Electroweak Symmetry Breaking and New Dynamics at the TeV Scale

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Outline

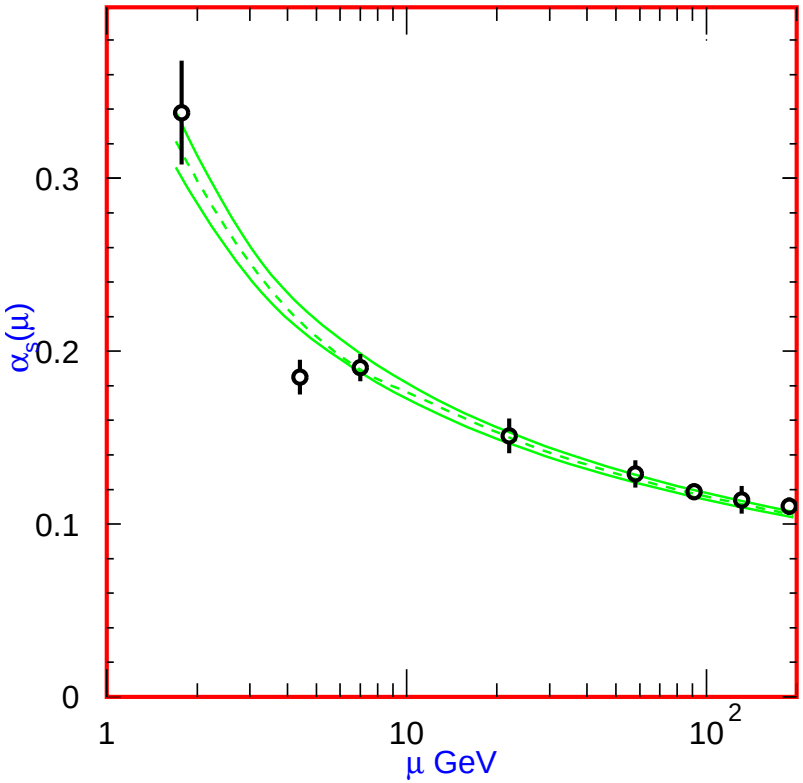
The Standard Model: a Gauge Theory

Interactions among known elementary particles described by

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

The Strong Interactions

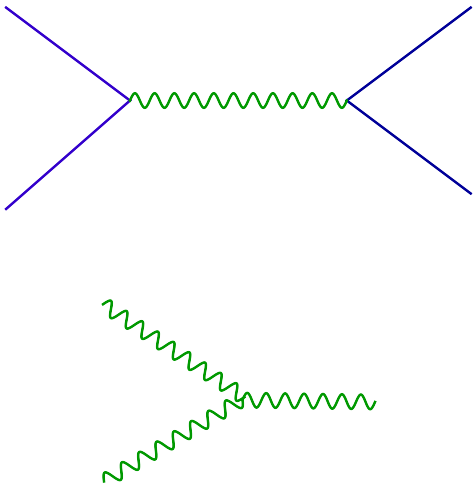
Described at high energies by $SU(3)_c$



The Electroweak Sector

Electroweak interactions described by $SU(2)_L \times U(1)_Y$

Gauge Interactions



	Measurement	Fit	$\lvert O^{meas} - O^{fit} \rvert / \sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ^0_{had} [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01643	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1480	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.399 ± 0.025	80.378	
Γ_W [GeV]	2.098 ± 0.048	2.092	
m_t [GeV]	173.1 ± 1.3	173.2	

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Spontaneously Broken Electroweak Sector

But the electroweak gauge theory actually is spontaneously broken:

$$SU(2)_L \times U(1)_Y \longrightarrow U(1)_{\rm EM}$$

- M_W, M_Z, $\sin^2\theta_W$
- Observations consistent with this pattern of symmetry breaking

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- Central question: What is the origin of this spontaneous breaking ?

