# EWSB in a Warped Dimension

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# Outline

- Introduction/Motivation
- Warped Dimension and AdS/CFT
- Examples of EWSB
- Conclusion

# Introduction *What is the origin of mass?*

## *Higgs mechanism*

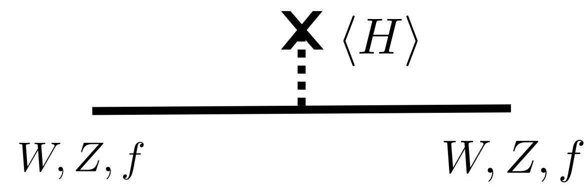
[Higgs `64; Englert, Brout `64; Guralnik, Hagen, Kibble `64]

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

- Elementary fermion and W, Z boson masses

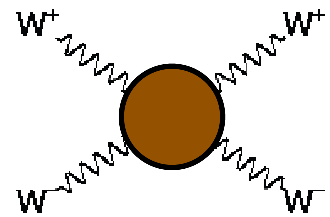
W, Z-boson: $m_{W,Z} \propto g \langle H \rangle$

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




- WW scattering

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

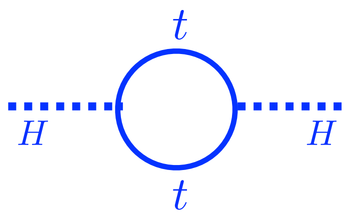



But, spin-0 Higgs boson ⇒ $\mathcal{A}(E) \overset{E \to \infty}{\sim} \text{constant}$

# *Gauge Hierarchy Problem:*

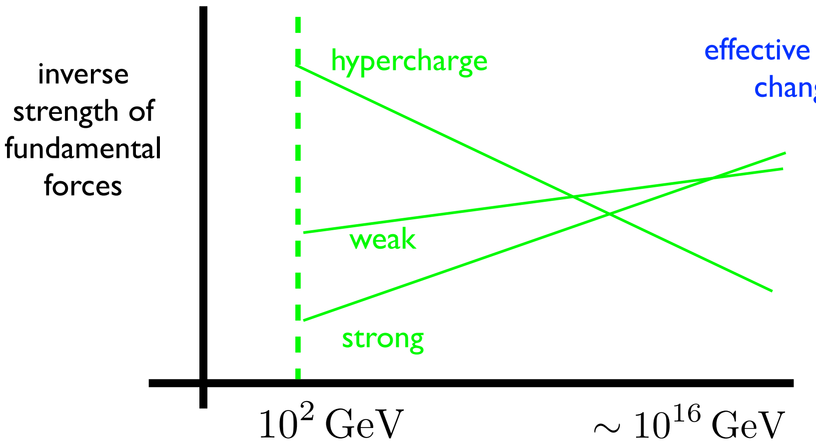
## Standard Model quantum corrections:

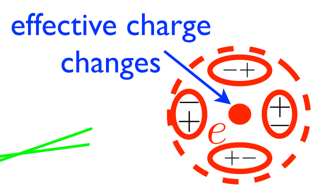
e.g. top quark




$$\delta m_H^2 = \Lambda^2 \qquad (\Lambda = \text{UV cutoff})$$

What is the value of cutoff scale $\Lambda$?




$$\Lambda \simeq 10^{16}\,\text{GeV}$$

$$\longrightarrow m_H^2 \gg (100\,\text{GeV})^2 \;\;!!$$

**Why is $m_H \ll \Lambda \sim 10^{16}\text{GeV}$?**

# Possible explanations:

Cancellation **or** No Cancellation

$$\delta m_H^2 = \Lambda^2 - \Lambda^2 + \ldots$$

e.g. supersymmetry, global symmetry

$$\Lambda \sim \mathrm{TeV}$$

e.g. strong dynamics, low-scale string theory

or just fine-tuned!

$$(\Lambda \sim M_P)$$

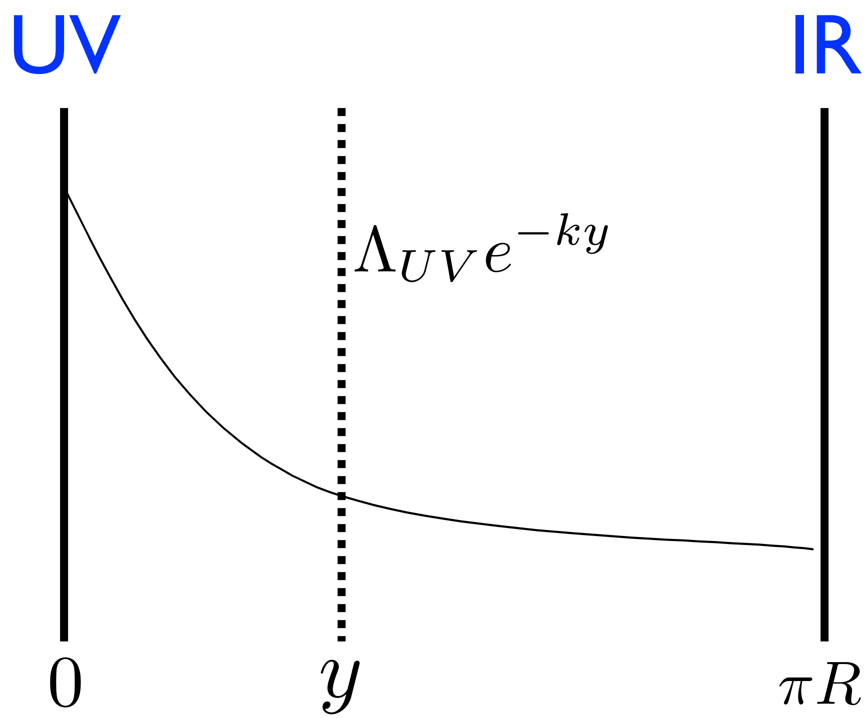
e.g. string theory Landscape!

