Contact interactions in the four-fermion processes at LEP2 and HERA

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Abstract

We consider the possibility of experimental observation of flavor-diagonal and helicity conserving contact terms in the four fermion reactions $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^-q \to e^-\mu^+\mu^-q$ at LEP2 and HERA.

1 Introduction

Speculations about the composite nature of leptons and quarks have been developed during a long period of time [1]. With the help of compositeness of fundamental fermions one could hope to inderstand a number of principal features of the Standard Model scheme such as the structure of fermion generations, mass spectrum of fermions and the symmetry breaking scenario.

A large number of phenomenological studies of the possibility to observe the sigatures of compositeness at the new generation of e^+e^-, ep and $p\bar{p}$ colliders exist (see [2, 3, 4] and references therein). One can imagine a simplified picture when leptons and quarks consist of some pointlike particles (preons) bound by some new interaction (metacolor force) which is probably confining and become strong at some energy scale Λ. If at the new colliders the momentun transfer exceeds Λ, leptons and quarks would interact in a manner completely different from their pointlike low energy structure, showing directly the hard scattering processes of the constituents. At the energies less than Λ one could observe some indications to the constituent dynamics (residual effective interactions) and describe this regime in the framework of some effective lagrangian approach. This effective lagrangian is given by a Standard Model lagrangian and some operators of higher dimension involving the fields of the SM. For instance, the simplest effective term of this type is given by dimension six four-fermion operator $(\psi\gamma\psi)(\psi\gamma\psi)$ multiplied by g^2/Λ^2 giving the effective term with correct dimension four. The strength of such nonrenormalisable effective interactions is determined by a dimensionless coupling g and powers of the compositeness scale Λ.

2 Distributions in the Standard Model with $LL-$ contact term for the process $e^+e^- \to e^+e^-\mu^+\mu^-$

2.1 Parametrization of contact interactions

We are using helicity conserving contact interactions of the form [5]

$$L_c = \frac{g^2}{2\Lambda^2}(\eta_{LL}\bar{\psi}_L\gamma_\mu\psi_L\bar{\psi}_L\gamma^\mu\psi_L + \eta_{RR}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_R\gamma^\mu\psi_R + 2\eta_{LR}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_L\gamma^\mu\psi_L) \qquad (1)$$

where $g^2/4\pi = 1$, $|\eta| = 1$ and $\psi_{L,R} = (1 \mp \gamma_5)\psi/2$. In the case of positive η the first and second terms are denoted by $LL+$ and $RR+$, if η is negative they are denoted by $LL-$ and $RR-$ correspondingly [2]. Particular choice of η_i gives VV and AA (vector-vector and axial-axial) current interactions. In the following we choose the $LL-$ contact term. No qualitative difference in the results appears if we choose any other variant from the six possible. Previous analyses performed in [5, 6] for the reactions $e^+e^- \to e^+e^-$, $e^+e^- \to \mu^+\mu^-$ showed that the effect of LL and RR terms is typically several times smaller than the effect of VV, AA terms.

