Gravity at the TeV Scale

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Searches for evidence of gravity at the TeV scale were reported. ....

1 TeV scale gravity in colliders

1.1 Theoretical Considerations

The tree level relation in Eq.1, predicts that the string mass scale is of the order of the Plank mass, M_P: k is a constant of the order unity and α_{gut} is the unified gauge coupling constant. A value for M_S of the order of M_P is too large to be compatible with unification of the gauge couplings observed at low energies.

$$M_S = M_P \frac{\sqrt{k\alpha_{gut}}}{2} \tag{1}$$

However, new developments in string duality theory [1], point to the fact that Eq.1 can receive large corrections, lowering M_S to to values compatible with gauge coupling unification. Models were constructed [2,3,4,6] in which gravity becomes strong at the TeV scale. The weakness of the gravitational force when compared to the electroweak force at low energies being explained by the propagation of gravity in extra dimensions, with compactification radius R. That is, the gravitons live in a higher-dimensional space, while SM particles propagate in the normal 3+1 dimensional space.

Newtons constant in the 3+1 dimensional space, representing the observed strength of gravity, is written in terms of the fundamental mass scale, M_D and of the radius of the compactified space R, by Eq.2, where n is the number of extra dimensions.

$$G_N^{-1} \propto M_D^{n+2} R^n \tag{2}$$

1.2 Phenomenology at LEP

Gravitons are assumed to move in the extra-dimensions, and to have their quantum states characterized by their momentum (in the extra-dimensions). The graviton quantic states are called Kaluza-Klein excitations and they can be described as spin 2 particles in the 3+1 dimensional space. The coupling between gravitons and SM particles has a strength of the order M_P^{-1} and it is the sum of all Kaluza-Klein excitations that makes gravity strong at scales $M_D << M_P$.

Developments on phenomenological implications of large extra dimensions have been considered which consist on the effects of virtual graviton exchange and of real graviton production.

At LEP, virtual graviton exchange would contribute to the scattering of SM particles, through the diagrams in figure 1.

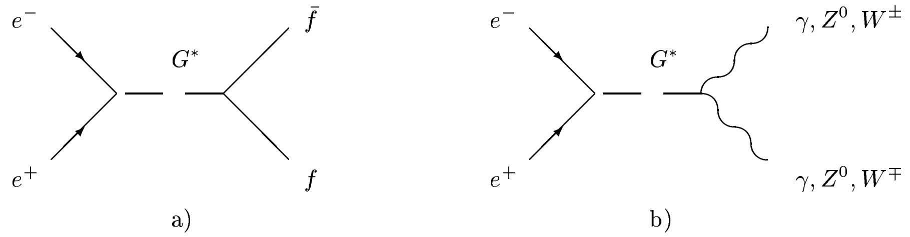

Figure 1: Feynman diagrams for virtual graviton exchange in e^+e^- collisions.

Such an exchange of virtual gravitons leading to two fermion and two boson final states, would cause a departure from the Standard Model of the measured cross-sections for those processes. Effects on the differential cross-sections would be especially visible, since the angular distributions of the final state particles due to the exchange of a spin 2 particle differ considerably either from the standard s-channel exchange of a vector boson such as in the case of $f\bar{f}$ final state or from the t-channel exchange of an electron or neutrino such as in the case of the $\gamma\gamma, Z^0Z^0$ and $W^\pm W^\mp$ final states.

For all the quoted processes, the differential cross-section can be parameterized as a function of the polar angle of the outgoing particles with respect to the incident electron, θ, and is dependent only on the string mass scale according to Eq.3. $A(\cos\theta)$ represents the SM term, $B(\cos\theta)$ represents the interference between the SM diagram and the Graviton exchange diagram term and $C(\cos\theta)$ is the pure gravitational term.

$$\left(\frac{d\sigma}{d\cos\theta}\right) = A(\cos\theta) + B(\cos\theta)\left[\frac{\lambda}{M_S^4}\right] + C(\cos\theta)\left[\frac{\lambda}{M_S^4}\right]^2 \tag{3}$$

The notation used here corresponds to that of [5], where λ is a $\mathcal{O}(1)$ parameter of the theory. It is related to the notation in [3] by Eq.4, where Λ_T is the unknown cutoff energy, presumably of the order of M_D, the fundamental mass scale.

$$\frac{\lambda}{M_S^4} = \frac{\pi}{2}\frac{1}{\Lambda_T^4} \tag{4}$$

Direct graviton production can be serched for at LEP in events with photons and missing energy, according to the Feynman diagram in Fig.2. As refered above, the mass of the gravitons correspond to their momentum in the extra-dimensions, and therefore, such signal would be characterized by a continuous mass spectrum.

