Title: Emergent Electroweak Symmetry Breaking

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Abstract: We explore a new scenario explaining mass origin of standard model (SM) particles without a Higgs boson. In this framework SM W, Z gauge bosons and fermions are composites getting masses from confinement of substructure at IR (conformal symmetry breaking). Therefore here SM electroweak gauge symmetry and its breaking are IR emergent phenomena. Using AdS/CFT we build a calculable warped 5D model. Realistic mass spectrum and good fit to electroweak precision data (S, T parameters) can be obtained. Furthermore the composite nature of W,Z may offer novel solution for WW scattering unitarization and predicts deviation from SM which can lead to distinctive signatures at the LHC.

Outline

- 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**→ 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 symmetry breaking (EWSB) via Higgs mechanism
  (elementary W,Z, massless in symmetric phase)
- *Is there alternative clue to 'mass origin' beyond this paradigm?*

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 all existing 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, not participants, acquire mass by coupling to the strong sector

- A 'wild' curiosity: Why this strong dynamics almost 'inevitable' for generating SM mass has to be external? Why not underlying the SM? (more economic and direct?)
- 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...)

Could our current view of SM be similar to seeing mesons, baryons before discovery of QCD quarks, gluons? SM: composites of new underlying constituents, mass directly generated by confinement?

⇒An **alternative** origin of mass where 'EWSB' is IR Emergent, true answer 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: $g^2_{\rho\pi\pi}/(4\pi) = 2.9$, $g_{\rho\pi\pi}g_{\rho NN}/(4\pi) = 2.8$
- ρ-dominance of hadron EM form factor $F(q^2) \sim \frac{f_\rho g_\rho}{q^2+\rho^2}$, easily explained with $\rho - \gamma$ mass mixing
- ρ-dominance 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: inspired by QCD ρ meson–early attempts at 1980's by Abbott and Farhi, Yanagida, Suzuki etc. Limited calculability for strongly-coupled model, well before precision data from LEP
- Our Goal: towards a realistic composite W, Z model with good calculability using powerful modern tool– AdS/CFT; then test it by precision electroweak data
- May provide a novel solution to another important question as well: unitarization of high energy $W_L W_L$ scattering; with compositeness, high E amplitude may be controlled by overall form factor suppression (existing mechanisms: add new states/graphs to cancel divergence)

Organizing principles, assumptions

- AdS/CFT correspondence(Maldacena, 1997):
  strongly-coupled 4D conformal gauge theory ⇔weakly coupled 5D (AdS_5) gravity theory
- CFT with a UV cutoff, undergos CFT-breaking confinement at IR ⇔ Warped 5D model (e.g. RS1) built on a slice of AdS_5 (Arkani-Hamed, Porrati, Randall 2001 etc.)
- Global symmetry (→ emergent gauge symmetry at IR) in 4D CFT, unbroken at IR⇔ 5D gauge symmetry broken on UV brane, preserved on IR brane
  Composite gauge boson ⇔ 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!⇒ possible interesting phenomenology (no partons!)**more 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 **(more later...)**

Getting realistic mass spectrum

- **Serious challenge:** composite W,Z⇔1st KK modes peaking at IR; Usual KK mass spectrum in RS1-type model $m_n \sim n z_1^{-1} \Rightarrow m_Z = m_1 \sim 90\mathrm{GeV}$ implies $m_2 \sim 200\mathrm{GeV} \Leftarrow$ LEP bound $m_{Z'} > 1500\mathrm{GeV}$
$\Rightarrow$ (On 4D side) W, Z needs to be 'special light mode' vs. confinement or typical resonance scale at O(TeV) . Not crazy, e.g. QCD $m_\pi \ll \Lambda_{QCD}$ (pseudo-Goldstone)
- How to realize in 5D model–a 'distorted' spectrum with ultra-light 1st KK?–Turn on brane kinetic term (BKT)
–Inspired by earlier work getting light W', Z' compatible with EWPT in RS with elementary SM W,Z (Carena, Ponton,Tait and Wagner 2003; Davoudiasl, Hewett and Rizzo 2003)

