Phenomenological Properties of Extra Dimensions

Carlos E.M. Wagner

EFI & KICP, Univ. of Chicago
HEP Division, Argonne National Laboratory

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New Physics at the Weak Scale ?

- Main reason: Understand what is the dynamics behind electroweak symmetry breaking, which is responsible for the generation of mass of all elementary particles known so far.
- Are there elementary Higgs bosons ?
- Why is the weak scale so much smaller than the Planck scale ?
- Neutrino Masses ?
- Dark Matter ?

Extra Dimensions

Extra Dimensions

- Extra dimensional scenarios can address some of these open questions
- I will talk about three possible implementations:
- Large extra dimensions: Only gravity propagate into them. They solve the hierarchy problem by lowering the fundamental Planck scale
- Universal Extra Dimensions: All fields propagate into them. The compactification radius should be at least of the order of the (inverse) TeV scale, in order to avoid phenomenological problems
- Warped extra dimensions: Non-trivial extra dimensional metric. All fundamental parameters are of the order of the Planck scale. Weak scale is obtained by exponentially small warp factor.

Large Extra Dimensions

Lowering the Planck Scale

- Idea: We live in a four dimensional wall, but there are extra dimensions and only gravity can penetrate into them.
- Problem: If gravity can penetrate intro the extra dimensions, Newton law will be modified

$$\vec{F} = \frac{m_1 m_2 \hat{r}}{\left(M_{Pl}^{\rm fund}\right)^{2+d} r^{2+d}}$$

- $M_{Pl}^{\rm fund}$ = Fundamental Planck Scale. Behaviour valid for $r \ll R$. For $r \gg R$, instead

$$\vec{F} = \frac{m_1 m_2 \hat{r}}{\left(M_{Pl}^{\rm fund}\right)^{2+d} r^2 R^d}$$

- Hence,

$$M_{Pl}^2 = \left(M_{Pl}^{\rm fund}\right)^{2+d} R^d$$

Arkani-Hamed, Dimopoulos, Dvali'98

Size of flat Extra Dimensions

- Let's assume that the fundamental Planck scale is of the order of 1 TeV, to solve the hierarchy problem.

$$M_{Pl}^2 = (1\text{TeV})^{2+d} R^d$$

- Then, the value of R is given by

$$R = 10^{32/d} 10^{-17} \text{cm}$$

- For $d = 1$ we get $R = 10^{15}$ cm $\longrightarrow$ Excluded
- For $d = 2$ we get $R \simeq 1$ mm $\longrightarrow$ Would demand somewhat larger fundamental Planck scale
- For $d = 6$ we get $R \simeq 10^{-12}$ cm.
- The scenario is allowed for $d \geq 2$

How can we probe ED from our 4D wall (brane)?

Flat case ($k = 0$) : 4-D effective theory:

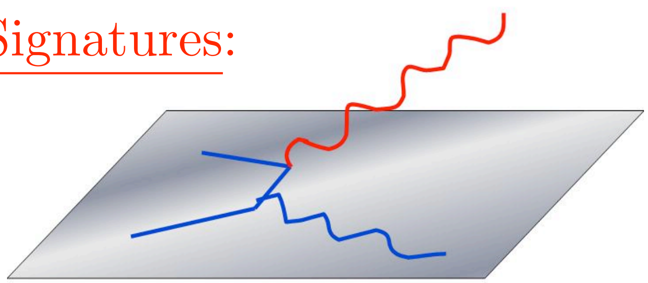
SM particles + gravitons + tower of new particles:

Kaluza Klein (KK) excited states with the same quantum numbers as the graviton and/or the SM particles

Mass of the KK modes $\Longrightarrow$ $E^2 - \vec{p}^2 = p_d^2 = \sum_{i=1,d} \frac{n_i^2}{R^2} = M^2_{G_{\vec{n}}}$

imbalance between measured energies and momentum in 4-D

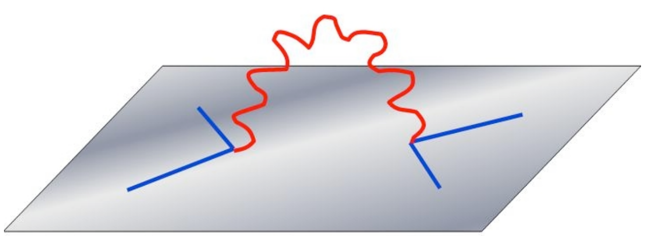
Signatures:



- Coupling of gravitons to matter with $1/M_{Pl}$ strength

  $R^{-1} \simeq 10^{-2}$ GeV $(d = 6)$;

  $1/R \simeq 10^{-4}$ eV $(d = 2)$;



(a) Emission of KK graviton states: $G_n \Leftrightarrow \not{E}_T$
(gravitons appear as continuous mass distribu

(b) Graviton exchange $2 \rightarrow 2$ scattering
deviations from SM cross sections

Han, Lykken, Zhang ; Giudice, Rattazzi, Wells'99

Fundamental Planck Scale

- The number of KK modes at energies below a given one can be easily computed.
- In $d = 1$, for instance, the KK masses are n/R and hence,

$$N_{KK}(M_{KK} < E) = E \times R$$

- It is simple to convince yourself that, for d extra dimensions, one gets

$$N_{KK}(M_{KK} < E) = (E \times R)^d$$

- Hence, the interactions becomes strong at $E \simeq M_{Pl}^{\rm fund}$

$$\frac{E^2}{M_{Pl}^2} R^d E^d = 1 \rightarrow M_{Pl}^2 = \left(M_{Pl}^{\rm fund}\right)^{2+d} R^d$$

- That is the same result we obtain before, by other methods.

Effective Cross Sections

- Let us consider the emission of gravitons in the collision of electrons and positrons (protons and antiprotons).
- Final state will be γ + Missing energy (jets + Missing Energy)
- Each graviton extremely weakly coupled but cross section will be given by the sum of the individual KK graviton production cross section, scaling with N_{KK}.
- Again, the effective gravitational constant appears and we get

$$\sigma \simeq \frac{1}{M_{Pl}^2}(E^d R^d) \tag{60}$$

$$\sigma \simeq \frac{1}{s}\left(\frac{\sqrt{s}}{M_{Pl}^{\text{fund}}}\right)^{2+d} \tag{61}$$

Flat Extra Dimensions

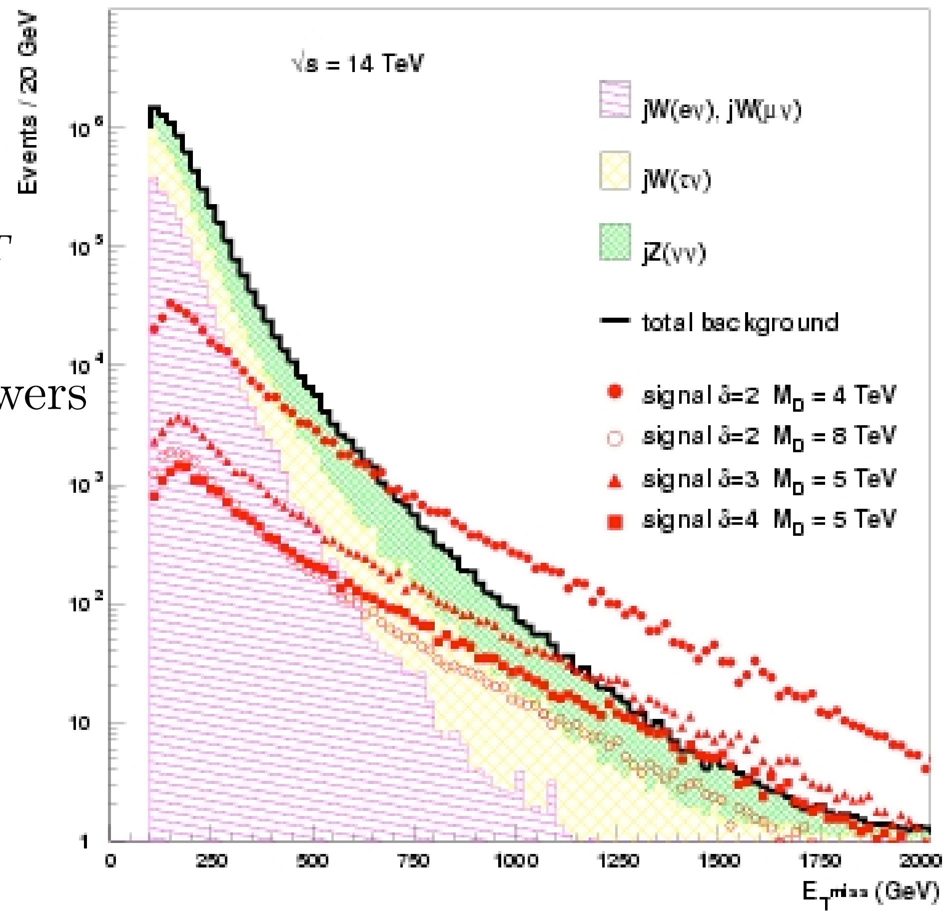
– Emission of KK graviton states

$$p\bar{p} \to g\, G_N \;(G_N \to \not{E}_T) \longrightarrow \text{jet}+\not{E}_T$$

Cross section summed over full KK towers

$$\Longrightarrow \qquad \sigma/\sigma_{SM} \propto (\sqrt{s}/M_{\rm Pl}^{\rm fund})^{2+d}$$

Emitted graviton appears as a continuous mass distribution.

