WUE-ITP-2004-030
LC-TH-2004-013
hep-ph/0408279
August 2004

Probing Minimal 5D Extensions of the Standard Model

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We analyze non-universal 5D standard model extension, where some or all of the gauge and Higgs fields propagate in a flat extra dimension, while all other degrees of freedom are localized on a S^1/Z_2 orbifold brane. From LEP data, model-dependent bounds on the compactification scale M between 4 and 6 TeV are derived. We analyze the correlations between M and the SM Higgs mass m_H. Investigating the prospects at an e^+e^- linear collider such as TESLA, we show that the so-called GigaZ option has the potential to improve the LEP bounds by about a factor 2. At the center of mass energy of 800 GeV and with an integrated luminosity of 10^3 fb^{-1}, linear collider experiments can probe compactification scales up to 20–30 TeV and beyond, depending on the systematic errors.

The fascinating possibility that our world may realize more than four dimensions has been a central theme of the last ten years [1,2,3,4]. Considering higher-dimensional extensions of the standard model, the lower limit on the compactification scale M of a single extra dimension is roughly 300 GeV in the so-called universal scenario, in which all standard model fields live in the 5D bulk. For non-universal models, i.e. if some of the SM fields, in particular the fermions, are confined to the familiar 4-dimensional world, M is constrained much more strongly, namely $M \gtrsim 4$ TeV [5]. This order of magnitude increase of the bound is due to the tree-level coupling of single KK excitations to light SM modes on a brane which induce contact interactions at low energies. Moreover, a Higgs field confined to a brane implies shifts in gauge-boson couplings and masses.

Here, we distinguish three non-universal five-dimensional scenarios on an S^1/Z_2 orbifold [5,6]: (i) all gauge fields propagate in the bulk of the extra dimension (bulk-bulk model); (ii) only the SU$(2)_L$ gauge bosons are bulk fields, while the U$(1)_Y$ gauge field is confined to a brane (bulk-brane model); (iii) only the U$(1)_Y$ boson propagates in the bulk (brane-bulk model). While the Higgs field has to be confined to the brane in the latter two models, it may also propagate in the extra dimension in the bulk-bulk model. As has been shown in [6], the above 5D models can be consistently quantized using appropriate 5D gauge-fixing conditions that lead, after the KK reduction, to the known class of R_ξ gauges.

[a] Talk presented at LCWS2004, Paris, France, April 2004

Concerning the phenomenology of such extra-dimensional extension of the standard model, the shifts in gauge-boson masses and couplings due to a Higgs boson which is confined to a brane are of the order of $X = \pi^2 m_Z^2/3M^2$. Moreover, input parameters like the Fermi constant G_F and the Z mass m_Z have to be reinterpreted. For example, the KK modes of the W boson contribute to muon decay and thus enter the determination of G_F. These shifts are particularly important for precision physics at the Z pole, where virtual KK exchange is negligible. To confront the different models with experiment, we calculate the tree-level shift $\Delta_{\mathcal{O}}^{5\mathrm{DSM}}$ for a given observable due to the extra dimension. Applying $\Delta_{\mathcal{O}}^{5\mathrm{DSM}}$ to the radiatively corrected SM prediction $\mathcal{O}^{\mathrm{SM}}$ to obtain the higher-dimensional prediction $\mathcal{O}^{5\mathrm{DSM}} = \mathcal{O}^{\mathrm{SM}}\big(1 + \Delta_{\mathcal{O}}^{5\mathrm{DSM}}\big)$, we perform a χ^2 analysis for a large number of precision observables. Using ZFITTER [7] to calculate $\mathcal{O}^{\mathrm{SM}}$, a multiparameter fit of the compactification scale M along with the standard model input parameters yields bounds on M between 3 TeV for the brane-bulk model and 4 TeV for the bulk-bulk model with a brane Higgs at the 2σ confidence level. The correlation between the SM Higgs mass and the compactification scale [8] is displayed in Fig. 1. One sees that in some of the models the existence of an extra dimension favors a heavier Higgs boson. The effect is most pronounced in the bulk-bulk model with a brane Higgs and in the brane-bulk model. Quantitatively, for $M = 5$ TeV, the best fit values increase from $m_H = 100^{+70}_{-40}$ GeV to $m_H = 170^{+105}_{-60}$ GeV and $m_H = 155^{+105}_{-60}$ GeV, respectively. If the compactification scale is included in the multi-parameter fit, the 2σ upper bound on m_H is relaxed from 280 GeV to 330 and 400 GeV, respectively. Note, that the data set [5] used for this analysis is not exactly the same as the one used for the familiar blue-band plot and that the recent change in the top mass is not taken into account.

