Physics and Detector Simulation Studies of B-Meson Decays in ATLAS

BY

JEROME DAMET
Physics and detector simulation studies of B-meson decays in ATLAS

by

Jérôme DAMET

ACTA UNIVERSITATIS UPSALIENSIS
UPPSALA 2001
Dissertation for the Degree of Doctor of Philosophy in High Energy Physics presented at Uppsala University in 2001

ABSTRACT


This thesis has two objectives; the first is to study the phenomenology of heavy quarks in high energy proton-proton collisions at the Large Hadron Collider (LHC) at the European Laboratory for Particle Physics (CERN). The second objective is to estimate the performance for B-physics analysis of the Inner Tracking Detector in the ATLAS experimental set-up at the LHC.

Phenomenological models of B-meson production-asymmetry and prompt J/ψ production are examined to investigate, and better understand, the different non perturbative QCD models and their description of potential sources of background in CP violation measurements.

A Monte Carlo evaluation is made of the precision that can be reached in measurements of CP-violation in the $B_d^0 \to J/ψK_S^0$ decay channel as well as of the possibilities of ATLAS to detect physics beyond the Standard Model in the $B^+ \to K^+K^+\pi^−$ decay channel. It is shown that after three years of running at low luminosity (30 fb$^{-1}$) with ATLAS at LHC:

- a statistical accuracy in the measurement of $\sin2\beta$,
  
  $\delta_{\text{stat}}(\sin2\beta) = 0.010$ for an assumed value of $\sin2\beta$ of 0.60 can be reached and

- an upper limit on R-parity violating couplings $\lambda'$ can be set:

  $$ \sqrt{\sum_{i=1}^{3} \lambda'_{32} \lambda'_{21}}^2 + \sum_{i=1}^{3} \lambda'_{1i2} \lambda'_{1i3}}^2 < 5.4 \cdot 10^{-5}. $$

Jérôme Damet, Department of Radiation Sciences, Uppsala University, Box 535, S-751 21 Uppsala, Sweden

©Jérôme Damet 2001

ISSN 1105-232X
ISBN 91-554-4942-5

Printed in Sweden by Fyris-Tryck AB, Uppsala.
Résumé

L’expérience ATLAS actuellement en cours de préparation au Laboratoire européen pour la physique des particules (CERN) a pour objectif d’étudier, entre autres, la physique des mésons beaux. Auprès du futur grand collisionneur de hadrons (LHC), ATLAS bénéficiera d’un cadre favorable à l’analyse de différents canaux de désintégration des mésons B.

Le travail de cette thèse de doctorat s’articule autour de l’étude des mésons beaux en abordant certains aspects phénoménologiques ainsi qu’en étudiant le potentiel du détecteur interne.

Les résultats quantitatifs principaux sont d’une part l’estimation de l’erreur sur la mesure dans ATLAS de l’angle $\beta$ du triangle unitaire, qui est une représentation graphique de l’interprétation de la violation de CP dans le cadre du Modèle Standard, et d’autre part une limite supérieure sur les paramètres de certains modèles supersymétriques à partir de l’étude de l’observation de la désintégration $B^+ \to K^+ K^+ \pi^-$. 

Ces résultats sont :

- une incertitude statistique sur $\sin 2\beta$ de 0.01 après les trois premières années de prise de données au LHC, soit une luminosité intégrée de 30 fb$^{-1}$, pour une valeur présumée de $\sin 2\beta$ de 0.60.

- une limite sur les couplages $\lambda'$ violant la conservation du nombre baryonique

$$\left| \sum_{i=1}^{3} \lambda'_{22}^{\alpha_2} \lambda'^{\alpha_2}_{21} \right|^2 + \left| \sum_{i=1}^{3} \lambda'_{11}^{\alpha_1} \lambda'^{\alpha_1}_{12} \right|^2 < 5.4 \cdot 10^{-5}.$$ 

De plus, l’asymétrie de production des mésons beaux ainsi que la production de charmonium ont été examinés comme source de bruit de fond du canal de désintégration $B_d^0 \to J/\psi K_s^0$ pour l’étude de la violation de CP.

A mes parents,
This thesis is based on the following papers:

I. B/\bar{B} production asymmetry at the LHC and HERA-B.
   by: Damet, J. ; Ingelman, G.
   TSL/ISV-2001-0242.

II. Prompt J/\psi production at the LHC
    by: Damet, J. ; Ingelman, G. ; Mariotto, C.
    TSL/ISV-2001-0243.

III. Measurement of \sin(2\beta) from B^0 \rightarrow J/\psi \K^0:
      statistical reach and estimate of the systematic uncertainties.
    by: Coadou, Y. ; Damet, J. ; Korsmo, H. ; Tartarelli, G.F.
    ATL-PHYS-99-022.
    - Nov. 1999.

IV. Measurement of CP violation effects in B^0 \rightarrow J/\psi \K^0
    in ATLAS.
    by: Damet, J.

V. Searching for physics beyond the Standard Model in the decay
   B^+ \rightarrow K^+K^+\pi^-.
   by: Damet, J. ; Eerola, P. ; Manara, A. ; Nooij, S.E.M.
   - Oct. 2000
   Scientific Note submitted to The European Physics Journal: EPJ Direct C

VI. K^0_s reconstruction in the ATLAS Inner Detector.
    by: Damet, J. ; Tartarelli, G.F.
    ATL-INDET-99-024.

Part of the work presented in this thesis has also been included in
the ATLAS Detector and Physics Performance Technical Design Report.

  ATLAS Collaboration. 1999; p.88-90
  - May 1999 - 966 p

  ATLAS Collaboration. 1999 ; p.565-577
  - May 1999 - 460 p
Contents

1 Introduction .......................................................... 1

2 Theoretical framework ............................................ 3
  2.1 CP violation .................................................. 3
  2.1.1 CKM matrix ............................................. 4
  2.1.2 Unitarity Triangle ..................................... 5
  2.1.3 Neutral B system ....................................... 5
  2.1.4 B-physics experiments ................................ 7
  2.1.5 Signatures of physics beyond the Standard Model .... 8
  2.2 Supersymmetry .............................................. 9
  2.2.1 Minimal Supersymmetric Standard Model .......... 9
  2.3 Summary .................................................... 11

3 Phenomenology ..................................................... 13
  3.1 Perturbative QCD ......................................... 13
  3.2 Phenomenological models ................................. 17
  3.3 Summary .................................................... 18

4 Detector and physics performance ............................... 19
  4.1 Trigger ..................................................... 20
  4.1.1 Charmomium channels ............................... 20
  4.1.2 Hadronic channels ................................ 22
  4.2 Reconstruction algorithms ............................... 22
  4.2.1 Full simulation .................................... 22
  4.2.2 Fast simulation ................................... 23
  4.3 Tagging methods .......................................... 25
  4.4 Summary .................................................... 25

5 Summary of papers ................................................ 27

Acknowledgements .................................................. 29

References .......................................................... 31
Chapter 1

Introduction

High energy physics investigates the structure of matter in terms of structureless fundamental matter particles and their interactions. The Standard Model of elementary particle physics is a theory that successfully describes all known kinds of matter with a minimal set of particles (leptons and quarks) which appear in three generations (see Table 1.1). Leptons can be directly observed as isolated particles. Individual quarks, however, do not occur isolated in nature, they are internal components of hadrons. There are two kinds of hadrons: mesons, which are made of a quark and an anti-quark, and baryons, which consist of three quarks. Quarks come in six categories and are identified by their flavour (up, down, charm, strange, top and bottom). The Standard Model is composed of electroweak theory and quantum chromodynamics (QCD). Each of these components of the Standard Model describes a fundamental force of nature as an interaction between the matter particles mediated by a field particle (see Table 1.2).

