HUNTING RANDALL-SUNDRUM RADIONS IN e^+e^- COLLISION

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• Hierarchy between M_{Planck} and M_{EW}: Fine tuning of Higgs mass

$$m_h^2(\sim M_{EW}^2) = m_h^2|_{tree} + \delta m_h^2(\sim M_{Plank}^2) + ...$$

Solution 1: SUSY $\rightarrow$ Doubling the particle spectra

M_{Planck} is fundamental scale, M_{EW} is derived...

from dynamics : radiative EWSB...

Solution 2: Shift the hierarchy to geometry of space-time

• Assumes extra space (time) like dimensions: Gravity propagates in the bulk while the Standard Model lives in a $3+1$ dimensional sub-space.

M_{Planck} and M_{EW} are connected by the geometry of space-time

• Extra space like dimensions must be compactified..We do not see any deviation from Newton's law...

Arkani-Hamed, Dimopoulos, Dvali: size of the extra compactified dimension can be of the order of mm

Geometry is that of a $R^4 \times S^\delta$

$$G_N^4 = \frac{G_N^{4+\delta}}{V_\delta}, \quad \delta \geq 2 \text{ (observation)}$$

weakness of gravity is due to large volume of extra dimension...

Randall, Sundrum : Only one extra space-like dimension and compactification radius close to Planck length but:

$$ds^2 = e^{2kr_c\phi}\, \eta^{\mu\nu} dx_\mu dx_\nu + r_c^2 d\phi^2$$

with two $3+1$ dimensional sub-spaces at $\phi = 0$ and $\phi = \pi$

SM is confined at $\phi = \pi$ sub-space..

- weakness of gravity connected to this exponential warp factor....

More about Randall-Sundrum........

- all dimensionfull parameters are scaled by a factor $e^{-kr_c\pi}$ at $\phi = \pi$ sub-space (visible brane !)....

- all large ($\sim M_{Planck}$) masses are at $\phi = 0$ brane

- at $\phi = \pi$, we see some reduced image of EW scale...

special value for : $kr_c(\sim 12)$

Effective theory at $\phi = \pi$ contains tower of gravitons separated by a gap of TeV...

Couplings of the KK gravitons are not suppressed by M^4_{Planck} any more..

What is a Radion ?

• Also have a mass-less (gravi-)scalar : (radion $\phi \sim e^{-k\pi T(x)}$) corresponding to g_{55} component of bulk metric...

• r_c can be thought as vev of a scalar field $T(x)$...

• but one needs a potential for dynamically generating this vev...

• Goldberger and Wise: introduce a scalar field in bulk and in turn generate a potential in bulk...

• Integrating out the ϕ from 5-dimensional scalar potential: Effective potential on $3+1$ dimensional sub-spaces at $\phi = \pi$ implies a mass and dynamically generated vev (Λ_ϕ) for the *radion* ...

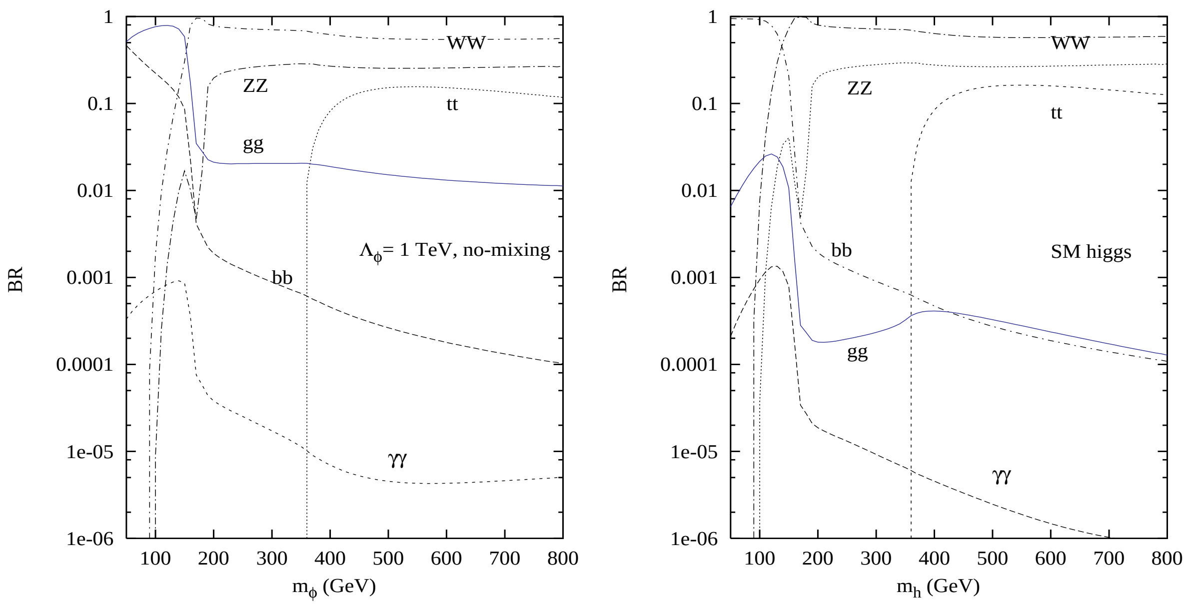
• Phenomenologically important: without any fine tuning with the parameters,
$\Lambda_\phi \sim 1$ TeV and m_ϕ can be below a TeV !!

