EXTRA DIMENSIONS

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(VLHC WORKSHOP, FERMILAB, 2003)

IDEA : KALUZA (1921), KLEIN (1926)

: POPULAR, PAST 5 YRS.
(Arkani-Hamed, Dimopoulos & Dvali)

THEORY BENEFITS :

: TRUE UNIFICATION (gogoladze, mimura + SN)

⇒ UNIFICATION OF "ALL PARTICLES, GAUGE, HIGGS, MATTER

⇒ UNIFICATION OF GAUGE & YUKAWA

$$g_3 = g_2 = g_1 = g_t = g_b = g_\tau$$

⇒ WORKS VERY WELL

: AN ALTERNATIVE TO HIGGS MECHANISM (Kawamura, Altarelli & Feruglio, Hall & Nomura, ..)

THEORY BENIFITS (CONTD.)

: NO GAUGE HIERARCHY PROBLEM (Arkani-Hamed, Dimopoulos + Dvali)

: A MECHANISM FOR SUSY BREAKING (Scherk & Schwarz, Hosatani)

: UNDERSTANDING OF WHY $m_\nu \ll m_q, m_\ell$

: POSSIBILITY OF MULTITEV SCALE GUT (Dienes, Dudas & Gherghetta)

: CANDIDATE FOR COLD DARK MATTER (Cheng, Matchev & Schmaltz)

: EXPLORING QUANTUM GRAVITY

EXPERIMENTAL IMPLICATIONS:

: EXISTENCE OF A TOWER OF NEW PARTICLES (KK EXCITATIONS)

: POWER LAW RUNNING OF GAUGE COUPLINGS

: DEVIATIONS FROM NEWTONS LAW OF GRAVITY

: BLACKHOLES AT COLLIDERS

: ASTROPHYSICAL IMPLICATIONS

: TRANSPLANKIAN PHYSICS

THIS TALK : HIGH ENERGY COLLIDER IMPLICATIONS

EXTRA DIMENSIONS

FLAT

WARPED (Randall & Sundram)
(talk by Chivukula, Rizzo)

NUMBER : ? STRING THEORY ⇒ 6

SIZE :

: INVERSE PLANCK SCALE

⇒ : INVERSE TEV SCALE *

: SUBMM SCALE

* MOST INTERESITING FOR HIGH ENERGY COLLIDERS

DO SM PARTICLES PROPAGATE IN EXTRA DIMENSIONS ?

NO
(ADD SCENARIO)
(talk by Han, Giudice, Rizo)

YES, BUT ONLY GAUGE BOSONS
(Antoniadis)

YES, ALL SM PARTICLES
(UNIVERSAL EXTRA DIM)
(Appelquist, Cheng & Dobrescu)

MOST INTERESITING FOR HE COLLIDERS

FLAT SUBMM EXTRA DIM

(Talk by Rizzo)

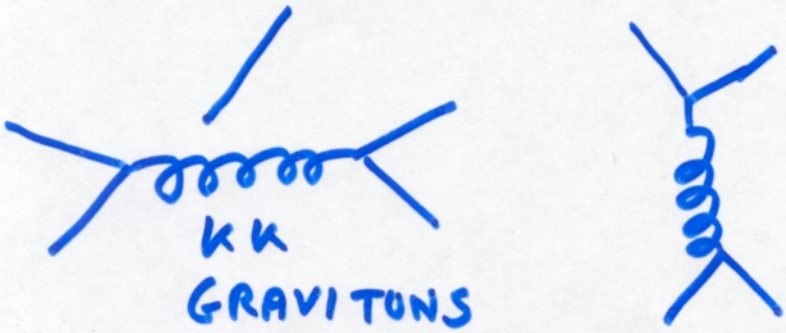
⇒ KK EXCITATIONS OF GRAVITONS

$$M_{KK} = (n)\left(\frac{1}{R}\right) \sim (n)\,(10^{-3}\,\mathrm{eV})$$

: DEVIATION FROM NEWTON'S LAW

: INTERESTING ASTROPH. IMPLICATIONS

: COLLIDERS



⇒ FOUR-FERMI INTERACTIONS

HYBRID SCENARIO:

1 submm + 5 $(\mathrm{TeV})^{-1}$ EXTRA DIM

(Lykken & SN)

$(\text{TeV})^{-1}$ SCALE EXTRA DIM

WHAT PHYSICS VLHC EXPORE ?

CLASSIC SIGNAL

: EXISTENCE OF KK EXCITATIONS OF SM PARTICLES

VLHC CAN EXPLORE:

: POWER LAW EVOLUTION OF GAUGE COUPLINGS

Figs.

: NEW SIGNALS FROM THE PRODUCTIONS OR EXCHANGES OF KK EXCITATIONS

Fig.

DIENES, DUDAS & GHERGHETTA
(NUCL. PHYS. B)

