At the Edge of Discovery

Beyond the Standard Model of Particle Physics

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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.
  – Supersymmetry
  – Composite scalar sectors (Technicolor, Topcolor, Little Higgs, ...)
  – Extra Dimensions (Large, Universal, Warped)

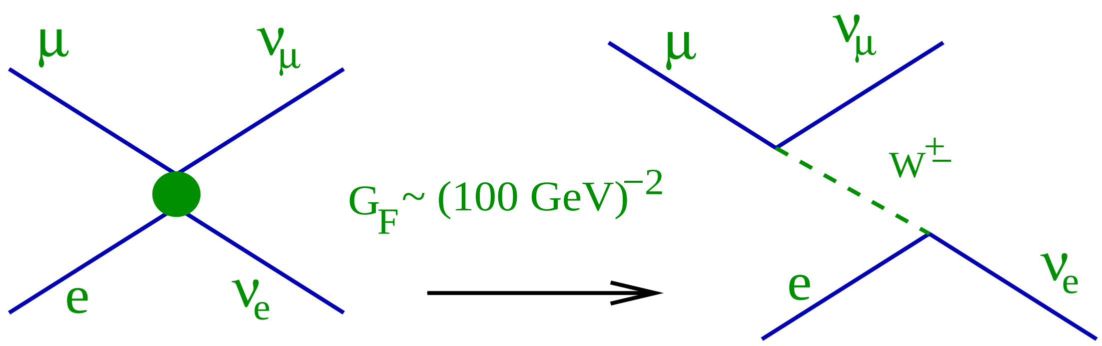
* Conclusions/Outlook

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 to 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.

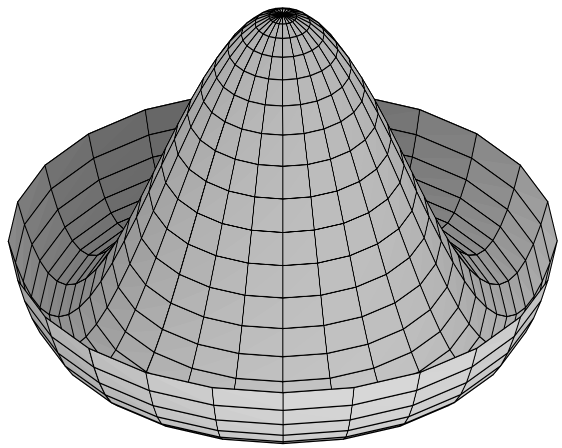
- Massive gauge boson => broken gauge symmetry !
  $\boxed{m^2 A_\mu A^\mu}$ not invariant under $\boxed{A_\mu(x) \rightarrow A_\mu(x) - \frac{1}{g}\partial_\mu \alpha(x)}$

  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

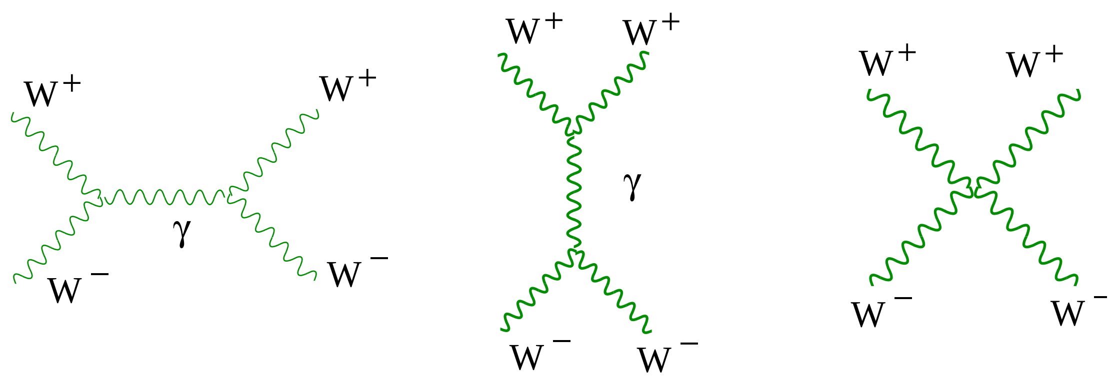
The Higgs Mechanism

- Need to spontaneously break $SU(2)_L \times U(1)_Y$ to $U(1)_{\rm EM}$. 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 $U(1)_{\rm EM}$.
- 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:

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

- 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.