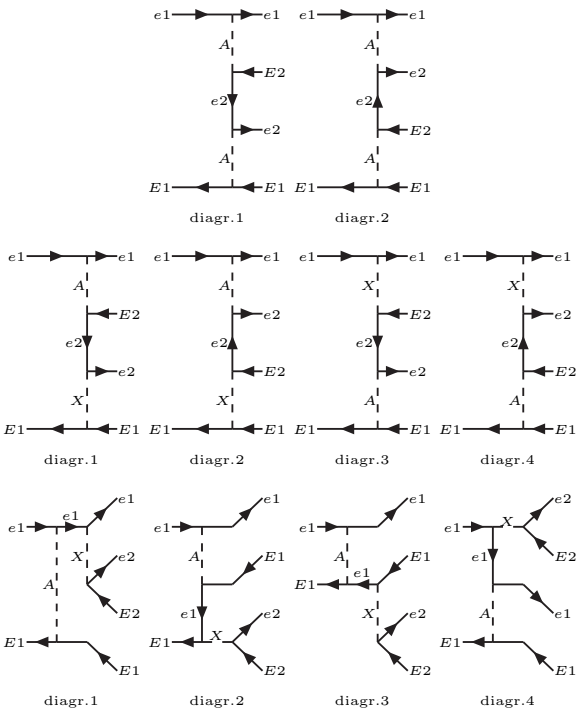

Figure 1: Subset of 10 t-channel diagrams for the process $e^+e^- \to e^+e^-\mu^+\mu^-$. SM diagrams are in the first row, in the second and third rows the X-particle exchange corresponds to some contact interaction.

2.2 Search strategies and kinematical cuts

Careful analysis is necessary in the Standard Model W and Higgs boson production for the definition of the signal versus the background in the four fermion final state [7]. Usually it is more difficult to separate the small signal of new physics, strongly restricted by the data from independent experiments, in the exclusive multiparticle final state. One can propose two contact terms search strategies. In the framework of the first strategy we impose loose kinematical cuts on the four fermion final state, the number of identifiable events is large enough, the contribution of the contact term in addition to the SM distribution is small, but the statistical error is also small and one can hope to observe a deviation from the SM cross section in the high statistics experiment. Especially interesting is the case if the interference of SM and $LL-$ defined amplitudes is large. In the framework of the second strategy we impose stringent kinematical cuts, the number of events is very small, but the contribution of the contact term in addition to the SM distribution can be large and one can hope to observe large deviation in the experiment with a small number of events. Generally speaking it is difficult to say in advance what strategy would be better.

For the first and second strategy we are using the following cuts:

Set I (Loose cuts):

muon pair mass cut $M(\mu^+\mu^-) \geq 30$, 60, 85 GeV (three cases)

final muon energy cut $E \geq 10$ GeV

final muon angle with the beams $\vartheta \geq 10$ degrees

Set II (Strong cuts):

muon pair mass cut $M(\mu^+\mu^-) \geq 30$, 60, 85 GeV (three cases)

electron pair mass cut $M(e^+e^-) \geq 3.16$ GeV

electrons angular cut with the beam $\vartheta \geq 10$ degrees

final lepton energy cut $E \geq 10$ GeV

Set I corresponds to "no-tag" experiment when the forward and backward electrons at very small

$\sigma(e^+e^- \to e^+e^-\mu^+\mu^-)$, pb, **set I** (loose cuts)			
$M(\mu\mu)$ cut (GeV)	30	60	85
SM	4.165	0.527	0.135
SM+$LL-$	4.180	0.535	0.142
deviation in %	0.4	1.5	4.9
N, see (2)	62500	4400	400
$\sigma(e^+e^- \to e^+e^-\mu^+\mu^-)$, pb, **set II** (strong cuts)			
$M(\mu\mu)$ cut (GeV)	30	60	85
SM	$1.4*10^{-2}$	$0.56*10^{-2}$	$0.24*10^{-2}$
SM+$LL-$	$1.6*10^{-2}$	$0.66*10^{-2}$	$0.29*10^{-2}$
deviation in %	14	18	21
N, see (2)	50	30	20

Table 1:

angles (less than 0.1 degree) in the dominant final state configuration are not detected.

2.3 Total cross sections and distributions

In the SM with $LL-$ contact term 110 tree level diagrams for the process $e^+e^- \to e^+e^-\mu^+\mu^-$ can be generated. In order to optimize the procedure of calculation we separate them into subsets. Each subset contains subgraph corresponding to (with in-(out-) particles taken on-shell) some gauge invariant process of lower order. Detailed description of this procedure can be found in [8]. We select the subset of two diagrams with t-channel photons (multiperipheral diagrams) in the SM case and for the case of contact terms we add to them eight diagrams with one t-channel photon and one contact interaction vertex (10 diagrams, see Fig.1). The contributions from these subsets are generally speaking not always dominant in the overall complete tree level set (under some conditions single resonant diagrams with Z boson in s-channel are not small), but usually about one order of magnitude larger than others.