Getting realistic mass spectrum

- Generally expected at tree-level by 4D Poincare symmetry on branes (5D translational symmetry broken)
  Even absent at tree-level, loop correction to propagator (e.g. interaction with brane matter) demands such term as counter-term to cancel log divergence(Dvali, Gabadadze and Shifman 2001, Georgi, Grant and Hailu 2001);
- NDA size: $\zeta \sim L$ ($L \sim 35k^{-1}$ in RS: 5th dim size), yet large BKT is perturbatively consistent (Ponton, Poppitz 2001)$\Rightarrow$ take ζ as a free parameter in an effective theory, fix later by fitting masses, EWPT (interesting to consider UV completion later...)

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The 5D Model

- Consider a slice of AdS_5 spacetime
  $ds^2 = (\frac{1}{kz})^2 (\eta_{\mu\nu} dx^\mu dx^\nu + dz^2)$ k: AdS curvature of Planck scale. $\mu = 0, 1, 2, 3$, $\eta_{\mu\nu} = \mathrm{Diag}(- + + +)$. 5th dim z is compactified on a Z_2 orbifold, with a with a UV (IR) brane located at the fixed point $z_{UV}(z_{IR}) = k^{-1}(\mathrm{TeV}^{-1})$.
- We have 5D bulk EW symmetry $SU(2)_L \times U(1)_Y$, with 5D gauge fields A^L_M, B_M, 5D gauge couplings g_{L5}, g_{Y5}, field strengths F^L_{MN}, F^Y_{MN}.
  EWSB on UV by BC: $SU(2)_L \times U(1)_Y \to U(1)_Q$, full symmetry preserved on IR, BKT compatible with brane symmetry are included: ζ_Q for $U(1)_Q$ on UV, ζ_L, ζ_Y for $SU(2)_L, U(1)_Y$ on IR

5D action is then given by

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

Boundary conditions implementing symmetry breaking, BKT effects

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

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

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KK decomposition:

$$A_\mu^{L3}(x,z) = f_0^{L3}(z)\gamma_\mu(x) + \sum_{n=1}^{\infty} f_n^{L3}(z) Z_\mu^{(n)}(x),$$

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Mass spectrum and profiles for lightest states (SM γ, W, Z):

- A flat zero mode exists: $f_0^{L3}, f_0^{B} \rightarrow$ photon
- Lightest KK mode: $f_1^{L3}, f_1^{B} \rightarrow$ SM Z boson

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

- No zero mode for W tower($f_n^{L\pm}$), 1st KK $\rightarrow$SM W boson

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W, Z 5D profiles:

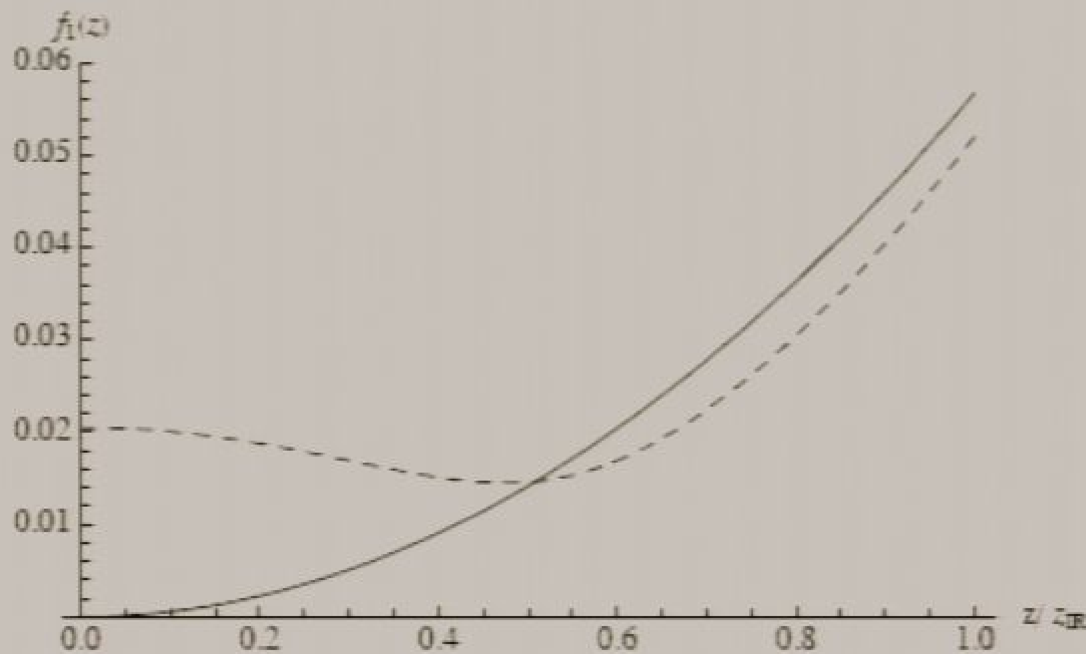

Figure: The W-boson (solid) and Z-boson (dashed) profiles in units of $\sqrt{k}$.–Peaking at IR ($\sim\propto z^2$), indeed dual composites

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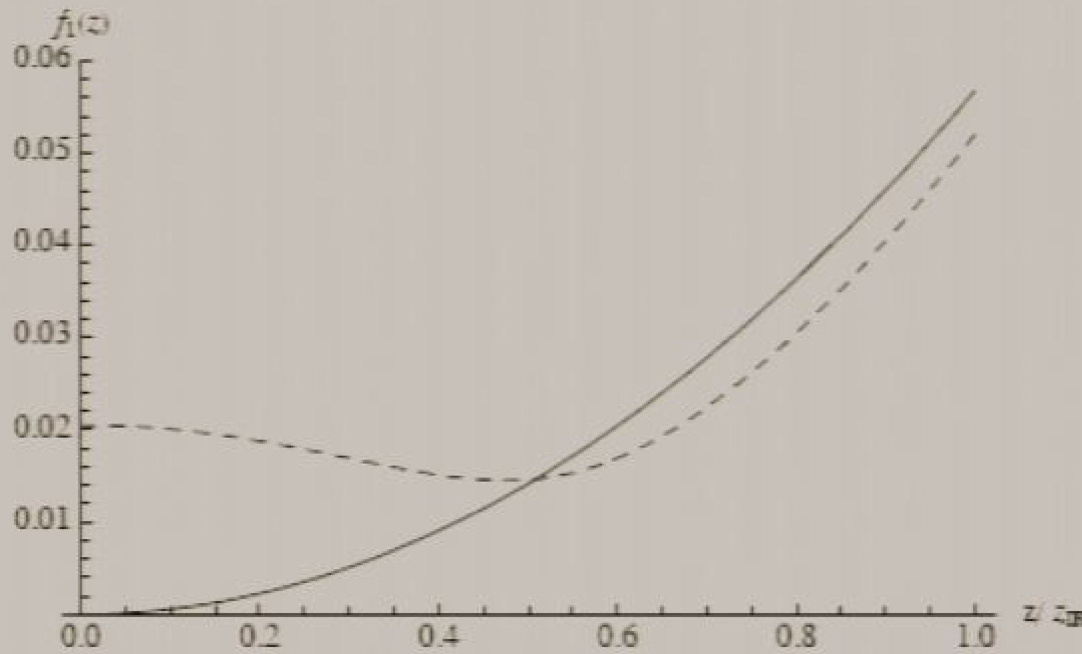

Figure: The W-boson (solid) and Z-boson (dashed) profiles in units of $\sqrt{k}$.–Peaking at IR ($\sim\propto z^2$), indeed dual composites

