JHEP HYPER VERSION

RECEIVED: *July 16, 1999*, ACCEPTED: *August 10, 1999*

Analysis of Bhabha scattering at LEP2 and limits on low scale gravity models

Dimitri Bourilkov

Institute for Particle Physics (IPP), ETH Zürich,
CH-8093 Zürich, Switzerland
E-mail: Dimitri.Bourilkov@cern.ch

ABSTRACT: A combined analysis of the data on Bhabha scattering from the four LEP experiments ALEPH, DELPHI, L3 and OPAL is performed to search for effects of virtual graviton exchange in models with low scale gravity. No statistically significant deviations from the Standard Model expectations are observed and lower limits on the scale of models with large extra dimensions of $\Lambda_{\mathrm{T}} = 1.077$ TeV for $\lambda = -1$ and $\Lambda_{\mathrm{T}} = 1.412$ TeV for $\lambda = +1$ at 95 % confidence level are derived.

KEYWORDS: LEP HERA and SLC Physics, Beyond Standard Model, Models of Quantum Gravity.

JHEP08(1999)006

Contents

1. Introduction

The Standard Model (SM) has been tremendously successful when confronting the theory with data coming from the highest energy accelerators. Still, we believe that it is not complete, and one of the first questions in all searches for new physics is what is the relevant scale, where new phenomena will become accessible to experiments. Recently, a radical proposal has been put forward by Arkani-Hamed, Dimopoulos and Dvali [1] for the solution of the hierarchy problem, which brings close the electroweak scale $m_{EW} \sim 1$ TeV and the Planck scale $M_{Pl} = 1/\sqrt{G_N} \sim 10^{15}$ TeV. In this framework [1, 2, 3] the effective 4 dimensional M_{Pl} is connected to a new $M_{Pl(4+n)}$ scale in a (4+n) dimensional theory:

$$M_{Pl}^2 \sim M_{Pl(4+n)}^{2+n} R^n \,, \tag{1.1}$$

where there are n extra compact spatial dimensions of radius $\sim R$. Putting $M_{Pl(4+n)} \sim m_{EW}$, for $n = 1$ we get $R \sim 10^{13}$ cm, which is excluded experimentally, but already for $n = 2$ the result is $R \sim 0.1 - 1$ mm, which is below the current experimental limits from gravitational experiments.

In this work we will adopt the notation from [4] and call the gravitational mass scale M_D. This scale is relevant in direct searches for graviton production. In the case of virtual graviton exchange, which is the subject of our analysis, the corresponding scale is the ultraviolet cutoff energy, denoted Λ_T in [4] and M_s in [5, 6], with the relation $M_s = (2/\pi)^{1/4}\Lambda_T$. The two scales are expected to be close to each other.

This paper is organized as follows. In section 2, we describe the effects of virtual graviton exchange in Bhabha scattering, which turns out to be the single most sensitive channel at LEP2 energies. In the following section the experimental data used in this analysis is presented. In section 4 the results of the global fit are shown and limits on low scale gravity models are derived.

2. Virtual graviton exchange in Bhabha scattering

The differential cross section for fermion-pair production in e^+e^- collisions can be decomposed in the usual way as:

$$\frac{d\sigma}{d\Omega} = SM(s,t) + \varepsilon \cdot C_{\mathrm{Int}}(s,t) + \varepsilon^2 \cdot C_{\mathrm{Graviton}}(s,t)\,, \tag{2.1}$$

where $SM(s,t)$ is the Standard Model contribution, $C_{\mathrm{Graviton}}(s,t)$ comes from the virtual graviton exchange and $C_{\mathrm{Int}}(s,t)$ is the interference between the SM and the low scale gravity terms. The exact form of these functions is given in [4] for all final states, in [5] for final states other than electrons and in [6] for Bhabha scattering. Here we will use the results from the calculations by Rizzo. The independent theoretical calculations in [4] give numerically values which are very close and produce the same final results.

In the formula above

$$\varepsilon = \frac{\lambda}{M_s^4}\,. \tag{2.2}$$

The coefficient λ is of $\mathcal{O}(1)$ and can not be calculated explicitly without knowledge of the full quantum gravity theory. In the following analysis we will assume that $\lambda = \pm 1$ in order to study both the cases of positive and negative interference.

It should be noted that the exchange of a spin 2 particle leads to terms $\sim \cos^3\theta$ and $\sim \cos^4\theta$, which makes the differential cross sections a unique signature for this type of physics. For fermions other than electrons the integrated interference term for scattering angles from zero to π is exactly zero, and the graviton exchange is suppressed by $1/M_s^8$. On the contrary, the interference between the graviton exchange and t-channel SM exchanges for Bhabha scattering is giving sizeable contributions, making the e^+e^- final state the most sensitive search field. This combines favourably with the larger cross section and the much higher statistical precision of this measurement. In the area of the forward peak the theory uncertainty in the SM predictions is the limiting factor in our study.