The calculation of multiperipheral amplitudes containing t-channel photons is known to be very untrivial [9], especially in the case when no cuts are imposed on final electrons ("no-tag" experiment, total rate is finite because $m_e \neq 0$) and gauge cancellations between diagrams are extremely strong. We used CompHEP 3.2 [10] and tested the results by means of EXCALIBUR [11]. In CompHEP numerical stability of the double poles $1/t^2$ cancellation to single ones is preserved by using quadruple precision and special algorithms of phase space generation [12].

At the compositeness scale Λ =1 TeV and the energy $\sqrt{s} = 200$ GeV total cross sections in pb for the process $e^+e^- \to e^+e^-\mu^+\mu^-$ are shown in Table 1.

We used a very rough criteria (similar to criteria accepted in [6]) that the number of events N needed to observe the $\delta\sigma/\sigma$ fractional deviation from the SM cross section can be estimated by using the relation

$$\frac{\delta\sigma}{\sigma} \sim \frac{1}{\sqrt{N}} \tag{2}$$

i.e. N is of order inverse fractional deviation squared. It follows from the Table that at the optimistic LEP2 integrated luminosity 500 pb^{-1} the effect of $\Lambda = 1$ TeV $LL-$ contact term cannot be observed in the total rate. For instance, 21% effect in the case $M(\mu^+\mu^-) \geq 85$ GeV, set II, requires the identification of 20 events while at LEP II luminosity we have only one event per year.

As usual in this sitiation, we inspected the influence of contact terms on the shape of various distributions, hoping that in the distributions the effect could be much more pronounced if some phase space region is controlled strongly by contact interaction dynamics. We calculated and compared distributions over muon pair invariant mass $d\sigma/dM_{\mu\bar{\mu}}$, muon angle $d\sigma/d\vartheta_\mu$, muon transverse momentum $d\sigma/dp_{t\,\mu}$, and muon energy $d\sigma/dE_\mu$. In this set of distributions for all cases the $LL-$ term effect looks like rather uniform background not changing significantly in the whole physical region of the process. For instance, we show the distributions over muon angle in Fig.2. Their forward- backward structure is of course

completely different from the central structure of $2 \to 2$ body reaction $e^+e^- \to \mu^+\mu^-$ [5, 6] (where only partial wave with angular momentum zero contributes), but the shape of $2 \to 4$ body distribution $e^+e^- \to e^+e^-\mu^+\mu^-$ with contact term is similar to standard distribution.

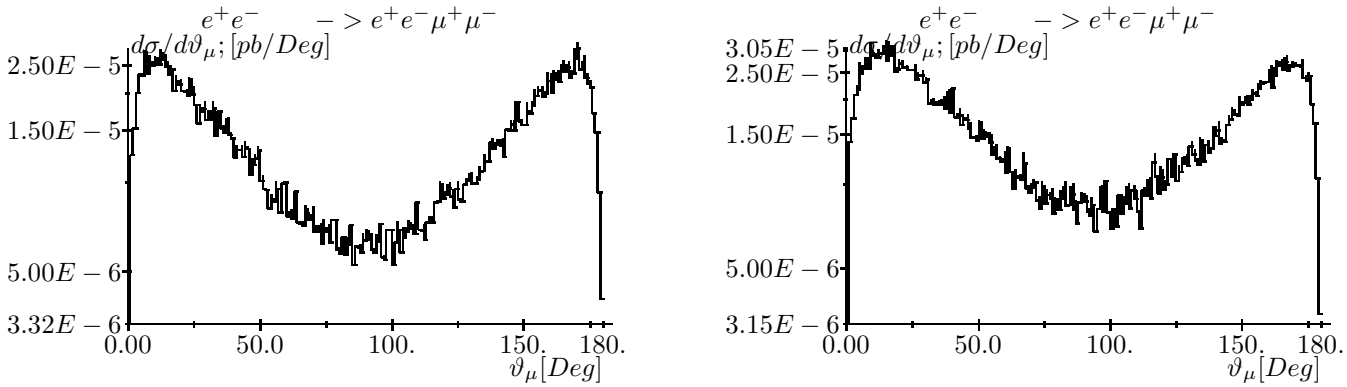

Figure 2: Left figure - $d\sigma/d\vartheta_\mu$, Standard Model, set II; right figure - $d\sigma/d\vartheta_\mu$, SM+$LL-$ contact term ($\Lambda = 1$ TeV, set II)

