Generating Fermion Masses in Emergent EWSB

Tony Gherghetta
(University of Melbourne)

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with Yanou Cui, James Stokes, James Wells

What is the origin of mass?

1. Higgs mechanism

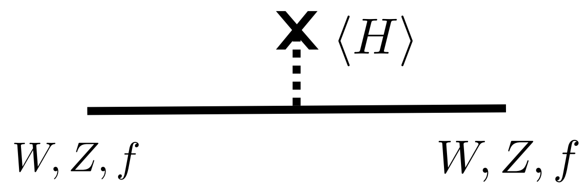
[Guralnik, Hagen, Kibble `64; Englert, Brout `64; Higgs `64]

Higgs boson: $\langle H \rangle$ vacuum expectation value

- Elementary fermion and W, Z boson masses

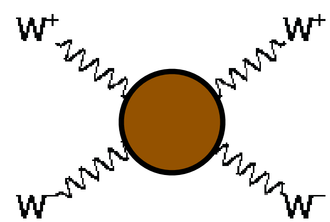
W, Z-boson: $m_{W,Z} \propto g\langle H \rangle$

Fermion: $m_f \propto \lambda\langle H \rangle$



- WW scattering

Bad high-energy behaviour $\mathcal{A}(E) \overset{E\to\infty}{\sim} \frac{g^2 E^2}{32\pi m_W^2}$



But, spin-0 Higgs boson ➡ $\mathcal{A}(E) \overset{E\to\infty}{\sim} \text{constant}$

2. Strong dynamics

e.g. QCD: strong coupling at $\Lambda_{QCD} = e^{-\frac{8\pi^2}{g^2 b_i}} M_P$

- Hadron mass spectrum

proton: $m_P \propto \Lambda_{QCD}$

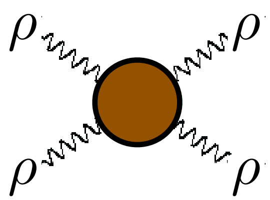
vector-mesons:

e.g. SU(2) isospin-triplet $\rho^{0,\pm}$ $m_\rho \propto \Lambda_{QCD}$

isospin SU(2) ➡ global symmetry

- No unitarity violation

$\rho\rho$ scattering



chiral Lagrangian ➡ QCD Lagrangian

Higgs boson not yet seen...maybe soon...

...or are there surprises in store?

Question:

Can one generate mass in the Standard Model without the Higgs mechanism?

Early work:

Bjorken, 1977; Hung, Sakaurai 1978

Abbot, Farhi 1981; Fritzsch, Schildknecht, Kogerler, 1982

Model building limited due to nonperturbative nature

New approach:

Use AdS/CFT correspondence! [Maldacena, 97; Gubser, Klebanov, Polyakov, 98; Witten 98]

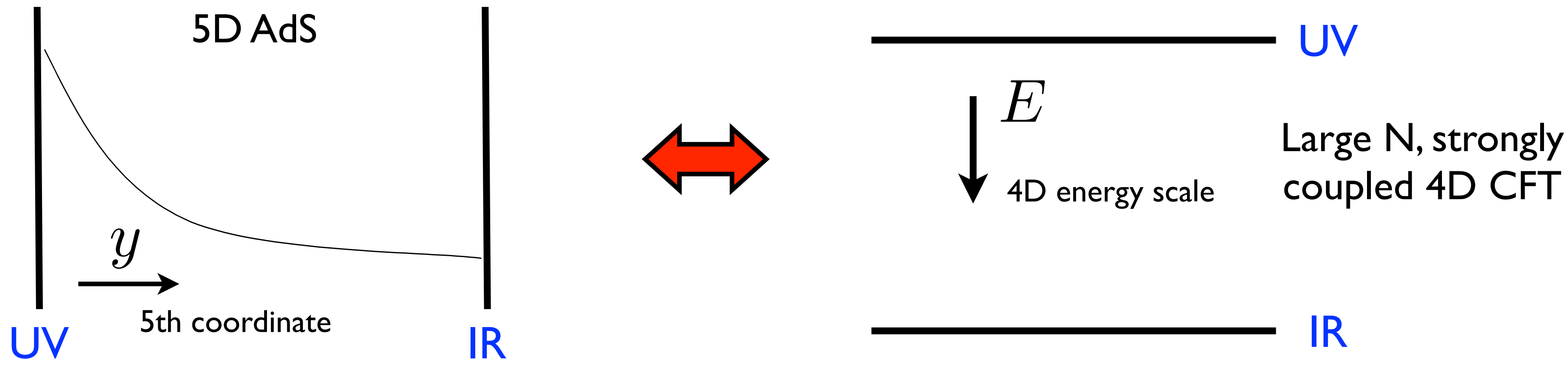
Effective 4D chiral Lagrangian of massive W, Z, fermions	⟷	5D Lagrangian in warped dimension! [Randall, Sundrum 99]

