PHYSICS WITH EXTRA DIMENSIONS

— Models and Collider Signatures

Tao Han, Univ. of Wisconsin-Madison

(ILC, Snowmass, Aug. 22, 2005)

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♠. Extra Dimensions: a fascinating thought

♠. Extra Dimensional Models

♠. Collider Signatures

♠. Summary

♠. Old Stories about Extra Dimensions

1914: G. Nordstrom considered

$$d = 5:$$

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

with scalar ϕ identified as gravitational field!

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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

$$d = 5:$$

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

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

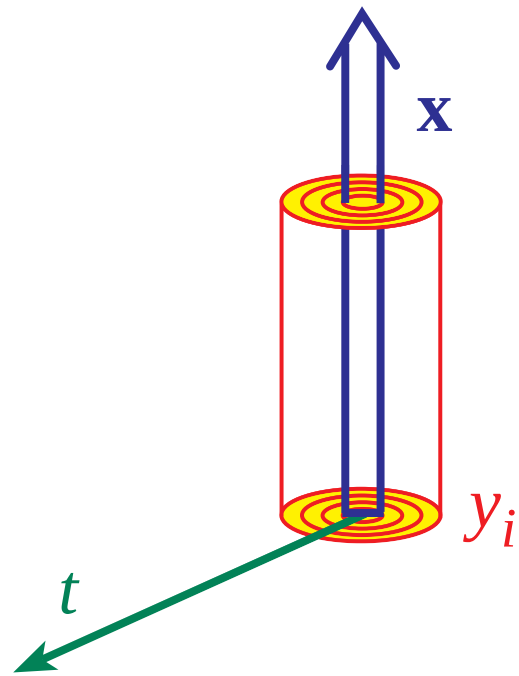
Wouldn't that be great !

(some quest with ϕ...)

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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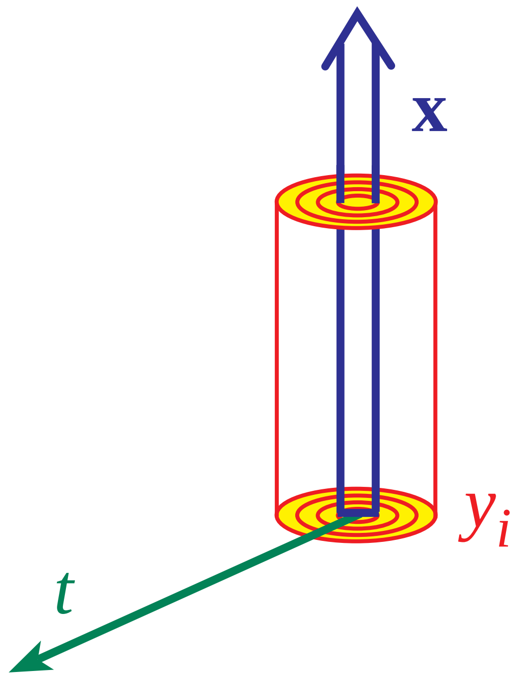

• Too elusive to probe ?

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 γ_{KK}, e^-_{KK}, ... found $\Rightarrow$ R^{-1} large; or γ, 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

Supergravity: 11-dim

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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:

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

where M_D: the $4 + n$-dim Planck scale.

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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:

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

With y_i compactified,

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

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:

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

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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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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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- 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:

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

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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;
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⋆ 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.

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Supernova bounds:

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

$$n = 2: \quad M_S > 30 - 130 \text{ TeV (!)}$$
$$n = 3: \quad M_S > 2 - 9 \text{ TeV.}$$

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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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†Chan, Long, Price et al., hep-ph/0009062, Nature **421**, 922,2003.

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

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All particles propagate in extra dimensions "universally".[¶]

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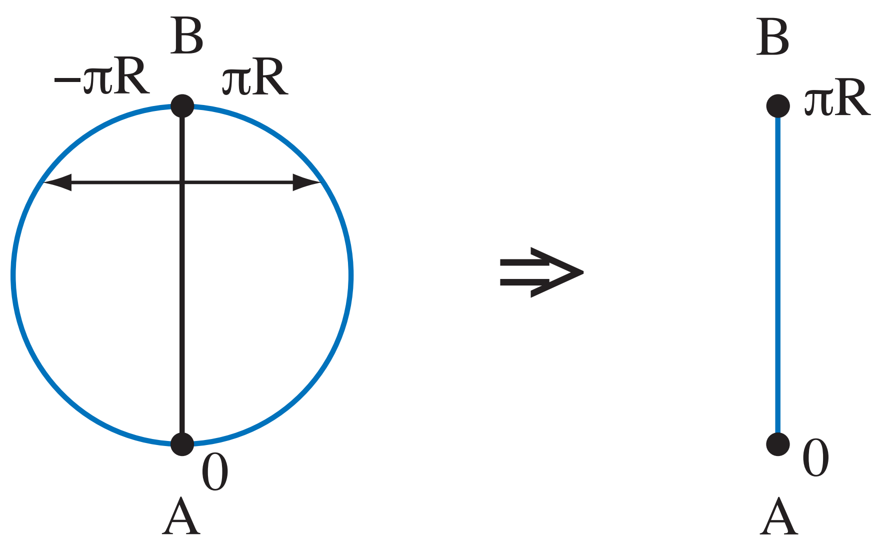

