Electroweak-Scale Strong

Dynamics

Lecture #1

Adam Martin Yale University

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Outline:

Lecture #1: Dynamical Electroweak Symmetry Breaking (DEWSB)

- Part 1: -> pros and cons of the SM Higgs, why alternatives may be good
 - -> Dynamical EWSB (Technicolor) as an alternative,
 - -> Extended Technicolor: fermion mass generation
 - -> problems with 'old' Technicolor

Part 2:

- -> Peculiarities of QCD and the phases of gauge theory
- -> Walking Technicolor (WTC) motivation and implementation,
- -> how walking saves the day & where it fails,
- -> walking studies on the lattice
- -> LHC phenomenology of 'modern' technicolor

Lecture #2: Related topics

- -> Other Tev-scale strong dynamics: Composite Higgs
- -> Extra-Dimensions models of Technicolor: Higgsless models
- -> Technicolor and Park Matter

We are finally in the LHC era



the most exciting time in particle physics in the last <u>three</u> <u>decades</u>

this machine is built to probe the 100 GeV - few TeV energy range

This is an incredibly exciting time for particle physics!

LHC is a 27 km circumference pp collider with center of mass energy 10-14 TeV (7 TeV initially)





SUPERCONDUCTING COIL

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14.00 m

29. PA M

HADRON CAL.

CHS 1886



cartoons don't quite do the size of these experiments justice!

Why did we build the LHC?

* The Standard Model is highly successful and describes all observations to date The Standard Model of

forces between matter are described by the exchange of 'force-carrying' particles





* Guiding principles are gauge invariance, renormalizability

* Massless photon, gluon, while massive W^{\pm}, Z

Why did we build the LHC?

- Gauge invariance prevents mass terms for gauge bosons or chiral fermions
 - under $SU(2)_W$

$$\begin{array}{ll} W^a_{\mu} \rightarrow U_L A^a_{\mu} U^{\dagger} - \frac{i}{g} (\partial_{\mu} U_L) U^{\dagger}_L & \text{forbid} & m_A^2 A^{\mu} A_{\mu} \\ q_L \rightarrow U_L q_L, & q_R \rightarrow q_R & \end{array}$$

* Gauge boson mass is possible only through the HIGGS MECHANSIM: spontaneous breakdown of $SU(2)_w \otimes U(1)_Y \to U(1)_{em}$

 How can such a breakdown occur? Simplest idea -- use a single scalar field with a very particular potential



The remaining combination $\cos(\theta_W)B + \sin(\theta_W)W_3 \equiv \gamma$ is massless





Higgs Mechanism vs. Higgs Boson * π_a can be removed by an $SU(2)_W \otimes U(1)_Y$ gauge transformation ---> Unitary Gauge

 π_a are eaten by the W^\pm, Z to become their longitudinal degrees of freedom (Higgs mechanism)

$$\overset{A_{\mu}}{\sim} \overset{A_{\mu}}{\sim} + \overset{A_{\mu}}{\sim} \overset{A_{\mu}}{\sim} - \overset{A_{\mu}}{\sim} \overset{A_{\mu}}{\sim}$$

* The Higgs mechanism doesn't care where the three degrees of freedom come from (independent of Higgs boson)



some operator, fundamental or composite, with $(2, \frac{1}{2})$ quantum numbers under $SU(2)_w \otimes U(1)_Y$

Why did we build the LHC?

- what's wrong with just adding mass terms for W, Z?
- Scattering amplitudes involving the longitudinal polarizations are BADLY behaved



 E^4 piece cancels between (a) - (c), but leftover E^2 piece

Something must cancel this growth or perturbative unitarity will be violated $\mathcal{A} > 1$

Adding the Higgs boson does this perfectly, provided it is LIGHT, $m_H \lesssim 1~{\rm TeV}$



Role of Custodial Symmetry

- Success of single SM Higgs tells us something deeper about whatever other mechanism for EWSB we might want to try:
- * Higgs potential has a LARGER (global) symmetry:

re-express:then $V = \lambda (H^{\dagger}H - \frac{v^2}{2})^2$ $H = \begin{pmatrix} h_1 + ih_2 \\ h_0 + ih_3 \end{pmatrix}$ depends only on $h_0^2 + h_1^2 + h_2^2 + h_3^2$ therefore is invariant under $SO(4) \cong SU(2) \otimes SU(2)$

in the vacuum, $\langle h_0 \rangle = v$ breaks this down to $SO(3) \cong SU(2)$

residual SU(2) is called a 'custodial symmetry'

If the rest of the Largangian were exactly SU(2) invariant, $h_1, h_2, h_3 \rightarrow W^{\pm}, Z^0$ would all have the same mass

Role of Custodial Symmetry, #2

BUT, SM interactions do NOT respect this symmetry, specifically hypercharge



So, we've learned:

• massless photon, • custodial symmetry when $g' \rightarrow 0$

experimentally verified result $\rho\cong 1$

Custodial Symmetry is an important part of any theory of EWSB!



Why theorists like a simple Higgs

- Once we consider quantum corrections to the tree level SM, couplings and parameters become sensitive to the Higgs properties (or other new physics)--> indirect tests
- * Example: oblique corrections



Precision Electroweak Tests

- * we have six corrections A, B, C, D, w, z, but three can be absorbed into the three parameters which define the EW theory g, g', v (more conveniently α_{em}, G_F, M_Z)
- * The remaining three corrections parameterize new physics, and are commonly combined into the combinations S,T,U

* Within SM: $S(m_h, m_t, ...)$, if new physics: $S(m_h, m_t, M_X, g_X, ...)$

* All deviations from the tree-level SM in the EW sector can be phrased in terms of S.T.U

$$\begin{split} \delta g_{iL(R)} &= \frac{\alpha T}{2} - Q_i \Big(\frac{\alpha S}{4(c_w^2 - s_w^2)} - \frac{c_w^2 s_w^2 \alpha T}{c_w^2 - s_w^2} \Big) \\ \frac{\delta M_W^2}{M_W^2} &= -\frac{\alpha S}{2(c_w^2 - s_w^2)} + \frac{c_w^2 \alpha T}{c_w^2 - s_w^2} + \frac{\alpha U}{4s_w^2} \text{ ,etc} \end{split}$$

Precision Electroweak Tests

* LEP, LEP II (1989 - 2000) experiments measured $\delta g_{iL(R)}, M_W, A_{LR}$, etc. precisely. $\sqrt{s} \leq 208 \text{ GeV}$



Why theorists dislike just a SM Higgs

- * NO fundamental scalars have been seen in nature
- * Higgs potential and vev are put in by hand: chosen so that V(0) = 0, V''(0) < 0
- * Quantum corrections in the Higgs sector are badly divergent:





no chiral renormalization of scalar mass is additive, not multiplicitive: symmetry!



ONLY by arranging a precise cancelation, $\delta m_H^2 \cong -m_{H,bare}^2$

Why theorists dislike just a SM Higgs, #2 How severe a cancelation do we need? $e^{x.}m_{H,phys}^2 = 120 \text{ GeV}$

$$\begin{split} \Lambda &= 10 \ {\rm TeV}, \ m_H^2/\Lambda^2 \cong 2\% \\ \Lambda &= 1000 \ {\rm TeV}, \ m_H^2/\Lambda^2 \cong 0.01\% \end{split}$$

 $\Lambda = M_{pl} \ , \ m_H^2 / \Lambda^2 \cong 10^{-32} \%$

Are there high scales? YES

more abstractly, less in terms of diagrams:

why is the weak scale so much less than the Planck scale?

this question is so important it has its own name: <u>THE HIERARCHY PROBLEM</u>

How incredible is this?



ITALY, LEAD BY NEW PLAYER HIGGS, WINS WORLD CUP FINAL 1000 - 0



theoretically possible, but hard to imagine within the rules we trust either Higgs is unlike the other particles/players we know, or there is more going on **Common Lore:**

<u>One possible solution</u>: reduce the dependence on the UV by adding new particles whose effects cancel the SM effects

such as: Supersymmetry (SUSY)



superparticles



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SUSY has enticing properties

* weakly coupled

BUT

- * PM candidate (observed)
- * Gauge coupling unification (theoretical bias)

* Not necessary for EWSB

- * No SUSY particles at LEP or Tevatron
- * DM: Any model with a discrete symmetry + TeV stuff

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Instead: Since the Higgs boson is the source of all the theoretical issues, why don't we just get rid of it?

Dynamical Symmetry Breaking

Mass generation **without** the Higgs boson

Why not Dynamical Symmetry Breaking?

- * For mass generation without scalars, lets turn to QCD for inspiration
- * No scalars, instead strong interactions
- * Inspired by QCP, we can imagine that the W and Z are composite objects, formed by from some new strong interaction $W^{\pm}, Z^0 \sim$

but if there is some new strong interaction, why are the W/Z the only composites we see?

The other composites must be heavy .. but how can this be?

Why not Dynamical Symmetry Breaking?

* The same question could be asked about QCP!

* In QCD we have massive hadrons composed of up and down quarks



from their constituents alone, it is unclear <u>why the pion is so light</u> <u>compared to the other (u,d) hadrons</u>

Dynamical Symmetry Breaking (DSB) in QCD

* Re-examine the Lagrangian for QCP (taking massless quarks)

 $\mathcal{L} = i\bar{u}_L \mathcal{D} u_L + i\bar{d}_L \mathcal{D} d_L + i\bar{u}_R \mathcal{D} u_R + i\bar{d}_R \mathcal{D} d_R$

displays a $SU(2)_L \otimes SU(2)_R$ global "chiral" symmetry

 $\left(\begin{array}{c}U_{L}'\\D_{L}'\end{array}\right)=V_{L}\left(\begin{array}{c}U_{L}\\D_{L}\end{array}\right)\quad\left(\begin{array}{c}U_{R}'\\D_{R}'\end{array}\right)=V_{R}\left(\begin{array}{c}U_{R}\\D_{R}\end{array}\right)$

* The QCD coupling changes with energy,



becoming strong at energies $\sim 1~{\rm GeV}$

Dynamical Symmetry Breaking in QCD

• as a result of the strong QCD DYNAMICS

 $\langle \bar{q}_L q_R \rangle \neq 0$ $\langle \bar{q}_L q_R \rangle = 4\pi f_\pi^3$ under a general $SU(2)_L \otimes SU(2)_R$ transformation

is only invariant if $U_L = U_R$ the `vectorial' subgroup

So, as a result of DYNAMICS alone $SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_V$

 $\langle \bar{q}_L q_R \rangle \rightarrow \langle \bar{q}_L U_L^{\dagger} U_R q_R \rangle$

 The remaining symmetry is broken -> we get a massless Nambu-Goldstone Boson for each broken generator

• Pions $\pi = (\bar{q}_L q_R)$ are the Goldstone bosons of QCP DSB: this is how we understand the light pion

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So, as a result of PYNAMICS alone $SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_V$ QCD DSB has a custodial symmetry!

