Universal Extra Dimensions
and
its signature @ the LHC

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7th June 2012

- First of all why should we look beyond 1 + 3 ?

Strong motivations come from the theories which try to incorporate gravity in a quantum theory.

Some of the models offer interesting solutions to some long standing problems : hierarchy, dark-matter, cosmological constant.

UED for example, provides DM, unification at a testable scale, prediction for number of fermion generations, naturally long proton life time....

Plan of this talk...

* UED : Boundary conditions/
  Orbifolding and spectra
* Radiative corrections
* New search strategies for mUED @ LHC
* Boundary Localised Kinetic Terms
* QED with BLKT
* Predictions @ the LHC ?
* Summary and Outlook....

Based on : arXiv : 1205.4334 (hep-ph)

Ujjal Dey, Avirup Shaw, Amitava Raychaudhury

&

Phys.Lett. B712 (2012) Amitava Datta, Sujoy Poddar

Universal Extra Dimension : in a nutshell

SU(3) x SU(2) x U(1) gauge field theory in 4 + 1 dimensions

** Extra space like dimension is of finite size ($2\pi R$)

Gauge, Higgs and Yukawa : negetive mass dimension

An effective theory valid upto a scale Λ

As usual apply KK-reduction on 5D fields :

** Apply periodic b.c. on 5d fields at $y = 0$ and $y = 2\pi R$

$$\Phi(x,y) = \frac{1}{\sqrt{2\pi R}} \sum_0^\infty \left[\phi_+^n(x) e^{\frac{iny}{R}} + \phi_-^n(x) e^{\frac{-iny}{R}} \right]$$

Two infinite towers of KK-excitations

**KK-number (n) : discretised momentum along y-direction conservation

AIm : to identify n=0 mode particles and their interactions with SM

Problem with compactification on circle

Look at the 5d fermionic field : $\Psi(x,y) = \frac{1}{\sqrt{2\pi R}} \sum_0^\infty \left[\psi_+^n(x) e^{\frac{iny}{R}} + \psi_-^n(x) e^{\frac{-iny}{R}}\right]$

4 x 4 matrices $\Gamma^M(\gamma^\mu,\ i\gamma_5)$ define the Clifford algebra in 1+4 dim.
One cannot have a chirality operator in 1+4 dim.

Ψ(x,y) in 5D is 4 component:

ψ_+^0 ψ_-^0 of L and R chiral or one of them is Left and the other is right

*at n=0 presence of both Left and right chiral projection

We would like to write SU(2) x U(1) gauge field theory in 5 dim

Suppose, Ψ is a member of SU(2) doublet of weak I-spin
**'SM' in 4D effective theory contains of both L-and R-chiral SU(2) doublets

Saving the compactification:

Way out : Demand some extra symmetry

Action to be invariant under $y \rightarrow -y$

Identify the (action at) points in upper half ($0 < y < \pi R$) with (acion at) those points in lower half ($-\pi R < y < 0$)

Effectively folding the full circle into a half-circle

Extra dimension is now restricted $[0: \pi R]$

Moving around $0- \leftrightarrow 0+$ as well as $\pi R + \leftrightarrow \pi R-$ is not smooth any more

$y = 0$ and $y = \pi R$: Fixed points on the orbifold

Fashionable name for this : Orbifolding

Saving the compactification: (contd....)

Components of 5D fields are assigned with a quantum number called KK-parity

$$\Phi_\alpha(x,-y) = \pm\Phi_\alpha(x,y)$$

All scalars, gauge and fermions whose 0-mode corresponds to any SM field are assigned with KK-parity +1

Operationally same as restricing the boundaries of y-direction from [0: πR] and imposing Neumann or Dirchilet b.cs.

Odd KK-parity : $\mathbf{\Phi}(x, y=0) = \mathbf{\Phi}(x, y=\pi R) = 0$

Even KK-parity : $\partial_y \mathbf{\Phi}(x, y)\,|_0 = \partial_y \mathbf{\Phi}(x, y)\,|_{\pi R} = 0$

Solving the compactification:

And how the fields look like after imposing b.c.s/orbifolding:

$$
\begin{aligned}
A_\mu(x,y) &= \frac{\sqrt{2}}{\sqrt{2\pi R}} A_\mu^0(x) + \frac{2}{\sqrt{2\pi R}} \sum_{n=1}^{\infty} A_\mu^n(x) \cos\frac{ny}{R}, \\
A_5(x,y) &= \frac{2}{\sqrt{2\pi R}} \sum_{n=1}^{\infty} A_5^n(x) \sin\frac{ny}{R}, \\
\phi(x,y) &= \frac{\sqrt{2}}{\sqrt{2\pi R}} \phi^0(x) + \frac{2}{\sqrt{2\pi R}} \sum_{n=1}^{\infty} \phi^n(x) \cos\frac{ny}{R}, \\
\mathcal{Q}_i(x,y) &= \frac{\sqrt{2}}{\sqrt{2\pi R}} \left[\begin{pmatrix} u_i(x) \\ d_i(x) \end{pmatrix}_L + \sqrt{2} \sum_{n=1}^{\infty} \left[\mathcal{Q}_{iL}^n(x) \cos\frac{ny}{R} + \mathcal{Q}_{iR}^n(x) \sin\frac{ny}{R} \right] \right], \\
\mathcal{U}_i(x,y) &= \frac{\sqrt{2}}{\sqrt{2\pi R}} \left[u_{iR}(x) + \sqrt{2} \sum_{n=1}^{\infty} \left[\mathcal{U}_{iR}^n(x) \cos\frac{ny}{R} + \mathcal{U}_{iL}^n(x) \sin\frac{ny}{R} \right] \right], \\
\mathcal{D}_i(x,y) &= \frac{\sqrt{2}}{\sqrt{2\pi R}} \left[d_{iR}(x) + \sqrt{2} \sum_{n=1}^{\infty} \left[\mathcal{D}_{iR}^n(x) \cos\frac{ny}{R} + \mathcal{D}_{iL}^n(x) \sin\frac{ny}{R} \right] \right],
\end{aligned}
$$

Summary : Infinite copies (for each n) of the (almost) SM

KK-number to KK-parity

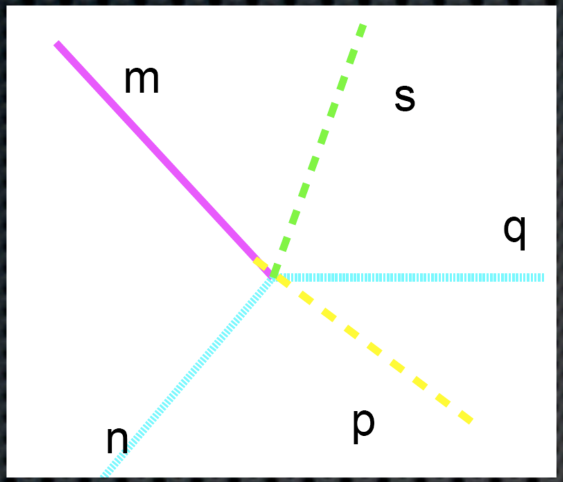
Space along y-direction is restricted at $y = 0$ and $y = \pi R$, Momentum conservation along y-direction is lost.

As $-\pi R \le y \le 0$ is identified with $\pi R \ge y \ge 0$, the residual symmetry is $y \to y + \pi R$.

Any 5D field at nth level has $(-1)^n$ under this symmetry. This is evidnt as the y-dependent functions are either cos or sin .

