Search for Low Scale Gravity Effects in e^+e^- Collisions at LEP

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Abstract

Recent theories propose that quantum gravity effects may be observable at LEP energies via gravitons that couple to Standard Model particles and propagate into extra spatial dimensions. The associated production of a graviton and a photon is searched for as well as the effects of virtual graviton exchange in the processes: $e^+e^- \rightarrow \gamma\gamma$, ZZ, W^+W^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$ and e^+e^-. No evidence for this new interaction is found in the data sample collected by the L3 detector at LEP at centre–of–mass energies up to 183 GeV. Limits close to 1 TeV on the scale of this new scenario of quantum gravity are set.

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1 Introduction

Two of the fundamental interactions of nature, the gravitational and the electroweak, have widely differing characteristic scales, namely the Planck ($M_{Pl} \sim 10^{19}$ GeV) and the electroweak ($M_{ew} \sim 10^2$ GeV). The Standard Model [1] (SM) successfully describes the electroweak interactions but leaves unexplained the difference between these two scales. While electroweak interactions are probed at distances of the order of M_{ew}^{-1}, the gravitational force is studied only down to distances of the order of a centimetre [2], thirty three orders of magnitude above its characteristic distance M_{Pl}^{-1}.

A recent theoretical scenario [3] proposes a modification of the present understanding of the gravitational force interpreting a single scale, M_{ew}, as the only fundamental one of nature. The known and tested behaviour of the gravitational force is accomodated by the existence of δ new space dimensions of size R such that for the new scale of gravity, M_D, the following relation holds:

$$M_{Pl}^2 \sim R^\delta M_D^{\delta+2}. \quad (1)$$

A single extra dimension, $\delta = 1$, with $M_D \sim M_{ew}$ implies values of R comparable to the dimensions of the solar system, which is not allowed by the experimental knowledge of the gravitational force, while starting from $\delta = 2$ the corresponding dimensions of $0.1 - 1\,\mathrm{mm}$ and below have yet to be investigated[1)].

A consequence of this picture are spin 2 gravitons, G, that propagate in $4 + \delta$ dimensions, interacting with SM particles in the ordinary 4 dimensions with a sizeable strength, related to M_D^{-1}. This new interaction is also referred to as Low Scale Gravity (LSG).

The associated production of a real graviton and a photon is searched for as well as the effects of virtual graviton exchange in gauge boson or fermion pair production. Data collected in 1997 by the L3 detector [5] in $\mathrm{e^+e^-}$ collisions at an average centre–of–mass energy $\sqrt{s} = 182.7$ GeV denoted hereafter as 183 GeV are analysed. Data samples at $\sqrt{s}$ between 130 GeV and 172 GeV are also considered for the $\gamma\gamma$ and $\mathrm{q\bar{q}}$ final states. Some of these channels are also investigated in Reference [6].

2 Real graviton production

Real gravitons can be produced at LEP via the process $\mathrm{e^+e^-} \to \gamma G$ and emitted in the extra dimensions carrying away energy. This process manifests itself through an enhancement of the single photon cross section and a modification of the expected energy and polar angle distributions of the detected photons [7, 8]. The differential cross section of this process, as a function of the fraction x_γ of the beam energy taken by the photon and its polar emission angle θ relative to the beam, is given by [7]:

$$\frac{d^2\sigma(\mathrm{e^+e^-} \to \gamma G)}{dx_\gamma d\cos\theta} = \frac{\alpha}{64}\, S_{\delta-1} \left(\frac{\sqrt{s}}{M_D}\right)^{\delta+2} \frac{1}{s} f(x_\gamma, \cos\theta, \delta), \quad (2)$$

where α is the QED coupling, chosen as $\alpha(\sqrt{s})$, the function $f(x, y, k)$ is given by:

$$f(x, y, k) = \frac{2(1-x)^{\frac{k}{2}-1}}{x(1-y^2)} \left[(2-x)^2(1-x+x^2) - 3y^2x^2(1-x) - y^4x^4\right], \quad (3)$$

1) Severe limits on the $\delta = 2$ scenario are derived from SN1987A [4], nonetheless a direct and complementary collider limit is desirable.

and for $\delta = 2n$ and n integer, $S_{\delta-1} = 2\pi^n/(n-1)!$, while for $\delta = 2n+1$, $S_{\delta-1} = 2\pi^n/\Pi_{k=0}^{n-1}(k+\frac{1}{2})$.