## Warped Extra Dimension

➡ New Example of "No Cancellation"

# Warped Extra Dimension

➡ Can explain hierarchies



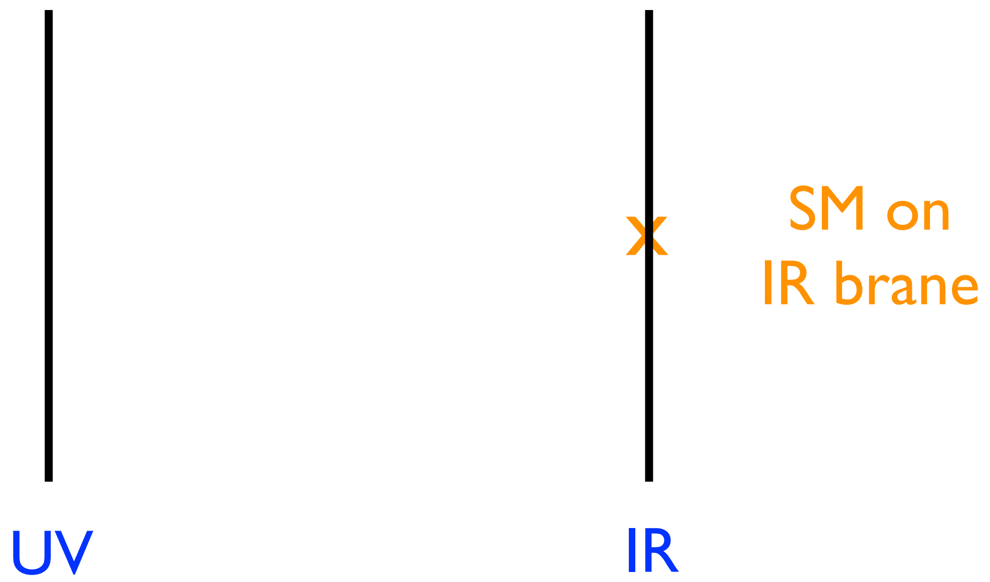

"Slice of $AdS_5$"

[Randall, Sundrum 99]

$k =$ *AdS curvature scale*

5D metric : $$ds^2 = e^{-2ky} dx^2 + dy^2$$

- Hierarchy problem: Higgs mass [Randall, Sundrum (1999)]

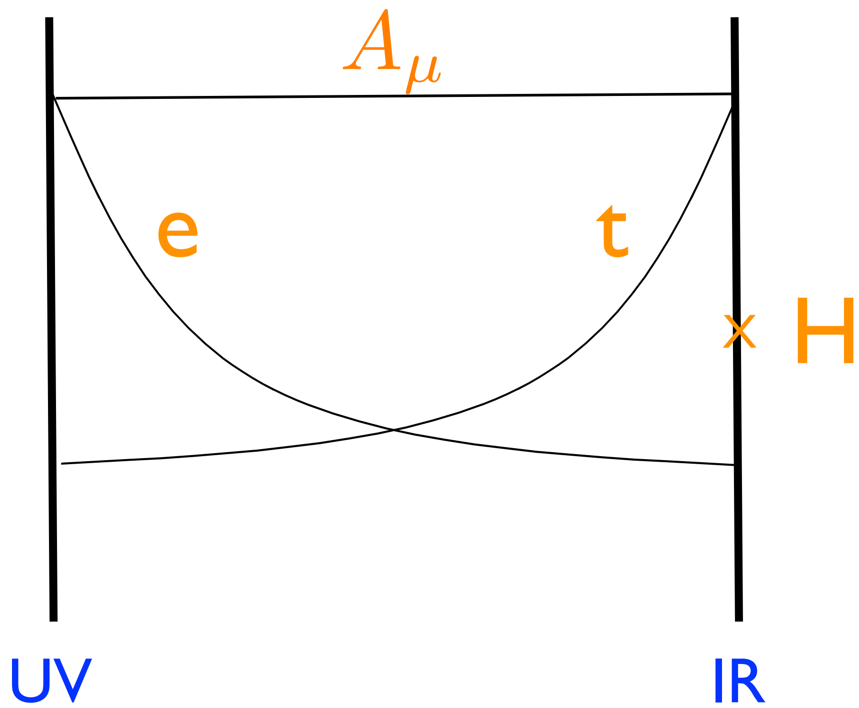



$$\Lambda_{SM} = \Lambda_{UV} e^{-\pi k R}$$

$$\Rightarrow \quad m_H \sim \Lambda_{SM} = \mathcal{O}(\mathrm{TeV})$$

$$(\Lambda_{UV} \sim M_P, \pi k R \simeq 35)$$

- **Fermion masses:** e.g. electron, top [TG, Pomarol (2000)]




$$\psi^{(0)} \sim e^{(\frac{1}{2}-c)ky}$$

$c =$ bulk mass parameter

$$S_\Psi = \int d^4x dz \sqrt{-g}\left(\bar{\Psi} e^M_A \gamma^A D_M \Psi + \underbrace{M_\Psi}_{\equiv c\, k} \bar{\Psi}\Psi\right)$$

## Yukawa interaction:

$$S = -\int d^5x\sqrt{-g}\,\lambda^5_{ij}\ \left[\overline{\Psi}_{iL}\Psi_{jR} + h.c.\right] H(x)\delta(y-\pi R)$$

$$\equiv -\int d^4x\sqrt{-g}\,\lambda_{ij}\ \left[\overline{\Psi}_{iL}\Psi_{jR}H + h.c.\right]$$

## Obtain:

$$\lambda_i = \begin{cases} (\lambda^{(5)}_i k)\left(c_i - \frac{1}{2}\right) e^{(1-2c_i)\pi k R} & c_i > \frac{1}{2} \\ (\lambda^{(5)}_i k)\left(\frac{1}{2} - c_i\right) & c_i < \frac{1}{2} \end{cases}$$

$-0.5 \lesssim c_i \lesssim 0.64$ explains fermion hierarchy $m_e \longrightarrow m_t$

# Reality Check:

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

Type IIB string theory on AdS5 x S5 $\longleftrightarrow$ $\mathcal{N}$=4 SYM in 4D

## More generally:

| 5D AdS gravity | $\Leftrightarrow$ | 4D gauge theory (CFT) |
| --- | --- | --- |
| $(R_{AdS} \gg l_s, g_s \to 0)$ | | $(g_{YM}^2 N \gg 1, N \gg 1)$ |

Boundary value of bulk field $\Leftrightarrow$ Source of CFT operator $O$

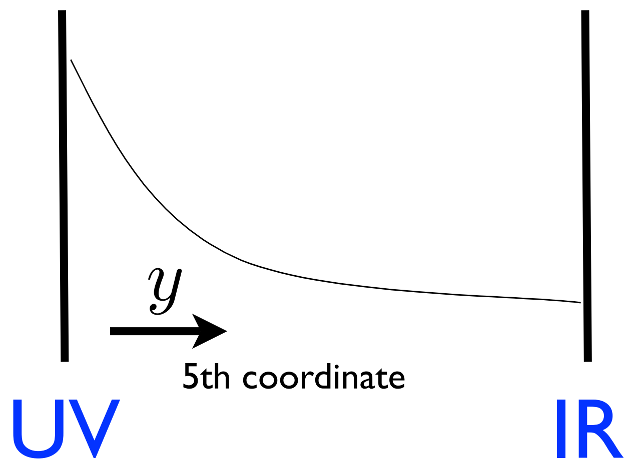
e.g $\Phi(x,z)\Big|_{UV} = \phi(x)$ $\qquad$ $\mathcal{L} = \phi(x)\mathcal{O}$

