# PHYSICS WITH EXTRA DIMENSIONS

— Models and Collider Signatures

Tao Han, Univ. of Wisconsin-Madison

(ILC, Snowmass, Aug. 22, 2005)

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♠. Collider Signatures

♠. Summary

## ♠. Old Stories about Extra Dimensions

1914: G. Nordstrom considered

$$d = 5:$$

$$A_{\hat{\mu}}(\hat{\mu} = 0, 1, 2, 3, 5) \Rightarrow A_{\mu}(\mu = 0, 1, 2, 3) + \phi$$

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$$g_{\mu\nu} \rightarrow \eta_{\mu\nu} + \kappa \ h_{\mu\nu}$$

metric $\text{dia}(\eta_{\mu\nu}) = (1, -1, -1, -1)$,

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1921: Th. Kaluza; 1926: O. Klein

$d = 5$ :

$\gamma_{\widehat{\mu}\widehat{\nu}}(\widehat{\mu} = 0, 1, 2, 3, 5) \Rightarrow g_{\mu\nu}(\mu = 0, 1, 2, 3) + A_\mu + \phi$

leads to gravity+$E\&M$ in 4D.

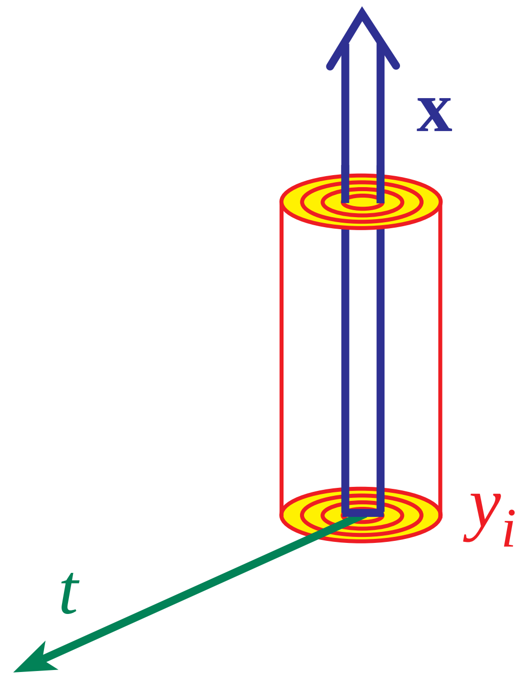
Wouldn't that be great !

(some quest with $\phi$...)

What happened to the extra dimension $y$ ?

- Too small to see ?

If our Universe $(\vec{x})$ is expanding as a function of $t$, why not some part $(y)$ has shrunk or compactified ?



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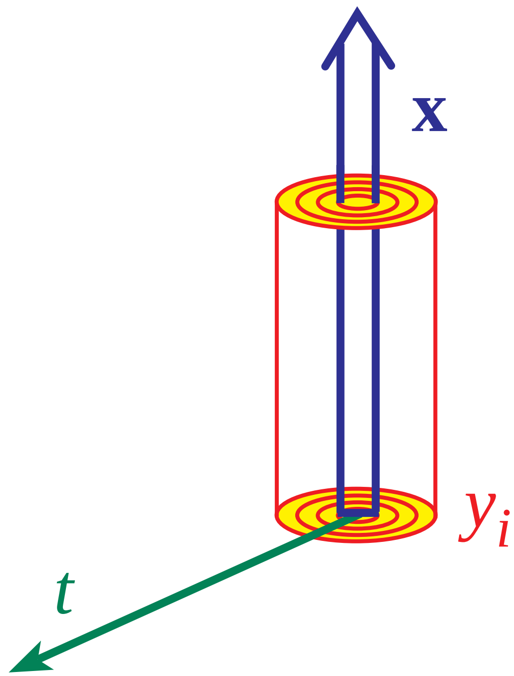


• Too elusive to probe ?

Our $E\&M$ probes can't get there ?

Only gravity lives there (possibly large).

If the extra dimension becomes compact (a circle of radius $R$), then all fields (gravitational, electromagnetic etc.) in $y$-dimension are periodic functions :

$$F(x,y) = \sum_{n=-\infty}^{\infty} F^n(x)\ e^{in \cdot y/R}.$$

Equation of motion:

$$(\partial^\mu \partial_\mu - \partial^y \partial_y) F(x,y) \Rightarrow (\partial^\mu \partial_\mu + \frac{n^2}{R^2}) F^n(x)$$

$$\Rightarrow \quad m_n \sim \frac{n}{R} \quad \text{(a set of tower!)}$$

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So, search for the massive KK states: equivalent to searching for compact extra dimensions

$$\Delta M_{KK} = 1/R.$$

No $\gamma_{KK}$, $e^-_{KK}$, ... found $\Rightarrow$ $R^{-1}$ large; or $\gamma$, $e^-$ ... don't go there.

⋆ Extra Dimensions in String Theory:

80's: Green-Schwarz-Witten et al.

Bosonic String: 26-dim (anomaly-free)

Superstring: 10-dim

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String theory ⇒ extra dimensions!

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String theory $\Rightarrow$ extra dimensions!

99–00's: Large extra dimensions ? ...
Arkani-Hamed, Antoniadis, Dimopoulos and Dvali: hierarchy
K. Dienes, E. Dudas, T. Gherghetta: coupling unification
Randall and Sundrum: hierarchy
Many more incarnations ...

## ♠ Low-Scale Extra Dimension Models (partial list)

General Consideration:

- In a factorizable flat metric:

$$ds^2 = \eta_{MN}\ dx^M dx^N, \quad M, N = (0, 1, ..., 4 + n),$$

with Minkowski metric $\eta_{MM} = (1, -1, -1, ...)$.
In general, a $4 + n$-dimensional gravity action:

$$S = \frac{1}{2} M_D^{n+2} \int d^{4+n}x\ \sqrt{-g}\mathcal{R},$$

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- The most general 4d Poincare invariant solution:

$$ds^2 = e^{2A(y)}\ \eta_{\mu\nu}\ dx^\mu dx^\nu - dy^i dy_i,$$

where $e^{2A(y)}$: a "warp" factor: the shape of space-time in $y$.
The 4-dim Planck scale is:

$$M_{pl}^2 = M_D^{n+2}\ \int d^n y\ e^{2A(y)} \equiv M_D^{n+2}\ V_n.$$

$M_{pl}$ is made of $M_D^{n+2}$, $V_n$.

- Theory in 4d and KK decomposition:

$$\mathcal{L}^{(4)} = \int d^n y \; \mathcal{L}^{(4+n)}(\hat{F}_{MN},\; \hat{\psi},\; \hat{H}).$$

With $y_i$ compactified,

$$\hat{F}(x,\; y_i) = \sum^{k} F_k(x)\; (a_k \sin\frac{ky}{R} + b_k \cos\frac{ky}{R}).$$

satisfying the boundary conditions in $y_i$.

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- Masses for KK modes: Stringy states: Winding modes:

$$M_{KK} \sim n/R, \qquad \sqrt{n} M_S, \qquad n R M_S^2.$$

- Graviton Interactions With Matter Fields:

$$S = \int d^4x \sqrt{-\hat{g}}\; \mathcal{L}^{(4)} \approx -\frac{\kappa}{2} \int d^4x (h^{\mu\nu}_{\vec{n}} + \phi_{\vec{n}} \eta^{\mu\nu})\; T_{\mu\nu},$$

where $h^{\vec{n}}_{\mu\nu}$ is a graviton, $\phi_{\vec{n}}$ a scalar dilaton (specified by $\vec{n}$).

