Associated Graviton production in Bhabha Scattering¶

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⊙ Theories with extra space like dimension(s) have got lots of attention as a solution to the Naturalness problem

⊙ Two main types of theories :

i. Models of large extra dimensions (ADD).*
ii. Models of warped space-time (RS).†

*Arkani-Hamed, Dimopoulos, Dvali [PLB429:263-272,98]
†Randall, Sundrum [PRL83:3370-3373,99]

ADD scenario

⊙ $(4+\delta)$ dimensional theory with extra δ dimension(s) which are compactified (with radius R).

⊙ Standard Model fields are confined on (1+3)-dimensional brane though gravity can propagate anywhere in the $(4+\delta)$ dimensional bulk.

⊙ Our 4 dimensional Planck scale (M_p) is related to the $(4+\delta)$ dimensional Planck scale $(\bar{M}_s)$ which is actually fundamental scale in this scenario.

$$M_p^2 = 8\pi . V_\delta \bar{M}_s^{\delta+2} R^\delta$$

Volume element $V_\delta = (2\pi)^\delta$ assuming toroidal compactification of extra dimensions.

⊙ By choosing large R (exp. limit $\approx \# \; mm$), fundamental scale $(\bar{M}_s \sim 1\,TeV)$ can produce the Planck scale $(M_p \sim 10^{19} GeV)$ in 4 dimension.

⊙ δ compact extra spatial dimensions, $\Rightarrow$ Infinite tower of Kaluza-Klain states with masses

$$m_n^2 \sim \frac{\vec{n}^2}{R^2} \qquad \begin{array}{l} \vec{n} = (n_1, n_2, \ldots n_\delta) \\ n_i = 0, \pm 1, \pm 2, \ldots \end{array}$$

⊙ The coupling of each graviton KK states to the SM fields remain small, being proportional to $1/M_p$.

⊙ But cumulative effect from full tower of KK states, considering KK state density

$$\rho(m)dm = \left[\frac{2\pi^{\frac{\delta}{2}}}{\Gamma(\frac{\delta}{2})}\right] \frac{\bar{M}_p^2}{M_s^{2+\delta}} m^{\delta-1} dm$$

$\longrightarrow$ keeps the cross-section sizable to have collider signature.
e.g. final cross section $\sim \frac{1}{M_s^2}$ for graviton emission (say).

ADD phenomenology

Two types of large extra dimension signals :

i. Virtual graviton exchange :

$\Rightarrow$ affecting the S.M. scattering signals.

ii. Real graviton emission :

$\Rightarrow$ missing energy-momentum.

We consider the second case.

A widely studied channel for discovering ADD [‡]

$$e^+e^- \to \gamma\, G$$

Note: γ is not monochromatic.

One can probe M_s upto [§] $(\sqrt{s} = 1Tev,\ \mathcal{L} = 200 fb^{-1})$

unpolarized	90% polarized	no of ex-dim(δ)
4.1 TeV	5.7 TeV	for $\delta = 2$
3.1 TeV	4.0 TeV	for $\delta = 3$
2.5 TeV	3.0 TeV	for $\delta = 4$
2.0 TeV	2.4 TeV	for $\delta = 5$

[‡] Mirabelli, Perelstein, Peskin [PRL82:2236-2239,99]

[§] Giudice, Rattazzi, Wells [NPB544:3-38,99]

Alternative channels are always helpful in establishing any new signal as of ADD origin.
Thus we look for,

$$e^+e^- \rightarrow e^+e^-G$$

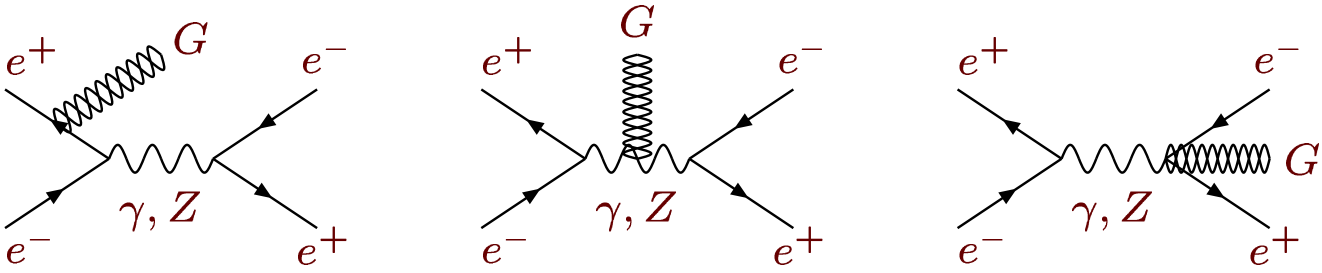
⊙ Bhaba scattering is widely used for calibration of beam.

