Czech Technical University in Prague
Faculty of Nuclear Science and Physical Engineering
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# RESEARCH PAPER

# STUDY OF B-QUARK PRODUCTION IN DECAY CHANNELS WITH $J/\psi$ ON ATLAS AT LHC

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August 27, 2008

## Acknowledgements

I would like to thank to my academic advisor Václav Vrba for introducing me to CERN and giving me the opportunity to learn more about particle physics experiments, without which this paper would never come into being. I am very thankful to Maria Smizanska for discussions about the decay chanels with $J/\psi$ (bound state $c\bar{c}$ quarks) one of which I tried to analyze and to Antonio Pitch for answering my questions concerning the theory of the Standard Model. I appreciate very much the aid of Pavel Řezníček and Christos Anastopoulos who provided me valuable advices and the discussions about object-oriented programming. Particularly I was aided in b-physics reconstruction algorithms and offline analysis by these messieurs. I should thank my colleague Pavel Jež for introducing me to the Athena framework and for useful hints with LaTeX and ROOT. I am also grateful to Guido Negri, Xavier Espinal and Jiří Chudoba for many useful discussions about GRID and for helping me with computing issues related to GRID shifts I participated in. Not least word of thanks go to Institute of Physics in Prague whereby I was allowed to spend several months in the CPPM and CERN laboratories which gives me very much, not only of the b-physics point of view. This thesis mostly rest on the experience and informations I gathered there. Last but not least, my big thanks belong to Characlia Petridou who provided me the most useful information about the decay channel and its properties described in this paper. I am also grateful to the Institute of Physics of the Academy of Sciences of the Czech Republic and mainly to Jiří Popule for the material and organizational support during my whole work.


### Declaration

I state that I wrote my research paper independently and exclusively with the use of cited bibliography.

Prague, August 27, 2008 Jaroslav Günther

**Abstract**

In the first chapter of this research paper there is an overview of the $b$ physics which will be performed especially after the initial run of LHC at the main detectors. The emphasis is put on the calibration of these detectors with help of presently already well known decay channels. Because of that next section is dedicated to the decay channel of the greatest interest $B^+ \rightarrow J/\psi K^+$. This channel is here introduced with all of it's main properties and in the next part of this paper is the process of reconstruction described. Finally I analyzed this decay with use of simulated detector data with misalignment geometry and reconstructed the invariant mass of $J/\psi$ and $B^+$ particle.

**Key words:** Standard Model, ATLAS, pixel detector, misalignments, Athena, $b$-physics.

# Contents

# Chapter 1

# Beauty physics at LHC

In a couple of days the rst collisions will be observed at the Large Hadron Collider (LHC). The LHC will collide protons at 14 TeV with a bunch crossing rate of 40MHz. ATLAS, CMS, ALICE and LHCb are the biggest ever built experiments, that will take the first data. The main purpose of the ALICE detector is the observation of the heavy ion collisions. This chapter is concerned mostly on the other three parts of the LHC, which are more focused on the $b$-physics.

## 1.1 General purpose detectors

The detectors shown in Fig.1.1 and Fig.1.2 will perform high-$p_T$ physics such as study the top quark and to search for the Higgs and supersymetric particles in $pp$ interactions. And what about the $b$-physics ? It plays very important role in this field as a tool. Since it will take several years for the accelerator to reach the luminosity of $10^{34}$ $cm^{-2}s^{-1}$ , the $B$-meson decays are supposed to be the most useful ones especially during the first few years of the LHC operation (when the LHC luminosity is expected to be $1-2$ $x$ $10^{33}$ $cm^{-2}s^{-1}$. Once the luminosity of LHC is close to $10^{34}$ $cm^{-2}s^{-1}$ in the subsequent years it is almost impossible to work with the ordinary $B$-decays due to the large background originating from many $pp$ interactions (prime vertex). At the final luminosity the LHC is required to be exploited for the very rare $B$-decays with clear signatures.

As it is known ATLAS and CMS were built as the detectors with different approach to some similar measurements with the aim to obtain independent likely the same results. Both experiments will be able to contribute to the measurements of CP violation and $B_q^0 - \overline{B}_q^0$ mixing , $q = d, s$, which is the domain of LHCb factory. One of the parameters on which ATALS and CMS