- SM particles are the zero-modes;
- All particles have KK tower;
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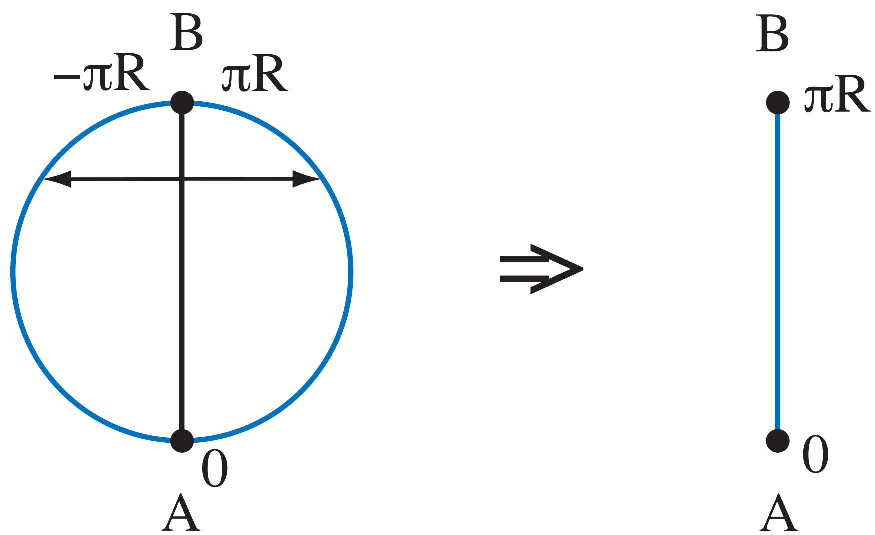

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⋆Current bounds (both precision EW and Tevatron search)

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

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

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 $A(y) = -ky$,
with k the curvature scale in the 5^{th}-dim.

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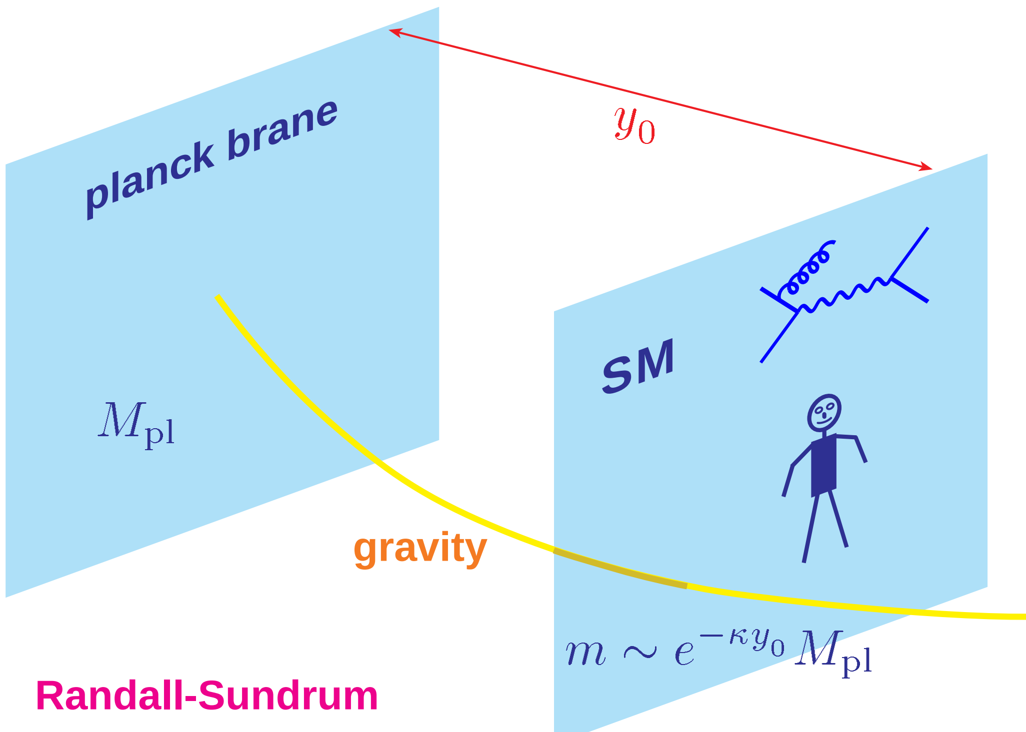

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$\star$ Mass hierarchy M_{pl}/M_{EW} generated on the two branes:

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

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:

$\star$ 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 ρ) 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

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- 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[††]
- ν 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:†

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

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

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

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

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

▷ 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).

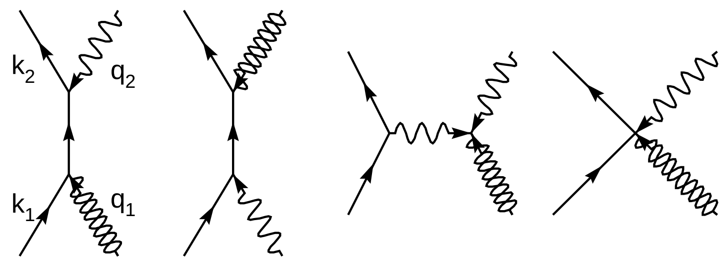
*T. Banks and W. Fischler (1999); E. Emparan et al. (2000);
S. Giddings and S. Thomas (2002);
S. Dimopoulos and G. Landsberg (2001).