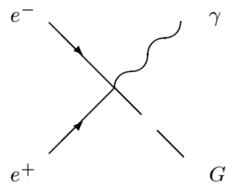

Figure 2: Feynman diagram describing the direct production of a graviton along with a photon, in e^+e^- collisions.

The differential cross-section for the production of a graviton associated with a photon depends both on the number of extra dimensions, n, and on the fundamental mass scale, M_D, according to Eq.5, where x_γ is the ratio of the photon energy to the beam energy.

$$\left(\frac{d^2\sigma}{dx_\gamma d\cos\theta}\right) \propto \frac{1}{s}\left(\frac{\sqrt{s}}{M_D}\right)^{n+2} \cdot f(x_\gamma, \cos\theta) \tag{5}$$

2 Experimental Results

The latest data analysed by the four LEP collaborations, ALEPH, DELPHI, L3 and OPAL, correspond to the data taken during 1999, at the highest e^+e^- collision energies acchieved up to now. The analyses results and final interpretations, however, are when possible based on a combination all LEP 2 datam, representing an integrated luminosity of about 480 pb^{-1} per experiment. In table 1, the LEP2 years of data taking, the respective centre-of-mass energies and integrated luminosities per experiment are presented.

Table 1: Years of LEP 2 data taking, respective center-of-mass energies and approximate values for the integrated luminosities collected in each period for each of the four LEP experiments.

Year	ECM (GeV)	$\sim \mathcal{L}$ pb^{-1}
before 1997	130-172	32
1997	183	57
1998	189	158
1999	192	26
	196	77
	200	83
	202	40

3 Dedicated Analyses

3.1 Search for virtual Graviton exchange

Searches for virtual graviton exchange are performed on the context of the particle pair production differential cross-section measurements. The analyses procedure is common to the analyses of the SM processes: $f\bar{f}$ and two boson events are selected are the respective differential cross-sections or assymetries are measured. The contributions of virtual graviton exchange are determined using the maximum likelihood method or a χ^2-fit to differential cross-section and assymetry measurements. 95% Confidence Limit for the model parameter (M_S or Λ_T) are then extracted.

The $e^+e^- \to \gamma\gamma$ channel

The analyses of the QED process yielding two photons, is based on the fact that these final states consist of two collinear and highly energetic photons, each with energy $\sim \sqrt{s}/2$. The Born level differential cross-section for $e^+e^- \to \gamma\gamma$ is given by Eq.6 (where α is the electromagnetic coupling constant).

$$\left(\frac{d\sigma}{d\Omega}\right)^{QED} = \frac{\alpha^2}{s}\frac{1+cos^2\theta}{1-cos^2\theta} \tag{6}$$

The most general parameterization of deviations to the QED cross-section, consists of introducing an energy cutoff in the electrons propagator, which represents the typical QED energy scale. In this parameterization, the $e^+e^- \to \gamma\gamma$ differential cross-section can be written as in Eq.**??**.

$$\left(\frac{d\sigma}{d\Omega}\right)^{cutoff} = \left(\frac{d\sigma}{d\Omega}\right)^{QED} \cdot \left(1 \pm \frac{s^2}{2}\frac{1}{(\Lambda_\pm^{QED})^4}sin^2\theta\right) \tag{7}$$

Using both the formulation in[3] and[5], Eq.?? is derived for the $e^+e^- \to \gamma\gamma$ differential cross-section including virtual graviton exchange.

$$\left(\frac{d\sigma}{d\Omega}\right)^G = \left(\frac{d\sigma}{d\Omega}\right)^{QED} \cdot \left\{1 + \frac{s}{2}\left[s\,\frac{sin^2\theta}{2\pi\alpha}\frac{\lambda}{M_S^4} + \left(s\,\frac{sin^2\theta}{2\pi\alpha}\frac{\lambda}{M_S^4}\right)^2\right]\right\} \tag{8}$$

