Beyond the Standard Model

Particle Physics at the Edge of Discovery

Gustavo Burdman

Department of Physics - USP

Outline

* The Standard Model: a successful description.

* The hierarchy problem. Why do we believe that the TeV scale will reveal new dynamics ?

* Physics beyond the Standard Model: understanding $M_{\mathrm{W}}/M_{\mathrm{Planck}}$. Old and New approaches to the TeV scale.

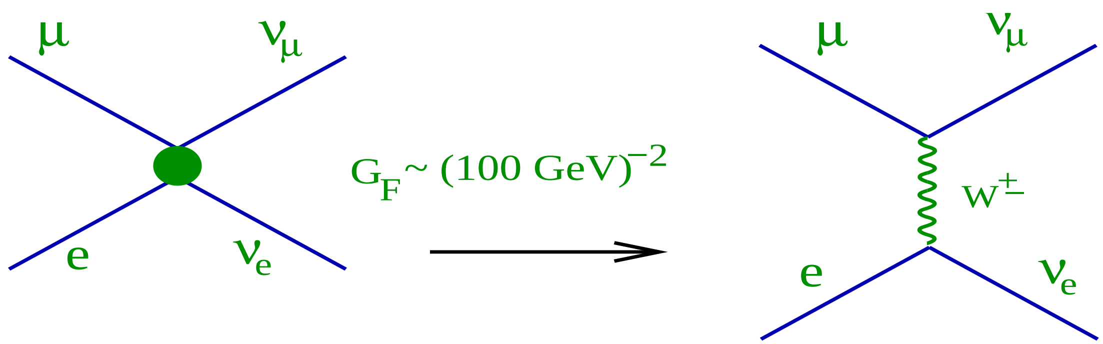
* Conclusions/Outlook

The Road to the Standard Model

- Quantum Electrodynamics (QED):
  - Successful description of Electromagnetism as a quantum field theory.
  - Local Gauge Symmetry: Theory invariant under local $U(1)$ transformations.
    => γ's are the force carriers, and they are massless.
  - Tested with great precision. (Lamb shift, $(g-2)$, $\cdots$).
- Weak Interactions:
  - Responsible for nuclear β decay: $n \longrightarrow p^+ + e^- + \bar{\nu}_e$.
  - Short range! => carriers are not massless!.
  - Inconsistent with Gauge Theories (e.g. QED)?

The Road to the Standard Model

- Weak Interactions: Mediated by massive vector bosons



- Gauge Symmetry now is $SU(2)_L \times U(1)_Y$:
  Discovery of neutral currents in 1970's => massive $(W^\pm, Z^0)$, plus a massless γ.

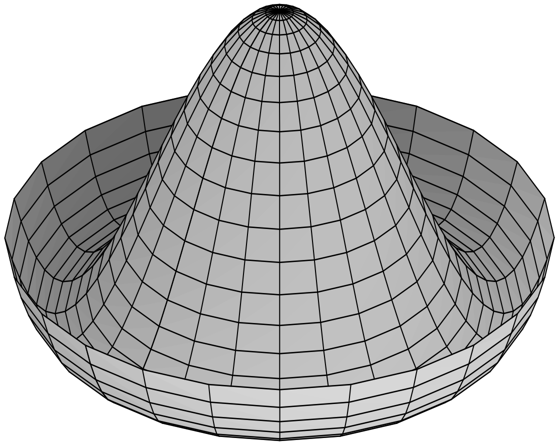
- Massive gauge boson => broken gauge symmetry !
  $\boxed{m^2\, A_\mu A^\mu}$ not invariant under $\boxed{A_\mu(x) \to A_\mu(x) - \frac{1}{g}\partial_\mu \alpha(x)}$

  Theory is inconsistent at high energies ? (Non-renormalizable)

Spontaneous Symmetry Breaking

Symmetry is not broken but hidden.

True vacuum not symmetric => spontaneously broken symmetry.



=> Massless excitations in the "symmetric" direction

$\longrightarrow$ Goldstone bosons

Superconductivity

Superconductor: Electromagnetic gauge invariance is spontaneously broken. Material obeys

$$\mathcal{E}_{\text{normal}} = \mathcal{E}_{\text{SC}} + \Delta$$

Superconducting vacuum breaks $U(1)_{\text{EM}}$ => Goldstone boson ϕ such that

$$\boxed{A_\mu = \partial_\mu \phi} \text{ minimizes energy.}$$

=> Magnetic Field vanishes inside → flux exclusion (Meissner effect.)
=> EM interactions become short range => "Massive" Photon

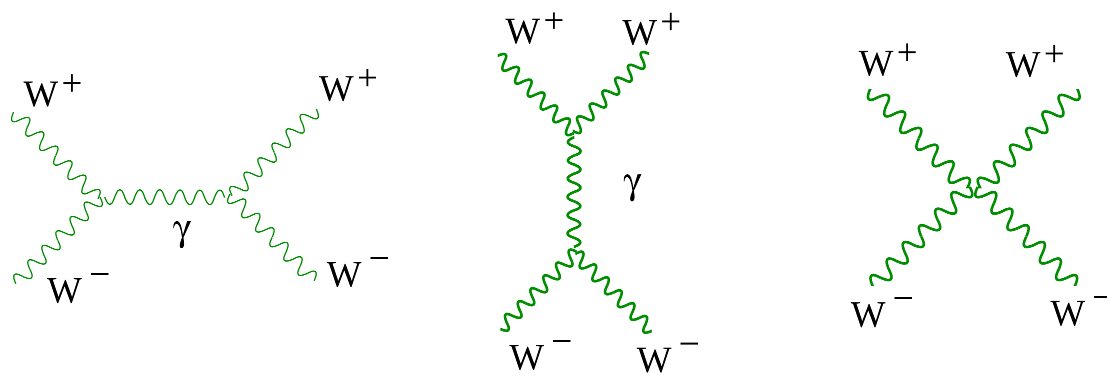
The Higgs Mechanism

- Need to spontaneously break $SU(2)_L \times U(1)_Y$ to $U(1)_{\mathrm{EM}}$. Only photon remains massless.
- Higgs: Goldstone bosons are "eaten" by $(W^{\pm}, Z^0)$. => (m_W, m_Z) => 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 $U(1)_{\mathrm{EM}}$.
- 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 $\Lambda \sim 1$ TeV

.

