+$ | $\epsilon_{\text{pid}}^-$ |
| $230 < p_K \leq 400$ | $0.918 \pm 0.004$         | $0.914 \pm 0.004$         | $0.943 \pm 0.002$         | $0.914 \pm 0.003$         |
| $400 < p_K \leq 500$ | $0.872 \pm 0.005$         | $0.871 \pm 0.004$         | $0.940 \pm 0.002$         | $0.924 \pm 0.003$         |
| $500 < p_K \leq 600$ | $0.622 \pm 0.007$         | $0.622 \pm 0.007$         | $0.798 \pm 0.004$         | $0.790 \pm 0.004$         |
| $600 < p_K \leq 700$ | $0.408 \pm 0.004$         | $0.327 \pm 0.004$         | $0.514 \pm 0.006$         | $0.485 \pm 0.006$         |
| $700 < p_K \leq 800$ | $0.066 \pm 0.002$         | $0.068 \pm 0.003$         | $0.207 \pm 0.007$         | $0.190 \pm 0.007$         |

Table 5.4: The extracted PID efficiencies as a function of  $p_K$  using the tag-and-probe method from data and PYTHIA 6.

giving the correct statistical uncertainty on the efficiency, which is generally referred to as the binomial uncertainty.

The extracted efficiencies using the tag-and-probe method from data and PYTHIA 6 are shown in figure 5.18 and they are summarized in table 5.4. If the difference between  $\epsilon_{\text{pid,TnP}}$  for positive and negative kaons is significant, the kaon identification efficiency for positive kaons is larger than for negative kaons. This is to be expected, because the expected number of clusters of pixel hits is larger for positive tracks. The PID efficiency is overestimated in PYTHIA 6 because the relative fraction of tracks with  $P_{\text{kaon}} > 0.95$  is overestimated and the relative fraction of tracks with  $P_{\text{pion}} < 0.01$  is underestimated, see figure 5.9. This underlines the need to use a data-driven method to determine the kaon identification efficiency. It was checked that the tag-and-probe method yields the expected PID efficiency when applied to simulated events from PYTHIA 6.

A final efficiency correction factor  $\epsilon_{\text{pid,corrected}}$  is defined by multiplying the two-dimensional efficiency  $\epsilon_{\text{pid,truth,MC}}$  from simulation (as shown in figure 5.16) by the ratio of data to Monte

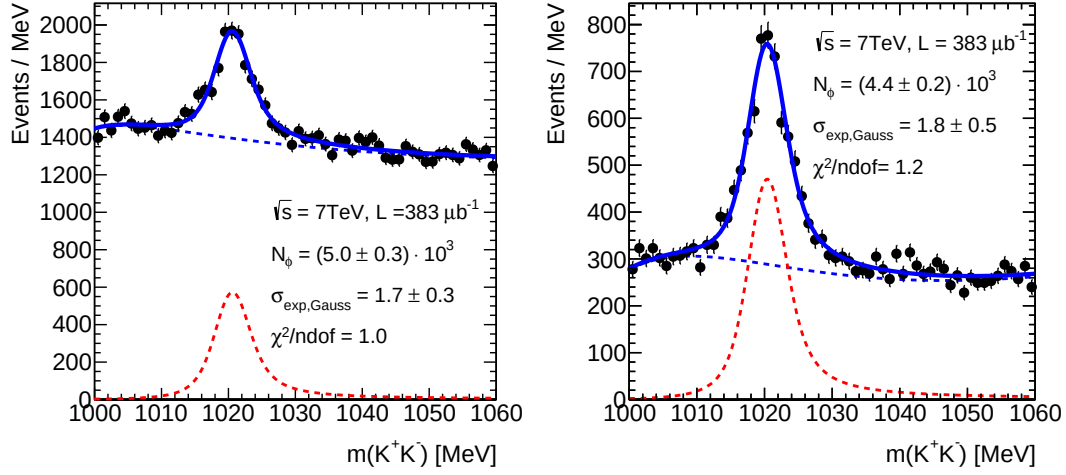


Figure 5.17:  $N_{\text{tag}}$  (left) and  $N_{\text{probe}}$  for  $400 < p_{K^+} \leq 500$  MeV that are used for the determination of  $\varepsilon_{\text{pid}}$ .

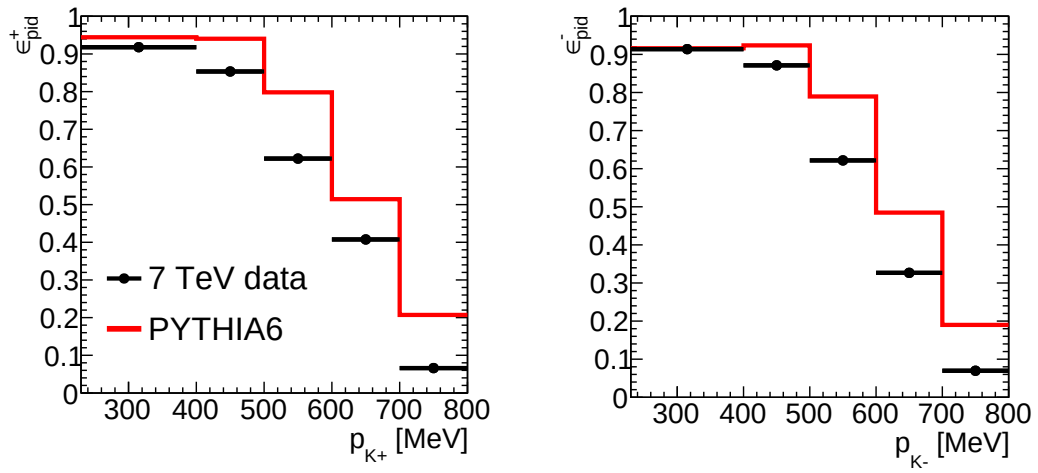


Figure 5.18: The PID efficiencies for positive kaons  $\varepsilon_{\text{pid}}^+$  (left) and negative kaons  $\varepsilon_{\text{pid}}^-$  as extracted using the tag-and-probe method from data and PYTHIA 6.

Carlo tag-and-probe efficiencies (as shown in figure 5.18):

$$\epsilon_{\text{pid,corrected}}^{\pm} = \epsilon_{\text{pid,truth,MC}}^{\pm} \cdot (\epsilon_{\text{pid,TnP}}^{\pm} / \epsilon_{\text{pid,TnP,MC}}^{\pm}) \quad (5.14)$$

and a weight  $w_{\text{pid}}$

$$w_{\text{pid}} = \frac{1}{\epsilon_{\text{pid,corrected}}^{+} \cdot \epsilon_{\text{pid,corrected}}^{-}} \quad (5.15)$$

is given to the kaons from a  $\phi \rightarrow K^{+}K^{-}$  candidate decay before yield extraction.

The size and accuracy of the PID correction in as a function of  $p_{T,\phi}$  and  $|y_{\phi}|$  is shown in figure 5.19. The PID efficiency decreases with increasing  $p_{T,\phi}$  and  $|y_{\phi}|$  due to the average increase in  $p_K$ . The agreement between the efficiency-corrected number of decays and the number of  $\phi$ -mesons with both tracks reconstructed demonstrates the validity of the PID correction factor to within 4%.

### Systematic uncertainty in the kaon efficiency determination

Several systematic effects are associated to determination of the correction for the kaon identification efficiency. The largest contribution arises from the yield determination in the tag sample. This contribution and the others are detailed in the next paragraphs.

#### Background normalization

The signal to background ratio in PYTHIA 6 is higher than in data. This may affect the extracted efficiencies using the tag-and-probe method. As the method is validated using PYTHIA 6, the PID efficiency is extracted again, while the background contribution is enhanced by a factor of two by adding the same-sign background to the fitted dataset. This makes the signal to background ratio very similar to data. The extracted PID efficiency differs from the extracted PID efficiency without the extra background contribution by a maximum of 2% for all bins, but by 7% for the bin  $600 < p_K < 700$  MeV.

The expected number of reconstructed decays in PYTHIA 6 as a function of  $p_{T,\phi}$  and  $|y_{\phi}|$  varies with a maximum of 4% when the background is enhanced in the tag-and-probe. The effect is summarized in table 5.5.

#### Background template tag sample

To test the validity of the background template for the extraction of  $N_{\text{tag}}$ , the background shape is fitted to the same-sign background sample and the background shape parameters are fixed before yield extraction. The background shape has a larger impact on the fit result with increasing momentum. For kaon momenta up to 600 MeV, the PID efficiency varies with maximum 2%, for  $600 < p_K < 700$  MeV this variation increases to 4% and for  $700 < p_K < 800$  MeV it is 6%. The systematic uncertainty on the cross section is estimated in the same way as above. The variation ranges from 5 to 10% as summarized in table 5.5.

#### Variation of PID requirement

Thirdly, the effect of using a different cut on  $P_K$  on the cross section is evaluated. The extracted tag-and-probe efficiencies when requiring  $P_K > 0.8, 0.84$  and  $0.9$  are shown in figure 5.20. The

| Bin                       | Bkg<br>Norm | Fix bkg<br>shape | Bin [MeV]                     | Bkg<br>Norm | Fix bkg<br>shape |
|---------------------------|-------------|------------------|-------------------------------|-------------|------------------|
| $0.0 <  y_\phi  \leq 0.1$ | 6%          | 2%               | $500 < p_{T,\phi} \leq 570$   | 1%          | 5%               |
| $0.1 <  y_\phi  \leq 0.2$ | 2%          | 7%               | $570 < p_{T,\phi} \leq 640$   | 1%          | 6%               |
| $0.2 <  y_\phi  \leq 0.3$ | 2%          | 7%               | $640 < p_{T,\phi} \leq 710$   | 1%          | 6%               |
| $0.3 <  y_\phi  \leq 0.4$ | 2%          | 8%               | $710 < p_{T,\phi} \leq 780$   | 2%          | 7%               |
| $0.4 <  y_\phi  \leq 0.5$ | 3%          | 8%               | $780 < p_{T,\phi} \leq 850$   | 2%          | 8%               |
| $0.5 <  y_\phi  \leq 0.6$ | 3%          | 9%               | $850 < p_{T,\phi} \leq 920$   | 2%          | 9%               |
| $0.6 <  y_\phi  \leq 0.7$ | 3%          | 9%               | $920 < p_{T,\phi} \leq 990$   | 3%          | 9%               |
| $0.7 <  y_\phi  \leq 0.8$ | 4%          | 9%               | $990 < p_{T,\phi} \leq 1060$  | 4%          | 9%               |
|                           |             |                  | $1060 < p_{T,\phi} \leq 1130$ | 4%          | 10%              |
|                           |             |                  | $1130 < p_{T,\phi} \leq 1200$ | 4%          | 10%              |

Table 5.5: The systematic uncertainty on the cross section as a result of uncertainties on the PID efficiency. See text for explanation.

variation in the extracted efficiencies are of the percent-level. The effect of this systematic would partial cancel, because  $P_K$  would be varied in both data and Monte Carlo in the same time before yield extraction and in the tag-and-probe method. Possible effects are well covered by the uncertainty on the yield extraction in the tag sample, so it is not considered as a separate source of systematic uncertainty.

#### Statistical uncertainty PID efficiency

The average kaon identification efficiency for the two tracks of  $\phi \rightarrow K^+ K^-$  candidate in a bin is calculated as

$$\epsilon_{\text{pid},\phi} = \frac{N_i}{\sum_i N_i w_{\text{pid}}}, \quad (5.16)$$

where  $N_i$  is the number of extracted decays. Again, binomial error propagation is used for the calculation of the statistical uncertainty on  $\epsilon_{\text{pid},\phi}$ . The statistic uncertainty on  $\epsilon_{\text{pid},\phi}$  is about 3% and it is included as a systematic uncertainty on the cross section.

#### Total systematic uncertainty in the PID efficiency determination

To calculate the total systematic uncertainty on the cross section due to the kaon identification efficiency, the uncertainties arising from using a double background contribution (maximum of 4%), from fixing the background shape parameters (maximum of 10%) and from the statistic uncertainty (maximum of 3%) are added in quadrature.