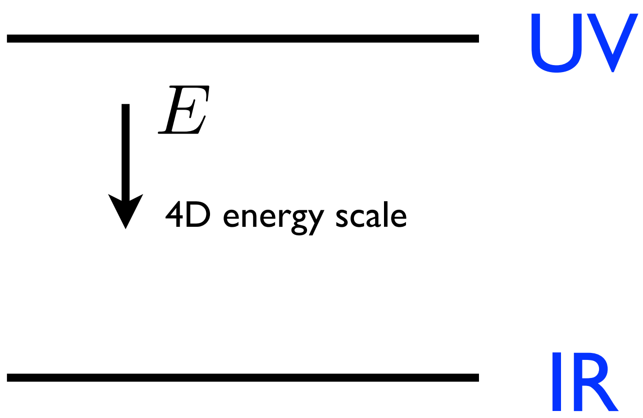
Bulk masses $\Leftrightarrow$ dimension of $O$

e.g. $m_\Phi^2$ $\qquad$ e.g. $\dim \mathcal{O} = 2 + \sqrt{4 + m_\Phi^2/k^2}$

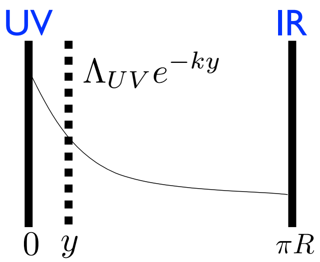
# AdS/CFT dictionary

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

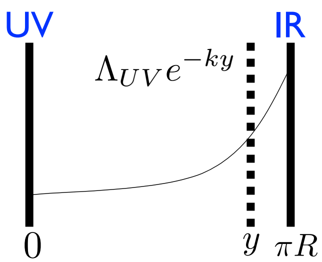



"Slice of AdS" ⟺ CFT + Dynamical elementary "source"

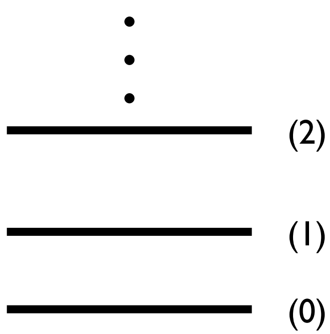



UV localized field ⟷ elementary “source” state




IR localized field ⟷ CFT bound state

Kaluza-Klein tower ⟷ Tower of resonances




$$\sum_{n=0}^{\infty} \frac{d_n^2}{p^2 + m_n^2}$$

## Warped dimension need not be real ➡ new mathematical tool!

### 4D interpretation:

☆ *Dynamical EW breaking (Weinberg `76; Susskind `79)* $M_{IR} = e^{-\frac{8\pi^2}{g^2 b_i}} M_P$

$$\text{AdS/CFT:} \quad e^{-\frac{8\pi^2}{g^2 b_i}} \leftrightarrow e^{-\pi k R}$$

☆ *Fermion masses: Large anomalous dimensions* $\lambda \bar{\Psi}\Psi H$ ➞ $\dim \lambda < 0$

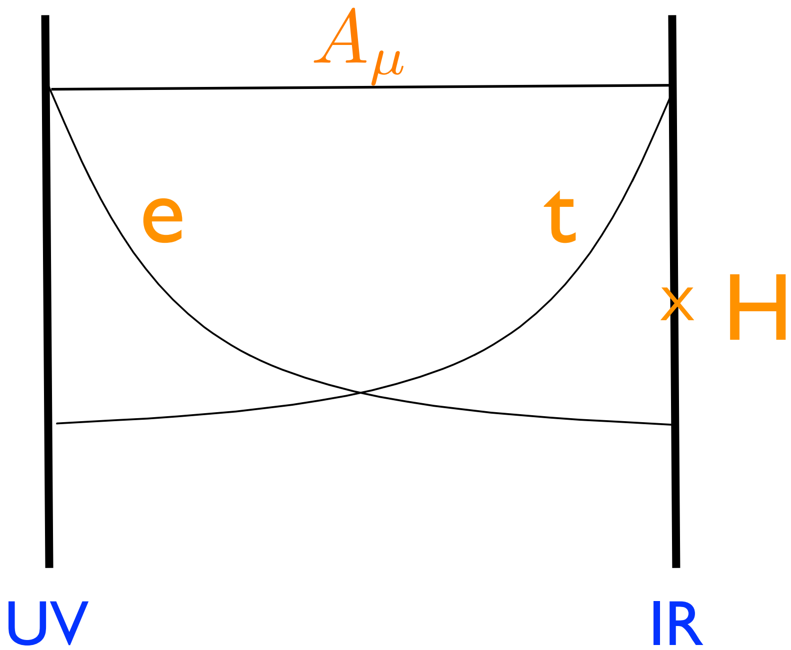
$$\text{AdS/CFT:} \quad [\Psi] = \frac{3}{2} + \gamma_\Psi \leftrightarrow ck\bar{\Psi}\Psi$$

