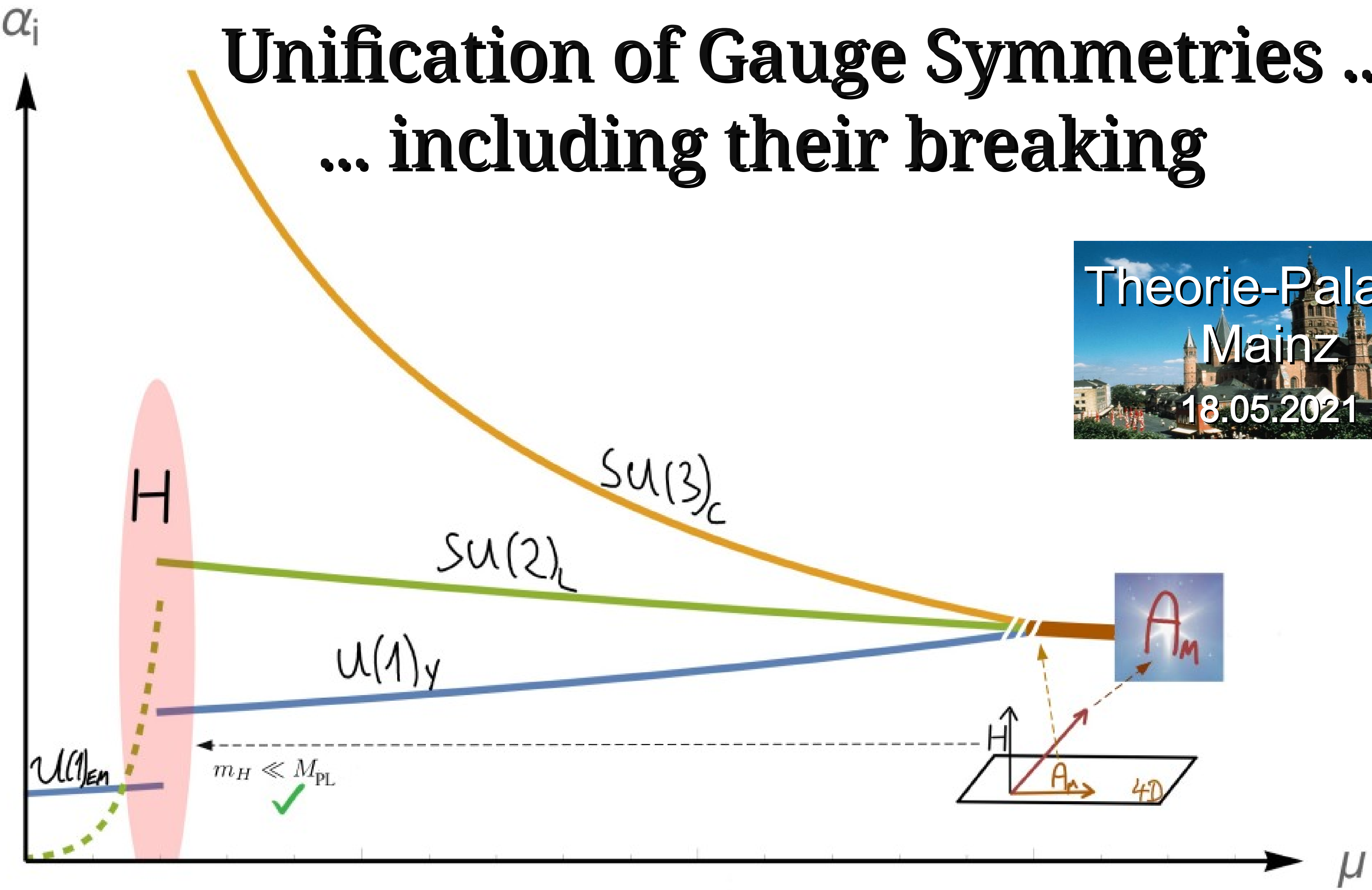
Unification of Gauge Symmetries ...
... including their breaking



Florian Goertz

Angelescu, Bally, Blasi, FG
2104.07366

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Max-Planck-Institut für Kernphysik Heidelberg

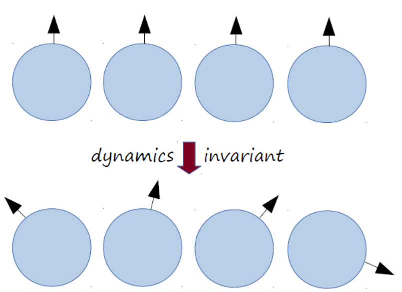
The SM

The Standard Model of Particle Physics:

renormalizable QFT, defined by

Local 'Gauge' Symmetries

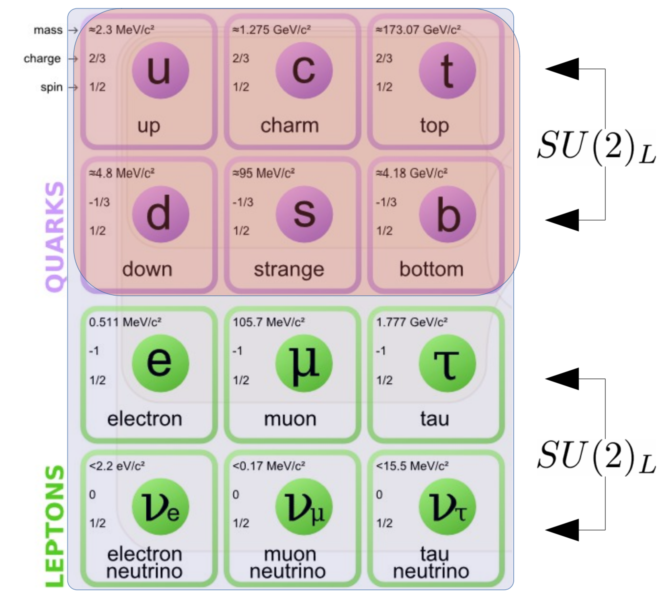
$$SU(3)_c \times SU(2)_L \times U(1)_Y$$



$\partial_\mu \to \partial_\mu + igA_\mu$

Forces

Matter Content



SM Gauge Symmetries

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$$D_\mu = \partial_\mu - ig_s\, t^a G^a_\mu - ig\, T^i W^i_\mu - ig'\, Y B_\mu$$

$$g_s(m_Z) \approx 1.22$$

$$g(m_Z) \approx 0.65$$

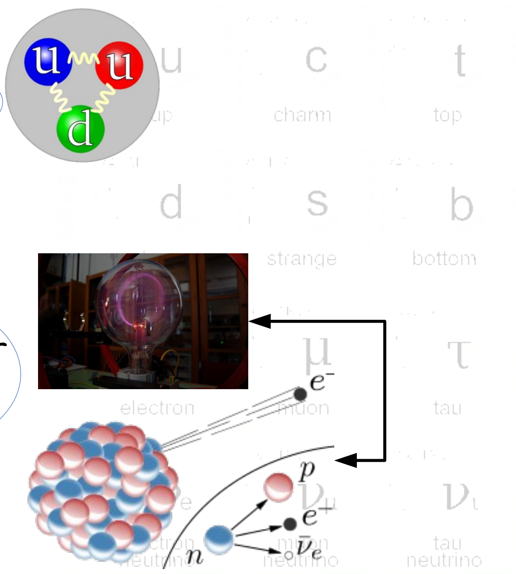
$$g'(m_Z) \approx 0.36$$

Forces

Strong

Electro-weak

Matter Content



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renormalizable QFT, defined by

Local <u>'Gauge' Symmetries</u>

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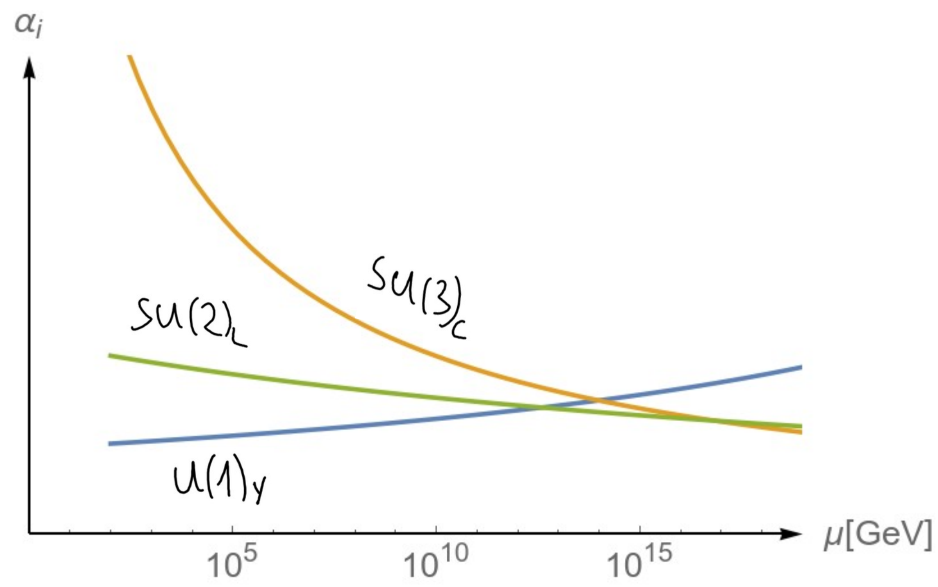
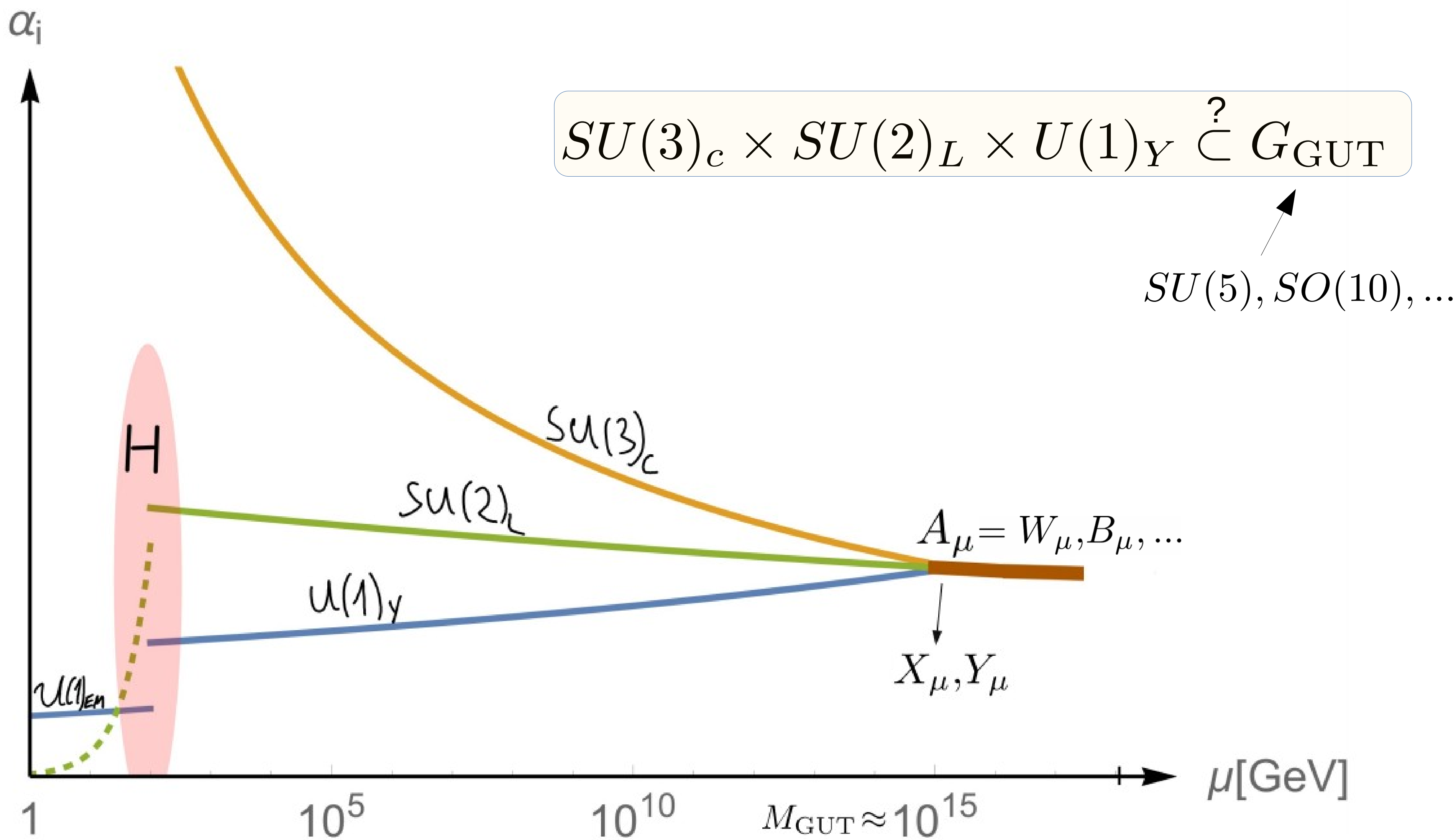


Unification of Forces



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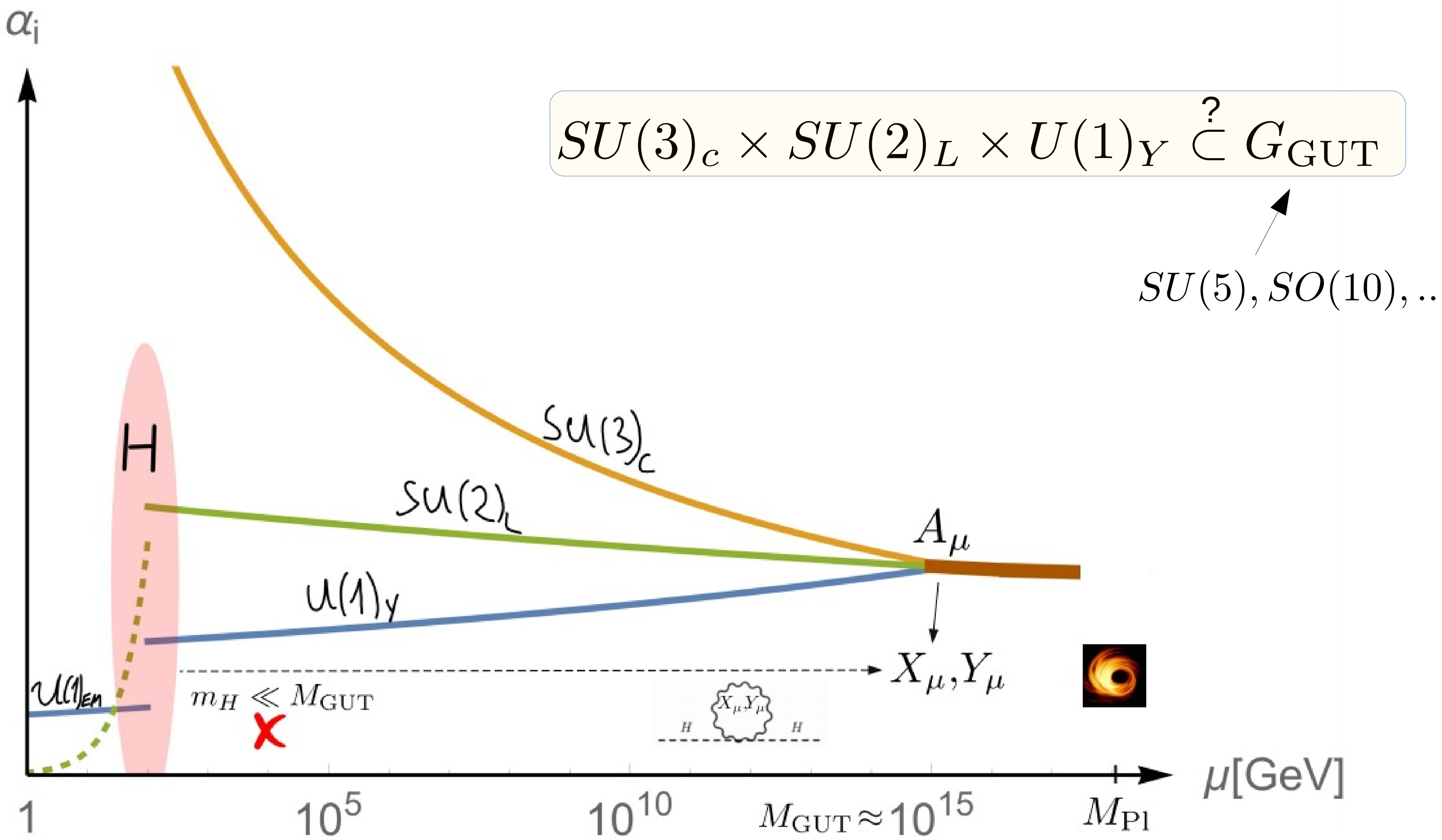
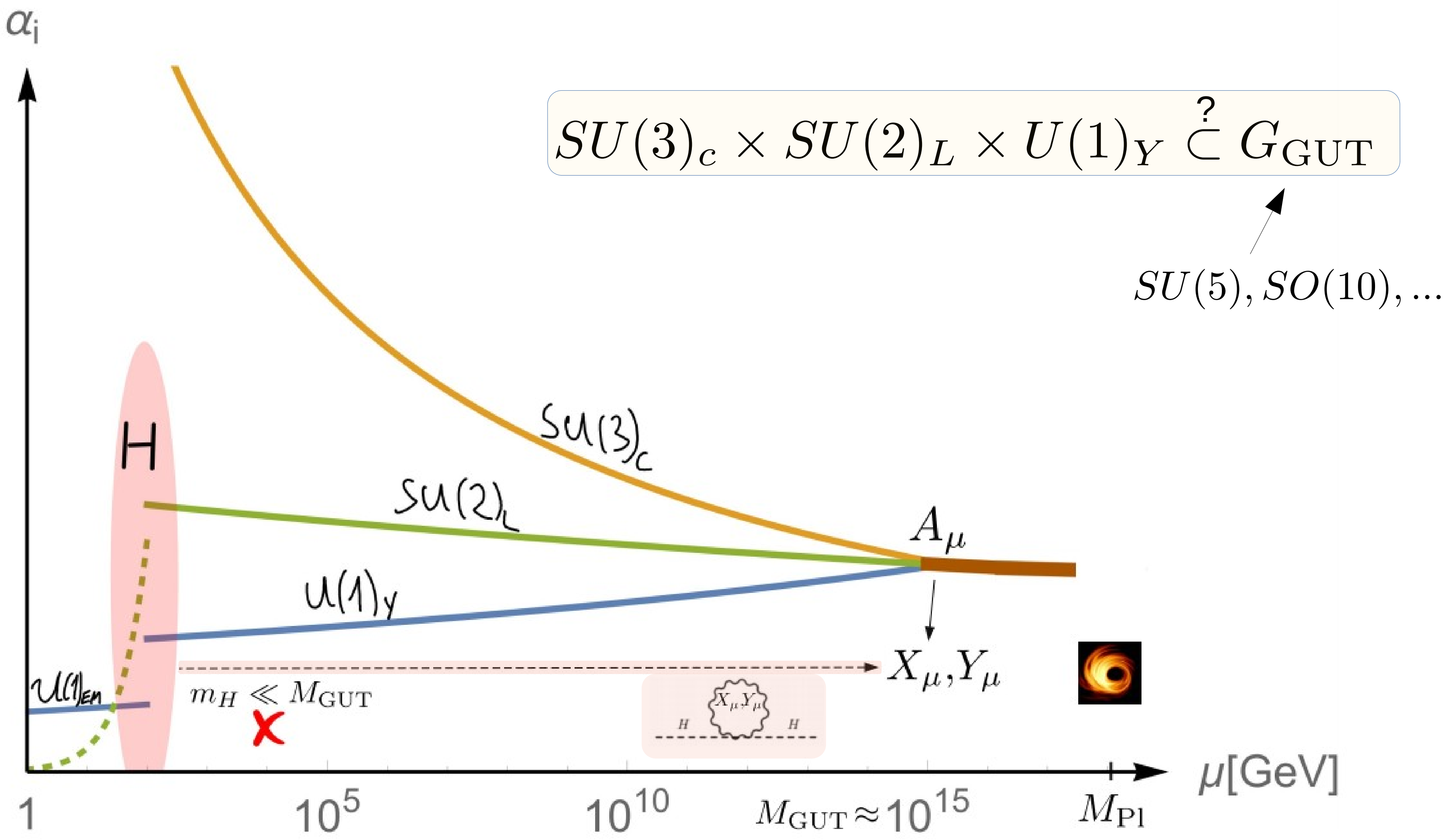
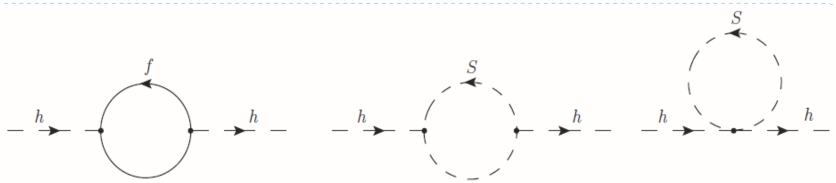


The Hierarchy Problem



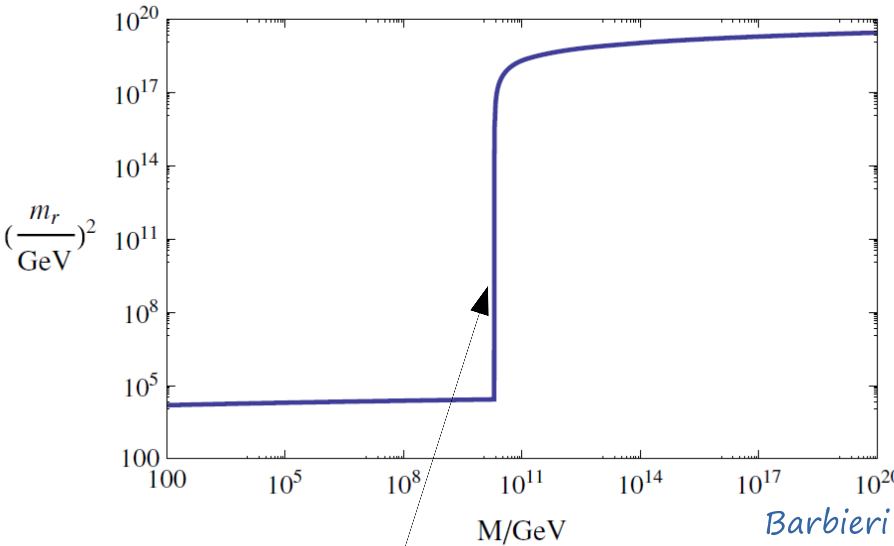
The Hierarchy Problem

$\Delta m_h^2 \sim \Lambda^2$ 

$\mathcal{L} \supset \boxed{m_H^2} |H|^2 + \frac{\mathcal{O}^{(6)}}{\Lambda^2}$ $\boxed{\Lambda^2 \gg m_H^2 \quad (??)}$

Expect coefficient of unprotected D=2 operator H^2 to reside at cutoff: $m_H^2 \sim \Lambda^2 \gg 100\,\mathrm{GeV}$

Running Higgs Mass



Barbieri
Phys. Scr. 2013 014006

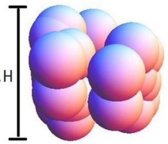
Jump at threshold of NP $\sim \frac{\lambda_{\mathrm{NP}}^2 M_{\mathrm{NP}}^2}{16\pi^2} \gg m_h^2$

→ large fine-tuning to achieve $m_h \ll M_{\mathrm{NP}}$

Composite Higgs Models

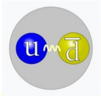
Kaplan, Georgi, Dimopoulos,. . .

- Higgs is composite at small distances

  ➡ m_H saturated in IR ➡ Hierarchy Problem solved l_H 

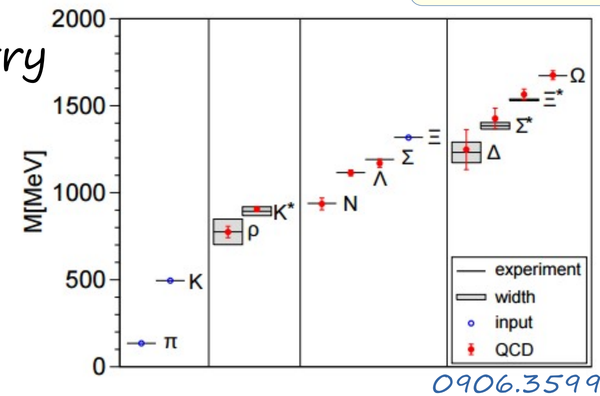
- Higgs = (pseudo) Goldstone Boson ➡ $m_H << m_\rho$

  of spon. broken global symmetry



like pions in QCD

$$SU(2)_L \times SU(2)_R \xrightarrow{\langle \bar{q} q \rangle \neq 0} SU(2)_V$$



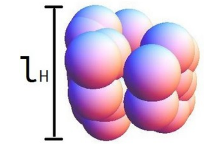
0906.3599

Composite Higgs Models

Kaplan, Georgi, Dimopoulos,. . .

- Higgs is composite at small distances

➡ m_H saturated in IR ➡ Hierarchy Problem solved



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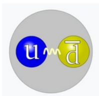

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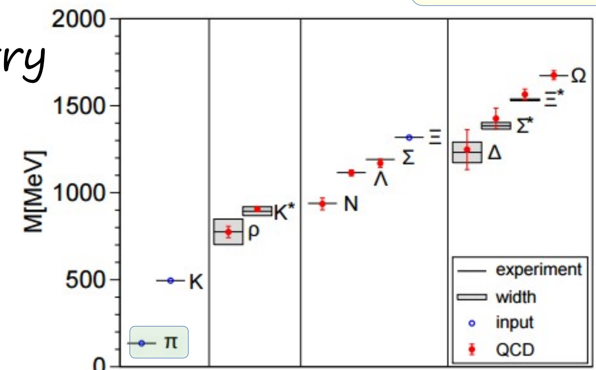


0906.3599

Naturally address

- Hierarchical Flavor Structure
- Dynamical EWSB
- Tiny Neutrino Masses

- Dark Matter
- Baryogenesis ...

