TRIUMF Summer Institute 2006
Collider and Energy Frontier Physics

Beyond the Standard Model

Lecture 5

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Plan

Lecture 1 Monday July 17
- Why BSM?
- Supersymmetry

Lecture 2 Monday July 17
- Supersymmetry continued: phenomenology

Lecture 3 Wednesday July 19
- Large extra dimensions: ADD
- Universal extra dimensions; particle spins and UED vs. SUSY

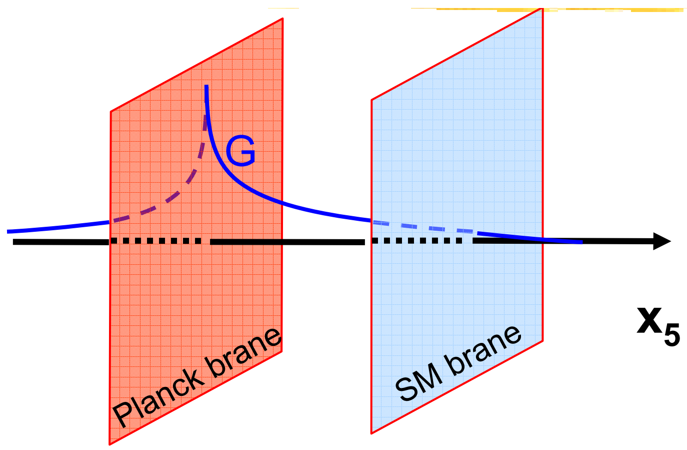
Lecture 4 Thursday July 20
- Deconstruction and the Little Higgs
- T-parity

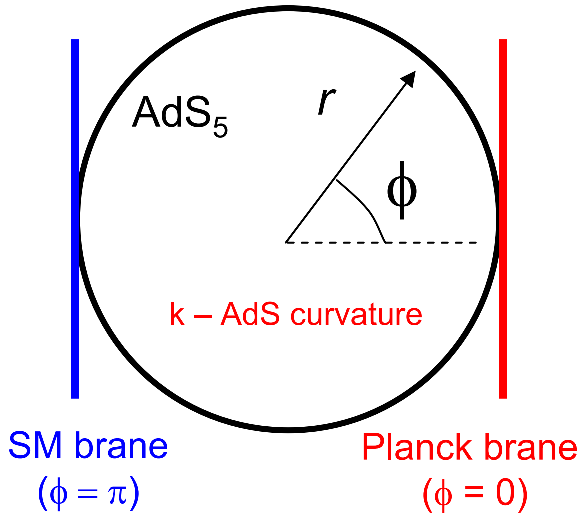
Lecture 5 Friday July 21
- Warped extra dimensions: RS
- RS and Technicolour

Randall-Sundrum (RS) model: a warped extra dimension (1999)

Model introduces a 5th dimension, but unlike our 4 dimensions:
5th dimension is "warped" (the metric is not flat).

$$ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2$$





figures from talk by Landsberg, SLAC Summer Institute 2004

$e^{-2kr|\phi|}$ is called the "warp factor".
$\phi = [0, \pi]$ is the coordinate in the 5th dimension.

Scales from the Planck brane ($\phi = 0$) get "warped down" on the SM brane ($\phi = \pi$):
The SM brane cutoff is $\Lambda_\pi = \overline{M}_{\rm Pl} e^{-kr\pi}$.
For $kr \sim 11$, the warp factor is $e^{-2kr\pi} \sim {\rm TeV}^2/M_{\rm Pl}^2$.
Extra dimension is small: $r \lesssim 10^3/M_{\rm Pl}$.

The SM particles are stuck on the SM brane (similar to ADD).
The 5th dimension contains gravity only.
Because of the branes at $\phi = 0$ and π the 5th dimension is compact: graviton gets KK modes.

The warped metric causes the zero-mode graviton to be localized near the Planck brane.
The overlap of the zero-mode graviton with us (on the SM brane) is small: suppressed by $1/M_{\mathrm{Pl}}$. Explains why gravity is so weak.

The graviton KK modes are localized near the SM brane.
Their couplings suppressed only by $1/\Lambda_\pi$: coupling is not weak.

