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

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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 chromo dynamics (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 the 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 $K^0 \to \pi^+ \pi^-$ 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 $K\overline{K}$ 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
STRANGENESS PRODUCTION

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 $\tau_0 = 1.55 \pm 0.01 \cdot 10^{-22}$ 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 $\frac{t}{\Gamma}$ and central mass $m_0$:

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

such that it will decay exponentially as

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

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

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

The integration yields:

\[ \psi(m) \propto \frac{1}{(m - m_0) + i \Gamma} \tag{1.4} \]

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

\[ |\psi(m)|^2 \propto \frac{1}{(m - m_0)^2 + \frac{\Gamma^2}{4}} \tag{1.5} \]

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 \( K^0_LK^0_S \), \( (34.2 \pm 0.4)\% \), 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.

Figure 1.2: An illustration of the decays \( \phi \to K^+K^- \) and \( \phi \to \pi^+\pi^-\pi^0 \).
W. Heisenberg in 1932 to explain symmetries of the then newly discovered neutron \cite{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 $I_z = \frac{1}{2}(n_u - n_d + n_d - n_u)$.

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

$$Q = I_z + \frac{B + S}{2},$$

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 $P = (-1)^{s+1}$ 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
1.2. THE QUARK MODEL

<table>
<thead>
<tr>
<th>Quantum number</th>
<th>Symbol</th>
<th>Expression</th>
<th>Allowed with s = 0, 1 and l = 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baryon number</td>
<td>B</td>
<td>B = 0, 1</td>
<td></td>
</tr>
<tr>
<td>Orbital momentum</td>
<td>l</td>
<td>l = 0</td>
<td></td>
</tr>
<tr>
<td>Spin momentum</td>
<td>s</td>
<td>s = 0, 1</td>
<td></td>
</tr>
<tr>
<td>Parity</td>
<td>P</td>
<td>(-1)^l+1</td>
<td>P = -1, 1</td>
</tr>
<tr>
<td>Meson spin</td>
<td>J</td>
<td></td>
<td>l − s</td>
</tr>
<tr>
<td>Charge conjugation</td>
<td>C</td>
<td>(-1)^l+s</td>
<td>C = −1, 1</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Isospin</th>
<th>I = 1</th>
<th>(I = \frac{1}{2})</th>
<th>I = 0</th>
<th>I = 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content</td>
<td>(u\bar{d}, \bar{u}d), (\frac{1}{\sqrt{2}}(d\bar{d} - u\bar{u}))</td>
<td>(u\bar{c}, d\bar{s}, \bar{d}s, -\bar{u}s)</td>
<td>(f')</td>
<td>(f)</td>
</tr>
<tr>
<td>Pseudoscalar: (J^{PC} = 0^{++})</td>
<td>(\pi)</td>
<td>(K)</td>
<td>(\eta)</td>
<td>(\eta'(958))</td>
</tr>
<tr>
<td>Vector: (J^{PC} = 1^{--})</td>
<td>(\rho(770))</td>
<td>(K^*(892))</td>
<td>(\phi(1020))</td>
<td>(\omega(782))</td>
</tr>
</tbody>
</table>

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:

\[
f' = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\cos\alpha - s\bar{s}\sin\alpha,
\]

\[
f = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\cos\alpha + s\bar{s}\sin\alpha.
\]

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 [13].

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
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 \[9\], is introduced in this paragraph.

Interactions with a large four-momentum $Q^2$ transfer 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 $\alpha_S$, or the usually more convenient $\alpha_S = g^2_S/4\pi$, 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-

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Footnote: In the remainder of this chapter, the four-momentum will be referred to as “momentum”.
1.3. PROTON-PROTON COLLISIONS

haves 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 \( \Lambda_{\text{UV}} \) 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

\[
Q^2 \frac{d \alpha_s}{d Q^2} = \beta(\alpha_s). \tag{1.8}
\]

The \( \beta \) function remains finite if \( \Lambda_{\text{UV}} \to \infty \) and in perturbative theory takes the from at first order

\[
\beta(\alpha_s) = - \left( \frac{33 - n_f}{12\pi} \right) \alpha_s^2. \tag{1.9}
\]

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:

\[
\alpha_s(m_Z^2) = 0.1184 \pm 0.0007. \tag{1.10}
\]

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

\[
\frac{1}{\alpha_s(Q^2)} = \frac{1}{\alpha_s(\mu^2)} + b \ln \left( \frac{Q^2}{\mu^2} \right) \equiv b \ln \left( \frac{Q^2}{\Lambda_{\text{QCD}}^2} \right). \tag{1.11}
\]

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

\[
\alpha_s(Q^2) = \frac{1}{b \ln(Q^2/\Lambda_{\text{QCD}}^2)}. \tag{1.12}
\]

At \( Q^2 \) values close to \( \Lambda_{\text{QCD}} \sim 200 \text{ MeV} \), the coupling constant becomes large and perturbative QCD breaks down. When momentum transfers are lower than \( \Lambda_{\text{QCD}} \) 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 partons. 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]:

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

(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 $y = \frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right)$ 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 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
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Figure 1.5: MSTW leading order parton distribution functions for the energy scales $Q^2 = 10$ GeV$^2$ and $Q^2 = 10^4$ 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
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 \cite{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 \cite{35} simulation toolkit. The geometry of the ATLAS detector is constructed in great detail with more than 316 thousand different types of shapes \cite{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-
1.5 Generators

$f$-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 $B^0_s \rightarrow J/\psi \phi$, 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

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

(1.14)
where the distributions for $f_{\pi^+}$ and $f_{\pi^-}$ 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:

$$f_{s,\text{val}} = f_{u,\text{val}} \quad f_{s,\text{sea}} = f_{u,\text{sea}}$$

(1.15)

and are thus estimated in a rather crude way.

After the hard process, $qg$, $qg$ 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 from 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:

$$\eta / \eta' = \frac{1}{2} (u\bar{u} + d\bar{d}) - / + \frac{1}{\sqrt{2}} s\bar{s}$$

$$\omega = \frac{1}{\sqrt{2}} (u\bar{u} + d\bar{d}) \quad \text{and} \quad \phi = s\bar{s},$$

(1.16)
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, \( Q_0 < 1 \text{ GeV} \), 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 \( e^+e^- \rightarrow \text{hadron final states} \). 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 in \( q\bar{q} \) 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 \( \sqrt{s} = 900 \text{ GeV} \) 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 mimicking the exchange of soft gluons during the non-perturbative hadronization. Using this extended model, the description of the underlying event at \( \sqrt{s} = 900 \text{ GeV} \) 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 Energy conserving quantum mechanical approach, based on Partons, parton ladders, strings, Off-shell remnants, and Splitting of parton ladders.

The motivation to model complete events is the observation that in \( p\overline{p} \) collision at the Teva-
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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 $d + Au$ 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.
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/π 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 √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 pT regime (pT < 2 GeV) is typically between the model predictions, indicating that strangeness production is not described perfectly. The total yield of the φ-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 pT, the normalized K0 s meson and Λ baryon yields as a function of pT are shown in figure 1.10 [60]. Data are compared to PYTHIA 6 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 K0 s yield is well-described by all these generators, only the HERWIG++ pT is too soft. In the very low pT domain, pT < 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 pT. Interestingly, all generators significantly overestimate the Λ yield from pT > 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.
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.

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