4D UV completions??

Barnard, Gherghetta, Ray 1311.6562,
Ferretti, Karateev, 1312.5330
Cacciapaglia, Sannino 1402.0233,
Vecchi, 1506.00623,
Ma, Cacciapaglia, 1508.07014

- MCHM: SO(5)→SO(4)

Contino, Nomura, Pomarol, ph/0306259
Agashe, Contino, Pomarol, ph/0412089

holographic construction / EFT

Minimal Composite Higgs Model (MCHM)

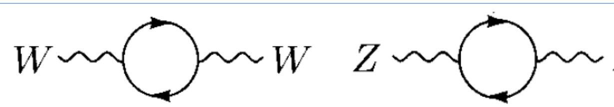
- Minimal models: SO(5)→SO(4) $SO(4)\cong SU(2)_L\times SU(2)_R$

Contino, Nomura, Pomarol, ph/0306259, Agashe, Contino, Pomarol, ph/0412089

$\dim[SO(5)/SO(4)] = 4\,\text{GB}$

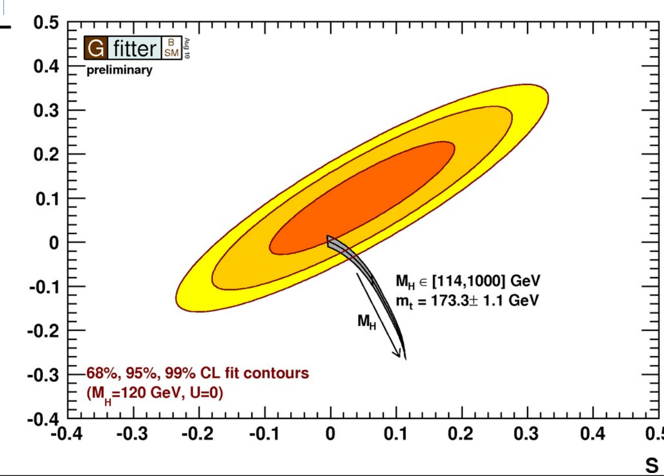
$\rightarrow$ Higgs $h_{1,..,4}$

→ 4 Goldstones, <u>custodial symmetry</u> → small T



$$T = \frac{4\pi}{e^2 c_w^2 m_Z^2}\left[\Pi_{WW}(0) - c_w^2 \Pi_{ZZ}(0) - 2 s_w c_w \Pi_{ZA}(0) - s_w^2 \Pi_{AA}(0)\right]$$

→isospin violation / m_W/m_Z



Composite Higgs Models

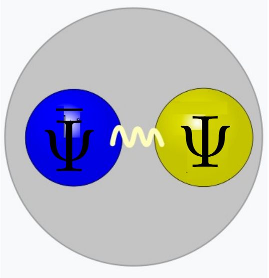
$\mathcal{G}$	$\mathcal{H}$	C	N_G	$\mathbf{r}_{\mathcal{H}} = \mathbf{r}_{SU(2)\times SU(2)}$ $(\mathbf{r}_{SU(2)\times U(1)})$
SO(5)	SO(4)	✓	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$
SU(3) × U(1)	SU(2) × U(1)		5	$\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$
SU(4)	Sp(4)	✓	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SU(4)	$[SU(2)]^2 \times U(1)$	✓*	8	$(\mathbf{2}, \mathbf{2})_{\pm 2} = 2 \cdot (\mathbf{2}, \mathbf{2})$
SO(7)	SO(6)	✓	6	$\mathbf{6} = 2 \cdot (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(7)	G_2	✓*	7	$\mathbf{7} = (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	SO(5) × U(1)	✓*	10	$\mathbf{10}_0 = (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	$[SU(2)]^3$	✓*	12	$(\mathbf{2}, \mathbf{2}, \mathbf{3}) = 3 \cdot (\mathbf{2}, \mathbf{2})$
Sp(6)	Sp(4) × SU(2)	✓	8	$(\mathbf{4}, \mathbf{2}) = 2 \cdot (\mathbf{2}, \mathbf{2})$
SU(5)	SU(4) × U(1)	✓*	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+5} = 2 \cdot (\mathbf{2}, \mathbf{2})$
SU(5)	SO(5)	✓*	14	$\mathbf{14} = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$
SO(8)	SO(7)	✓	7	$\mathbf{7} = 3 \cdot (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(9)	SO(8)	✓	8	$\mathbf{8} = 2 \cdot (\mathbf{2}, \mathbf{2})$
SO(9)	SO(5) × SO(4)	✓*	20	$(\mathbf{5}, \mathbf{4}) = (\mathbf{2}, \mathbf{2}) + (\mathbf{1} + \mathbf{3}, \mathbf{1} + \mathbf{3})$
$[SU(3)]^2$	SU(3)		8	$\mathbf{8} = \mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0$
$[SO(5)]^2$	SO(5)	✓*	10	$\mathbf{10} = (\mathbf{1}, \mathbf{3}) + (\mathbf{3}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SU(4) × U(1)	SU(3) × U(1)		7	$\mathbf{3}_{-1/3} + \bar{\mathbf{3}}_{+1/3} + \mathbf{1}_0 = 3 \cdot \mathbf{1}_0 + \mathbf{2}_{\pm 1/2}$
SU(6)	Sp(6)	✓*	14	$\mathbf{14} = 2 \cdot (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{3}) + 3 \cdot (\mathbf{1}, \mathbf{1})$
$[SO(6)]^2$	SO(6)	✓*	15	$\mathbf{15} = (\mathbf{1}, \mathbf{1}) + 2 \cdot (\mathbf{2}, \mathbf{2}) + (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3})$

Bellazzinia, Csaki, Serra 1401.2457 (Review)

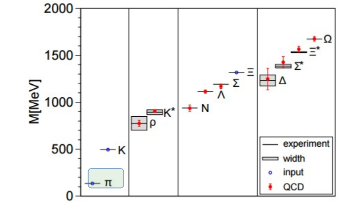
Composite Higgs

- Higgs = composite of a new strong interaction

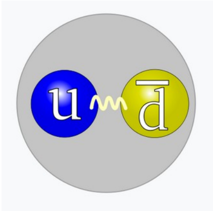
- New <u>confining force</u> (e.g. SU(N)) breaks global SO(5) spontaneously via condensation $(\langle\bar{\Psi}\Psi\rangle \neq 0)$ of fermions charged under that force, at scale $\Lambda_{\rm c}$

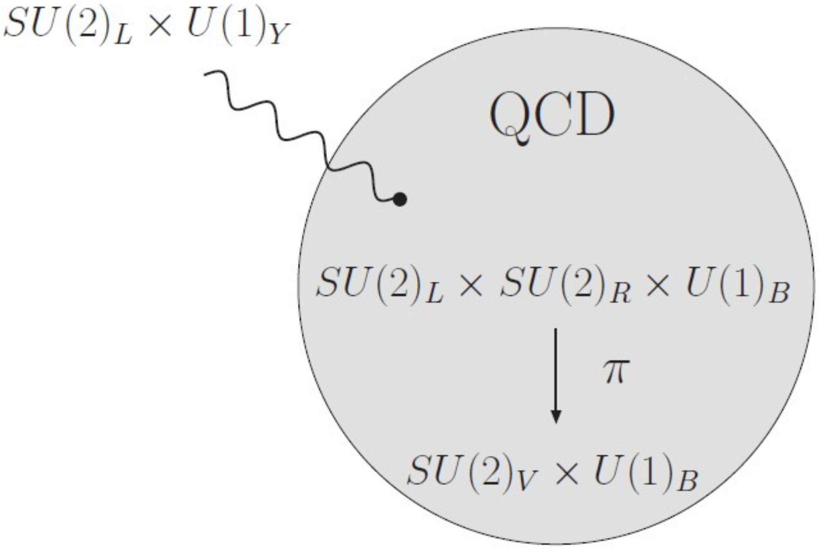


- Higgs: Goldstone of global symmetry breaking $SO(5) \to SO(4)$
  → massless w/o explicit SO(5) breaking (V(H)=0)
  + corrections to m_h cut off by compositeness scale $\Lambda_{\rm c}$



The Analogy with QCD

- 2-flavor QCD with $m_u = m_d = 0$ $\rightarrow SU(2)_L \times SU(2)_R$ chiral sym.
- Spontaneously broken by quark condensate $\langle \bar{q}q \rangle \neq 0$:
  (condensation of color force)
  $\boxed{SU(2)_L \times SU(2)_R \rightarrow SU(2)_V}$
- Goldstone bosons: 3 pions (π^+, π^0, π^-) 



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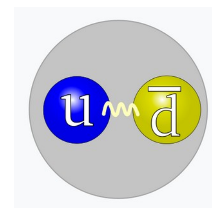
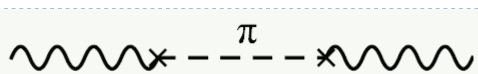
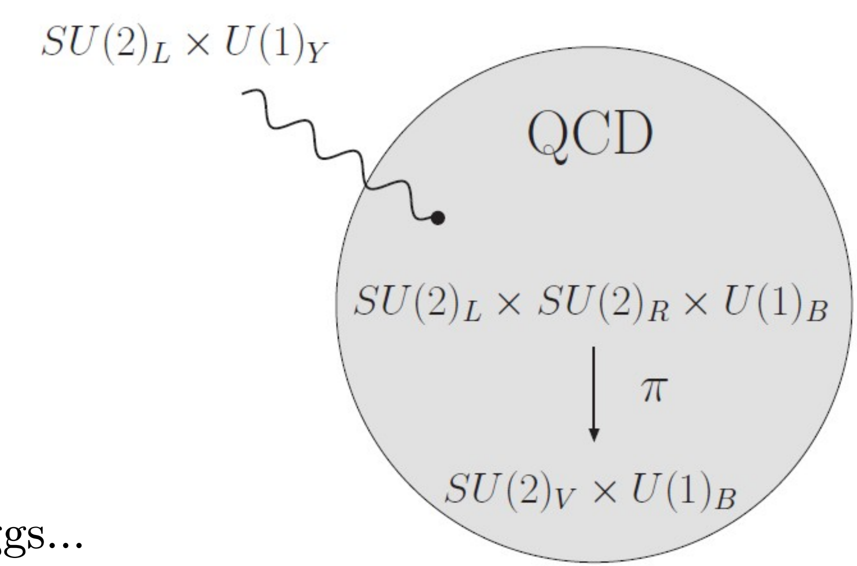


- $\boxed{\mathrm{G}_{\mathrm{EW}}}$ broken by $\langle \bar{q} q \rangle \neq 0$:
  $\boxed{SU(2)_L \times U(1)_Y \to U(1)_{\mathrm{EM}}}$
  → W,Z become massive, absorb π^a



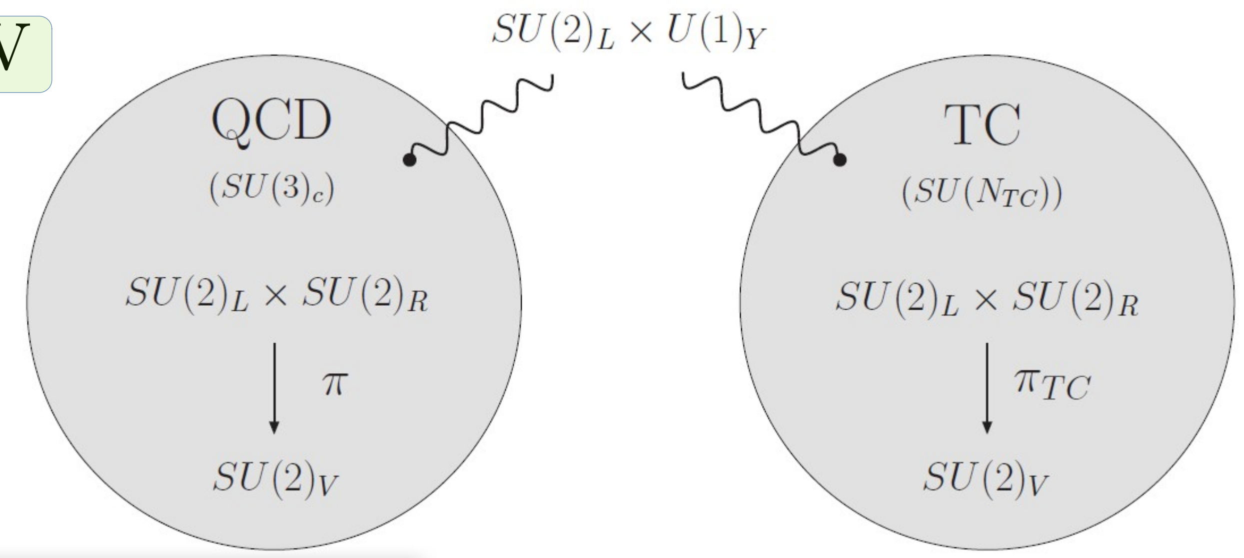
$$\Rightarrow \; m_W = \frac{g f_\pi}{2} \simeq 29\,\mathrm{MeV}$$

so far no Higgs...



Up-Scaled Version: Technicolor

- $f_\pi \to F_\pi \simeq v = 246\,\mathrm{GeV}$



longitudinal (Goldstone) modes

$$|V_L\rangle = \sin\alpha|\pi_{\mathrm{QCD}}\rangle + \cos\alpha|\pi_{\mathrm{TC}}\rangle$$

$$v^2 = f_\pi^2 + F_\pi^2\,, \quad \tan\alpha = \frac{f_\pi}{F_\pi}$$

Solution to the HP: <u>Dimensional Transmutation</u>

- g_{TC} grows strong in infrared → techniquark condensate breaks EW symmetry

$$\mu \frac{d}{d\mu} \frac{1}{g_{TC}^2}(\mu) = -\frac{\beta_0}{8\pi^2} \quad \Longrightarrow \quad v = M_{Pl} \exp\left(-\frac{8\pi^2}{g_{TC}^2(M_{Pl})(-\beta_0)}\right)$$

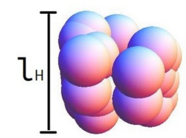
- *Large separation* of v and M_{Pl} possible

However:

- Large corrections to S Parameter
- No Higgs
- No decoupling limit ($f_\pi = v$)

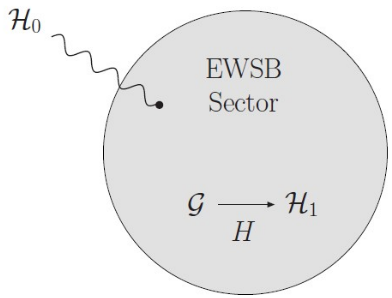
Composite Higgs Models

CH interpolates between Technicolor and elementary Higgs: light Higgs as pNGB

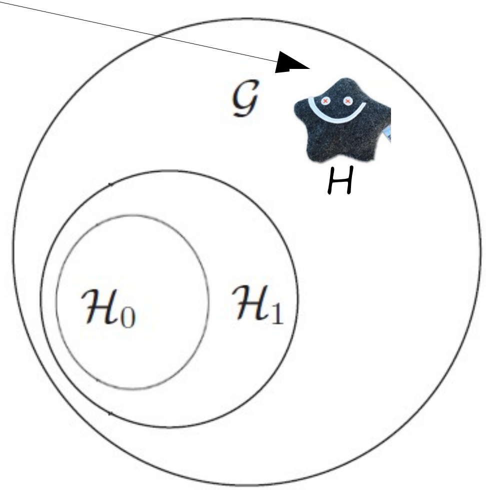


- Strongly interacting sector with global $\mathcal{G} \to \mathcal{H}_1$

  $SO(5) \to SO(4)$



- $\mathcal{G}/\mathcal{H}_1$ contains a $SU(2)_L$ doublet $\to$ Higgs



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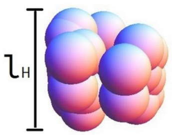

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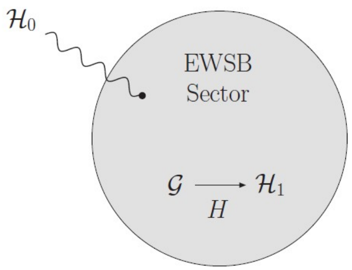

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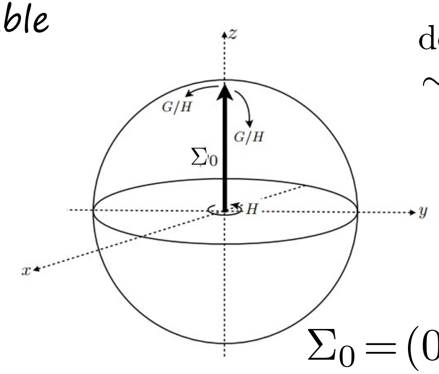
Rotation of vacuum $\Sigma(x) = \Sigma_0\, e^{-i\frac{\sqrt{2}}{f} h_{\hat{a}}(x) T^{\hat{a}}}$

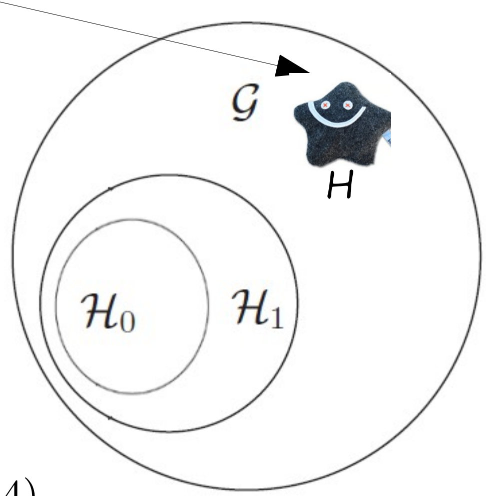
Goldstone-Higgs = angular variable

decay constant $\sim$ TeV

broken gener.



$\Sigma_0 = (0,0,0,0,1) : SO(5) \to SO(4)$



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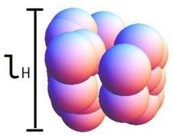

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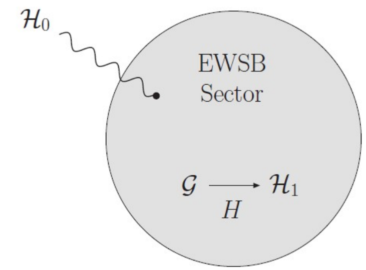
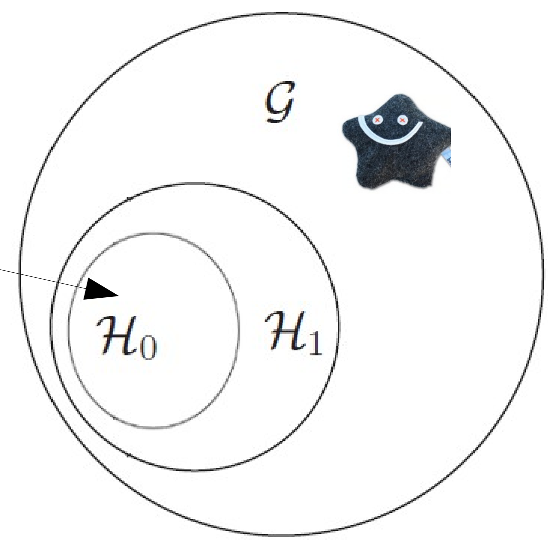


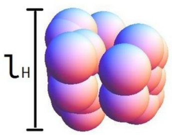
- $\mathcal{G}/\mathcal{H}_1$ contains a $SU(2)_L$ doublet $\to$ Higgs

- Subgroup $\mathcal{H}_0 = G_{\mathrm{SM}} \subset \mathcal{G}$ gauged
  no Higgs potential & G_{SM} unbroken at *tree level*

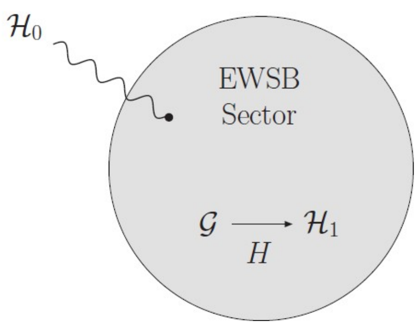


Vacuum Misalignment

CH interpolates between Technicolor and elementary Higgs: <u>light Higgs as pNGB</u>



- $\mathcal{G}$ *explicitly* broken by couplings to SM (only invariant under $\mathcal{H}_0 \equiv G_{\mathrm{SM}}$)



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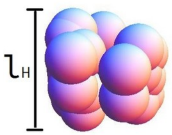
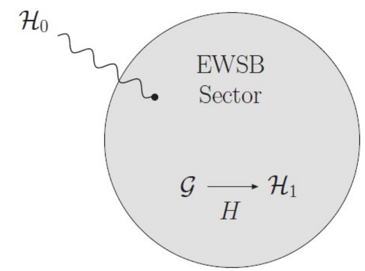
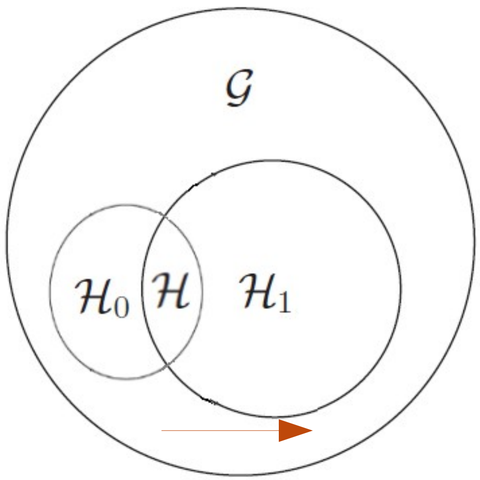


- $\mathcal{G}$ *explicitly* broken by couplings to SM (only invariant under $\mathcal{H}_0 \equiv G_{\rm SM}$)
- One-loop Higgs potential $\to \mathcal{H}_0$ broken $\to$ dynamically determine EW scale $v > 0$, allows separation $v \ll f$ (different than TC)



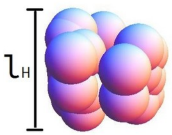


$\mathcal{H} = H_0 \cap \mathcal{H}_1$ unbroken gauge group

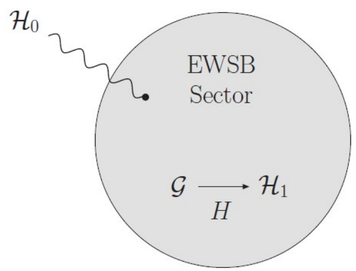
$U(1)_{\rm EM}$

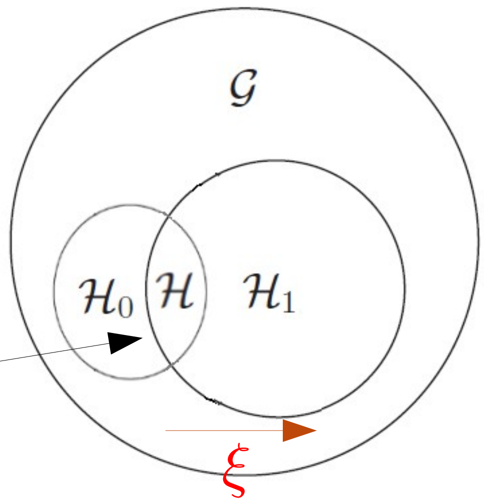
Vacuum Misalignment

CH interpolates between Technicolor and elementary Higgs: light Higgs as pNGB



- $\mathcal{G}$ *explicitly* broken by couplings to SM (only invariant under $G_{\rm SM}$)
- One-loop Higgs potential $\to \mathcal{H}_0$ broken $\to$ dynamically determine EW scale $v > 0$





$\to$ ratio $\xi \equiv (v/f)^2$ measures 'misalignment': orientation of $G_{\rm SM}$ with respect to $\mathcal{H}_1$ in *true* vacuum

$\to$ size of all corrections to precision observables $\sim \xi$

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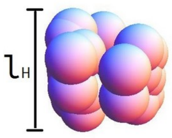

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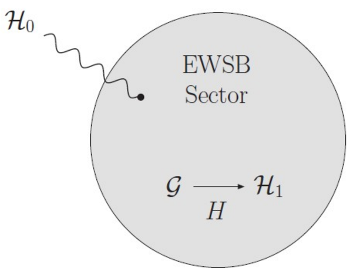

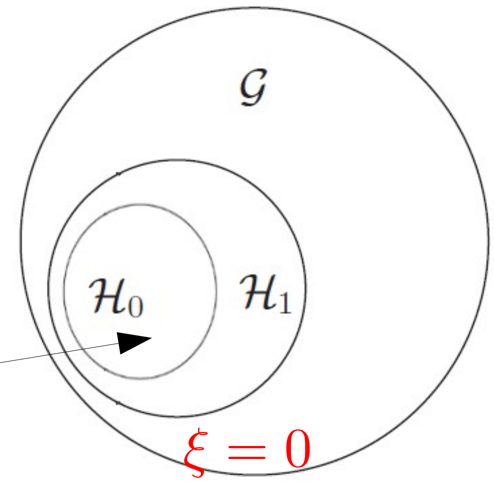

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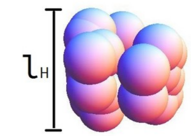

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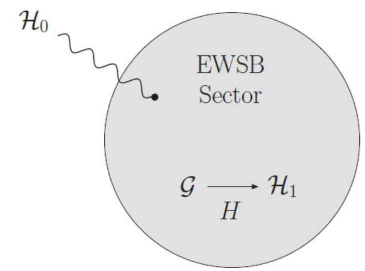

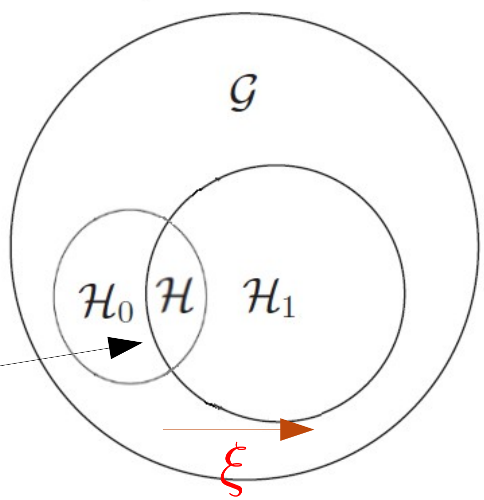

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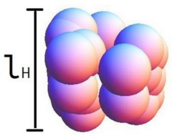

