COLLIDER IMPLICATIONS OF MODELS WITH EXTRA DIMENSIONS

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(in Collaboration with: Dicus, MacoSanu, McMullen)

: Brief review of extra dimension

- Symmetric Compactification
- asym. Compact.

: Models with TeV^{-1} scale extra dim

: Collider signals

: only gauge bosons in extra dim

: all SM particles in extra dim (Universal Extra Dim)

: Conclusions

EXTRA DIMENSIONS → motivated by string theory but may be more general

Superstring Theory → 1 + 9
↑ time ↑ space

⇒ 6 extra space-like dim
⇒ must be compact

: Physics depends on how compactified and at what scale

TWO BROAD POSSIBILITIES

/ all sizes $\sim M_P^{-1}$
↓
Very little phenomenological implications

\ (Witten, Lykken)
Some or all much <u>larger</u> than M_{PL}^{-1}

$\sim$ submm , TeV^{-1}, ...
⇓
many interesting phenomenological consequences

: modify Newton's law of gravity
: effects in low energy astrophysical phenomena
: new physics in high energy colliders.

High Energy Colliders ⇒ new physics from the KK excitations of gravity and/or SM fields.

: where do the SM particles live ??

4 + N DIM SPACE

TWO SCENARIOS

- SM particles do <u>not</u> see any extra dim (confined to D_3 brane)
  ⇒ only gravity propagate to extra dim.
  ⇒ ADD scenario

- Some or all SM particles <u>do</u> see one or more extra dimensions
  (Antoniadis, 1991)
  Dienes, Dudas, Gherghetta, Lykken, Nandi)

: For time limitation, I will not talk about ADD or RS Models.

Contribution by Kim, Lee and Song
⇒ interesting enhancement of Higgs pair productions in ADD & RS models at the LHC

: how extra dims are compactified ?

$$D = 4 + N$$

Symmetric compactification :

All extra dim. sym., same size R

Scaling law : $M_{PL}^2 = M_D^{n+2} R^n$

$N = 1$ excluded, $N = 2 \sim$ sub mm

$N = 6$, $\sim (10\,\text{MeV})^{-1}$

$\Rightarrow$ all SM particles must be confined to D_3-brane

Assymmetric compactification :

N extra dim diff sizes and shapes

Simplest possibility : Two sizes

$r \rightarrow$ sub mm

$R \rightarrow \text{TeV}^{-1}$

Scaling law : $M_{PL}^2 = M_D^{n+m+2} R^n r^m$

$n + m \leq 6$

For simplicity, we consider

: 1 TeV^{-1} extra dim where SM particles propagate

: 5 much larger extra dim where gravity propagate

1 TeV^{-1} scale extra dim

Two Possibilities

- only gauge bosons propagate into the extra dim
- all SM particles propagate into the extra dim

⇒ SM will have KK towers of excitations with masses starting at ~ TeV

⇓

Collider implications due to the productions or off shell effects of these KK excitations

⇒ : new signals

: modification of SM signals

SCENARIO 1:

: only gauge bosons see the extra dim, fermions confined to D_3 brane

gauge bosons ⇒ KK excitations

$$g \to g_n^*, \quad W, Z, \gamma \to W_n^*, Z_n^*, \gamma_n^*$$

$$M_n^2 = \frac{n^2}{R^2} + m_0^2$$

m_0 → mass of g, W, Z, γ

: 5 dim momentum or KK # not conserved (Brane can absorb momenta in the 5th dir.)

new couplings: $\bar{q} q g^*$, $\bar{q} q W^*$, ...

new collider processes:

$\bar{q} q \to g_n^* \to \bar{q} q$ ↓ dijet, $\quad \bar{q} q \to g g^*$ ($g^* \to q\bar{q}$) ↓ 3jet, $\quad \bar{q} q \to g^* g^*$ ↓ 4jets

observable signal above background

⇒ modification of dijet crossections at high P_T at Tevatron & LHC

Run 1 bounds, $1/R \equiv \mu \gtrsim$ TeV

(Figs) Run 2 ⇒ $\mu \gtrsim 2$ TeV

LHC ⇒ $\mu \gtrsim 7$ TeV

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Dicus, McMullen + Nandi: PRD