Single photon events are selected at 183 GeV for an integrated luminosity of 55.3 pb^{-1} [9]. They are characterised by missing energy and at least one detected photon of energy greater than 4 GeV and polar angle above 14°. A minimal transverse momentum of 5 GeV is required for the photons whose energy is greater than 5 GeV, this cut being reduced to 2.7 GeV otherwise. The efficiency for a LSG signal is derived on a $x_\gamma - \cos\theta$ grid from the KORALZ [10] $\mathrm{e^+e^-} \rightarrow \nu\bar{\nu}\gamma(\gamma)$ Monte Carlo. Table 1 reports the efficiencies as a function of δ for a signal within the described experimental energy and angular limits. The x_γ spectrum expected from γG production and the SM is then compared with data to derive upper limits at 95% confidence level (CL) on the cross section of this process ($\sigma_{\gamma G}^{\mathrm{lim}}$) and subsequently lower limits on M_D following a Bayesian approach. These limits are listed in Table 1 as a function of δ. Figure 1 shows the x_γ spectra for data and SM Monte Carlo together with the modification expected from LSG with $M_D = 400$ GeV and $\delta = 6$.

δ	2	3	4	5	6	7	8	9	10
ε (%)	43.4	41.4	39.7	38.3	37.1	36.1	35.2	34.5	33.8
$\sigma_{\gamma G}^{\mathrm{lim}}$ (pb)	0.79	0.76	0.73	0.72	0.70	0.69	0.68	0.67	0.66
M_D (GeV)	945	769	644	555	489	439	399	367	340

Table 1: Detection efficiencies for the real graviton plus photon signal, upper limit at 95 % CL on its cross section and lower limit on the scale M_D as a function of the number of extra dimensions.

3 Virtual graviton effects

The production of $\gamma\gamma$, ZZ, $\mathrm{W^+W^-}$, $\mu^+\mu^-$ $\tau^+\tau^-$, $\mathrm{q\bar{q}}$ and $\mathrm{e^+e^-}$ via a virtual graviton and its interference with the SM description of those processes can be analysed in term of the LSG cutoff energy, M_S[2)], expected to be of the order of M_D [7]. In the following radiative corrections to SM and LSG processes are assumed to factorize.

3.1 The $\mathrm{e^+e^-} \rightarrow \gamma\gamma$ process

The differential cross section for photon pair production in $\mathrm{e^+e^-}$ collisions is modified by $s-$channel graviton exchange as [7, 12]:

$$\frac{d\sigma(\mathrm{e^+e^-} \rightarrow \gamma\gamma)}{d\cos\theta} = \frac{\pi}{s}\left[\alpha F_1\left(-\sin^2\frac{\theta}{2}\right) - \lambda\frac{4s^2}{\pi M_S^4}F_2\left(-\sin^2\frac{\theta}{2}\right)\right]^2, \quad (4)$$

where:

$$F_1(x) = \sqrt{\frac{1+2x+2x^2}{-x(1+x)}}, \text{ and } F_2(x) = \sqrt{\frac{-x(1+x)(1+2x+2x^2)}{16}}, \quad (5)$$

and the angle θ is the photon emission angle with respect to the beam axis. The LSG contribution is weighted by a further factor λ [11], which incorporates other possible model dependences. It is chosen as ±1 in the following to allow for different signs in the interference.

2)The M_S used here corresponds to the one of [11], and is related to the Λ_T cutoff of [7] by $\Lambda_T = (\pi/2)^{1/4}M_S$.