⊙ So, such scattering accompanied with missing energy ($\not{E}$) can hopefully be measured with precision.

⊙ As, both s and t channel processes are responsible, it may be advantageous over $e^+e^- \rightarrow \mu^+\mu^-G$ [♭] due to s channel suppression.

[♭] Eboli *et al.* [PRD64:035005,01]

⊙ We want to see how far $e^+e^- \rightarrow e^+e^-G$ can probe, side by side with $e^+e^- \rightarrow \gamma G$.



Generic diagrams for the process
$e^+e^- \to e^+e^-G$

⊙ As Graviton couples to all particles with energy-momentum, there are 28 Feynman diagrams contributing to the processes both in s & t channel.

⊙ 8 more diagrams would be added, if we consider virtual graviton exchange also. But their contributions are insignificantly small.

⊙ Full calculation has been done numerically by using the helicity amplitude method. We developed some new HELAS routines, which incudes `G-F-F`, `G-V-V`, `G-F-F-V` vertices.

Checks :

⊙ Calculation of 28 Feynman graphs, even using HELAS, is long and cumbersome, some checks on the numerical results are called for.

⊙ Ward identities arising from general coordinate invariance — an essential feature of any theory involving gravity — turn out to be the most useful : with $\epsilon^{(n)}_{\mu\nu}(p_1)$ as the polarisation tensor,

$$M_n(\lambda_1,\lambda_2) = T^{\mu\nu}(\lambda_1,\lambda_2)\ \epsilon^{(n)*}_{\mu\nu}(p_1)$$

must now satisfy the Ward identities

$$p_1^{\mu} T_{\mu\nu}(\lambda_1,\lambda_2) = p_1^{\nu} T_{\mu\nu}(\lambda_1,\lambda_2) = 0$$

⊙ Only the s-channel contributions of our numerical results are in close agreement with $e^+e^- \to \mu^+\mu^- G$.

⊙ So, t -channel contributions can be easily checked using crossing symmetry.

Background :

