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A study of B-tagging in ATLAS using jet charge techniques

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Abstract

The future ATLAS detector at LHC is briefly described, and some background to CP violation is given, with an account of the Cabbibo Kobayashi Maskawa unitarity triangle, especially of the angle β which is a measure of the CP violation. The tagging of the decays $B_d^0 \rightarrow J/\psi K_S^0$ and $\bar{B}_d^0 \rightarrow J/\psi K_S^0$ is then investigated through Monte Carlo simulations, from the point of view of different jet charge techniques.

1 Introduction

At the beginning of the next millennium, a new era of particle physics will start at the European Particle Physics Laboratory, CERN, in Geneva. The present accelerator LEP (Large Electron Positron collider) will then be replaced by the Large Hadron Collider, LHC. Steered by superconducting magnets, proton beams will be accelerated and made to collide at a centre of mass energy of $\sqrt{s} = 14$ TeV, resulting in a wide variety of particle production. The luminosity will be extremely high, $\mathcal{L} \propto 10^{34}\ cm^{-2}s^{-1}$, thus placing very high demands on the electronics and detectors. Several experiments have been planned for LHC, both for p–p and heavy ion collisions. In this paper, the ATLAS experiment will be described, mainly covering the parts of the detector that are relevant for B physics. Also, a brief account on CP violation and the unitarity triangle is given. The main purpose of this paper, however, is to investigate the possibility of using jet charge techniques for B-tagging in ATLAS.

2 The ATLAS detector

Just as its namesake, ATLAS will be a gigantic detector (to understand the dimensions, compare the detector with the men drawn in Figure 1). The detector is mainly designed to search for the Higgs boson, supersymmetric particles, and other new physics. However, ATLAS will also be used to study CP violation in B meson decays, for example through the decay $\mathrm{pp} \to \mathrm{b\overline{b}}$, $(\mathrm{b} \to \mathrm{X},\ \mathrm{B^0_d} \ \to \mathrm{J/\psi K^0_S})$ and $(\mathrm{\bar{b}} \to \mathrm{X},\ \mathrm{\bar{B}^0_d} \ \to \mathrm{J/\psi K^0_S})$. This study will mainly be carried out during the first years of LHC-running when the luminosity still remains moderate ($\mathcal{L} \propto 10^{33}\ cm^{-2}s^{-1}$); thus pile-up effects will be small.

The detector will consist of several parts (see Figure 1) . An inner detector surrounded by a superconducting solenoid will be placed at the centre, followed by electromagnetic and hadronic calorimeters. The outer layer is a superconducting air-core toroid for muon spectrometry. The superconducting solenoid will give a magnetic field of 2T in which the inner detector is placed. This detector includes a Transition-Radiation-Tracker (TRT), a Semi-Conductor Tracker (SCT) and, closest to the beam pipe, a vertex detector. These are especially important for B-physics; the SCT with the vertex detector gives high resolution secondary vertex measurements, while the TRT can separate electrons from hadrons at momenta as low as 1 GeV. Due to the strong radiation the vertex detector is not expected to survive more than six years of low-luminosity running. This however has been estimated to suffice for the planned B physics programme.

The electromagnetic calorimeters consist of liquid-argon calorimeters, with accordion-shaped lead radiators, and can be used to identify b-jet-electrons with p_{T} over 2 GeV. The barrel hadron calorimeter in turn will be an iron-scintillator tile calorimeter. Its main purpose will be to measure jet energies, and to measure the total transverse energy and its missing component in each event. With the air-core-toroid muon spectrometer, muons with transverse momenta as low as 5 GeV can be identified. Also, sharper trigger resolutions can be achieved with the air-core toroid, than if an iron-core toriod had been used.

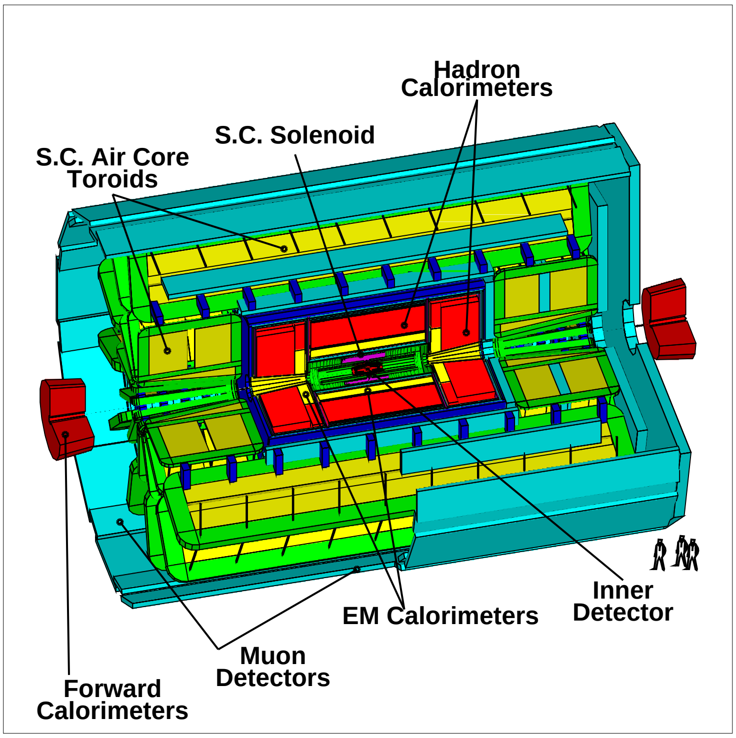

Figure 1: The ATLAS detector intersected. From B physics in ATLAS, P. Eerola *et al.*, 1994, p. 85.