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• Pions $\pi = (\bar{q}_L q_R)$ are the Goldstone bosons of QCD DSB: this is how we understand the light pion





 $\langle \phi^{++} \rangle \neq 0$



"Abelian Higgs Model"

Weinberg: "Superconductivity for Particular Theorists"

Naturalness

 Pynamical symmetry breaking by asymptotically free gauge interactions explains hierarchies between scales naturally:



In fact, it is the only explanation!

Let's use this to solve the hierarchy problem by <u>dynamically breaking electroweak symmetry</u>

What is Technicolor?

• A new strong interaction at the EW scale causes a nonzero expectation value for a (techni) fermion bilinear with $(2, \pm \frac{1}{2})$ quantum numbers \longrightarrow EWSB

Higgs mechanism, but no Higgs particle! W/Z are the "pions" of the new strong dynamics

 a <u>natural</u> solution to hierarchy problem, BUT we understand very little about strong interactions:

Limited tools: QCD, lattice, and (recently) 5D theories

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same quant. # as higgs scalar

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Ingredients for Technicolor #1 (Weinberg '78, Susskind '79) N_D doublets of massless (techni) fermions $SU(N_{TC})$ strong gauge theory (technicolor) $T_L = (U_L, D_L) \text{ are electroweak doublets} \\ U_R, D_R \text{ are electroweak singlets} \\ SU(N_{TC}) \\ \text{fundamentals}$ $\mathcal{L}_{TC} = i\bar{T}_L \not\!\!\!D T_L + i\bar{U}_R \not\!\!\!D U_R + i\bar{D}_R \not\!\!\!D D_R - \frac{1}{4}G^a_{TC,\mu\nu}G^{a,\mu\nu}_{TC}$ The global chiral symmetry is $SU(2N_D)_L \otimes SU(2N_D)_R \supset SU(2)_w \otimes U(1)_Y$ Envision $SU(N)_{TC}$ is stronger than QCD, becoming confining at $\Lambda_{TC} \sim 1 \text{ TeV}$
Details of Technicolor #2

once TC becomes confining:

$$\langle \bar{U}_{Li} U_{Rj} \rangle = \langle \bar{D}_{Li} D_{Rj} \rangle = 4\pi F_T^3 \delta_{ij} \neq 0$$

just like in QCP, this condensate spontaneously breaks chiral symmetry

 $SU(2N_D)_L \otimes SU(2N_D)_R \to SU(2N_D)_V$

because the TC condensate has EW quantum numbers, $\langle \bar{T}_L T_R \rangle \neq 0 \longleftrightarrow$ ELECTROWEAK SYMMETRY is broken

 $M_W^2 = \frac{g^2 N_D F_T^2}{4} = M_Z^2 \cos^2 \theta_W \quad \therefore \text{ identify} \quad \frac{N_D F_T^2}{\Lambda_T} = v^2$ $\Lambda_T \cong 4\pi F_T \sim \text{TeV}$



 $= \frac{(2N_D)^2 - 1}{-3} \frac{\text{Nambu-Goldstone Bosons}}{\text{eaten by W/Z}}$ $\frac{(2N_D)^2 - 4}{(2N_D)^2 - 4} \frac{\text{leftover "technipions"}}{1000}$

A Technicolor Example, #1

to describe low-energy QCD, use chiral lagrangian

 $\mathcal{L} = i\bar{u}_L \not D u_L + i\bar{d}_L \not D d_L + i\bar{u}_R \not D u_R + i\bar{d}_R \not D d_R \qquad U = e^{2i\vec{\pi}/f_\pi} \quad \vec{\pi} = \pi_a \tau^a$ $\mathcal{L}_{\chi} = \frac{f_\pi^2}{4} \operatorname{tr}(\partial_{\mu} U \partial^{\mu} U^{\dagger}) + \cdots \qquad U \to V_L^{\dagger} U V_R$ $j \text{ust like } \langle \bar{q}_L q_R \rangle$

EW chiral lagrangian: lets take the simplest example, one technidoublet. We have to adjust for the heavier scale, and new ingredient: SU(2), U(1) gauge

$$\mathcal{L}_{EW\chi} = \frac{F_T^2}{4} \operatorname{tr}(D_{\mu} \Sigma D^{\mu} \Sigma^{\dagger}) + \cdots \qquad \Sigma = e^{2i\pi_T^2} / F_T \\ \pi_T = \pi_{T,a} \tau^a \\ D_{\mu} \Sigma = \partial_{\mu} \Sigma - ig \vec{W}_{\mu} \Sigma + i \frac{g'}{2} \Sigma B_{\mu}$$

use gauge invariance to remove π_T --> go to unitary gauge $\Sigma=1$

$$\mathcal{L}_{EW\chi} = \frac{F_T^2}{4} g^2 W_{\mu}^+ W^{-\mu} + \frac{F_T^2}{8\cos^2 \theta_W} Z_{\mu}^2 + \cdots \qquad \text{[what else?]}$$

for more than two techniflavors ($N_D > 1$), there will be extra π_T

A Technicolor Example #2:

* For a more complicated examples, consider a toy model with 2 technidoublets ($N_D=2$)

The chiral symmetry breaking pattern is: $SU(4)_L \otimes SU(4)_R o SU(4)_V$

$$\Sigma = e^{2i\pi \vec{T}/F_T} \quad \vec{\pi}_T = \pi_{T,a} X^a$$

Axial combination, $SU(4)_A$ is broken. The NGBs correspond to these broken symmetry generators: $(2N_D)^2 - 1 = 15 \pi_T$

decompose:

$$X^{a} = \begin{pmatrix} \tau_{a} & 0 \\ 0 & \tau_{a} \end{pmatrix} \begin{pmatrix} U_{L1} \\ D_{L1} \\ U_{L2} \\ D_{L2} \end{pmatrix}$$
• these are the fields eaten by the W, Z
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• uneaten π_{T} , charged under $SU(2)_{W}$
 $\begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix} \cdot \begin{pmatrix} 0 & -iI \\ iI & 0 \end{pmatrix} \cdot \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}$
• uneaten π_{T} , neutral under $SU(2)_{W}$
all 15 NGB accounted for
(Hill, Simmons (03)

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how can WW scattering make sense without a Higgs?



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increasing E, higher order diagrams become important, same size as the tree-level terms.



... but when loop-level diagrams are as important as tree-level diagrams, we have strong coupling and cannot rely on perturbation theory



the S-matrix is perfectly unitary, we just can't calculate

in addition to the strongly-interacting W's, the strong dynamics may also lead to new resonances. The properties (mass, spin, couplings) of the new resonances depend on the details of the underlying theory and cannot be calculated from first principles.



WARNING: new strong interaction may not obey QCD-model rules

Details of Technicolor #2

What other TC bound states are there besides the π_T

* Simplest idea: Estimate TC by rescaling QCD + N_C, N_D counting

$$f_{\pi} \to F_{T}$$

$$\pi \to W^{\pm}, Z, \pi_{T}$$

$$\rho (I = 1) \to \rho_{T}^{\pm}, \rho_{T}^{0}$$

$$a_{1} (I = 1) \to a_{T}^{\pm}, a_{T}^{0}$$

$$\omega (I = 0) \to \omega_{T}$$

$$M_{\rho_{T}} \approx \sqrt{\frac{3}{N_{TC}}} \times 2 \text{ TeV}$$

$$\Gamma(\rho_{T} \to W_{L}W_{L}) \approx 500 \left(\frac{3}{N_{TC}}\right)^{3/2} \text{ GeV}$$

$$\cdots$$







TECHNICOLOR

What about the fermions?

As we have seen, in Technicolor: a new strong interaction at the EW scale is responsible for breaking EW symmetry, thereby giving mass to the W,Z

But what about SM fermion masses ?

SU(2) gauge invariance prevents us from writing down explicit mass terms in \mathcal{L}

 $m_t(t_L^{\dagger}t_R + h.c.) \begin{cases} t_L \text{ carries SU(2) charge} \\ t_R \text{ does NOT} \end{cases}$

In the SM, Yukawa couplings between fermions and Higgs are allowed by all symmetries and become mass terms once EWSB occurs

$$y_t H Q_L^{\dagger} u_R \to m_t u_L^{\dagger} u_R$$

How are we going to generate a mass term with no Higgs?

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Extending Technicolor

- * SM fermions don't feel the strong TC force, but we need them to communicate somehow with the technifermions
- Simplest Idea: Create a new gauge interaction under which both SM fermions and TC fermions transform, and put them in the same representations



* new gauge interaction, called EXTENDED TECHNICOLOR is huge. It contains all techni-flavor and SM flavor as subgroups $G_{ETC} \supset SU(2N_D)_L \otimes SU(2N_D)_R \otimes$ `techni-flavor'

SM flavor $SU(3)_Q \otimes SU(3)_U \otimes SU(3)_D \otimes \cdots$

* Acting on an ETC representation:



* Acting on an ETC representation:



- * The gigantic ETC group has to be broken at some point
- * Assume it is broken at some high scale Λ_{ETC}
- * Integrating out the massive ETC gauge bosons, we are left with higher dimension operators



Concentrating on the β_{ab} terms and performing a Fierz rearrangement:

 $\frac{g_{ETC}^2}{M_{ETC}^2} (\bar{T}_L \gamma_\mu q_R) (\bar{q}_L \gamma^\mu T_R) \rightarrow \frac{g_{ETC}^2}{M_{ETC}^2} (\bar{T}_L T_R) (\bar{q}_L q_R) \quad \begin{array}{l} \text{Instruction} \\ \text{generated at} \\ \text{the scale} \end{array}$

this operator is the scale Λ_{ETC}

Don't get confused!!

