One way to look for Kaluza-Klein excitations at the LHC

Confronting particle-cosmology with Planck and LHC, IUCAA

Amitava Raychaudhuri

University of Calcutta, Kolkata

with Gautam Bhattacharyya, Anindya Datta, and S.K. Majee, (Nucl. Phys. B821 (2009) 48-64)

Plan

1. Minimal Universal Extra Dimensions
2. Kaluza-Klein particles
3. KK Particle production at the LHC
4. The (KK EW gauge boson + KK Quark) production option
5. Production cross sections, kinematic cuts
6. LHC Luminosity required for 5σ signal
7. Conclusions

Talk of S. Raychaudhuri

Minimal UED

- Models with extra dimensions beyond four much discussed.
- One extra coordinate (y) compactified on a circle, $y = y + 2\pi R$, $R \Rightarrow$ compactification radius.
- Orbifolding ($y \equiv -y$) to get chiral fermions.
- $y = 0$ and $y = \pi R$ are fixed points $\equiv$ “branes".
- S^1/Z_2. All particles experience five dimensions (Universal). (UED: Appelquist, Cheng, Dobrescu).
- p_y quantised as n/R.
  KK parity $(-)^n$ is conserved. n conserved at all tree vertices.
- KK-excitation masses $\sim n/R$. SM particles are zero modes.

Extra compactified dimensions

UED is a well-studied model:

- $(g-2)_\mu$ (Nath, Yamaguchi)
- FCNC (Buras, Spranger, Poschenrieder, Weiler)
- $Z \to b\bar{b}$ (Oliver, Papavassiliou, Santamaria)
- $\Delta\rho$ (Appelquist, Cheng, Dobrescu, Yee)
- All EW precision observables (Gogoladze, Mascesanu)
- Direct search at Colliders

$\boxed{\mathbf{R^{-1}} \gtrsim \text{ 300 GeV (pre-LHC)}}$

Earlier Collider limits

UED signals have been searched for at the Tevatron

Imp: The lightest KK particle (γ^1) is stable. A dark matter candidate.

All KK particles eventually cascade to γ^1. In colliders it is 'seen' as missing energy/missing p_T.

- One analysis: Assume KK states do not decay within the detector
- Another analysis: γ^1 is unstable and decays to a photon and a graviton (missing).

From both analyses: $\mathbf{R}^{-1} \gtrsim$ 500 GeV

The Kaluza-Klein fields

5-D scalar field:

$$\phi^+(x,y) = \frac{\sqrt{2}}{\sqrt{2\pi R}}\phi^0(x) + \frac{2}{\sqrt{2\pi R}}\sum_{n=1}^{\infty}\phi^n(x)\cos\frac{ny}{R} \quad (even)$$

$$\phi^-(x,y) = \frac{2}{\sqrt{2\pi R}}\sum_{n=1}^{\infty}\phi^n(x)\sin\frac{ny}{R} \quad (odd)$$

The Kaluza-Klein fields (contd.)

Scalar field:

$$\phi^+(x,y) = \frac{\sqrt{2}}{\sqrt{2\pi R}}\phi^0(x) + \frac{2}{\sqrt{2\pi R}}\sum_{n=1}^{\infty}\phi^n(x)\cos\frac{ny}{R}$$

Vector field:

$$\begin{aligned} A_\mu(x,y) &= \frac{\sqrt{2}}{\sqrt{2\pi R}}A_\mu^0(x) + \frac{2}{\sqrt{2\pi R}}\sum_{n=1}^{\infty}A_\mu^n(x)\cos\frac{ny}{R}, \\ A_5(x,y) &= \frac{2}{\sqrt{2\pi R}}\sum_{n=1}^{\infty}A_5^n(x)\sin\frac{ny}{R} \end{aligned}$$

The Kaluza-Klein fields (contd.)

