Track and vertex reconstruction in the ATLAS inner detector

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Chapter 1

$J/\psi$ physics at LHC

The $J/\psi$ particle represents a bound state of a charm and anti-charm quark pair. The $J/\psi$ decay to two muons provides a striking signature for measuring the $J/\psi$ in particle collider events. Understanding the details of prompt $J/\psi$ production at 14 TeV proton-proton collisions is a challenging task and good testbed for various predictions of the theory of Quantum Chromo Dynamics. The $J/\psi$ is among the decay products of heavier particle states (such as particles containing beauty quarks) and serves as a good signature for studying B-physics related processes. Another reason to study $J/\psi \rightarrow \mu^+\mu^-$ events, is that they can be used for alignment of the detector, as will be demonstrated later in this thesis.

This chapter provides some information on the current knowledge of the $J/\psi$ particle properties and discusses the production of heavy quarks at proton-proton collisions. The expected cross-section for $J/\psi \rightarrow \mu^+\mu^-$ events at LHC within the phase-space reached by the ATLAS experiment is discussed.

1.1 The $J/\psi$ particle

In 1974 about half of the number of elementary particles currently described in the Standard Model were not yet discovered and the basic constituents of nature were described by three quarks and four leptons. On November 10, 1974, two separate groups, one at BNL\textsuperscript{1} studying collisions of accelerated protons on a beryllium target \textsuperscript{2} and another at SLAC\textsuperscript{3} studying electron positron collisions \textsuperscript{4}, simultaneously announced the discovery of a new particle with a mass at around 3095 MeV and a narrow width. BNL called the new particle $J$ and SLAC named it $\psi$, so it became known in literature as the $J/\psi$ particle. Figure [1.1] illustrates the simultaneous $J/\psi$ discovery in the two experiments using plots from the original papers.

\begin{footnotesize}
\begin{itemize}
\item[1] Brookhaven National Laboratory, U.S.A.
\item[2] Stanford Linear Accelerator Center, U.S.A.
\end{itemize}
\end{footnotesize}
Soon after the \( J/\psi \) discovery the experiment at SLAC discovered another vector meson \( \psi' \) at 3695 MeV followed by the discovery through radiative transitions of three more states, whose masses were between those of the \( \psi' \) and \( J/\psi \). Within about one year after its discovery it was clear that the \( J/\psi \) is the first excited state of the charmonium, the bound state of a charm and anti-charm quark pair, with the other states being other excited charmonium states. These discoveries confirmed the hypothesis of the existence of a fourth quark, the charm quark.

The charmonium appears in various resonance states with different quantum numbers\(^3\). The \( J/\psi \) and some of the other charmonium states are listed in table 1.1 together with the current knowledge of their mass and width. The lowest mass charmonium, \( \eta_c \), is a spin-0 particle which can not directly couple to a photon (spin-1) and as consequence the \( \eta_c \) has no leptonic decay channels.

Figure 1.2 shows the Feynman diagrams for the main \( J/\psi \) decay modes. The \( J/\psi \) decays about 30% of the time electromagnetically resulting in the production of hadrons or charged leptons. The other 70% of the \( J/\psi \) decays proceed via the strong force resulting in various hadronic final states. In most particle decays the strong force would dominate the electromagnetic force, but

\(^3\)Spectroscopic notation: \( n^{2s+1}L_j \), where \( n \) is the principle quantum number, \( s \) is the spin, \( L \) the orbital quantum number and \( J \) the angular momentum.
## 1.1 The $J/\psi$ particle

The $J/\psi$ decay is suppressed for several reasons. First, the $J/\psi$ mass is less than the masses of the $D$-mesons that separately contain charm quarks, so the decay into $D$-mesons is not possible. Secondly, at least three gluons are required to conserve colour and spin.

<table>
<thead>
<tr>
<th>Spectroscopic notation</th>
<th>Particle name</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^3S_0$</td>
<td>$\eta_c$</td>
<td>2980.3±1.2</td>
<td>17.3±2.6</td>
</tr>
<tr>
<td>$1^3S_1$</td>
<td>$J/\psi$</td>
<td>3096.916±0.011</td>
<td>0.0910±0.0032</td>
</tr>
<tr>
<td>$1^3P_1$</td>
<td>$h_c$</td>
<td>3525.93±0.27</td>
<td>&lt;1.1</td>
</tr>
<tr>
<td>$1^3P_0$</td>
<td>$\chi_{c0}$</td>
<td>3414.75±0.31</td>
<td>10.2±0.9</td>
</tr>
<tr>
<td>$1^3P_1$</td>
<td>$\chi_{c1}$</td>
<td>3510.66±0.07</td>
<td>0.91±0.13</td>
</tr>
<tr>
<td>$1^3P_2$</td>
<td>$\chi_{c2}$</td>
<td>3556.20±0.09</td>
<td>2.11±0.16</td>
</tr>
<tr>
<td>$2^1S_0$</td>
<td>$\eta'_c$</td>
<td>3637±4.</td>
<td>&lt;55</td>
</tr>
<tr>
<td>$2^3S_1$</td>
<td>$\psi'$</td>
<td>3686.09±0.04</td>
<td>0.281±0.017</td>
</tr>
</tbody>
</table>