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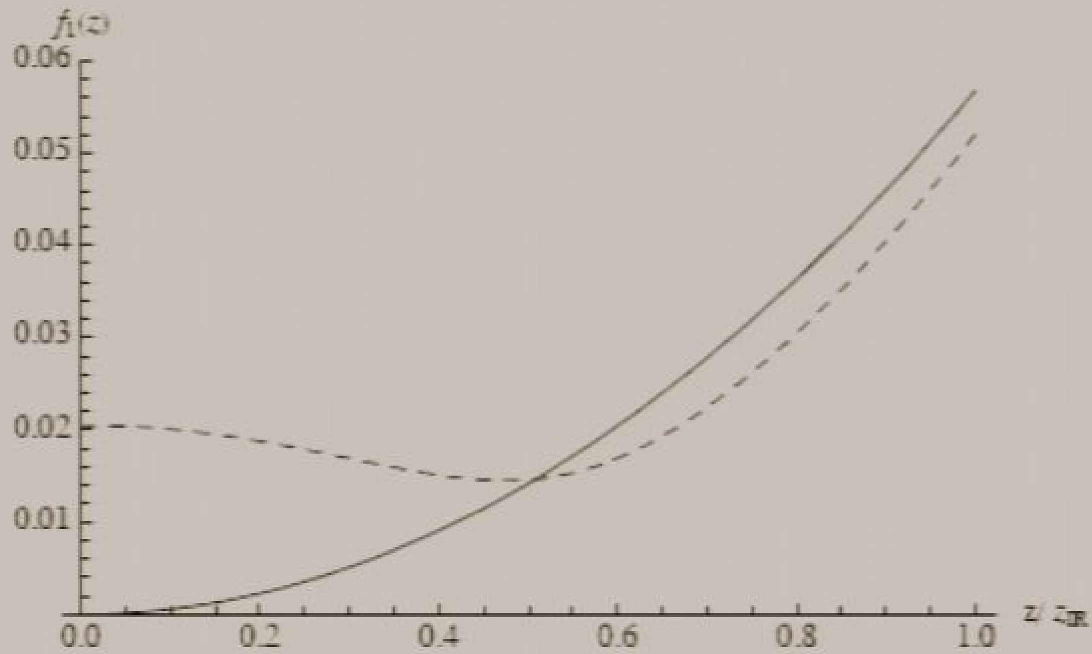

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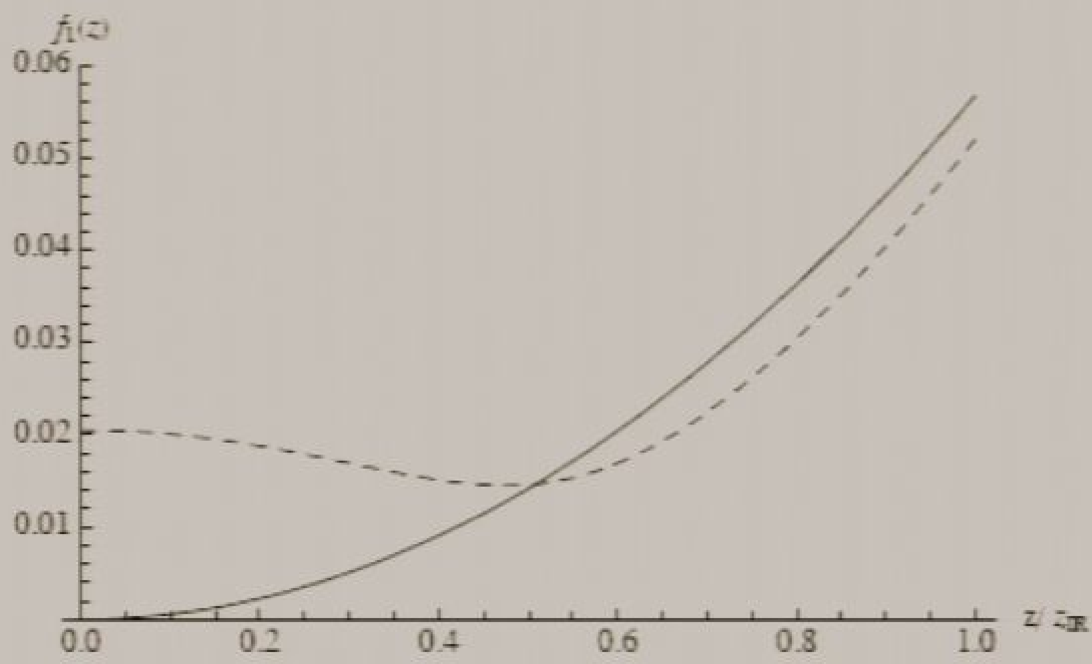

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Electroweak Precision Test-1: T-parameter

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)

No need for additional $SU(2)$ for our model, $SU(2)_L$ itself play the role!