<table>
<thead>
<tr>
<th>Elementary particle generations</th>
<th>1\textsuperscript{st}</th>
<th>2\textsuperscript{nd}</th>
<th>3\textsuperscript{rd}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons</td>
<td>e</td>
<td>(\mu)</td>
<td>(\tau)</td>
</tr>
<tr>
<td></td>
<td>(\nu_e)</td>
<td>(\nu_\mu)</td>
<td>(\nu_\tau)</td>
</tr>
<tr>
<td>Quarks</td>
<td>u</td>
<td>c</td>
<td>t</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>s</td>
<td>b</td>
</tr>
</tbody>
</table>

Table 1.1: The elementary constituents of matter in the Standard Model

This thesis is comprised of two parts. In the first part phenomenological aspects of heavy-quark physics are investigated [Papers I and II]. In the second part \(b\)-flavoured meson decays [Papers III, IV and V] as well as the ATLAS Inner Detector performance [Paper VI] are studied.

The theoretical framework of this thesis is presented in Chapter 2. Computer
<table>
<thead>
<tr>
<th>Force</th>
<th>Force mediators, Gauge bosons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>gluons, ( g )</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>photon, ( \gamma )</td>
</tr>
<tr>
<td>Weak</td>
<td>( W^+, W^- ) and Z</td>
</tr>
</tbody>
</table>

Table 1.2: Force mediators of the Standard Model

Simulation procedures are discussed in Chapter 3. Experimental equipment and software analyses are described in Chapter 4. Emphasis is put on the performance of the ATLAS Inner Detector which constitutes a powerful tracking and vertexing system that is essential for the location of a secondary vertex after a B-meson decay.
Chapter 2

Theoretical framework

The Standard Model of high energy physics describes, so far, successfully and in
great detail the elementary particles of matter and their interactions. Charge-
Parity (CP) violation is, however, one facet of the model which has not yet been
tested to high accuracy and many dedicated as well as more general purpose
experiments are now being prepared to study and understand its origin.

CP violation does play a key role in the baryogenesis and the evolution of
the universe since it is an ingredient of the Sakharov conditions to account for
the observed baryon asymmetry [1]. Indeed, direct searches for hard gamma
rays from matter-antimatter annihilation has excluded the presence of antimatter
until the closest cluster of galaxies to the Milky Way (the Virgo cluster, 20 Mpc
away) and this result combined with further investigations of a diffuse gamma ray
spectrum indicates that there is no antimatter within a domain as large as 1000
Mpc. Expected CP violation effects predicted by the Standard Model are not
large enough to explain the observed baryon asymmetry in the universe [2], and
cosmological constraints suggest thereby physics beyond the Standard Model.

The following section describes the mechanism of CP violation in the Standard
Model as well as the potential to observe CP violation effects at the B factories
and summarises how physics beyond the Standard Model could be detected.
Section 2.2 further explains why physics beyond the Standard Model is expected
and supersymmetry is introduced.

2.1 CP violation

The Standard Model is based on symmetries of the Lagrangian under certain
transformations. A symmetry is conserved/violated if the Lagrangian is un-
changed/modified. The CP transformation is the combined effect of C, the charge
conjugation which replaces each particle with its anti-particle, and P, the parity
transformation which is the spatial inversion of coordinates:

\[ C|f(\vec{p}, \vec{s})\rangle = \eta_C|\tilde{f}(\vec{p}, \vec{s})\rangle \]
\[ P|f(\vec{p}, \vec{s})\rangle = \eta_P|f(-\vec{p}, \vec{s})\rangle \]
\[ CP|f(\vec{p}, \vec{s})\rangle = \eta_{CP}|\tilde{f}(-\vec{p}, \vec{s})\rangle \]

where \( \vec{p} \) is the momentum, \( \vec{s} \) the spin and the \( \eta \)'s are phase factors.

The Lagrangian is CP-violating if some terms do not convert into their hermitian conjugate under CP transformation.

In the quark sector the weak interaction eigenstates differ from the mass eigenstates and are related by the quark mixing matrix. By definition quarks with a positive charge are unaffected and mixing of quarks with a negative charge is described by the Cabibbo-Kobayashi-Maskawa matrix (CKM matrix or \( V_{\text{CKM}} \)). In charged current electroweak interactions W bosons couple to \( u \)-type quarks and a linear combination of \( d \)-type quarks. Their coupling coefficients in the Lagrangian are the source of CP violation in the Standard Model as some do not convert into their hermitian conjugate under CP transformation. The main features of CP violation in the Standard Model framework are that it occurs only in the quark sector, only in charged current interactions and only in flavour changing interactions.

### 2.1.1 CKM matrix

The most generic form of the CKM matrix is:

\[
\begin{pmatrix}
\begin{pmatrix}
d' \\
\end{pmatrix} \\
\begin{pmatrix}
s' \\
\end{pmatrix} \\
\begin{pmatrix}
h' \\
\end{pmatrix}
\end{pmatrix} = 
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\times 
\begin{pmatrix}
d \\
\end{pmatrix}
\times 
\begin{pmatrix}
s \\
\end{pmatrix}
\times 
\begin{pmatrix}
h \\
\end{pmatrix}
\]

which can be expressed in the Wolfenstein’s parametrisation with only four parameters (three real coefficients and one phase). The matrix elements are expressed as a polynomial function of the sine of the Cabibbo angle \( (\lambda = \sin\theta_c \simeq 0.22) \).

\[
V_{\text{CKM}} = 
\begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
+ O(\lambda^4)
\]

In this representation there is a single and irreducible imaginary part, \( \eta \), which is the unique source of CP violation in the Standard Model. The diagonal terms which represent the transition from the heavier to the lighter quark in the same generation are of order of one and real. The complex terms that produce CP violation effects are proportional to \( \lambda^3 \).
### 2.1.2 Unitarity Triangle

The unitarity of the CKM matrix leads to a set of relations between the elements related to neutral meson systems composed of a quark and an anti-quark of different generations, i.e. $D^0(uu), K^0(ds), B^0_d(d\bar{b}), B^0_s(s\bar{b})$. These equations are particularly interesting for the study of CP violation since they can be checked experimentally:

- $V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$ related to the neutral D system
- $V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{ub}V_{tb}^* = 0$ related to the neutral K system
- $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ related to the neutral $B_d$ system
- $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$ related to the neutral $B_s$ system

Each equation can be represented by a triangle in the complex plane with $\rho$ and $\eta$ axes. The area of the triangles, $A$, is model independent and can be directly related to the Jarlskog CP violation parameter $|J|$, by $A = |J|/2$ with $J \simeq A^2 \lambda^0 \eta$ in the Wolfenstein’s parametrisation. In the Standard Model, CP violation occurs if and only if $J \neq 0$.