$\star$ Collider Searches for Extra Dimensions:

A. Collider Signals I (ADD)

Real KK Emission: Missing Energy Signature*

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



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

*Giudice, Rattazzi and Wells;
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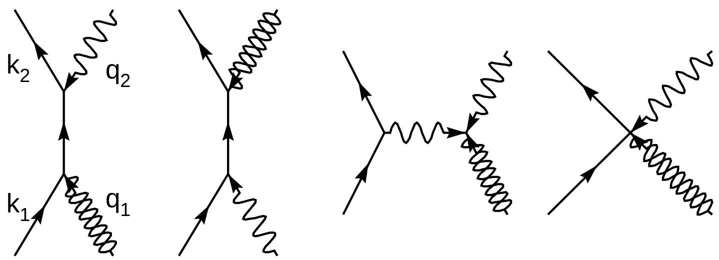

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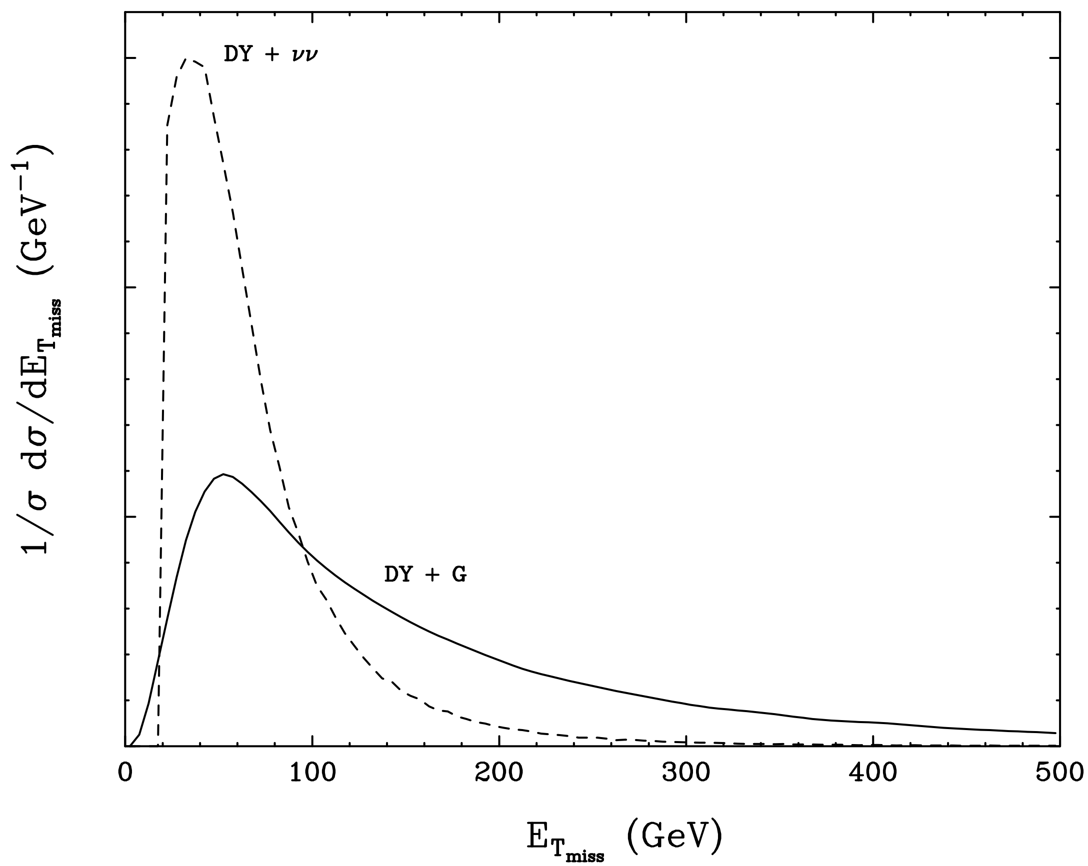
b. $p\bar{p} \to jet + KK$ (mono-jet+missing energy)

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 ... ...

