CP violation with the ATLAS detector

David Rousseau^a, *contribution to the IIT^d Conference on Hyperons, Charms and Beauty Hadrons, Genova, 1998, to be published in Nuclear Physics B*

^aCERN, EP division, CH-1211 Geneva 23, Switzerland

Measurements of CP violation parameters in the B system with the ATLAS detector at LHC are reviewed. Measurements of $\sin 2\beta$ in the $B_d^0 \rightarrow J/\psi K_S^0$ channel and of $\sin 2\alpha$ in the $B_d^0 \rightarrow \pi^+\pi^-$ channel are described in details. Other channels sensitive to the angles γ and $\delta\gamma$ are also presented.

1. Introduction

At the LHC approximately 10^{12} $b\bar{b}$ pair will be produced per year and per experiment during the first 3 years of running at low luminosity ($10^{33} \text{ cm}^{-2}\text{s}^{-1}$). This will provide the opportunity for the ATLAS experiment to perform accurate measurement of some of the Unitarity Triangle parameters. The design of the ATLAS detector is essentially frozen. The full GEANT description of the detector has been tuned to reproduce test-beam data, and passive material in the simulation updated to the engineering design. Several B-physics simulation, first presented in the ATLAS technical proposal [3], are being updated and improved [4,5], with this more realistic simulation and new experimental inputs. An overview of the most recent simulation results is presented here. This talk concentrates on CP violation. The ATLAS detector, particle identification and reconstruction, and the measurement of other parameters are described in Ref. [2].

Results are given for one year of running at low luminosity, corresponding to an integrated luminosity of 10^4 pb^{-1} .

2. $\sin 2\beta$: the $J/\psi K_S^0$ channel

The decay $B_d^0 \rightarrow J/\psi K_S^0$ is generally considered to be the gold-plated channel for measuring the angle β . It is theoretically clean, with penguin diagrams contributing by less than 1%. The time-dependent CP asymmetry has the following form:

$$A(t) = \sin 2\beta \sin(x_d t / \tau_{B_d^0}).$$

The current standard model best fit of the Unitarity Triangle yields $\sin 2\beta = 0.68 \pm 0.1$ [6].

2.1. Trigger

The B physics trigger in ATLAS relies on a 6 GeV/c p_T muon trigger at Level 1 [2]. Full reconstruction of the event and lepton identification is done at Level 2: muons are identified with p_T down to 5 GeV/c using the muon spectrometer (identification down to 3 GeV/c using the hadron calorimeter is being studied), electrons are identified down to $p_T=1$ GeV/c using the transition radiation in the TRT.

Two J/ψ samples are available: the $J/\psi \rightarrow e^+e^-$ sample, with a trigger on the muon from the accompanying B hadron, and the self-triggering $J/\psi \rightarrow \mu^+\mu^-$ sample. This sample is more copious, but initial state tagging is more difficult.

2.2. Event reconstruction

The J/ψ is reconstructed from two opposite sign identified leptons, forming a good 3D vertex separated from the beam-line. The J/ψ and the identified K_S^0 [2] are then combined to form a B candidate, with good vertex probability (see Ref. [5] for details). The B_d^0 mass plot is shown in Fig. 1. The mass resolution is $22 \text{ MeV}/c^2$ and a mass cut of three standard deviations is applied.

2.3. Background

The dominant combinatorial background is the combination of a true J/ψ from B decay, with a K_S^0 from fragmentation. The contribution of fake J/ψ (lepton-lepton, lepton-hadron, hadron-hadron) and fake K_S^0 is small. The contribution of direct J/ψ is removed by the displaced vertex requirement. Backgrounds cause a dilution of the asymmetry: $D_{bkg} = N_S/(N_S + N_B)$, where N_S (N_B) is the number of signal (background) events.

Figure 1. $J/\psi K_S^0$ mass spectrum, with signal (white) and backgrounds (hatched).

