

New Solutions to the Hierarchy Problem

What to Expect at the TeV Scale

Gustavo Burdman

Instituto de Física - USP

Latin American Workshop on High Energy Phenomenology

Porto Alegre, December 1-3 2005

Outline

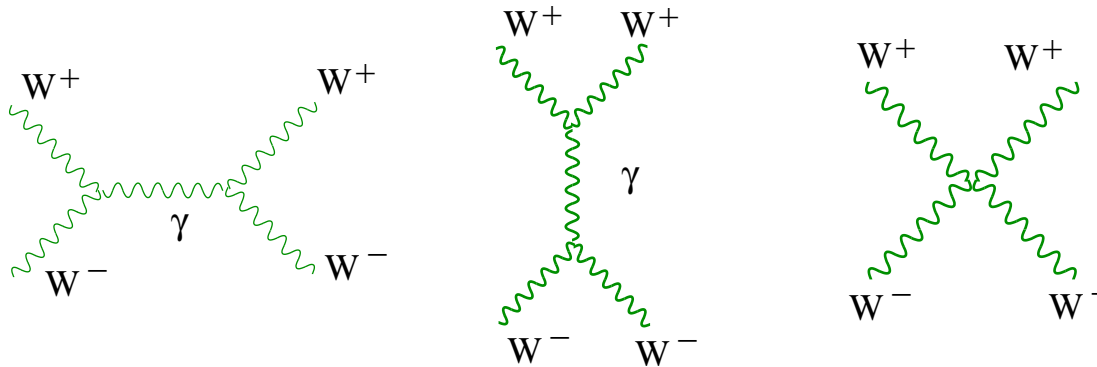
- * The Standard Model: a successful description.
- * The hierarchy problem. Why do we believe that the TeV scale will reveal new dynamics ?
- * Theories with Extra Spatial Dimensions.
- * Conclusions/Outlook

The Higgs Mechanism

- Need to spontaneously break $SU(2)_L \times U(1)_Y$ to $U(1)_{EM}$. Only **photon** remains massless.
- Higgs: Goldstone bosons are “eaten” by (W^\pm, Z^0) .
 $\Rightarrow (m_W, m_Z) \Rightarrow$ **Weak Interactions** become short range.
- In the Standard Model, one scalar particle (**The Higgs Boson**) remains in the spectrum.
- In the case of Superconductivity, **Cooper pairs** form a condensate that breaks $U(1)_{EM}$.
- Assume the universe is a “superconductor”. Condensate breaks the electroweak symmetry.

The Higgs Mechanism

- At what energy scale should the condensate occur ?
- E.g. in W^+W^- scattering



Amplitudes grow like $\sim s/(M_W^2)$
They would violate unitarity at $\Lambda \sim 1 \text{ TeV}$

The Standard Model

- Introduce $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$, the Higgs doublet:

$$\mathcal{L} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) \quad SU(2) \times U(1) \text{ invariant}$$

- Interactions with gauge bosons in $D_\mu = \partial_\mu - g\vec{W}_\mu - g'B_\mu$

- $V(\Phi) \Rightarrow$ vacuum not invariant: $\langle \Phi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$
 \Rightarrow masses for 3 out of the 4 gauge bosons.

The Standard Model

- $(\vec{W}, B) \longrightarrow (W^\pm, Z^0)$, plus a massless γ

$$M_W, M_Z \neq 0, \quad m_\gamma = 0$$

- To avoid unitarity violation in cross sections

$$\Rightarrow m_h < 1 \text{ TeV}$$

The Success of the Standard Model

- Precision Tests (1990's):

