Phenomenology of two Universal Extra Dimensions

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Based on:

KG and A. Datta [arXiv:0801.0943 and 0802.2162(hep-ph)]

Plan of talk

- Introduction to *2-Universal Extra Dimensions (2-UED)*
- *Particle Spectra*
- *Spinless Adjoints* and *Interactions*
- Production of *Spinless Adjoints* at the LHC.
- Signature of EW *KK Gauge Bosons* at the ILC.
- Concluding Remarks

Introduction to *2-UED*

As the name suggests, in *2UED* all the *SM fields* can propagate universally in the six-dimensional space-time $x^\alpha,\ \alpha = 0, .., 5$.

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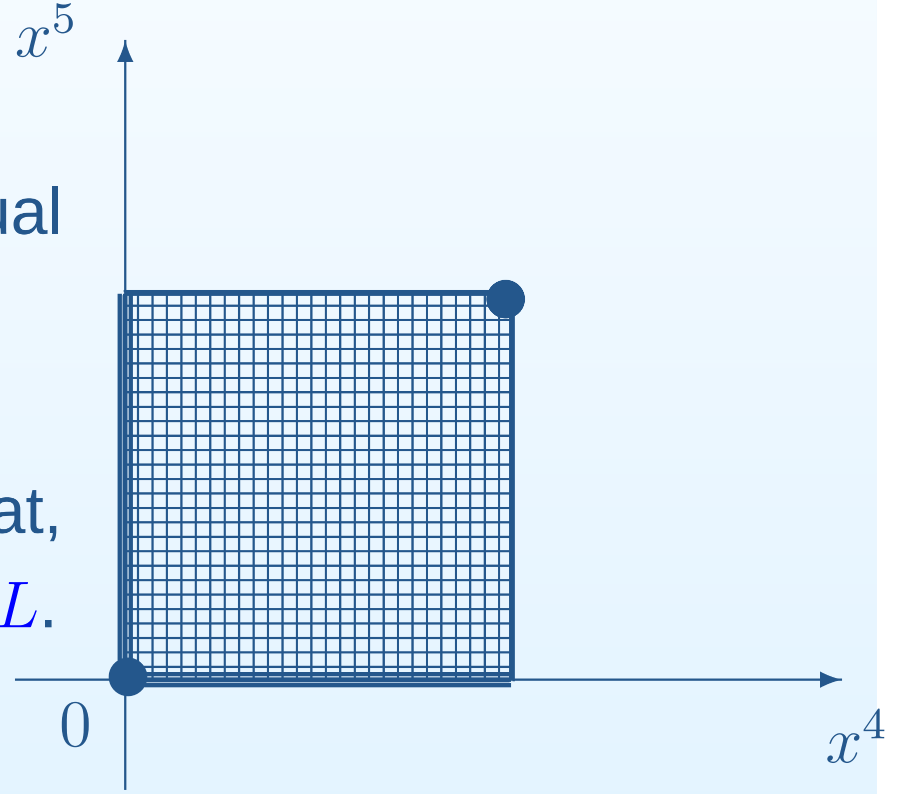
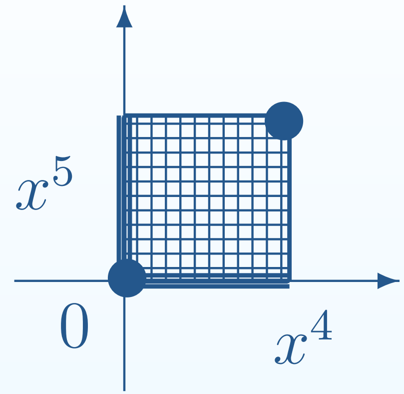


Compactification

- Toroidal Compactification



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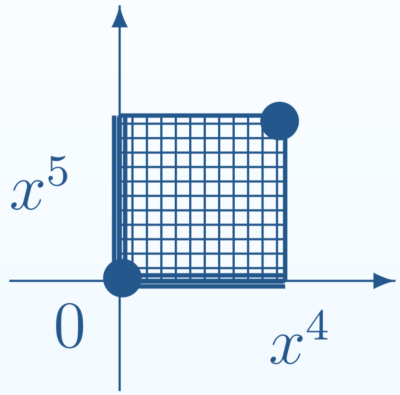

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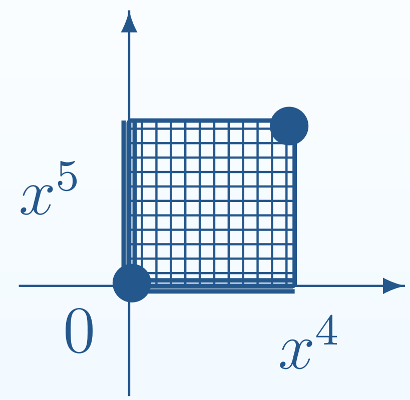

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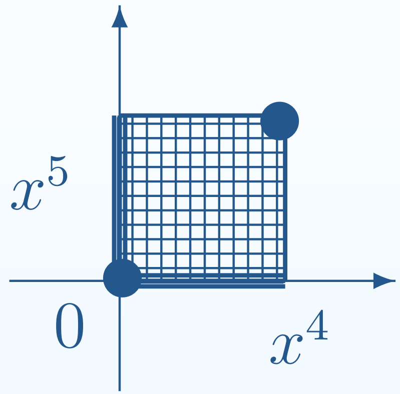

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  - Leaves at least a single 4D fermion of definite chirality.

Continued...

The physics at identified points is identical if the *Lagrangian* takes the same value for any field configuration:

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- Gauge Symmetry + BC for scalar fields $\Phi(x^\alpha)$ or Weyl fermions $\Psi_\pm(x^\alpha)$.
    - Fixes the BC's for 6D gauge fields.

Decomposition

Any 6D field (fermion/gauge or scalar) $\Phi(x^\mu, x^4, x^5)$ can be decomposed as:

$$\Phi(x^\mu, x^4, x^5) \; = \; \frac{1}{L} \sum_{j,k} f_n^{(j,k)}(x^4, x^5) \Phi^{(j,k)}(x^\mu)$$

$$f_n^{(j,k)}(x^4, x^5) = \frac{1}{1 + \delta_{j,0}\delta_{k,0}} \left[e^{-in\pi/2} cos \left(\frac{jx^4 + kx^5}{R} + \frac{n\pi}{2} \right) + cos \left(\frac{kx^4 - jx^5}{R} + \frac{n\pi}{2} \right) \right]$$

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- Form of $f_n^{(j,k)}(x^4, x^5)$ tells that only $n = 0$ and $l = 0$ allows zero mode ($j = k = 0$) fields in the 4D effective theory.