The process $e^+e^- \to \gamma\gamma$ is investigated at $\sqrt{s} = 130$ GeV $-$ 140 GeV [13], $\sqrt{s} = 161$ GeV $-$ 172 GeV [14] and $\sqrt{s} = 183$ GeV [15]. Figure 2a shows the distribution of the polar angle of the events selected in this total sample. A fit to this distribution for each energy point with the relation (4) yields the likelihood curve presented in Figure 3 as a function of λ/M_S^4. This result is compatible with SM predictions and allows the extraction of a 95 % CL limit on M_S of 630 GeV for $\lambda = +1$ and 670 GeV for $\lambda = -1$, by integrating the likelihood over the physical region of positive M_S^4. These limits are unaffected by the estimated 1% systematic uncertainty on the measured differential cross section. In this and in the following fits, the background dependence on LSG effects is negligible.

3.2 The $e^+e^- \to ZZ$ process

The contribution of virtual graviton exchange to the pair production of Z bosons is given in Reference [12]. The total cross section of this process at $\sqrt{s} = 183$ GeV is expected to change by 43% for M_S equal to 500 GeV.

The same distributions used to derive limits [16] on the triple neutral gauge boson anomalous couplings $f_{4,5}^{Z,\gamma}$ are used to investigate possible LSG contributions to this process. The EXCALIBUR Monte Carlo program [17] is modified to include the matrix element for graviton exchange [12]. Monte Carlo events are then reweighted as a function of λ/M_S^4 and compared to data yielding the likelihood curve presented in Figure 3. No deviations from the SM are observed, giving 95 % CL limits on M_S of 470 GeV and 460 GeV for $\lambda = +1$ and $\lambda = -1$ respectively. Systematic effects are found to be negligible.

3.3 The $e^+e^- \to W^+W^-$ process

The LSG contributions to W pair production modify the differential cross section [12]. The polar angle of the emitted W^- boson for semileptonic and hadronic decays of the W pair is studied [18]. The Monte Carlo events are reweighted to model LSG effects using a modified version of the EXCALIBUR Monte Carlo program which includes the virtual graviton exchange matrix element [12] as a function of λ/M_S^4. Only the effects for the double–resonant processes are taken into account. A 5% correction is applied for other diagrams for the semileptonic electron final states. Figure 2b presents the $\cos\theta$ distributions for data, background and reconstructed $e^+e^- \to W^+W^- \to \ell\nu_\ell q\bar{q}'$ events as expected from the SM Monte Carlo alone and with the addition of LSG effects.

Separate fits are performed on the reconstructed $\cos\theta$ distributions for each of the three semileptonic classes of events and the hadronic one. The combined likelihood curve is plotted in Figure 3. This curve is compatible with the hypothesis of no contribution from extra dimensions to the $e^+e^- \to W^+W^-$ process and 95% CL limits on M_S can thus be extracted as 650 GeV if $\lambda = +1$ and 520 GeV if $\lambda = -1$. This procedure takes into account 7% experimental and 2% theoretical systematic uncertainties on the total cross section.

3.4 The $e^+e^- \to f\bar{f}$ process

The effect of the s–channel graviton exchange in fermion pair production other than Bhabha scattering is described in References [7,11]. In the massless fermion limit the formula reads [11]:

$$\frac{d\sigma(e^+e^- \to f\bar{f})}{d\cos\theta} = \frac{d\sigma^{SM}(e^+e^- \to f\bar{f})}{d\cos\theta} + \frac{N_c \alpha s \lambda}{4M_S^4}$$

$$
\begin{aligned}
&\times \left\{2Q_eQ_f\cos^3\theta + \frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\left[(2v_ev_f\cos^3\theta - a_ea_f(1-3\cos^2\theta)\right]\right\} \\
&+ \frac{N_c s^3\lambda^2}{32\pi M_S^8}(1-3\cos^2\theta+4\cos^4\theta), \qquad (6)
\end{aligned}
$$

where θ is the fermion production angle with respect to the incoming electron, Q_i, a_i and v_i are the charge, axial and vector couplings of the fermion i, Γ_Z and M_Z stand for the Z width and mass and N_c is the number of colours of the fermion f. The first term is the SM cross section which is calculated with ZFITTER [19].

