Emergent Electroweak Symmetry Breaking

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Outline

Motivation

- Standard Model: Benchmark model of particle physics, based on gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$
  Story incomplete: W, Z bosons, fermions are **MASSIVE**$\longrightarrow$ EW gauge symmetry not exact
  Big mystery to unveil at the LHC: Origin of masses for SM particles**?**
- Most existing solutions: mass origin *equivalent to* (fundamental) Electroweak gauge symmetry breaking (EWSB) via Higgs mechanism
- Higgs Mechanism: ♣; Higgs boson: in hot pursuit (but not seen yet...)
  Is there alternative clue to 'mass origin' beyond this paradigm? Surprises from Nature?

A brief Review of existing EWSB models

- Elementary Higgs: EW scale stabilized by SUSY, EWSB triggered by dynamical SUSY breaking in a strong hidden sector
- Composite Higgs (5D dual): pseudo-Goldstone boson of chiral symmetry breaking
- Technicolor-like Higgsless (5D dual): decoupled heavy σ mode, strong TC sector

Common features of these EWSB models (4D)

- To naturally solve 'gauge hierarchy' problem–i.e.generate a TeV mass gap via dimensional transmutation, require a new external sector beyond the SM with confining strong dynamics
- Most of SM fields, esp. gauge fields stay elementary, spectators of strong dynamics, acquire mass by coupling to the strong sector via Higgs mechanism

- A 'wild' curiosity: Why this strong dynamics almost 'inevitable' for generating SM mass has to be external? Why not underlying the SM?
- Actually not 'wild': familiar example–QCD! Mesons, baryons–composites getting mass *directly* from quark confinement; esp. vector ρ meson acts like a massive 'gauge field' of spontaneously broken hidden local symmetry (more later...)
- Different origins of mass:
  - Higgs mechanism: W, Z slowed down when 'swimming' through dark medium-Higgs (*'cosmic superconductor'*)
  - Compositeness: W, Z gain mass from binding energy of internal constituents, like tension of a string

$\Rightarrow$An **alternative** origin of mass where 'EWSB' is IR Emergent, opens up deeper substructure in Nature?

More on emergent gauge theory

- Emergent gauge symmetry (breaking) (or composite gauge boson) is conceptually innocuous, even inspiring: 'Gauge symmetry, unlike global symmetry, is not a true symmetry of nature, does not lead to new conserved charge, merely reflect redundancy in the description' (D. J. Gross, "Gauge theory - past, present and future," 1997)
- Theoretical example–Seiberg duality: in conformal window $\mathcal{N} = 1$ SUSY QCD, a dual 'magnetic gauge theory' $SU(N_f - N_c)$ *emerges at composite level*, with same IR physics as original $SU(N_c)$ 'electric gauge theory' *"gauge symmetry may not be fundamental, some gauge symmetries in the SM or even general relativity may be long distance artifacts."* (N. Seiberg, "The power of duality: Exact results in 4D SUSY field theory,"1995)
- Realistic example– Hidden local symmetry (HLS) in QCD→

Intriguing story of QCD ρ meson

QCD ρ meson: vector boson in $SU(2)_V$ triplet, $\rho^{\pm}, \rho^0$ obtain almost degenerate masses from QCD confinement.

Phenomenology: Universal coupling to matter (π, N...); ρ-dominance of hadron EM form factor and of $\pi\pi$ scattering

A neat theory to describe all these observations: ρ meson is a dynamical gauge boson of spontaneously-broken HLS $SU(2)_V$

(Sakurai first conjectured in 1960, M. Bando etc. 1985)

Remarkable similarity to W, Z in EW theory

- Unbroken QCD $SU(2)_V$ (global) acts like custodial symmetry ensures degenerate $\rho^{1,2,3}$ masses with no $\rho - \gamma$ mixing
- $\rho - \gamma$ mixing is in exactly the same pattern as $W^3 - B$ mixing in EW theory ($SU(2)_{HL} \times U(1)_Q \to U(1)'$) and splits $\rho^0, \rho^{\pm}$ masses

Could EWSB be another example of ‘emergent gauge theory’? W,Z composites?