Fields in 6D

- **Spin-1/2 fields** in 6D:
  - There six anti-commuting matrices $\Gamma^{\alpha},\ \alpha = 1,..,5$ with minimum dimensionality 8×8, defined as $\Gamma^{\mu} = \gamma^{\mu} \otimes \sigma^{0} \quad , \quad \Gamma^{4,5} = i\gamma_5 \otimes \sigma^{1,2}$
  - 6D fermions have $+$ or $-$ chirality, defined by the eigenvalue of the $\bar{\Gamma} = -\gamma_5 \otimes \sigma^3$ 6D chirality operator: $\bar{\Gamma}\Psi_{\pm} = \pm\Psi_{\pm}$.
  - A 6D chiral fermion include both 4D chiralities: $\gamma_5 \otimes \sigma^0 \Psi_{\pm L} = -\Psi_{\pm L}$ and $\gamma_5 \otimes \sigma^0 \Psi_{\pm R} = -\Psi_{\pm R}$
  - BC for Left and Right chiral components 6D Weyl fermions are related by: $n_L^{\pm} - n_R^{\pm} = \pm 1$
- **Spin-1 fields** in 6D:
  - In 6D, the gauge fields has six components $A_{\alpha}(x^{\mu}, x^4, x^5),\ \alpha = 0,..,5$.
  - Upon compactification, they decompose into towers of 4D spin-1 fields $A_{\nu}^{(j,k)}(x^{\mu})$, two towers of spin-0 fields $A_4^{(j,k)}(x^{\mu})$ and $A_5^{(j,k)}(x^{\mu})$.

Continued...

- $A_{4,5}^{(j,k)}(x^\mu)$ are not the physical fields. Define at each KK label two scalar fields, $A_G^{(j,k)}$ and $A_H^{(j,k)}$ such that:

$$\partial_4 A_5 - \partial_5 A_4 = \frac{1}{L}\sum_{j\geq 1}\sum_{k\geq 0} M_{(j,k)} A_H^{(j,k)}(x^\nu) f_0^{(j,k)}(x^4, x^5)$$

$$\partial_4 A_4 + \partial_5 A_5 = \frac{1}{L}\sum_{j\geq 1}\sum_{k\geq 0} M_{(j,k)} A_G^{(j,k)}(x^\nu) f_0^{(j,k)}(x^4, x^5)$$

  - Under 6D gauge transformations: $A_\alpha \to A_\alpha + \partial_\alpha \xi / g_6$, $A_H^{(j,k)}$ remains invariant but $A_G^{(j,k)}$ does not.

- Spin-0 fields in 6D
  - $\mathcal{L}_\Phi = |D_\alpha \Phi|^2 - \frac{\lambda_6}{2}\left(\Phi^\dagger\Phi - \frac{1}{2}v_6^2\right)^2$ with $\Phi = \frac{1}{\sqrt{2}}(v_6 + h)\, e^{i\frac{\eta}{v_6}}$
  - Compactification: $h^{(j,k)}(x^\mu)$ and $\eta^{(j,k)}(x^\mu)$, (j,k) includes $(0,0)$.
  - Mixing with Spinless Adjoints And Physical fields:
    - $h^{(j,k)}(x^\mu)$: KK tower of SM Higgs, $M_h^{(j,k)} = \sqrt{M_{j,k}^2 + \lambda_4 v_4^2}$
    - $A_H^{(j,k)}(x^\mu)$: KK tower of Spinless Adjoints, $M_{A_H}^{(j,k)} = \sqrt{M_{j,k}^2 + g_4^2 v_4^2}$

$$\tilde{A}_G^{(j,k)} = \left(M_{j,k} A_G^{(j,k)} + g_4 v_6\, \eta^{(j,k)}\right) / M_A^{(j,k)}$$

The SM in 6D

In 6D, the fields and BC's of the fields are chosen such that upon compactification the Zero-Modes reproduce SM.

- Anomaly cancellation + fermion mass generation: Force the choice of quarks generations to be $Q_+ \equiv (U_+, D_+),\ U_-,\ D_-$.

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  - 6D singlet fermions $\psi_- \ : \ \psi_{-L}^{(j,k)} + \psi_{-R}^{(j,k)} + \psi_{-R}^{(0,0)}$
  - These zero mode fields are identified with the SM fermions. As for example, $(u_L, d_L) \equiv Q_{+L}^{(0,0)}(x^\mu)$, $u_R \equiv U_{-R}^{(0,0)}(x^\mu)$ and $d_R \equiv D_{-R}^{(0,0)}(x^\mu)$.

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- **6D Higgs Doublet:** A tower of 4D Scalar Weak Doublets.
  - Zero-mode doublet: W and Z-boson mass + and the SM Higgs.
  - KK-doublet: KK tower for SM Higgs + mix with longitudinal modes of KK EW gauge bosons. (mixing is suppressed by R^{-1}).

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- Complete 4D effective *Lagrangian*:

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- Contributions to those *Localized Operators*:

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The tree-level masses for (j,k)-th KK-mode particles are given by $\sqrt{M_{j,k}^2 \ + \ m_0^2}$, where $M_{j,k} = \sqrt{j^2+k^2}/R$. m_0 is the mass of the corresponding zero mode particle.

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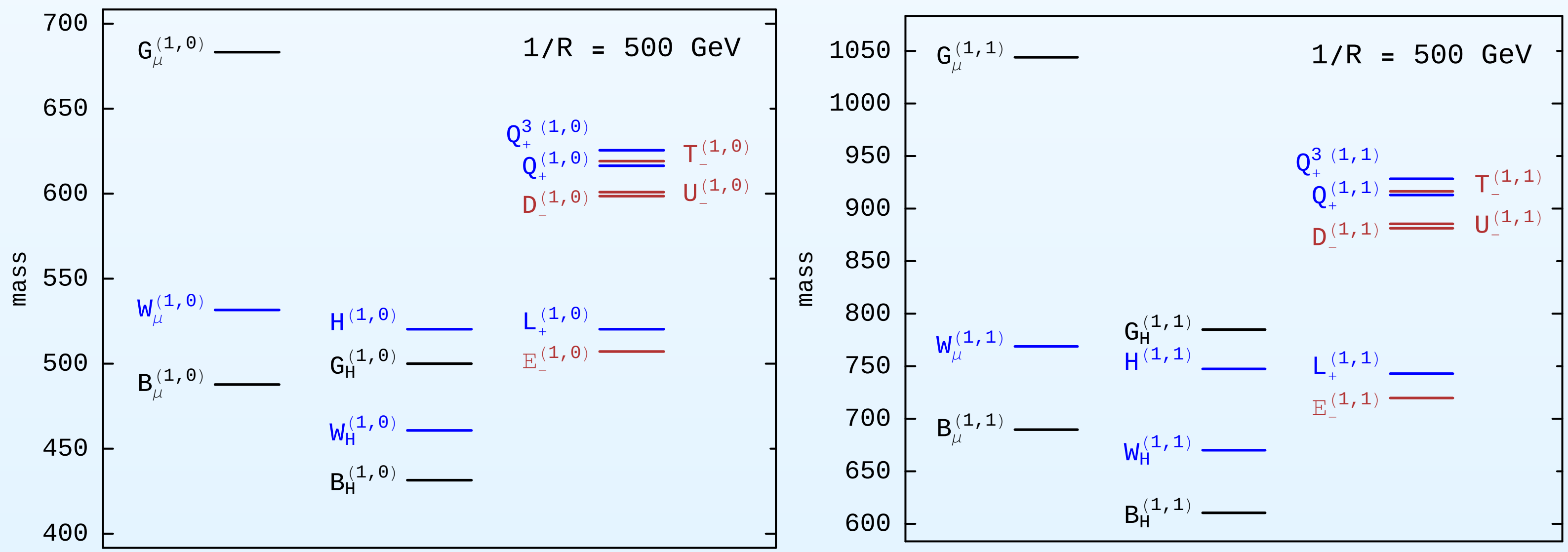
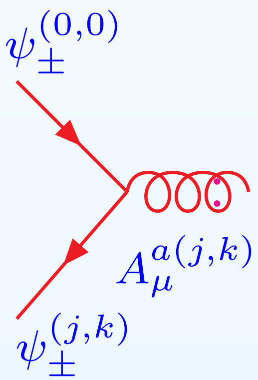


