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Determination of A^{b}_{FB} at the Z pole using inclusive charge reconstruction and lifetime tagging

DELPHI Collaboration

Abstract

A novel high precision method measures the b-quark forward-backward asymmetry at the Z pole on a sample of 3,560,890 hadronic events collected with the DELPHI detector in 1992 to 2000. An enhanced impact parameter tag provides a high purity b sample. For event hemispheres with a reconstructed secondary vertex the charge of the corresponding quark or anti-quark is determined using a neural network which combines in an optimal way the full available charge information from the vertex charge, the jet charge and from identified leptons and hadrons. The probability of correctly identifying b-quarks and anti-quarks is measured on the data themselves comparing the rates of double hemisphere tagged like-sign and unlike-sign events. The b-quark forward-backward asymmetry is determined from the differential asymmetry, taking small corrections due to hemisphere correlations and background contributions into account. The results for different centre-of-mass energies are:

$$\begin{aligned} A^{b}_{FB}\,(89.449\,\text{GeV}) &= 0.0637 \pm 0.0143(\text{stat.}) \pm 0.0017(\text{syst.}) \\ A^{b}_{FB}\,(91.231\,\text{GeV}) &= 0.0958 \pm 0.0032(\text{stat.}) \pm 0.0014(\text{syst.}) \\ A^{b}_{FB}\,(92.990\,\text{GeV}) &= 0.1041 \pm 0.0115(\text{stat.}) \pm 0.0024(\text{syst.}) \end{aligned}$$

Combining these results yields the b-quark pole asymmetry

$$A^{b,0}_{FB} = 0.0972 \pm 0.0030(\text{stat.}) \pm 0.0014(\text{syst.})$$

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1 Introduction

The measurements of the b-quark forward-backward asymmetry at the Z pole provide the most precise determination of the effective electroweak mixing angle, $\sin^2\theta^{\ell}_{\rm eff}$, at LEP. For pure Z exchange and to lowest order the forward-backward pole asymmetry of b-quarks, $A^{0,b}_{FB}$, can be written in terms of the vector and axial-vector couplings of the initial electrons (v_e, a_e) and the final b-quarks (v_b, a_b):

$$A^{0,b}_{FB} = \frac{3}{4}\frac{2a_e v_e}{a_e^2+v_e^2}\frac{2a_b v_b}{a_b^2+v_b^2} \tag{1}$$

Higher order electroweak corrections are taken into account by means of an improved Born approximation [1], which leaves the above relation unchanged, but defines the modified couplings ($\bar{a}_f$, $\bar{v}_f$) and an effective mixing angle $\theta^{f}_{\rm eff}$:

$$\frac{\bar{v}_f}{\bar{a}_f} = 1 - 4|q_f|\sin^2\theta^{f}_{\rm eff} \tag{2}$$

using the electric charge q_f of the fermion. The b-quark forward-backward asymmetry determines the ratio of these couplings. It is essentially only sensitive to $\sin^2\theta^{\ell}_{\rm eff}$ defined by the ratio of the electron couplings.

Previously established methods to measure the b-quark forward-backward asymmetry in DELPHI [2,3] either exploited the charge correlation of the semileptonic decay lepton (muon or electron) to the initial b charge or used the jet charge information in selected b events. These methods suffer from either the limited efficiency, because of the relatively small semileptonic branching ratio or from the limited charge tagging performance because of the small jet charge separation between a b-quark and anti-quark jet.

The present analysis improves on the charge tagging performance by using the full available experimental charge information from b jets. Such an improvement is achievable because of the different sensitivities of charged and neutral b hadrons to the original b-quark, and because of the separation between fragmentation and decay charge. The excellent DELPHI microvertex detector separates the particles from B decays from fragmentation products on the basis of the impact parameter measurement. The hadron identification capability, facilitated by the DELPHI Ring Imaging CHerenkov counters (RICH), provides a means of exploiting charge correlations of kaons or baryons in b jets. Thus, not only can the secondary b decay vertex charge be measured directly but also further information for a single jet, like the decay flavour for the different B types (B^0, B^+, B_s and b baryon), can be obtained. A set of Neural Networks is used to combine the additional input with the jet and vertex charge information in an optimal way.