- Millions of Z^0 's produced at LEP I via

$$e^+e^- \longrightarrow Z^0 \longrightarrow f\bar{f}$$

Non-abelian couplings tested at LEP II in

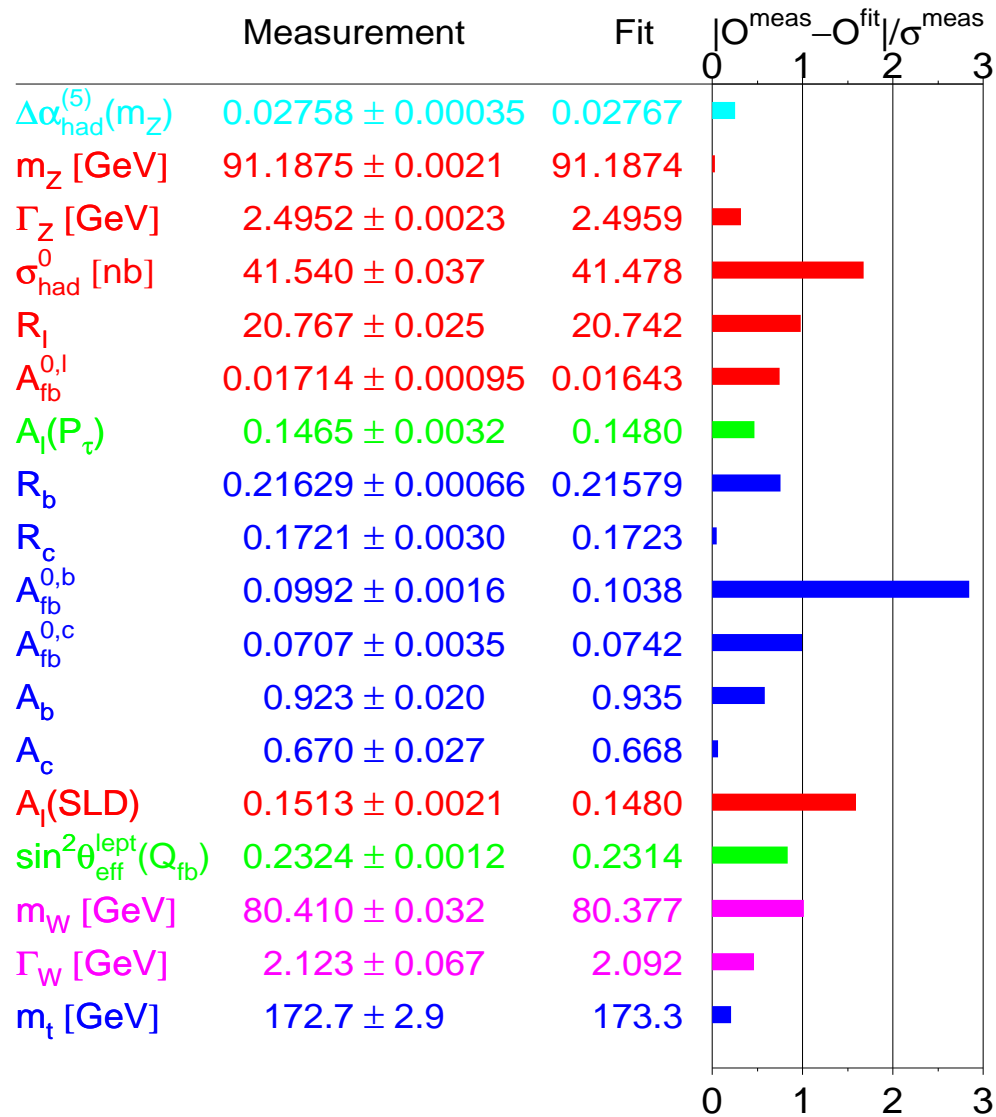
$$e^+e^- \longrightarrow W^+W^-$$

- Also precision νN and Atomic Parity Violation experiments.
- Input most precise measurements