The Standard Model

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

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

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

- $V(\Phi) \Rightarrow$ vacuum not invariant: $\langle \Phi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$

  $\Rightarrow$ masses for 3 out of the 4 gauge bosons.

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

$$\boxed{M_W, M_Z \neq 0, \quad m_\gamma = 0}$$

The Standard Model

- To avoid unitarity violation in cross sections

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

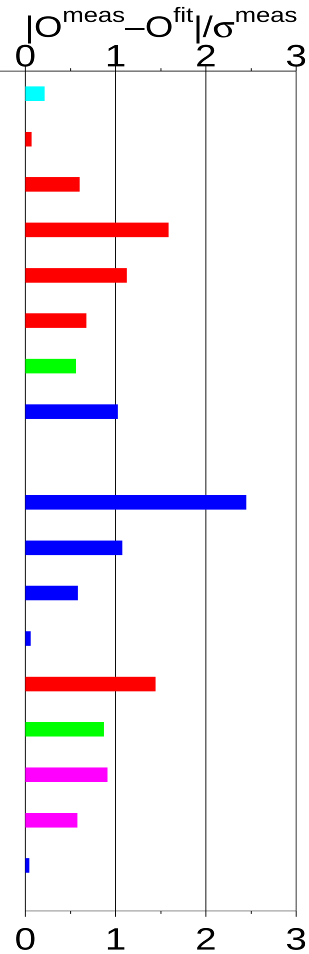
The Success of the Standard Model

- Precision Tests (1990's):
  - Millions of Z^0's produced at LEPI via
    $$e^+e^- \longrightarrow Z^0 \longrightarrow f\bar{f}$$
    Non-abelian couplings tested at LEPII in
    $$e^+e^- \longrightarrow W^+W^-$$
  - Also precision νN and Atomic Parity Violation experiments.
  - Input most precise measurements
    $\boxed{M_Z,\ \alpha \text{ and } G_F}$ (where G_F is mostly from $\mu^\pm \to \nu_\mu e^\pm \nu_e$)

$\Longrightarrow$ Standard Model fit to all data

Summer 2004

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02769
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4966
σ_{had}^{0} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01650
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1483
R_b	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A_{fb}^{0,b}$	0.0998 ± 0.0017	0.1040
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0744
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1483
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.394
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.2



The Limitations of the Standard Model

- The Hierarchy Problem:

  Why is

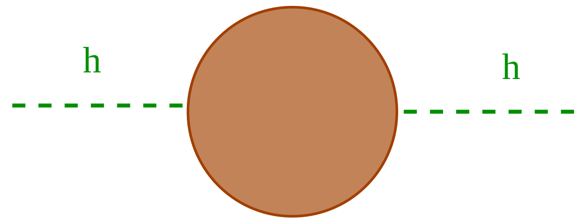
  $$M_W \ (\sim 100 \text{ GeV}) \ll M_P \ (\sim 10^{19} \text{ GeV})?$$

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

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

  This requires exquisite fine-tuning of the SM parameters, since quantum corrections naturally drive v to M_P

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

$\Delta m_h^2 =$ 

$$\Rightarrow \boxed{\Delta m_h^2 \sim \mathrm{E}_{\mathrm{UV}}^2 \sim M_P^2}$$

$\Rightarrow$ We need

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

Thus, in the Standard Model the weak scale is not naturally stable.

But we need $\Lambda < 1$ TeV

- 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. The analogy with Superconductivity: The Higgs sector of the Standard Model is the "Landau-Ginzburg" theory. The BCS dynamics must appear at the TeV scale
  - $(\text{TeV})^{-1}$ is the size of Extra Spatial dimensions

$$\vdots$$

The Limitations of the Standard Model

- What is the origin of Fermion masses ?:

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

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

- Do interactions Unify at high energies ?

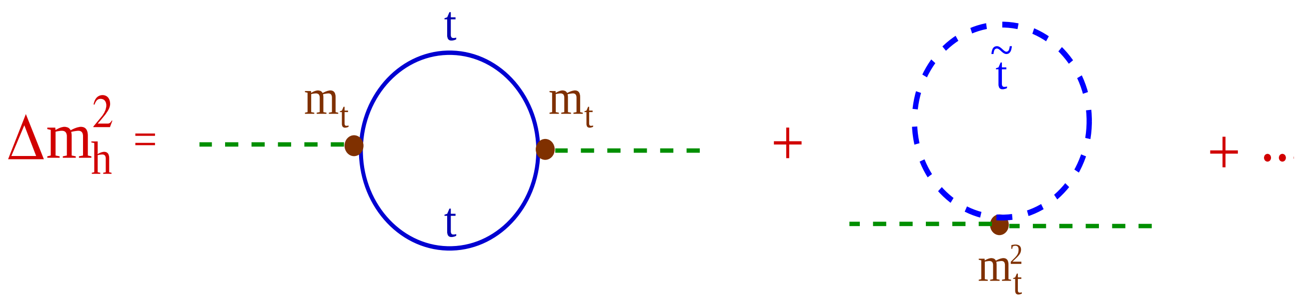
$$SU(3) \times SU(2)_L \times U(1) \longrightarrow G\ ?$$