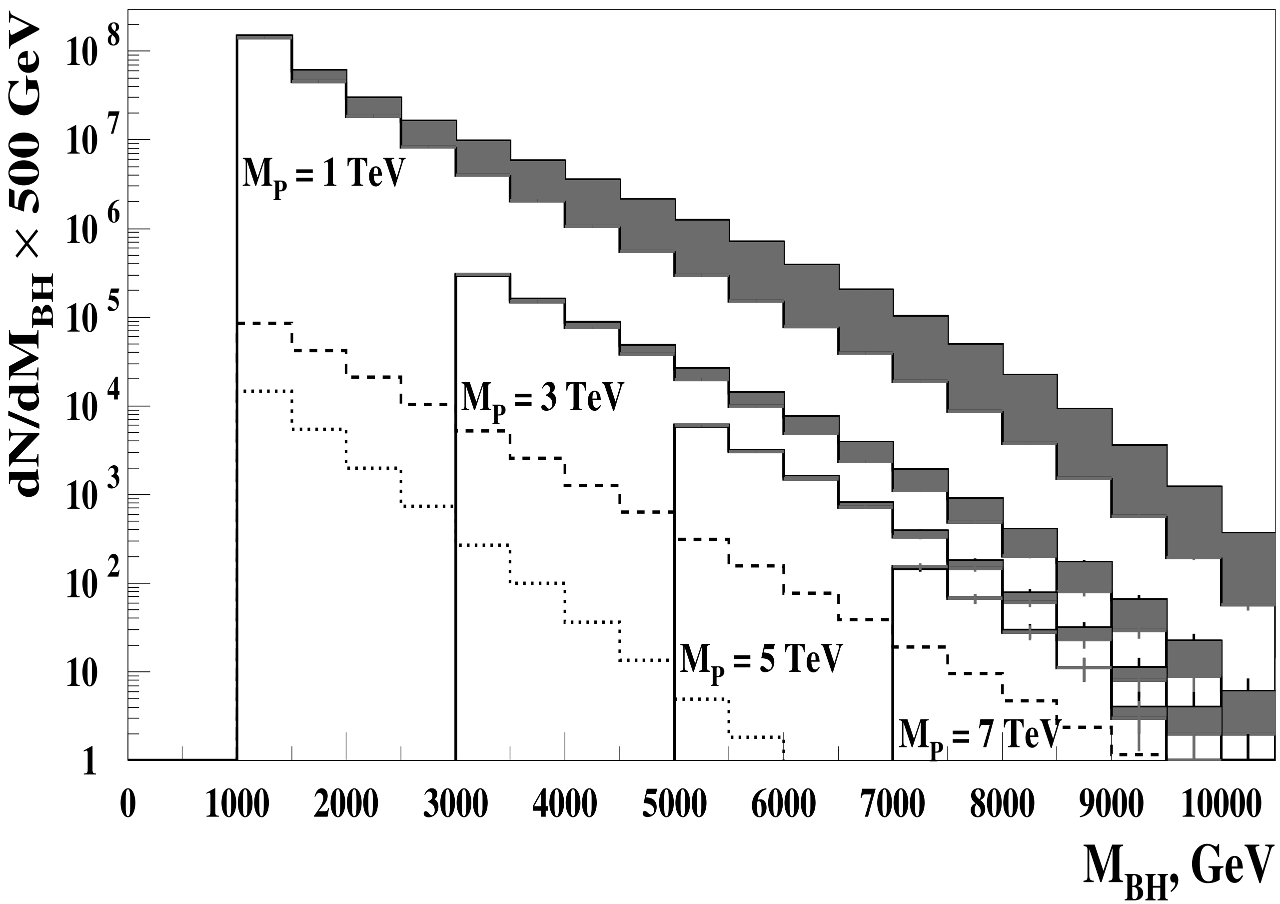


Discovery reach for fundamental Planck scales on the order of 5–10 TeV (depending on d = 4,3,2)

Black Hole Production ?

- Two partons with center of mass energy $\sqrt{s} = M_{BH}$, with $M_{BH} > M_{Pl}^{fund}$ collide with a impact parameter that may be smaller than the Schwarzschild radius.
  $R_S \simeq \frac{1}{M_{Pl}^{fund}} \left(\frac{M_{BH}}{M_{Pl}^{fund}} \right)^{\frac{1}{d+1}}$
- Under these conditions, a blackhole may form
- If $M_{Pl}^{fund} \simeq 1$ TeV $\rightarrow$ more than 10^7 BH per year at the LHC (assuming that a black hole will be formed whenever two partons have energies above M_{Pl}^{fund}).
- Decay dictaded by blackhole radiation, with a temperature of order $1/R_S$. Signal is a spray of SM particles in equal abundances: hard leptons and photons.
- At LHC, limited space for trans-Planckian region and quantum gravity.

Black Hole production at the LHC



Dimopoulos and Lansberg; Thomas and Giddings '01

Sensitivity up to $M_{Pl}^{\text{fund}} \simeq 5 - 10$ TeV for 100 fb^{-1}.

Universal Extra Dimensions

Universal Extra Dimensions

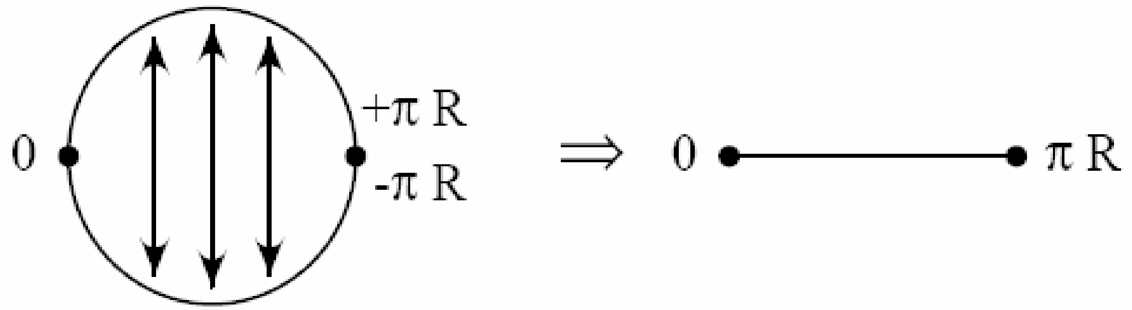
Appelquist, Cheng, Dobrescu'01

Most natural extension of four dimensional description:

- All particles live in all dimensions, including quarks, leptons, Higgs bosons, gauge bosons and gravitons.
- Universality implies a translational invariance along the extra dimension, and thus conservation of the component of momentum in the that direction.
- This implies that a KK state with $n \neq 0$, carrying non-zero momentum in the extra dimension, cannot decay into standard, zero modes.
- The lightest KK particle is stable, being a good dark matter candidate.

Orbifold

- Massless 5d spinors have 4 components, leading to mirror fermions at low energies.
- If extra dimension is compactified in a circle, no standard chiral theory may be obtained.
- Chiral theories may be obtained by invoking orbifold boundary conditions, projecting out unwanted degrees of freedom.
- Fold the extra dimension, identifying y with $-y$



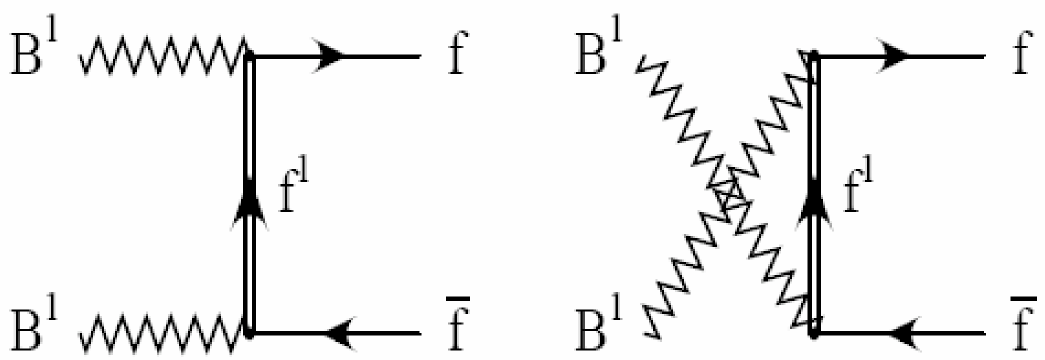
- Boundary Conditions:
  $\Psi(-y) = \gamma_5 \Psi(y)$
  $V_\mu(-y) = V_\mu(y), V_5(-y) = -V_5(y)$

KK Parity

- Conservation of KK number is broken to conservation of KK parity: $(-1)^n$.
- KK-parity requires odd KK modes to couple in pairs:
- The lightest first-level KK mode is stable.
- First level KK modes must be pair-produced.
- The Lightest Kaluza-Klein Particle plays a crucial role in phenomenology, similar to the LSP of SUSY:
- All relic KK particles decay to LKPs.
- Any first level KK particle produced in a collider decays to zero modes and an LKP.
- KK parity is also present with boundary fields, provided the same fields live on both boundaries.

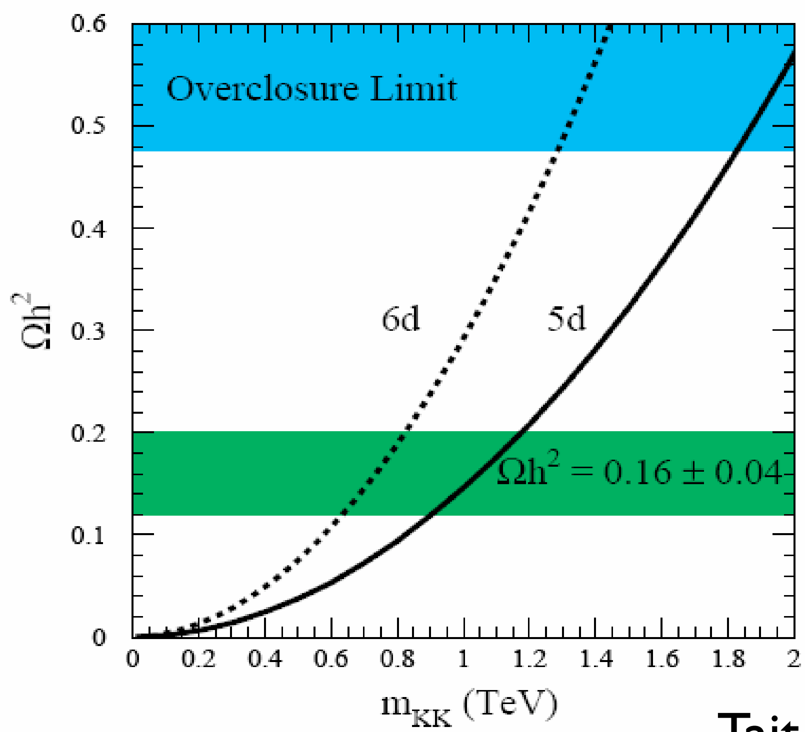
Dark Matter

- Relic Density depends strongly on annihilation cross section.
- In the case of universal extra dimensions, dominant annihilation diagram is given by interchange of first tower of KK particles.