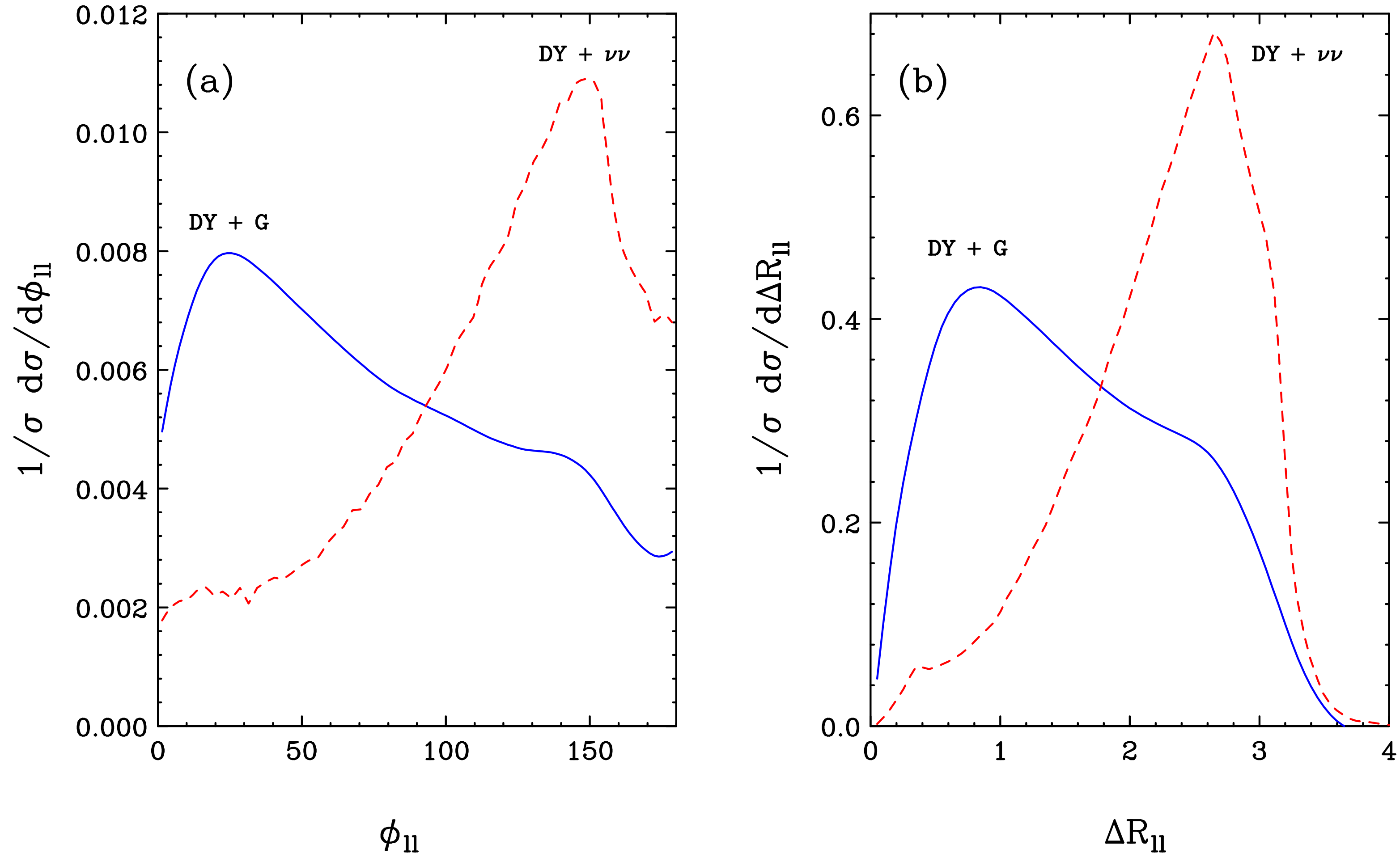
c. $p\bar{p} \to \ell^+\ell^- + KK$: Qualitative features? †

Larger/harder missing energies for the KK signal:



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

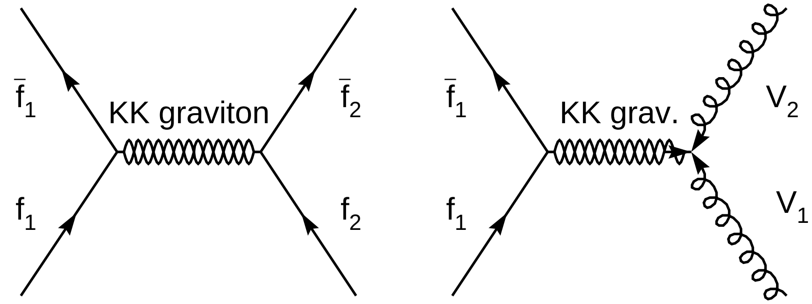
Consequently, the lepton opening angle is sensitive to it:



B. Collider Signals II (ADD)

Virtual KK Graviton Effects[‡]

On four-particle contact interactions:



Sum over virtual KK exchanges:

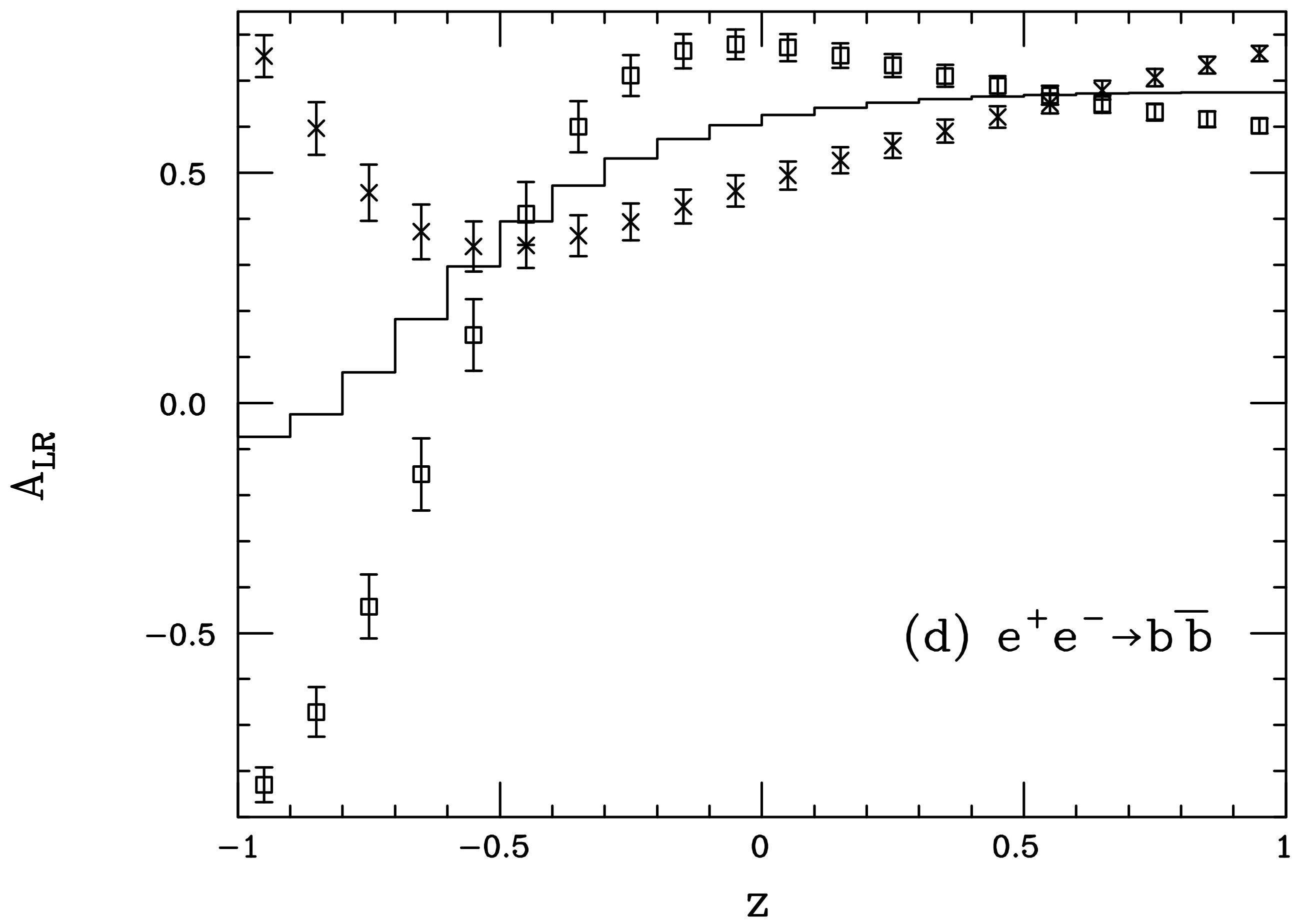
$$i\mathcal{M} \;\sim\; \overline{f}\mathcal{O}_i f\;\overline{f}\mathcal{O}_j f\int_0^\infty \frac{dm_{\vec{n}}^2\;\kappa^2\rho(m_{\vec{n}})}{s-m_{\vec{n}}^2+i\epsilon}$$

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

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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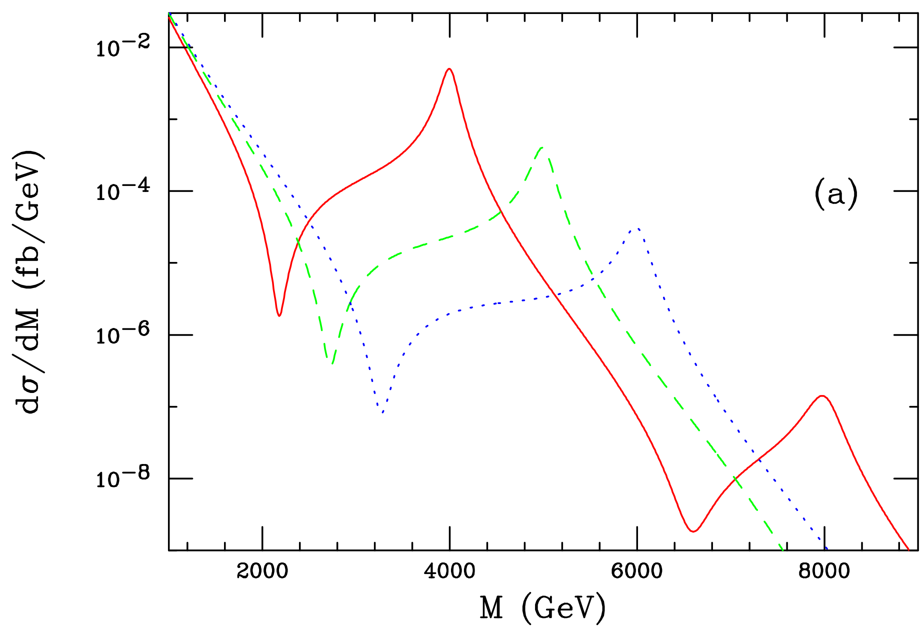
Resonant production at the LHC:



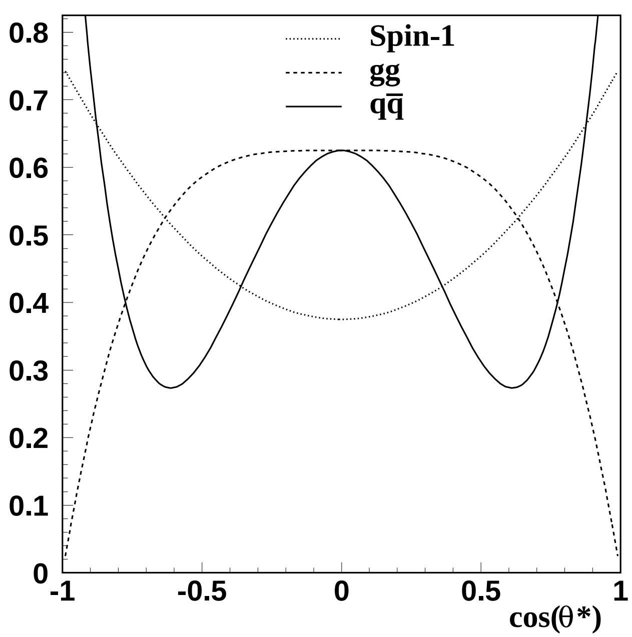
‡Davoudiasl, Hewett, Rizzo, `hep-ph/9911262`.