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The energy-momentum tensor, $T_{\mu\nu}$, includes all matter:

$$T^{\text{fermions}}_{\mu\nu}, \ T^{\text{scalars}}_{\mu\nu}, \ T^{\text{EW}}_{\mu\nu}, \ T^{\text{QCD}}_{\mu\nu} \ldots$$

The rule: a graviton couples to EVERYTHING

# Large Extra Dimensions (ADD) :

With $n$ extra dimensions compactified on a torus of radius $R$,

$$M_{pl}^2 \sim R^n M_D^{n+2}$$

**Two fundamental scales:** $R$ and $M_D$ (or $M_S$),*

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Low Scale Superstring: †

If $M_S \ll M_{pl}$ as low as $\mathcal{O}(1 \text{ TeV})$, (**Good!**) then

$$R \sim \frac{M_{pl}^{2/n}}{M_S^{2/n+1}} \approx \begin{cases} \mathcal{O}(0.1\ mm) & \text{for } n = 2 \\ \mathcal{O}(1.0\ fm) & \text{for } n = 7 \end{cases}$$

**leads to "large" extra dimensions.**

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**leads to "large" extra dimensions.**

- Table-top gravity experiments to reach $R \sim 0.1\ mm$,
- may search for light KK gravitons:

  $m = n/R \sim 10^{-3}$ eV − 100 MeV.

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Although only gravitons in the extra dimensions, it is more than just gravitational effects:

⋆ KK Graviton Density[‡]

If $R$ is large, there will be a high degeneracy:

$$\Delta\vec{n}^2 = \rho(m) dm^2,$$
$$\rho(m) = \frac{\pi^{n/2}}{\Gamma(n/2)} R^n m^{n-2}.$$

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*Although each graviton couples gravitationally, the high-degeneracy leads to*

$$\kappa^2 \rho(m) dm^2 \sim \kappa^2 R^n m^{n-2} dm^2 \sim E^n / M_S^{n+2}$$

Effective coupling $\kappa^2 \sim \frac{1}{M_{pl}^2} \to \frac{1}{M_S^2}$ !

$\Rightarrow$ leads to possibly observable effeccts.

[‡]G. Giudice, R. Rattazzi and J. Wells;
T. Han, J. Lykken and R.-J. Zhang.

⋆ Bounds on the ADD model:

Table-Top Gravity Experiments:

A torsion pendulum/attractor experiment*

and a forced oscillator experiment†

New force with $r > 0.2$ mm excluded.

*E. Adelberger et al., Phys.Rev.Lett.86, 1418 (2001).

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Supernova bounds:

SN1987A energy-loss rate (mainly to $\nu' s$), which leads to bounds§

$$n = 2: \quad M_S > 30 - 130 \text{ TeV (!)}$$
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Neutron star heating:

Trapped KK gravitons in the SN core may overheat the NS.†

$$n = 2: \quad M_S > 100 \text{ TeV}$$
$$n = 3: \quad M_S > 10 \text{ TeV (!)}$$

These results have very little model-dependence.
$n < 3$ is strongly disfavored, if $M_S \sim \mathcal{O}(1 \text{ TeV})$.

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†S. Hannestad and G. Raffelt, hep-ph/0110067.

## Universal Extra Dimensions (UED) :

All particles propagate in extra dimensions "universally".¶

¶T. Appelquist, H.-C. Cheng, B.A. Dobrescu (2001).

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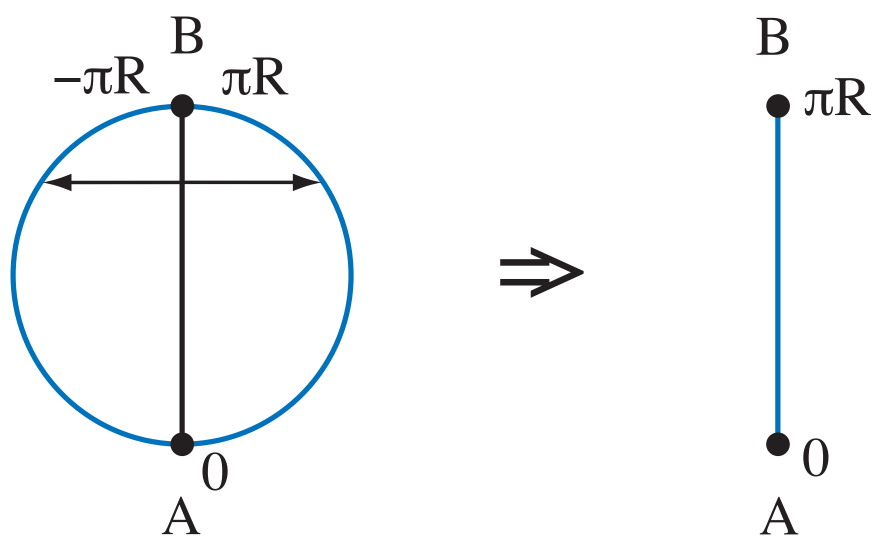


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- All particles have KK tower;
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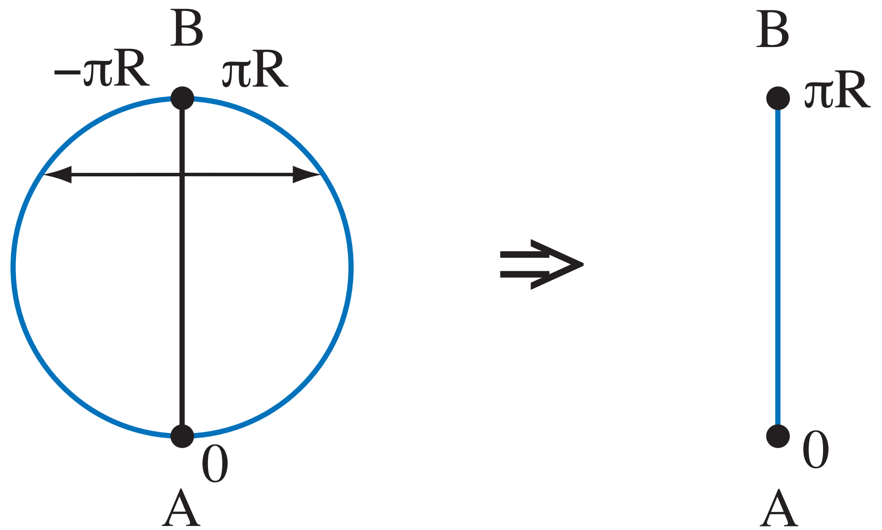


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⋆Current bounds (both precision EW and Tevatron search)

$$M_{KK} \gtrsim 400 \text{ GeV} \quad \text{or} \quad R \lesssim \frac{1}{0.5 \text{ TeV}} \sim 10^{-15} \text{ mm}.$$

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# The Randall-Sundrum Scenario:

In a 5-dim space, Randall and Sundrum found a static solution:*

$$ds^2 = e^{2A(y)} \; \eta_{\mu\nu} \; dx^\mu dx^\nu - dy^2,$$

where the "warp" factor $\qquad A(y) = -ky,$
with $k$ the curvature scale in the $5^{th}$-dim.