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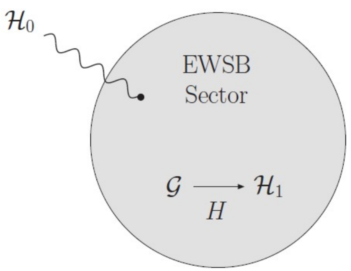
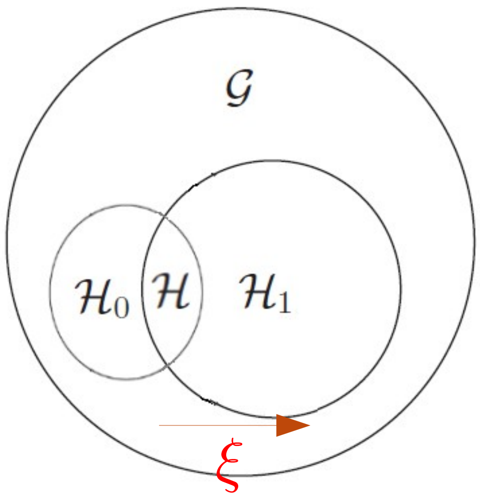


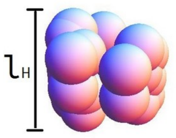


$\to$ ratio $\xi \equiv (v/f)^2$ measures 'misalignment': orientation of $G_{\rm SM}$ with respect to $\mathcal{H}_1$ in *true* vacuum

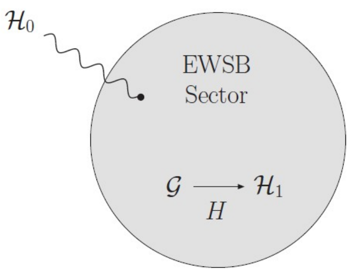
$\to$ decoupling limit: $\xi \to 0$ ($f \to \infty$)

Counting

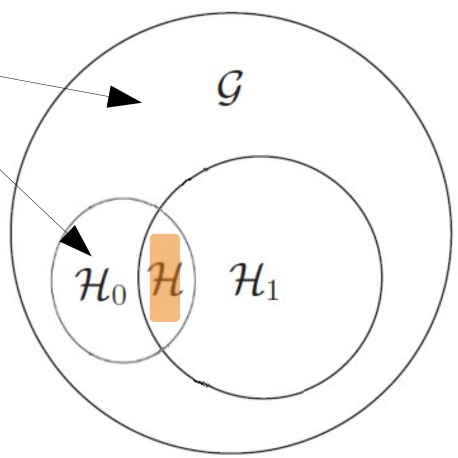
CH interpolates between Technicolor and elementary Higgs: <u>light Higgs as pNGB</u>



- $\mathcal{G}$ dynamically broken at scale f: $\mathcal{G} \to \mathcal{H}_1$
  $\mathcal{H}_0 \subset \mathcal{G}$ gauged



- $n = \dim(\mathcal{G}) - \dim(\mathcal{H}_1)$ goldstone bosons,
  $n_0 = \dim(\mathcal{H}_0) - \dim(\mathcal{H})$ absorbed by gauge fields,
  where $\mathcal{H} = \mathcal{H}_0 \cap \mathcal{H}_1$ unbroken gauge group
- $(n - n_0)$ pNGBs $\to$ Higgs   TC: n=n$_0$



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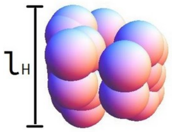

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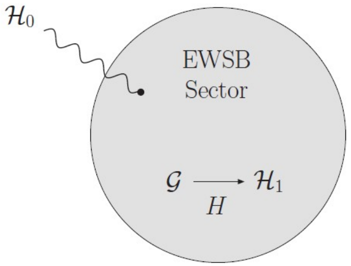

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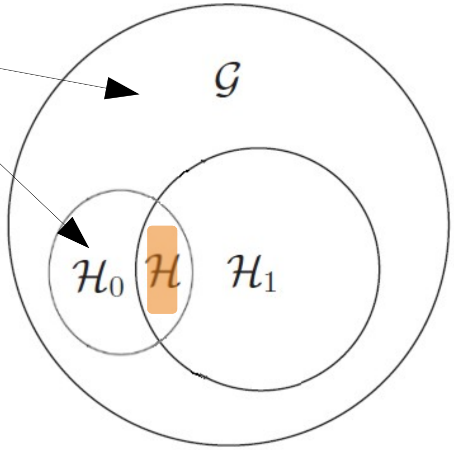
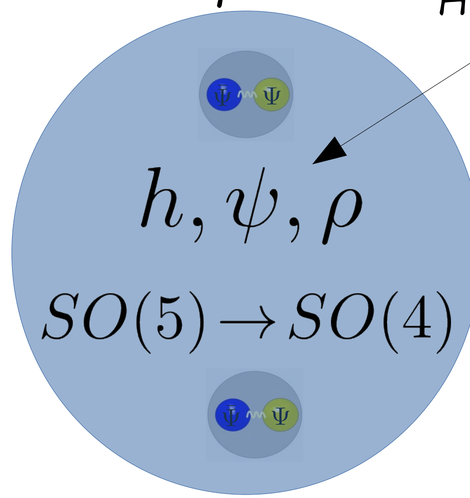


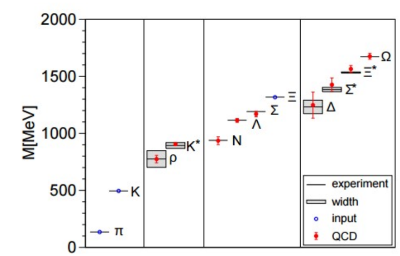
- $(n - n_0)$ pNGBs $\to$ Higgs CH: $n>n_0$

SO(5) → SO(4) Composite Higgs

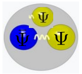
composite



Higgs + fermionic
and bosonic
resonances
of strong
sector



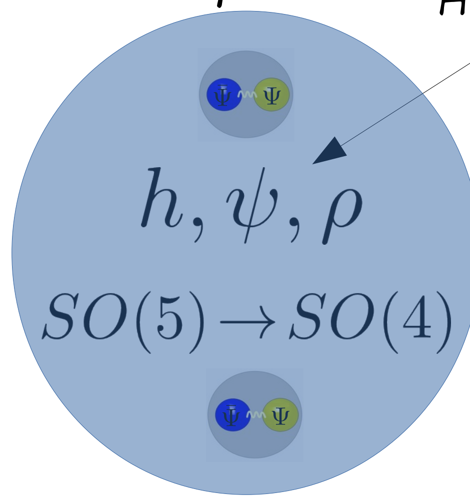
$$\boxed{V(h) \propto 0}$$



$$\psi = \frac{1}{\sqrt{2}} \begin{pmatrix} \psi_{++} + \psi_{--} \\ i\psi_{++} - i\psi_{--} \\ -\psi_{-+} + \psi_{+-} \\ i\psi_{-+} + i\psi_{+-} \\ \psi_{00} \end{pmatrix}$$

SO(5) → SO(4) Composite Higgs

composite



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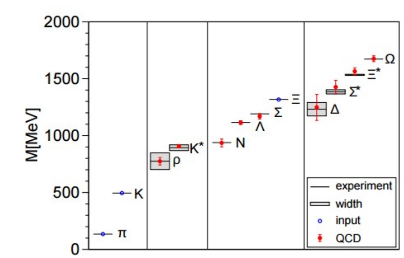


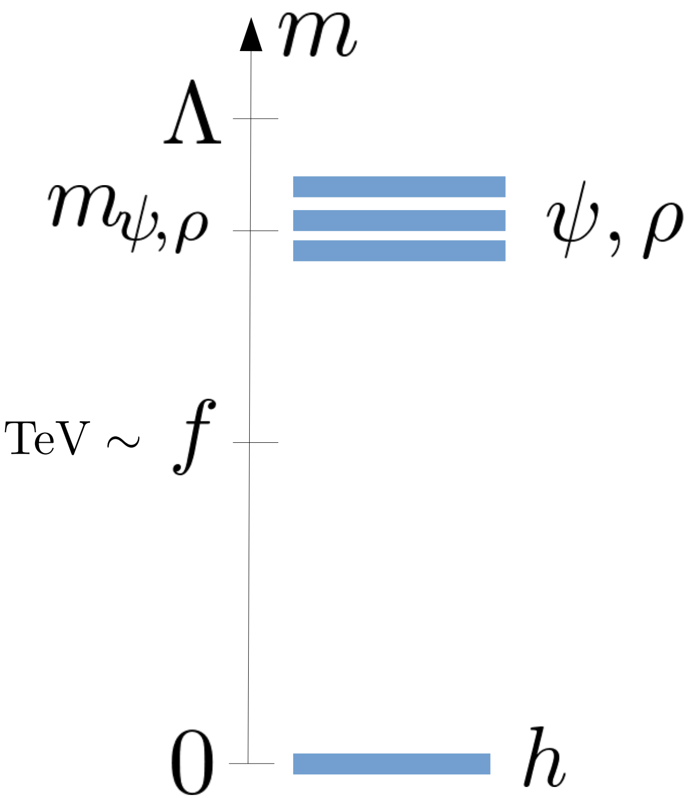
$$V(h) \propto 0$$

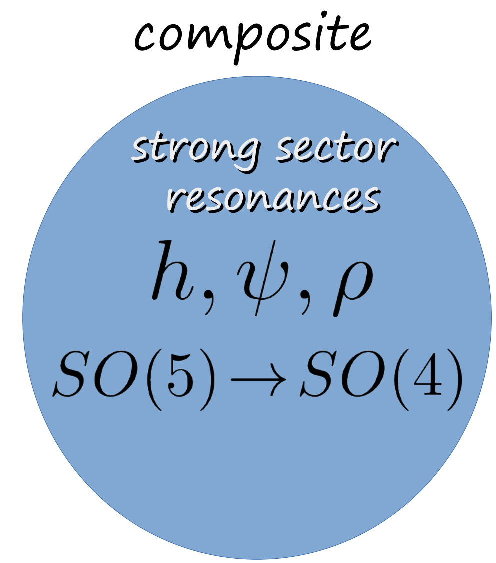
Below condensation scale Λ_c: $NL\Sigma M \quad \Sigma = \Sigma_0 \, e^{-i \frac{\sqrt{2}}{f} h_{\hat{a}} T^{\hat{a}}}$

Composite Goldstone Higgs

$\Sigma_0 = (0,0,0,0,1) : SO(5) \to SO(4)$ $\qquad T^{\hat{a}} : SO(5)/SO(4)$

SO(5) → SO(4) Composite Higgs

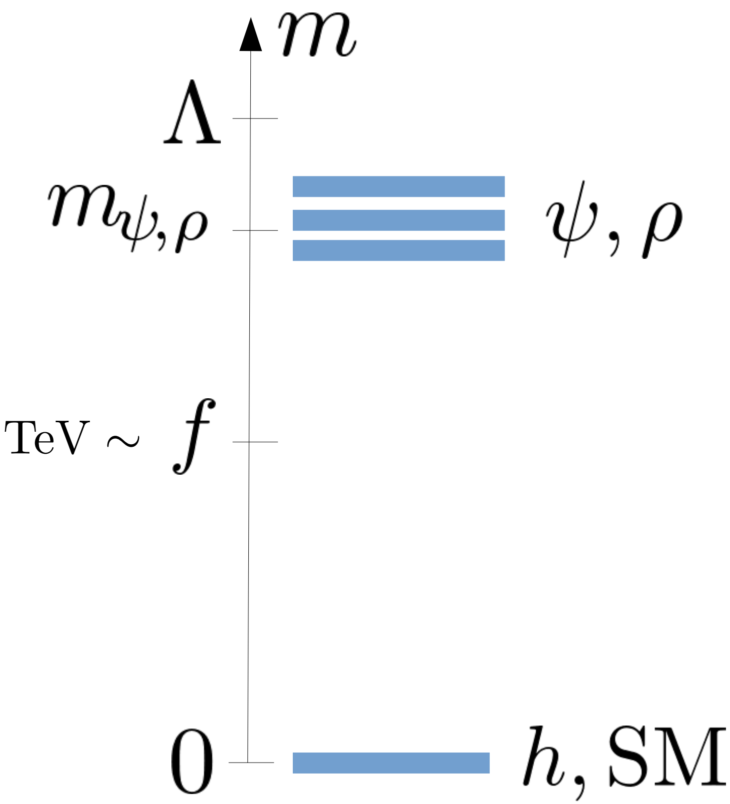


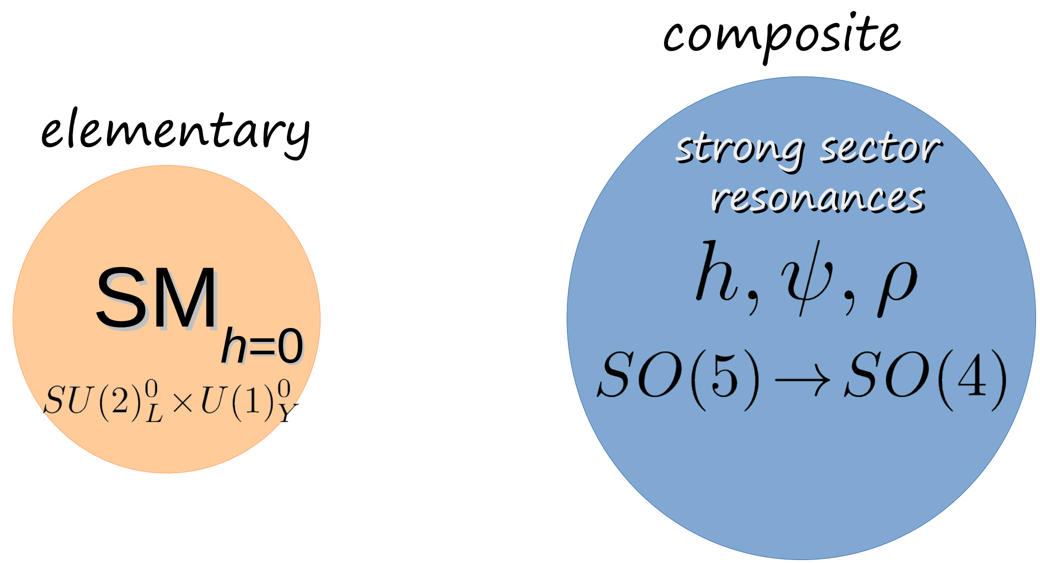


$$\boxed{V(h) \propto 0}$$

$$\Sigma = \Sigma_0\, e^{-i\frac{\sqrt{2}}{f}\boxed{h_{\hat{a}}}T^{\hat{a}}}$$

SO(5) → SO(4) Composite Higgs

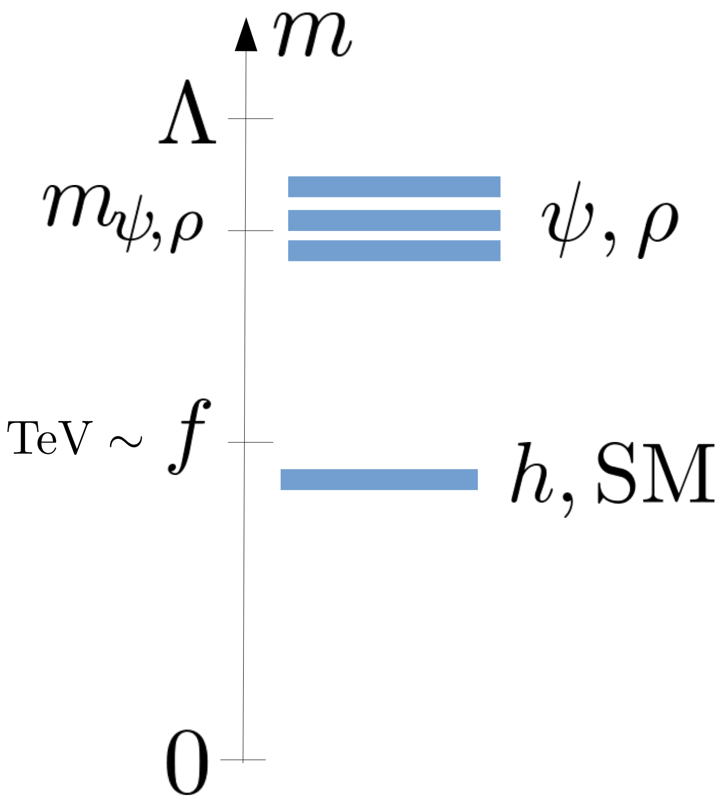


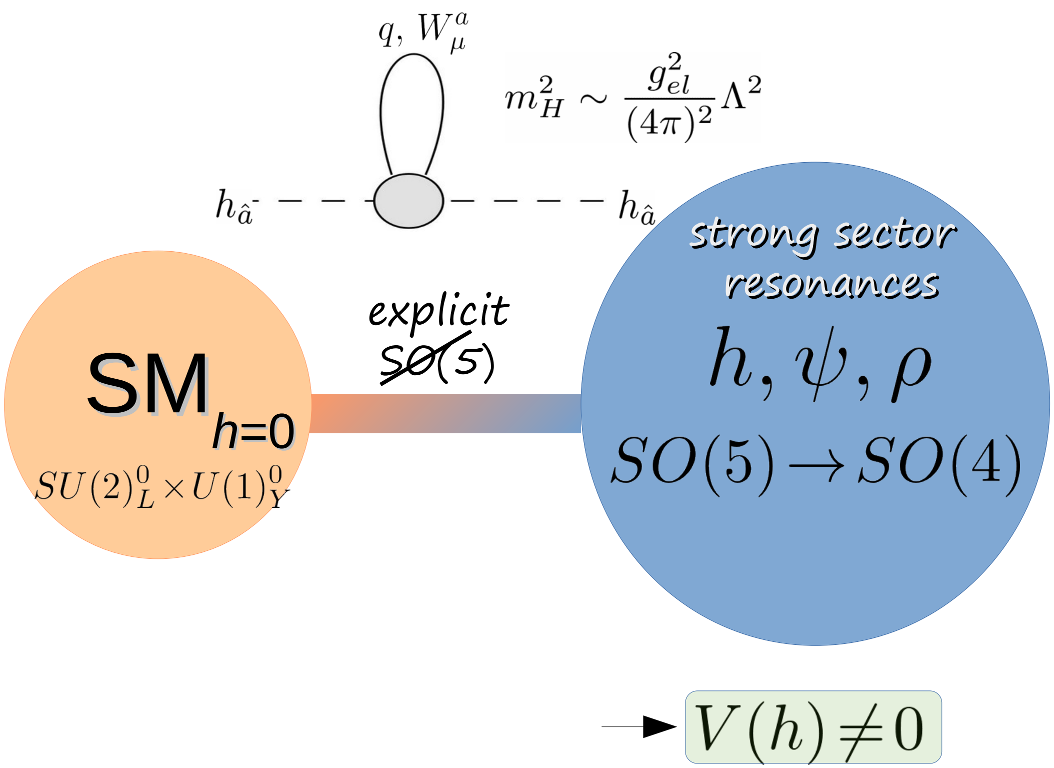


$$\boxed{V(h) \propto 0}$$

$$\Sigma = \Sigma_0 \, e^{-i\frac{\sqrt{2}}{f}\boxed{h_{\hat{a}}}T^{\hat{a}}}$$

Coupling to SM breaks SO(5)

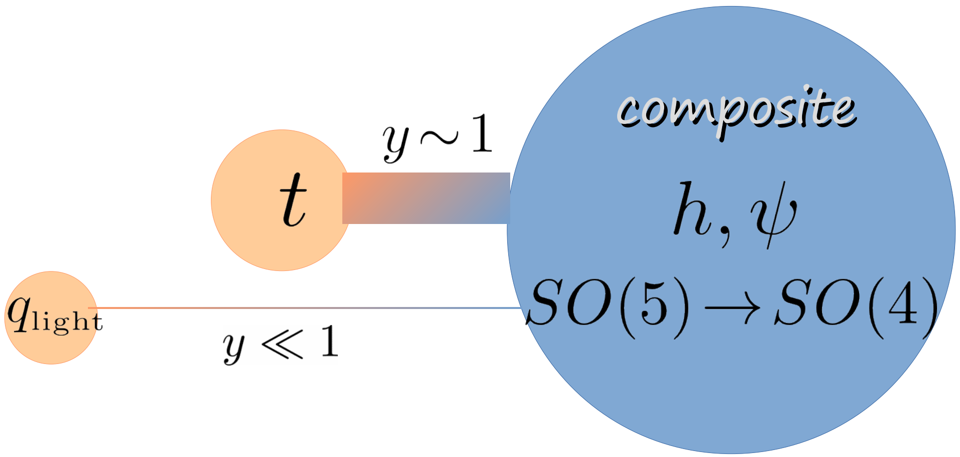




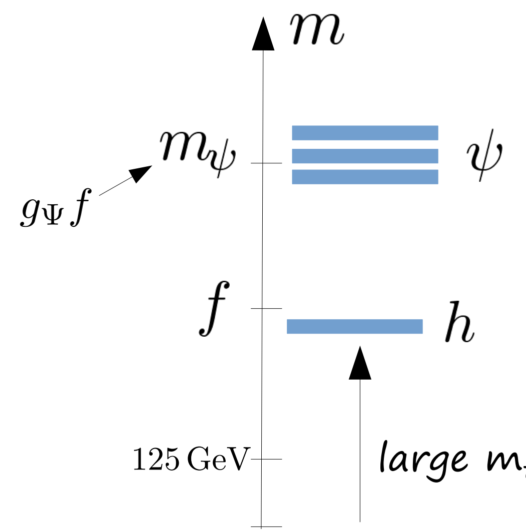
$$V(h) \approx \alpha \sin^2(h/f) + \beta \sin^4(h/f) \neq 0$$

Partially Composite Fermions

Kaplan; Agashe, Contino, Nomura, Pomarol



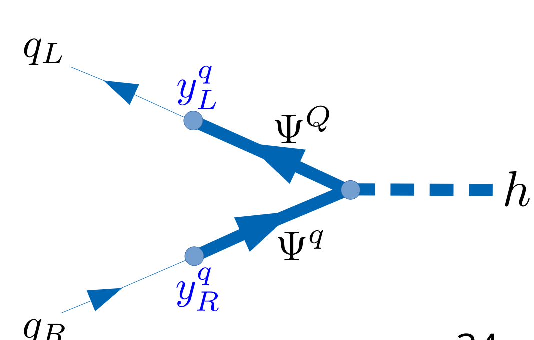
$\to V(h) \neq 0$



$$\mathcal{L} \supset -(\boxed{y_L^q}\ \bar{q}_L \cdot \Psi_R^Q + \boxed{y_R^q}\ \bar{q}_R \cdot \Psi_L^q)\, f$$

$\mathbf{5}$ of $SO(5)$
$\mathbf{10}$ of $SO(5)$
$\dots$

$\to$ induce m_q

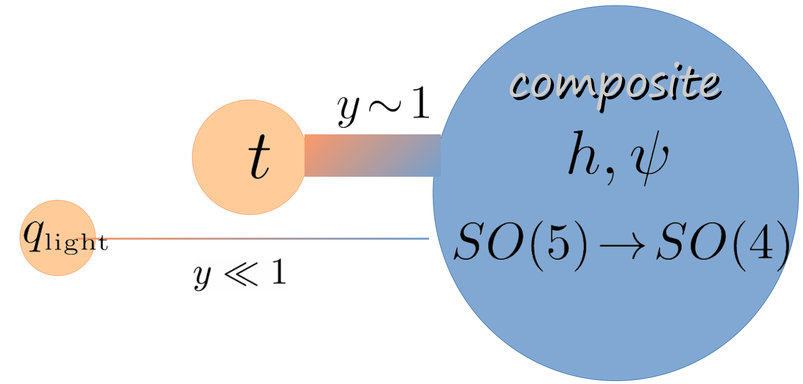


Partial Compositeness

- Addresses the flavor puzzle:

$$y^q_{L,R} \leftrightarrow (\Lambda/\Lambda_{UV})^{\gamma_L+\gamma_R}$$

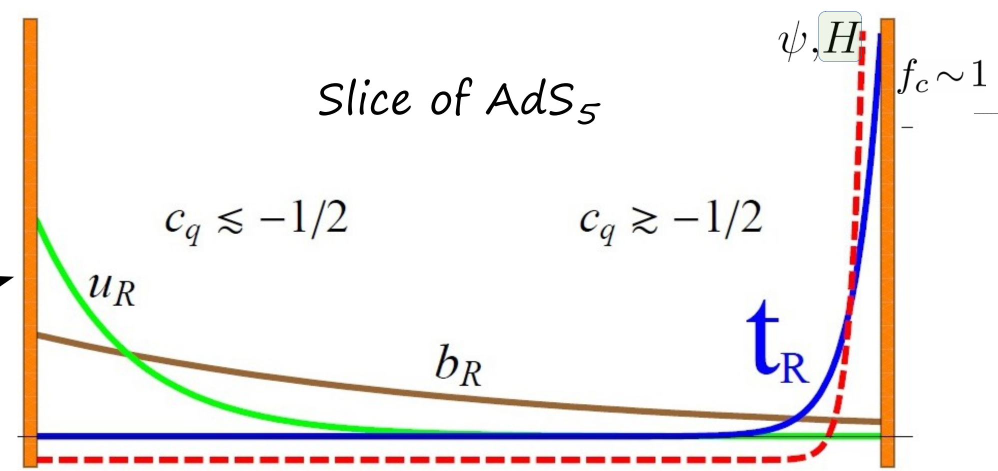
→ Hierarchies generated naturally from small differences in anomalous dimensions



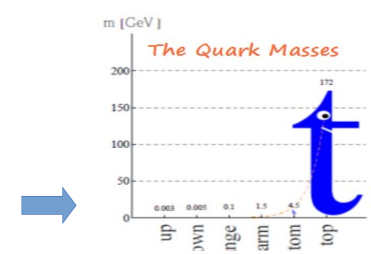
Dual picture: Warped Extra Dimension

→ later

UV brane: elementary sector



Froggatt-Nielsen-like mass matrices



$$V_{\text{CKM}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

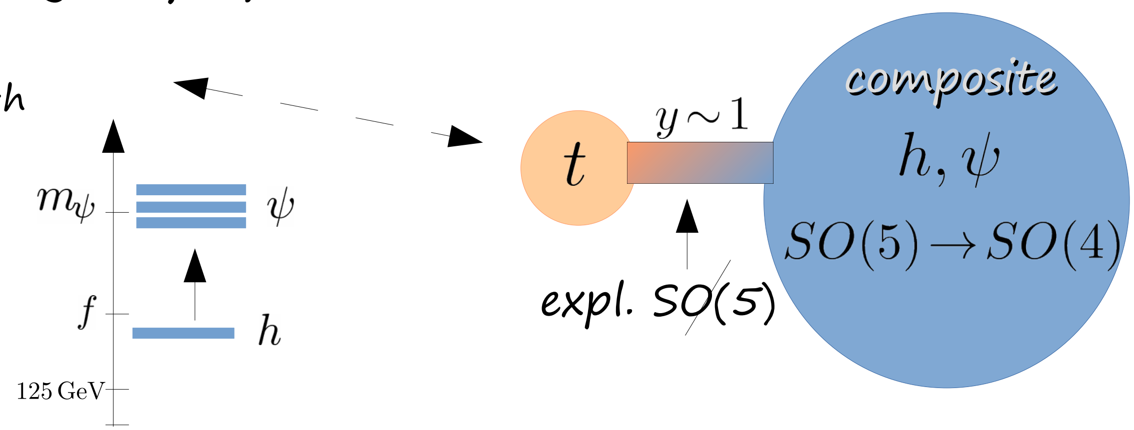
→ Different c~O(1) mass parameters (↔y)

→ Localization → Hierarchies in overlap with Higgs!