TEVATRON RUN 2, $\sqrt{s} = 2$ TeV

DIJETS + $\not{E}_T$ signal

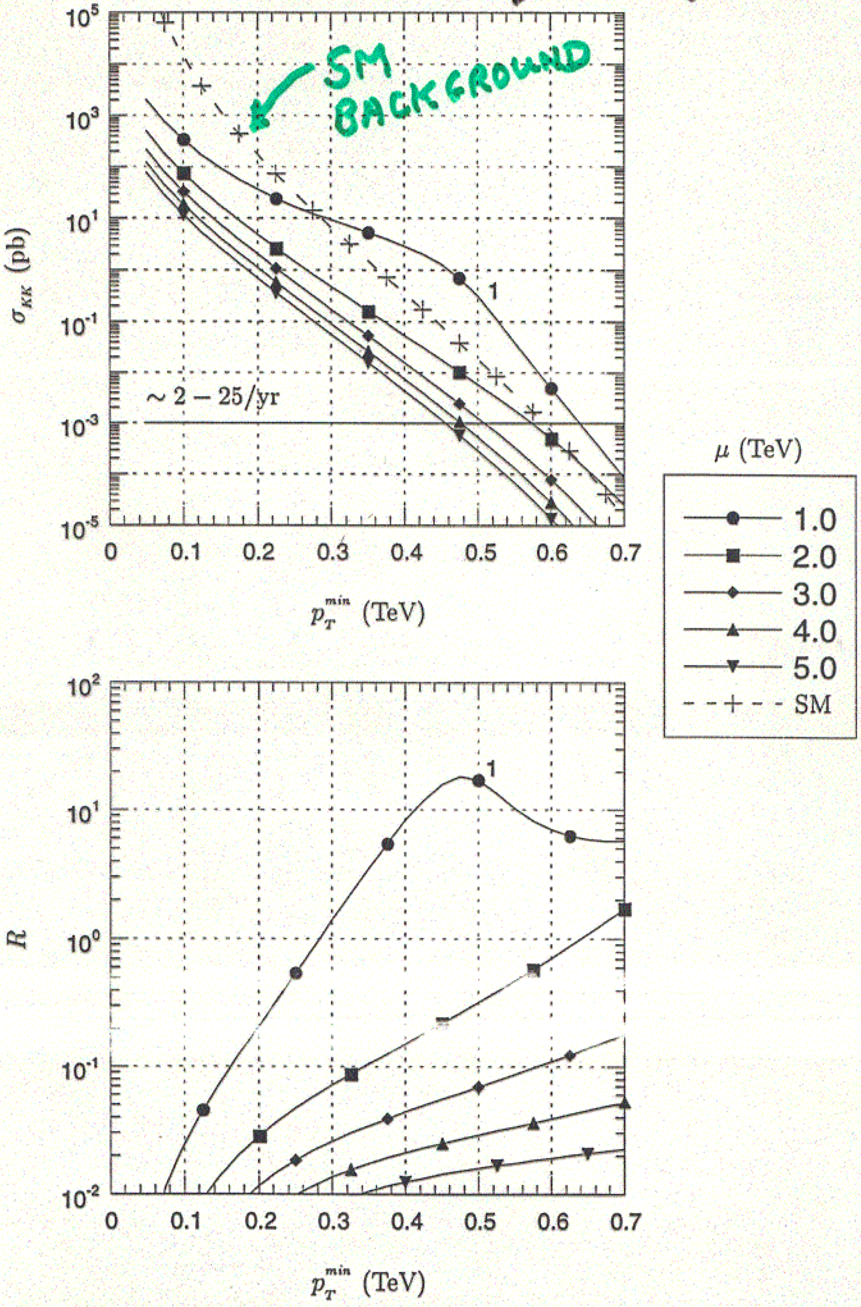


Figure 7: The contributions of the virtual exchanges of g^*'s to the Tevatron dijet production cross section, $\sigma_{KK} = \sigma - \sigma_{SM}$, (top) and the ratio of the KK contribution to the SM background, $R = \sigma_{KK}/\sigma_{SM}$, (bottom) are illustrated as a function of the minimum transverse momentum p_T^{min} for fixed values of the compactification scale μ. The solid horizontal line represents ~ 2 (25) events/yr at the projected initial (final) Run 2 integrated luminosity. Discernible bumps in regions for which $p_T^{min} = k\mu/2$ are indicated by the corresponding value of $k \in \{1, 2, \ldots\}$.