Full energy muon and tau pairs are selected at $\sqrt{s} = 183$ GeV [20]. The polar angle distribution of the identified negative charged lepton is compared in Figures 2c and 2d with Monte Carlo events simulated with KORALZ. The LSG effects are included by reweighting. The expected effects for $\lambda = \pm 1$ and $M_S = 450$ GeV are also presented in Figures 2c and 2d.

From the muon distribution 95% CL lower limits on M_S are derived as 550 GeV and 490 GeV for $\lambda = +1$ and $\lambda = -1$, respectively. The investigation of tau pairs yields the corresponding limits of 510 GeV and 460 GeV at 95% CL. The experimental and theoretical systematic uncertainties on the total cross sections amount to 2.4% for muons and 3.5% for taus. They are included in the derivation of the limit.

For the $\mathrm{q\bar{q}}$ final states only the integrated cross section is investigated, where the higher sensitivity interference term proportional to $1/M_S^4$ vanishes, leaving the $1/M_S^8$ factor of the pure graviton exchange. The samples collected for full energy $\mathrm{q\bar{q}}$ final states at $\sqrt{s}$ of 130 GeV – 136 GeV [21], 161 GeV – 172 GeV [22] and 183 GeV [20] are studied. The large statistics, the enhancement due to the colour factor and the sum over five flavours, allow to set lower limits on M_S as high as 490 GeV at 95% CL, independent of the sign of λ. A systematic uncertainty of 1.4% is included in the limit calculation.

For Bhabha scattering the differential cross section in presence of LSG is [7,23]:

$$
\begin{aligned}
\frac{d\sigma(\mathrm{e^+e^-\to e^+e^-})}{d\cos\theta} &= \frac{d\sigma^{SM}(\mathrm{e^+e^-\to e^+e^-})}{d\cos\theta} - \frac{\alpha\lambda}{2sM_S^4} \\
&\times \left\{\mathcal{F}_1(s,t) + \frac{v_e^2\mathcal{F}_2(s,t)+a_e^2\mathcal{F}_3(s,t)}{s-M_Z^2} + \frac{v_e^2\mathcal{F}_2(t,s)+a_e^2\mathcal{F}_3(t,s)}{t-M_Z^2}\right\} \\
&+ \frac{\lambda^2}{16\pi s M_S^8}\mathcal{F}_4(s,t), \qquad (7)
\end{aligned}
$$

where the functions $\mathcal{F}_i$ of s and t are written as:

$$
\begin{aligned}
\mathcal{F}_1(s,t) &= 9\left(s^3/t + t^3/s\right) + 23(s^2+t^2) + 30st\,, \\
\mathcal{F}_2(s,t) &= 5s^3 + 10s^2t + 18st^2 + 9t^3\,, \\
\mathcal{F}_3(s,t) &= 5s^3 + 15s^2t + 12st^2 + t^3\,, \\
\mathcal{F}_4(s,t) &= 41(s^4+t^4) + 124st(s^2+t^2) + 148s^2t^2\,. \qquad (8)
\end{aligned}
$$

The differential cross section for Bhabha scattering at 183 GeV for full energy events between 44° and 136° of polar angle [20] is compared with equation (7). The first term of this equation represents the SM predictions, calculated using the BHWIDE [24] Monte Carlo and normalised to the TOPAZ0 [25] semi–analytical calculation. This yields limits on M_S of 810 GeV and 720 GeV at 95% CL for $\lambda = +1$ and $\lambda = -1$, respectively. Experimental and theoretical systematic uncertainties are included in the fit and amount in total to 3.7%. Figure 4 shows the measured and expected SM differential cross sections and their differences, together with the LSG predictions.

A simultaneous fit to all the fermion pair channels improves the $\lambda = +1$ limit to 820 GeV. The likelihood curve of this combined fit is displayed in Figure 3 as a function of λ/M_S^4.

3.5 Combined Results

Assuming that no higher order operators give sizeable contributions to the Equations (4), (6) and (7), and to the LSG ZZ and W^+W^- matrix elements and that the meaning of the cutoff parameter is the same for all the investigated processes, it is possible to combine the likelihood curves obtained for all pair production processes into a single one, also displayed in Figure 3.