For B physics the LVL1 single-muon trigger threshold is set to $p_{\mathrm{T}} > 6$ GeV and $|\eta| < 2.2$ for an event to be accepted. The LVL1 trigger is followed by a LVL2 trigger, which requires additional signatures. For example, in $\mathrm{B_d^0} \rightarrow \mathrm{J}/\psi\mathrm{K_S^0}$ it is required that the decay is followed by $\mathrm{J}/\psi \rightarrow e^+e^-$ or $\mathrm{J}/\psi \rightarrow \mu^+\mu^-$. With these demands the number of events to investigate further is thus reduced to a more manageable level.

A detailed description of the ATLAS detector can be found in the ATLAS Technical Proposal [1].

3 CP violation

As in the $\mathrm{K^0}$–$\mathrm{\bar{K}^0}$ system, the charge parity symmetry in $\mathrm{B_d^0}$–$\mathrm{\bar{B}_d^0}$ systems is expected to be broken. For K mesons the CP asymmetry is rather small, while for B mesons it is expected to be quite large. In the decay process $\mathrm{pp} \rightarrow \mathrm{b\bar{b}}$, ($\mathrm{b} \rightarrow \mathrm{X}$, $\mathrm{B_d^0} \rightarrow \mathrm{J}/\psi\mathrm{K_S^0}$) and ($\mathrm{\bar{b}} \rightarrow \mathrm{X}$, $\mathrm{\bar{B}_d^0} \rightarrow \mathrm{J}/\psi\mathrm{K_S^0}$) for example, the two decay modes should be equally probable if CP symmetry was conserved. This however is not expected to be the case; instead the second mode is expected to be more common than the first. The difference in the rates of these processes is a measure of the CP violation. The question is how to tag the events, that is how to see which of the two processes took place. For ATLAS, a lepton tag method has already been investigated with very good results [2], and tagging by using the $\mathrm{B^{**+}} \rightarrow \mathrm{B^{0(*)}}\,\pi^+$ decay channel has also been studied [3], amongst other possible methods. Recently jet charge techniques have successfully been used for flavour tagging in DELPHI [4], ALEPH [5] and OPAL [6], and in the following sections it will be investigated if jet charge techniques can be used in ATLAS as well. But first a little more about CP violation.

3.1 The unitarity triangle

In a four-quark version of the Standard Model we are used to the Cabbibo mixing angle $\theta_C = 12.8 \pm 0.2$ degrees [7]. In this theory of quark mixing the doublets

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$$

are replaced by

$$\begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} c \\ s' \end{pmatrix},$$

where $d^{'} = dcos\theta_C + ssin\theta_C$ and $s^{'} = -dsin\theta_C + scos\theta_C$. This can be written as

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} cos\theta_C & sin\theta_C \\ -sin\theta_C & cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}.$$

In a generalization to six quarks, the doublets

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

are replaced by

$$\begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} c \\ s' \end{pmatrix} \begin{pmatrix} t \\ b' \end{pmatrix},$$

where d', s' and b' are given by

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}.$$

One parametrization of this so called Cabbibo Kobayashi Maskawa matrix is the Wolfenstein parametrization:

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

where $\lambda = sin\theta_C = 0.22$, and $A = 0.79 \pm\ 0.06$ [8] is determined from studies of V_{cb}. The CKM matrix is unitary, so that

$$(V^*V)_{ij} = \sum V^*_{ki} V_{kj} = \delta_{ij}.$$

This leads to the unitarity condition

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0.$$

It has been shown that V_{ud} and V_{tb} are approximately one, so that we have

$$V_{ub}^* + V_{cd}V_{cb}^* + V_{td} = A\lambda^3(\rho + i\eta) + (-\lambda)A\lambda^2 + A\lambda^3(1-\rho-i\eta) = 0$$

or

$$\rho + i\eta + (1 - \rho - i\eta) = 1.$$

This can be pictured as a triangle in the complex (ρ,η) plane as in Figure 2.

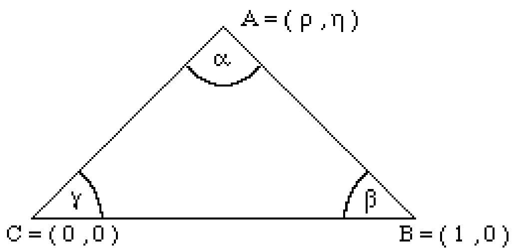

Figure 2: The (b,d) unitarity triangle. From Particle Physics Booklet, Particle data group, 1994, p. 216.

If the angles α, β, and γ are separated from zero, we have CP-violation.

3.2 The statistical error on sin 2β

For the neutral B mesons B^0 and $\bar{B}^0$ we have the CP eigenstates

$$B_1 = \frac{1}{\sqrt{2}}(B^0 + \bar{B}^0)$$

and

$$B_2 = \frac{1}{\sqrt{2}}(B^0 - \bar{B}^0).$$

These are mixed in a similar way as the K mesons, for which we have

$$K_S{}^0 = \frac{1}{\sqrt{1+\varepsilon^2}}(K_1{}^0 - \varepsilon K_2{}^0)$$

and

$$K_L{}^0 = \frac{1}{\sqrt{1+\varepsilon^2}}(\varepsilon K_1{}^0 + K_2{}^0)$$

where $\varepsilon \approx 0.002$, and

$$K_1 = \tfrac{1}{\sqrt{2}}(K^0 + \bar{K^0}) \text{ and } K_2 = \tfrac{1}{\sqrt{2}}(K^0 - \bar{K^0}),$$

except that there are two different neutral B meson states, B_d^0 and B_s^0. In this paper it is the former that will be investigated, in the decay $\bar{B}_d^0 \rightarrow J/\psi K_S^0$.