5c

Dicus, McMullen + Nandi : PRD

LHC, $\sqrt{s} = 14$ TeV

Dijet + $\not{E}_T$ signal

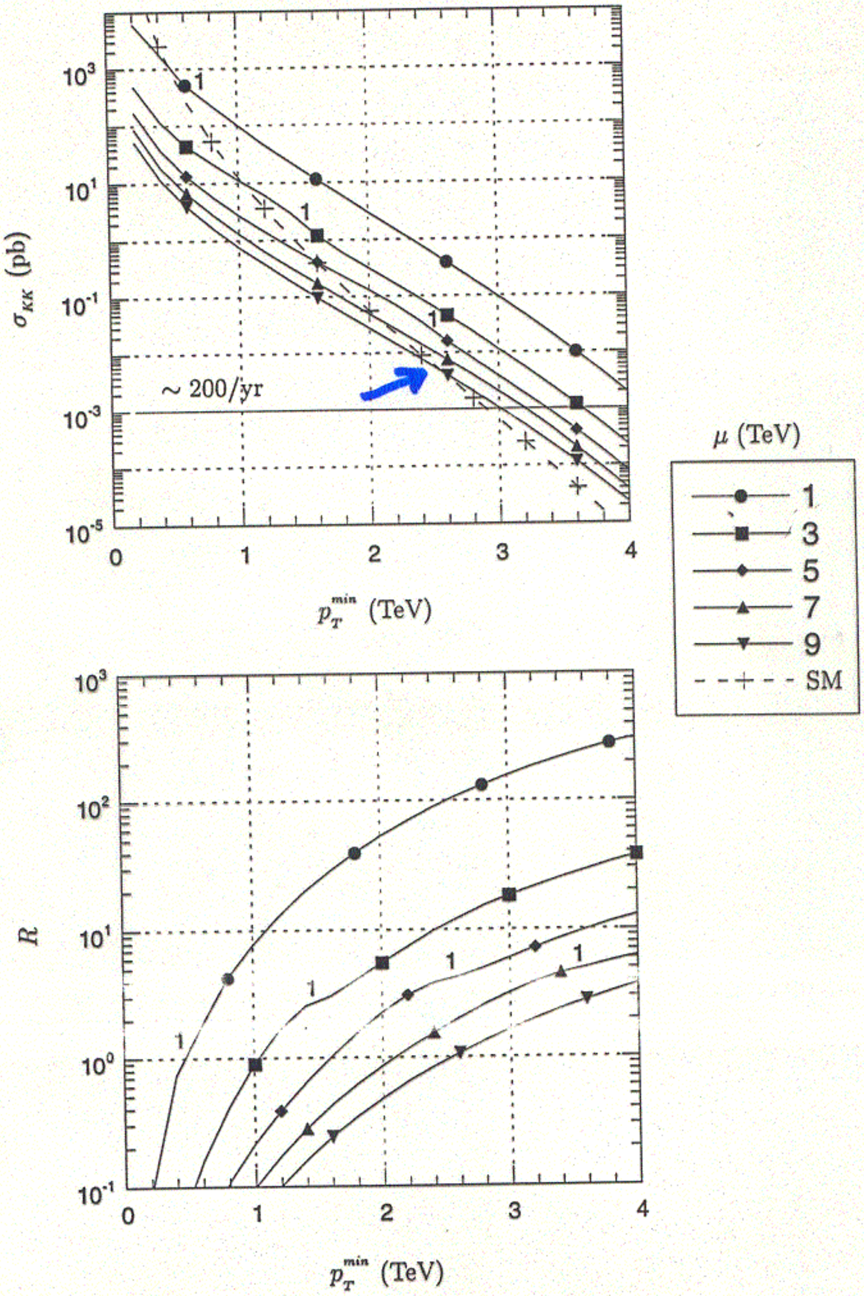


Figure 3: The contributions of the virtual exchanges of g^*'s to the LHC dijet production cross section, $\sigma_{KK} = \sigma - \sigma_{SM}$, (top) and the ratio of the KK contribution to the SM background, $R = \sigma_{KK}/\sigma_{SM}$, (bottom) are illustrated as a function of the minimum transverse momentum p_T^{min} for fixed values of the compactification scale μ. The solid horizontal line represents ~ 200 events/yr at the projected integrated luminosity. Discernible bumps in regions for which $p_T^{min} = k\mu/2$ are indicated by the corresponding value of $k \in \{1, 2, \dots\}$.

SCENARIO 2

: All SM particles propagate into TeV^{-1} size extra dim. ⇒ Universal Extra Dim (UED)
(Applelquist, Cheng, Dobrescu)

⇒ all SM have KK excitations

: consider one TeV^{-1} size extra dim.

: 5D fermions are 4-compo, vector-like Dirac spinors

⇓

use S_1/Z_2 orbifold to project out the fermions with wrong chirality zero modes.

$$Q(x,y) = \frac{1}{\sqrt{\pi R}}\left\{\begin{pmatrix} u(x) \\ d(x) \end{pmatrix}_L + \sqrt{2}\sum_{n=1}^{\infty}\left[Q_L^{(n)}(x)\cos\frac{ny}{R} + Q_R^{(n)}(x)\sin\frac{ny}{R}\right]\right.$$

$$U(x,y) = \frac{1}{\sqrt{\pi R}}\left\{u_R(x) + \sqrt{2}\sum_{n=1}^{\infty}\left[U_R^{(n)}(x)\cos\frac{ny}{R} + U_L^{(n)}\sin\frac{ny}{R}\right]\right.$$

$$Q_L^{(n)}, Q_R^{(n)} \Rightarrow Q^{(n)} \quad , \quad U_R^{(n)}, U_L^{(n)} \rightarrow U^{(n)}$$

⇒ two KK towers for each flavor q.

$$M_n = \sqrt{n^2/R^2 + m_q^2}$$

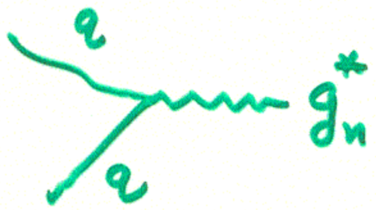
(m_q) → zero mode mass → from Yukawa couplings

$$Q^{(n)} \rightarrow q^{\bullet} \quad , \quad U^{(n)} \rightarrow q_n^{\circ}$$

$g_n^* \rightarrow$ KK excitation of gluons, W_n^*, Z_n^*, γ_n^*

$q_n^\bullet, q_n^\circ \rightarrow$ two KK towers for each flavor of quarks (also leptons)

new $\Rightarrow$ KK number is conserved at tree level



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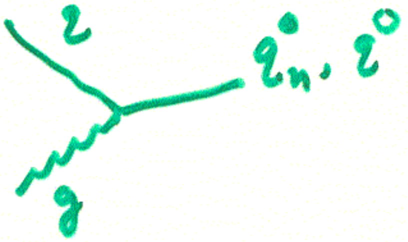
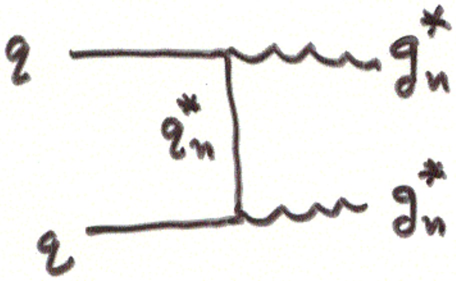
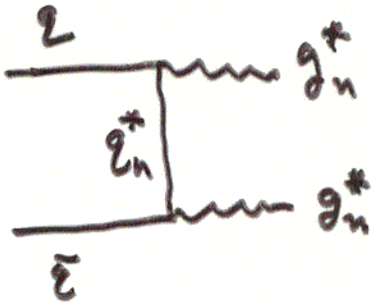