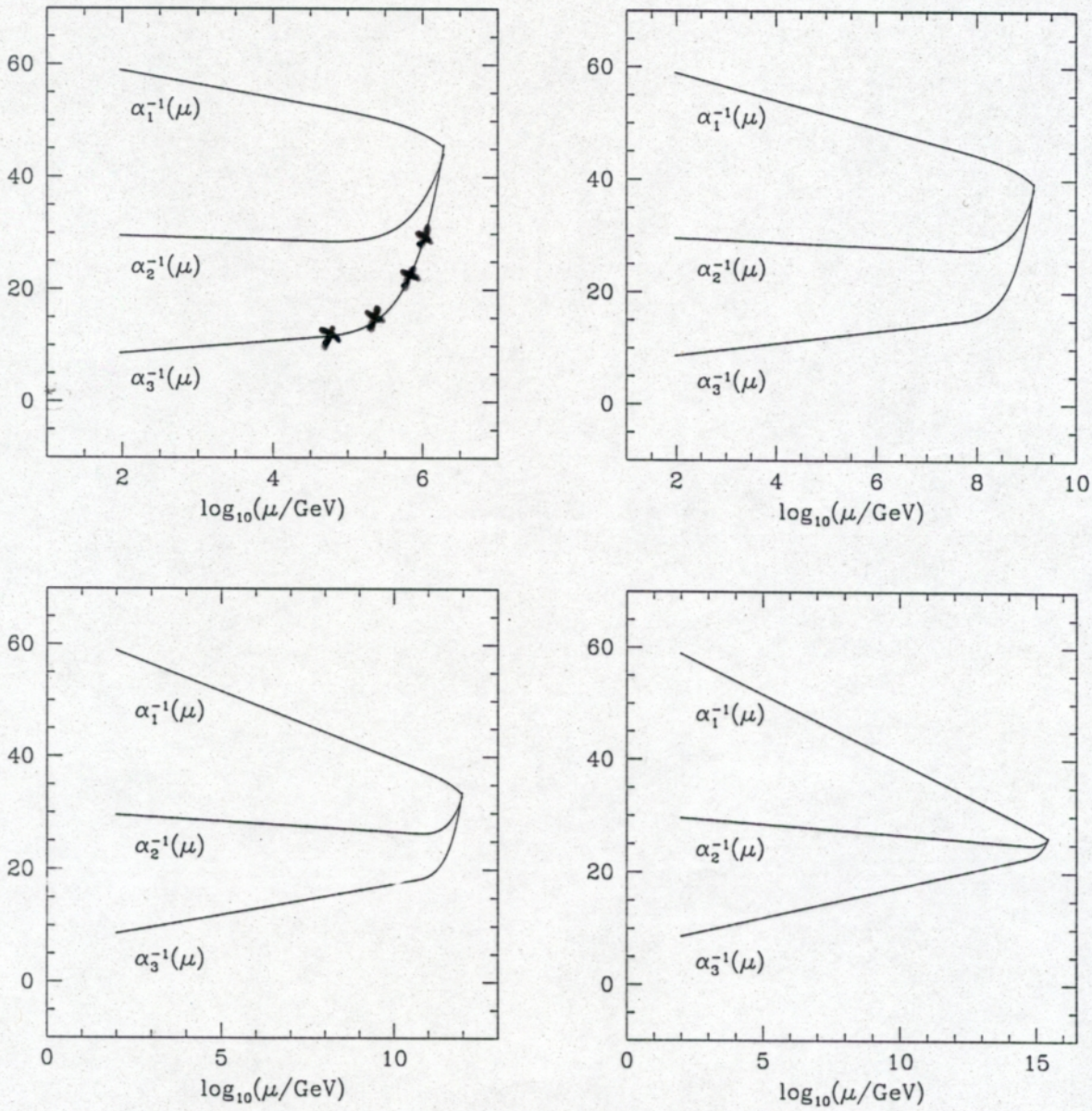


Figure 1: Unification of gauge couplings in the presence of extra spacetime dimensions. We consider four representative cases: $\mu_0 = 10^5$ GeV (top left), $\mu_0 = 10^8$ GeV (top right), $\mu_0 = 10^{11}$ GeV (bottom left), and $\mu_0 = 10^{15}$ GeV (bottom right). In each case we have taken $\delta = 1$.

DUMITRU + SN

(PHYS. REV. D)