These mixing effects have already been observed at LEP, and for a beam that initially contains only B_d^0 or $\bar{B}_d^0$, B^0 mixing is expected to cause the beam to contain a fraction of the other B meson after some time has evolved. If at time $t = 0$ we have identified the B_d^0 and $\bar{B}_d^0$ states, which then decay to $J/\psi K_S^0$, the decay rates will be given by [9]

$$\frac{dN}{dt} = e^{-\Gamma t}(1 - \sin\, 2\beta \sin \Delta m t)$$

and

$$\frac{dN}{dt} = e^{-\Gamma t}(1 + \sin\, 2\beta \sin \Delta m t)$$

for $(B_d^0 \rightarrow J/\psi K_S^0)$ and $(\bar{B}_d^0 \rightarrow J/\psi K_S^0)$ respectively. Here $\Gamma = 1/\tau$ is the width of the B meson, and Δm the difference in mass between the two CP eigenstates, while β is one of the angles in the unitarity triangle. Furthermore we have

$$\sin\, 2\beta = \frac{2\eta(1-\rho)}{(1-\rho)^2 + \eta^2}.$$

If $\sin\, 2\beta = 0$ we do not have CP violation (B^0 mixing can still occur however).
The time-dependent asymmetry due to mixing effects will be given by

$$A(t) = \sin\, 2\beta \sin \Delta m t$$

so that the time-integrated asymmetry is given by

$$\begin{aligned} A &= \frac{N(B_d^0 \rightarrow J/\psi K_S^0) - N(\bar{B}_d^0 \rightarrow J/\psi K_S^0)}{N(B_d^0 \rightarrow J/\psi K_S^0) + N(\bar{B}_d^0 \rightarrow J/\psi K_S^0)} \\ &= \frac{x_d}{1 + {x_d}^2} \sin\, 2\beta \\ &= D_{int} \sin\, 2\beta \end{aligned}$$

where $x_d = \frac{\Delta m}{\Gamma}$, and the integration has been carried out from $t = 0$. The dilution factor D_{int} thus results from integrating over time.

Since other corrections must be added the observed asymmetry will have a slightly different form, approximately given by [9]

$$A_{obs} \cong D_{tag} D_{back} (D_{int} \sin\, 2\beta + A_p)$$

where A_p is a correction due to the production asymmetry, and $D_{back} = D_{background} = N_s/N_{total}$ where $N_s =$ the number of signal events and N_{total} the total number of events. (The background is assumed to be assymmetry free.) D_{tag} on the other hand is the correction due to tagging and is given by $D_{tag} = 1 - 2W$. Here W is the wrong tag fraction, which will be described in more detail in Section 5.

For $A_{obs} \ll 1$ this gives a statistical error for $\sin\, 2\beta$:

$$\delta \sin\, 2\beta = \frac{1}{D_{tag}\sqrt{D_{back}} D_{int} \sqrt{N_s}}$$

where N_s is the total number of signal events as above.

The error in sin 2β will be an important measure of how well a certain tagging method works, if it works at all. Since only a small fracion of the events produced at LHC can be used for B physics, all different decay channels become important. Each of them might need its own tagging method, and the more events that can be identified and used, the better the statistics will be. In the remaining part of this of this paper, jet charge techniques will be investigated, with the hope that these can be used in ATLAS.

4 Generation of data samples

For the generation Pythia 5.7 was used to simulate the pp-collisions, with B^{**} states, flavour excitation and gluon splitting included. If at least one b-quark had $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 5.0$, the event was hadronized with Jetset 7.4. To save CPU-time, the same event was hadronized up to 20 times, until it fulfilled the following requirements:

- There had to be a $\bar{\mathrm{B}}_{\mathrm{d}}^0$, which was forced to decay to $\mathrm{J}/\psi\mathrm{K}^0$. It was then required that $\mathrm{K}^0 \to \mathrm{K}_{\mathrm{S}}^0$.
- The J/ψ was forced to decay to $\mu^+\mu^-$, and events with $p_{\mathrm{T}} > 5.0$ GeV and $|\eta| < 2.5$ for both muons were retained.
- The $\mathrm{K}_{\mathrm{S}}^0$ was forced to decay to $\pi^+\pi^-$, and if both pions had $p_{\mathrm{T}} > 0.5$ GeV and $|\eta| < 2.5$, the event was kept.

Four sets of data samples were generated, two containing 1000 events each [1], one set with 552 events, and one with 520 events. Thus all in all 3072 events were generated and used for the analysis.

A more detailed description of the generation is given in [3].

5 Analysis

The pp $\to \mathrm{b}\overline{\mathrm{b}}$ process is followed by the hadronization of the $\mathrm{b}\overline{\mathrm{b}}$ pair, which will give two b-quark jets. The jets will be back-to-back in a first order approximation, unless the $\mathrm{b}\overline{\mathrm{b}}$ pair originates from gluon splitting. In this case the jets will be close to each other in the pp centre of mass frame, which makes identification and separation of the two jets more difficult.

If one of the b-quark jets contains a $\mathrm{B}_{\mathrm{d}}^0$ meson which decays to $\mathrm{J}/\psi\mathrm{K}_{\mathrm{S}}^0$, we cannot know if it was a $\mathrm{B}_{\mathrm{d}}^0 = \mathrm{d}\bar{\mathrm{b}}$ or a $\bar{\mathrm{B}}_{\mathrm{d}}^0 = \bar{\mathrm{d}}\mathrm{b}$ that decayed. But if we add up all the charges of the particles in the jet with the $\mathrm{B}_{\mathrm{d}}^0$ meson, the total charge of that jet is expected on average to have the same sign as the original b-quark causing the jet. In this way the jet charge can be used to reveal the flavour of the $\mathrm{B}_{\mathrm{d}}^0$ at production, and thus also the asymmetry in the original process.

In this study the existence of a $\bar{\mathrm{B}}_{\mathrm{d}}^0$ is required, therefore the wrong tag fraction, i.e. the fraction of events where the jet charge has the wrong sign, is defined as those events

[1] These data samples are saved on the tapes LH1286-87.

where $Q_{jet} > c$ (since $q_b = -e/3$), where c is a constant which was varied between 0 and 0.5. The efficiency, i.e. the fraction of events that can be used with this method, is also studied. These values are then used in the evaluation of the statistical error of sin 2β, β being one of the angles of the Cabibbo Kobayashi Maskawa unitarity triangle described in Section 3.