- What is the origin of the Baryon Asymmetry ?
- What is the Dark Matter ?
- What is the Dark Energy ?

$$\vdots$$

Supersymmetry at the Weak Scale

- In the Supersymmetric limit quadratic div. from superpartners cancel the ones from the SM particles:



- Remaining div. is logarithmic

$$\Rightarrow \quad \boxed{\Delta m_h^2 \simeq m_{\rm soft}{}^2\, c/(16\pi^2)\, \ln(E_{\rm SUSY}/m_{\rm soft}) + \cdots}$$

- Weak scale SUSY also helps SU(5) coupling unification, results in radiative EWSB because m_t is large, has DM candidates, $\cdots$

$\boxed{\text{Supersymmetry at the Weak Scale}}$ - The Problems

- In SUSY, at tree-level $m_h < m_Z$.
- But we know $m_h^{\text{exp.}} \geq 114$ GeV. The logarithmic radiative corrections must lift m_h.
- $\Rightarrow m_{\text{soft}}$ (e.g. squark masses) must be high ($\simeq$ TeV)
- This results in fine tuning of radiative EWSB

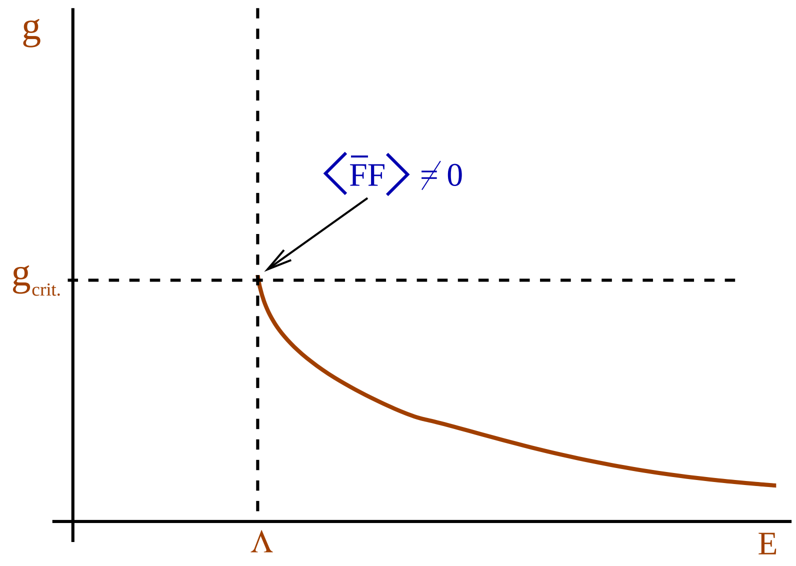
- Extensions of the MSSM: NMSSM, Extra Dimensions, Split SUSY (still unnatural), $\cdots$

A Composite Higgs Sector

Vacuum is "Electroweak Superconductor". New gauge interactions at the TeV scale $\Longrightarrow$ Fermion condensate (Cooper pairs):

$$\boxed{\langle \bar{F} F \rangle \neq 0} \text{ breaks electroweak symmetry } \to U(1)_{\mathrm{EM}}$$

E.g. if interactions are asymptotically free



- “Technicolor” becomes strong at $\Lambda \sim 1$ TeV $\Rightarrow$ 3 Goldstone bosons “eaten” by $W^{\pm}$ and Z^0
  $\Rightarrow M_W, M_Z$.
- Higgs dissolves into its constituents at $\Lambda \sim 1$ TeV
- The weak scale is *naturally* generated. It’s encoded in $g(E)$.
  (Just as Λ_{QCD} for the strong interactions.)

A Composite Higgs Sector

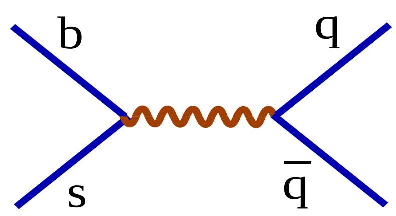
- Topcolor:
  In QCD $\langle \bar{Q}_L Q_R \rangle \neq 0 \to m_Q \simeq 300$ MeV.
  $m_t \sim 178$ GeV $\sim v$ is a constituent mass (C. Hill)

- New gauge interaction couples strongly to the top quark
  $\Rightarrow \langle \bar{t}_L t_R \rangle \neq 0 \Rightarrow m_t$

  But $\begin{pmatrix} t \\ b \end{pmatrix}_L \Rightarrow SU(2)_L \times U(1)_Y$ broken to EM.

Stronger coupling to third generation leads to
Flavor violation at tree level (FCNCs).

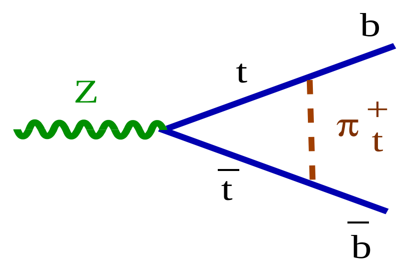
Tight constraints to model building from precision measurements and weak decays of heavy quarks (G. Buchalla, G.B., D. Kominis, C. Hill).
For instance in B decays (G.B., K. Lane, T. Rador; G.B.)



Constraints from $B^0 - \bar{B}^0$ mixing, potential deviations from the SM in $b \longrightarrow \bar{s}ss$ decays (E.g. CP asymmetry in $B \longrightarrow \phi K_s$)

Higgs sector: Higgs boson (mostly) a $\bar{t}t$ composite h_t pseudo-Goldstone bosons $(\pi_t^{\pm}, \pi_t^0)$, All couple strongly to the third generation quarks t, b.