* Technicolor and Extended Technicolor sound similar, but they have very different roles and properties

<u>Technicolor:</u> unbroken, strong gauge interaction felt only by technifermions. Causes technifermion chiral symmetry to be broken, leading to NGBs, three of which become the W/ Z longitudinal polarizations

$$\langle \bar{U}_L U_R \rangle = \langle \bar{D}_L D_R \rangle \neq 0 = \langle 4\pi F_T^3 \rangle \quad 4\pi F_T \sim \text{TeV}$$

Extended Technicolor: broken, weak gauge interaction felt by both SM fermions and technifermions. Below the scale of ETC breaking we get higher dimension operators

$$\alpha_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a T) (\bar{T}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \gamma_{ab} \frac{g_{ETC}^2 (\bar{q}\gamma_\mu t^a q) (\bar{q}'\gamma^\mu t^b q')}{M_{ETC}^2}$$

 $M_{ETC} \sim 10 - 1000 \text{ TeV}$

When the technicolor interaction becomes strong at * energies $\Lambda_{TC} \sim 1$ TeV, the four fermion interaction becomes a mass term for the SM fermions



 $\frac{g_{ETC}^2}{M_{ETC}^2} \langle \bar{T}_L T_R \rangle (\bar{q}_L q_R) \equiv m_q \bar{q}_L q_R$

Not quite so simple:

The four fermi operator is generated at Λ_{ETC} , much higher than the scale $\sim 1~{
m TeV}$ where we know the value of $\langle T_L T_R \rangle$.

We need a way to connect $\langle \bar{T}_L T_R \rangle \Big|_{TC}$ and $\langle \bar{T}_L T_R \rangle \Big|_{ETC}$ fixed by EW scaleenters SM mass formulae

Renormalization Group Equations (RGE) relates operators at differing energies

 q_L

* To connect an operator \mathcal{O} at different energy scales we need to know the anomalous dimension ($\gamma \mathcal{O}$) of the operator

$$\gamma_{\mathcal{O}} = \underbrace{\mathcal{O}}_{\underbrace{\mathcal{O}}} \underbrace{\mathcal{O}} \underbrace{\mathcal{O}}_{\underbrace{\mathcal{O}}} \underbrace{\mathcal{O}} \underbrace{\mathcalO} \underbrace{\mathcalO}$$

- * Then: RGE is simply solved $\mathcal{O}(\Lambda_1) = \mathcal{O}(\Lambda_0)exp\left(\int_{\Lambda_0}^{\Lambda_1} \frac{d\mu}{\mu}\gamma_{\mathcal{O}}\right)$
- * For ETC-generated fermion masses $\langle \bar{T}_L T_R \rangle |_{ETC} = \langle \bar{T}_L T_R \rangle |_{TC} \times exp \left(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu} \gamma_{(\bar{T}_L T_R)}(\mu) \right)$

* BUT, how do we calculate the anomalous dimension of in the presence of the strong TC interaction?

* In QCD, $\gamma_{(\bar{q}_L q_R)} \ll 1$ as the coupling is quickly running. ASSUMING this is also the case for TC, we arrive at the ETC mass formula:

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- * BUT, how do we calculate the anomalous dimension of in the presence of the strong TC interaction?
- * In QCP, $\gamma_{(\bar{q}_L q_R)} \ll 1$ as the coupling is quickly running. ASSUMING this is also the case for TC, we arrive at the ETC mass formula:

- ETC also plays another crucial role -- as it explicitly breaks all of the techniflavor symmetry it gives a mass to the uneaten technipions
- * Without ETC , the $SU(2)_W \otimes U(1)_Y$ neutral π_T would be massless and a phenomenological disaster

adding explicit techiflavor symmetry breaking

 $m_{\pi_T,ab}^2 \sim \frac{g_{ETC}^2 \Lambda_{TC}^2 F_{TC}^2}{M_{ETC}^2} \operatorname{Tr}([t^a, t_{ETC}][t^b, t_{ETC}])$

(see Georgi "Weak Interactions in Particle Physics")

* As with the SM fermion masses, the π_T masses are generated by gauge interaction dynamics and NOT by fundamental scalars

Scales and degrees of freedom:

<u>TC:</u> asymptotically free <u>ETC:</u> unbroken <u>EWS:</u> unbroken

massless: SM fermions, technifermions, and gauge bosons



 Λ_{TC}

<u>TC:</u> getting stronger <u>ETC:</u> **broken** <u>EWS:</u> unbroken

massless: SM fermions, technifermions, and SM/TC gauge bosons

massive: ETC gauge bosons,

 $M_{ETC} \sim g_{ETC} \Lambda_{ETC}$

 M_{ETC}

+ dim-6 operators

 $\alpha_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a T) (\bar{T}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^a q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^b q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^b q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^b q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^b q) (\bar{q}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma_\mu t^b q) (\bar{T}\gamma^\mu t^b T)}{M_{ETC}^2} + \beta_{ab} \frac{g_{ETC}^2 (\bar{T}\gamma^\mu t^b T)}{M_{ETC}$

<u>TC:</u> **Confined** • <u>EWS:</u> **broken** TC-condensate forms, causes chiral symmetry breaking/EWSB

all technifermions confined into technihadrons

• SM fermion masses, π_T mass

Technicolor/Extended Technicolor Review:

- NO HIGGS: EWSB occurs as a result of spontaneous chiral symmetry breakdown in a new sector which feels a new strong interaction, technicolor
- * NATURAL: v_{EW} $\wedge \Lambda_{UV}$ is naturally generated
- FERMION MASSES: can't be obtained by TC dynamics alone. To keep the theme of naturalness, these masses must be generated by gauge interactions alone (no new scalars, please!). To accomplish this, we invoke EXTENDED TECHNICOLOR
- Looks good so far!







FCNC, #2

* Requiring the ETC-induced contribution to be within experimental errors, we can turn this into a constraint on one combination of ETC parameters



Similar, but looser constraints from other flavor observables ($\Delta m_{B_d}, \Delta m_{B_s} \Gamma(B \to s\gamma), \Gamma(\mu^{\pm} \to e^{\pm}\gamma), \Gamma(B \to \mu^{+}\mu^{-})$, etc)

* Tension arises as these SAME ETC parameters enter into the quark and lepton mass formulae

$\begin{array}{l} \textbf{satisfying FCNC conditions:} \\ m_q, m_l \sim \frac{g_{ETC}^2}{M_{ETC}^2} \langle \bar{T}T \rangle_{ETC} \overbrace{(\gamma_m \ll 1)}^{\bullet} & \frac{0.5 \text{ MeV}}{N_D^{3/2} |\theta_{ds}|^2} \\ \\ \textbf{assumes QCD-like } \gamma_m \end{array}$

WAY TOO SMALL!!! even second generation (c, s) masses difficult !

Precision Electroweak Observables

- * As we've seen, we can indirectly probe new physics by making precise measurements at lower energies
- * To test Technicolor with this approach we must compute the TC effects in the EW gauge boson sector



Unfortunately, in generic strongly interacting theories we have NO idea how to calculate these effects



custodial symmetry protects T,U

 $S = 4\pi \frac{d}{dq^2} (\Pi_{VV}(q^2) - \Pi_{AA}(q^2)) \Big|_{q^2 = 0}$

Some ideas in how to calculate S in a TC theory

<u>S parameter</u> is the most important/unknown:

i.) stick with lowest order perturbation theory

but NO reason why lowest order perturbation theory should be adequate/accurate (the theory confines, makes bound states, etc. none of which can be captured in pert. theory)

 $S \propto \begin{matrix} W_{\mu}^{3} & B_{\mu} \\ \hline & \ddots & S_{pert} = \dfrac{N_{T}N_{D}}{6\pi} \end{matrix}$

ii.) Take QCD result from data ($\pi\pi$ scattering), then rescale from QCD scale to TC scale (Golden, Randall '91

Peskin, Takeuchi '91) rewrite S as a 'dispersion integral' over the spectrum

custodial symmetry protects T,U



Some ideas in how to calculate S in a TC theory

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 $S \propto W^3_{\mu}$ M_{μ} M_{μ}

ii.) Take QCD result from data ($\pi\pi$ scattering), then rescale from QCD scale to TC scale (Golden, Randal '91 Peskin, Takeuchi '91)

in this approach it is more convenient to rewrite S as a 'dispersion integral' over the spectrum

* **Dispersion techniques:** $S = 4\pi \frac{d}{dq^2} (\Pi_{VV}(q^2) - \Pi_{AA}(q^2)) \Big|_{q^2=0}$ what we really want to compute is a current-current correlator $J^{3}_{\mu} = \frac{1}{2} (J_{V,\mu} - J_{A,\mu}), \quad J^{Q}_{\mu} = J_{V\mu} + \frac{1}{2} J^{Y}_{\mu}$ $S \propto i \int d^4x e^{iq \cdot x} \langle T\{J_{3\mu}(x)J_Q^{\mu}(0)\} \rangle \equiv -\frac{i}{4} \int d^4x e^{iq \cdot x} (\langle T\{J_{V\mu}(x)J_V^{\mu}\} \rangle - \langle T\{J_{A\mu}(x)J_A^{\mu}\} \rangle)$ but each of these can be rewritten as a integral in the complex momentum plane $\int d^4x e^{ip \cdot x} \langle T\{J_{V,\mu}(x)J_{V,\nu}(0)\} \rangle \equiv \eta_{\mu\nu}\Pi_{VV}(p^2) + (p^{\mu}p^{\nu} \text{ pieces})$ $\Pi_{VV}(t) = \frac{1}{\pi} \int ds \frac{\operatorname{Im}(\Pi_{VV}(s))}{t - s + i\epsilon}, \text{ + similar for axial part}$ current conservation tells us: $\Pi_{VV}(q^2) = q^2 \Pi'_{VV}(q^2) + \cdots$ $\Pi_{AA}(q^2) = \Pi_{AA}(0) + q^2 \Pi'_{AA}(q^2) + \cdots$ In this language: $S \equiv 4\pi \int_0^\infty \frac{ds}{\pi} \frac{(\operatorname{Im}(\Pi'_{VV}(s)) - \operatorname{Im}(\Pi'_{AA}(s)))}{s}$

* Why does this help?