- History: Early attempts– Bjorken 1977; Hung, Sakurai 1978; Abott, Farhi 1981; Fritzsch, Schildnecht, Kogerlert 1982; Kugo, Uehara, Yanagida 1984; Suzuki 1987,arXiv:1006.1319...
  Model Building, calculability limited due to nonperturbative nature
- Our Goal: towards a realistic composite W, Z model with good calculability using powerful modern tool– AdS/CFT: 5D physics in warped Xdim⇒Effective 4D chiral $\mathcal{L}$ of massive W, Z, fermions
- Job list:
  - Generate masses for W, Z, fermions
  - Ensure universality of gauge couplings
  - EW precision tests
  - Novel solution for unitarizing high E $W_L W_L$ scattering: form factor suppression for composites...

Organizing Principles, AdS/CFT Dictionary

- AdS/CFT correspondence(Maldacena, 1997): strongly-coupled 4D conformal gauge theory $\Leftrightarrow$weakly coupled 5D (AdS_5) gravity theory
- CFT with a UV cutoff, undergos CFT-breaking confinement at IR $\Leftrightarrow$ Warped 5D model (e.g. RS1) built on a slice of AdS_5 (Arkani-Hamed, Porrati, Randall 2001 etc.)
- Global symmetry ($\longrightarrow$ emergent gauge symmetry at IR) in 4D CFT, unbroken at IR$\Leftrightarrow$ 5D gauge symmetry broken on UV brane, preserved on IR brane
  Composite gauge boson $\Leftrightarrow$ KK mode of 5D gauge field peaking on IR brane

Two points to keep in mind:

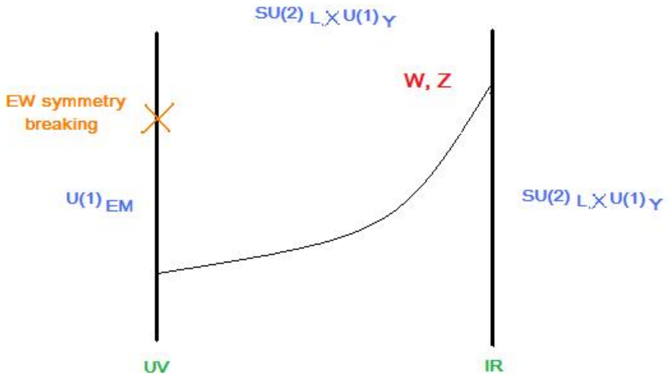
- To ensure a **robust** weakly coupled gravity dual, implicitly assume the 4D side is large N, large t' Hooft coupling(unlike QCD!$\Rightarrow$ possible interesting phenomenology **later...**)
- 5D EW gauge symmetry broken at UV: different from original RS and all existing warped models where EWSB occurs on IR
  Simple picture: ‘would-be’ elementary gauge field (flat zero mode) get Planck scale mass upon EWSB at UV, decouples from low energy theory; TeV physics described by light KK modes, W, Z are lightest KK, mass do not come from 4D Higgs mechanism

Getting realistic mass spectrum

- **Challenge:** composite W,Z⇔1st KK modes peaking at IR; Usual KK mass spectrum in RS1-type model $m_n \sim nz_1^{-1} \Rightarrow$ $m_Z = m_1 \sim 90\text{GeV}$ implies $m_2 \sim 200\text{GeV} \Leftarrow$ LEP bound $m_{Z'} > 1500\text{GeV}$
  $\Rightarrow$ (On 4D side) W, Z needs to be 'special light mode' vs. confinement or typical resonance scale at O(TeV) . Known e.g. QCD $m_\pi \ll \Lambda_{QCD}$
- How to realize in 5D model–a 'distorted' spectrum with ultra-light 1st KK?–Turn on brane kinetic term (BKT): Generic, compatible with 4D Poincare symmetry on brane
  – (Carena, Ponton,Tait and Wagner 2003; Davoudiasl, Hewett and Rizzo 2003)

The 5D Model

Model Setup:



5D action

$$\begin{aligned} S &= \int d^4x\, dz \sqrt{-g}[-\frac{1}{4}(F^{La}_{MN})^2 - \frac{1}{4}(F^{Y}_{MN})^2 \\ &- \frac{1}{2}(kz)\delta(z-z_{UV})\frac{\zeta_Q}{g^2_{Y5}+g^2_{L5}}(g_{Y5}F^{L3}_{\mu\nu} + g_{L5}F^{Y}_{\mu\nu})^2 \\ &- \frac{1}{2}(kz)\delta(z-z_{IR})\left(\zeta_L(F^{La}_{\mu\nu})^2 + \zeta_Y(F^{Y}_{\mu\nu})^2\right)]. \end{aligned}$$