Interactions : KK-parity conservation

KK-parity conservation implies algebraic sum of KK-parities of the particles in the vertex should add up to a even integer. (Similar to R-parity in SUSY)



m+n+p+q+s+ ...= even integer

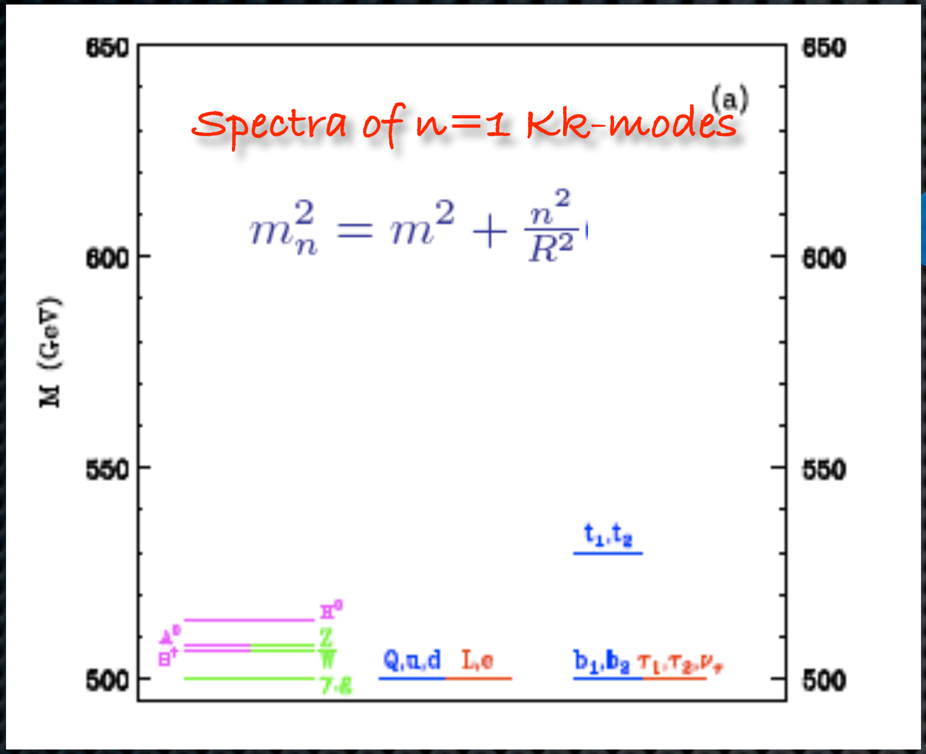
SM particle (n=0) can only couple to a pair of n =1 KK-particle.

The lightest KK (n=1) particle is thus stable. Possible DM !!

Radiative Corrections ? Why?

Tree level mass for nth kk-mode : $E^2 = p_1^2 + p_2^2 + p_3^2 + (p_4^2 + m^2)$

Consider the decay $f^1 \rightarrow f^0 \gamma^1$



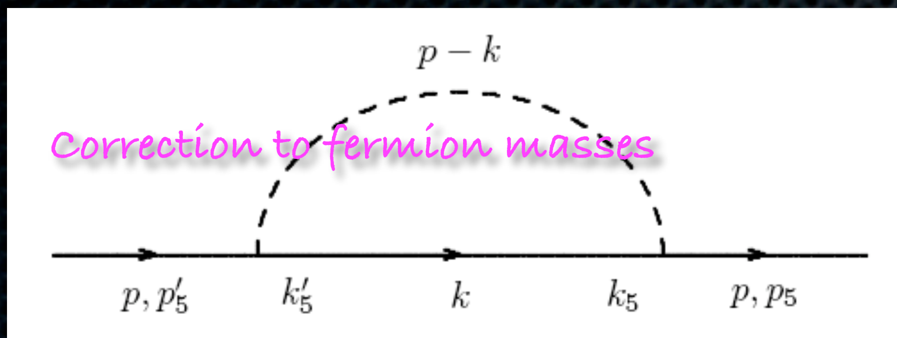
$$(m_{e^1} - m_{\gamma^1}) / m_{e^1} < \alpha_{EM}^2$$

$$\Downarrow$$

Radiative corrections are extremely important !!

Radiative Corrections ? How?

Prescription : Georgi, Grant and Hailu, PLB506 (2001)



In momentum space :
Two distinct kinds of terms
** |p5| conserving
** |p5| violating...

$$\sum_{k_5,k_5'} \int \frac{d^Dk}{(2\pi)^D} \frac{\not k + i\gamma_5 k_5}{(k^2-k_5^2)[(p-k)^2-(p_5-k_5)^2]} \left\{\delta_{p_5 p_5'} + \delta_{p_5,-p_5'}\gamma_5 - \delta_{2k_5,(p_5+p_5')} - \delta_{2k_5,(p_5-p_5')}\gamma_5\right\}$$

$$\Downarrow$$

$$\sum_{p_5=p_5'+2\pi n/L} \overline{\psi}(p,p_5)\Gamma\psi(p,p_5') \quad \overset{FT}{\Longrightarrow} \quad (\delta(x_5)+\delta(L-x_5))\,\overline{\psi}(x,x_5)\Gamma\psi(x,x_5)$$

Back in co-ordinate space : Bulk Corrections (p5 conserving)
Brane corrections (p5 violating)

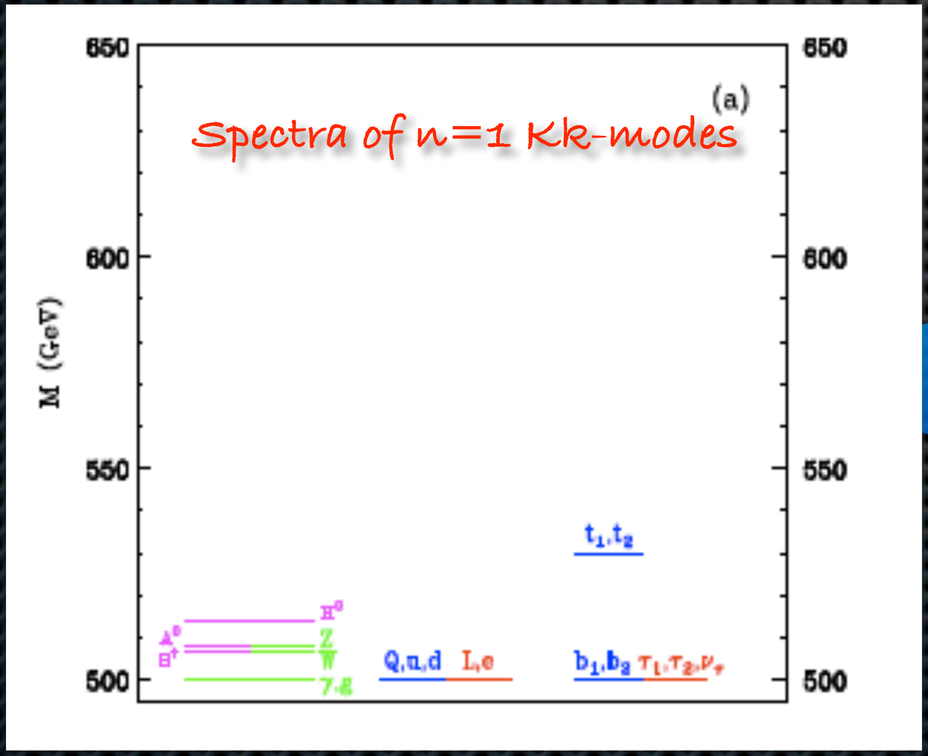
** Brane bound terms are logarithmically divergent:
corrections are sensitive to cut off Λ only via Log..

Radiative Corrections ...More...