Challenges:

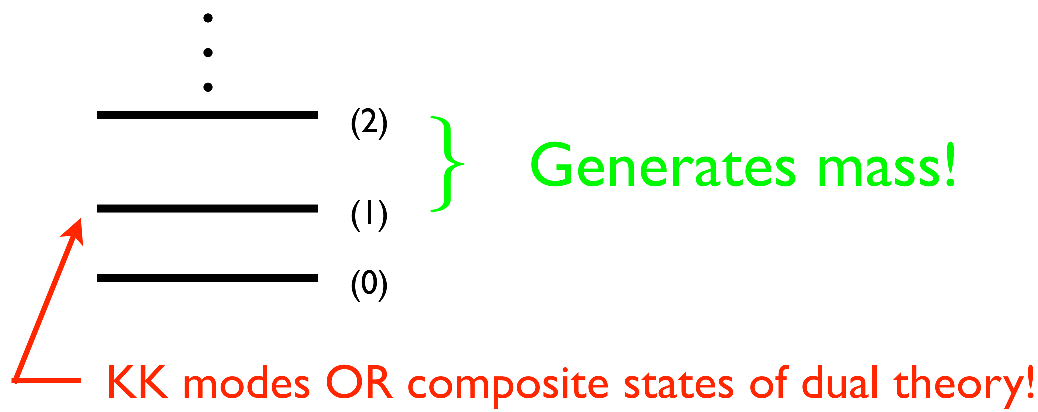
- Generate fermion and W, Z boson masses
- Universality of gauge couplings
- Consistent with EW precision tests
- Natural, no fine tuning.....

AdS/CFT dictionary

[Arkani-Hamed, Randall, Porrati 00; Rattazzi, Zaffaroni 00; Perez-Victoria 01]