Initial-state radiation (ISR) changes the effective centre-of-mass energy in a large fraction of the observed events. We take these effects into account by computing the first order exponentiated cross sections and asymmetries following [7]. Other QED corrections give smaller effects and are neglected.

3. Experimental data

All LEP collaborations have submitted for publication or send to recent conferences their measurements of fermion-pair production at 183 and 189 GeV centre-of-mass energies. As explained in the previous section, the golden channel to search for virtual graviton exchange effects is Bhabha scattering and in the following we will concentrate on the data for these two highest energy points, where large data samples have been accumulated during the very successful LEP runs in 1997 and 1998.

JHEP08(1999)006

The DELPHI [8] and L3 [9] collaborations have presented preliminary results for total cross sections and forward-backward asymmetries in the angular range $44^\circ < \theta < 136^\circ$, where θ is the angle between the incoming and the outgoing electrons. The ALEPH [10, 11] and OPAL [12, 13] collaborations have presented results for the differential cross sections in the angular range $|\cos\theta| < 0.9$. The scattering angle is defined by OPAL to be in the laboratory frame, and by ALEPH to be in the outgoing e^+e^- rest frame. The experiments use different strategies to isolate the high energy sample, where the energy of the propagator is close to the full available centre-of-mass energy. This sample is the main search field for new physics. DELPHI and OPAL apply an acolinearity cut of 20° and 10° respectively. ALEPH defines the effective energy, s', as the square mass of the outgoing fermion pair. It is determined from the angles of the outgoing fermions. L3 defines s' as the mass squared of the γ^*/Z propagator. It is determined from the invariant mass squared of the final state e^+e^- pair, computed from the energies measured in the electromagnetic calorimeter. Close-by final state radiation photons are absorbed in the same energy cluster, and consequently included in the invariant mass.

For details of the selection procedures, the statistical and systematic errors we refer the reader to the publications of the four LEP experiments.

4. Results and discussion

The Standard Model predictions for Bhabha scattering at 183 and 189 GeV are computed with the program TOPAZ0 [14] for total cross sections and forward-backward asymmetries in the angular range of each experiment. This is sufficient for the global analysis of the data from the DELPHI and L3 experiments. We assign a theory uncertainty of 2 % to the absolute scale of the SM predictions. In order to analyze the differential cross section measurements of the ALEPH and OPAL collaborations, we compute the *form* of the differential spectra using the generator BHWIDE [15], and then normalize the total cross section to the TOPAZ0 prediction. Here a theory error of 3 % is assigned. In all cases the individual experimental cuts of the selection procedures and the isolation of the high energy samples are taken into account.

In total we have 44 data points: 36 from the 4 differential spectra, 4 from the cross sections and 4 from the forward-backward asymmetries. The effects coming from virtual graviton exchange are computed as a function of the parameter $\varepsilon = \lambda/M_s^4$. A fitting procedure similar to the one in [16] is applied.

A negative log-likelihood function is constructed by combining all data points at the two centre-of-mass energies:

$$-\log\mathcal{L} = \sum_{r=1}^{n} \left(\frac{(\text{Prediction}(SM,\varepsilon) - \text{Measurement})^2}{2 \cdot \Delta^2_{\text{Measurement}}} \right)_r \tag{4.1}$$

$$\Delta_{\text{Measurement}} = \text{error}(\text{Prediction}(SM,\varepsilon) - \text{Measurement})\,, \tag{4.2}$$