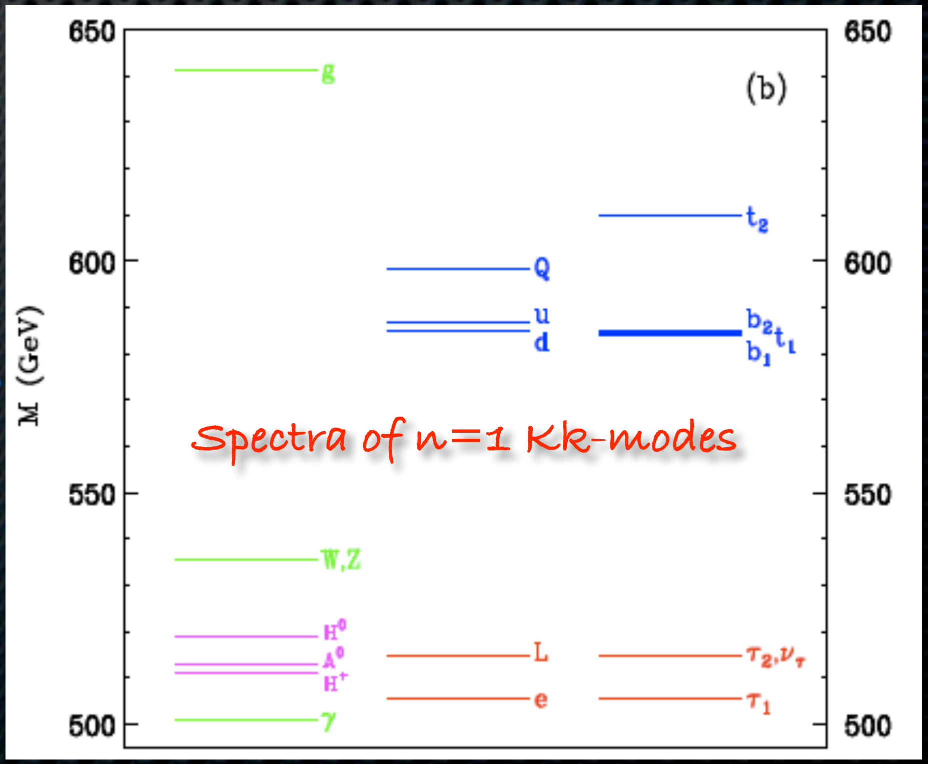
Contributions to radiative corrections from the energy scale above Λ are completely unknown ...

Similar to choosing m0 =0 in mSUGRA

✻✻ mUED : the contribution above Λ is parametrised in such a way that total contribution at Λ vanishes..



include corrections



mUED @ LHC

**Signature : m jets + n leptons + missing energy

1 hard jet + 2/3/4 leptons + missing energy @ LHC 14 TeV
Bhattacharyya, AD, Majee, Raychaudhury NPB 821 (2009)

2b-jets + 2- leptons + missing energy @ LHC 14 TeV
Choudhury, AD, Ghosh, JHEP 1008 (2010)

jets + missing energy @ LHC 7 TeV
Datta, AD, Poddar, PLB 712 (2012)

Reach in 1/R
~ 800 - 900 GeV

jets + missing energy @ LHC 7 TeV

Large pair production cross-section for coloured n=1 KK-modes @ LHC 7 TeV

For $1/R = 500$ GeV and $\Lambda R = 20$

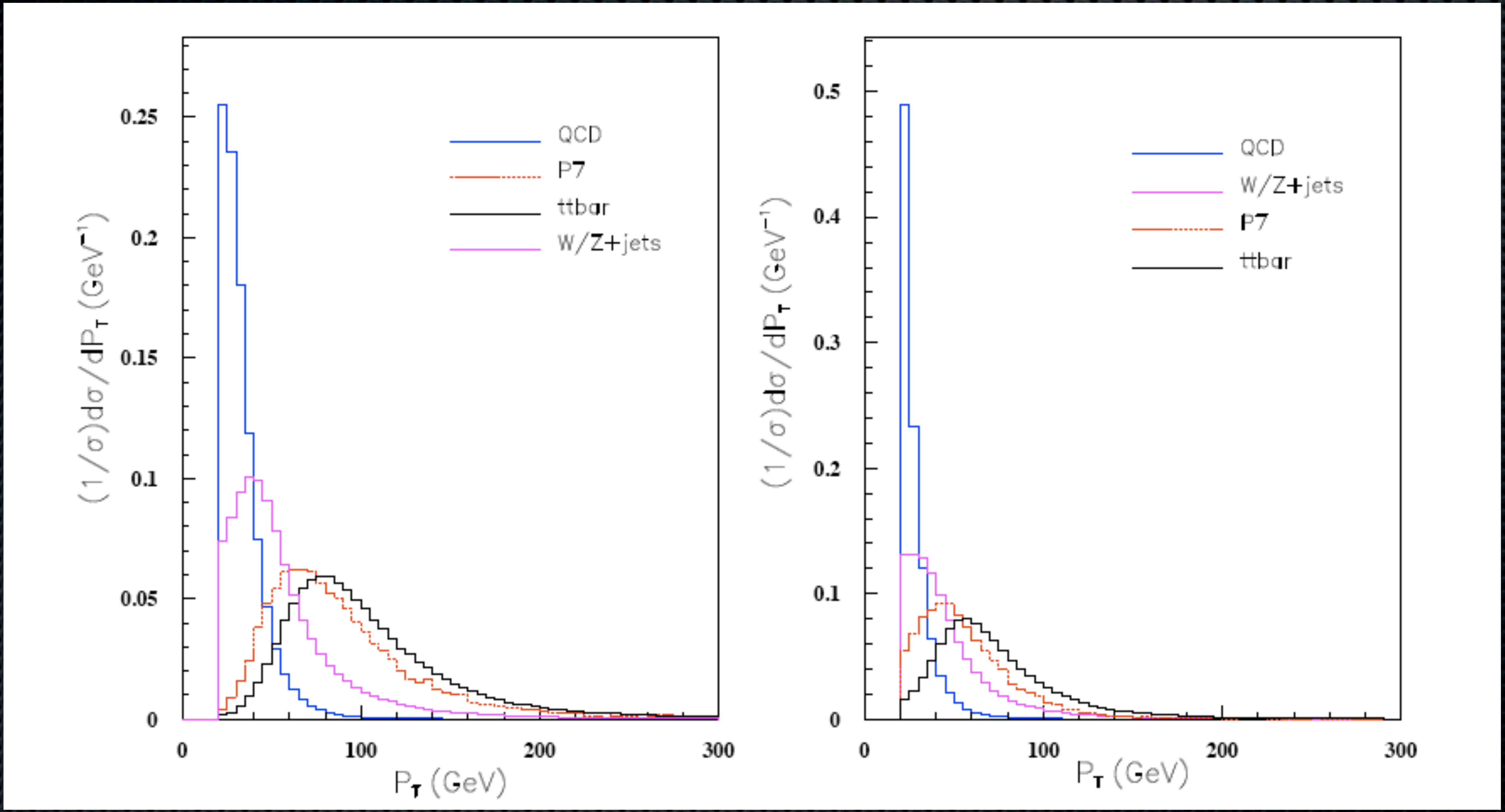
$\sigma \approx 250$ pb

$$g + g \to g^* + g^*$$
$$g + q \to g^* + q^*_D;\ g^* + q^*_S$$
$$q_i + q_j \to q^*_{Di} + q^*_{Dj};\ q^*_{Si} + q^*_{Sj}$$
$$g + g \to q^*_D + \bar{q}^*_D;\ q^*_S + \bar{q}^*_S$$
$$q + \bar{q} \to q^*_D + \bar{q}^*_D;\ q^*_S + \bar{q}^*_S$$
$$q_i + \bar{q}_j \to q^*_{Di} + \bar{q}^*_{Sj}$$
$$q_i + \bar{q}_j \to q^*_{Di} + \bar{q}^*_{Dj};\ q^*_{Si} + \bar{q}^*_{Sj}$$
$$q_i + q_j \to q^*_{Di} + q^*_{Sj}$$
$$q_i + \bar{q}_i \to q^*_{Dj} + \bar{q}^*_{Dj}$$

Unfortunately small mass seperations :
softer jets and hence low MET events...