• Radion couples to matter/SM fields via T^μ_μ

$$\mathcal{L} = \frac{1}{\Lambda_\phi}\,\phi\,T^\mu_\mu$$

$$\begin{aligned} T^\mu_\mu &= \Sigma m_f \bar{f} f + m_V^2 V_\mu V^\mu \\ &\quad + \frac{\beta(g_s)}{2g_s}\, G^{\mu\nu}G_{\mu\nu} + \frac{\beta(e)}{2e}\, F^{\mu\nu}F_{\mu\nu} \\ &\quad + (2m_h^2 h^2 - \partial_\mu h \partial^\mu h) \end{aligned}$$

• Couplings are very similar to the SM higgs



Gluon Gluon decay branching ratio is drastically enhanced w.r.t the SM higgs !

∗ At LHC, enhanced coupling to gg was exploited:

$$pp(gg) \to \phi \to \gamma\gamma, ZZ, WW$$

- Apart from this.....Radion-Higgs mixing:

$$S = -\xi \int d^4x \sqrt{-g_{vis}} R(g_{vis}) H^\dagger H$$

$R(g_{vis}) \rightarrow$ Ricci scalar on SM brane..with metric g_{vis}

$$\langle H \rangle = v, \quad \langle \phi \rangle = \Lambda_\phi, \quad \text{with} \quad \gamma \equiv \frac{v}{\Lambda_\phi}$$

- Kinetic Mixing between Higgs and Radion.....

$$\begin{pmatrix} \phi \\ H \end{pmatrix} \rightarrow \begin{pmatrix} \phi' \\ H' \end{pmatrix} \equiv Z_R \mathcal{M}^{-1} \begin{pmatrix} \phi \\ H \end{pmatrix}$$

$$\mathcal{M} = \begin{pmatrix} \cos\theta & -\sin\theta \\ Z_R \sin\theta - 6\xi\gamma\cos\theta & Z_R\cos\theta + 6\xi\gamma\sin\theta \end{pmatrix}$$

where

$$Z_R^2 = 1 - 6\xi\gamma^2(1+6\xi) \quad \tan 2\theta = \frac{12\xi\gamma Z_R m_h^2}{m_H^2(Z_R^2 - 36\xi^2\gamma^2) - m_\phi^2}.$$

$$m_{\phi'}^2 = (\mathcal{M}_{21}^2 m_h^2 + \mathcal{M}_{11}^2 m_\phi^2)/Z_R^2 \quad m_{h'}^2 = (\mathcal{M}_{22}^2 m_h^2 + \mathcal{M}_{12}^2 m_\phi^2)/Z_R^2$$

- Kinetic terms must be positive...

$$\frac{-1}{12}\left(1 + \sqrt{1+4/\gamma^2}\right) \le \xi \le \frac{1}{12}\left(\sqrt{1+4/\gamma^2} - 1\right)$$

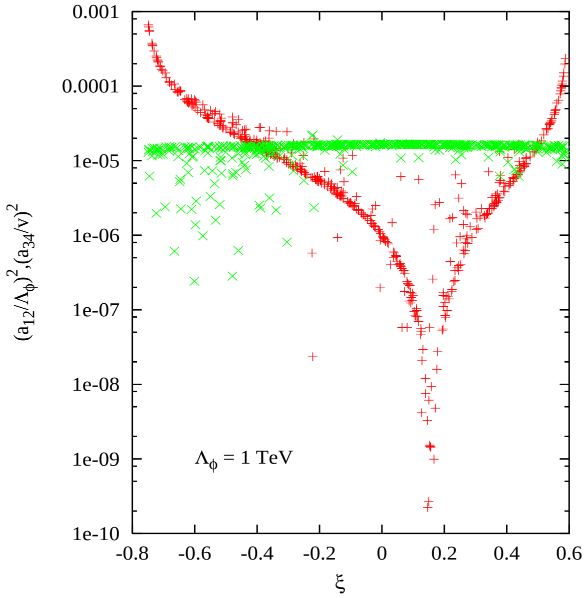
$$\Lambda = 1 \text{ TeV} \rightarrow -0.75 < \xi < 0.59$$
$$\Lambda = 10 \text{ TeV} \rightarrow -6.7 < \xi < 6.6.$$