## Bottom line:

Build 4D model with strong dynamics using 5D warped model

## 5D warped bulk SM

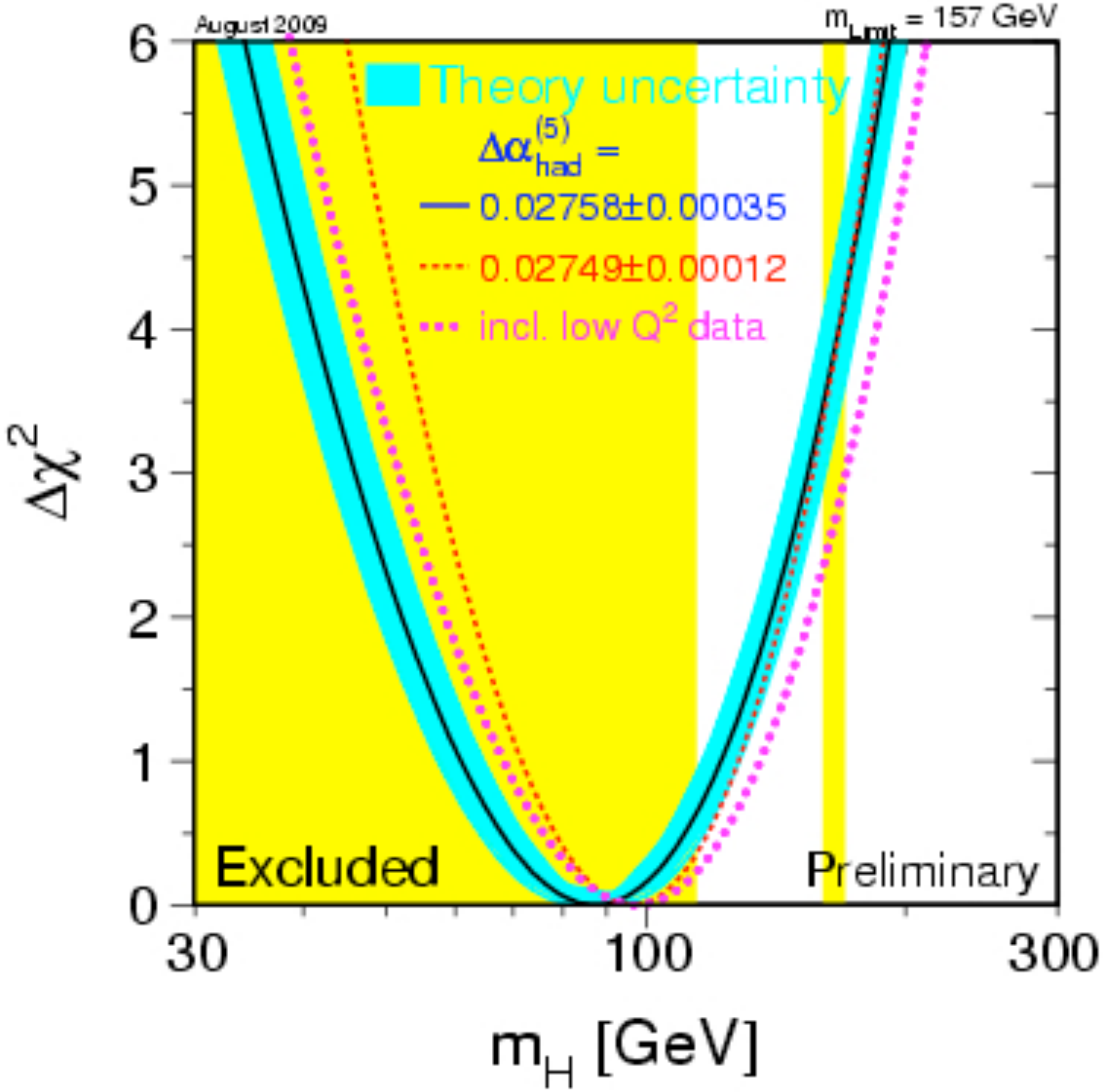
## 4D Partially Composite SM




Composite: Higgs, top quark

Elementary: light fermions, gauge bosons

What about electroweak precision tests?




Higgs boson must be light

# Higgs sector must be custodially invariant

Global symmetry breaking

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

$$(SO(4) \to SO(3))$$

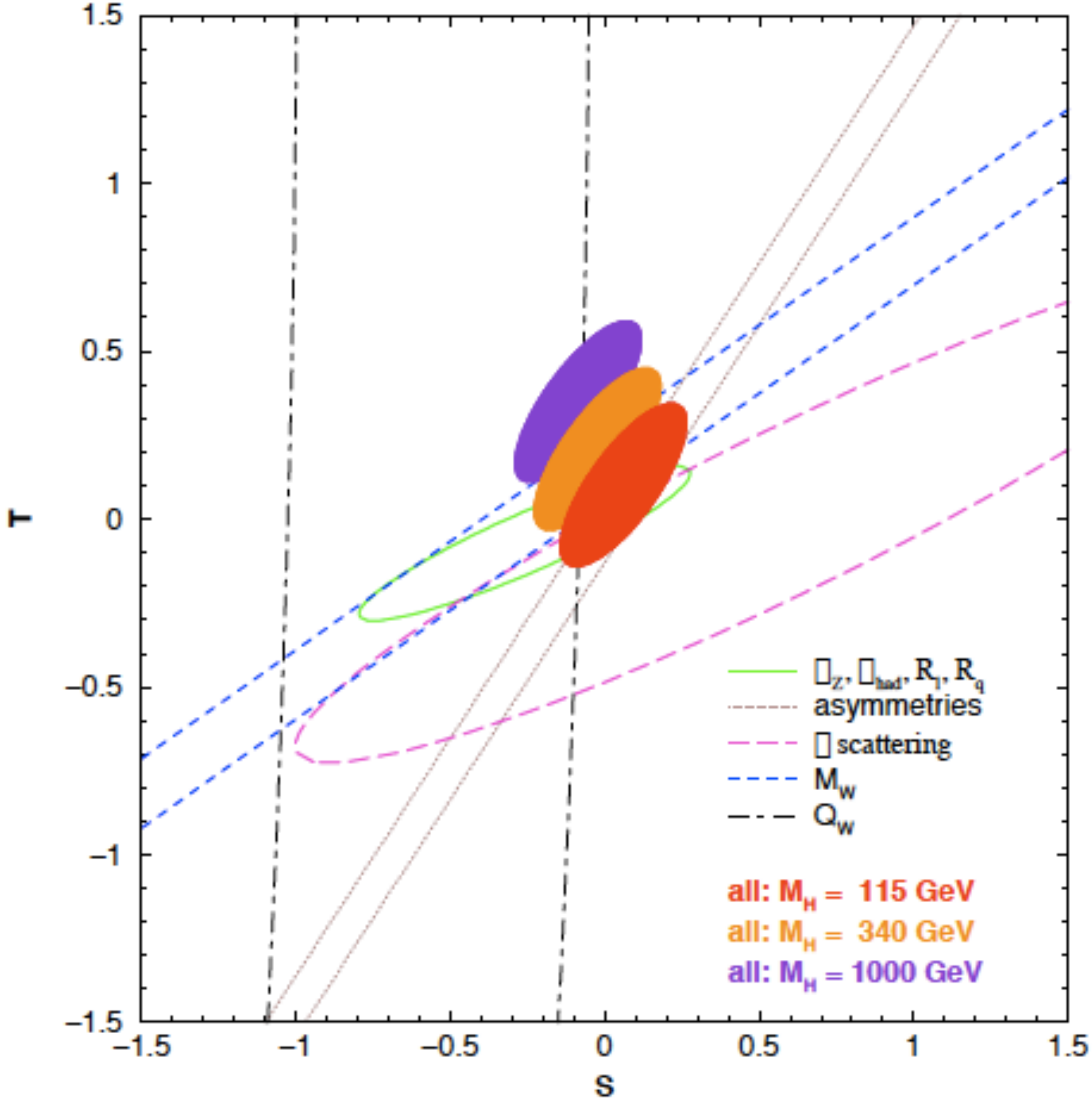
## to ensure

$$\rho = \frac{M_W}{M_Z \cos\theta_w} = 1 \qquad (\text{or} \quad T = 0)$$

Peskin-Takeuchi parameters

$$\alpha S = 4g^2 \sin^2\theta_w \Pi'_{3B}(0) \qquad \alpha T = 1 - \frac{\Pi_{33}(0)}{\Pi_{+-}(0)}$$