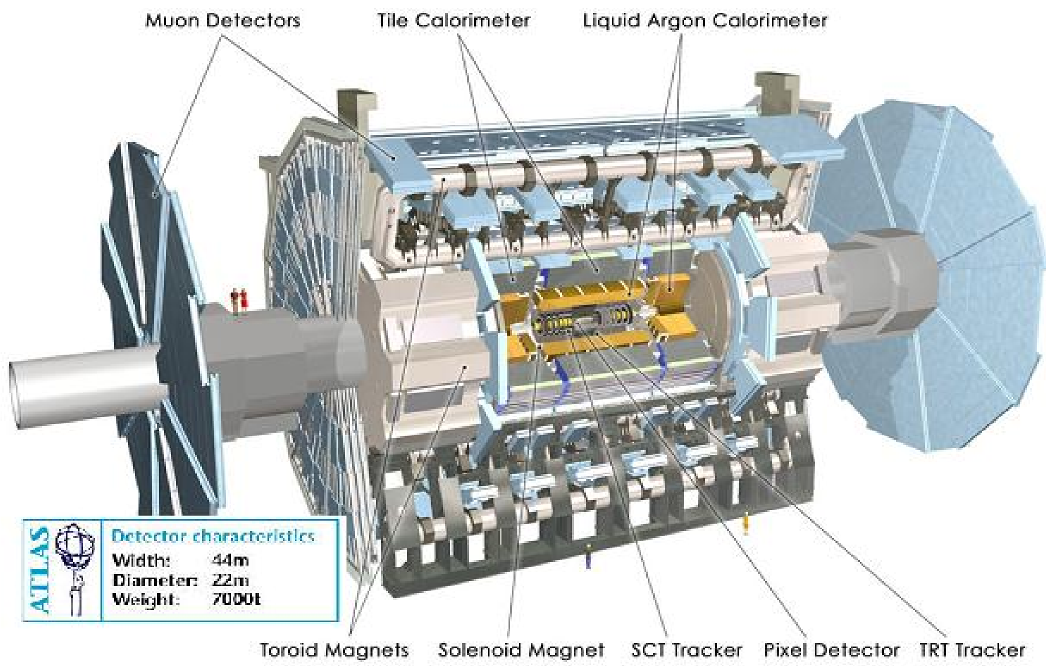



Figure 1.1: Look at the ATLAS detector.

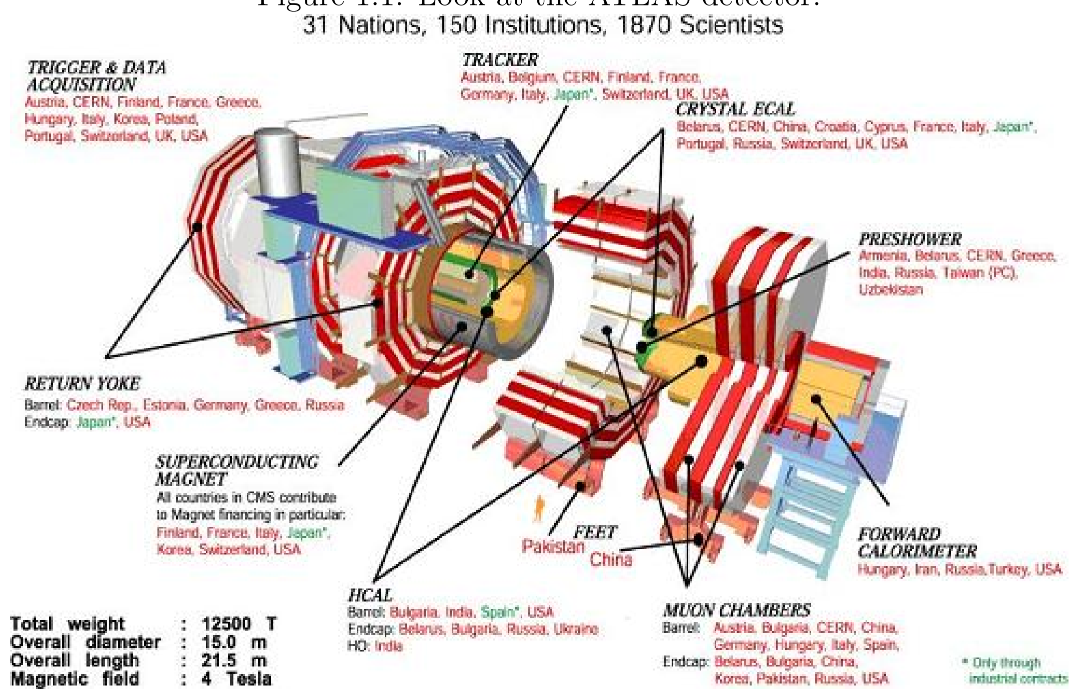
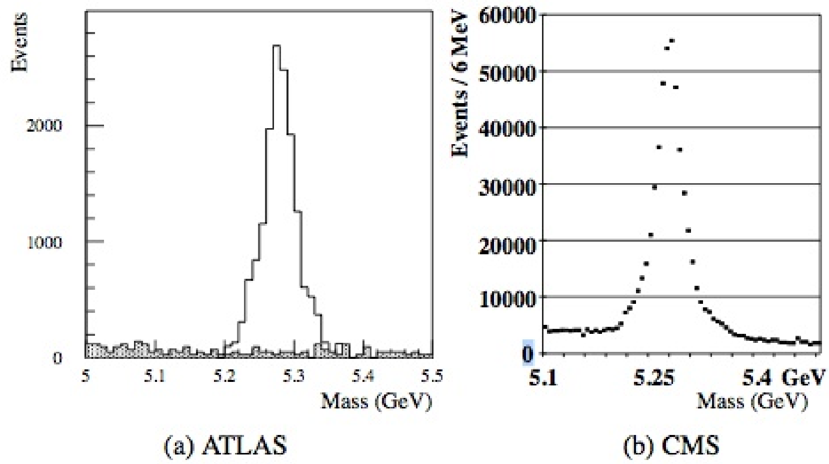



Figure 1.2: Description of the CMS detector.