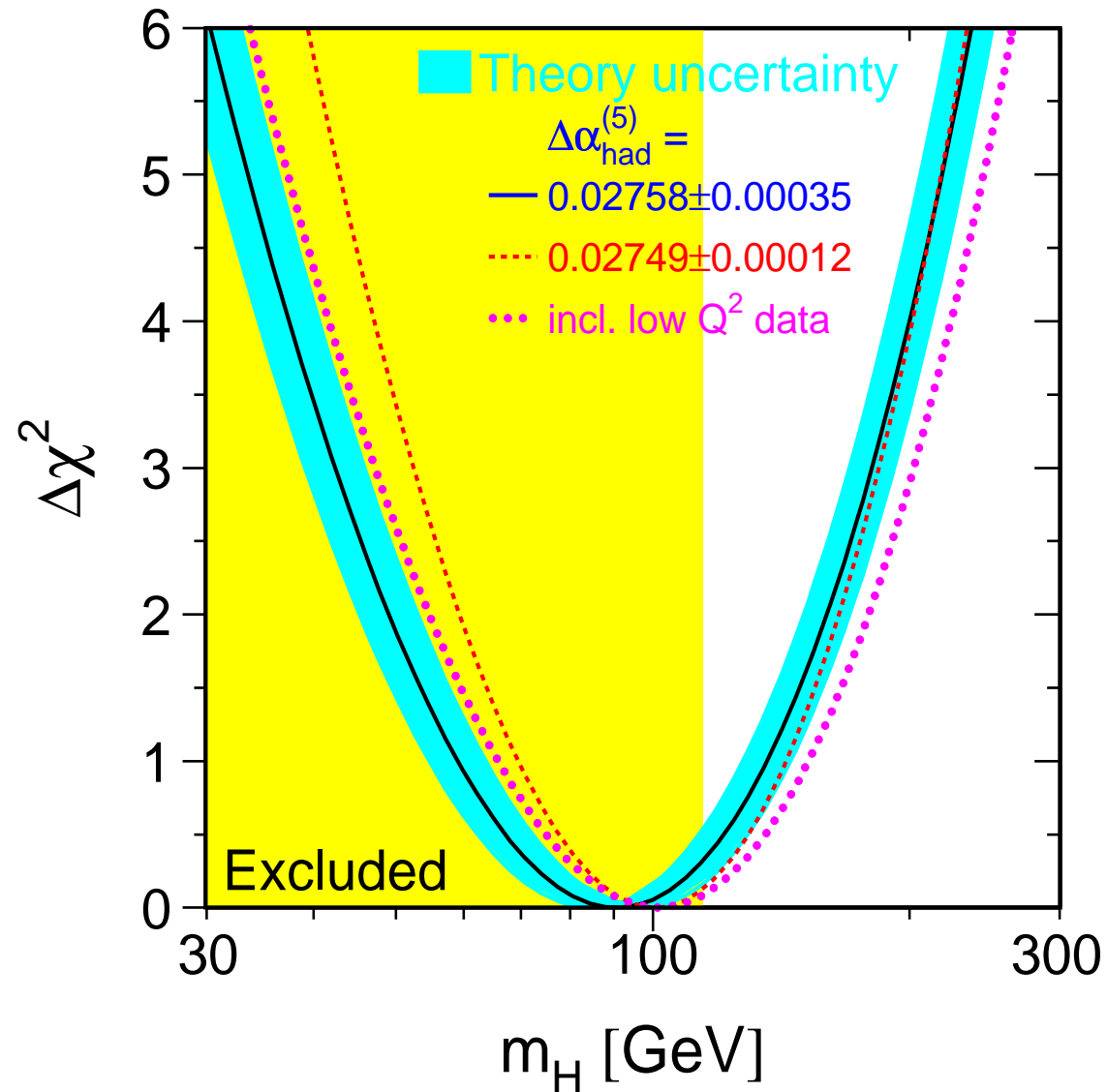
M_Z, α and G_F (where G_F is mostly from $\mu^\pm \rightarrow \nu_\mu e^\pm \nu_e$)

\implies Standard Model fit to all data

Electroweak Measurements - 2005



Higgs Mass in the SM



Limitations of the Standard Model

Many questions unanswered:

- What is the origin of Fermion masses ?:

In the Standard Model, *ad hoc* couplings of Higgs to fermions are adjusted to obtain

$$(m_e)/(m_t) \sim 10^{-6}, \quad m_\nu \lesssim 1 \text{ eV}$$

- Do interactions Unify at high energies ?

$$SU(3) \times SU(2)_L \times U(1) \longrightarrow G ?$$

Limitations of the Standard Model

- What is the origin of the **Baryon Asymmetry** ?
- What is the **Dark Matter** ?
- Why is the **Cosmological Constant** so small ?
- What is the **Dark Energy** ?

⋮

The Question at the TeV Scale

- The Hierarchy Problem:

Why is

$$M_W (\sim 100 \text{ GeV}) \ll M_P (\sim 10^{19} \text{ GeV})?$$

If **Higgs** elementary and the SM is valid up to M_P then what generates

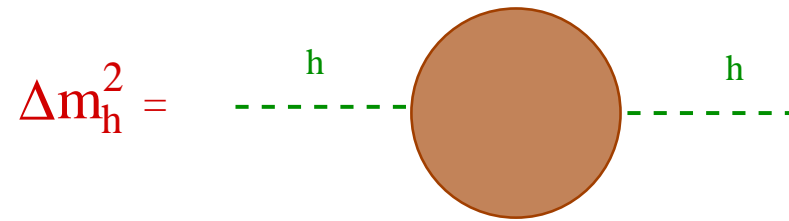
$$\frac{M_W}{M_P} \ll 1$$

This requires fine-tuning of the SM parameters.

Quantum corrections naturally drive v to M_P

The Hierarchy Problem

Quantum corrections to $m_h = \sqrt{2\lambda v}$:



$$\Rightarrow \boxed{\Delta m_h^2 \sim E_{UV}^2 \sim M_P^2}$$

\Rightarrow We need

$$\left. \begin{array}{l} (m_h^{\text{bare}} - \text{Radiative Corrections}) \sim m_h^{\text{phys.}} \\ (\mathcal{O}(M_P) - \mathcal{O}(M_P)) \sim 100\text{GeV} \end{array} \right\}$$

In the **Standard Model** weak scale **not naturally stable**.