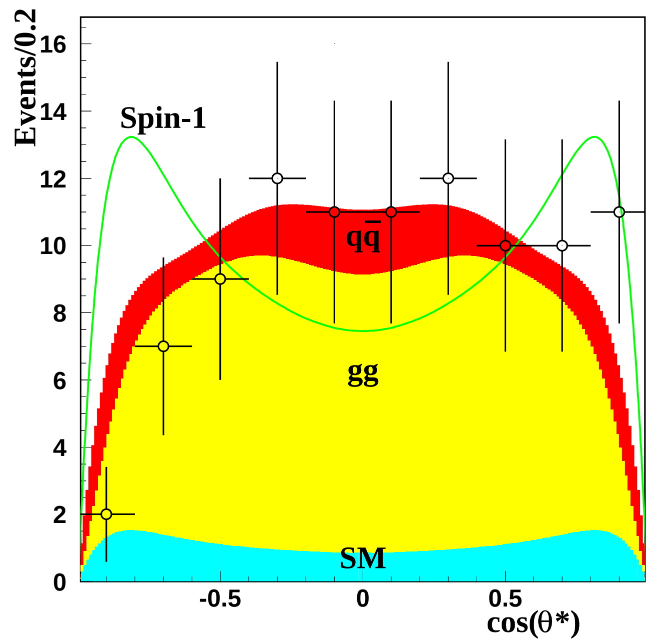
b. Heavy KK gravitons

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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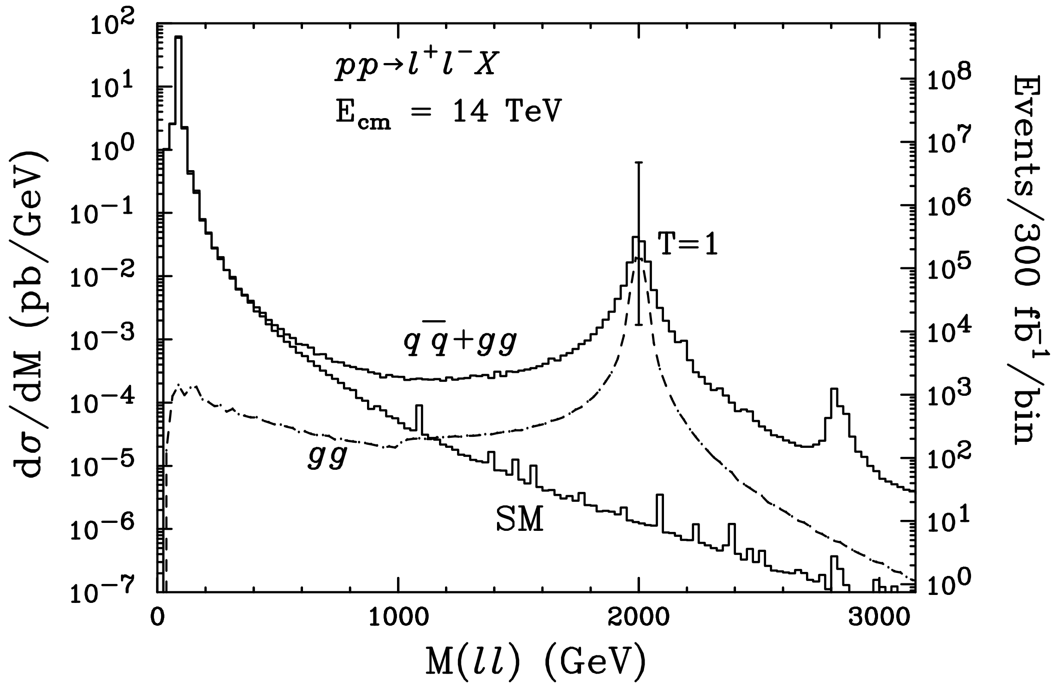
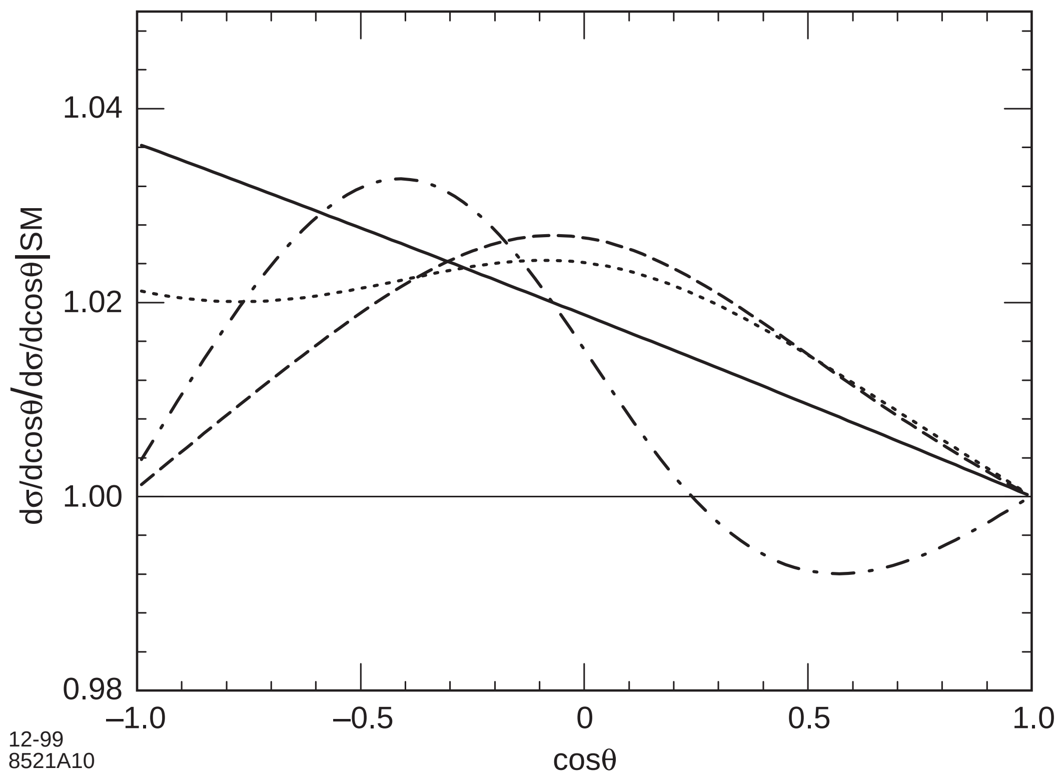