- Whenever the KK mode of the right-handed leptons is close enough in mass to the LKP, coannihilation should be also taken into account

Relic Density: Results



Tait, Servant'02

Universal extra dimensions of the order of 500 GeV–1 TeV preferred for the LKP to be a good dark matter candidate

Coannihilation and Graviton effects may modify this picture

Matchev and Kong'06; Feng, Rajamaran, Takayama'03; Shah & Wagner'06

Warped Extra Dimensions

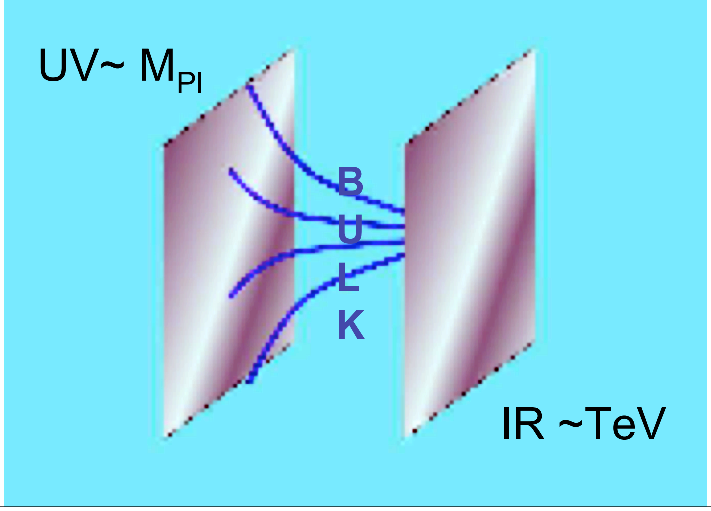
Warped Extra Dimensions

Randall, Sundrum'99

Solution to the Hierarchy Problem

- Space is compact, of size 2 L, with orbifold conditions x, y → x,-y
- Brane at y = 0 (Ultraviolet or Planck Brane)
  Brane at y = L (Infrared or TeV Brane)
- Non-factorizable metric: $ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$ solution to 5d Einstein equations
- Newton's law modified: 5d Planck mass relates to M_{Pl}: $M_{Pl}^2 = \frac{(M_{Pl}^{fund.})^3}{2k}(1-e^{-2kL})$

➔ Natural energy scale at the UV brane: Fundamental Planck scale $\Rightarrow M_{Pl}^{fund.}$
At the TeV brane, all masses are affected by an exponential warp factor: $e^{-kL} << 1$



Assuming fundamental scales all of same order:

$$M_{Pl} \approx M_{Pl}^{fund.} \approx \mathrm{k}$$

Solution to Hierarchy problem :

Higgs field lives on the TeV brane

$$\mathrm{v} \sim \tilde{\mathrm{k}} \equiv \mathrm{k}\, \mathrm{e}^{-\mathrm{kL}} \approx M_{Pl}\, \mathrm{e}^{-\mathrm{kL}} \sim \mathrm{TeV}$$

with kL ~30

The Randall-Sundrum Model of Warped Space:

==> elegant solution to the hierarchy problem

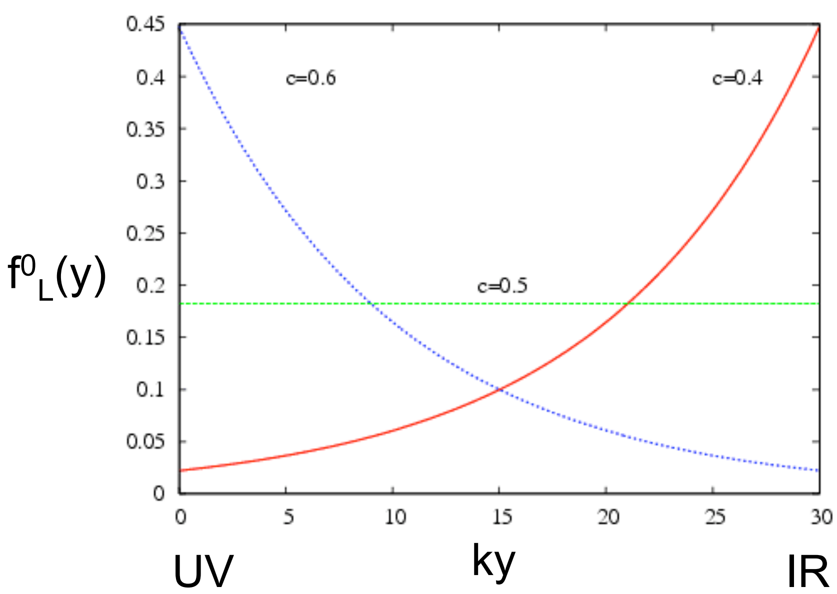
RS With Bulk Fermions and Gauge bosons:

- Higgs field must be located in the IR brane, but SM fields may live in the bulk.
- Fermions in the bulk: ==> suggestive theory of flavor

-- SM fermion masses related to the size of their zero mode wave function at the IR

Localization determined from bulk mass term: $L_m = c_f k \bar{\Psi}\Psi$

$\Downarrow$



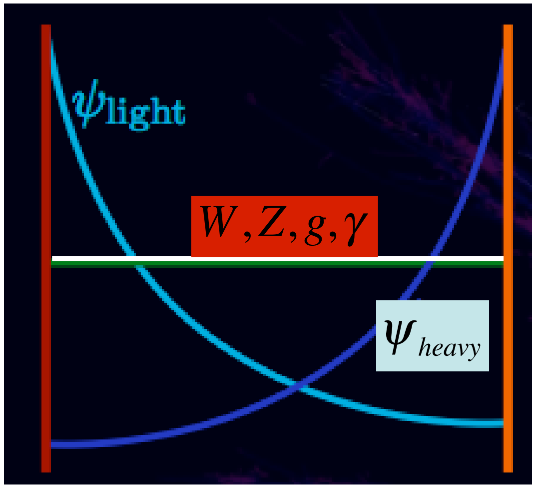
KK mode expansion:

$$\Psi_{L,R}(x,y) = e^{3ky/2} \sum_n \psi^n_{L,R}(x) f^n_{L.R}(y)$$

Boundary conditions for f(y) at the branes (UV, IR) = (+,+) ==> zero mode

If b.c. (-,+), (+,-) or (-,-) ==> no zero mode

-- The KK spectrum is defined in units of $\tilde{k} = ke^{-kL}$ of factors that depend on c_f and is localized towards the IR brane



UV brane

IR brane
Higgs + KK modes

Hierarchical fermion masses from localization

FCNC and higher dimensional operators
suppressed for the light fermion families
(see Neubert's talk)

Many KK excitations of bulk SM fields
==> rich phenomenology

All KK mode masses are quantized in units of $\pi\ k\ \exp(-kL)$,

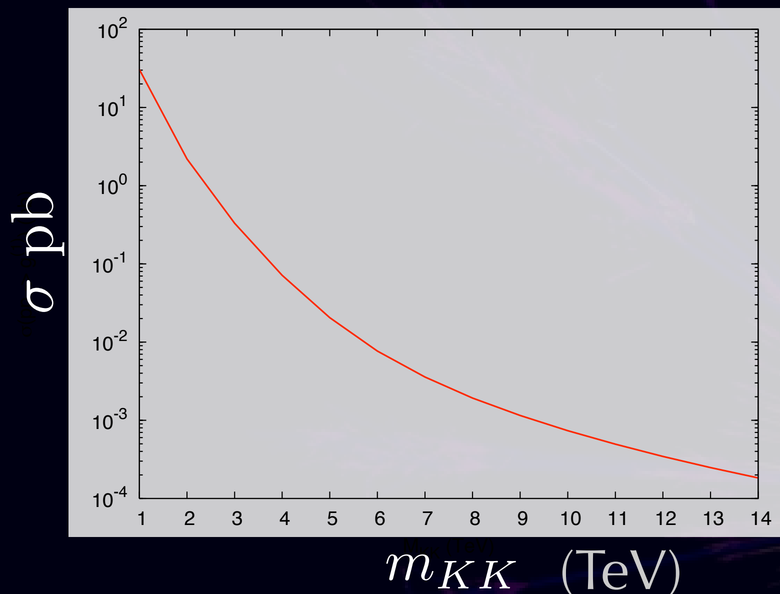
$$m_n = (x_1 + \ (n-1)\pi) k \exp(-kL)$$

where $x_1 \simeq 2.5$ for gauge bosons and 3.8 for gravitons. For even fermions, it depends on the localization, but it is similar to gauge bosons.
In general, it depends on localization and on brane terms.

- Since all KK modes tend to be localized towards the IR brane, and the heavy SM fermions should also be localized towards this brane, KK glons couple strongly to top quarks.

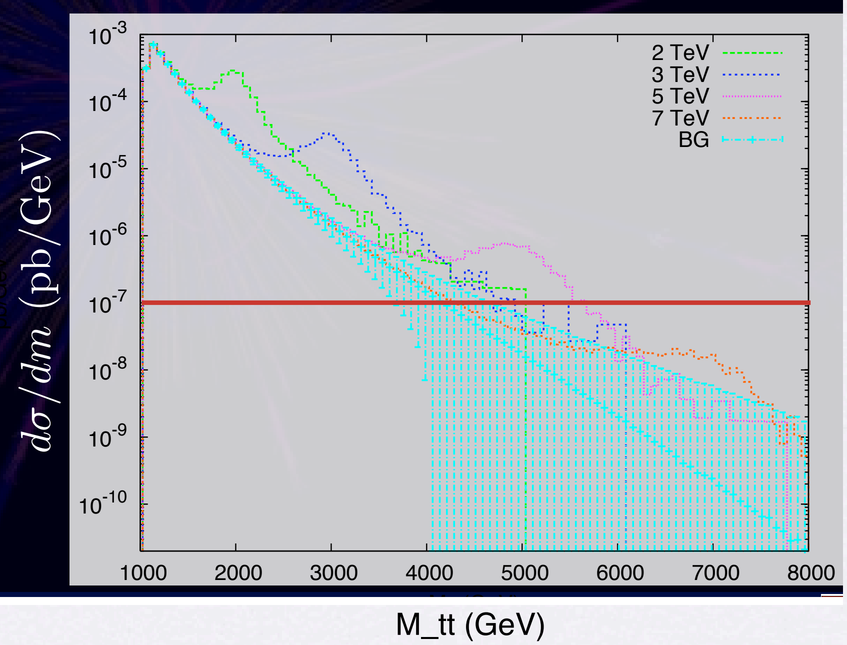
B. Lillie, L. Randall, L. Wang hep-ph/0701166

Top pairs from KK gluons



Cross-section at LHC reasonable, limited by small coupling to light fermions, and lack of glue-glue coupling

- Nice signal above SM top production
  - PDF and stat. errors shown, assuming $100 fb^{-1}$
- Width/Mass ~17%



More realistic reach estimates

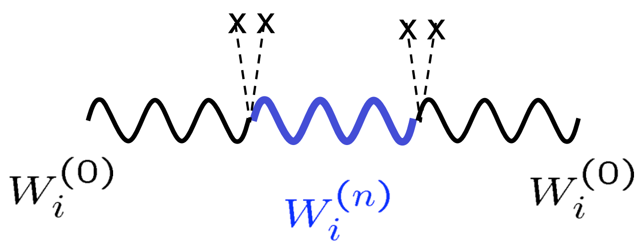
- When heavy gluon KK modes decay into top-quarks, tops are heavily boosted
- Reach depends on proper top quark identification and control of backgrounds.
- KK gluons decaying dominantly into right-handed top quarks may be discovered up to masses of 4 TeV. (Agashe et al'07, U. Baur, L. Ohr'08)
- Measurement of the inclusive top cross section may provide information on the particular RS model, and, in particular of the size of the IR brane kinetic terms. (Lillie, Tait, Shu'07).

