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

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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, $N_{\text{sig,weighted}}$ 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:

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

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

$$f_{\text{BKG}}(m) = \left(1 - e^{(2m_K - m)/C}\right) \cdot \left(\frac{m}{2m_K}\right)^A + B \left(\frac{m}{2m_K} - 1\right),$$  \hspace{1cm} (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 $p_T$ range, the effect being most pronounced in lowest $p_T$ 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:

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

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 Crystall 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:

$$f_{\text{sig}}(m) = f_{\text{RelBW}}(m) \otimes CB(m; m_\phi, \sigma_{\text{exp}}, \alpha, n),$$  \hspace{1cm} (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 [5.3]. 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 PYTHIA6, as will be seen in section [6.5]. Low statistics in the HERWIG++ sample do not allow for yield extraction.
100

Φ-MESON CROSS-SECTION

<table>
<thead>
<tr>
<th>Bin [MeV]</th>
<th>(\langle \epsilon_{\text{rec}} \rangle)</th>
<th>(\langle \epsilon_{\text{pid}} \rangle)</th>
<th>(\langle \epsilon_{\text{tot}} \rangle)</th>
<th>(A_{\text{fid}})</th>
<th>(A_{\text{av}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 &lt; (p_{T,\phi}) ≤ 570</td>
<td>0.36</td>
<td>0.80</td>
<td>0.29</td>
<td>0.37</td>
<td>0.11</td>
</tr>
<tr>
<td>570 &lt; (p_{T,\phi}) ≤ 640</td>
<td>0.42</td>
<td>0.76</td>
<td>0.32</td>
<td>0.57</td>
<td>0.18</td>
</tr>
<tr>
<td>640 &lt; (p_{T,\phi}) ≤ 710</td>
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<td>0.72</td>
<td>0.34</td>
<td>0.76</td>
<td>0.26</td>
</tr>
<tr>
<td>710 &lt; (p_{T,\phi}) ≤ 780</td>
<td>0.51</td>
<td>0.66</td>
<td>0.34</td>
<td>0.89</td>
<td>0.30</td>
</tr>
<tr>
<td>780 &lt; (p_{T,\phi}) ≤ 850</td>
<td>0.54</td>
<td>0.58</td>
<td>0.31</td>
<td>0.93</td>
<td>0.29</td>
</tr>
<tr>
<td>850 &lt; (p_{T,\phi}) ≤ 920</td>
<td>0.58</td>
<td>0.52</td>
<td>0.30</td>
<td>0.89</td>
<td>0.27</td>
</tr>
<tr>
<td>920 &lt; (p_{T,\phi}) ≤ 990</td>
<td>0.60</td>
<td>0.43</td>
<td>0.26</td>
<td>0.82</td>
<td>0.21</td>
</tr>
<tr>
<td>990 &lt; (p_{T,\phi}) ≤ 1060</td>
<td>0.64</td>
<td>0.34</td>
<td>0.22</td>
<td>0.74</td>
<td>0.16</td>
</tr>
<tr>
<td>1060 &lt; (p_{T,\phi}) ≤ 1130</td>
<td>0.64</td>
<td>0.26</td>
<td>0.17</td>
<td>0.66</td>
<td>0.11</td>
</tr>
<tr>
<td>1130 &lt; (p_{T,\phi}) ≤ 1200</td>
<td>0.65</td>
<td>0.19</td>
<td>0.12</td>
<td>0.55</td>
<td>0.07</td>
</tr>
</tbody>
</table>

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 \(\Delta p_{T,\phi} = p_{T,\phi,\text{true}} - p_{T,\phi,\text{reco}}\) and \(\Delta |y_\phi| = |y_{\phi,\text{true}}| - |y_{\phi,\text{reco}}|\). (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:

\[
A_{\text{av}} = \langle \epsilon_{\text{rec}} \rangle \cdot \langle \epsilon_{\text{pid}} \rangle \cdot A_{\text{fid}},
\]

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 $|y|$. 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 $p_{T, \phi}$, $\phi$ and $|y_\phi|$. 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 momentum, 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

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

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

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

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.
6.3. THE DIFFERENTIAL CROSS SECTION

The differential cross section \( \frac{d\sigma}{dp_T} \) for the reaction \( K^+K^- \rightarrow \phi \) is shown in Figure 6.7. The data are compared to PYTHIA 6 and EPOS predictions. 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.
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 ±10% to ±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 extenion 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 $\phi \rightarrow K^+K^-$

<table>
<thead>
<tr>
<th>Source</th>
<th>Effect</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield extraction</td>
<td>Signal p.d.f.</td>
<td>5–6%</td>
</tr>
<tr>
<td></td>
<td>Resolution model</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Background p.d.f.</td>
<td>3%</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>Statistical</td>
<td>1–2%</td>
</tr>
<tr>
<td></td>
<td>Relative efficiency</td>
<td>0.7%</td>
</tr>
<tr>
<td></td>
<td>Material description</td>
<td>4–6%</td>
</tr>
<tr>
<td></td>
<td>Migration</td>
<td>0–1%</td>
</tr>
<tr>
<td>Kaon identification efficiency</td>
<td>Statistical</td>
<td>1–2%</td>
</tr>
<tr>
<td></td>
<td>Background normalization</td>
<td>2–6%</td>
</tr>
<tr>
<td></td>
<td>Extraction yield tag sample</td>
<td>7–10%</td>
</tr>
</tbody>
</table>

Table 6.3: The systematic uncertainties on the $\phi$-meson cross section.
6.4. **EXTRAPOLATED DIFFERENTIAL CROSS SECTION**

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

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

(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 $p_{T,\phi}$ with $|y_{\phi}| < 0.5$ 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

$$\frac{d\sigma}{dp_{T,\phi}} = 1.6 \pm 0.1\,(\text{stat}) \pm 0.2\,(\text{syst}) \, [\mu\text{b}/\text{MeV}].$$
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 $K^0_S$ 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 $|y_\phi| < 2$.
6.4. EXTRAPOLATED DIFFERENTIAL CROSS SECTION

$\phi_T, \phi \sigma_d$

$-1$

$b/\mu b/MeV$

$0.5$

$1$

$1.5$

$2$

$[MeV]\phi_T, p$

$\mu$ $7 TeV, L = 383 s$

$\text{ATLAS}$ $\text{ALICE}$

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].
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 $|\phi|$, which was validated using simulation, and that the fiducial corrections in the central rapidity region are correct, the correction factors in bins of $|\phi|$ 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 $|\phi|$ is tested by comparing the generated yields in bins of $p_T, \phi$ for $|\phi| < 0.4$ and $0.4 < |\phi| < 0.8$ from the different generators. A maximum of 5% variation is observed and included as an extra systematic uncertainty on the corrected result within $|\phi| < 0.8$.

The extrapolated cross section in $|\phi| < 0.8$ as a function of $|\phi|$ is shown in figure 6.11. The cross section is flat as a function of $|\phi|$, 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
6.5. DISCUSSION

![Graph showing 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 \( 570 < p_{T,\phi} < 920 \text{ MeV} \), 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 \( p_{T,\phi} < 600 \text{ MeV} \) and is less than \( \sim 0.1% \) for \( p_{T,\phi} > 1000 \text{ MeV} \). 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 \( 0.5 < p_{T,\phi} < 6 \text{ GeV} \) is compared to predictions from several tunes of PYTHIA 6. The predicted cross section at \( p_{T,\phi} \sim 500 \text{ MeV} \) 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
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.
6.6. **SUMMARY**

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.