- Our W,Z are true KK modes, masses correlated by bulk $SU(2)_L$ upon dim-reduction (unlike other RS models with W,Z as elementary zero modes getting mass from IR boundary)
- 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

W. Z 5D profiles:

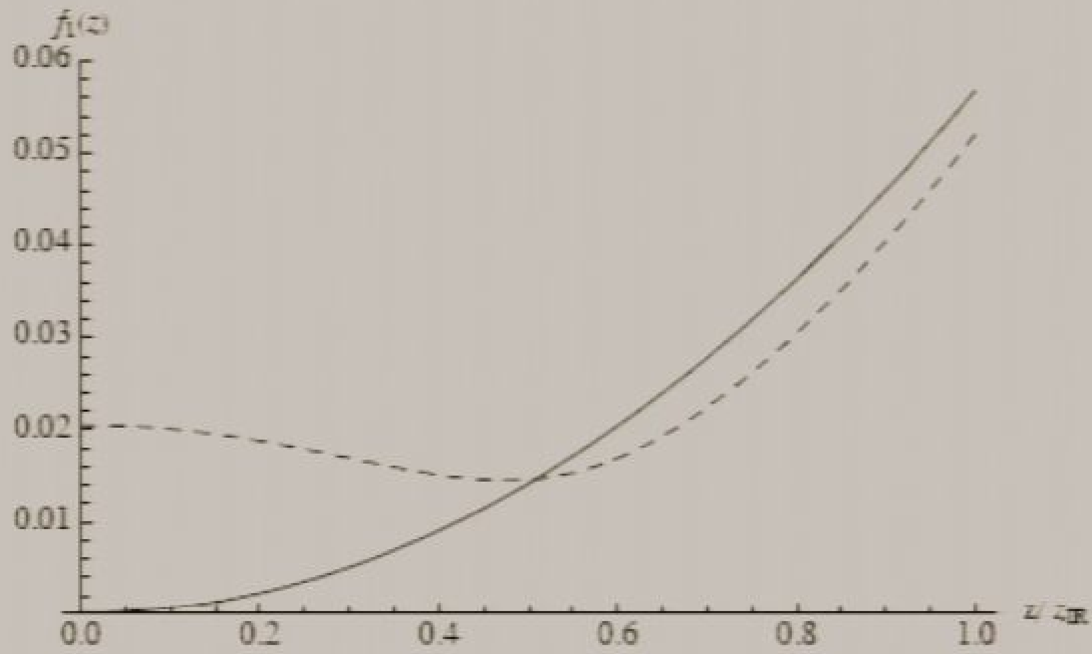

Figure: The W-boson (solid) and Z-boson (dashed) profiles in units of $\sqrt{k}$.–Peaking at IR ($\sim\propto z^2$), indeed dual composites

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

Electroweak Precision Test-1: T-parameter

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Electroweak Precision Test-2: S-parameter

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 coupling), in TC or its 5D variations typically g_n big, M_n relatively light $\Rightarrow S \sim O(1)$, too big
- Tension between S-parameter and WW scattering unitarization: for most Higgsless models, perturbative unitarity prefers light KK ($\lesssim 1.8\mathrm{TeV}$) (substitution of Higgs)$\Rightarrow$ 'kills' the hope to reduce S by lifting m_{KK} (e.g. add BKT: Cacciapaglia, Csaki, Grojean, Tering, 2004)
- No such tension in our model: different unitarization scheme–form factor suppression (details work in progress...); so innocuous to reduce S by lifting KK mass (increase BKT)