Models with Custodial Symmetries

Effects of KK modes of the gauge bosons on Z pole observables

SM in the bulk

- Large mixing with Z and W zero modes through Higgs



Large corrections to the M_z/M_w ratio (T parameter)

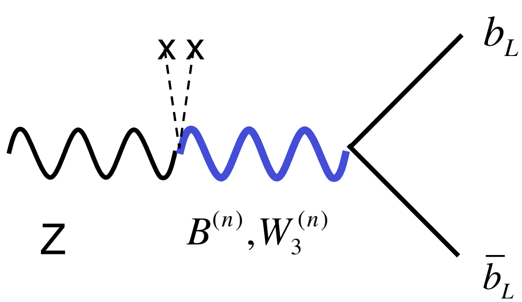
$$\Downarrow$$

$$M_{KK} \geq 5-10 \ \text{TeV}$$

- Top and bottom zero modes localized closer to the IR brane

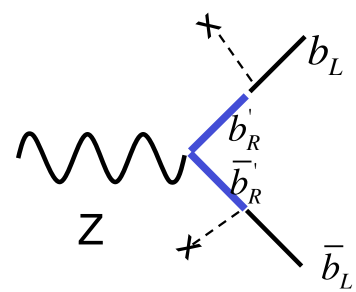
Large gauge and Yukawa couplings to Gauge Bosons and fermion KK modes

Large corrections to the Zbb coupling



$$\Downarrow$$

$$M_{KK} \gtrsim 7-8 \, \text{TeV}$$



Csaki et al'02; Hewett et al'02, Pomarol et al'02

How to obtain a phenomenologically interesting theory?

1) Extend SM bulk gauge symmetry to a custodial symmetry

$SU(2)_L$ x $SU(2)_R$

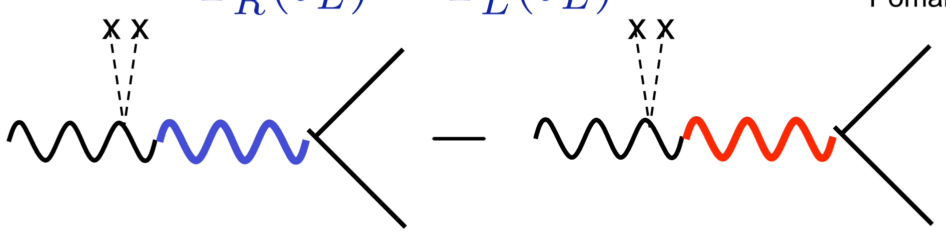
Agashe, Delgado, May, Sundrum '03

$T \propto$  ~ 0

2) The custodial symmetry together with a discrete L $\leftrightarrow$ R symmetry
and a specific bidoublet structure of the fermions under $SU(2)_L$ x $SU(2)_R$

$$T^3_R(b_L) = T^3_L(b_L)$$

Agashe, Contino, DaRold, Pomarol '06

$\delta g_{b_L} \propto$  ~ 0

==> reduce tree level contributions to the T parameter and the Zbb coupling
that allow for lightest KK gauge bosons with $M_{KK} \sim 3$ TeV

How light can the KK modes be?

Corrections to the M_z/M_w ratio and the Zbb coupling:

At tree level:

- T and Zbb protected by custodial symmetry only broken by b.c. at UV brane:
  - Governed by KK gauge boson mixing with gauge bosons
  - mixing with fermion KK modes affecting Zbb naturally reduced by bidoublet structure
- Contributions to S are less model dependent and always positive

$$S \simeq 0.15 \left(\frac{1.5\text{TeV}}{\tilde{k}}\right)^2$$

At loop level:

- One loop corrections are important

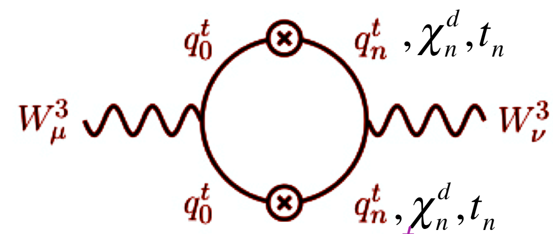
Quantum corrections are calculable (finite)

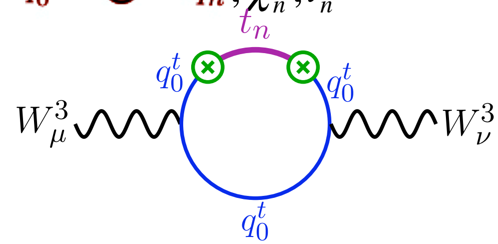
-- Bidoublets contribute negatively to T

– Singlets contribute positively to T (need singlets)

– Vector like contributions to S are small and positive

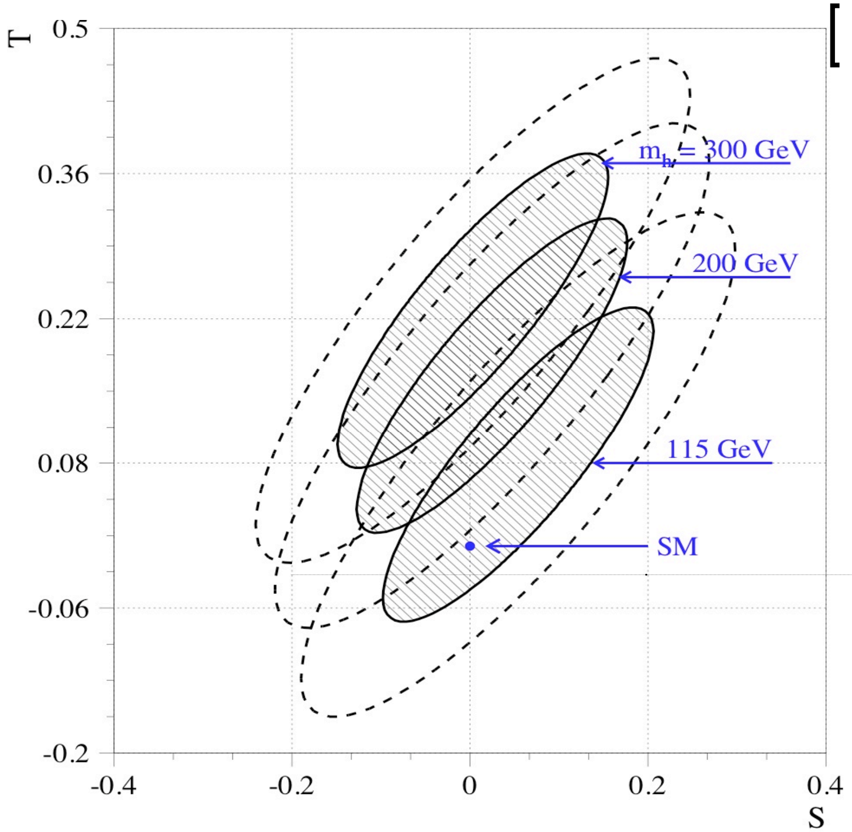
– Large positive T leads to large positive $\delta g_{bL} \equiv \delta_{Zbb}$





M. Carena, E. Ponton, J. Santiago, C.W., 06-07

T-S fit to Electroweak Precision observables



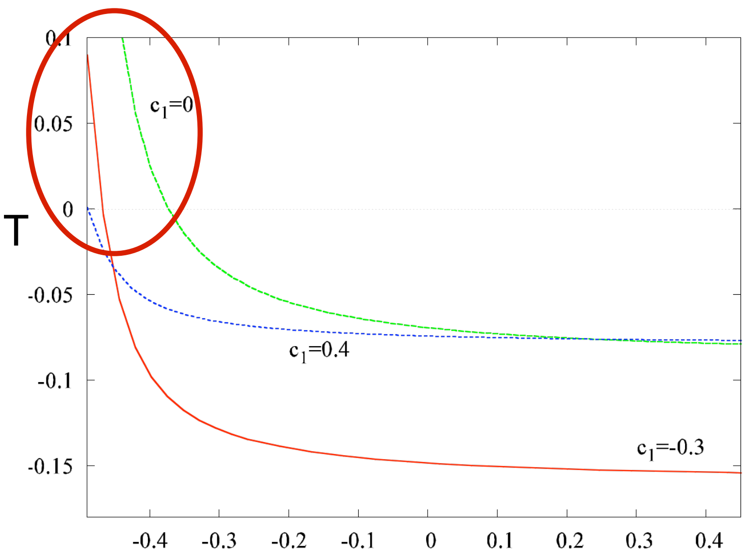
Solid lines: 68% C.L
Dashed lines: 95% C.L. contours

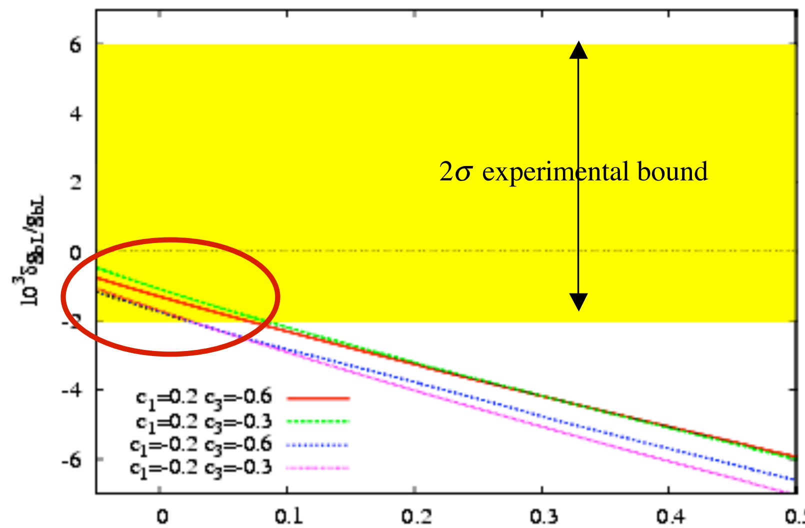
For mh ~ 120 GeV: Positive S ~ 0.1 <==> positive T

Correlation between corrections to T and Zbb

T has negative values in most of the parameter space. Positive values require: RH top "almost flat" and LH top/bottom near the IR