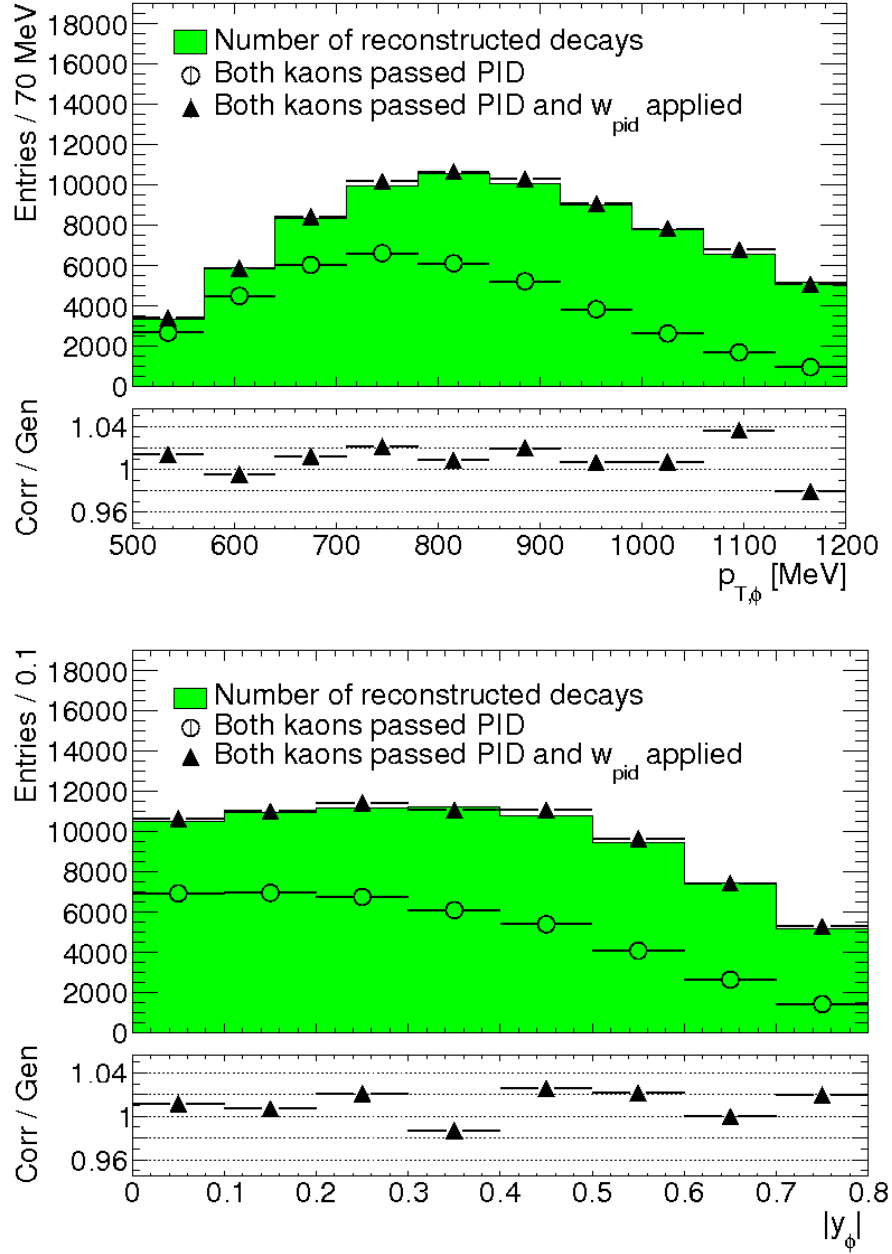


Figure 5.19: Reconstructed distributions of  $p_{T,\phi}$  and  $|y_\phi|$  for a generated sample of  $\phi(1020)$ -mesons. The solid histogram shows all  $\phi \rightarrow K^+K^-$  decays generated in the fiducial volume, for which both tracks are reconstructed, the lower set of points with error bars shows the number of candidates for which both tracks are reconstructed and passed PID requirements and the upper set of points shows the reconstructed candidates after applying the PID corrections in equation 5.15.

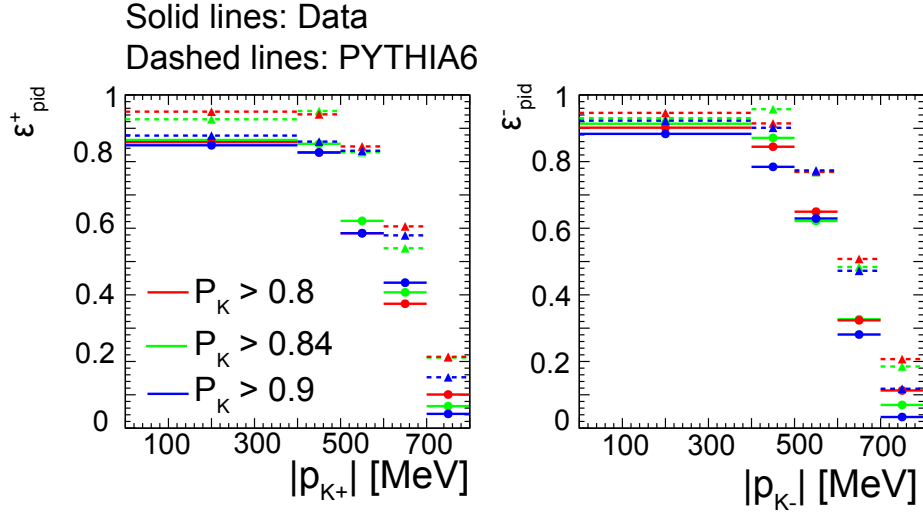


Figure 5.20: The tag-and-probe PID efficiency measured from data (solid lines) and PYTHIA 6 (dashed lines) when requiring  $P_K > 0.8$  (red), 0.84 (green) and 0.9 (blue).

## 5.5 Summary

The selection efficiencies for  $\phi \rightarrow K^+ K^-$  decays in data and simulation are measured in detail. To reconstruct a  $\phi$ -meson candidate, tracks are required to (1) originate from the primary vertex, (2) have opposite charge and (3) pass a requirement on their energy loss in the pixel detector to distinguish kaons from other charged particles, mostly pions.

The track reconstruction efficiency is calculated using simulated data and it increases with increasing  $\phi$ -meson  $p_T$  from about 35% to 65%. The kaon identification efficiency is measured using a data-driven method and decreases with increasing  $\phi$ -meson  $p_T$  from about 65% to 10% in the fiducial range. As a result the kinematic acceptance is limited. The systematic uncertainty on the cross section in the determination of the efficiency corrections arises from e.g. uncertainties in the material description in simulation and depends on  $p_{T,\phi}$  or  $|y_\phi|$ .

## Chapter 6

### The $\phi$ -meson production cross section

In this chapter the  $\phi$ -meson production cross section measured at a centre-of-mass energy of  $\sqrt{s} = 7$  TeV using the  $\phi \rightarrow K^+ K^-$  decay mode is presented. The cross section is compared to predictions from Monte Carlo event generators, based on different underlying physics models. The main result is presented in a *fiducial* volume where the differential cross section can be measured and where the efficiency corrections can be calculated.

The yield extraction from the efficiency-corrected invariant mass spectra is detailed in section 6.1, the systematic effects in the yield determination are detailed in section 6.1.1 and three cross checks that were conducted using simulation are presented in section 6.2. The fiducial cross section will be presented in section 6.3 and an assessment of the systematic uncertainties on this cross section is given. In section 6.4 the corrections for the requirements on kaon momentum are discussed and the extrapolated cross section is presented. First the data are described and the underlying physics agreement of the different generators with the data is discussed in section 6.5.

#### 6.1 Signal extraction

The  $\phi$ -meson cross section is determined as the efficiency-corrected signal yield in each region of phase space divided by the luminosity in the datasample. To find the signal yields,  $N_{\text{reco}}^{i,\text{weighted}}$  in equation 5.2, the efficiency-corrected invariant mass distributions are fitted with a probability density function (p.d.f.) that describes the signal and background contributions separately. Because the  $\phi$ -meson natural width is comparable with the detector resolution, the invariant mass distribution is described by a relativistic Breit–Wigner line shape:

$$f_{\text{RelBW}}(m) = \frac{m^2}{(m^2 - m_\phi^2)^2 + m_\phi^2 \Gamma_\phi^2(m)}, \quad (6.1)$$

where  $m_\phi$  is the  $\phi$ -meson mass of 1019.45 MeV and  $\Gamma_\phi$  is the  $\phi$ -meson width of 4.26 MeV. This signal shape is explained in more detail in appendix A.

To account for the detector resolution, the signal shape is convoluted with a Gaussian resolution function

$$f_{\text{sig}}(m) = f_{\text{RelBW}}(m) \otimes \text{Gauss}(m, \sigma_{\text{exp}}). \quad (6.2)$$

The standard deviation of the Gaussian function,  $\sigma_{\text{exp}}$ , is interpreted as the experimental resolution and is found to be of the order of 1.4–2.5 MeV, depending on  $p_{T,\phi}$  and  $|y_\phi|$ .

This signal description is added to an empirical near-threshold background description [133], which includes the turn-on of the combinatorial distribution at twice the kaon rest-mass:

$$f_{\text{BKG}}(m) = \left(1 - e^{(2m_K - m)/C}\right) \cdot \left(\frac{m}{2m_K}\right)^A + B \left(\frac{m}{2m_K} - 1\right), \quad (6.3)$$

where  $A$ ,  $B$  and  $C$  determine the background shape. Start values for  $A$ ,  $B$  and  $C$  are found by fitting the background p.d.f. to a sample of events where, instead of requiring the kaons to have opposite charge, we make the invariant mass distributions with two kaons of the same charge. This same-sign sample contains the same sources of combinatorial background as the nominal selection but no true  $\phi$ -mesons, and so provides a good initial description of the background shape.

Figure 6.1 shows the invariant mass  $m(K^+K^-)$  distribution for all  $\phi$ -meson candidates in the fiducial volume before corrections for tracking and kaon identification efficiencies. The total number of reconstructed  $\phi$  mesons is  $(4.46 \pm 0.05) \cdot 10^4$ .

In figure 6.2 the uncorrected and the efficiency-corrected invariant mass distributions and fit results are shown for the lowest bin in  $p_{T,\phi}$  and for the most central bin in  $|y_\phi|$ . The fitted values for  $\sigma_{\text{exp}}$  range from  $1.9 \pm 0.1$  MeV to  $2.4 \pm 0.1$  MeV. The fitted values for the position of the peak deviate from expectation in the low  $p_{T,\phi}$  range, the effect being most pronounced in lowest  $p_{T,\phi}$  bin as shown in figure 6.2 a) and b), where the maximum of the signal peak is shifted upwards by  $1.1 \pm 0.1$  MeV. The uncertainty on the momentum scale for the low momentum tracks contributing in this bin is about 0.1%, which may result in the momentum and thus the invariant mass to be overestimated.

Table 6.1 shows the uncorrected fitted number of  $\phi$ -meson candidates in each bin in  $p_{T,\phi}$  and  $|y_\phi|$ . The efficiency-corrected yields are quoted in appendix B. The cross section is expected to decrease as a function of  $p_{T,\phi}$ , but the extracted yield per bin increases over the momentum range  $500 < p_{T,\phi} < 780$  MeV. This is due to the  $p_{T,K} > 230$  MeV requirement having a lower efficiency at low  $p_{T,\phi}$ . The cross section is expected to be roughly constant as a function of rapidity up to  $|y_\phi| < 2$ . The extracted yields decrease as a function of  $|y_\phi|$ , because the cut on kaon momentum  $p_K < 800$  MeV has a bigger impact at more forward rapidity.

### 6.1.1 Systematic uncertainty in yield determination

A non-relativistic Breit–Wigner p.d.f. convoluted with a Gaussian resolution function can be used to extract the signal yield from a resonance in the invariant mass distribution:

$$f_{\text{BW}}(m) = \frac{1}{(m - m_0)^2 + (\Gamma/2)^2}, \quad (6.4)$$

where  $m$  is the two-track invariant mass,  $m_0$  is the position of the peak and  $\Gamma$  is the natural width of the peak. This p.d.f. is also used in the analysis conducted by the ALICE Collaboration [134] to which this measurement is compared. To test the dependence of the choice of signal p.d.f. the signal yields are also extracted using this line-shape. The resulting  $\chi^2/\text{ndof}$  are slightly

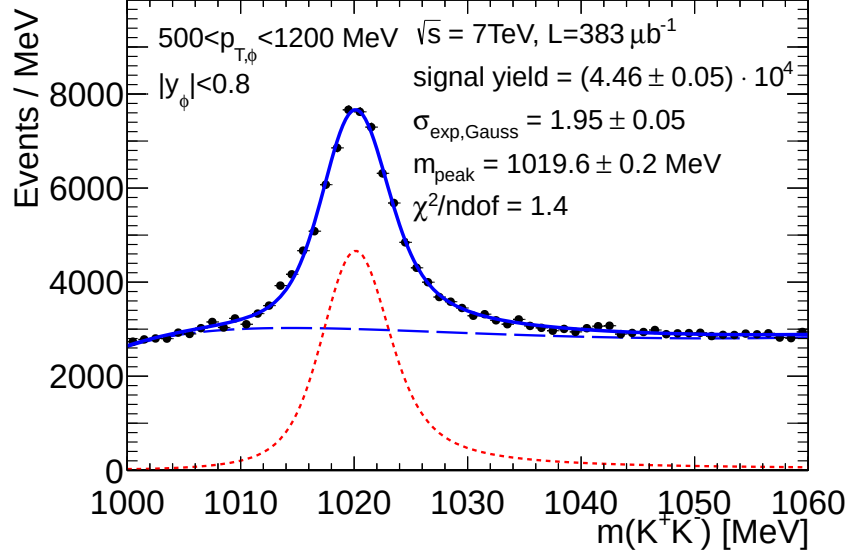


Figure 6.1: Invariant mass  $m(K^+K^-)$  distribution for all  $\phi$ -meson candidates in the fiducial volume before corrections, fitted to the sum of a relativistic Breit–Wigner signal and an empirical near-threshold background description. The black dots are data. The solid blue curve represents the result of the fit, the dashed blue curve the background and the dotted red curve the signal contribution.