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

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

The Standard Model

- To avoid unitarity violation in cross sections

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

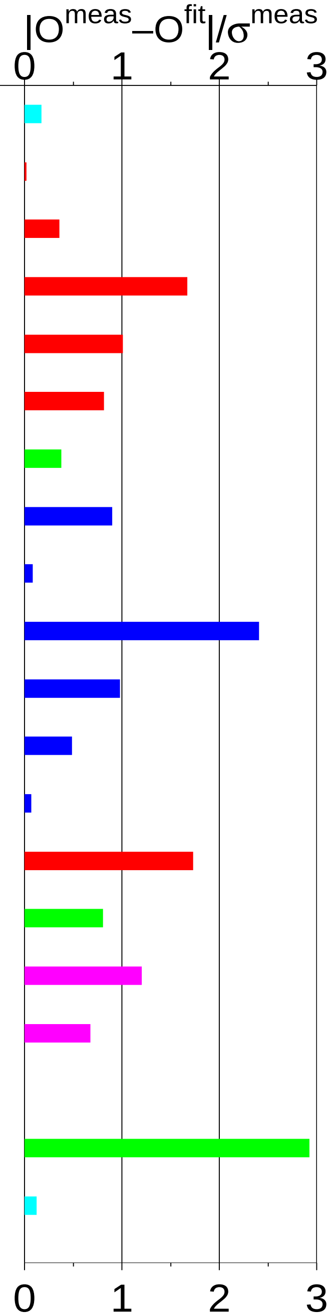
The Success of the Standard Model

- 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
    M_Z, α 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 2003

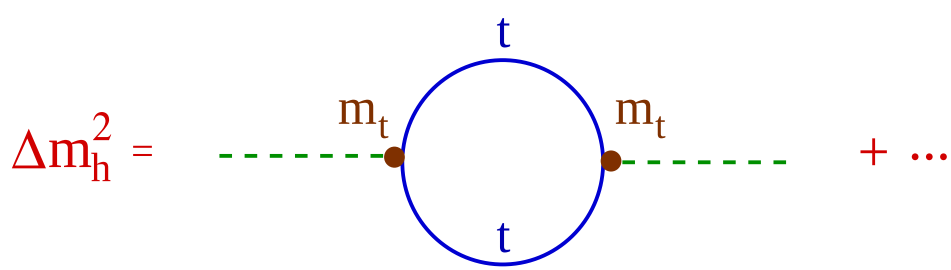
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4960
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1036
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.426 ± 0.034	80.385
Γ_W [GeV]	2.139 ± 0.069	2.093
m_t [GeV]	174.3 ± 5.1	174.3
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	0.2229
Q_W(Cs)	-72.84 ± 0.46	-72.90



The Limitations of the Standard Model

- The Hierarchy Problem:
  Why is the weak scale ($\lesssim 10^3$ GeV), so much smaller than the gravitational scale ($M_{\rm P} \simeq 10^{19}$ GeV) ?

- In the Standard Model the weak scale is not stable !!!



$$\Rightarrow \boxed{\Delta m_h^2 \simeq 3\Lambda^2 \left(2M_W^2 + M_Z^2 + m_h^2 - 4m_t^2\right) / (32\pi^2 v^2)}$$

But we need $\Lambda < 1$ TeV

Another Ultraviolet Catastrophe ?

- Need 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.
  - $(\mathrm{TeV})^{-1}$ is the size of Extra Spatial dimensions

$$\vdots$$

- 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

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

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

- Do interactions Unify at high energies ?