2.4. Initial state tagging and dilutions

The tagging of the initial state is necessary to distinguish B_d^0 from $\bar{B}_d^0$. Any tagging algorithm is characterized by its efficiency $\epsilon = (N^+ + N^-)/N_S$ and its mistag fraction $W = N^-/(N^+ + N^-)$, where N^+ (N^-) is the number of correctly (incorrectly) tagged signal events. The tagging dilution is $D_{tag} = 1 - 2W$. Finally, the tagging quality factor is $Q = \epsilon D_{tag}^2$, which is the equivalent loss in luminosity compared to a perfect tag with $D = \epsilon = 1$.

The time-integration of the CP asymmetry is an additional source of dilution: $D_{int} = (\sin(xt_0/\tau) + x \cos(xt_0/\tau))/(1 + x^2)$, where t_0 is the minimum accepted proper-time and x the usual mixing parameter. If a fit to the time-dependent asymmetry is performed, D_{int} is replaced by D_{fit} which is one for a perfect time resolution and no threshold on the proper-time.

Finally, the observed asymmetry is:

$$A_{obs} = D_{tag} D_{bkg} D_{int} \sin 2\beta,$$

and the sensitivity,

$$\delta(\sin 2\beta) = \frac{\sqrt{1 - A_{obs}^2}}{D_{tag} D_{int} \sqrt{D_{bkg} N_S}}.$$

2.5. Tagging algorithms

The lepton tagging uses the correlation between the flavour of the B_d^0 and the charge of the lepton from the decay of the second B hadron in the event. The mistag fraction of 22% is partly due to the mixing of the second B hadron, partly to the cascade $b \rightarrow c \rightarrow \ell$ decays. The efficiency is 100% for the $J/\psi \rightarrow e^+e^-$ sample where the trigger muon is used for tagging, but only 5% in the $J/\psi \rightarrow \mu^+\mu^-$ sample, where an additional lepton with $p_T > 5$ GeV/c is searched for.

Two additional algorithms can be used, especially in the $J/\psi \rightarrow \mu^+\mu^-$ channel, to supplement the absence of tagging lepton. The B- π algorithm uses the correlation between the flavour of the B meson and the charge of the adjacent hadron in the fragmentation chain. The same side-jet algorithm uses the charge correlation between the primary b quark and the nearby fragmentation tracks. Both algorithms have similar performance and are highly correlated, so that, up to now, only one can be used at a time. Their high mistag fraction compared to the lepton tag is compensated by a much higher efficiency [5,7].

Table 1
 $J/\psi K_S^0$ yields and $\sin 2\beta$ sensitivity.

Channel	e^+e^-	$\mu^+\mu^-$
$N(B_d^0 \rightarrow J/\psi K_S^0)$	7000	213000
N background	480	3600
$\delta(\sin 2\beta)$ lepton tag	0.036	0.029
$\delta(\sin 2\beta)$ B- π tag	0.16	0.025
$\delta(\sin 2\beta)$ time fit	0.026	0.017

2.6. Results

The yields and sensitivity are shown in Table 1, for an input value $\sin 2\beta = 0.6$. The last line shows the sensitivity of a time-dependent fit combining the two tags. The two samples combined

yield a final sensitivity of

$$\delta_{stat}(\sin 2\beta) = 0.014.$$

The sensitivity degrades to 0.017 if muon identification in the p_T range 3-5 GeV/c cannot be performed at trigger Level 2. The systematic uncertainties are expected to be of order 0.01[3]. The production and detection asymmetry and the tagging performances will be measured on control channels such as $B_d^0 \rightarrow J/\psi K^{*0}$ and $B^+ \rightarrow J/\psi K^+$ where no asymmetry is expected. Lowering the electron minimum p_T to 0.5 GeV/c and improvement to tagging are under study.

