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Search for $\mathcal{CP}$ Violation in the Decay $Z \to b\,\bar{b}\,g$

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About three million hadronic decays of the Z collected by ALEPH in the years 1991 to 1994 are used to search for anomalous $\mathcal{CP}$ violation beyond the Standard Model in the decay $Z \to b\bar{b}g$. The study is performed by analyzing angular correlations between the two quarks and the gluon in three-jet events and by measuring the differential two-jet rate. No signal of $\mathcal{CP}$ violation is found. For the combinations of anomalous $\mathcal{CP}$ violating couplings, $\hat{h}_b = \hat{h}_{Ab}g_{Vb} - \hat{h}_{Vb}g_{Ab}$ and $h_b^* = \sqrt{\hat{h}_{Vb}^2 + \hat{h}_{Ab}^2}$, limits of $\mid \hat{h}_b \mid < 0.59$ and $h_b^* < 3.02$ are given at 95% CL.

1. Introduction

The Standard Model predicts only negligible $\mathcal{CP}$ violating effects in decays of the Z into quarks or leptons [1]. Therefore, a search for $\mathcal{CP}$ violation at the Z resonance is a test for physics beyond the Standard Model. Simple extensions [2] of the Standard Model with $\mathcal{CP}$-odd and $\mathcal{CP}$-even Higgs states are expected to contain $\mathcal{CP}$ violating terms. As couplings of Higgs particles are functions of the masses of the interacting particles, decays with heavy quarks deserve special interest. In this analysis [3] a search for $\mathcal{CP}$ violating anomalous couplings is performed, as proposed by the authors of [1,4].

2. Theoretical Framework

In [4] $\mathcal{CP}$-odd couplings are introduced in a model independent way using an effective Lagrangian. The Standard Model Lagrangian density is extended to include all $\mathcal{CP}$-odd local operators that can be constructed with Standard Model fields, up to the mass dimension $d = 6$. Effects in $Z \to b\bar{b}$ from $\mathcal{CP}$ violating dipole form factors would require the measurement of the spin directions of the quarks. As for quarks no spin analyzers exist, the search for $\mathcal{CP}$ violation is restricted to the analysis of the $\mathcal{CP}$-odd operator at the vertex $Z \to b\bar{b}g$. In [1,4] it is shown that all $\mathcal{CP}$-odd effects are proportional to the dimensionless coupling $\hat{h}_b$:

$$\hat{h}_b = \hat{h}_{Ab}g_{Vb} - \hat{h}_{Vb}g_{Ab} \qquad (1)$$

with

$$\hat{h}_{Ab/Vb} = h_{Ab/Vb}\frac{\sin\vartheta_W \cos\vartheta_W m_Z^2}{e g_s} ,$$

where g_s is the strong coupling and g_{Vb}, g_{Ab} are the Standard Model vector and axial vector couplings of the b quark to the Z.

In a first study, $\mathcal{CP}$-odd variables are analyzed, probing the coupling $\hat{h}_b$. To measure $\hat{h}_b$ the $\mathcal{CP}$-odd tensor T'_{ij} [4] is used:

$$T'_{ij} = (\hat{k}_{\bar{q}} - \hat{k}_q)_i \left(\frac{\hat{k}_{\bar{q}} \times \hat{k}_q}{\mid \hat{k}_{\bar{q}} \times \hat{k}_q \mid} \right)_j + (i \leftrightarrow j) , \qquad (2)$$

where $\hat{k}_q$, $\hat{k}_{\bar{q}}$ denote the normalized momentum vectors of the quark and anti-quark, respectively, and i, j are the cartesian coordinates with $i, j = 3$ defined to be along the beam axis. The tensor T'_{ij} is symmetric in i and j, traceless, and invariant when exchanging $\hat{k}_q$ and $\hat{k}_{\bar{q}}$. Therefore only the gluon jet has to be tagged. If $\mathcal{CP}$ is violated then $\langle T'_{ij} \rangle \neq 0$. The most sensitive observable is $\langle T'_{33} \rangle$ [3]), it is related to $\hat{h}_b$ [4] by:

$$\langle T'_{33} \rangle = \hat{h}_b Y' . \qquad (3)$$

The sensitivity Y' is a constant derived by integration of the experimentally accessible phase space.