5.1 Jet definitions

In this investigation, three different methods of defining jets were used. Method I was based upon finding the $\bar{B}_d^0$ meson in the event, and then define a jet as all the particles that pass within a cone defined by $dr = \sqrt{(\triangle\phi)^2 + (\triangle\eta)^2}$ surrounding this track. Method II on the other hand used the Jetset 7.4 routine LUCELL (see the Jetset manual [10]), called with parameters as given in Table 1. LUCELL uses a jet algorithm to find all the jets in the event, and the jet with the highest total energy, after the $\bar{B}_d^0$ jet had been removed, was then assumed to be the jet resulting from the other b-quark in the original $pp \rightarrow b\bar{b}$ process. This jet was then used in the analysis, in combination with the $\bar{B}_d^0$ jet.

The third method, method III, also used two jets, but instead of using a jet algorithm, the other b-quark jet was found by looking at 'the Monte Carlo truth'; all B mesons were reconstructed, and the one that did not have daughter particles containing a b-quark was kept as the B meson originating from the other b-quark. (This could clearly be done in a better way, for example through a life-time-cut, but method III still represents more or less an 'ideal' situation, and may be too optimistic. The possibility of using vertex-tagging for identification of the other b-quark jet should be investigated however, to see if this method is realistic at all.)

Table 1: Parameters for which other values than the default values were used, when calling the Jetset 7.4 routine LUCELL (see the Jetset manual).

Parameter	Value	Purpose
PARU(51)	2.5	$\|\eta\|_{\max}$
PARU(52)	0.5	Minimum E_T for cell to be investigated further by LUCELL.
PARU(53)	5.0	Minimum total jet energy, for jet to be accepted.
PARU(54)	0.7	dr; 0.6,0.5 and 0.4 were also used.
MSTU(41)	2	LUCELL will only consider partons/ particles that have not fragmented/ decayed, with the exception of neutrinos and unknown particles.
MSTU(51)	100	Number of η bins.
MSTU(52)	100	Number of ϕ bins.
MSTU(54)	1	Specifies the contents of the P vector given by LUCELL.

5.2 Jet charge algorithms

Three different jet charge algorithms were used for the analysis:

$$Q_{jet} = \frac{\sum_{i=1}^{n} q_i {p_{\mathrm{T}}}_i^{\,a}}{\sum_{i=1}^{n} {p_{\mathrm{T}}}_i^{\,a}} \tag{1}$$

where ${p_{\mathrm{T}}}_i$ is the momentum of particle i transverse to the beam direction,

$$Q_{jet} = \frac{\sum_{i=1}^{n} q_i \mid p_{\|_i} \mid^a}{\sum_{i=1}^{n} \mid p_{\|_i} \mid^a} \tag{2}$$

$p_{\|_i}$ being the momentum component along the jet axis, and

$$Q_{jet} = \frac{\sum_{i=1}^{n} q_i y_i}{\sum_{i=1}^{n} y_i} \tag{3}$$

with the rapidity y_i given by

$$y_i = \frac{1}{2} \log \frac{E_i + p_{\|_i}}{E_i - p_{\|_i}}.$$

Here E_i is the energy of the particle and $p_{\|_i}$ is the momentum component along the jet axis. In all three Equations 1–3, q_i is the charge of particle i, and the sums are taken over all particles in the jet. For algorithms 1 and 2 several values of the exponent a have been investigated, as given in Table 2.

The algorithms have been investigated for each of the methods mentioned in Section 5.1. In method I it was the jet charge itself that was studied, and the event was counted as wrongly tagged if $Q_{jet} > c$, with several different values of c investigated.

For the two jet methods on the other hand, it was the charge separation [11]

$$dQ = \langle Q_- - Q_+ \rangle \tag{4}$$

rather than Q_{jet} itself, that was studied, Q_- being the jet charge of the $\bar{\mathrm{B}}_{\mathrm{d}}^0$ jet (which originates from the negatively charged b quark), and Q_+ the jet charge of the other jet. Since Q_- is expected to be negative, dQ is also expected to be negative, or rather $dQ < -c$, when the tagging is correct. The wrong tag fraction W in methods II and III is thus given as the fraction of events with $dQ > c$, where c was varied between 0 and 0.5. Events with $\mid dQ \mid < c$ were thrown away.

In all cases the efficiency ε was defined as the ratio between the number of tagged events (both rightly and wrongly tagged), and the total number of events.

5.3 Cuts and requirements

Several cuts and requirements were placed on the events in the analysis, as follows:

- For the one jet method, method I, three different p_{T}-cuts were used for the particles in the cone, $p_{\mathrm{T}} > 0.5$ GeV, $p_{\mathrm{T}} > 0.6$ GeV, and $p_{\mathrm{T}} > 0.7$ GeV. The cone size was also varied with $dr = 0.7$, $dr = 0.6$, $dr = 0.5$, and $dr = 0.4$, and the c cut, described in Section 5.2 was varied with $c = 0.0$, $c = 0.1$, $c = 0.2$, $c = 0.3$, $c = 0.4$, and $c = 0.5$.

- For the two jet method using the LUCELL routine, method II, it was required that there should be at least two jets, otherwise the event was rejected. Also it was required that $|\eta| < 2.5$ and $E_{jet} > 5.0$ GeV. If the $\bar{B}^0_d$ was found in the jet with the highest E_{jet}, the jet with the second highest energy was chosen. Otherwise the highest energy jet was selected to be the jet originating from the other b-quark, and used in the analysis. The cone sizes were the same as in method I, as were the c and p_T cuts.

- For method III, the two jet method using another B meson (as described in Section 5.1), it was required that the B meson and the $\bar{B}^0_d$ were not in the same jet. The p_T and c cuts, and the cone sizes used, were the same as in methods I and II.