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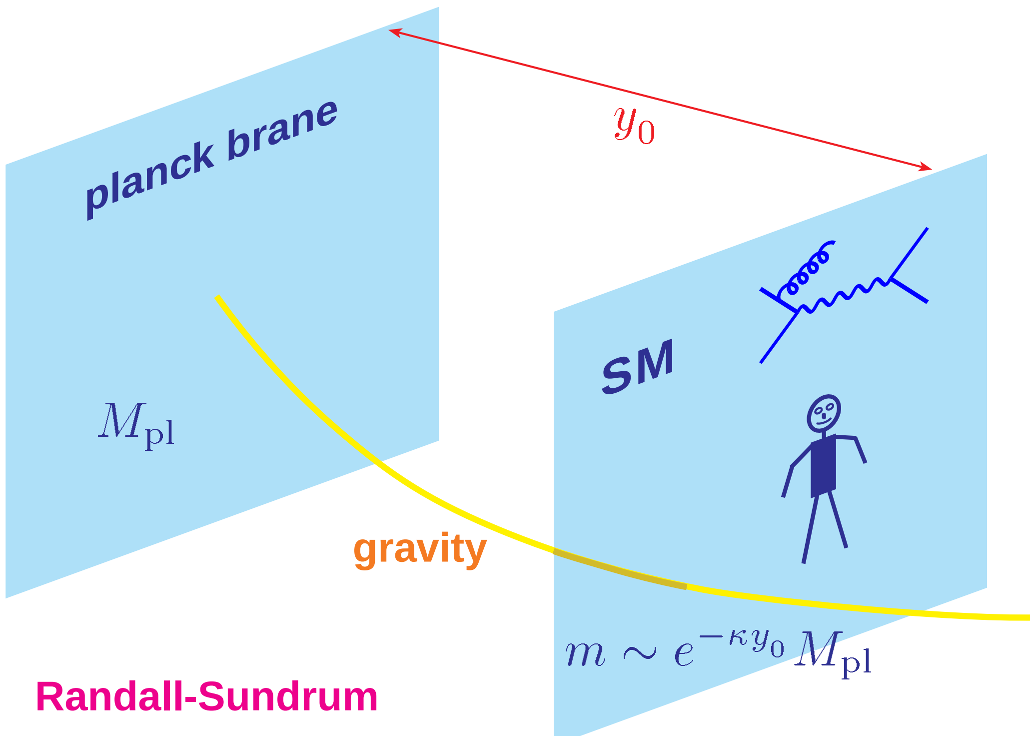
The extra dimension $y$ is "warped".

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⋆ Mass hierarchy $M_{pl}/M_{EW}$ generated on the two branes:

$$v = e^{-ky_0} M_{pl}.$$

To get $v \approx 246$ GeV, need $ky_0 \approx 40$.

The "size" of extra-dim: $y_0 \sim (10 - 100)\ l_{pl}$.

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⋆ KK decomposition:[‡]
Bulk fields:

$$\hat{F}_q(x, y_i) \sim \sum^{k} F_k(x)(a_k J_q + b_k Y_q),$$

where $J_q, Y_q$ are Bessel functions of order $q$=1,2, half-integers for a gauge boson, graviton, fermion, respectively.
KK states $h^{\mu\nu}_{KK}$, $A^{\mu}_{KK}$, $f_{KK}$... with masses $M_{KK} \sim e^{-ky_0} M_{pl}$, and with 1/TeV couplings.

Tension with EW data were studied and more involved configuration needed.[‖]

[‡]Davoudiasl, Hewett, Rizzo, hep-ph/9909255.

[‖]Gherhetta and Pomarol, hep-ph/0003129; Hewett, Petriello, Rizzo, hep-ph/0203091.

## Variations of The RS Model:

⋆ Bulk Fields with Custodial Symmetry**

All fields in the bulk, with an enhanced gauge symmetry $SU_R(2) \times SU_L(2) \times U(1)$.

Electroweak symmetry broken by the Higgs field on the TeV brane.

Corrections to $T$ (or $\rho$) small if $M_{KK} \sim$ a few TeV.

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⋆ Higgsless Model*

No Higgs fields at all;

Electroweak symmetry broken by the TeV brane boundary condition.

Tension between $W_L W_L$ scattering unitarity and the precision EW data severe ‡

**Agashe, Delgado, May, and Sundrum, hep-ph/0308036

*C.Csaki et al. hep-ph/0305237, hep-ph/0308038; Y.Nomura, hep-ph/0309189.

‡Hewett, Lillie, Rizzo, hep-ph/0407059.

⋆ Orbifolding SUSY GUTS*

SUSY and GUTs breaking by orbifolding boundary conditions;
Electroweak scale generated by warping;

Distinctive feature: TeV scale GUT gauginos $XY$;
However, the symmetry forbidding prompt proton decay makes $XY$ hard to observe:
stable charged hadrons $X$, $Y$, $(Xq...)$ ?

*Y.Nomura et al. `hep-ph/0209158; hep-ph/0212134; 0305214.`

# Outcomes of Extra Dimensions Models:

an exciting frontier for explorers

## Outcomes of Extra Dimensions Models:

an exciting frontier for explorers

- Newton's law: modified at both short and long distances.*
- EWSB: gauge-boson masses and the Higgs†, or "Higgsless".‡
- fermion masses: Yukawa couplings by displacement/overlapping††
- $\nu$ masses/mixings: bulk neutrinos¶
- GUTs: gauge coupling power-law running* or log-running‡‡
- SUSY GUTs: breaking by orbifolding‡
- new cosmology;§ cosmological const.‖

*ADD; RS; Dvali et al.

†Cheng et al.; Luty et al.; Hall et al.; Ignatius et al.; Z. Chacko and A. Nelson

‡C. Csaki et al.

††Mirabelli and Schmaltz; Arkani-Hamed et al.

¶Mohapatra, Nandi, Perez-Lorenzana; Dienes et al.; Dimopoulos et al.

*Dienes, Dudas, Gherghetta; Dumitru and Nandi.

‡‡Agashe, Delgado and Sundrum, hep-ph/0212028.

‡Hall and Nomura; Hebecker and March-Russell et al.

§Binetruy et al.; Kaloper et al.; Csaki et al.; Flanagan et al.; Cline et al.; Kanti et al.; Mohapatra et al.

‖Arkani-Hamed et al.; Silverstein et al.; Luty et al.

## ♠. Phenomenological Implications

▷ At "low" energies

- "very low": $E \ll 1/R,\ M_S$:

4−dim effective theory: Standard Model + weak classical gravity.

(as our present experimental knowledge.)

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▷ At "low" energies

- "very low" : $E \ll 1/R,\ M_S$:

4−dim effective theory: Standard Model + weak classical gravity.

(as our present experimental knowledge.)

- march into the extra-dimensions: $1/R < E \ll M_S$,

$(4+n)$−dim world directly probed, and gravity effects observable:* mainly via light KK gravitons of mass

$$m_{KK} \sim 1/R,$$

or whatever propagate there ⇒ an effective theory (SM+KK).

*N. Arkani-Hamed, S. Dimopoulos, G. Dvali (1998);
G. Giudice, R. Rattazzi, J. Wells (1999);
T. Han, J. Lykken, R.J. Zhang. (1999);
Mirabelli, M. Peskin, M. Perelstein (1999);
J. Hewett (1999); T. Rizzo (1999); ...

▷ At intermediate energies $E \sim M_D,\ M_S$:
Stringy states significant* and resonances at the $s$-channel poles dominant:†

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▷ At "trans Planckian" energies $E > M_D, M_S$:
$(4+n)-$dim physics directly probed;
gravity dominant: black hole production*

$$M_{bh} = \sqrt{s} > M_D \text{ for } b < r_{bh}.$$

copiously produced at LHC or other TeV-scale experiments!

*G. Shui and H. Tye (1998); K. Benakli (1999).