Light Top Partners

- *Most important SO(5) breaking: top quark*
- *Large top yukawa → large m_h*

$$\boxed{m_h} \sim y_t^2\, v \sim \boxed{m_T^{\min}/f\;\, m_t}$$



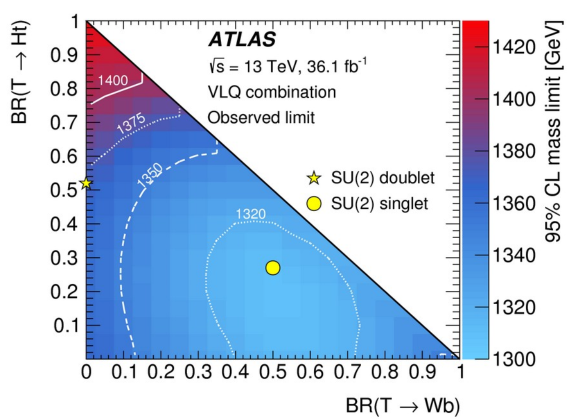
=> *light top partners*:

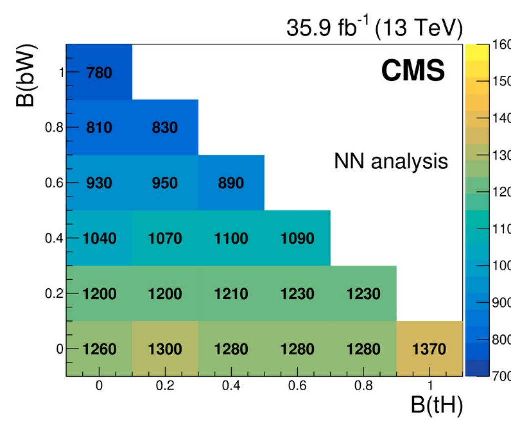
$$\boxed{m_T^{min} < f} \sim \boxed{\text{TeV}}$$

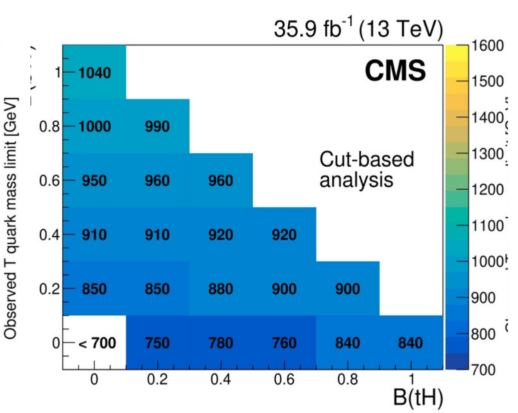
LHC Searches

$$\rightarrow m_{t'} \gtrsim 1300\,\text{GeV}$$

Assumes $BR(T \to Ht) + BR(T \to Wb) + BR(T \to Zt) = 1$







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=> light top partners:

$$\boxed{m_T^{min} < f} \sim \boxed{TeV}$$

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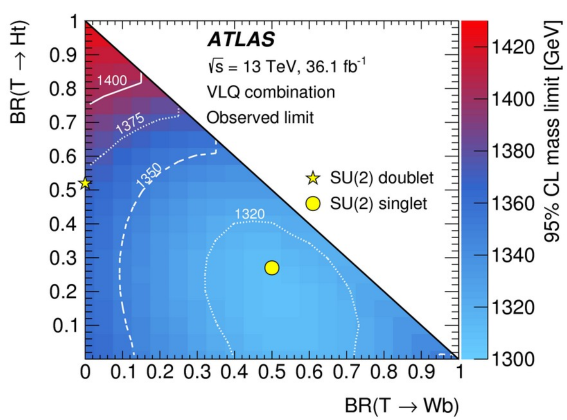
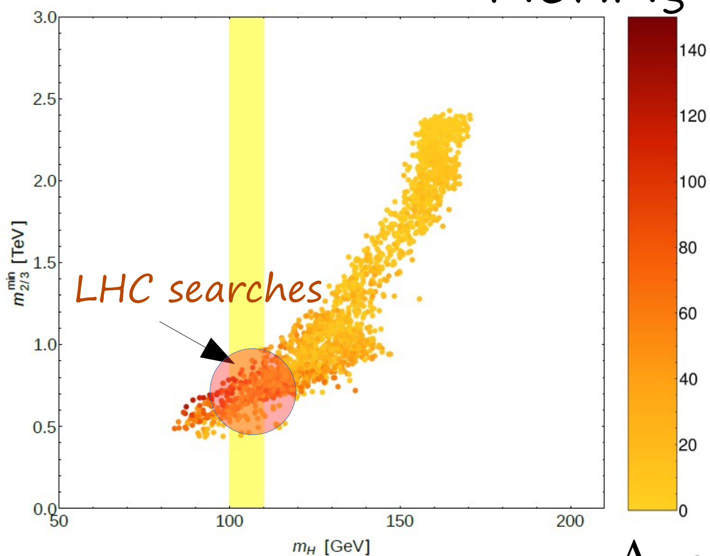


MCHM5



Δ_{BG}

$f = 800\,\mathrm{GeV}$

Carmona, FG, JHEP (1410.8555)

potentially strongest constraints on CH

Avoiding Light Top Partners

- Larger quark representations: $\mathbf{14}$ of $SO(5)$ Panico, Redi, Tesi, Wulzer, JHEP (1210.7114)

- Fits naturally in the lepton sector (keep quark sector [even more] minimal)

$$\xi_{2\tau} = \boxed{\tau_2'[-,-]} \oplus \begin{pmatrix} \nu_2^\tau[+,-] & \tilde{\tau}_2[+,-] \\ \tau_2[+,-] & \tilde{Y}_2^\tau[+,-] \end{pmatrix} \oplus \begin{pmatrix} \hat{\lambda}_2^\tau[-,-] & \nu_2^{\tau\prime\prime}[+,-] & \tau_2^{\prime\prime\prime}[+,-] \\ \hat{\nu}_2^\tau[-,-] & \tau_2^{\prime\prime}[+,-] & Y_2^{\tau\prime\prime\prime}[+,-] \\ \hat{\tau}_2[-,-] & Y_2^{\tau\prime\prime}[+,-] & \Theta_2^{\tau\prime\prime\prime}[+,-] \end{pmatrix}$$

Carmona, FG, JHEP (1410.8555)

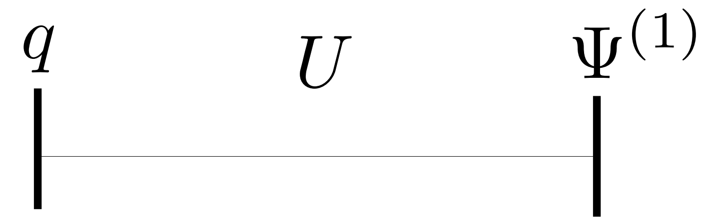
  - Type-III seesaw, 'unification' of RH leptons, address LHCb anomalies
    Carmona, FG, PRL (1510.07658), EPJC (1712.02536)

- Breaking the global (Goldstone) symmetry softly
  Blasi, FG, PRL (1903.06146), Blasi, Csáki FG, 2004.06120

Explicit Models of Strong Sector

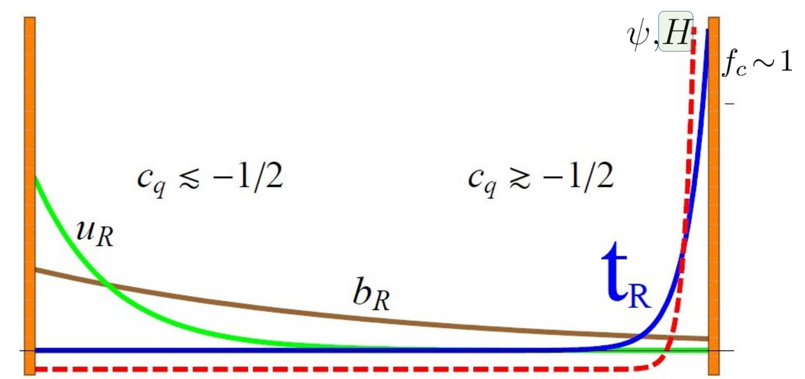
Calculable Implementations ...

1) N-Site Models



2) Extra Dimensions

(Holographic Models)

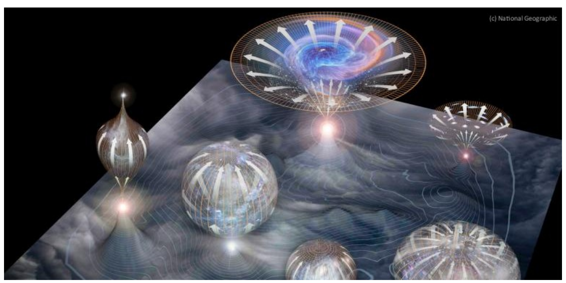


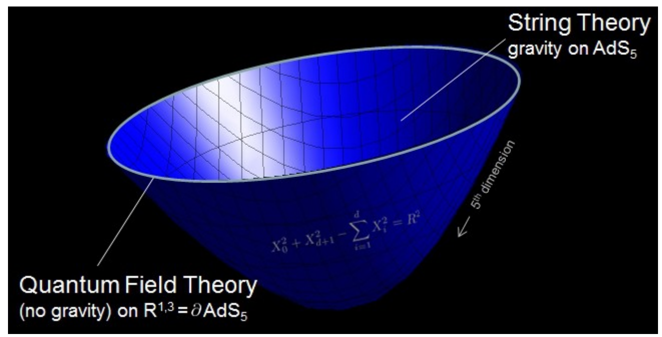
UV brane:
elementary sector

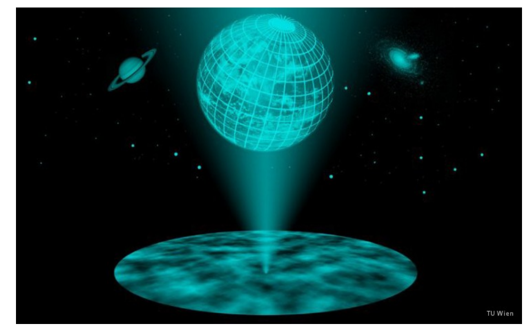
IR brane:
composite sector

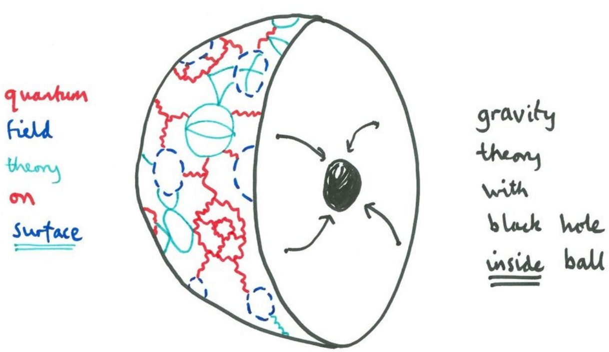
...

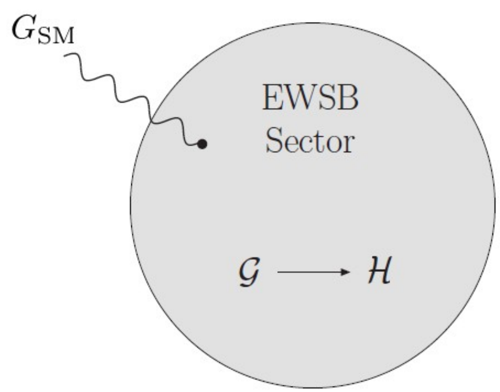
Dual Description of Composite Models

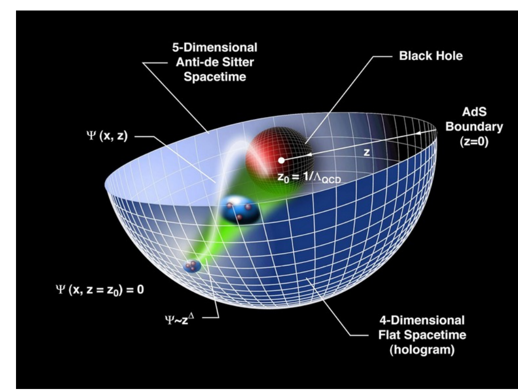










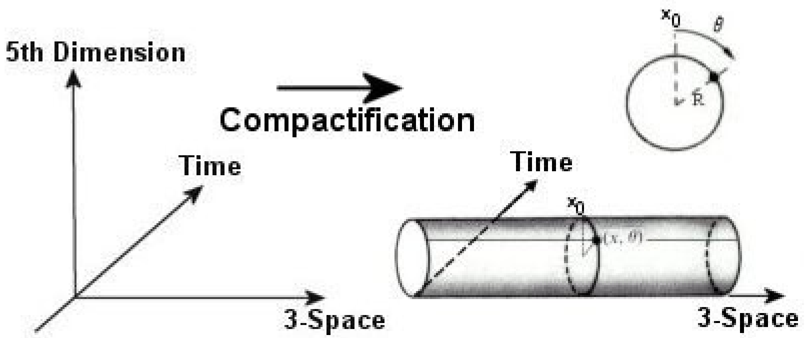


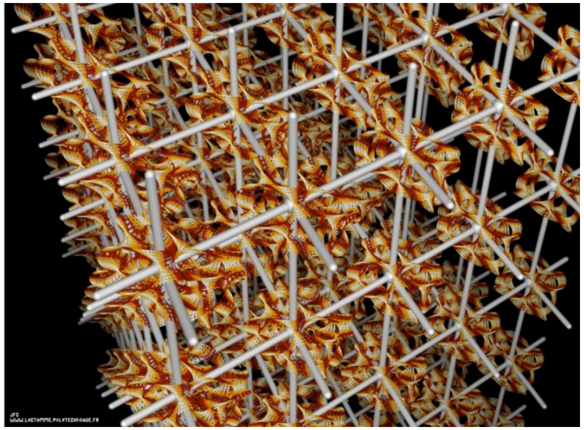
Extra Dimensions

Extra Dimensions? I don't see any...

Extra Dimensions

- Additional Dimensions *compactified* to escape detection





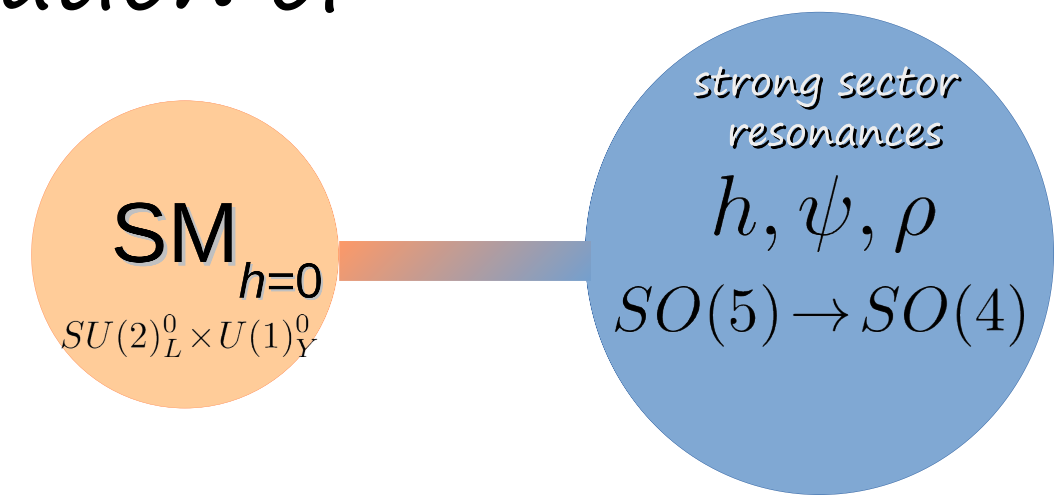
Colonna (http://www.lactamme.polytechnique.fr/)

Compactified D>4 space-time:
Calabi-Yau manifold attached to every point of 4D space-time

or braneworlds...

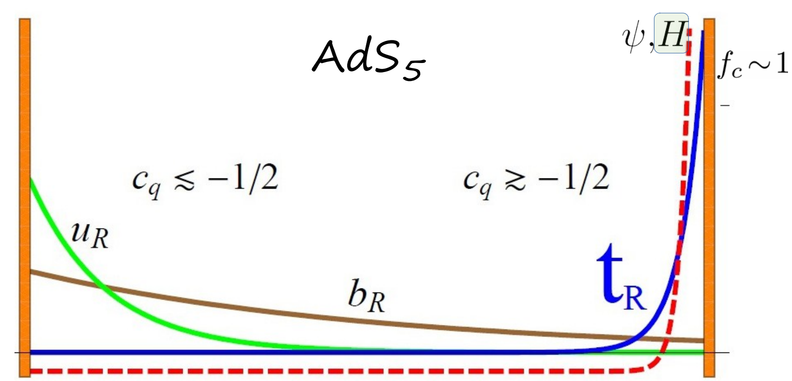
Extra Dimensions

Calculable Implementation of Strong Sector:
(Resonances, ….)



4D CH Model

5D Dual: slice of AdS_5
(weakly coupled)



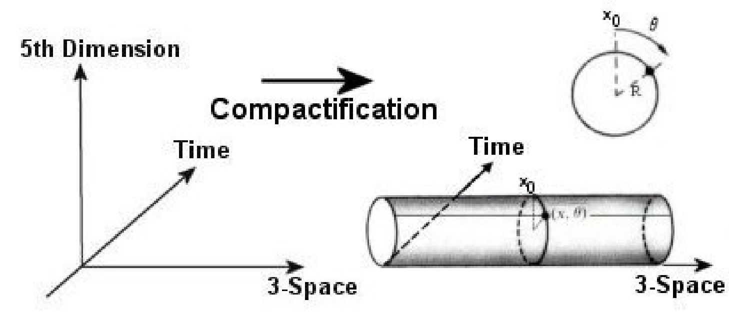
UV brane:
elementary sector

IR brane:
composite sector

AdS/CFT correspondence
'Maldacena conjecture'
Adv. Theor. Math. Phys. 2,231 (1998)
Int. J. Theor. Phys. 38,1113 (1999)
Gubser, Klebanov, Polyakov, PLB 428,105 (1998)
Witten, Adv. Theor. Math. Phys. 2, 253 (1998)

Kaluza-Klein Decomposition

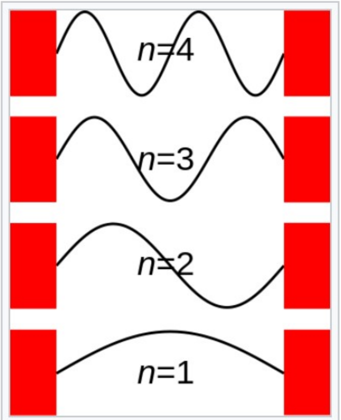
- Additional Dimensions compactified to escape detection



- Particle propagating into comp. extra dimension → infinite tower of (4D) Kaluza-Klein excitations
  [like energy levels of particle in a box]

$$\Phi(x,y) = \sum_n \phi_n(x) f_n(y)$$

4D fields 'profile' along extra dimension

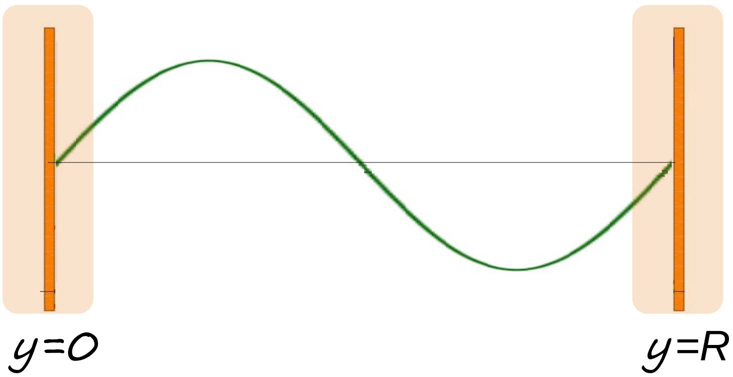


Composite resonances in dual picture

T. Kaluza, Sitzungs. Preuss. Ak. Wiss. Berlin, 966 (1921)
O. Klein, Z. Phys.37, 895 (1926)

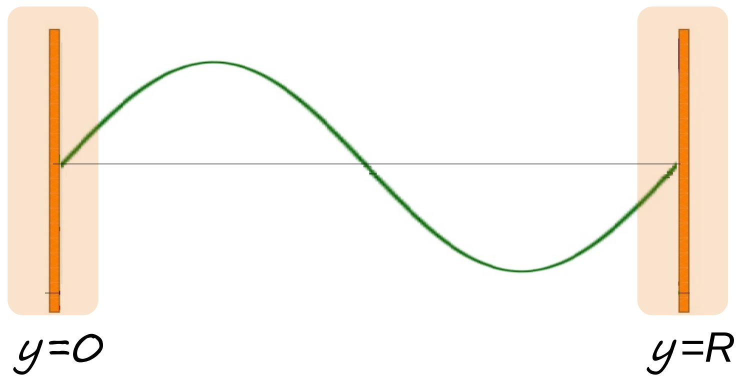
Original Idea: unify gravity and electromagnetism, by merging the photon vector field together with the 4D Minkowski metric into a 5×5 metric

Kaluza-Klein Decomposition



$$\Phi(x,y) = \sum_n \underbrace{\phi_n(x)}_{\text{4D fields}} \underbrace{f_n(y)}_{\text{‘profile’}}$$

Kaluza-Klein Decomposition



$$\Phi(x,y) = \sum_n \phi_n(x) f_n(y)$$

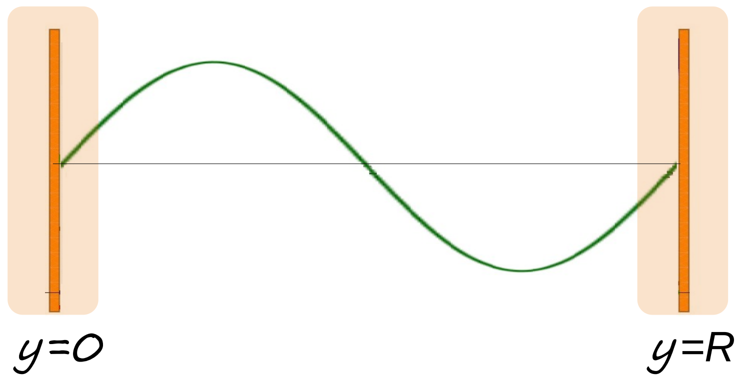
4D fields 'profile'

Simple Example: Scalar field in (flat) 5D

$$S_5 = \frac{1}{2}\int d^4x \int_0^R dy\ \partial_M \Phi(x,y)\partial^M \Phi(x,y) - m_5^2 \Phi^2(x,y)$$

$$M = \overbrace{0,1,2,3,}^{x^\mu}\ \overset{y}{\mathbf{4}}$$

Kaluza-Klein Decomposition



$$\Phi(x,y) = \sum_n \phi_n(x) f_n(y)$$

4D fields 'profile'

$$f_n(y) = c_n \cos(a_n y) + d_n \sin(a_n y)$$

Simple Example: Scalar field in 5D

$$S_5 = \frac{1}{2}\int d^4x \int_0^R dy\ \partial_M \Phi(x,y)\partial^M \Phi(x,y) - m_5^2 \Phi^2(x,y)$$

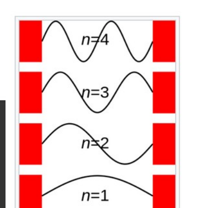
variation of S

$\partial_y \to \mathrm{mass}$

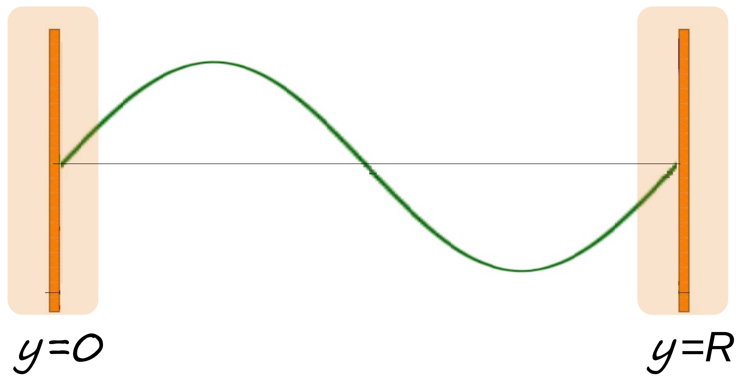
$$S = \frac{1}{2}\int d^4x \sum_n \{\partial_\mu \phi_n(x)\partial^\mu \phi_n(x) - m_n^2 \phi_n^2(x)\}$$

$$\partial_y^2 f_n(y) = -a_n^2 f_n(y)$$
$$m_n^2 = m_5^2 + a_n^2$$

= infinite tower of 4D scalars with different masses



Boundary Conditions and Spectrum



$$f_n(y) = c_n \cos(a_n y) + d_n \sin(a_n y)$$

$$\boxed{f_n(y) = 0 \vee f_n'(y) = 0\,, \; y = 0, R}$$

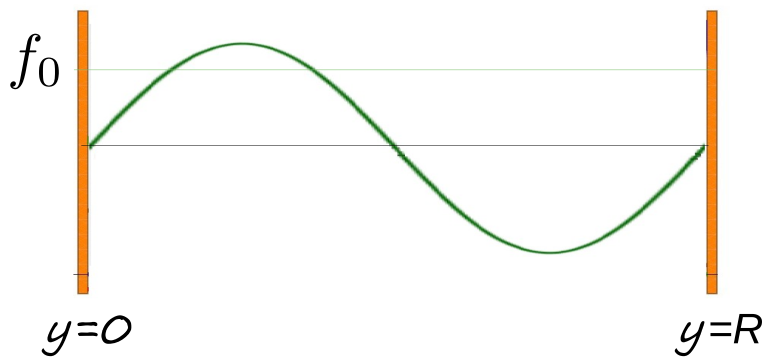
$$(--)\;\; \underline{\textbf{D}\text{irichlet-BCs}}: \; f_n(0) = f_n(R) = 0 \;\Rightarrow\; c_n = 0$$

$$(++)\;\; \underline{\textbf{N}\text{eumann BCs}}: \; f_n'(0) = f_n'(R) = 0 \;\Rightarrow\; d_n = 0$$

$$a_n = \frac{n\pi}{R} \qquad n \in \mathbb{N}_0 \qquad n \in \mathbb{N}_0$$

$$\boxed{m_n^2 = \underbrace{m_5^2}_{0} + n^2\pi^2/R^2}$$

Boundary Conditions and Spectrum



$$f_n(y) = \sqrt{\frac{2}{R}}\cos(a_n y) \qquad f_n(y) = \sqrt{\frac{2}{R}}\sin(a_n y)$$

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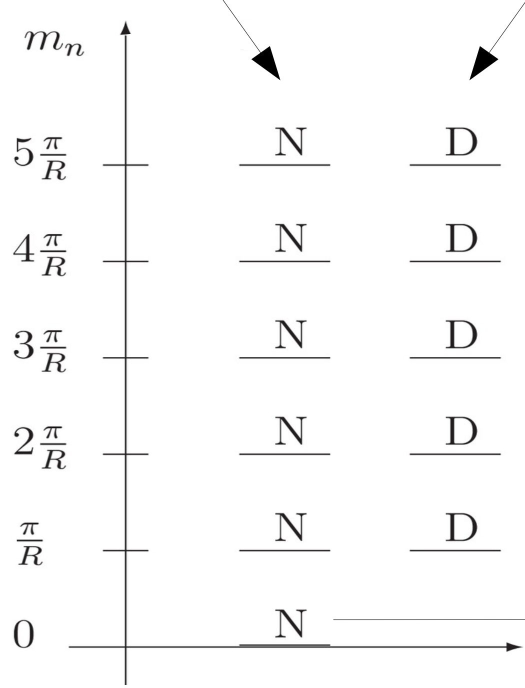


KK excitations

Can be SM particles, similarly for spin ½, 1...