(a) ATLAS (b) CMS

Figure 1.3: Reconstructed invariant mass distribution for $B_d \rightarrow J/\psi K_s$ decay with the simulated ATLAS and CMS lay-out.

will be sensitive are $\Delta m_s$, the $sin(\Phi_s)$, $\Delta\Gamma_s/\Gamma_s$ (for better description please see my Bachelor Thesis)

These two experiments have different trigger strategy and allocated band-width on which the $B$-physics achievement will depend. $B$ events will be mainly triggered by high-$p_T$ muons or di- muon triggers. CMS uses on-line tracking for the selection of exclusive $B$ events. This detector is designed for recognition of both muons and electrons for the first level trigger. The ATLAS foresees a exible trigger strategy with the progressive addition of other triggers and it uses mainly single high $p_T$ muon for the first level trigger.

In general either a single high $p_T$ muon or electron, or di-lepton ($ee,\ \mu\mu,\ and\ e\mu$) with lower $p_T$ are required. These requirements allow us to be sensitive to $B$-meson decay final states with leptons, such as $K * l^+l^-$, $J/\psi(l^+l^-)K_s$ and semileptonic decays $l\nu X$ which can provide a good flavour tag. For the fully reconstructed $B$-meson is expected a proper time resolution of approx. 60 fs. Some signals of the channels like: $B_d \rightarrow J/\psi K_s$ or $B_s \rightarrow J/\psi\Phi$ are expected to be reconstructed cleanly as it could be seen at the Fig. 1.3 .

Unfortunately, the triggers of the both experiments are hardly sensitive to the hadronic final states. Therefore, those decays will be collected only through the semileptonic decay of the succeeding $b$ hadrons and event statistic will be limited. Moreover, the background is very high because of the lack of an adequate $K/\pi$ identification capability. Some decays ($B_s \rightarrow D_sK$ or $B_s \rightarrow D_s\pi$ for example) with exactly the same topologies are determined to wash out totally and even a good resolution does not help and the invariant mass resolution of ATLAS and CMS are as well not able enough to separate the two decay modes kinematically. Therefore particle identification is crucial to distinguish whatever two-body b-hadron decay such as $B_d \rightarrow \pi^{+-}K^{+-}$ and $B_s \rightarrow K^+K^-$ from $B_d \rightarrow \pi^+\pi^-$ from the invariant mass distribution. It induce the need of an experiment dedicated to study of CP violation in $B$-meson decays with particle identification capability. One such experiment is the LHCb device mentioned further in this chapter.

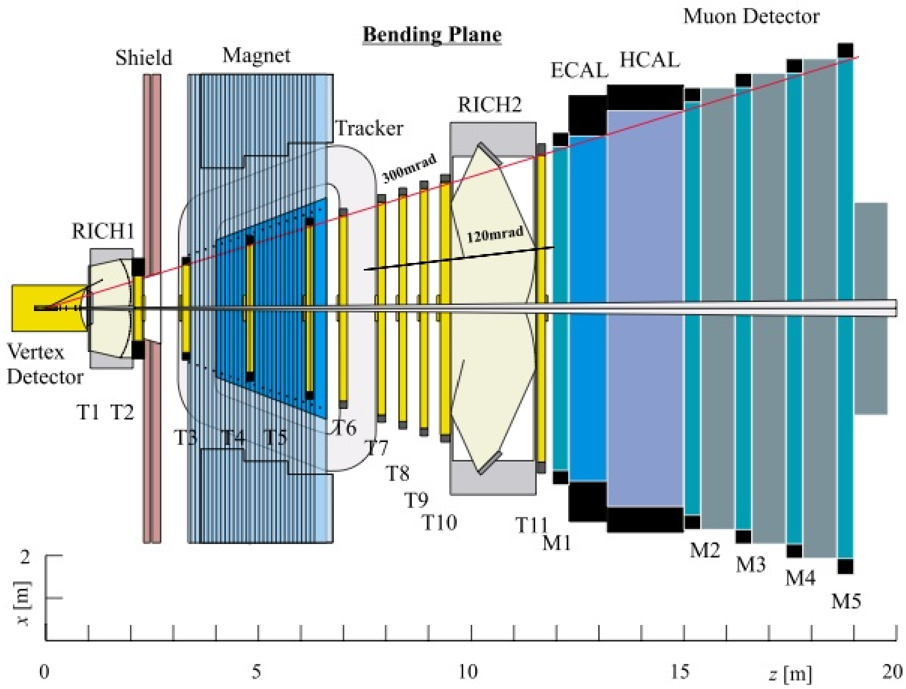



Figure 1.4: Schematic view of the LHCb detector.

## 1.2 Purpose of the LHCb detector

LHCb (see Fig.1.4) is constructed for precise measurement of CP violation and rare decays of beauty particles. In this field very good results have been already obtained by the BELLE, BABAR, CDF and D0 Collaborations, which allowed to obtain the fit of the CKM unitary triangle as it can be seen in the Fig.1.6. So far, there are no indications for new physics. However the e?ects of di?erent new physics models have been predicted by many theorists and their non-observation results in strong constraints on the parameters of these models.

The luminosity at the LHCb interaction point is intentionally limited to $2?10^{32}cm^{?2}s^{?1}$ in order to observe one interaction per bunch crossing on average. It is a spectrometer in which a forward geometry was chosen as the best for example because the $B$-meson production angles are mostly in the forward and backward direction regarding to a beam.

