Study of extra space dimensions in vector boson pair production at LEP

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Recent theoretical scenarios propose that quantum gravity effects may manifest at LEP energies by means of gravitons that couple to standard model particles and propagate into extra space dimensions. These predictions are checked against the most recent experimental results on photon, *W*, and *Z* pair production. No deviations from the standard model expectations are found and limits of the order of 1 TeV on the scale of these models are set.

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I. INTRODUCTION

One of the great unsolved questions of contemporary physics is the wide difference between the scales of two fundamental interactions of nature, the gravitational and the electroweak. Denoting with G_N the gravitational constant it indeed follows that the Planck ($M_{\rm Pl}\sim G_N^{-1/2}\sim 10^{19}$ GeV) and the electroweak ($M_{\rm EW}\sim 10^2$ GeV) scales differ by seventeen orders of magnitude.

The standard model [1] (SM) successfully describes the electroweak interactions but leaves this difference unexplained. While the SM is tested by the present colliders at distances comparable to $M_{\rm EW}^{-1}$, the experimental knowledge of the gravitational force reach only distances around a centimeter [2], thirty three orders of magnitude above its characteristic distance $M_{\rm Pl}^{-1}$.

A recent theoretical scenario [3], proposes a modification of the present description of the gravitational force in this large unexplored domain. A scale M_S of the order of $M_{\rm EW}$ is postulated for quantum gravity, then referred to as low scale gravity (LSG). The known behavior of the gravitational force is recovered by the existence of n new space dimensions of size R such that

$$M_{\rm Pl}^2\sim R^n M_S^{n+2}. \tag{1.1}$$

A single extra dimension with $M_S\sim M_{\rm EW}$ is ruled out as it implies values of R comparable to the dimensions of the solar system. Two or more extra dimensions correspond to $R<0.1-1$ mm, in the unexplored regime of gravity. Severe limits are derived for $n=2$ from SN 1987A [4].

Spin two gravitons are predicted to propagate in $4+n$ dimensions and interact with SM particles with a sizeable strength. The effects of graviton exchange diagrams in vector boson pair production are predicted to be experimentally accessible [5,6] at the CERN e^+e^- collider LEP. Data collected by the four LEP experiments up to July 1999 on photon, *W*, and *Z* pair production are investigated to search for these effects.

II. $\gamma\gamma$ PRODUCTION

The four LEP experiments have studied [7,8] the differential distribution of $e^+e^-\to\gamma\gamma$ events collected above the Z pole to extract limits on the QED cutoff parameters Λ_+ and Λ_-. They are defined by an additional term in the $e^+e^-\to\gamma\gamma$ cross section [9]:

$$\frac{d\sigma(e^+e^-\to\gamma\gamma)}{d\cos\theta}=\frac{2\alpha^2\pi}{s}\frac{(1+\cos^2\theta)}{(1-\cos^2\theta)}\pm\frac{\alpha^2\pi s}{\Lambda_\pm^4}(1+\cos^2\theta), \tag{2.1}$$

θ is the polar photon production angle, s the square of the center-of-mass energy, and α the electromagnetic coupling.

No signals of deviation from QED are observed by any of the experiments that quote the 95% confidence level (C.L.) limits presented in Table I. These limits are obtained with a maximum likelihood fit to the distribution of $\cos\theta$ in data with Eq. (2.1) with $1/\Lambda_\pm^4$ as a free parameter. The limits Λ_+^{95} and Λ_-^{95} follow from the integration of the likelihood functions $\mathcal{L}$ over the physical region $1/\Lambda_\pm^4>0$:

$$\int_0^{\Lambda_+^{95}}\mathcal{L}(x)dx=0.95\int_0^{+\infty}\mathcal{L}(x)dx$$

and (2.2)

$$\int_{-\Lambda_-^{95}}^{0}\mathcal{L}(x)dx=0.95\int_{-\infty}^{0}\mathcal{L}(x)dx.$$

The investigated data samples are large enough to expect a normal distribution of the likelihood functions. Hence Eqs.

TABLE I. Reported limits on the QED cutoff parameters Λ_+ and Λ_- at 95% C.L.

Experiment	$\sqrt{s}$ (GeV)	Λ_+ (GeV)	Λ_- (GeV)
ALEPH	189	269	308
ALEPH	161–183	270	230
DELPHI	130–189	284	278
L3	130–196	323	294
OPAL	183–196	271	331
OPAL	130–172	195	210

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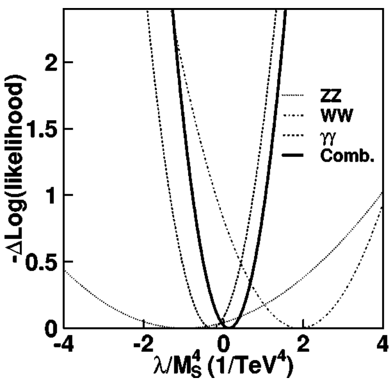

FIG. 1. Difference with respect to the minimum of the negative logarithm of the individual and combined likelihood functions in terms of λ/M_S^4.

