

Title: Non-minimal Universal Extra Dimensions

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Abstract: We study the effects of boundary terms in models with a flat 'Universal' Extra Dimension in which all Standard Model fields propagate in the bulk. We show how non-minimal boundary terms change the mass spectrum and interactions of Kaluza-Klein modes, allow for new dark matter candidates from UED, and how they alter collider phenomenology.



Non-minimal universal extra dimensions (and new dark matter candidates)

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(to appear soon)



Outline

- Review of universal extra dimensions
- UED as an effective field theory
- Changing the lightest Kaluza-Klein particle via boundary localized terms
- Conclusions



UED review

- Consider a 5D model in which *all* fields propagate in a flat extra dimension. [Appelquist, Cheng, Dobrescu (2001)]
- Identify the zero mode spectrum with the SM.
- Compactification on S^1/Z_2 ($y \in [0, \pi R]$) allows for chiral fermion zero modes.
- Compactification on S^1/Z_2 preserves a Z_2 parity (“KK-parity”).
 - KK excitations can only be produced pairwise.
 - stable lightest KK particle (“LKP”) \rightarrow dark matter.



UED review

- All fields can be expanded in the *same* Kaluza-Klein basis f_n

$$\Phi(x, y) = \sum_n \Phi^{(n)}(x) f_n(y)$$

- By canonically normalizing the zero modes, all 5D couplings are related to the Standard Model couplings by rescaling with the appropriate powers of πR .
- At tree level, UED has two undetermined parameters:
The Higgs mass m_h
and the compactification scale $M_{kk} \equiv R^{-1}$.



UED review

The UED action:

$$S_{UED,bulk} = S_g + S_H + S_f$$

with

$$S_g = \int d^5x \left\{ -\frac{1}{4\hat{g}_3^2} G_{MN}^A G^{AMN} - \frac{1}{4\hat{g}_2^2} W_{MN}^I W^{IMN} - \frac{1}{4\hat{g}_Y^2} B_{MN} B^{MN} \right\}$$

$$S_H = \int d^5x \left\{ (D_M H)^\dagger (D^M H) + \hat{\mu}^2 H^\dagger H - \hat{\lambda} (H^\dagger H)^2 \right\}$$

$$S_f = \int d^5x \left\{ i\bar{\psi}\gamma^M D_M \psi + \left(\hat{\lambda}_E \bar{L} E H + \hat{\lambda}_U \bar{Q} U \tilde{H} + \hat{\lambda}_D \bar{Q} D H + \text{h.c.} \right) \right\}$$



UED as an effective field theory

- UED is a five dimensional model \rightarrow non-renormalizable.
- It should be considered as an effective field theory with a cutoff Λ .
- NDA result: $\Lambda \sim 50/R$. *This cutoff is low!*
- *Without knowledge of the underlying theory, all operators allowed by all symmetries should be considered.*
- This includes:
 - higher dimensional bulk and boundary operators
 - boundary localized operators allowed by the 4D effective gauge symmetries. Eg:

$$S_{tot} \supset d^5x \frac{r_W}{4} W_{\mu\nu} W^{\mu\nu} (\delta(y) + \delta(y - \pi R))$$



UED as an EFT

The well-studied example: “Minimal” UED

[Cheng, Matchev, Schmaltz (2002)]