- G. Burdman, B. Dobrescu, E. Ponton, [Phys. Rev. D **74**, 075008 (2006)]

Interactions of Spinless Adjoints

- KK-number conserving (KKNC) interactions.

$$\left[i \int_0^L dx^4 \int_0^L dx^5 \left(\bar{\Psi}_\pm \Gamma^\alpha D_\alpha \Psi_\pm \right) \right]$$



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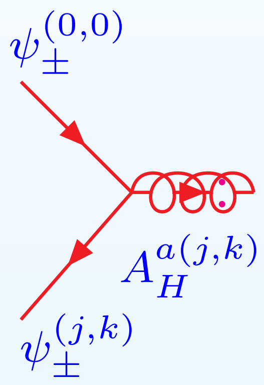

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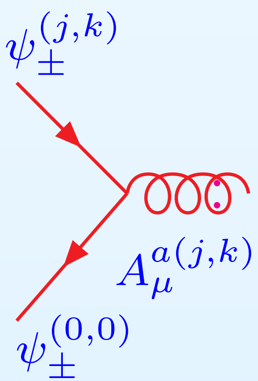

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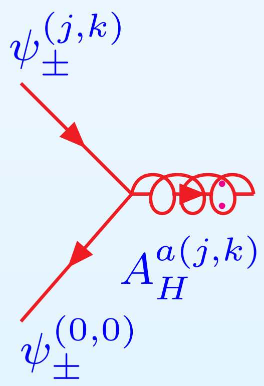

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Localized Operators, after compactification, give rise to the KK number violating (KKNV) 2-point and 3-point functions.

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KG, A. Datta [arXiv:0801.0943(hep-ph)]

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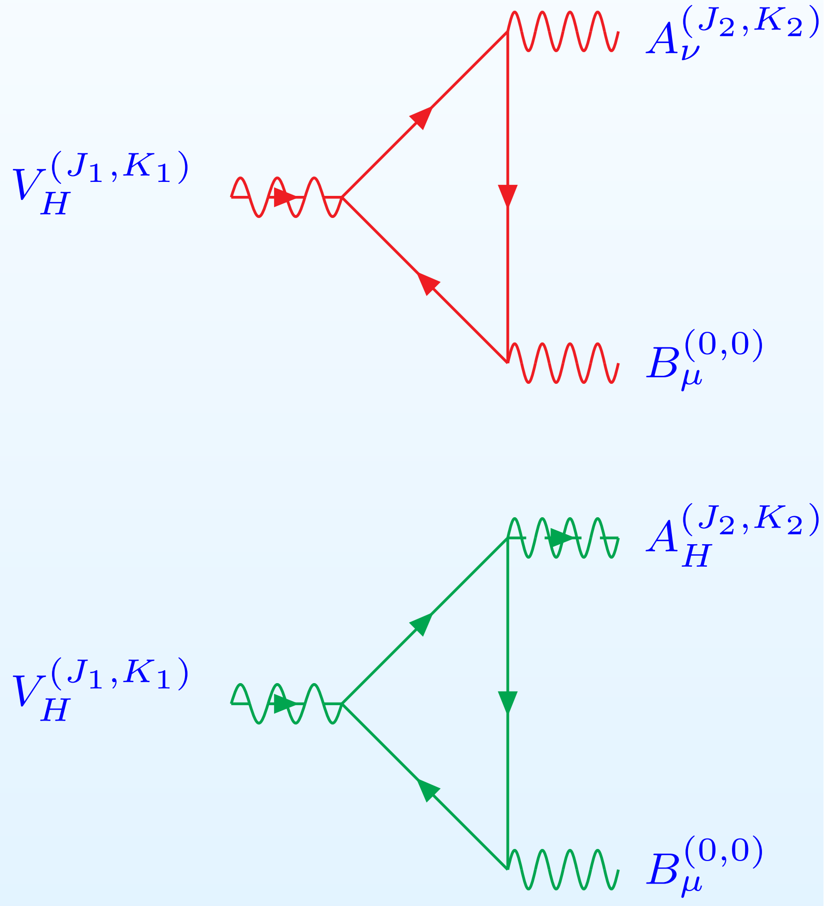

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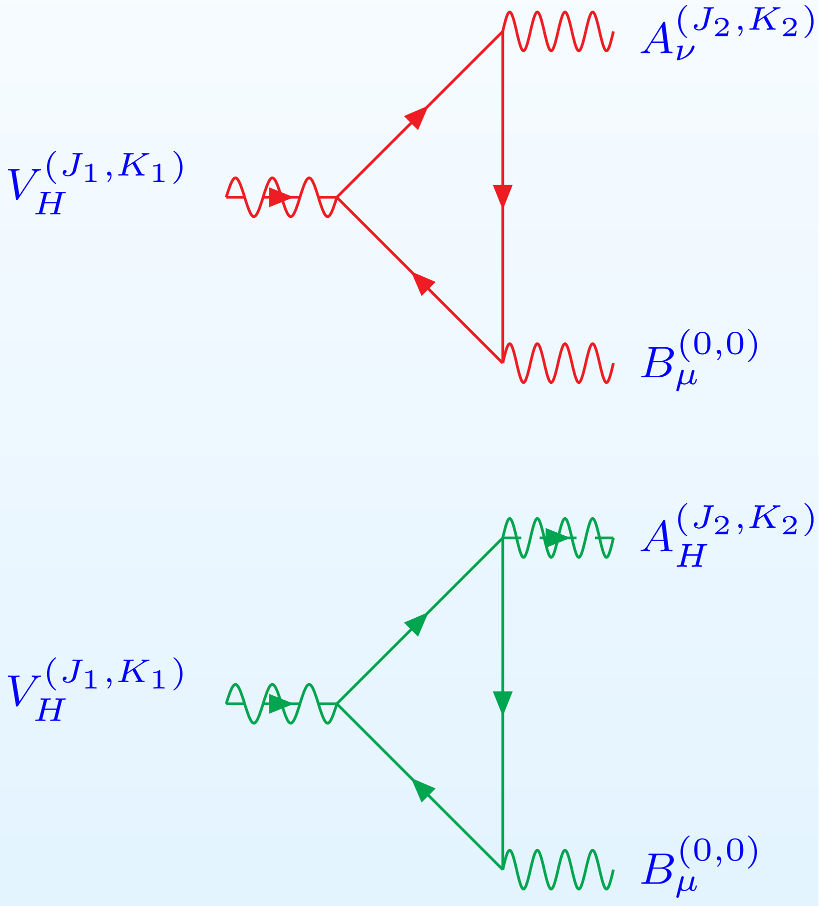