UNITARITY (Optical Theorem) tells us that there is a relation



goes beyond perturbation theory!

physical, measurable cross section $\sigma(e^+e^- \rightarrow \text{technihadrons})$

 $\mathrm{Im}'(\Pi)$, exactly what we need for S calculation

of course, we don't have $\sigma(e^+e^- \rightarrow \text{technihadrons})$ but we can:

MOPEL it without relying on lowest order perturbation theory.

Or we can try to make an educated guess by using something we have measured, $\sigma(e^+e^- \rightarrow \text{QCD hadrons})$ (Peskin, Takeuchi '91)

Simple model: saturate the vector and axial spectral functions with single (narrow) resonances

 $\operatorname{Im}(\Pi'_{VV}(s)) = F_{\rho_T}^2 \delta(s - m_{\rho_T}^2), \quad \operatorname{Im}(\Pi'_{AA}(s)) = F_{a_T}^2 \delta(s - m_{a_T}^2)$

we approximate TC blob with

 ho_T exchange Π_{VV}

 a_T exchange Π_{AA}

 $S = 4\pi \frac{F_T^2}{m_{\rho_T}^2} \left[1 + \frac{m_{\rho_T}^2}{m_{a_T}^2} \right]$ $S \simeq 0.25 N_D \frac{N_{TC}}{3}$

or, from data :



Obtain Π_{VV} , Π_{AA} from QCP $e^+e^- \rightarrow$ hadrons data, then rescale by: F_T $\frac{F_T}{f_\pi}$, N_C , N_D incorporates resonance widths $S \cong 0.30 N_D \frac{N_{TC}}{3}$

(for more details, see Peskin, Takeuchi '91)
Precision Electroweak

Either way, results are STRONGLY disfavored by current bounds on S



-QCD-like, ND=2 & NC=3

 $S \propto N_D N_{TC}$

only gets bigger for more matter!

PDG2006: Erler and Langacker

TECHNICOLOR

Precision Electroweak

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—QCD-like, Nd=2 & Nc=3 $S \propto N_D N_T C$

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PDG2006: Erler and Langacker

(QCD-like) TECHNICOLOR

Precision Electrow

Terning

Either way, results are







PD

Precision Electrow Either way, results are



Terning

sfavored by unds on S SQUASHED by LEP (1989-2000)

> ...but is that the end of the story?









Peculiarities of QCD

 All of our troubles in Technicolor came from assuming that QCD-like dynamics at the EW scale was a good model for Technicolor

Precision Electroweak: Work too BIG!
 Quark masses: too SMALL!

but why should a generic strong interaction be just like QCD?

"Peculiarities" of QCD

QCD is the only strong interaction we know, BUT

- only one complex representation: fundamental
- all colored fermions carry SU(2) X U(1) charge
- quickly running coupling:



• $m_{
ho} < m_{\sigma}$

leptons are required to cancel gauge anomalies

what happens if we relax some of these?

Different phases of gauge theories

Lets think about the running behavior of QCD and how we might change it

the running of the gauge coupling is described by the beta function $\beta(\alpha)$



gauge group: SU(N), SO(N), Sp(N), etc

matter representations: fundamental, Adj, (anti)-symmetric, etc.



 $b_0 = \left(\frac{11}{3}N_C - \frac{4}{3}\sum_{F,r}C(r)\right) \quad b_1 = \frac{34}{2}N_C^2 - \frac{20}{3}\sum_{F,r}C(r)N_F N_C - 2\sum_{F,r}C_2(r)N_F$

amount of matter: $N_{F,r}$

confinement scale

Wednesday, September 2, 2009

* We are used to seeing the QCD coupling pictured as



...this picture is helpful when we consider possibilities other than QCP-like behavior

asymptotic freedom appears as $\alpha \to 0$ in the UV

* How could we change things? Well, if we add enough matter, eventually we lose asymptotic freedom



Notice the different locations of the UV and IR scales!!

 interesting, but a non-asymptotically free theory gets weaker in the IR so it won't spontaneously break EWSB

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* What about a theory which has $\beta(\alpha^*) = 0$ at some nonzero value of $\alpha^* \neq 0$



as we go from the UV to the IR the coupling flows towards α^{\ast}

once $\alpha \to \alpha^*$, $\beta = 0$: the coupling STOPS RUNNING-> it remains fixed for all lower energies

 $lpha^*$ is known as a fixed point, where the theory becomes conformal

to say more, we need to know how strong the fixed point coupling is

weakly coupled fixed point $lpha^* \ll 1$



weak fixed point: no symmetry breaking or confinement occurs.. the theory consists of weakly interacting matter and gluons

increasing α^* eventually we pass another important value, the value where the coupling is strong enough for chiral symmetry breaking to happen,

$$\alpha^* > \alpha_{\chi SB}$$

once confining, states become massive (dynamically) and decouple, changing the beta function

in this scenario we never actually hit the fixed point

*

*

* What does this "near conformal" theory look like?



Near conformal theories are also called "Walking" theories the coupling changes with energy, but very slowly



Schwinger-Dyson (SD) approach

(Kugo, Fukuda '70's)

* To demonstrate how walking effects physical quantities, compute the technifermion propagator at 1-loop



$$iS^{-1}(p) = Z(p)\left(\not p - \Sigma(p)\right)$$

working in Landau gauge: Z(p) = 1

$$\Sigma(p^2) = \frac{3C_2(r)}{(2\pi)^4} \int d^4k \frac{g_T^2((k-p)^2)}{(k-p)^2} \frac{\Sigma(k^2)}{k^2 - \Sigma^2(p^2)}$$

approximate the coupling as constant, linearize, and perform the angular integral using $(k-p)^2 = (k^2 + p^2 - 2pk\cos\psi)$

$$\Sigma(p^2) = \frac{3C_2(r)g_T^2}{(2\pi)^4} \Big(\int_0^{p^2} d(k^2) \frac{\Sigma(k^2)}{p^2} + \int_{p^2}^{\Lambda^2} d(k^2) \frac{\Sigma(k^2)}{k^2} \Big)$$

* Derivatives $\frac{d}{dp^2}$ convert this integral equation into a differential one

$$\frac{d}{dp^2} \left(p^4 \frac{d\Sigma(p^2)}{dp^2} \right) = \frac{3C_2(r)g_T^2}{4\pi} \Sigma(p^2)$$

Solving: $\Sigma(p^2) \sim const. \left(\frac{\mu}{p}\right)^{1 \pm \sqrt{1-4r}}, \quad r = \frac{3C_2(r)g_T^2}{4\pi}$

 $m_F \langle \bar\psi\psi\rangle$ is independent of $\,\mu\,$ so we can convert the $\,\mu\,$ dependence of $\,\Sigma(p^2)$ into the anomalous dimension of $\langle\bar\psi\psi\rangle$



this reproduces the perturbative result for γ_m when $\alpha_T \ll \alpha_c$ but, for large coupling $\alpha_T \sim \alpha_c$ we find large anomalous dimension:

Walking theory (in SP analysis) has $\,\gamma_m\sim 1$

 Large anomalous dimension is a nice, intuitive result of walking, BUT we had to make many approximations (some severe!) in order to use the SD method

- constant coupling
- linearized fermion propagator
- gauge specific
- tree-level technigluon propagator
- ONE LOOP RESULT

* Also, some subtleties in interpreting the solution we have:

- two solutions
- what happens when $\alpha_T > \alpha_c$?

 Large anomalous dimension is a nice, intuitive result of walking, BUT we had to make many approximations (some severe!) in order to use the SD method

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Lots of effort to improve this method

> (Appelquist et al '88 Cohen, Georgi '89 Mahanta '89)

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* Also, some subtleties in interpreting the solution we have:

- two solutions
- what happens when $\alpha_T > \alpha_c$?

chiral symmetry breaking happens when $\alpha_T \geq \alpha_c$

Take-home message:

A near-conformal/walking coupling leads to large anomalous dimensions

Calculating the anomalous dimension in a strongly interacting theory is no easy task...

 $\frac{\rm Schwinger-Dyson\,approach:}{\rm The\,method\,has\,many\,shortcomings,\,so\,it\,is\,difficult\,to\,judge\,the\,exact\,numerics,\,but\,the\,conclusion\,that\,}{\gamma_m\sim 1\,appears\,robust}$

Further Evidence: SUSY conformal field theoriesO(1) anomalous dimensions for $(\bar{Q}Q)$ in certainSQCD theories(Seiberg hep-ph/9411149, 9402044)

Why do we want a walking coupling?

- * An extremely important place where the anomalous coupling played a role is in calculating the SM fermion mass $m_f \propto \langle \bar{T}_L T_R \rangle|_{ETC}$
- * The anomalous dimension of the techicondensate $\langle \overline{T}_L T_R \rangle$ appears when we connect the ETC and TC scales

 $\langle \bar{T}_L T_R \rangle |_{ETC} = \langle T_L T_R \rangle |_{TC} \times exp \Big(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} \frac{d\mu}{\mu} \gamma_{\bar{T}_L T_R}(\mu) \Big)$ for QCD-like, we assumed $\gamma_{(\bar{T}_L T_R)} \ll 1$

* What do we get for a WALKING technicolor theory?