2 Principles of the method to extract the b asymmetry

The differential cross-section for b-quarks from the process $e^+e^- \rightarrow Z \rightarrow b\bar{b}$ as a function of the polar angle[1] θ can be expressed as :

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \frac{8}{3}A^{b}_{FB}\cos\theta + \cos^2\theta\,. \tag{3}$$

[1] In the DELPHI coordinate system the z-axis is the direction of the e^- beam. The radius R and the azimuth angle ϕ are defined in the plane perpendicular to z. The polar angle θ is measured with respect to the z-axis.

Hence the forward-backward asymmetry generates a linear $\cos\theta$ dependence in the production of b-quarks. For anti-quarks the orientation (sign) of the production angle is reversed.

The thrust axis is used to approximate the quark direction in the analysis [4]. The plane perpendicular to the thrust axis defines the two event hemispheres. The charge of the primary quark or anti-quark in a hemisphere is necessary to determine the orientation of the quark polar angle $\theta_{\vec{T}}$. This charge information can be obtained separately for both event hemispheres using the hemisphere charge Neural Network output.

In order to exploit the much improved b charge tagging fully, a self-calibrated method to extract the forward-backward asymmetry has been developed. The b-quark charge sign is measured in event hemispheres with a reconstructed secondary vertex. The different possible combinations of negative, positive and untagged event hemispheres define classes of single and double charge tagged events, with the double tagged distinguished into like-sign and unlike-sign. The forward and backward rates of single and double unlike-sign events provide sensitivity to the asymmetry. As the $\mathrm{b\bar{b}}$ final state is neutral, one of the two hemispheres in like-sign events is known to be mistagged. By comparing the like-sign and unlike-sign rates of double hemisphere charge tagged events it is hence possible to extract the probability of correctly assigning the b-quark charge directly from the data.

A b-tagging variable constructed from lifetime information as well as secondary vertex and track observables provides an additional strong means of rejecting charm and light quark events in which a secondary vertex occurred. Separate event samples of successively enhanced b purity are used in the analysis to allow for a statistical correlation between the b purity and the probability of correctly assigning the quark charge.

The asymmetry measurement as well as the self-calibration method rely on the good knowledge of the true b content and residual non-b background in the individual rates of differently charge-tagged events. Therefore the b efficiency in each rate is measured directly on the real data. For the most important background contribution, c-quark events, additional calibration techniques are used: the c-quark efficiency of the enhanced impact parameter tag is measured using a double tag method while the c charge tagging probability is calibrated on data by means of D decays reconstructed in the opposite hemisphere.

The b-quark forward-backward asymmetry is determined from the differential asymmetry of the two classes of single tagged and unlike-sign double tagged events. The differential asymmetry is measured independently in consecutive bins of the polar angle and in the different b purity samples. Here small corrections due to residual background contributions and due to charge tagging hemisphere correlations are taken into account.

The paper is organised as follows. First a short summary of the hadronic event selection is given. In Section 4 the b event tagging used to obtain the high-purity b-quark sample is described in conjunction with the calibration of its efficiency. Section 5 details the charge tagging technique using Neural Networks and the self-calibrating method to extract the forward-backward asymmetry. Section 6 describes the measurement of A^{b}_{FB} from the DELPHI data of 1992 to 2000. Section 7 discusses the systematic errors. Finally the conclusion is given in Section 8, and combined final values on A^{b}_{FB} and A^{c}_{FB} are presented in Section 9. Technical information on the self-calibration method can be found in the appendix.

3 Selection of Z decays to hadrons

A detailed description of the DELPHI apparatus for both the LEP 1 and LEP 2 phases can be found in [5] and in the references therein. This analysis makes full use of the information provided by the tracking system, the calorimetry and the detectors for hadron and lepton identification. Of special importance is the silicon Vertex Detector providing three precise $R\phi$ measurements. For the years 1992 to 1993 the lowest polar angle θ for obtaining at least one $R\phi$ measurement is 31°, while for the years 1994 to 1995 the enhanced detector measured particles down to a θ of 25° and provided additional z measurements in the outer shell and the shell close to the beam [6]. From 1996 onwards the fully replaced DELPHI silicon tracker provided $R\phi$ and z measurements down to a θ of 21°. For the exact number of measurements as a function of polar and azimuthal angles we refer to reference [7].

This analysis uses all the DELPHI data taken from 1992 to 2000 at centre-of-mass energies close to the Z pole. In addition to the LEP 1 data in an interval of ± 0.5 GeV around the Z pole, the data taken at 2 GeV above and below as well as the LEP 2 calibration runs taken at the Z pole are included. The different years and centre-of-mass energies divide the data into nine sets which are analysed separately and compared to individually generated simulated data.