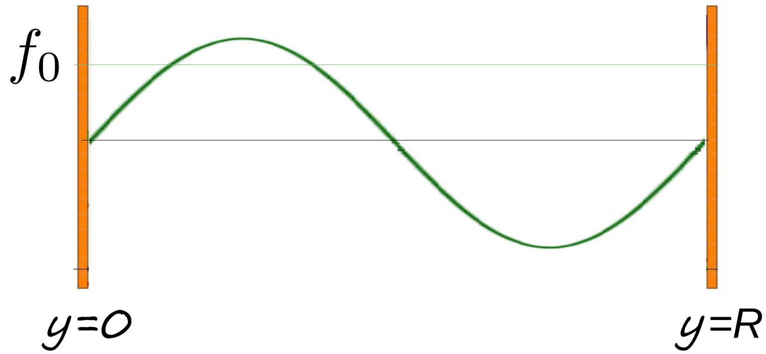
$m_0 = 0$

light "zero mode"

$$f_0(y) = \frac{1}{\sqrt{R}}$$

flat

Boundary Conditions and Spectrum



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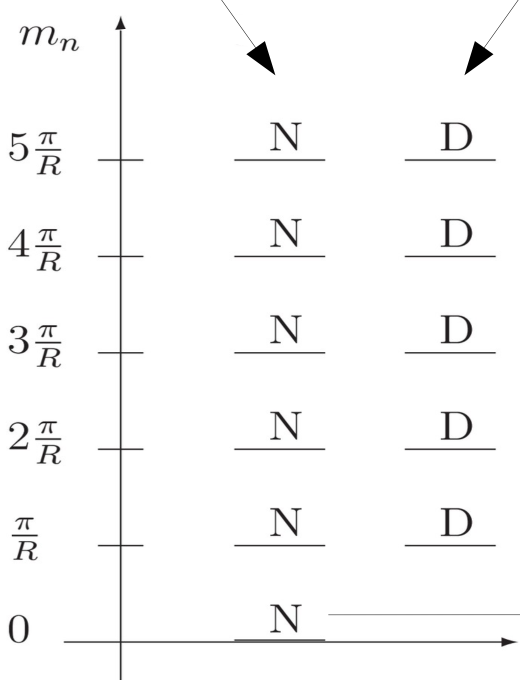
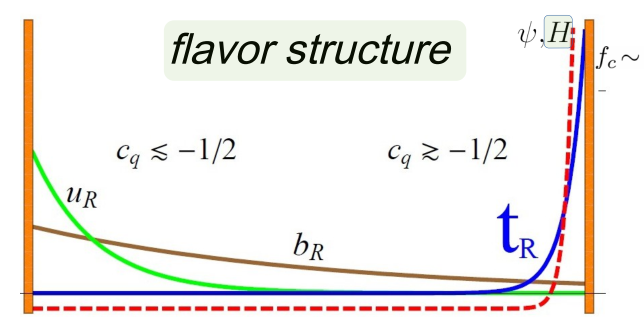


KK excitations

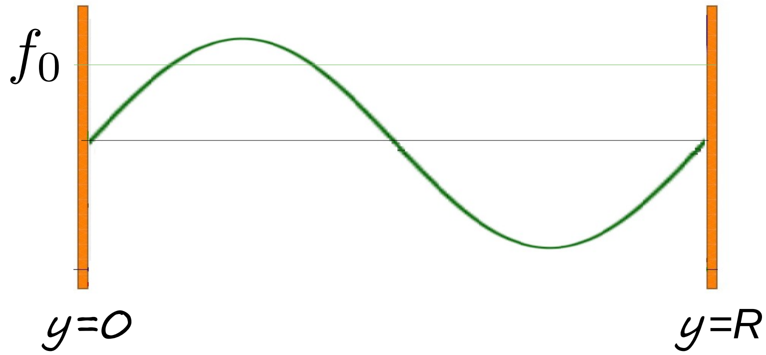
KK modes



Different with warped metric
(later)

light "zero mode" $f_0(y) = \dfrac{1}{\sqrt{R}}$ → flat

Boundary Conditions and Spectrum



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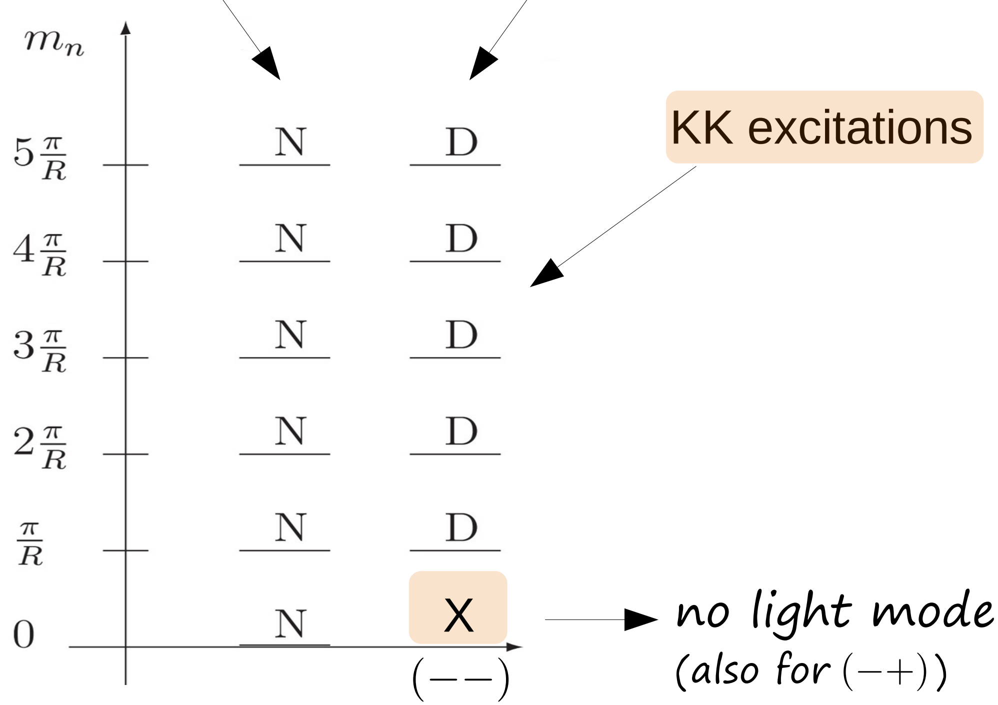
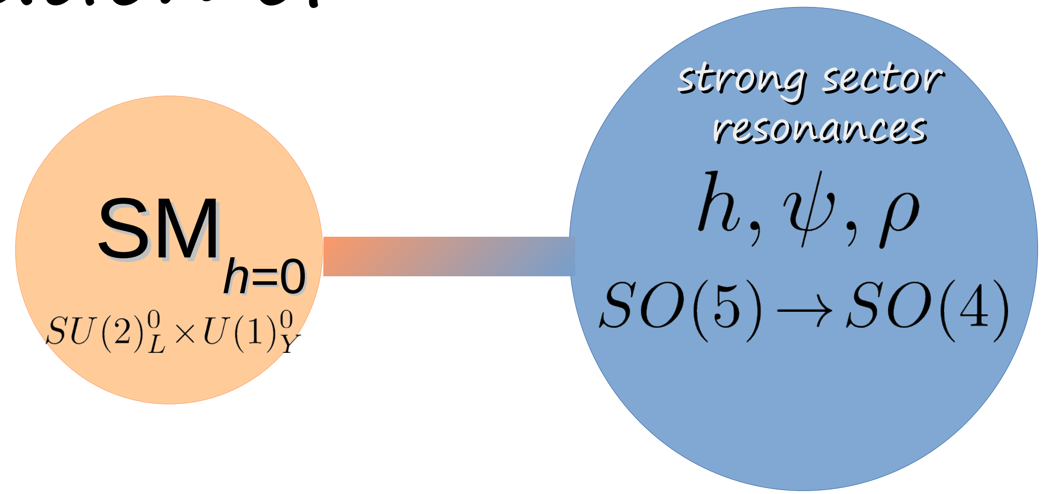


Extra Dimensions

Calculable Implementation of Strong Sector:

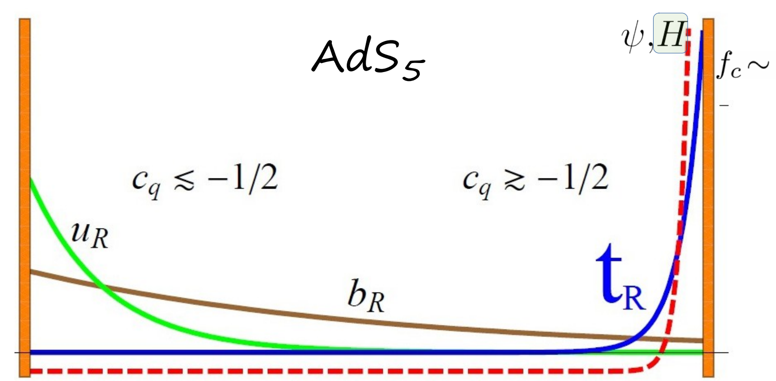
(Resonances, ….)



4D CH Model

5D Dual: slice of AdS_5

(weakly coupled)



UV brane:
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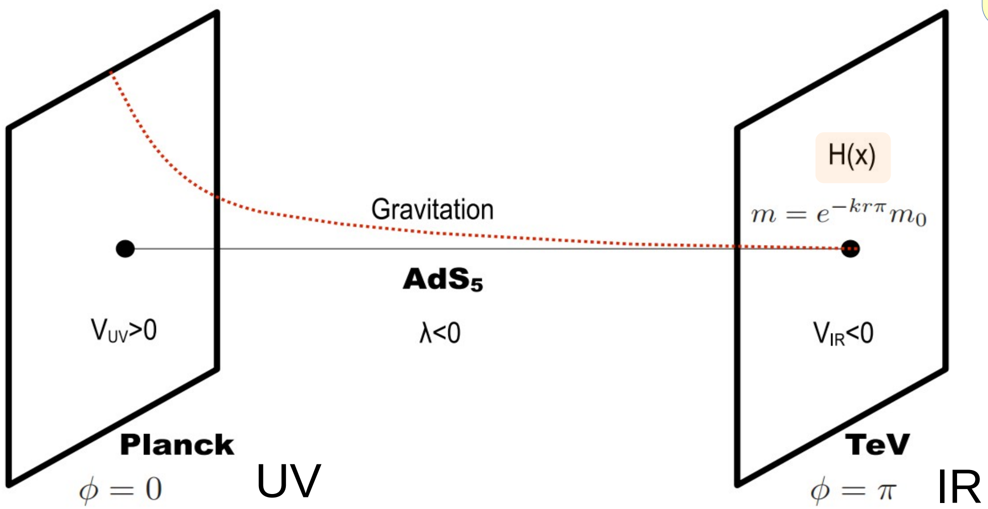
-> Warped Extra Dimensions

Randall, Sundrum, hep-ph/9905221

- Non-trivial metric such that (4D) length scales get contracted differently along fifth dimension → '**warp factor**'

$$\boxed{ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2}$$

General solution to Einstein Equations



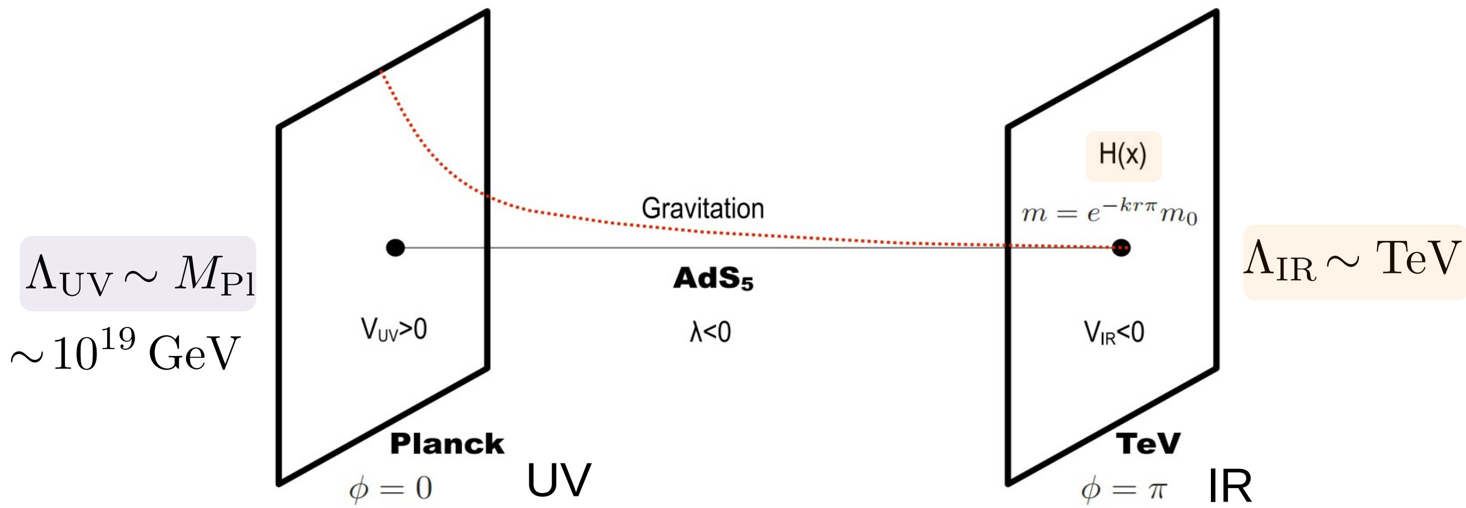
Anti-de Sitter (AdS) space

Warped Extra Dimensions

Randall, Sundrum, hep-ph/9905221

- Non-trivial metric such that (4D) length scales get contracted differently along fifth dimension → ‘**warp factor**’

$$\boxed{ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2}$$



- effective scale at ‘IR’ boundary exponentially suppressed

$$\Lambda_{\rm IR} \sim e^{-kr\pi}\Lambda_{\rm UV} \sim \text{TeV for } kr \approx 12 \sim \mathcal{O}(1)$$

curvature

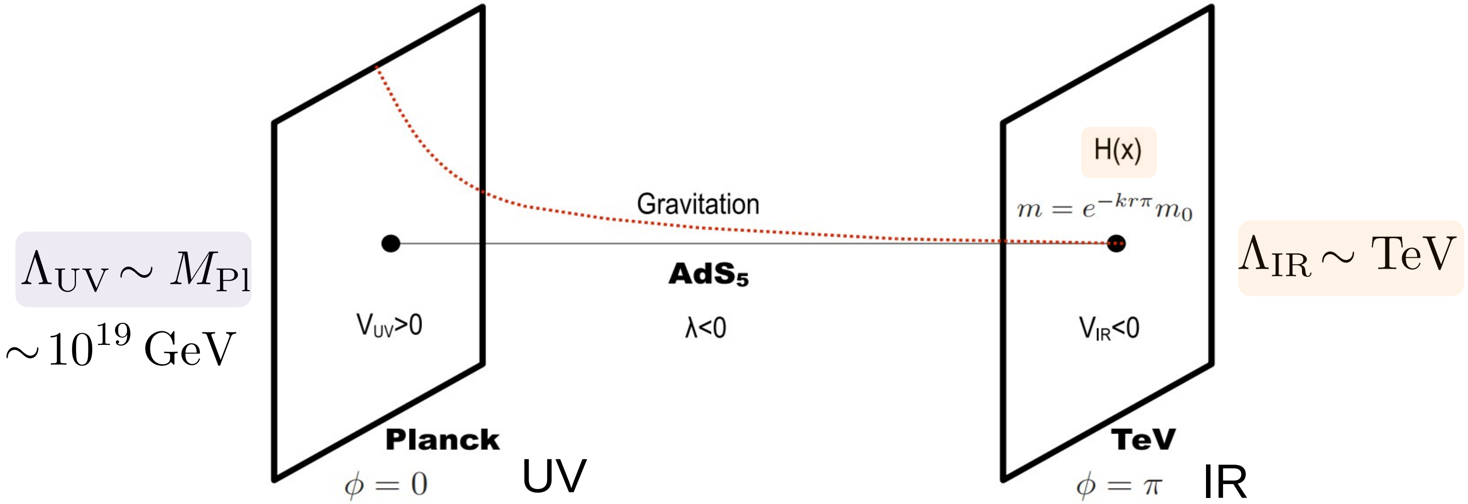
→ quantum corrections cut off

Warped Extra Dimensions

Randall, Sundrum, hep-ph/9905221

- Non-trivial metric such that (4D) length scales get contracted differently along fifth dimension → '**warp factor**'

$$\boxed{ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2}$$

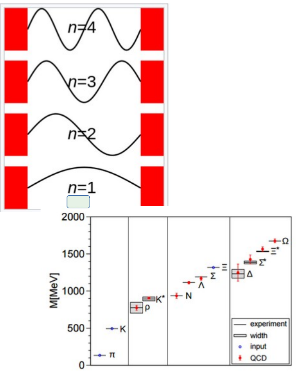


- effective scale at 'IR' boundary exponentially suppressed
- *Higgs* (and composites) localized at that boundary → **HP solved**

Warped Extra Dimensions

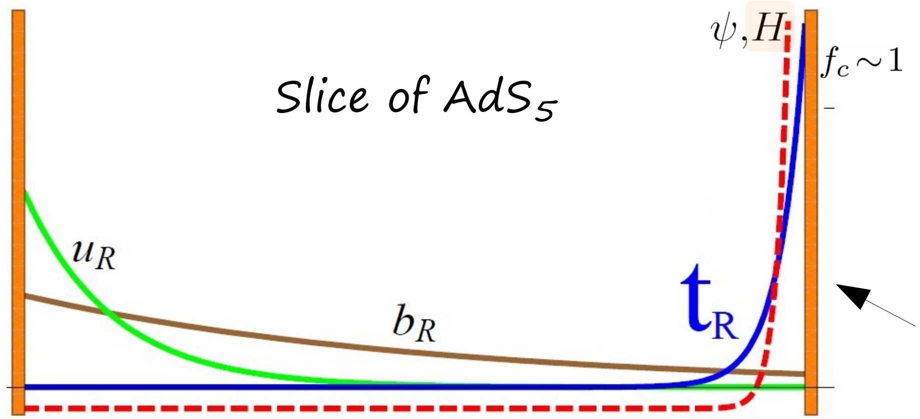
Randall, Sundrum, hep-ph/9905221

- Composite Higgs dual to Higgs in warped 5D, localized towards IR brane
- Warped cutoff $\Lambda_{\rm IR} \sim \mathrm{TeV} \longleftrightarrow$ compositeness scale $\Lambda_{\rm c}$
- Kaluza-Klein excitation $\longleftrightarrow$ composite resonances



Masses fixed from geometry, calculable!

KK modes



Planck brane: elementary

$\Lambda \sim M_{\rm Pl}$

TeV brane: Composites (Higgs,...)

