Extra Dimensions at the ILC

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Large Extra Dimensions

- SM on a 3-brane and gravitons in the full 10-d spacetime.
- The low-energy effective scale is related to the compactification radius R of n extra dimensions by

(1) $$M_{\rm P}^2 = M_S^{n+2} R^n \ ,$$

- If R is large then M_S can be $\sim$ TeV For such a value of M_S, $R = 10^{32/n-19}$ m.

Direct Production Signals

- Graviton Production processes and virtual graviton processes.
- At the ILC, $e^+e^- \to \gamma + G$ yield striking photon + missing-energy signatures.
- Dominant background is $e^+e^- \to \gamma\nu\bar{\nu}$ and can be reduced using polarisation of the initial beams.
- Strong bounds between 3 – 7 TeV on M_S result assuming 5% accuracy on cross-section measurement at $\sqrt{s} = 1$ TeV.

Distinguishing from SUSY

- γ+missing energy signatures can also arise in SUSY with superlight gravitinos via $e^+e^- \to \tilde{G}\tilde{G}\gamma$.
- Can be distinguished by looking at photon energy distributions and scaling of the cross-section with c.m. energy.

Distinguishing from contact-interac

- ILC may also be used to distinguish virtual graviton exchange from four fermion-contact interactions of dimension-6.
- For example, in the process is $e^+e^- \longrightarrow f\bar{f}$ the cos θ distribution can be used to distinguish between the two case using suitably defined asymmetries.

Virtual signals

- Virtual graviton exchange processes at ILC: $e^+e^- \to f\bar{f},\ \gamma\gamma,\ WW,\ ZZ\ \gamma\gamma \to \gamma\gamma$ etc. $e\gamma \to e\gamma$
- Bounds are sensitive to the cut-off used to regulate the infinite tower of KK graviton modes.
- Bounds range between 3 and 6 TeV.
- Polarisation is again an important tool in getting strong bounds.

So what's new?

- NLO QCD corrections to $e^+e^- \longrightarrow q\bar{q}$ with graviton exchange have been computed.
- Stability with repsect to scale variation is demonstrated.
- Corrections are of a few percent but possibly significant given the high statistics involved.

Minimal Length

- Several motivations in theories of quantum gravity to suggest the existence of a minimal length.
- One such: Analysis of string scattering amplitudes suggests the existence of a minimal length.
- Existence of minimal length modifies the relationship between p and k. Even though k is bounded from above, p can be arbitrarily large. Ditto for ω and E.

Minimal Length and ADD

- $p = \hbar k$ (and $E = \hbar\omega$) replaced by Unruh relations:

(2) $$l_p k(p) = \tanh^{1/\gamma}\left[\left(\frac{p}{M_S}\right)^{\gamma}\right]$$

- Interesting union: ADD and MLS. l_p is of the order of TeV^{-1}. Avoids the UV problem in summing over virtual gravitons.
- Predictions for LHC already exist. Work for ILC-related processes in progress.

The RS Model

- In this 5-d model, the fifth dimension ϕ, with strong AdS curvature and of a small radius R_c is compactified on a $\mathbf{S}^1/\mathbf{Z}^2$ orbifold.
- Two branes are at the orbifold fixed points: a Planck brane at $\phi = 0$ and a TeV brane at $\phi = \pi$.
- The model uses a warped metric

$$ds^2 = e^{-KR_c\phi}\eta_{\mu\nu}dx^\mu dx^\nu + R_c^2 d\phi^2. \tag{3}$$

where K is related to the curvature.

More on the RS Model

- The warp factor acts as a conformal factor for the fields localised on the TeV brane.
- So $M_P = 10^{19}$ GeV for the Planck brane at $\phi = 0$ gets rescaled to $M_P \exp(-K R_c \pi)$ for the TeV brane at $\phi = \pi$.
- Brane separation is stabilised by a bulk scalar field which generates a stabilising potential.
- The KK-spectrum is discrete with the masses being given by a common mass factor multiplied by the zeroes of the Bessel function.

Signals

- The zero-mode of the KK tower couples very weakly (suppressed by M_P^{-1}). The couplings of the massive KK states are enhanced by $e^{\pi K R_c}$ (electroweak strength).
- There are no light KK modes but ILC could produce individual graviton resonances. Again, $e^+e^- \to \gamma\nu\bar{\nu}$ can give a handle on the resonances.
- Alternatively virtual effects in fermion pair production or gauge boson pair production can be studied.

ADS/CFT and the RS Model

- AdS/CFT tells us that the RS model is dual to a 4-d effective theory incorporating gravity and a strongly coupled sector.
- The dual theory is conformally invariant from the Planck scale down to the TeV scale.
- The K-K excitations as well as the fields localised on the TeV brane are TeV-scale composites.
- The original RS theory is dual to a theory of TeV-scale compositeness of the entire SM.

The New RS Model

- One can alter the RS model with only the Higgs field localised on the IR brane $\Longrightarrow$ only the Higgs is a composite.
- To avoid problems with electroweak observables an $SU(2)_L \times SU(2)_R \times U(1)_{(X)}$ is invoked.
- KK gauge boson masses are still constrained by precison tests to be greater than 3 TeV.
- The t_R is localised closed to the TeV brane to account for the large top Yukawa $\longrightarrow$ new signals with t_R expected.

Testing the RS Model

- The Tevatron direct limit on the KK gluon mass is only 800 GeV, while KK gauge bosons will be probed to masses of about 3 TeV at the LHC.
- $e^+e^- \to t\bar{t}$ at $\sqrt{s} = 500$ GeV and with 500 fb^{-1} (and longitudinally polarised electron) at the ILC can probe KK gauge boson masses to more than 10 TeV.