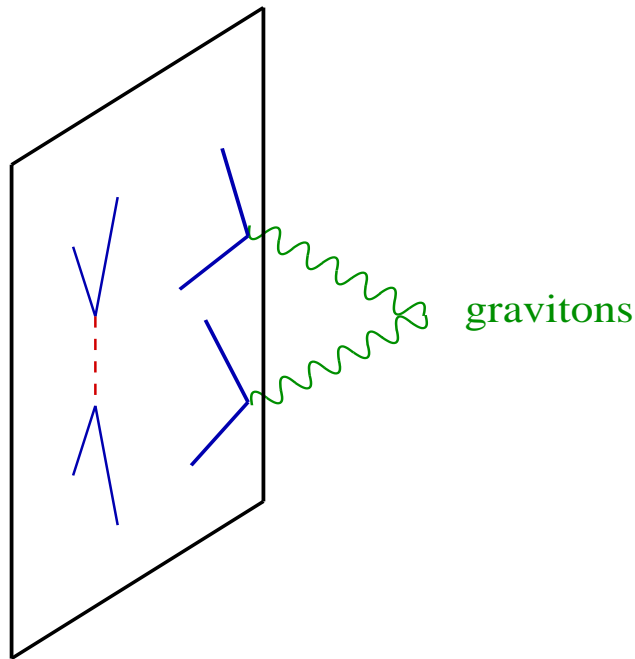
The Hierarchy Problem

- New physics at the **TeV** scale to stabilize the weak scale.
 - Additional states cancel divergences due to symmetries (e.g. **Supersymmetry**)
 - Higgs is composite and “comes apart” at scale Λ .
Technicolor/Topcolor/Little Higgs.
 - Extra Spatial Dimensions.

⋮

Extra Dimensions and the Hierarchy Problem

- Assume space has $3 + n$ dimensions.
- The extra n dimensions are compact and with radius R .
- All particles are confined to a **3-dimensional** slice (“brane”).
- Gravity propagates in **all** $3 + n$ dimensions.



Large Extra Dimensions

(Arkani-Hamed, Dimopoulos, Dvali '98)

- Gravity appears weak ($M_P \ll M_W$), because it propagates in large extra dimensions... Its strength is diluted by the volume of the n extra dimensions.
- Fundamental scale is $M_* \sim M_W$, not M_P

$$M_P^2 \sim M_*^{n+2} R^n$$

- There is no hierarchy problem:
The fundamental scale of Gravity

$$M_* \sim 1 \text{ TeV}$$

Large Extra Dimensions

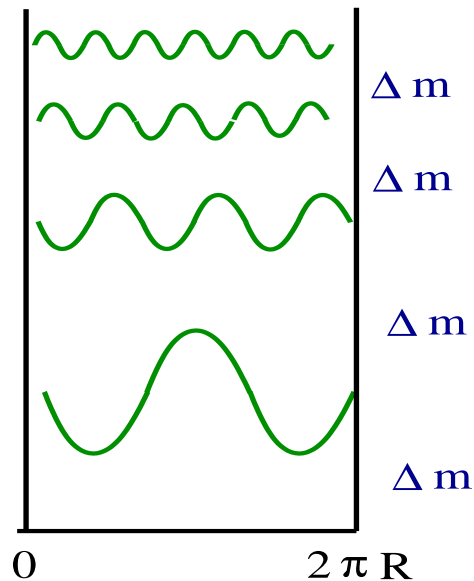
If we require $M_* = 1$ TeV:

$$R \sim 2 \cdot 10^{-17} 10^{\frac{32}{n}} \text{ cm}$$

- $n = 1 \implies R = 10^8$ Km. Already excluded!
- $n = 2 \implies R \simeq 2$ mm. Barely allowed by current gravity experiments.
- $n > 2 \implies R < 10^{-6}$ mm. This is fine.