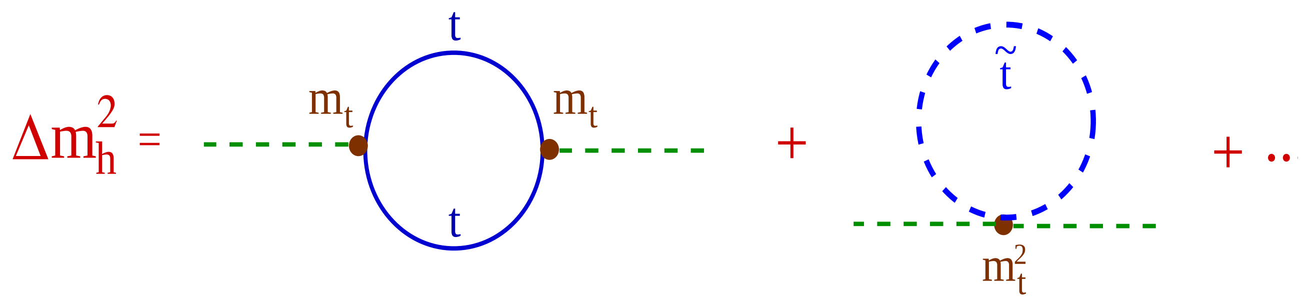
$$SU(3) \times SU(2)_L \times U(1) \longrightarrow G \ ?$$

- What is the 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

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

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

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_{soft} (e.g. squark masses) must be high ($\simeq$ TeV)
- This results in (*severe ?*) 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):

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

- In QCD condensate breaks chiral symmetry
$\Rightarrow$ "constituent" quark masses $m_q \sim \Lambda_{\rm QCD} \sim 300$ MeV.

- "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
$\Rightarrow$ No hierarchy problem .

A Composite Higgs Sector

- Topcolor: $m_t \sim 175$ GeV $\sim v$ ...suggestive ...(C. Hill)

$$m_t \sim O(\Lambda) \rightarrow \text{is a constituent mass ?}$$

- 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.

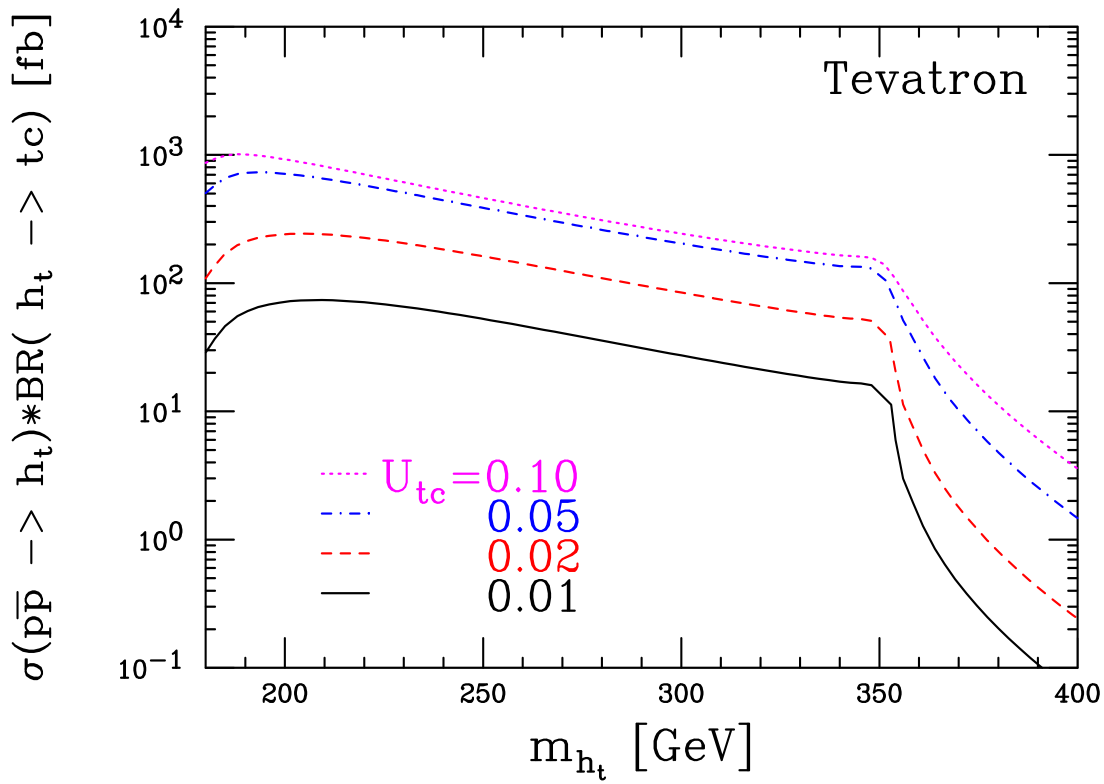
- Higgs sector: Higgs boson (mostly) a $\bar{t}t$ composite.
$\Rightarrow$ couples strongly to the third generation quarks t, b.
$\Rightarrow$ Flavor violation at tree level (FCNCs).
Tight constraints to model building from precision measurements and weak decays of heavy quarks (G. Buchalla, G.B., D. Kominis, C. Hill).