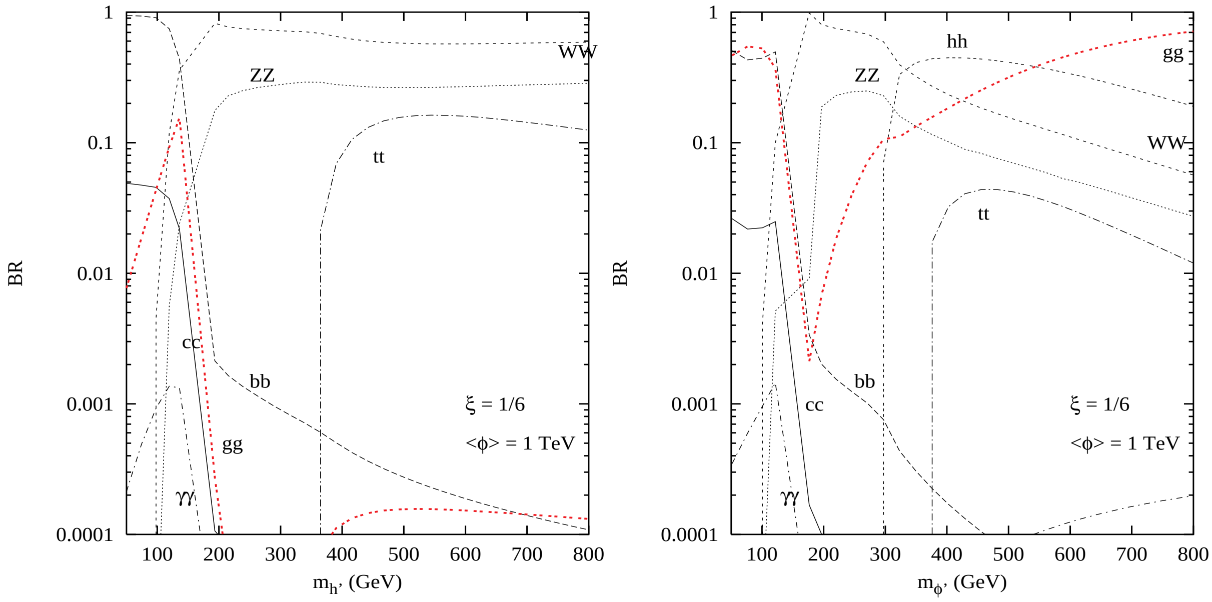
Unitarity in $W_L W_L$ scattering amplitudes constrain ξ, Λ_ϕ

Effects of Higgs-Radion mixing on the couplings

$$\mathcal{L} = -\frac{1}{\Lambda_\phi}(m_{ij}\bar{\psi}_i\psi_j - M_V^2 V_{A\mu}V_A^\mu)\left[a_{34}\frac{\Lambda_\phi}{v}h' + a_{12}\phi'\right]$$

also non-trivial effect on gg coupling





around $\xi = \frac{1}{6}$, gg branching ratio is close to 1 for heavy radions

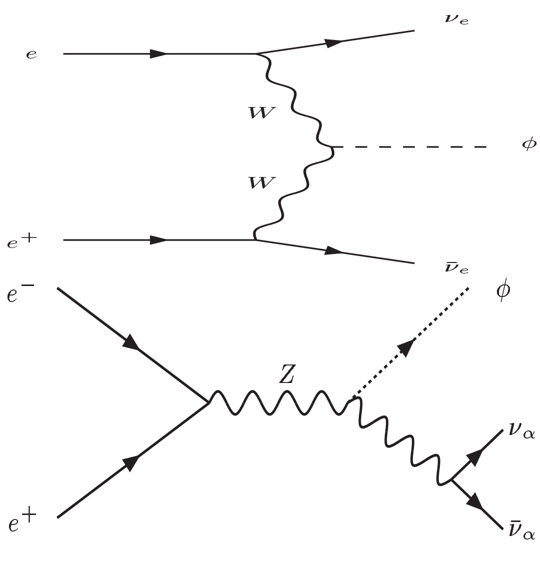
also..due to smallness of ϕ coupling to $V, f\ldots$ (soon see it is a no-lose situation for us..!!)