The LHCb trigger is operating in three stages. The Level-0 reduces the rate to 1 MHz requiring the presence of leptons or photons or hadrons with high $p_T$ while the Level-1 selects on high impact parameter, high $p_T$ tracks. The High Level Trigger is a software trigger using the full information on the event. Its output contains 200 Hz of exclusive $B$ candidates and about 1.8 KHz

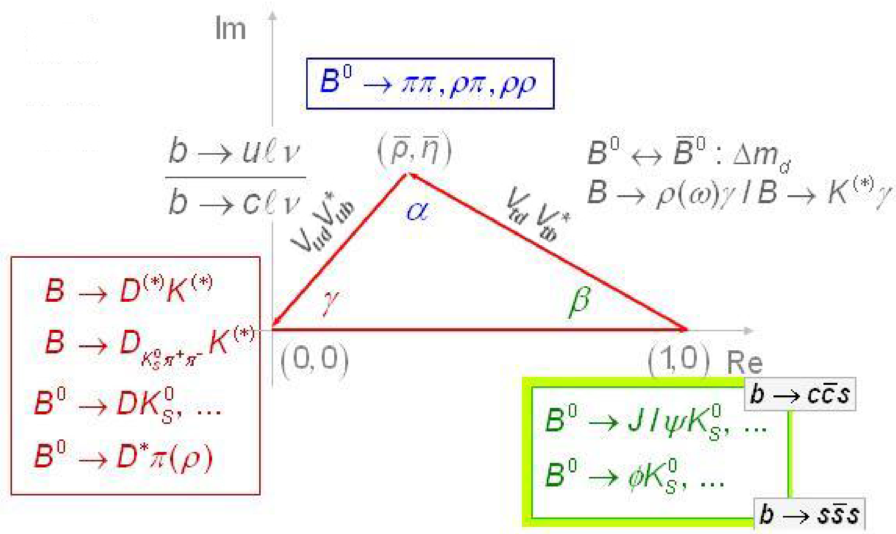



Figure 1.5: Picture of the Unitarity Triangle indicate the examples of $B$ decay modes which give access to its angles and sides.

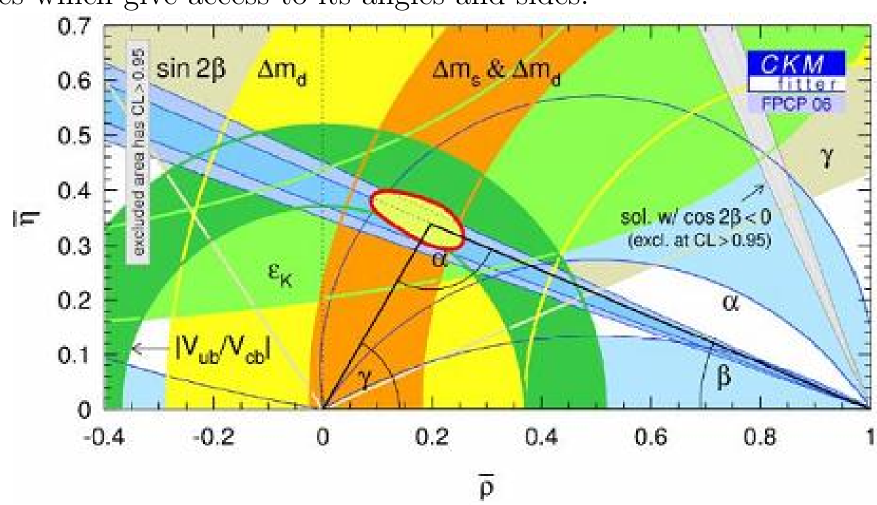



Figure 1.6: Illustration of the current experimental constraints on the CKM Unitarity Triangle.

of inclusive channels to be used also for calibration purposes and systematic studies.

CP asymmetry in $B_s^0$ and $\overline{B}_s^0$ decaying into $J/\psi\Phi$ ($J/\psi \to \mu\mu, \Phi_s \to KK$) will be measured with an error of approx. 0.01 combining all three experiments. The phase $\Phi_s$ of $B_s^0$ - $\overline{B}_s^0$ mixing is expected to be very small in the Standard Model resulting in a high sensitivity to possible new physics contributions in $b \to s$ quark transitions. The presence of new physics could be found also in the measurement of the decay width di?erence between the two CP eigenstates $\Delta\Gamma_s$. In one year of data-taking LHCb expects to collect 100.000 $J/\psi(\mu\mu)\Phi$ decays . The sensitivity will be increased adding $B_s^0 \to J/\psi\eta$ events, which are pure CP eigenstates. About 7000 events per year are expected in this channel.

The investigation of the $\gamma$ angle of the mentioned unitary triangle will be performed with help of the channels where $B_s^0$ and $\overline{B}_s^0$ decays into $D_s^{+-}K^{-+}$ or $B_d \to D^*\pi$ and of other decay modes.

Those measurements will allow us to separate the contribution from the Standard Model and that from new physics unambiguously.

