Hint for axial-vector contact interactions in the data on $e^+e^-\rightarrow e^+e^-(\gamma)$ at center-of-mass energies 192–208 GeV

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For the first time the experiments ALEPH, DELPHI, L3 and OPAL have presented preliminary results for fermion-pair production in $e^+e^-$ collisions on the full data set above the $Z$ pole. A combined analysis of the Bhabha scattering measurements is performed to search for effects of contact interactions. In the case of two axial-vector (AA) currents the best fit to the data is 2.6 standard deviations away from the standard model expectation, corresponding to an energy scale $\Lambda = 10.3^{+2.8}_{-1.6}$ TeV for contact interactions. For other models no statistically significant deviations are observed, and the data are used to set lower limits at 95% confidence level on the contact interaction scales ranging from 8.2 to 21.3 TeV, depending on the helicity structure.

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I. INTRODUCTION

The standard model (SM) is very successful in confronting the data coming from the highest energy accelerators. Still, there are theoretical reasons to expect that it is an effective theory, valid in a limited energy range, and one of the first questions in the quest for physics beyond the standard model is what is the relevant scale, where new phenomena will give experimental signatures. In this paper we will follow a data-driven approach and analyze the full set of measurements on the reaction

$$e^+e^-\rightarrow e^+e^-(\gamma),$$

at center-of-mass energies $\sqrt{s}$ above the $Z$ resonance from 183 up to 208 GeV. Rather than concentrating on a particular model, we will look for something unexpected. Bhabha scattering is chosen as a very sensitive probe, affected in many new physics scenarios. This analysis is a continuation of the work presented in [1], based on the published differential cross sections for Bhabha scattering at energies 183 and 189 GeV.

In the standard model the production of a fermion-pair $ff$ in $e^+e^-$ collisions is described by the exchange of $\gamma$ or $Z$ in the $s$ channel, and if the final state is identical to the initial one, also in the $t$ channel. The interest in studying fermion-pair final states above the $Z$ pole at the CERN $e^+e^-$ collider LEP2 is driven by the fact that many types of new physics scenarios can contribute to these processes. For this to happen, the couplings to the initial and final states should be different from zero. In the case of Bhabha scattering we just need a coupling to the electron and the positron. Even if the standard model extension operates at an energy scale much higher than the accessible center-of-mass energy for a direct observation, it can still give measurable effects by modifying the differential cross section through interference with the SM amplitudes.

II. CONTACT INTERACTIONS

Contact interactions offer a general framework for describing a new interaction with typical energy scale $\Lambda \gg \sqrt{s}$.

The presence of operators with canonical dimension $N>4$ in the Lagrangian gives rise to effects $\sim 1/\Lambda^{N-4}$. Such interactions can occur for instance, if the SM particles are composite, or when new heavy particles are exchanged.

For fermion-pair production, the lowest order flavor-diagonal and helicity-conserving operators have dimension six [2]. The differential cross section takes the form

$$\frac{d\sigma}{d\Omega} = \text{SM}(s,t) + e \cdot C_{\text{int}}(s,t) + e^2 \cdot C_{\ell}(s,t),$$

where the first term is the standard model contribution, the second comes from interference between the SM and the contact interaction, and the third is the pure contact interaction effect. The Mandelstam variables are denoted as $s$, $t$ and $u$. Usually the coupling is fixed, $g^2/4\pi = 1$, and the structure of the interaction is parametrized by coefficients for the helicity amplitudes: $|\eta_{ij}| \leq 1$, where $(i,j=L,R)$ labels the helicity of the incoming and outgoing fermions. We define

$$e = \frac{g^2}{4\pi} \frac{\text{sgn}(\eta)}{\Lambda^2},$$

where the sign of $\eta$ enables us to study both the cases of positive and negative interference.

III. EXPERIMENTAL DATA

Measurements on fermion-pair production for the full data set of the LEP2 Collider have become available recently. They include preliminary data from 192 to 208 GeV center-of-mass energies and published results at 183 and 189 GeV. In the following we will concentrate on the measurements of Bhabha scattering, where large data samples have been accumulated during the very successful LEP runs from 1997 to 2000.

The ALEPH [3–6], DELPHI [7–9], L3 [10–12] and OPAL [13–16] Collaborations have presented results for the total cross section and the forward-backward asymmetry $A_{FB}$ of Bhabha scattering. In the case of DELPHI, L3 and OPAL the results are for all energy points and the scattering angle $\theta$. 