| Bin                       | Yield $\cdot 10^3$ | Bin [MeV]                     | Yield $\cdot 10^3$ |
|---------------------------|--------------------|-------------------------------|--------------------|
| $0.0 <  y_\phi  \leq 0.1$ | $8.3 \pm 0.1$      | $500 < p_{T,\phi} \leq 570$   | $3.1 \pm 0.2$      |
| $0.1 <  y_\phi  \leq 0.2$ | $8.3 \pm 0.2$      | $570 < p_{T,\phi} \leq 640$   | $6.0 \pm 0.3$      |
| $0.2 <  y_\phi  \leq 0.3$ | $7.8 \pm 0.2$      | $640 < p_{T,\phi} \leq 710$   | $7.0 \pm 0.2$      |
| $0.3 <  y_\phi  \leq 0.4$ | $6.7 \pm 0.2$      | $710 < p_{T,\phi} \leq 780$   | $7.9 \pm 0.2$      |
| $0.4 <  y_\phi  \leq 0.5$ | $5.9 \pm 0.2$      | $780 < p_{T,\phi} \leq 850$   | $7.0 \pm 0.1$      |
| $0.5 <  y_\phi  \leq 0.6$ | $4.0 \pm 0.2$      | $850 < p_{T,\phi} \leq 920$   | $5.5 \pm 0.2$      |
| $0.6 <  y_\phi  \leq 0.7$ | $2.8 \pm 0.1$      | $920 < p_{T,\phi} \leq 990$   | $3.7 \pm 0.1$      |
| $0.7 <  y_\phi  \leq 0.8$ | $0.92 \pm 0.09$    | $990 < p_{T,\phi} \leq 1060$  | $2.4 \pm 0.3$      |
|                           |                    | $1060 < p_{T,\phi} \leq 1130$ | $1.4 \pm 0.1$      |
|                           |                    | $1130 < p_{T,\phi} \leq 1200$ | $0.64 \pm 0.06$    |

Table 6.1: The fitted number of  $\phi$ -meson candidates before efficiency corrections as a function of  $p_{T,\phi}$  and  $|y_\phi|$ .

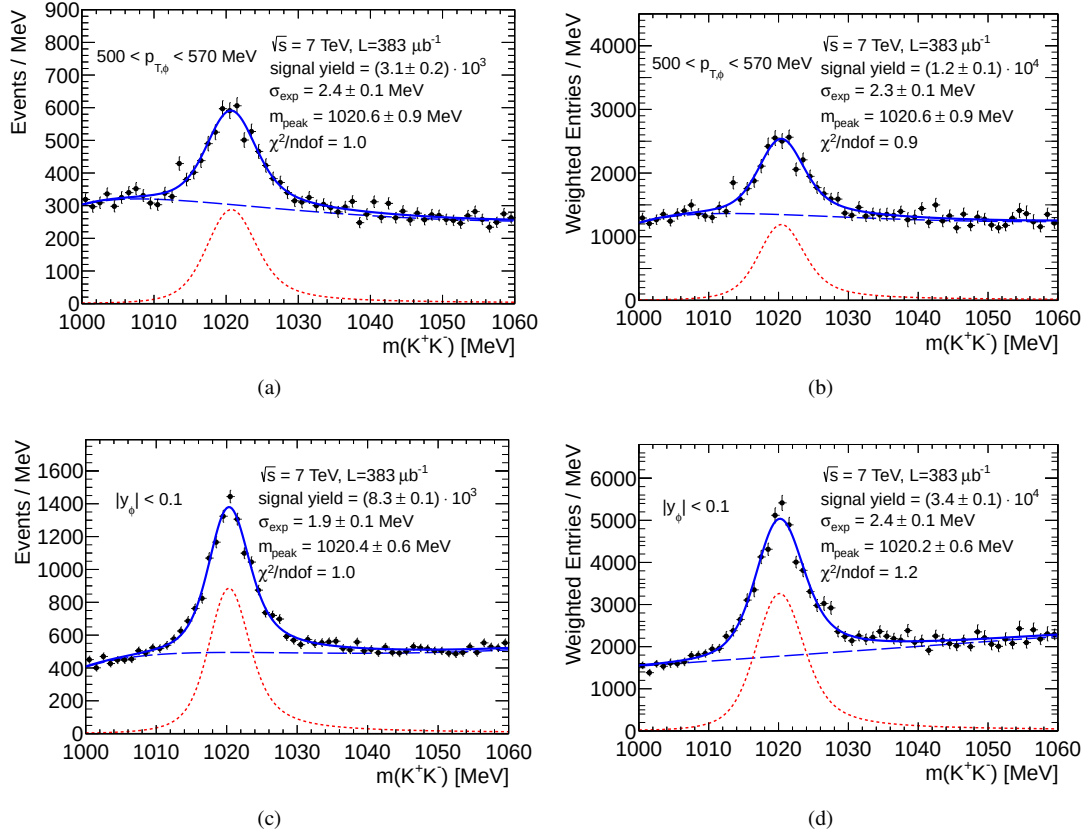


Figure 6.2: The effect of the efficiency corrections on the invariant mass distribution is shown for the lowest  $p_{T,\phi}$  bin in a) and b) and for the most central bin in  $|y_\phi|$  in c) and d). The invariant mass distributions in a) and c) have not been corrected for tracking and kaon identification efficiencies and b) and d) show the fit after event weighted efficiency corrections. The solid blue curves represent the result of the fit, the dashed blue curves the background and the dotted red curves the signal contributions.

worse compared to the fitting results obtained with the relativistic Breit–Wigner, especially in the higher  $p_{T,\phi}$  and  $|y_\phi|$  bins. The maximum variation of 6% on the extracted yield is taken as a systematic uncertainty on the cross section. This test is described here, because it is also used in the ATLAS publication [135] on the  $\phi$ -meson cross section, but we find this systematic test conservative, since the invariant mass distribution should be described by the relativistic Breit–Wigner line-shape.

Another systematic effect may arise from the assumption that the resolution is symmetric and can therefore be best described with a Gaussian resolution function. If the resolution is not symmetric, convolving the signal shape with a Crystal Ball resolution model [125] would yield more reliable fitting results. To test the influence of a different resolution model, a second signal p.d.f. is constructed:

$$f_{\text{sig}}(m) = f_{\text{RelBW}}(m) \otimes CB(m; m_\phi, \sigma_{\text{exp}}, \alpha, n), \quad (6.5)$$

with  $CB$  a Crystal Ball function, that peaks at  $m_\phi$ ,  $\alpha$  the distance from the peak where the Gaussian gives place to a power law behavior in the higher-end tail, and the power coefficient  $n$  describing this tail. The parameters  $\sigma_{\text{exp}}$ ,  $\alpha$  and  $n$  are left free in the fit. The fit quality does not differ significantly using a Gaussian or Crystal Ball. The measured yield differs by a maximum of 2% when using a Crystal Ball resolution model and is taken as a systematic uncertainty on the cross section.

Furthermore, to check the dependence of the measured yield on the choice of the background description, the background p.d.f. is fitted to the same-sign background sample in each bin. The resulting parameters are fixed and they are used to calculate the signal yield. The extracted yields vary by a maximum of 3% and this variation is interpreted as a systematic uncertainty on the cross section.

The uncertainties correlated with the choice of line-shape, resolution function and background description are assumed to be uncorrelated. Adding the different components in quadrature yields a conservative estimate of a total systematic uncertainty of a maximum of 7% on the cross section.

## 6.2 Monte Carlo cross checks

To validate the entire sequence of selection criteria and correction algorithms a Monte Carlo only study is presented. The ultimate consistency test is proving that the number of events generated equals the number of selected and corrected events after detector simulation. Since there are no differences in these event sets, such a test is usually called a *closure test*. The result of the closure test is presented in figure 6.3. The uncertainty on the number of reconstructed decays reflects the statistical and systematic uncertainty on the signal yield determination and the statistical uncertainties on tracking and kaon identification efficiencies. The closure test shows validity of the full  $\phi$ -meson reconstruction to within 4%.

To test the dependence of the validity of the reconstruction on the underlying  $p_{T,\phi}$  and  $|y_\phi|$  distributions, the test was partly repeated using fully reconstructed events from the HERWIG++ generator. The  $p_{T,\phi}$  distribution from HERWIG++ is steeper than from PYTHIA 6, as will be seen in section 6.5. Low statistics in the HERWIG++ sample do not allow for yield extraction

| Bin [MeV]                     | $\langle \epsilon_{\text{rec}} \rangle$ | $\langle \epsilon_{\text{pid}} \rangle$ | $\langle \epsilon_{\text{tot}} \rangle$ | $A_{\text{fid}}$ | $A_{\text{av}}$ |
|-------------------------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|------------------|-----------------|
| $500 < p_{T,\phi} \leq 570$   | 0.36                                    | 0.80                                    | 0.29                                    | 0.37             | 0.11            |
| $570 < p_{T,\phi} \leq 640$   | 0.42                                    | 0.76                                    | 0.32                                    | 0.57             | 0.18            |
| $640 < p_{T,\phi} \leq 710$   | 0.47                                    | 0.72                                    | 0.34                                    | 0.76             | 0.26            |
| $710 < p_{T,\phi} \leq 780$   | 0.51                                    | 0.66                                    | 0.34                                    | 0.89             | 0.30            |
| $780 < p_{T,\phi} \leq 850$   | 0.54                                    | 0.58                                    | 0.31                                    | 0.93             | 0.29            |
| $850 < p_{T,\phi} \leq 920$   | 0.58                                    | 0.52                                    | 0.30                                    | 0.89             | 0.27            |
| $920 < p_{T,\phi} \leq 990$   | 0.60                                    | 0.43                                    | 0.26                                    | 0.82             | 0.21            |
| $990 < p_{T,\phi} \leq 1060$  | 0.64                                    | 0.34                                    | 0.22                                    | 0.74             | 0.16            |
| $1060 < p_{T,\phi} \leq 1130$ | 0.64                                    | 0.26                                    | 0.17                                    | 0.66             | 0.11            |
| $1130 < p_{T,\phi} \leq 1200$ | 0.65                                    | 0.19                                    | 0.12                                    | 0.55             | 0.07            |
| Bin                           | $\langle \epsilon_{\text{rec}} \rangle$ | $\langle \epsilon_{\text{pid}} \rangle$ | $\langle \epsilon_{\text{tot}} \rangle$ | $A_{\text{fid}}$ | $A_{\text{av}}$ |
| $0.0 <  y_\phi  \leq 0.1$     | 0.51                                    | 0.66                                    | 0.34                                    | 0.83             | 0.28            |
| $0.1 <  y_\phi  \leq 0.2$     | 0.53                                    | 0.64                                    | 0.34                                    | 0.83             | 0.28            |
| $0.2 <  y_\phi  \leq 0.3$     | 0.54                                    | 0.60                                    | 0.33                                    | 0.82             | 0.27            |
| $0.3 <  y_\phi  \leq 0.4$     | 0.55                                    | 0.54                                    | 0.30                                    | 0.80             | 0.24            |
| $0.4 <  y_\phi  \leq 0.5$     | 0.56                                    | 0.50                                    | 0.28                                    | 0.77             | 0.21            |
| $0.5 <  y_\phi  \leq 0.6$     | 0.55                                    | 0.43                                    | 0.24                                    | 0.69             | 0.16            |
| $0.6 <  y_\phi  \leq 0.7$     | 0.53                                    | 0.36                                    | 0.19                                    | 0.56             | 0.11            |
| $0.7 <  y_\phi  \leq 0.8$     | 0.52                                    | 0.28                                    | 0.14                                    | 0.40             | 0.06            |

Table 6.2: The expected average acceptance from PYTHIA 6.  $\langle \epsilon_{\text{tot}} \rangle$  is defined as  $\langle \epsilon_{\text{rec}} \rangle \cdot \langle \epsilon_{\text{pid}} \rangle$  and is interpreted as the average efficiency to reconstruct a  $\phi \rightarrow K^+ K^-$  decay that was generated in the fiducial region. See text for detailed explanation.

with the fit, but the number of signal events in each region of phase space was counted after efficiency corrections. The number of selected and corrected decays agrees within statistical uncertainty with the number of generated decays. With these tests we have shown that our data-driven method for  $\phi$ -meson reconstruction works, regardless of the underlying physics model.

The bias and resolution for the reconstruction of  $p_{T,\phi}$  and  $|y_\phi|$  is obtained from simulation. This is done by taking the mean and standard deviation of the distributions of

$$\Delta p_{T,\phi} = p_{T,\phi,\text{true}} - p_{T,\phi,\text{reco}}, \quad \Delta |y_\phi| = |y_{\phi,\text{true}}| - |y_{\phi,\text{reco}}|. \quad (6.6)$$

The mean and standard deviation,  $\sigma$ , of the distributions of  $\Delta p_{T,\phi}$  and  $\Delta |y_\phi|$  are shown in figures 6.4 and 6.5. The reconstruction is found to have no significant bias and a resolution of  $\sim 25\%$  and  $\sim 10\%$  of the binwidth in  $p_{T,\phi}$  and  $|y_\phi|$ , respectively. This proves that no additional unfolding in terms of  $\phi$ -meson kinematics is needed.