Constraints from electroweak precision measurements.
E.g. $Z \to \bar{b}b$ (G.B., D. Kominis):

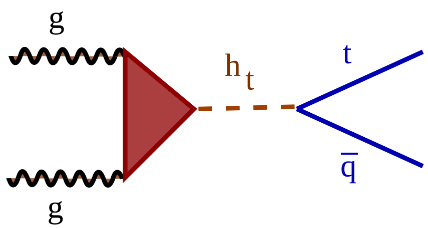


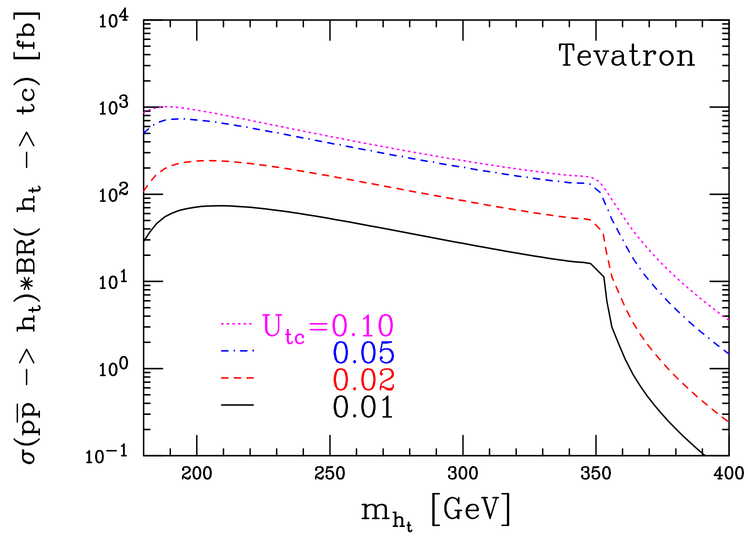
$$\Rightarrow m_{\pi_t} \geq 300 \text{ GeV}$$

Experimental Signals of a Composite Higgs Sector

The "top-Higgs" h_t decays mostly to flavor violating channel (G.B.)

$$p\bar{p} \to \quad \boxed{gg \longrightarrow h_t \longrightarrow tq} \to b\ell\nu_\ell + \text{jet}$$

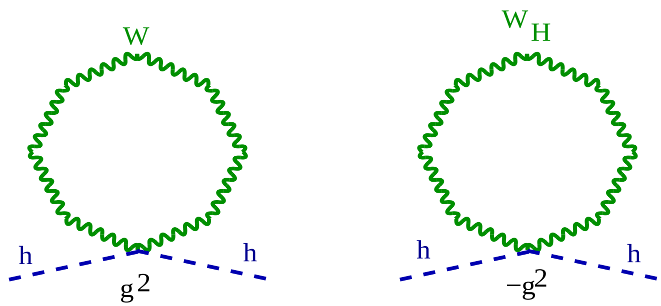




Little Higgs Theories

- Theories of composite Higgs highly constrained by precision data. Strong dynamics at $\Lambda \sim$ TeV scale is difficult. Raising Λ reintroduces "little hierarchy".

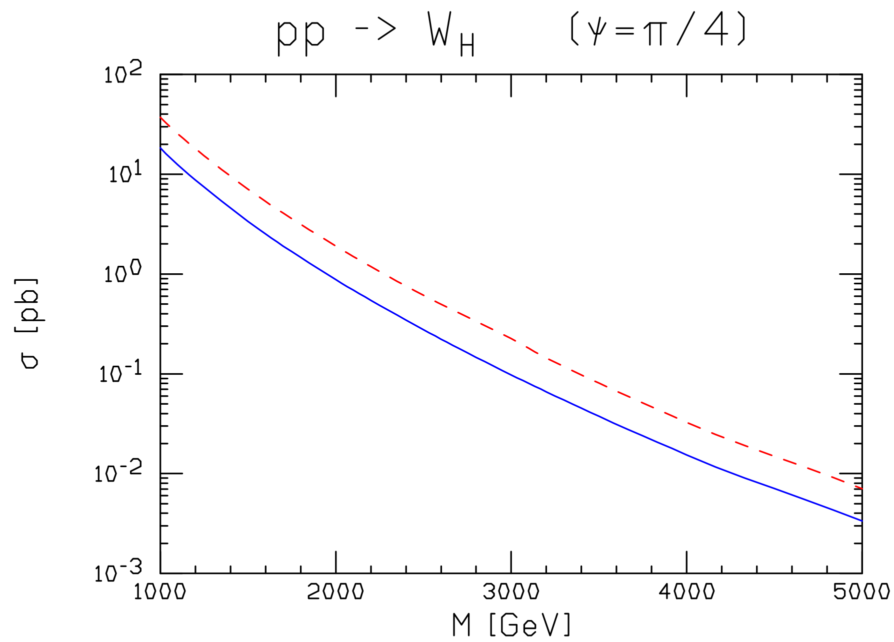
- Can raise Λ as long as we cancel Δm_h^2 at the TeV scale. Introduce new global (and gauged) symmetries $\Rightarrow$ cancellations from loops (Arkani-Hamed, Cohen, Georgi). For instance, to cancel the divergences from gauge boson loops:



- New particles at the TeV scale: 4 new gauge bosons, 1 or more new heavy quarks.