†Accomando, Antoniadis, Benakli (2000); Cullen, Perelstein, Peskin (2000).

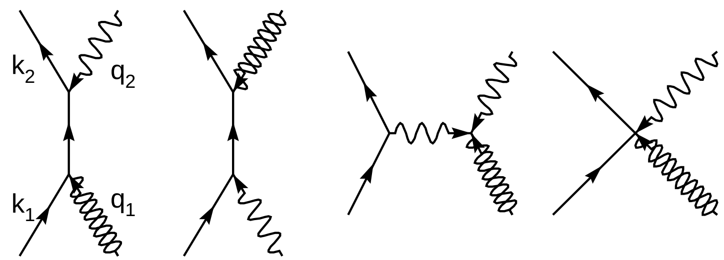
*T. Banks and W. Fischler (1999); E. Emparan et al. (2000);
S. Giddings and S. Thomas (2002);
S. Dimopoulos and G. Landsberg (2001).

## ⋆ Collider Searches for Extra Dimensions:

### A. Collider Signals I (ADD)

Real KK Emission: Missing Energy Signature*

a. $e^+e^- \to \gamma + KK$ ($\gamma$+missing energy)




| n − dim : | at LEP2 | at LC(500) |
|---|---|---|
| $n = 4$ | $M_S >$ 730 (GeV) | 4500 |
| $n = 6$ | $M_S >$ 520 (GeV) | 3100 |

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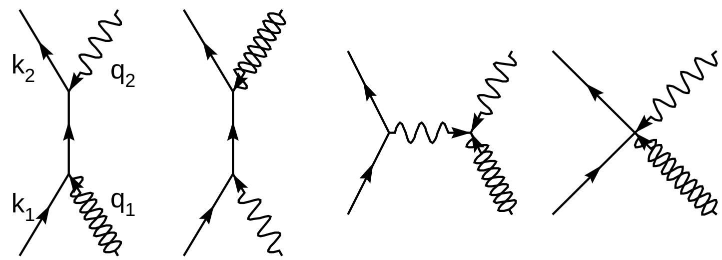


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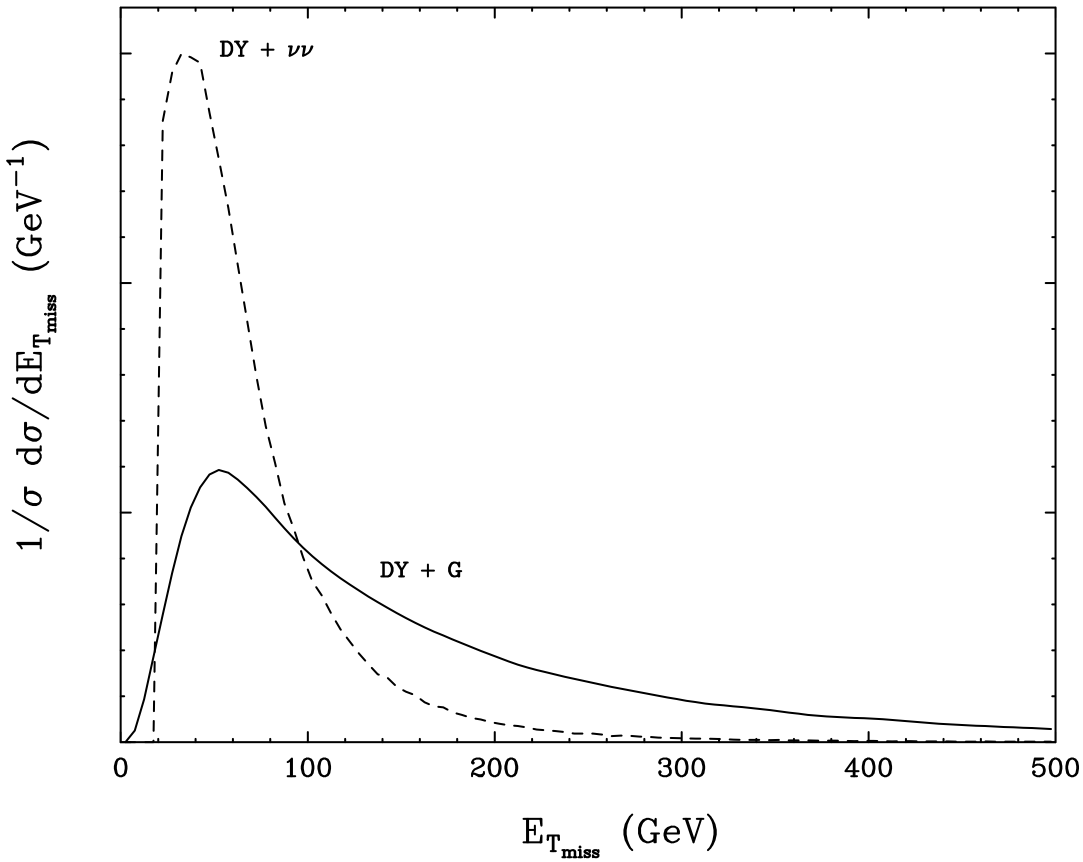
b. $p\bar{p} \to jet + KK$ (mono-jet+missing energy)

| n − dim : | at Tevatron | at LHC |
|---|---|---|
| $n = 4$ | $M_S >$ 900 (GeV) | 3400 |
| $n = 6$ | $M_S >$ 810 (GeV) | 3300 |

*Giudice, Rattazzi and Wells;
Mirabelli, Perelstein and Peskin;
Cheung and Keung ... ...

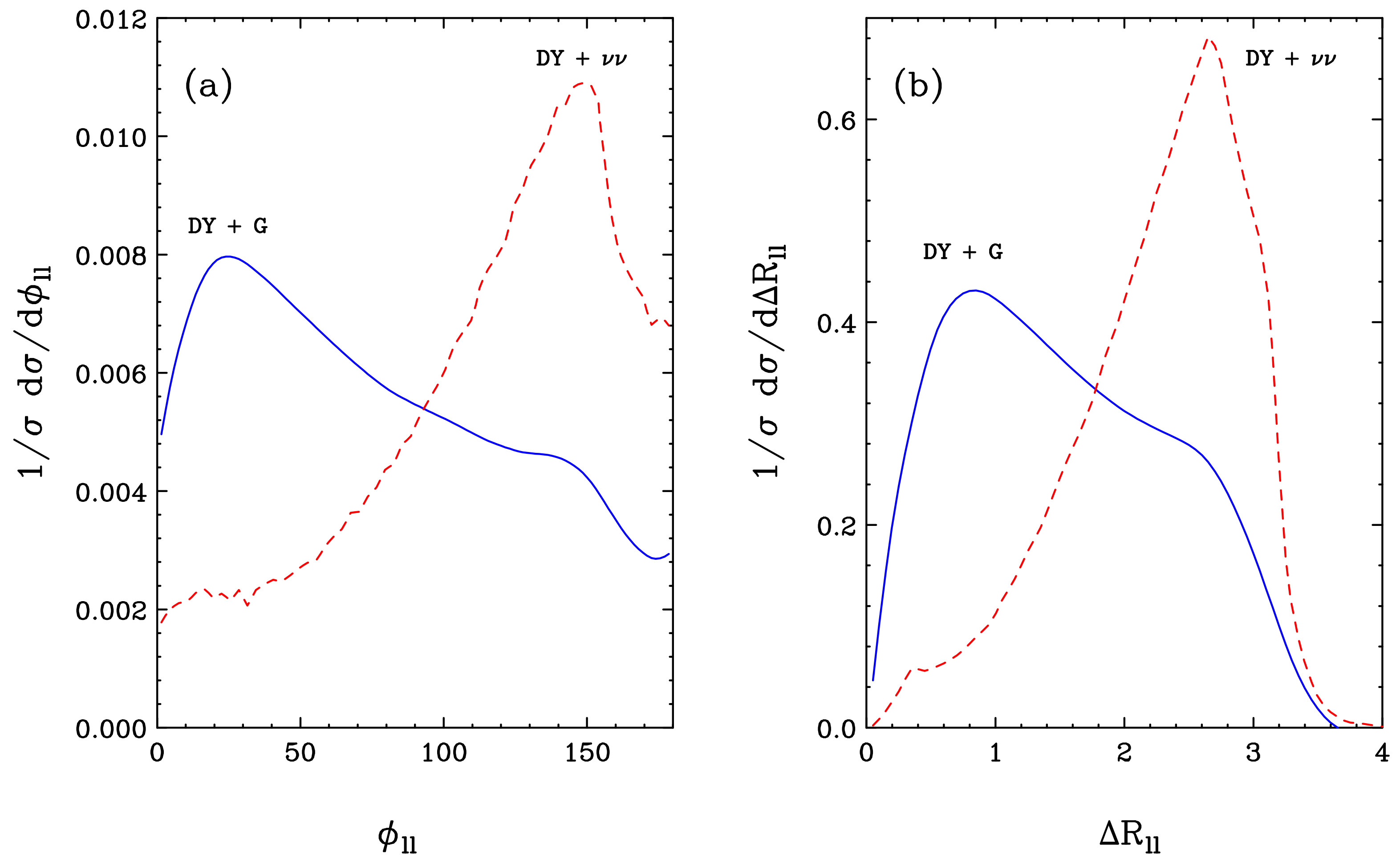
c. $p\bar{p} \to \ell^+\ell^- + KK$: Qualitative features? †