To estimate CP violation effects in the four neutral meson systems one can compare the area of the triangle and the quark transition which dominates the meson decay (excluding the mixing); the results are listed in Table 2.1.

The CP violation effects in the neutral $B_{d,s}$ meson systems predicted by the Standard Model are larger than the observed asymmetry in the neutral kaon system by a factor thirty ($1/A^2 \lambda^2 \simeq 30$).

| Meson | Quark transition | Amplitude $|V_{ij}|^2$ | CP violation effects $A/|V_{ij}|^2$ |
|-------|------------------|----------------------|-----------------------------------|
| D     | $c \to s$        | 1                    | $A^2 \lambda^0 \eta$             |
| K     | $s \to u$        | $\lambda^2$         | $A^2 \lambda^0 \eta$             |
| $B_{d,s}$ | $b \to c$ | $A^2 \lambda^1$ | $\lambda^2 \eta$ |

Table 2.1: CP violation effects in the neutral meson systems - Standard Model predictions.

### 2.1.3 Neutral B system

As mentioned in the previous section large CP violation effects are expected in the neutral B meson system in the Standard Model. The direct decay of the $B^0_d$ meson to $J/\psi K^0_s$ is not CP violating. The B meson oscillation mechanism involves a complex coupling constant between the top and down quarks (see Figure 2.1). The interference of this coupling with the direct decay coupling leads to CP
Unitarity Triangle

\[ \alpha, \beta, \gamma \]

\[ B_s^0 \rightarrow \rho K_S^0 \]

\[ B_d^0 \rightarrow \pi^+ \pi^- \]

\[ B_d^0 \rightarrow \psi K_S^0 \]

\[ (0,1) \]

\[ \eta \]

\[ \eta^\prime \]

\[ V_{ub}/V_{cb} \]

\[ V_{ud}/V_{cb} \]

\[ \Re \]

\[ \Im \]

\[ (\rho, \eta) \]

\[ B_d^0 \rightarrow \pi^+ \pi^- \]

\[ B_d^0 \rightarrow \psi K_S^0 \]

Figure 2.2: Unitarity Triangle associated with the neutral B system.

violation. The CP violation effect is measured from the different decay rates for the two neutral B mesons decaying into the same final state.

The triangle associated with the neutral B\(_d\) system, shown in Figure 2.2, is by convention called the Unitarity Triangle. By measuring the CP asymmetry of various decay modes of the B mesons one gets a set of independent measurements which enable the reconstruction of the Unitarity Triangle to be overconstrained and which test the Standard Model. The OPAL collaboration at CERN has estimated the angles by measuring the sides of the triangle [5]. The CDF collabor-
2.1. CP VIOLATION

2.1.4 B-physics experiments

The branching fraction of neutral B meson to CP eigenstate modes is small, \( \mathcal{O}(10^{-4}) \), and a large number of B mesons is thus required for the study of CP violation effects. So-called ‘B-factories’ have been set up both at \( e^+ e^- \) machines and at hadron colliders. In both cases one needs to obtain a high luminosity, \( \mathcal{L} \sim \mathcal{O}(10^{33}\text{cm}^{-2}\text{s}^{-1}) \), in order to reach the large statistics of CP violating events required to probe the predictions of the Standard Model with good statistical accuracy.

\( e^+ e^- \) colliders

At the \( e^+ e^- \) machines dedicated to B physics, electrons and positrons collide at the centre of mass energy corresponding to the threshold of \( \Upsilon(4s) \) resonance production. The \( \Upsilon(4s) \) decays almost exclusively to B-meson pairs (with a ratio \( \mathcal{B}(\Upsilon(4s) \to B^0\bar{B}_d^0) : \mathcal{B}(\Upsilon(4s) \to B^+B^-) \sim 1 \)). To be able to study \( B_d^0 \) mesons, the centre of mass energy would have to be raised to the \( \Upsilon(5s) \) resonance but the final states of the \( \Upsilon(5s) \) are not as clean as those of the \( \Upsilon(4s) \) (they include some excited B states) and the \( b\bar{b} \) cross-section is dramatically reduced.

Two complementary techniques have been developed: BABAR at SLAC (CA, USA) and Belle at KEK (Japan), operate with asymmetric beams, i.e. the electron and positron beams have different energies, while CLEO at Cornell (NY, USA) operates with symmetric beam energies. In both cases BB pairs are produced in coherent quantum states until one of the mesons decays.

In the case of BABAR and Belle the B mesons will travel a measurable distance before decaying because of the Lorentz boost resulting from the beam asymmetry. The B meson decay points can be reconstructed with high precision and the time separation of the B decays can thereby be measured to study CP violation in BB mixing. At the time \( t_1 \), the first meson \( B_1 \) decays directly through a channel which can be tagged; the second meson \( B_2 \) can then be assigned the opposite flavour. The time of flight of the second meson can be measured if \( B_2 \) decays at the time \( t_2 \) to a CP eigenstate which is identified and the oscillation parameter \( \Delta t = t_2 - t_1 \) can be determined.

The CLEO experiment cannot measure CP violation parameters in BB mixing and focuses on the measurements of the matrix elements, the reconstruction of rare B decays and measurements of CP violation parameters in the charged B system [7].

Experiments have started, both BABAR and Belle recently presented their first results ([8], [9]) which are consistent with the predictions of the Standard Model but more statistics are needed to rule on the CP asymmetry in the \( B_d^0 \)-meson system:

**BABAR** measured \( \sin 2\beta = 0.12 \pm 0.37(\text{stat}) \pm 0.09(\text{sys}) \)
Belle measured $\sin2\beta = 0.45 \pm 0.43^{+0.07}_{-0.06}(\text{stat}) \pm 0.09(\text{syst})$

Hadron colliders

Another way to get an even larger amount of B mesons is to make experiments at high energy hadron colliders. At the LHC, the B meson production cross-section is of the order of hundreds of microbarns compared to few nanobarns of the $e^+e^-$-machines.

B-physics studies at hadron colliders are already in progress in a fixed target experiment, HERA-B at DESY (Germany) and in two collider experiments (CDF and DØ) at Fermilab (IL, USA). Two general purpose experiments, ATLAS and CMS, and a dedicated experiment, LHC-b, will perform B-physics programs at the LHC at CERN (Switzerland).

One advantage of hadron colliders is that they allow for an enhancement of the constraint on Standard Model parameters by studying, in a complementary way, both $B_d$ and $B_s$ meson decays.

Hadron colliders have a $b\bar{b}$ production rate much higher than $e^+e^-$-machines, of the order of ten kHz at the LHC compared to 4 Hz at SLAC or KEK. On the other hand, hadron collisions are much more complex than $e^+e^-$-collisions, the reconstruction and tagging of B mesons therefore become more complicated and less efficient at hadron collider as compared to $e^+e^-$-colliders.