Large Little Higgs Signals at the LHC

- LHC will discover these particles. E.g. New gauge bosons at 10^5/year ! (G.B., M. Perelstein, A. Pierce)

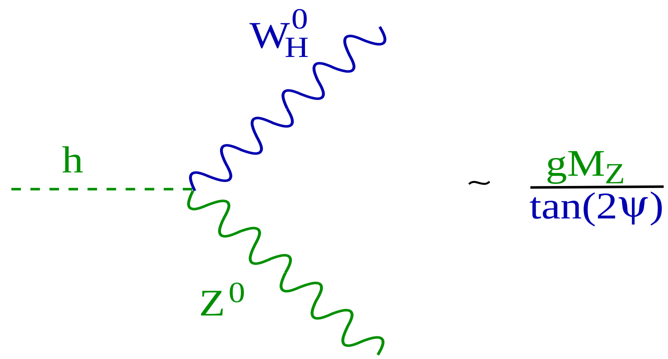


- But many many extensions of the SM predict extra gauge bosons ... How do we know is the Little Higgs ?

Little Higgs Signals at the LHC

- Little Higgs prediction: Symmetries dictate how the new gauge bosons couple to the Higgs (loop cancellations). $\Rightarrow$ need to measure this coupling.

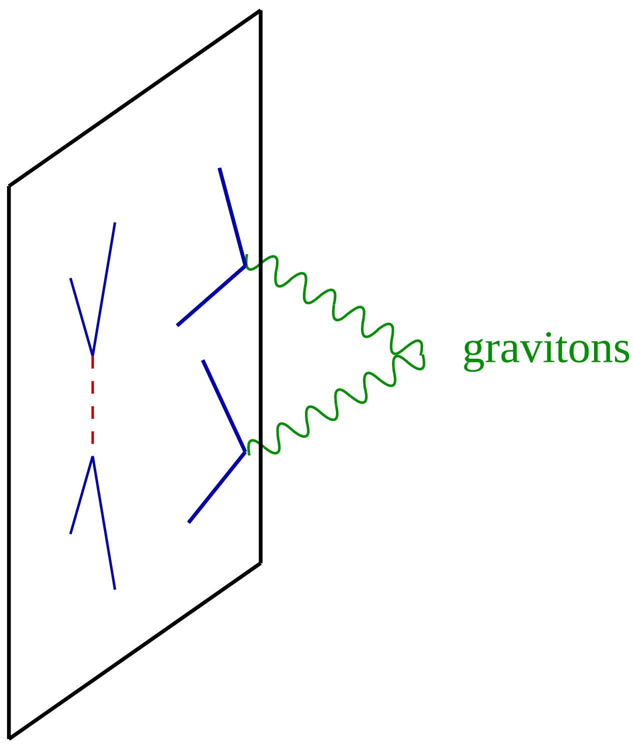
- Strategy: study the decays of W_H (G.B., M. Perelstein, A. Pierce)



- Measuring the W_H production $\Rightarrow$ mixing angle ψ. Gives prediction for $(W_H \to Z\,h)$, test model.

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

(Arkhani-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

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

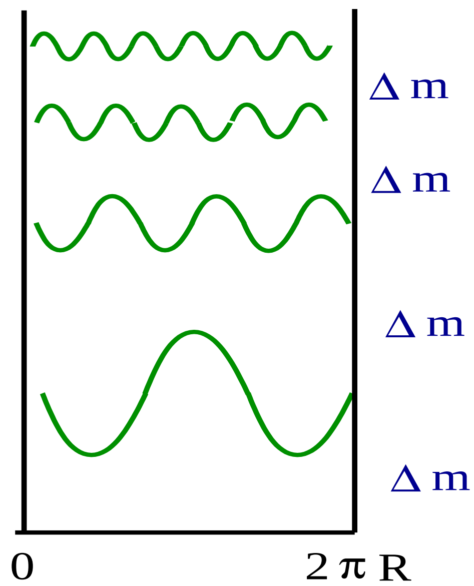
Large Extra Dimensions

If we require $M_* = 1$ TeV:

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

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

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



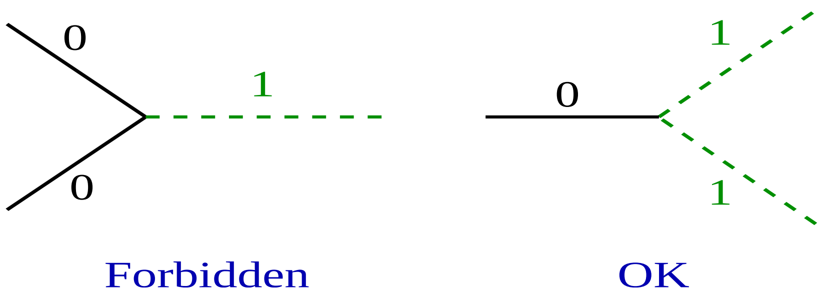
Mass gap $\Delta m \sim 1/R$ E.g. for

$$
\begin{aligned}
n = 2 &\longrightarrow \Delta m = 10^{-3} \text{ eV.}\\
n = 3 &\longrightarrow \Delta m = 100 \text{ eV.}\\
&\vdots\\
n = 7 &\longrightarrow \Delta m = 100 \text{ MeV.}
\end{aligned}
$$

Universal Extra Dimensions

(Appelquist, Cheng, Dobrescu '01)

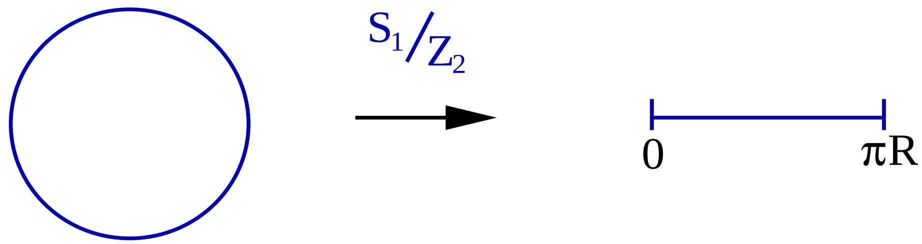
- If some SM fields propagate in the bulk $\Rightarrow$ $\boxed{1/R \gtrsim 1 \text{ TeV}}$.
- But if we assume *all* fields can propagate in the extra dimensions. What is the allowed R ?
- Momentum conservation in the extra dimensions $\Rightarrow$ $\boxed{\text{KK-number conservation}}$ E.g.