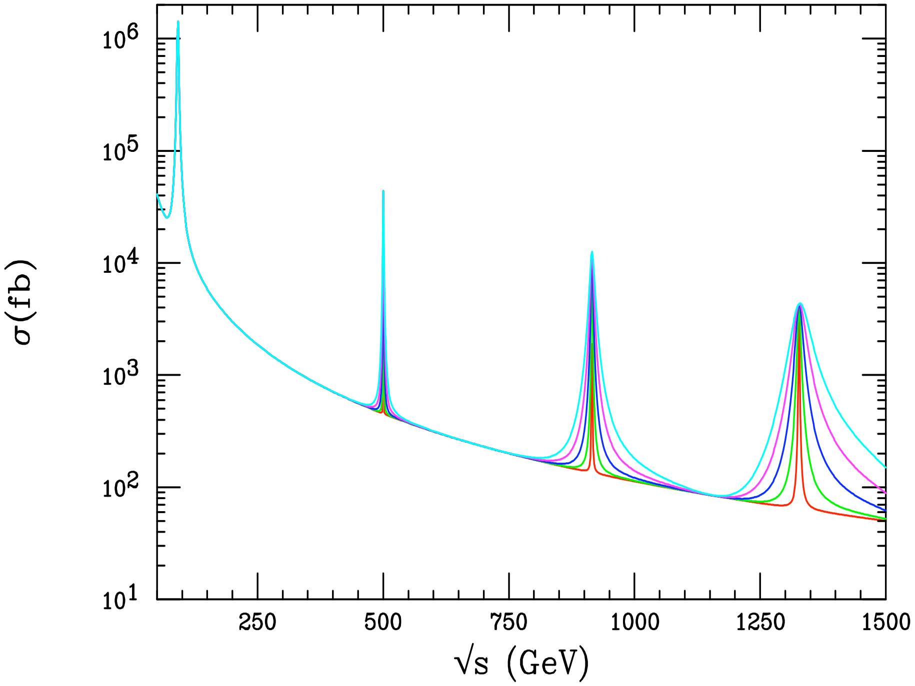
Planck-brane cutoff M_{Pl} gets "warped down" to Λ_π on the SM brane: Loop effects on SM side are controlled by Λ_π.
Can get the required $\mathrm{TeV}^2/M_{\mathrm{Pl}}^2$ hierarchy by putting in one reasonable-size number, $kr \sim 11$.
[k is the curvature and r is the size of the 5th dimension in M_{Pl} units.]
No need for a size $\gg M_{\mathrm{Pl}}$, because of the exponential warping.

This solves the hierarchy problem!

Graviton KK mode resonances in RS

These graviton resonances have reasonable-sized couplings – not super-weak like gravity! This is different from the ADD model.

The reason is that the KK graviton resonances live near our TeV brane. Normal gravity is so weak because the graviton zero mode lives far away from our brane.



$$e^+e^- \to G^{(n)} \to \mu\mu$$

$M_{G^{(1)}} = 500$ GeV

Colours correspond to curvature k of the extra dimension:

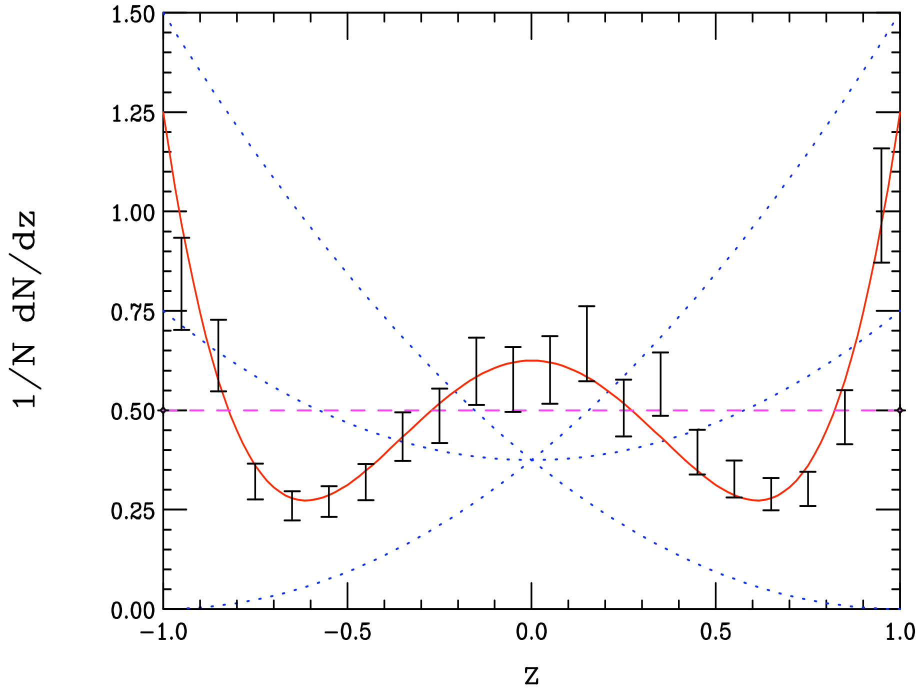
$k/\overline{M}_{\rm Pl} = 0.01$–$0.05$

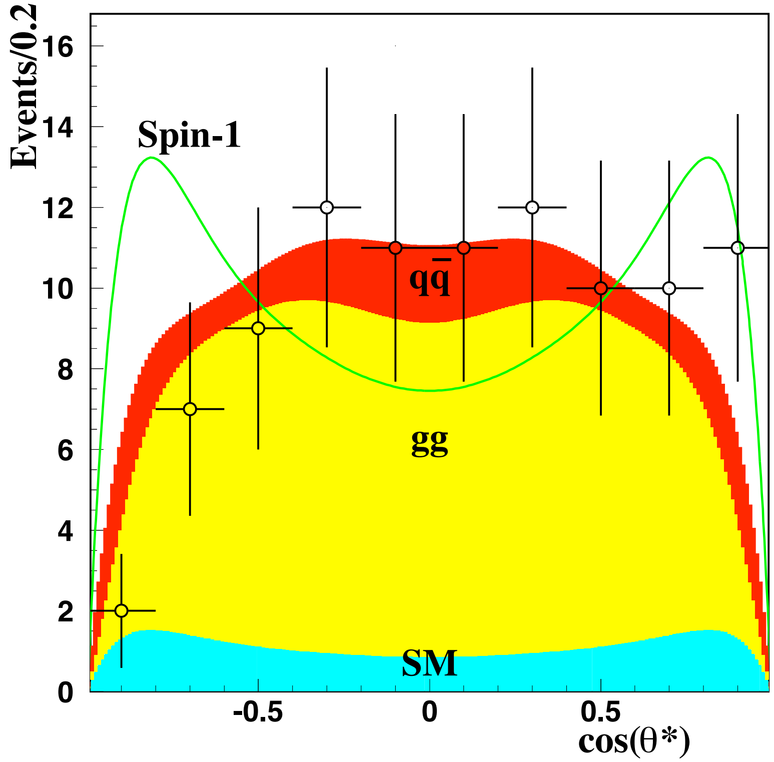
from Hewett & Spiropulu, hep-ph/0205106

How could we tell they are KK gravitons?

Detect the characteristic spin-2 nature of the KK graviton by looking at the angular distribution of the final-state particles! Distribution in $\cos\theta^*$, the angle between beam direction and final-state particle direction in the CM frame.

$pp \to G^{(1)} \to gg, q\bar{q}$ for 1.5 TeV $G^{(1)}$, 100 fb^{-1} at LHC:



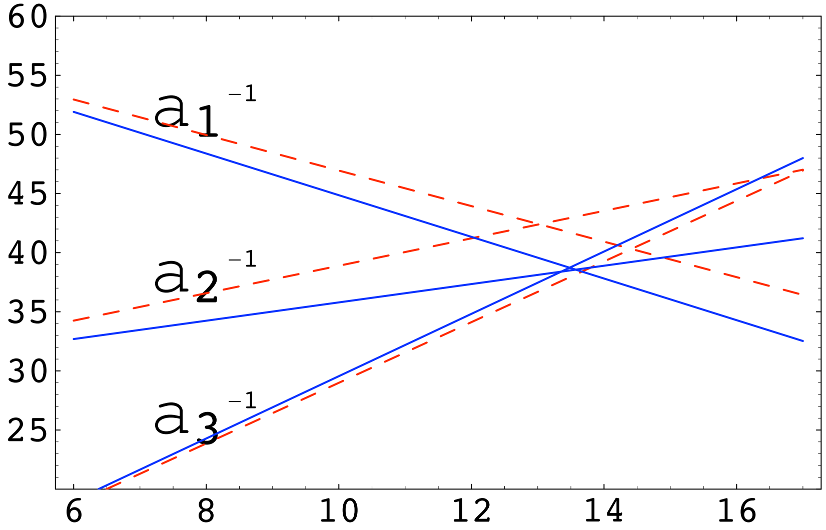


Graviton vs spin-1:
Signal only, from Davoudiasl, Hewett & Rizzo, hep-ph/0006041

Signal + background + cuts, from Allanach, Odagiri, Parker, & Webber, hep-ph/0006114

A variant of RS: Let the SM particles propagate in the bulk!

Gauge fields in the bulk: meaningful theory up to M_{Pl}; can talk about gauge coupling unification.