Finally, the average acceptance, defined as the fraction of the number of simulated decays in the probe sample (both kaons passed tracking and kaon identification requirements) divided by the total number of simulated decays, is examined. The average acceptance,  $A_{\text{av}}$ , is calculated using PYTHIA 6 as:

$$A_{\text{av}} = \langle \epsilon_{\text{rec}} \rangle \cdot \langle \epsilon_{\text{pid}} \rangle \cdot A_{\text{fid}}, \quad (6.7)$$

where the average tracking efficiency,  $\langle \epsilon_{\text{rec}} \rangle$ , the average kaon identification efficiency  $\langle \epsilon_{\text{pid}} \rangle$  and the fiducial acceptance,  $A_{\text{fid}}$ , are calculated using PYTHIA 6. The number of reconstructed



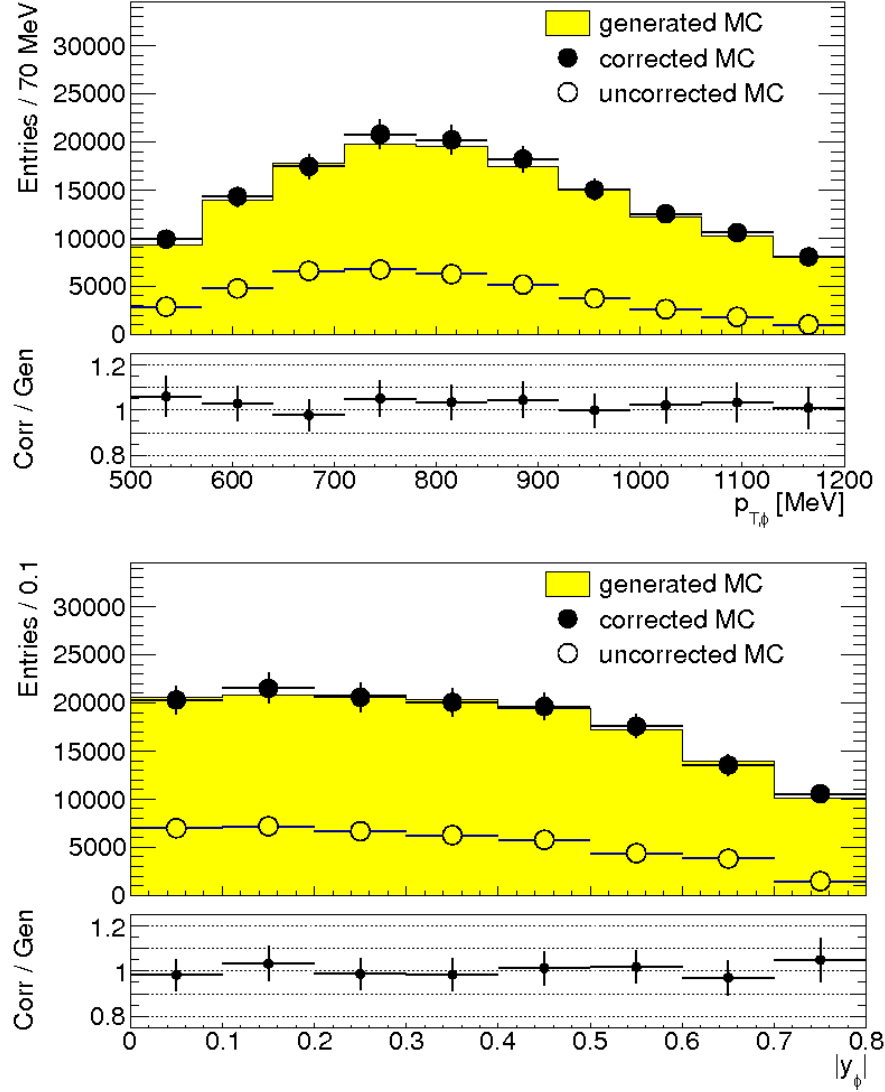


Figure 6.3: Consistency test of the full analysis chain as a function of  $p_{T,\phi}$  and  $|y_\phi|$ . The solid histogram shows all  $\phi \rightarrow K^+K^-$  decays generated in the fiducial volume, the lower set of open points shows the number of candidates that pass all selections and the upper set of points shows the reconstructed candidates after applying the efficiency corrections.

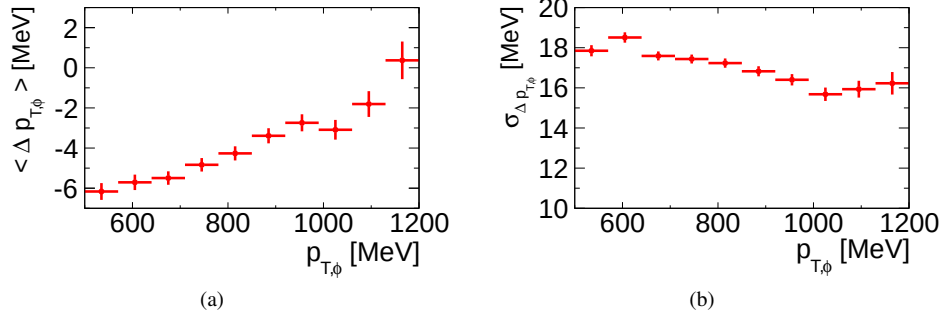


Figure 6.4: The a) mean and b) resolution for the reconstruction of  $p_{T,\phi}$  obtained using generated  $\phi \rightarrow K^+ K^-$  decays from PYTHIA 6.

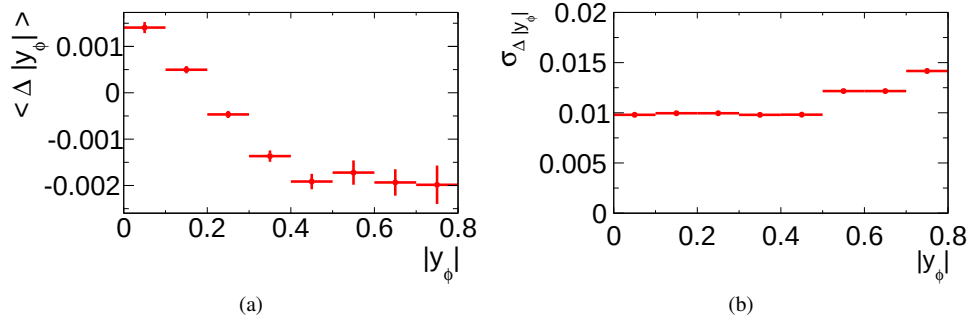


Figure 6.5: The a) mean and b) resolution for the reconstruction of  $|y_\phi|$  obtained using generated  $\phi \rightarrow K^+ K^-$  decays from PYTHIA 6.

decays is found after applying tracking and kaon identification efficiencies event-by-event in terms of the kaon kinematics, cancelling possible resolution effects. The average acceptance varies between 6–30% and is listed as a function of  $p_{T,\phi}$  and  $|y_\phi|$  in table 6.2.

### 6.3 The differential cross section

The region with accepted  $\phi$ -mesons after the requirements on kaon (transverse) momentum is referred to as the fiducial region. The fiducial cross section is model-independent, because the implementations of the efficiency corrections for tracking and kaon identification are on a track-by-track basis as has been explained in chapter 5. The fiducial volume is limited to  $500 < p_{T,\phi} < 1200$  MeV and  $|y_\phi| < 0.8$ . The measurement is repeated with the same requirements on the momentum of the kaons, but with the  $\phi$ -meson rapidity limited to  $|y_\phi| < 0.5$  to facilitate comparison to the published result from the ALICE Collaboration.

Figure 6.6 shows the fiducial cross section within  $|y_\phi| < 0.8$  as a function of  $p_{T,\phi}$ ,  $\frac{d\sigma(\phi \rightarrow K^+ K^-)}{dp_{T,\phi}}$ , and as a function of rapidity,  $\frac{d\sigma(\phi \rightarrow K^+ K^-)}{dy_\phi}$ . In figure 6.7 the fiducial cross section within  $|y_\phi| < 0.5$  as a function of  $p_{T,\phi}$  is presented. Limiting the  $|y_\phi|$  region yields the same measurement as a function of  $|y_\phi|$ , whereas the cross section as a function of  $p_{T,\phi}$  will be smaller.

For both cases the cross section increases as a function of  $p_{T,\phi}$  in the range 500–700 MeV and decreases from  $p_{T,\phi} \geq 850$  MeV. The increase of the number of measured decays at low  $p_{T,\phi}$  is due to cut on kaon transverse momentum  $p_{T,K} > 230$  MeV. Without requirements on kaon momenta, the cross section is expected to be flat as a function of  $|y_\phi|$  up to  $|y_\phi| \sim 2$ . When the  $\phi$ -meson is produced in the more forward direction, the kaons will have larger momenta and the restriction of  $p_K < 800$  MeV has a bigger impact, invoking the decreasing behavior as a function of  $|y_\phi|$ .

The integrated cross section is obtained as the linear sum of the cross section per bin in  $p_{T,\phi}$  times the binwidth. The sums over ten bins in  $p_{T,\phi}$  and eight bins in  $|y_\phi|$  agree within the uncertainty obtained from the fitting procedure for the yield extraction. The integrated cross section in the fiducial volume with  $|y_\phi| < 0.8$  is

$$|y_\phi| < 0.8: \quad \sigma_{\phi \rightarrow K^+ K^-} = 570 \pm 7 \text{ (stat)} \pm 69 \text{ (syst)} \pm 20 \text{ (lumi)} \mu\text{b}, \quad (6.8)$$

and integrated cross section in the fiducial volume with  $|y_\phi| < 0.5$  is

$$|y_\phi| < 0.5: \quad \sigma_{\phi \rightarrow K^+ K^-} = 423 \pm 5 \text{ (stat)} \pm 50 \text{ (syst)} \pm 15 \text{ (lumi)} \mu\text{b}. \quad (6.9)$$

The statistical uncertainty on the cross section is the same as the statistical uncertainty in the yield determination and as such takes in account the statistical fluctuation of the background. The statistical uncertainty is shown as the error bars in figures 6.6 and 6.7. The systematic uncertainty on the cross section shown as the green bands around the data points in figures 6.6 and 6.7 represents the total systematic uncertainty, excluding the 3.5% uncertainty on the luminosity calculation [136].

The systematic uncertainty stems from several sources in each step of the analysis; yield extraction, tracking and kaon identification efficiency, as determined in chapter 5. Uncertainties in the yield determination are estimated by extraction of the signal with a different signal p.d.f.,

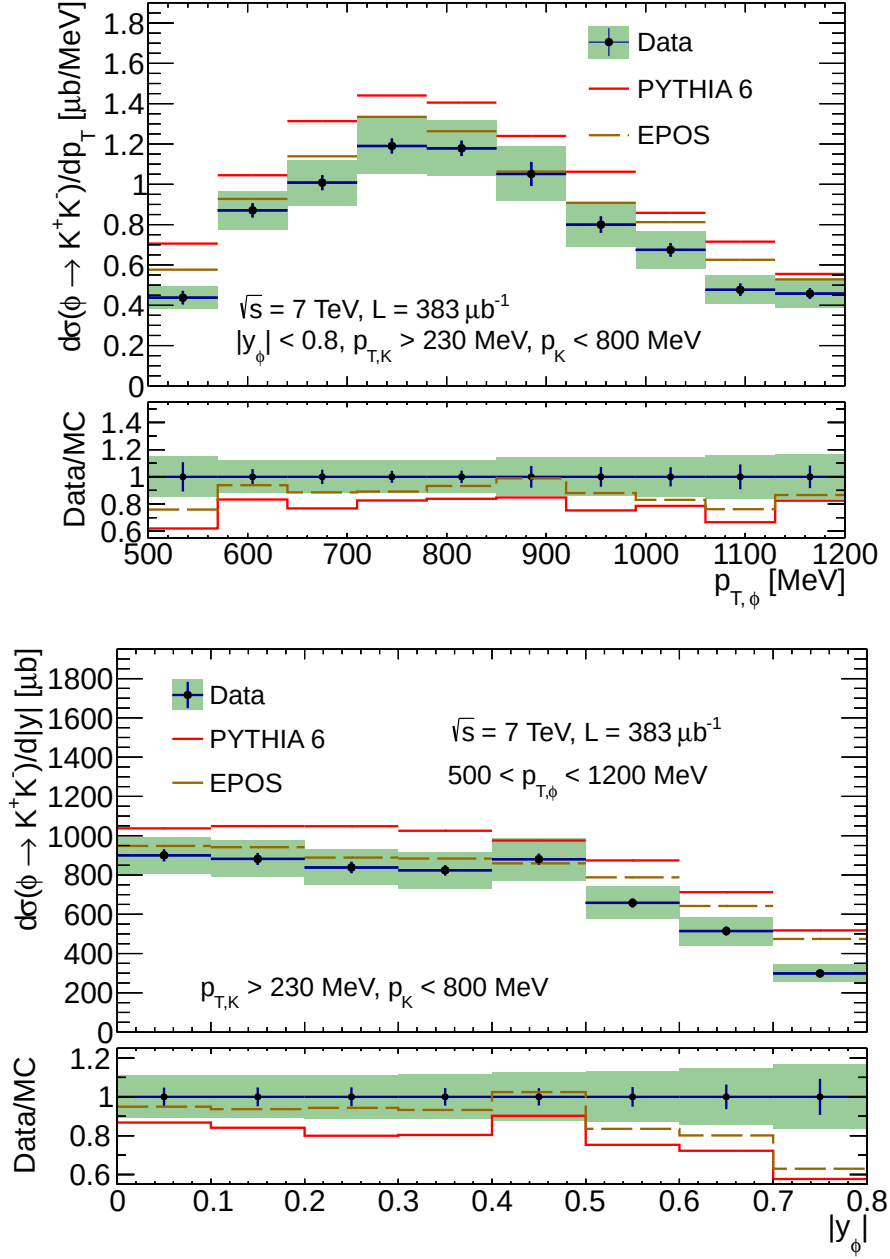


Figure 6.6: The differential  $\phi$ -meson cross section in the fiducial region as a function of  $p_{T,\phi}$  (upper) and  $|y_\phi|$ . The error bars represent the statistical uncertainty and the green boxes represent the quadratic sum of the statistical and systematic uncertainties. The 3.5% uncertainty on the luminosity is not included. The data are compared to PYTHIA 6 and EPOS predictions.

