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

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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 ~ 8 m apart. At design luminosity (further discussed below) of $L = 10^{34}$ cm$^{-2}$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
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 $\mathcal{L} = 5.6$ fb$^{-1}$ of collision data at $\sqrt{s} = 7$ 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 $\mathcal{L} = f_r (n_1 n_2) / (4 \pi \sigma_x \sigma_y)$, 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
2.1. THE LARGE HADRON COLLIDER

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].

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

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

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 pb$^{-1}$ and in 2011 in 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 $383 \mu$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].
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].

<table>
<thead>
<tr>
<th>Sub-detector</th>
<th>Required resolution</th>
<th>$\eta$ coverage</th>
<th>measurement</th>
<th>trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner tracker</td>
<td>$p_T/p_T = 0.05%p_T \oplus 1%$</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 2.7$</td>
</tr>
<tr>
<td>EM calorimeter</td>
<td>$E/E = 10%/\sqrt{E} \oplus 0.7%$</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 2.7$</td>
</tr>
<tr>
<td>Hadronic calorimeter</td>
<td>$E/E = 50%/\sqrt{E} \oplus 3%$</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.3$</td>
</tr>
<tr>
<td>Muon spectrometer</td>
<td>$p_T/p_T = 10%p_T$ at $p_T = 1$ TeV</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 2.7$</td>
</tr>
</tbody>
</table>

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 $|\eta| < 1.3$.

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<table>
<thead>
<tr>
<th>Type</th>
<th>Goal</th>
<th>Coverage</th>
<th>Readout channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon Drift Tubes (MDT)</td>
<td>Tracking</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Cathode Strip Chambers (CSC)</td>
<td>Tracking</td>
<td>$2.0 &lt;</td>
<td>\eta</td>
</tr>
<tr>
<td>Resistive Plate Chambers (RPC)</td>
<td>Triggering and 2nd coordinate</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Thin Gap Chambers (TGC)</td>
<td>Triggering and 2nd coordinate</td>
<td>$1.05 &lt;</td>
<td>\eta</td>
</tr>
</tbody>
</table>

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\text{--}1.6\% in the central regions and 2\text{--}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 $\pm2\%$ 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
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.