Fermion fields:

Left-handed doublets:

$$\begin{aligned} \mathcal{Q}_i(x,y) &= \frac{\sqrt{2}}{\sqrt{2\pi R}}\left[\begin{pmatrix} u_i \\ d_i \end{pmatrix}_L (x)\right. \\ &+ \left.\sqrt{2}\sum_{n=1}^{\infty}\left[\mathcal{Q}^n_{iL}(x)\cos\frac{ny}{R} + \mathcal{Q}^n_{iR}(x)\sin\frac{ny}{R}\right]\right], \end{aligned}$$

Right-handed singlets:

$$\begin{aligned} \mathcal{U}_i(x,y) &= \frac{\sqrt{2}}{\sqrt{2\pi R}}\left[u_{iR}(x) + \sqrt{2}\sum_{n=1}^{\infty}\left[\mathcal{U}^n_{iR}(x)\cos\frac{ny}{R} + \mathcal{U}^n_{iL}(x)\sin\frac{ny}{R}\right]\right], \\ \mathcal{D}_i(x,y) &= \frac{\sqrt{2}}{\sqrt{2\pi R}}\left[d_{iR}(x) + \sqrt{2}\sum_{n=1}^{\infty}\left[\mathcal{D}^n_{iR}(x)\cos\frac{ny}{R} + \mathcal{D}^n_{iL}(x)\sin\frac{ny}{R}\right]\right] \end{aligned}$$

Corrections to KK particle masses

- At tree level, all the n-th level KK states have mass n/R.
- There are 'bulk' loop corrections (only for bosons), and brane-localised interactions (for all particles) which contribute to the masses.
- Corrections depend on R and the cut-off scale Λ.

For $1/R = 500$ GeV and $\Lambda R =$ 20, one has (in GeV):

States	g^1	Q^1	u^1, d^1	$W^{\pm 1}$, Z^1	L^1	e^1	γ^1
Mass	642.3	599.9	586.5	539	515	505.5	501.0

KK signals at the LHC

- KK Parity conservation: n= 1 KK particles (which are odd) must be produced in pairs.
- Compare Q^1Q^1, Q^1V^1, V^1V^1 production (V^1 (Q^1) $\equiv$ generic n=1 electroweak vector boson (quark)).

Comparison of the different options

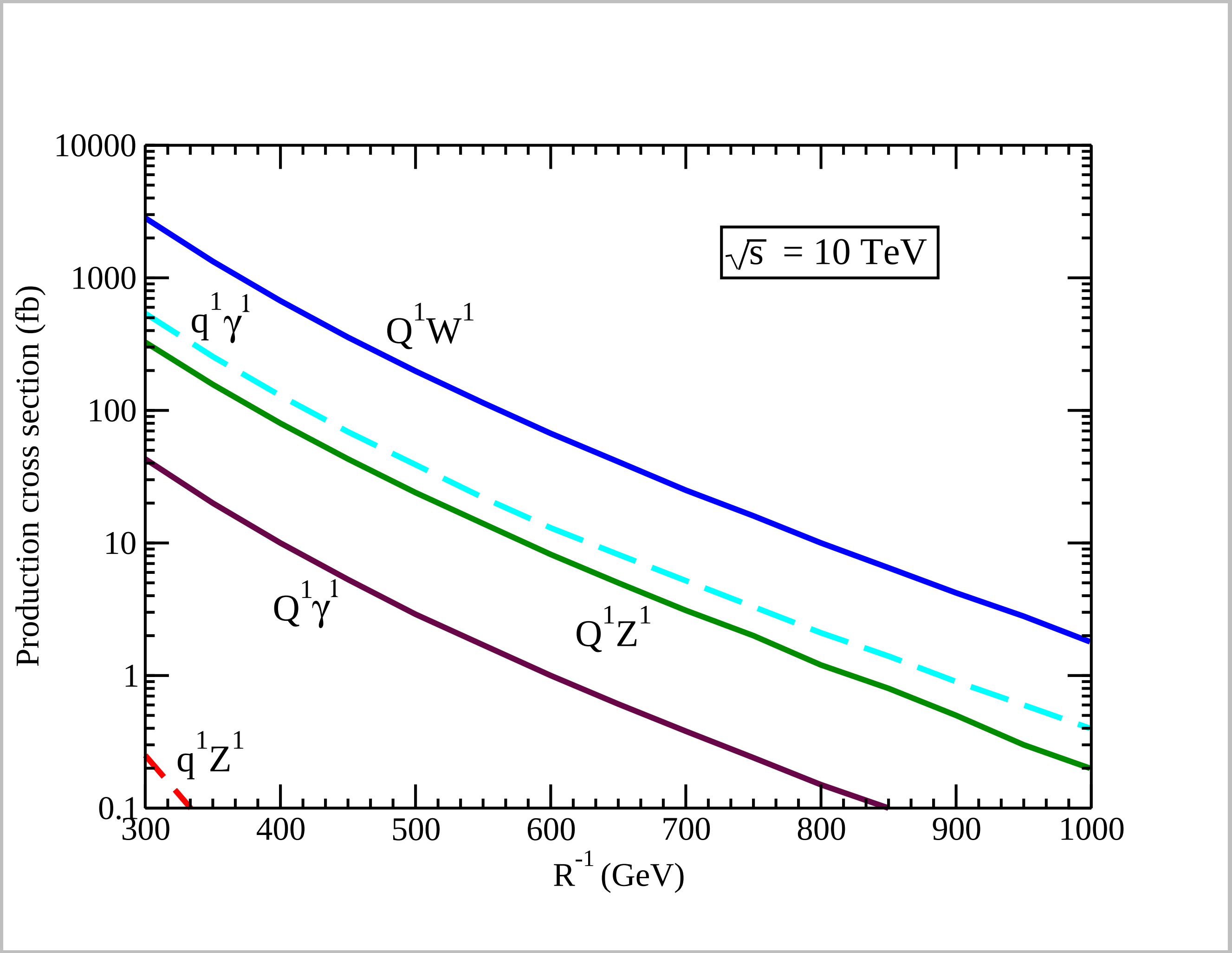
Q^1Q^1 production cross section highest, produces two jets and missing p_T. Background very high.