Boundary conditions

$$z = z_{UV} : \begin{cases} \partial_z(g_{Y5}A^{L3}_\mu + g_{L5}B_\mu) + \zeta_Q\Box(g_{Y5}A^{L3}_\mu + g_{L5}B_\mu) = 0, \\ g_{L5}A^{L3}_\mu - g_{Y5}B_\mu = 0, \\ A^{L1,2}_\mu = 0, \end{cases}$$

$$z = z_{IR} : \begin{cases} \partial_z A^{La}_\mu - \zeta_L k z_{IR}\Box A^{La}_\mu = 0, \\ \partial_z B_\mu - \zeta_Y k z_{IR}\Box B_\mu = 0, \end{cases}$$

Mass spectrum and Profiles

- A flat zero mode exists: photon
- Lightest KK mode: SM W, Z boson

$$m_Z \simeq \sqrt{\frac{2}{\zeta_L k} + \frac{2}{\zeta_Q k(1+\beta^2)}} z_{IR}^{-1} \ .$$

$$m_W \simeq \sqrt{\frac{2}{\zeta_L k}} z_{IR}^{-1} .$$

- Higher KK modes have 'normal' masses of $O(z_{IR}^{-1})$ (TeV), suppressed IR coupling due to BKT induced repelling (Carena, Ponton,Tait and Wagner 2003; Davoudiasl, Hewett and Rizzo 2003)

W, Z 5D profiles:

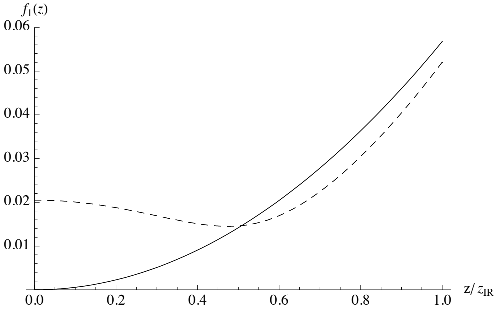


Figure: The W-boson (solid) and Z-boson (dashed) profiles in units of $\sqrt{k}$.–Peaking at IR ($\sim\propto z^2$), indeed dual composites

Electroweak Precision Test

T **parameter:** deviation from relation $\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_w} = 1$

- Sufficient protection requires custodial symmetry $SU(2) \Rightarrow$ $m_W^{\pm} = m_Z$ at $g_1 = 0$, Automatic in SM Higgs with potential $SO(4)$
- Most new models need to add global $SU(2)_R$ in addition to $SU(2)_L \times U(1)_Y$ (e.g. additional bulk $SU(2)$ in most RS models)

Our model: No need for new $SU(2)$, $SU(2)_L$ itself play the role!

- Our W,Z are true KK modes, masses correlated by bulk $SU(2)_L$ upon dim-reduction
- In 4D dual picture, masses originate from CFT breaking at IR which breaks 'emergent' local $SU(2)$, while BC ensures global $SU(2)_L$ unbroken there
- Recall ρ meson in QCD!–upon confinement $SU(2)_V$ global survives, emerged $SU(2)$ local is 'broken' since triplet ρ get masses (degenerate due to $SU(2)_V$ global)

S-parameter: new physics contribution to Π'_{33}, Π'_{3Q}

- A challenge for Higgsless models: $S \sim \frac{g_n}{M_n^2}$ (M_n: KK mass, g_n: KK V'-SM V coupling), in TC or its 5D variations typically g_n big, M_n relatively light $\Rightarrow S \sim O(1)$, too big
- In our model: BKT effects increases m_{KK}, decreases $g_n \Rightarrow$ reduce S

Matching to SM: Assumption for fermions: predominantly on IR brane (details on fermion sector, see later slides)

Calculation of S, T

- By definition $S \equiv 16\pi(\Pi'_{33} - \Pi'_{3Q})$, in 5D model gives $S = \frac{16\pi}{g^2+g'^2}(1 - Z_Z)$ where

$$Z_Z = \left\{\int \frac{dz}{kz}\left[(f_1^{L3}(z))^2 + (f_1^B(z))^2\right] + \frac{\zeta_Q}{1+\beta_5^2}\left[f_1^{L3}(z_{UV}) + \beta_5 f_1^B(z_{UV})\right]^2 + \zeta_L(f_1^{L3}(z_{IR}))^2 + \zeta_Y(f_1^B(z_{IR}))^2\right\},$$