In a subsequent analysis, additional contributions from anomalous couplings to the three-jet rate in the process $Z \to b\bar{b}g$ have been searched for. Such additional contributions are proportional to the combination ${h_b^*}^2$, with

$$h_b^* = \sqrt{\hat{h}_{Vb}^2 + \hat{h}_{Ab}^2}\,, \qquad (4)$$

and would manifest themselves in a higher value of the strong coupling constant for b quarks, $\alpha_s^b(M_Z^2)$ (for a complementary but related study see [5])

The analysis of h_b^* is based on the differential two-jet rate D_2, which is the normalized distribution of the event shape variable Y_3, $D_2(Y_3) = 1/\sigma\ d\sigma(Y_3)/dY_3$, with Y_3 being the $y_{\rm cut}$ at which an event changes its classification from three jets to two jets.

Additional couplings at the vertex $Z \to b\bar{b}g$ could also contribute to the partial width $\Gamma_{b\bar{b}}$, thus possibly enhancing R_b beyond its Standard Model value [4]. By attributing the observed deviation of $R_b^{exp} = 0.2209 \pm 0.0021$ from the Standard Model expectation $R_b = 0.2155 \pm 0.0005$ [6] entirely to these anomalous couplings, a value of $h_b^* = 1.93 \pm 0.75$ can be calculated.

3. Data Reduction

The ALEPH detector and its performance are described in detail in [7]. The selection of hadronic events is detailed in [3]. Jets are defined using the JADE and Durham algorithms [8]. In the $\hat{h}_b$ analysis the JADE algorithm with a fixed cut off value of $y_{\rm cut} = 0.03$ is used. In the h_b^* analysis both jet schemes are employed to measure the differential two-jet rate $D_2(Y_3)$. The b events are selected exploiting the sizeable impact parameters due to b decays. The b tagging algorithm is described in detail in reference [9]. The probability for each charged particle to originate from the primary vertex is calculated using the track impact parameter. They are combined into probabilities $\mathcal{P}$ associated to sets of tracks like jets ($\mathcal{P}_J$) or whole events ($\mathcal{P}_E$). In both analyses b events are selected with a cut on the event probability $\mathcal{P}_E$, resulting in b purities of more than 85%.

4. Analysis of Anomalous Couplings from $Z \to b\bar{b}g$ Topologies

In the study of $\mathcal{CP}$-odd contributions three-jet events are selected as described in [3]. The energies of the three reconstructed jets are ordered, $E_{\rm jet\,1} > E_{\rm jet\,2} > E_{\rm jet\,3}$. In the b sample the gluon jet candidate is selected using the probability $\mathcal{P}_J$ of the individual jets: from the two lower energy jets, the jet with the higher $\mathcal{P}_J$ is chosen as the gluon jet candidate.

The purity of the sample is estimated using simulated events generated with JETSET [10]. The matching procedure of partons to jets found after reconstruction is detailed in [3].

A purity of $73.6\% \pm 0.4_{stat} \pm 0.9_{syst}$ is achieved. The efficiency, defined as selected $b\bar{b}g$ events with successfully tagged gluon compared to the total rate of $Z \to b\bar{b}g$ events, is about 19%.

The measurement is performed on the data collected until 1994. After applying the data selection, a sample of 85342 $b\bar{b}g$ candidates remains for the T'_{33} measurement. The following mean value of $\langle T'_{33}\rangle$ is obtained:

$$\langle T'_{33}\rangle = (-0.5 \pm 3.7_{\rm stat}) \times 10^{-3}$$

The measurement is also performed on a sample enriched with light quarks to ensure that no effect due to the selection mechanism is present and to check the assumption that no $\mathcal{CP}$ violating effect exists in events with light quarks. Light flavours are selected with the cut $\mathcal{P}_E > 0.5$. The gluon jet in this sample is defined to be the one having the lowest energy in the event. The following mean value of $\langle T'_{33}\rangle$ is obtained:

$$\langle T'_{33}\rangle = (-0.9 \pm 3.1_{\rm stat}) \times 10^{-3}$$

Obviously no significant discrepancy between the two completely independent samples is found. Hence it is concluded that no significant fake $\mathcal{CP}$ violating effect due to the selection is present.