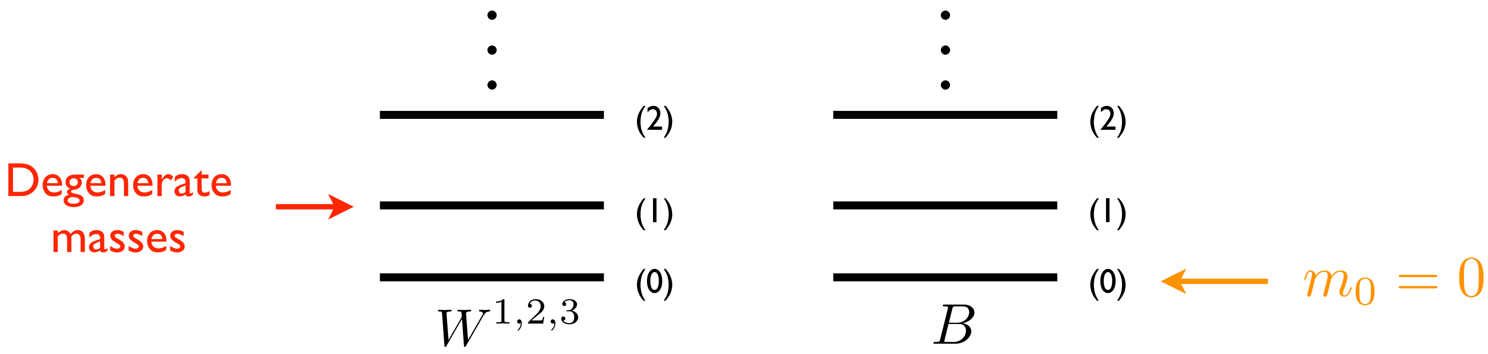


IR brane breaks conformal symmetry



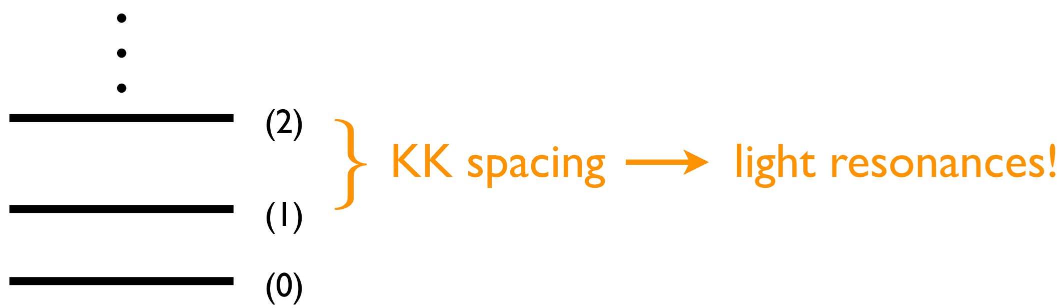
But,

- Massless mode



Break EW symmetry at Planck scale
to decouple massless modes!

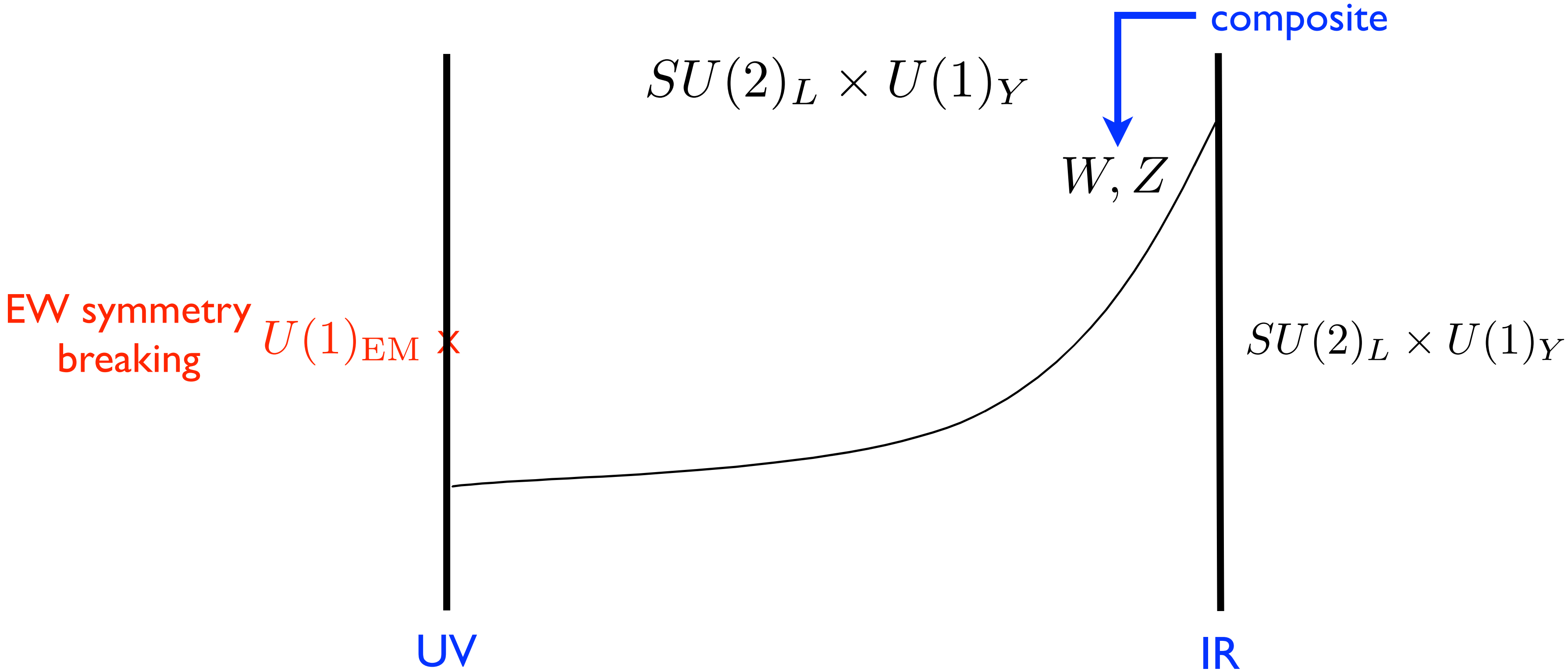
- Heavy KK modes



Separate lightest KK mode from rest of tower
with brane kinetic terms!