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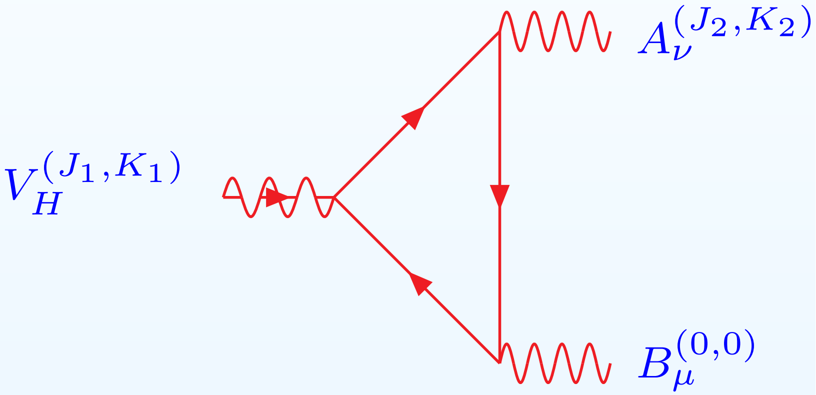

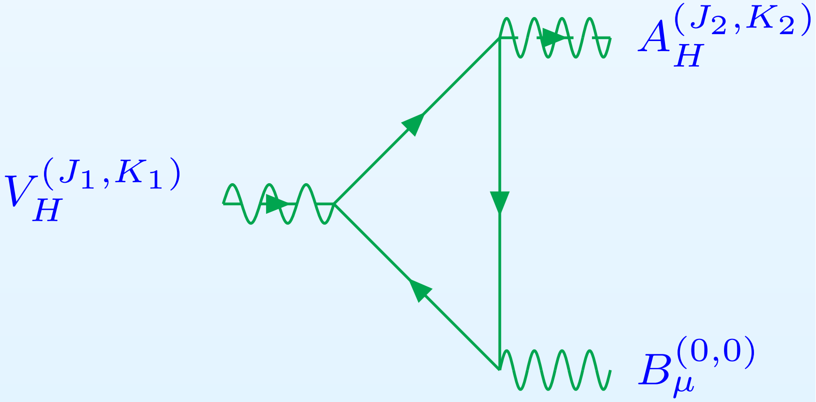

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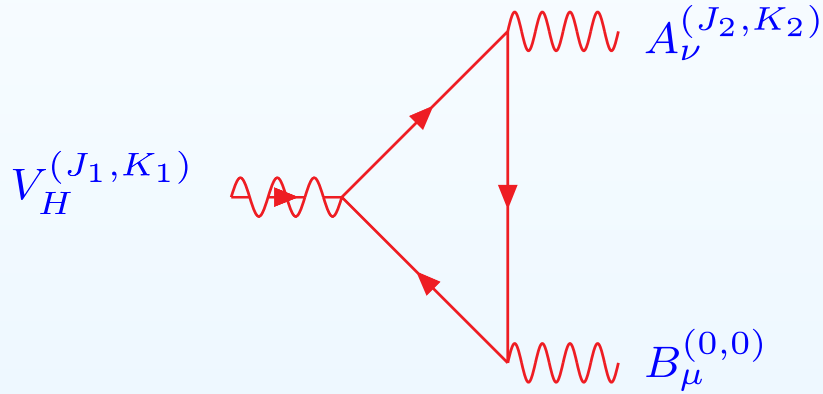