where $\Pi(p^2) = \Pi(0) + p^2\Pi'(0) + \ldots$


1.5
1
0.5
0
−0.5
−1
−1.5
T
−1.5
−1
−0.5
0
0.5
1
1.5
S
asymmetries
scattering
M_W
Q_W
all: M_H = 115 GeV
all: M_H = 340 GeV
all: M_H = 1000 GeV

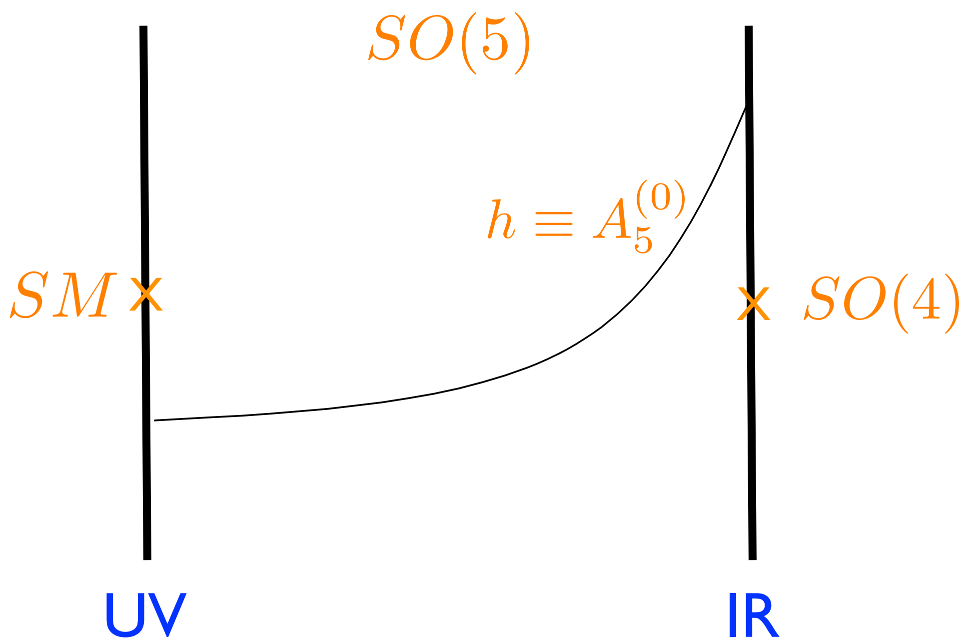
# Examples

## *1. Higgs as a pseudo Nambu-Goldstone boson*

[Agashe, Contino, Pomarol (2004)]

5D gauge field: $A_M = (A_\mu, \underbrace{A_5}_{})$

Scalar component--Identify as Higgs!




Elementary SM gauge bosons

$$SO(5)/SO(4) = \mathbf{2} \text{ of } SU(2)_L$$

→ Composite Higgs !

# Fermions

e.g. top quark: $$\mathbf{5} = \underbrace{2_{7/6}} + \overbrace{2_{1/6}}^{t_L} + \overbrace{1_{2/3}}^{t_R}$$

Exotic states of charge 5/3!

## SO(5) broken by top-quark $(m_{2_{7/6}} \gg m_t)$

$$\Rightarrow \quad m_H^2 = 0 + \frac{g^2}{16\pi^2}(ke^{-\pi kR})^2$$

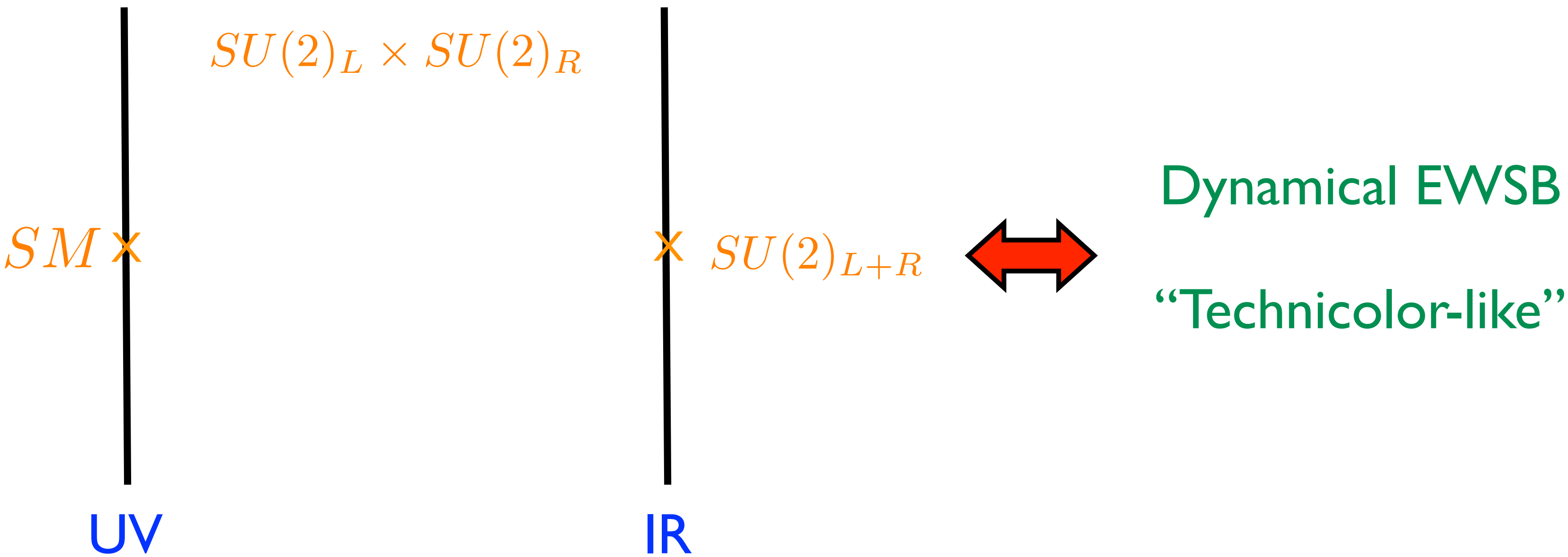
↑ gauge symmetry

## Obtain:

$$m_H \lesssim 160\,\mathrm{GeV} \qquad S \lesssim 0.3 \qquad T \simeq 0$$

## 2. *Higgsless* [Csaki, Grojean, Pilo, Terning (2003)]

Break EW symmetry on IR brane via boundary conditions




WW scattering: Unitarized by exchange of Kaluza-Klein W-bosons

**Obtain:**

$T \simeq 0 \qquad S \simeq 1.15$ X (but can be tuned by delocalizing light fermions)