M.~Carena, E.~Ponton, J.~Santiago and C.~E.~M.~Wagner,
Nucl.Phys.B759:202-227,2006 and hep-ph/0701055



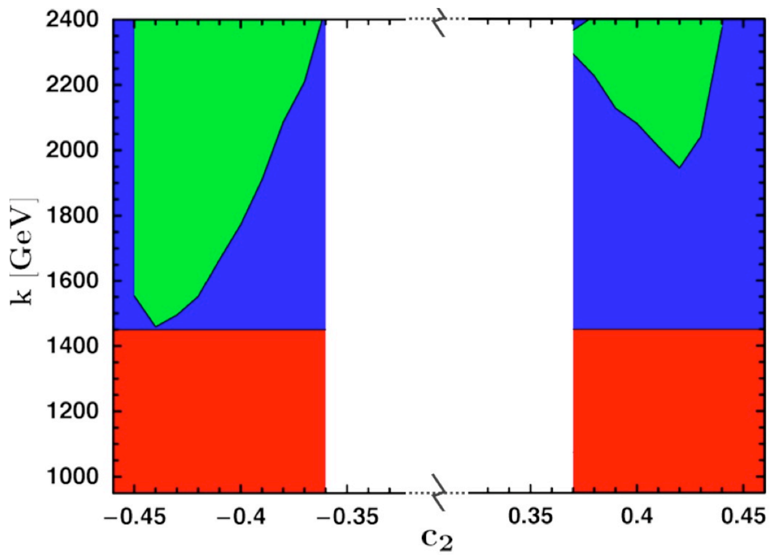


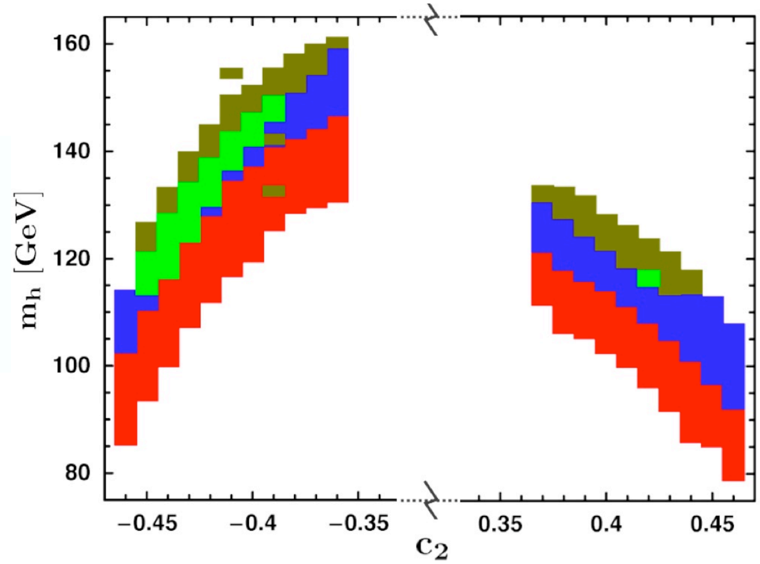
UV (singlet localization) IR

c_2 : Right-handed top bulk mass

Positive T leads to deviations from allowed experimental values of Zbb

Preferred Region of parameters

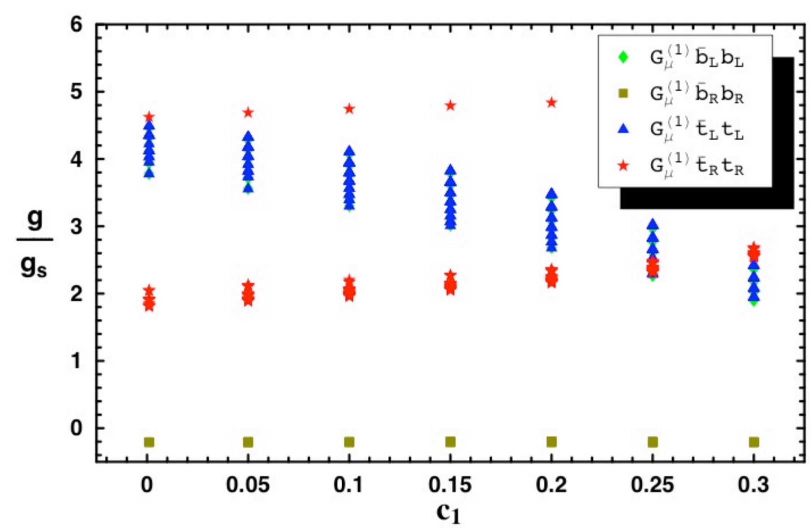




Information on bulk mass parameter values of the right- and left-handed top quark fields determined

$c_2 \simeq \pm 0.4$
$|c_1| < 0.3$

Best fit obtained for negative values of c_2.



Gauge Higgs Unification

Manton'79, Hosotani'83

- Idea: Can we get the Higgs from the scalar, five dimensional component, of the gauge fields
- Problem: The quantum numbers of the gauge fields we discussed so far do not allow such a possibility
- Can we extend the gauge symmetry to realize such a possibility
- New symmetry must be broken on both branes (Dirichlet)
- Scalars acquire Neumann boundary conditions in such a case and present zero modes (Higgs bosons)

Higgs From Gauge Fields in Warped Extra Dimensions

Contino, Da Rold, Pomarol'06

Bulk gauge symm: $SU(3)_c \times SO(5) \times U(1)_X \longrightarrow SO(5) \supset SU(2)_L \times SU(2)_R$

UV: $SU(2)_L \times U(1)_Y$ IR: $SO(4) \times U(1)_X \simeq SU(2)_L \times SU(2)_R \times U(1)_X$

Extra gauge bosons have the quantum numbers of the Higgs

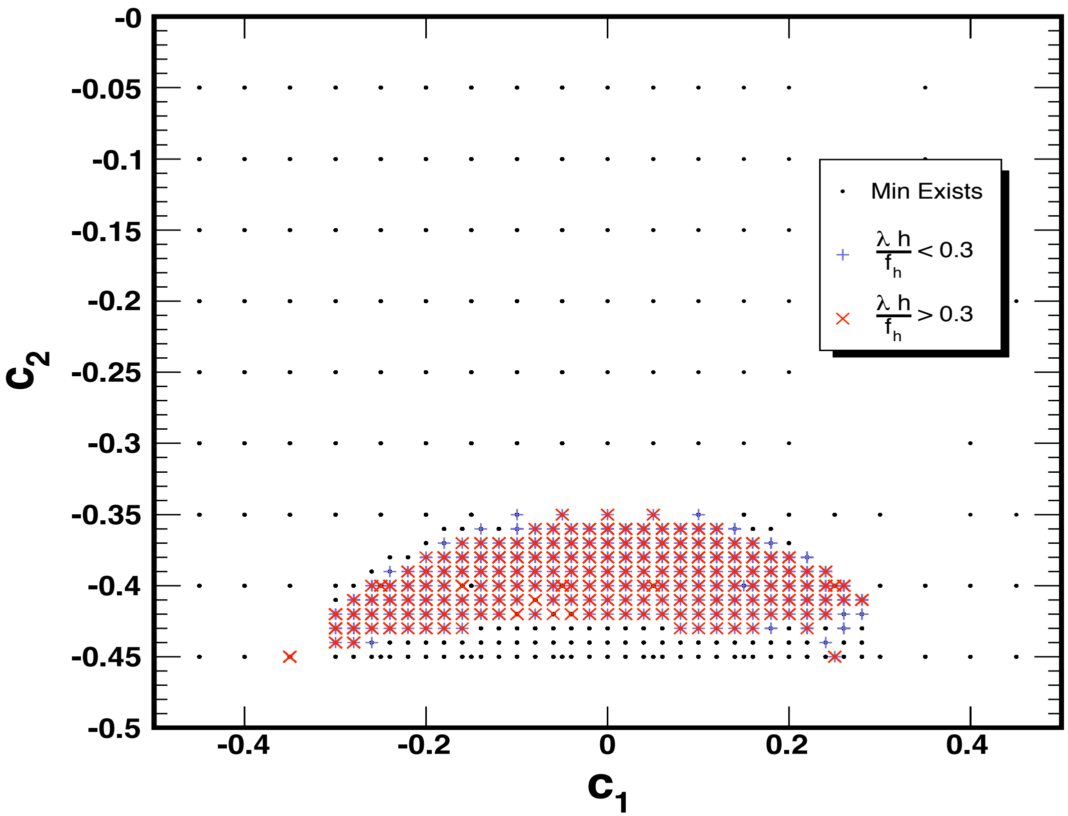
$SO(5)/SO(4) \longrightarrow A_\mu^{\hat{a}}(-,-) \quad A_5^{\hat{a}}(+,+)$ ⟸ **Identify with H**

No tree-level Higgs potential $\longrightarrow$ induced at one-loop (calculable)

Coleman-Weinberg potential has been computed for the model considered here by A. Medina, N. Shah, C.W. , Phys. Rev. D 76: 095010 (2007)

- EWSB minima in large regions of parameter space
- Can be consistent with Z, W, top masses and Higgs LEP bound