$\Rightarrow$ <u>forbidden</u>

$\Rightarrow$ KK particles must be pair produced

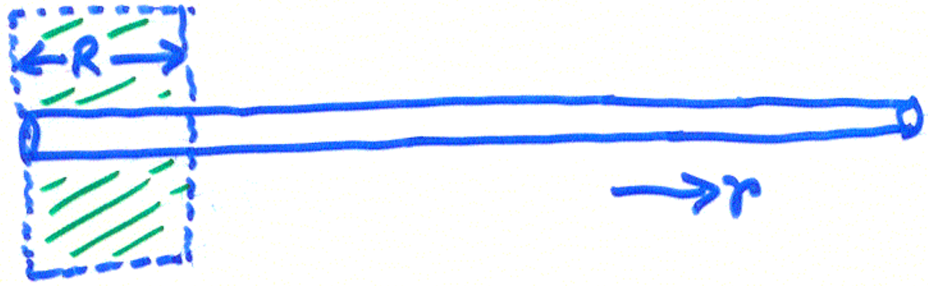




$\Rightarrow$ Mass bounds get reduced from 1 TeV to $\sim \sqrt{1\,\text{TeV}^2} \sim 300$ GeV

SIGNALS WITH KK NUMBER VIOLATING TREE LEVEL INTERACTION :

: Use "FAT BRANE SCENARIO"



$r \sim$ submm

$1/R \sim$ TeV

: coupling of the KK violating interaction is proportional to the overlap of the wave functions in the 5^{th} dim. The extra momenta along the y dir from the KK violation is absorbed by the brane.

⇒ KK states can decay via grav. int.

$$g^* \to g\, G_m\,, \qquad q^* \to q\, G_m$$

: Life-time depends on N = # of extra dim grav. propagate

→ always fast enough for g^*, q^* decays inside the detector.

Signal ⇒ dijets events with high p_T + large missing energy >> Background

Run 1 bound : ~400 GeV, Run 2 : ~ 450-550 GeV

LHC : ~ 3 TeV

(figs)

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Macesanu, McMullen + Nandi, hep-ph/0210300

UED, DIJETS

TEVATRON RUN2

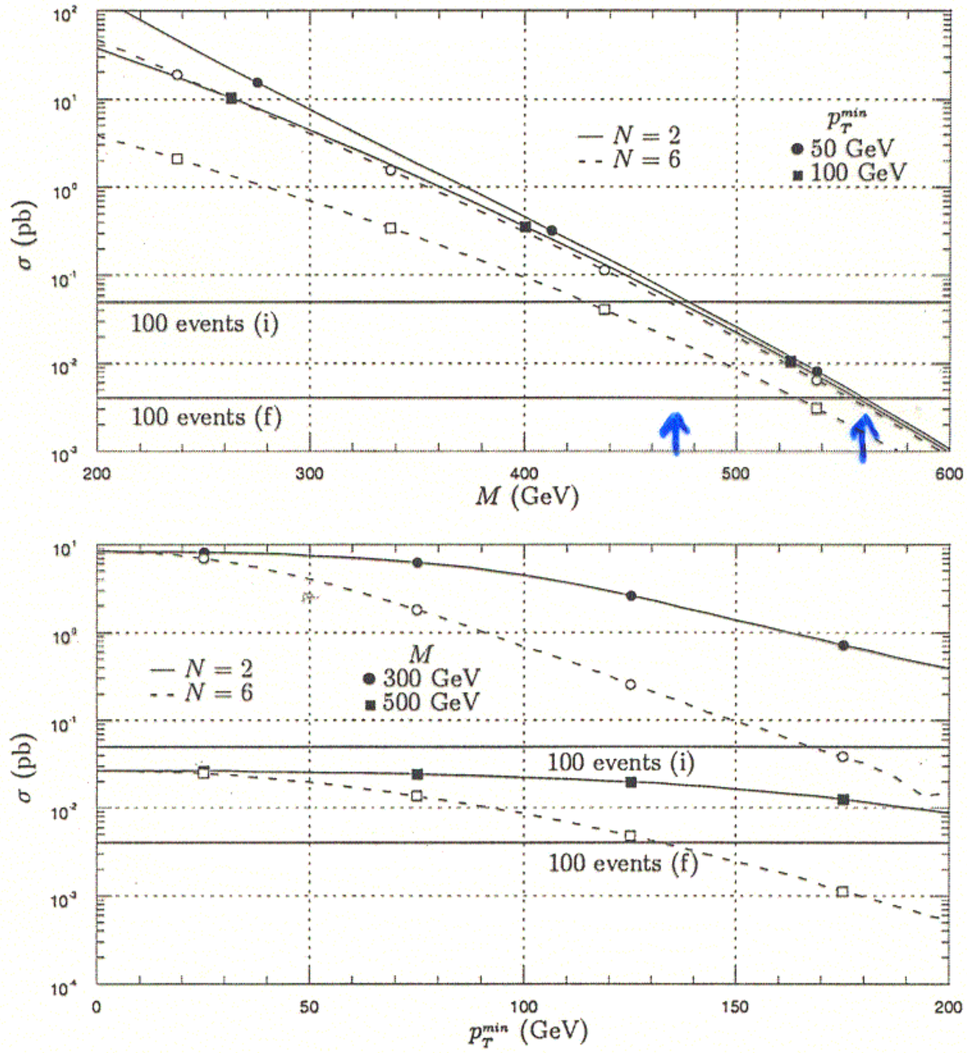


Figure 7: The total cross section for the dijet production plus missing energy from decaying KK final states at the Tevatron Run II energy is illustrated as a function of μ for fixed p_T^{min} (top) and as a function of the minimum transverse momentum p_T^{min} for fixed values of the compactification scale μ (bottom). Solid horizontal lines mark 100 events at the initial and final projected luminosities. In this and the following figures, we implement cuts on the p_T, rapidity, and separation of the jets.