(2.2) can be solved numerically for each of the pair of entries of Table I inferring the original likelihood functions. As a cross check, limits on Λ_+ and Λ_- for each of the data samples are derived from the inferred likelihood functions and found to be in agreement with those in Table I within all the quoted digits.

A combined likelihood function is built from the sum of the individual inferred ones. It shows no deviations from the QED expectations and yields the following limits at 95% C.L.:

$$\Lambda_+ > 343 \text{ GeV}, \quad \Lambda_- > 367 \text{ GeV},$$

these limits improve all those reported by the single collaborations.

The differential cross section for photon pair production in e^+e^- collisions is modified by *s*-channel graviton exchange [5,6]. From the formula in Ref. [6] it follows:

$$\frac{d\sigma(e^+e^-\to\gamma\gamma)}{d\cos\theta} = \frac{2\alpha^2\pi}{s}\frac{(1+\cos^2\theta)}{(1-\cos^2\theta)} - \frac{\alpha\lambda s}{M_S^4}(1+\cos^2\theta) + \frac{\lambda^2 s^3}{8\pi M_S^8}(1+\cos^2\theta)(1-\cos^2\theta). \quad (2.3)$$

The LSG contributions are weighted by a factor λ [10] that include the dependence on the full theory. In the following $\lambda = \pm 1$ is chosen to allow for the different signs of the interference. The pure gravitational part in the third term never exceeds 1% of the second term, the interference one, and can be neglected. From a comparison of Eqs. (2.3) and (2.1) it then follows:

$$-\frac{\lambda}{M_S^4} = \pm\frac{\pi\alpha}{\Lambda_\pm^4}.$$

The combined likelihood function described above can therefore be translated in terms of λ/M_S^4. Figure 1 displays this likelihood function that agrees with the SM expectations. Limits on the scale M_S of LSG are then extracted as listed in Table II. A similar analysis based on a reduced data sample is described in Ref. [11].

TABLE II. Lower limits on M_S at 95% C.L.

Process	$\lambda=-1$ M_S (TeV)	$\lambda=+1$ M_S (TeV)
$e^+e^-\to\gamma\gamma$	0.88	0.94
$e^+e^-\to W^+W^-$	0.85	0.68
$e^+e^-\to ZZ$	0.62	0.63
Combined	0.96	0.93

III. W^+W^- PRODUCTION

Since 1996 LEP is running above the *W* pair production threshold. The combined [12] results of the four experiments for the $e^+e^-\to W^+W^-$ cross section at different $\sqrt{s}$ are reported in Table III. SM prediction obtained with the KORALW [13] Monte Carlo program are also listed.

The LSG contributions to *W* pair is described at Born level in Ref. [6]. To take into account higher order corrections the following procedure is applied. First the SM $e^+e^-\to W^+W^-$ cross section is calculated from the Born level amplitudes [14]. Then a correction factor $\mathcal{A}$ is calculated as the ratio of the KORALW cross section to this Born level calculation at different energies. The values of $\mathcal{A}$ are reported in Table III. This correction factor is assumed to hold for LSG diagrams as well.

The $e^+e^-\to W^+W^-$ cross section in the presence of LSG is calculated from the matrix elements [6,14] and multiplied by $\mathcal{A}$. From the comparison of this value with data at the different energies a likelihood function is built. It takes into account the experimental uncertainties quoted in Table III and a 2% uncertainty on the theoretical treatment of the initial state radiation. This likelihood function is displayed in Fig. 1 in terms of λ/M_S^4 and shows no significant deviations from the SM. Lower limits on M_S are derived by integrating the likelihood over the physical region and are summarized in Table II.

The sensitivity of the *WW* channel to LSG effects is limited by the initial state radiation error. In the hypothesis of its reduction to 0.5% [15] the tightest of these limits would improve to 0.99 TeV.

IV. *ZZ* PRODUCTION

In 1997 the pair production of *Z* bosons became accessible at LEP. The four collaborations reported a combined

TABLE III. Measured and expected *W* pair production cross sections at the different LEP energies. Correction factors to Born level calculations are also given.

s (GeV)	$\sigma(e^+e^-\to W^+W^-)$ (pb)	$\sigma^{\rm SM}(e^+e^-\to W^+W^-)$ (pb)	$\mathcal{A}$
172	12.0 ± 0.7	12.40	0.82
183	15.83 ± 0.36	15.70	0.89
189	16.05 ± 0.22	16.65	0.92
192	16.5 ± 0.5	16.97	0.93
196	17.2 ± 0.5	17.28	0.95

measured cross section of 0.17 ± 0.09 pb at $\sqrt{s}=183$ GeV and 0.70 ± 0.08 pb at $\sqrt{s}=189$ GeV [16]. The SM predictions are 0.26 pb and 0.65 pb respectively, as calculated with YFSZZ [17].

The LSG matrix element for Z pair production is similar to the W pair one [6]. The same procedure described above is used to extract limits on M_S. The values of the correction factor $\mathcal{A}$ to the Born level predictions for the $e^+e^-\rightarrow ZZ$ cross sections with respect to the YFSZZ ones are 1.12 and 0.80 at 183 GeV and 189 GeV, respectively.