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- Other questions: Fermion mass hierarchy, Dark Matter, Baryogenesis, $\cdots$

Electroweak Symmetry Breaking and the Standard Model

Implementation of the Higgs Mechanism:

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

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

- Interactions with gauge bosons in $D_\mu = \partial_\mu - g\vec{W}_\mu - g' B_\mu$
- $V(H) \Rightarrow$ vacuum not invariant: $\langle H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$

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

Spontaneous Symmetry Breaking

Superconductor: Electromagnetic gauge invariance is spontaneously broken. Material obeys

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

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

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

- Magnetic Field vanishes inside $\longrightarrow$ flux exclusion (Meissner effect.)
- EM interactions become short range $\Rightarrow$ "Massive" Photon

$\Rightarrow$ Higgs mechanism

SSB in a Superconductor

- Effective Description: Superconductivity described by order parameter ϕ and the Landau-Ginzburg theory

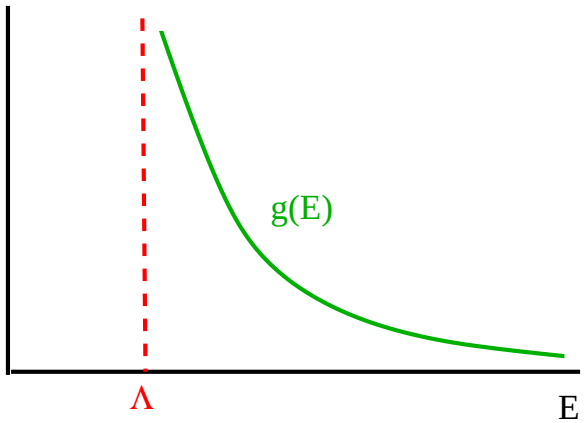
$$V(\phi) = -\mu^2 |\phi|^2 + \lambda \left(|\phi|^2 \right)^2$$

- Microscopic Description: BCS theory

$$\langle e^- e^- \rangle \neq 0$$

$V(\phi)$ only an effective description of underlying dynamics

Spontaneous Chiral Symmetry Breaking in QCD



At low energies, $\Lambda \sim \Lambda_{\rm QCD}$

$$\langle \bar{Q}_L Q_R \rangle \neq 0$$

$$\Rightarrow SU(3)_L \times SU(3)_R \longrightarrow SU(3)_V$$

Below Λ: π's, K's, η's and baryons.

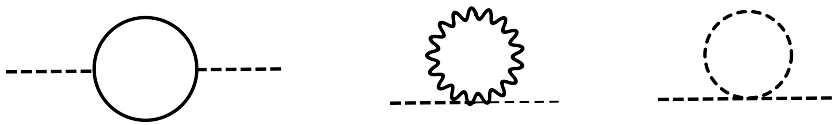
Above Λ: quarks and gluons. QCD UV completion of strong interactions.

What is the underlying dynamics of EWSB ?

Examples suggest new dynamics underlying Higgs mechanism of EWSB

The Hierarchy Problem

But if Higgs elementary scalar quantum corrections drive m_h up



$$\delta m_h^2 \sim \frac{c^2}{16\pi^2}\Lambda^2$$

- We need $\Rightarrow m_h \lesssim 1$ TeV
- But if $\Lambda \rightarrow M_P \sim 10^{19}\ GeV$, unnatural

$\Rightarrow$ Gauge Hierarchy Problem

Solving the Hierarchy Problem and EWSB

Need new physics at $\Lambda \sim 1$ TeV

New Dynamics

New Dynamics generate Hierarchy and break Electroweak Symmetry

- Technicolor, Topcolor, Top see-saw, $\cdots$
- Most compact extra-dimensional theories: mostly warped extra dimensions, LED

New Symmetries

Symmetries cancel quadratic divergencies, defer need for new dynamics. Electroweak symmetry broken radiatively.