$\Rightarrow$ 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 $\boxed{\text{KK-number} \longrightarrow \text{KK-parity}}$

$\Rightarrow$ Lightest KK Particle (LKP) is stable $\rightarrow$ $\boxed{\text{Dark Matter candidate}}$

- Direct and EW constraints:

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

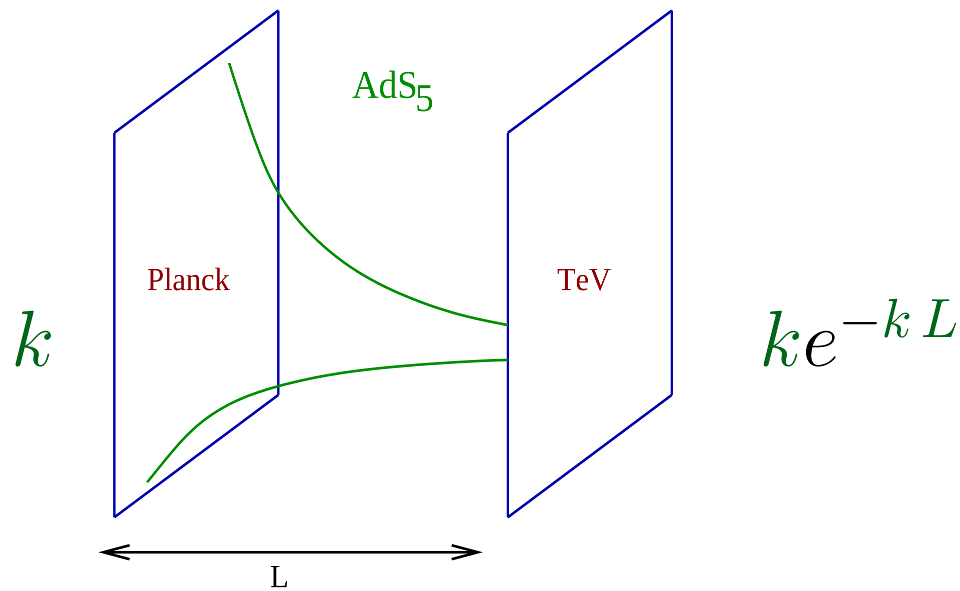
Universal Extra Dimensions

- Light KK modes $\Rightarrow$ large cross sections.
- But, almost degenerate KK levels $\Rightarrow$ little energy release:
  E.g. $q\bar{q} \to Q_1 Q_1 \to Z_1 Z_1 + \not{E}_T \to 4\ell + \not{E}_T$ (Cheng, Matchev, Schmaltz '02).
- 6D case well motivated:
  - Proton Stability (Appelquist, Dobrescu, Pontón, Yee '01).
  - Three generations (Dobrescu, Poppitz '01)

  Signals somewhat different from 5D (Burdman, Dobrescu, Pontón '05)
  E.g. Second KK level *cannot* decay to two level-1 KK modes:
  $m_2 \simeq \sqrt{2}/R$.
  Can decay to two zero-modes through KK-number violating brane kinetic terms.

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!

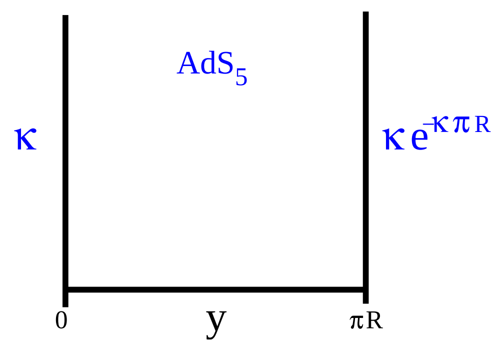
$\boxed{\Lambda_{\rm TeV} \sim M_{\rm Planck}\, e^{-k\,L}}$ with k the curvature

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.

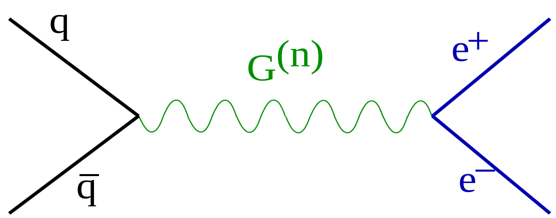
- For $kR \simeq (11 - 12)$

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

Warped Extra Dimensions

If only gravity propagates in the bulk (SM fields on TeV brane):
$\Longrightarrow$ Kaluza-Klein graviton tower

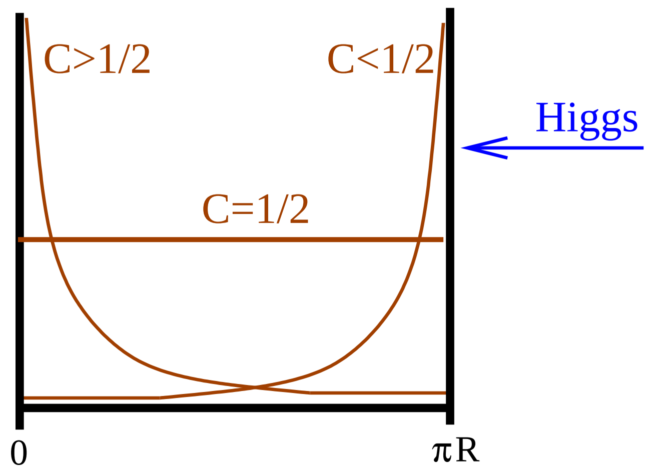
- Zero-mode graviton $G^{(0)}$ localized toward the Planck brane. This is why gravity is weak! $G^{(0)}$ couples to SM fields as $1/M_P^2$
- First few KK graviton excitations localized toward TeV brane
  $\rightarrow$ They couple strongly (as $(1/\text{TeV})^2$ to fields there.
  E.g.: Drell-Yan at hadron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