<u>then</u>: $\gamma_{(\bar{T}_L T_R)} \approx 1$ is big

 $\langle \bar{T}_L T_R \rangle |_{ETC} \sim \langle T_L T_R \rangle |_{TC} \times exp \left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} \frac{d\mu}{\mu} \right)$

Benefits of a walking coupling, #2

plugging in to get the fermion masses $m_q, m_l \sim \frac{g_{ETC}^2}{M_{ETC}^2} \langle \bar{T}T \rangle_{ETC} \sim \frac{g_{ETC}^2}{M_{ETC}^2} (4\pi F_T^3) \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)$

for ETC scales compatible with FCNC we get

$n_{q,\ell} \cong$	$50-500~{\rm MeV}$	femion masses $\lesssim m_b$
	$\overline{N_D^{3/2} \theta_{ds} ^2}$	
		are now possible

consistent with FCNC and without fine tuning!!

Similar enhancement for the technipion masses

for simplicity: $m_{\pi}^2 \sim \frac{g_{ETC}^2}{M_{ETC}^2 F_T^2} \langle \bar{T}T\bar{T}T \rangle_{ETC} \sim \frac{g_{ETC}^2}{M_{ETC}^2 F_T^2} \langle \bar{T}T \rangle_{ETC}^2$ plug in $\gamma_m \sim 1 \begin{pmatrix} m_{\pi_T}^2 \sim \frac{g_{ETC}^2 \Lambda_{TC}^2 F_T^2}{M_{ETC}^2} \langle \Lambda_{ETC} \rangle^2 \\ M_{ETC}^2 & M_{ETC}^2 \end{pmatrix}^2 \gtrsim \mathcal{O}(100 \text{ GeV})$

Wednesday, September 2, 2009

Where are the walking theories?

- * OK, walking techicolor sounds helpful, but how do we get it?
- Perturbative analysis suggests that there is a regime before asymptotic freedom is lost where the theories become conformal in the infrared: a "conformal window"

$$\beta(g) \equiv \mu \frac{dg}{d\mu} = -\frac{b_0 g^3}{(4\pi)^2} - \frac{b_1 g^5}{(4\pi)^4} - \frac{b_1$$

 $\boldsymbol{b_0} = \left(\frac{11}{3}N_C - \frac{4}{3}\sum_{F,r}C(r)\right) \qquad \boldsymbol{b_1} = \frac{34}{2}N_C^2 - \frac{20}{3}\sum_{F,r}C(r)N_F N_C - 2\sum_{F,r}C_2(r)N_F$

increasing the matter content, b_0 decreases

at least within 2-loop perturbation theory, there is a range where b_0 is small enough that the b_1 term, despite being, $\mathcal{O}(g^5)$ can compensate and cause $\beta(g) = 0$ at some nonzero value, g^*

Where are the walking theories?, #2

- * Exactly where this regime is depends on N_C and the matter content of the theory (number of fermions, their representations)
- Further evidence for conformal windows comes from supersymmetry:

specifically for Super Yang Mills + fundamental matter (SQCD), Seiberg et al mapped out this window

SU(N) SQCP conformal window: $\frac{3}{2}N_C < N_F < 3N_C$

but conformal SUSY has a lot of powerful tools: holomorphy, non-renormalization, R-symmetry, etc.

Where are the walking theories? #3

Similar attempts have been made in non-SUSY gauge theories, though the tools available are less powerful



shaded regions are estimates of conformal window
















Can we actually get a walking theory?

Inspiration for walking comes from looking at beta functions in perturbation theory

 $\mathbf{b_0} = \left(\frac{11}{3}N_C - \frac{4}{3}\sum_{F,r}C(r)\right) \quad \mathbf{b_1} = \frac{34}{2}N_C^2 - \frac{20}{3}\sum_{F,r}C(r)N_F N_C - 2\sum_{F,r}C_2(r)N_F$

* We would like some proof that conformal/walking behavior can exist which doesn't rely on perturbation theory

Lattice is the perfect place for this!

* Lots of lattice effort underway:

- Appelquist, Fleming, et al
- DeGrand, Shamir, Svetivsky
- Catterall, Sannino
- Fodor, Holland, Kuti, et al
- Deuzeman, Lombardo, Pallante
- Bilgici et al

• ...

Hietanen, Rummukainen, Tuominen

Summary of Lattice results

Appelquist, Fleming, Neil (arXiv:0712.0609, 0901.3766)





$$N_C = 3, N_F = 8$$

confining behavior seen at N_F = 8, while N_F = 12 theory appears to be conformal

neither one is walking, but shape of $\beta(\alpha)$ doesn't look so crazy anymore

looking into $N_F = 10$ now!

<u>Summary of Lattice results</u> being checked by other methods/groups now!

Appelquist, Fleming, Neil (arXiv:0712.0609, 0901.3766)





 $N_C = 3, N_F = 8$

confining behavior seen at N_F = 8, while N_F = 12 theory appears to be conformal

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looking into $N_F = 10$ now!

Summary of Lattice results, #2

Appelquist et al result is the running coupling, but the beta function is a scheme-dependent quantity beyond two loops



coefficients of these terms are universal

coefficient of this and higher terms depend on what observable is used, how subtraction is done

in a strongly-coupled theory, $\alpha \gg 1$ so we may worry scheme dependence is interfering with how we interpret our results

Can we see evidence of conformality (or walking) a in schemeindependent way?

- scaling dimension of operators
- free energy

lots of active research on this tricky problem!

Assuming we have a walking theory, the tension between quark masses and FCNC can be relieved... but FCNC weren't technicolor's only problem

$$S \sim 4\pi \frac{N_D F_T^3}{M_{\rho_T}^2} \left(1 + \frac{M_{a_T}^2}{M_{\rho_T}^2} \right) \sim 0.25 N_D \frac{N_{TC}}{3}$$

(Peskin, Takeuchi '91)

* However this result came from assuming the techni-meson spectrum

is analogous to QCP, and saturating dispersive form of ${f S}$

 $S=4\pi\int\frac{dm^2}{m^4}(\rho_V^3(m^2)-\rho_A^3(m^2))~~{\rm with~single~resonances}~~1~\rho_T,a_T$

Not a valid assumption in a walking theory! CANNOT use the QCD-based argument

*

Iots of speculation that S should be smaller in a walking theory:

- large coupling implies spectral integrals converge more slowly, manifest in whole tower of spin-1 vector and axial resonances
- near conformal behavior leads to a parity-doubled spectrum, and therefore:

(Appelquist '97 Shrock, Kurachi '06)

 $M_{\rho_T} \sim M_{a_T}, g_{\rho_T} \sim g_{a_T}$

which leads to a reduced (or even negative) S parameter

- OPE analysis suggests large $\langle \bar\psi\psi\rangle$ anomalous dimension leads to smaller S

(Sundrum, Hsu '90)

* but NO systematic complete derivation of S in non-QCD theory

Is speculation the best we can do?

 Additional positive corrections to T are rather easy to generate, and help the overall fit.

 $\Delta T = \frac{M_D^2 + M_U^2}{16\pi M_W^2 \sin^2 \theta_W}$



* Extra multiplets, with appropriate mass ratios and charges can generate negative contributions to S $S_{Dirac} = \frac{1}{6\pi} \left(1 - 2Y \log\left(\frac{M_U^2}{M_D^2}\right) \right)$ $S_{Maj} = \frac{1}{6\pi} \left(c_{\theta}^2 \log\left(\frac{M_1^2}{M_E^2}\right) + s_{\theta}^2 \log\left(\frac{M_2^2}{M_E^2}\right) + \frac{3}{2} - s_{\theta}^2 c_{\theta}^2 \left(\frac{8}{3} + f_1(M_1, M_2) - f_2(M_1, M_2) \log\left(\frac{M_1^2}{M_2^2}\right) \right)$

Loops of technipions could have a big effect too, depending on their mass and number -- difficult to estimate

* No clear path to take which resolves all problems

Lattice efforts underway! (JLQCD, LSD)

Is speculation the best we can do?

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Lattice efforts underway! (JLQCD, LSD)

Walking and the third generation

• Even with $\gamma_m\cong 1$, large m_t is still a problem

Several `solutions':

i.) Several ETC scales, dynamical 'tumbling'

 $SU(N_{TC}+3)$

$$\Lambda_1 \qquad \downarrow \qquad m_1 \approx \frac{4\pi F^3}{\Lambda_1^2}$$
$$SU(N_{TC} + 2)$$

 $\Lambda_2 \qquad \downarrow \qquad m_2 \approx \frac{4\pi F^3}{\Lambda_2^2}$ $SU(N_{TC} + 1)$

$$\Lambda_3 \qquad \downarrow \qquad m_3 \approx \frac{4\pi F^3}{\Lambda_3^2}$$

 $SU(N_{TC})$

(Baluni '79, Dimopoulos & Susskind '80 Appelquist + Shrock '04) ii.) Special 3rd generation dynamics $SU(3)_1 \otimes SU(3)_2 \rightarrow SU(3)_c$ $U(1)_1 \otimes U(1)_2 \rightarrow U(1)_Y$ Topcolor-Assisted Technicolor (Hill '94)

iii.) More exotic UV behavior, $\gamma_m > 1$ Conformal Technicolor (Luty '04)

...none are completely satisfactory



Walking TC summary

There is good evidence, from perturbation theory and the lattice that walking 4D gauge theories do exist

- expect large anomalous dimensions, especially for $\langle \bar{\psi}\psi \rangle$ from SDE-analysis and similar SUSY calculations
- large anomalous dimension eases tension between FCNC and realistic quark masses
- $\gamma_m\sim 1$ also opens the possibility of consistent PEW and top quark mass, though the exact mechanism is less clear

All of this is completely irrelevant if we don't know what to expect at the LHC!

Walking Technicolor Phenomenology

What will we see at the LHC if walking technicolor lurks at the EW scale?

walking technicolor requires lots of matter. all EW-charged matter contributes to EW scale:

lots of matter -- > generically low TC scale

$$v^2 = \sum_i F_{Ti}^2$$

 $i \in \text{all } SU(2)_w$
techni-doublets

new states must communicate with SM EW gauge bosons (at least), so all states have open decay channels to SM matter techni-resonances must be light!