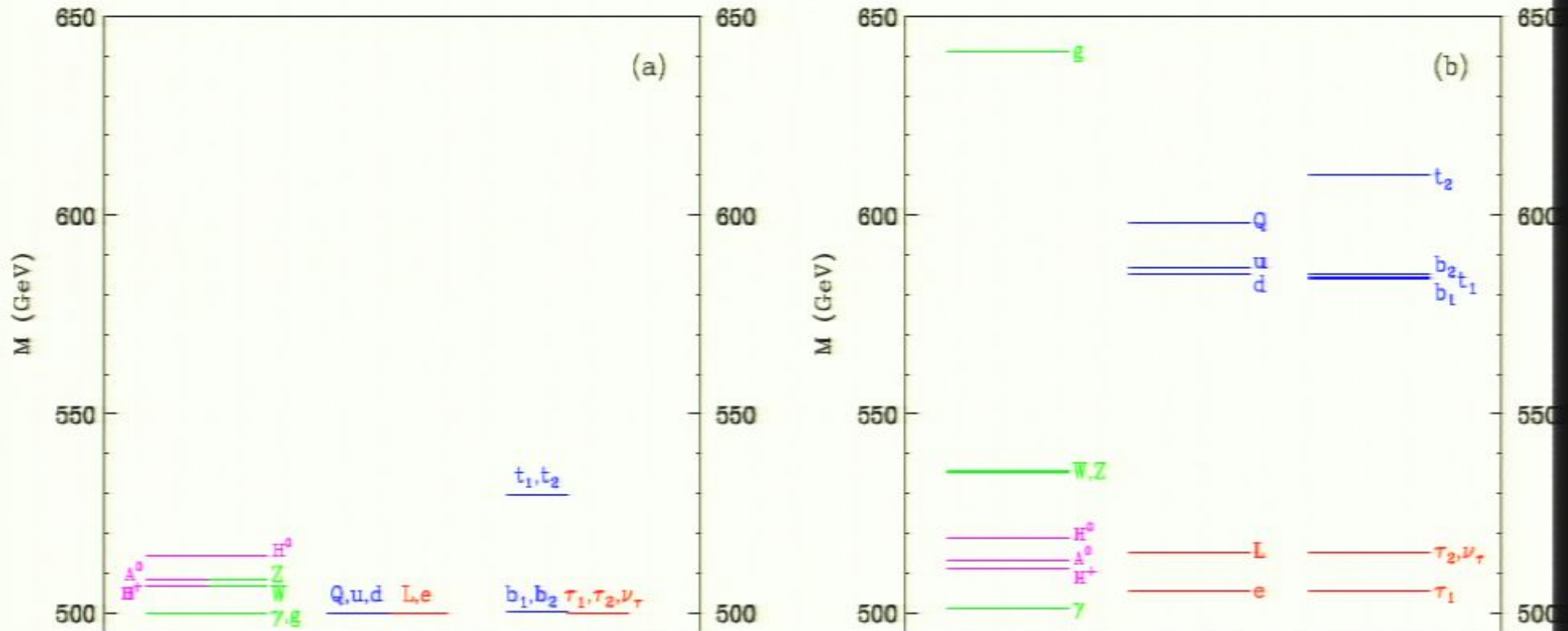
- In compactifications on S^1/Z_2 , loop corrections induce boundary localized kinetic terms.
[Georgi, Grant, Hailu (2000)]
- Definition of MUED: Assume that *all* boundary localized terms vanish at the cutoff Λ .
- Still, the boundary localized terms are induced at lower scale due to renormalization group evolution.



UED as an EFT

The one-loop corrected MUED spectrum:

[Cheng, Matchev, Schmaltz, (2002)]



$R^{-1} = 500\text{GeV}, \Lambda R = 20, m_h = 120\text{ GeV}$. Left: tree level. Right: one-loop corrected MUED.



Mini (M)UED pheno review

Phenomenology constrains R^{-1}

● lower bound: $\Rightarrow R^{-1} \gtrsim 300 \text{ GeV}$

● No detection of KK-modes

[Appelquist *et al.* (2001); Rizzo (2001); Macesanu *et al.* (2002)]

● FCNCs [Buras, Weiler *et al.* (2003)]

● EWPT [Appelquist, Yee (2002)]

● upper bound: preventing over closure of the universe by the $B^{(1)}$ $\Rightarrow R^{-1} \lesssim 1.5 \text{ TeV}$

[Servant, Tait (2002); Matchev, Kong (2005); Burnell, Kribs (2005)]

Distinguishing UED and SUSY at LHC [Datta, Kong, Matchev (2005);

Smillie, Webber (2005); Kane *et al.* (2005, 2008); Csaki *et al.* (2008)]

For an extensive review see [Hooper, Profumo (2007)].