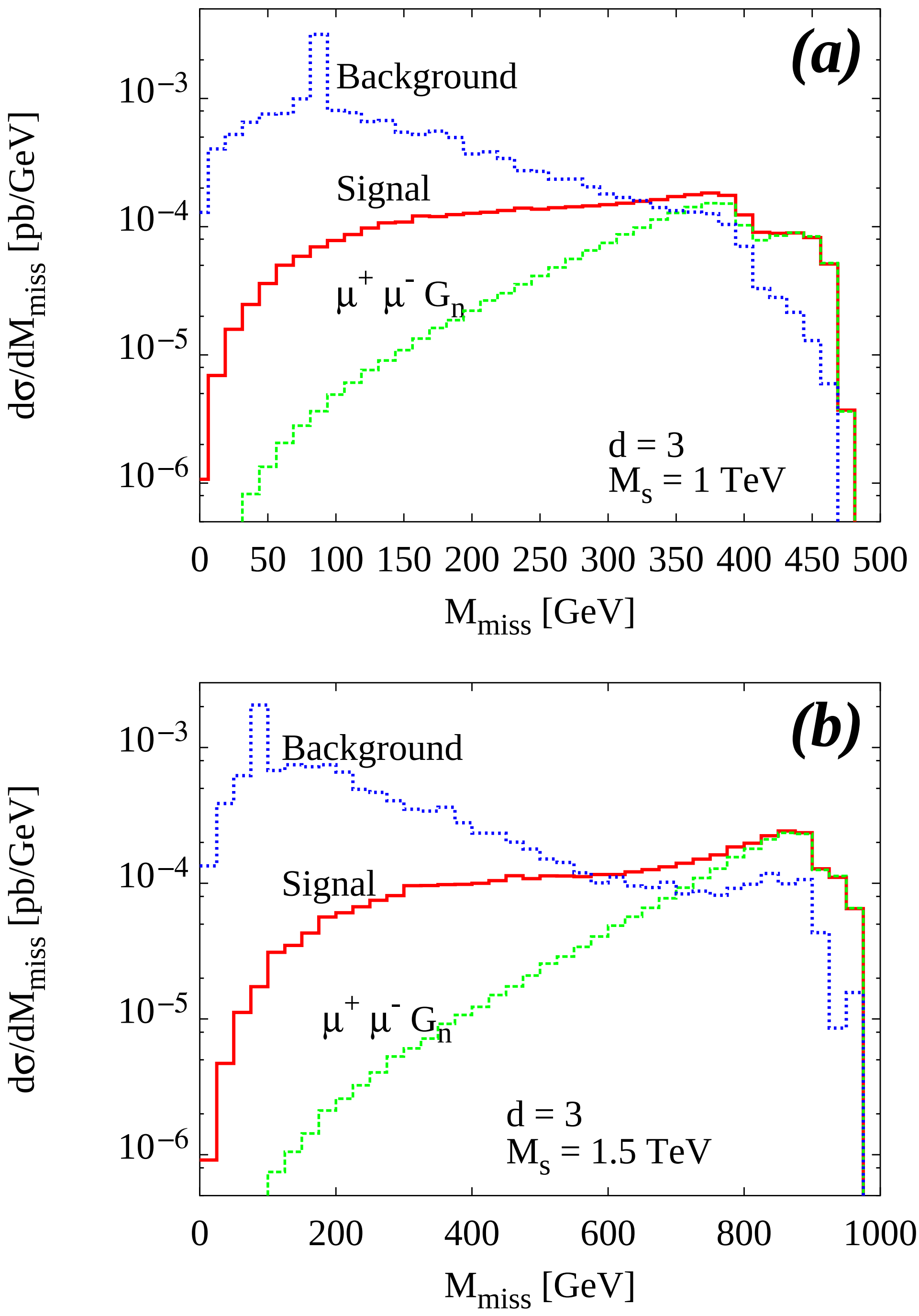
⊙ $e^+e^- \to e^+e^-\nu_l\bar{\nu}_l$

⊙ $e^+e^- \to e^\pm\nu W^\mp \quad \longrightarrow$ Large.

⊙ $e^+e^- \to e^+e^-Z \quad \longrightarrow$ Eliminated by missing mass near m_Z

event selection criteria:

- Electrons are 15^o away from the beam pipe
- $(P_T)_e > 10$ Gev
- $P_T(miss) > (15)$ 25 GeV for $\sqrt{s} =$ (500 GeV) 1 TeV.
- $\Delta R_{e^+e^-} > 0.2$
- Angle between two electrons $< 175^o$
- M_{miss} not inside $m_Z \pm 10$ GeV



⊙ *Missing invariant mass ($M_{\rm miss}$) distribution for $\sqrt{s}$ = (a) 500 GeV & (b) 1 TeV.*

Missing invariant mass distribution:

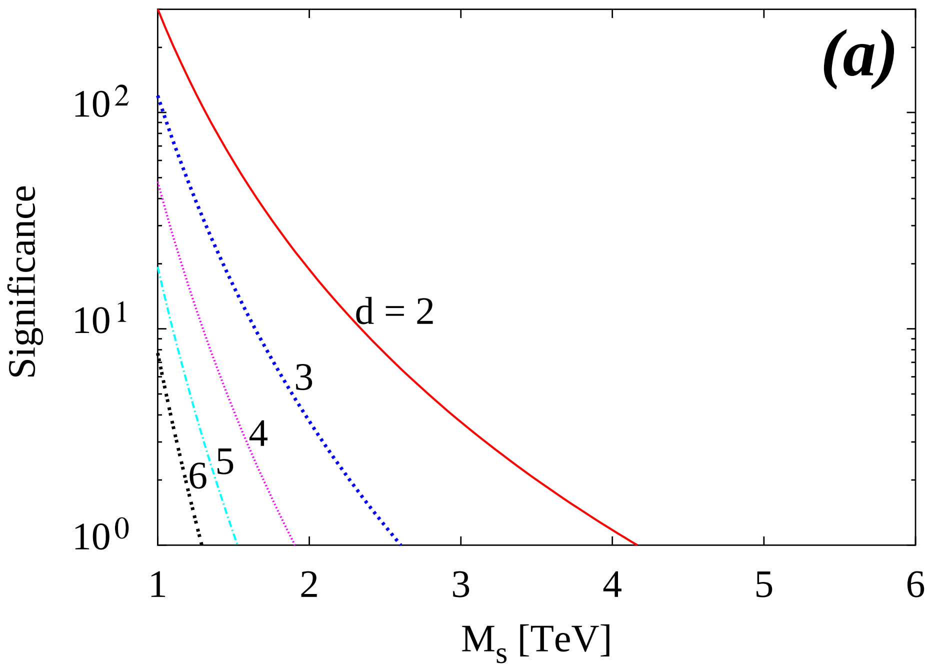
⊙ Background distribution is characterised by the neutrino pair (missing energy) arising from a real Z.