No indication of the contribution of virtual graviton exchange is found and lower limits at 95% CL on the value of the scale M_S are derived as 860 GeV for $\lambda = +1$ and 740 GeV for $\lambda = -1$. The individual and combined limits are summarised in Table 2.

Process	M_S (GeV) $\lambda = +1$	M_S (GeV) $\lambda = -1$
$e^+e^- \rightarrow \gamma\gamma$	630	670
$e^+e^- \rightarrow ZZ$	470	460
$e^+e^- \rightarrow W^+W^-$	650	520
Bosons Combined	700	670
$e^+e^- \rightarrow q\bar{q}$	490	490
$e^+e^- \rightarrow e^+e^-$	810	720
$e^+e^- \rightarrow \mu^+\mu^-$	550	490
$e^+e^- \rightarrow \tau^+\tau^-$	510	460
Fermions Combined	820	720
Bosons + Fermions	860	740

Table 2: Lower limits at 95 % CL on the cutoff M_S for different processes and values of λ. Combined results are also given.

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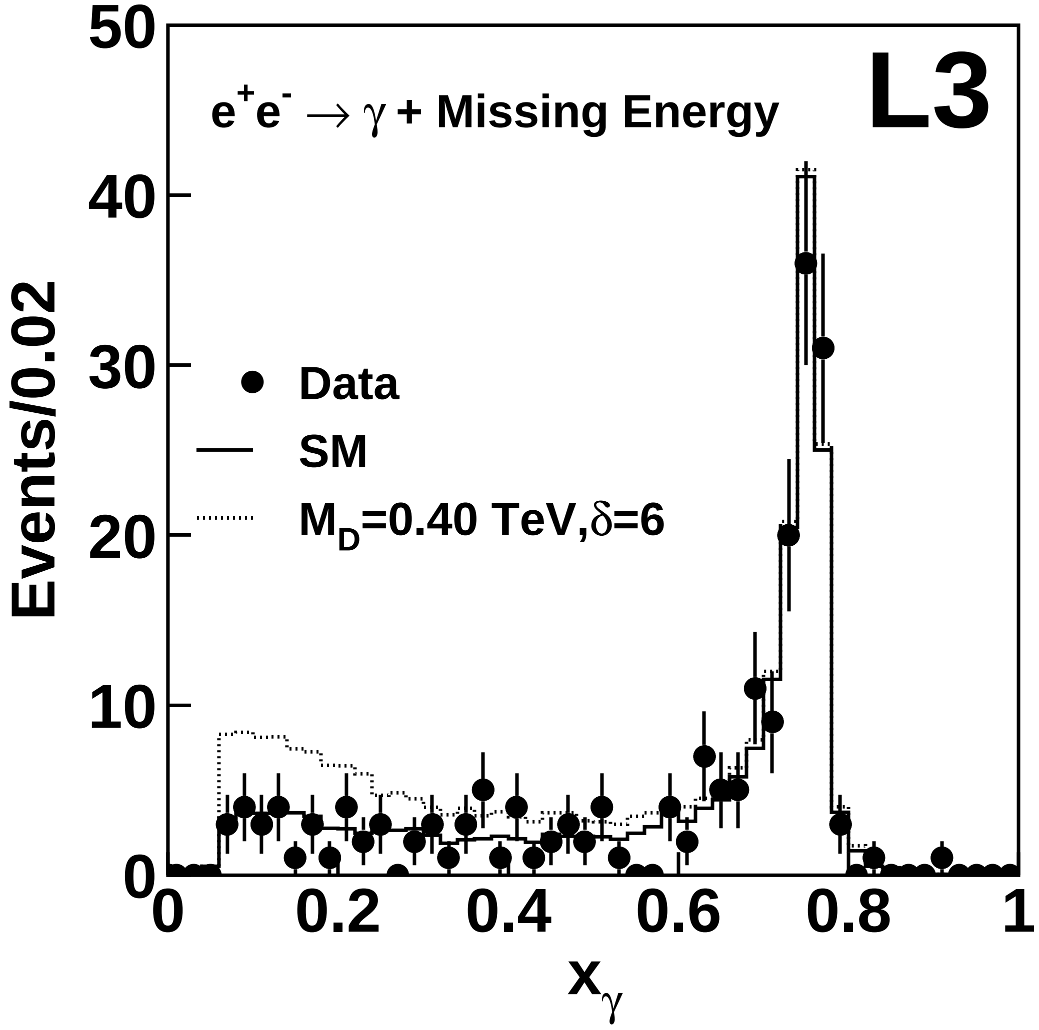