Larger/harder missing energies for the KK signal:




†Han, Rainwater and Zeppenfeld, hep-ph/9905423, Phys.Lett.**B463**, 93(1999).

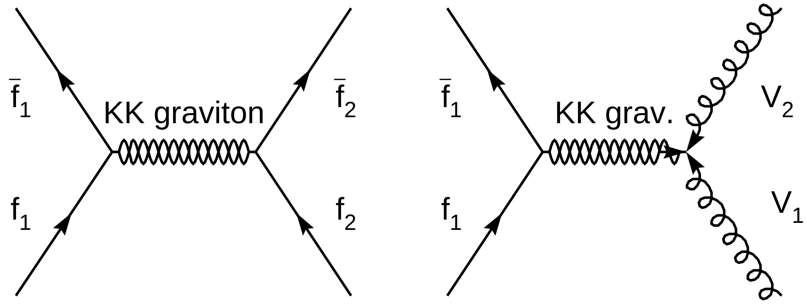
Consequently, the lepton opening angle is sensitive to it:



B. Collider Signals II (ADD)

Virtual KK Graviton Effects‡

On four-particle contact interactions:




Sum over virtual KK exchanges:

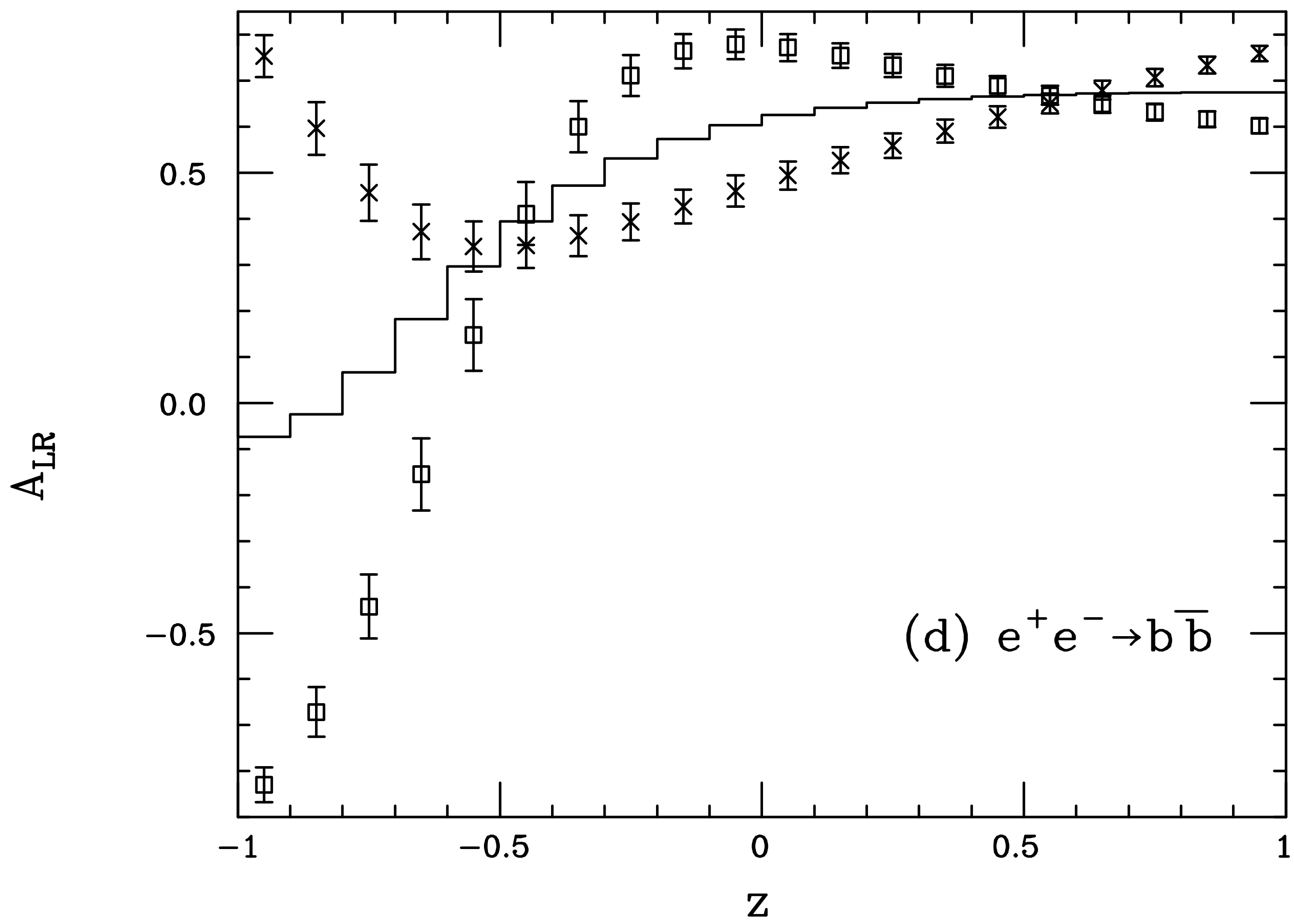
$$i\mathcal{M} \sim \overline{f}\mathcal{O}_i f \; \overline{f}\mathcal{O}_j f \int_0^\infty \frac{dm_{\vec{n}}^2 \; \kappa^2 \rho(m_{\vec{n}})}{s - m_{\vec{n}}^2 + i\epsilon}$$

$$\sim \frac{s^2}{M_S^4} \overline{f}\mathcal{O}_i f \; \overline{f}\mathcal{O}_j f.$$

Again, effective coupling $\kappa^2 \sim \frac{1}{M_{pl}^2} \to \frac{1}{M_S^2}$ !