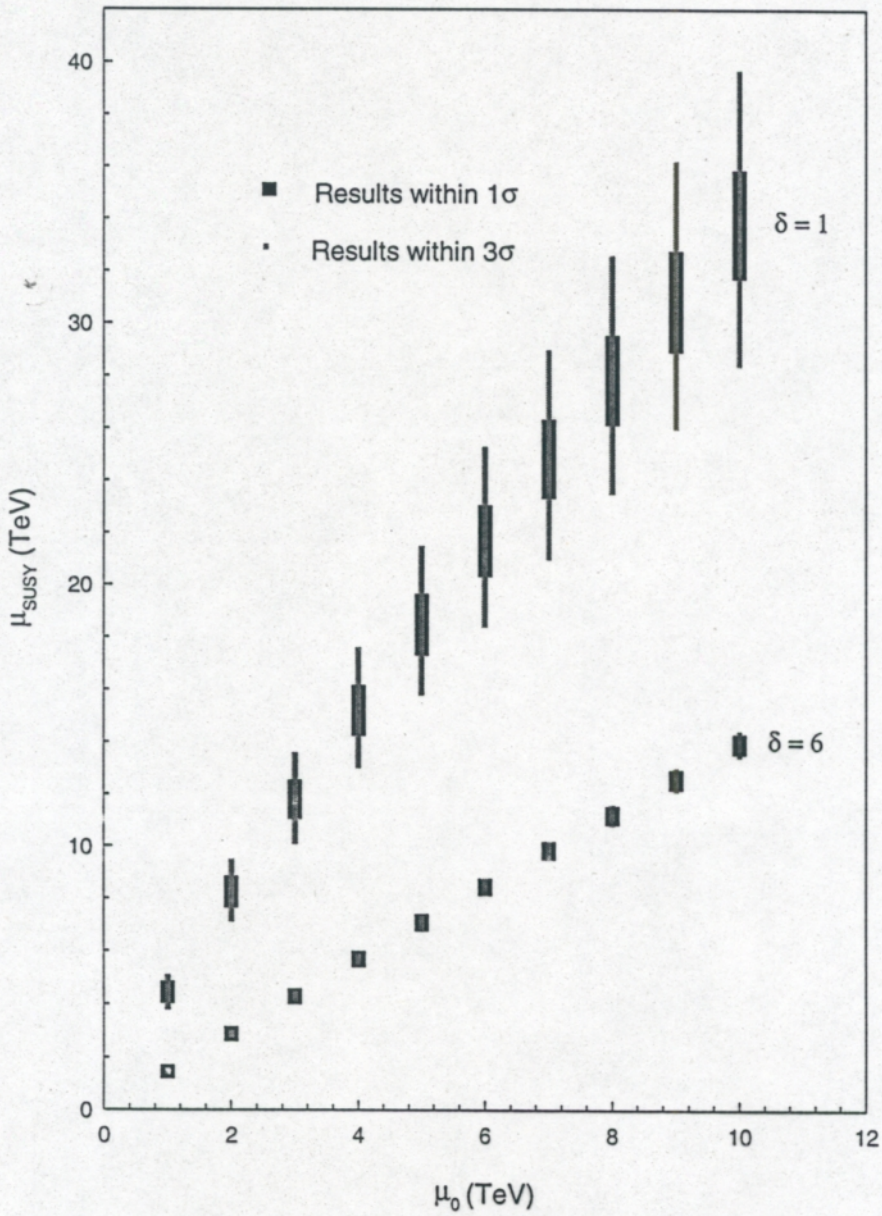


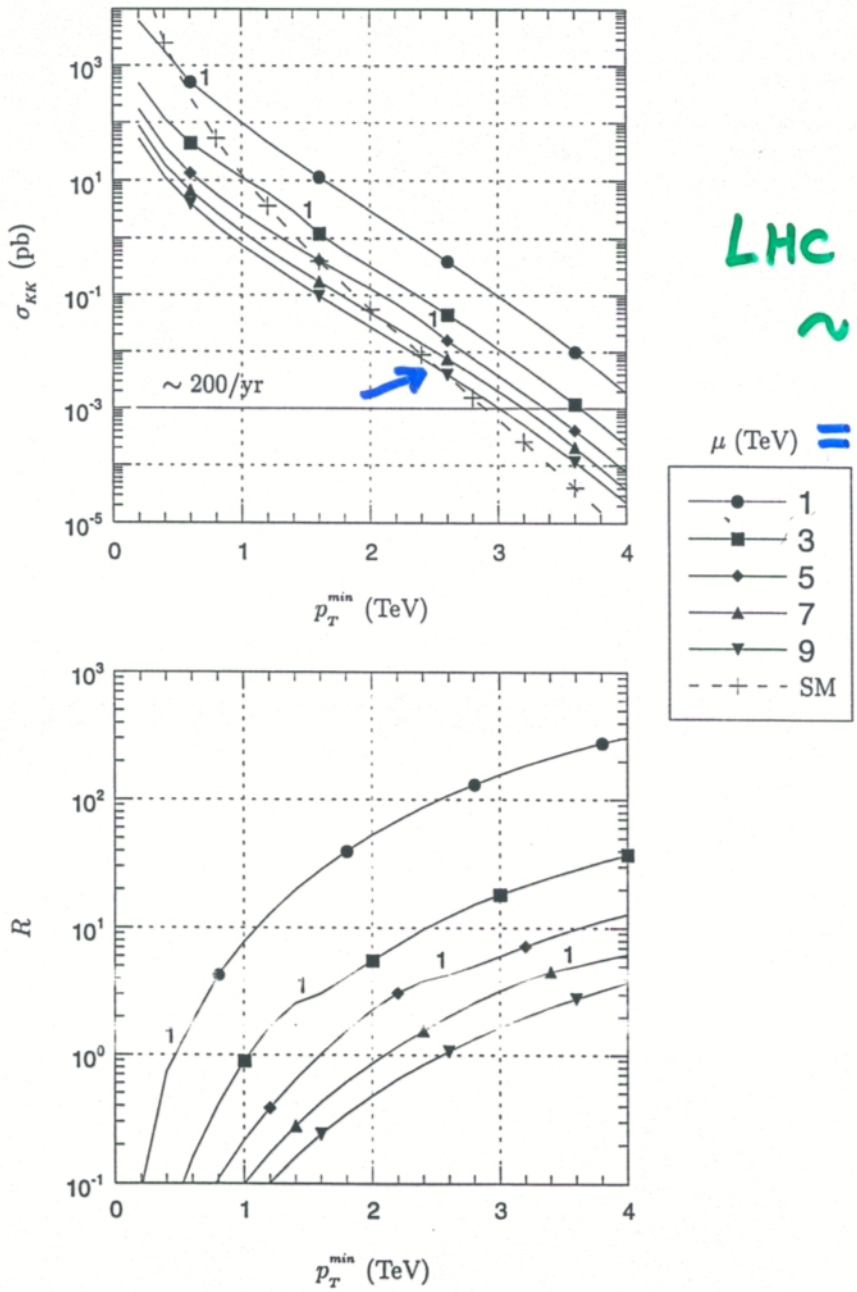
Figure 3: Allowed values of SUSY breaking scale, μ_{SUSY}, for various choices of μ_0 in a scenario with $\mu_0 < \mu_{SUSY}$. Results within 1σ and 3σ of $\alpha_3(M_Z)$ are presented, for $\delta = 1$ and $\delta = 6$. Unification is spoiled if μ_{SUSY} lies outside the corresponding vertical spreads shown in the plot.

Dicus, McMullen + Nandi : PRD

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

HIGH P_T DIJET SIGNAL

ONLY GAUGE BOSONS IN EXTRA DIM



LHC REACH ~ 7 TeV

μ (TeV) = M_{KK}

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 $k \in \{1, 2, \ldots\}$.

$(\text{TEV})^{-1}$ SCALE UNIVERAL EXTRA DIM

(Appelquist, Cheng & Dobrescu)

: ALL SM PARTICLES IN EXTRA DIM

: KK # IS CONSERVED

$\Rightarrow$ KK EXCITATIONS TO BE PAIR PRODUCED

$$g \longrightarrow g_n^*$$

$$q \begin{cases} q_n^* \\ q_n^0 \end{cases}$$: TWO TOWERS

$$M_n^* = \sqrt{\frac{n^2}{R^2} + m^2}$$

$\Rightarrow$ ALL KK EXCITATION ESSENTIALLY DEGENERATE

Fig. : 1 LOOP CORRECTION $\Rightarrow$ SPLIT DEGENERACY (Cheng, Matchev & Schmaltz)

$\gamma^* \longrightarrow$ LIGHTEST (LKP) : DARK MATTER CANDIDATE

$g^* \longrightarrow$ HEAVIEST

CURRENT BOUND ON $M^* \sim 350$ GeV (TEVATRON)

COLLIDER SIGNALS

Pair-Production rates at hadron colliders

Processes:

Double KK gluon production		KK quark-gluon production	
$gg \to g_n^\star g_n^\star$	$q\bar{q} \to g_n^\star g_n^\star$	$qg \to q_n^\bullet g_n^\star$	$qg \to q_n^\circ g_n^\star$
Double KK quark production			
$q\bar{q} \to q_n^\bullet \bar{q}_n^\bullet$	$q\bar{q} \to q_n^\circ \bar{q}_n^\circ$	$gg \to q_n^\bullet \bar{q}_n^\bullet$	$gg \to q_n^\circ \bar{q}_n^\circ$
$q\bar{q} \to q'^\bullet_n \bar{q}'^\bullet_n$	$q\bar{q} \to q'^\circ_n \bar{q}'^\circ_n$	$qq \to q_n^\bullet q_n^\bullet$	$qq \to q_n^\circ q_n^\circ$
$q\bar{q}' \to q_n^\bullet \bar{q}'^\bullet_n$	$q\bar{q}' \to q_n^\circ \bar{q}'^\circ_n$	$qq' \to q_n^\bullet q'^\bullet_n$	$qq' \to q_n^\circ q'^\circ_n$
$q\bar{q} \to q_n^\bullet \bar{q}_n^\circ$	$q\bar{q} \to q_n^\circ \bar{q}_n^\bullet$	$qq' \to q_n^\bullet q'^\circ_n$	$qq' \to q_n^\circ q'^\bullet_n$
$q\bar{q}' \to q_n^\bullet \bar{q}'^\circ_n$	$q\bar{q}' \to q_n^\circ \bar{q}'^\bullet_n$	$qq \to q_n^\bullet q_n^\circ$	

Figure 2: Subprocesses leading to double KK production at hadronic colliders. Not shown are subprocesses that are simply related by the exchange of a particle and antiparticle.

Collider reach (100 events):

Tevatron Run I : $1/R = 350$ GeV

Run II : 480 (with 2fb^{-1}) to 540 GeV (with 15fb^{-1})

LHC : 3 TeV, with 100 fb^{-1} of luminosity.