In proton-proton collisions a new source of asymmetry of B mesons is introduced at the production level due to the asymmetry in having two protons colliding rather than a proton and an antiproton. The phenomenology of the production asymmetry is discussed in Paper I.

Furthermore at hadron colliders the production processes of heavy quarks are dominated by gluon fusion which implies significant theoretical uncertainties. The new generation of hadron colliders reaches high energies where the reaction mechanisms are not thoroughly understood. For instance, a few years ago CDF observed an excess of prompt $J/\psi$ that contemporary models could not accommodate for. Since new models that describe data have been elaborated. The phenomenology of prompt $J/\psi$ is discussed in Paper II.

2.1.5 Signatures of physics beyond the Standard Model

There are reasons to expect physics beyond the Standard Model. One reason is that the Standard Model does not produce an asymmetry large enough to account for the apparent large excess of baryons over antibaryons in the universe. Many extensions of the Standard Model such as a fourth quark generation, a Z boson exchange with flavour-changing couplings, multi-Higgs doublet models or supersymmetric models, introduce additional sources of CP violation. In all cases the phases associated with physics beyond the Standard Model break the Unitarity Triangle condition.
The CP asymmetry in the $B^0_d \rightarrow J/\psi K^0_s$ measures the relative angle between the $B^0_d/B^0_d$ mixing and the $b \rightarrow c\bar{s}s$ decay amplitudes. In the Standard Model, the neutral B mixing is explained by box diagrams dominated by intermediate top quarks (see Figure 2.1) and the decay is mediated by a tree-level diagram. The present uncertainties in the determination of the $V_{td}$ parameter in the CKM matrix allow for processes from new physics to constitute the dominant contribution to the mixing. On the other hand the $b \rightarrow c\bar{s}s$ amplitude is a tree contribution that will most likely not be different in Standard Model extensions [10]. The $B^0_d/B^0_d$ mixing phase could, for instance, be modified by tree-level exchange of a $Z$ with flavour-changing. A new phase, $\theta_d$, is then introduced in the CP asymmetry parametrisation and releases the Standard Model constraint ($0.3 < \sin 2\beta < 0.9$) and any value of $\sin 2(\beta + \theta_d)$ between -1 and +1 could be measured.

If the Unitarity Triangle angles are such that $\alpha + \beta + \gamma \neq \pi$, or if the ratio between the lengths of the triangle sides do not fit with the observed angles, this would be an unequivocal signature of physics beyond the Standard Model [11].

### 2.2 Supersymmetry

Studies in elementary particle physics are related to observations in cosmology and hence to the evolution of the universe. In the scenario of the Big Bang fundamental forces are unified at the Planck energy scale. Extrapolations of the strength of the Standard Model gauge couplings do not coincide at any energy scale, whereas extrapolations using supersymmetric models give a common value at high energy for the electromagnetic, strong and weak couplings.

Despite the success of the Standard Model in accounting for experimental data over the energy span of present colliders and fixed target experiments, many questions remain unsolved. The generation structure, the origin of the flavour mixing and the mechanism of mass generation, for instance, are not understood. Extensions of the Standard Model may provide answers to these questions.

#### 2.2.1 Minimal Supersymmetric Standard Model

Supersymmetry imposes the Lagrangian to be unchanged under a transformation, $Q$, that interchanges bosons and fermions, i.e.

$$Q|Fermion\rangle = |Boson\rangle$$

$$Q|Boson\rangle = |Fermion\rangle$$

A new particle is associated with each particle of the Standard Model. With new bosonic and fermionic fields introduced by the supersymmetry, superpotential couplings that violate lepton or baryon number are introduced:

$$W_{\mu,\nu} = \lambda_{ijk}^{\mu \nu} \bar{L}_a^i \gamma_\mu L_b^j + \lambda_{ijk}^{\nu} \bar{L}_a^i Q_b^j + \lambda_{ijk}^{\nu} \bar{L}_a^i \gamma_\mu \bar{D}_b^j \sum_{c_1, c_2, c_3} \mathcal{U}_{c_1}^{c_1} \mathcal{D}_{c_2}^{c_2} \mathcal{D}_{c_3}^{c_3}$$
<table>
<thead>
<tr>
<th>Superfields</th>
<th>Bosonic fields</th>
<th>spin</th>
<th>Fermionic fields</th>
<th>spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge multiplets</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$G$</td>
<td>Gluons</td>
<td>1</td>
<td>Gluinos</td>
<td>1/2</td>
</tr>
<tr>
<td>$W$</td>
<td>W</td>
<td>1</td>
<td>Winos</td>
<td>1/2</td>
</tr>
<tr>
<td>$Z$</td>
<td>Z</td>
<td>1</td>
<td>Zino</td>
<td>1/2</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Photon</td>
<td>1</td>
<td>photino</td>
<td>1/2</td>
</tr>
<tr>
<td>Matter multiplets</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_i$</td>
<td>$(\tilde{\nu}, \tilde{l}^{-})_L$</td>
<td>0</td>
<td>$(\nu, l)_L$</td>
<td>1/2</td>
</tr>
<tr>
<td>$E_i$</td>
<td>$\tilde{e}_R$</td>
<td>0</td>
<td>$l_R$</td>
<td>1/2</td>
</tr>
<tr>
<td>$Q_i$</td>
<td>$(\tilde{u}, \tilde{d})_L$</td>
<td>0</td>
<td>$(u, d)_L$</td>
<td>1/2</td>
</tr>
<tr>
<td>$U_i$</td>
<td>$\tilde{u}_R$</td>
<td>0</td>
<td>$u_R$</td>
<td>1/2</td>
</tr>
<tr>
<td>$D_i$</td>
<td>$\tilde{d}_R$</td>
<td>0</td>
<td>$d_R$</td>
<td>1/2</td>
</tr>
<tr>
<td>Higgs multiplets</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_1$</td>
<td>$(H_1^+, H_1^-)$</td>
<td>0</td>
<td>$(H_1^0, H_1^0)_L$</td>
<td>1/2</td>
</tr>
<tr>
<td>$H_2$</td>
<td>$(H_2^+, H_2^-)$</td>
<td>0</td>
<td>$(H_2^0, H_2^0)_L$</td>
<td>1/2</td>
</tr>
</tbody>
</table>

Table 2.2: Bosonic and Fermionic components of the superfields in the MSSM.

where $L$, $E$, $Q$, $D$, $U$ and $H$ are the superfields given in Table 2.2 and $\lambda$, $\lambda'$, $\lambda''$ are the coupling constants and $i$, $j$, $k$ are generation indices. The SU(2) indices are denoted $a$, $b$ and $c_1$, $c_2$, $c_3$ are the SU(3) indices.

The two first terms in the $W_{R_p}$ expression violate the conservation of the lepton number and the last term violates the conservation of the baryon number.