- 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 => *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

$$\Longrightarrow \boxed{\text{Fermion Geography}}$$

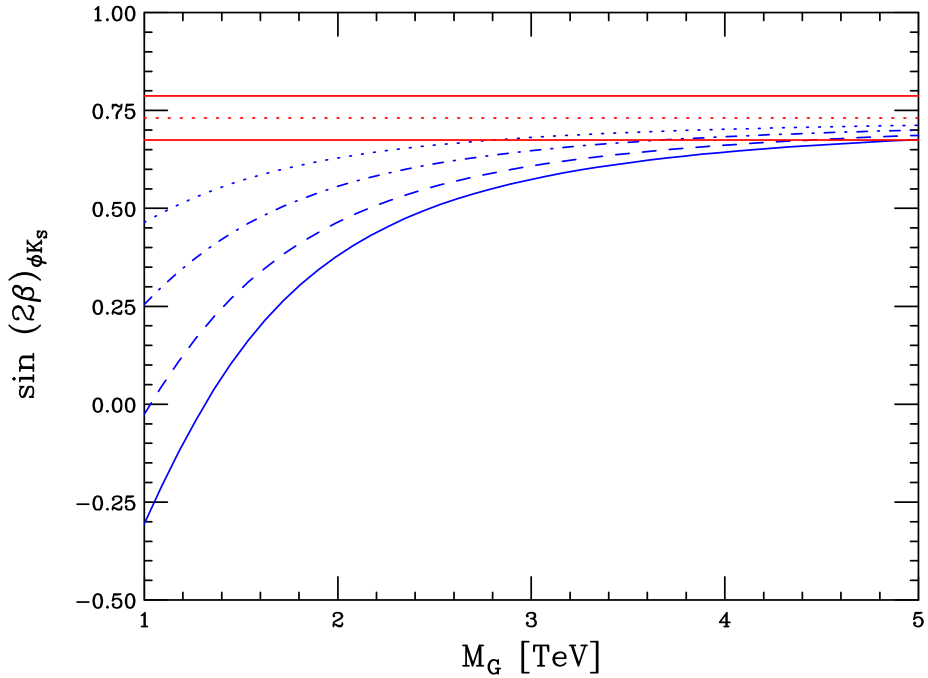
- $O(1)$ flavor breaking in bulk can generate fermion mass hierarchy:



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

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

- Shift in the value of $\sin(2\beta)$ in $B_d \to \phi K_s$ (G.B.):

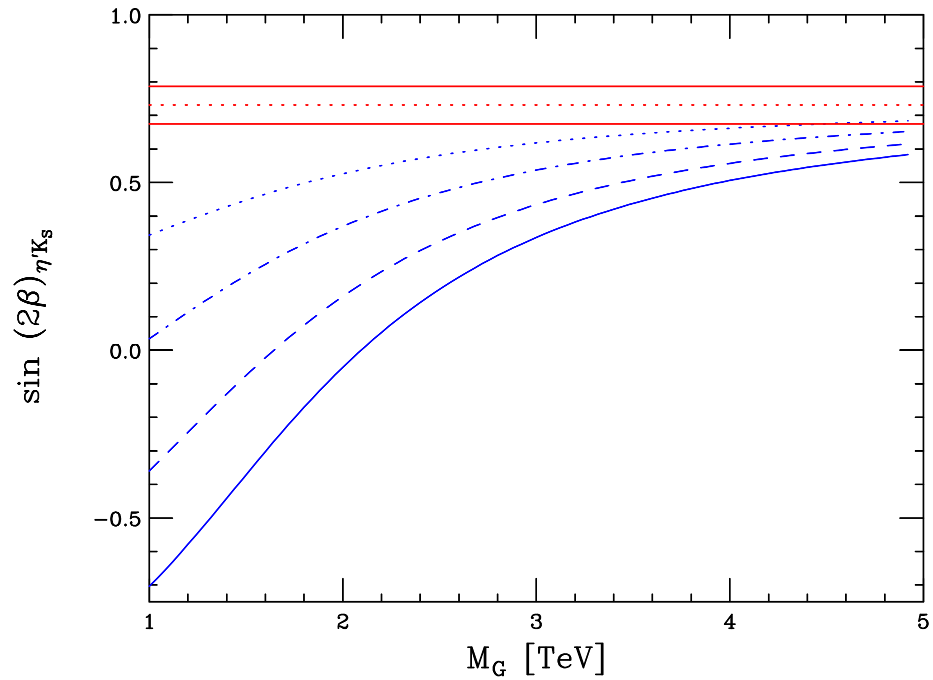


for $\omega = \pi/3,\ \pi/4,\ \pi/6,\ \pi/10$.