 N_D doublets: $v^2 = N_D F_T^2$ multiple reps.: $v^2 = F_{T1}^2 + F_{T2}^2 + \cdots$

no BSM missing energy!

a general scan over all possible resonances, their masses, their interactions would be great! but totally impractical

 $\dots \quad M_{a_T}^{\pm} \quad M_{\rho_T}^{\pm}$ $g_{\rho_T W^+W^-}$ $g_{a_TW^+\gamma}$ # π_T M_{π_T} $\begin{array}{ccc}g_{\pi_T^{\pm}\bar{f}f} & g_{\rho_T^{\pm}ff'} & g_{\rho_T\pi_T\pi_T}\\ & & g_{\rho_TW\pi_T} & g_{\sigma_T\sigma_T}\end{array}$ $\Gamma(a_T \to \pi_T \pi_T \pi_T)$ M_{ω_T} $g_{
ho_T W \pi_T} \quad g_{\omega_T Z \gamma}$... $g_{\rho_T W^+ Z}$ $M_{\rho_T'} \qquad g_{\rho_T \pi \gamma} \\ M_{a_T'} \qquad M_{a_T'} \\ \Gamma(\rho_T \to \pi_T \pi_T)$ g_{a_TW+Z} ... $g_{\omega_T ff} \qquad g_{\pi_T \gamma \gamma}$ $g_{\omega_T\pi\gamma}$

techni-baryons?

scalar bound states?

WAY to many parameters, all of which have important phenomenological impact : <u>we need models</u>



 $\mathcal{L} \supset \frac{v^2}{4} \operatorname{Tr}(D_{\mu} \Sigma D^{\mu} \Sigma^{\dagger}) + \frac{v^2}{4} \operatorname{Tr}(D_{\mu} U D^{\mu} U^{\dagger}) + a \frac{v^2}{4} \operatorname{Tr}((D_{\mu} \Sigma^{\dagger}) \Sigma (D_{\mu} U) U^{\dagger}) + \cdots - \frac{1}{4g_T^2} \operatorname{Tr}(V_{\mu\nu}^a V^{a\mu\nu})$

'hidden' gauge group coupling $g_T \gg g, g'$. Kinetic term is simply added to \mathcal{L} , assumed to come from strong dynamics

integrating out the V, we get predictions for the $\,C_i$ plus we have modeled the masses and interactions of the $\,\rho_T^a$

(same technique goes by many names: BESS (Casalbuoni et al), three-site model (Chivukula et al))

BUT, this setup is very restricted...

- where has the walking entered?
- where are the technipions?
- how do the fermions enter?
- how can we get more than one set of resonances?

more sophisticated models allow us to add more TC-features



• we now have a small parameter to play with: $\sin\chi=F_1/F_2$

for example: suppresses fermionresonance couplings

$$g_{\bar{f}f\rho_T} \sim g_{EW} \left(\frac{M_W}{M_o}\right) \sin \chi$$

- hidden groups are U(2) , extra resonance is ω_T - one π_T remains in the spectrum

(Lane, AM '09)

HLS is still very limited:

- * higher dimensional operators? can we really stop at 2derivative, d < 4 operators in a strongly coupled theory?</p>
- anomaly terms? global anomalies of the underlying UV theory are present in the effective theory -- WZW interactions

HLS models should NOT be taken too seriously, but they are a useful and simple tool for making predictions. Studying the phenomenology of these models will hopefully prepare us to recognize signals of new strong dynamics should they appear at the LHC

examples: Drell-Yan production of resonances:

$$\rho_T^{\pm} \to W^{\pm} Z^0 \to \ell^+ \ell^- \ell' \nu$$

Enhancement from decays to longitudinal polarizations

Relatively **Unstudied!**

past
$$Z' \to \overline{f}f$$

studies: $W' \to \ell + \nu$





Early LHC discovery!

- large cross section
- multi-lepton final states
- single MET source -> can reconstruct $M_{\rho_T}^2$



S+B,L=20 fb¹

 $a_T^{\pm} \to \gamma W^{\pm} \to (\gamma \ell^{\pm} \nu)$

- cannot go to $W^\pm_L Z^0_L$ as techniparity is imposed

- requires further HLS interactions! so this mode tells us something about how to best model new strong dynamics
 - very few collider studies! SUSY bias, where there are no resonance decays to $W^\pm Z^0, \gamma W$ at tree level

very clean,

sharp peak

$$\omega_T \to \gamma Z^0 \to \ell^+ \ell^- \gamma$$

NO missing energy, only EM objects

- observation of ω_T tells us something about the global symmetries of TC $U(N_D)$ vs. $SU(N_D), \cdots$



Technipion discovery: Important since π_T don't exist in all models. However, few studies have been done

more model dependent, especially in the $\,\pi_T$ coupling to the top quark

 $pp \to \rho_T / a_T \to Z\pi_T \to \ell\ell bq$



(Azuelos et al, ATLAS-PHYS-CONF-2008-003)

• with $\mathcal{L} \sim 50 \text{ fb}^{-1} m_{\pi_T}, m_{\rho_T}, m_{a_T}$ all can be determined

For all LSTC signals

with more luminosity, detailed studies possible for

Angular distributions: necessary to determine spin-1 (see hep-ph/0802.3714)

Widthscouplings

<u>High-luminosity signatures:</u> Not the `smoking gun' detection signal for TC, but important nonetheless



<u>Summary so far</u>

 Tension between FCNC and realistic fermion masses can be avoided if the technifermion bilinear has a large (+ve) anomalous dimension

* to have $\gamma_m \cong 1$ we expect the technicolor coupling must remain large for a wide range of energies, and is therefore nearly conformal or `walking'

* guided by the perturbative b_0 , b_1 , we expect walking theories will have lots of technimatter or involve large (non-fundamental) representations

<u>Summary so far</u>

- * Walking implies a low TC scale and therefore resonances in the 500 GeV - 1 TeV scale range
- New resonances must couple strongly to W,Z, though couplings to SM fermions are also possible. TC events will have no BSM missing energy <-> complementary to other BSM searches
- Precision Electroweak (S!!) arguments relied on technicolor being a rescaled version of QCD -- these arguments won't apply to a walking theory. There are arguments that a walking theory will have a naturally small S, but no solid evidence



* Where does this leave us?

Modern Technicolor must be unlike QCP to avoid phenomenological problems -- the most investigated option is a walking technicolor theory. A walking theory CANNOT be ruled out by PEW tests, but we cannot calculate its contributions

NECESSARILY will have new states at the sub-TeV level, therefore it will be found or ruled out at the LHC

some new/better calculation tools would be great!

Sample References:

On Techicolor basics:

- Hill, Simmons, hep-ph/0203079
- Chivukula, hep-ph/9803219
- Lane, hep-ph/02022025

+ references within

On the phases of gauge theories:

- Intrilligator, Seiberg, hep-ph/9402044, 9411149
- Applequist, Sannino, hep-ph/0001043
 Applequist et al. hep-ph/0001043
- Appelquist et al, hep-ph/9806472

On walking TC at the LHC:

- Eichten, Lane arXiv:0702339
- Azuelos et al, 2007 Les Houches proceedings, hep-ph/0802.3714
- Lane, Martin, arXiv:0907.3737

Electroweak-Scale Strong

Dynamics

Lecture #2

Adam Martin Yale University

Parma International School of Theoretical Physics Aug. 31 - Sept. 4, 2009

Outline:

Lecture #1: Dynamical Electroweak Symmetry Breaking (EWSB)

- Part 1: -> pros and cons of the SM Higgs, why alternatives may be good
 - -> Dynamical EWSB (Technicolor) as an alternative,
 - -> Extended Technicolor: fermion mass generation
 - -> problems with 'old' Technicolor

Part 2:

- -> Peculiarities of QCD and the phases of gauge theory
- -> Walking Technicolor (WTC) motivation and implementation,
- -> how walking saves the day & where it fails,
- -> walking studies on the lattice

Lecture #2: Related topics

- -> LHC phenomenology of 'modern' technicolor
- -> Extra-Dimensional models of Technicolor: Higgsless models
- -> Other Tev-scale strong dynamics: Composite Higgs
- -> Technicolor and Park Matter

Dynamical EWSB Recap:

Electroweak Symmetry breaking by new strong dynamics (Technicolor) is a compelling solution to the hierarchy problem



Dynamical EWSB Recap:

Technicolor alone could not generate masses for the SM fermions. To do this we needed Extended Technicolor



Dynamical EWSB Recap:

AND to avoid conflict with experiment, the new strong dynamics cannot simply be a copy of QCD. The most studied deviation from QCD-like behavior is "walking technicolor"



What will we see at the LHC if walking technicolor lurks at the EW scale?

Walking Technicolor Phenomenology

walking technicolor requires a lot oftechni-matter:

 $b_0 = \left(\frac{11}{3}N_C - \frac{4}{3}\sum_{Fr}C(r)\right)$ needs to be small

- all EW-charged matter contributes to EW scale: $v^2 = \sum_i F_{Ti}^2$



lots of matter -- > generically low TC scale

 N_D doublets: $v^2 = N_D F_T^2$

new states must communicate with SM EW gauge bosons (at least), so all states have open decay channels to SM matter

techni-resonances must be light!

multiple reps.: $v^2 = F_{T1}^2 + F_{T2}^2 + \cdots$

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'hidden' gauge group coupling $\tilde{g} \gg g, g'$. Kinetic term is simply added to \mathcal{L} , assumed to come from strong dynamics

 $+\cdots - \frac{1}{4\tilde{q}^2} \operatorname{Tr}(V^a_{\mu} V^{a\mu\nu})$

<u>Go to the unitary gauge:</u> $U = \mathbf{1}, \Sigma = \mathbf{1}$

we can read off the mass matrices for the charged and neutral gauge bosons + resonances

$$\begin{split} M_{\pm}^{2} &= \frac{\tilde{g}^{2}f^{2}}{8} \begin{pmatrix} x^{2}(1+a) & -2xa \\ -2xa & 4a \end{pmatrix} \\ M_{n}^{2} &= \frac{\tilde{g}^{2}f^{2}}{8} \begin{pmatrix} x^{2}(1+a) & -2xa & -tx^{2}(1-a) \\ -2xa & 4a & -2txa \\ -tx^{2}(1-a) & -2txa & t^{2}x^{2}(1+a) \end{pmatrix} \\ M_{W}^{2} &= \frac{g^{2}f^{2}}{4} + \mathcal{O}(x^{2}), \\ M_{W'}^{2} &= \frac{\tilde{g}^{2}f^{2}a}{4} + \mathcal{O}(x^{2}) \\ \end{split}$$

+ similar expressions for neutral (see Chivukula et al, hep-ph/0607124)
$$\mathcal{C} \supset \frac{F^2}{4} \operatorname{Tr}(D_{\mu} \Sigma D^{\mu} \Sigma^{\dagger}) + \frac{F^2}{4} \operatorname{Tr}(D_{\mu} U D^{\mu} U^{\dagger}) + a \frac{F^2}{4} \operatorname{Tr}((D_{\mu} \Sigma^{\dagger}) \Sigma (D_{\mu} U) U^{\dagger})$$

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Add fermions with usual couplings only to the outer 'sites'



once the gauge boson mass matrix is diagonalized, the fermions acquire a coupling to the heavy eigenstate 'resonance'

we also get mixed gauge boson resonance vertices



(N. Christensen)

integrating out the V, we get predictions for the $\,C_i$ plus we have modeled the masses and interactions of the $\,
ho_T^a$

(same technique goes by many names: BESS (Casalbuoni et al), 'three-site model' (Chivukula et al))

BUT, this setup is very restricted...