4.1. Systematic Errors of the Measurement

To estimate the effect of the selection cuts, all the cuts are varied in a wide range. Only the cuts applied to select well-defined three-jet configurations ($y_{\rm cut}$, aplanarity, jet energies, multiplicities and angles) have a sizeable influence on the selected sample. Therefore, the systematic error is estimated using these cuts only [3]. The $\mathcal{CP}$ invariance of the b tag is checked by dividing the three-jet sample into disjoint subsamples with different $\mathcal{P}_E$ values. Using these subsamples, a sample of $\langle T'_{33}\rangle$ values is measured to test the bias of the $\mathcal{P}_{\rm E}$ cut. The $\langle T'_{33}\rangle$ values are found to be well compatible with statistical fluctuations. The uncertainty is estimated from a Gaussian fit to the distribution. The $\mathcal{CP}$ symmetry of the detector is estimated by measuring $\langle T'_{33}\rangle$ on a sample of track pairs in hadronic events [3]. The resulting asymmetry is compatible with zero within one standard deviation. The quality of the reconstruction of the jet direction is estimated by measuring the difference of the $\langle T'_{33}\rangle$ at the parton level and after the full detector simulation. The error is derived from the width of the difference distribution. A more detailed description of the systematic uncertainties is given in [3]

4.2. Determination of $\hat{h}_b$

To extract the coupling $\hat{h}_b$ from the measurement of $\langle T'_{33}\rangle$ the effective sensitivity Y' has to be calculated. This has been done by means of a Monte Carlo generator [11], which includes the $\mathcal{CP}$ violating couplings. The calculated sensitivity $Y' = -0.0167 \pm 0.0002_{\rm stat}$ is constant, showing no dependence on $\hat{h}_b$ [3].

The systematic errors on the sensitivity stem from the errors on the tagging purity and from the influence of the b quark mass. The largest error is caused by the dependence of the sensitivity on the b quark mass [12]. Taking into account the total systematic uncertainty [3] the sensitivity is given by

$$Y' = -0.0167 \pm 0.0002_{\rm stat} \pm 0.0015_{\rm syst}\,.$$

4.3. Results of the $\hat{h}_b$ Analysis

Taking the systematic errors into account the measurement of the $\mathcal{CP}$-odd observable in a sample of $Z \to b\bar{b}g$ events yields:

$$\langle T'_{33}\rangle = (-0.5 \pm 3.7_{\rm stat} \pm 3.3_{\rm syst}) \times 10^{-3}\,.$$

The measurement is consistent with $\langle T'_{33}\rangle = 0$. The size of the $\mathcal{CP}$-odd coupling $\hat{h}_b$ is extracted using eq. 3:

$$\hat{h}_b = 0.03 \pm 0.22_{\rm stat} \pm 0.20_{\rm syst}\,.$$

From this measurement a limit on the coupling of $\mid \hat{h}_b \mid < 0.59$ (95% CL) is derived.

5. Measurement of Anomalous Couplings from the Differential Two-Jet Rate

Of all the event shape variables studied in [5], only for Y_3 theoretical calculations including anomalous couplings are available [12]. Therefore, the second analysis concentrates on possible additional contributions to the differential two-jet rate $D_2(Y_3)$ due to the anomalous coupling h_b^*. The theoretical prediction for $D_2(Y_3)$ is given by

$$D_2^b(Y_3) = \frac{\alpha_s(\mu^2)}{2\pi}\left(A'(Y_3) + h_b^{*2}C'(Y_3)\right)$$
$$+\left(\frac{\alpha_s(\mu^2)}{2\pi}\right)^2\left[A'(Y_3)2\pi b_0 \ln\left(\frac{\mu^2}{M_Z^2}\right) + B'(Y_3)\right]$$