Choose appropriate set of particles to enter the bulk: can even get unification with only SM on the TeV brane.

from Randall & Schwartz, hep-th/0108114

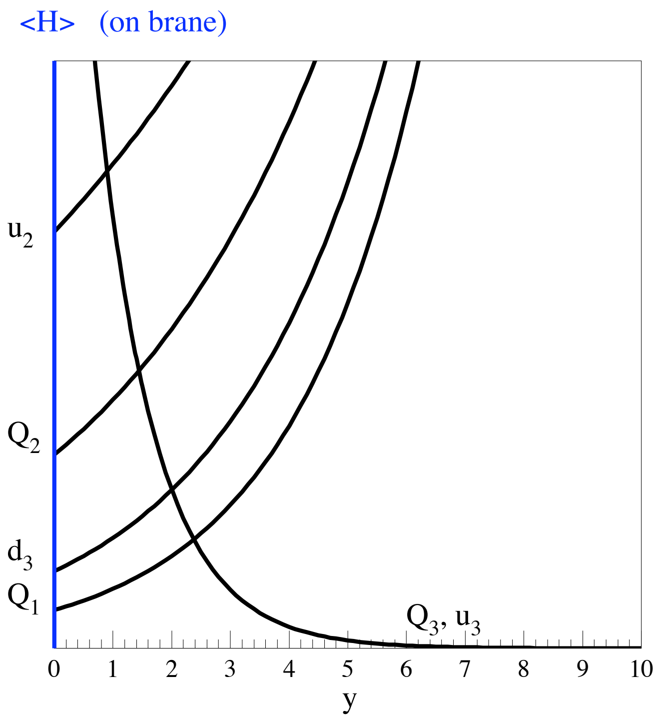
Fermions in the bulk: avoid possible FCNC operators cut off by $\Lambda_\pi \sim$ TeV by putting them near the Planck brane: effective cutoff becomes very high.

Higgs must still be localized on or near the "TeV brane":
Want the Higgs to feel the low cutoff $\Lambda_\pi \sim$ TeV to retain solution to the hierarchy problem.

Higgs-fermion couplings: fermion wavefunctions have to overlap with the Higgs wavefunction.

Light fermions can be localized near the Planck brane: offers warped-extra-dimensional explanation of large fermion mass hierarchy: warp exponential converts reasonable parameter range to huge mass hierarchy.

Top quark is heavy: need large overlap with the Higgs: must be localized near the TeV brane.



from Kaplan & Tait, hep-ph/0110126

Expect to get new physics operators affecting the top quark with a low cutoff $\Lambda_\pi \sim$ TeV.

Everything that lives in the bulk gets KK modes starting at the scale Λ_π. Spacing of the modes depends on warp factor and where the zero-mode is localized in the bulk.

Couplings between particles depend on the overlap of the wavefunctions in the 5-dim space.
Can get enhancements or suppressions of KK mode production cross sections, flavour dependence, etc.

Phenomenology:

KK modes are produced as resonances.

Gauge boson KK excitations: use the usual Z', W' searches.

Fermion KK excitations: produce them in pairs, or singly if they mix with the SM fermions [mixing is constrained by FCNC considerations].

Graviton KK modes are still there, just like in the RS model with the SM on the TeV brane.

And now for something (apparently) completely different:

Technicolour

[as promised in Lecture 1]

There are no fundamental scalars that we've discovered.
The only scalar particles that we know of are the mesons of QCD, composite quark+antiquark bound-states confined by the strong interaction.

Let's take a closer look at this in QCD.

Ignore the electroweak couplings and masses of the quarks. To QCD, all the quarks look alike; without masses the quarks are chiral (q_L and q_R are separate states).
There is a global chiral flavour symmetry [$n_G = \#$ of generations]:

$$\mathcal{G}_\chi = \mathrm{SU}(2n_G)_L \times \mathrm{SU}(2n_G)_R.$$

The strong coupling runs stronger in the infrared (low energies) until QCD confines.
After confinement there is a quark condensate $\langle \bar{q}_L q_R \rangle \neq 0$.

The quark condensate breaks the global chiral flavour symmetry:

$$\mathrm{SU}(2n_G)_L \times \mathrm{SU}(2n_G)_R \longrightarrow \mathrm{SU}(2n_G)_V.$$

[SU$(2n_G)_V$ is the diagonal subgroup.]

There are thus $(2n_G)^2 - 1$ Goldstone bosons (massless pseudoscalar mesons): these are the pions ($\bar{q}q$ bound states).

Now turn the electroweak interactions back on. The quark condensate $\langle \bar{q}_L q_R \rangle \neq 0$ breaks SU$(2)_L\times$ U$(1)_Y$ down to U$(1)_{\mathrm{EM}}$.