‡ Hewett; Han, Lykken and Zhang; Rizzo; Cheung; Agashe and Deshpande; Nussinov and Shrock; Shiu, Shrock and Tye; Atwood, Bar-Shalom and Soni; Mathews, Raychaudhuri and Sridhar; ... ...

Qualitative differences for signal/background distributions, due to the spin-2 exchange:*




$LR$ asymmetry for $e^+e^- \to b\bar{b}$ at $\sqrt{s} = 500$ GeV.
Solid: SM; “data” points for $\lambda = \pm 1$ with 75 $fb^{-1}$.

*J.Hewett.

C. KK Resonant States at Colliders: (RS)

a. SM KK Particles:

If the SM fields (photons, electrons, $Z, W, H^0$...) also propagate in extra dimensions, then they have KK excitations.[‡]

[‡] Davoudiasl, Hewett, Rizzo, hep-ph/9911262.

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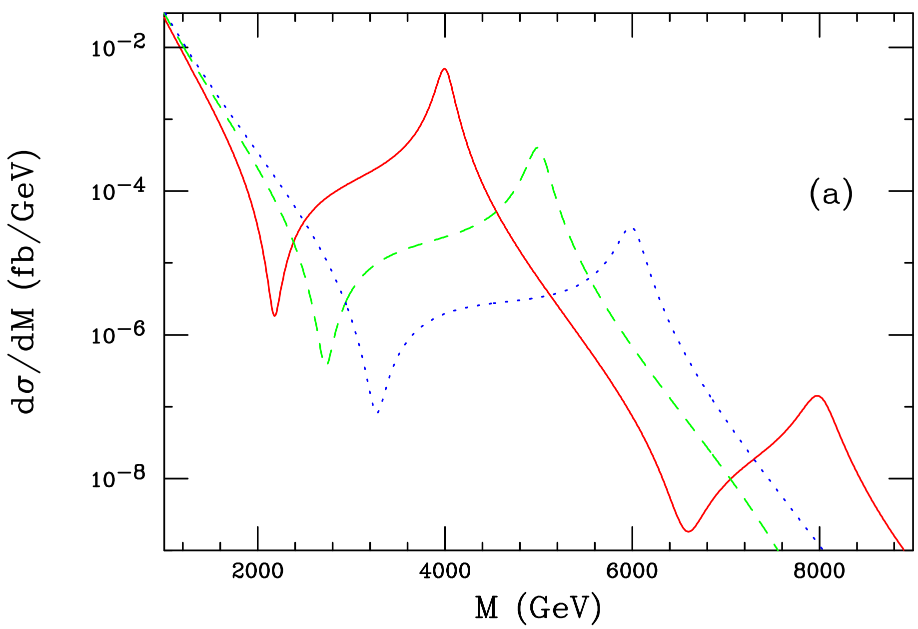
Resonant production at the LHC:



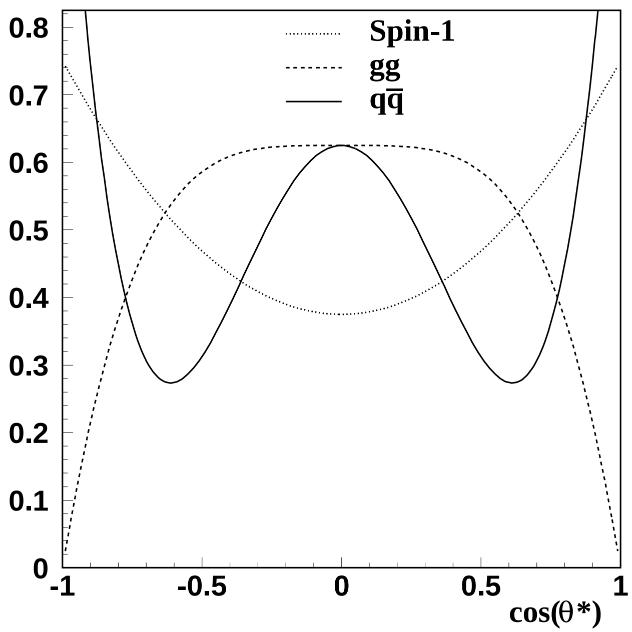

‡Davoudiasl, Hewett, Rizzo, hep-ph/9911262.

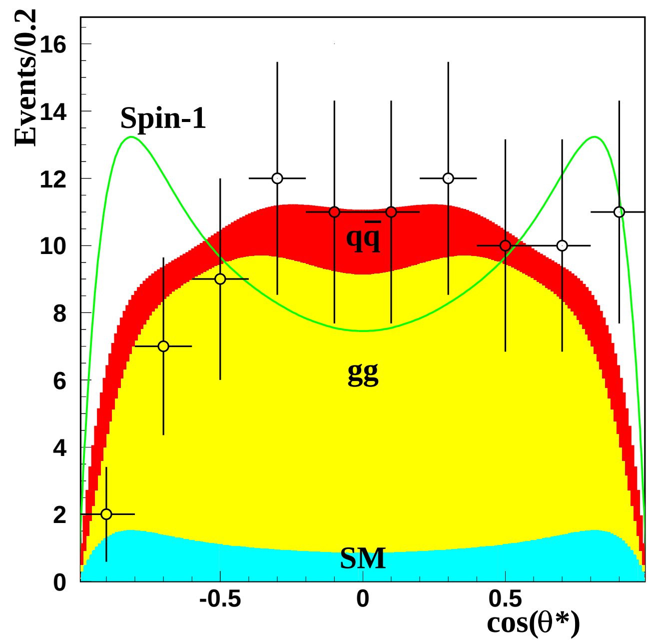
## b. Heavy KK gravitons

DY $\ell^+\ell^-$ angular distributions:

| | |
|---|---|
| $gg \to G \to e^+e^-$ | $1 - \cos^4\theta^*$ |
| $q\bar{q} \to G \to e^+e^-$ | $1 - 3\cos^2\theta^* + 4\cos^4\theta^*$ |
| $q\bar{q},\ gg \to V \to e^+e^-$ | $1 + \alpha\cos^2\theta^*$ |
| $q\bar{q},\ gg \to S \to e^+e^-$ | $1$ |

At the LHC (ATLAS simulation*),




*Allanach et al., hep-ph/0006114

D. Stringy resonances at Colliders

Future colliders may reach the TeV string threshold thus directly produce the "stringy" resonant states.[†]

Amplitude factor near the resonance

$$\mathcal{M}(s,t) \sim \frac{t}{s - nM_S^2}, \quad \text{its mass } M_n = \sqrt{n}M_S.$$