3. $\sin 2\alpha$: the $\pi^+\pi^-$ channel

The decay asymmetry in the $B_d^0 \rightarrow \pi^+\pi^-$ channel is related to the angle α :

$$A(t) = a \cos(x_d t / \tau_{B_d^0}) + b \sin(x_d t / \tau_{B_d^0})$$

with, a , the direct CP violation component,

$$a = -2 \frac{A_P}{A_T} \sin \delta \sin \alpha$$

and, b , the mixing-induced component,

$$b = -\sin 2\alpha - 2 \frac{A_P}{A_T} \cos \delta \cos 2\alpha \sin \alpha,$$

where A_P/A_T is the ratio of the penguin and tree amplitude, δ is the penguin and tree amplitude phase difference. It is assumed that $\alpha = \pi - (\beta + \gamma)$. Since there are three unknowns and only two observables (a and b), and since δ is not believed to be calculable, a theoretical estimation of A_P/A_T is needed. Much theoretical work is currently going on this subject, to which measurements from the near-future B-factory will be valuable inputs. To set the scale, Fleischer and Manel [8] estimate that, with the help of the measurement of the $B^+ \rightarrow \pi^+ K^0$ and $B^+ \rightarrow \pi^+ \pi^0$ branching ratios, the theoretical uncertainty on the penguin contribution would yield an uncertainty on α of less than 3° . The current standard model best fit of the Unitarity Triangle yields the estimate $\sin 2\alpha = -0.1 \pm 0.40$ [6]. A small value of $\sin 2\alpha$ could mean no observable CP asymmetry in this channel, but tight bounds on $\sin 2\alpha$ would in any case be valuable constraint to the Unitarity Triangle.

3.1. Trigger

After the Level 1 muon trigger, $B_d^0 \rightarrow \pi^+\pi^-$ candidates are searched for at Level 2 by combining opposite sign particles with $p_T > 5.5$ GeV/c and requiring the invariant mass of the pair to be in the range 4.5 - 6.5 GeV/c². Lowering as much as possible the minimum pion p_T to significantly increase the event yield is being studied. A value of 4 GeV/c has been retained in the following, allowing a doubling of the statistics.

3.2. Reconstruction

The offline selection requires two charged particles with $p_T > 4$ GeV/c, separated from the beam-line by more than three standard deviations and forming a good vertex. The B_d^0 vertex, beam-line and flight direction should be consistent. To remove the main background where the tracks come from two different B hadrons, each track is required to be separated from the triggering muon. Finally, a mass cut of one standard deviation (± 70 MeV/c²) is applied.

3.3. Backgrounds

The list of background branching ratios and yields is shown in Table 2. The combinatorial background can be kept small. Since it is caused by random coincidence of high impact parameter tracks, the use of full simulation and reconstruction is mandatory to measure accurately the tracking resolution, including tails. A high statistic fast simulation is then used to demonstrate

Table 2
Branching ratios and yields in the $B_d^0 \rightarrow \pi^+\pi^-$ channel.

Channel	BR's	Yield
$B_d^0 \rightarrow \pi^+\pi^-$	0.7×10^{-5}	2500
$B_d^0 \rightarrow K^+\pi^-$	1.5×10^{-5}	4600
$B \rightarrow \rho\pi^-$	0.7×10^{-5}	70
$B \rightarrow \pi^+\pi^-\pi$	5.0×10^{-5}	<20
$B_s^0 \rightarrow \pi^+K^-$	0.7×10^{-5}	600
$B_s^0 \rightarrow K^+K^-$	1.5×10^{-5}	1300
$\Lambda_b \rightarrow p\pi^-$	8.0×10^{-5}	600
$\Lambda_b \rightarrow pK^-$	8.0×10^{-5}	1000
Comb.	-	900
Total bkg	-	9000

the $> 10^7$ rejection factor on the trigger Level 1 output.

The $B_d^0 \rightarrow K^+\pi^-$ and $\pi^+\pi^-$ branching ratios are recent, still imprecise first measurements from CLEO [9]. The other branching ratios have been inferred from the first two with simple SU(3) symmetry, except the Λ_b decays which have been set to their experimental upper limits [10].