The $W^{\pm}$ and Z get masses from the pion decay constant f_π:

$$m_W = g\sqrt{n_G} f_\pi/2, \qquad m_Z = \sqrt{g^2 + g'^2}\sqrt{n_G} f_\pi/2$$

where the "pion decay constant" $f_\pi \simeq 93$ GeV is related to the condensate by $\langle \bar{q}_L q_R \rangle \sim 4\pi f_\pi^3$.

Electroweak symmetry has been broken!

Unfortunately f_π gives way too small masses:

$m_W \simeq 52.7$ MeV, $m_Z \simeq 59.6$ MeV.

Compare actual masses: $m_W = 80.42$ GeV, $m_Z = 91.188$ GeV.

This points the way to Technicolour.

Replicate QCD at 1 TeV instead of 1 GeV. (1976/1979)

New gauge group G_{TC} that gets strong around a TeV

Have N_D doublets of fermions charged under G_{TC}

"Pion decay constant" becomes:

$$\sqrt{n_G} f_\pi \rightarrow \sqrt{N_D} F_{\pi_T} = 246 \text{ GeV}$$

"QCD compositeness scale" becomes:

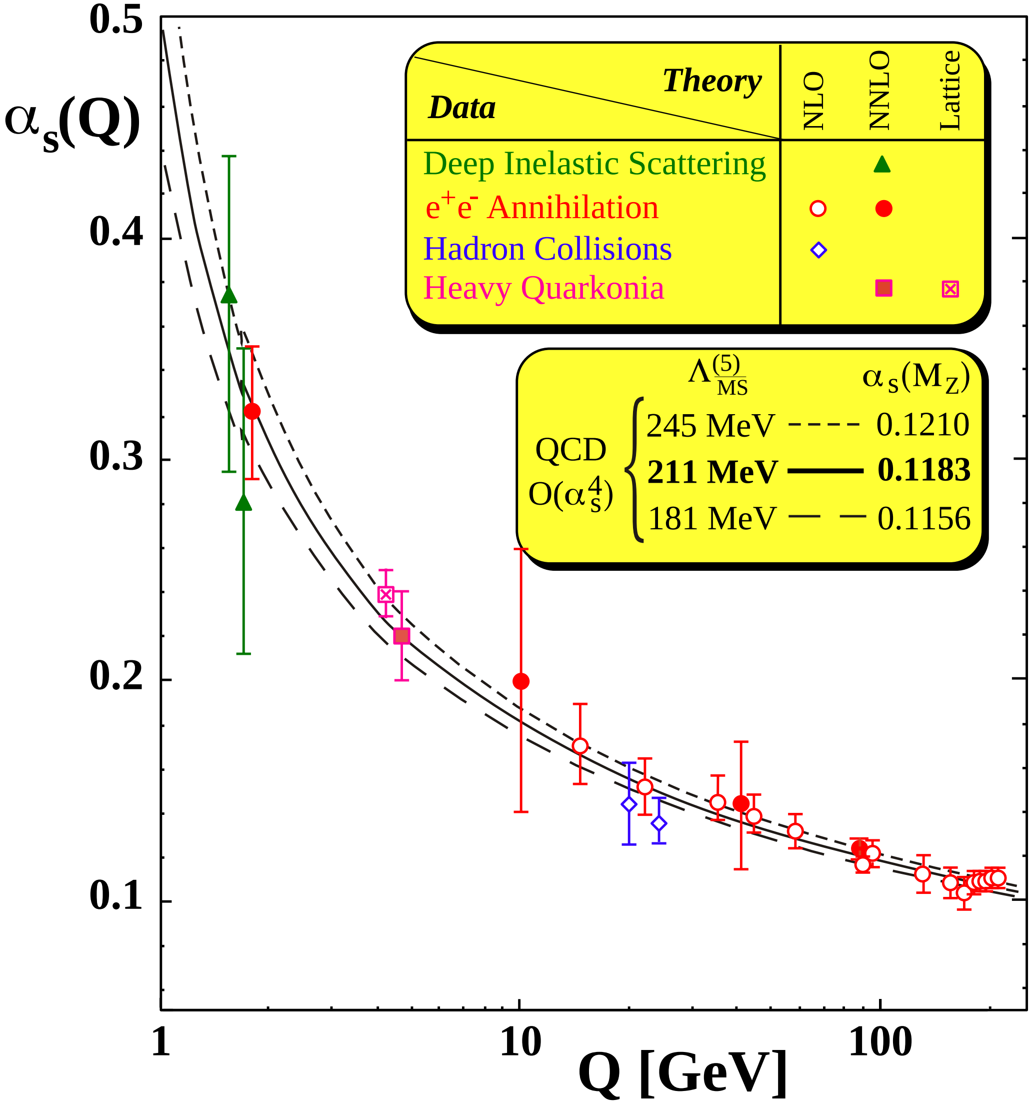
$$\Lambda_{QCD} \rightarrow \Lambda_{TC} = \text{few} \times F_{\pi_T}$$

As in QCD, the model should have an infinite tower of bound states – technihadrons.