9c

Macesanu, McMullen + Nandi

hep-ph/0210301

UED, DIJETS

LHC

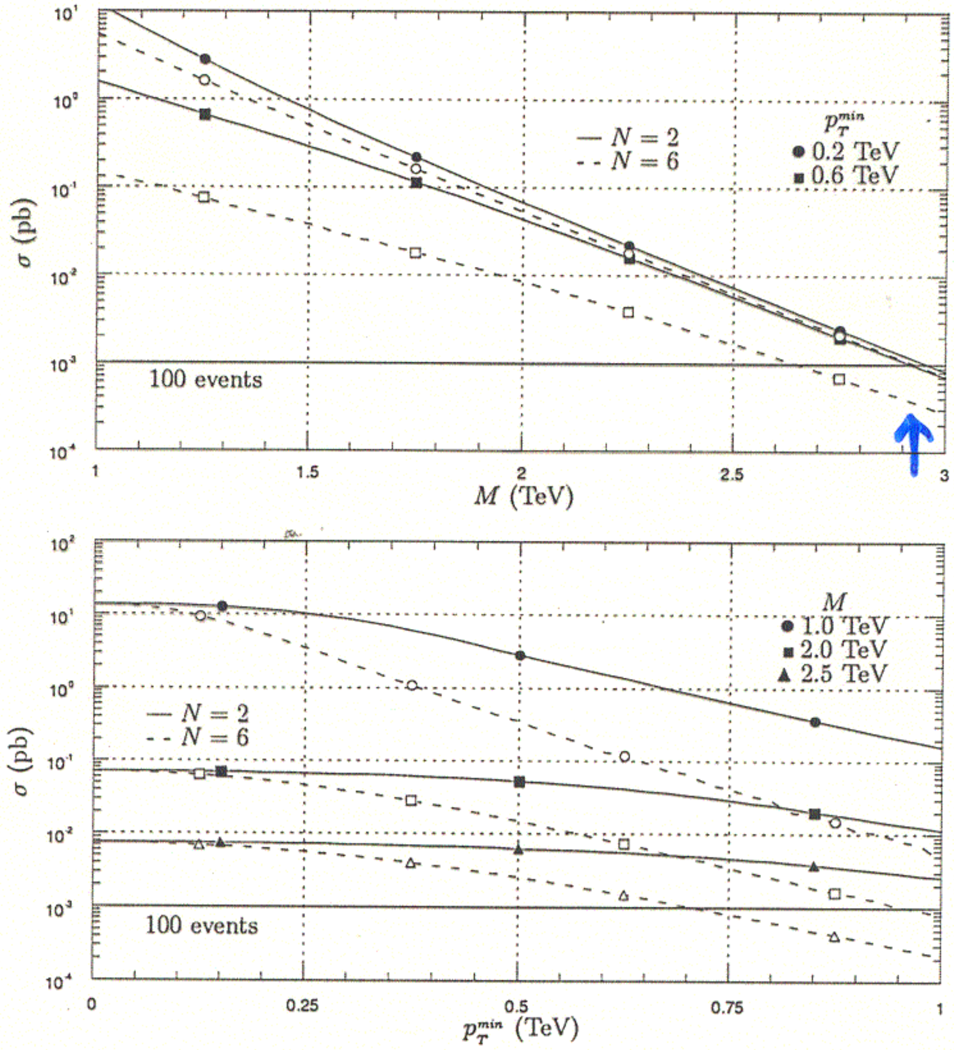


Figure 8: The same as Fig. 7, but for the LHC. The solid horizontal line marks 100 annual events at the projected luminosity.

SCENARIO B : Include one loop correction to the KK masses, but KK violating interaction absent

(Cheng, Matchev, Martin)

: degeneracy of KK excitations split

1st level : $g_1^* \to$ heaviest (20–30% correction)

$\sim$ 150–200 GeV split for MR ~ 20

next : q_1°, q_1°, W_1^*, Z_1^*, h_1, l_1°, ...

Lightest KK particle $\Rightarrow \gamma_1^*$ (LKP)

$\Rightarrow$ STABLE $\quad \hookrightarrow \sim B^*$

$\Rightarrow$ Decays allowed

$g_1^* \to q_1^\circ \bar{q}$, $q_1 \bar{q}$

$q_1^\circ \to q Z_1^* \to q l l_1^* \to q l l \gamma_1^*$, BR ~ 33%

$q_1^\circ \to q W_1^* \to q l' l_1^\circ \to q l' l \gamma_1^*$, BR ~ 65%

: Pair produced at collider, after decay chain,

$\Longrightarrow$ end up with $\gamma_1^* \gamma_1^*$ + soft like quarks and leptons.

Signal $\Rightarrow$ soft leptons + missing energy

(like SUSY with almost deg. superpartners)

Reach : Run2 : ~ 350 GeV

LHC : ~ 1.5 TeV

(10a)