# 3. Emergent EWSB [Cui, TG, Wells (2009)]

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

- Hadron mass spectrum

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

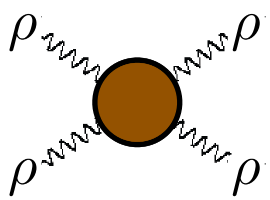
vector-mesons:

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

In fact, hidden local gauge symmetry! [Bando, Kugo, Uehara, Yamawaki, Yanagida 1985]

- No Unitarity violation

$\rho\rho$ scattering

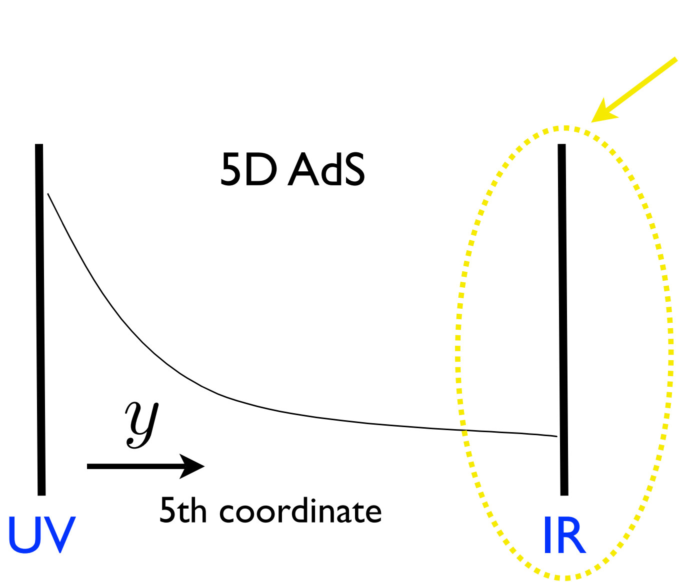


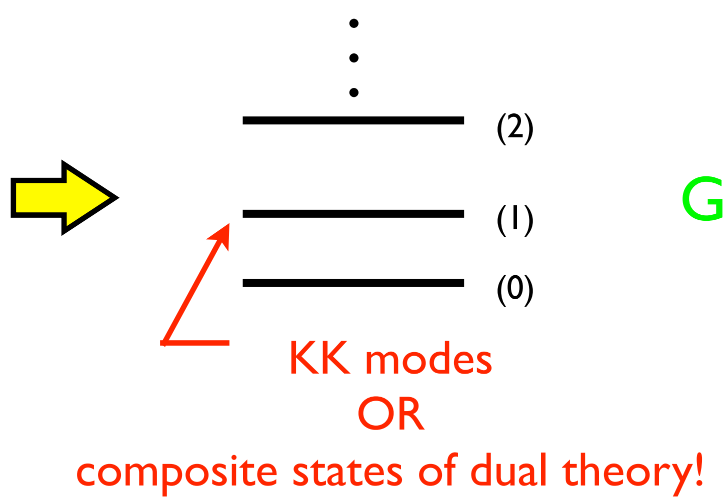

chiral Lagrangian ➡ QCD Lagrangian

*Question:*

**Can one generate mass in the Standard Model with strong dynamics?**

Use IR brane:

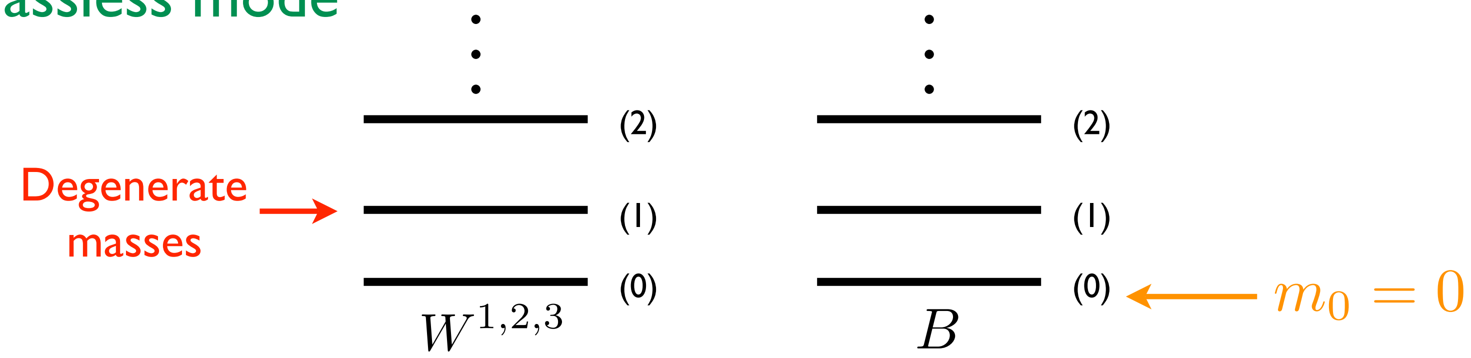



Generates mass!

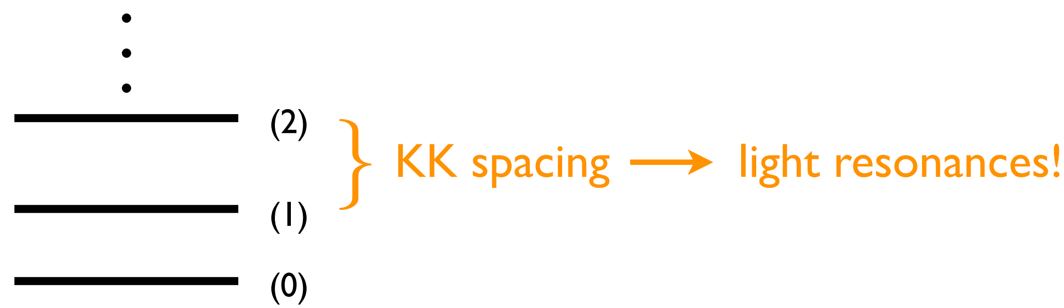
# But,

- Massless mode




➡ Break EW symmetry at Planck scale!