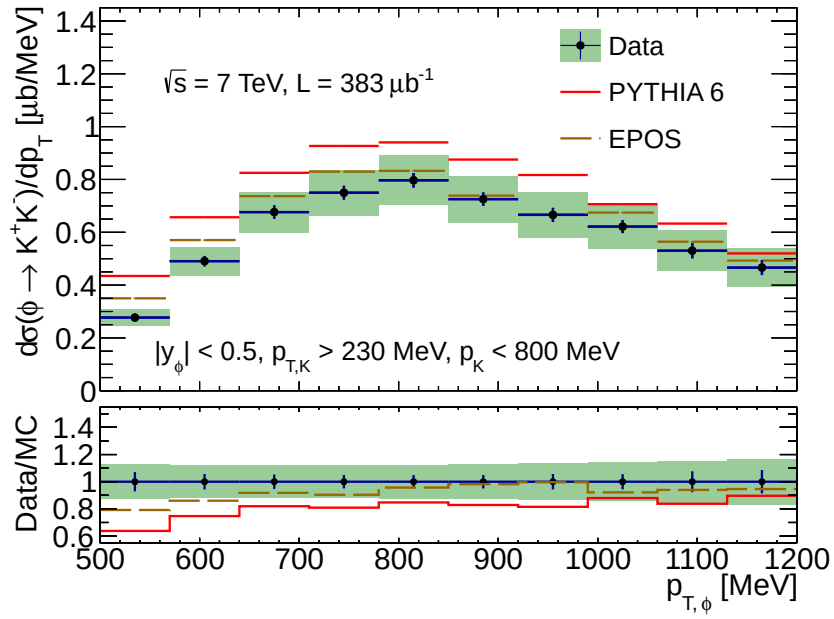


Figure 6.7: The differential  $\phi$ -meson cross section in the fiducial volume within  $|y_\phi| < 0.5$  as a function of  $p_{T,\phi}$ . The error bars represent the statistical uncertainty and the green boxes represent the quadratic sum of the statistical and systematic uncertainties. The 3.5% uncertainty on the luminosity is not included. The data are compared to PYTHIA 6 and EPOS predictions.

| Source                         | Effect                      | Uncertainty |
|--------------------------------|-----------------------------|-------------|
| Yield extraction               | Signal p.d.f.               | 5–6%        |
|                                | Resolution model            | 2%          |
|                                | Background p.d.f.           | 3%          |
| Tracking efficiency            | Statistical                 | 1–2%        |
|                                | Relative efficiency         | 0.7%        |
|                                | Material description        | 4–6%        |
|                                | Migration                   | 0–1%        |
| Kaon identification efficiency | Statistical                 | 1–2%        |
|                                | Background normalization    | 2–6%        |
|                                | Extraction yield tag sample | 7–10%       |

Table 6.3: The systematic uncertainties on the  $\phi$ -meson cross section.

by using a different resolution model and by fixing the background parameters to the same-sign background spectrum fit. The tracking efficiency determination depends on uncertainties in the material description, from a correction for migration of tracks into the fiducial region and from the comparison of the relative efficiency in data and simulation. The systematic uncertainties in the kaon identification efficiency calculation arise from using a double background contribution and from fixing the background shape parameters. Assuming these uncertainties are independent, which is reasonable given the different types of systematic effects considered, they are added in quadrature to calculate the total uncertainty.

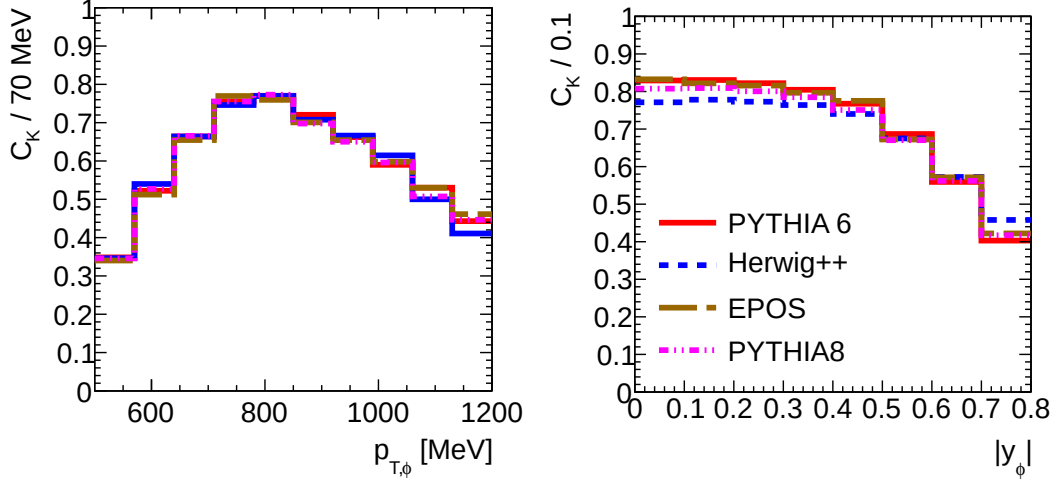
The uncertainty, ranging from  $\pm 10\%$  to  $\pm 14\%$  in different kinematic regions, is summarized in table 6.3. The uncertainty does not depend on the momentum range and is 10–11% in all bins. The systematic uncertainty increases as a function of  $|y_\phi|$ , again due to a larger contribution of the uncertainties in the kaon identification with increasing kaon momentum. For the estimation of the systematic uncertainty in the fiducial range with  $|y_\phi| < 0.5$  in figure 6.7, the conservative assumption that the errors are the same as in the range within  $|y_\phi| < 0.8$  is used. This is conservative as the uncertainties increase with increasing kaon momentum and there is a positive correlation between kaon momentum and  $\phi$  rapidity.

The 3.5% systematic uncertainty on the luminosity is included separately, because this is the only uncertainty that would have the effect of a scale factor on the cross section.

## 6.4 Extrapolated differential cross section

For the fiducial cross sections presented above, tracking and identification inefficiencies have been corrected. In the fiducial cross section no extensions outside the fiducial region are made, nor has the branching ratio been taken into account. Extrapolation to the full cross section is needed for meaningful comparison to the cross section presented by other experiments. After this simulation-driven correction further comparison between data and predictions is not meaningful, because the extension procedure is the same for data and simulation by construction.

The size of the fiducial correction factor  $C_K$  for the number of rejected  $\phi$ -mesons is calculated per bin in  $p_{T,\phi}$  or  $|y_\phi|$  separately as the ratio of the number of generated  $\phi \rightarrow K^+K^-$

Figure 6.8: Correction factor  $C_K$  as a function of  $p_{T,\phi}$  and  $|y_\phi|$ .

decays with and without the requirements on kaon (transverse) momentum. For example in the lowest  $p_{T,\phi}$  bin:

$$C_K = \frac{\int_{500}^{570} dp_{T,\phi} \int d|y_\phi| N_\phi^{\text{fid}}}{\int_{500}^{570} dp_{T,\phi} \int d|y_\phi| N_\phi} = 0.36 \pm 0.04, \quad (6.10)$$

where  $N_\phi^{\text{fid}}$  is the number of decays after the requirements on kaon momentum and  $N_\phi$  is the total number of decays. In this case, two out of three generated decays with  $500 < p_{T,\phi} < 570$  MeV and  $|y_\phi| < 0.8$  are rejected.

In figure 6.8 the correction factors  $C_K$  are shown as estimated using the four generators described in chapter 1. To correct the cross section result, the corrections from PYTHIA 6 are used. The choice of this generator is motivated by the reasonable  $p_{T,\phi}$  dependence of the cross section in both PYTHIA 6 and EPOS, as seen in figure 6.6 and the large data sample available for PYTHIA 6. The difference in correction factors is 10% in the worst bins and this is included as an additional systematic uncertainty on the extrapolated results.

The corrections  $C_K$  in the central rapidity region  $|y_\phi| < 0.5$  are calculated using PYTHIA 6. From the right panel in figure 6.8 it is clear that the corrections are about 0.8 in this region. The extrapolated cross section as a function of  $p_{T,\phi}$  within  $|y_\phi| < 0.5$  is presented in figure 6.9. Comparing the first bin of figures 6.7 and 6.9, the fiducial and extrapolated cross section as a function of  $p_{T,\phi}$  within  $|y_\phi| < 0.5$ , the cross section has increased from

$$\frac{d\sigma(\phi \rightarrow K^+ K^-)}{dp_{T,\phi}} = 0.29 \pm 0.02(\text{stat}) \pm 0.03(\text{syst}) [\mu\text{b}/\text{MeV}]$$

to

$$\frac{d\sigma_\phi}{dp_{T,\phi}} = 1.6 \pm 0.1(\text{stat}) \pm 0.2(\text{syst}) [\mu\text{b}/\text{MeV}].$$

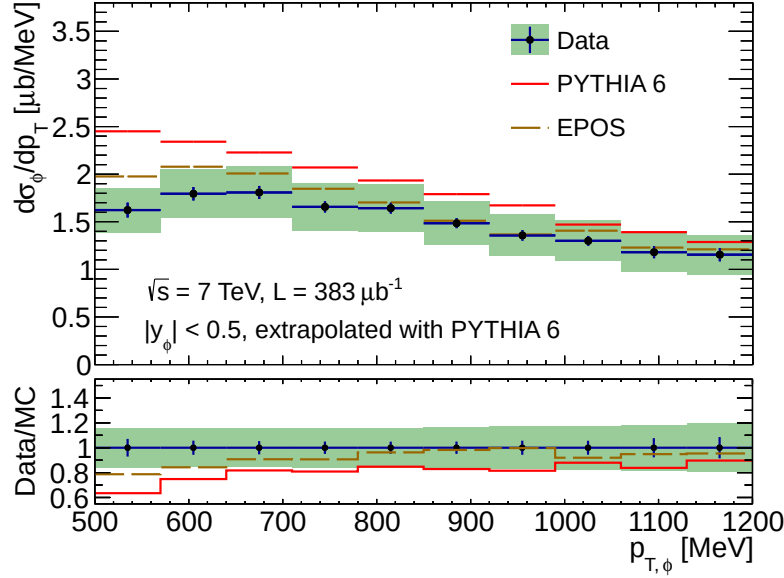


Figure 6.9: The  $\phi$ -meson cross section as a function of  $p_{T,\phi}$ , corrected for the fiducial acceptance using PYTHIA 6 to the cross section with  $500 < p_{T,\phi} < 1200$  MeV and  $|y_\phi| < 0.5$ . The error bars represent the statistical uncertainty and the green boxes represent the quadratic sum of the statistical and systematic uncertainties. The 3.5% uncertainty on the luminosity is not included. Data are compared to PYTHIA 6 and EPOS predictions.

The larger relative systematic error on the corrected cross section is due to the extra uncertainty in the correction  $C_K$  of 10% and the 1% uncertainty on the branching fraction. From the lower panels of figures 6.7 and 6.9 it is clear that the relative behaviour between data and PYTHIA 6 has not changed.

More interestingly, the extrapolated cross section is compared to the measurement of the ALICE Collaboration of the  $\phi$  production cross section for  $|y_\phi| < 0.5$  and  $0.5 < p_{T,\phi} < 5$  GeV using the  $K^+K^-$  decay mode as described in reference [134]. The cross sections agree and a comparison is shown in figure 6.10. The larger systematic uncertainty on the ATLAS data points is due to the 10% extra uncertainty on the corrections. The systematic uncertainties on the efficiencies quoted in reference [134] are very comparable to the uncertainties in the ATLAS measurement. The model dependent errors are likely to be correlated.

Finally, we found that if the extrapolated cross section in the region with  $|y_\phi| < 0.8$  is calculated using the corrections from PYTHIA 6 directly, the cross section falls as a function of  $|y_\phi|$  from  $|y_\phi| \sim 0.5$ . This is not the expected behavior. In ref. [60] the multiplicities for the  $\Lambda$  baryon and  $K_S^0$  meson are presented as a function of  $p_T$  and rapidity. The multiplicities are found to be flat up to rapidity of  $\sim 2$ , suggesting the strangeness production is constant up to  $|y_\phi| < 2$ .