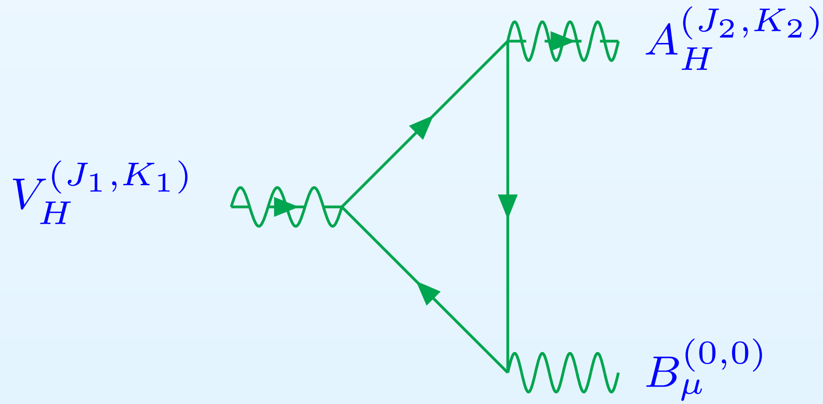

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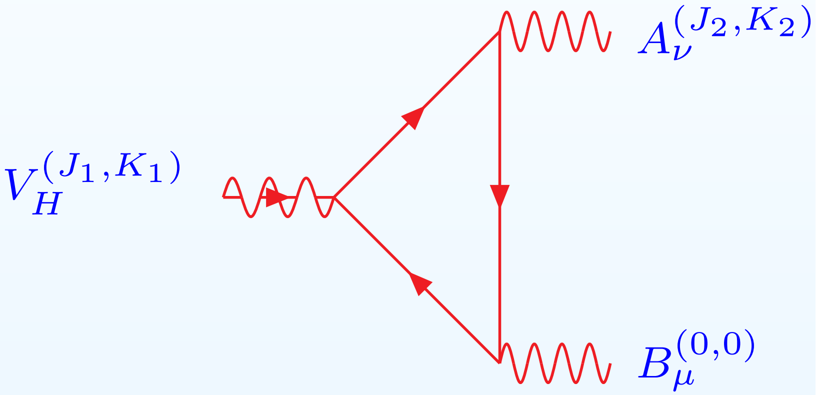
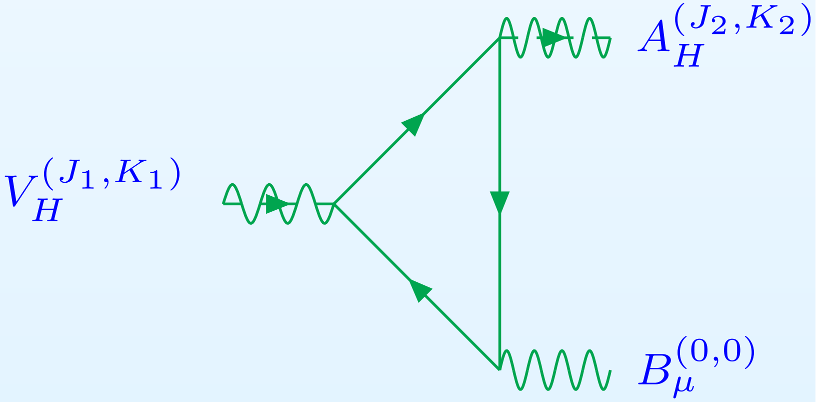
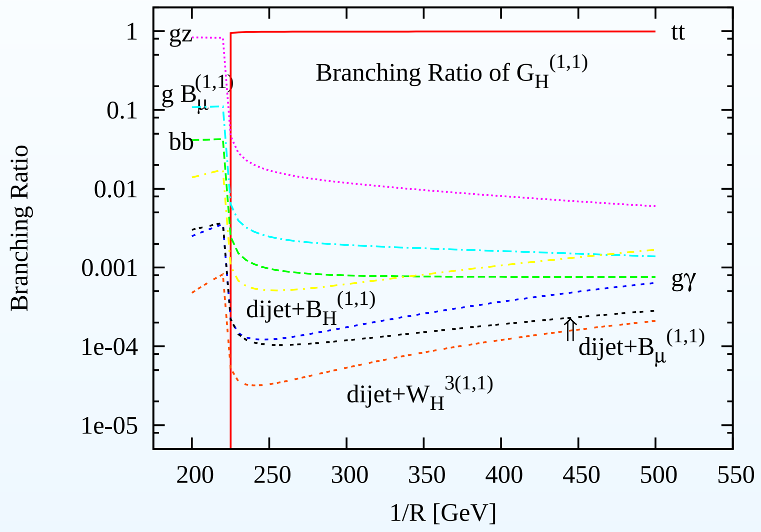
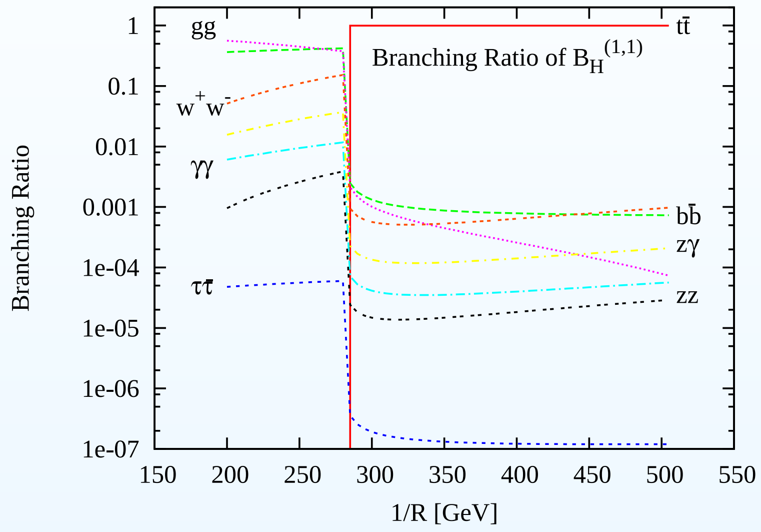
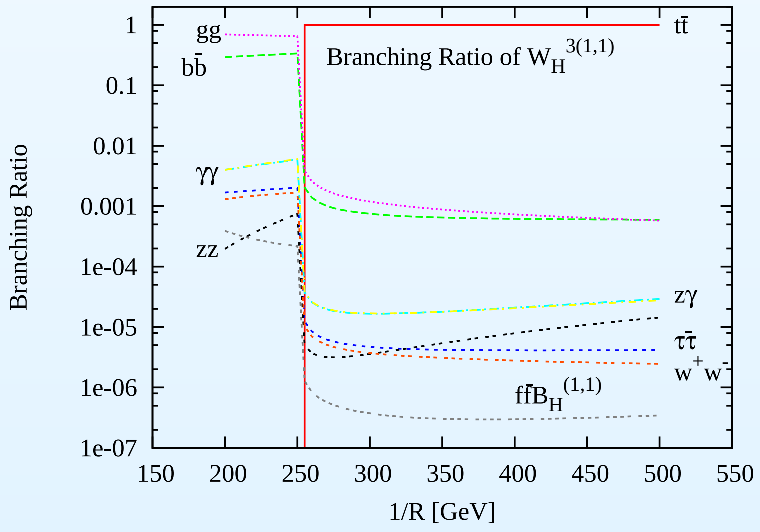




Decays of (1,1) Spinless Adjoints







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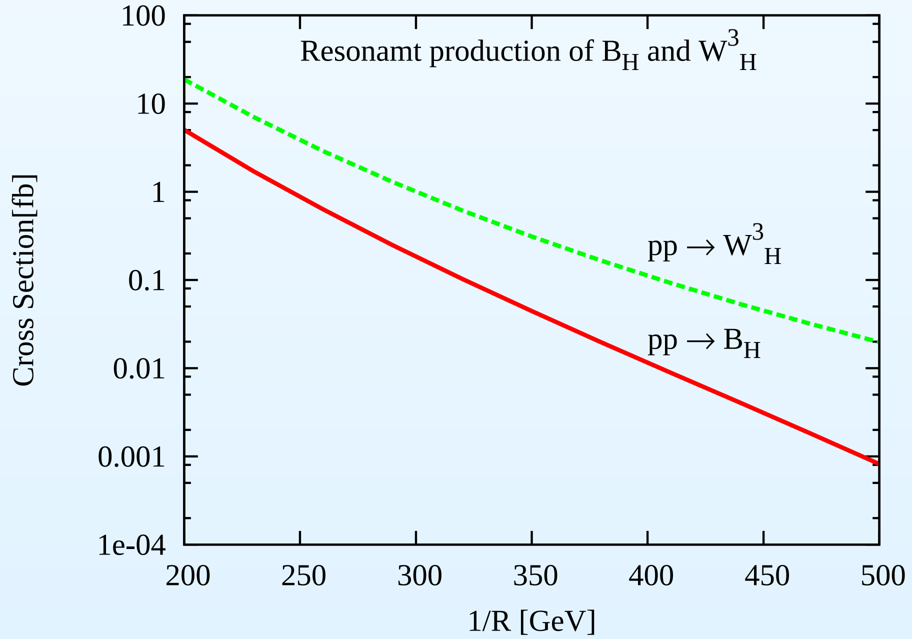
- Coupling with SM gluons generated by finite 1-Loop Effect.

$$\sigma(pp \to V_H^{(1,1)} + X) = \frac{\pi^2}{36 s m_{V_H}} \Gamma(V_H^{(1,1)} \to gg) \int_\tau^1 \frac{dx}{x} g(x, m_V^2) g(\frac{\tau}{x}, m_V^2)$$