- SUSY (e.g. dynamics to generate μ term)
- Little Higgs, Twin Higgs, $\cdots$

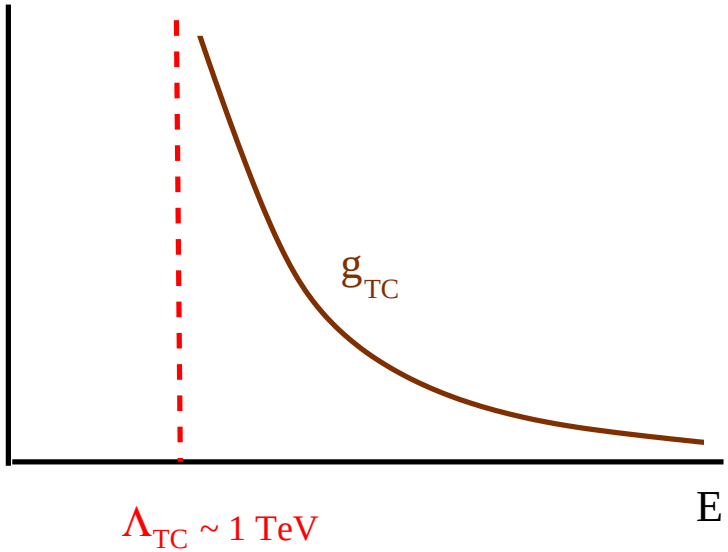
New Dynamics at the TeV Scale

New Dynamics at the TeV Scale

Strong Dynamics at the TeV Scale

Analogy with QCD:

- New Strong Interaction: Technicolor
- Strong at $M_W \ll M_P$
- Breaks Electroweak symmetry: $\langle \bar{F}_L F_R \rangle \neq 0$



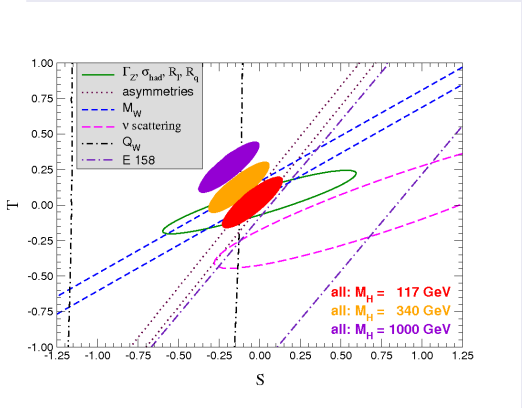
Higgs Mechanism:

$(\tilde{\pi}^{\pm}, \tilde{\pi}^{0}) \Rightarrow (W_L^{\pm}, Z_L)$

$\Rightarrow M_W, M_Z$

Problems with Technicolor

Electroweak Precision Bounds



S parameter constraints:

$$S_{\rm TC} \sim N$$

But Minimal TC models OK

Fermion Masses

Need Extended Technicolor

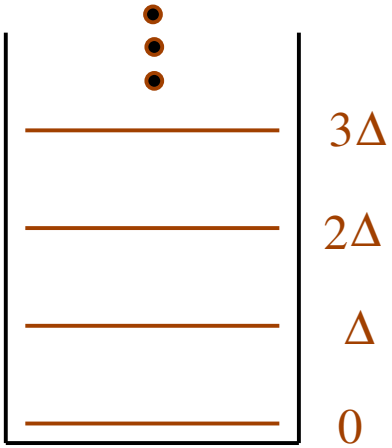
- Fermion mass hierarchy $\Rightarrow$ need many ETC scales
- Heavier masses (m_c, m_τ) require "walking".
- ETC cannot get m_t

  $\Rightarrow$ Fermion mass hierarchy main problem for Technicolor

Modeling the New Dynamics of the TeV Scale

New tools for modeling strongly coupled theories:

Theories with Compact Extra Dimensions $\leftrightarrow$ Strongly Coupled 4D Theories