In the Minimal Supersymmetric Standard Model (MSSM), the $W_{R_p}$ is cancelled by demanding the conservation of a new quantum number, $R_p$, that distinguishes between particles of the Standard Model and their superpartners [12]:

$$R_p = (-1)^{3B+L+S}$$

where $B$ is the baryon number, $L$ the lepton number and $S$ the spin of the particle. The MSSM doubles the amount of the elementary particles [13]. The classification of the MSSM superfields is given in Table 2.2. The superpartners have $R_p = -1$ and particles of the Standard Model have $R_p = +1$.

In the MSSM R parity is conserved. There is no clear theoretical motivation to favour neither conservation nor violation of the R-parity transformation, ergo both alternatives have to be treated in all earnestness. It is, however, a crucial point in cosmology to ascertain if R parity is conserved or not. Indeed, if R parity is broken the Lightest Supersymmetric Particle may not be a valid candidate to the dark matter as it may decay into standard particles. Besides cosmological constraints, R-parity violation affects approaches for searching for
supersymmetric particles, as single production is possible.

To date, experimental bounds on R-parity violating couplings come from neutrino and B physics. Strong indications of neutrino oscillations [14] are interpreted in terms of neutrino having non-zero mass and constitute a strong hint for physics beyond the Standard Model. Solar and atmospheric neutrino anomalies are solved in the framework of the MSSM with R-parity violation. Measurements of the neutrino oscillation parameters constrain R-parity-violating couplings which are involved in loop diagrams contributing to the mass of neutrinos [15]. Supersymmetry and R-parity violation can enhance decay probabilities of B decays, such as $B^+ \rightarrow K^+K^+\pi^-$ [16], which are suppressed in the Standard Model and offer an opportunity to search for physics beyond the Standard Model [17] (see also Paper V).

2.3 Summary

The two B decays under study in this thesis can be used to verify the Standard Model and extensions of this theory and, in addition, to investigate aspects (CP violation and R-parity violation) of importance for cosmology, i.e. the baryon asymmetry and the identification of the dark matter.
Chapter 3

Phenomenology

The Standard Model is a powerful theory. Analytical calculations in this theory are, however, often mathematically complex and cumbersome. Computer simulations create high energy physics events using programs that aim to contain all theoretical features. So-called Monte Carlo programs provide an important tool to better understand and analyse data collected by experiments and also to improve the design and the performances of the detectors in preparation. The simulation procedure is discussed in the following sections.

The running coupling constant of Quantum Chromodynamics (QCD) can be written as a function of momentum transfer, $Q$, and a scale parameter, $\Lambda \sim 200$ MeV:

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\ln\left(\frac{Q^2}{\Lambda^2}\right)} \quad \text{with } Q^2 \gg \Lambda^2$$

where $n_f$ is the number of quark flavour with $(2m_q)^2 < Q^2$.

The strength of the coupling increases as the momentum transfer decreases. At momentum transfers of order $\Lambda$ or below, perturbative QCD cannot be used any more and phenomenological models have to be developed to describe the data. Models for the hadronisation of the partonic system used in Monte Carlo programs are discussed in section 3.2.

3.1 Perturbative QCD

The parton model [18] (see also [19, 20]), which was originally formulated to explain the results obtained in deep inelastic electron-proton scattering, can be used to write the cross-section for hard processes in proton-proton collisions as the sum of parton cross-sections multiplied by the probabilities of finding, in the colliding hadrons, partons $i$ and $j$ with momentum fractions $x_1$ and $x_2$:

$$\sigma(pp \rightarrow F) = \int dx_1 dx_2 \sum_{i,j} f_i(x_1, Q)f_j(x_2, Q)d\hat{s}(ij \rightarrow F)$$
The hard process in an event is defined in terms of interactions between quarks (valence or sea quarks) or gluons from the colliding protons. Examples of Feynman diagrams for such processes are shown in Figure 3.1. The corresponding matrix element can be calculated using perturbative QCD with the initial momenta of the quarks and gluons derived from the collision energy and the proton structure functions (for parton distribution functions and cross-section at the LHC see, for instance, [21]). The parton densities in the protons vary with Q and can be estimated from the Gribov-Lipatov-Altarelli-Parisi (GLAP) equations [22, 23].

\[
\frac{d \sigma}{d \log Q^2} = \frac{\alpha_s(Q)}{2\pi} \int_x^1 \frac{dz}{z} \left( P_{qg}(x/z) f_g(z, Q^2) + P_{gq}(x/z) f_q(z, Q^2) \right)
\]

\[
\frac{d \sigma}{d \log Q^2} = \frac{\alpha_s(Q)}{2\pi} \int_x^1 \frac{dz}{z} \left( \sum_{i=q,\bar{q}} P_{qi}(x/z) f_i(z, Q^2) + P_{gg}(x/z) f_g(z, Q^2) \right)
\]

where the \( P \)'s are the splitting functions, given with their associated Feynman diagram in Table 3.1, and the \( f \)'s the parton density functions.

Parton distributions calculated using the CTEQ4M distribution [24] are given in Figures 3.2 and 3.3 for different values of Q and show that the gluon distribution dominates at low \( x \).

<table>
<thead>
<tr>
<th>( P_{qg}(z) )</th>
<th>( C_F \left( \frac{1+z^2}{(1-z)_v} + \frac{3}{2} \delta(1-z) \right) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{qg}(z) )</td>
<td>( T_F(z^2 + (1-z)^2) )</td>
</tr>
<tr>
<td>( P_{qg}(z) )</td>
<td>( C_F \frac{1+(1-z)^2}{z} )</td>
</tr>
<tr>
<td>( P_{gg}(z) )</td>
<td>( 2C_A \left( \frac{1-z}{z} + \frac{z}{(1-z)_v} + z(1-z) \right) + \left( \frac{4}{9} C_A - \frac{1}{3} T_F n_f \right) \delta(1-z) )</td>
</tr>
</tbody>
</table>

Table 3.1: Splitting functions, where \( C_F = 4/3, T_F = 1/2, C_A = 3 \) and \( n_f \) is the number of active quark flavours, with the associated Feynman diagram.

Monte Carlo simulations are based on the calculation of matrix elements for hard processes at leading order. Matrix elements at next-to-leading order (NLO), i.e. \( O(\alpha_s^3) \), in hadron collisions are not directly implemented in Monte Carlo
programs. Another technique, the parton shower [26], is exploited to get an approximation of the contribution from higher order diagrams. Indeed, NLO processes must be taken into account, especially in heavy quark pair production, since they may have cross-sections of the same order of magnitude as the leading order. For instance, in the case of $b\bar{b}$ pair production, gluon scattering (Figure 3.4.b) has a higher cross-section than the LO process (Figure 3.4.a), even though it is suppressed by a factor $\alpha_s$, and contributes significantly to $b\bar{b}$ pair production at the LHC.

![Feynman diagram](image)

Figure 3.4: Feynman diagram of $b\bar{b}$ pair production at leading order (a) and at next-to-leading order via gluon scattering (b).

The parton shower in the initial and final states models the possibility for the incoming and outgoing partons involved in the hard process to radiate and initiate a parton cascade. The radiation probabilities are calculated using splitting functions (see Table 3.1).