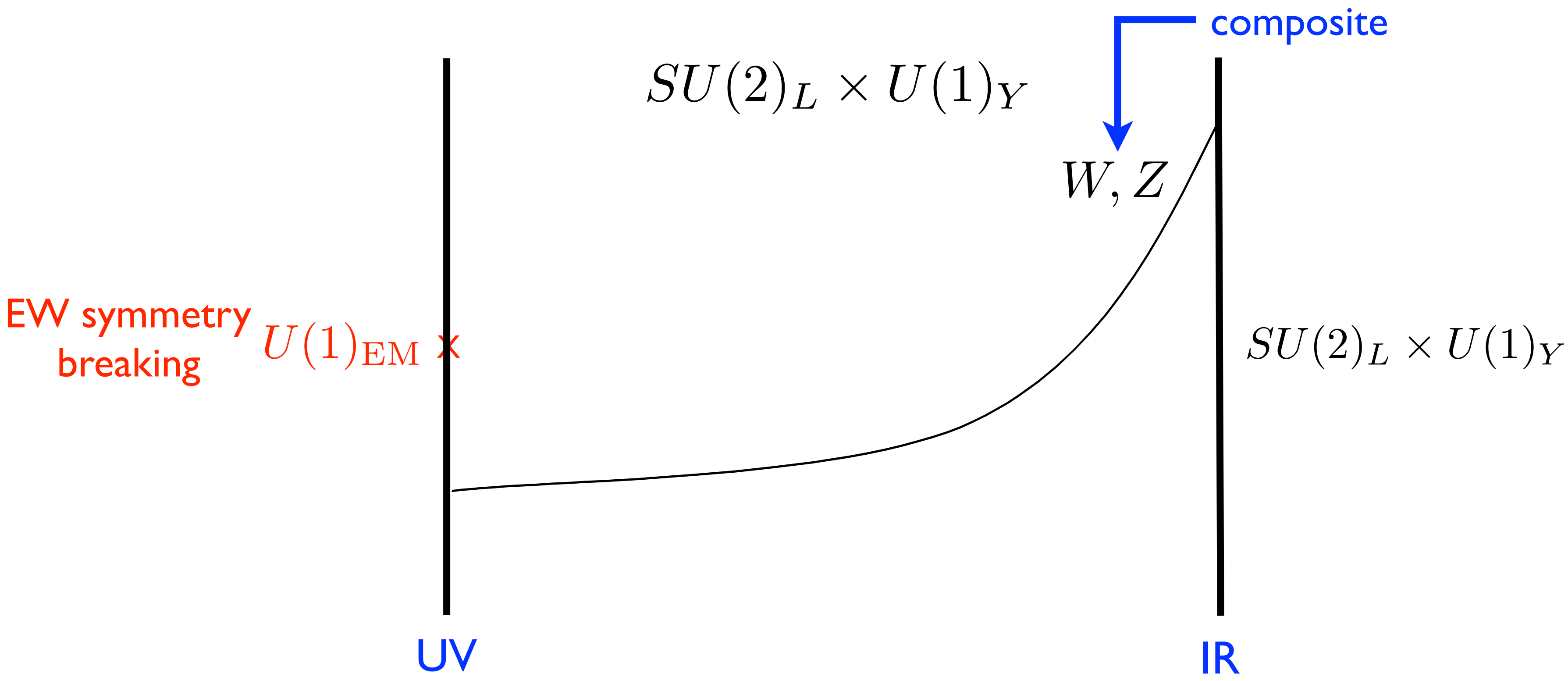
- Heavy KK modes




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

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

# 5D Model




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:

$$m_\gamma = 0$$

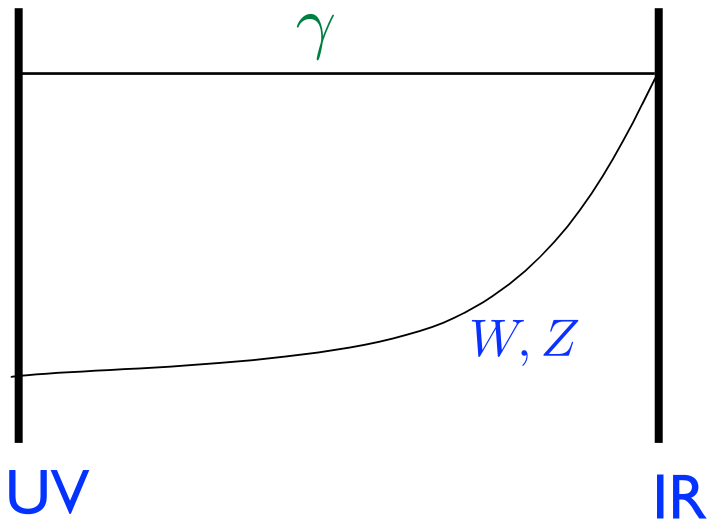
$$m_W \simeq \sqrt{\frac{2}{\zeta_L k}} m_{IR}$$

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

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

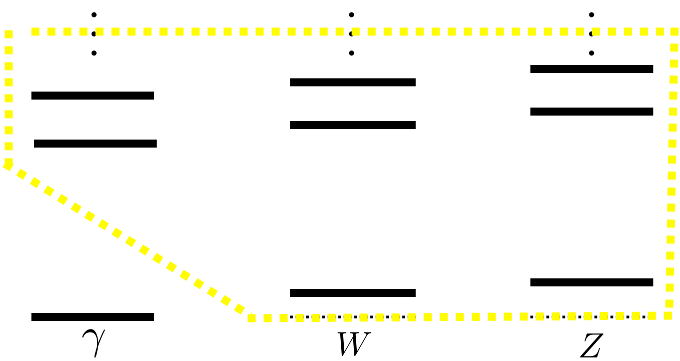
⇨ $m_W \simeq 80.4\,\mathrm{GeV}, \quad m_Z \simeq 91.2\,\mathrm{GeV}$

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




Composite W, Z but elementary photon!