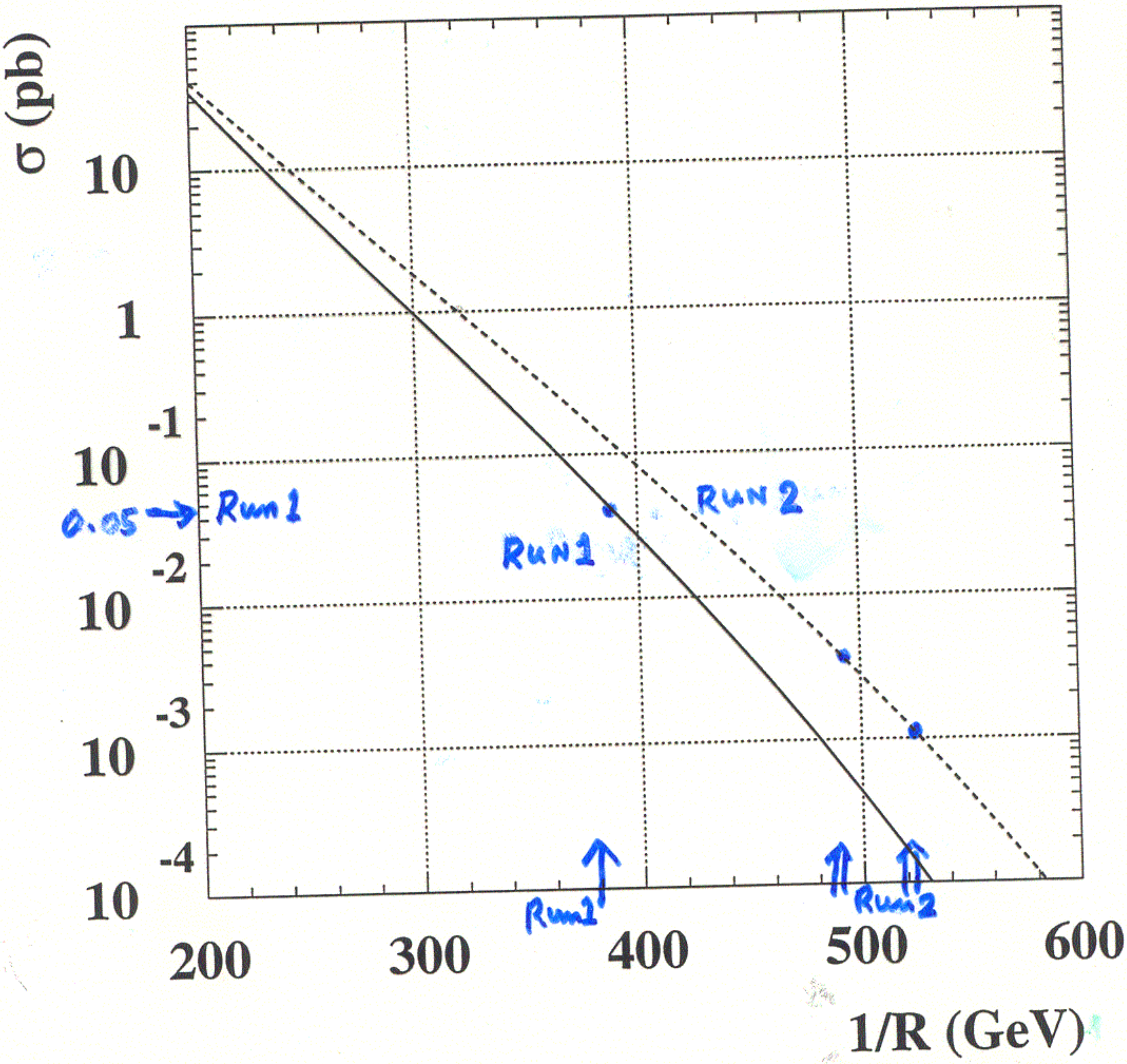
Macesanu, McMullen + Nandi, hep-ph/0207269

TEVATRON,

UED, 1 LOOP MASS CORRECTIONS,

$\gamma\gamma + \not{E}_T$ SIGNAL

BACKGD ~ 0.6 fb



10b

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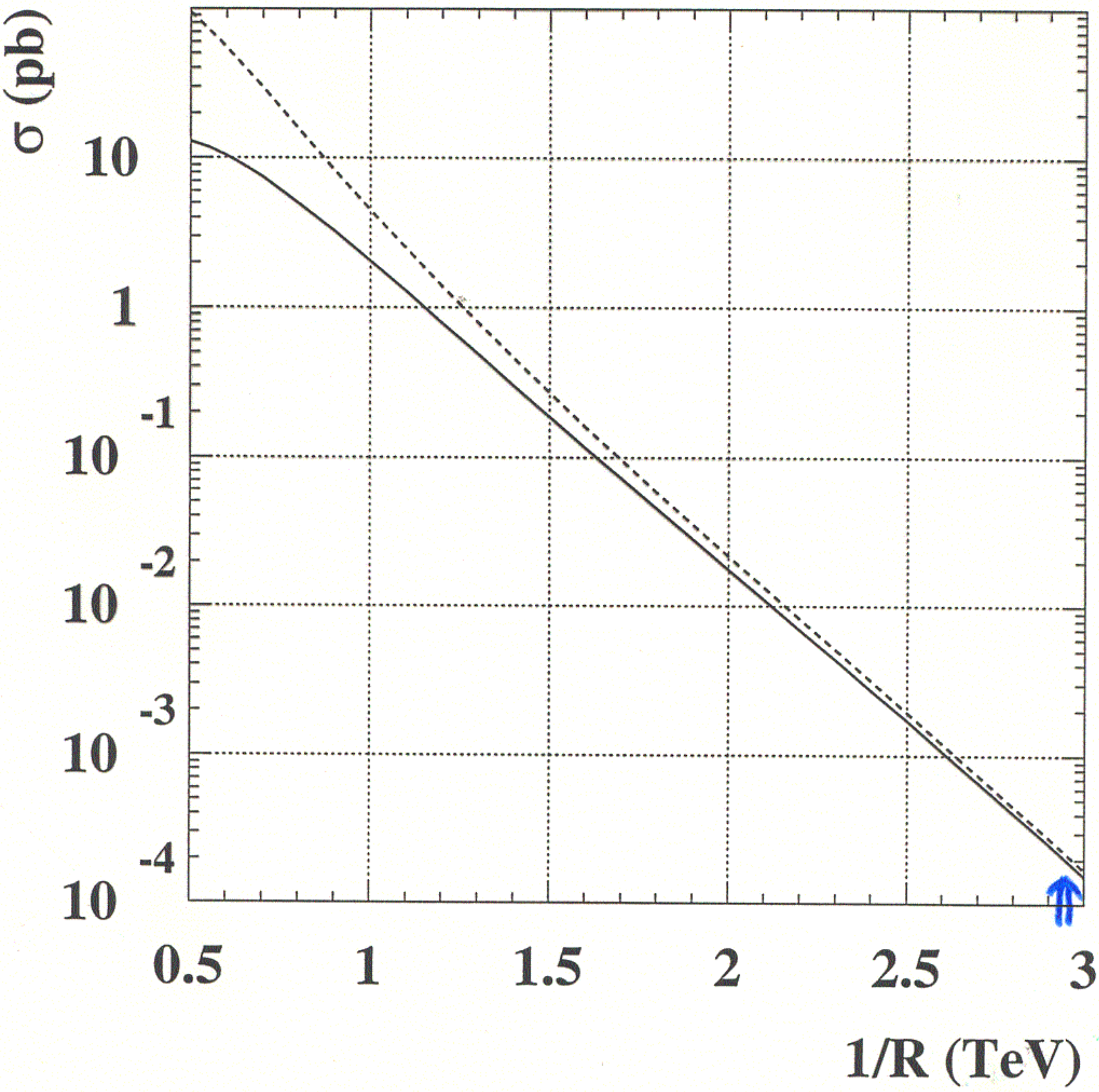
UED, 1 LOOP MASS CORRECTED