In all cases it was demanded that the jet should consist of at least two particles. Due to the LVL1 trigger requirements, one of the muons in the decay $J/\psi \rightarrow \mu^+\mu^-$ was required to have $p_T > 6.0$ GeV. Also, since the muon trigger only covers $|\eta| < 2.2$, both muons were required to be within these limits.

5.4 The tagging quality factor and δsin 2β

For all the different jet charge algorithms, and for each of the methods I–III, the different parameters involved were varied as summarized in Table 2.

Table 2: Parameter values used in algorithms 1 – 3.

Algorithm	Parameter	Values investigated
1 - 3	dr	0.4,0.5,0.6,0.7
1 - 3	$p_T$cut	0.5,0.6,0.7
1 - 3	c	0.,0.1,0.2,0.3,0.4,0.5
1 and 2	a	0.5,0.75,1.0,...,2.0

For all possible combinations of these parameters, the tagging quality factor

$$Q = (1 - 2W)^2 \varepsilon$$

was optimized, with W being the wrong tag fraction, and ε the efficiency. This tagging quality factor is then connected to the statistical error of sin 2β through

$$\delta \sin 2\beta = \frac{1}{D_{tag}\sqrt{D_{back}}D_{int}\sqrt{N_s}} = \frac{1}{\sqrt{D_{back}}D_{int}\sqrt{N_{prod}}\sqrt{Q}}$$

since $D_{tag} = 1 - 2W$ and $N_s = \varepsilon N_{prod}$, where $N_{prod} = 59000$ is the estimated number of reconstructed but untagged events per year [14] (this number includes e.g. the cross section and reconstruction efficiencies, which are expected to be 80% for leptons and 95% for hadrons). Furthermore, in the calculations of δsin 2β, $D_{int} = 0.63$ [2] and $D_{back} = 0.975$ [2] were used.

6 Results

6.1 Parameter optimization

By investigating all possible parameter combinations it was realized that only general conclusions can be drawn, for example that the cone size dr should probably be 0.7, i.e. fairly large. It also seems as if a p_{T}-cut of 0.5 GeV is to be preferred. Nothing certain can be said about the c-cut however, or about the exponent a in algorithms 1 and 2.

The result of this optimization is presented in Table 3.

Table 3: The parameter combinations giving the best results for each of the algorithms used.

Method	Alg.	Parameter combination				Results			
		dr	p_{T} cut	c	a	W	ε	Q	$\delta \sin 2\beta$
I	1	0.7	0.5	0.2	0.75	0.358	0.347	0.028 ± 0.009	0.041 ± 0.003
	2	0.7	0.5	0.0	0.75	0.390	0.524	0.025 ± 0.009	0.043 ± 0.004
	3	0.7	0.5	0.2	–	0.345	0.320	0.031 ± 0.009	0.039 ± 0.003
II	1	0.7	0.5	0.4	1.25	0.339	0.318	0.033 ± 0.009	0.037 ± 0.003
	2	0.7	0.5	0.5	1.50	0.342	0.259	0.026 ± 0.008	0.042 ± 0.003
	3	0.7	0.5	0.2	–	0.368	0.310	0.022 ± 0.008	0.046 ± 0.004
III	1	0.7	0.5	0.3	1.00	0.274	0.204	0.042 ± 0.009	0.033 ± 0.002
	2	0.7	0.5	0.3	1.00	0.267	0.190	0.041 ± 0.009	0.033 ± 0.002
	3	0.7	0.5	0.2	–	0.295	0.210	0.035 ± 0.009	0.036 ± 0.002

6.2 Comparing the algorithms

The overall difference beween the three agorithms has been studied, for each of the three jet methods. As can be seen from the diagrams in Appendix A, the difference between the algorithms was very small and in fact, algorithms 1 and 2 look almost identical. When using method I, algorithm 3 seems to be somewhat better than the other algorithms, while for method II algorithm 1 gives the best results. In both cases, as well as for method III, the three algorithms are equal within the error limits.

But even though nothing specific could be said about which of the three algorithms is to be preferred, one can see that using two jets instead of only one gives better overall results, as might be expected. Method II, which uses the LUCELL routine to find all jets in the event, assumes that the jet with the highest total transverse energy, after the $\bar{\mathrm{B}}_{\mathrm{d}}^{0}$ jet has been removed, is the jet that originates from the $\bar{\mathrm{b}}$-quark. This assumption has been tested against the 'Monte Carlo truth', and it turned out to be correct in 795 out of the 3072 generated events (i.e. in 25.9%) for $dr = 0.7$, while for $dr = 0.6$ the assumption was correct in 24.1%, or in 740 out of 3072 events. For $dr = 0.5$ the result was 21.5%, or 661 events, and finally for $dr = 0.4$ method II can be used correctly in 548 of the generated events, corresponding to 17.8%. The reason for these relatively low percentages seems to be that LUCELL finds only about 43% of the B meson jets (not counting the $\bar{\mathrm{B}}_{\mathrm{d}}^{0}$ jet). On the other hand, the requirement that LUCELL must find at least two jets for an event to be counted only resulted in a cut-off of 2.3% of the events (72/3072). A diagram over the number of jets found by LUCELL can be seen in Figure 3.

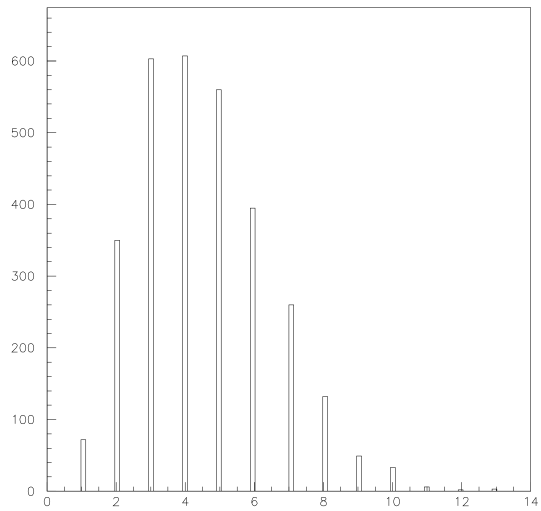

Figure 3: The number of jets given by LUCELL.