If Eq.7 and Eq.8 are compared, and noticing that the term in $1/M_S^8$ is negligible when compared to the remaining terms in Eq.8, it is easy to see that the relation between M_S and the QED cut off is simply given by Eq.9, yielding two solutions for M_S, one for negative and another for positive values of λ. Eq.9, provides therefore a straightforward derivation of confidence limits on M_S, using the results derived for $\Lambda_{\pm}^{QED}$.

$$M_{S\pm} = \left(\frac{1}{2\pi\alpha}\right)^{\frac{1}{4}} \Lambda_{\pm}^{QED} \text{ for } |\lambda| = 1 \tag{9}$$

95% Confidence limits on M_S including the LEP 2 most recent data[7,10,11] of .... were derived.

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

Analyses of fermion pair production aim at selecting a pure sample of two fermion final states with the highest efficiency possible. At LEP 2 energies, two fermion events are classified according to two main categories which can be distinguished through several variables, one of them, the invariant mass of the $f\bar{f}$ pair. Events resulting from radiative returns to the Z^0 with emission of a hard, unseen photon (usually lost on the beam pipe), which have invariant masses about the Z^0 mass, have their sensitivity to new physics processes suppressed due to the large Z^0 exchange cross-section. However, two fermion final states yielding visible energies and invariant masses of about $\sqrt{s}$, are more sensitive to new physics processes. A way to separate these two types of events is to perform a cut in the reduced centre-of-mass energy $\sqrt{s'}$. Usually it is required that $\sqrt{s'}/\sqrt{s}$ is greater that 0.80-0.85.

Fits to the differential cross-section of the selected high-energy $f\bar{f}$ events including the 1999 data, result on 95% Confidence limits on M_S, which are of the order of .... [9,12].

3.2 Search for direct Graviton production

The $e^+e^- \to \gamma + E_{miss}$ channel

Dedicated analyses for single photon final states and missing energy dedicated at probing direct graviton production at LEP. These searches are distinct from other single photon searches due to the continuous missing mass spectrum expected for the γG channel. The main background process for this channel is the $\nu\bar{nu}\gamma$ final state, produced by a radiative decay to the Z^0 which decays to $\nu\bar{\nu}$. The main characteristic of the event selection is the requirement of single photon events with a low photon energy, which is favoured in γG production.

The 95% confidence level lower limits on M_D as a function of the number of extra dimensions, n, are derived either taking into account the $\cos\theta$ dependence on the cross-section or just by determining the total cross-section 95%CL upper limit. In the first case, fits to the two dimensional distribution $M_miss, \cos\theta$ are performed and 95% CL lower limits on M_D are obtained for each n. In the second case, the 95% CL lower limits on M_D for each n correspond to the intersection of the model cross-section curves as a function of M_D as displayed in figure 3

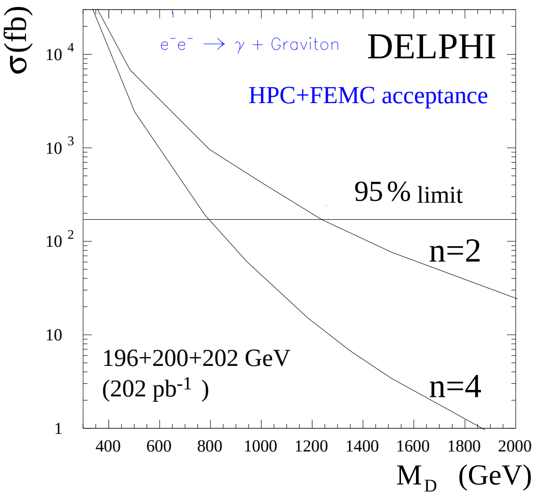

Figure 3: .

4 Interpretation of the results

5 Conclusions

The possibility of a quantum gravity scale as low as the electroweak scale in theories with gravity propagating in extra-dimensions is being explored at LEP (and other colliders ?). Limits on the fundamental mass scale of the order of 0.6 TeV to 1 TeV were derived by the LEP experiments using results from direct and indirect searches. New results and interpretations will surelly be considered in the future.

Acknowledgments

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