Experimental Signals of a Composite Higgs Sector

The "top-Higgs" h_t decays mostly to flavor violating channel $h_t \longrightarrow tq$.

$\Rightarrow$ It can be observed at Tevatron RunII and LHC !! (G.B.).

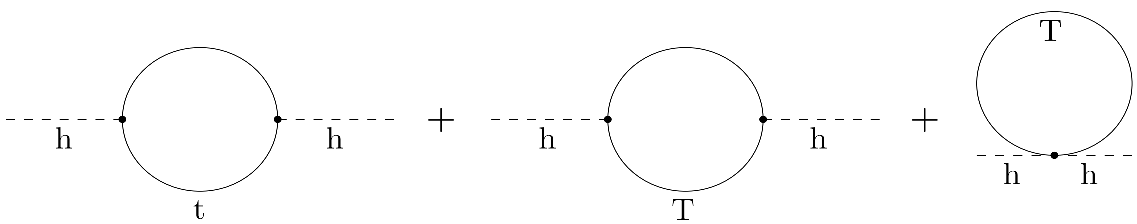
$$p\bar{p} \longrightarrow \boxed{gg \longrightarrow h_t \longrightarrow tq} \longrightarrow b\ell\nu_\ell + \text{jet}$$



A Little Help from a Little Higgs

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

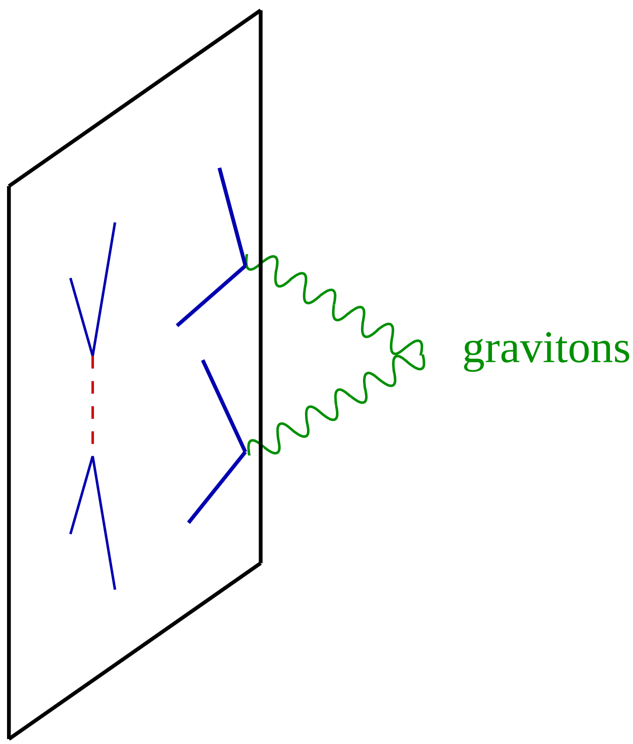
- Can raise Λ as long as we cancel Δm_h^2 at the TeV scale. Introduce new global (and gauged) symmetries $\Rightarrow$ cancellations from loops (Arkani-Hamed, Cohen, Georgi).