V^1V^1 , produces hadronically quiet events with missing p_T which has low background. But the cross section is very low.

Q^1V^1 production cross section not too low, one jet, leptons and missing p_T. Background controllable.

Explore Q^1V^1 production at the LHC

Production rates



CTEQ6 parton distributions, Leading order parametrisation

Decays of n = 1 KK states

For $1/R = 500$ GeV and $\Lambda R =$ 20, (in GeV):

States	g^1	Q^1	u^1, d^1	$W^{\pm 1}$, Z^1	L^1	e^1	γ^1
Mass	642.3	599.9	586.5	539	515	505.5	501.0

The decay channels which are kinematically open can be read off from the Table

Note $\sin^2 \theta_w^1 \ll \sin^2 \theta_w$

n=1 photon: γ^1 is stable due to KK-parity conservation

n=1 Leptons: $L^1, l^1 \to l\gamma^1$

n=1 W-boson: $W^1 \to L^1\nu, l\nu^1$ followed by L^1 decay

n=1 Z-boson: $Z^1 \to L^1 l, \nu^1\nu$ followed by L^1 decay. (e^+e^- or $\mu^+\mu^-$ + missing p_T).

n=1 singlet quark: $q^1 \to q\gamma^1$

n=1 doublet quarks: $Q^1 \to qZ^1$ or $q'W^1$ followed by Z^1, W^1 decay

Decays of n = 1 KK states (contd)

- Missing p_T due to two γ^1 or $\gamma^1\nu^1$ in the final state.
- Electrons, muons produced from KK lepton or Z^1, W^1 decay are of relatively low energy due to kinematic constraint..
- Final states contain 1 jet + m_l charged leptons + missing p_T, m_l = 0 . . . 4.