## 1.3 Initial measurements

In the initial run of the LHC at lower luminosity some measurements have to be performed in order to validate the ATLAS detector and trigger system. About one of these very important relative channels you can read in the next chapter. There are more measurements of great interest especially then the inclusive and exclusive decays of $B$-mesons . The expression "inclusive rare $B$ decay" shall be dened. Within this paper it is understood as a flavour or neutral current process $B^+ \to X\, Y$, where $B$ denotes a $B^{+-}$, $B_d$ or $B_s$ meson. $X$ is an inclusive hadronic state containing no charmed particles, and $Y$ is a state built out of leptons, neutrinos and photons. The possibilities for $Y$ are for example $\gamma$ (one particle), $l^+\ l^-$, $\gamma\ \gamma$ or $v\overline{v}$ (two particles), etc. Only for better picture, the important inclusive decays are of the following look:

$$B \to X_{s,d}\, \gamma\ B \to X_s\, l^+l^-\ B^+ \to X_s\, v\overline{v}$$

The cases of $B^+ \to X\ Y$ with X = 0 are regarded as exclusive decay modes. In contrast to the exclusive rare $B$ decay modes, the inclusive ones are theoretically clean observables, because no specic model is needed to describe the hadronic nal states. The additional contributions to the decay rate, in which SM particles are replaced by new particles, such as the supersymmetric charginos or gluinos, are not suppressed by additional factors $\alpha/(4\pi)$ relative to the SM contribution. Thank to this, it is possible with these inclusive channels to observe new physics indirectly.

# Chapter 2

# Decay $B^+ \rightarrow J/\psi K^+$

The $B^+ \rightarrow J/\psi K^+$ channel will be easily observed with the rst ATLAS data at LHC due to it's rather large branching ratio and clear event topology . The channel is of great interest as it will be a reference channel for the search of dimuons from rare $B$ decays (for example from very rare on new physics sensitive $B^+ \rightarrow \mu^-\mu^+$ decay ) and a control channel for the CP violation measurement, where it will be used to estimate systematic uncertainties and tagging algorithm efficiencies. The total and differential cross-sections of the rare $B$- decays can then be measured relative to the cross-section of this decay since in a relative measurement, common systematic effects mostly cancel out.

The following properties of the $B^+$ will be studied at the start of the LHC operation: mass, lifetime, differential and total cross section. Since the extrapolation of the $b$- cross-section measurement at the Tevatron energy of 1.81.96 TeV to the LHC energy of 14 TeV can be suffers from large uncertainties and given that the $\bar{b}b$ represents the largest physics background for many processes and causes large trigger rates, the need for it's precise knowledge is evident. Not least that thanks to this we have the opportunity to measure in parallel inclusive and exclusive cross-sections with high statistics. The inclusive and exclusive methods have different systematic uncertainties and model dependencies allowing for a better constrain on the QCD prediction for the $\bar{b}b$ production cross-section. In particular, the precise measurement of the from BaBar and Belle well-known mass and lifetime from this exclusive decay channel can be used for Inner Detector calibration and alignment studies. I tried to

## 2.1 $B$-decay cross-section measurements

When $b$ flavoured hadrons decay weakly, daughter particles originate on which the $b\bar{b}$ cross section measurement is based. The final muons can be always well

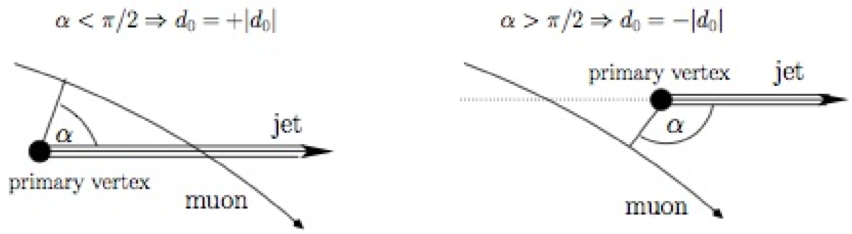



Figure 2.1: Impact parameter definition

reconstructed. Therefore semileptonic and the $B \rightarrow J/\psi X$ decay modes that lead to single or di-muon states are the most interesting for our measurements of the mentioned cross section. The muon recognition is provided by the muon spectrometer in combination with the inner detector, the jet information is given by algorithms combining the information from the electromagnetic and hadronic calorimeters and the $K^+$ and vertex information are provided by the inner detector system.

Single muons from $c\bar{c}$ decays and direct $J/\psi$'s from $pp$ prime vertex are the main backgrounds that are impacting the proper signal. The former case the $p_T$ distribution of the muons is softer as compared to the muon spectrum from $b\bar{b}$ decays while in the second case no displaced secondary vertex is expected. Subsequently the following parameters are used for b-tagging:

- the transverse impact parameters $d_0$ of charged particles originating form $B$-meson decays at a secondary vertex due to the large life-time of $B$-mesons. The impact parameter is dened as the distance of closest approach of a muon track to the primary vertex. Usually, the transverse impact parameter $d_0$ is used, denoting the closest distance between the beam line and the track in the transverse plane. A positive sign is associated with $d_0$, if the track intersects the jet axis after the primary vertex and a negative otherwise (see Fig. 2.1 .

- the transverse momentum of the muon from the $b$-decay, relative to the ight direction of the decaying massive $B$-meson. The relative transverse momentum $p_T^{rel}$ is dened as the transverse momentum of the associated muon with respect to the combined axis of the muon and the jet.

## 2.2 Identification of $J/\psi$

Very important role for the analyze of the decay $B^+ \rightarrow J/\psi K^+$ the identification of the $J/\psi$ and reconstruction of the primary and secondary vertices plays.