For events entering the analysis, nominal working conditions during data taking are required at least for the central tracking detector, a Time Projection Chamber (TPC), for the electromagnetic calorimeters and for the barrel muon detector system. The operating conditions and efficiency of the RICH detectors varied widely for the different data sets. These variations are included in the corresponding simulated data samples.

charged particle momentum	$\geq$	0.4 GeV/c
neutral particle energy		see text
length of tracks measured only with TPC	$\geq$	30 cm
polar angle	$\geq$	20°
uncertainty of the momentum measured	$\leq$	100 %
impact parameter ($R\phi$)	$\leq$	4 cm
impact parameter (z)	$\leq$	10 cm

Table 1: *Cuts to select particles. Impact parameters are defined relative to the primary vertex.*

For each event cuts are applied to the measured particles to ensure both good quality of the reconstruction and also good agreement of data and simulation. The selections are summarised in Table 1. In addition, for neutral clusters measured in the calorimeters the reconstructed shower energy had to be above 0.3 GeV for the barrel electromagnetic calorimeter (HPC) and the small angle luminosity calorimeters (STIC/SAT), and above 0.4 GeV for the Forward ElectroMagnetic Calorimeter (FEMC).

A second step selects Z decays to hadrons as detailed in Table 2. Here each event is divided into two hemispheres by the plane perpendicular to the thrust axis $\vec{T}$ which is computed using the charged and neutral particles. $\theta_{\vec{T}}$ is the polar angle of the thrust axis. In addition, the negligible number of events with an unphysically high momentum particle are discarded.

In total $3.56 \cdot 10^6$ Z decays to hadrons are selected using data from mean centre-of-mass energies of 89.449 GeV, 91.231 GeV and 92.990 GeV (see Table 3). The data taking periods with centre-of-mass energies below and above the Z peak (called "peak-2" and "peak+2" in the following) are analysed separately. The remaining backgrounds due to $\tau\tau$, Bhabha, and $\gamma\gamma$ events as well as contributions from beam-gas or beam-wall interactions are estimated to be below 0.5 %. After the subsequent selection of Z decays to b-quarks with a reconstructed secondary vertex, they are safely neglected.

The data are compared to $10.43 \cdot 10^6$ fully simulated hadronic decays using JETSET 7.3 [8] with DELPHI tuning of fragmentation, b production and decay parameters [9].

total energy of charged particles	$\geq$	$0.15 \times \sqrt{s}$
sum of energy of charged particles in a hemisphere	$\geq$	$0.03 \times \sqrt{s}$
total multiplicity of charged particles	$\geq$	7
multiplicity of charged particles in hemisphere	$\geq$	1
forward electromagnetic energy $E_{\text{FEMC}} := \sqrt{E_{\text{F}}^2 + E_{\text{B}}^2}$	$\leq$	$85\%\, E_{\text{beam}}$

Table 2: *Selections for Z decays to hadrons. $\sqrt{s}$ is the centre-of-mass energy, $E_{\text{F/B}}$ the total shower energy per FEMC side.*

year	data	simulation	$\langle\sqrt{s}\rangle$
1992	636401	1827321	91.280 GeV
1993	454895	1901060	91.225 GeV
1994	1303131	3260752	91.202 GeV
1995	416560	1206974	91.288 GeV
1996-2000	332944	971299	91.260 GeV
1993 peak-2	86601	269027	89.431 GeV
1993 peak+2	126648	339528	93.015 GeV
1995 peak-2	79989	268899	89.468 GeV
1995 peak+2	123721	385648	92.965 GeV

Table 3: *Number of selected (data) and generated (simulation) Z decays to hadrons for the different years of data taking and different centre-of-mass energies.*

4 Selection of Z decays to b-quarks using an enhanced impact parameter method

4.1 The b tagging method

Decays to b-quarks are selected from the sample of hadronic Z decays using the DELPHI high-purity b tagging technique. It is based on the well established hemisphere b-tag method used by DELPHI for the precision measurement of R_{b} [10,11]. The analysis uses the apparent lifetime calculated from the track impact parameters, information from the decay vertex when it is reconstructed and the rapidities of charged particles. The latter are defined with respect to the jet direction as reconstructed with the LUCLUS algorithm [8]. The information from the secondary decay vertex consists of the invariant mass, the transverse momentum, and the energy fraction of the decay products. All the variables are combined into one discriminator which is defined independently in each of