CHENG, MATCHEV & SCHMALTZ

MASSES SCALE $\sim \frac{1}{R}$

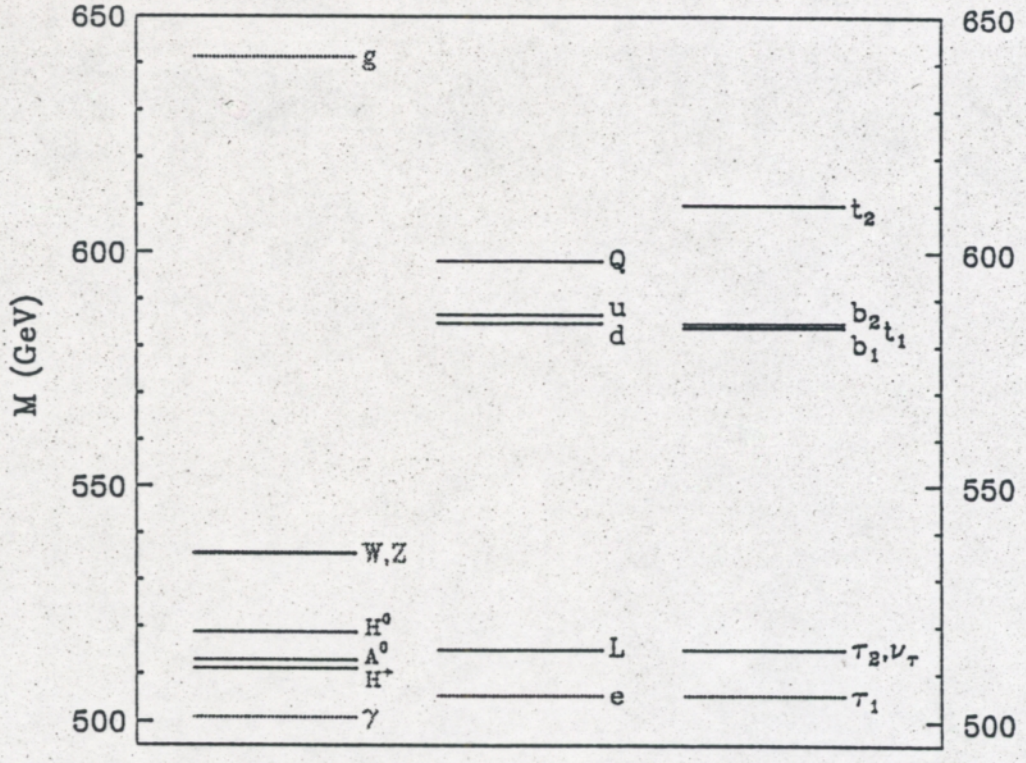


FIG. 1: *One-loop corrected mass spectrum of the first KK level in MUEDs for $R^{-1} = 500$ GeV, $\Lambda R = 20$ and $m_h = 120$ GeV.*

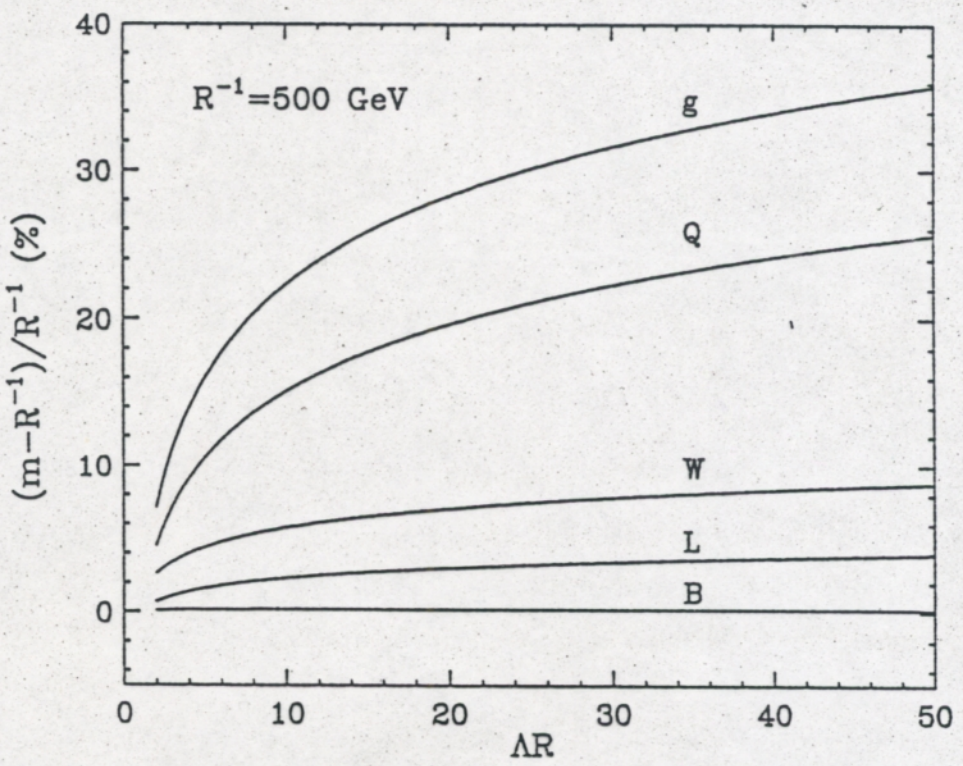


FIG. 2: *Radiative corrections (in %) to the spectrum of the first KK level for $R^{-1} = 500$ GeV, versus ΛR.*

WHAT LHC & VLHC CAN EXPLORE ?

: LHC CAN OBSERVE SIGNALS UPTO $M_{KK} \sim 3$ TeV

: VLHC :

100 TeV, $\mathcal{L} \sim 5 \times 10^{34}$, REACH $\sim$ 15 TeV

Figs. 200 TeV, $\mathcal{L} \sim 2 \times 10^{34}$, REACH $\sim$ 25 TeV

$$PP \longrightarrow \begin{array}{c} g^* g^* \\ g^* q^* \\ q^* q^* \end{array}$$

SIGNALS

: DEPENDS ON DECAY SCENARIO

KK CONSERVING DECAYS:

$$g^* \to \bar{q} q^*, \quad q^* \to q Z^*, \quad Z^* \to \ell \ell^*, \quad \ell^* \to \ell \gamma^*$$

$$\Rightarrow \bar{q} q \ell \ell \gamma^*$$

LKP

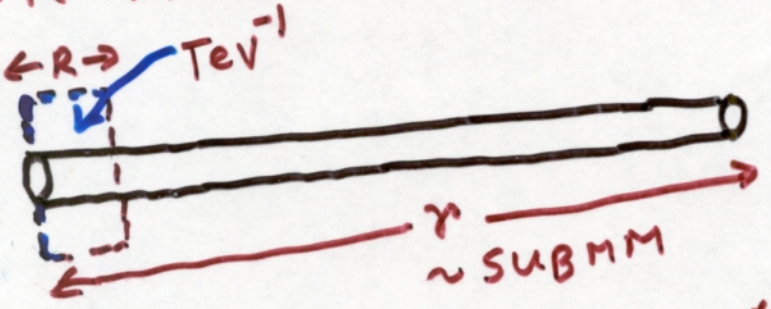
or

$$\bar{q} q \ell \ell' \gamma^*$$

SIGNAL $\Rightarrow \gamma^* \gamma^*$ + SOFT QUARKS & LEPTONS

$\not{E}_T$

KK VIOLATING DECAYS: (FAT BRANE)