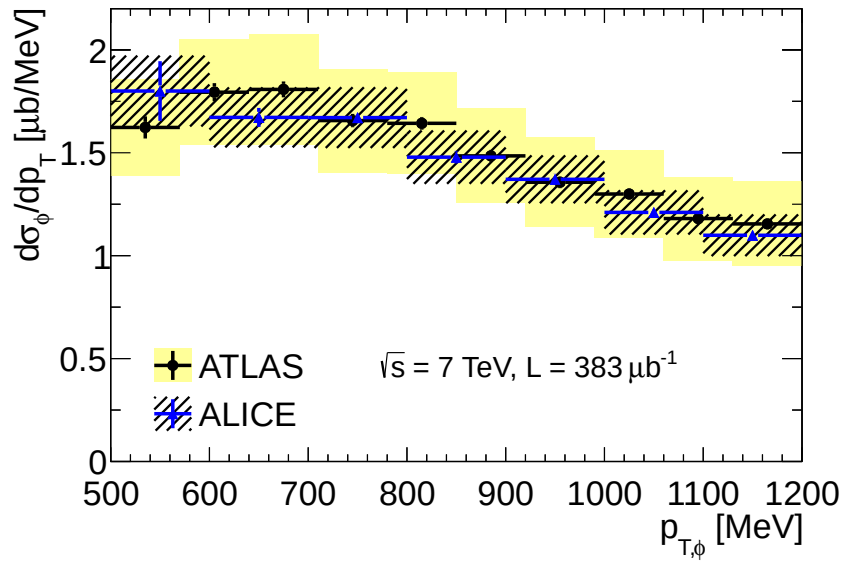


Figure 6.10: The  $\phi$ -meson cross section as a function of  $p_{T,\phi}$  corrected using PYTHIA 6 to the cross section with  $500 < p_{T,\phi} < 1200$  MeV and  $|y_\phi| < 0.5$ . The error bars represent the statistical uncertainty and the boxes represent the quadratic sum of the statistical and systematic uncertainties. The 3.5% uncertainty on the luminosity is not included. ALICE data from reference [134].

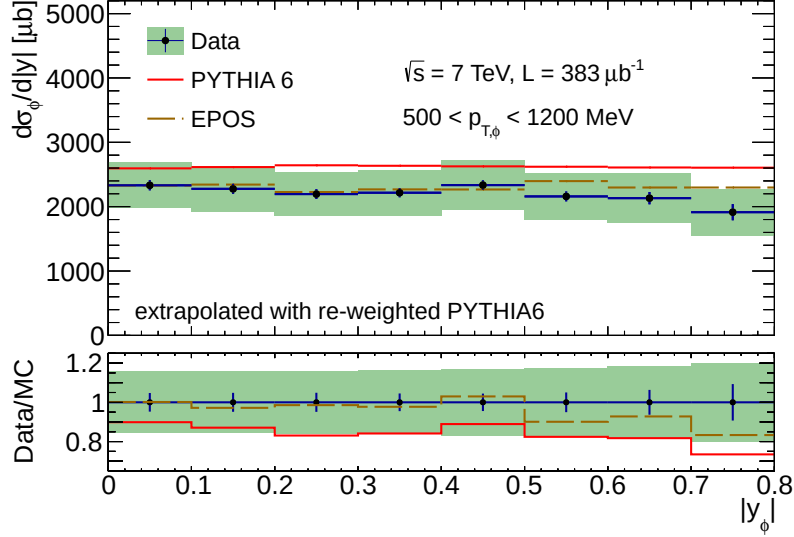


Figure 6.11: The  $\phi$ -meson cross section as a function of  $|y_\phi|$ , corrected using PYTHIA 6 to the cross section with  $500 < p_{T,\phi} < 1200$  MeV and  $|y_\phi| < 0.8$ . The error bars represent the statistical uncertainty and the green boxes represent the quadratic sum of the statistical and systematic uncertainties. The 3.5% uncertainty on the luminosity is not included. The data are compared to PYTHIA 6 and EPOS predictions.

To test if the decreasing behavior in rapidity after extrapolation is due to a mis-modelling of the  $p_{T,\phi}$  distribution in the forward region, the generated  $p_{T,\phi}$  distribution is re-weighted using data. Assuming the  $p_{T,\phi}$  distribution is invariant in  $|y_\phi|$ , which was validated using simulation, and that the fiducial corrections in the central rapidity region are correct, the correction factors in bins of  $|y_\phi|$  are re-weighted using data according to the  $p_{T,\phi}$  distribution in the central region. The extra systematic uncertainty arising from the assumption of invariance of the  $p_{T,\phi}$  distribution as a function of  $|y_\phi|$  is tested by comparing the generated yields in bins of  $p_{T,\phi}$  for  $|y_\phi| < 0.4$  and  $0.4 < |y_\phi| < 0.8$  from the different generators. A maximum of 5% variation is observed and included as an extra systematic uncertainty on the corrected result within  $|y_\phi| < 0.8$ .

The extrapolated cross section in  $|y_\phi| < 0.8$  as a function of  $|y_\phi|$  is shown in figure 6.11. The cross section is flat as a function of  $|y_\phi|$ , also due to the usage of the re-weighted correction factors. The validity of using this re-weighting is further discussed in the next section.

## 6.5 Discussion

The fiducial cross section is compared to predictions from Monte Carlo event generators PYTHIA 6 and EPOS in figures 6.6 and 6.7. PYTHIA 6 overestimates the cross section by about 20%, while

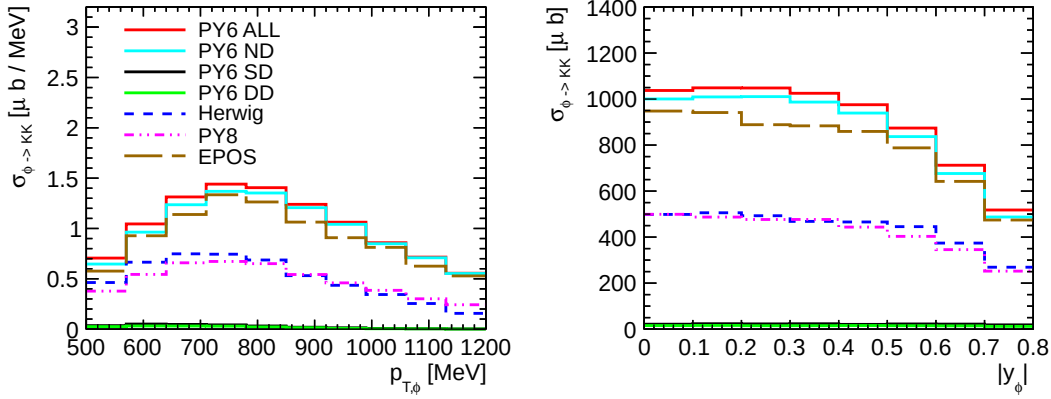


Figure 6.12: The predicted  $\phi \rightarrow K^+K^-$  cross section as a function of  $p_{T,\phi}$  and  $|y_\phi|$  for PYTHIA 6 (with breakdown to the non diffractive, single diffractive and double diffractive samples), PYTHIA 8, HERWIG++ and EPOS.

the predicted  $p_{T,\phi}$  distribution is similar to the data. EPOS calculates the cross section within uncertainty in the range  $570 < p_{T,\phi} < 920$  MeV, and overestimates the cross section in the outer bins by about 15%. Both generators overestimate the cross section for  $|y_\phi| > 0.5$ .

Figure 6.12 shows the predicted  $\phi \rightarrow K^+K^-$  production cross section for PYTHIA 6 (with breakdown to the non diffractive, single diffractive and double diffractive samples), PYTHIA 8, HERWIG++ and EPOS. The contribution of the single- and double-diffractive samples to the cross section predicted by PYTHIA 6 is about 4% for  $p_{T,\phi} < 600$  MeV and is less than  $\sim 0.1\%$  for  $p_{T,\phi} > 1000$  MeV. The predicted cross sections from HERWIG++ and PYTHIA 8 are almost a factor of two smaller than the predictions by PYTHIA 6 and EPOS (and thus the data). The dependence of the cross section on  $p_{T,\phi}$  predicted by HERWIG++ and PYTHIA 8 is also too steep.

A similar large spread between generators is also seen in figure 6.13, which is taken from reference [134]. The  $\phi$ -meson production cross section within  $|y_\phi| < 0.5$  in the range  $0.5 < p_{T,\phi} < 6$  GeV is compared to predictions from several tunes of PYTHIA 6. The predicted cross section at  $p_{T,\phi} \sim 500$  MeV ranges from a factor  $\sim 1.7$  below the data (PYTHIA 6 D6T) to  $\sim 2.2$  above the data (PYTHIA 6 ATLAS-CSC). The large spread between the generators cannot be attributed to uncertainties in the diffractive samples, as their contribution is small.

The generators are compared to the fiducial cross section, because this cross section was measured in a model-independent way. After the simulation-driven corrections for the fiducial acceptance, a comparison between data and prediction is less meaningful, because the size of the correction is the same for data and simulation by construction. Still the corrected cross section allows for a comparison between the ATLAS and ALICE measurements. The two measurements agree well within the uncertainties and the magnitude of the uncertainties is also compatible.

For the fiducial correction of the rapidity distribution within  $|y_\phi| < 0.8$ , the corrections have

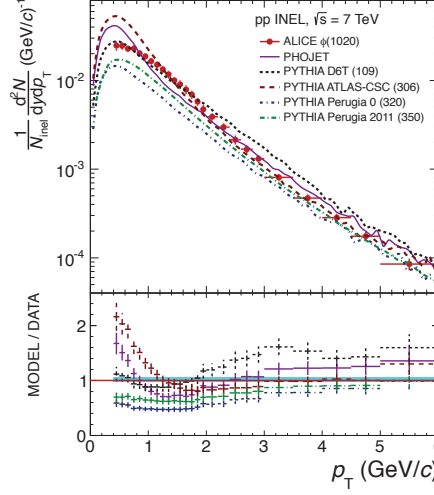


Figure 6.13: Comparison of the  $p_{T,\phi}$  spectra within  $|y_\phi| < 0.5$  in inelastic  $pp$  collisions with PHOJET and PYTHIA6 tunes D6T (109), ATLAS-CSC (306), Perugia 0 (320), and Perugia 2011 (350) as measured by the ALICE Collaboration. [134]

been re-weighted according to the  $p_{T,\phi}$  distribution in data. The  $p_{T,\phi}$  re-weighting may wash out true differences between data and simulation.

Improving the measurement by reducing the systematic uncertainty would be most effective if the uncertainties in the yield determination and due to uncertainties in the description of the amount and location of traversed materials would be improved. The cross section is measured up to 1200 MeV, because only low-momentum tracks can be identified as kaon effectively. To improve the measurement, it would be interesting to extend the measurement to higher  $p_T$  and more forward rapidities. Kaon identification using energy loss is no longer possible then, but identifying  $\phi$ -mesons can be done in different ways, for example using only tracking requirements as was done in reference [137]. Another interesting study would be to investigate the  $\omega/\phi$  ratio to see if the assumption of ideal mixing used in the event generation is valid. Studying the ratio  $K^\pm/\pi^\pm$  can constrain models more stringently, because the systematic uncertainties are much lower due to canceling factors.

## 6.6 Summary

In this chapter the measurement of the differential production cross section for the  $\phi$  meson with the ATLAS experiment using the  $K^+K^-$  decay mode is presented. To avoid model-dependent extrapolations outside the detector acceptance, the cross section is measured in a fiducial region, with  $500 < p_{T,\phi} < 1200$  MeV,  $|y_\phi| < 0.8$ , kaon  $p_{T,K} > 230$  MeV and kaon momentum  $p_K < 800$  MeV requirements, which are determined by particle identification and track reconstruction constraints.

The  $\phi$  production cross section is in reasonable agreement with the theoretical predictions implemented in the generators PYTHIA 6 and EPOS. The cross section calculated by the generators PYTHIA 8 and HERWIG++ are too small and show too steep a  $p_{T,\phi}$  dependence, the effect being more pronounced for HERWIG++. This measurement can provide useful input for tuning and development of phenomenological models and to improve Monte Carlo generators.



## Appendix A

### Relativistic Breit–Wigner signal shape

In this section the relativistic Breit–Wigner signal shape used for signal extraction is explained in more detail. The convolution of a Breit–Wigner p.d.f. with a Gaussian resolution function results in a p.d.f. that is often used to extract the  $\phi(1020)$  yield.