Large Extra Dimensions

Compact extra dimensions \Rightarrow graviton excitations (Kaluza-Klein)



Mass gap $\Delta m \sim 1/R$

Large Extra Dimensions

E.g. for

$$n = 2 \longrightarrow \Delta m = 10^{-3} \text{ eV.}$$

$$n = 3 \longrightarrow \Delta m = 100 \text{ eV.}$$

⋮

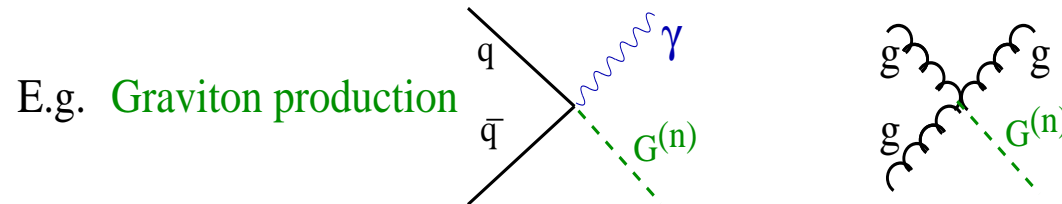
$$n = 7 \longrightarrow \Delta m = 100 \text{ MeV.}$$

Large Extra Dimensions - Phenomenology

- Individual KK graviton couplings gravitationally suppressed ($\sim 1/M_P$).
- But for $E \gg 1/R \rightarrow$ sum of KK mode results in

$$\sigma \sim \frac{E^n}{M_*^{n+2}}.$$

- Collider Processes:

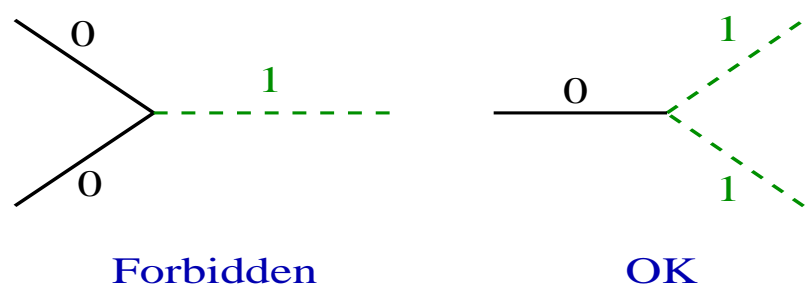


Individual graviton decay rates $\sim 1/M_P^2$, $\Rightarrow \cancel{E}_T$ signals at colliders.
Bounds on M_* from LEP and Tevatron (1 – 10) TeV.

Universal Extra Dimensions

(Appelquist, Cheng, Dobrescu '01)

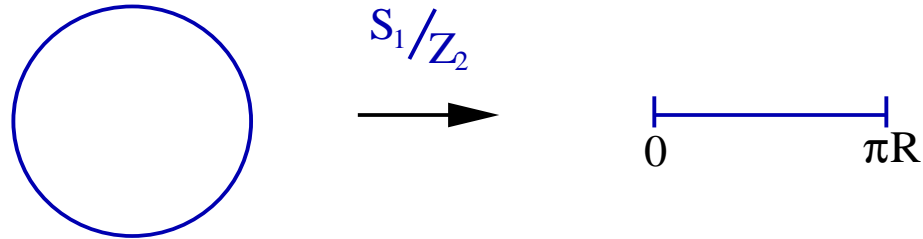
- If some SM fields propagate in the bulk \Rightarrow $1/R \gtrsim 1 \text{ TeV}$.
- But if we assume *all* fields can propagate in the extra dimensions. What is the allowed R ?
- Momentum conservation in the extra dimensions \Rightarrow $\text{KK-number conservation}$ E.g.



\Rightarrow KK excitations must be pair produced, direct bounds on $1/R$ are lower.

Universal Extra Dimensions

- Orbifold Compactification: Allows to have chiral fermions



- It breaks KK-number \longrightarrow KK-parity
 \Rightarrow Lightest KK Particle (LKP) is **stable** \longrightarrow Dark Matter candidate
- Direct and EW constraints:

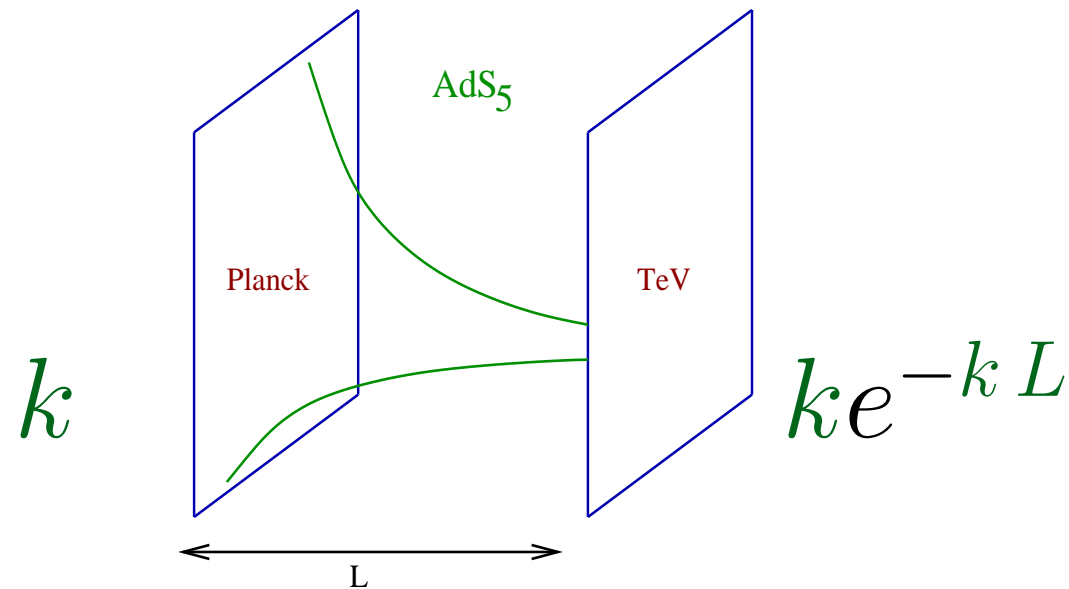
$$\begin{aligned} 1/R &\gtrsim 300 \text{ GeV for 5D} \\ 1/R &\gtrsim (400 - 600) \text{ GeV for 6D} \end{aligned}$$