As the next step we need a positively charged track ($K^+$) originating from the $J/\psi$ secondary vertex which is superimposed to form the $B^+$ candidate. The distance between the $pp$ interaction vertex and the secondary vertex of the $B$-decay in the transverse plane is denoted by the vector from the primary to the secondary $B$-decay vertex: $\overline{x} = \overline{x}_{prim} - \overline{x}_B$. $\overline{x}_B$ lies in the plane normal to the incoming proton beam and is used to dene the transverse decay length $L_{xy}$ , which is actually the projection of $\overline{x}$ onto the direction of the transverse momentum of the $B$ meson:

$$L_{xy} = \frac{\overline{x} \times \overline{p}_T}{|p_T|} \tag{2.1}$$

The transverse decay length $L_{xy}$ is a signed variable, which is negative if the particle seems to decay before the secondary vertex of its production and positive otherwise. For a zero life-time sample, a Gaussian distribution peaked at $L_{xy} = 0$ is expected.

The proper decay length for the exclusive decasy is given by:

$$\lambda = L_{xy} \frac{m_B}{{p_T}^B} \tag{2.2}$$

Using the ATLAS inner detector parameters, the determination of the position of the primary vertex on an event-by-event basis was demonstrated by my colleagues, and for this decay concretely we have some exact vertex resolutions of $\sigma_x = 29\mu m$ and $\sigma_y = 27\mu m$. With these numbers we can take into account the uncertainty:

$\sigma^2_{L_{xy}} = \frac{1}{(p_T^B)^2} \times (\sigma^2_x (p^B_x)^2 + 2\sigma^2_{xy} p^B_x p^B_y + \sigma^2_y (p^B_y)^2 + \sigma^2_{x1} (p^B_x)^2 + \sigma^2_{y1} (p^B_y)^2)$

of the transverse decay length $L_{xy}$ originating in the primary and secondary vertex. The sigmas are the covariant matrix elements fo the secondary vertex fit and the $\sigma_{x/y1}$ are the resolutions of the primary vertex in x or y. The $p^B_T$ is the transverse momentum of the $B$ meson and $p_{x/y}$ are the corresponding components of the $B$ meson momentum.

In advance it is crucial to identify the two in general low $p_T$ $\mu$s into which the $J/\psi$ decays. As soon as the track of two muons is identified in the muon spectrometer it is checked if it fits to some inner detector track. If this ID track is declared as muon candidate than it is likely to form the $J/\psi$ candidate. For inner detector track to be a muon candidate it is sufcient to have associated hits or track segments in the inner most stations of the muon spectrometer. For the $J/\psi$ mass calculation the momentum is provided by the inner detector, because of its better resolution in this $p_T$ region, even in the case of a fully reconstructed track in the muon spectrometer. Now we going to point out the main cuts, which are preformed by the analysis of this decay channel for $J/\psi$:

- All di-$\mu$ with $p_{T,1}$ greater than 3.0 GeV and $p_{T,2}$ greater than 6.0 GeV are formed.
- Muon pairs are fitted to a common vertex.
- Only vertices with $\chi^2/ndf$ less than 10 are taken into account
- To select $J/\psi$'s originating from the decay of a $B^+$, a cut on the proper decay length $\lambda$, that needs to be greater than 0.1mm, is imposed to reduce combinatorial background from prompt $J/\psi$. If this cut is not imposed, the algorithm identies all possible combinations consistent with the $J/\psi$ muons in the event.
- $J/\psi$ canditdates inside a mass window of 120 MeV around $m_{J/\psi}$ are retained.

In order to study the effect of misalignment, displaced magnetic eld and incorrect material map, on the $J/\psi$ mass resolution, the reader can find below in this paper the reconstructed mass of $J/\psi$ originated from the software simulation of different ATLAS geometry than the ideal ones and computed by the misalignments algorithms to avoid whatever strong effect on the output.

## 2.3 $B^+$ lifetime

The investigation of a lifetime $\tau$ of selected $B^+$ candidates is really sensitive to the number of reconstruted decays $B^+ \rightarrow J/\psi K^+$ obtained in the dataset. The proper decay time is defined as $t = \lambda/c$. I need to mention only that no cut is applied on the decay length $\lambda$ of the $J/\psi$ or $B^+$ candidate. The decay-time distribution is usually parametrized by this channel as a convolution of an exponencial function with a Gaussian resolution function. Moreover the background distribution parametrization consist of two different exponencial functions, where is convoluted with a Gaussian resolution function. In order to properly describe these events is good to know that If there appear some zero lifetime event (which is not expected) , an extra Gausian centered at zero is necessary. Gausian resolution functions depend on the reconstucted uncertainities on an event-by event basis. Now I will try to sketch only this topic. The exponential part of the life-time distribution has the form: $F_t(t) = e^{\frac{-t}{\tau}}$ , where $t$ is the proper decay time and $\tau$ is the life-time. Accordingly the convoluted function is then

$F_c(t) = e^{\frac{-t}{\tau} \otimes G(t,\mu,s\ .\ \sigma_i)}$,

where $\mu$ is the mean value of the Gaussian resolution function which parameterizes the average bias in each proper decaytime measurement. s is a

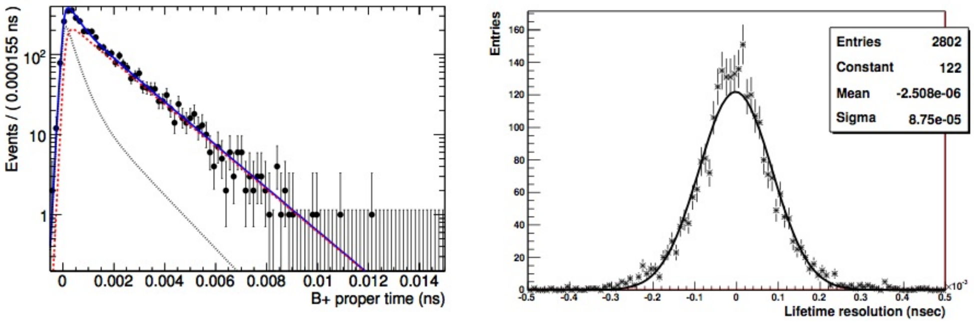



Figure 2.2: The $B^+$ life-time t (left) with the signal (dashed red) and the background (dashed black) contributions shown separately. Also the $B^+$ time resolution is presented (right).