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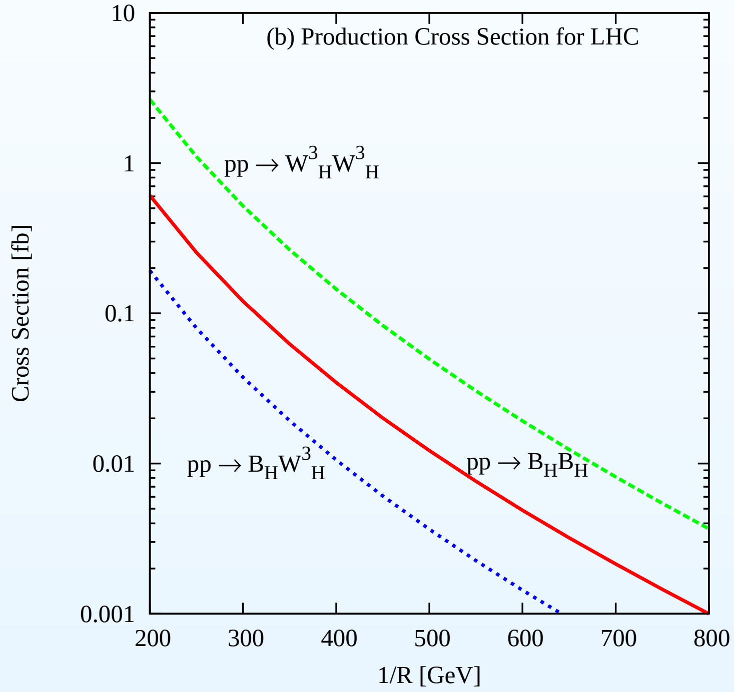

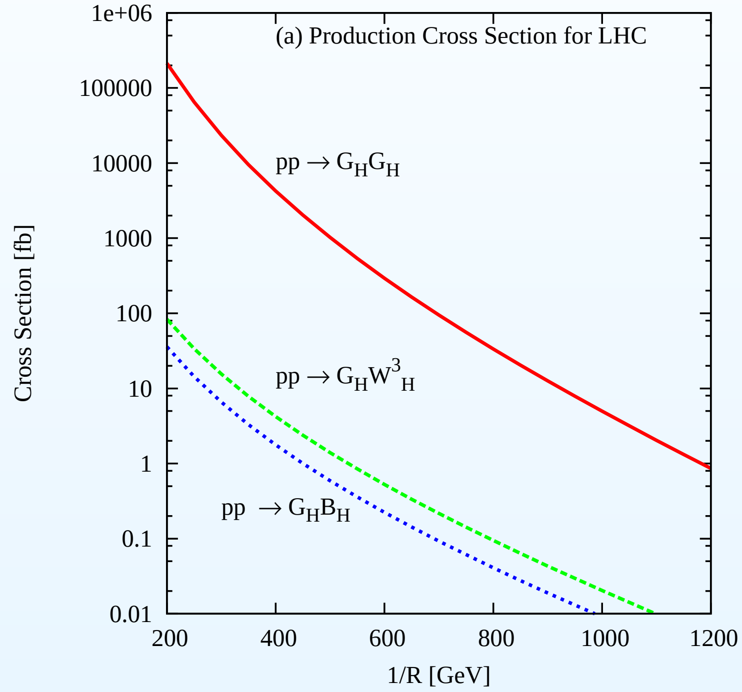

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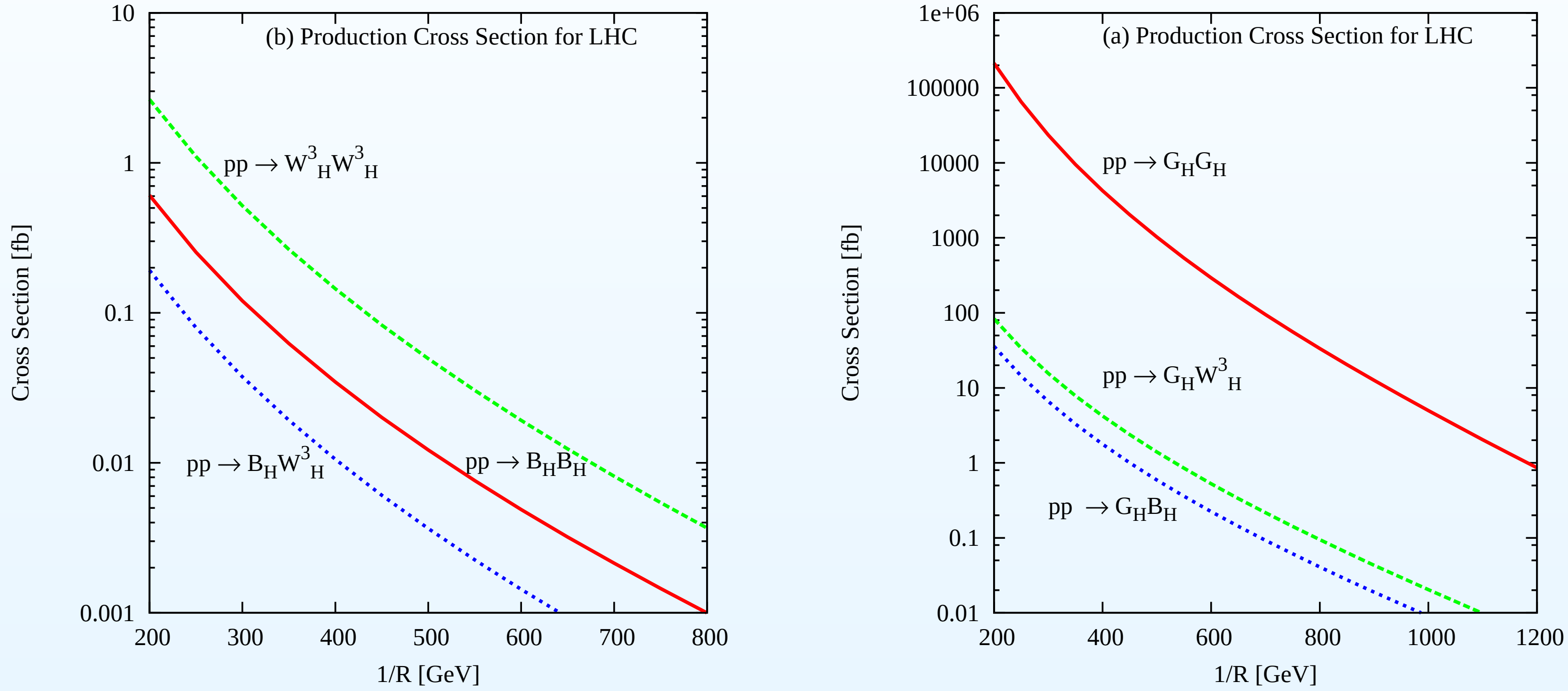

- Being a pure QCD process $G_H^{(1,1)}$ has a large cross-section at the LHC.
- Pair productions of EW Spinless Adjoint are miniscule even for lower values of R^{-1}.