UED Phenomenology

- Light KK modes \Rightarrow large cross sections.
- But, almost degenerate KK levels \Rightarrow little energy release:
E.g. $q\bar{q} \rightarrow Q_1\bar{Q}_1 \rightarrow Z_1Z_1 + \cancel{E}_T \rightarrow 4\ell + \cancel{E}_T$ (Cheng, Matchev, Schmaltz '02).
- Decays to Second KK Level:
 - They couple to 2 zero modes through brane couplings (loop generated). (Datta, Kong, Matchev '05)
 - Signals different in 5D from 6D (Burdman, Dobrescu, Pontón '05)
 - At the LHC is possible to produce 2nd KK level gluon in s-channel.

Warped Extra Dimensions

- One compact extra dimension. Non-trivial metric induces small energy scale from Planck scale! (L. Randall, R. Sundrum).



- Geometry of extra dimension generates hierarchy exponentially!

$$\Lambda_{\text{TeV}} \sim M_{\text{Planck}} e^{-kL}$$

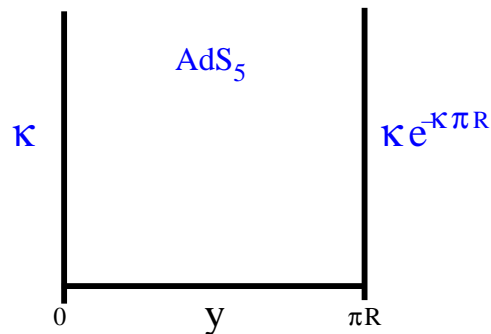
with k the curvature

Warped Extra Dimensions

- Warped 5D metric in RS

$$ds^2 = e^{-2\kappa|y|} \eta^{\mu\nu} dx_\mu dx_\nu + dy^2$$

- Compactified on S_1/Z_2 with $L = \pi R$



and $k \lesssim M_P$, AdS_5 curvature.

- For $kR \simeq (11 - 12)$

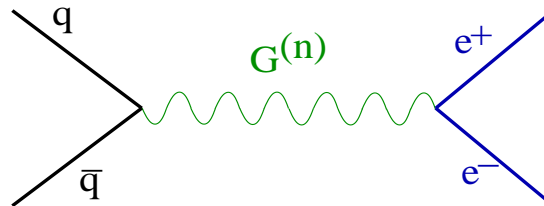
$$\longrightarrow \kappa e^{-\kappa\pi R} \simeq O(\text{TeV}).$$

Warped Extra Dimensions

If only gravity propagates in the bulk (SM fields on TeV brane):

⇒ Kaluza-Klein graviton tower

- Zero-mode graviton $G^{(0)}$ localized toward the Planck brane. This is why gravity is weak! $G^{(0)}$ couples to SM fields as $1/M_P^2$
- First few KK graviton excitations localized toward TeV brane
→ They couple strongly (as $(1/\text{TeV})^2$) to fields there.
E.g.: Drell-Yan at hadron colliders



Bulk Life in WED

- In original proposal, *only gravity* propagates in 5D bulk.
- **RS** is a solution of the hierarchy problem. But origin of **EWSB**?
And flavor ? ...
- Allowing gauge fields and matter to propagate in the bulk opens many possibilities: models of EWSB, GUTs, flavor, ...
- The 5D mass of a bulk fermion \Rightarrow *localization* of zero-mode.
- If Higgs remains on TeV brane:
Fermions localized toward TeV brane are more massive
Fermions localized toward the Planck brane are lighter

\Rightarrow **Fermion Geography**

Gauge Fields in the 5D bulk

- Gauge Fields in the 5D bulk: KK decomposition in 4D (for $A_y = 0$ gauge):

$$A_\mu(x, y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=0}^{\infty} A_\mu^{(n)}(x) \chi^{(n)}(y) ,$$

Zero-mode $A_\mu(x)^{(0)}$ + KK tower of massive gauge bosons for $n > 0$,
with masses

$$m_n \simeq (n - O(1)) \times \pi \kappa e^{-\kappa \pi R}$$

I.e. for appropriate choice of κR 1st KK excitations are $O(\text{TeV})$.