$\Lambda \sim \mathrm{TeV}$

Holographic Higgs

slice of AdS_5 (5D gravity) $\overset{\text{DUAL}}{\Longleftrightarrow}$ 4D elementary (source) sector + strongly-coupled 4D CFT (spontaneously broken in IR)

Arkani-Hamed, Porrati, Randall, hep-th/0012148
Rattazzi, Zaffaroni, hep-th/0012248
Contino, Pomarol, hep-th/0406257 …

- **Zero modes** $(m_0 = 0)$

UV brane localized field $\overset{\text{DUAL}}{\Longleftrightarrow}$ $|\phi^{(0)}\rangle \simeq |\varphi^s\rangle + \epsilon|\varphi_{CFT}\rangle \qquad (\epsilon \ll 1)$

IR brane localized field $\overset{\text{DUAL}}{\Longleftrightarrow}$ $|\phi^{(0)}\rangle \simeq \epsilon\,|\varphi^s\rangle + |\varphi_{CFT}\rangle \qquad (\epsilon \ll 1)$

- **Kaluza-Klein modes** $(m_n \neq 0)$

$\phi^{(n)}(x^\mu)$ $\overset{\text{DUAL}}{\Longleftrightarrow}$ CFT bound states! $(|\phi^{(n)}\rangle \simeq \epsilon\,|\varphi^s\rangle + |\varphi_{CFT}\rangle \qquad (\epsilon \ll 1)$

- **Bulk mass,** m_Φ

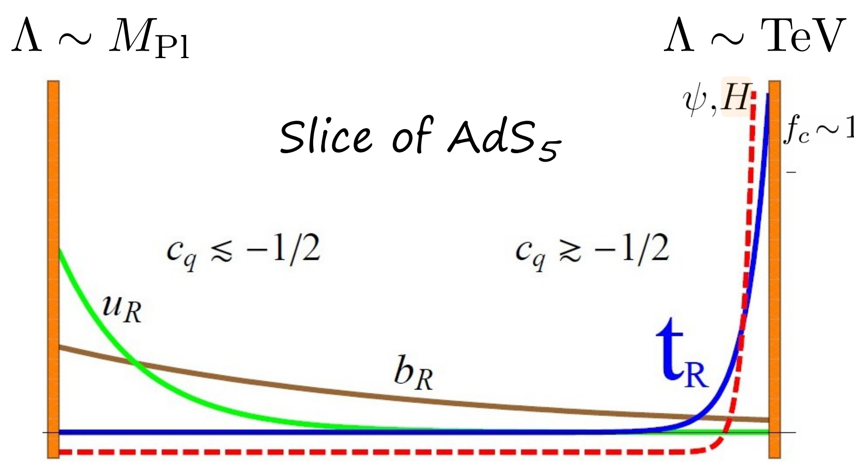
	mass
$\phi^{(0)}$	a
$\psi_\pm^{(0)}$	c
$A_\mu^{(0)}$	0
$h_{\mu\nu}^{(0)}$	0

DUAL $\Longleftrightarrow$

	dim $\mathcal{O}$
$\phi^{(0)}$	$2+\sqrt{4+a}$
$\psi_\pm^{(0)}$	$\frac{3}{2}+\lvert c\pm\frac{1}{2}\rvert$
$A_\mu^{(0)}$	3
$h_{\mu\nu}^{(0)}$	4

- **Symmetries**

Bulk gauge symmetry G, broken to H on UV brane $\overset{\text{DUAL}}{\Longleftrightarrow}$ *CFT global symmetry G, with weakly gauged subgroup H*



UV brane: elementary sector

IR brane: composite sector

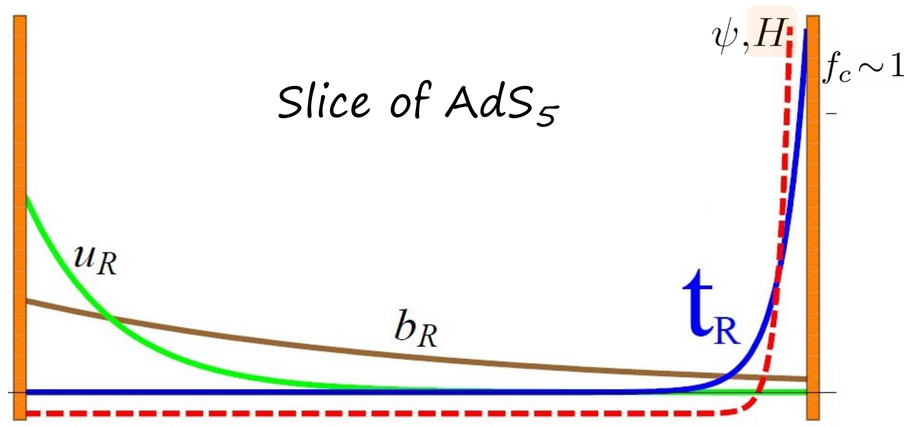
Gherghetta, 1008.2570

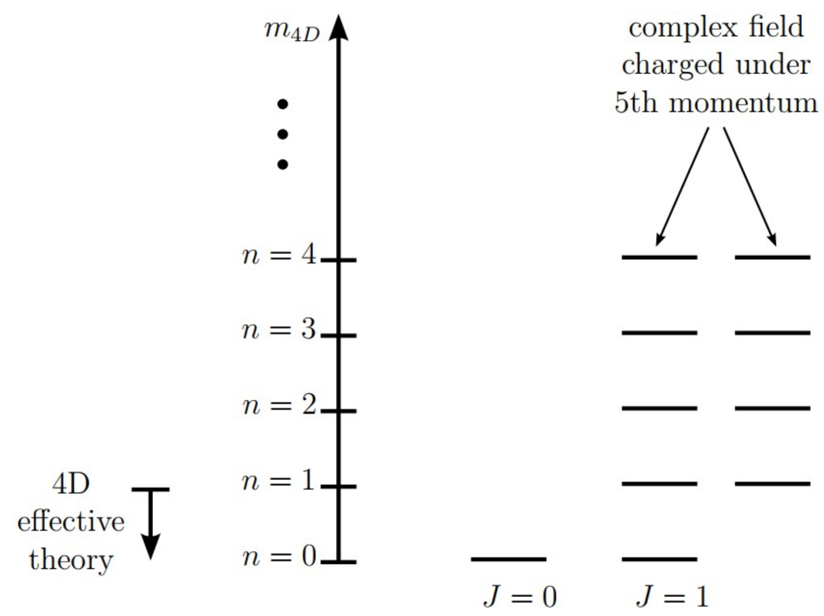
Holographic pNGB Higgs

Contino, Nomura, Pomarol, ph/0306259
Agashe, Contino, Pomarol, ph/0412089

- CH identified as fifths component of gauge field in AdS_5 space → pNGB

→ Gauge-Higgs Unification





Planck brane:
elementary
$\Lambda \sim M_{\rm Pl}$

TeV brane:
Composites (Higgs,...)
$\Lambda \sim \text{TeV}$

Gauge-Higgs Unification

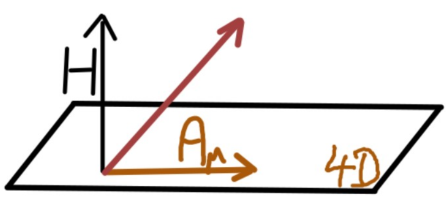
Manton, Hosotani, Fairlie,
Hatanaka, Inami, Lim...

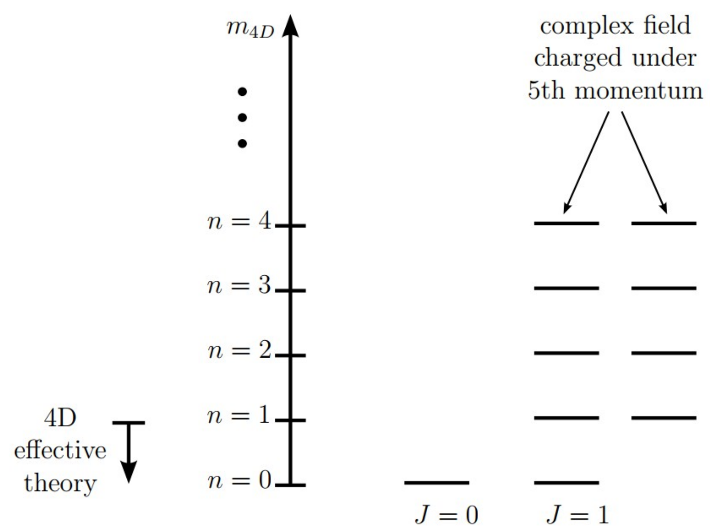
- CH identified as fifths component of gauge field in AdS_5 space → pNGB

5D vector field $A_M^A = (A_\mu^A, \boxed{A_5^A})$

4D vector

4D scalar
→ Higgs





Massless pNGB: 4D shift sym. ↔ 5D gauge sym.

SO(5) Gauge-Higgs Unification

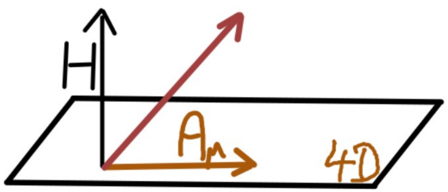
Manton, Hosotani, Fairlie,
Hatanaka, Inami, Lim...

SO(5)

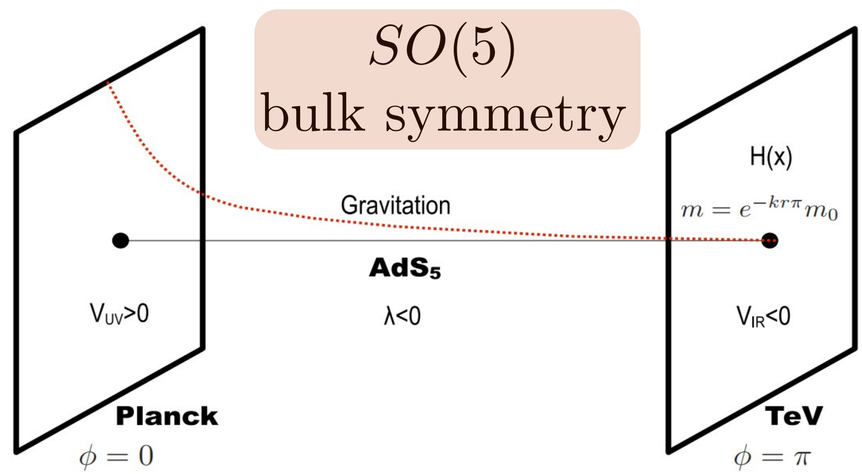
5D vector $A_M^A = (A_\mu^A, A_5^A)$

4D vector

4D scalar
→ Higgs



$$ds^2 = a^2(z)\left(\eta_{\mu\nu}\mathrm{d}x^\mu x^\nu - \mathrm{d}z^2\right) \qquad a(z) = \frac{R}{z}$$



$z \in [R, R'] = [M_{\rm Pl}^{-1}, \mathrm{TeV}^{-1}]$

$$\mathcal{S} \supset \sum_{k=1,2} \int \mathrm{d}^4x \int_R^{R'} \mathrm{d}z\; a^4 \left\{ \bar{\zeta}_k \left[i\not{D} + \left(D_5 + 2\frac{a'}{a} \right) \gamma^5 - aM_k \right] \zeta_k \right\}$$

5D fermion

5D gauge field
$A_M^A = (A_\mu^A, A_5^A)$

SO(5) Gauge-Higgs Unification

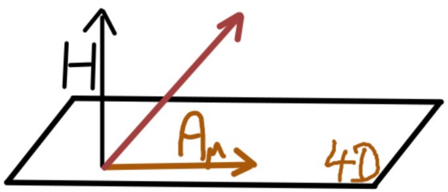
Manton, Hosotani, Fairlie, Hatanaka, Inami, Lim...

SO(5)

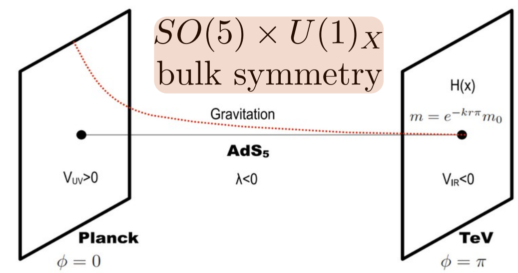
5D vector $A_M^A = (A_\mu^A, A_5^A)$

4D vector

4D scalar → Higgs



$$\mathrm{d}s^2 = a^2(z)\left(\eta_{\mu\nu}\mathrm{d}x^\mu x^\nu - \mathrm{d}z^2\right) \qquad a(z) = \frac{R}{z}$$



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$$SO(5)\times U(1)_X \supset SU(2)_L \times SU(2)_R \times U(1)_Y \times U(1)$$

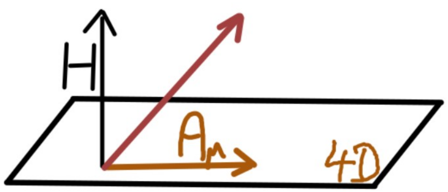
$$D_M = \partial_M - ig_5 T_L^a L_M^a - ig_5 T_R^b R_M^b - ig_Y Y B_M - i\frac{g_Y}{c_\phi s_\phi} Z'_M\left(T_R^3 - s_\phi^2 Y\right)$$

$$-ig_5 T^{\hat{a}} C_M^{\hat{a}}, \quad \text{with } M = \mu, 5 \quad \text{and} \quad g_Y \equiv g_5 g_X / \sqrt{g_5^2 + g_X^2},$$

SO(5) Gauge-Higgs Unification

Manton, Hosotani, Fairlie,
Hatanaka, Inami, Lim...

5D vector $A_M^A = (A_\mu^A, A_5^A)$



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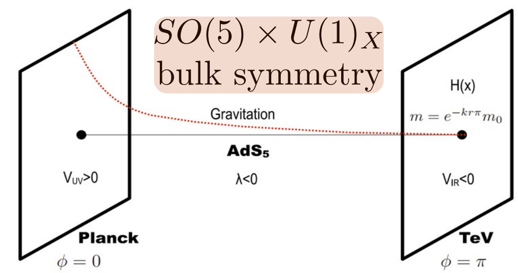

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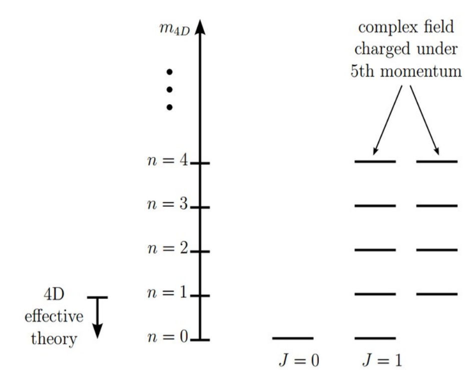
$$-ig_5 T^{\hat{a}} C_M^{\hat{a}}$$



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$$\underrightarrow{E \ll \mathrm{TeV}}: G_{\mathrm{EW}} = SU(2)_L \times U(1)_Y$$

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Manton, Hosotani, Fairlie,
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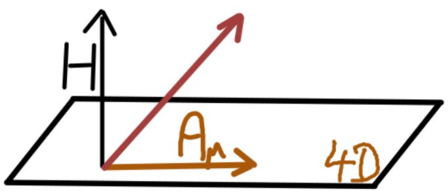

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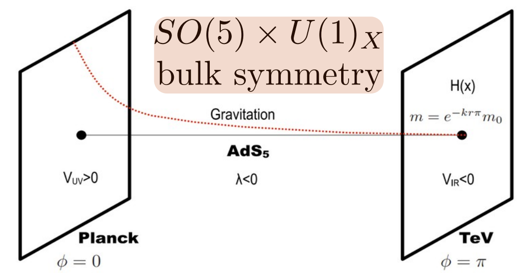

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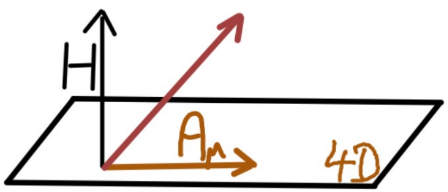
$L_\mu^a(+,+)$
$R_\mu^b(-,+)$
$B_\mu(+,+)$
$Z'_\mu(-,+)$
$C_\mu^{\hat{a}}(-,-)$

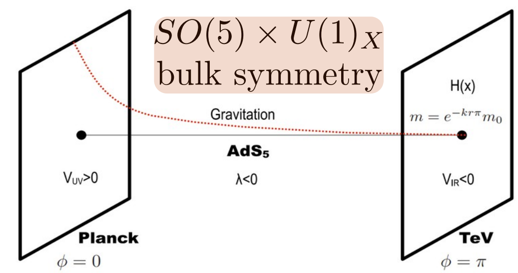
SO(5) Gauge-Higgs Unification

Manton, Hosotani, Fairlie, Hatanaka, Inami, Lim...

5D vector $A_M^A = (A_\mu^A, A_5^A)$



$$ds^2 = a^2(z)\left(\eta_{\mu\nu} dx^\mu x^\nu - dz^2\right) \qquad a(z) = \frac{R}{z}$$



$$\mathcal{S} \supset \sum_{k=1,2} \int d^4x \int_R^{R'} dz\, a^4 \left\{ \bar{\zeta}_k \left[i\not{D} + \left(D_5 + 2\frac{a'}{a} \right) \gamma^5 - a M_k \right] \zeta_k \right\}$$

$$D_M = \partial_M - i g_5 T_L^a L_M^a - i g_5 T_R^b R_M^b - i g_Y Y B_M - i \frac{g_Y}{c_\phi s_\phi} Z'_M (T_R^3 - s_\phi^2 Y)$$
$$- i g_5 T^{\hat{a}} C_M^{\hat{a}}$$

$$SO(5) \times U(1)_X \supset SU(2)_L \times SU(2)_R \times U(1)_Y \times U(1)$$

$$\downarrow$$

$$E \ll \text{TeV}: \; G_{\text{EW}} = SU(2)_L \times U(1)_Y$$

$\Rightarrow$

$L_\mu^a(+,+)$
$\cancel{R}_\mu^b(-,+)$
$B_\mu(+,+)$
$\cancel{Z'}_\mu(-,+)$
$\cancel{C}_\mu^{\hat{a}}(-,-)$

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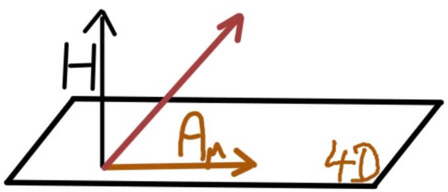

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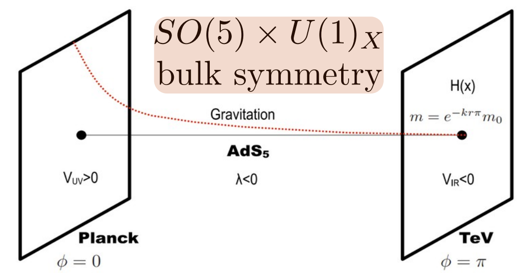

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$$-ig_5 T^{\hat{a}} \boxed{C_M^{\hat{a}}} \leftarrow SO(5)/SO(4)$$

$$SO(5)\times U(1)_X \supset SU(2)_L \times SU(2)_R \times U(1)_Y \times U(1)$$

$$\downarrow$$

$$E \ll \text{TeV}: G_{\text{EW}} = SU(2)_L \times U(1)_Y \quad \Rightarrow$$

$L_\mu^a(+,+)$	$L_5^a(-,-)$
$\cancel{R}_\mu^b(-,+)$	$R_5^b(+,-)$
$B_\mu(+,+)$	$B_5(-,-)$
$\cancel{Z}'_\mu(-,+)$	$Z'_5(+,-)$
$\cancel{C}_\mu^{\hat{a}}(-,-)$	$\boxed{C_5^{\hat{a}}(+,+)}$

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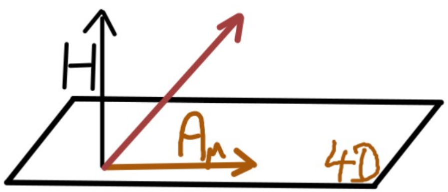

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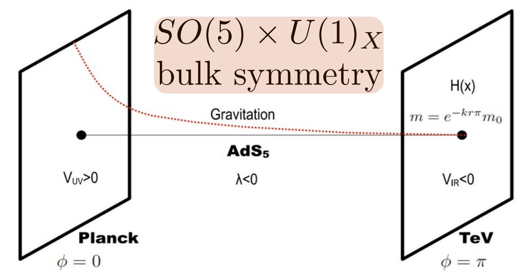

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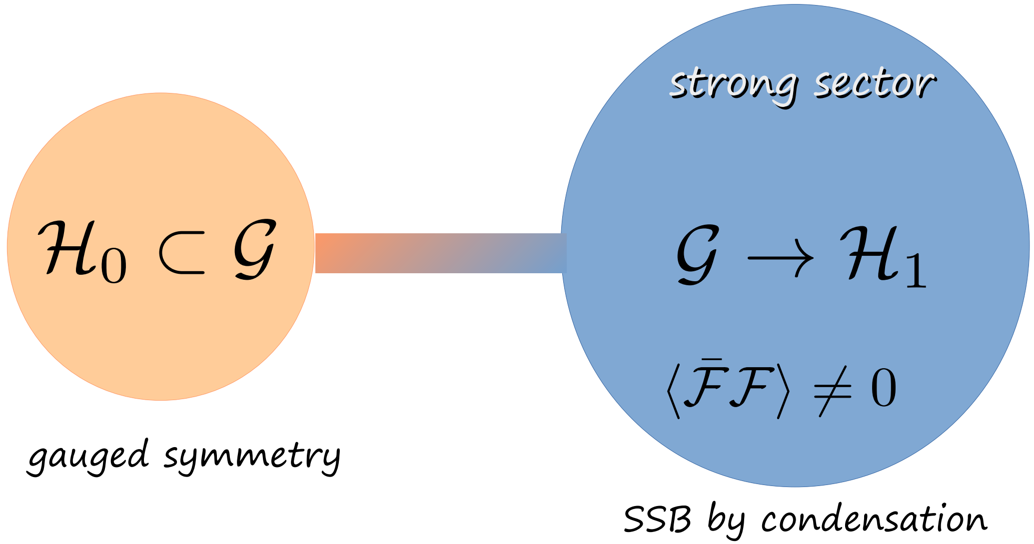
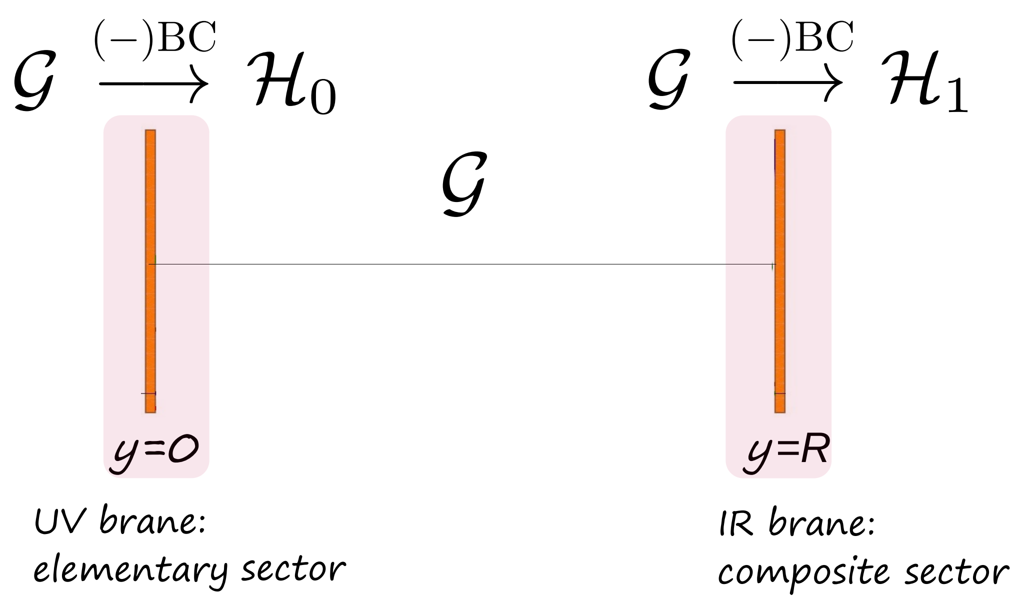
$L_\mu^a(+,+)$
$B_\mu(+,+)$
$C_5^{\hat{a}}(+,+)$ Higgs

Symmetry Breaking by Boundary Conditions





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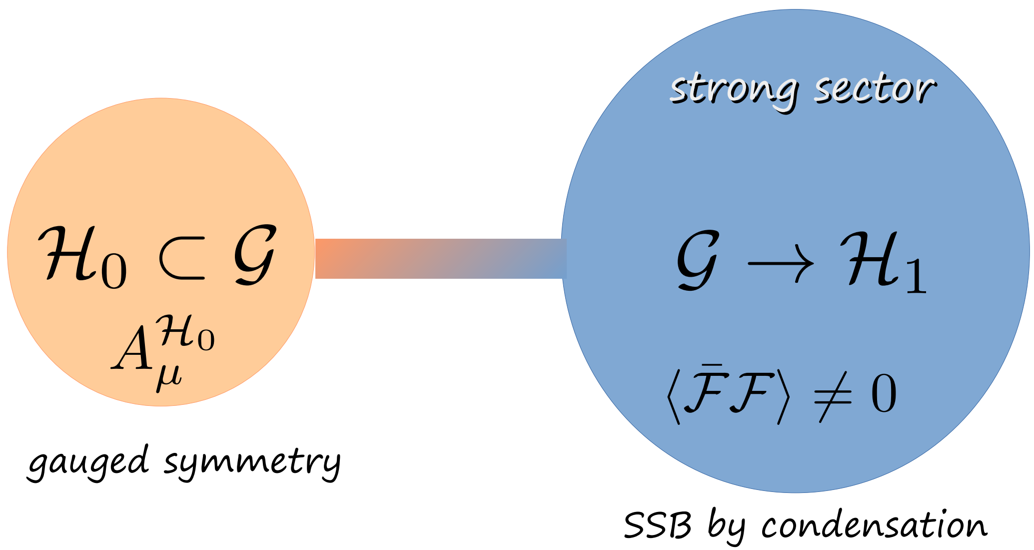
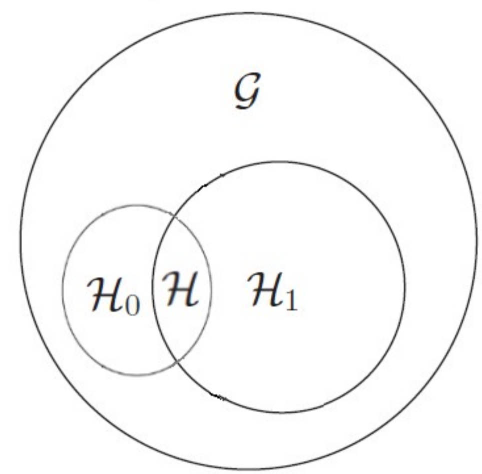
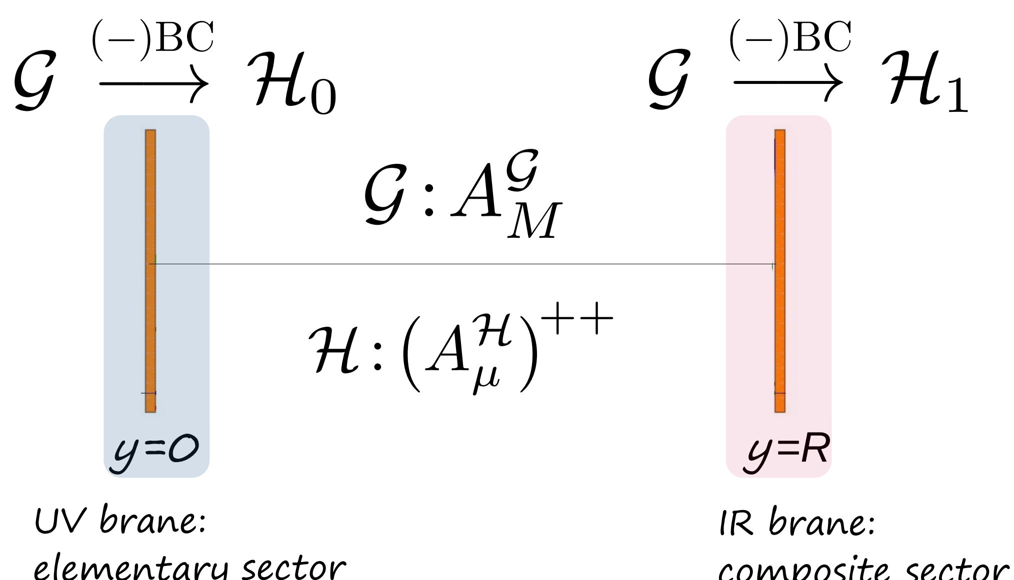