Changing the LKP via boundary localized terms

The ambitious questions:

- *How do non-minimal terms in UED affect the mass spectrum and couplings?*
- *What are the implications for collider phenomenology and dark matter?*

Changing the LKP via boundary localized terms

As a more modest start-up, we ask:

Can non-minimal terms change the LKP to a WIMP other than the $B^{(1)}$?

Candidates:

- The neutral SU(2) gauge boson $W^{3(1)}$
- The scalar Higgs KK partner $h^{(1)}$
- The pseudoscalar Higgs KK partner $a^{(1)}$
- (The KK neutrino $\nu^{(1)}$ is ruled out [Servant, Tait (2002)])

Changing the LKP via boundary localized terms

We consider boundary localized kinetic terms (BLKTs) for the gauge fields and study their effect on the LKP.

$$S_{tot} \supset d^5x \frac{r_i}{4} F_{\mu\nu}^I F^{I,\mu\nu} (\delta(y) + \delta(y - \pi R))$$

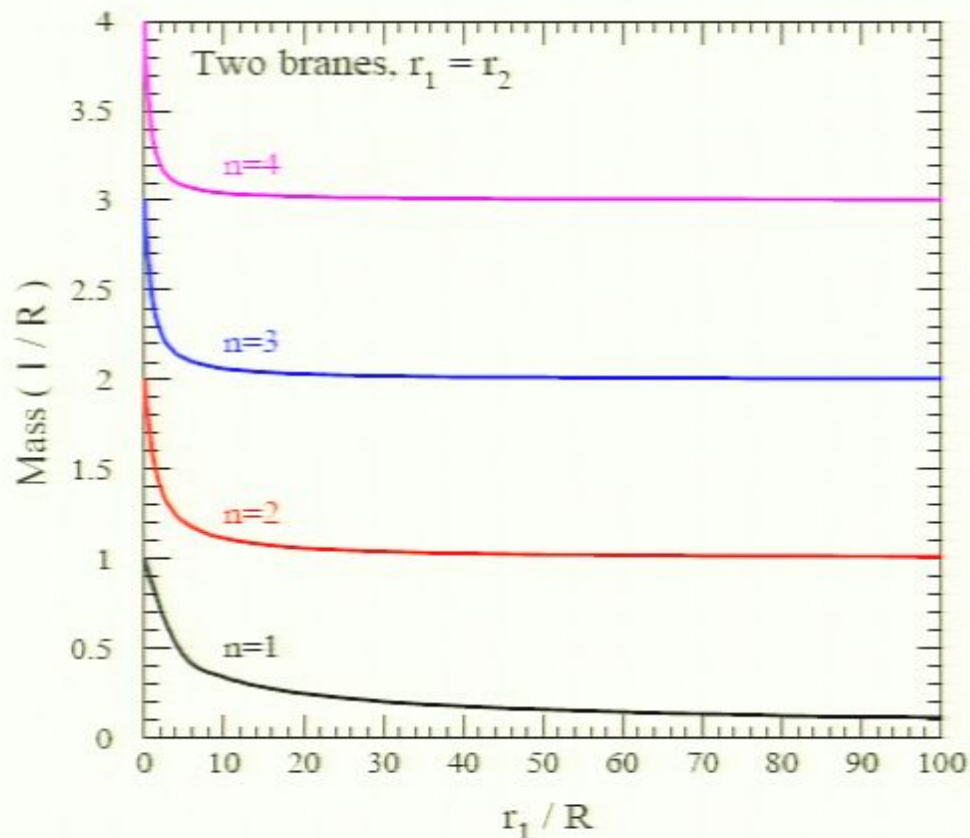
- NDA: $r_i \sim 6\pi/\Lambda R$.
- BLKTs induce mixing between the KK modes.
- [\[Carena, Tait, Wagner \(2002\)\]](#)
In a pure gauge theory, the mixing can be accounted for by modifying the KK orthogonality relations to

$$\frac{1}{\hat{g}^2} \int dy [1 + r (\delta(y) + \delta(y - \pi R))] f_n(y) f_m(y) = Z_n \delta_{nm}$$