LHC

$\gamma\gamma + \not{E}_T$ SIGNAL

BACKGD ~ 0.05 fb



SCENARIO C: Include one loop correction to KK masses **AND** KK violating interactions (Macesanu, McMullen + Nandi)

Case 1: Assume decay ~~width~~ due to mass splitting >> KK violating grav. widths (happens for $N = 6$)

role of KK violating int: $\gamma_1^* \to \gamma\, G_m$

Signal: gg^*, $g^* q^*$, $q^* q^*$

$\Rightarrow \gamma_1^* \gamma_1^* \longrightarrow \gamma\gamma\, G_m G_m$ + soft particles

- $\gamma\gamma$ → two photons with high p_T
- $G_m G_m$ → missing energy

Backgrounds $\Rightarrow$ $W+\gamma$, W+jets, $Z \to ee$, $Z \to \gamma\gamma ee$ (with misidentified photons)

$\Rightarrow$ easily eliminated by p_T and $\not{E}_T$ cuts.

(figs)

Run 1 bound: ~ 380 GeV
Run 2: ~ 520 GeV
LHC: ~ 3 TeV

Opposite case: grav. dominate $(N=2)$ $\Rightarrow$ Signal: dijet + $\not{E}_T$

GENERAL CASE: Both decays comparable,

(figs)

Signal: $\gamma\gamma + \not{E}_T$, dijet + $\not{E}_T$

BR depends on N, $1/R$.

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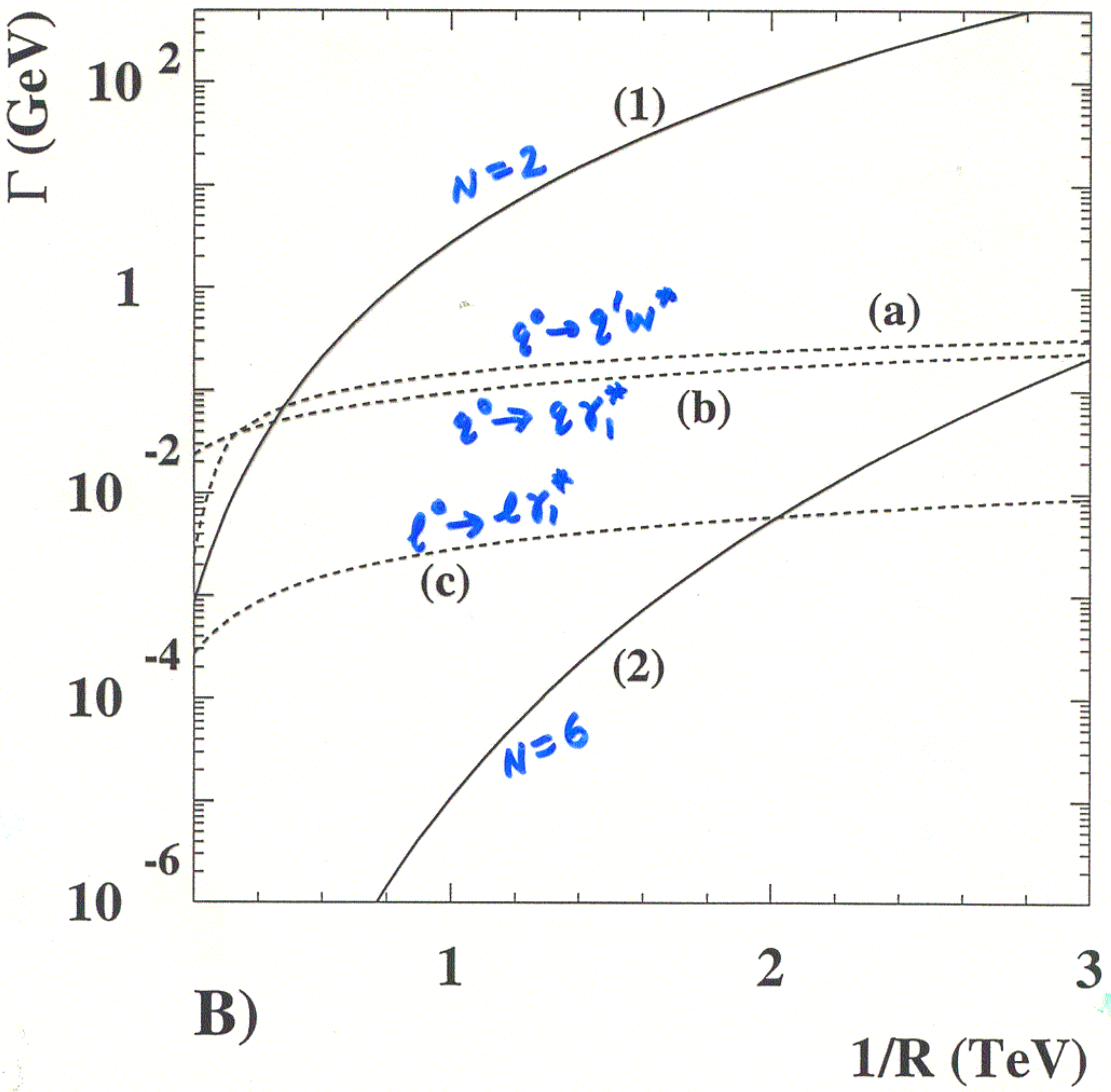
Macesanu, McMullen + Nandi, hep-ph/0207269