Possibilities:

1) No charged leptons: $q^1\gamma^1$ or q^1Z^1 followed by $Z^1 \to \nu\nu^1$

2) One charged lepton: (i) $Q^1\gamma^1$ or Q^1Z^1 followed by $Z^1 \to \nu\nu^1$ and $Q^1 \to q'W^1$ decay, or (ii) Q^1W^1 followed by $Q^1 \to qZ^1$ with the Z^1 decaying invisibly

3) Two charged leptons: (i) Q^1W^1 and $Q^1 \to q'W^1$ or (ii) Q^1Z^1 and $Q^1 \to qZ^1$ followed by invisible decay of one of the Z^1. Could lead to e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$ states.

4) Three charged leptons: (i) Q^1W^1 with $Q^1 \to qZ$ followed by leptonic decay of the Z, or (ii) Q^1Z^1 followed by $Q^1 \to q'W^1$.

5) Four charged leptons: Q^1Z^1 followed by $Q^1 \to qZ^1$ followed by $Z^1 \to L^1l$ for both Z^1.

Kinematic cuts

For all channels there are huge Standard Model backgrounds.

These have to be reduced by judicial kinematic cuts on the events.

Basic cuts:

a) $p_T^{miss} > 25$ GeV, $p_T^{jet} > 20$ GeV, $p_T^{leptons} > 5$ GeV.

b) Rapidity cut: $|\eta| > 2.5$ for all leptons and the jet.

c) To eliminate soft photons also impose $M_{l_i l_j} > 5$ GeV for all charged lepton pairs.

The $0l$ and $1l$ cases have too large SM backgrounds.

A) Zero lepton Signal: 106.4 fb, SM background: $4.7 \times 10^5\ fb$.

B) One lepton Signal: 17.92 fb, SM background: $1.3 \times 10^5\ fb$.

Concentrate on 2,3, and 4 lepton options

Kinematic cuts (contd.)

Two charged leptons: (i) $Q^1 W^1$ and $Q^1 \to q' W^1$ or (ii) $Q^1 Z^1$ and $Q^1 \to q Z^1$ followed by invisible decay of one of the Z^1.

Because the KK state mass splittings are not large, the leptons are not of high energy by LHC standards.

The main SM backgrounds arise from $t\bar{t}$ and $b\bar{b}$ production whch are huge at the LHC.

Also, $t\bar{b}$ and $\bar{t}b$ result in substantial backgrounds.

These have to be reduced by judicial kinematic cuts on the events.

Due to the high energy of the t, b quarks, the leptons from t, b-decay are nearly aligned with the quark that is also produced.

Lepton isolation: $\Delta R >$ 0.7 where $\Delta R^2 = (\Delta\phi^2 + \Delta\eta^2)$. significantly reduces the SM backgrounds

i) Also apply $p_T^{lepton} <$ 25 GeV for both leptons.

ii) And $|M_{l_1 l_2} - M_Z| <$ 10 GeV to eliminate SM backgrounds arising from the Z-boson.

