News from Universal Extra Dimensions

Bogdan Dobrescu (*Fermilab*)

work with Gustavo Burdman and Eduardo Ponton

Bosons in compact spatial dimensions

4D flat spacetime $\perp$ one dimension of size πR:

$$\text{Boundary conditions : } \frac{\partial}{\partial y}\phi(x,0) = \frac{\partial}{\partial y}\phi(x,\pi R) = 0$$

$$\text{KK decomposition : } \phi(x,y) = \frac{1}{\sqrt{\pi R}}\left[\phi^0(x) + \sqrt{2}\sum_{j\geq 1}\phi^j(x)\cos\left(\frac{jy}{R}\right)\right]$$

Zero-mode: ϕ^0 - wave function is flat along the extra dimension.

Kaluza-Klein modes, $\phi^j(x)$:

particles with momentum in extra dimensions,

or 4D point of view: a tower of massive particles: $\quad m_j^2 = m_0^2 + \frac{j^2}{R^2}$

Gauge bosons in 5D:

$A_\mu(x^\nu, y)$, $\mu, \nu = 0, 1, 2, 3$, and

$A_y(x^\nu, y)$ – polarization along the extra dimension.

4D point of view: $A_y(x^\nu, y)$ is a tower of spin-0 KK modes.

$$\text{Dirichlet B.C}: \quad A_y(x^\nu, 0) = A_y(x^\nu, \pi R) = 0$$

$$\text{KK decomposition}: \quad A_y(x^\nu, y) = \sqrt{\frac{2}{L}} \sum_{j \geq 1} A_y^j(x^\nu) \sin\left(\frac{jy}{R}\right)$$

→ $A_y(x^\nu, y)$ does not have a 0-mode! *(Odd field)*

$A_y^j(x^\nu)$ becomes the longitudinal degree of freedom of the spin-1 KK mode $A_\mu^j(x^\nu)$.

Fermions in a compact dimension

Lorentz group in 5D $\Rightarrow$ vector-like fermions:

$$\chi = \chi_L + \chi_R$$

Chiral boundary conditions:

$$\begin{aligned} \chi_L(x^\mu, 0) &= \chi_L(x^\mu, \pi R) = 0 \\ \frac{\partial}{\partial y}\chi_R(x^\mu, 0) &= \frac{\partial}{\partial y}\chi_R(x^\mu, \pi R) = 0 \end{aligned}$$

Kaluza-Klein decomposition:

$$\chi = \frac{1}{\sqrt{\pi R}}\left\{\chi_R^0(x^\mu) + \sqrt{2}\sum_{j\geq 1}\left[\chi_R^j(x^\mu)\cos\left(\frac{\pi j y}{L}\right) + \chi_L^j(x^\mu)\sin\left(\frac{\pi j y}{L}\right)\right]\right\}$$

Universal Extra Dimensions

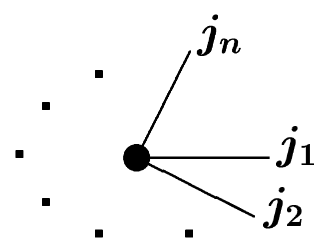
T. Appelquist, H.-C. Cheng, B. Dobrescu, Phys.Rev.D64 (2001)

All Standard Model particles propagate in $D \geq 5$ dimensions.

Kaluza-Klein modes are states of definite momentum along the compact dimensions.

Momentum conservation $\rightarrow$ KK-number conservation

$$\mathcal{L}_{4D} = \int dy \, \mathcal{L}_{5D}$$



At each interaction vertex:

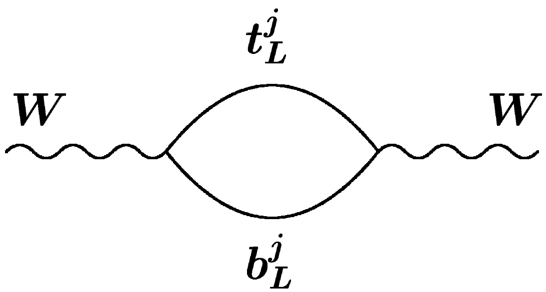
$j_1 \pm j_2 \pm ... \pm j_n = 0$ **for a certain choice of $\pm$**