[Carena, Ponton, Tait, Wagner 2002; Davoudiasl, Hewett, Rizzo 2002]

5D Model [Cui, TG, Wells, arXiv:0907.0906]



5D action:

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

$\zeta_Q, \zeta_L, \zeta_Y$ = boundary kinetic term coefficients

Mass spectrum:

Boundary conditions:

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

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

Obtain:

$$m_\gamma = 0$$

$$m_W \simeq \sqrt{\frac{2}{\zeta_L k}} m_{IR}$$

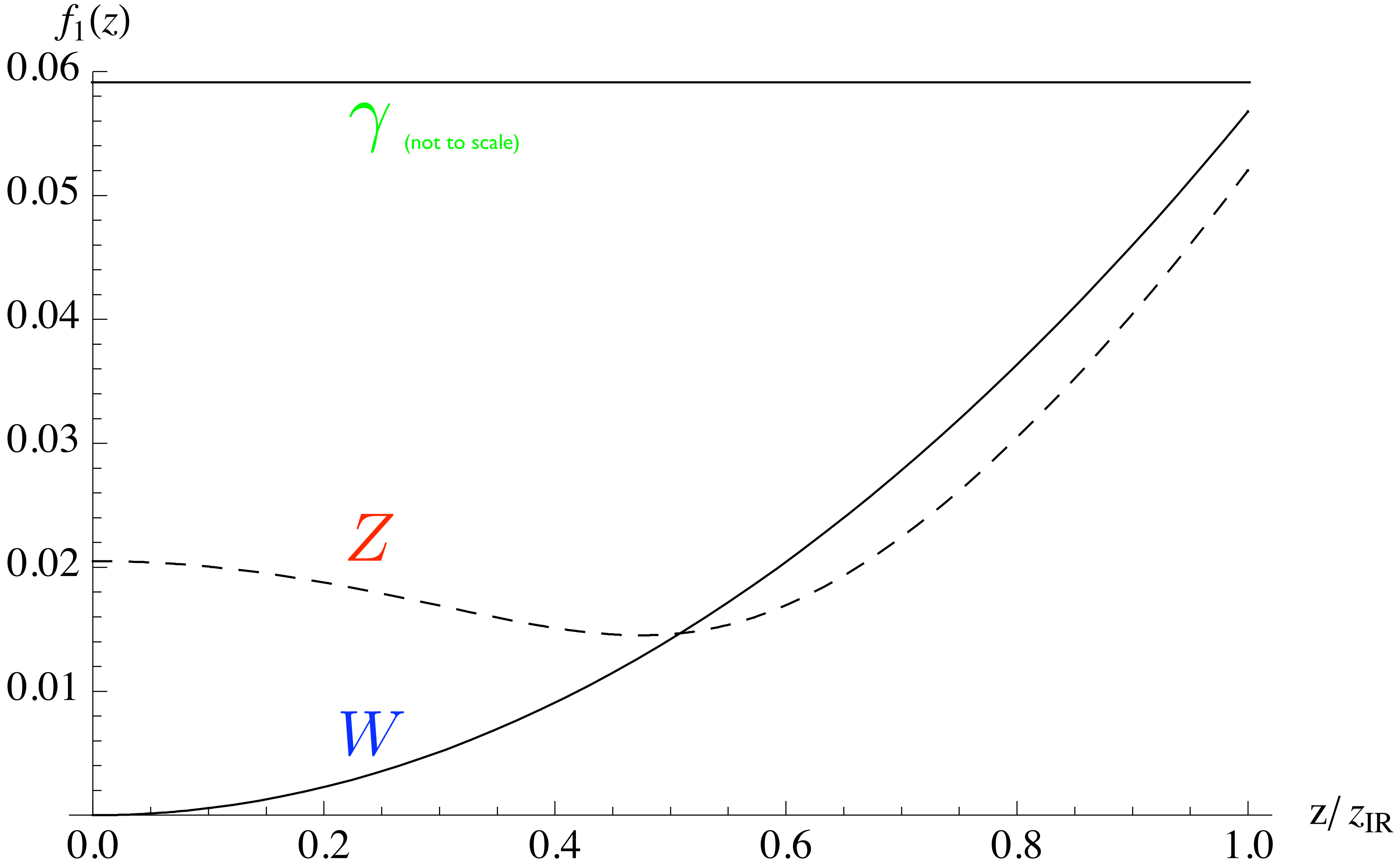
$$m_Z \simeq \sqrt{\frac{2}{\zeta_L k} + \frac{2}{\zeta_Q k(1 + g_{L5}^2/g_{Y5}^2)}} m_{IR}$$