∴



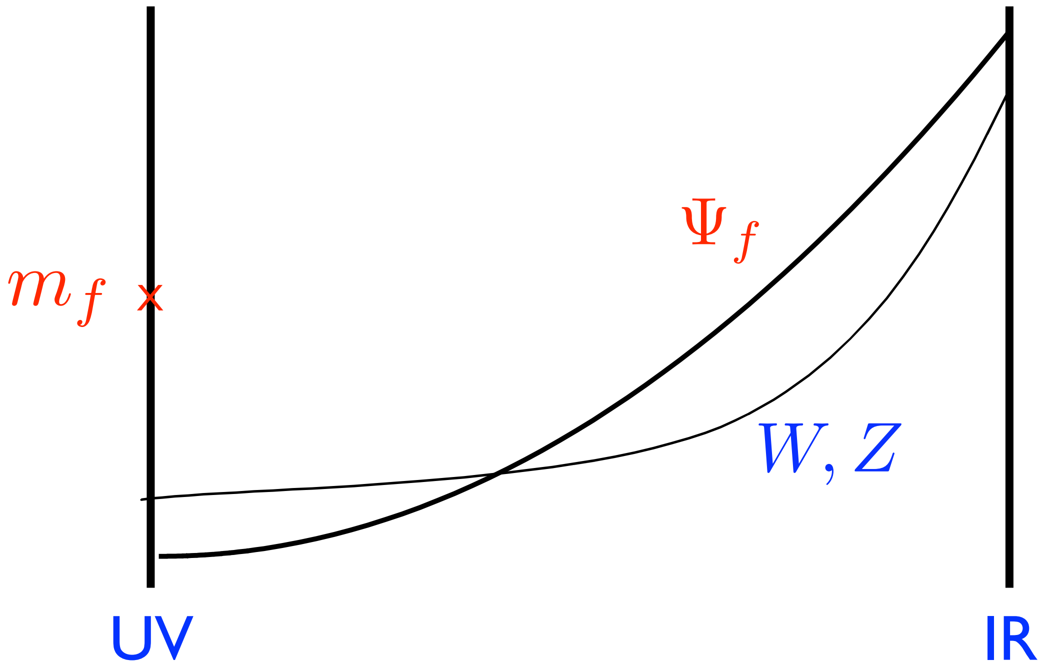

EWSB emerges at IR scale

"Emergent" EWSB

# Fermion masses

Assume universal bulk fermion profile

- Add UV boundary fermion masses




Froggatt-Nielsen mechanism on UV brane generates fermion mass hierarchy

# Electroweak constraints

## Assume fermions on IR brane

Matching at IR brane requires: $g_5^2 k \simeq \frac{425}{1+\zeta/\Delta}$ $\Delta =$ brane thickness

- 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

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

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

⇨ $S \simeq 0.1, \quad T \simeq 0.02$

But depends on fermion details....

# 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

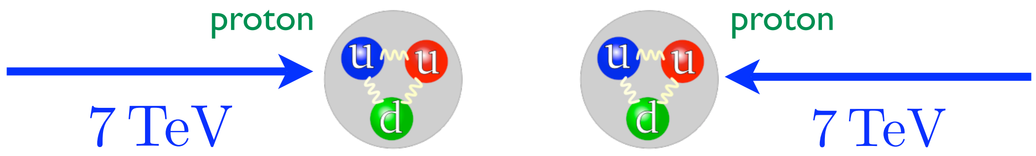
(in progress)

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!

# CERN-Large Hadron Collider

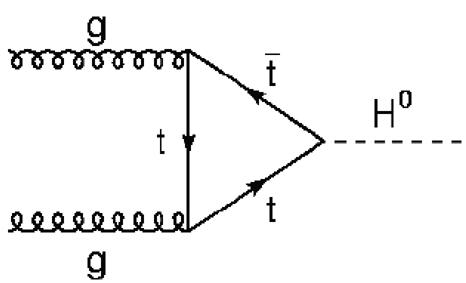
# Large Hadron Collider



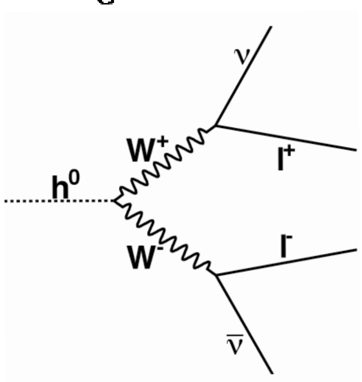

Predominantly gluon-gluon, gluon-quark interactions

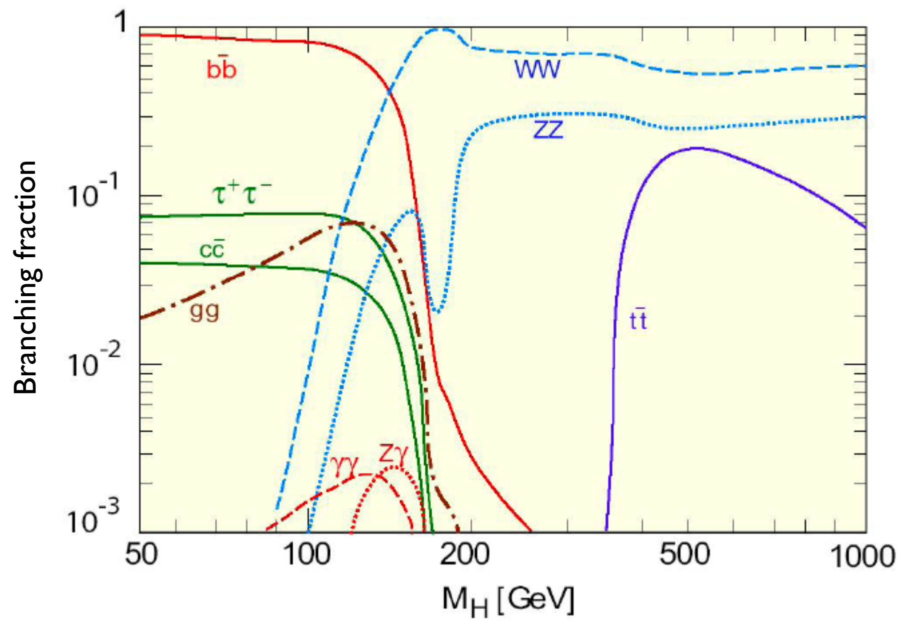
## HIGGS BOSON

Dominant production: gluon fusion




Decay channel



# Summary

- Warped dimension provides new ways to break EW symmetry

  e.g Composite Higgs, Higgsless, Emergent EWSB

- AdS/CFT ➡ equivalent to 4D strong dynamics
- Models are consistent with electroweak precision tests (S, T parameters)
- Will be tested at LHC

LHC First Beam: September 10, 2008

LHC First Collisions: mid Nov. 2009

# STAY TUNED!