In particular: $0 \pm \cdots \pm 0 \neq 1$

$\Rightarrow$ tree-level exchange of KK modes does not contribute to currently measurable quantities

$\Rightarrow$ no single KK 1-mode production at colliders

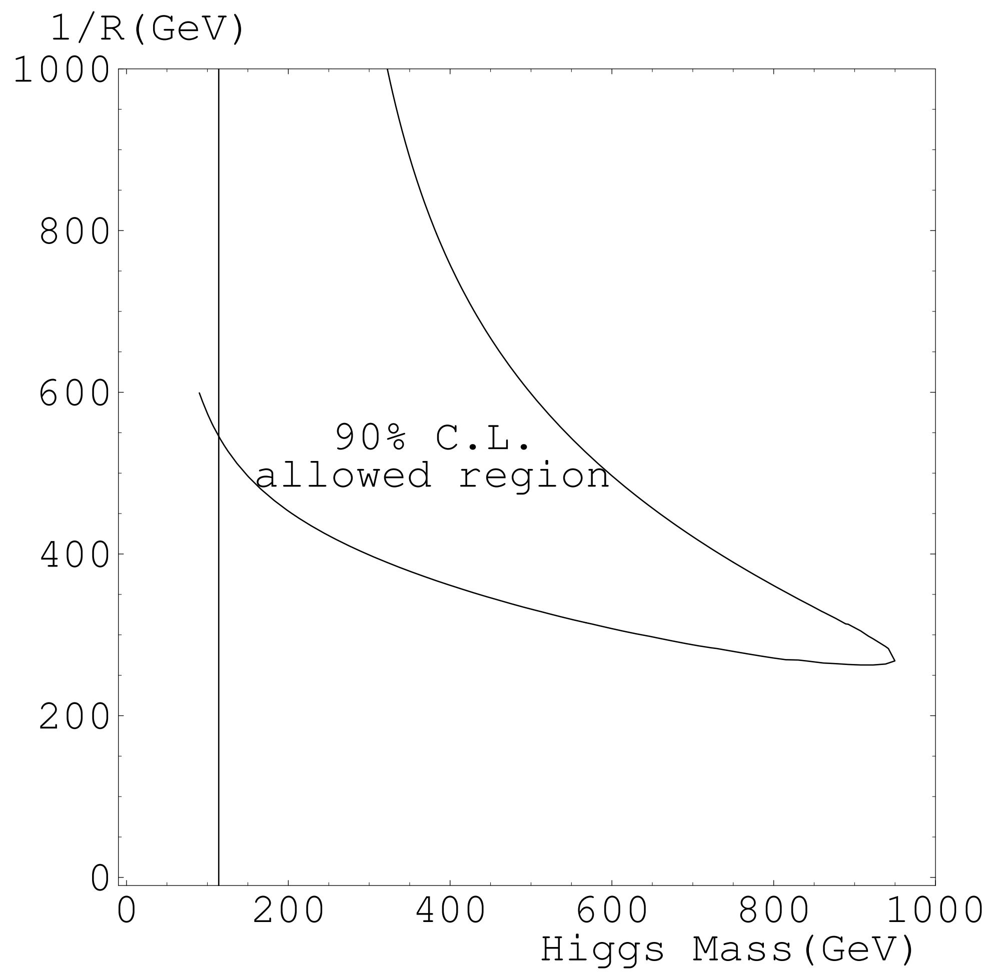
Bounds from one-loop shifts in W and Z masses, and other observables:



$$\frac{1}{R} \gtrsim 300 - 500 \text{ GeV}$$

Contributions to the T parameter from top KK modes may compensate for the effect of a heavy Higgs boson on the electroweak fits.