**Table 1.1:** Charmonium states as listed by the Particle Data Group [4].

The world average of the measured $J/\psi$ decay fractions is summarized in table 1.2. The $J/\psi$’s narrow resonance combined with its possible decay to a $\mu^+\mu^-$ pair create a striking signature to observe the $J/\psi$ in any particle physics experiment.

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4Decays of states such as $\eta_c$ are mediated via two gluons, resulting in the much wider width of the $\eta_c$ compared to the $J/\psi$.

\[\begin{array}{c}
\begin{aligned}
\bar{c} & \rightarrow g & \rightarrow g & \rightarrow g \\
\end{aligned}
\end{array}\]

**Figure 1.2:** Feynman diagrams for $J/\psi$ decay modes showing (a) strong-force mediated decay via three gluons and (b) electro-magnetic decay via a virtual photon.
Table 1.2: $J/\psi$ decay fraction as listed by the Particle Data Group [4].

1.2 Prompt $J/\psi$ production at proton-proton collisions

The $J/\psi$ particle at LHC is produced by the interactions between the partons (quarks and gluons) inside the colliding protons. Quarks and gluons interact via the strong force as is described in the theory Quantum Chromo Dynamics (QCD). Predictions of cross-sections at LHC rely on the use of Monte Carlo event generators. All events in this thesis are simulated using the Pythia event generator [3].

1.2.1 Event generation

The collision of protons at high energy can be seen as a collision between the partons inside the proton. Due to the quantum field description of the strong interaction inside a proton, gluons are continuously exchanged and quarks and anti-quarks are continuously created and annihilated. As a result, the proton contains not only the three valence quarks ($u,u,d$) but also gluons and a ‘sea’ of quarks and anti-quarks.

The density of quarks and gluons inside the proton is described by the “parton distribution functions” (PDF). These PDFs $f(x)$ describe the probability to find a parton with flavor $f$ with a momentum fraction $x$ of the total proton momentum. PDFs are obtained by means of a global fit to experimental data, typically from experiments studying proton-electron collisions. The production cross section in a proton-proton collision can factorized as follows:

$$\sigma_{pp\rightarrow X} = \sum_{i,j} \int_0^1 \int_0^1 dx_1 dx_2 f_i(x_1)f_j(x_2) \hat{\sigma}_{i,j\rightarrow X}$$  \hspace{1cm} (1.1)$$

where $i,j$ denote the different partons in the proton and $\hat{\sigma}_{i,j\rightarrow X}$ represents the production cross-sections with the initial state partons $i,j$.

The hard parton scattering cross section $\hat{\sigma}_{i,j\rightarrow X}$ can be computed within the framework of perturbative QCD. Pythia implements calculations made at lowest order in the coupling constant in terms of transitions probabilities.
into various final states. Higher orders are approximated by a parton shower process in which the particles before and after the interaction radiate gluons and photons, or quark anti-quark pairs. This process continues until the parton energy reaches the hadronisation scale (at around 1 GeV) where the colored partons combine to form hadrons. Hadron formation in Pythia is based on the Lund string model [6], which is a phenomenological model within which the long-range confinement forces are allowed to distribute the energies and flavors of a parton configuration among a collection of primary hadrons, which subsequently may decay further.

### 1.2.2 Prediction of the $J/\psi$ cross-section

At very high energies the strong coupling $\alpha_s$ becomes small, allowing accurate predictions using perturbative QCD [7]. The creation of a $c\bar{c}$ pair involves the interaction of quarks and gluons with relatively high momenta and can be calculated in perturbation theory. However, the subsequent transition from the $c\bar{c}$ pair to a $J/\psi$ particle is a non-perturbative process that involves radiation of low momenta gluons and cannot be calculated directly.