$n = \dim(\mathcal{G}) - \dim(\mathcal{H}_1)$ goldstone bosons

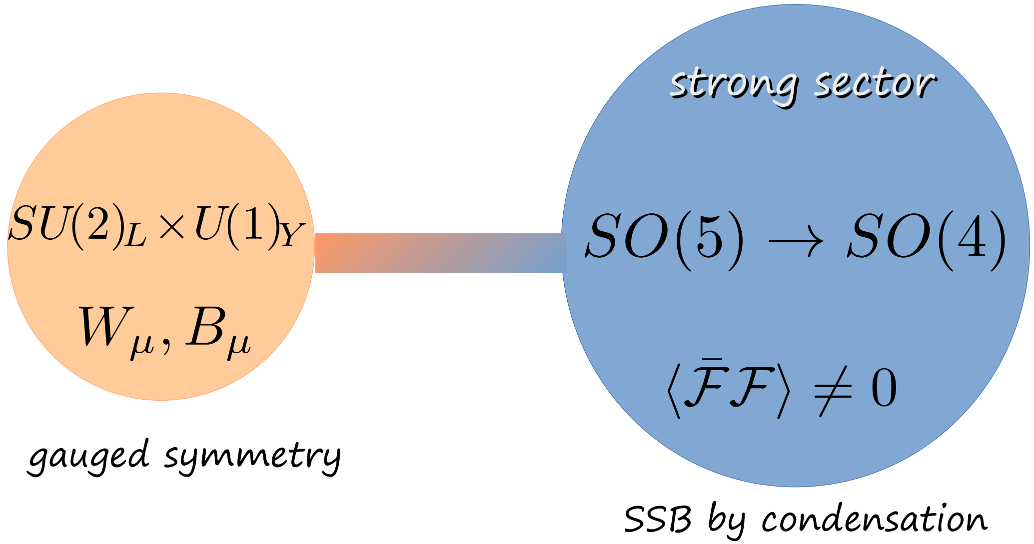
$n_0 = \dim(\mathcal{H}_0) - \dim(\mathcal{H})$ absorbed by gauging

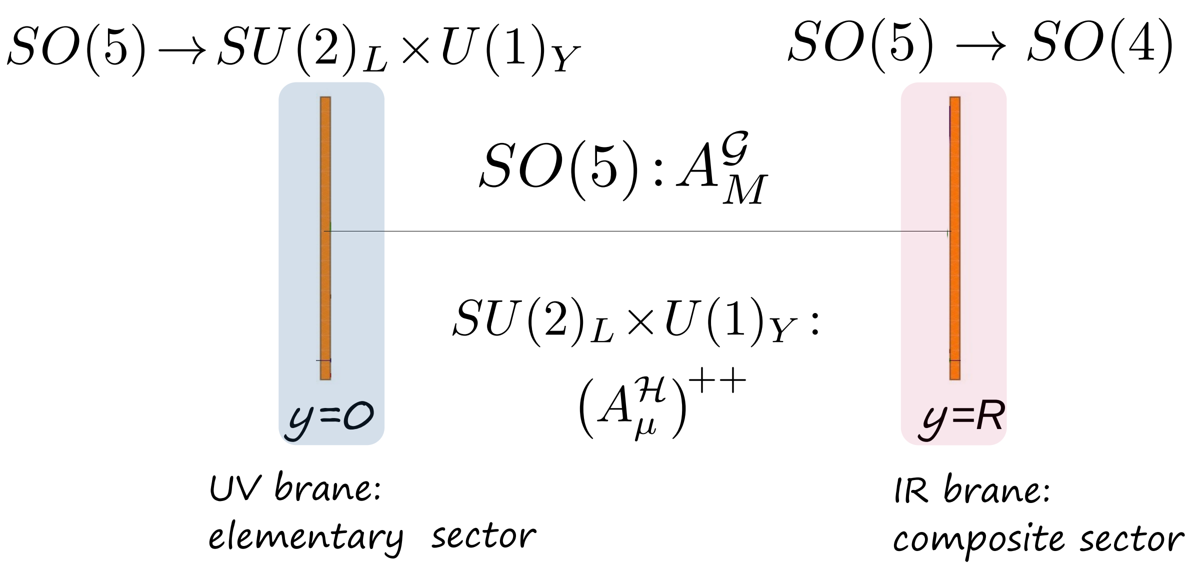
where $\mathcal{H} = \mathcal{H}_0 \cap \mathcal{H}_1$ unbroken gauge group

$\Rightarrow (n - n_0)$ pNGBs

$C_5^{\hat{a}}(+,+)\,, \quad \hat{a} = 1, .., 4$

Symmetry Breaking by Boundary Conditions





$$
\begin{array}{ll}
L_\mu^a(+,+) & L_5^a(-,-) \\
\cancel{R_\mu^b}(-,+) & R_5^b(+,-) \\
B_\mu(+,+) & B_5(-,-) \\
\cancel{Z'_\mu}(-,+) & Z'_5(+,-) \\
\cancel{C_\mu^{\hat{a}}}(-,-) & \boxed{C_5^{\hat{a}}(+,+)}
\end{array}
$$

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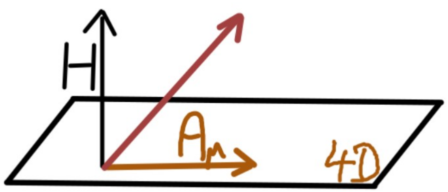

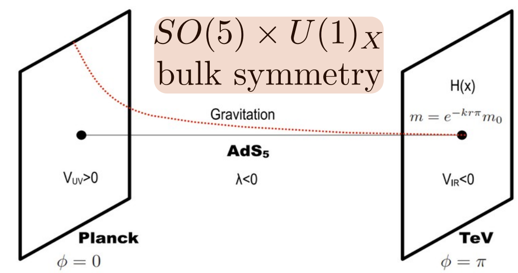

$$\mathcal{S} \supset \sum_{k=1,2} \int \mathrm{d}^4x \int_R^{R'} \mathrm{d}z\; a^4 \left\{ \bar{\zeta}_k \left[i\not{D} + \left(D_5 + 2\frac{a'}{a} \right)\gamma^5 - aM_k \right] \zeta_k \right\}$$

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$$-ig_5 T^{\hat{a}} C_M^{\hat{a}}$$

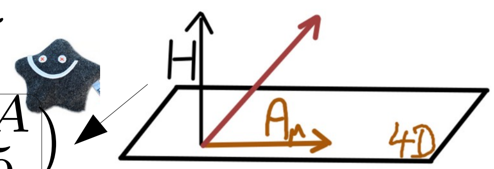
$\longrightarrow$ Yukawa $\mathcal{S} \supset -\sum_{k=1,2} ig_5 \int \mathrm{d}^4x \int_R^{R'} \mathrm{d}z\; a^4 \bar{\zeta}_k(x,z)\gamma^5 T^4 \zeta_k(x,z) C_5^4(x,z)$

One Step Further:

- Embed GUT group in enhanced global symmetry of CH:
  Unification of all forces & EWSB (Higgs)!

Gauge-Higgs Unification

$$SO(5): \ A_M^A = (A_\mu^A, \boxed{A_5^A})$$



$$U(1)_X: \ X_M = (X_\mu, X_5)$$

$$SU(3)_c: \ G_M^A = (G_\mu^A, G_5^A)$$

Gauge-Higgs Grand Unification

$$A_M^A = (A_\mu^A, \boxed{A_5^A}) \quad G_{\mathrm{GUT}}$$

Gauge-Higgs Grand Unification

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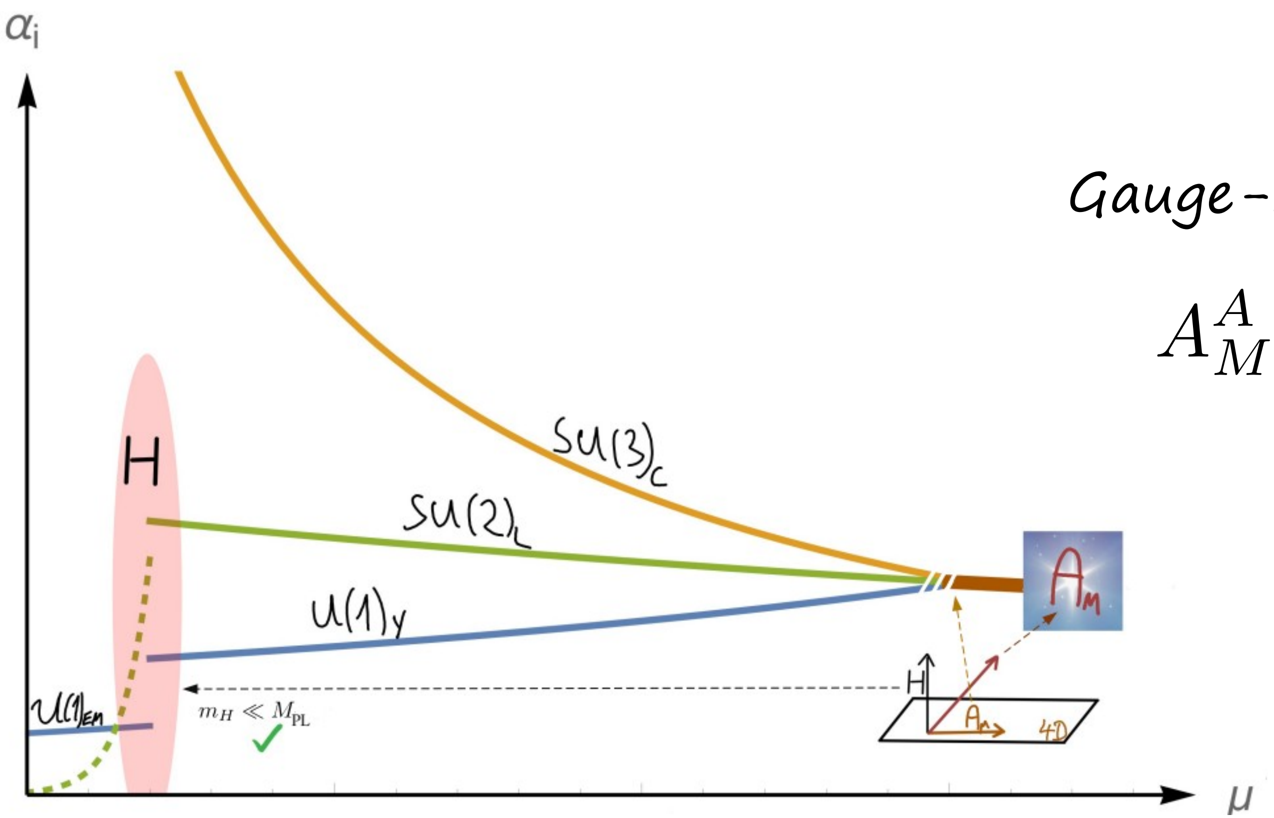

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Gauge-Higgs Grand Unification

- Embed GUT group in enhanced global symmetry of CH:
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- Two considered setups:

$SO(11)$

Hosotani, Yamatsu, 1504.03817
Furui, Hosotani, Yamatsu, 1606.07222
Hosotani, 1606.08108
(see also Agashe, Contino, Sundrum, hep-ph/0502222, Frigerio, Serra, Varagnolo, 1103.2997,...)

$SU(6)$

Burdman, Nomura, hep-ph/0210257
Lim, Maru, 0706.1397
...

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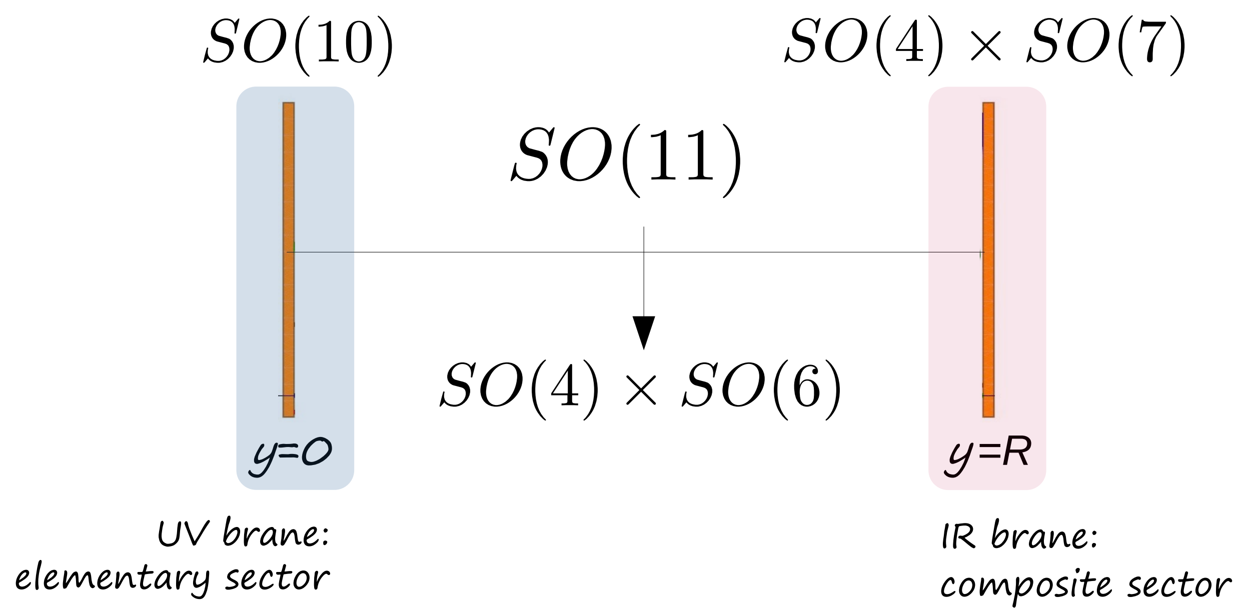

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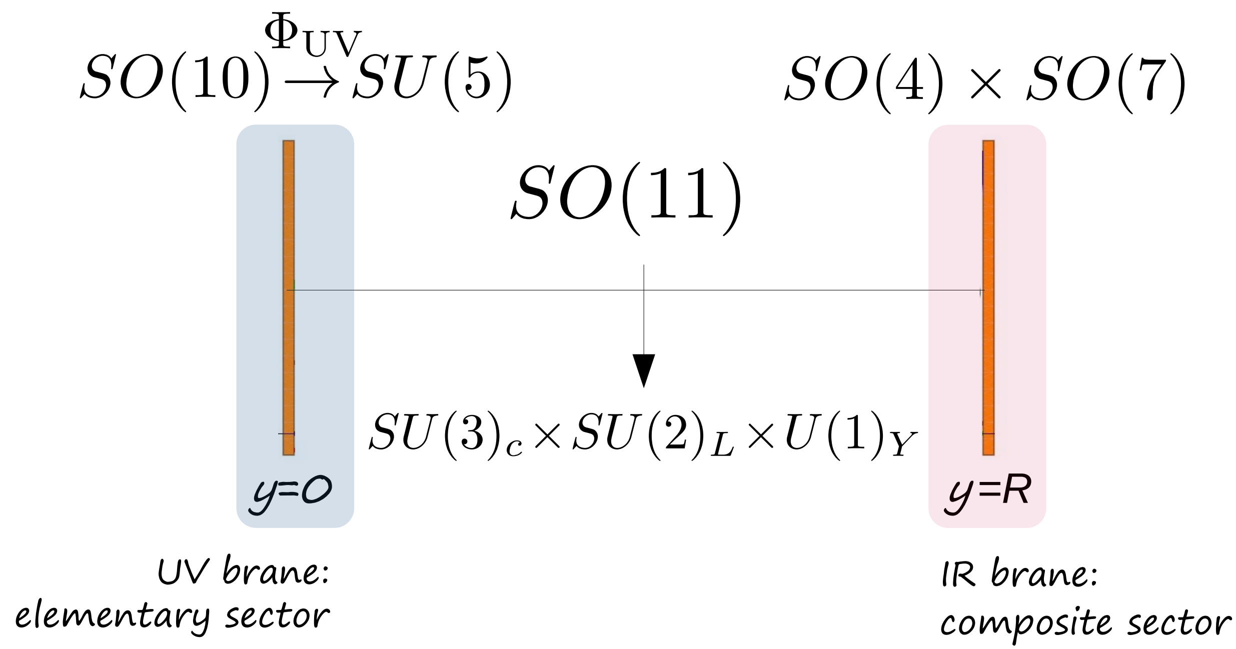

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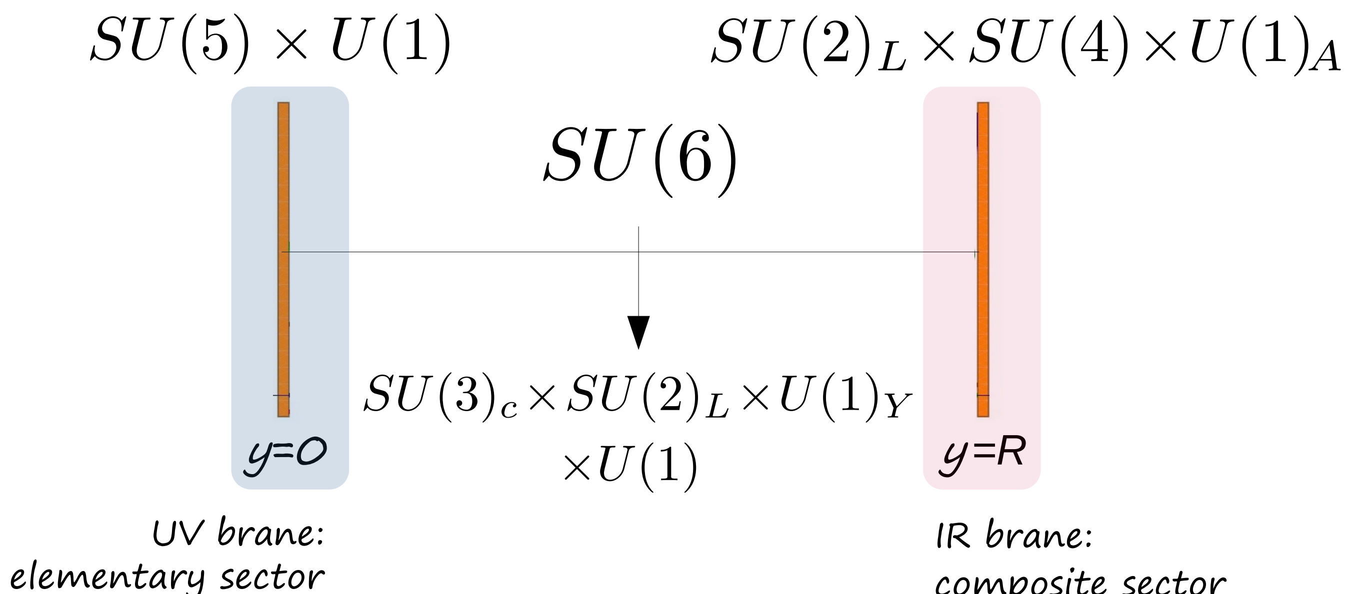

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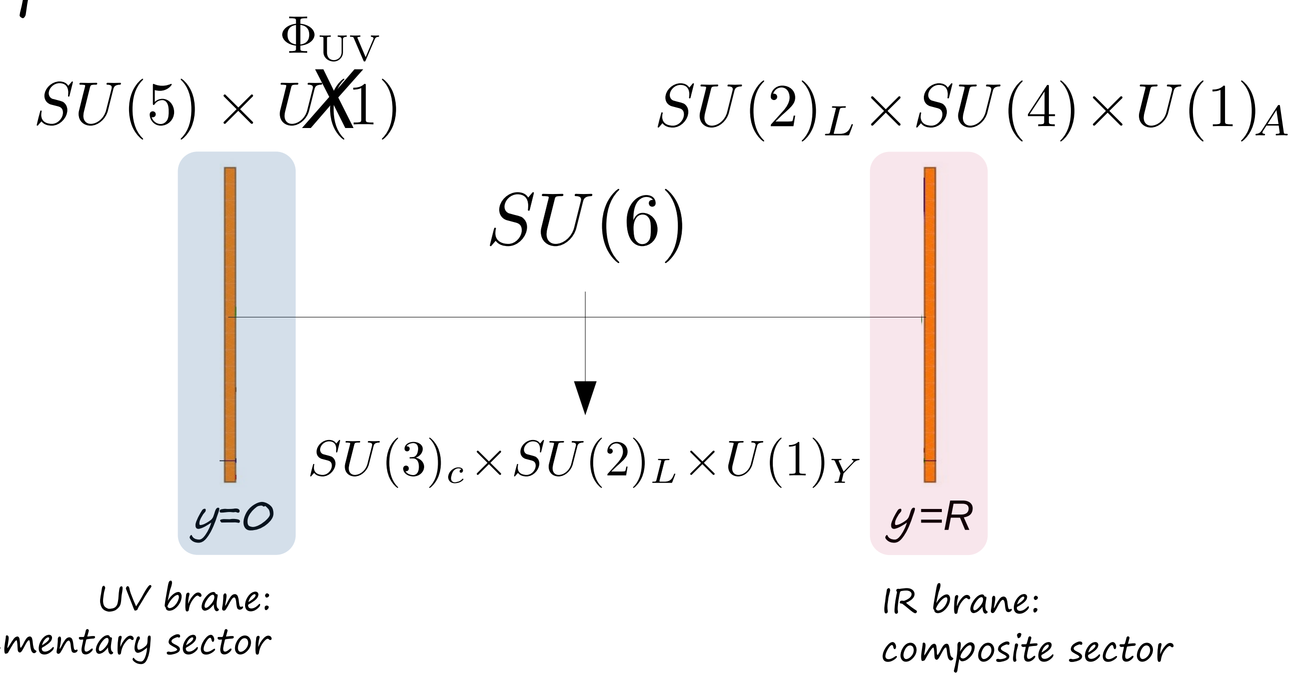


Too Good To be True?

- Embed GUT group in enhanced global symmetry of CH:
  Unification of all forces & EWSB (Higgs)!

Severe phenomenological challenges:

$SO(11)$

$SU(6)$

- (too) light exotic states due to large irreps of bigger symmetry
- Difficult to obtain correct EWSB/m_H
- Degenerate/massless quarks&leptons

...

Too Good To be True?

- Embed GUT group in enhanced global symmetry of CH:
  Unification of all forces & EWSB (Higgs)!

Severe phenomenological challenges:

$SO(11)$ — go to 6D Hosotani, Yamatsu, 1706.03503, 1710.04811

$SU(6)$ — abandon bulk SM & introduce new BSM 5D multiplets + addtl. mirror fermions

Maru, Yatagai, 1903.08359, 1911.03465 ...

Too Good To be True?

- Embed GUT group in enhanced global symmetry of CH:
  Unification of all forces & EWSB (Higgs)!

Minimal Alternative

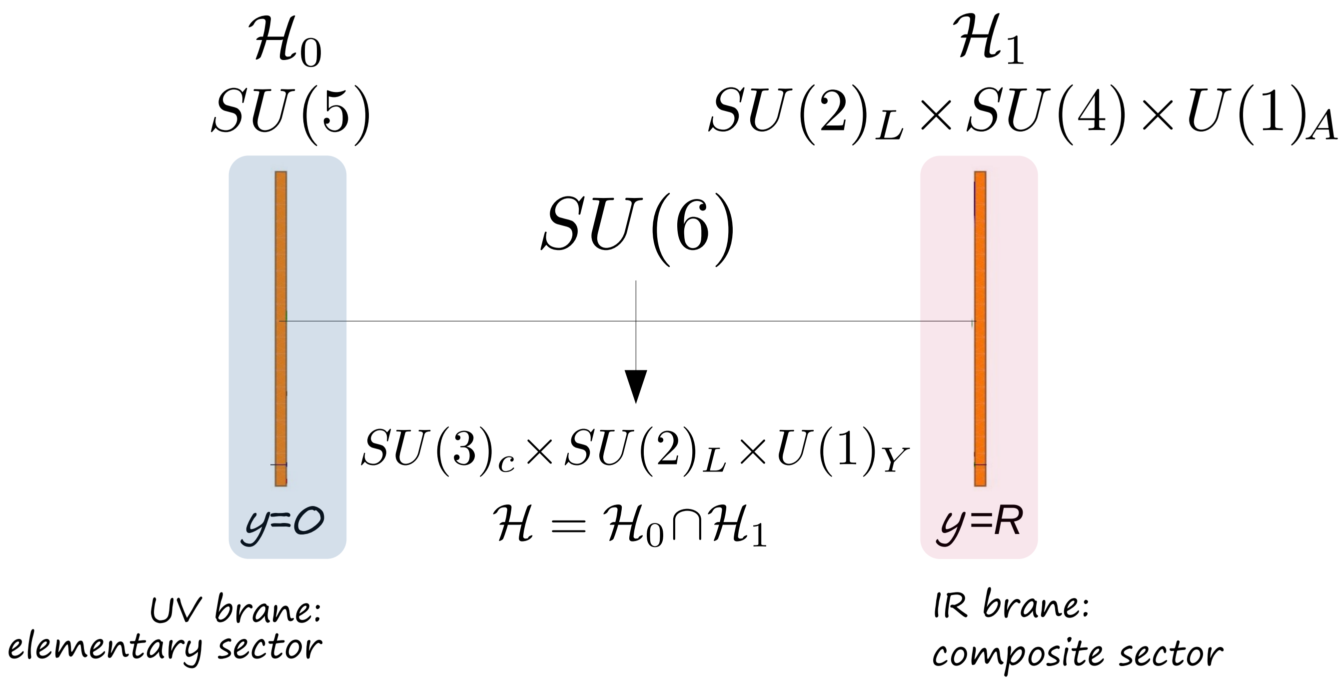
$SO(11)$

$SU(6)$

SU(6) In warped space with different breaking pattern and brane masses

Original SU(6) Breaking

but warped...