In the Monte Carlo approach of PYTHIA [27] the simulation starts with the evaluation of the matrix element for the parton-parton hard process and proceeds by adding the parton showers first in the final state and then in the initial state.
The beam remnant, i.e. the spectator partons which did not enter the hard process, is then taken into account. This stage is followed by the hadronisation during which the partons in the showers combine into pairs and triplets to form mesons and baryons.

Figure 3.5 gives a schematic view of a typical process at the LHC including the parton showers. In Paper I are reported predictions of different Monte Carlo generators about the production asymmetry in B-meson systems in hadron colliders as a function of the parameters that describe the beam remnant.

Figure 3.5: Schematic diagram of the parton evolution in a typical process at the LHC with the various stages included in Monte Carlo programs: the beam remnant treatment (points 1 and 2), the initial state parton showers (points 3 and 4), the hard process (point 5) and the final state parton showers (points 6 and 7). This is then followed by hadronisation (not represented).
3.2 Phenomenological models

The hadronisation process, i.e. the transition from the partons in the hard process and the parton showers to hadrons, cannot be performed using perturbative QCD as it involves low momentum transfers. Instead, phenomenological models are used. The main variant of such models is the Lund string model [28] which is based on the assumption that the partons are interconnected by colour flux tubes. The potential energy stored in the tube (string) increases as the partons move apart and will eventually lead to the creation of a \( q\bar{q} \) pair. For instance, the string between a \( q_i\bar{q}_j \) pair, where \( i \) and \( j \) denote two different flavours, may split into two string pieces between a \( q_i\bar{q}_k \) pair and a \( q_k\bar{q}_j \) pair as illustrated in Figure 3.6. In this process the creation of heavy-quark pairs is suppressed relative to the production of light-quark pairs. The procedure continues iteratively until the energy in each of the string pieces is too small to create a new quark-antiquark pair. The quarks from the beam remnant are also colour connected to the partonic system and are integrated in the hadronisation procedure.

Phenomenological models for prompt \( J/\psi \) production at the LHC are studied in Paper II. The Soft Colour Interaction model (SCI) [29] and the Generalised Area Law (GAL) [30] for hadronic string reinteractions have been used for this study. Both models propose phenomenological approaches to modify the hadronisation that is based on the Lund string model. A \( Q\bar{Q} \) pair produced in a colour-octet state within an appropriate invariant mass range (between the \( Q\bar{Q} \) production threshold and the open heavy flavour production threshold) may thereby be converted into a singlet state and form a charmonium. In the SCI model, the colour topology in the partonic final state may be modified by soft interaction with the colour background in the beam remnant. A soft colour interaction may occur between each pair of partons. The probability of soft colour interaction is the only free parameter of the model and is fitted to HERA data on
rapidity gaps in deep inelastic scattering. The GAL model is based on the string topology and does not affect the partons themselves. The string configuration of an event may be reorganised and the string rearrangement probability between two strings pieces is exponentially suppressed by a factor related to the length of the possible string pieces.

3.3 Summary

The analysis of hadron collider event is rather complex since the two colliding protons have a non-trivial partonic structure. The role played by the beam remnant is not well understood and there is no strict constraint on the parameters that control its treatment in Monte Carlo programs. Part of this thesis is dedicated to the study of the beam remnant treatment in PYTHIA. In Paper I estimates are made of the impact of uncertainties in the beam remnant parameters on B-physics analyses. In Paper II the prompt $J/\psi$ production is investigated as a potential source of background to B decays.

In Papers III and IV the CP violation is studied. The background to the $B_s^0 \to J/\psi K_s^0$ decay is dominated by a $J/\psi$ combined with a $K_s^0$ from other B decay channels or from fragmentation or with misreconstructed kaons.
Chapter 4

Detector and physics performance

The future Large Hadron Collider, LHC, at the European Laboratory for Particle Physics, CERN, in Geneva will provide excellent conditions for the study of low cross-section processes. Two proton beams will be accelerated to collide at an energy in the centre-of-mass of $\sqrt{s} = 14$ TeV which will be the highest collision energy reached so far at a collider. The LHC will also be characterised by a very high luminosity, $\mathcal{L} = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ initially and $\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ later.

The total proton-proton cross-section is estimated by extrapolation to be $\sigma_{\text{tot}} = 110 \pm 20\text{mbarn}$, including 26% elastic collisions [31]. The $b\bar{b}$ pair production represents only a small fraction of the processes, $\sigma(b\bar{b})/\sigma_{\text{inelastic}} = 0.7\%$, i.e. the cross-section is $\sigma \sim 500 \mu\text{barn}$. At low luminosity the LHC will produce approximately $5 \times 10^{12}$ $b\bar{b}$ pairs per year. It will be a B-factory indeed. Figure 4.1 shows cross-sections for proton-proton collisions as a function of the energy available in the centre-of-mass.

The ATLAS experiment, A Toroidal LHC Apparatus, has a powerful Inner Detector which combines the semiconductor detector technique (Pixel Detector and SemiConductor Tracker) with the drift straw technique (Transition Radiation Tracker). It is well suited for B-physics investigations which put high demands on the resolution for track reconstruction of charged particles. The B-physics programme in ATLAS may have to be performed essentially during the first years when the LHC machine is running in low luminosity mode and the pile-up effects are limited. The innermost layers of the Pixel Detector close to the beam pipe may not survive the high level of radiation more than a few years.

One of the aims of the B-physics programme is to probe the Standard Model. This thesis focuses on the analysis of two B decay channels.

The first decay to be considered is the so-called gold plated $B^0_d \rightarrow J/\psi K^0_S$ decay mode which is a clean channel, both theoretically and experimentally, for CP-violation studies [Papers III and IV].

The second decay to be analysed, $B^+ \rightarrow K^+ K^+ \pi^-$, is a purely hadronic decay
mode. The reconstruction of this final state is a real challenge for ATLAS as the signal must be extracted from a huge combinatorial background. A statistical charged hadron identification method based on Time over Threshold information from the Transition Radiation Detector has recently been proposed [32] and tested [Paper V]. The $B^+ \to K^+K^+\pi^-$ decay mode is used to probe the decay probabilities in the Standard Model and in physics scenarios beyond the Standard Model. The structure of this chapter follows the analysis scheme. The trigger strategy is presented, then the reconstruction algorithms are described and finally the tagging methods are discussed.

4.1 Trigger

The level one (LVL1) trigger scheme for B-physics in ATLAS, based on a single lepton, selects a sample of events composed of approximately a third of the number of $b$-quark decays. Other contributions come from other heavy-quark decays ($c$ and $t$), from $W$ and $Z$-boson decays and charmonium decays as well as Drell-Yan production. The LVL1 trigger requiring a muon with a transverse momentum greater than 6 GeV within the pseudorapidity range $|\eta| < 2.4$ is common to all B channel studies.