- 1st KK excitations have $\chi^{(n)}(y)$ localized toward TeV fixed point.
- The Gauge Symmetry usually either is or embeds the SM:
e.g. $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$ (restores custodial symm.)

WED and Flavor

- Fermion Fields in the bulk: 5D fermion field KK decomposition

$$\Psi_{L,R}(x, y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=0} \psi_n^{L,R}(x) e^{2\kappa|y|} f_n^{L,R}(y)$$

- 5D fermion bulk mass term \longrightarrow localization of fermion fields:

$$S_f = \int d^4x dy \sqrt{-g} \{ \dots - c \kappa \bar{\Psi}(x, y) \Psi(x, y) \} ,$$

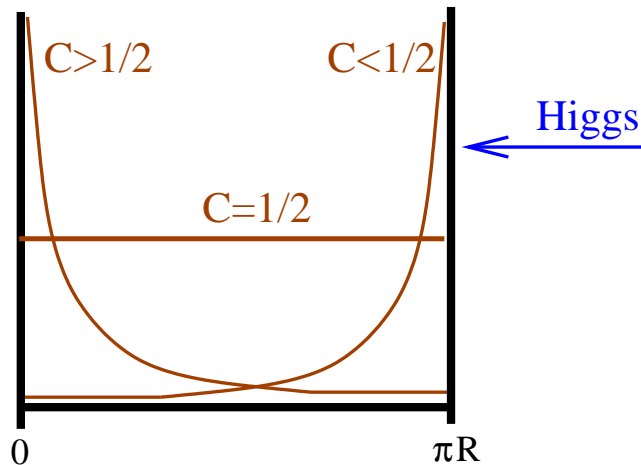
with $c \simeq O(1)$.

- \Rightarrow Fermion zero-modes can be localized by choosing c :

$$f_0^{R,L}(y) = \sqrt{\frac{\kappa\pi R (1 \pm 2c)}{e^{\kappa\pi R(1 \pm 2c)} - 1}} e^{\pm c \kappa y}$$

Flavor Models in WED

- $O(1)$ flavor breaking in bulk can generate fermion mass hierarchy:

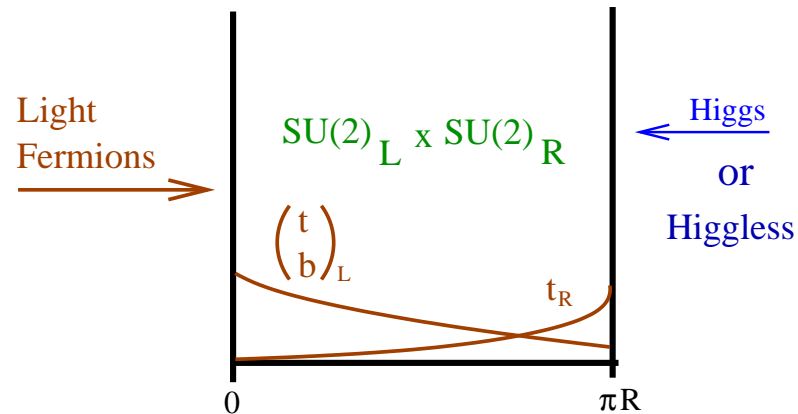


Fermions localized toward the TeV brane can have larger Yukawas, Those localized toward the Planck brane have highly suppressed ones.

- But fermions at $\simeq \pi R \Rightarrow$ strong couplings to 1st KK gauge bosons!
E.g: 3rd generation quarks might have large couplings \rightarrow flavor violation.