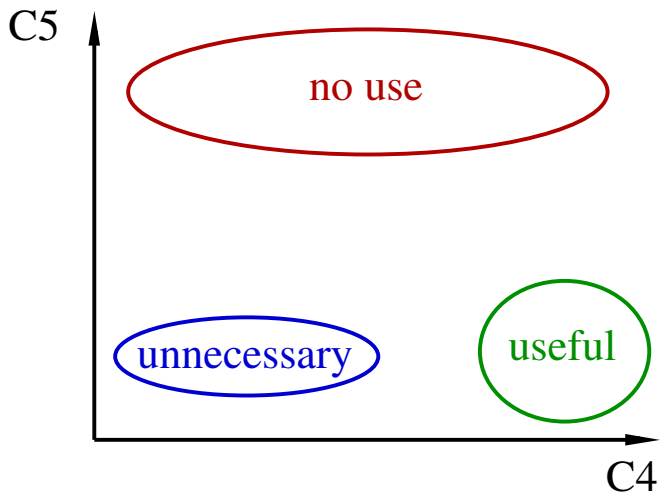
KK Modes $\leftrightarrow$ Radial Excitations

$M_{KK} \sim \Delta \leftrightarrow$ Scale of Strong Interaction

Δ related to size of extra dimension

Strong Dynamics from Extra Dimensions

When is it useful ?



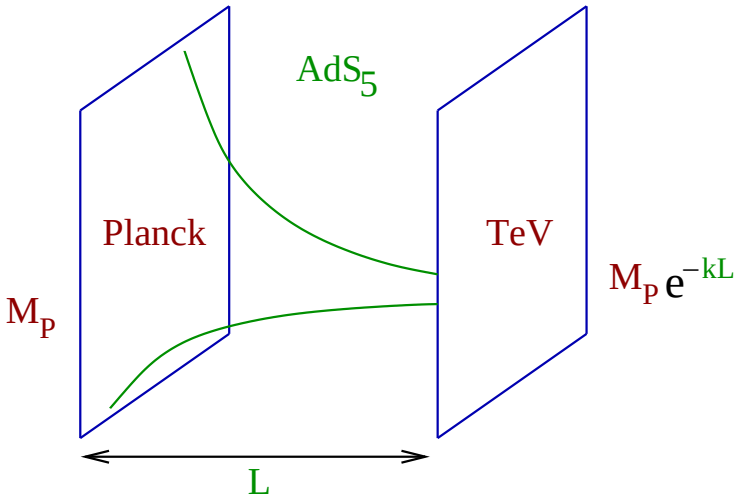
For instance: in *QCD* with large N_c, hadrons couple weakly

$\Rightarrow$ If strong dynamics is "large N", extra-dimensional theory is weakly coupled

Strong Dynamics from One Curved Extra Dimension

Solving the Hierarchy Problem with one curved extra dimension:

Metric in extra dimension $\Rightarrow$ small energy scale from M_P (Randall-Sundrum)



Corrections to m_h OK
If Higgs close to TeV brane

Need Higgs IR localization

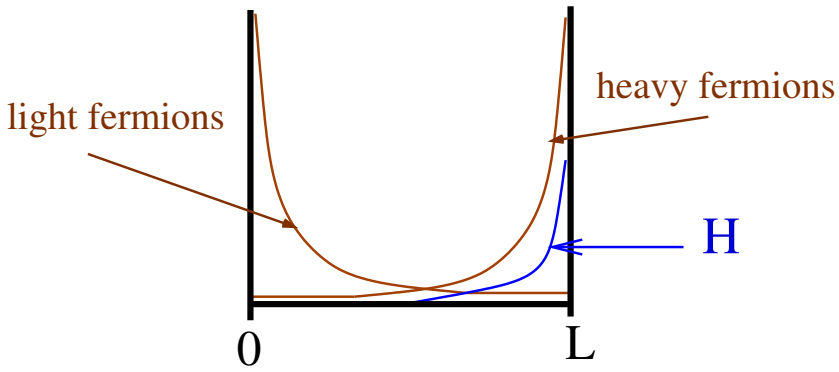
Dynamical Origin of the Higgs Sector

Different 4D Strong Dynamics depends on what localizes the Higgs to/near the IR/TeV brane