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is the angle between the incoming and the outgoing electrons in the laboratory frame. In the ALEPH case the forward-backward asymmetry is available only at 183 GeV and the scattering angle \( \theta^e \) is defined in the outgoing \( e^+ e^- \) rest frame. The acceptance is given by the angular range \(-0.9 < \cos \theta^e < 0.7\) for ALEPH, by \(44^\circ < \theta < 136^\circ\) for DELPHI and L3, and by \(|\cos \theta|<0.7\) for OPAL.

The experiments use different strategies to isolate the high energy sample, where the interactions take place at energies close to the full available center-of-mass energy. This sample is the main search field for new physics.\(^1\) DELPHI, L3 and OPAL apply an acollinearity cut of 20°, 25° and 10° respectively. ALEPH defines the effective energy, \( \sqrt{s'} \), as the invariant mass of the outgoing fermion pair. It is determined from the angles of the outgoing fermions. For details of the selection procedures, the statistical and systematic errors we refer the reader to the publications of the LEP experiments.

### IV. ANALYSIS METHOD

The standard model predictions for Bhabha scattering are computed with the Monte Carlo generator BHWIDE [19]. A theory uncertainty of 1.5% on the absolute scale of the predictions is assigned, as discussed in [20]. In all cases the individual experimental cuts of the selection procedures and the isolation of the high energy samples are taken into account. The results are cross-checked with the semi-analytic program TOPAZO [21] and the Monte Carlo generator LABSMC [22].

The effects of new phenomena are computed as a function of the parameter \( \varepsilon \), defined in Sec. II. Initial-state radiation (ISR) changes the effective center-of-mass energy in a large fraction of the observed events. We use these effects into account by computing the first order exponentiated cross section following [23]. Other QED and electroweak corrections give smaller effects and are neglected.

In total we have 57 data points: 32 from the cross sections (eight energy points and four experiments) and 25 from the forward-backward asymmetries. A fitting procedure as in [24] is applied. A negative log-likelihood function is constructed by combining all data points at the eight center-of-mass energies

\[
-\log L = \sum_{i=1}^{n} \left( \frac{[\text{prediction(SM, } \varepsilon]\text{ measurement}]^2}{2 \cdot \Delta^2} \right)_i,
\]

(4.1)

where prediction \((\text{SM, } \varepsilon)\) is the SM expectation for a given measurement (total cross section or forward-backward asymmetry) combined with the additional effect of contact interactions as a function of the scale \( \Lambda \). Measurement is the corresponding measured quantity and \( \Delta = \text{error(prediction(SM, } \varepsilon)\text{ measurement)} \). The index \( r \) runs over all data points. The error on a deviation consists of three parts, which are combined in quadrature: a statistical error and a systematic error (as given by the experiments) and the theoretical error assigned above. The systematic errors account for small correlations between data points. The minimum of the negative log-likelihood function gives the central value of the fitted parameter \( \varepsilon \) for each model, and the interval containing 68% of the total probability around the minimum is used to determine the values corresponding to one standard deviation in the positive and negative directions.

### V. RESULTS AND DISCUSSION

The results of the fits for the different contact interaction models are summarized in Table I. In the same table the coefficients specifying the helicity structure of the investi-

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\(^1\)For reviews see e.g. [17,18].
gated models are given. For all models the central value of the parameter \( \varepsilon \) is no more than 1.05 standard deviations away from the standard model value \( \varepsilon = 0 \), with one exception. The fitted value for the AA model is \( \varepsilon = 0.0095^{+0.0036}_{-0.0037} \) TeV\(^{-2} \), or 2.6 standard deviations from the SM expectation. The quality of all fits is good, with \( \chi^2 \) values \( \sim 52/56 \) degrees of freedom. For the AA model the \( \chi^2 \) value is 46.8/56 degrees of freedom. The differences between the experimental measurements and the standard model predictions are displayed in Fig. 1. While good agreement for the total cross section measurements is observed, above center-of-mass energies of 192 GeV the measured forward-backward asymmetries show a trend to lie below the predictions. The log-likelihood curves for the VV and AA models are shown in Fig. 2.

In the cases where the data from the LEP Collaborations show no statistically significant deviations from the SM predictions, we can derive one-sided lower limits on the scale \( \Lambda \) of contact interactions at 95% confidence level. This is done by integrating the log-likelihood functions in the physically allowed range of the parameters describing new physics phenomena, assuming a uniform prior distribution. The exact definition can be found in [24]. The limits for positive or negative interference are summarized in Table I. The results presented here improve on the limits obtained by individual LEP experiments [3,7,25,26,14] or in a combined analysis [1].