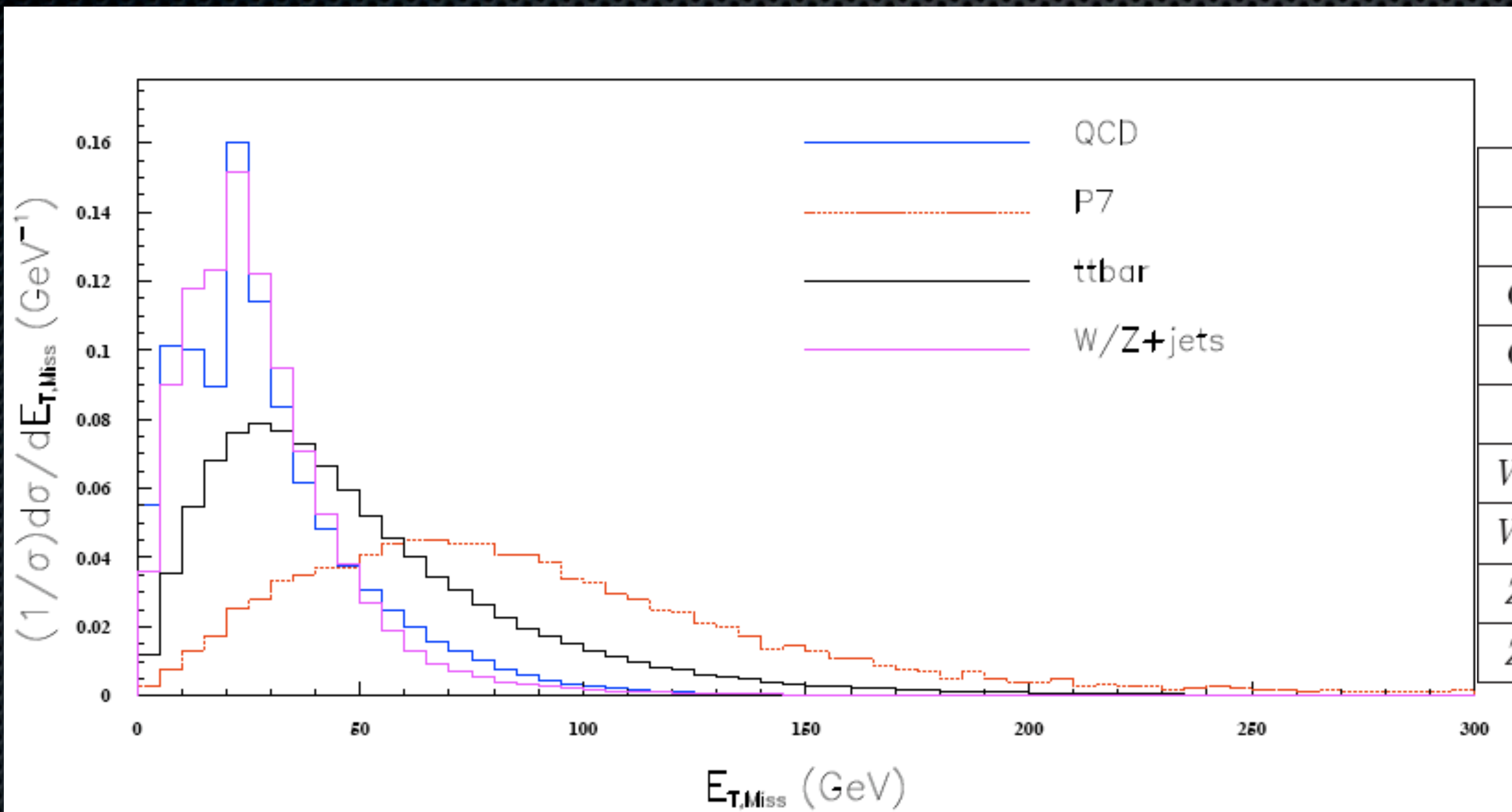
P_T spectrum of the jets

Hadronisation, ISR,FSR by PYTHIA, PYCELL



This is normalised to 1, QCD, tt have long tail...

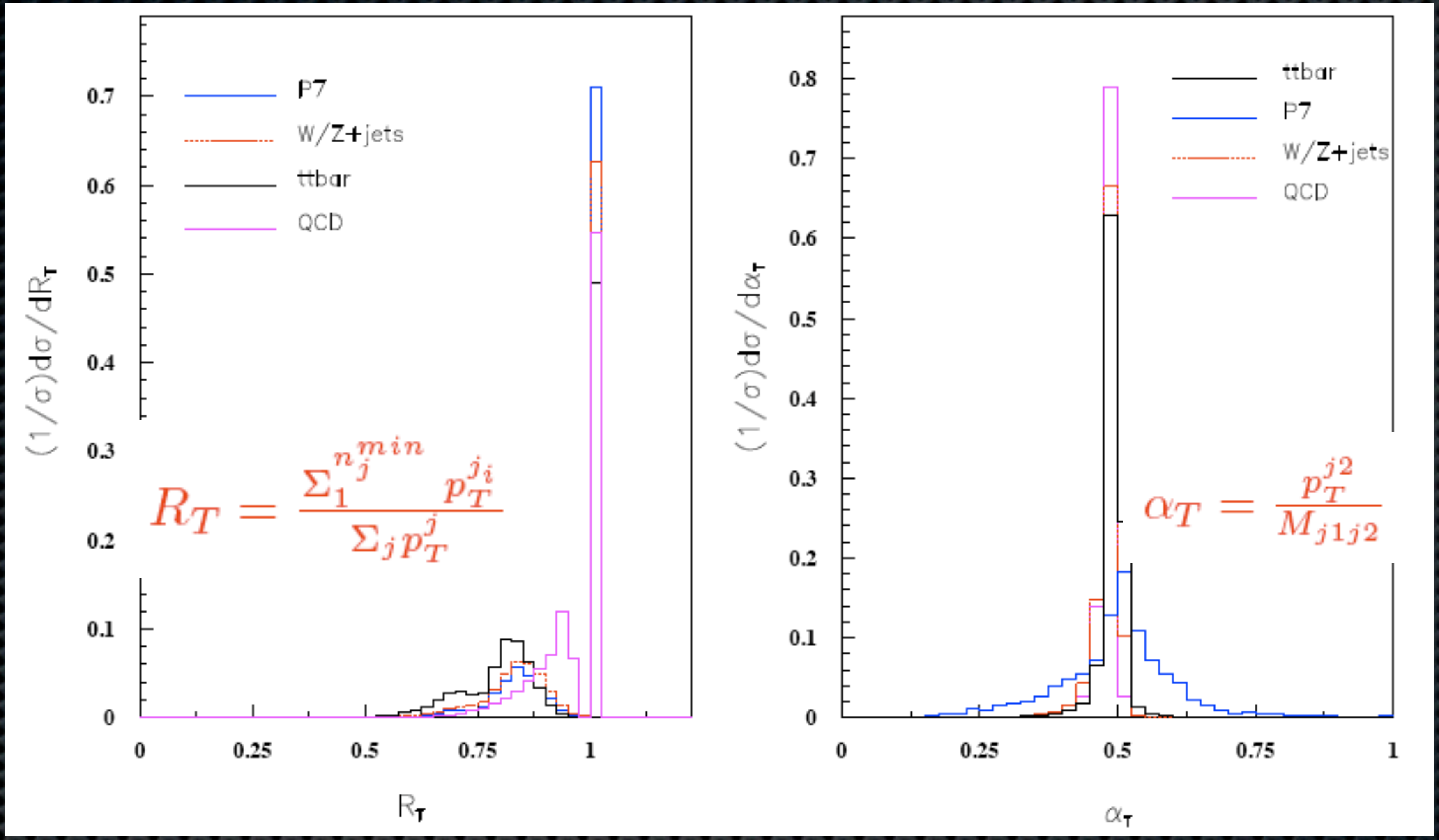
Missing p_T spectrum



	σ(pb)
P7	1.9
QCD1	8.6×10^7
QCD2	1775.0
$t\bar{t}$	56.8
$W + 1j$	13390
$W + 2j$	3073
$Z + 1j$	4235
$Z + 2j$	970

Cannot fight with SM (QCD, tt) with traditional weapons (p , MET, H)...