E.g., techni-rho ρ_T (isotriplet vector meson); techni-omega ω_T (isosinglet vector meson).

Both are colour singlets: produced by weak interactions.

Technicolour scale Λ_{TC} is where the gauge coupling α_{TC} runs strong: just like for Λ_{QCD}.



Experimental plot of the running of α_s.

Note the fit to Λ_{QCD} and the corresponding $\alpha_s(M_Z)$.

from Bethke, hep-ex/0211012

Scale of Λ_{TC}, and hence the EW scale, is ultimately set by the starting value of α_{TC} at M_{Pl}.

Main problem with minimal Technicolour:

No masses for quarks and leptons, since there is nothing to break their chiral symmetry!

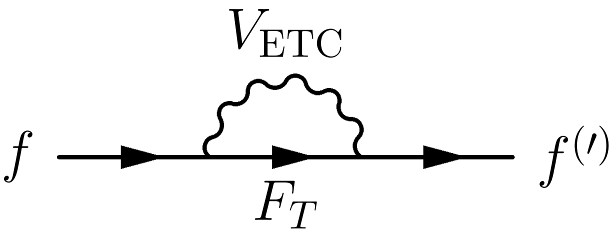
To solve this, we need to break the chiral symmetry.

Introduce new interactions that break the unwanted symmetry!

To break the quark, lepton, and technifermion flavour symmetries, we can gauge all or part of these symmetries.

Extend the gauge group at higher energies.

This is called Extended Technicolour (ETC).



Fermion masses are loop generated: suppressed by M_{ETC}.

If TC is like QCD and runs weak quickly above Λ_{TC}, then we can ignore the running of the technifermion condensate. Plugging in the TC scale one gets:

$$m_q/1\ \text{GeV} \simeq (14\ \text{TeV}/N_D^3\Lambda_{ETC})^2$$

Light quarks are ok; charm is hard; bottom is really iffy, top is impossible!

Constraints and problems of Technicolour

There are two main problems with QCD-like (extended) Technicolour:

Flavour-changing neutral currents

The ETC interactions that generate quark masses also give flavour-changing interactions.

These cause big problems if Λ_{ETC} is below ~ 100 TeV.

But we need Λ_{ETC} low to generate c, b (t??) masses.

Electroweak precision constraints

Technicolour is a strongly coupled theory: we can't calculate things well.

But we have QCD as a model: assume TC is QCD-like, then read off corrections to EW precision observables.

It's ruled out. :P

The way around both of these problems is Technicolour that is not like QCD: the coupling α_{TC} should stay strong for a long time above Λ_{TC}, so that masses and couplings run significantly.

Called "Walking Technicolour" (instead of "running").