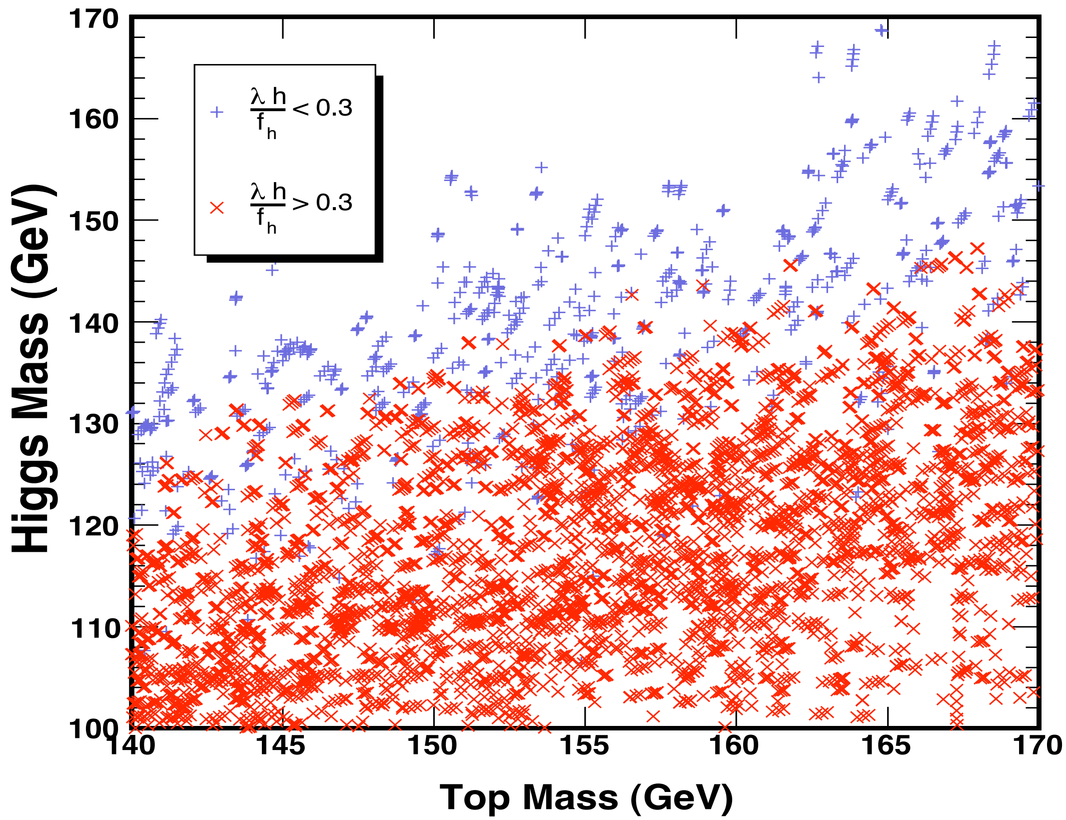
Values of c_2 and c_1 leading to consistent values of the gauge boson and third generation masses



A. Medina, N. Shah, C.W. , Phys. Rev. D 76: 095010 (2007)

Consitent with values necessary for a good agreement with precision electroweak measurements

Blue points: Couplings of Higgs SM-like (linear regime)
Good agreement with precision measurements

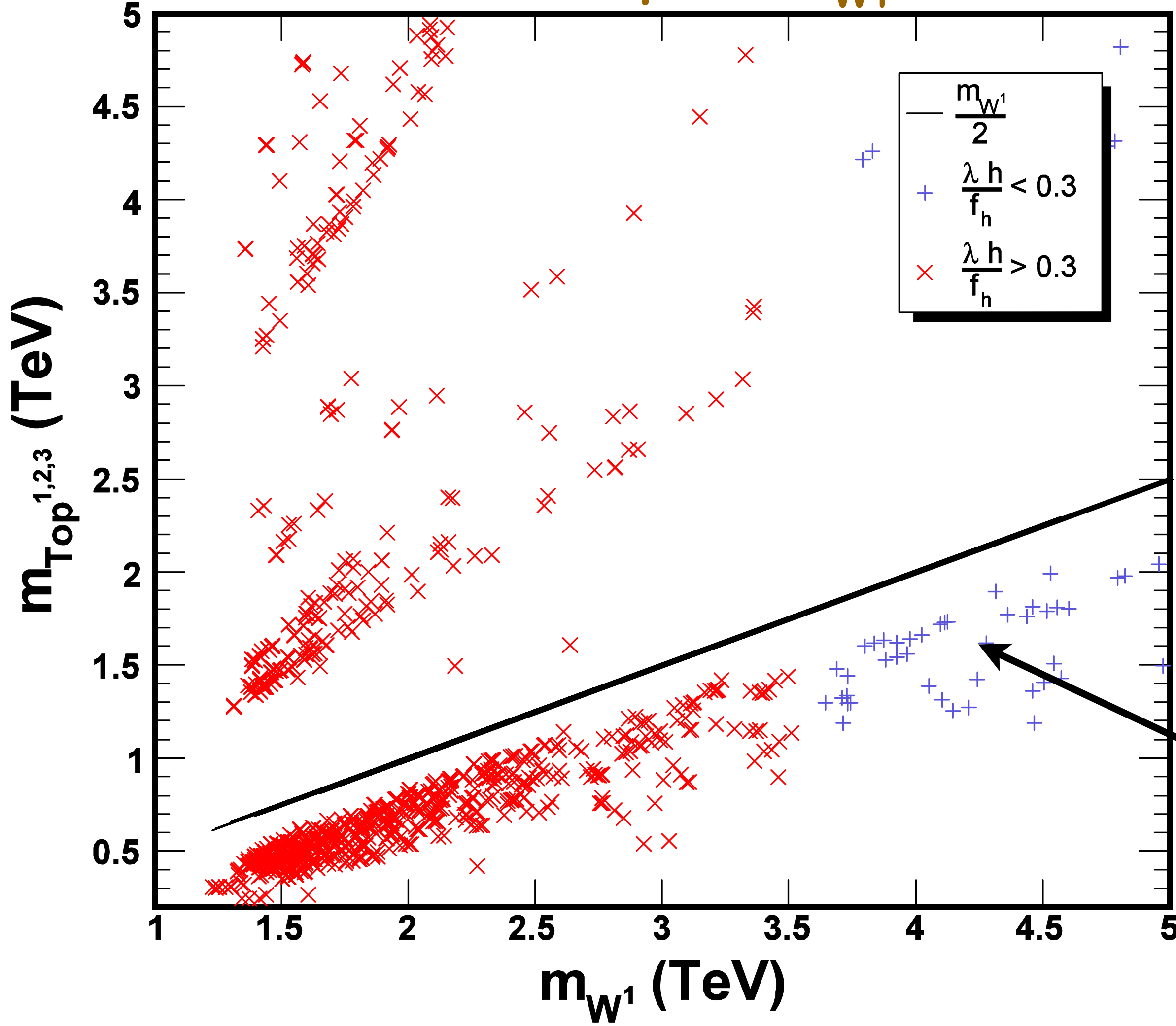


Medina, Shah, Wagner '07

In the linear regime, Higgs mass is predicted to be between the current experimental limit and 160 GeV

First few KK mode of the Top vs. m_{W1}

Medina, Shah, Wagner '07



Half of the KK gluon mass

In these models KK gluons are strongly coupled to KK tops and KK tops provide their dominant decay branching ratio

Gauge-Higgs Unification: Collider Phenomenology

- t^1 production cross section through QCD alone and through QCD+G^1 for M_{G1}=4 TeV.

M. Carena, A. Medina, B. Panes, N. Shah, C.W. '08

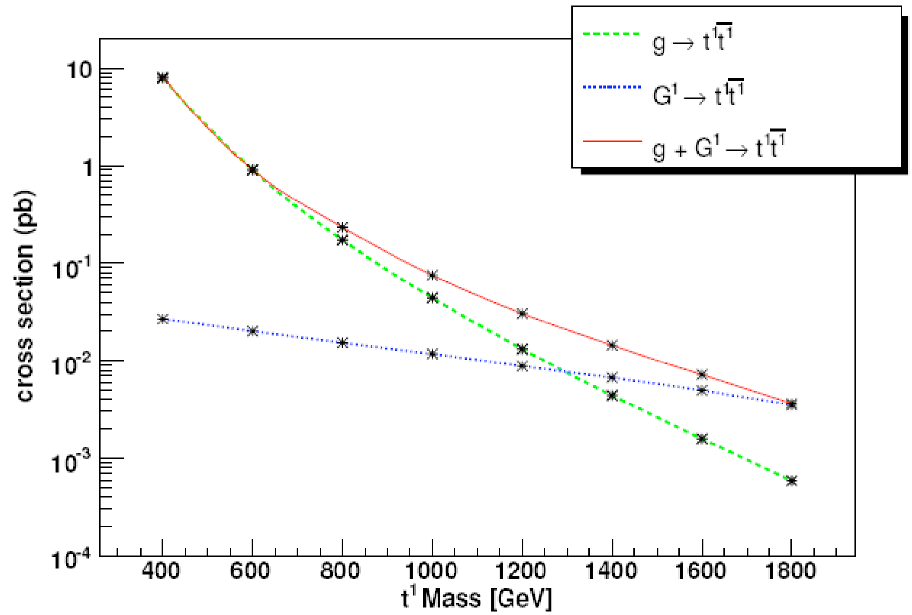


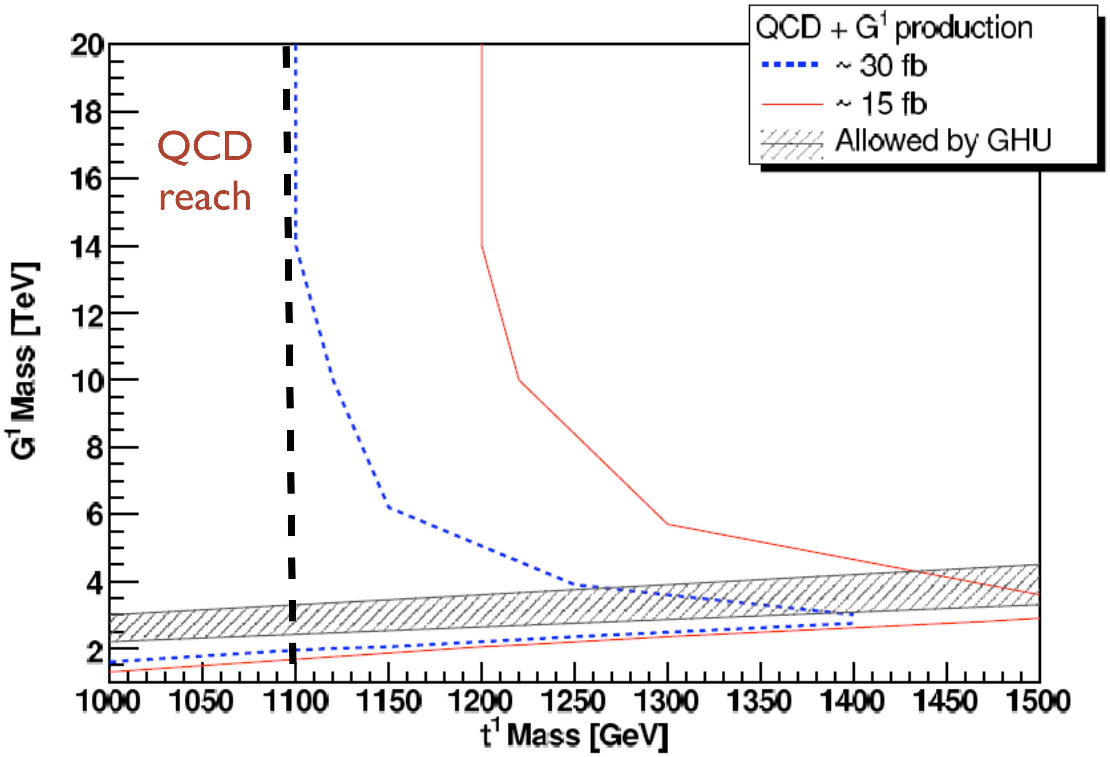
Figure 5: Cross section for $M_{G^1} = 4.0$ TeV with couplings $g_{G^1\bar{t}^1{}_L t^1_L}/g_s(\tilde{k}) = -5.18$ and $g_{G^1\bar{t}^1{}_R t^1_R}/g_s(\tilde{k}) = -2.77$.