Few Event-shape variables come handy



SM background can be completely tamed using

$R_T < 0.8$ and $\alpha_T > 0.6$

Bottomline of this analysis :

** Obtained so far the best mass reach at LHC for mUED

$1/R > 900$ GeV @ 7 TeV

criteria : 20 signal events in a background free environment

** Very important : this analysis is equally applicable to LHC search to any model with compressed mass spectra...

** SUSY search should be relooked thro' event shape analysis

Twist in the tale...

Minimality assumption can be evaded by parametrising the contribution above Λ, by treating them as free parameters

Equivalent to write all posible operators present at the classical action at the boundaries however with their co-efficients as free parameters...

Boundary Localised Kinetic Terms

Unknown UV completion can be the main motivation for adding boundary localised terms.

One is allowed to add all possible Lorentz/ gauge invariant terms to the acion at the boundaries.

Leads us to introduce a set of BLKTs (only) and investigate the so called non-minimal UED

Like adding $\not{R}$-terms in superpotential

Life (UED) with BLKTs..

For warm up: confine ourselves with QED only...

Remember :

ψ_L ψ_R are four component fields in 5D →

$$S = \int d^4x\, dy \Big[\bar{\Psi}_L i\Gamma^M \partial_M \Psi_L + r_f^a \delta(y) \phi_L^\dagger i\bar{\sigma}^\mu \partial_\mu \phi_L + r_f^b \delta(y-\pi R)\phi_L^\dagger i\bar{\sigma}^\mu \partial_\mu \phi_L$$
$$+\bar{\Psi}_R i\Gamma^M \partial_M \Psi_R + r_f^a \delta(y)\chi_R^\dagger i\sigma^\mu \partial_\mu \chi_R + r_f^b \delta(y-\pi R)\chi_R^\dagger i\sigma^\mu \partial_\mu \chi_R\Big]$$
$$+\tfrac{1}{4}\int d^4x\, dy \left[F_{MN}F^{MN} + r_\gamma^a \delta(y) F_{\mu\nu}F^{\mu\nu} + r_\gamma^b \delta(y-\pi R) F_{\mu\nu}F^{\mu\nu}\right]$$
$$+\int d^4x\, dy \Big[e_5\, \bar{\Psi}_L i\Gamma^M A_M \Psi_L + e_4 \left(r_f^a \delta(y)\phi_L^\dagger i\bar{\sigma}^\mu A_\mu \phi_L + r_f^b \delta(y-\pi R)\phi_L^\dagger i\bar{\sigma}^\mu A_\mu \phi_L\right)$$
$$+e_5\, \bar{\Psi}_R i\Gamma^M A_M \Psi_R + e_4 \left(r_f^a \delta(y)\chi_R^\dagger i A^\mu \partial_\mu \chi_R + r_f^b \delta(y-\pi R)\chi_R^\dagger i\sigma^\mu A_\mu \chi_R\right)\Big]$$

A has 5 commponents, choose $A_4 = 0$ (gauge choice)

KK-expansion of the photon →

$$A_\mu(x,y) = \sum_{n=0}^{\infty} A_\mu^{(n)}(x)\, a_n(y)$$

KK-expansion of the fermions →

$$\Psi_L(x,y) = \begin{pmatrix} \phi_L(x,y) \\ \chi_L(x,y) \end{pmatrix} = \sum_n \begin{pmatrix} \phi_n(x) f_L^n(y) \\ \chi_n(x) g_L^n(y) \end{pmatrix}$$

$$\Psi_R(x,y) = \begin{pmatrix} \phi_R(x,y) \\ \chi_R(x,y) \end{pmatrix} = \sum_n \begin{pmatrix} \phi_n(x) f_R^n(y) \\ \chi_n(x) g_R^n(y) \end{pmatrix}$$

Aim is to find the y-dependence of a(y), f(y) and g(y)

Equations of motions in y and their solutions...

**Variation of S w.r.t the 5D fields and then seperating the variables x and y

$$\left[1+r_f^a\delta(y)+r_f^b\delta(y-\pi R)\right] m_n f_L^n - \partial_y g_L^n = 0, \quad m_n g_L^n + \partial_y f_L^n = 0$$

$$\left[1+r_f^a\delta(y)+r_f^b\delta(y-\pi R)\right] m_n g_R^n + \partial_y f_R^n = 0, \quad m_n f_R^n - \partial_y g_R^n = 0$$

→

$$\partial_y^2 f_L^n + \left[1+r_f^a\delta(y)+r_f^b\delta(y-\pi R)\right] m_n^2 f_L^n = 0,$$

$$\partial_y^2 g_R^n + \left[1+r_f^a\delta(y)+r_f^b\delta(y-\pi R)\right] m_n^2 g_R^n = 0,$$

need b.cs → $\phi|_{0,\pi R} = 0 \Rightarrow f^n(y)|_{0,\pi R} = 0, \quad \partial_y \chi|_{0,\pi R} = 0 \Rightarrow \partial_y g^n(y)|_{0,\pi R} = 0$

Finally we arrive at the solutions: →

$$f^n(y) = N_n \left[\cos(m_n y) - \frac{r_f^a m_n}{2} \sin(m_n y)\right]$$

Orthogonality → $\int dy \left[1+r_f^a\delta(y)+r_f^b\delta(y-\pi R)\right] f^n(y)\, f^m(y) = \delta^{nm}$

Spectra can be solved from → $(r_f^a r_f^b\, m_n^2 - 4)\tan(m_n \pi R) = 2(r_f^a + r_f^b) m_n$