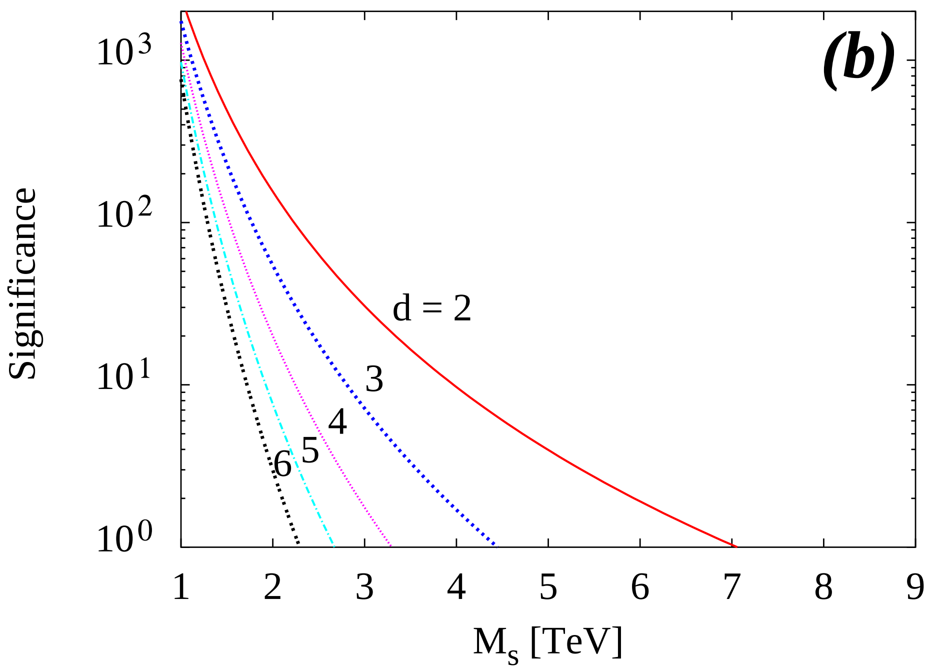
⊙ Missing invariant mass of the signal is much harder than that of the background.

⊙ The missing mass is a measure of the energy of the emitted graviton. Now it is well-known that the higher the energy, the more strongly the graviton is coupled to matter and consequently the higher the production cross-section. Moreover, a higher energy leads to a higher density of states, and this further enhances the cross-section.

⊙ Peaking behaviour is from radiative return to the Z-pole through graviton emission.

⊙ We can therefore obtain a clear separation of signal from background by imposing a cut : $M_{\text{miss}} >$ (350 Gev) 450 GeV for $\sqrt{s} =$ (500 GeV) 1 TeV





⊙ *Significance* $[\sigma^{signal}\sqrt{\mathcal{L}}/\sqrt{\sigma^{bg}}]$ *Vs.* M_S*, for unpolarized beams and* $\sqrt{s} =$ *(a) 500 GeV (b) 1 TeV.*