where $b_0 = (33 - 2n_f)/12\pi$, μ is the renormalization scale, and the coefficients A' and B' have been computed to second order of perturbative QCD [13]. Here $h_b^* \gg h_{udsc}^*$ is assumed. Hence the prediction for $udsc$ quarks is entirely fixed by the Standard Model and does not depend on h^*. In contrast, D_2 for b quarks receives contributions from new physics and the prediction is modified by an additional term proportional to h_b^{*2}. Note that in the coefficients A' and B' the total cross section needed for normalization is changed if anomalous couplings are present. The coefficient C' has been calculated to leading order [12].

A theoretical description $R^{\rm th}$ of the observable can be derived:

$$R^{th} = \frac{P_b D_2^{b,b\,\rm tag}(Y_3) + (1-P_b)D_2^{udsc,b\,\rm tag}(Y_3)}{R_b D_2^{b\,\rm incl}(Y_3) + (1-R_b)D_2^{udsc\,\rm incl}(Y_3)}$$

where P_b is the purity of the lifetime-enriched b sample, R_b is the fraction of Z's decaying into

b quarks and $D_2^{q\,tag}$ stands for the distribution of a flavour q in a sample of type *tag*. These distributions are constructed from the parton level predictions and have to be corrected for the following effects: mass corrections for b quarks, initial and final state radiation, hadronization effects, the detector acceptance, the influence of the detector resolution, and the tagging bias. After applying these corrections to $R^{\rm th}$, a value of h_b^* is extracted from a binned least-square fit to the data (see fig. 1).

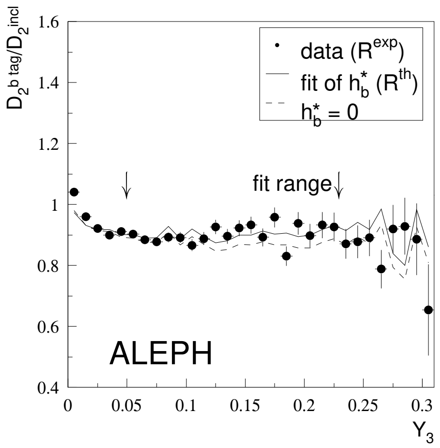

Figure 1. Fit of the theoretical description R^{th} to the experimental observable R^{exp}. The fit result with the Durham algorithm ($h_b^* = 1.19 \pm 0.25\,, \chi^2 = 8.0\,, d.o.f. = 17$) is shown. Included are also the expectations for $h_b^* = 0$.

5.1. Determination of h_b^* and Systematic Errors

The fit function $R^{\rm th}$ depends explicitly on h_b^*, α_s and μ. The value of the strong coupling constant is set in the fit function to $\alpha_s(M_Z^2) = 0.118$ and is varied by ± 0.007. The renormalization scale is set to 15 GeV. This symmetrizes the error from the scale uncertainty, which is varied from $\mu = m_b$ to $\mu = M_Z$. The fit range is chosen to optimize the sensitivity and to guarantee a good perturbative description. To take into account systematic uncertainties due to the limited fit range the fit is repeated with a range modified by two bins. Jets are reconstructed using charged tracks and neutral calorimeter objects. The uncertainty of the reconstruction procedure is estimated by repeating the analysis with charged tracks only. The b sample is enriched by means of a lifetime tag, which leads to a distortion of the differential two-jet rate of less than 10%. Therefore, a correction is elaborated using full detector simulation. The stability of these corrections is checked by varying the lifetime cuts in the data resulting in a change of the purity of the sample of 10%. The same cuts are applied to the simulated data and the corrections for the tagging bias recalculated. The b quark fragmentation is described by the fragmentation function of Peterson et al. [14]. The main parameter of this function is ϵ_b, measured to be $\epsilon_b = (3.2 \pm 1.7) \times 10^{-3}$ [15]. Monte Carlo simulations with a corresponding range of values are done to study the effect on h_b^*. Another source of uncertainty is related to mass corrections. These have been calculated in [16] at tree level. These calculations are only complete to $\mathcal{O}(\alpha_s)$ and are applied to the coefficient A'. The uncertainty on the b quark mass is set to 0.5 GeV$/c^2$ and the corresponding correction recalculated. In order to account for missing higher orders, the available $\mathcal{O}(\alpha_s^2)$ four-jet computation is used for correction as well and the difference to the $\mathcal{O}(\alpha_s)$ result taken as systematic error. Finally, the parameters R_b and P_b are varied in the fit function within their errors and an error on the normalization is derived. The typical systematic uncertainty of the cluster algorith is $\Delta h_b^* = 0.38$ [3].