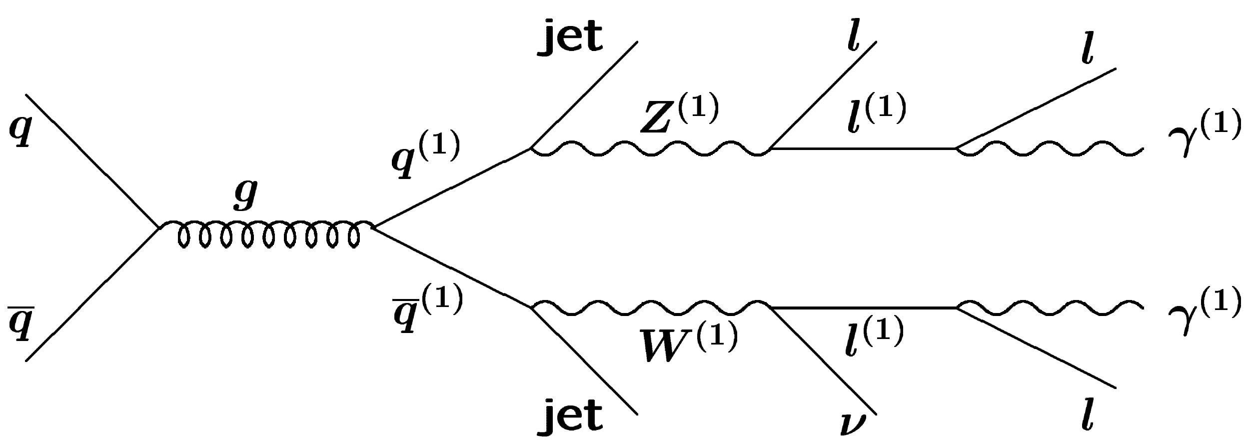
Appelquist, Yee, hep-ph/0211023



- Pair production of KK 1-modes at colliders: cascade decays to $4l + \not{E}_T$ (soft leptons). Could be discovered soon!

(Cheng, Matchev, Schmaltz, hep-ph/0205314)

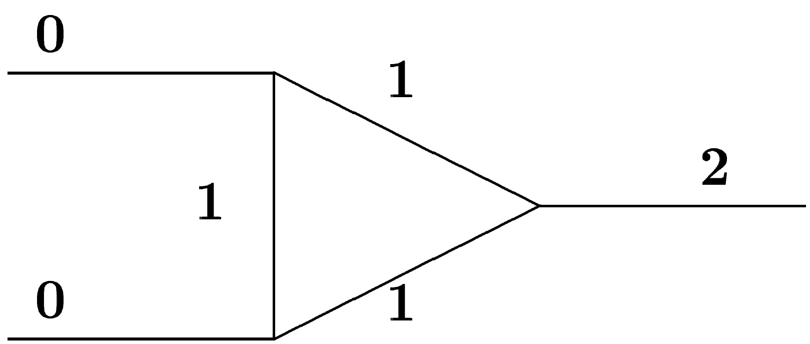
CDF analysis of $3l + \not{E}_T$ (soft leptons): $1/R > 280$ GeV (Run I)



At one-loop level: $j_1 \pm j_2 \pm ... \pm j_n =$ even

KK parity is conserved: $(-1)^j \Rightarrow$ Lightest KK Particle is a viable dark matter candidate.