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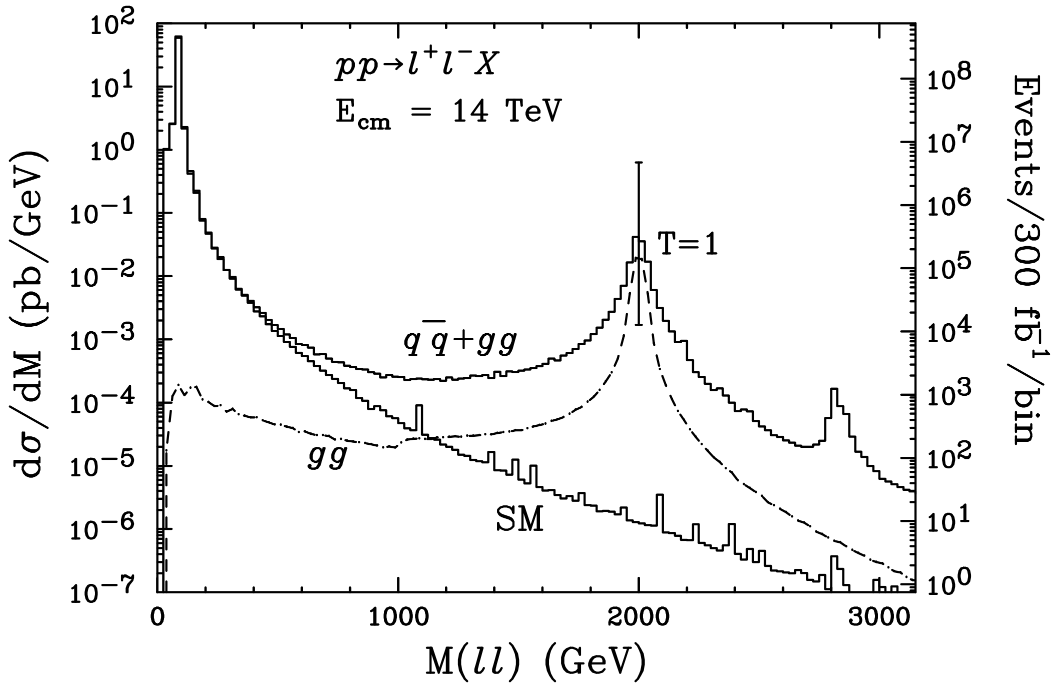


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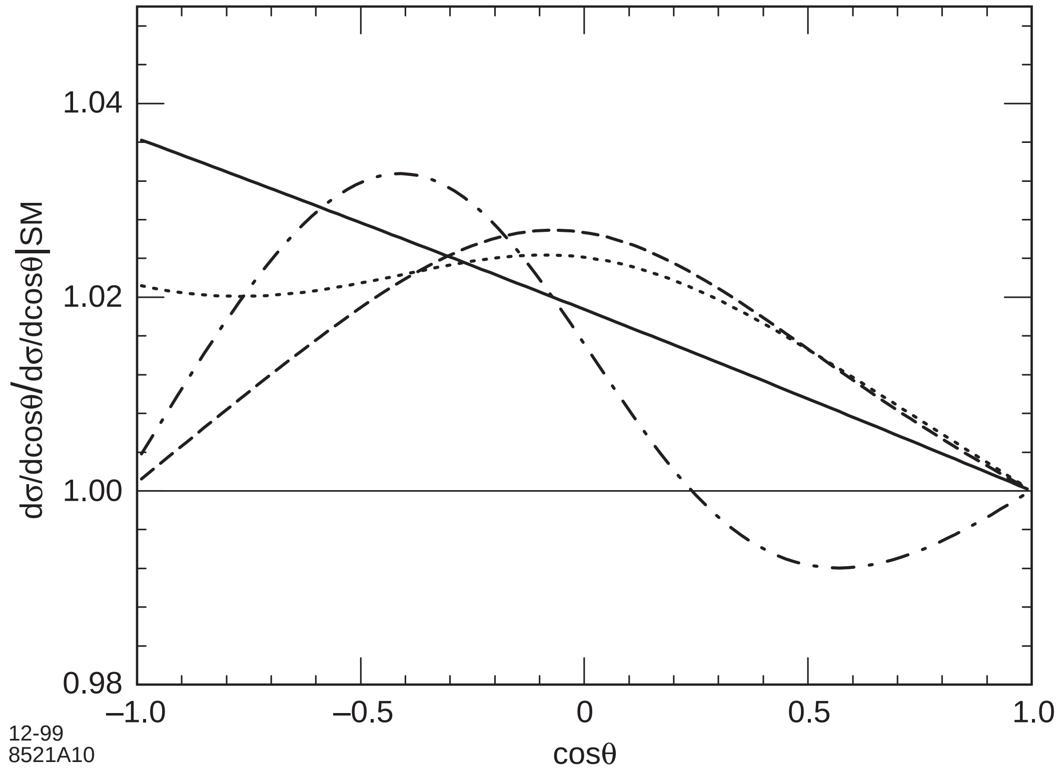
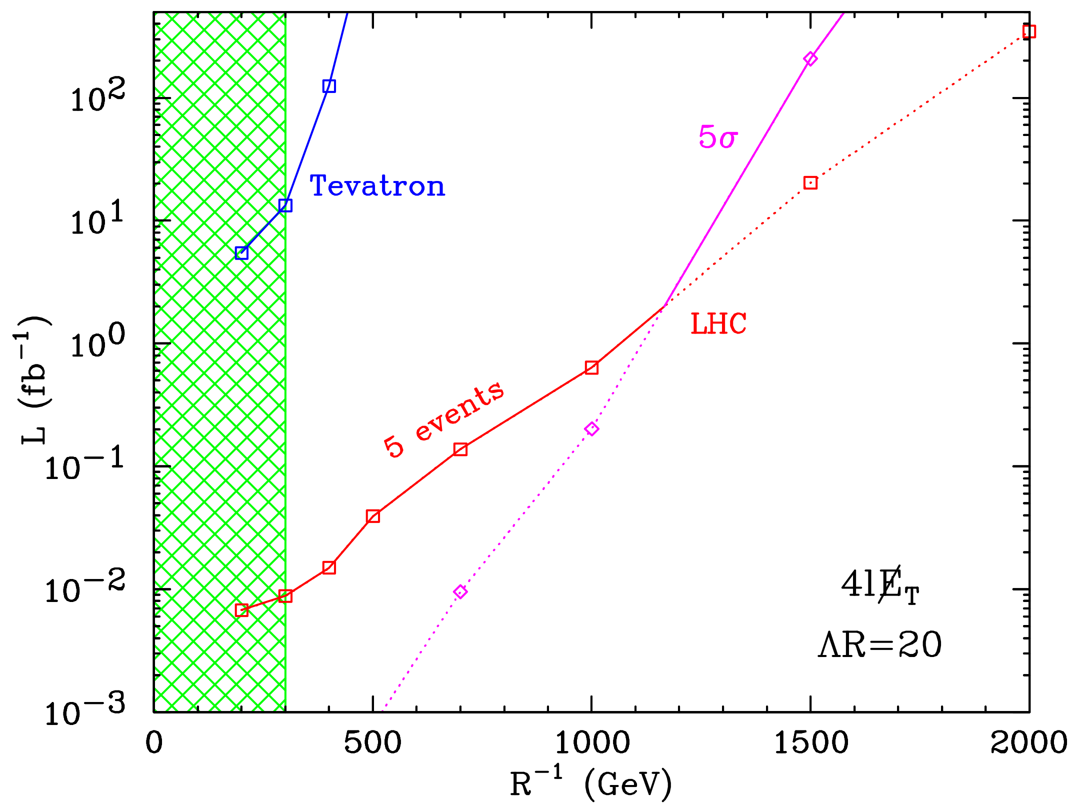
# At the ILC:*




Comparison of deviations from the Standard Model prediction for Bhabha scattering at 1 TeV due to corrections from higher-dimension operators. The four curves represent: solid, string model with $M_S = 3.1$ TeV; dotted, KK exchange with $M_H = 6.2$ TeV; dashed, VV contact interactions with $\Lambda = 88$ TeV; dot-dash, AA contact interactions with $\Lambda = 62$ TeV.

*Cullen, Perelstein and Peskin hep-ph/0001166.