Already at LEP2 energies, the exchange of heavy KK modes dominates the higher-dimensional shifts for fermion-pair production. Investigating the cross section for Bhabha scattering and the production of muon and tau pairs, hadrons, and W pairs, the compactification scale is constraint to be larger than 4 TeV for the brane bulk model and 6 TeV for the bulk-bulk model with a brane Higgs boson. Muon-pair, tau-pair, and hadron production have been again analyzed in a multi-parameter fit. The correlations of M with the Higgs mass only change little.

At a future e^+e^- linear collider, the GigaZ option allows for tests of the higher-dimensional shifts in masses and couplings with increased statistics. In particular, the precise measurement of the left-right asymmetry A_{LR} using polarized beams can be utilized to explore the compactification scale. GigaZ is sensitive to a compactification scale M from 7 TeV for the bulk-brane model to about 12 TeV for the other models considered. At $\sqrt{s} = 800$ GeV, the

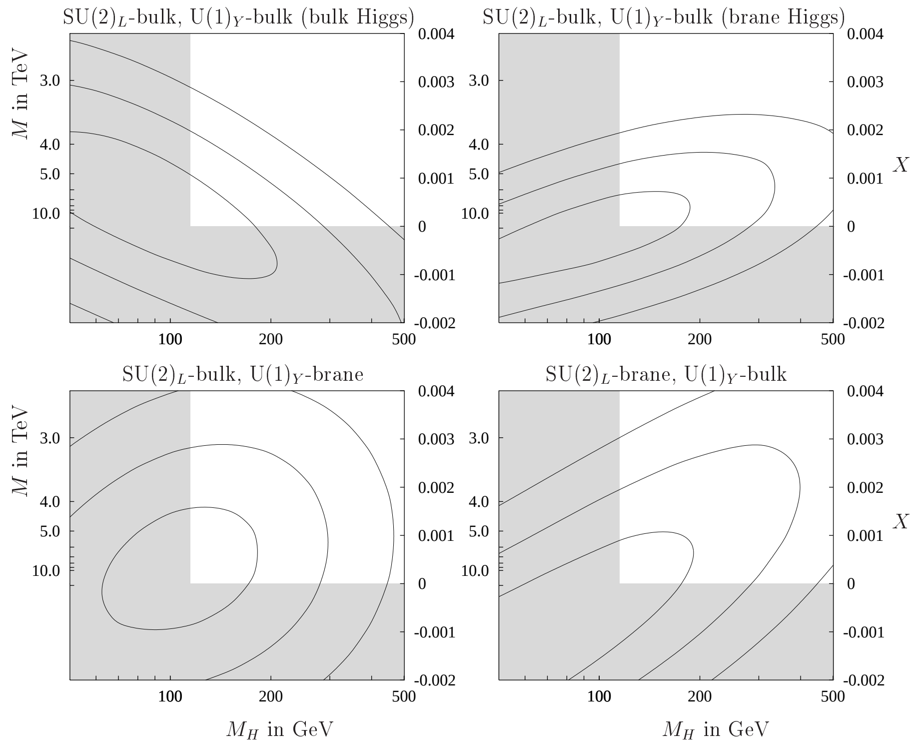

Figure 1: Contours of $\Delta\chi^2 = 1$, 4, 9 derived from multi-parameter fits to electroweak precision data. The shaded regions of the parameter space correspond to $m_H < 114$ GeV and/or $M^2 < 0$.