Walking Technicolour

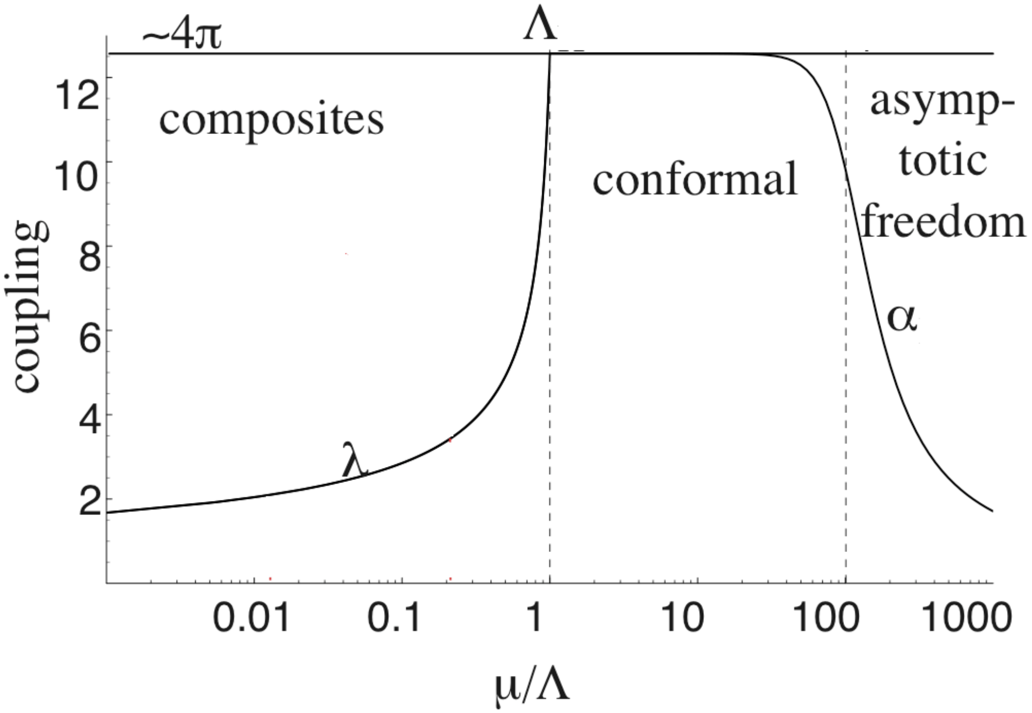


figure adapted from Harnik, Kribs, Larson & Murayama, hep-ph/0311349

It's not like QCD: α_{TC} stays strong for a long time above Λ_{TC}.

Fermion masses get renormalized strongly; can put Λ_{ETC} higher.

Helps with FCNC problem!

Corrections to electroweak observables are different from the QCD analogue.

They might not be too big!

But without the guidance of QCD data, we don't know how to calculate things.

This is where the Randall-Sundrum framework comes back in.

Randall-Sundrum warped spacetime is an Anti–de Sitter (AdS) space: a space with negative curvature (in the 5th dimension).
There is a (conjectured) correspondence between theories in AdS space and conformal field theories (CFT) on the edge bounding the space [AdS/CFT or Maldacena conjecture (1997)]
Conformal means scale-invariant: the couplings don't run.
Walking Technicolour is approximately conformal in the energy range we're interested in.

The AdS is weakly curved (gravity is weakly coupled) where the CFT is strongly coupled: this gives us a way to calculate! (to the extent that the correspondence is valid.)

5-dim states on or near the TeV brane correspond to bound states of the CFT.
5-dim states on or near the Planck brane correspond to fundamental (pointlike) particles.

A Composite Higgs model and AdS/CFT

AdS/CFT correspondence has been used recently to make a concrete composite Higgs model.

Agashe, Contino, & Pomarol, hep-ph/0412089

It's straightforward to make a 4-dim effective theory of a composite Higgs.
Higgs is a bound-state of some fundamental fermions confined by a new strong interaction.
Let's assume the strong interaction is conformal for some energy range above the compositeness scale.
Effects of the strongly-coupled CFT are parameterized as unknown operator coefficients in effective theory:
can't calculate them in the CFT because of strong coupling.

Use the AdS/CFT correspondence:
5-dim AdS theory is weakly coupled where CFT is strongly coupled. Can calculate the operator coefficients!

Fermion sector

4-dim CFT picture:
Higgs boson is composite; right-handed top quark is mostly composite [a mixture of fundamental fermion and CFT bound-state].
Other SM particles are fundamental (or mostly fundamental [mixtures of fundamental fermion and CFT bound-state]).
5-dim AdS picture:
Higgs lives on the TeV brane; right-handed top quark is localized near TeV brane.
Other SM particles live near the Planck brane.

Fermions are set up this way so that the top can get a large enough mass:
overlap with Higgs wavefunction in 5-dim picture;
mostly-composite mixture of CFT bound-state and fundamental fermion in 4-dim picture.

Lighter fermions don't need big overlap with Higgs wavefunction:
can be localized near Planck brane in 5-dim picture;
can be fundamental fermions in 4-dim picture.

Gauge & global symmetry sector

4-dim picture:

Model has an SO(5) $\times$ U(1)$_{B-L}$ global symmetry, which spontaneously breaks to SO(4).

Higgs doublet is a PNGB; transforms as a **4** of SO(4).

After EWSB, a "custodial" SO(3) global symmetry is still preserved [protects the m_W/m_Z ratio from corrections: good for EW precision].

5-dim picture:

A global symmetry in the 4-dim picture corresponds to a gauge symmetry in the bulk of the 5-dim theory but broken on the branes.

Bulk gauge symmetry is SU(3)$_c\times$ SO(5) $\times$ U(1)$_{B-L}$.

On TeV brane the gauge symmetry is SU(3)$_c\times$ SO(4) $\times$ U(1)$_{B-L}$.

On Planck brane the gauge symmetry is SU(3)$_c\times$ SU(2)$_L\times$ U(1)$_Y$.

Breaking on the branes is easy to achieve by imposing appropriate boundary conditions on the gauge bosons whose generators we want to break.