: NO COLD DARK MATTER

$$g^* \to g G_n, \quad q^* \to q G_n, \quad \gamma^* \to \gamma G_n$$

SIGNAL $\Rightarrow$ HIGH P_T DIJETS + $\not{E}_T$

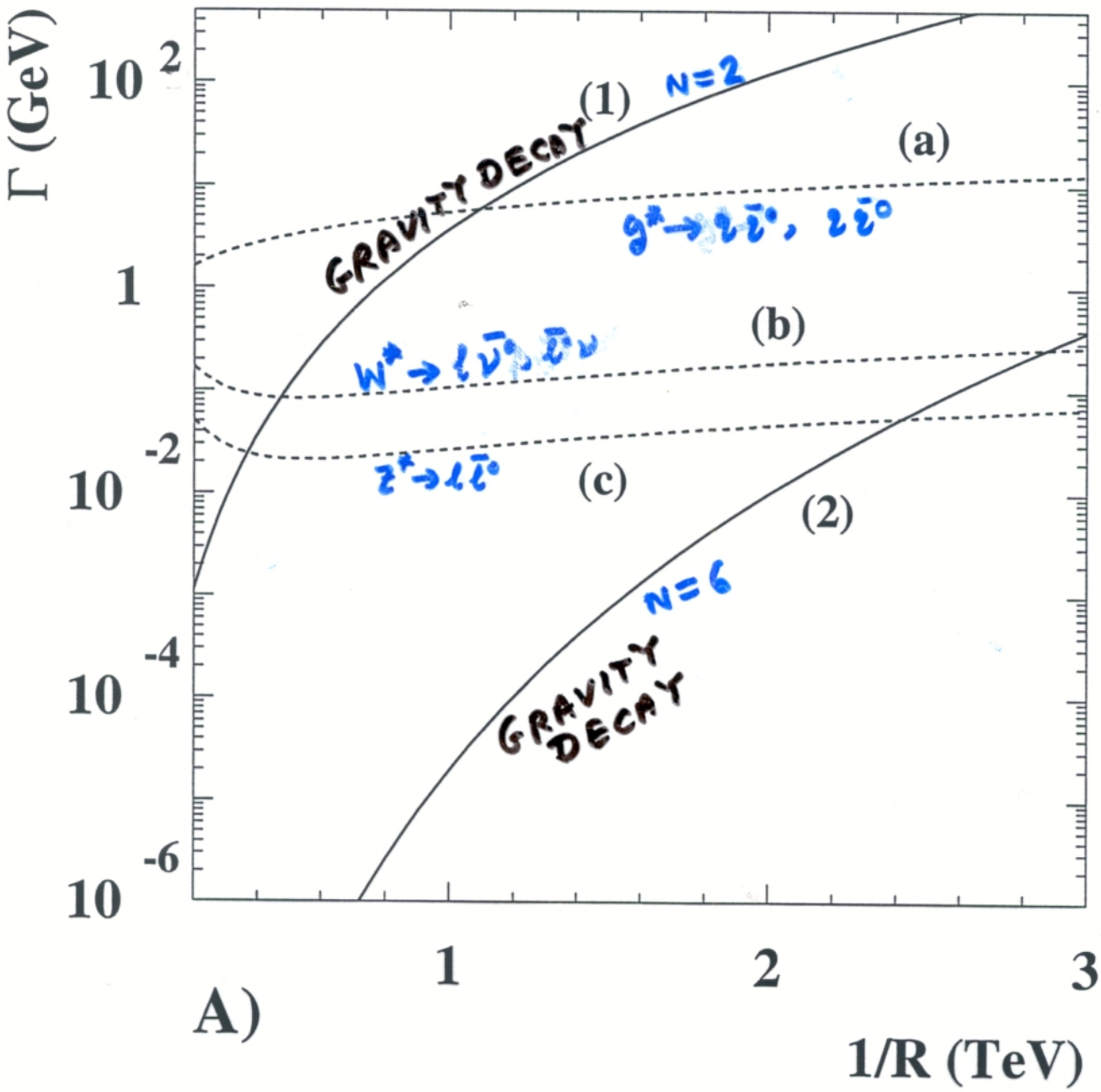
OR

HIGH P_T DIPHOTONS + $\not{E}_T$

Macesanu, McMullen + Nandi, PHYS. LETT. B

ULED, 1 LOOP MASS CORRECTED

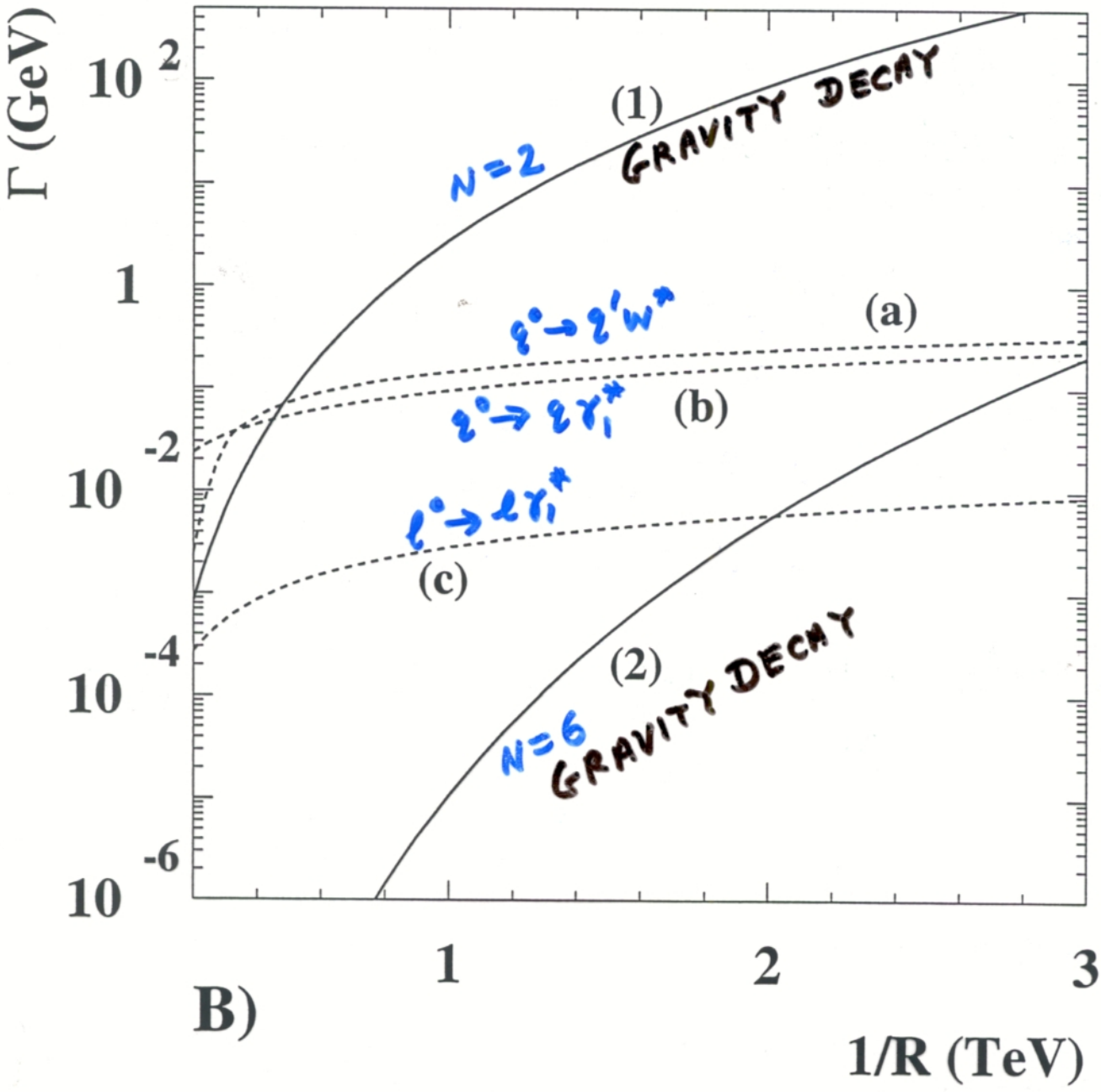
VS KK VIOLATING DECAYS



A)