Similar results for photon hold

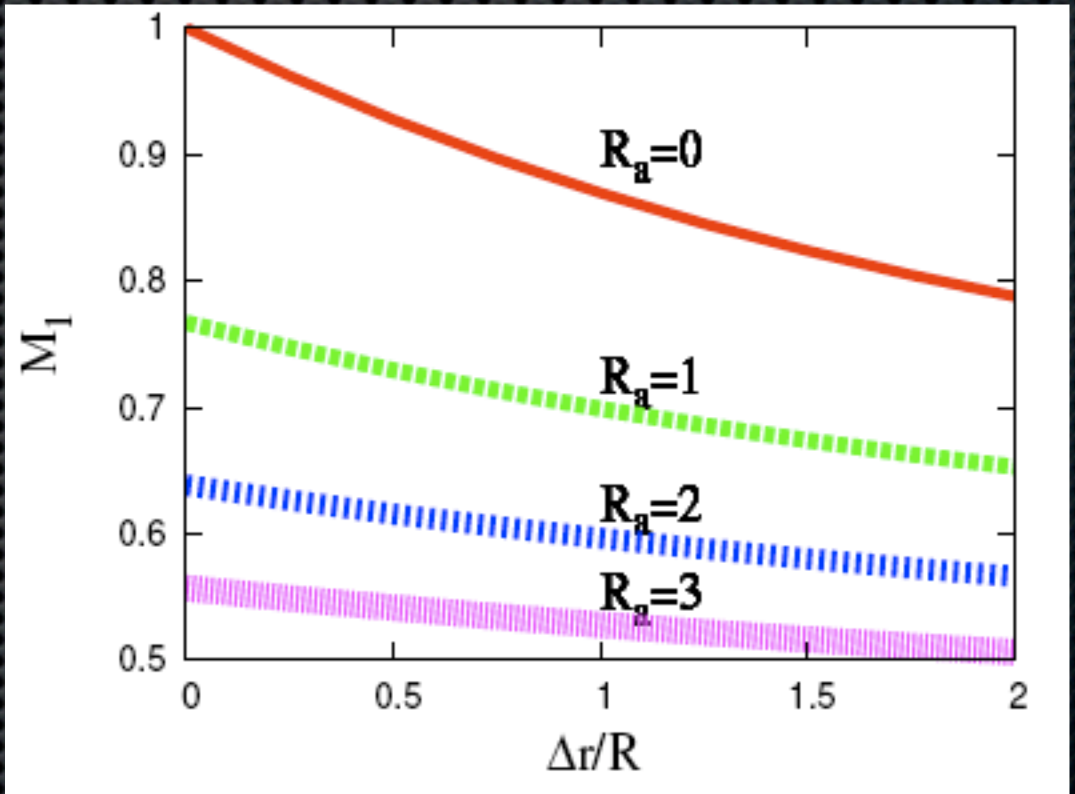
Look at some numerical results...

Made some assumptions :

$$r_f^a = r_f^b = r_f$$
$$r_\gamma^a - r_\gamma^b \equiv \Delta r$$

Consider the mass of n=1 KK photon →

$$M_1 \equiv m_{\gamma(1)} R, \quad R_a \equiv r^a/R, \quad R_b \equiv r^b/R.$$



Similar variation of n=1 KK-fermion masses on R_fs

$R_a^\gamma = 0$ corresponds to the case with BLKT at one of the branes

$\Delta r \neq 0$ implies breakdown of $y \rightarrow y + \pi R$ symmetry (KK-parity)

Look at the couplings

General strategy for evaluating the couplings in 4D effective theory → $\mathcal{L}_4 = \int_0^{\pi R} dy\, \mathcal{L}_5$

**Let us find out coupling of n=1 KK photon to two SM (n=0) fermions

Hallmark of KK-parity of violation, not-present in mUED → $$g_{\gamma^{(1)}e^{(0)}e^{(0)}} = e_4 \int_0^{\pi R} (1 + r_f\{\delta(y) + \delta(y - \pi R)\}) f_L^{(0)} f_L^{(0)} a^{(1)} dy$$

$$a^{(1)} = \sqrt{\frac{8(4 + M_1^2 R_b^2)}{-2\left(\frac{R_b}{\pi}\right)(4 + M_1^2 R_a R_b) + (4 + M_1^2 R_a^2)(4 + M_1^2 R_b^2)}} \left[\cos\left(\frac{M_1 y}{R}\right) - \frac{R_a M_1}{2} \sin\left(\frac{M_1 y}{R}\right)\right]$$

$$f_L^{(0)} = g_R^{(0)} = \frac{1}{\sqrt{\pi R}}$$

**This coupling should vanish when $\Delta r = 0$

A small caveat..

**KK-parity violation does not allow you to couple photon (γ^0) to charged fermions with different kk-number due to EM gauge invariance.

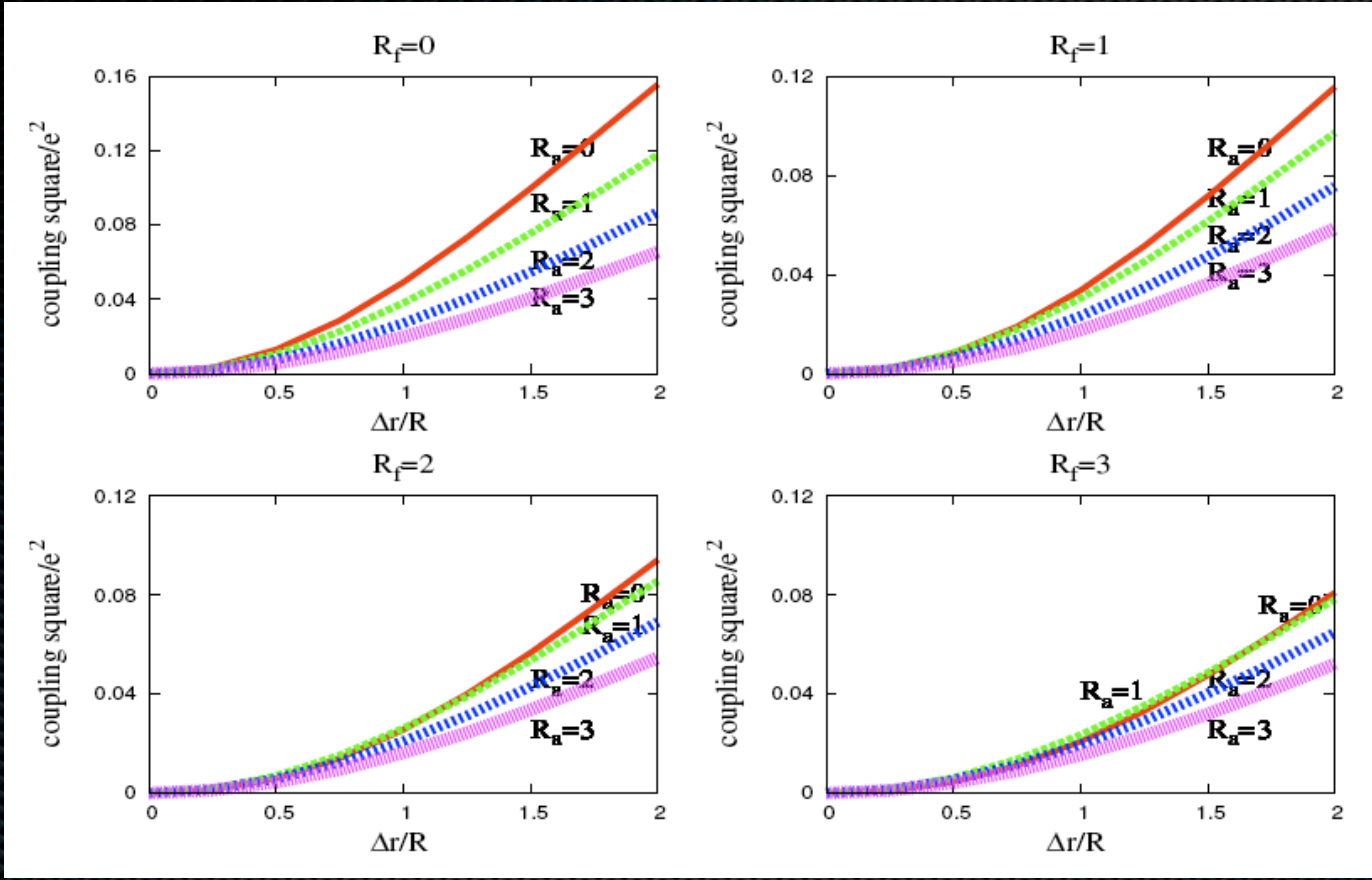
** EM gauge invariance : 0-mode photon remains massless.