The most abundant background is the $B_d^0 \rightarrow K^+\pi^-$ decay, because of the absence of π/K separation, and because the mass resolution is higher than the separation between the peaks (~ 40 MeV/c²) (see Fig. 2).

Figure 2. $\pi^+\pi^-$ mass spectrum. The arrows indicate the signal window.

3.4. Results

The background dilution is $D_{bkg} = 0.21$. Initial state tagging is done with the triggering muon, yielding a tagging dilution of $D_{tag} = 0.56$. The time-integrated method yields a dilution $D_{int} = 0.63$. The statistical sensitivity to $\sin 2\alpha$

is then, in the absence of penguin decays:

$$\delta_{stat}(\sin 2\alpha) = 0.12.$$

If the minimum pion p_T at trigger Level 2 cannot be lowered from 5.5 to 4 GeV/c, the sensitivity degrades to 0.18. Systematic uncertainties arising from asymmetry in the detection efficiency and from the lepton tagging are expected to be of order 0.01, as in the $B_d^0 \rightarrow J/\psi K_S^0$ channel.

By year 2005, near-future B factories will have measured precisely the branching ratios of the two-body decay channels. A 5% relative uncertainty on these branching ratios, will give a *relative* uncertainty on the asymmetry of less than 5%. More problematic is the possibility that these backgrounds exhibit some CP asymmetry themselves (in fact the asymmetry in $B_d^0 \rightarrow K^+\pi^-$ could help constraint γ [11]). A more sophisticated fitting method (now under study) will have to be used, taking into account on a event by event basis the invariant mass and the lifetime. The Λ_b decays (which does not oscillate) and the B_s^0 decays (with rapid oscillation period ~ 0.5 ps) will then be distinguished from B_d^0 decays (with slow oscillation period ~ 14 ps). The $B_d^0 \rightarrow \pi^+\pi^-$ decay and the $B_d^0 \rightarrow K^+\pi^-$ decay will not be completely separated. ATLAS will measure a linear combination of the CP asymmetries in these decays, which will be combined with results from other experiments.

There is also a potential factor four increase of the statistics from the lowering of the minimum p_T of the pions from 4 to 1 GeV/c (now under study). This requires more sophisticated cuts to keep the combinatorial background and the trigger Level 2 rate low enough.

4. $\delta\gamma$: the $B_s^0 \rightarrow J/\psi\phi$ channel

If the decay $B_s^0 \rightarrow J/\psi\phi$ is a pure CP=+1 amplitude, the asymmetry in the channel $B_s^0 \rightarrow J/\psi\phi$ is:

$$A(t) = \sin(2\delta\gamma) \sin(x_s t / \tau_{B_s^0}).$$

Dropping this assumption necessitates to introduce a new fit parameter, the ratio of the CP=-1 and CP=+1 amplitudes. Nevertheless, the sensitivity on the CP violating oscillation amplitude

A_{CP} is still a good measure of the sensitivity on $\delta\gamma$. $\delta\gamma$ is expected to be small (~ 0.01 rad) in the standard model. A high value would be a signature for new physics.

The measurement of this asymmetry is similar to the one for the $B_d^0 \rightarrow J/\psi K_S^0$ channel, except that the fast B_s^0 oscillations make it necessary to resolve them with a good proper-time resolution. With a resolution of 0.07 ps, the dilution of the asymmetry with a time-dependent fit is $D_{fit} = 0.47$, for $x_s = 20$ (the current standard model fit favoured value [6]).

The event selection is similar to the $B_d^0 \rightarrow J/\psi K_S^0$ one. The absence of K identification is not a problem for the reconstruction of $\phi \rightarrow K^+K^-$. The yields are shown in Table 3. All samples combined, the sensitivity to A_{CP} is:

$$\delta(A_{CP}) = 0.027.$$

The sensitivity varies from 0.025 to 0.045 if x_s varies in the currently allowed range 15 to 30 [6].