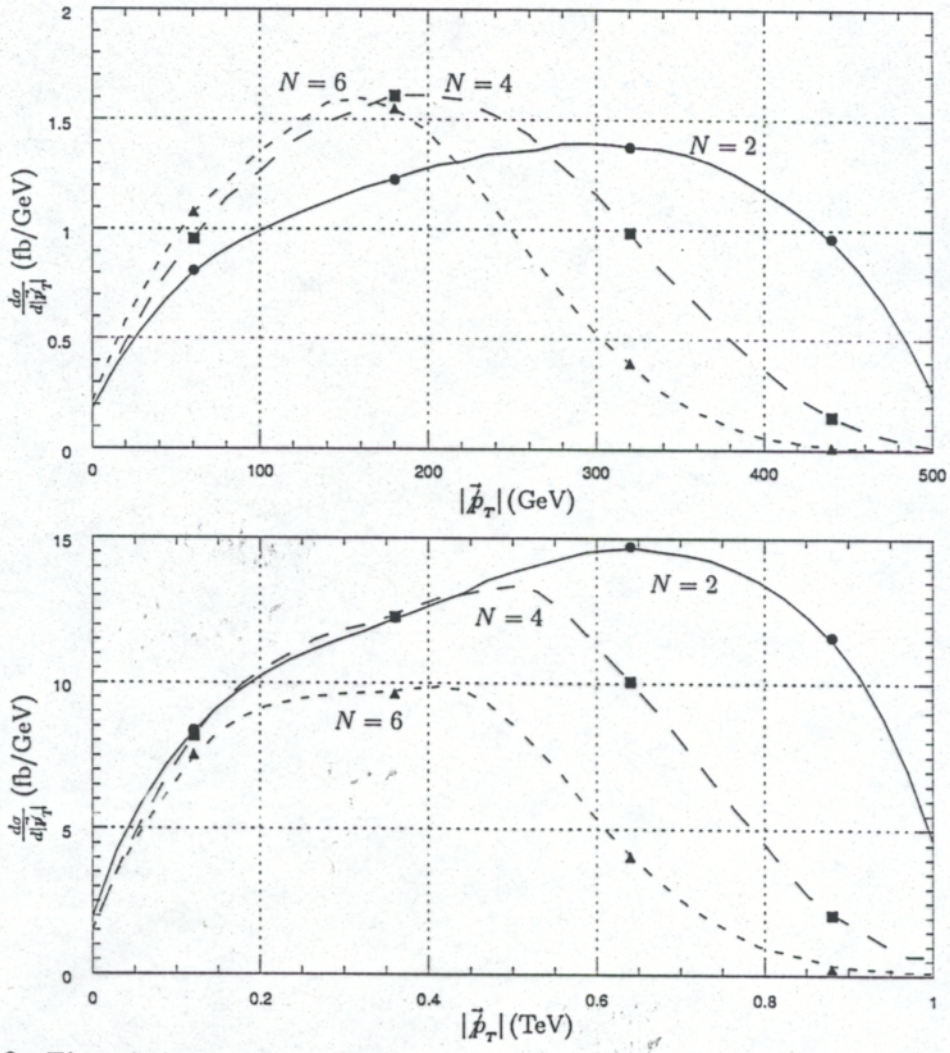
Macesanu, McMullen + Nandi, PHYS. LETT. B

UED, 1 LOOP MASS CORRECTED DECAYS
VS
KK VIOLATING DECAYS



B)

MISSING E_T DISTRIBUTION



TETATRON

LHC

Figure 9: The missing transverse momentum distribution is illustrated for Run II of the Tevatron (top) and the LHC (bottom). The three curves represent 2, 4, and 6 extra dimensions. By $|\vec{p}_T|$ we denote the vectorial sum of the transverse momentum of the two emitted gravitons (which is equal and opposite to that of the quarks). The compactification scale and minimum transverse momentum are 400 GeV and 50 GeV for the Tevatron and 1 TeV and 200 GeV for the LHC, respectively.