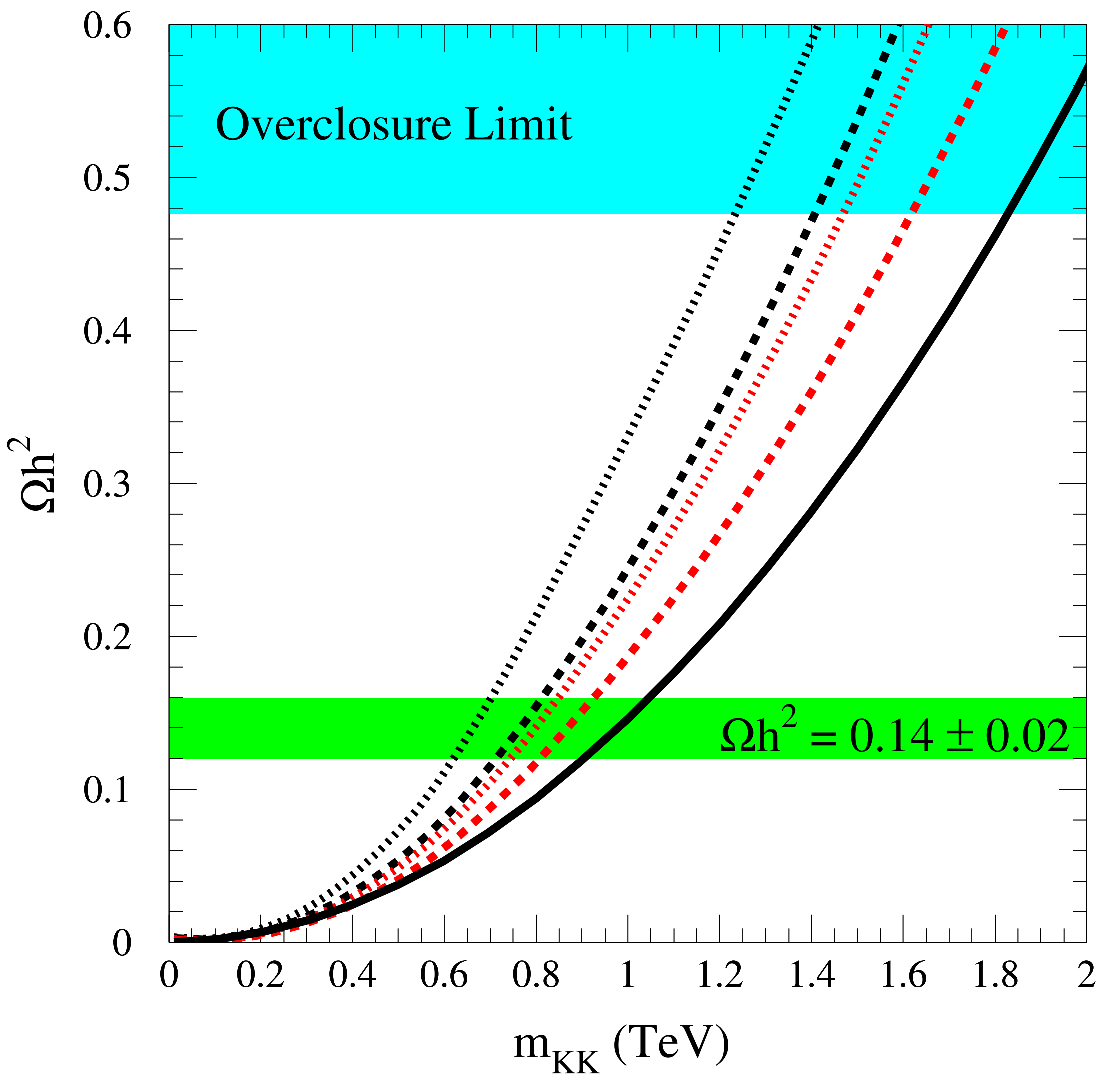
At colliders: s-channel production of the 2-modes



Lightest KK particle is stable in UED:

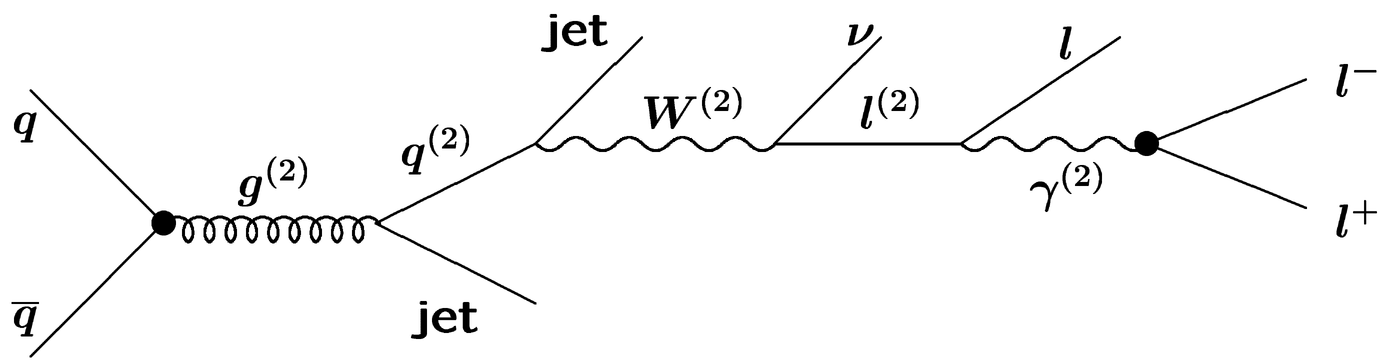
$\gamma^{(1)}$ is a viable dark matter candidate

(from Servant, Tait, hep-ph/0206071)



Second-level masses: $\sim 2/R$.