Electroweak Symmetry Breaking and WED

Several possibilities for model building:

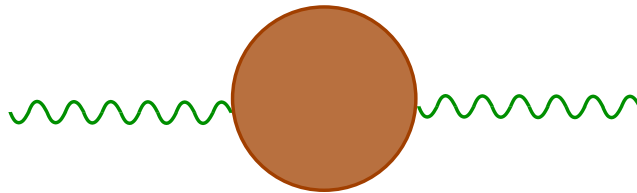


- Higgs or Higgsless (BC breaking)
- Light fermions on Planck brane or off (reduces S)
- Third generation remains a challenge

Agashe, Delgado, Sundrum '03; Csaki, Grojean, Murayama, Terning '03; Barbieri, Pomarol, Rattazzi '03; Burdman, Nomura '03; Cacciapaglia, Csaki, Grojean, Terning '04, '05; . . . ,

Electroweak Symmetry Breaking and WED

- EW Precision constraints: potentially large corrections to gauge boson propagators



$$S \sim \frac{N}{\pi} = 16\pi \frac{v^2}{m_{KK}^2}$$

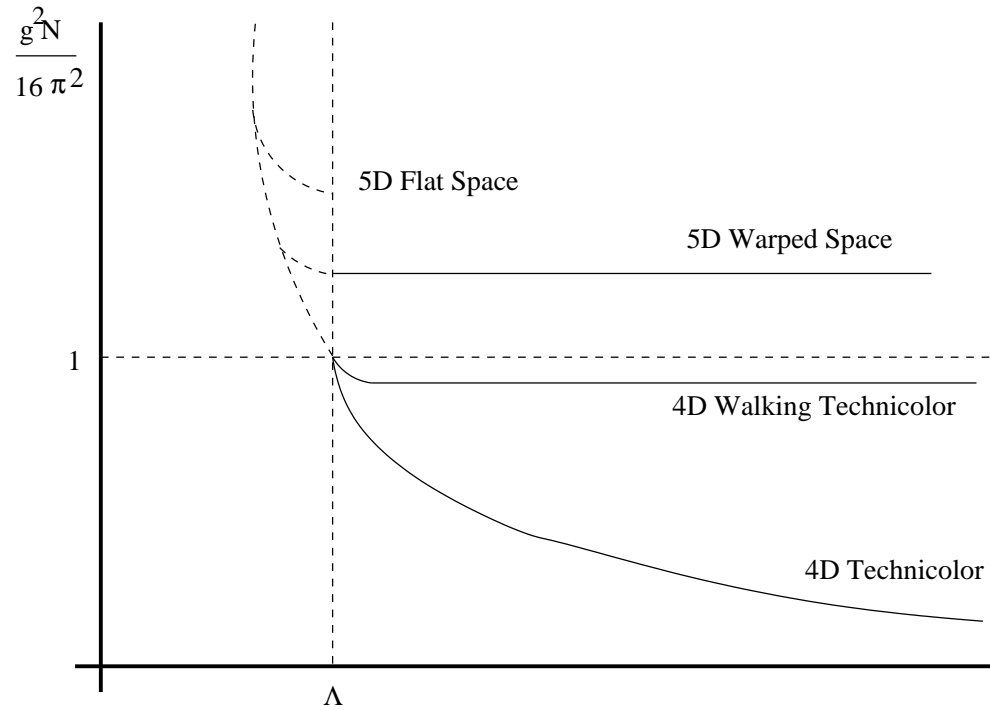
(Burdman, Nomura; Cacciapaglia, Csaki, Grojean, Terning)

- Important constraints for building models:
Canceling the effect of S vs. small N .

Warped Extra Dimensions - Signals

- Narrow states \rightarrow KK modes (Large N).
Spin 2 (graviton), possibly all other SM fields.
- No spaced resonances, but broad enhancements in cross sections (Small N).
- Flavor violation at tree level \rightarrow Potentially rich array of deviations:
Effects of KK gluons in CP asymmetries in $B \rightarrow \phi K_s$, $B \rightarrow \pi K_s$, B_s mixing, . . . (Burdman '03);
Z mixing with KK excitations in $b \rightarrow s \ell^+ \ell^-$ (Burdman, Nomura '03; Agashe, Perez, Soni '04).
- Conclusion: Back to strong dynamics at the TeV scale. Can the extra dimensional picture help ?

Warped Extra Dimensions vs. Strong Dynamics



Conclusions

- Theories with extra spatial dimensions provide possible solutions to the Hierarchy problem.
- **Large Extra Dimensions** bring scale of Quantum Gravity to the LHC: $M_s \simeq 1$ TeV.
Black holes at the LHC ?
- Theories with **Universal Extra Dimensions**: more model building possibilities. EWSB models, dark matter. Also $M_s \simeq 10$'s of TeV.
- **Warped Extra Dimensions (RS1)**: Rich model building possibilities in EWSB, Flavor, GUTs, etc.
AdS/CFT \leftrightarrow Strong Dynamics ? (Some of QCD seems to be well described by RS1).