Here we take

$$\left|\frac{D_L^{bs*}}{V_{tb}V_{ts}^*}\right| = 1$$

- Shift in the value of $\sin(2\beta)$ in $B_d \to \eta' K_s$(G.B.):



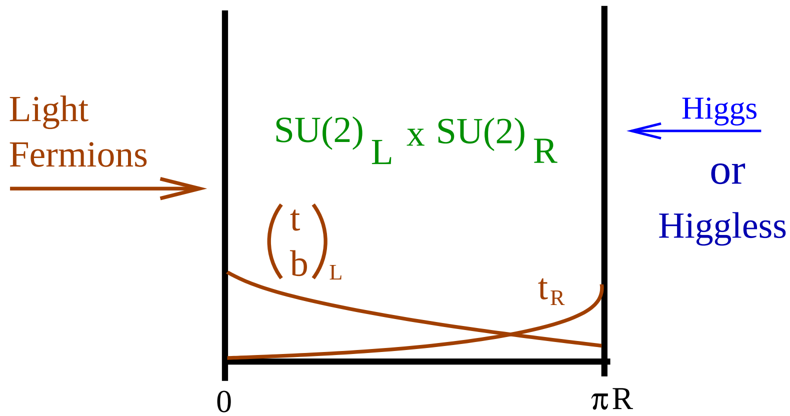
for $\omega = \pi/3,\ \pi/4,\ \pi/6,\ \pi/10$.

Here we take

$$\left| \frac{D_L^{bs*}}{V_{tb}V_{ts}^*} \right| = 1$$

Electroweak Symmetry Breaking and Warped Extra Dimensions

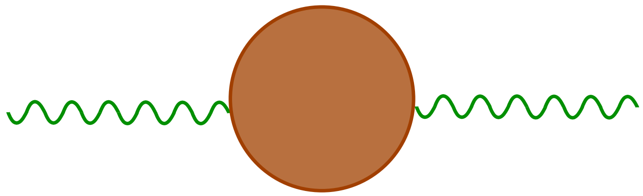
- EWSB by Higgs in the TeV brane. But Electroweak Precision Constraints $\Rightarrow$ bulk gauge symmetry must be $SU(2)_L \times SU(2)_R$ to restore custodial symmetry or T is too large.(Agashe, Delgado, Sundrum '03).



- Can we do without the Higgs ? Higgless EWSB given by the orbifold boundary conditions (Csaki, Grojean, Murayama, Terning '03). Unitarity is restored by KK gauge bosons. (Chivukula, Dicus, He '01).

EWSB and Warped Extra Dimensions

- 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

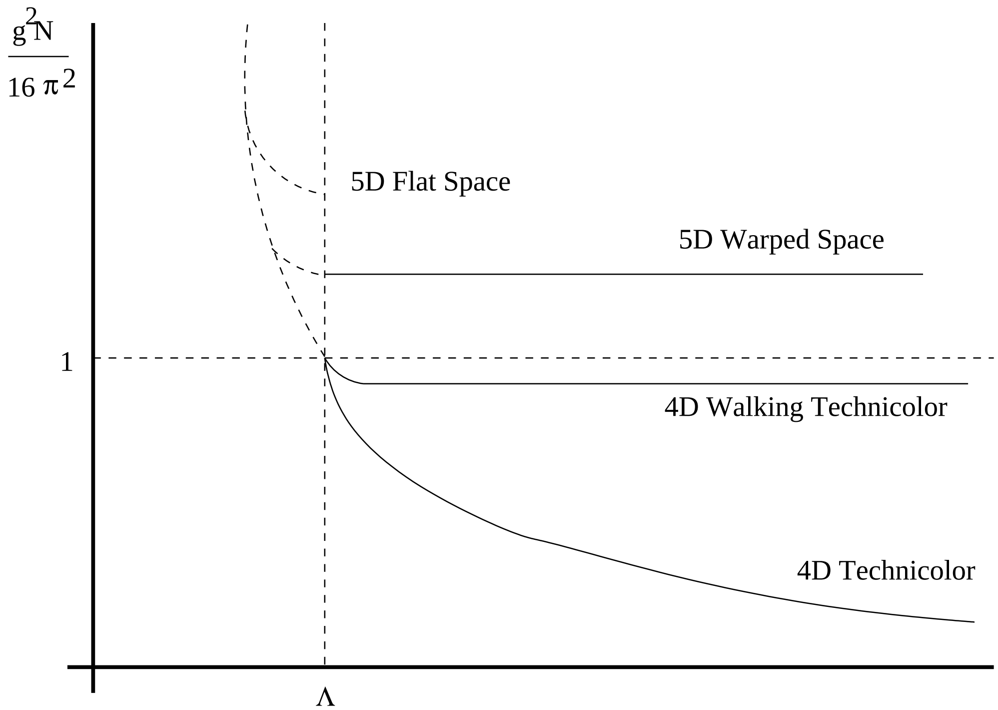
- Narrow states $\longrightarrow$ KK modes (Large N).
  Spin 2 (graviton), possibly all other SM fields.

- No spaced resonances, but broad enhancements in cross sections (Small N).

- Flavor violation at tree level $\longrightarrow$ Potentially rich array of deviations:
  Effects of KK gluons in CP asymmetries in $B \to \phi K_s$, $B \to \pi K_s$, B_s mixing, ... (Burdman '03);
  Z mixing with KK excitations in $b \to s\ell^+\ell^-$ (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/Outlook

- The Standard Model is an effective description of EWSB below the TeV scale.
- Physics beyond the SM must be introduced at the TeV scale: the SM with a sole Higgs is not radiatively stable.
- The LHC will thoroughly explore this energy scale. Starting in 2007.
- What is the solution to the hierarchy problem ?
  Supersymmetry, Strong dynamics, Extra dimensions, $\cdots$ X ?
- Connections with: Fermion Masses, Grand Unified Theories, Dark Matter. Maybe even Dark Energy.
- Complementarity with Astrophysics/Cosmology/Low energy precision tests.