The 4-dim PNGBs correspond to the A_5 components of the bulk gauge generators in SO(5)/SO(4).

Higgs potential:

Generated by SM particle loops. EWSB is triggered by contribution from top quark loop (Δm^2 is negative).

Fermion resonances:

5-dim picture: get KK resonances because they live at least partly in the bulk.

4-dim picture: fermions contain a small admixture of composite CFT bound-state, so they have a corresponding tower of CFT states (like the tower of hadrons in QCD).

Weak gauge group in the bulk is SO(5):

Fermions are expanded to full SO(5) representations in the bulk.

Fermion and vector boson resonances (KK modes) come in complete representations of SO(5).

Electroweak precision constraints:

Unlike in the 4-dim CFT, the contributions to EW precision observables are calculable in the 5-dim AdS theory!

Constraints: lightest vector state ρ ("techni-rho" in CFT; KK gauge boson in AdS) must be heavier than about 2 TeV.

Phenomenology:

Can calculate masses! Model is remarkably well under control.
Scan over model's free parameters:

Higgs mass $m_H \lesssim 140$ GeV in minimal model.
LEP direct search rules out $m_H < 114$ GeV already.

3rd generation fermion resonances (KK modes) $\hat{q}_L = (\hat{t}_L, \hat{b}_L)$, $\hat{t}_R$, and $\hat{b}_R$ are usually lighter than the vector resonances (gauge KK modes).

For allowed Higgs mass values:
3rd gen. fermion resonances (KK modes) lie around 1.5–2 TeV.
"Techni-rho" (lightest gauge KK mode) lies around 2–3 TeV.

Fermion resonances can be singly produced via their interactions with the Higgs doublet [longitudinal components of W, Z are the Goldstone bosons]:

$$b_L + W_{long} \to \hat{t}_R$$
$$b_L + Z_{long} \to \hat{b}_R$$

Production of $\hat{t}_R$ is very similar to T in Little Higgs models.
Coupling is enhanced between CFT states (5-dim bulk states): get enhanced production.

Fermion resonances can also be singly produced via a KK gluon resonance: $q\bar{q} \to \hat{g}^* \to t_L \hat{t}_L$, $b_L \hat{b}_L$, etc.

Fermion resonances can be pair produced via QCD
[suppressed by 2 heavy masses in final state].

Gauge resonances (KK modes) can be singly produced:
Look for them in dileptons (Drell-Yan).

Finally, Technicolour itself has an analogue in AdS:
the warped 5-dim "Higgsless models".

5-dim picture: SM gauge sector is in the bulk.
Boundary conditions chosen so there is no zero mode: Lightest gauge boson is 1st KK excitation!
EWSB is caused by extra-dimensional boundary conditions.

Go down to 4-dim: Models contain KK excitations of the W, Z which play some of the role of the Higgs in regularizing longitudinal gauge boson scattering.
Presumably corresponds to a Walking Technicolour–like CFT theory: new vectors interpreted as techni-rho–like states.
The theory stays under control up to somewhat higher energies than the SM without a Higgs.

EW precision constraints:
Walking Technicolour wasn't calculable.
But now the 5-dim theory is (more or less) calculable:
there appear to be issues with electroweak precision observables that severely costrain the model.

This hasn't been entirely thrashed out yet.

Summary (1/2)

We talked about:

Warped extra dimensions: RS model
Can have only gravity in the bulk, or the whole SM.
Solution to the hierarchy problem!
Phenomenology: KK resonances at the TeV scale.

Technicolour
Breaking of EW symmetry by strong interactions: analogue of QCD.
Solution to the hierarchy problem!
Strongly coupled: can't calculate reliably.

Composite Higgs models and AdS/CFT correspondence
Take advantage of Technicolour-like model, but with Higgs as a PNGB.
Use AdS/CFT correspondence to calculate in strongly-coupled theory!
Spectrum is rather like RS model: RS KK resonances correspond to Technihadron resonances!

Summary (2/2)

I've tried to give you a flavour of the "landscape" of Beyond the Standard Model physics.

BSM model-building motivated mainly by the Hierarchy Problem.

BSM models try to solve the hierarchy problem and reduce fine-tuning in the Higgs mass parameter.

To do so, they all introduce new particles and new symmetries near the TeV scale.

We covered:

- SUSY
- Extra dimensions: ADD, UED
- Little Higgs (Higgs as a PNGB)
- Warped extra-dim (RS), Technicolour, composite Higgs

Themes were discovery and measurements to uncover the mechanism of Higgs mass stabilization and the new physics principles that govern the TeV scale.

What we need now is data!

"Nothing focuses the mind like interesting experimental results." – Ken Lane