The framework of non-relativistic QCD [8] separates the perturbative and non-perturbative processes such that the $J/\psi$ formation is factorized into universal non-perturbative parameters. This way a prediction for the cross-section for $J/\psi$ production at LHC can be calculated from the following expression [9]:

$$d\sigma(pp \rightarrow J/\psi + X) = \sum_{i,j} \int \int dx_1 dx_2 f_i(x_1) f_j(x_2) \times \sum_n d\hat{\sigma}(i + j \rightarrow c\bar{c}[n] + X) \langle O^{J/\psi}[n] \rangle$$  (1.2)

where the term $d\hat{\sigma}(i + j \rightarrow c\bar{c}[n] + X)$ is the cross section for producing a $c\bar{c}$ in a state $n$, described by perturbative QCD, and $\langle O^{J/\psi}[n] \rangle$ are the corresponding non-perturbative elements that describe the probability for a state $n$ to form a $J/\psi$ particle. Gluon fusion processes give the highest contribution to the cross-section due to the large gluon densities of the high-momentum protons.

$J/\psi$ production was originally described in the Color Singlet Model (CSM) [10] where the $c\bar{c}$ pair is assumed to be produced endowed with quantum numbers of the state it eventually involves into. The leading order process in the Color Singlet Model, $g + g \rightarrow c\bar{c}[1^3S_1]$, is illustrated in figure [1.3]. The radiation of one gluon is necessary to conserve the spin in the process.

The first tests of the color-singlet model were performed by the CDF experiment [11] that studied proton-anti-proton collisions with a center of mass energy of 1.8 TeV. The resulting measured prompt $J/\psi$ cross-section at CDF turned out to be an order of magnitude larger than the leading order color-singlet prediction.
The Color Octet Model (COM) [12] attempts to provide a solution to this problem by assuming that heavy quark pairs produced in the hard process do not necessarily need to be produced with the quantum numbers of the $J/\psi$, but can evolve into the particular charmonium state through radiation of soft gluons and photons later on during hadronisation.

Figure 1.4 shows two examples of the Feynman diagrams for $J/\psi$ production in hadron-hadron collisions of leading order color octet contributions. Example (a) includes $\eta_c$ production from $^3P_J$ color singlet states and $^1S_1$ and $^3P_J$ octet states that can produce $J/\psi$ and $\chi_c$ particles through the radiation of soft gluons. The process in example (b) is predicted to produce almost only octet $^3S_1$ states and is unlikely to include any radiative $\chi_c$ decays.

The CDF results on $J/\psi$ production are described by including the leading color-octet contributions, and adjusting the corresponding non-perturbative parameters to fit the data. This way the color-octet model provides a good fit.
1.2 Prompt $J/\psi$ production at proton-proton collisions

description of the measured cross-section of the $J/\psi$ at the CDF experiment as shown in figure 1.5.

Figure 1.5: Differential cross-section of $J/\psi$ production measured at CDF, with predictions from the color-singlet and color-octet mechanisms [9].

The analysis of the CDF data cross-section alone, although very encouraging, does not provide a conclusive test of NRQCD factorization because free parameters have to be introduced in the fit. However, if factorization holds, the non-perturbative matrix elements are universal and can be used to make predictions for various processes and observables. Measurements of the $J/\psi$ production at LHC will provide more detailed checks of this model. The color-octet model currently provides the best description of $J/\psi$ production at hadron-colliders and so it will be used to provide a benchmark for cross-section predictions at LHC. Given the substantial uncertainty in the determination of the non-perturbative matrix elements from present data, cross-section prediction made with the color-octet model should be regarded as order-of-magnitude estimates.

It should be noted that the CDF results in figure 1.5 represent the prompt $J/\psi$ production after contributions from both B-decays and radiative $\chi_c$ decays have been removed. For the studies done in this thesis we will consider ‘prompt’ $J/\psi$ production to include the contributions of radiative $\chi_c$ decays. The production of $J/\psi$’s through the decay of B-hadrons is considered separate from ‘prompt’ $J/\psi$ production.

$\chi_c$ states contribute to $J/\psi$ production through $\chi_c \rightarrow J/\psi + \gamma$
1.2.3 Kinematics of $J/\psi \to \mu^+\mu^-$ events in ATLAS

To study the kinematics of $J/\psi$ decays as they will be measured in ATLAS, generated $J/\psi \to \mu^+\mu^-$ events were produced with Pythia using the CTEQ5L parton distribution functions. Prediction of $J/\psi$ production in Pythia incorporates the Color Octet Mechanism, with model parameters fixed through a combination of theoretical and experimental constraints \[14\]. Figure 1.6 shows the distribution of prompt $J/\psi \to \mu^+\mu^-$ events generated with Pythia as function of the $J/\psi$ momentum, showing the contributions from the different production mechanisms.