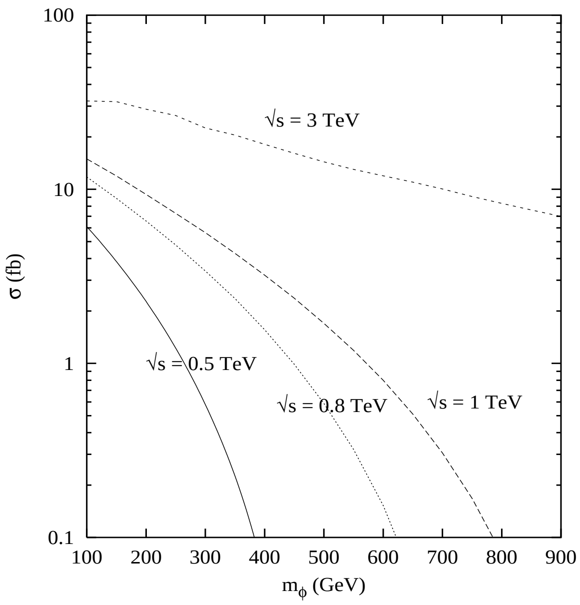
• What can we say at the Linear e^+e^- colliders ?

Important: Can we also differentiate it from SM higgs ?

Should use some production/decay mode which is different from SM higgs ? $\gamma\gamma$ or gg

For $\sqrt{s_{ee}} > 500$ GeV $e^+e^- \to \nu\bar{\nu}\phi$ is the dominant production mode.





ϕ production at $\Lambda_\phi = 1$ TeV : suppressed w.r.t h_{SM} production by a factor of 16 ($\sim \frac{v}{\Lambda_\phi}$)

Choose a decay mode to compensate this suppression.... We propose to investigate $e^+e^- \to \nu\bar{\nu}(\phi \to)gg$

At an e^+e^- collider gg final state is not difficult to handle !

Similar final state can arise in SM from

$$e^+e^- \to (\gamma^*, Z^*/Z \to)\nu\bar{\nu}jj$$

$e^+e^- \to \nu\bar{\nu}(\gamma^*, Z^*/Z, WW)jj$: same topology with signal...

Discriminating features:

1. Invariant mass of the jets....

for signal it is coming from ϕ, peaked around m_ϕ

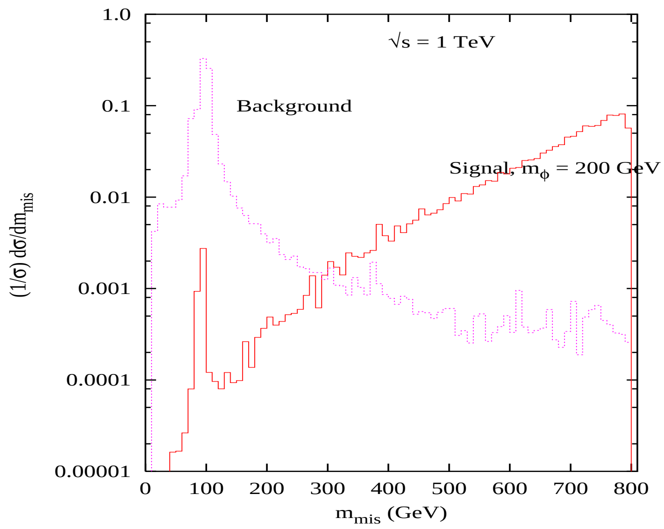
a dominant part of background also comes from Z...

around Z mass our channel is not efficient.....