In the analysis the signal shape is described a relativistic Breit–Wigner form:

$$f_{\text{RelBW}}(m; m_0, \Gamma_0, J, R) = \frac{m^2}{(m^2 - m_0^2)^2 + m_0^2 \Gamma^2(m)}, \quad (\text{A.1})$$

where the mass dependent width  $\Gamma$  is defined as

$$\Gamma(m) = \Gamma_0 \frac{m_0}{m} \left( \frac{k(m)}{k(m_0)} \right)^{2J+1} \frac{F(Rk(m))}{F(Rk(m_0))}, \quad (\text{A.2})$$

$$k(m) = \frac{m}{2} \left( 1 - \frac{(m_a + m_b)^2}{m^2} \right)^{1/2} \left( 1 - \frac{(m_a - m_b)^2}{m^2} \right)^{1/2}, \quad (\text{A.3})$$

with the function  $F$  spin dependent Blatt–Weisskopf form factor [138],

$$F^{J=0}(x) = 1 \quad (\text{A.4})$$

$$F^{J=1}(x) = \frac{1}{1 + x^2} \quad (\text{A.5})$$

$$F^{J=2}(x) = \frac{1}{9 + 3x^2 + x^4}. \quad (\text{A.6})$$

The Blatt–Weisskopf form factors provide a better description of the shape of the resonance if the decaying particle has a non-zero spin. The interaction radius  $R$  in equation A.2 has an effect on the width of the resonance if the peak of the resonance is near-threshold and is zero for the  $\phi(1020)$ -meson [139]. This reduces the form factor to:

$$F^{J=1}(0) = 1, \quad (\text{A.7})$$

so that also the fraction in equation A.2 is unity. The parameters  $m_a$  and  $m_b$  are the masses of the daughters of the decaying resonance, in this case  $m_a = m_b = m_K$ , the kaon mass. Using this

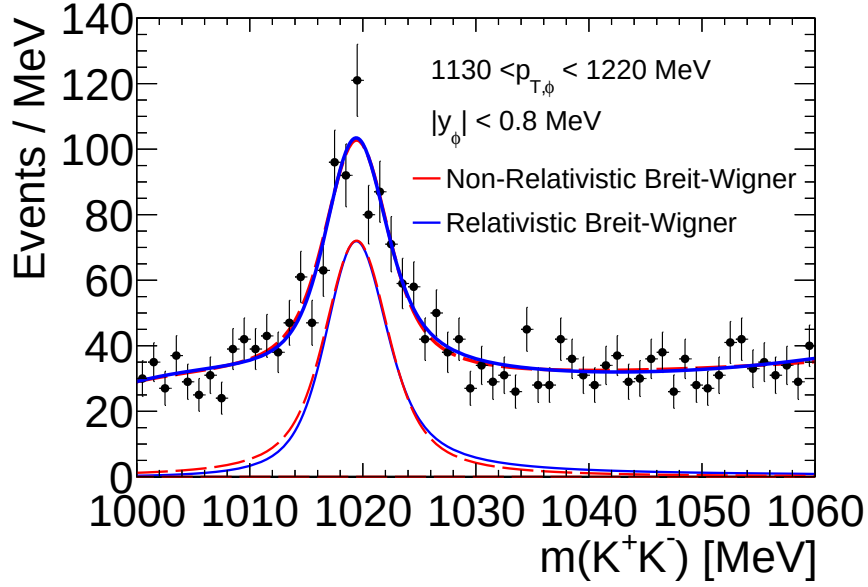


Figure A.1: The invariant mass distribution fitted with the non-relativistic Breit-Wigner (dashed line) and with the relativistic Breit–Wigner (solid line).

and that the spin  $J = 1$ , the mass dependent width reduces to:

$$\Gamma(m) = \Gamma_0 \left[ \frac{m^2 - 4m_K^2}{m_0^2 - 4m_K^2} \right]^{3/2} \quad (\text{A.8})$$

The difference between the non-relativistic Breit-Wigner in equation 6.1 and the relativistic Breit-Wigner in equation 1.5 is illustrated in figure A.1. The difference between the two line shapes is small, but the better description of the shoulder of the resonance at the high end by the relativistic Breit-Wigner is visible.



## Appendix B

### Tabulated result $\phi(1020)$ -meson cross section

In this appendix the extracted yields after corrections for tracking and kaon identification efficiencies, the cross section per bin of  $p_{T,\phi}$  and  $|y_\phi|$  and the uncertainties in the tracking and PID efficiency determinations and on the luminosity are summarized in tables B.1 and B.2

In table B.3 the correction factors  $C_K$  for the fiducial acceptance in the kinematic range with  $|y_\phi| < 0.5$  as a function of  $p_{T,\phi}$  and  $|y_\phi|$  are listed. The re-weighted correction factors that are used in the kinematic range with  $|y_\phi| < 0.8$  are listed in table B.4.

| Bin [MeV]                     | Yield $\cdot 10^4$ | $d\sigma/dp_T$ [ $\mu\text{b}/\text{MeV}$ ] | Systematic uncertainty  |                         |            |
|-------------------------------|--------------------|---------------------------------------------|-------------------------|-------------------------|------------|
|                               |                    |                                             | $\epsilon_{\text{rec}}$ | $\epsilon_{\text{pid}}$ | Lumi       |
| $500 < p_{T,\phi} \leq 570$   | $1.22 \pm 0.07$    | $0.45 \pm 0.04$                             | $\pm 0.03$              | $\pm 0.03$              | $\pm 0.02$ |
| $570 < p_{T,\phi} \leq 640$   | $2.34 \pm 0.09$    | $0.87 \pm 0.04$                             | $\pm 0.06$              | $\pm 0.05$              | $\pm 0.03$ |
| $640 < p_{T,\phi} \leq 710$   | $2.71 \pm 0.10$    | $1.01 \pm 0.04$                             | $\pm 0.06$              | $\pm 0.06$              | $\pm 0.04$ |
| $710 < p_{T,\phi} \leq 780$   | $3.19 \pm 0.11$    | $1.19 \pm 0.04$                             | $\pm 0.07$              | $\pm 0.09$              | $\pm 0.04$ |
| $780 < p_{T,\phi} \leq 850$   | $3.16 \pm 0.11$    | $1.18 \pm 0.04$                             | $\pm 0.06$              | $\pm 0.10$              | $\pm 0.04$ |
| $850 < p_{T,\phi} \leq 920$   | $2.85 \pm 0.10$    | $1.05 \pm 0.04$                             | $\pm 0.05$              | $\pm 0.09$              | $\pm 0.04$ |
| $920 < p_{T,\phi} \leq 990$   | $2.15 \pm 0.09$    | $0.80 \pm 0.04$                             | $\pm 0.03$              | $\pm 0.08$              | $\pm 0.03$ |
| $990 < p_{T,\phi} \leq 1060$  | $1.81 \pm 0.07$    | $0.68 \pm 0.04$                             | $\pm 0.03$              | $\pm 0.07$              | $\pm 0.02$ |
| $1060 < p_{T,\phi} \leq 1130$ | $1.30 \pm 0.06$    | $0.48 \pm 0.04$                             | $\pm 0.02$              | $\pm 0.05$              | $\pm 0.02$ |
| $1130 < p_{T,\phi} \leq 1200$ | $1.23 \pm 0.08$    | $0.46 \pm 0.04$                             | $\pm 0.02$              | $\pm 0.06$              | $\pm 0.02$ |

Table B.1: Measured  $\phi(1020) \rightarrow K^+ K^-$  cross section  $d\sigma/dp_T$  ( $\mu\text{b}/\text{MeV}$ ) in bins of  $p_{T,\phi}$  in the fiducial region and the systematic uncertainties due to track reconstruction efficiency, kaon identification and luminosity measurement. The systematic uncertainties on the selection efficiencies are calculated by adding the statistical and systematic uncertainties on the selections in quadrature.

| Bin                       | Yield $\cdot 10^4$ | $d\sigma/d y $ [mb] | Systematic uncertainty  |                         |            |
|---------------------------|--------------------|---------------------|-------------------------|-------------------------|------------|
|                           |                    |                     | $\epsilon_{\text{rec}}$ | $\epsilon_{\text{pid}}$ | Lumi       |
| $0.0 <  y_\phi  \leq 0.1$ | $3.44 \pm 0.10$    | $0.91 \pm 0.03$     | $\pm 0.04$              | $\pm 0.06$              | $\pm 0.03$ |
| $0.1 <  y_\phi  \leq 0.2$ | $3.39 \pm 0.10$    | $0.88 \pm 0.03$     | $\pm 0.04$              | $\pm 0.07$              | $\pm 0.03$ |
| $0.2 <  y_\phi  \leq 0.3$ | $3.22 \pm 0.09$    | $0.84 \pm 0.03$     | $\pm 0.04$              | $\pm 0.06$              | $\pm 0.03$ |
| $0.3 <  y_\phi  \leq 0.4$ | $3.18 \pm 0.09$    | $0.83 \pm 0.03$     | $\pm 0.04$              | $\pm 0.06$              | $\pm 0.03$ |
| $0.4 <  y_\phi  \leq 0.5$ | $3.36 \pm 0.11$    | $0.88 \pm 0.03$     | $\pm 0.05$              | $\pm 0.08$              | $\pm 0.03$ |
| $0.5 <  y_\phi  \leq 0.6$ | $2.53 \pm 0.12$    | $0.66 \pm 0.03$     | $\pm 0.04$              | $\pm 0.06$              | $\pm 0.02$ |
| $0.6 <  y_\phi  \leq 0.7$ | $2.01 \pm 0.11$    | $0.52 \pm 0.02$     | $\pm 0.03$              | $\pm 0.05$              | $\pm 0.02$ |
| $0.7 <  y_\phi  \leq 0.8$ | $1.18 \pm 0.07$    | $0.31 \pm 0.02$     | $\pm 0.02$              | $\pm 0.04$              | $\pm 0.01$ |

Table B.2: Measured  $\phi(1020) \rightarrow K^+K^-$  cross section  $d\sigma/d|y|$  in bins of  $|y_\phi|$  in the fiducial region and the combined systematic uncertainties due to track reconstruction efficiency, kaon identification and luminosity measurement. The systematic uncertainties on the selection efficiencies are calculated by adding the statistical and systematic uncertainties on the selections in quadrature.

| Bin [MeV]                     | $C_K$ | Bin                       | $C_K$ |
|-------------------------------|-------|---------------------------|-------|
| $500 < p_{T,\phi} \leq 570$   | 0.36  | $0.0 <  y_\phi  \leq 0.1$ | 0.83  |
| $570 < p_{T,\phi} \leq 640$   | 0.57  | $0.1 <  y_\phi  \leq 0.2$ | 0.83  |
| $640 < p_{T,\phi} \leq 710$   | 0.76  | $0.2 <  y_\phi  \leq 0.3$ | 0.82  |
| $710 < p_{T,\phi} \leq 780$   | 0.92  | $0.3 <  y_\phi  \leq 0.4$ | 0.80  |
| $780 < p_{T,\phi} \leq 850$   | 0.99  | $0.4 <  y_\phi  \leq 0.5$ | 0.77  |
| $850 < p_{T,\phi} \leq 920$   | 1.00  |                           |       |
| $920 < p_{T,\phi} \leq 990$   | 1.00  |                           |       |
| $990 < p_{T,\phi} \leq 1060$  | 0.98  |                           |       |
| $1060 < p_{T,\phi} \leq 1130$ | 0.93  |                           |       |
| $1130 < p_{T,\phi} \leq 1200$ | 0.83  |                           |       |

Table B.3: The correction factors as a function of  $p_{T,\phi}$  and  $|y_\phi|$  for  $|y_\phi| < 0.5$ .

| Bin                       | $C_K$ default | $C_K$ re-weighted |
|---------------------------|---------------|-------------------|
| $0.0 <  y_\phi  \leq 0.1$ | 0.83          | 0.79              |
| $0.1 <  y_\phi  \leq 0.2$ | 0.83          | 0.79              |
| $0.2 <  y_\phi  \leq 0.3$ | 0.82          | 0.78              |
| $0.3 <  y_\phi  \leq 0.4$ | 0.80          | 0.76              |
| $0.4 <  y_\phi  \leq 0.5$ | 0.77          | 0.74              |
| $0.5 <  y_\phi  \leq 0.6$ | 0.69          | 0.62              |
| $0.6 <  y_\phi  \leq 0.7$ | 0.56          | 0.59              |
| $0.7 <  y_\phi  \leq 0.8$ | 0.40          | 0.32              |

Table B.4: The correction factors as a function of  $|y_\phi|$  in  $|y_\phi| < 0.8$  are re-weighted according the  $p_{T,\phi}$  distribution in data.

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## Summary

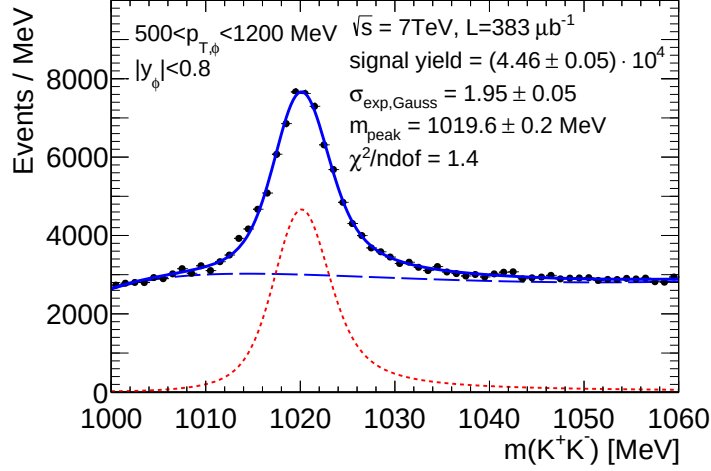
In this thesis the  $\phi$ -meson production cross section in proton-proton interactions at a center-of-mass energy of  $\sqrt{s} = 7$  TeV measured with the ATLAS experiment at the LHC is presented. The main aim of the ATLAS detector is to study and explore physics around and above the electroweak symmetry-breaking scale. These processes typically take place at high energy transfers, which separates them from the prevalent processes in  $pp$  interactions: namely strong force interactions with low momentum transfers described by non-perturbative quantum chromodynamics (QCD). Monte Carlo event generators are used to simulate these soft processes, but for reliable predictions the models rely on data.