For the other two jet method, method III, it was required that the $\bar{B}^0_d$ and B mesons were not in the same jet. With this requirement 205 out of the 3072 generated events (= 6.7 %) were thrown away. Another requirement was of course that there should be a B meson (besides the $\bar{B}^0_d$), and 247 events were rejected due to this cut, corresponding to 8%.

7 Discussion

It is clear that the jet charge method is of some use since it points toward an asymmetry. As can be seen from Figure 4, there are clearly more events with $Q_{jet} < c$ than there are those with $Q_{jet} > c$. (For this specific diagram the wrong tag fraction is $W \approx 34\%$, with $c = 0.20$.)

Even if the results from the three algorithms and the three jet defining methods are very similar, one can say that most likely a p_T-cut of 0.5 GeV, and a cone size of $dr = 0.7$ are to be preferred, independent of which of algorithms 1–3 is used. All three jet methods have very low efficiencies, especially method III. Method I had better efficiencies in comparison, but using two jets instead of only one still gives better results, if some way of selecting the other b-jet (the one that does not contain a B^0_d or a $\bar{B}^0_d$) can be found. Assuming this to be the jet with the highest total transverse energy (next to the $J/\psi K^0_S$ jet) is not satisfactory since this assumption is correct in less than 30% of the events. Method III requires that the B meson originating from the other b-quark can be

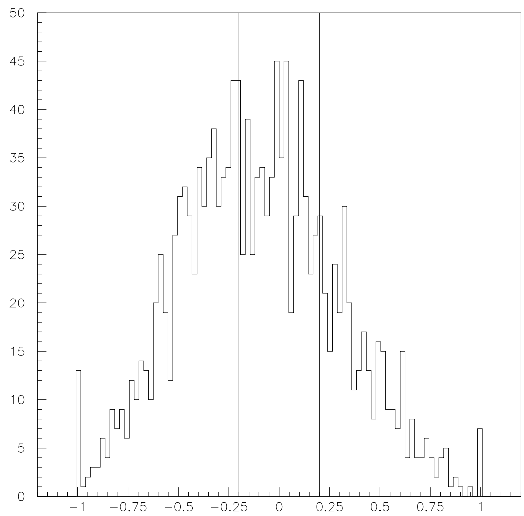

Figure 4: An example of dQ (see Equation 4) for method II and algorithm 1, with p_T-cut $= 0.5$, $dr = 0.7$, $a = 1.25$. With $c = 0.2$ this corresponds to a wrong tag fraction $W \approx 34\%$.

found, and with secondary vertex tagging this may become possible. If this is the case, method III would most likely give very good results on $\delta \sin 2\beta$, even though for example smearing has to be added.

With the 3072 events that have been investigated in this paper, the best result for the statistical error on sin 2β is $\delta \sin 2\beta = 0.033 \pm 0.002$, which was achieved by using method III and algorithm 1. This can be compared with the result of the lepton tag studied in [2], which gave $\delta \sin 2\beta = 0.02$. Since the lepton tag relies on J/$\psi \rightarrow e^+e^-$, which will be experimentally difficult, the jet charge techniques are safer and thus well comparable with the lepton tag.

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A Appendix

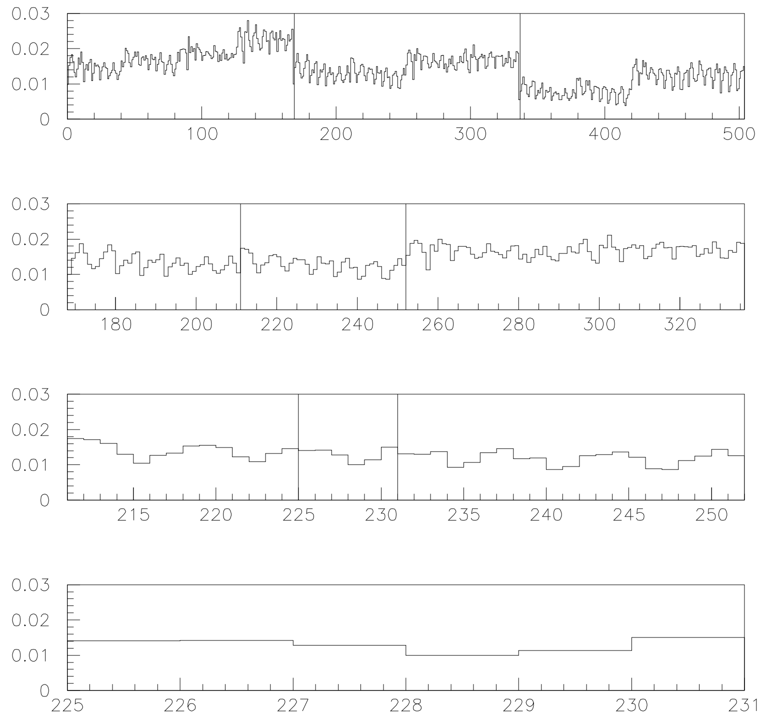

Figure 5: The quality factor given by method I with algorithm 1, shown for all possible parameter combinations in the top-most diagram, and with the number of parameters combined reduced in the lower diagrams. In the second diagram from the top p_{T}-cut $=$ 0.6 while the other parameters are varied as in Table 2. In the next diagram p_{T}-cut is still 0.6, and $dr = 0.5$; a and c are varied as before. In the last diagram $a = 1.00$ has been zoomed in, and only c is varied. The same order is used in all of the diagrams in Figures 6– 8, except in the ones describing algorithm 3, since this algorithm does not include the exponent a, which reduces the number of combinations in these diagrams, from 504 to 72.