M Changing the LKP via boundary localized terms

from [Carena, Tait, Wagner (2002)]

The masses of the KK mass eigenmodes $m_{w^{(n)}}$, $m_{b^{(n)}}$, $m_{g^{(n)}}$ get reduced by the presence of the BLKT.



Changing the LKP via boundary localized terms

Consequences in a full UED setup:

- The Kaluza-Klein basis of the BLKT modified gauge field *differs* from the standard KK basis.
- Implications for an $SU(3)$ BLKT are simple. The $g^{(1)}$ mass gets reduced and can be pushed down to provide the LKP
→ phenomenologically very problematic (SIMP Dark Matter).
- EWSB is more complicated as the B , W , and H KK basis now all differ.
- Technical problem: Gauge-fixing in the presence of BLKTs *and* electroweak symmetry breaking.



Changing the LKP via boundary localized terms

When working in unitary gauge, the physical gauge- and Higgs KK modes can be identified. Results:

- The Higgs KK masses remain at the KK-scale

$$m_{h^{(n)}, h_{\pm}^{(n)}, a_0^{(n)}}^2 \approx n^2/R^2 + (m_h^2, m_W^2, m_Z^2).$$

- In the gauge sector, KK mixing occurs due to the EWSB terms in the 5D action.

B_{μ} and $W_{\mu}^{3,\pm}$ KK modes are orthogonal with respect to the *modified* scalar product.

Thus, 5D terms $\propto \hat{v}^2 W_{\mu} W^{\mu}$, $\propto \hat{v}^2 B_{\mu} W^{\mu}$, and $\propto \hat{v}^2 B_{\mu} B^{\mu}$ induce KK mixing.

- KK parity is still preserved.



Changing the LKP via boundary localized terms

- Great simplification: The KK mixing terms are bounded by

$$(M^2)_{ij} < g_2^2 v^2 / 4, \text{ for } W^{(i)} - W^{(j)}$$

$$(M^2)_{ij} < g_2 g_Y v^2 / 4, \text{ for } W^{3,(i)} - B^{(j)}$$

$$(M^2)_{ij} < g_Y^2 v^2 / 4, \text{ for } B^{(i)} - B^{(j)}$$

- The diagonal terms also receive KK contributions

$$(M^2)_{ii} > m_{w^{(i)}, b^{(i)}}^2.$$

- Hence, KK mixing is suppressed. We can treat it as mass insertions.

- Charged gauge boson masses:

$$m_{W^{\pm,(i)}}^2 \approx m_{w^{(i)}}^2 + g_2^2 v^2 / 4.$$

Changing the LKP via boundary localized terms

The dominant mixing for neutral gauge bosons occurs at equal KK level $B^{(i)} - W^{3,(i)}$.

Mass matrix at the first KK level:

$$M_{B,W^3}^2 = \begin{pmatrix} m_{b(1)}^2 + \frac{g_Y^2 v^2}{4} & \frac{g_Y g_2 v^2}{4} \int dy f_{B,1} f_{W,1} \\ \frac{g_Y g_2 v^2}{4} \int dy f_{B,1} f_{W,1} & m_{w(1)}^2 + \frac{g_2^2 v^2}{4} \end{pmatrix}$$

If BLKTs for B and W are chosen such that

$$m_{B(1)}^2 + \frac{g_Y^2 v^2}{4} > m_{W(1)}^2 + \frac{g_2^2 v^2}{4},$$

the LKP is W^3 -like.