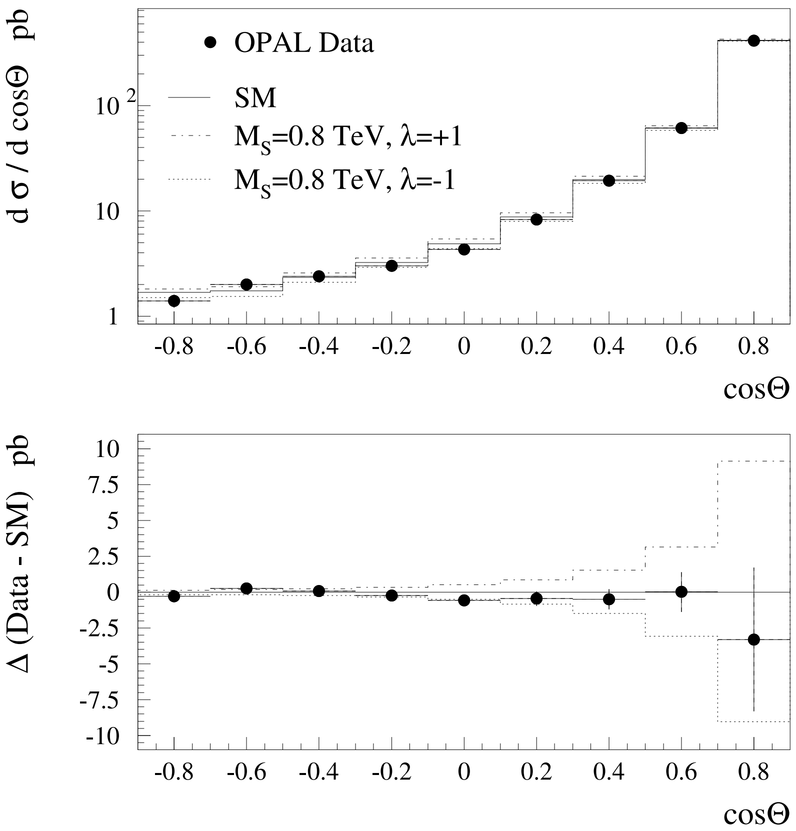

Figure 1: The differential cross section for Bhabha scattering at LEP2 in the Standard Model and models of low scale gravity. The data is from the OPAL collaboration at 189 GeV. The errors are statistical and systematic; the theory uncertainty is not shown. The lower plot shows the difference between the data and the SM expectation together with the expected deviations from the SM in models with large extra dimensions. The experimental sensitivity peaks in the forward direction.

where Prediction(SM, ε) is the SM expectation for the given measurement (cross section or forward-backward asymmetry or a point in the differential spectra) combined with the additional effect of graviton exchange as a function of the mass scale, and Measurement is the corresponding measured quantity. 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 result of the combined fit is:

$$\varepsilon = -0.46 \,^{+0.37}_{-0.36} \ \mathrm{TeV}^{-4} \tag{4.3}$$

or 1.24 σ away from the Standard Model expectation $\varepsilon = 0$.

One example of the data analysis is shown in figure 1, where the SM predictions and the expectations from the low scale gravity model are compared to the measurements of the OPAL collaboration at 189 GeV.

So the data from the four LEP collaborations shows no statistically significant deviations from the SM predictions due to the effects of virtual graviton exchange. In their absence, we use the log-likelihood method to determine a one sided upper limit on the scales M_s or Λ_T at the 95% confidence level. After proper normalization it gives the confidence level for any value of M_s in the physically allowed region. The exact definition is

$$\int_0^{\varepsilon_{95}^+} \mathcal{L}(\varepsilon')d\varepsilon' = 0.95 \int_0^{\infty} \mathcal{L}(\varepsilon')d\varepsilon'$$
$$\int_{-\varepsilon_{95}^-}^{0} \mathcal{L}(\varepsilon')d\varepsilon' = 0.95 \int_{-\infty}^{0} \mathcal{L}(\varepsilon')d\varepsilon'.$$

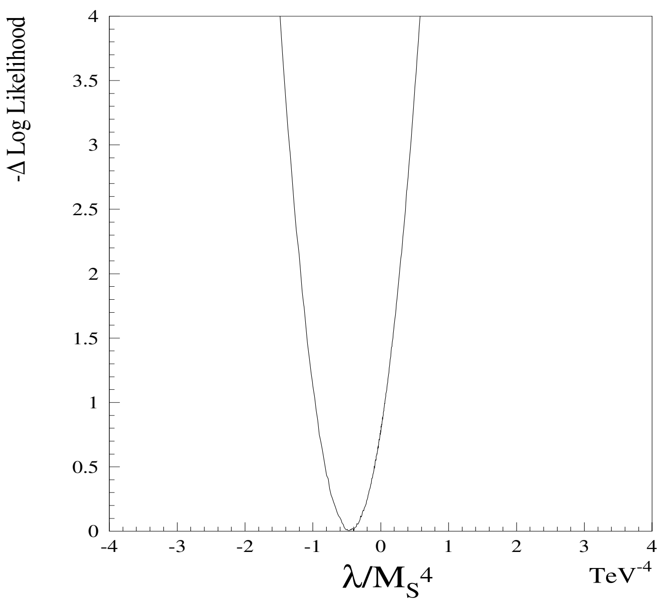

Figure 2: Log-likelihood curve of the global fit to the data on Bhabha scattering from the four LEP experiments.