- Gauge-Higgs Unification $\longleftrightarrow$ Composite Higgs (Agashe, Contino, Pomarol)
  - Extract H from a 5D gauge field: $A_M^a \to (A_\mu^a, A_5^a)$
  - m_h protected by 5D gauge symmetry (or H is a pseudo NGB)
- Zero-mode Fermion Condensation $\longleftrightarrow$ Strongly Coupled 4th Generation (G.B., Da Rold)
  - 4th Generation localized near IR $\Rightarrow$ strongly coupled to KK gauge bosons
  - E.g. $\langle \bar{U}_4 U_4 \rangle \neq 0 \Rightarrow$ EWSB
- Higgsless (EWSB by boundary conditions) $\longleftrightarrow$ Walking Technicolor (Csaki, Grojean, Pilo, Terning)

Origin of Fermion Mass Hierarchy

$O(1)$ flavor breaking in 5D bulk can generate fermion mass hierarchy:



TeV localization $\longrightarrow$ larger Yukawas,
Planck localization $\longrightarrow$ suppressed Yukawas.

These Strongly Coupled Theories include
a *working* model of fermions masses and mixings

Signals at the LHC

These theories are characterized by:

- S-channel resonances: KK Gauge Bosons / Vector Mesons
- Flavor violation: resonances couple stronger to heavier fermions
  - $V_{KK} \to \bar{t}t$
  - $V_{KK} \to \bar{t}j$
  - Flavor physics: Lepton flavor violation, Rare B decays, Charm mixing/CPV

  Other model-dependent signals:
  - Light Higgs vs. Heavy Higgs (or no Higgs)
  - Heavy Fourth Generation vs. Light KK Fermions
  - Gauge symmetries $\Rightarrow$ Spectrum of resonances

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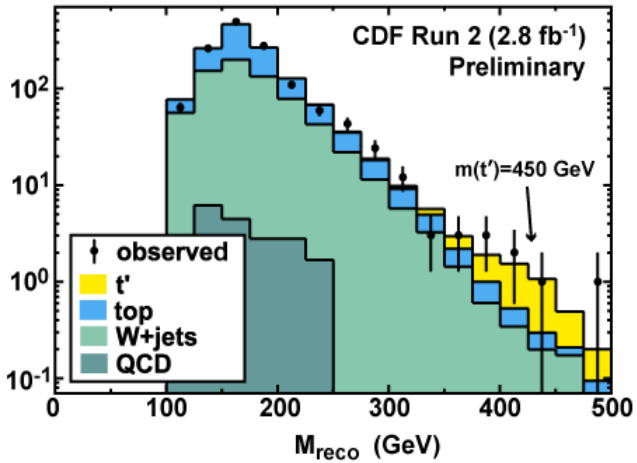
Map as many strongly coupled theories as possible
Better chance to reconstruct dynamics from signals

Signals at the Tevatron ?!

Has the Tevatron seen strongly coupled new fermions ?

(Dobrescu, Kong, Mahbubani '09; G.B. Da Rold, Matheus, in progress)



Consistent with $M_{KK} \simeq 1$ TeV

Summary/Outlook

- The TeV scale could be a window to new strong dynamics
- Weakly coupled theories in curved 5D map to Strongly Coupled 4D Dynamics
- Viable Models of EWSB *and* Flavor
- Resonant spectrum $\simeq$ few TeV
- Couplings of KK gauge bosons to fermions reveal flavor theory
- Models and Signals defined by mechanism of Higgs localization, flavor
- If LHC reveals Strongly Coupled TeV scale
  $\Rightarrow$ Model Building in 5D could be a useful tool
- Other useful tools:
  - Lattice simulations
  - Deconstruction of extra-dimensional theories