Matching to SM, calculation of S, T-1

- Semi-realistic assumption for fermions: 'on' IR brane
  Cannot 'on' UV ($f_W = 0$ there!); 'on' IR is not realistic–fermion mass term incompatible with IR symmetry, but a good approximation–
  realistic expectation: profile peaking towards IR–allow nonzero mass and universal gauge couplings
  (work in progress on fermion sector, see later slides...)
- 'Renormalization factor' for brane interaction term (BIT):
  (important for 5D coupling perturbativity (later))
  Bulk fields interaction: $g_5 \bar{\Psi} \Gamma^\mu A_\mu \Psi$; 5D Poincare→ 4D Poincare at brane: related BIT can have different prefactor ξ
  $\xi g_5 \bar{\psi} \gamma^\mu A_\mu \psi \delta(y - y_{IR})$ –in analogy to BKT, consistent with symmetries
- Correlation between BKT and BIT: **BKT–field renormalization on brane** $A \to Z^{1/2} A$, induces rescaling for BIT involving A as well (external leg correction). Reasonable to expect large BIT at presence of large BKT

Collider Signatures (preliminary)-1

- New states: lightest–1st KK photon $\sim 3\mathrm{TeV}$, 1st $W', Z' \sim 6\mathrm{TeV}$
- Deviation from SM prediction: high energy WW scattering amplitude (work in progress)
  - In SM E^4 growth neatly canceled by exact gauge symmetry, E^2 divergence remains
    'Emergent' gauge symmetry valid in low E, expect seeing gauge-violating effects at high $E \Rightarrow$ may grow faster than E^2 before unitarization
  - An opposite (unitarizing) force: form factor suppression $\sim q^{-\alpha}$, composites of finite size needs to **'shrink'** (Lorentz contraction) to scatter at high q (E.g. High E elastic scattering of QCD hadrons; Polchinski and Strassler, 2003, *"Deep inelastic scattering and gauge/string duality."*)$\Rightarrow$ falling amplitude at unitarization scale

Collider Signatures (preliminary)-2

- Novel features of substructure (constituents of $W, Z-$ 'hadrons'), DIS:
  A solid AdS/CFT duality $\Rightarrow$ 4D dual is UV strongly-coupled gauge theory, no known physics like this: unlike QCD!–something exotically new
  Most relevant reference by now: (Polchinski and Strassler, 2003, *"Deep inelastic scattering and gauge/string duality,"*)
  Partons in hadron in large 't Hooft coupling theory has huge splitting rate $\Rightarrow$ except for very small x region, effectively no partons inside the hadron, at high q whole hadron needs to shrink to size q^{-1} and scatter coherently–kinematic suppression due to compositeness, q^{-2} for vector boson
  DIS without breaking up 'hadrons'–unlike QCD!

Completing the Framework–Fermion Sector

- 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:
  $m \sim y \cdot k(\psi(y)^{(0)})^2 \sim y \cdot ke^{2(c-1/2)ky_{IR}} \Rightarrow$ with $c = 0$, $y \sim O(1)$ gives $m \sim \mathrm{TeV}$ (top)
  –Magic from warping!–the same as solving hierarchy problem $\mathrm{TeV} \sim \mathrm{M_{pl}e^{-ky_{IR}}}$
- Gauge coupling universality: usually automatic with flat gauge profile (elementary) once fermions canonically normalized
  Our model: non-flat gauge profile $\Rightarrow$ need universal fermion bulk mass c, still small non-universality from UV Yukawa...

Preliminary results: Hierarchical masses achieved with almost universal coupling, light fermions fit experimental bound, larger Ztt non-universality can be testable prediction!

Conclusions-1

- We explore a new scenario explaining mass origin of SM particles without a Higgs. SM W, Z are composites getting masses from confinement of substructure (CFT breaking) at IR. Fermions can also be incorporated in the framework as composites. Here 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 is achieved by turning on brane kinetic terms. We do EWPT analysis for the model, find there are built-in mechanisms to ensure good fit to S, T parameters in a natural way
- The composite nature of W, Z offers novel solution for WW scattering unitarization; predicts deviation from SM which can lead to distinctive signatures at the LHC

Conclusions-2

Novel prospects at the LHC:

- **Maybe** at LHC we will find a new world hidden inside the SM which unravels the mystery of SM mass origin, and get to a deeper level of substructure in Nature
- **Maybe** at LHC we will find realistic evidence and clue for some deep principles of Nature incarnated in SM itself: (non-)fundamentality of gauge symmetry, two types of dualities (AdS/CFT, Seiberg type duality) that descended from theoretical labs

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