## E. UED:*

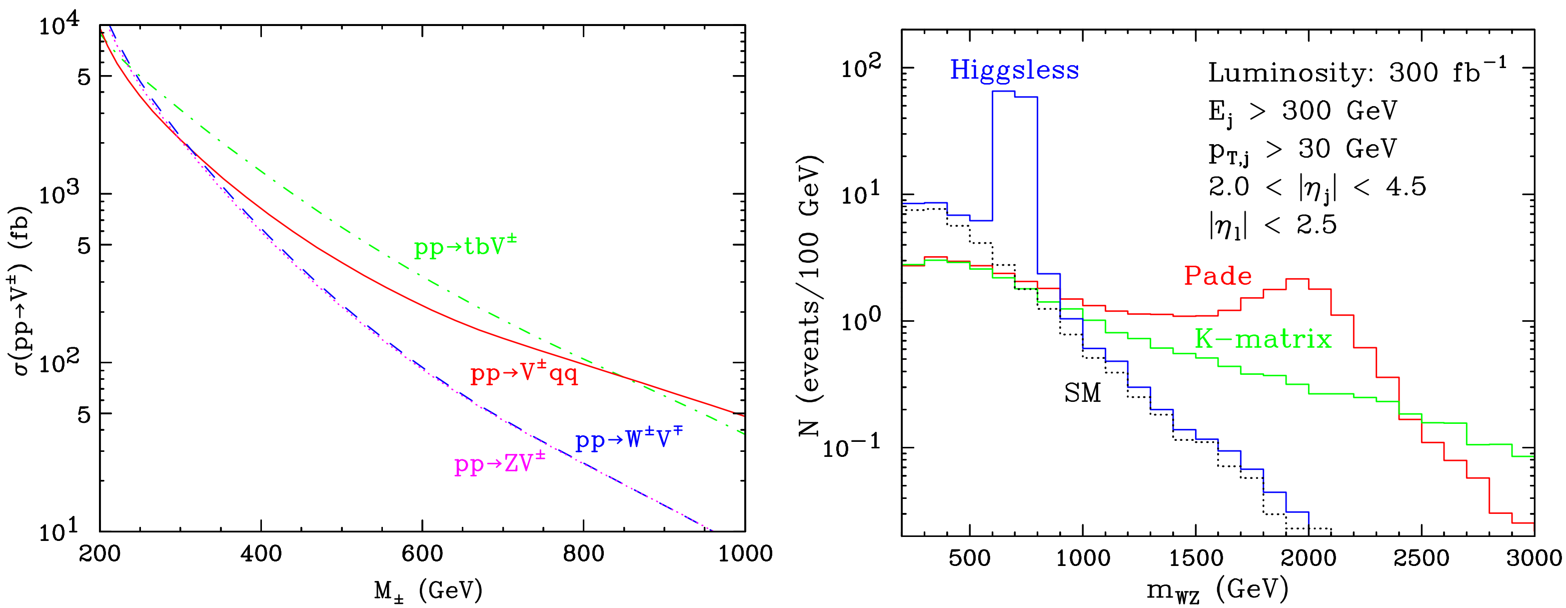



*Discovery reach for MUEDs at the Tevatron (blue) and the LHC (red) in the $4\ell\not{E}_T$ channel. We require a $5\sigma$ excess or the observation of 5 signal events, and show the required total integrated luminosity per experiment (in fb$^{-1}$) as a function of $R^{-1}$, for $\Lambda R = 20$. (In either case we do not combine the two experiments).*

*Cheng, Matchev, and Schmaltz, hep-ph/0205314.

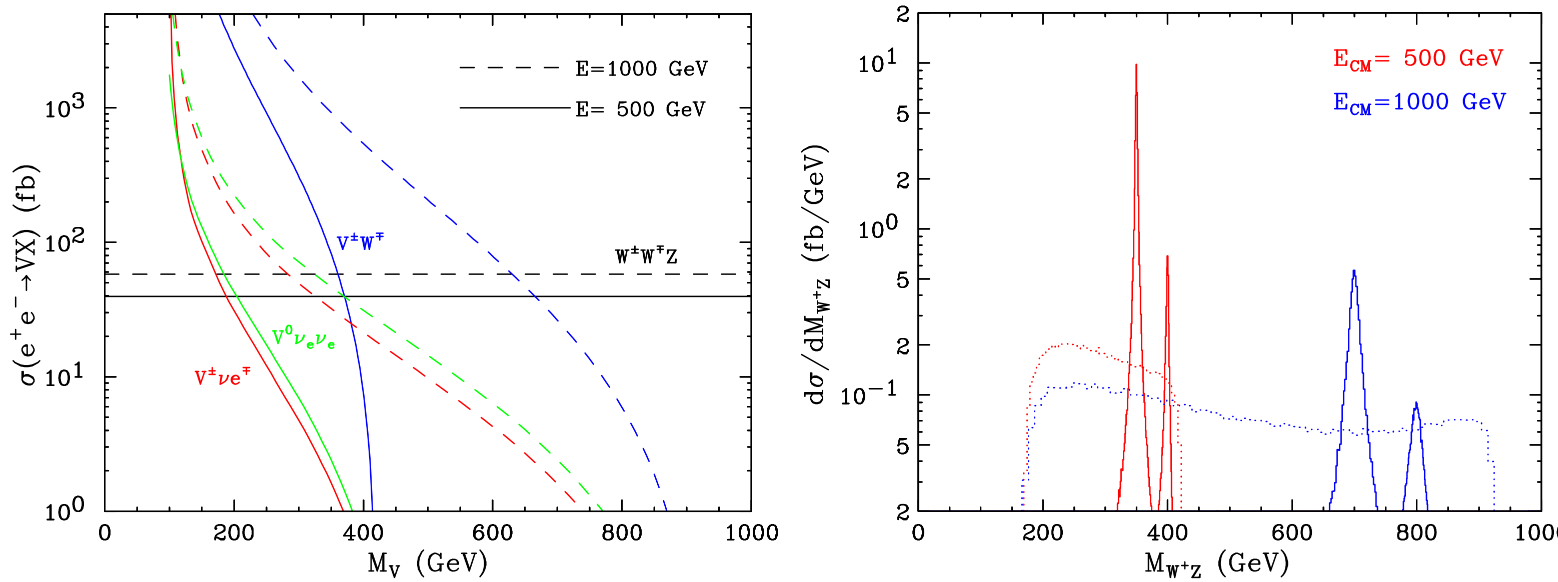
## F. Higgsless:*

$$pp \to jj\ V_1^{\pm} \to jjWZ.$$




Left: Production cross-sections of $V^{\pm}$ at the LHC. Here $tbV^{\pm}$ production assumes SM-like couplings to third generation quarks. Right: The number of events per 100 GeV bin in the $2j + 3\ell + \nu$ channel at the LHC with an integrated luminosity of 300 fb$^{-1}$ and cuts as indicated in the figure. Results are shown for the SM (dotted), the Higgsless model with $M_1^{\pm} = 700$ GeV (blue), and two "unitarization" models: Padé (red) and K-matrix (green).

*Birkedal, Matchev, and Perelstein, hep-ph/0508185.




Left: $V_1$ production cross-sections and the continuum SM background at an $e^+e^-$ lepton collider of center of mass energy 500 GeV (solid) or 1 TeV (dashed). Right: $WZ$ invariant mass distribution for Higgsless signals (solid) and SM background (dotted), at $E_{CM} = 500$ GeV (red, $M^{\pm} = 350, 400$ GeV) and $E_{CM} = 1$ TeV (blue, $M^{\pm} = 700, 800$ GeV).

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**Go Search for the Extra Dimensions !**