Table 3
Yields and sensitivity in the $J/\psi\phi$ channel.

Channel	e^+e^-	$\mu^+\mu^-$
N $B_s^0 \rightarrow J/\psi\phi$	3500	134000
N background	200	3200
$\delta(A)$ lepton tag	0.059	0.049
$\delta(A)$ jet tag	0.224	0.044

5. γ : the $B_d^0 \rightarrow D_{(1)}^0 K^{*0}$ channel

The set of the three decays $B_d^0 \rightarrow \bar{D}^0 K^{*0}$, $B_d^0 \rightarrow D^0 K^{*0}$, $B_d^0 \rightarrow D_1^0 K^{*0}$ (D_1^0 is the D^0 CP eigenstate, decaying to $\pi^+\pi^-$ and K^+K^-) and their charge conjugate can be described by two triangles differing only by the side corresponding to the CP asymmetric decays $B_d^0 \rightarrow D_1^0 K^{*0}$ and $\bar{B}_d^0 \rightarrow D_1^0 \bar{K}^{*0}$. The measurement of the six rates determined the angle γ . The current standard model best fit to the Unitarity Triangle yields $\gamma = (64 \pm 12)^\circ$ [6].

No initial state tagging is necessary since the flavour of the K^{*0} tags the flavour of the B_d^0 . How-

ever, ATLAS needs a high p_T muon for trigger Level 1. The decays $D^0 \rightarrow K^-\pi^+$, $\bar{D}^0 \rightarrow K^+\pi^-$, D^0 or $\bar{D}^0 \rightarrow K^+K^-$ or $\pi^+\pi^-$ and $K^{*0} \rightarrow K^+\pi^-$, $\bar{K}^{*0} \rightarrow K^-\pi^+$ must be separated without π/K separation. It is possible to veto all ambiguous events with an efficiency loss less than 50%. It is also necessary to separate these events from the combinatorial background as only a yield of a few events a year is expected in some of these decays. Nevertheless, assuming a signal to background ratio of one (now under study), a sensitivity to γ of 20° in three years data-taking can be reached.

6. Conclusion

Improved analyses with full simulation of the final ATLAS detector show that ATLAS will have an excellent sensitivity on $\sin 2\beta$ in the $J/\psi K_S^0$ channel. The measurement of $\sin 2\alpha$ in the $B_d^0 \rightarrow \pi^+\pi^-$ channel will be difficult, but ATLAS will be able to contribute valuable information. Sensitivity to $\delta\gamma$ in the $B_s^0 \rightarrow J/\psi\phi$ channel is sufficient to allow a precise test of the standard model prediction. Measurement of γ in the channels $B_d^0 \rightarrow D_{(1)}^0 K^{*0}$ may be feasible if rates are more favourable than current estimates.

REFERENCES

1. C. Caso *et al.* (Particle Data Group), Eur. Phys. J. **C3** (1998) 1.
2. P. Sherwood, these proceedings.
3. The ATLAS Collaboration, Technical Proposal, CERN/LHCC/94-43, 1994.
4. P. Eerola, Nucl. Instr. and Meth. A **384** (1996) 93.
5. G.F. Tartarelli, Nucl. Instr. and Meth. A **408** (1998) 110.
6. F. Parodi *et al.*, hep-ph/9802289
7. K. Kelley, these proceedings.
8. R. Fleischer and T. Mannel, Phys. Lett. **B397** (1997) 269.
9. R. Godang *et al.* (CLEO Collaboration), Phys. Rev. Lett. **80** (1998) 3456.
10. D. Buskulic *et al.* (ALEPH Collaboration), Phys. Lett. **B384** (1996) 471.
11. R. Fleischer, CERN-TH/98-60, to appear in Eur. Phys. J. **C**.