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$$g_{\bar{f}f\rho_T} \sim g_{EW} \Big(\frac{M_W}{M_o} \Big)$$
si

$$\left(\frac{M_W}{M_{
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• hidden groups are U(2), extra resonance is ω_T • one π_T remains in the spectrum

(Lane, AM '09)

HLS is still very limited:

- higher dimensional operators? can we really stop at 2derivative, d < 4 operators in a strongly coupled theory?</p>
- <u>anomaly terms?</u> global anomalies of the underlying UV theory are present in the effective theory -- WZW interactions
- * spin-1 resonances only: a new strong interaction can certainly have resonances for other spins (0, 2, ..). Technibaryons should also occur, with spin depending on N_{TC} and potentially having electromagnetic charge |Q| > 1

Model dependent, and requires introducing more unknown parameters. Very little phenomenology done for these states

HLS models should NOT be taken too seriously, but they are a useful and simple tool for making predictions. Studying the phenomenology of these models will hopefully prepare us to recognize signals of new strong dynamics should they appear at the LHC

but we should always remember that HLS is just a model!

examples: Drell-Yan production of resonances:

$$\rho_T^{\pm} \to W^{\pm} Z^0 \to \ell^+ \ell^- \ell' \nu$$

Enhancement from decays to longitudinal polarizations

> Relatively **Unstudied!**

past
$$Z' \to \overline{f}f$$

studies: $W' \to \ell + \nu$





 single MET source -> can reconstruct $M_{\rho_T}^2$

 W^{\pm}

 ρ_T

Why so narrow? In a strongly interacting theory expect states should be broad Unless...

1.) kinematically forbidden from decaying to most states, i.e. $\rho_T \rightarrow \pi_T \pi_T$ not allowed because $m_{\pi_T} > \frac{m_{\rho_T}}{2}$

Assuming $m_{\pi_T} > \frac{m_{\rho_T}}{2}$ is not completely ridiculous

because the $\pi_T\,$ mass depends on the techni-condensate and is enhanced by walking, while the $\rho_T\,$ mass only depends on the TC confinement scale Λ_T

In this case, only $\rho_T \rightarrow WW, W\pi_T$ are allowed. Resonance becomes narrower, and rate of respective processes is sensitive to $m_{\rho_T} - m_{\pi_T}$

2.) Large N_{TC} : Result of 5D theories of strong dynmics

I mention the narrowness of ρ_T because ALL dedicated technicolor searches assume $m_{\pi_T} > \frac{m_{\rho_T}}{2}$

ex:
$$p\bar{p} \rightarrow \rho_T \rightarrow W\pi_T \rightarrow (\ell\nu)(bq)$$
 at the Tevatron





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WHY?

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WHY? It's in PYTHIA

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S+B, L=20 fb¹

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NECESSARILY will have new states at the sub-TeV level, therefore it will be found or ruled out at the LHC

some new/better calculation tools would be great!







Extra-Dimensions??

* How could an extra dimension help things? we are confused enough in 40...

We expect a strong interaction to give us bound states whose masses form a discrete spectrum.



 The masses of the new states, along with the interactions of the new states with the SM are EXACTLY the quantities we would like to predict, since they are what will be measured at a collider

Extra Dimensions??

- BUT, these quantities are not computable from perturbation theory. This is a problem of any strongly coupled theory, not just technicolor
- The underlying 4D description (techifermions, technigluons, etc.) uses the wrong degrees of freedom for the EW-scale strong dynamics

just like quarks and gluons are the wrong degrees of freedom for QCD at 1 GeV



Extra-Dimensions!!

* BUT, we are ALL familiar with a setup which yields discretized energy levels

Quantum Mechanics: particle in a potential well



Extra Dimensions!!

* For a quantum field theory, the rules are somewhat more complicated, but the idea is the same:

Use a compact extra-dimension to model the bound states and composites from a new strong interaction



We no longer know the underlying 4D theory (the microscopic degrees of freedom), but we do model the observables which are relevant at the LHC

A first attempt:

Geometry and boundary conditions determine the spectrum and which symmetries are broken (see lectures by C. Grojean)

For our purposes, an extra-dimensional interval is best. Let's only worry about the EW gauge fields and try a flat dimension first

 $SU(2) \otimes U(1)$ $g_5 \qquad \tilde{g}_5$ z = 0 z = RSolve classical 50 EOM by KK decomposition, $\Phi(z, x) = \phi_0(x) + \sum_{n=1}^{\infty} e^{inz/R} \phi_n(x)$ features in extra dimensions are masses in 40 $\Box_5 \Phi \supset (\Box_4 - \partial_5^2) \phi_n = (\Box_4 + \frac{n^2}{R^2}) \phi_n$

zero mode/first KK mode = SM gauge fields
Higher KK modes = resonances

Multi-resonance couplings are set by overlaps of profiles :

 $g_{ABC} \propto \int dz \phi_A(z) \phi_B(z) \phi_C(z)$

Phenomenological problems with the simplest setup drive us to consider:

Warped Extra Dimensions

$$ds^2 = \left(\frac{\ell_0}{z}\right)^2 (\eta_{\mu\nu} dx^{\mu} dx^{\nu} - dz^2)$$

Friday, September 4, 2009

Ads/Technicolor

* Additional motivation for AdS extra dimensions: AdS/CFT correspondence (Maldacena '98)

type II-B string theory on $AdS_5\otimes S_5$

large 't Hooft coupling limit of N = 4 supersymmetric Yang-Mills

AdS/CFT	Dictionary
---------	------------

duality

\leftrightarrow	CFT
\leftrightarrow	Energy scale in CFT
\leftrightarrow	CFT has a cutoff
\leftrightarrow	conformal symmetry broken spontaneously by CFT
\leftrightarrow	composites of CFT
\leftrightarrow	Elementary fields coupled to CFT
\leftrightarrow	CFT has a global symmetry
\leftrightarrow	Global symmetry not gauged
\leftrightarrow	Global symmetry weakly gauged
\leftrightarrow	CFT becoming strong produces composite Higgs
\leftrightarrow	Strong dynamics that breaks CFT also breaks gauge symmetry (Csaki)
	$\begin{array}{c} \downarrow \\ \downarrow $

AdS/Technicolor, #2

- * We don't have N=1 SUSY, not to mention N=4, so why should we care?
- To capture LHC phenomenology, we don't need an exact duality to hold. Perhaps just the essential symmetries and important operators are enough
- * pure AdS (no branes) has a rescaling invariance: $z
 ightarrow \lambda z, x^{\mu}
 ightarrow \lambda x^{\mu}$

AdS dictionary: $z \leftrightarrow RGE$ scale, therefore models 4D conformal dynamics, a perfect laboratory for modeling walking technicolor.

These AdS-based technicolor models are known as Higgsless models

see WARPED extra dimensions in lectures by C. Grojean

Mission Accomplished?

NOPE. Extra dimensions allow us to model another subset of Technicolor theories, but there is still a lot of unknown territory out there



<u>Strong dynamics beyond</u> <u>Technicolor</u>



What are our options?

We need to break electroweak symmetry somehow:

- Forget strong dynamics and stick with the Standard Model or with weakly coupled UV physics (SUSY)
- Make modifications to technicolor so it is compatible with FCNC/fermion masses and precision electroweak (S,T,U): Walking TC.
- * Some non-technicolor strong dynamics

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* Make modifications to technips or so it is compatible with the set of the s

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Other EW-scale strong dynamics

* Are there other (non-technicolor) possibilities for strong dynamics at the EW scale? OF COURSE

Composite Higgs models/Little Higgs models

strongly coupled SM: arge Yukawas $arge \lambda_H$

topcolor/top-condensation

top-seesaw

+ many variations

no time to go into detail on these, so I'll just pick one



<u>Alternative Strong Dynamics, #2</u>

* <u>one example: Composite Higgs theories</u>

to make the Higgs mass insensitive to high scales: link scalars and fermions, then chiral symmetry protects m_h

get rid of the Higgs, have strong dynamics break EWS (TC)

shift symmetry: $h \rightarrow h + c$ forbids mass terms! m^2h^2 NGB's have this symmetry, so lets make the Higgs a pseudo-NGB (pNGB)

this is what composite Higgs models try to do

(Georgi, Kaplan '84 Agashe, Contino, Nomura '04,..)

(SUSY)
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(Georgi, Kaplan '84 Agashe, Contino, Nomura '04,..)

How do you get pNGB, naturally??



Alternative Strong Dynamics, #3

Composite Higgs setup: looks similar to technicolor, but different!

start with constituent fermions, but with non-TC charge assignments.