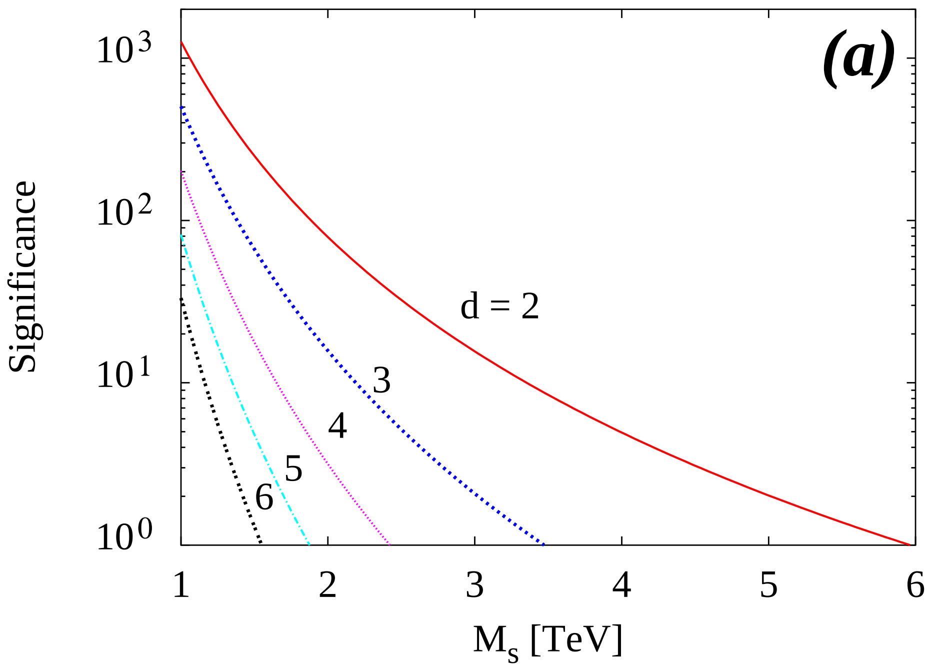
Used integrated luminosity $\mathcal{L} = 500 fb^{-1}$

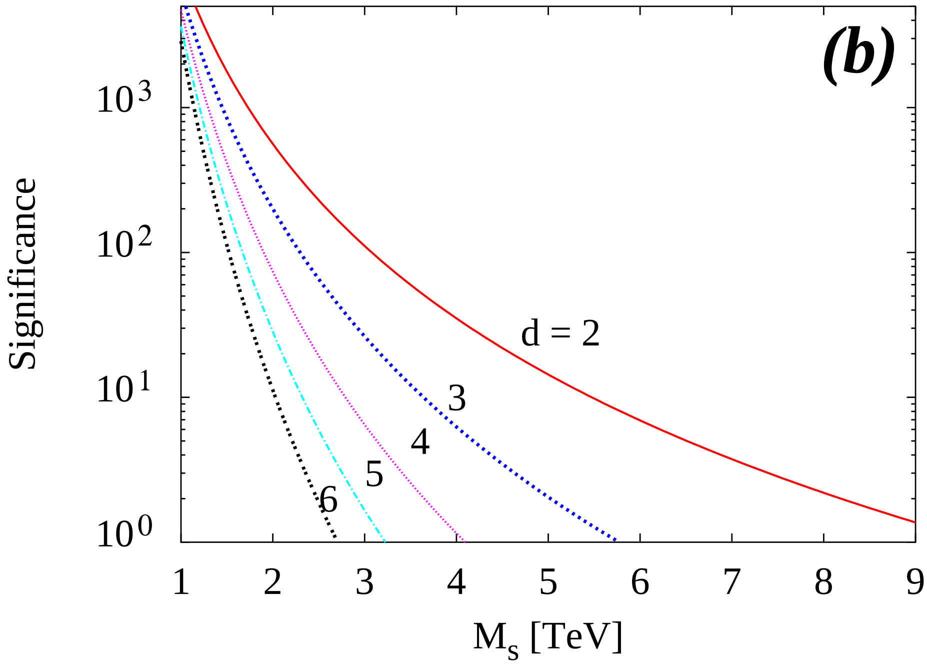
additional criterion $M_{miss} > (a)\ 350\ GeV\ (b)\ 450\ GeV$

⊙ Main background : $e^+e^- \to e^\pm \nu W^\mp$ with further decay of $W^\mp$
⇒ eliminated by considering polarized beam.

Of course we will loss some signal in this way. But, the experiment with Right-handed e^- and Left-handed e^+ beam would explore farther beyond the reach using unpolarized beam.

⊙ Typical values for the polarization efficiencies used in this analysis are $\mathcal{P}_{e^-} = 0.8$ and $\mathcal{P}_{e^+} = 0.6$.





⊙ *Significance Vs.* M_S *for polarized beams (80% & 60%)*
for $\sqrt{s} =$ *(a) 500 GeV (b) 1 TeV.*
Used integrated luminosity $\mathcal{L} = 500 fb^{-1}$
additional criterion $M_{miss} > (a)$ 350 GeV (b) 450 GeV