Macesanu, McMullen + Nandi

PHYS. REV. D

UED, DIJETS

LHC

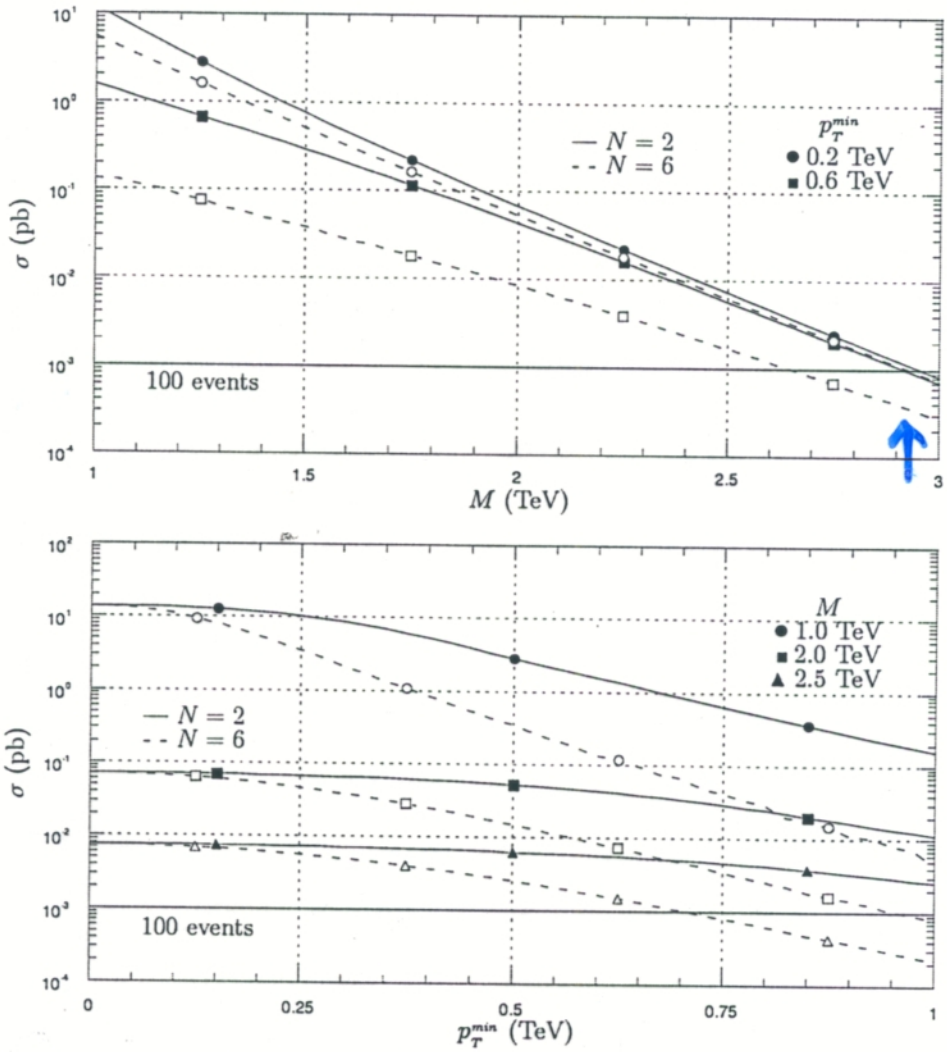


Figure 8: The same as Fig. 7, but for the LHC. The solid horizontal line marks 100 annual events at the projected luminosity.

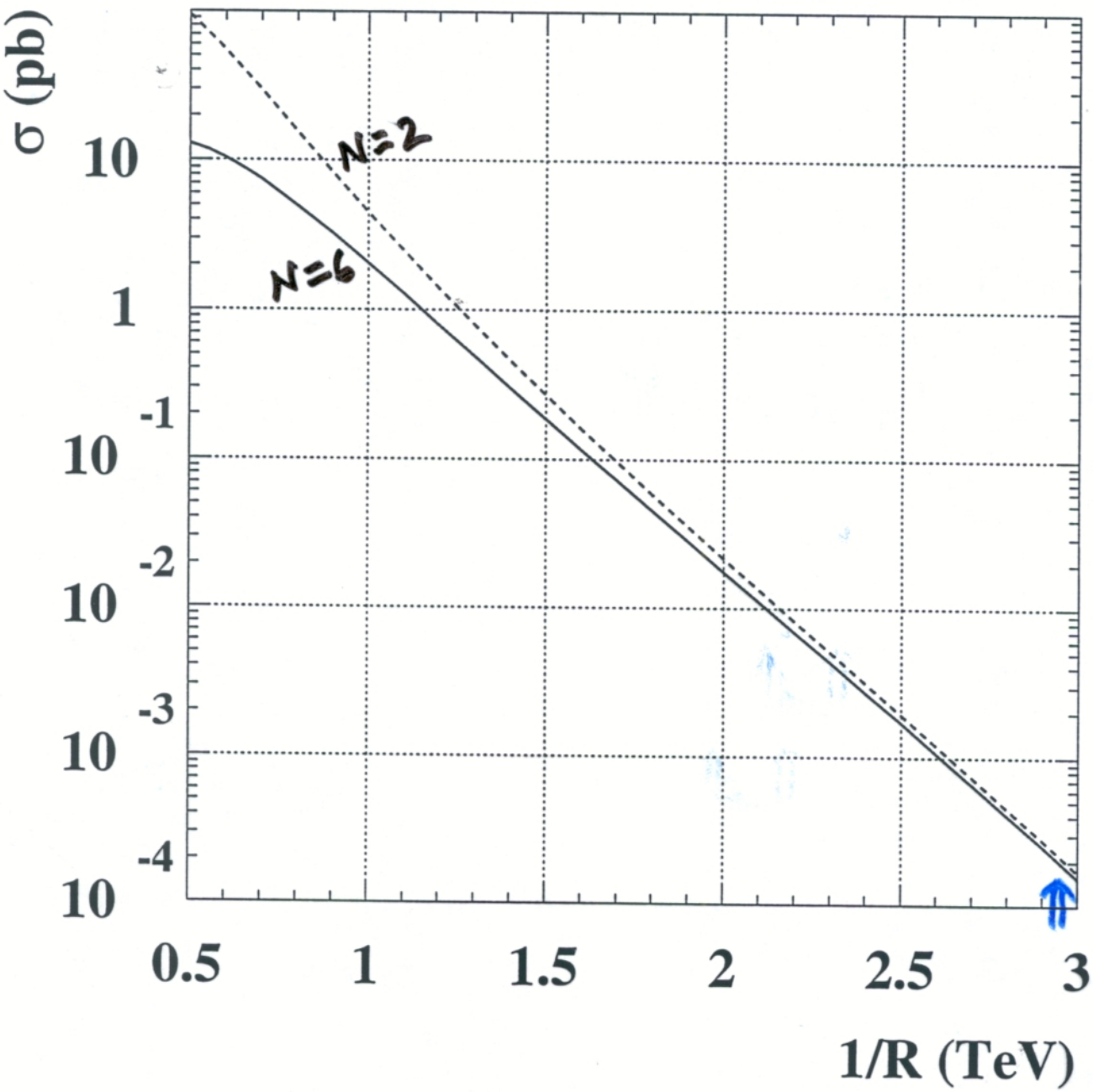
Macesanu, McMullen + Nandi, PHYS. LETT. B