4.1.1 Charmonium channels

For the whole class of B decays into charmonium ($B^0 \to J/\psi K^0_S, B^+ \to J/\psi K^+, B^0 \to J/\psi \phi, \Lambda_b \to \Lambda^0 J/\psi$, etc.) the level two (LVL2) trigger is based on the presence of a $J/\psi$ and sets a $p_T$ threshold on the two decay leptons. The level of the two thresholds depends on the leptonic decay mode of charmonium. The topology of the electron channel is rather straightforward as the opposite primary $b$ quark should decay semileptonically with a LVL1 muon; the $p_T$ threshold is set to 0.5 GeV for each electron. In the muon channel no special conditions are imposed on the opposite $b$ quark since a muon from a $J/\psi$ may set the LVL1 trigger. Two threshold options are investigated. The first is to set a LVL2 $p_T$ threshold at 5 GeV for each of the two muons ($\mu\delta\mu3$ sample$^1$), the second alternative is to lower one $p_T$ threshold to 3 GeV ($\mu\delta\mu3$ sample). Note that the $\mu\delta\mu3$ sample is a subset of the $\mu\delta\mu3$ sample. In the $J/\psi \to \mu^+\mu^-$ sample, an extra lepton with $p_T > 5$ GeV is needed to be able to use the lepton tagging method (see section 4.3).

$^1$The samples are identified by labels; $\mu6\mu$. $\mu6$ is the LVL1 muon trigger and $\mu\mu$ is the lower $p_T$ threshold on the other muons.
Figure 4.1: Cross-sections for different processes in proton-proton collisions as a function of the centre-of-mass energy [31] with different colliders indicated, in particular the LHC (dashed line). The scale on the right-hand side of the plot gives the event rates at high luminosity at the LHC.
4.1.2 Hadronic channels

A second level trigger for hadronic channels is slightly more delicate to set as it will not be possible to select a class of decays. It will only be possible to identify specific channels in the off-line selections. The hadron trigger is dominated by a large combinatorial background that may restrict the number of selected channels. The trigger that is suggested in the $B^+ \rightarrow K^+ K^+ \pi^-$ analysis [Paper V] is similar to the one used in previous studies on the $D_s \pi \rightarrow \phi(K^+K^-)\pi\pi$ decays [33]. It is, however, clear that hadron triggers necessitate further investigations mainly to be able to add new channels and satisfy the strict output rate conditions (i.e. a trigger rate not exceeding $\sim 1\text{-}2\text{kHz}$).

4.2 Reconstruction algorithms

4.2.1 Full simulation

In the CP violation study [Papers III and IV], the analysis in this thesis has been performed with event samples generated using PYTHIA (version 5.7) including a full simulation of the ATLAS Inner Detector done with GEANT [34].

The event record provided by the Monte Carlo generator stores and retrieves information on all partons and particles involved in the hard process, the fragmentation and the decays. The event data record is then interfaced to a second record (Kine level) which is responsible for controlling long-lived or stable particles. The event kinematics is used to describe the passage of particles through the detector matter by simulating their interaction with the material taking into account the effect of the magnetic field. For each interaction of a particle in a sensitive detector element, the GEANT programme generates a hit and a digit which corresponds to the information provided by the read-out parametrisation (ADC and TDC outputs, etc). The information of all hits and digits in the Inner Detector is then used by the pattern recognition algorithm to find potential tracks.

Several algorithms are currently under development in ATLAS to reconstruct tracks from the hits. They differ from one another by using information from a different subpart of the Inner Detector to initiate the track reconstruction.

IpatRec [35] initiates the reconstruction from hits collected in the SemiConductor Tracker detector, matching to calorimeter clusters or muon detector tracks. PixRec [36] is based on the high granularity of the Pixel detector and starts the reconstruction from the innermost pixel layer to go outwards. PixRec is made to tag the $b$-jets using information from the vertex detector and in particular to search for the Higgs boson in the 100 GeV mass range. Its development includes two main parts: the reconstruction of the tracks inside a jet and the tagging of the $b$-jets.
In Papers III and IV tracks have been reconstructed using the xKalman pattern recognition [37]. The reconstruction algorithm includes the treatment of multiple scattering and bremsstrahlung energy losses during the track search procedure using the Kalman filter. The xKalman algorithm defines trial track segments in the Transition Radiation Tracker detector to initiate the reconstruction program and proceeds then step by step towards the pixel B-layer close to the beam pipe.

The reconstruction of the $K^0_S$ is a non-trivial problem as the particle may travel a significant path length (up to tens of centimeters) before decaying into two charged pions resulting in a reduced number of hits in the tracker subdetectors. The xKalman algorithm has therefore been chosen to study the reconstruction of the $K^0_S$. It is solely for the $K^0_S$ decaying within a certain volume inside the Inner Detector that the pattern recognition can be successfully made. The volume is determined by the condition that there must be a minimal number of hits recorded by the SemiConductor Tracker and the Pixel detector for each of the two pions. Each SemiConductor Tracker layer records space position information in stereo. One side of a layer provides the $R\phi$ coordinate and the other gives information on the position along the $z$ axis, in the barrel region, and in $R$, in the end-caps area.

The overall $K^0_S$ reconstruction is affected by two limiting factors. The first factor is the inefficiency of 3\% per hit which affects the quality of the reconstructed track. The second factor is that the geometrical acceptance for the $K^0_S$ decreases with increasing minimal number of hits imposed by the pattern recognition. A requirement of at least six hits recorded in the precision layers (Pixel and SemiConductor Tracker) allows the $K^0_S$ to decay within the cylindrical volume shown in Figure 4.2. This condition was chosen for the analysis made for the ATLAS detector and physics performance Technical Design Report [38].

### 4.2.2 Fast simulation

The $B^+ \rightarrow K^+K^+\pi^-$ decay channel has been implemented in PYTHIA to allow the Monte Carlo simulation of this mode. The analysis has been done using a fast simulation code for the Inner Detector. All track parameters at the Kine level are smeared using a parametrisation of the Inner Detector performances. The amount of smearing to be used was obtained from the full simulation studies. Smeared tracks are then directly used in the analysis programme. Hence no pattern recognition is needed in this procedure.

In both the $B^0_d \rightarrow J/\psi K^0_S$ channel and the $B^+ \rightarrow K^+K^+\pi^-$ channel, the background contamination has been estimated using fast simulation code by studying large samples of inclusive $pp \rightarrow \mu\ell X$ decays occurring in standard QCD high $p_T$ processes.
Figure 4.2: Cross-section view of a quarter of the Inner Detector with the limiting area within which $K^0_s$ should decay to be reconstructed if a minimum of six precision hits (three SemiConductor Tracker layers) are required by the pattern recognition algorithm.
4.3 Tagging methods

The neutral B meson and its antiparticle may decay into the same final state which makes it impossible to distinguish them by their decay products. The mesons thus have to be tagged in the production process, at the proton-proton collision vertex, in order to know their flavour. The challenge is to fully understand which particles are produced at the primary collision vertex and in the subsequent decay vertices.