UED, 1 LOOP MASS CORRECTED
VS
KK VIOLATING DECAYS



B)

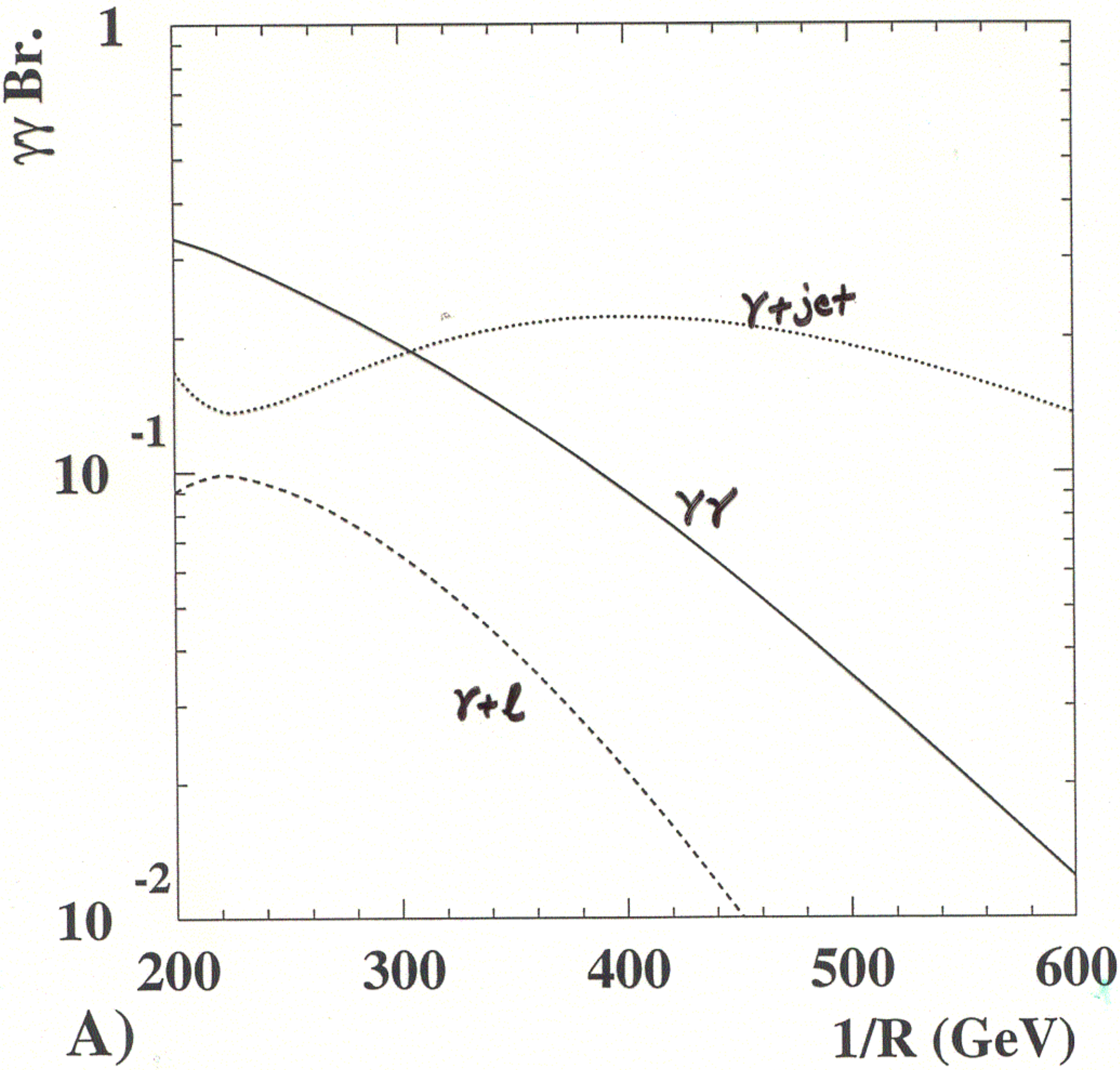
(11c)

Macesanu, McMullen + Nandi, hep-ph/0207269

UED, 1 LOOP + KK VIOLATING DECAYS

γγ BRANCHING RATIOS

N = 2



A)

CONCLUSIONS :

: Models with TeV^{-1} scale extra dim gives exciting new physics signals at colliders

: Signals

: high p_T dijets + $\not{E}_T$

: high p_T $\gamma\gamma$ + $\not{E}_T$

⋮

: Tevatron Run 2 : 500 GeV to ~ 2 TeV

LHC : 1.5 TeV to ~ 7 TeV

: Allowed scale low enough to see 2nd KK excitations at LHC

⇒ existence of extra dim.