The limits are summarized in table 1 and the combined log-likelihood curve is shown in figure 2.

The limits obtained here are higher than those in other global fits to collider data [17, 18]. In these papers the best limits ~ 1 TeV come from the TEVATRON data on Drell-Yan production due to the higher accessible centre-of-mass energies, but with small data samples. In [18] fermion-pair production at LEP2 has been considered for all cases except Bhabha scattering. The results presented here improve on the limits obtained by individual LEP experiments [19, 20].

λ = -1	λ = +1
M_s [TeV]	
0.962	1.261
Λ_T [TeV]	
1.077	1.412

Table 1: Limits on the gravity scales M_s and Λ_T from Bhabha scattering at LEP2 at the 95 % confidence level.

At this point the alert reader may begin to worry: if Bhabha scattering is such a sensitive tool to search for low scale gravity, maybe the luminosity measurements of the LEP experiments, based on the very same process, will also be affected and the results obtained here will not be strictly valid. To close this loophole, a check is performed for a typical angular range for luminosity measurements: for scattering angles from 24 to 54 mrad. For a scale as low as $M_s = 0.750$ TeV, excluded by this analysis, the change in the cross section is 0.008 % for centre-of-mass energy of 188.7 GeV.

5. Conclusions

The results of this work can be summarized as follows:

- Bhabha scattering is the golden channel to search for virtual graviton exchange at LEP2
- a global fit to the LEP2 data on Bhabha scattering is performed and limits on the mass scale of quantum gravity models with large extra dimensions of $\Lambda_T = 1.077$ TeV for $\lambda = -1$ and $\Lambda_T = 1.412$ TeV for $\lambda = +1$ at 95 % confidence level are set
- the precision of the Standard Model predictions for Bhabha scattering starts to be the limiting factor in this search; improved theory predictions are very desirable in view of the expected large data samples from the LEP running in 1999 and 2000.

Acknowledgments

The author is grateful to G. Giudice, J. Hewett, T. Rizzo, S. Mele, E. Sanchez and A. Dominguez for discussions on some of the theoretical and experimental aspects of this work.

References

[1] N.Arkani-Hamed, S. Dimopoulos and G. Dvali, *Phys. Lett.* **B 429** (1998) 263 [hep-ph/9803315].

[2] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. Dvali, *Phys. Lett.* **B 436** (1998) 257 [hep-ph/9804398].

[3] N.Arkani-Hamed, S. Dimopoulos and G. Dvali, *Phys. Rev.* **D 59** (1999) 086004 [hep-ph/9807344].

[4] G. Giudice, R. Rattazi and J. Wells, *Nucl. Phys.* **B 544** (1999) 3 [hep-ph/9811291].

[5] J. Hewett, *Phys. Rev. Lett.* **82** (1999) 4765 [hep-ph/9811356].

[6] T. Rizzo, *Phys. Rev.* **D 59** (1999) 115010 [hep-ph/9901209]

[7] R. Kleiss et al., *Z Physics at LEP 1*, volume 3, CERN, Geneva 1989.

[8] DELPHI Collaboration, DELPHI 99-135, submitted to EPS-HEP99 # 6-362.

[9] L3 Collaboration, L3 Note 2398, submitted to EPS-HEP99 # 6-262

[10] ALEPH Collaboration, CERN-EP/99-042, submitted to *Eur. Phys. J.* **C**.

[11] ALEPH Collaboration, ALEPH 99-018, submitted to EPS-HEP99 # 6-694.

[12] OPAL Collaboration, G. Abbiendi et al., *Eur. Phys. J.* **C6** (1999) 1 [hep-ex/9808023].

[13] OPAL Collaboration, CERN-EP/99-097, July 8, 1999, submitted to *Eur. Phys. J.* **C**.

[14] G. Montagna, O. Nicrosini, G. Passarino, F. Piccinini and R. Pittau, *Nucl. Phys.* **B 401** (1993) 3.

[15] S. Jadach, W. Placzek and B.Ward, *Phys. Lett.* **B 390** (1997) 298 [hep-ph/9608412].

[16] L3 Collab., M.Acciarri et al., *Phys. Lett.* **B 414** (1997) 373.

[17] A. Gupta, N. Mondal and S. Raychaudhuri, *Constraining large extra dimensions using dilepton data from the Tevatron collider*, hep-ph/9904234.

[18] K. Cheung, *Global lepton-quark neutral current constraint on low scale gravity model*, hep-ph/9904510.

[19] ALEPH Collaboration, ALEPH 99-051, submitted to EPS-HEP99 # 6-417.

[20] L3 Collaboration, L3 Note 2418, submitted to EPS-HEP99 # 7-252.