Notice that for $M_{t1} \approx$ 1.5 TeV, G^1-induced production contributes in a significant amount to the t production cross section.

LHC Discovery Reach

- First KK mode of the top decays mostly into W and bottom-quarks

- Two points were explored, on the blue and red lines. In the first the KK top may be discovered with 100 inverse fb, in the second with 300 inverse fb.



M. Carena, A. Medina, B. Panes, N. Shah, C.W. '08

Figure 20: Curves of constant cross section for QCD in addition of G^1 decay, in (m_{G^1}, m_{t^1}) plane.

Dark Matter

- Dark Matter may be included by extending the model to include a new Z_2 discrete symmetry which affects certain states
- New symmetry relates the localization of new odd states with the new ones
- KK gauge bosons, odd under this symmetry may provide a dark matter candidate

Panico, Ponton, Santiago, Serone; Agashe, Falkowski,Low, Servant'08

- Lepton sector of the model: Neutrino masses may be generated by a five dimensional generation of the See-Saw mechanism. Odd Neutrinos, mostly right-handed, can also provide alternative dark matter candidates.

Carena, Medina, Shah, Wagner'09

- Such model predicts a direct dark matter detection rate only an order of magnitude below the present limits and therefore soon testable at XENON and CDMS.

Conclusions

- Extra Dimensions present an exciting alternative scenario for physics beyond the standard model
- If large extra dimensions exist, they may provide a test of quantum gravity effects at the weak scale
- Universal extra dimensions lead to a scenario with similar signatures and properties of supersymmetry, including Dark Matter and Missing Energy signatures.
- Warped extra dimensions with SM fields propagating in the extra dimension, lead to a solution of the hierarchy problem, to interesting approach to the flavor problem and to possible exciting signatures at the LHC. Gauge Higgs unification may be realized and dark matter may be incorporated.
- Only a fraction of the volume of work in this field has been presented here. I invite you to explore the fascinating world of extra dimensions.

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Black Hole at RHIC

By ABBY GOODNOUGH and MARIA NEWMAN 7:01 PM ET

Scientists at the RHIC atom smasher, located at Brookhaven National Lab on Long Island, created a black hole in a gold-gold particle collision. The black hole is not sucking the Earth in, yet.

- Video: The Times's Adam Liptak
- Text: The Schiavo Case (*Findlaw.com*)

In Lebanon, Factions Deadlocked in Talks for New Government

By DEXTER FILKINS 6:22 PM ET

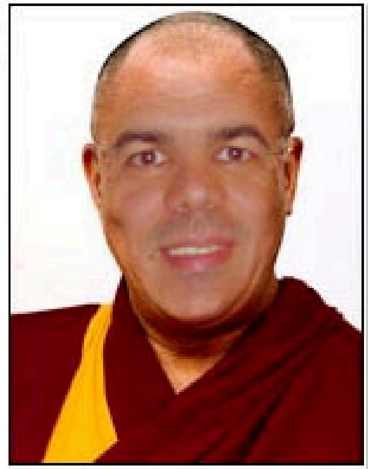
Allies of the pro-Syrian government and the opposition said the two sides disagreed on a number of important issues, which raises the possibility that elections may be postponed.

- Explosion Rocks Beirut Suburb

Wal-Mart Settles Illegal Immigrant Case

By TERENCE NEILAN 1:12 PM ET

Wal-Mart Stores has agreed to pay $11 million to settle federal allegations it used illegal immigrants to clean its stores.



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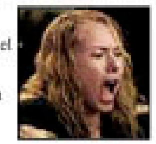

The Ring Two
The inevitable sequel to "The Ring" is "a dud," says Manohla Dargis.
- Melinda and Melinda | Schizo
- Video: Movie Minutes

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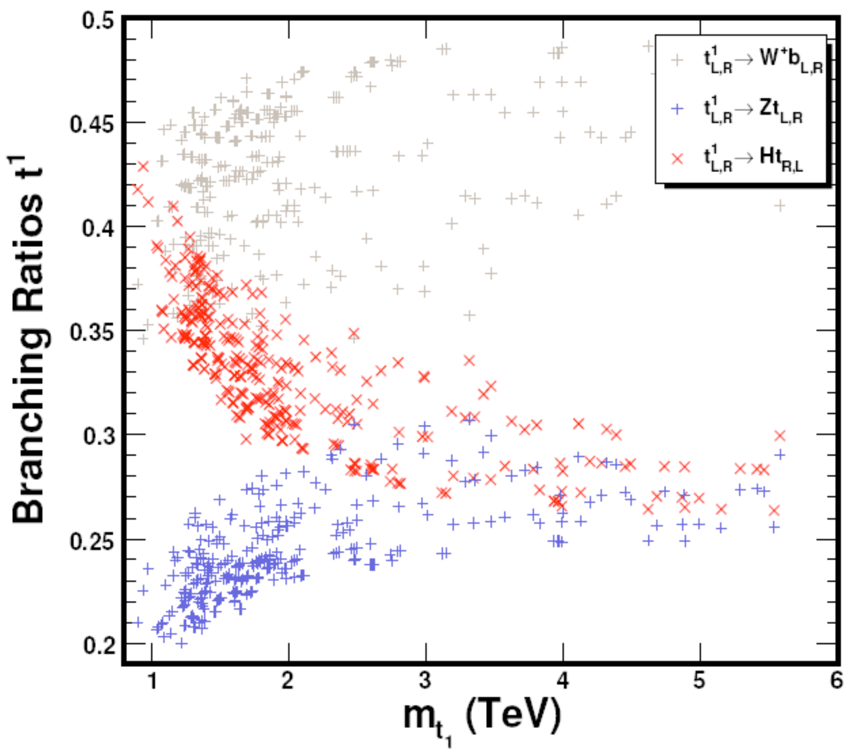
Gauge-Higgs Unification: Collider Phenomenology

- t^1 decay branching ratios,



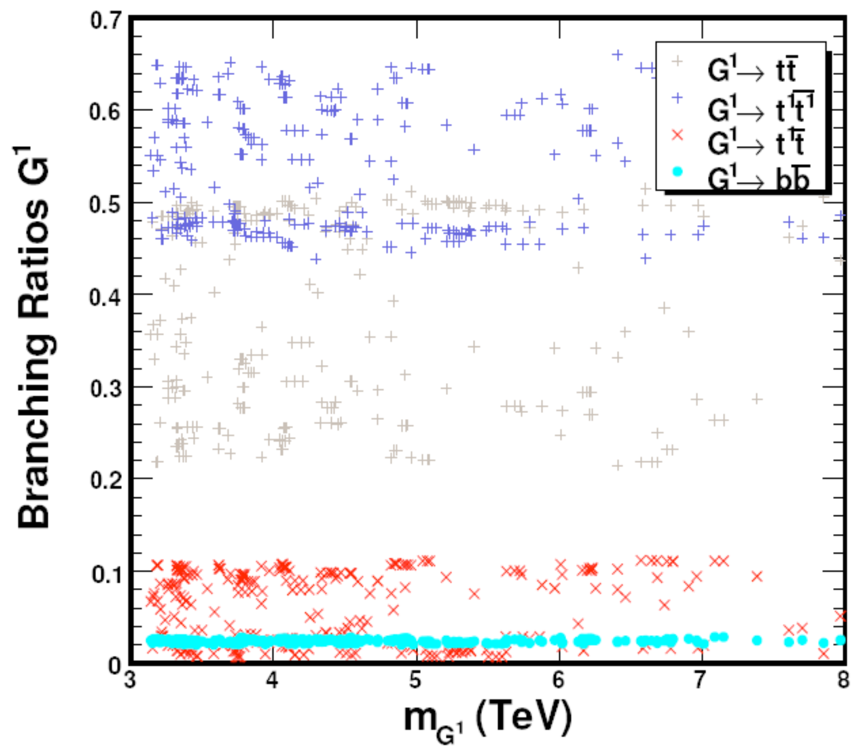


Figure 4: Branching ratios for the decay of t^1 vs m_{t^1} (GeV). Notice that the 2:1:1 relations holds for large m_{t^1}.

Figure 5: Branching ratios for the decay of G^1 vs m_{G^1} (GeV). Notice that G^1 decays mostly to t^1 pairs.

The model

The gauge sector:

Bulk gauge symmetry : $SU(2)_L \times SU(2)_R \times U(1)_X \times P_{LR}$

Broken by Boundary conditions to $SU(2)_L \times U(1)_Y$ in the UV

$W^a_{L\mu} \sim (+,+)$ $\quad B_\mu \sim (+,+)$

$W^b_{R\mu} \sim (-,+)$ $\quad Z'_\mu \sim (-,+)$

(+,+) zero modes
==> Unbroken gauge symmetries

(-,+); (+,-); (-,-) no zero modes
==> broken gauge symmetries

$a = 1,2,3, \quad b = 1,2$

B_μ and Z'_μ are orthogonal l.c. of $W^3_{R\mu}$ and X_μ

Hypercharge : $\frac{Y}{2} = T^3_R + Q_X$ $\qquad$ Electric charge: $Q = T^3_L + T^3_R + Q_X$

P_{LR} symmetry ==> $g_L = g_R$

Fermion Quantum Numbers

$$\boxed{T^3_R(b_L) = T^3_L(b_L)} \quad \Leftrightarrow$$

The simplest option is bidoublets under $SU(2)_L \times SU(2)_R$

$$SU(2)_L \updownarrow \overset{SU(2)_R \,\leftrightarrow}{\begin{pmatrix} \chi^u_L(-+) & t_L(+,+) \\ \chi^d_L(-+) & b_L(+,+) \end{pmatrix}_X} \sim (2,2)_{2/3} \sim \overset{U(1)_Q}{\begin{pmatrix} 5/3 & 2/3 \\ 2/3 & -1/3 \end{pmatrix}}$$

$$t_R(+,+) \sim (1,1)_{2/3} \quad \text{with} \quad Q = 2/3$$

The Higgs is also a bidoublet with $Q_X = 0$

Effective Potential

- $f_h \simeq k \ \exp(-kL) \rightarrow$ As $\lambda h/f_h$ goes down, the KK scale goes up
- Simultaneously, the linear coupling of the Higgs becomes more SM-like

$$m_W^2 \approx \frac{g^2 f_h^2}{2} \sin^2\left(\frac{\lambda_G h}{f_h}\right) + \mathcal{O}(m_W^4/\tilde{k}^2).$$