 $\Psi_{CH} = \{(\chi_1, \chi_2), (\psi_1, \psi_2), \lambda\}$

has an SU(5) flavor symmetry ____ EW doublets

these fermions have a new strong interaction, which we assume causes the breaking to SO(5) at a scale Λ_{CH}

chiral symmetry breaking pattern SU(N)/SO(N)

Composite Higgs: Assign underlying fermion charges/ symmetry breaking pattern such that EW symmetry unbroken by strong dynamics

<u>Alternative Strong Dynamics, #4</u>

 NOT like Technicolor, where strong dynamics breaks EWS

 Composite Higgs
 Technicolor

SU(5)/SO(5) $\Sigma = \begin{pmatrix} 1 & -1 \\ 1 & 1 \\ -1 & 1 \end{pmatrix}$ condensate $\langle \epsilon^{ab} \chi_a \psi_b + \lambda^2 \rangle$ is an EW singlet

 $SU(2N)_L \otimes SU(2N)_R / SU(2N)_V$

 $\Sigma_{TC} = \mathbf{1}_{2N \times 2N}$

condensate $\langle \overline{U_L} D_R \rangle$ is an EW doublet

but we do get 14 NGBs, 4 of which form a multiplet with the exact quantum numbers at the SM Higgs

$$U = e^{i\mathbf{H}/\Lambda_{CH}} \sum_{\mathbf{h}} \mathbf{H} = \frac{1}{\sqrt{2}} \begin{pmatrix} \tilde{h} \\ h \\ \tilde{h}^{\dagger} & h^{\dagger} & 0 \end{pmatrix} \in (2,2), \qquad h = \begin{pmatrix} h_1 + i & h_2 \\ h_0 + i & h_3 \end{pmatrix}, \quad \tilde{h} = i\sigma_2 h^*$$

Alternative Strong Dynamics, #4

 $V(h)_{tree}$

At tree level, the Higgs is an exact NGB and has no potential

BUT, the higgs develops a potential radiatively, through other interactions

SU(2) x U(1) gauge interactions, Yukawa interactions pull the Higgs potential in different directions and can result in a non-trivial minimum



<u>Alternative Strong Dynamics, #4</u> Scales and degrees of freedom

fundamental fermions Ψ_{CH} are massless new strong interaction is asymptotically free

$$f_{CH} \sim \Lambda_{CH}/(4\pi)$$

new interaction confines, Ψ_{CH} bound into composites

some of these composites have the same quantum numbers as the Higgs boson.

There is a physical Higgs boson in the theory. No potential at tree level, but gets a loop-level potential. If V(H) minimized at $\langle H \rangle = v \neq 0$, EWSB occurs

v = 246 GeV

Composite Higgs: we can get $v \ll f_{CH}$

remember, in Technicolor we had $v\equiv F_T$

<u>Alternative Strong Dynamics,#5</u> strong dynamics itself does NOT break EWS

- ... but leads to a Higgs `pion', which ultimately gets a vev
 - Interesting idea, as we can have $v \ll \Lambda_{CH}$ but haunted by many familiar problems:
- <u>calculabiliy</u>: $m_H^2 < 0$ is vital for EWSB. Can we be sure of our potential in a strongly interacting theory? (add extra symmetry to make V(h) less UVsensitive and more predictable = Little Higgs models) (Arkani-Hamed et al '01, '02)
- <u>fermion masses</u>: what generates the operators which eventually become Yukawas interactions?
- Flavor: how do we avoid FCNC from these new states hot topic of research !

<u>Alternative Strong Dynamics,#5</u> strong dynamics itself does NOT break EWS

Extra-dimesnional 'holographic' techniques can help here too!

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• <u>calculabiliy</u>: $m_H^2 < 0$ is vital for EWSB. Can we be sure of our potential in a strongly interacting theory? (add extra symmetry to make V(h) less UVsensitive and more predictable = Little Higgs models) (Arkani-Hamed et al '01, '02)

 <u>fermion masses</u>: what generates the operators which eventually become Yukawas interactions?

 Flavor: how do we avoid FCNC from these new states hot topic of research !

Strong Dynamics is here to stay!

still not convinced? really like SUSY?

* Supersymmetry only solves the hierarchy problem IF the superpartners are at the \sim TeV scale. Though stable, you still need to naturally generate a TeV $\ll M_{pl}$ hierarchy. How?

Dynamical SUSY breaking $M_{SUSY} \sim M_{pl} e^{-8\pi/g^2}$

(Witten '82, Affleck, Dine, Seiberg '80's)

strong dynamics at or above the weak scale are necessary in (almost) ANY natural BSM model, with or without SUSY

Technicolor and Dark Matter

Motivation for Park Matter







73% DARK ENERGY

23% DARK MATTER

(see lectures by P. Ullio)

we are here

3.6% INTERGALACTIC GAS 0.4% STARS, ETC.

Motivation for Park Matter, #2

it's a 'smoking gun' signal for new physics





complementary experiments going on, either to detect DM directly

or indirectly..



 The usual story of BSM Dark Matter -- many BSM scenarios insist on a discrete symmetry under which SM particles are even, BSM particles are odd.

$$\begin{array}{ll} \text{SM: EVEN} & f \to f \\ h \to h \end{array}$$

EW PHYICS: ODD

$$Z' \rightarrow -Z'$$

 $\tilde{f} \rightarrow -\tilde{f}$

lightest odd particle is stable <u>DM candidate!</u>

this BSM-Parity is often needed for other phenomenological reasons (proton stability, FCNC, PEW)

* BUT exact discrete symmetry is a foreign concept in the Standard Model

in the SM, ALL discrete symmetries:



are known to be violated.



In this light, imposing an exact parity on the new physics seems strange

* Why is the proton stable?

* No discrete symmetry protects it... Instead the low-energy SM theory has an approximate continuous symmetry, $U(1)_B$ baryon number $q_{Li} \rightarrow e^{iB/3}q_{Li}, \ q_{Ri} \rightarrow e^{iB/3}q_{Ri}$

may be violated by higher dimensional operators, but as long as they lead to $au_p \gg au_{universe}$, no cosmological problems

* Baryon # keeps p stable, but doesn't explain why we have more matter than anti-matter. For that we need an initial asymmetry

 $n_B \gg n_{\bar{B}}$ at $t = t_0$

Initial $p - \bar{p}$ asymmetry + approximate $U(1)_B$

stable proton

let's apply the same logic to BSM dark matter

<u>Techni-baryons are the perfect candidate</u>

need to make Technibaryon number an accidental symmetry of the EW-scale theory



* charge, weak quantum numbers are set by Fermi statistics, N_{TC} , the number of technifermions and their representation

<u>BSM Dark Matter, #5</u> Not quite that simple..

- Can't have technibaryon-number violating interactions -- constrains the ETC theory somewhat
- if the lightest technibaryon is charged -- ruled out by heavy isotope searches
- if the lightest techibaryon has EW quantum numbers -large cross section nuclei from Z exchange, so ruled by direct DM detection experiments





* To see how viable a PM candidate is, we need its annihilation cross section:



BUT how do you know the annihilation cross section for a technibaryon -- a new strongly bound state?

* neat trick to get $\Omega_X h^2$ without direct calculation

(Nussinov, Barr Chivulkula Farhi, Kaplan)

As technifermions have EW charges, technibaryon # is violated by anomalies, just like baryon # and lepton #, but the difference is not

* Therefore all three types of matter: quarks, leptons, technibaryons are connected by sphaleron processes



Poesn't the fact that $\Lambda_T \gg \Lambda_{QCD}$ imply $ho_{TC} \gg
ho_p$

not quite -- number density of heavy particles (compared to T) are Boltzman suppressed

$$n \sim \begin{cases} \mu_i & m \ll T \\ \mu_i e^{-m/T} & m > T \end{cases}$$

Y

* So starting with some initial asymmetry, it gets spread in calculable ways between baryons, techibaryons, leptons

$$\rho_{TC} = \frac{6g_{TC}}{N_{TC}} f(m_{TC}^*/T^*) \Big| \frac{3}{4} + \frac{L}{3B} \Big| \frac{m_{TC}}{m_p} \rho_p$$

Accurately connects proton relic abundance to DM abundance $\rho_{TC} \sim 5\rho_p$ without fine tuning resurgent topic of research recently

 $Q=0, SU(2)_w$ singlet Technibaryons have very weak interactions with the SM

no renormalizable interactions with SM

most important terms are (for scalar technibaryon):

(in NR EFT power counting)

 $\frac{T^*Tv_{\mu}\partial_{\nu}F^{\mu\nu}}{\Lambda_{TC}^2} \quad charge-radius operator \\ (Bagnasco, Dine, Thomas '91)$

(Kribs) $rac{T^*TF^{\mu
u}F_{\mu
u}}{\Lambda^3_{TC}}$ "polarizability" operator (Chiv

(Chivukula, Cohen..)

other states with mass $\sim M_T$ possible



LHC implications?

A word of caution before the fun starts

with so many ideas







LHC

The Large Hadron Collider in the LEP Tunnel

Proton- Proton Collider

7 TeV + 7 TeV

Luminosity = 10^{34} cm⁻²sec⁻¹

first targets: •Higgs boson (s) •Supersymmetric Particles •Quark-Gluon Plasma •CP violation in B

From CERN education program webpage





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> < =

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From CERN education program webpage

Not convinced?

ATLAS working groups

ATLAS Publications

- ATLAS Detector Paper (journal, chapt
- Expected Performance of the ATLAS

Physics Groups

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Overall responsibility: Physics Coordinat

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TRE	ATM	ENT!	? ~	1
Te	chnicol	or,		
Littl	e Higgs,	etc.	-	_
A	-			

Group	Link to public results		
Standard Model	Results		
B Physics	Results		
Top Physics	Results		
Higgs	<u>Results</u>		
SUSY	Results		
Exotics	Results		
Heavy lons	Results		
Monte Carlo	coming soon		

We should keep an open mind about what to expect at the LHC!



We should keep an open mind about what to expect at the LHC!



* it is an incredibly exciting time for particle physics, so we should keep an open mind and enjoy it!



THANK YOU

Sample References:

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