Conclusions

- Respecting all symmetries in UED, for every Standard Model term there exists an a priori free UED parameter corresponding to a boundary localized operator.
- With LHC on the horizon, and to face the challenges of distinguishing UED from other Standard Model extensions (in particular SUSY), a more complete mapping of the UED parameter space would be desirable.
- By including BLKTs for the gauge fields, we showed that the UED parameter space contains regions with a W^3 -like LKP.
- A start has been made: First results of UED models with non-standard dark matter candidates appeared last week. [Matchev *et al.*, arXiv 0805.4210]. Further open questions



Outlook

Theory questions:

- Implications of a Higgs BLKT/Is it possible to get $h^{(1)}$ or $a^{(1)}$ LKP? (to appear)
- Implications for fermion BLKTs?
- One-loop corrections to non-minimal UED?
- How do BLKTs arise from an underlying theory?

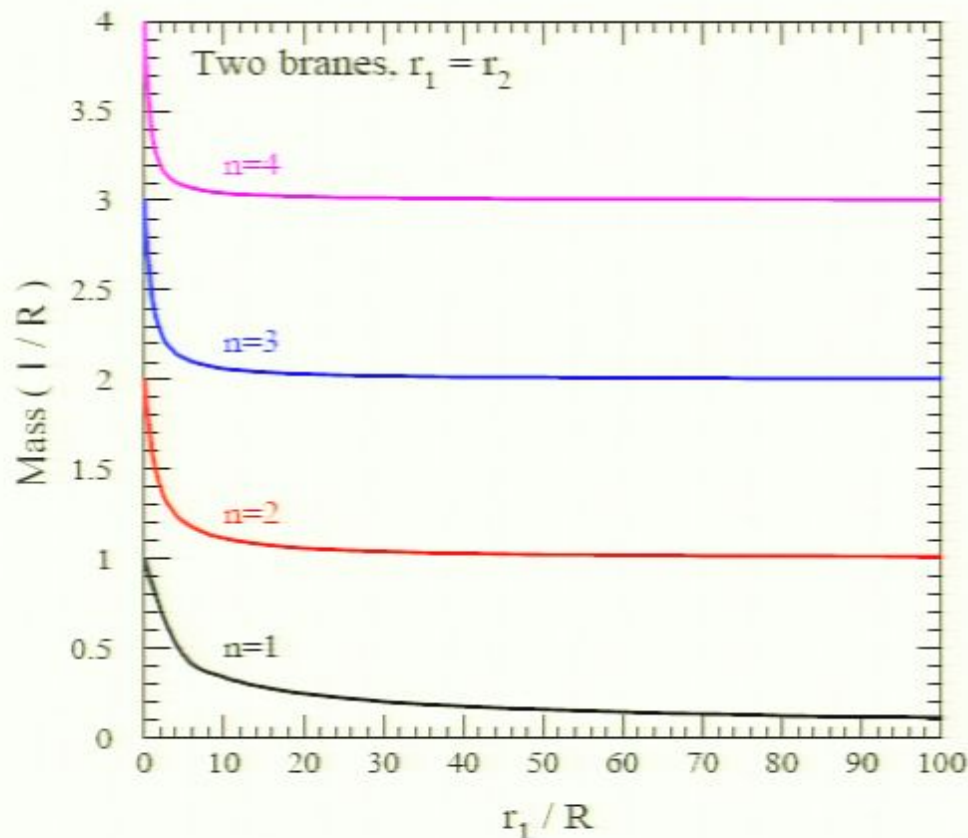
Phenomenology of UED with $W^{3,(1)}$ dark matter:

- Changes of UED collider constraints
 - Bounds from non-detection of KK-modes? eg. a la [Rizzo; Maccesanu *et al.*]
 - Modification of bounds from EWPT ?eg. a la [Appelquist, Yee]
 - Modifications of other collider bounds? see UED review of [Hooper, Profumo]
- Changes to DM bounds:
 - Relic density of the $W^{3,(1)}$ and over closure bound?
[Matchev *et al.*, arXiv 0805.4210]
 - Bounds from direct detection? [Matchev *et al.*, arXiv 0805.4210]
 - Indirect detection: ν , \bar{p} , e^+ , γ , synchrotron radiation, ...?
[Hooper, Silk; Hooper, Kribs; Bergstrom *et al.*; Brinkmann; ...]

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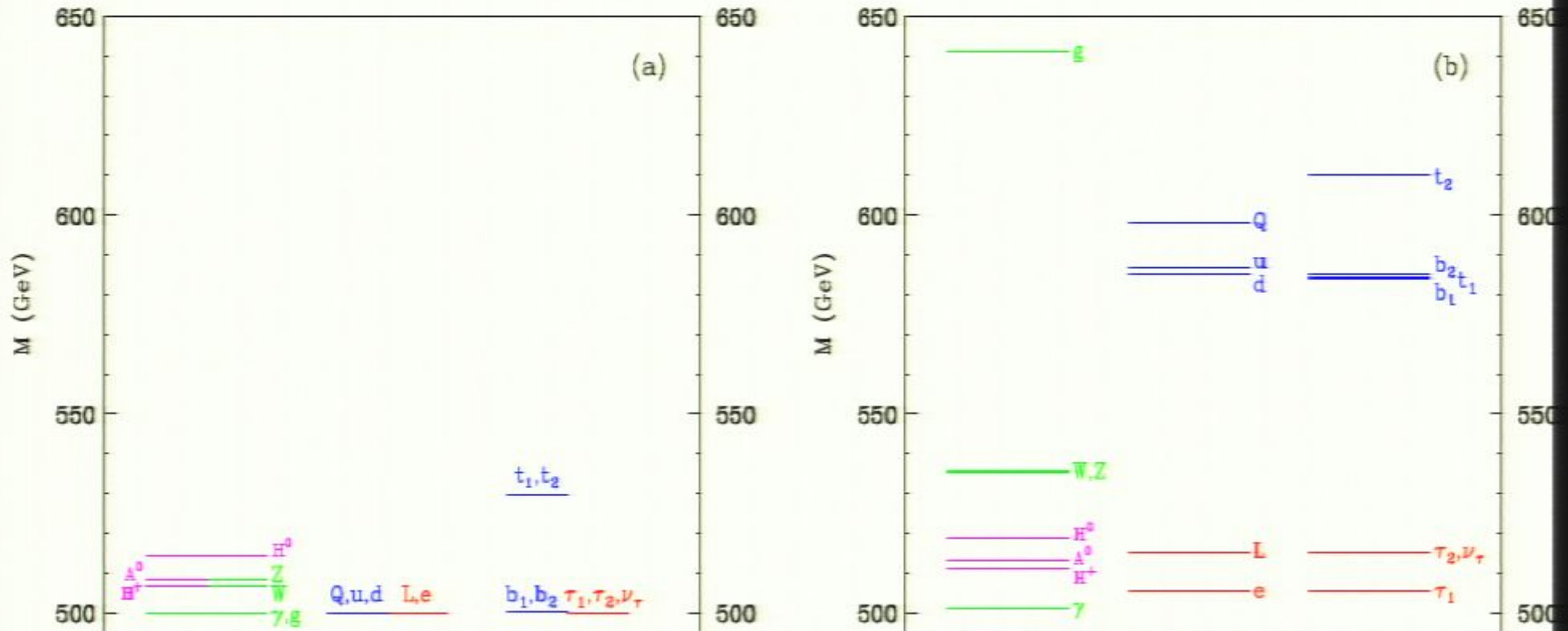




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