Three techniques to identify the B-meson flavour (\(b\) or \(\bar{b}\)) at production are currently under study in the ATLAS B-physics working group. One is the jet charge method which uses the information of all the charged particles in the jet containing the neutral B meson originating from the primary \(b\) quark. The weighted average of all the charges of these particles, using the transverse momentum as weight, has the same sign as the primary \(b\) quark contained in the neutral B meson. Another technique is the \(B\pi\) correlation method for which the charge of the pion closest in phase-space to the B meson is used to tag the flavour of the B meson. A third technique to tag the B-meson flavour is to determine the charge of the lepton emitted in the semileptonic decay of the opposite \(b\) quark. This technique leads to a high purity but a low efficiency in the sample of tagged events and can therefore only be used with large data sets; it has been used by LEP experiments with good results. A schematic view of the trigger and tagging strategy for the \(B_d^0 \rightarrow J/\psi(\mu^+\mu^-)K_n^0\) channel is shown in Figure 4.3.

4.4 Summary

The effects on the \(K^0\) reconstruction efficiency of pion interactions in the Inner Detector material have been studied in Paper VI. The results underline the importance of the details of the layout of the precision layers and their services. The difficulties to extrapolate tracks in a non-instrumented region like the gap between the Pixel detector and the SemiConductor Tracker lead to a drop in the \(K^0\) reconstruction efficiency as a function of the decay radius. As yet the ATLAS detector is designed with no dedicated hadron identification subdetector. A novel technique of charged hadron identification based on the Time-over-Threshold information from the Transition Radiation Detector has been proposed [32] and tested for the reconstruction of hadronic B decays [Paper V and [32]]. The \(K/\pi\) separation provided by this method will, if implemented, enhance the ATLAS B-physics capabilities.

The studies performed in this thesis highlight two aspects of the Inner Detector performance: the pion interactions with the detector material and the role of the Transition Radiation Detector in the hadron identification.
Muons from the $J/\psi$ have a $p_T$ threshold of 3 and 5 GeV.

The LVL1 trigger is coming from the semileptonic decay of the other primary $b$ quark.

The LVL1 trigger is one of the muons from the $J/\psi$ decay.

The LVL2 trigger is the reconstruction of the $J/\psi (\mu 6 \mu 3)$

Events are tagged by an extra lepton (electron or muon) with $p_T > 5$ GeV.

The LVL1 trigger is one of the muons from the $J/\psi$ decay.

The LVL2 trigger is the reconstruction of the $J/\psi (\mu 6 \mu 3)$

Events are tagged by "Same Side Methods".

Figure 4.3: Trigger strategy for the $B^0_d \rightarrow J/\psi (\mu 6 \mu 3) K^0_s$ events.
Chapter 5

Summary of papers

I.
In this paper theoretical uncertainties on the B-meson production asymmetry are estimated and shown to limit high precision measurements of CP violation parameters. The theoretical uncertainties are at the level of 1% which is of the same order as the statistical error after three years of data taking at low luminosity in ATLAS as estimated in Paper III. The beam remnant treatment in Monte Carlo programs is examined and suggestions for constraining the parameters of the spectators using results of the HERA-B experiment are made.

II.
In this paper various models have been compared to estimate the prompt $J/\psi$ production at the LHC. The role of QCD higher order corrections for prompt charmonium production and the impact of the prompt $J/\psi$ event yield in LHC experiments are discussed. All models studied in this paper give a higher background from prompt $J/\psi$ to $B^0_s \rightarrow J/\psi \phi$ and show that the signal-to-background ratio can be significantly lowered with regard to the results obtained using the Colour Octet Model.

III.
In this note an estimation of the statistical and systematic uncertainties in the measurement of the CP-violation parameter $\sin(2\beta)$ in ATLAS is presented. The main results are a better understanding of the $J/\psi$ and $K^0_s$ reconstruction efficiencies and of how the background rejection and tagging efficiency influence the statistical and systematic uncertainties. The estimated statistical error in the measurement of $\sin2\beta$, after three years of running at low luminosity (30fb$^{-1}$) using the $B^0_s \rightarrow J/\psi(e^+e^- + \mu\mu\bar{\mu})K^0_s$ decay channel, is 0.01 for an assumed value of $\sin2\beta$ of 0.60.

IV.
This paper is the written version of a presentation given at the 15th International Conference On Particle And Nuclei, PANIC’99, of the results obtained in Paper III.

V.
In this paper the use of a novel method for K/π separation is investigated for the reconstruction of a specific hadronic decay. The paper discusses the potentiality of ATLAS to study the B⁺ → K⁺K⁺π⁻ decay mode. The analysis shows that after three years of running at low luminosity a 95% confidence level upper limit on the B⁺ → K⁺K⁺π⁻ branching ratio of 9.1 \times 10⁻⁷ can be set. This result is discussed in physics scenarios beyond the Standard Model and is used to set an upper limit on R-parity violating couplings:

\[
\sqrt{\sum_{i=1}^{3} \left| \chi_{i32} \chi_{i21}^* \right|^2 + \sum_{i=1}^{3} \left| \chi_{1i2} \chi_{22i}^* \right|^2} < 5.4 \times 10^{-5}.
\]

VI.
In this note the reconstruction efficiency of the K_S⁰ → π⁺π⁻ decay is studied. The impact of particle interactions with the material in the Inner Detector of the ATLAS experiment on the K_S⁰ reconstruction is investigated.
Acknowledgements

Det var en gång en pojke. Den här pojken studerade i Lausanne när svenska vänner berättade hur kul det är att plugga i Uppsala. Sånt började det......


Jag är jättetacksam för all hjälp jag har fått av Gunnar Ingelman, tack så mycket för dina råd och hjälp med fenomenologiska delarbeten samt korrekturläseringen.

I also would like to thank Paula Erola for her help in guiding me through the B-meson decays analysis, paljon kiitosia! Merci aussi à David Rousseau pour avoir répondu à chaque fois rapidement et avec beaucoup de clarté aux questions sur les algorithmes de reconstruction de traces dans le détecteur interne.

Special thanks to Andrea Manara and Cristiano Mariotto with whom it has been nice to collaborate.

Merci à Fredrik Tegenfeldt pour son aide précieuse dans la phase finale de cette aventure et dans le déchiffrement des règles qui régissent la défense d’une thèse. Cela vaut bien une bonne bouteille de grand cru classé!

“Always one week too late!”. That’s what Jan Greiff taught me.....NOW, I understand.

On the side of this thesis, it was also a great pleasure to work with Barbara Badeluk in organising the Scandinavian Neutrino Workshop.

Merci aussi à Yann Coadou pour les discussions de physique mais aussi pour les longues discussions sur l’un des points essentiels quand on est loin de notre bon vil hexagone.....l’art culinaire!

I also would like to thank my old pal, Dave Dobson, for interesting discussions about the subtleties of the English grammar that is sometimes beyond my ken.

Muchas gracias a la compañía de mi vida, Pia, para su ayuda, su enorme paciencia y el más importante de todo su amor.

Finalement, mes plus tendres pensées vont, tout naturellement, à mes parents que je ne serais jamais assez remercier pour leur soutien tout au long de mes études.
References

[34] R. Brun et al., GEANT Detector Description and Simulation Tool (1994) CERN Program Library, W5013.