We calculated also the fractional deviations $d\sigma_{LL-}/d\sigma_{SM}$ for the cases of loose (set I) and strong (set II) cuts. The accuracy of our Monte Carlo (MC) calculation of the total rate is around 0.5%. The accuracy of distributions is quite satisfactory for the most important regions of the phase space (several percent in one bin). The error in the ratio of distributions is of course more sensitive to these statistical mistakes. Fig.3 shows that the accuracy of our MC is not sufficient to show the 0.4% effect in the ratio $(d\sigma_{LL-}/dM)/(d\sigma_{SM}/dM)$ for the case of loose cuts. Of course for practical purpose we do not need so precise calculation in so far as at LEP2 only 2000 events could be observed while 60000 are necessary (see Table 1). The effect of contact term could be clearly separated (Fig. 4) in the same ratio for the case of strong cuts (set II), but here we need the luminosity of order 10^4 pb^{-1} for experimental observation.

3 Distributions in the Standard Model with $LL-$ contact term for the process $e^-p \to e^-\mu^+\mu^-X$

In the case of deep inelastic scattering we are using the MRS parametrization of proton structure functions [13], developed on the basis of latest experimental data from HERA. Available parametrizations of proton structure functions can be used at the Q^2 scale sufficiently large, so the calculations for the process $e^-q \to e^-\mu^+\mu^-q$ were performed applying $|Q| = 3$ GeV cut for the momentum transferred from the constituent quark. Muon energy cut is equal to 10 GeV and we used 30 GeV for the muon pair invariant mass cut. For HERA ep collider the energy $\sqrt{s} = 314$ GeV, the electron-positron center of mass system is moving in the laboratory system with the rapidity $y = 1.654$ and the integrated luminosity at present time is several pb^{-1}.

initial state	eu	ed	$e\bar{u}$	ed	$es, e\bar{s}$	$ec, e\bar{c}$	total
SM	35.88	3.24	1.16	0.52	0.46	0.50	41.76
SM+$LL-$	36.19	3.25	1.17	0.52	0.47	0.50	42.10

Table 2: Total cross sections (fb) for partonic spieces in the process $e^-p \to e^-\mu^+\mu^-X$, $q = u, d, s, c$, $M(\mu^+\mu^-) \geq 30$ GeV, $\Lambda = 1$ TeV.