scale factor of the error and $\sigma_i$ is the per event proper decaytime error. The final probability density function is then:

$F_t(t) = F_c(t!\sigma_i)$ . $P(\sigma_i)$, where $P(\sigma_i)$ is the distribution of the proper decaytime error. The distribution of the proper decay-time uncertainty is approximated by a superposition of Gaussian function. Just for illustration see Fig.2.2.

# Chapter 3

# Reconstruction of the decay $B^+ \rightarrow J/\psi K^+$

Regarding my Bachelor thesis I decided to continue in he reconstruction and to dig in the corresponding C++ scripts for the ATHENA run reconstruction. Just to recall the usuall run of the analysis.The selection of the $J/\psi$ candidates is performed according to the Section 2.2 . These are combined with the $K^+$ candidates, which are identified relying on the inner detector information. The original collection of tracks is scanned once again (excluding those already denoted as muons) and those with the transverse momentum greater than 1.5 GeV and $|\eta|$ smaller than 2.7 are retained. From this selection, those tracks with positive charge and inconsistent with coming from the primary vertex at one standard deviation level $|d_0| / \sigma_{d_0}$ greater than 1 are consideren to be $K^+$. The $\mu^+\mu^-$ pair considered to be originating from the $J/\psi \rightarrow \mu^+\mu^-$ decay and the $K^+$ candidates are fitted to a common vertex. The vector defined by the sum of the $J/\psi$ and $K^+$ momentum vectors is required to point to the primary vertex, and the two $\mu$ tracks are constrainted to $m_{J/\psi}$. Only vertices with $\chi^2/ndf$ ¡ 6, $p_T(\mu)$ ¿ 5 GeV and $\lambda$ ¿ 0.1 mm are retained. The invariant mass of all previously accepted $B^+$ candidates is calculated. Those candidates, whose invariant mass falls inside the window of 120 MeV around $m_{B^+}$ are accepted. In the case that more than two $B^+$ candidates were found in the same event, the one with the smallest $\chi^2/ndf$ is accepted.

I would like only to point out that the measurement of the $J/\psi$ and $B^+$ mass and its detection efciency is a central task for the analysis of the rst ATLAS data, providing the tools to validate the detector by extracting muon energy scale determination in the low $p_T$ region and detector misalignments. Finally, the mass measurement and reconstruction efciency for $B^+$, the total and differential cross-sections and its lifetime measurements will be of interest for other B-physics analyses.

## 3.1 ID Misalignments

Some alignments sets have been produced which represent guesses as to the level of residual misalignment one might expect after aligning the detectors in order to study the effects of misalignments on reconstruction performance and physics. To get realistic residual misalignments which will contain various systematics the best way is to run the actual alignment algorithms. However, the sets described here allow one to makes some studies independent of the schedule for producing realistic alignment sets. They also allow one to misalign in a controlled way which will be useful for comparison with realistic alignments when they become available. Two Monte Carlo simulations of misalignments were developed for the inner detector. The first one I used for my reconstruction and is concerned on the mass shift and the second fixes the blur effect of the decay length. Two residual misalignment sets have been produced. The first set, called initial, represents the expected residual misalignments after an early running period of say 100 $pb^{-1}$. The second set called final represents the residual misalignments expected after a few years of running. I used the initial set for my reconstruction and I adjusted the ATHENA run in the "jobOptions" file for this purpose and tried to catch the most ideal setup of options and reconstruction code so that the result was similar to the reconstruction in the ideal case.

I used the BPlus.cxx code written by Christos Anastopoulos again to analyze this decay channel. I tried to adjust this code in more detail and tune it for my purpose to reconstruct the data samples with misalignment geometry. I implemented the misalignment data and worked with them as stated above in this section.

Also the athena analyse the example events and write the results to an Athena-Aware NTuple file which I inspected with ROOT. I had to write a ROOT code for working with this file to receive the histogram of the invariant mass of the $J/\psi$ (see Fig.3.1) and $B^+$ (see Fig.3.2) from the corresponding muon pairs. The width of the fitted gauss distribution is larger than it should be in reality by reason of the detector multiple scattering effects and the misalignment geometry. The tails at the edges of the histograms should not be fitted by Gauss, because they originate from muon energy loss along its track and so their nature is not "gaussian".