† Antoniadis, Benakli and Quiros; Cullen, Perelstein and Peskin; Han and Burikham ... ...

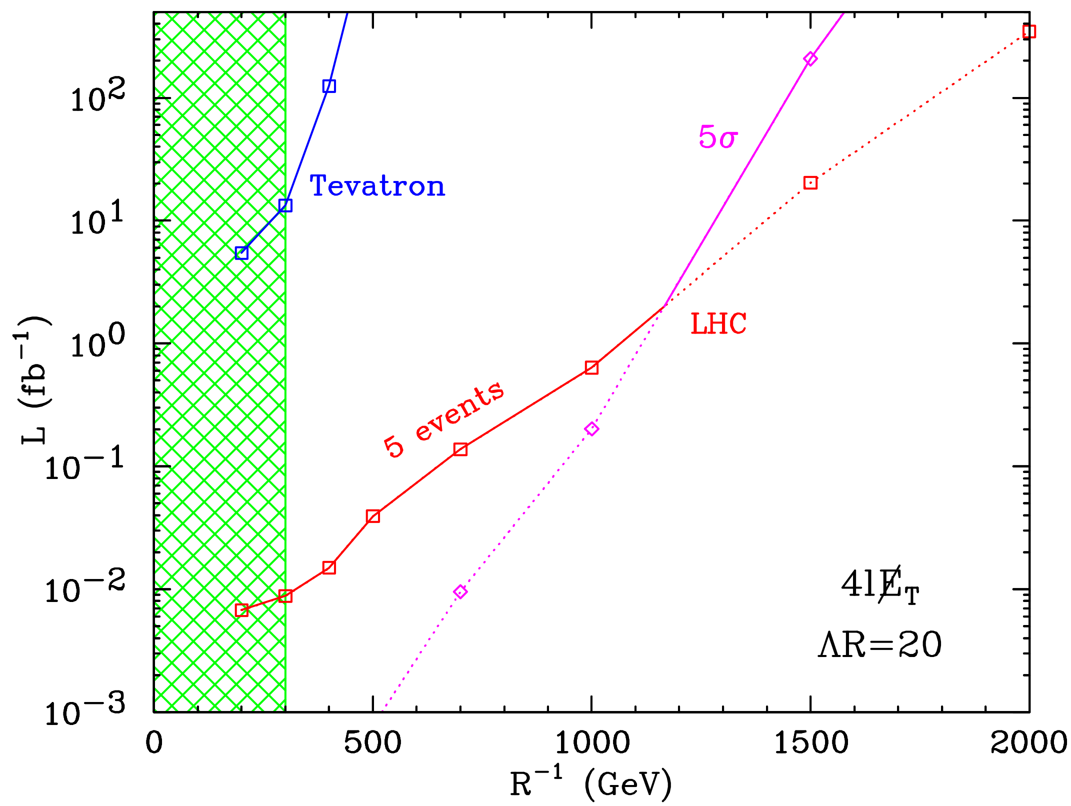
At the ILC:*



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:*

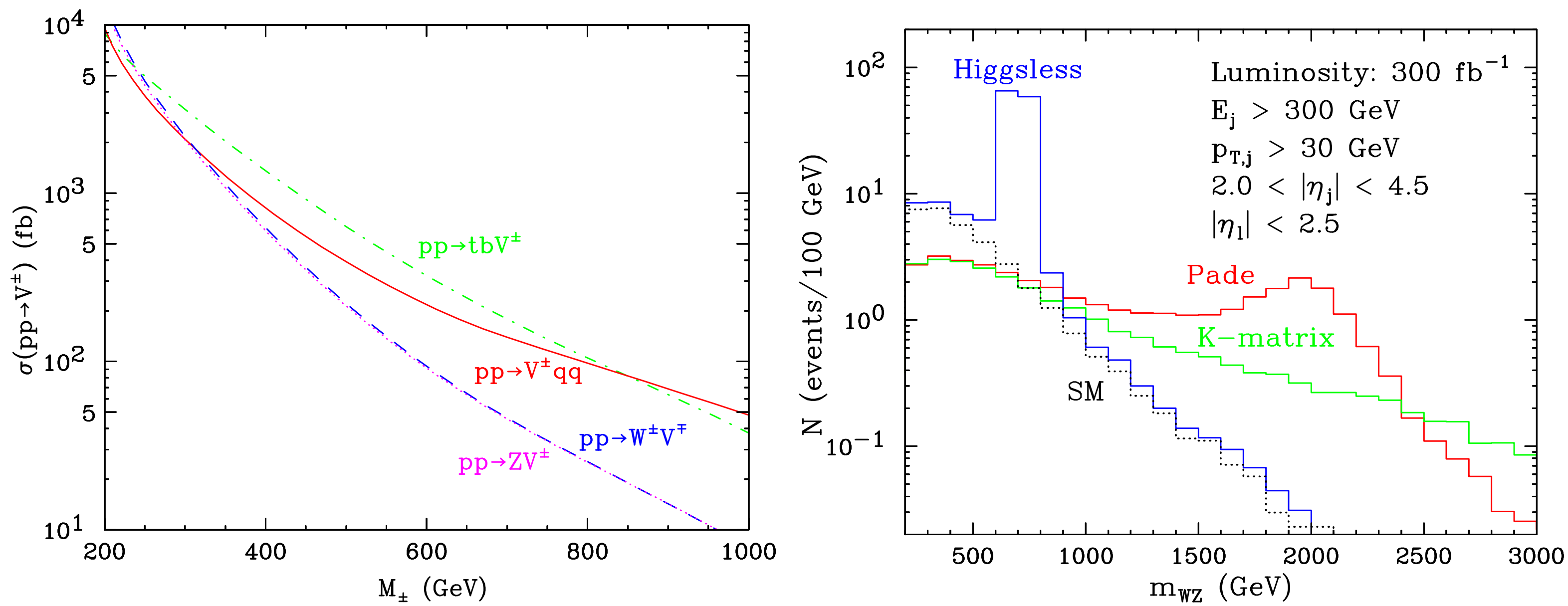


Discovery reach for MUEDs at the Tevatron (blue) and the LHC (red) in the $4\ell\not{E}_T$ channel. We require a 5σ excess or the observation of 5 signal events, and show the required total integrated luminosity per experiment (in fb^{-1}) as