contact-like interactions due to the exchange of heavy KK modes completely dominate the higher-dimensional shifts of cross sections. For an integrated luminosity of 1000 fb^{-1} the discovery potential will crucially depend on the control of systematic errors, as shown in Fig. 2 for different search channels. For a systematic uncertainty of 1% in each search channel and combining all data, one will be able to reach compactification scales in the range 15-20 TeV. For systematic uncertainties smaller than the statistical uncertainties, the sensitivity limit would saturate in the range M = 35-50 TeV. Moreover, for a sufficiently low compactification scale, $M \lesssim 10$ TeV, Higgsstrahlung and angular distributions of 2-fermion final states can be used to discriminate between different 5D models. In particular, Higgsstrahlung is useful for distinguishing brane from bulk Higgs bosons.

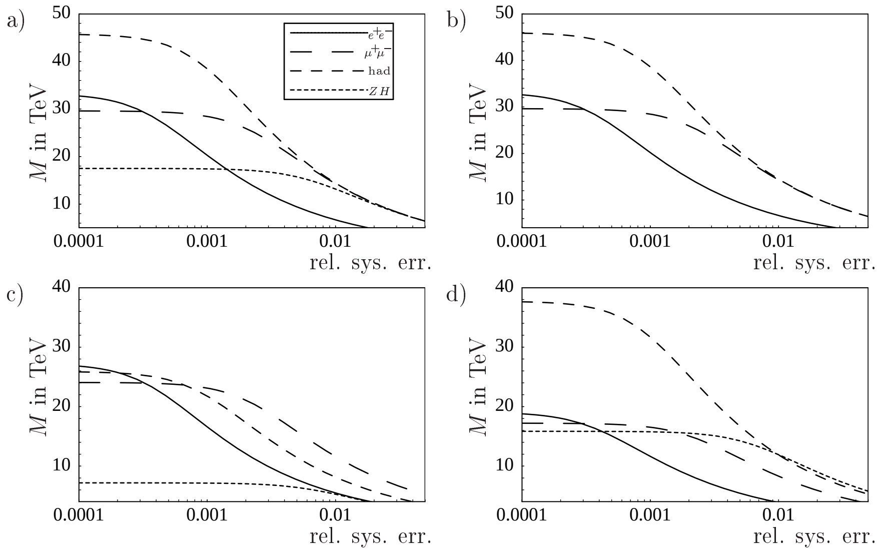

Figure 2: Expected sensitivity to the compactification scale M as a function of the relative systematic error for Bhabha scattering, muon-pair production, hadron production, and Higgsstrahlung at $\sqrt{s} = 800$ GeV and for an integrated luminosity of 1000 fb^{-1}: (a) bulk-bulk model with brane Higgs, (b) bulk-bulk model with bulk Higgs, (c) brane-bulk model, and (d) bulk-brane model.

This work was supported by the Bundesministerium für Bildung und Forschung (BMBF, Bonn, Germany) under the contract number 05HT4WWA2, and PPARC grant number PPA/G/O/2000/00461.

1. N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, Phys. Lett. **B429** (1998) 263; Phys. Rev. **D59** (1999) 086004; I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, Phys. Lett. **B436** (1998) 257.
2. C. Csaki, TASI lectures on extra dimensions and branes, arXiv:hep-ph/0404096, and references therein.
3. K.R. Dienes, E. Dudas, and T. Gherghetta, Phys. Lett. **B436** (1998) 55.
4. F. Feruglio, Extra dimensions in particle physics, arXiv:hep-ph/0401033, and references therein.
5. A. Mück, A. Pilaftsis, and R. Rückl, Nucl. Phys. **B687** (2004) 55.
6. A. Mück, A. Pilaftsis, and R. Rückl, Phys. Rev. **D65** (2002) 085037.
7. D. Bardin *et al.*, Comp. Phys. Comm. **133** (2001) 229.
8. T. Rizzo and J. Wells, Phys. Rev. **D61** (2000) 016007; A. Strumia, Phys. Lett. **B466** (1999) 107.