![Figure 1.6: Distribution of prompt $J/\psi \to \mu^+\mu^-$ events generated with Pythia as function of the $J/\psi$ momentum, showing the contributions from the different production mechanisms.](image)

Figure 1.7 illustrates the transverse momentum and pseudo-rapidity distributions of the muons from prompt $J/\psi$ decay. The two muons have an average transverse momentum of 2.8 GeV and are produced over a large range of pseudo-rapidity $\eta$. The distribution of the events over the phase-space of the muons is shown in figure 1.8. The transverse momentum and $\eta$ of the muons are clearly correlated, which is the logical result of the invariant mass of the two muons being equal to the $J/\psi$ value.

In general the ATLAS detector is unable to select and identify muons with a $p_T$ less than 4 GeV which directly influences the range of the transverse momentum of the $J/\psi$ that is accessible. In addition, the ATLAS experiment was designed to measure charged particle trajectories with a pseudo-rapidity $\eta$ up to 2.5, which further limits the available phase-space for which $J/\psi \to \mu^+\mu^-$ events can be detected.

The $J/\psi$ events that are recorded in ATLAS depend on the selection re-
1.2 Prompt $J/\psi$ production at proton-proton collisions

Figure 1.7: Distribution of $J/\psi \rightarrow \mu^+\mu^-$ events as a function of the transverse momenta (left) and the pseudo-rapidity $\eta$ of the muons (right).

Figure 1.8: Distribution of $J/\psi \rightarrow \mu^+\mu^-$ events versus the transverse momenta (left) and versus the pseudo-rapidity $\eta$ of the high and low $p_T$ muon (right).

requirements. Figure 1.9 illustrates the $p_T$ of the measured $J/\psi$’s with various requirements on the $p_T$ of the $J/\psi$’s. It can be seen that the number of $J/\psi \rightarrow \mu^+\mu^-$ events that can be detected in ATLAS strongly depends on the minimum $p_T$ requirements on the tracks.

The distribution of the opening angle of the two muons, described by the variable $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$, is shown in figure 1.10. It can be seen that requirements on the transverse momentum results in the reduction of the max-
Figure 1.9: Distribution of $J/\psi \rightarrow \mu^+\mu^-$ events as function of the $J/\psi$ momentum, with and without cuts on the transverse momentum $p_T$ and pseudo-rapidity $\eta$.

Figure 1.10: Distribution of $\Delta R$ separation of the two muons from $J/\psi$ decay with and without cuts on the transverse momentum $p_T$ and pseudo-rapidity $\eta$.  

With cuts on the transverse momenta of the muons of 6 and 4 GeV and pseudo-rapidity cuts on both muons of $|\eta| < 2.5$, the predicted cross-section from Pythia of prompt $J/\psi \rightarrow \mu^+\mu^-$ events is 23 nb \cite{15}. At the design luminosity of the LHC of $10^{-34}$ cm$^{-2}$s$^{-1}$ this corresponds to a rate of 230 events per second.
1.3 $J/\psi$ production from B-decays

Production of $c\bar{c}$ pairs at the hard parton collision is not the only source of $J/\psi$ production at LHC. The $J/\psi$ is among the decay products of the particles containing bottom quarks and serve as an important signature for studying various B-physics processes. The perturbative QCD cross section for $b\bar{b}$ production can be calculated in a similar way as for $c\bar{c}$ production and the next-to-leading order prediction of the total $b\bar{b}$ cross section at $\sqrt{s}=14$ TeV proton-proton collisions is around 0.5 mb \[14\].

Produced $b$ and $\bar{b}$ quarks hadronise forming B-hadrons as listed in table 1.3. B-hadrons are characterized by their relatively long lifetimes, so that with a precise track detector it is possible to measure the decay-vertex of these particles as a separate vertex relative to the primary vertex of the proton-proton collision. A fraction of 1.2% of the B-hadron decays will produce a $J/\psi$. In the case where a $J/\psi$ decaying to two muons was among the b-hadron decay products, the decay-vertex can be detected as the intersection point of two muon trajectories with an invariant mass equal to the $J/\psi$ mass.