Cascade decay of the 2-mode is followed by $\gamma^{(2)}$ decay into hard leptons:



Particularly useful at the LHC (K. Kong, K. Matchev, hep-ph/0509246)

$\longrightarrow$ *would allow discrimination of UED & MSSM.*

6-Dimensional Standard Model

Motivation

- 3 generations of quarks and leptons are required for global $SU(2)_W$ anomaly cancellation
- proton is long-lived due to 6D Lorentz invariance
- neutrinos are interesting (Dirac masses)

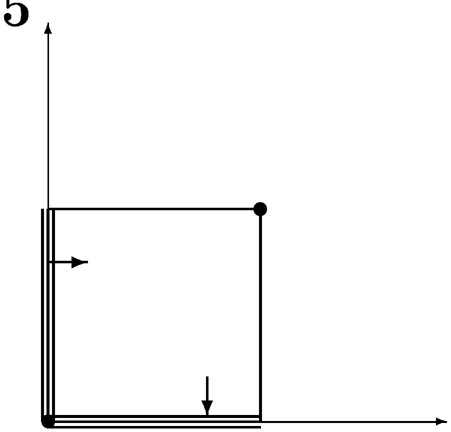
Two possible chirality assignments for the 6D quarks and leptons:

$$\mathcal{Q}_+ \, , \, \mathcal{U}_- \, , \, \mathcal{D}_- \, , \begin{cases} \mathcal{L}_+ \, , \;\; \mathcal{E}_- \, , \;\; \mathcal{N}_- \\ \qquad\quad \text{or} \\ \mathcal{L}_- \, , \;\; \mathcal{E}_+ \, , \;\; \mathcal{N}_+ \end{cases}$$

Chiral boundary conditions on a square

(Dobrescu, Ponton, hep-ph/0401032; G. Burdman and E. Ponton, hep-ph/0506334)

Identify pairs of adjacent sides:



$$\mathcal{L}(x^\mu, y, 0) = \mathcal{L}(x^\mu, 0, y)$$

$$\mathcal{L}(x^\mu, y, L) = \mathcal{L}(x^\mu, L, y)$$

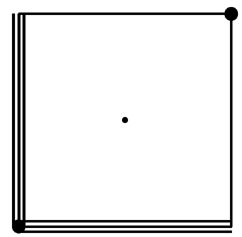
$\Phi(y, 0) = e^{in\pi/2}\Phi(0, y)$, ...

$$\partial_5\Phi|_{(x^4,x^5)=(y,0)} = -e^{in\pi/2}\,\partial_4\Phi|_{(x^4,x^5)=(0,y)}$$

Spectrum of KK modes:

(j,k)	(1,0)	(1,1)	(2,0)	$(2,1)$ $(1,2)$	(2,2)	(3,0)	$(3,1)$ $(1,3)$
$M_{j,k}R$	1	$\sqrt{2}$	2	$\sqrt{5}$	$2\sqrt{2}$	3	$\sqrt{10}$