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

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:

$$V(r) \sim \begin{cases} \frac{m_1 m_2}{M_*{}^{(n+2)}} \frac{1}{r^n} & (r \ll R) \ , \\ \\ \frac{m_1 m_2}{M_*{}^{(n+2)}} \frac{1}{R^n} & (r \gg R) \ , \end{cases}$$

- Fundamental scale is $M_* \sim M_W$, not M_P

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

- There is no hierarchy problem!

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

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

Large Extra Dimensions

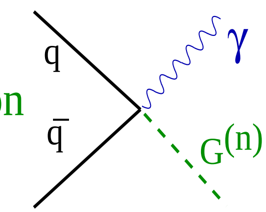
- Individual KK graviton couplings gravitationally suppressed ($\sim 1/M_P$).

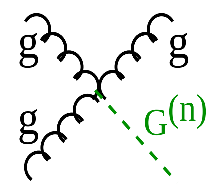
- But for $E \gg 1/R \rightarrow$ sum of KK mode results in

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

- Collider Processes:

E.g. Graviton production





Individual graviton decay rates $\sim 1/M_P^2$, $\Rightarrow \not{E}_T$ signals at colliders. Bounds on M_* from LEP and Tevatron (see next).

Large Extra Dimensions

- Virtual KK Graviton Exchange: Induces operators

$$\text{dim}-6 \quad \sim \quad [\bar{f}\gamma_\mu\gamma_5 f]^2$$
$$\text{dim}-8 \quad \sim \quad T_{\mu\nu}T^{\mu\nu}$$

  – dim-8 operator leads to $f\bar{f} \to \gamma\gamma, ZZ, \ldots$, pure d-wave.

  – Bounds on M_* from these ops. are in the (1-10's) TeV range.

- Black Holes at the LHC? (Giddings, Thomas '02)

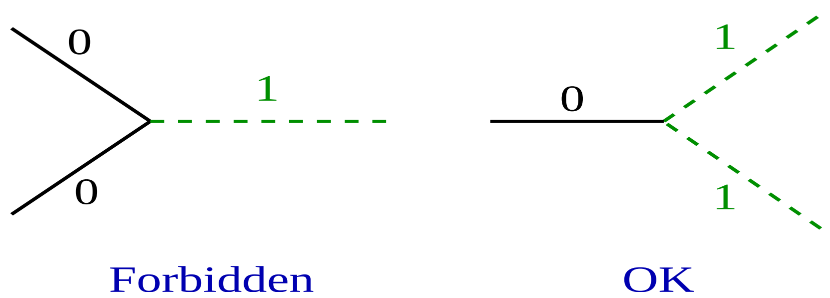
- Astrophysical Constraints

  Supernova Cooling: Graviton emission carries too much energy, cooling SN too fast. For $n = 2$, $M_* > (10 - 100)$ TeV.
  (Cullen, Perelstein '99, Hall, Smith '99).

Universal Extra Dimensions

(Appelquist, Cheng, Dobrescu '01)

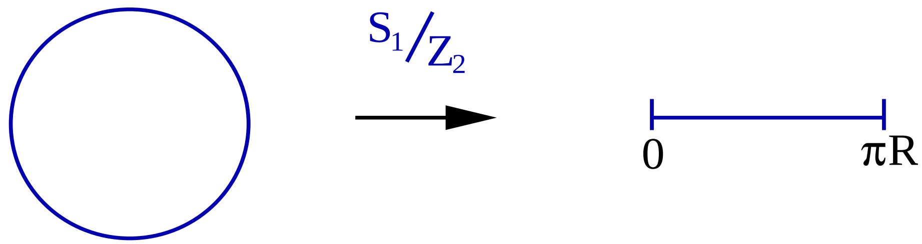
- If some SM fields propagate in the bulk $\Rightarrow$ $\boxed{1/R \gtrsim 1 \text{ TeV}}$.
- But if we assume *all* fields can propagate in the extra dimensions. What is the allowed R ?
- Momentum conservation in the extra dimensions
  $\Rightarrow$ KK-number conservation E.g.