5.2. Hadronization Model Uncertainty and Results of the h_b^* Analysis

The main theoretical uncertainty is caused by the hadronization of partons to hadrons. The results achieved with four different generators are compared in table 1: the matrix element with string fragmentation (ME), the parton shower ($Q_0 = 1$ GeV, being the cut-off of the parton shower) as implemented in JETSET [10] with string fragmentation (PS), the model of cluster fragmentation in HERWIG [17] (HW) and the dipole cascade model implemented in ARIADNE [18] (AR). Taking into account the correlations between the two algorithms, a combined result for each hadronization model can be derived which minimizes the total statistical error.

Model	h_b^*
ME	$1.05 \pm 0.26 \pm 0.40$
AR	$0.79 \pm 0.30 \pm 0.40$
PS	$1.75 \pm 0.16 \pm 0.35$
HW	$1.79 \pm 0.16 \pm 0.36$

Table 1
Results on h_b^* from the least-square fit for four different hadronization models. The first error is the statistical one, the second the total systematic uncertainty.

After averaging the combined results of the different hadronization models the following result ist obtained:

$$h_b^* = 1.34 \pm 0.22_{\mathrm{stat}} \pm 0.38_{\mathrm{syst}} \pm 0.50_{\mathrm{hadr}} \,.$$

where the first error is the statistical one, the second error contains all systematic uncertainties but the hadronization model and the last one reflects the systematic uncertainty due to the hadronization model itself. The upper limit is derived by adding linearly the systematic and statistical errors:

$$h_b^* < 3.02 \; (95\% \; \mathrm{CL}) \,.$$

6. Conclusions

A search for $\mathcal{CP}$ violation beyond the standard model in the decay $Z \to b\bar{b}g$ has been performed. Two combinations of $\mathcal{CP}$-odd couplings, namely h_b^* and $\hat{h}_b$ have been analyzed. No evidence for $\mathcal{CP}$-odd couplings is found in both analyses. The derived limit on h_b^* is consistent with the value calculated from the R_b measurement.

Using eq. 1 and eq. 4, the two measurements presented in this paper can be used to constrain the couplings h_{Ab}, h_{Vb}. In fig. 2 the 95% CL limits of both measurements on h_{Ab} and h_{Vb} are shown, being well consistent with each other.

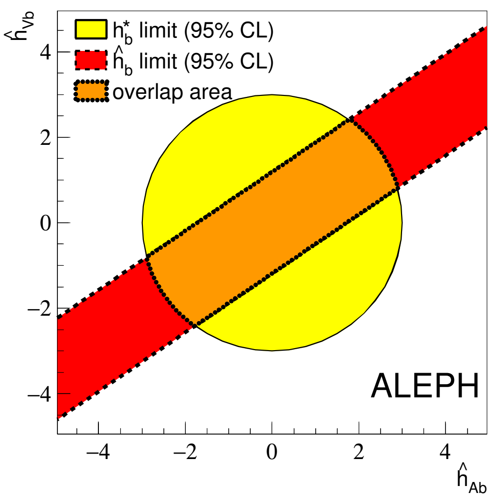

Figure 2. Combined results. The shaded areas depict the constraints of the measurements on the couplings $\hat{h}_{Ab}$ and $\hat{h}_{Vb}$.

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