Kaluza-Klein parity



Reflections about the center of the square $(L/2, L/2)$,

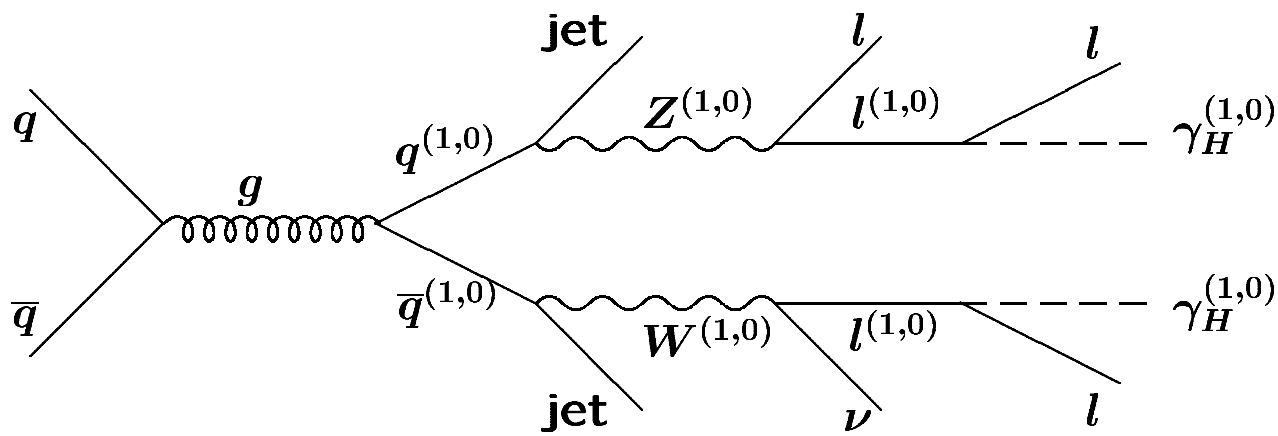
$$(x^4, x^5) \mapsto (L - x^4, L - x^5)$$

$\Rightarrow$ invariance under Z_2 transformation

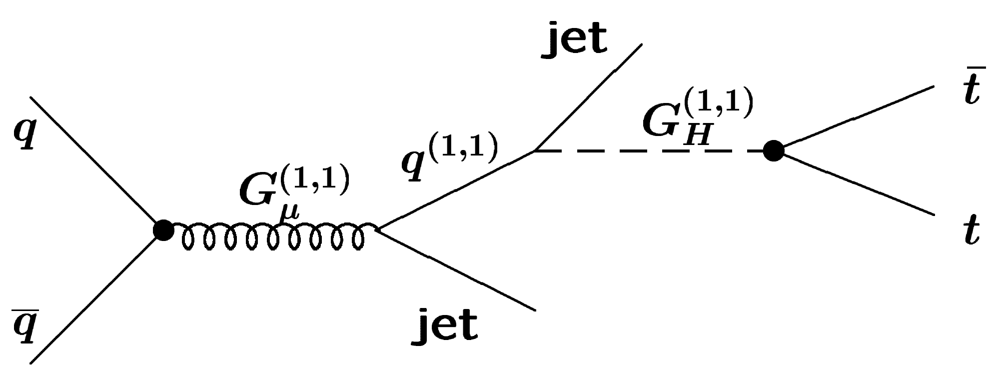
$$\Phi^{(j,k)}(x^\mu) \mapsto (-1)^{j+k}\, \Phi^{(j,k)}(x^\mu)$$

Signals at colliders:

Pair production of (1,0) modes: $3l + \not{E}_T$ (soft leptons)