Figure 1: Distribution of ratio of the photon energy to the beam energy for single photon events in data at $\sqrt{s} = 183$ GeV together with SM expectations. The effect of real graviton production with six extra space dimensions and $M_D = 0.4$ TeV is also shown.

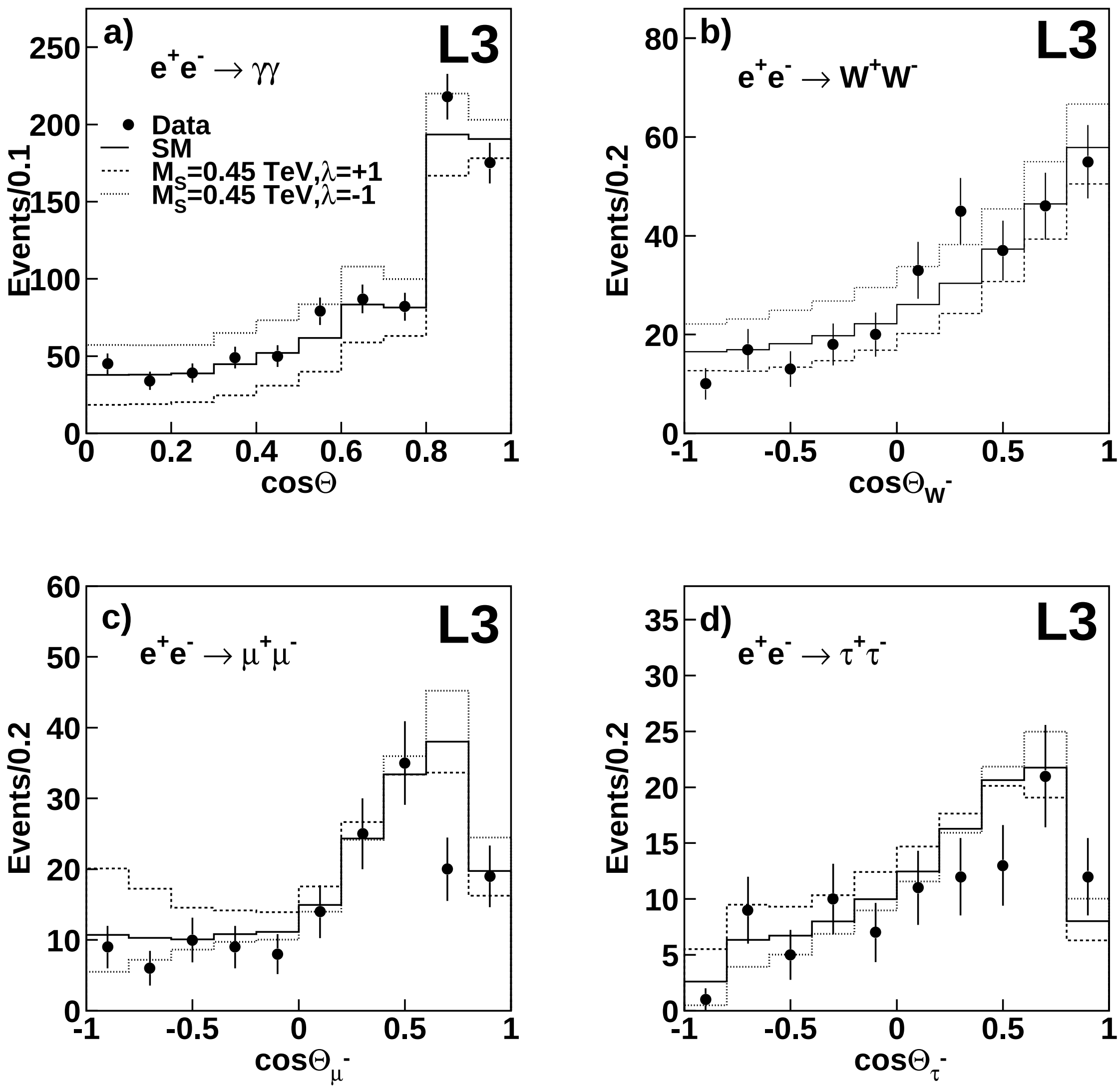

Figure 2: Distributions of the polar angle for: (a) $e^+e^- \to \gamma\gamma$ events selected at $\sqrt{s} = 130 - 183$ GeV, (b) semileptonic $e^+e^- \to W^+W^-$ events, (c) $e^+e^- \to \mu^+\mu^-$ and (d) $e^+e^- \to \tau^+\tau^-$ processes. The last three plots refer to the $\sqrt{s} = 183$ GeV data sample only. Data, SM expectations and LSG effects for $M_S = 0.45$ TeV are shown.

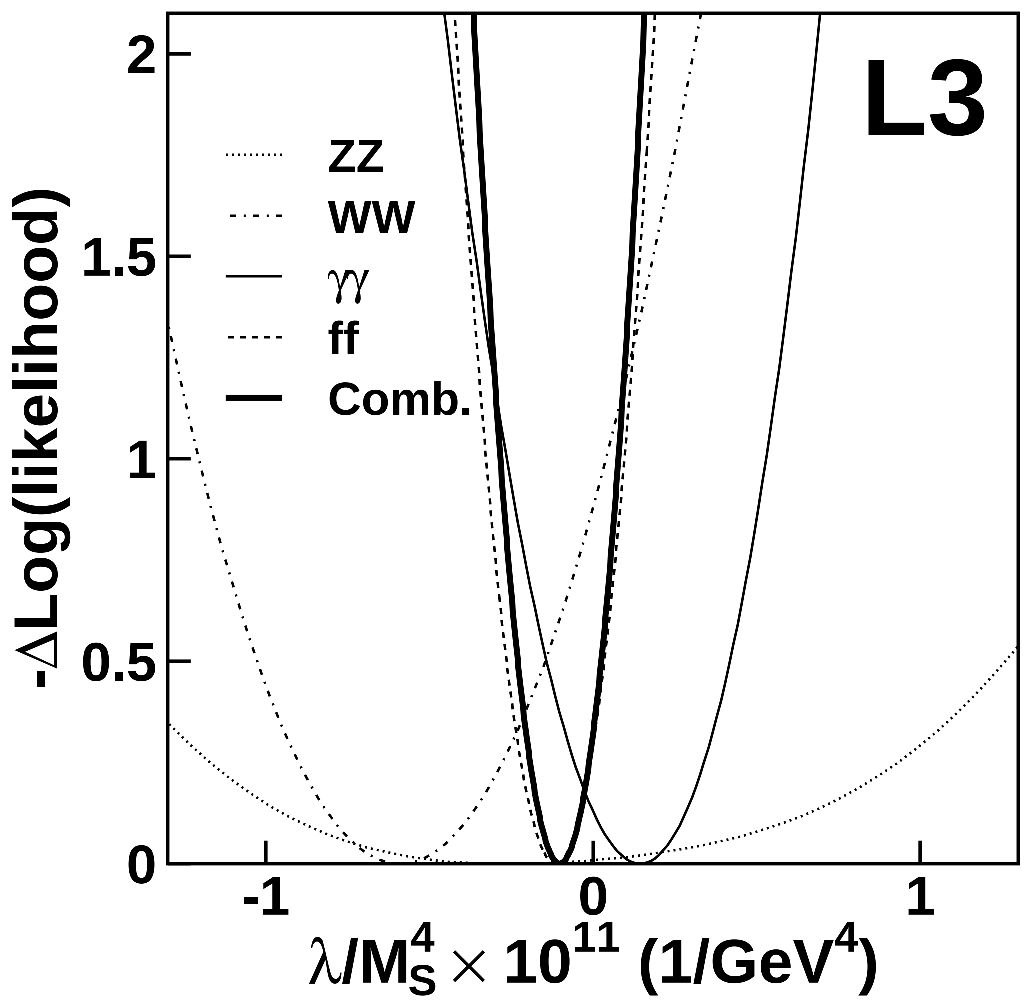

Figure 3: Likelihood curves for $\frac{\lambda}{M_S^4}$ for all the processes described in the text and their combination.