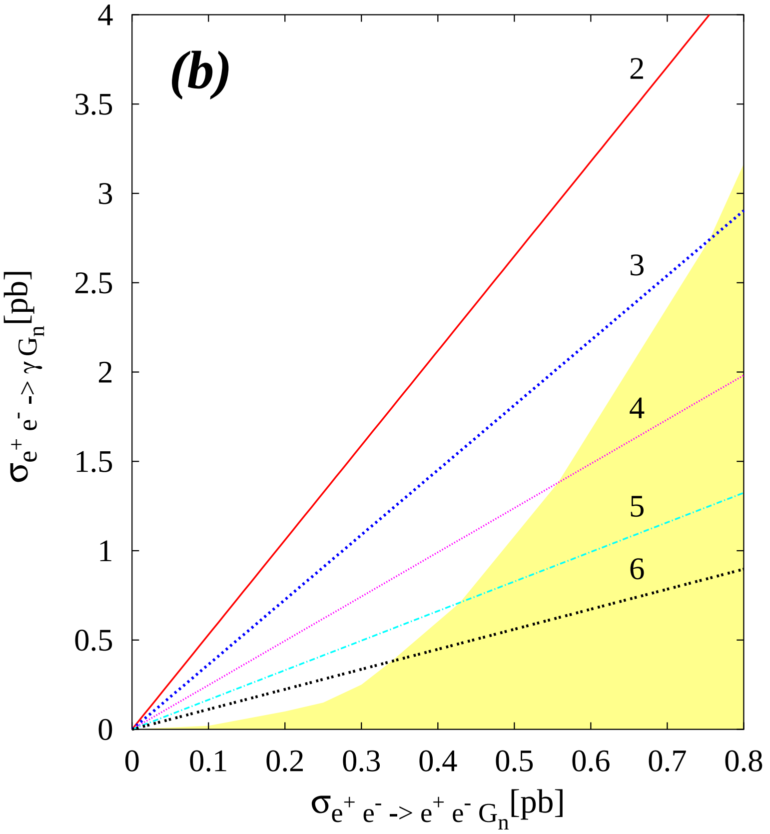
Results :

⊙ Here we have presented some results on string scale (M_s) sensitivity which can be achieved by studying $e^+e^- \to e^+e^-G$ for various numbers of extra dimensions ($\delta = 2, 3, 4, 5$).

⊙ Both Unpolarized and Polarized case has been studied.

Defining the statistical significant discovery to be Significance $[\sigma^{signal}\sqrt{\mathcal{L}}/\sqrt{\sigma^{bg}}] > 3$ at an e^+e^- collider with $\sqrt{s} = 1TeV$ and integrated luminosity $\mathcal{L} = 500 fb^{-1}$:

unpolarised	Polarised beams	no of ex-dim(δ)
5.4 TeV	7.4 TeV	for $\delta = 2$
3.6 TeV	4.6 TeV	for $\delta = 3$
2.7 TeV	3.4 TeV	for $\delta = 4$
2.3 TeV	2.8 TeV	for $\delta = 5$
2.0 TeV	2.4 TeV	for $\delta = 6$



⊙ *Correlation plot showing the polarized cross-sections for the processes* $e^+e^- \to \gamma G_n$ *and* $e^+e^- \to e^+e^-G_n$ *for different values of* d*. Each curve is generated by varying* M_S *for* $\sqrt{s} = 1$ *TeV.*

⊙ A more elegant way of distinguishing these signals from other forms of new physics is to compare the cross-sections arising from *both* the processes $e^+e^- \to \gamma G_n$ and $e^+e^- \to e^+e^-G_n$, both of which are determined by the two parameters d and M_S, and hence, will have some correlation.

⊙ Each curve corresponds to variation of M_S over the range allowed by current experimental constraints.

⊙ Using experimental data from a high energy e^+e^- machine, we should be able to pinpoint a small region (ideally a point) on the graphs.

⊙ The position of these would immediately direct one to the value of d; comparison of the cross-sections would now yield a measurement of the value of M_S.

Distinguishing graviton signal :

⊙ Supersymmetric signals (through a pair of sparticle production) can be distinguished by looking at the angular correlation between two leptons.

⊙ A more elegant way is to compare the signals arising from *both* the processes $e^+e^- \to \gamma G_n$ and $e^+e^- \to e^+e^- G_n \Rightarrow$ possible to pinpoint the value of d as well as M_S.

Conclusions :

⊙ To explore large extra dimensions, $e^+e^- \to \gamma G$ is most sensitive channel, but is not a unique demonstration of ADD.

⊙ If $e^+e^- \to e^+e^- G$ works upto string scale M_s, with a given $\sqrt{s}$, then one can have a clear idea on the string scale which can be probed in terms of both signals. This will consolidate the search strategy.