For: $m_{IR} = \text{TeV}$ $\quad \zeta_Q k \simeq 500, \zeta_L k \simeq 310, \zeta_Y k \simeq 0.1$

⇨ $m_W \simeq 80.4\,\text{GeV}, \quad m_Z \simeq 91.2\,\text{GeV}$

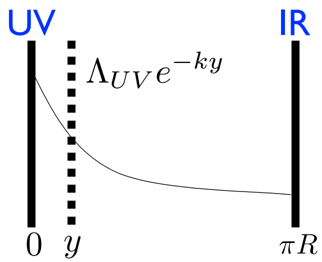
$(m_{KK} \gtrsim 2\,\text{TeV})$

W, Z, photon profiles

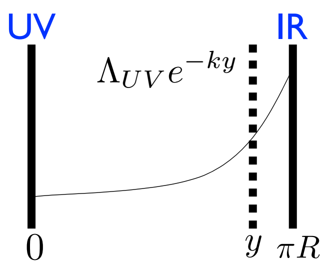


NB: Boundary kinetic terms introduce discontinuity at endpoints.

Dual 4D interpretation

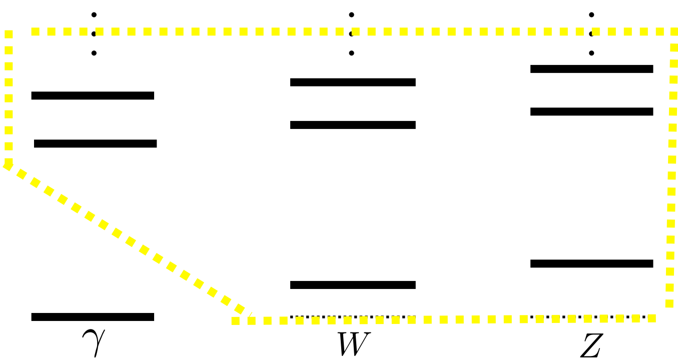


UV localized field ⟷ elementary "source" state



IR localized field ⟷ CFT bound state

∴ Composite W, Z but elementary photon!