$\Rightarrow$ 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 ⟶ KK-parity

  ⇒ Lightest KK Particle (LKP) is stable → Dark Matter candidate

- Direct and EW constraints:

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

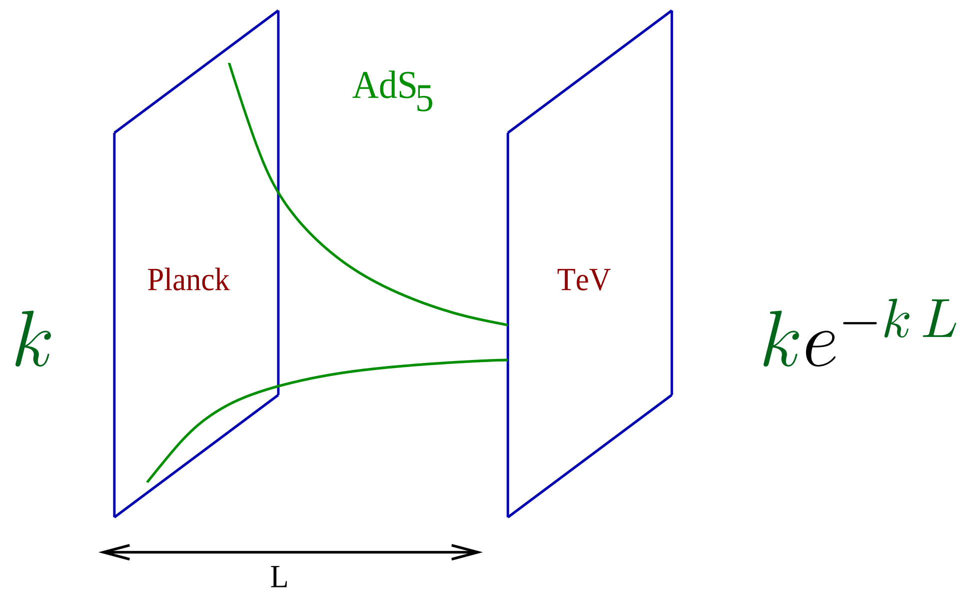
Universal Extra Dimensions

- 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 '04)
  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!

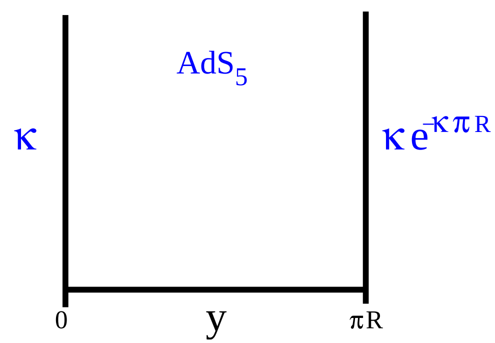
$$\boxed{\Lambda_{\text{TeV}} \sim M_{\text{Planck}}\, e^{-k\,L}} \qquad \text{with } k \text{ the curvature}$$

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.

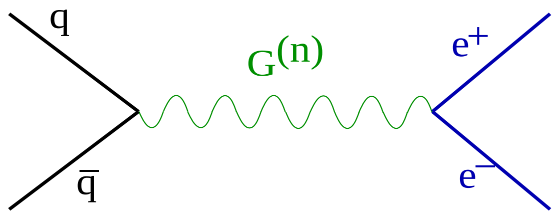
- For $kR \simeq (11 - 12)$

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

Warped Extra Dimensions

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

$\Longrightarrow$ Fermion Geography

- 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.)