a function of R^{-1}, for $\Lambda R = 20$. (In either case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

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

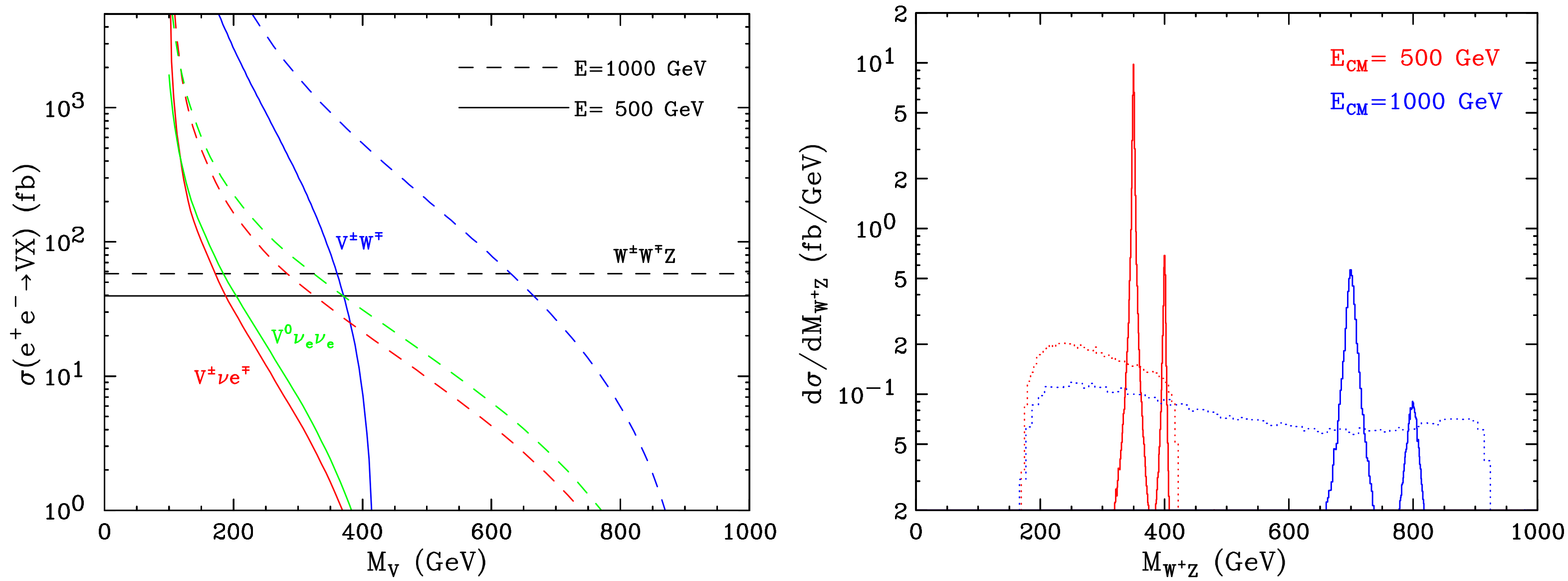
F. Higgsless:*

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



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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  colliders: if $M_S \sim 1 - 5$ TeV:
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