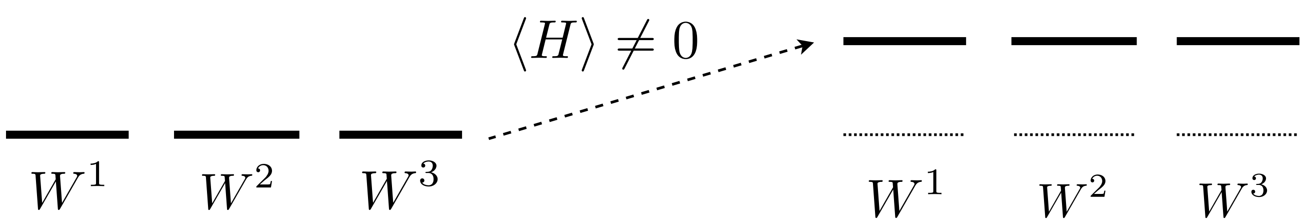


EWSB emerges at IR scale

⇨ "Emergent" EWSB

Custodial Symmetry

- Higgs Mechanism in SM

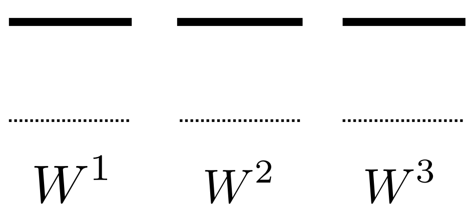


massless SU(2) triplet
--fundamental local gauge symmetry

degenerate mass
-- Higgs sector has SU(2) global symmetry

- Emergent EWSB

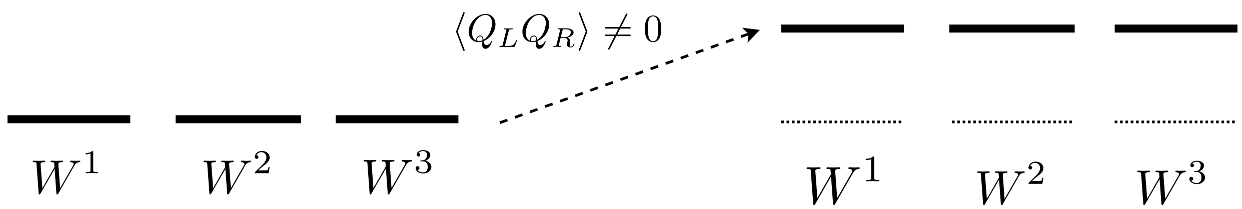
SU(2) symmetry is NOT fundamental



degenerate SU(2) triplet
appears from strong dynamics

Emergent EWSB is Higgsless...
but no Higgs mechanism!

- Usual ``Higgsless” (technicolor-like) [Csaki, Grojean, Pilo, Terning 04]

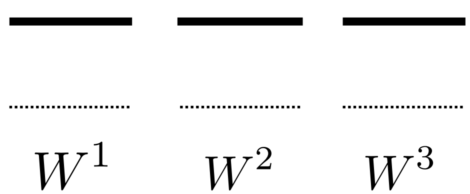


degenerate SU(2) triplet
-- strong-dynamics has SU(2)
custodial symmetry

massless SU(2) triplet
-- fundamental local gauge symmetry

- Emergent EWSB

No Higgs mechanism



degenerate SU(2) triplet
appears from strong dynamics
-- like rho-meson in QCD!

Electroweak constraints

Assume fermions predominantly on IR brane

- T parameter

Custodial symmetry in limit $\zeta_Y \to 0, \zeta_Q \to \infty$

i.e. same boundary condition for $A^{L1,2,3}$

- S parameter

$$S \simeq \frac{8\pi}{g^2 + g'^2} \cos 2\theta_w \sin^2 \theta_w (1+\beta^2)(m_Z z_{IR})^2$$

$$\zeta_L k \simeq 1000, \zeta_Q k \simeq 1700, \zeta_Y k \simeq 0.2$$
$$m_{IR} \simeq 1.8\,\mathrm{TeV}$$

⇒

$$S \simeq 0.1, \quad T \simeq 0.02$$

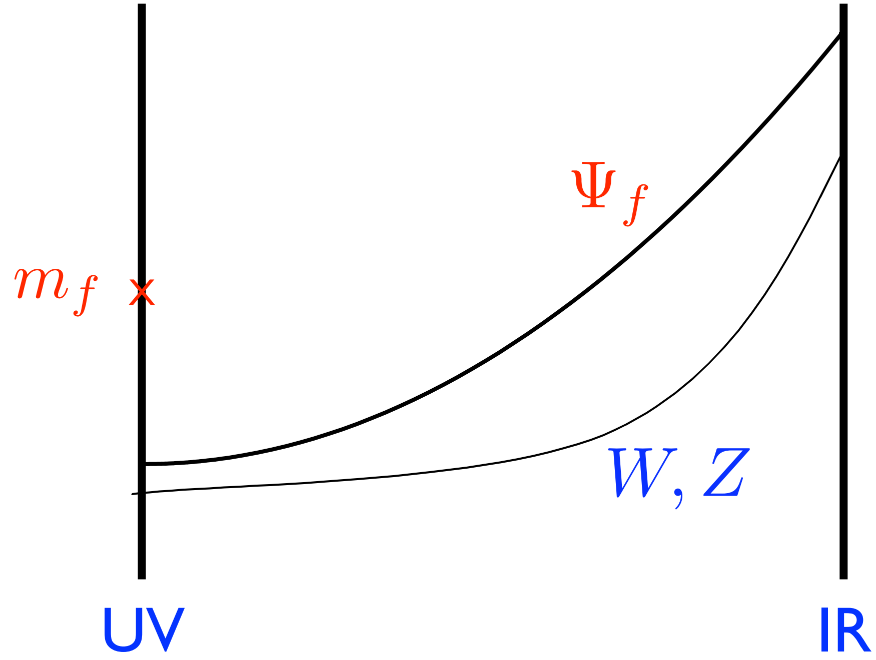
What about fermion masses?