2. Mass of the system recoiling against the jets...

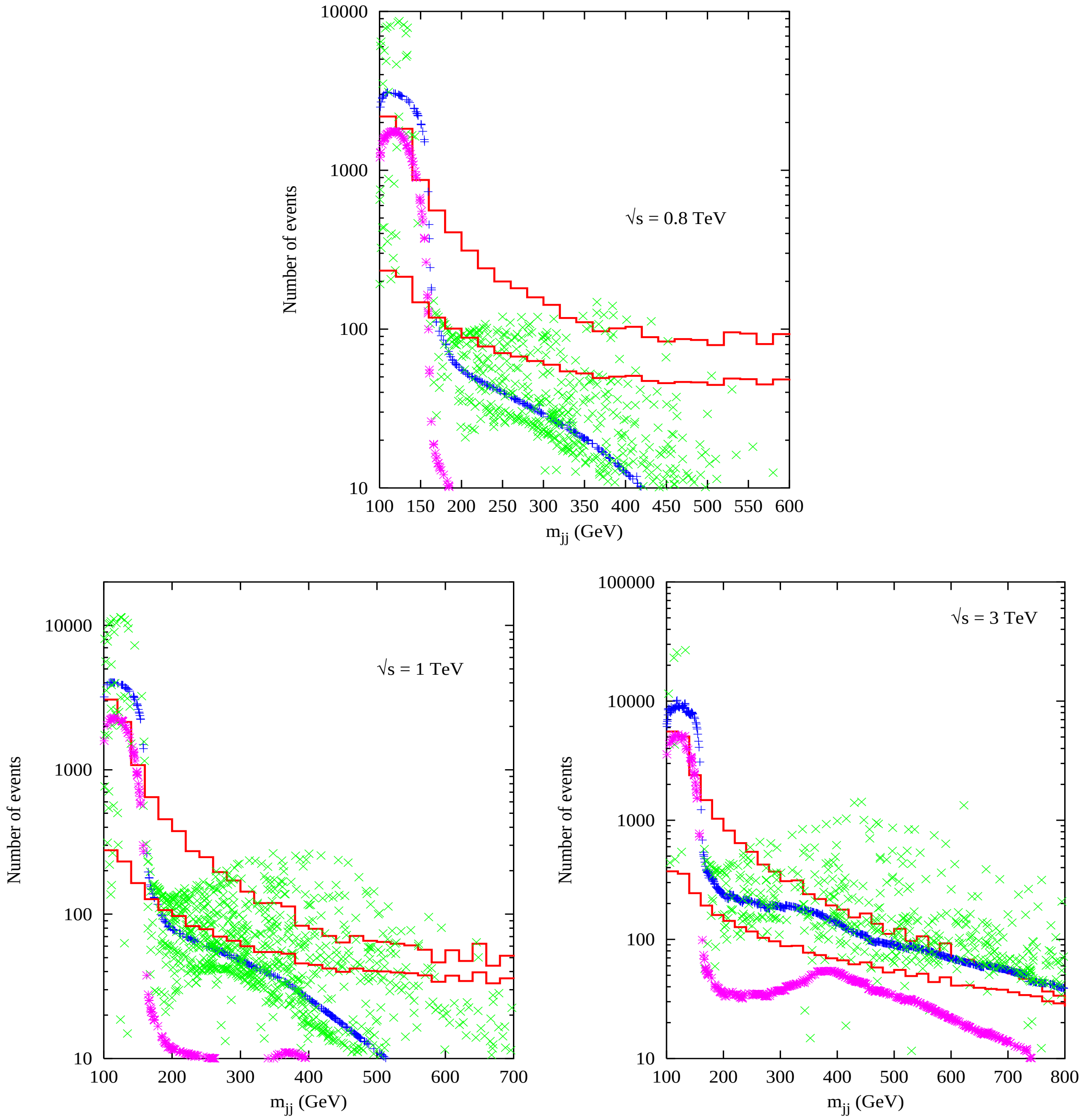
has a sharp edge for signal $\sim (\sqrt{s} - m_\phi)$

has a peak $\sim m_Z$ for background...



Apart from selection cuts....E_j, η etc....use $m_{mis} >$ 120 GeV then compare the invariant mass of the jet-pair for signal and background..

Let us look at some numbers....



Used some simple selection cuts like
$E_j > 15$ GeV, $\not{p} > 15$ GeV, $|\eta| < 2.5$

1 TeV and 3 TeV cases are promising !!

To Summarise....

- Randall-Sundrum scenario provides a well motivated alternative for SUSY....

- The lowest lying gravitational excitation, the radion , can be of mass less than a TeV...

- Being a graviscalar couples to the SM particles via the trace of T^{μ}_{ν}...

- Radion coupling to a pair of gluons is quite big due to conformal anomaly...

- Higgs Radion mixing (kinetic mixing) can also enhance the radion couplings in a non-trivial way...

- At the hadronically clean environment of an e^+e^- collider, $\phi \to gg$ can be exploited to look and probably differentiate it from a SM higgs...

- Our investigation (at a basic level) shows the process $e^+e^- \to \nu\bar{\nu}(\phi \to)gg$ resulting in missing momentum + 2 jet final state can be used as a good probe to look for radion, differentiate it from SM higgs and also to some extent probe higgs-radion mixing....

- Though at center of mass energy 500 GeV the results are not very promising at higher energies from 800 GeV and above one can expect 5σ effects upto quite high radion mass..

- Need for more careful background analysis..

- $\gamma\gamma \to \phi \to gg$ may also be helpful in this line..