** $a^0(y)$ for 0-mode photon remains independent of y.

$$g_{\gamma^0 f^{(m)} f^{(n)}} = e_5 \int_0^{\pi R} (1 + r_f\{\delta(y) + \delta(y - \pi R)\}) f_L^{(m)} f_L^{(n)} a^{(0)} dy$$

** coupling vanishes due to orthogonality of fermions .

How this coupling depends on the parameters ?

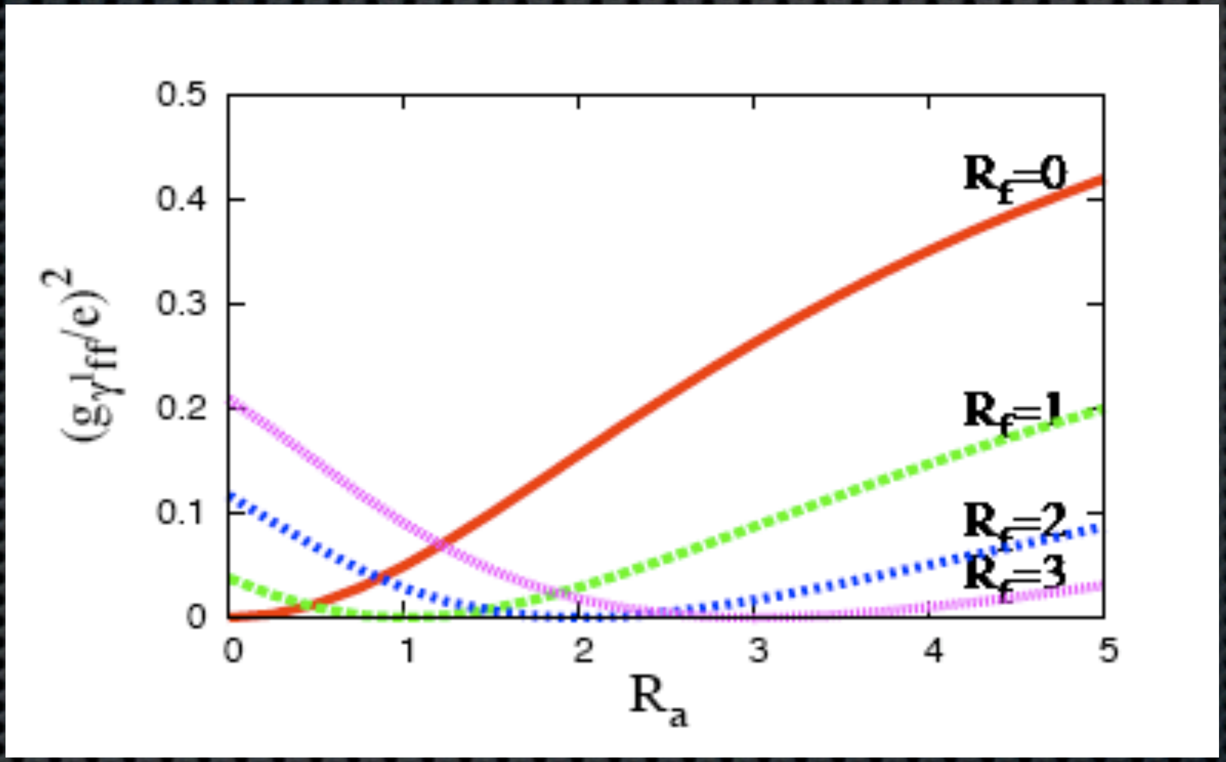


KK-parity violating coupling vanishes as $\Delta r \to 0$, decreases with R_a and R_f

Similar to R-parity violation, but there is no flavour violation as in R-parity violating scenarios.

Coupling : Presence of BLKT at one boundary

$$g_{\gamma^1 f^{(0)} f^{(0)}} \quad \frac{\sqrt{2}\, e}{\left(1+\frac{R_f}{2\pi}\right)\sqrt{1+\left(\frac{R_a M_1}{2}\right)^2-\frac{R_a}{2\pi}}}\left(\frac{R_f-R_a}{2\pi}\right)$$



**Coupling vanishes at $r_a = r_f$

Testability at the LHC ?

**Further assumption : BLKT parameter for all the fermions (r_f) are universal

**n=1 KK photon, γ^1, decay to all the fermions with equal strength, with Branching ratio ~ 1/8

**Consider production of γ^1 in pp collision @the LHC (@ 8 TeV) and decay to e/μ pair in association with jet..

$$pp\ (q\bar{q},\ gq) \rightarrow e\,e\,/\,\mu\,\mu + jet$$

Both production and decay via KK-parity violating coupling

How much we can probe @ the LHC at 8 TeV ?

**Signal is practically free of SM backgrounds. Only arise from Z/γ^* production with jets. Can be reduced to negligible level by demanding high mass leptons in the final state

**20 signal events can be a benchmark for discovery

** Selection criteria

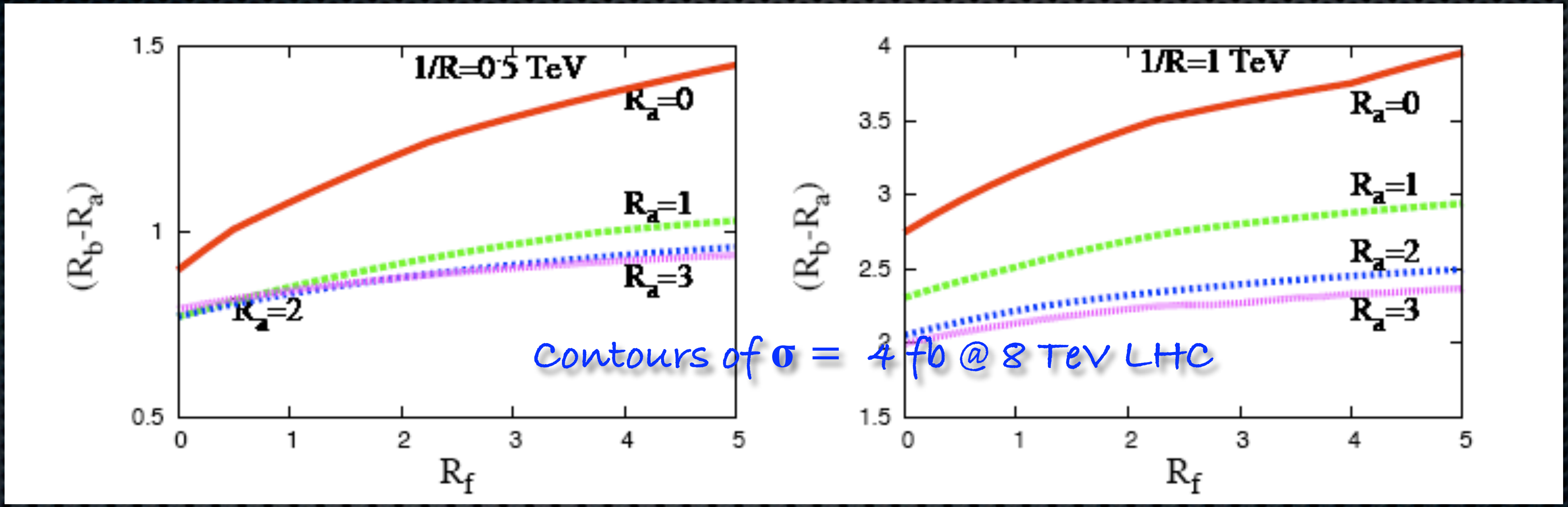
p^T (jet) > 50 GeV, p^T (lepton) > 20 GeV

$|\eta$ (lepton, jet)$| < 3$

ΔR (ll, lj, jj) > 0.5

Reach of LHC at 8 TeV :

(Case of BLKTs at both the boundaries)