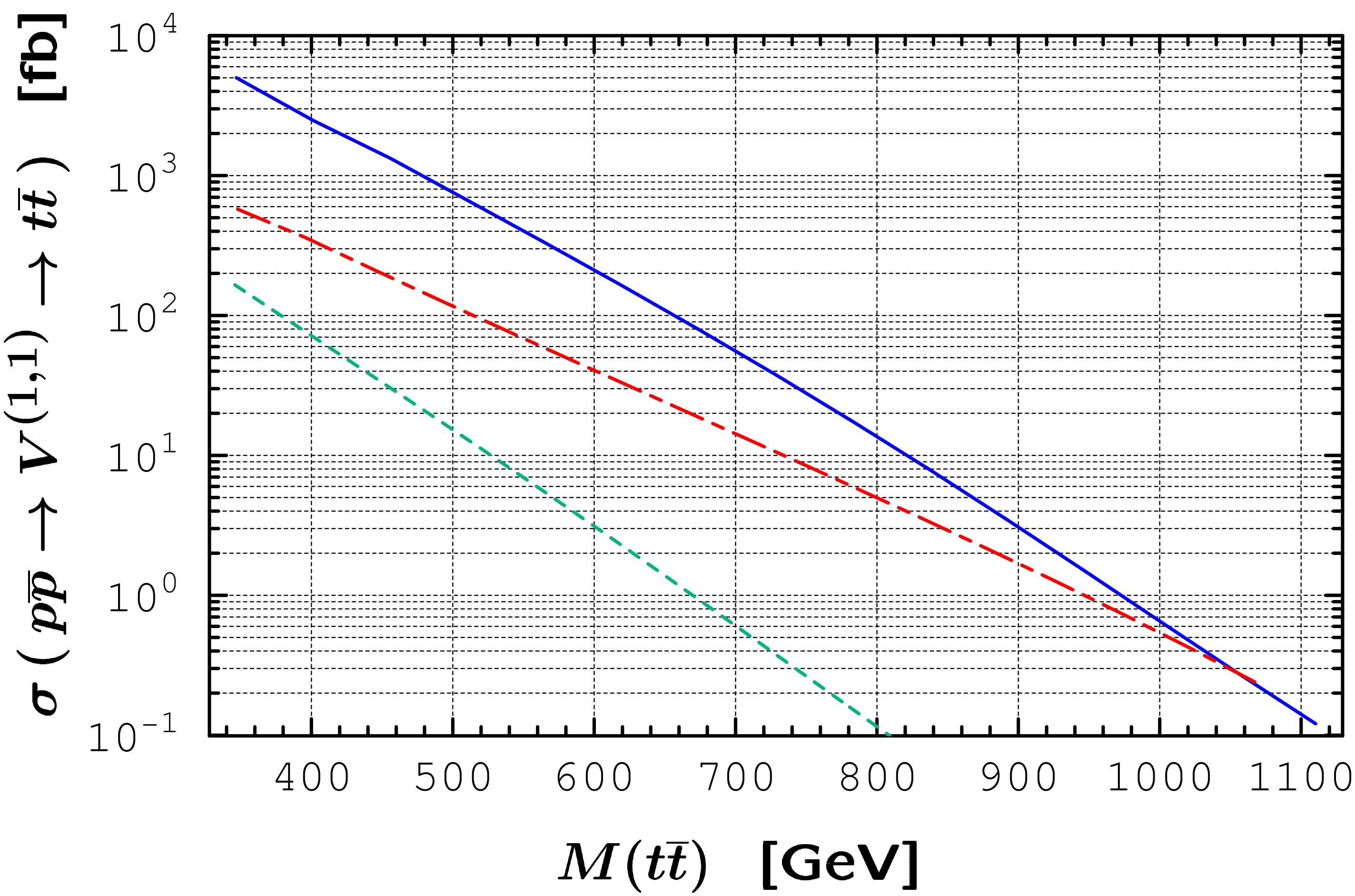


s-channel production of a (1,1) mode of mass $\sqrt{2}/R$
$\rightarrow$ $t\bar{t}$ resonance