Now we turn to a discussion of the result for the AA model. Clearly this result is unexpected and requires careful analysis. The central value and the one standard deviation band of Eq. (5.1) correspond to a scale for axial-vector contact interactions

\[
\Lambda_+ = 10.3^{+13.1}_{-8.7} (-1 + 1 \sigma) \text{ TeV.} \tag{5.2}
\]

Let us use this central value in our investigation. We can reverse the view point and ask ourselves what are the expected deviations from the SM predictions for the total cross section and the forward-backward asymmetry of Bhabha scattering. The result as a function of the center-of-mass energy is illustrated in Fig. 3. The AA model changes the total cross section by less than 0.5% in this energy range. The relative effect is practically constant for rising energy. For comparison, the combined error on the total cross section of the four experiments for the highest energy point \( \sim 207 \) GeV is 1.2%. An additional factor is the theoretical uncertainty of 1.5% on the absolute scale, discussed in Sec. IV. On the contrary, the forward-backward asymmetry is changed by \( (-0.0066) \) in absolute value \( \sim 0.8\% \) at 183 GeV and by \( (-0.0083) \) or \( (-1.0\%) \) at 207 GeV. The effect is rising with energy. It is clear that the AA model manifests itself mainly in the forward-backward asymmetry, which is not affected by the uncertainty on the absolute scale. Another favorable fact is that the statistical error on \( A_{FB} \) is given by

\[
\sigma(A_{FB}) = \sqrt{(1-A_{FB}^2)/N},
\]

so for the same number of events \( N \) we have a reduction factor \( \sim 0.6 \) due to the large value of the asymmetry \( \sim 0.8 \). On the minus side this measurement requires recognition of the electron and positron charges, and hence stricter event selection asking for good tracks. For comparison, the combined error on the forward-backward asymmetry for three experiments and the highest energy point (207 GeV) is 1.1%. As the ALEPH Collaboration has
not presented results on \( A_{FB} \) above 183 GeV, the result discussed here is based on the asymmetry measurements of the other three Collaborations.

The experiments apply charge confusion corrections to their measurements of the forward-backward asymmetry,

\[
A_{FB}^{\text{corrected}} = \frac{A_{FB}^{\text{measured}}}{1 - 2c},
\]

where \( c \) is the amount of events with wrong sign assignment. For example, if \( c = 0.05 \), an underestimation of the charge confusion by 9% will underestimate the asymmetry by 1%. For \( c = 0.02 \), one has to underestimate the charge confusion already by 24% in order to underestimate the asymmetry by 1%. The statistical error in the size of this correction is an important component of the systematic error, quoted by the experiments.

The forward-backward asymmetry can be affected by the interference between initial-state and final-state radiation, which is known to change the form of the differential cross section. This effect is estimated using the program TOPAZ. If we switch the interference on, \( A_{FB} \) is increasing by 0.1% for an acollinearity cut of 10° and by 0.07% for an acollinearity cut of 25°. So the effects are very small, and as the experiments use differential efficiency in the scattering angle, the impact on the measured asymmetry values is much smaller. We can conclude that the interference is under control.

Another interesting point are the preliminary results on contact interactions presented by DELPHI \(^@\) 9,\(^@\) 27, L3 \(^@\) 16,\(^@\) and OPAL \(^@\) 16. The deviations of \( \epsilon \) from the SM value show a positive pull in all cases, but the contact interaction scale under discussion here is at the sensitivity limit of individual experiments. In \(^@\) 1 a limit of \( \Lambda > 10.4 \) TeV at 95% confidence level is obtained, which covers about 40% of the favored region from this analysis at higher energies.

The measurements of Bhabha scattering from 192 to 208 GeV are preliminary. The systematic errors and the central values may still change. In order to clarify the situation, the final results of the four LEP Collaborations are needed. The best option is to combine the measurements of the differential cross sections in the four experiments, as illustrated in Fig. 4. The AA model gives a specific signature, enhancing the cross section in the central part and backwards, and only slightly reducing the forward peak.

When interpreting the physical meaning of contact interaction scales, we should remember that a strong coupling \( g^2/4\pi = 1 \) for the novel interactions is postulated by convention. If we assume a coupling of different strength, \( g^2/4\pi = \alpha' \), the limits can be translated as \( \Lambda' = \sqrt{\alpha' \cdot \Lambda} \). For the extreme case of a coupling of electromagnetic strength the real scale can be around 1 TeV.

The measurements of Bhabha scattering above the \( Z \) resonance have reached a high level of precision. In order to take full advantage of the large data samples collected during the LEP running from 1997 to 2000, new or improved theory predictions will be beneficial \(^@\) 20. A combined effort of the four LEP Collaborations is needed to answer the question: is Bhabha scattering opening a window to new physics at the TeV scale?
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