UED, 1 LOOP MASS CORRECTED

LHC

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

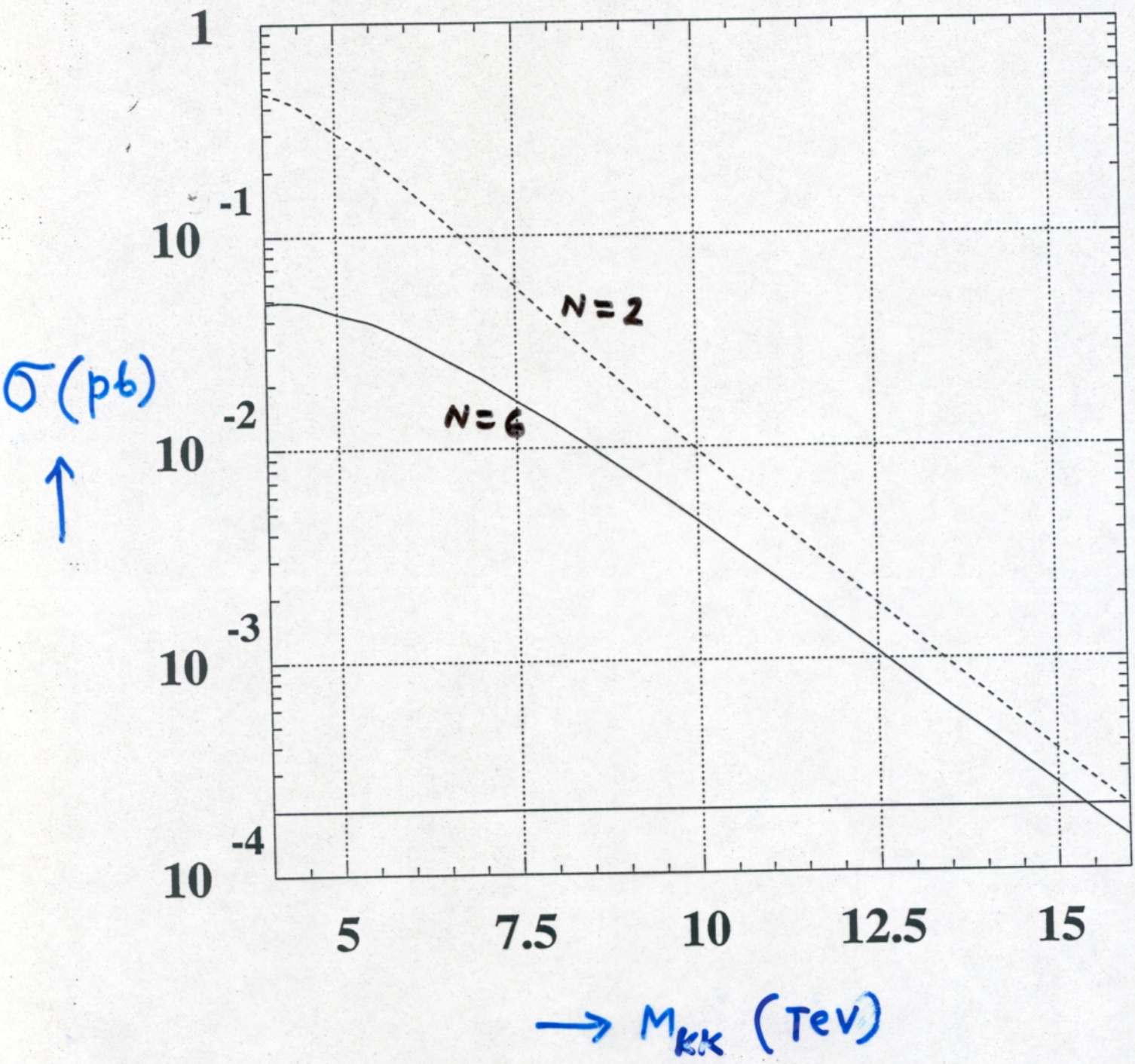
BACKGD ~ 0.05 fb



VLHC, $\sqrt{s} = 100$ TeV

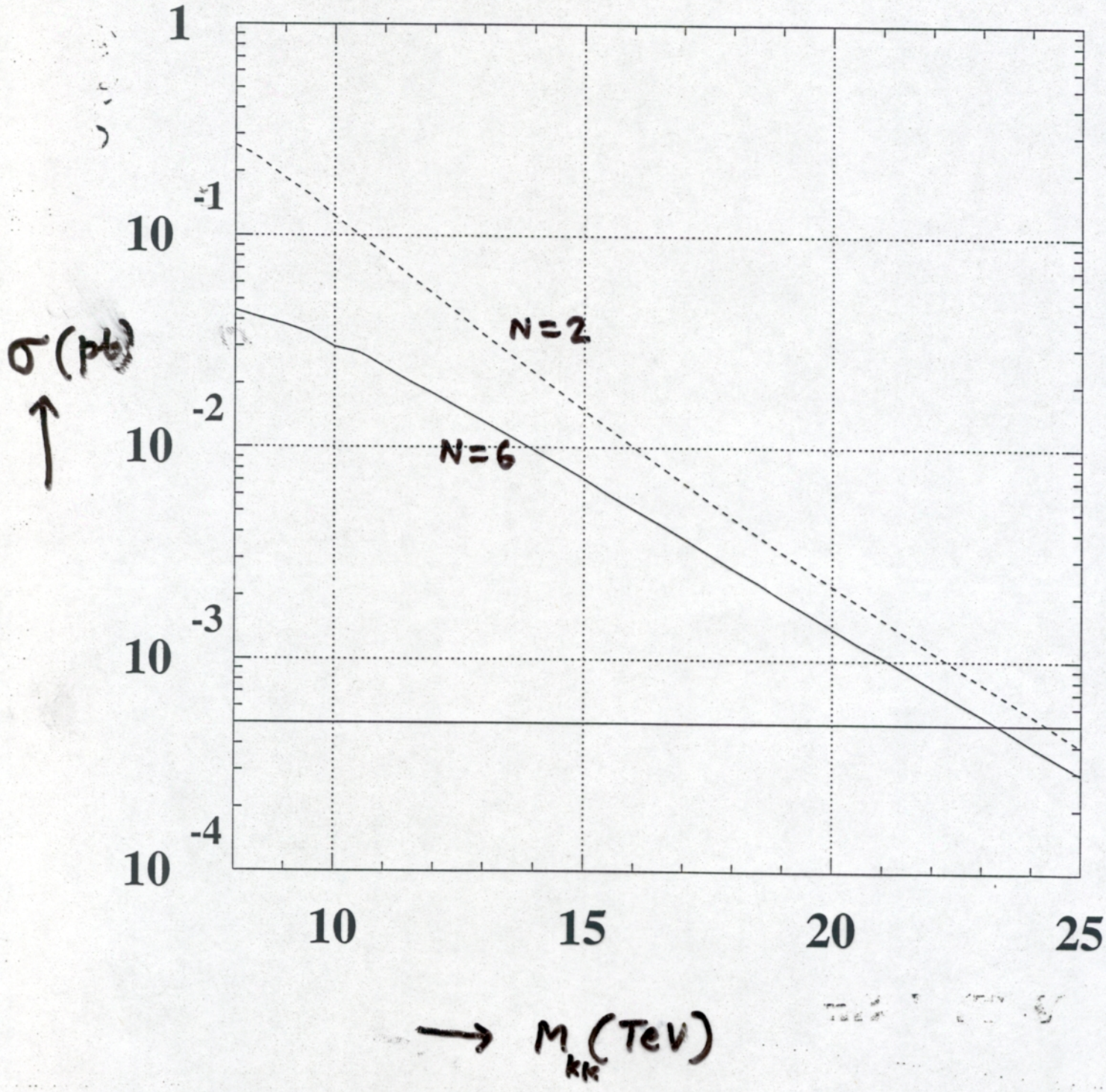
(Macesanu + SN)

$P_T > 2$ TeV, $\not{E}_T > 2$ TeV



VLHC, $\sqrt{s} = 200$ TeV

$P_T > 2$ TeV, $\not{E}_T > 2$ TeV (Macesanu + SN)



CONCLUSIONS

: VLHC (100 – 200 TeV, $\mathcal{L} \sim 10^{34}$) CAN EXPLORE $M_{KK} \sim 15 - 25$ TeV

: MAY OBSERVE FEW LOW LYING KK STATES, MASS $= \eta\,(M_{KK})$

$\Rightarrow$ CLASSIC SIGNATURE OF EXTRA DIM

: SIGNALS VERY DISTINCT

: MAY OBSERVE POWER LAW EVOLUTION OF GAUGE COUPLINGS

: UNIFICATION SCALE $\sim M_D \sim 10\, M_{KK}$

$\Rightarrow$ VLHC $\Rightarrow M_D \sim 200$ TeV

$\Rightarrow$ EFFECTS OF QUANTUM GRAVITY

$\Rightarrow$ EXTRA DIMENSIONS EXCITING AT VLHC