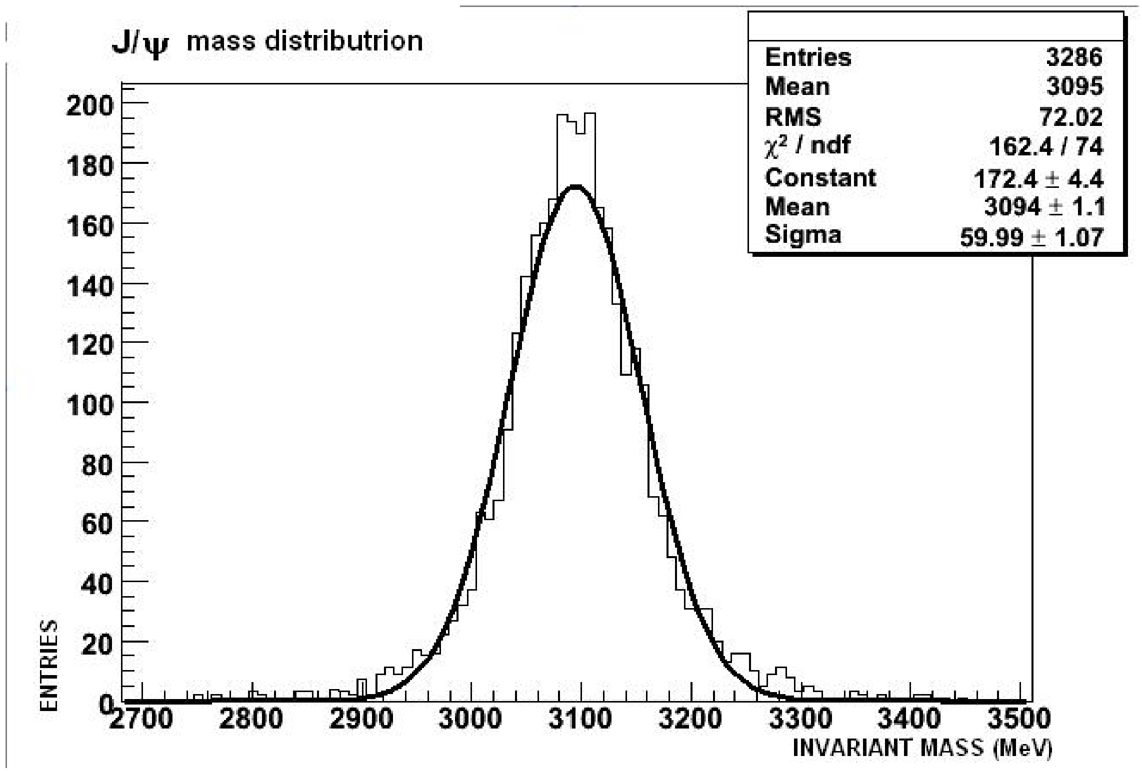



Figure 3.1: The reconstructed invariant mass of $J/\psi$ particle from simulated misalignment data samples.

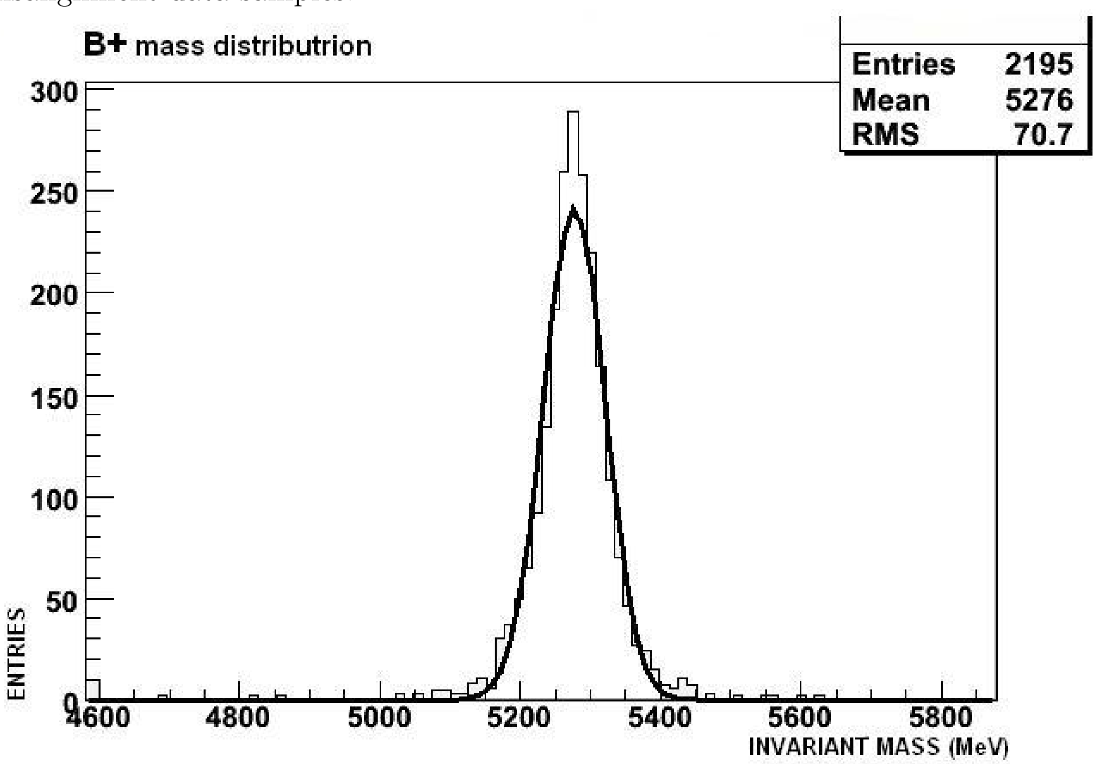





Figure 3.2: The reconstructed invariant mass of $B^+$ particle from simulated misalignment data samples.

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