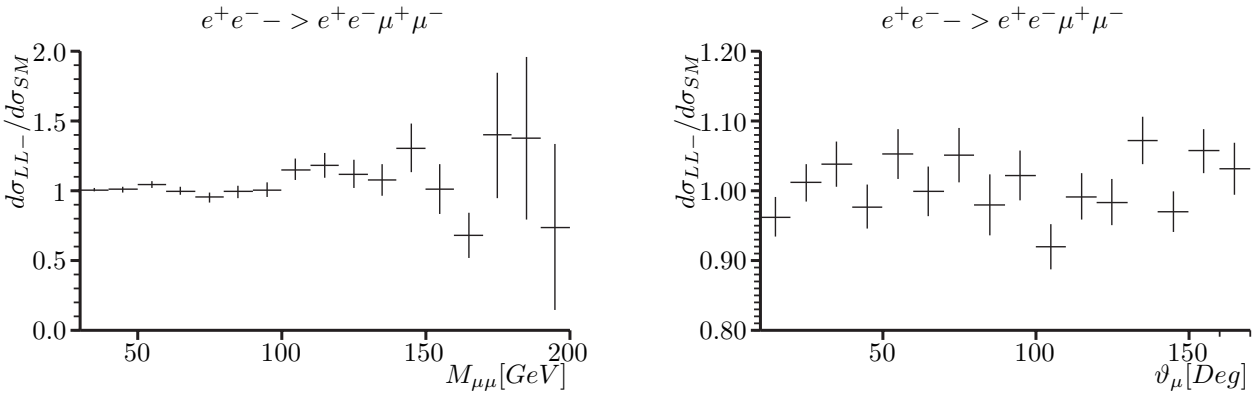

Figure 3: Left figure - ratio $d\sigma_{LL-}/d\sigma_{SM}$ for the muon pair invariant mass, $\Lambda = 1$ TeV, set I; right figure - ratio $d\sigma_{LL-}/d\sigma_{SM}$ for the muon pair angle, $\Lambda = 1$ TeV, set I. The error of Monte Carlo calculation in the ratio is indicated.

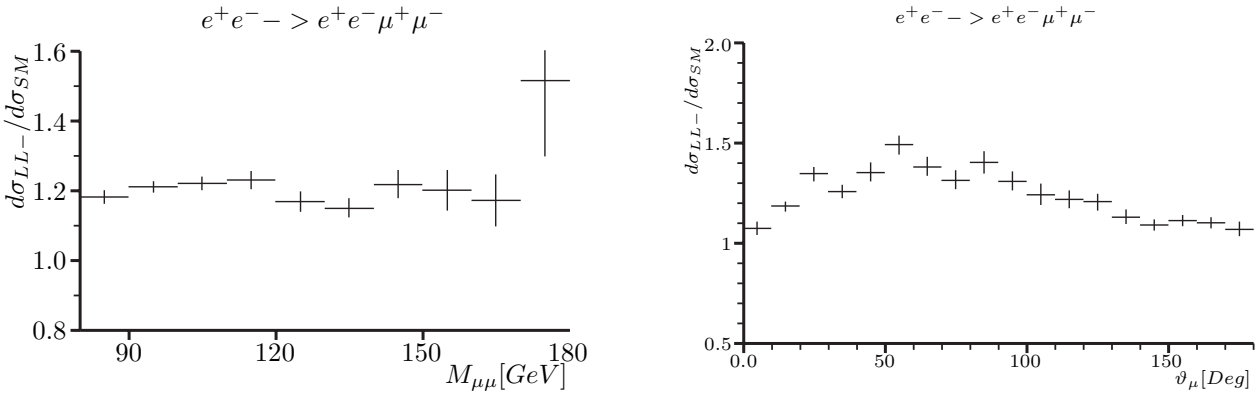

Figure 4: Left figure - ratio $d\sigma_{LL-}/d\sigma_{SM}$ for the muon pair invariant mass, $\Lambda = 1$ TeV, set II, right figure - ratio $d\sigma_{LL-}/d\sigma_{SM}$ for the muon angle, $\Lambda = 1$ TeV, set II. The error of Monte Carlo calculation in the ratio is indicated.

Total cross sections for valence and sea quarks are shown in Table 2. Similar to e^+e^- case with loose cuts (set I), the contribution of the contact term in ep scattering is very small. According to criteria (2) in order to observe the deviation in total rate of order 1% it is necessary to identify approximately 10^4 events, while even at upgraded high luminosity HERA ($L \sim 10^2\, pb^{-1}$) it would be possible to observe of order 10^1 events. We show the fractional deviations of the muon pair invariant mass distribution and muon angle distribution in Fig.5. In the distributions the effect is also practically unobservable.

4 Conclusion

We calculated the effect of $LL-$ contact term in the four-fermion channel $e^+e^- \to e^+e^-\mu^+\mu^-$ at the energy 200 GeV. Search strategies with loose and strong cuts imposed on the final state were considered.