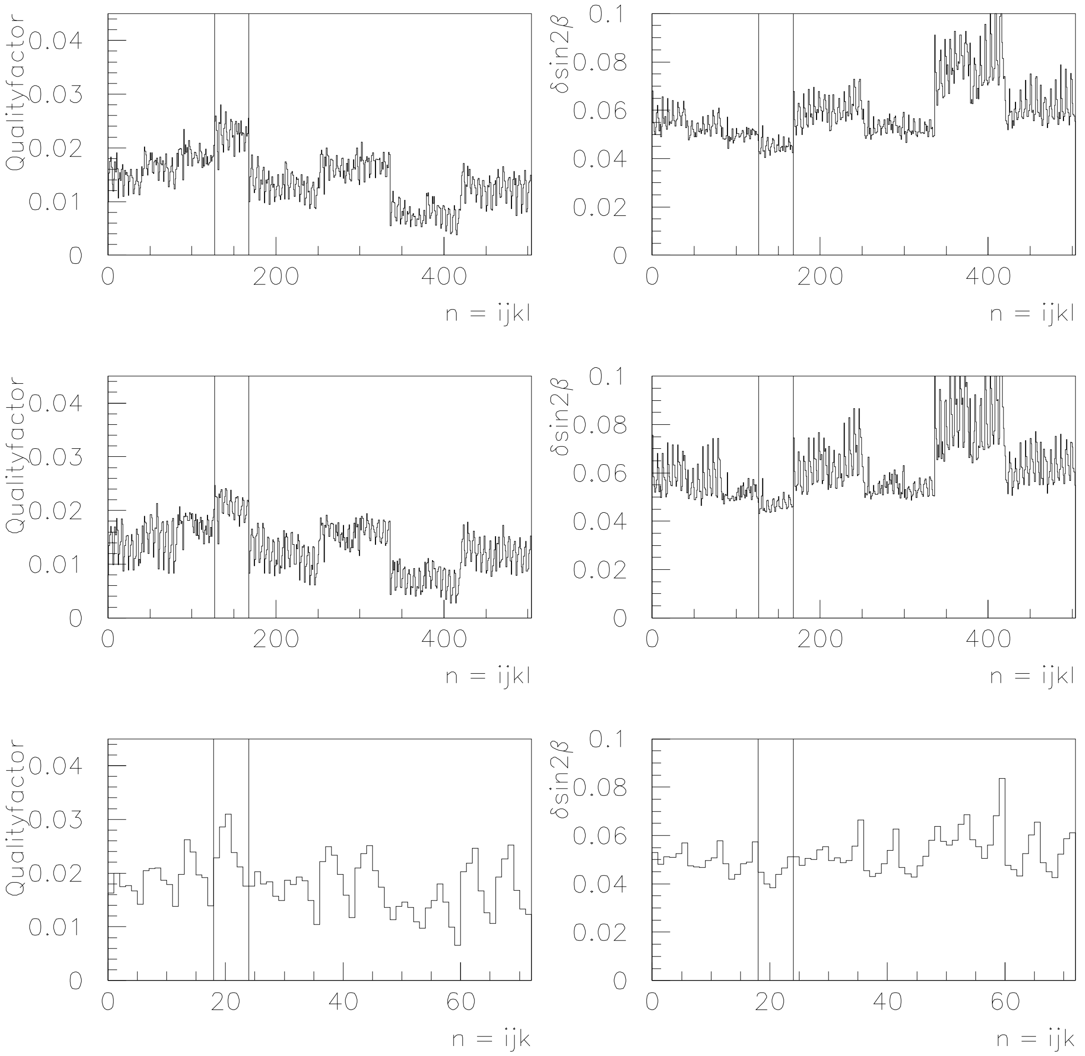

Figure 6: The qualityfactor and the statistical error of sin 2β, for method I and algorithms 1–3, with the results corresponding to p_{T}-cut $= 0.5$ and $dr = 0.7$ marked.