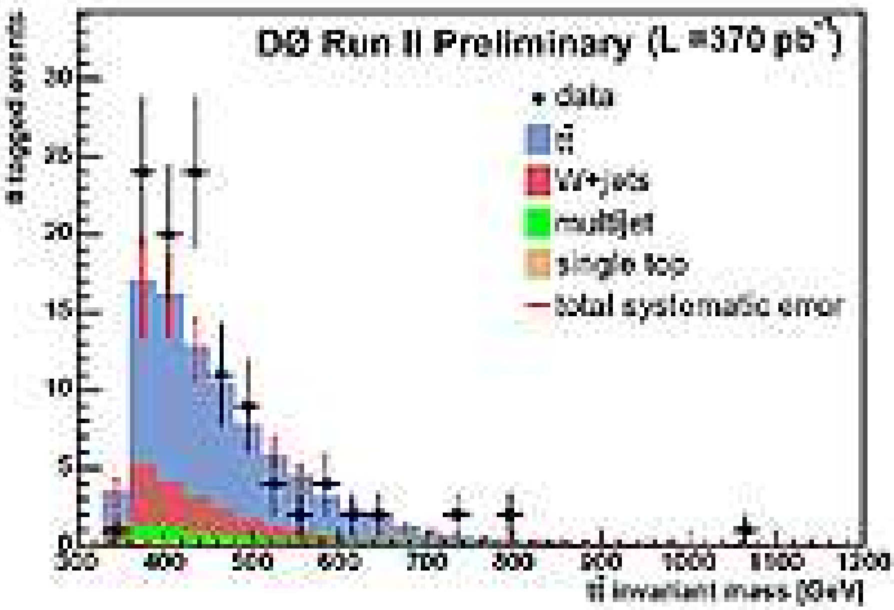


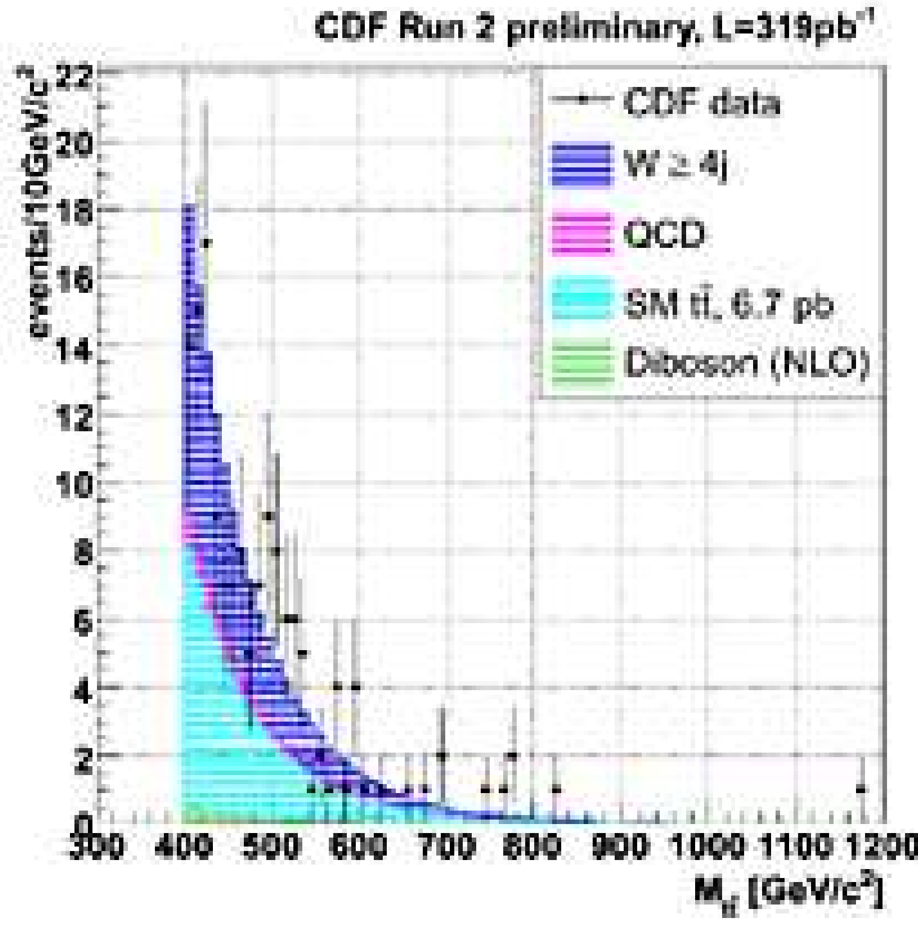
Production of $t\bar{t}$ pairs at the Tevatron from mass peaks at:

- $G_H^{(1,1)} + W_\mu^{(1,1)3}$ —— $M_{t\bar{t}} \simeq 1.10\sqrt{2}/R$
- $W_H^{(1,1)3} + B_\mu^{(1,1)}$ – – – $M_{t\bar{t}} \simeq 0.96\sqrt{2}/R$
- $B_H^{(1,1)}$ – – – $M_{t\bar{t}} \simeq 0.87\sqrt{2}/R$



D0 and CDF searches





Conclusions

- **Universal Extra Dimensions**

– compactification scale can be as low as ~ 300 GeV.

– lightest KK mode is a dark matter candidate

- **6-Dimensional Standard Model**

– 3 generations of quarks and leptons are required for global $SU(2)_W$ anomaly cancellation

– proton is long-lived due to 6D Lorentz invariance

- **Look for Kaluza-Klein modes at colliders:**

– 3 soft leptons + jets + $\not{E}_T$

– series of narrow $t\bar{t}$ resonances (or $\ell^+\ell^-$ resonances in the 5D case)