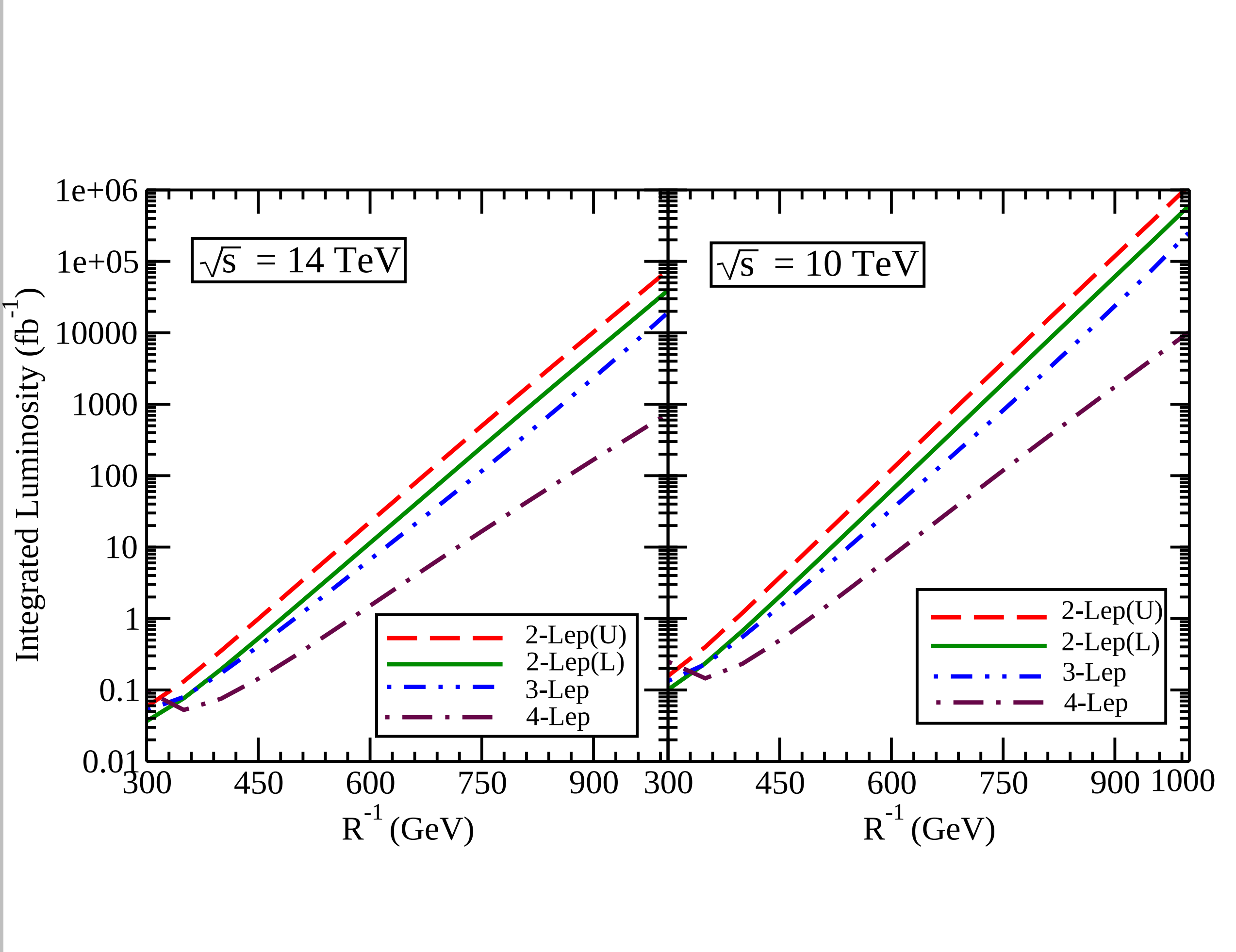
Impact of Kinematic cuts

Cross sections in fb:

Cuts	e^+e^- or $\mu^+\mu^-$		μ^+e^- or $\mathcal{E}^+\mu^-$	
	Signal	Background	Signal	Background
Basic cuts	10.0	4.8×10^4	14.60	9.6×10^4
Lepton isolation	8.28	108.54	12.06	212.78
$p_T^{l_1} <$ 25 GeV	7.52	41.10	10.74	80.70
$p_T^{l_2} <$ 25 GeV	4.53	5.27	6.52	10.22
$\lvert M_{l_1 l_2} - M_Z \rvert <$ 10 GeV	4.51	5.17	6.48	10.08

Similar analyses performed for the 3-lepton and 4-lepton cases

LHC Luminosity for 5σ signal



Multilepton + 1 jet + missing energy signal (with kinematic cuts to reduce backgrounds).

L (U) for Like (Unlike) lepton flavours.

Conclusions

- Universal Extra Dimensions: A theory where all particles live in 4D *and* extra dimensions.
- In simplest theory, there is one extra dimension compactified on an S^1/Z^2 orbifold.
- 5-D fields can be interpreted in terms of 4D Kaluza-Klein excitations.
- Mass degeneracy of KK states at any level split by Lorentz violation in 5-D.
- Because of conserved KK parity, KK excitations can only be produced in pairs.
- n=1 KK quarks and electroweak gauge bosons produced at the LHC result in multilepton+ 1 jet + missing p_T signals.
- The signal can be extracted from the background by judicial cuts.

THANK YOU!