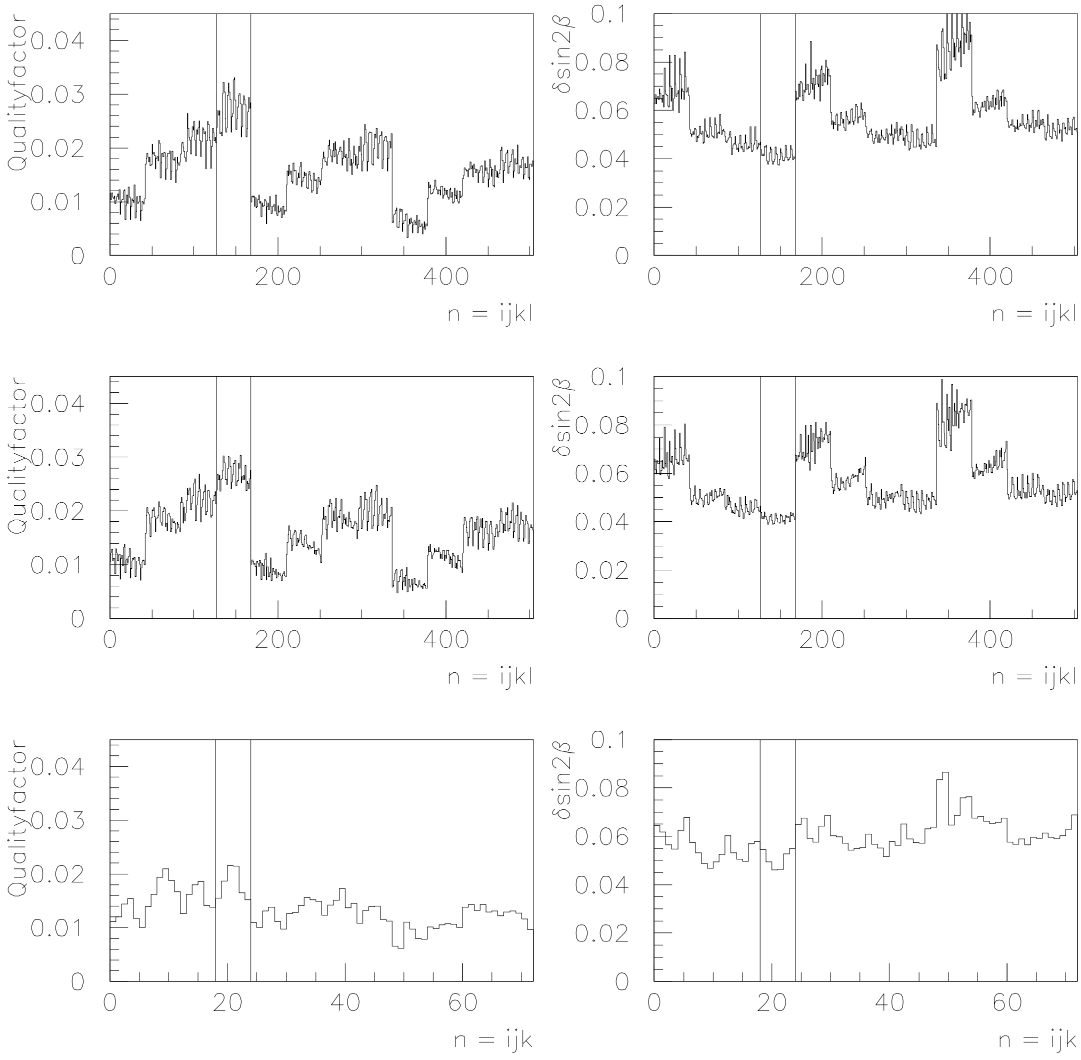

Figure 7: The qualityfactor and the statistical error of sin 2β, for method II and algorithms 1–3, with the results corresponding to p_{T}-cut $= 0.5$ and $dr = 0.7$ marked.

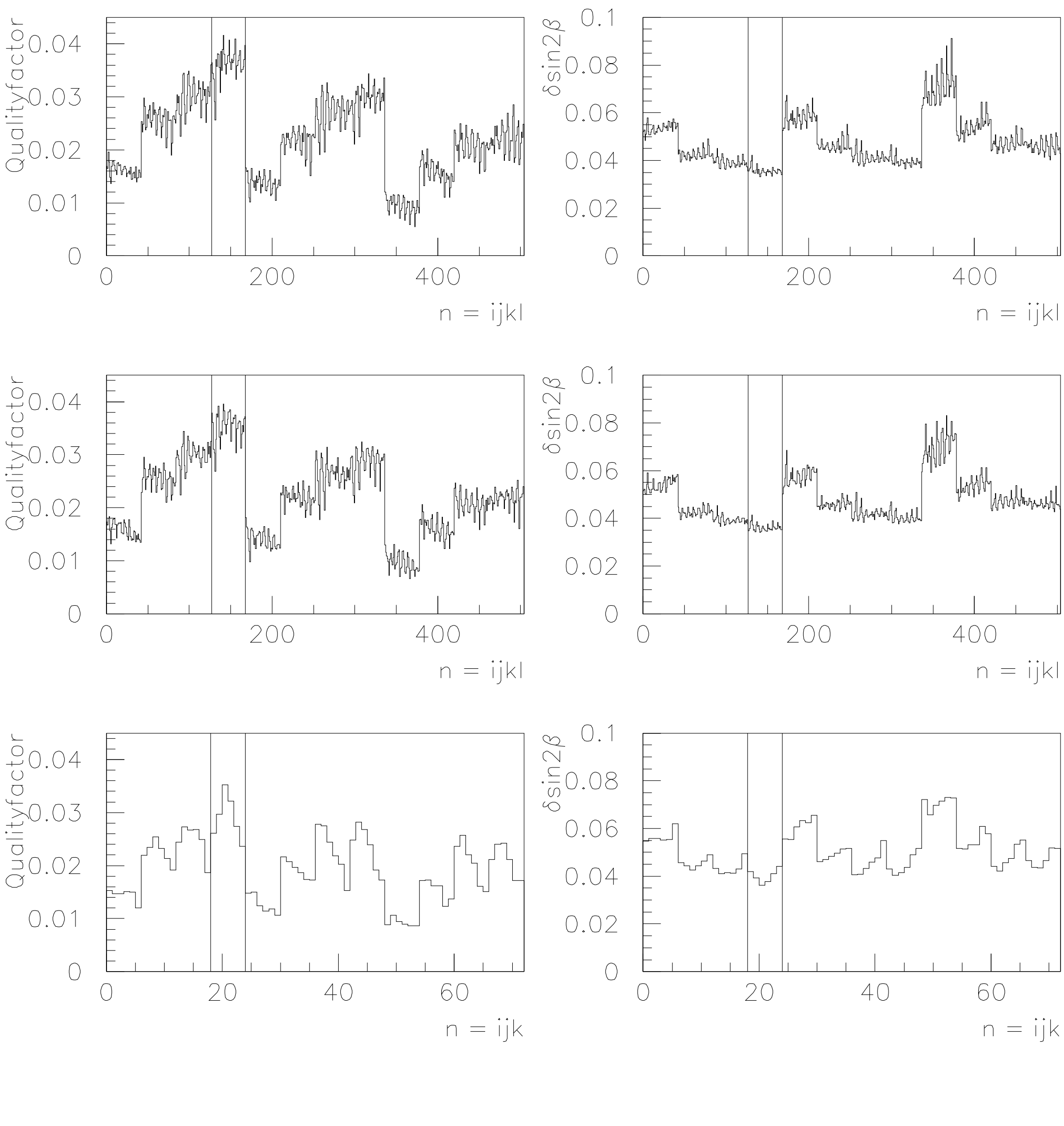

Figure 8: The qualityfactor and the statistical error of sin 2β, for method III and algorithms 1–3, with the results corresponding to $p_{\rm T}$-cut $= 0.5$ and $dr = 0.7$ marked.