- Correct W, Z and top quark masses marked by blue and red in the following
- We will denote $\lambda h/f_h$ less than 0.3 as linear regime (blue) and larger than 0.3 as non-linear regime

Warped Case

- Graviton KK modes have 1/TeV coupling strength to SM fields and masses starting with a few hundred GeV.
- KK graviton states produced as resonances.
- One can rewrite the warp factor and the massive graviton couplings in terms of mass parameters as:

$$\exp(-kL) = \frac{m_n}{kx_n}$$
$$\Lambda_\pi \simeq \frac{\bar{M}_{Pl} m_1}{kx_1} \tag{62}$$

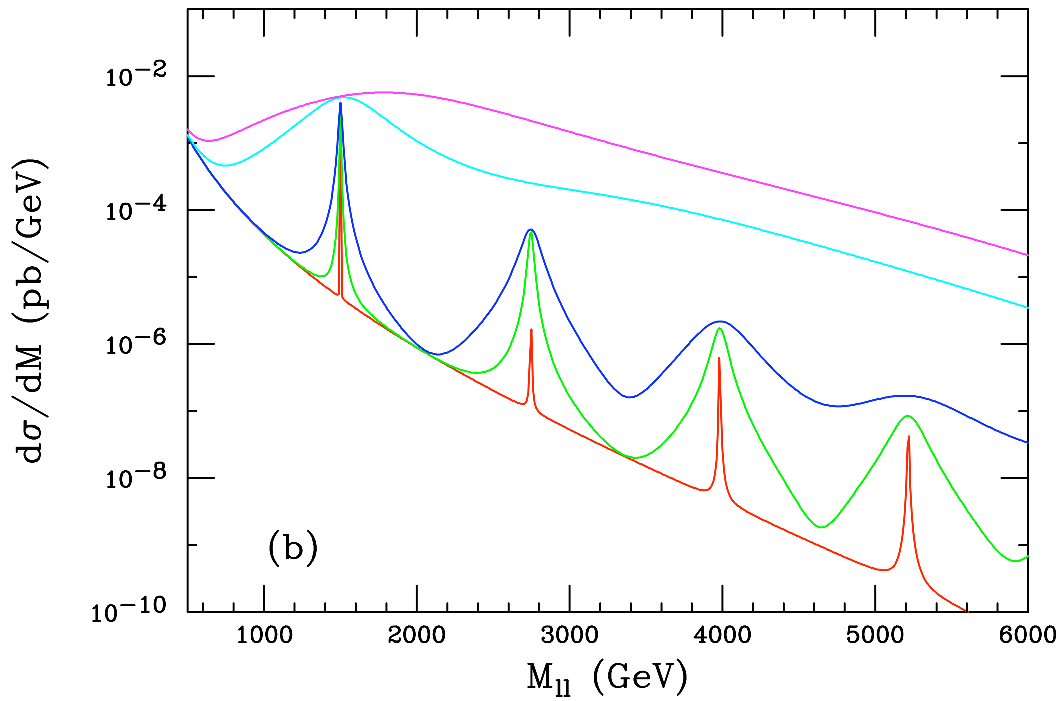
with $x_1 \simeq 3.8$, $x_n \simeq x_1 + (n-1)\pi$.

- Calling $\eta = k/\bar{M}_{Pl}$, one gets that the graviton width is

$$\Gamma(G^n) \simeq m_1 \eta^2 \frac{x_n^3}{x_1} \tag{63}$$

• Warped Extra Dimensions

Narrow graviton resonances: $pp \to G_N \to e^+e^-$



From top to bottom: $k/M_{Pl} = 1, 0.5, 0.1, 0.05, 0.01$

Searches for new quarks from warped space at the Tevatron

$p\bar{p} \to q'\bar{q}' \to 2W + 2j$ in lepton plus jets events, (CDF note 8495)

==> examine W+j mass spectrum distributions and compare with a fourth gen. q'

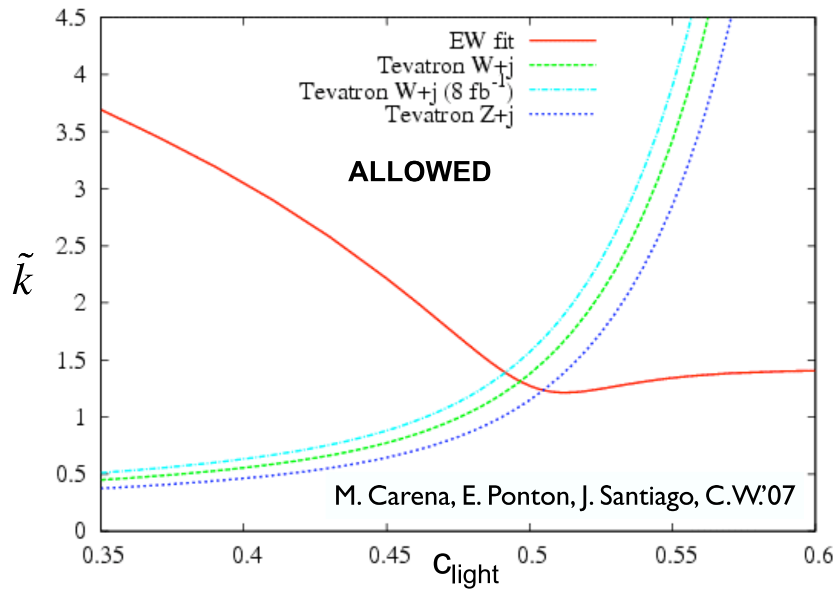
$p\bar{p} \to q'\bar{q}' \to 2Z + 2j$ in events with 2 leptons + >3 energetic jets (CDF note 8590)

==> look at the tails of the jet energy distribution for an excess over SM

Tevatron lower bounds on KK quark of 1. and 2. Generations (~1fb^{-1})

$$m_q \geq \begin{cases} 325\ (410)\ \text{GeV}, & \text{==> W+j} \\ 300\ \text{GeV}, & \text{==> Z+j} \end{cases}$$

Combined lower limit on $\tilde{k}$ from EW fit and ==> direct Tevatron searches



If KK modes of light quarks exist, Tevatron searches disfavor strong localization of such KK quarks towards the UV brane

Details of fermion sector

The fermion sector is more model dependent. Built out of

$$5 \sim (2,2) \oplus 1 \quad \text{and} \quad 10 \sim (2,2) \oplus (3,1) \oplus (1,3)$$

In gauge-Higgs unification scenarios Yukawa's arise from gauge coupl.

Flavour structure from mixing via IR localized mass terms

$$\xi^i_{1L} \sim Q^i_{1L} = \begin{pmatrix} \chi^{u_i}_{1L}(-,+) & q^{u_i}_L(+,+) \\ \chi^{d_i}_{1L}(-,+) & q^{d_i}_L(+,+) \end{pmatrix} \oplus u'^i_L(-,+)\,,$$

$$\xi^i_{2R} \sim Q^i_{2R} = \begin{pmatrix} \chi^{u_i}_{2R}(-,+) & q'^{u_i}_R(-,+) \\ \chi^{d_i}_{2R}(-,+) & q'^{d_i}_R(-,+) \end{pmatrix} \oplus u^i_R(+,+)\,,$$

$$\xi^i_{3R} \sim T^i_{1R} = \begin{pmatrix} \psi'^i_R(-,+) \\ U'^i_R(-,+) \\ D'^i_R(-,+) \end{pmatrix} \oplus T^i_{2R} = \begin{pmatrix} \psi''^i_R(-,+) \\ U''^i_R(-,+) \\ D^i_R(+,+) \end{pmatrix} \oplus Q^i_{3R} = \begin{pmatrix} \chi^{u_i}_{3R}(-,+) & q''^{u_i}_R(-,+) \\ \chi^{d_i}_{3R}(-,+) & q''^{d_i}_R(-,+) \end{pmatrix}$$

$$\mathcal{L}_m = \delta(y-L)\Big[\bar{u}'_L \tilde{M}_u u_R + \bar{Q}_{1L} M_u Q_{2R} + \bar{Q}_{1L} M_d Q_{3R} + \text{h.c.}\Big]$$

Other parameters relevant the for EW fit: $\longrightarrow$

c_L, c_R localization of $1^{st}, 2^{nd}$ gen.

c_1, c_2, c_3 localization of 3^{rd} gen.

KK Fermion Signatures from Warped Space at the LHC

- 3 generation KK fermions with masses ~1TeV can be discovered at the LHC with high luminosities ~100 fb^{-1}

Aguilar-Saavedra '05;
Skiba, Tucker-Smith'07;
Holdom'07

$pp \to t\bar{t}\,' \to W^+ b W^- \bar{b}$ with one W decaying leptonically

Reach may be extended in GHU models M. Carena, A. Medina, B. Panes, N. Shah, C.W. '08

For smaller masses ~500 GeV < 10 fb^{-1} suffice + observability in Higgs decays viable

- Exotic quantum numbers of the KK fermions ==> spectacular new signatures

Quarks with charge 5/3 and -1/3 have similar decay channels:

$$pp \to q'\bar{q}' \to W^+W^-t\bar{t} \to W^+W^+W^-W^-b\bar{b}$$

Non-negligible BR of KK fermion of Q= 2/3 decaying into KK fermion of Q= -1/3

==> $pp \to u_{2/3}\bar{u}_{2/3} \to W^+ d_{-1/3} W^- \bar{d}_{1/3} \to 4W + t\bar{t} \to 6W + b\bar{b}$

Channels with 4 or even 6 W's may allow early discovery of q'

Dennis, Ünel, Servant, Tseng '07

Reach of quarks of charge 5/3 decaying into two equal sign leptons of about 1 TeV for 30 fb^{-1}

Contino, Servant '08

A Word on FCNC

- KK Gauge Boson (gluon) couplings depend on the localization of fermions.
- Therefore, in general, once the fermion mass matrices are diagonalized, FCNC coupling of gluons arise
- This induce strong constraints on the KK spectrum (larger than 10 TeV) which, are, however, model dependent.
- Particularly acute if one would like to get masses and mixing angle just from wave function profiles (C. Csaki et al'07)
- One can demand a framework of "minimal flavor violation" in which the bulk c-masses are diagonalized together with the fermion Yukawa couplings (G. Perez, L. Randall'07). Other flavor symmetries invoked (Cacciapaglia et al '07, Santiago '08)
- With a little bit of fine tuning, however, flavor constraints may be avoided (Neubert et al'08)