- By definition $T \equiv \frac{4\pi}{\sin^2\theta_w \cos^2\theta_w m_Z^2}(\Pi_{11}(0) - \Pi_{33}(0))$, in 5D model

$$g^2\Pi_{11}(0) = \int \frac{dz}{kz}\left|\partial_z f_W(z)\right|^2,$$

$$(g^2+g'^2)\Pi_{33}(0) = \int \frac{dz}{kz}\left[\left|\partial_z f_1^{L3}(z)\right|^2 + \left|\partial_z f_1^B(z)\right|^2\right].$$

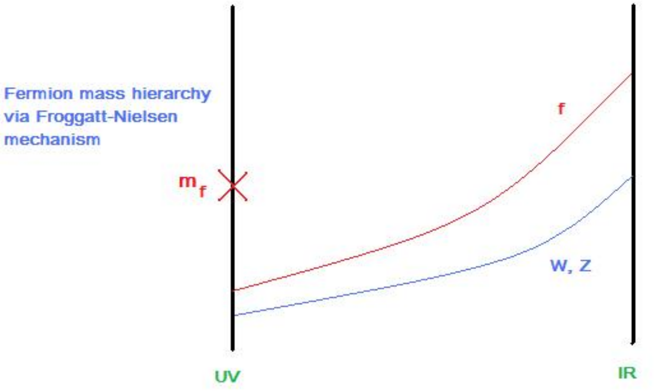
Numerically find with $z_{IR} = 1.8\mathrm{TeV}$,
$S \simeq 0.1$, $T \simeq 0.05$–good fit with LEP EWPT data, confirm the built-in protection mechanisms discussed earlier

Fermion Sector

Guidelines:

- Gauge coupling universality: usually automatic with flat gauge profile (elementary) once fermions canonically normalized
  Our model: non-flat gauge profile $\Rightarrow$ need universal fermion profile, same bulk mass c, $\Rightarrow$ fermion mass hierarchy cannot result from 'geography'
- Mass origin: hierarchical UV Yukawa (Froggatt-Nielsen)+ exponential suppression of UV profile
  Fermion zero mode can have very different profile depending on bulk mass c: $\psi(y)^{(0)} \propto e^{(\frac{1}{2}-c)ky}$
  Naive estimation of mass from UV Yukawa y:
  $m \sim y \cdot k(\psi(y_{UV})^{(0)})^2 \sim y \cdot ke^{2(c-1/2)ky_{IR}}$ $\Rightarrow$ with $c = 0$, $y \sim O(1)$ gives $m \sim \mathrm{TeV}$ (top) –Magic from warping!
- Predominantly IR localized: add IR BKT

Model Setup


Fermion mass hierarchy
via Froggatt-Nielsen
mechanism
m f
f
W, Z
UV
IR

5D action

$$S_\Psi = \int d^5x\sqrt{-g}\left[\frac{1}{2}(\overline{\Psi}_i^{(L)}\Gamma^M D_M\Psi_i^{(L)} - D_M\overline{\Psi}_i^{(L)}\Gamma^M\Psi_i^{(\mathrm{L})}) + m_L^{(i)}\overline{\Psi}_i^{(L)}\Psi_i^{(L)} + (L\leftrightarrow R)\right].$$

$$S_m^{(UV)} = \int d^5x\sqrt{-g}\,\lambda_5^{(i)}\left[\overline{\Psi}_i^{(L)}\Psi_i^{(R)} + \overline{\Psi}_i^{(R)}\Psi_i^{(L)}\right](kz)\delta(z-z_{\mathrm{UV}}),$$

$$S_{KE}^{(IR)} = \int d^5x\sqrt{-g}\left[\frac{1}{2}\eta_{iL}(\overline{\Psi}_i^{(L)}\Gamma^\mu D_\mu\Psi_i^{(L)} - D_\mu\overline{\Psi}_i^{(L)}\Gamma^\mu\Psi_i^{(\mathrm{L})}) + (L\leftrightarrow R)\right](kz)\delta(z-z_{IR})$$

Boundary Conditions

$$f_{L+}^{(n)}(z_{\mathrm{UV}}^+) = -\lambda_5 f_{R+}^{(n)}(z_{\mathrm{UV}}), \quad f_{L+}^{(n)}(z_{\mathrm{IR}}^-) = -(\eta_L k)(m_n z_{IR})f_{L-}^{(n)}(z_{IR}),$$

$$f_{R-}^{(n)}(z_{\mathrm{UV}}^+) = \lambda_5 f_{L-}^{(n)}(z_{\mathrm{UV}}), \quad f_{R-}^{(n)}(z_{\mathrm{IR}}^-) = (\eta_R k)(m_n z_{IR})f_{R+}^{(n)}(z_{IR}),$$