Figure 1 presents the likelihood function used to determine the limits in Table II. The impact of the theory uncertainty in this channel is negligible when compared to the experimental one.

V. COMBINED RESULTS

The results described so far can be compared and combined under the hypotheses that no higher order operators contribute to Eq. (2.3) and to the LSG ZZ and WW matrix elements and that both the meaning of M_S and the value of λ are the same for all the investigated channels. Being the full LSG theory unknown, caution should be exercised for this last hypothesis. The three likelihood functions described above are then added and the combined likelihood function is found to be in agreement with the SM predictions as shown in Fig. 1. Lower limits on M_S at 95% C.L. can be derived as 0.92 and 0.96 TeV for $\lambda=+1$ and $\lambda=-1$, respectively. The second of this limits does not improve the $e^+e^-\rightarrow\gamma\gamma$ one as the effect of the $e^+e^-\rightarrow W^+W^-$ likelihood is to shift the combined maximum toward higher values without a major narrowing of its width.

The LEP data on Bhabha scattering were also recently analyzed in terms of possible LSG contributions [18]. The original likelihood is inferred from the quoted limits with the same procedure used for the $e^+e^-\rightarrow\gamma\gamma$ process and is added to the combined likelihood described above. The $\lambda=-1$ 95% C.L. lower limit on M_S reads then 1.01 TeV, improving the limits of both the boson and Bhabha analyses. The $\lambda=+1$ limit derived from the Bhabha scattering dominates this combination that does not improve it.

In conclusion the first limits on LSG from combined LEP data for all vector boson pair production processes are derived, improving those reported by the single collaborations [8,19]. A combined analysis of boson and fermion pairs improves the sensitivity to LSG effects.

[1] S. L. Glashow, Nucl. Phys. **22**, 579 (1961); A. Salam, in *Elementary Particle Theory: Relativistic Groups and Analyticity (Nobel Symposium No. 8)*, edited by N. Svartholm (Almqvist and Wiksell, Stockholm, 1968), p. 367; S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967).
[2] J. C. Long *et al.*, Nucl. Phys. **B539**, 23 (1999).
[3] N. Arkani-Hamed *et al.*, Phys. Lett. B **429**, 263 (1999).
[4] N. Arkani-Hamed *et al.*, Phys. Rev. D **59**, 086004 (1999).
[5] G. F. Giudice *et al.*, Nucl. Phys. **B544**, 3 (1999).
[6] K. Agashe and N. G. Deshpande, Phys. Lett. B **456**, 60 (1999).
[7] ALEPH Collaboration, R. Barate *et al.*, Contributed paper No. 6_429 to the EPS-HEP99, Tampere, Finland, 1999; Phys. Lett. B **429**, 201 (1998); DELPHI Collaboration, P. Abreu *et al.*, Contributed paper No. 6_364 to the EPS-HEP99, Tampere, Finland, 1999; L3 Collaboration, M. Acciarri *et al.*, Contributed paper No. 7_233 to the EPS-HEP99, Tampere, Finland, 1999.
[8] OPAL Collaboration, K. Ackerstaff *et al.*, Contributed paper No. 1_80 To The EPS-HEP99, Tampere, Finland, 1999; Eur. Phys. J. C **1**, 21 (1998).
[9] F. E. Low, Phys. Rev. Lett. **14**, 238 (1965); R. P. Feynman, Phys. Rev. **74**, 939 (1948); F. M. Renard, Phys. Lett. **116B**, 264 (1982); S. Drell, Ann. Phys. (N.Y.) **4**, 75 (1958).
[10] J. Hewett, Phys. Rev. Lett. **82**, 4765 (1999).
[11] K. Cheung, Phys. Rev. D **61**, 015005 (2000).
[12] The LEP Electroweak Working Group, D. Abbaneo *et al.*, Report No. CERN-EP/99-15 (unpublished); F. Cavallari, to appear in the proceedings of the XXXIVth Rencontres de Moriond, Electroweak Interactions and Unified Theories, 1999; A. Barczyk, to appear in the proceedings of the EPS-HEP99 Tampere, Finland, 1999.
[13] M. Skrzypek *et al.*, Comput. Phys. Commun. **94**, 216 (1996); M. Skrzypek *et al.*, Phys. Lett. B **372**, 289 (1996).
[14] W. Beenaker and A. Denner, Int. J. Mod. Phys. A **9**, 4837 (1994).
[15] A. Ballestrero, to appear in the proceedings of the EPS-HEP99 Tampere, Finland, 1999.
[16] E. Sanchez, to appear in the proceedings of the EPS-HEP99 Tampere, Finland, 1999.
[17] S. Jadach *et al.*, Phys. Rev. D **56**, 6939 (1997).
[18] D. Bourilkov, J. High Energy Phys. **08**, 006 (1999).
[19] ALEPH Collaboration, R. Barate *et al.*, Contributed paper No. 7_252 to the EPS-HEP99; L3 Collaboration, M. Acciarri *et al.*, Contributed paper No. 7_233 to the EPS-HEP99; OPAL Collaboration, G. Abbiendi *et al.*, Report No. CERN-EP/99-088; Report No. CERN-EP/99-097.