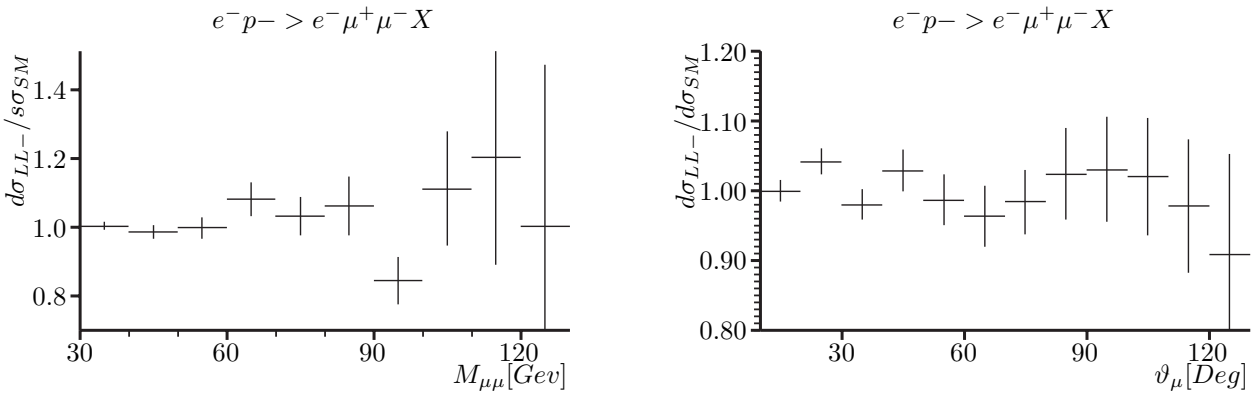

Figure 5: Left figure - ratio $d\sigma_{LL-}/d\sigma_{SM}$ for the muon pair invariant mass, $\Lambda = 1$ TeV; right figure - ratio $d\sigma_{LL-}/d\sigma_{SM}$ for the muon angle, $\Lambda = 1$ TeV.

In the case of loose cuts (set I) at the compositeness scale 1 TeV the difference in the total rates is around 1%. It would be hardly possible to observe the deviations from the SM in the distibutions. In the case of strong cuts (set II) the effect of contact terms is much more pronounced and is of order 20% in the total rate and could be clearly observed in the distributions, but the number of events at LEP2 luminosity of several hundred pb^{-1} is too small. Separation of the contact term is possible at the integrated luminosity of order 10 fb^{-1}.

The deviation from the SM distributions caused by contact terms is rather uniform and in all cases considered it looks like some bias of constant level in the whole physical region. At the compositeness scale 4 TeV the difference of SM and SM+$LL-$ distributions in the same four fermionic channel decreases approximately by one order of magnitude.

	σ_{tot} (pb) SM	deviation in σ_{tot}	deviation in $d\sigma/dcos\vartheta_\mu$
$e^+e^- \to \mu^+\mu^-$	3.0	about 300%	up to 300%
$e^+e^- \to e^+e^-\mu^+\mu^-$, set I	4.2	0.4%	negligible
$e^+e^- \to e^+e^-\mu^+\mu^-$, set II	2*10^{-2}	15%	up to 50%

Table 3: Typical deviations in the total rate and muon angular distribution of the reactions $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to e^+e^-\mu^+\mu^-$ caused by $LL-$ contact term at the energy $\sqrt{s} = 200$ GeV and compositeness scale $\Lambda = 1$ TeV. Muon pair mass $M_{\mu\mu} \geq 30$ GeV in the case of set I,II.

We calculated also the "four-fermion" channel $e^-q \to e^-\mu^+\mu^-q$ at the energy of HERA $\sqrt{s} = 314$ GeV. The effect of the contact term in the total rate at the compositeness scale 1 TeV is about 1%. Again, it would be hardly possible to observe any deviations from the SM distributions.

Four-fermion channel considered by us does not show new critical advantages over the possibilities of the compositeness search considered earlier [2]. We compare the magnitude of the effect for the reactions $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to e^+e^-\mu^+\mu^-$ in Table 3. The discovery potential of four-fermion reactions is critically dependent from the collider luminosity.

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