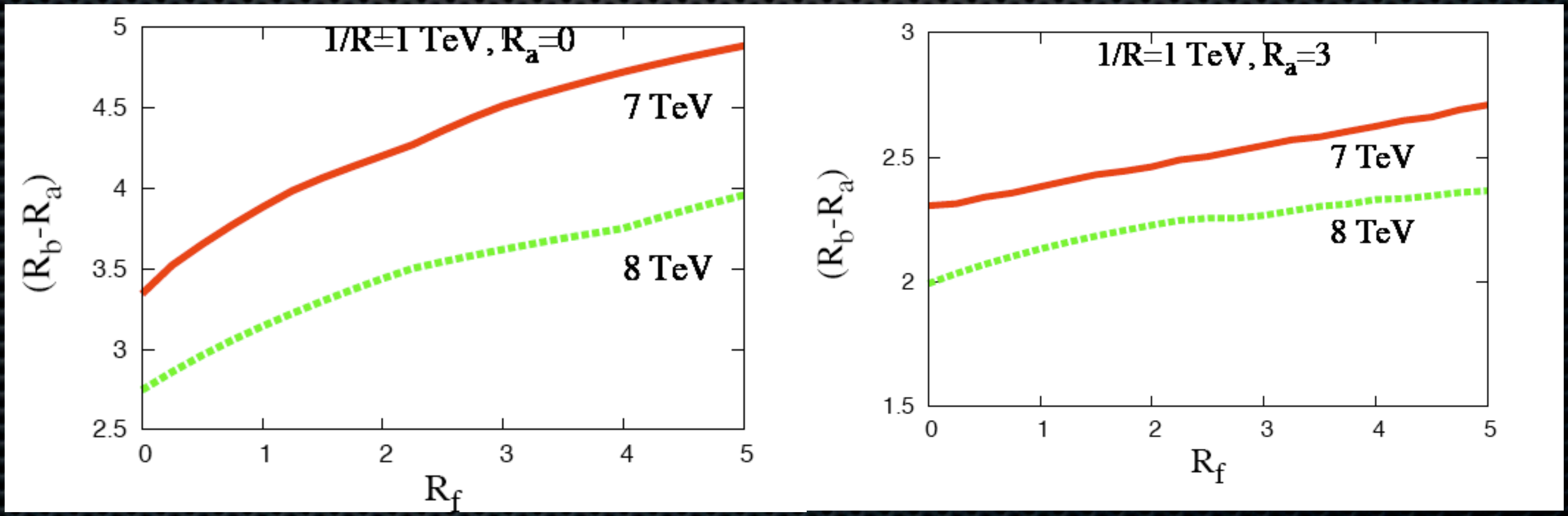


With 5 fb^{-1} collected data, region above the lines can be ruled out.

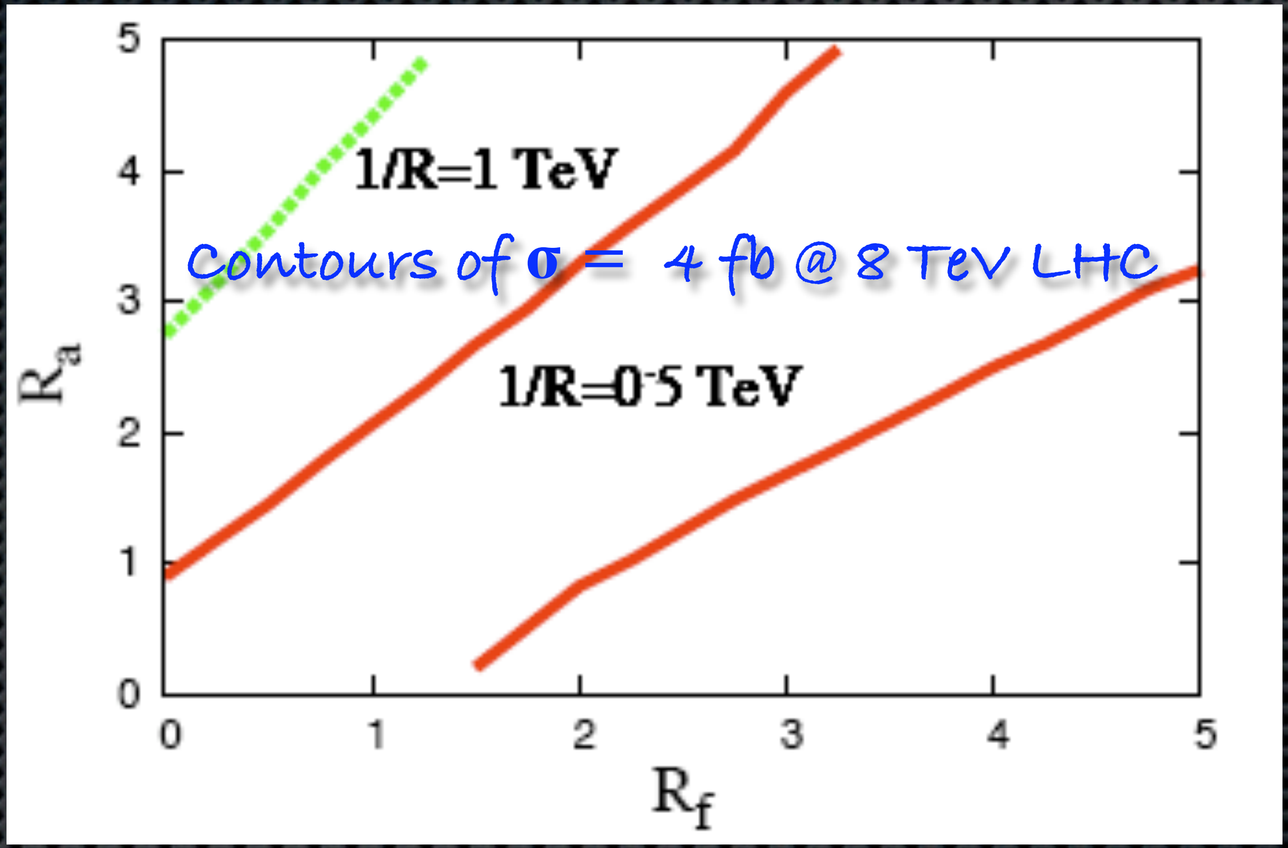
Already probed at LHC at 7 TeV :

**Signal very similar to extra Z' from LR symmetric model or models with extra U(1) symmetry

**No such signal have been reported at LHS so far.



Results with BLKT at one boundary



**region bounded by the red lines (around $r_a = r_f$) cannot be probed..

Summary & Outlook :

- ❊ Search strategies based on event shape variables offer a new and powerful technique for LHC search of models with compressed spectra like mUED.

- ❊ BLKTs are ways to introduce the unknown radiative corrections that can arise from the enegy scale above the cut-off Λ, in UED.

- ❊ For illustration, effects of a set of BLKTs have been investigaed in QED in 1+4 dimensions.

- ❊ BLKTs can change the pattern of mass spectra of KK modes. These can used to 'cure' the pathological compressed mass spectra of mUED.

- Having asymmetric BLKTs at orbifold fixed points will lead to violation of KK-parity. Any KK-level paticle can couple to any other KK-level particles, provided this coupling is not otherwise prohibited.

- This non-minimal model of UED can be testable at the LHC. We have Proposed a di-lepton + jet signature as the signal of KK-parity violation .

- Interesting to study the SM with possible set of BLKT parameters. With symmetric BLKT parameters at orbifold fixed points, one can have several possibilities of Dark Matter candidate (n=1, KK-photon, KK-Z or KK-higgs).

- One should also investigate the other existing experimental data (S,T parameters, B and K physics) to constrain the set of BLKT parameters in SM in 1+4 D.