Signatures at future e^+e^- collider

Even KK parity gauge bosons couples with e^+e^- via KKNV interactions.

- We consider $B_\mu^{(1,1)}$, $W_\mu^{3(1,1)}$ production in association with a photon. This has some interesting consequences.

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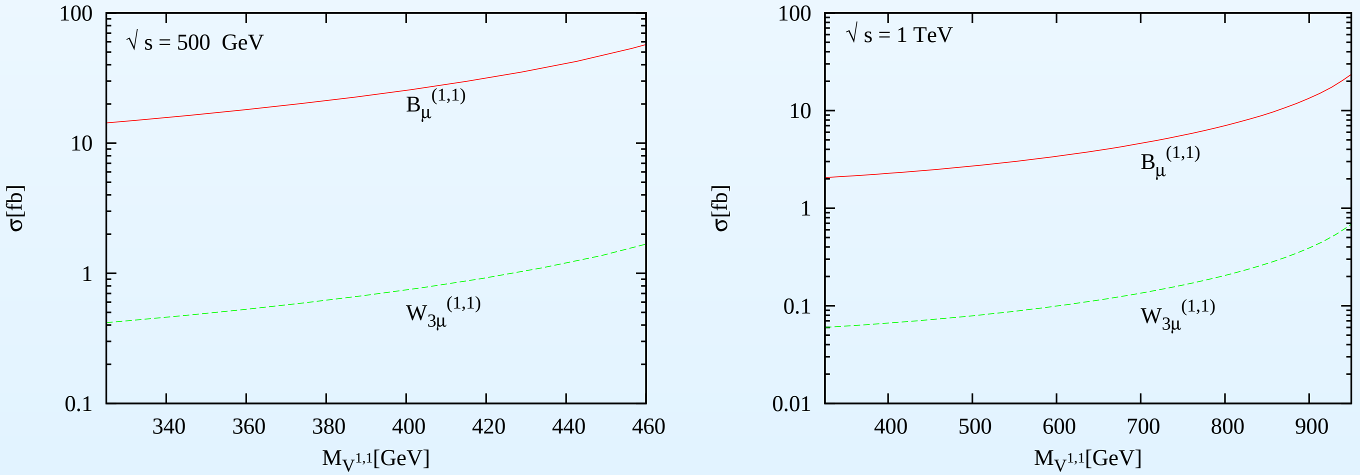

KG, A. Datta [arXiv:0802.2162(hep-ph)]

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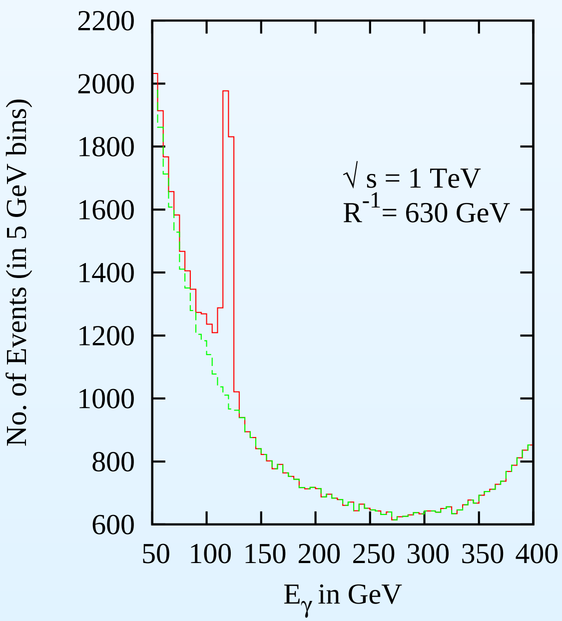

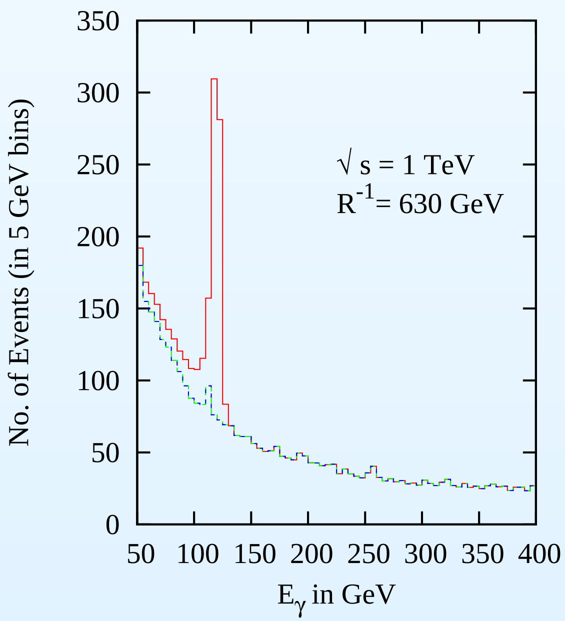

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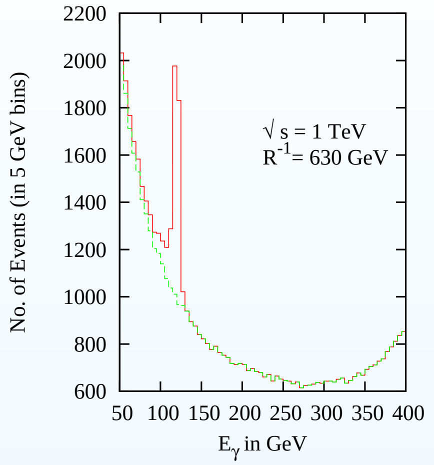

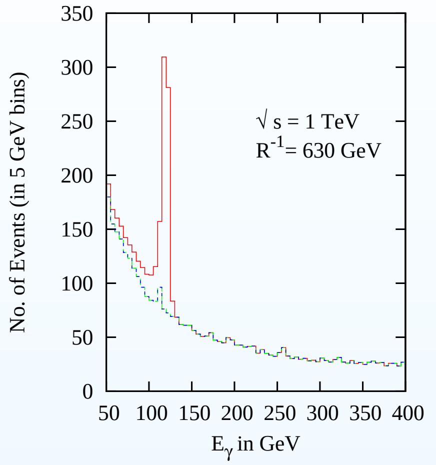

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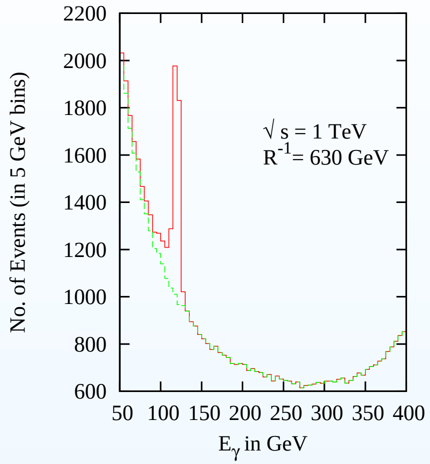