- 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:

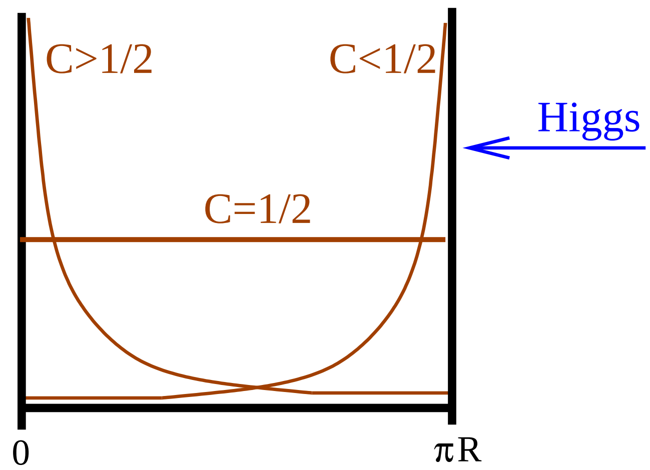
$$S_f = \int d^4x \; dy \; \sqrt{-g} \left\{ \cdots - \; c \; \kappa \bar{\Psi}(x,y)\Psi(x,y) \right\} \; ,$$

with $c \simeq O(1)$.

- => Fermion zero-modes can be localized by choosing c :

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

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

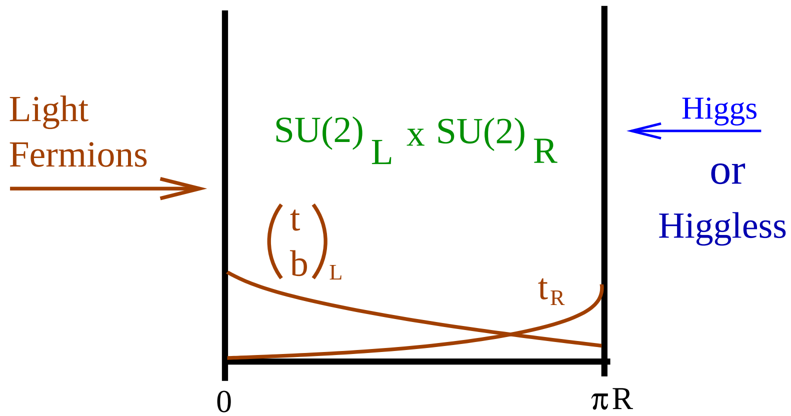


Fermions localized toward the TeV brane can have larger Yukawas, Those localized toward the Planck brane have highly suppressed ones.

- 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.

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).

Higgless EWSB and Warped Extra Dimensions

- It is possible to build theories of EWSB and Flavor without a Higgs. (Csaki, Grojean, Pilo, Terning '03; Nomura '03)
- EW Precision constraints: S tends to be large in AdS/CFT corresp. $\longrightarrow$ large N: (Barbieri, Pomarol, Rattazzi '03; Burdman, Nomura '03)

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

- Alternatives:
  - Large m_{KK}, $\rightarrow$ small N. Leads to strongly coupled "KK" sector. Technicolor-like.
  - Find source of negative S. E.g. kinetic terms on TeV brane (Cacciapaglia, Csaki, Grojean, Terning '04). Allows for low m_{KK}.
    But generally constrained by combination of S, T (Chivukula, He, Kurachi, Simmons, Tanabashi '04)

Higgless Warped Extra Dimensions - Signals

- If cancellation of S is naturally achieved, KK gauge bosons can be rather light and narrow.
- Alternatively, dynamics may be strongly coupled at $O(TeV)$ scale. No spaced resonances, but broad enhancements in cross sections.
- Flavor violation at tree level → 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); etc.
- Conclusion: Getting back to strong dynamics at the TeV scale. Can the extra dimensional picture help ?

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.