[Cui, TG, Stokes, to appear]

Assume universal bulk fermion profile

- Add UV boundary fermion masses

Fermion mass hierarchy via Froggatt-Nielsen mechanism



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

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

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

Example: massless bulk fermions (c=0)

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

where $$N_n^{(0)} \simeq \frac{1}{\sqrt{z_{\rm IR}}}\sqrt{\frac{1}{1+(\eta k)/2+(\eta k)^2\widehat{m}_n^2}} \qquad \widehat{m} = \frac{m}{m_{IR}}$$

Obtain for $(\eta k = 10)$

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

W,Z boson couplings

Determined by wavefunction overlap:

e.g. $$g_W \simeq \frac{g_{5L}}{\sqrt{\zeta_L}} \frac{2}{\eta k} \left[\underbrace{\frac{1}{3} + \xi_{IR} k}_{\text{universal}} (1 - \underbrace{2(\eta k) \widehat{m}_i \widehat{m}_j}_{\text{flavor-dependent}}) \right]$$

$$\widehat{m} = \frac{m}{m_{IR}} \ll 1$$

$$\xi_{IR} = \sqrt{\frac{\zeta_L}{2} \Lambda \, \eta}$$

⇒ Light fermions: nonuniversality at the per-mille level!
3rd generation: nonuniversality at 15%-25% level

$$\frac{g_{W-}(\text{tb})}{g_{W-}(\text{ud})} = 0.854 \qquad \frac{g_{Z-}(\text{top})}{g_{Z-}^{(SM)}(\text{top})} = 0.746 \qquad \frac{g_{Z+}(\text{top})}{g_{Z+}^{(SM)}(\text{top})} = 0.745$$

Wtb: 20% level @Tevatron arXiv:0903.0850 Single top production

Ztt: 40% level @LHC with 300 fb^-1

Gauge coupling universality due to light fermion masses!

Anomalous top couplings ➡ electroweak corrections

[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:

$$4.4 \times 10^{-3} \leq \epsilon_1^{exp} \leq 6.4 \times 10^{-3}, \qquad \text{68\% C.L.}$$
$$-6.2 \times 10^{-3} \leq \epsilon_b^{exp} \leq -3.1 \times 10^{-3} \qquad \text{68\% C.L.}$$

➡ Requires special treatment of top quark

e.g. separate brane for top [Cacciapaglia, Csaki, Grojean, Reece, Terning '05]

WW scattering

Composite W,Z boson → Momentum dependent form factor

$$F_{WWZ}(q^2) = \frac{1}{N_Z(q^2)N_W^2}\left\{\left[\int_{z_{UV}}^{z_{IR}} \frac{dz}{kz} f^{L3}(q^2,z)(f_W(z))^2\right] + \zeta_L f^{L3}(q^2,z_{IR})(f_W(z_{IR}))^2\right\}$$

→ Possible deviation in W, Z-boson vertices at LHC

(in progress)

Interestingly, in large N theory there are no partons inside hadrons!

[Polchinski-Strassler 02]

i.e. composite W, Z bosons are unlike vector-mesons in QCD!

Summary

- Generate W, Z boson and fermion masses from strong dynamics, not Higgs mechanism
- Electroweak symmetry breaking "emerges" at IR scale
- Composite W, Z bosons lead to deviations in couplings at the LHC
- Requires further model-building to successfully incorporate top quark....