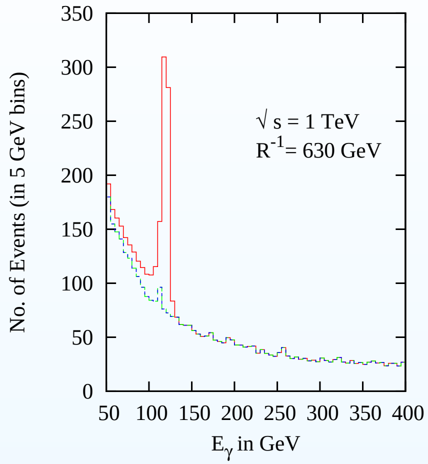

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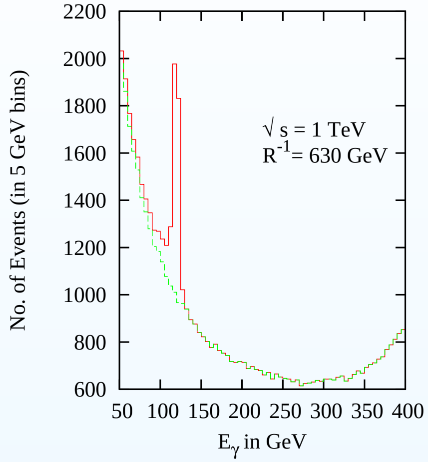

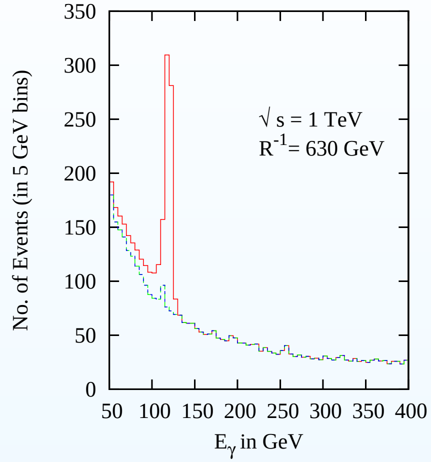

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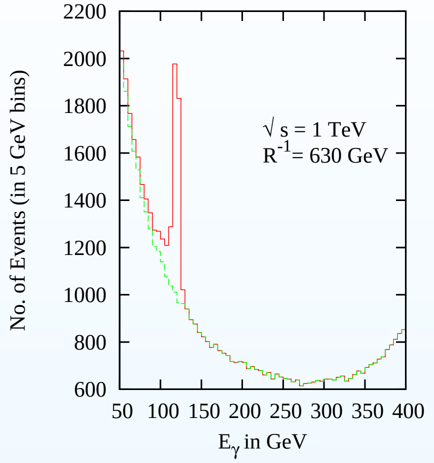

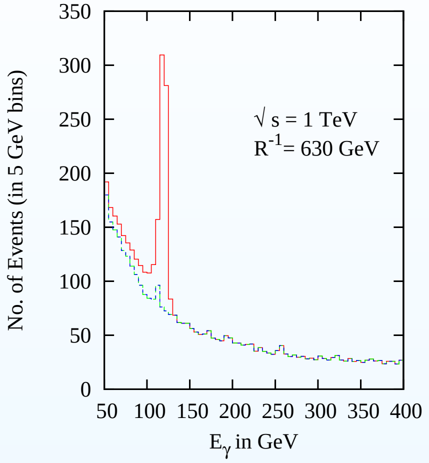

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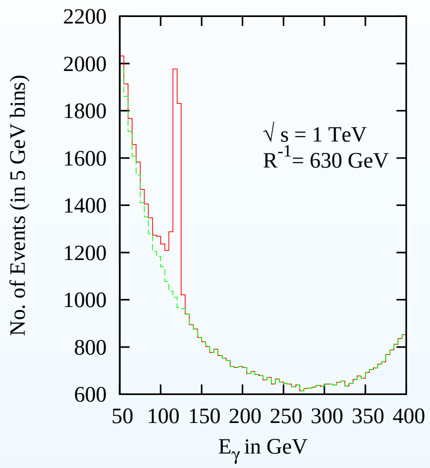

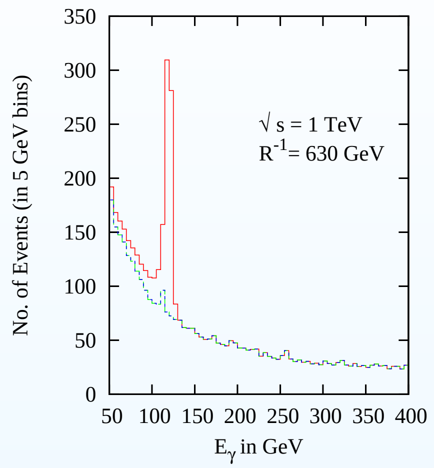

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  - Mass can be measured independently from the peak position of E_γ distribution.
  - Theoretical number can be compared with the experimentally measured ratio of decay widths.

Results

Number of $\gamma + 2j$ signal and SM background events.

(assuming 500 fb^{-1} integrated luminosity).

e^+e^- C-o-M Energy	R^{-1} in GeV	$B_\mu^{(1,1)}$ $m_{B_\mu^{(1,1)}}$ GeV	$B_\mu^{(1,1)}$ Signal Event	$B_\mu^{(1,1)}$ Background Event	$W_\mu^{3(1,1)}$ $m_{W_\mu^{3(1,1)}}$ GeV	$W_\mu^{3(1,1)}$ Signal Event	$W_\mu^{3(1,1)}$ Background Event
500 GeV	280	387.3	5900	19258 (139)	433.8	253	26593 (163)
	290	401.1	6713	20368 (143)	448.7	349	34031 (184)
	300	414.9	7701	22207 (149)	463.7	520	50011 (224)
	310	428.8	9005	24814 (158)	478.7	-	-
	340	470.3	24296	59938 (245)	523.6	-	-
1 TeV	300	414.9	348	2889 (54)	463.7	10	2499 (50)
	400	553.3	430	2038 (45)	613.8	14	1932 (44)
	550	760.8	948	2096 (46)	840.4	43	2538 (50)
	630	871.4	2082	3013 (55)	961.5	210	8444 (92)
	690	954.4	6552	7482 (87)	1052.4	-	-

Concluding Remarks

- 2UED: No. of Extra Dimension is 2, flat and compactified.
- Spinless Adjoints are the characteristics of this theory.
- If kinematically possible Spinless Adjoints dominantly decay to $t\bar{t}$, otherwise $b\bar{b}$ is not the dominant decay mode.
- Pair poroduction of coloured Spinless Adjoints vary from pb to few fb.
- Single Production of EW Spinless Adjoints at the LHC are miniscule.
- Discovery of $B_\mu^{(1,1)}$ in association with a photon at the ILC is possible for all R^{-1}, if kinematically possible.