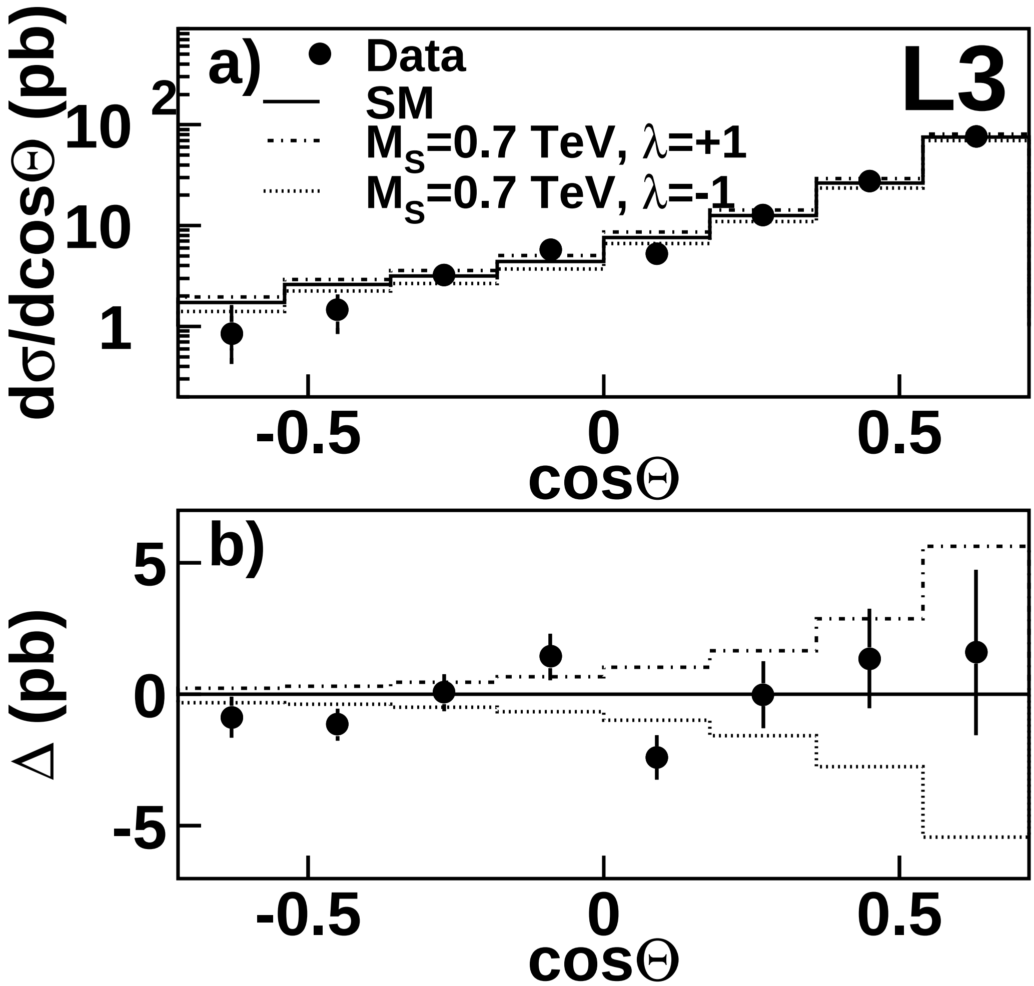

Figure 4: a) Differential cross section for Bhabha scattering in data and the SM expectations. LSG modifications for $M_S = 0.7$ TeV are also displayed for $\lambda = \pm 1$. b) Differences Δ of the above with SM prediction.