<table>
<thead>
<tr>
<th>B-hadron</th>
<th>Mass (MeV)</th>
<th>Lifetime (ps)</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ (\bar{b}u)$</td>
<td>5279.0±0.5</td>
<td>1.638±0.011</td>
<td>39.9±1.1%</td>
</tr>
<tr>
<td>$B^0 (\bar{bd})$</td>
<td>5279.4±0.5</td>
<td>1.530±0.009</td>
<td>39.9±1.1%</td>
</tr>
<tr>
<td>$B^+_s (\bar{bs})$</td>
<td>5367.5±1.8</td>
<td>1.466±0.059</td>
<td>11.0±1.2%</td>
</tr>
<tr>
<td>$B^- \text{ baryon} (\bar{u}bd)$</td>
<td>5624.±9.($A_b$)</td>
<td>1.209±0.049</td>
<td>9.2±1.9%</td>
</tr>
<tr>
<td>$\Lambda_b$, $\Xi_b$, $\Sigma_b$, $\Omega_b$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 1.3:** B-hadrons produced in the hadronisation of a $b$-quark \[4\]. Identical numbers apply for the anti $b$-hadrons produced in the hadronisation of $b$-quark.

The Pythia event generator was used to generate events of $pp \to b\bar{b} \to X + (J/\psi \to \mu^+\mu^-)$. The generator cuts were set such that the transverse momenta of the muons was required to be $>6$ GeV for one muon and $>4$ GeV for the second muon with pseudo-rapidity cuts on both muons of $|\eta| < 2.5$.

The predicted cross-section from Pythia of $b\bar{b}$ pairs producing a $J/\psi \to \mu^+\mu^-$ with these requirements is 11.1 nb \[16\]. This means that in this selection region approximately 30% of the $J/\psi \to \mu^+\mu^-$ events are expected to originate from $b\bar{b}$ pair production.

Figure 1.11 shows the distance between the proton-proton interaction that produced the $b$-quarks and the position where the $J/\psi$-decay took place, in the plane perpendicular to the beam-axis. For each $J/\psi \to \mu^+\mu^-$ event, this distance is equal to zero, so the measurement of the decay distance helps to differentiate between prompt $J/\psi$’s and $J/\psi$’s produced in B-hadron decays.
1.4 Other di-muon final states

Various other particles beside the \( J/\psi \) can result in di-muon final states. The ground state of bottomonium \( \Upsilon \), the bound state of a \( b \) and an anti-\( b \) quark, can also decay to two muons, providing a similar striking signature as for the \( J/\psi \) but at a mass of \( 9.460 \pm 0.26 \) GeV.

Several other processes may lead to the production of two muons in one event in ATLAS, creating background events that have to be taken into account when studying di-muon decay signatures. The expected sources of background for di-muon events are [15]:

- Continuum of muon pairs from \( b\bar{b} \) events
- Continuum of muon pairs from \( c\bar{c} \) events
- Di-muon production via the Drell-Yan process [17]
- Decays in flight of \( \pi^{\pm} \) and \( K^{\pm} \) mesons

Figure 1.12 shows the contributions of the various di-muon backgrounds expected in the measurement of \( J/\psi \) and \( \Upsilon \) in the ATLAS experiment [15].

For Drell-Yan muons or muons coming from \( c\bar{c} \), the transverse momentum spectrum of the muon falls very steeply and the probability of producing an invariant mass within the trigger acceptance is well below the level from \( b\bar{b} \) events. Muons from decays in flight also have a steeply falling muon momentum spectrum, and in addition require random coincidences with muons from other sources in the \( J/\psi \) invariant mass range. The most important background contributions for events with di-muon signatures is expected to come from
1.4 Other di-muon final states

Figure 1.12: Invariant mass of di-muons from various sources as expected to be reconstructed in the ATLAS experiment when triggering on two muons with minimum $p_T$ of 6 and 4 GeV, after optimization of cuts on the decay-time \[15\]. The dotted line shows the result without cuts on the decay-time.

muons from $b\bar{b}$ events, as these events can produce muons with relatively high transverse momentum.

The $b\bar{b}$ events are also the main background for another important process with a di-muon signature: $Z \rightarrow \mu^+\mu^-$. The decay of the Z-boson into two muons has a clear signature at an invariant mass of around 91 GeV, and a cross-section of $\approx 2$ nb at LHC \[15\]. The expected invariant mass distribution for the measurement of $Z \rightarrow \mu^+\mu^-$ events in ATLAS is illustrated in figure 1.13.

Figure 1.13: Di-muon invariant mass distribution in the $Z \rightarrow \mu\mu$ channel, for signal and background, as expected to be reconstructed in ATLAS, for 50 pb$^{-1}$ \[15\].