Example: Massless bulk fermions ($c = 0$)

Even modes profile:

$$|f_{L-}^{(n)}(z)| = |f_{R+}^{(n)}(z)| = N_n^{(0)}(kz)^2\left[\cos(\widehat{m}_n - m_n z) - (\eta k)\widehat{m}_n \sin(\widehat{m}_n - m_n z)\right]$$

where

$$N_n^{(0)} \simeq \frac{1}{\sqrt{z_{\rm IR}}}\sqrt{\frac{1}{1+(\eta k)/2+(\eta k)^2\widehat{m}_n^2}}, \quad \hat{m} = m z_{IR}^{-1}$$

Obtain for BKT ($\eta = 10$):

$m_e \leq m \leq m_t$ with $3.1 \times 10^{-6} \leq \lambda_5 \leq 1.15$

W, Z Couplings

Fermion-gauge couplings determined by wavefunction overlap, e.g:

$$g_W \simeq \frac{g_{5L}}{\sqrt{\zeta_L}} \frac{2}{\eta k} \left[\frac{1}{3} + \xi_{IR} k (1 - 2(\eta k) \widehat{m}_i \widehat{m}_j) \right],$$

where BIT $\xi_{IR} = \sqrt{\zeta_L / 2\Lambda \eta}$, $\hat{m} = m z_{IR}^{-1} \ll 1$

$\Rightarrow$Light fermions: nonuniversality at the per-mille level

Top-related: nonuniversality at $15 - 25\%$ level:

$$\frac{g_{W-}(\mathrm{tb})}{g_{W-}(\mathrm{ud})} = 0.854; \qquad \frac{g_{Z-}(\mathrm{top})}{g_{Z-}^{(SM)}(\mathrm{top})} = 0.731; \qquad \frac{g_{Z+}(\mathrm{top})}{g_{Z+}^{(SM)}(\mathrm{top})} = 0.732$$

Compatible with current direct bound:

Wtb: 20%@ Tevatron, Ztt: 40%@ LHC with $300\mathrm{fb}^{-1}$

Gauge coupling universality due to light fermion masses!

Top anomaly

Anomalous top couplings⇒ **Indirect** bound from EWPT data (Larios, Perez, Yuan '99)
Obtain:

$$\epsilon_1^{SM} + \delta\epsilon_1 \simeq 19 \times 10^{-3}; \qquad \epsilon_b^{SM} + \delta\epsilon_b \simeq -13 \times 10^{-3},$$

This compares with (68% C.L.)

$$\begin{aligned} 4.4 \times 10^{-3} \leq \quad \epsilon_1^{exp} \quad \leq 6.4 \times 10^{-3}, \\ -6.2 \times 10^{-3} \leq \quad \epsilon_b^{exp} \quad \leq -3.1 \times 10^{-3}. \end{aligned}$$

⇒ Requires special treatment for top quark (common issue for Higgsless models)
e.g. separate brane for the top (Cacciapaglia, Csaki, Grojean, reece, Terning '05)

Some Interesting Phenomenology

- Anomalous top coupling; lightest KK–t': $1.5\mathrm{TeV}$ well in LHC reach (2t+2γ/Z signal)
- **Compositeness**$\Rightarrow$ form factor falling at high p $\Rightarrow$Different story for WW scattering unitarization, anomalous WWZ, $WW\gamma$ couplings
- 4D dual theory: large N, large t'Hooft coupling$\Rightarrow$ huge splitting rate$\Rightarrow$No partons inside hadrons, coherent scattering at DIS with p-falling form factor!
  (Polchinski, Strassler 2002)

Conclusions

- We explore a new scenario where SM W, Z, fermions are **composites** getting masses from strong dynamics confining at IR, without Higgs mechanism. SM EW gauge symmetry, EWSB are IR "emergent" phenomena.
- Using AdS/CFT we build a calculable 5D warped model where EWSB on UV. ⇒realistic mass spectrum & good fit to S, T parameters
- The composite nature of $W, Z \Rightarrow$ novel solution for WW scattering unitarization; coupling deviations from SM can be probed at the LHC
- Indirect constraints: further model building required to successfully incorporate top

***Novel Prospect at LHC:* Mystery of SM mass origin⇒Deeper level of substructure in Nature?**