Sources of  $\phi$ -mesons in  $pp$  collisions are direct production from strange sea quarks, gluon fusion or fragmentation processes. This makes the  $\phi$  meson a probe of the phenomenology of the hadronization, in contrast to the third generation quarks that are rarely produced in hadronisation. The strange quark mass cannot be assumed to be zero in the calculations, unlike the  $u$  and  $d$  quark mass.

In this thesis the  $\phi$  meson is measured through its decay into two kaons. The identification of kaons is based on their energy deposition in the pixel detector. The track reconstruction is provided by the ATLAS inner detector, which comprises the pixel detector, a silicon strip detector and a transition radiation tracker. The energy loss depends on the particle velocity as described by the Bethe–Bloch formula and the mass difference between pion, kaons and protons is used as a discriminating variable, providing discriminating power of momenta below 800 MeV. On the other hand, kaons with momenta below 230 MeV are not reconstructed at all, because they lose all their energy in the construction materials of the pixel detector.

Kaons can thus be reconstructed and identified in a limited momentum range. To avoid model-dependent extrapolations outside this range, the cross section result is presented in a so-called fiducial volume. Being restricted by the requirements on kaon momentum, this volume covers  $500 < p_{T,\phi} < 1200$  MeV and  $|y_\phi| < 0.8$ . Figure S1 shows the invariant mass of all oppositely charged combinations of pairs of tracks that have successfully been identified as kaons. The number of reconstructed  $\phi$  mesons is measured by fitting the invariant mass spectrum with a probability density function (p.d.f.) that describes the signal and background contributions separately in each region of phase space.

In order to create the invariant mass spectrum shown in figure S1, both kaons from a  $\phi$  decay need to be reconstructed and both tracks need to pass the kaon identification requirements. The tracking efficiency is determined from simulated data as the ratio of the number of generated particles reconstructed as a track to the total number of generated particles. The leading systematic uncertainty in the tracking efficiency determination originates from the simulation of the amount and location of detector material. The kaon identification efficiency is determined using



**Figure S1:** The invariant mass spectrum is fitted with a probability density function that described signal and background contributions separately to obtain the number of  $\phi$ -meson candidates.

a data-driven tag-and-probe method. The method counts the number of “tag” instances (with at least one kaon passing the identification requirements) and the number of “probe” (both kaons passing) instances as an independent subset. The tag-and-probe efficiency is then defined as:

$$\epsilon_{\text{TnP}} = \frac{N_{\text{probe}}}{N_{\text{tag}}}.$$

This data-driven method is needed, because it was found that the Monte Carlo overestimates the discrimination power between pions and kaons. The tag-and-probe efficiency is observed to be up to a factor of three lower in data. The largest systematic uncertainty in the kaon identification efficiency determination is due to signal extraction in the tag sample.

Both the track reconstruction efficiency and the kaon identification efficiency are determined as a function of kaon momentum. To calculate the number of efficiency-corrected reconstructed  $\phi$  mesons, each kaon in figure S1 is given a weight to correct for experimental losses. Finally, signal extraction is performed on the corrected invariant mass spectra and the cross section is calculated as the number of efficiency-corrected decays divided by the integrated luminosity. The integrated cross section is found to be

$$\sigma_{\phi \rightarrow K^+ K^-} = 570 \pm 7 \text{ (stat)} \pm 69 \text{ (syst)} \pm 20 \text{ (lumi)} \mu\text{b},$$

for  $500 < p_{T,\phi} < 1200 \text{ MeV}$ ,  $|y_\phi| < 0.8$ ,  $p_{T,K} > 230 \text{ MeV}$  and  $p_K < 800 \text{ MeV}$ .

The  $\phi$ -meson production cross section is in fair agreement with two of the predictions under examination. Different tunes of the same generator result in significantly different predictions. This measurement can provide useful input for tuning and development of phenomenological models in order to improve Monte Carlo event generators.

# De werkzame doorsnede van het $\phi$ -meson bij $\sqrt{s} = 7$ TeV gemeten met het ATLAS experiment

Dit proefschrift presenteert de meting van de werkzame doorsnede van het  $\phi$ -meson bij een botsingsenergie van  $\sqrt{s} = 7$  TeV gemeten met het ATLAS experiment. Deze samenvatting beschrijft de inhoud van mijn proefschrift voor geïnteresseerden zonder specifieke voorkennis. Ook de motivatie voor de gedane meting wordt besproken. In de laatste paragraaf worden de conclusies uitgelegd.

## De LHC en het ATLAS experiment

Net ten westen van Genève in Zwitserland ligt het onderzoekslaboratorium CERN, Conseil Européenne pour la Recherche Nucléaire. Sinds begin 2009 is op CERN de Large Hadron Collider (LHC) in gebruik. In deze versneller met een omtrek van 27 km maken bundels van protonen in twee richtingen 11000 keer per seconde rondjes. Op vier plaatsen kruisen de bundels en kunnen de protonen met elkaar in botsing worden gebracht. De LHC is de krachtigste deeltjesversneller tot nu toe gebouwd. De maximale botsingsenergie van de protonen was 7 TeV in 2010 en 2011 en 8 TeV in 2012. In die botsingen ontstaat een zeer hoge energiedichtheid, zo hoog dat er nieuwe massa kan worden gemaakt.

De deeltjes die geproduceerd worden in de botsingen zijn meestal bekende deeltjes die al door het Standaard Model der elementaire deeltjes worden beschreven, of deeltjes die door dat model voorspeld werden, maar nog niet waren geobserveerd, of misschien deeltjes die zelfs nog helemaal onbekend zijn. Want hoewel het Standaard Model de natuur op haar allerkleinste schaal met zeer grote precisie beschrijft, was het incompleet tot de ontdekking van het Higgsdeeltje in 2012.

Om de geproduceerde deeltjes te meten zijn op vier botsingspunten langs de LHC detectoren geïnstalleerd, waaronder het ATLAS experiment. In ATLAS worden deeltjes op verschillende manieren gedetecteerd; met twee soorten silicium detectoren en een detector met een gas als actief materiaal het dichtste bij de botsingen. Daarna wordt de energie van de deeltjes berekend aan de hand van de gemeten penetratiediepte in het materiaal van twee soorten calorimeters. De deeltjes die ongestoord al deze detectoren passeren worden heel precies gemeten met onder andere gasgevulde buizen die ATLAS aan de buitenkant omvatten.

Omdat de versneller 24 uur per dag, 7 dagen per week botsingen produceert, moeten de detectoren altijd operationeel zijn. De controlekamer van ATLAS is daarom permanent bemand.

Behalve de functionaliteit, wordt ook de kwaliteit van de gemeten data constant bewaakt. Ik was van januari 2010 tot en met juni 2011 verantwoordelijk voor de kwaliteit van de data gemeten met de silicium strip detector van ATLAS. Ik heb ervoor gezorgd dat de detector de transitie van de opstart fase naar continue operatie zonder grote problemen heeft gemaakt.

### Het $\phi$ meson

Het Standaard Model der Elementaire deeltjes beschrijft de elementaire deeltjes, onder andere quarks, en de krachten tussen die deeltjes. Losse quarks komen in de natuur niet voor, ze zijn altijd gebonden in sets van twee of drie quarks. Een proton is een combinatie van twee ‘up’ en een ‘down’ quark. Combinaties van twee quarks heten mesonen. Het  $\phi$  meson is een combinatie van een ‘strange’ en anti-strange quark. Het strange quark is een zwaarder broertje van het up quark.

In een botsing tussen twee protonen met een botsingsenergie van 7 TeV wordt gemiddeld één  $\phi$ -meson geproduceerd. Deze  $\phi$  mesonen vervallen zeer snel, meestal naar twee kaonen, mesonen met een up en een strange quark. Het interessante aan  $\phi$ -mesonen is dat ze niet alleen direct in de botsing worden geproduceerd, maar ook in de processen met lagere energieoverdracht daarna. De processen met lagere energie omzetting zijn niet exact te berekenen met wiskundige modellen en dus kan de hoeveelheid geproduceerde  $\phi$  deeltjes niet precies worden uitgerekend. De modellen worden gekalibreerd met behulp van data, bijvoorbeeld aan de meting in dit proefschrift.

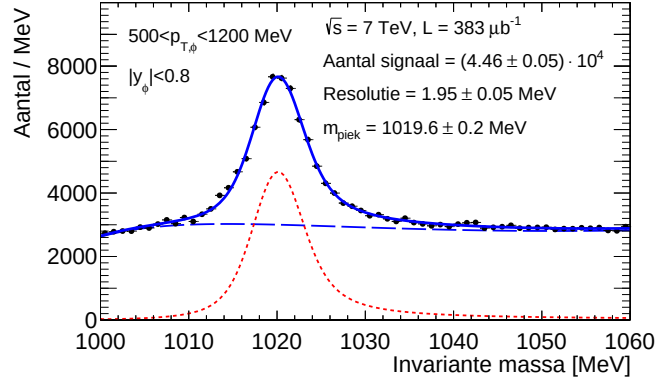
### De meting

Deeltjes die in de botsingen ontstaan worden niet altijd direct door de detector gemeten, maar indirect door reconstructie van de banen die secundaire deeltjes in de detector afleggen. Een geladen deeltje dat door een materiaal gaat, verliest energie door elektromagnetische interacties. In de silicium detectoren van ATLAS wordt die energiedepositie omgezet in een elektrisch signaal. In de pixeldetector wordt ook de duur, en daarmee de grootte van het signaal en dus de hoeveelheid verloren energie, geregistreerd. Dit energieverlies heb ik gebruikt om kaonen te onderscheiden van de grote achtergrond van geladen pionen (mesonen met een up en down quark).

Omdat het  $\phi$  meson geen elektrische lading heeft moeten de twee kaonen waarin het vervalt dus tegengestelde ladingen hebben. Door de wetten van massa-en energiebehoud toe te passen op een vervalsreactie kan de massa worden bepaald van de “moeder” van de twee kaonen. Deze massa wordt de *invariante massa* genoemd en als ik van alle paren van kaonen met tegengestelde lading de invariante massa plot, krijg ik de invariante massa piek zoals te zien in figuur S1. Combinaties die geen gezamenlijk ‘moederdeeltje’ hebben, of die van een ander verval afkomstig zijn, vormen de achtergrond. De paren afkomstig van de  $\phi$  steken (zichtbaar) boven de achtergrond uit.

Om een  $\phi$  meson te kunnen reconstrueren, moeten beide kaonen in de detector gemeten zijn en moeten ze beide als kaon geïdentificeerd zijn door hun energieverlies. Deeltjes met een te lage impuls worden niet gemeten en deeltjes met een te hoge impuls kunnen niet worden geïdentificeerd. Hierdoor is de meting slechts mogelijk in een beperkt zichtbaar gebied. Maar ook binnen dit gebied, zal een bepaalde fractie van de kaonen niet worden gemeten of geïdentificeerd. Die fracties heb ik bepaald met simulaties en botsingsdata en daarmee vervol-





**Figuur S1:** Om het aantal gereconstrueerde  $\phi$ -mesonen te tellen, doe ik een fit aan het invariante massa spectrum.

gens voor de verliezen gecorrigeerd.

### Resultaat

De kans op productie van een  $\phi$  meson in een gegeven hoeveelheid botsingen is evenredig met de *werkzame doorsnede*,  $\sigma$ . Deze werkzame doorsnede wordt gepresenteerd als functie van de impuls en hoek. De werkzame doorsnede daalt als functie van beide, mede door de snedes op de kwaliteit van de kaonen. De geïntegreerde werkzame doorsnede in het zichtbare gebied is

$$\sigma_{\phi \rightarrow K+K-} = 570 \pm 8 \text{ (stat)} \pm 66 \text{ (syst)} \pm 20 \text{ (lumi)} \mu\text{b}.$$

De statistische fout neemt de onzekerheid in het tellen van het aantal  $\phi$  mesonen in de piek en het aantal achtergrond events mee, de systematische fout is afkomstig van de berekening van de fractie niet gereconstrueerde  $\phi$  mesonen. De systematische fout op de luminositeit is de onzekerheid op het aantal geproduceerde botsingen.

### Conclusies

Ondanks dat de hoeveelheid geproduceerde strange quarks en dus het aantal  $\phi$  mesonen niet exact te voorspellen is, beschrijven twee van de onderzochte modellen de data vrij goed, terwijl twee andere modellen de productie met ongeveer een factor twee onderschatten. De meting is vergeleken met een meting van een ander LHC experiment en komen overeen binnen de systematische onzekerheid. De werkzame doorsnede van het  $\phi$ -meson kan worden gebruikt om simulatiemodellen te kalibreren en nieuwe modellen te testen.



# Dankwoord

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