- $n = \dim(\mathcal{G}) - \dim(\mathcal{H}_1) = 35 - 19 = 16$ GBs,

  $n_0 = \dim(\mathcal{H}_0) - \dim(\mathcal{H}) = 24 - 12 = 12$ GBs absorbed
- $(n - n_0) =$ 4 GBs remain $\rightarrow$ Higgs

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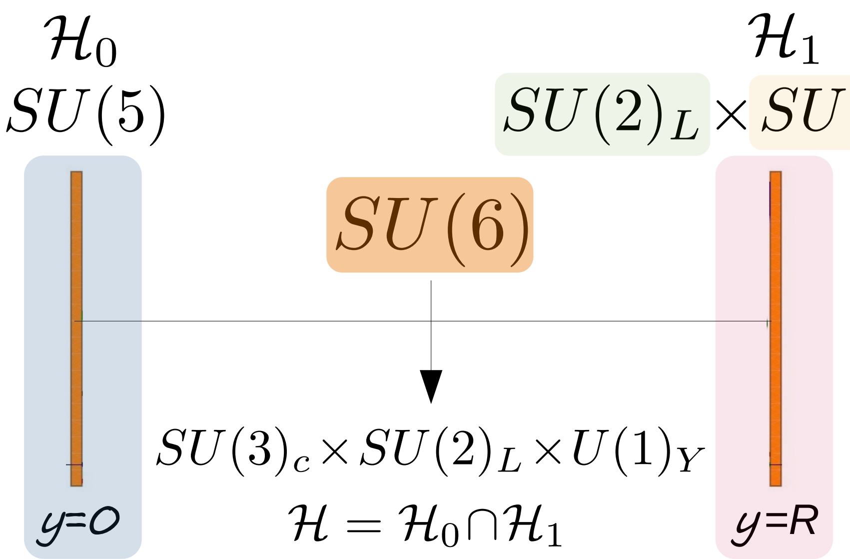

UV brane:
elementary sector

IR brane:
composite sector

$$A_\mu = \left(\begin{array}{cc|ccc|c} (++) & (++) & (+-) & (+-) & (+-) & (--) \\ (++) & (++) & (+-) & (+-) & (+-) & (--) \\ \hline (+-) & (+-) & (++) & (++) & (++) & (-+) \\ (+-) & (+-) & (++) & (++) & (++) & (-+) \\ (+-) & (+-) & (++) & (++) & (++) & (-+) \\ \hline (--) & (--) & (-+) & (-+) & (-+) & (-+) \end{array}\right)$$

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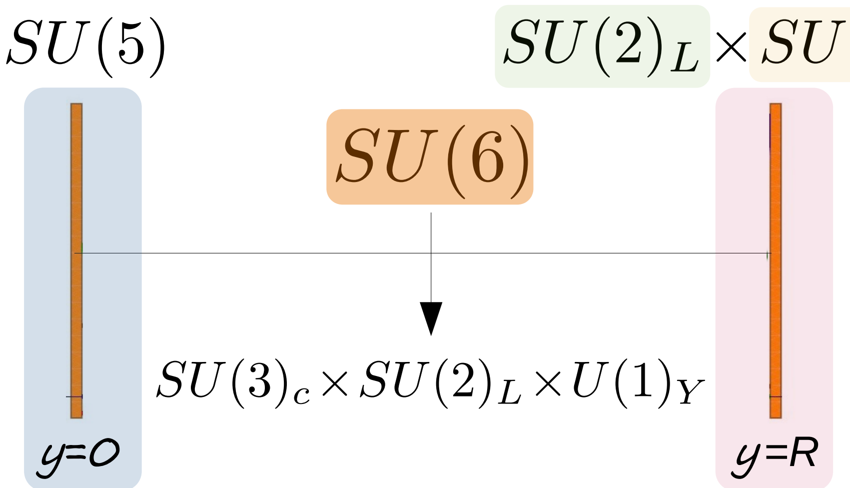

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Fermion irreps (min. attempt):

$$\mathbf{20_L} \to (\mathbf{3},\mathbf{2})^{-,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{-,+}_{-2/3} \oplus \tilde{e}_R(\mathbf{1},\mathbf{1})^{-,-}_{1}$$
$$(\mathbf{3}^*,\mathbf{2})^{-,+}_{-1/6} \oplus u_R(\mathbf{3},\mathbf{1})^{-,-}_{2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{-1}$$

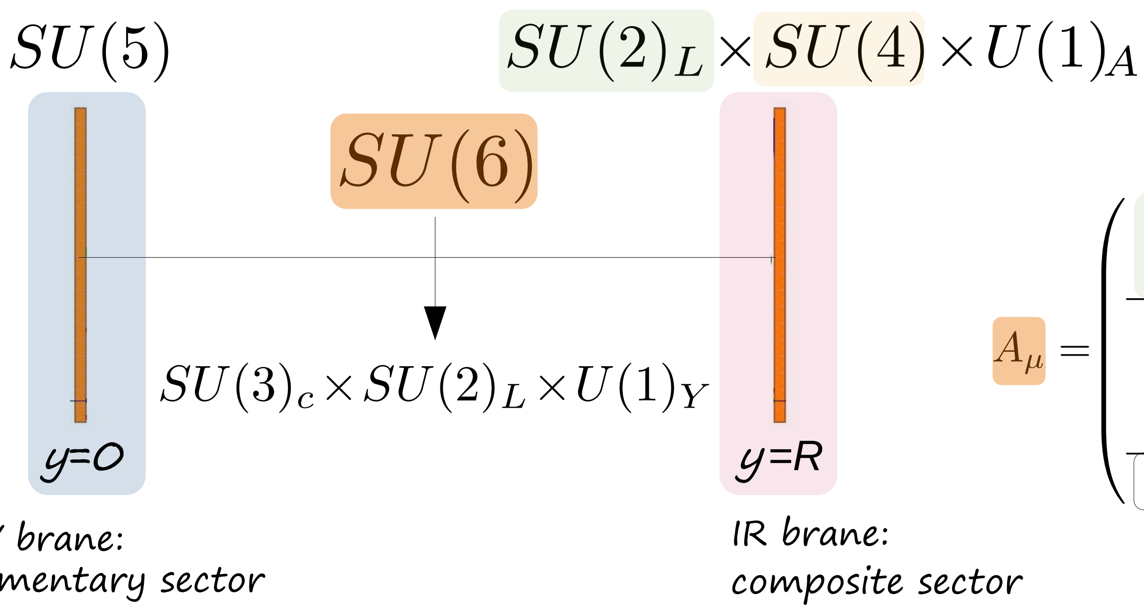
$$\mathbf{15_L} \to q_L(\mathbf{3},\mathbf{2})^{+,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{+,-}_{-2/3} \oplus e^c_R(\mathbf{1},\mathbf{1})^{+,+}_{1}$$
$$\oplus\, d_R(\mathbf{3},\mathbf{1})^{-,-}_{-1/3} \oplus (\mathbf{1},\mathbf{2})^{-,+}_{1/2}$$

$$\mathbf{6_L} \to (\mathbf{3},\mathbf{1})^{-,+}_{-1/3} \oplus l^c_L(\mathbf{1},\mathbf{2})^{-,-}_{1/2} \oplus \nu^c_R(\mathbf{1},\mathbf{1})^{+,+}_{0}$$

$$\mathbf{1_L} \to (\mathbf{1},\mathbf{1})^{+,-}_{0} \qquad m_e(=m_u)=0$$

Original SU(6) Breaking

but warped...



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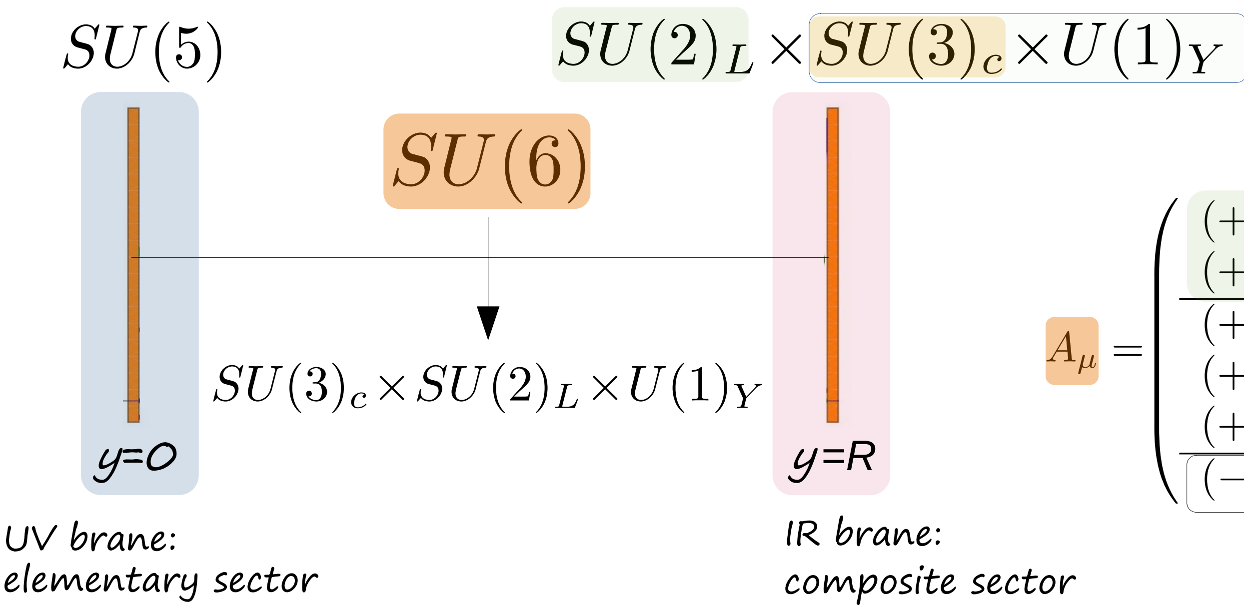
$m_e(=m_u) = 0$

Novel Breaking Pattern

but warped...



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- $(n - n_0) = 11$ GBs remain $\rightarrow$ $\boxed{\text{Higgs} + \text{singlet} + (\mathbf{3},\mathbf{1})_{-1/3}\,\text{LQ}}$

Novel Breaking Pattern

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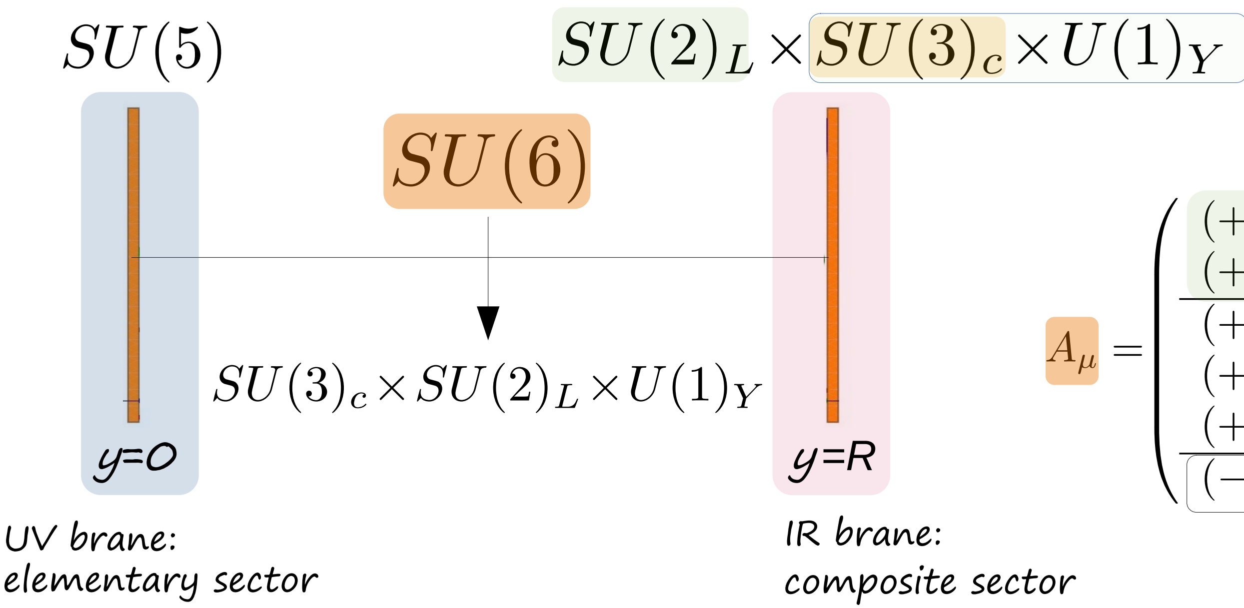

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- Scalars want to be heavy ... :)
- Could make use of them ...

Novel Breaking Pattern

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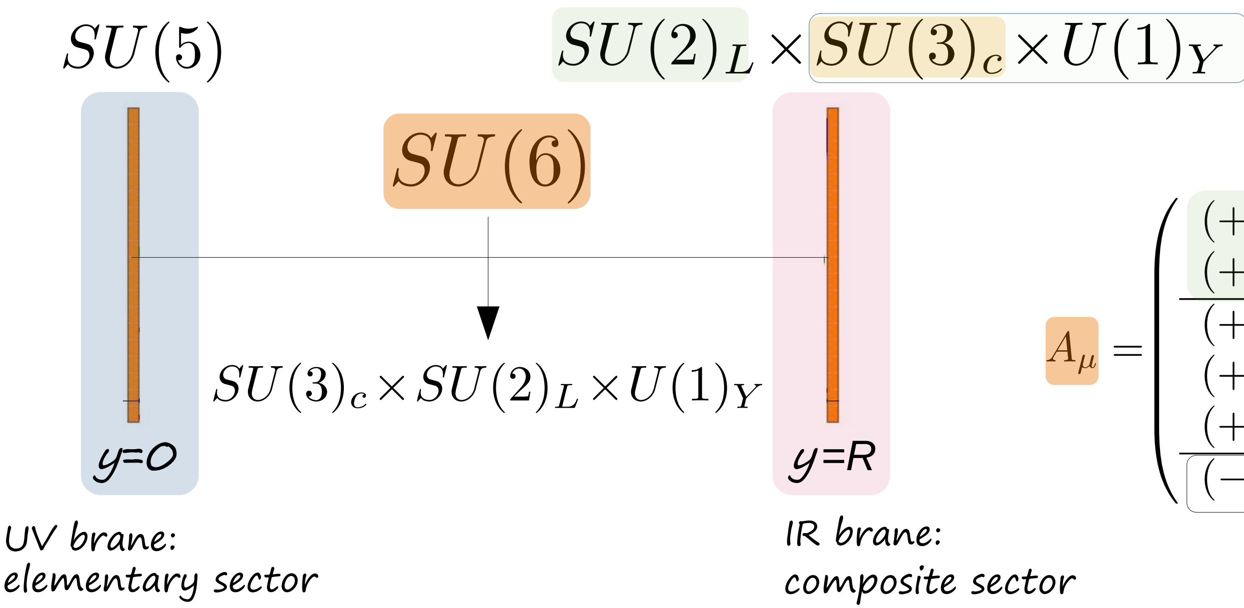

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$A_5 : + \leftrightarrow -$

Fermion irreps:

$$\mathbf{20_L} \to (\mathbf{3},\mathbf{2})^{-,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{-,+}_{-2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{1}$$
$$(\mathbf{3}^*,\mathbf{2})^{-,+}_{-1/6} \oplus u_R(\mathbf{3},\mathbf{1})^{-,-}_{2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{-1}$$

$$\mathbf{15_L} \to q_L(\mathbf{3},\mathbf{2})^{+,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{+,-}_{-2/3} \oplus e^c_R(\mathbf{1},\mathbf{1})^{+,+}_{1}$$
$$\oplus (\mathbf{3},\mathbf{1})^{-,+}_{-1/3} \oplus (\mathbf{1},\mathbf{2})^{-,+}_{1/2}$$

$$\mathbf{6_L} \to d_R(\mathbf{3},\mathbf{1})^{-,-}_{-1/3} \oplus l^c_L(\mathbf{1},\mathbf{2})^{-,-}_{1/2} \oplus \nu^c_R(\mathbf{1},\mathbf{1})^{+,+}_{0}$$

$$\mathbf{1_L} \to (\mathbf{1},\mathbf{1})^{+,-}_{0}$$

Novel Breaking Pattern

Fermion irreps:

$$\mathbf{20_L} \to (\mathbf{3},\mathbf{2})^{-,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{-,+}_{-2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{1} \oplus (\mathbf{3}^*,\mathbf{2})^{-,+}_{-1/6} \oplus u_R(\mathbf{3},\mathbf{1})^{-,-}_{2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{-1}$$

$$\mathbf{15_L} \to q_L(\mathbf{3},\mathbf{2})^{+,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{+,-}_{-2/3} \oplus e^c_R(\mathbf{1},\mathbf{1})^{+,+}_{1} \oplus (\mathbf{3},\mathbf{1})^{-,+}_{-1/3} \oplus (\mathbf{1},\mathbf{2})^{-,+}_{1/2}$$

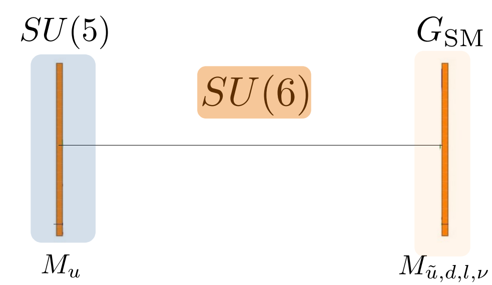
$$\mathbf{6_L} \to d_R(\mathbf{3},\mathbf{1})^{-,-}_{-1/3} \oplus l^c_L(\mathbf{1},\mathbf{2})^{-,-}_{1/2} \oplus \nu^c_R(\mathbf{1},\mathbf{1})^{+,+}_{0}$$

$$\mathbf{1_L} \to (\mathbf{1},\mathbf{1})^{+,-}_{0}$$

\+ boundary mass terms!

$$S_{UV} = \int \mathrm{d}^4x \left(M_u \psi_{\mathbf{20},10}\chi_{\mathbf{15},10} + \text{h.c.}\right)$$

$$S_{IR} = \int \mathrm{d}^4x \left(\frac{R}{R'}\right)^4 \Big(M_{\tilde{u}}\psi_{\mathbf{15},(3^*,1)}\chi_{\mathbf{20},(3^*,1)} + M_d\chi_{\mathbf{15},(3,1)}\psi_{\mathbf{6},(3,1)} + M_l\chi_{\mathbf{15},(1,2)}\psi_{\mathbf{6},(1,2)} + M_\nu\chi_{\mathbf{6},1}\psi_{\mathbf{1}} + \text{h.c.}\Big)$$



Breaks SU(4), but crucial to get spectrum (and correct EWSB)!

Novel Breaking Pattern

Fermion irreps:

$$\mathbf{20_L} \to (\mathbf{3},\mathbf{2})^{-,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{-,+}_{-2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{1} \\ (\mathbf{3}^*,\mathbf{2})^{-,+}_{-1/6} \oplus u_R(\mathbf{3},\mathbf{1})^{-,-}_{2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{-1}$$

$$\mathbf{15_L} \to q_L(\mathbf{3},\mathbf{2})^{+,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{+,-}_{-2/3} \oplus e^c_R(\mathbf{1},\mathbf{1})^{+,+}_{1} \\ \oplus (\mathbf{3},\mathbf{1})^{-,+}_{-1/3} \oplus (\mathbf{1},\mathbf{2})^{-,+}_{1/2}$$

$$\mathbf{6_L} \to d_R(\mathbf{3},\mathbf{1})^{-,-}_{-1/3} \oplus l^c_L(\mathbf{1},\mathbf{2})^{-,-}_{1/2} \oplus \nu^c_R(\mathbf{1},\mathbf{1})^{+,+}_{0}$$

$$\mathbf{1_L} \to (\mathbf{1},\mathbf{1})^{+,-}_{0}$$

\+ boundary mass terms!

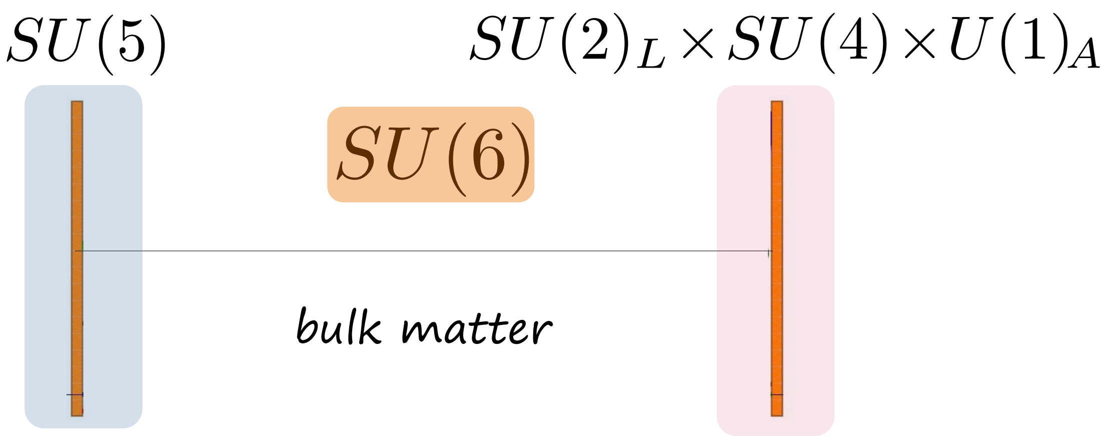
$$S_{UV} = \int \mathrm{d}^4x \big(M_u \psi_{\mathbf{20},10}\chi_{\mathbf{15},10} + \text{h.c.}\big)$$

$$S_{IR} = \int \mathrm{d}^4x \left(\frac{R}{R'}\right)^4 \Big(M_{\tilde u}\psi_{\mathbf{15},(3^*,1)}\chi_{\mathbf{20},(3^*,1)} + M_d \chi_{\mathbf{15},(3,1)}\psi_{\mathbf{6},(3,1)} \\ + M_l \chi_{\mathbf{15},(1,2)}\psi_{\mathbf{6},(1,2)} + M_\nu \chi_{\mathbf{6},1}\psi_{\mathbf{1}} + \text{h.c.}\Big)$$

$$M_u \to m_u \\ M_{\tilde u} \to V(H) \\ M_{d,l} \to m_e \neq m_d \\ M_\nu \to \textit{light } \nu$$

Viable spectrum for 3 gen.

SU(6) GHGUT

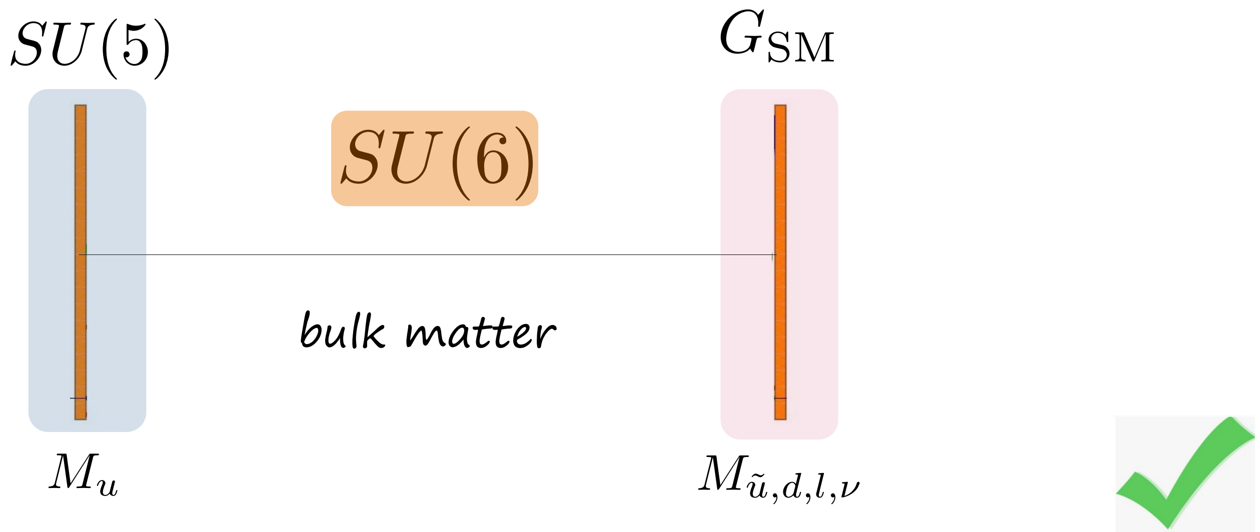


SM at low energies? ✗

SU(6) GHGUT w/ novel breaking pattern

Reproduces SM at low energies!

Phenomenology



Reproduces SM at low energies!

- Extended Scalar Sector (incl. Higgs Mass)
- New X,Y Gauge Bosons
- Proton Decay?
- Running of Gauge Couplings, different variants

Scalar Potential

$\text{Higgs} + \text{singlet} + (\mathbf{3},\mathbf{1})_{-1/3}\,\text{LQ}$

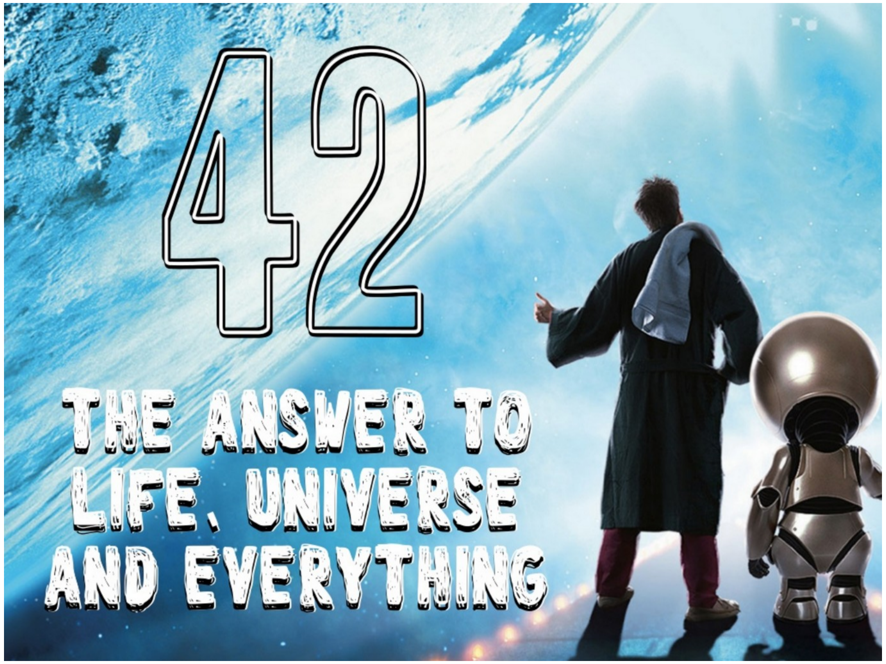
The Model is True!

- The mode is true….

The Model is True!

- The mode is true….

… well, because 20+15+6+1 =  :)



Scalar Potential

Higgs + singlet + $(\mathbf{3},\mathbf{1})_{-1/3}$ LQ

$-4N_c$ (3) quarks (gauge bos.)

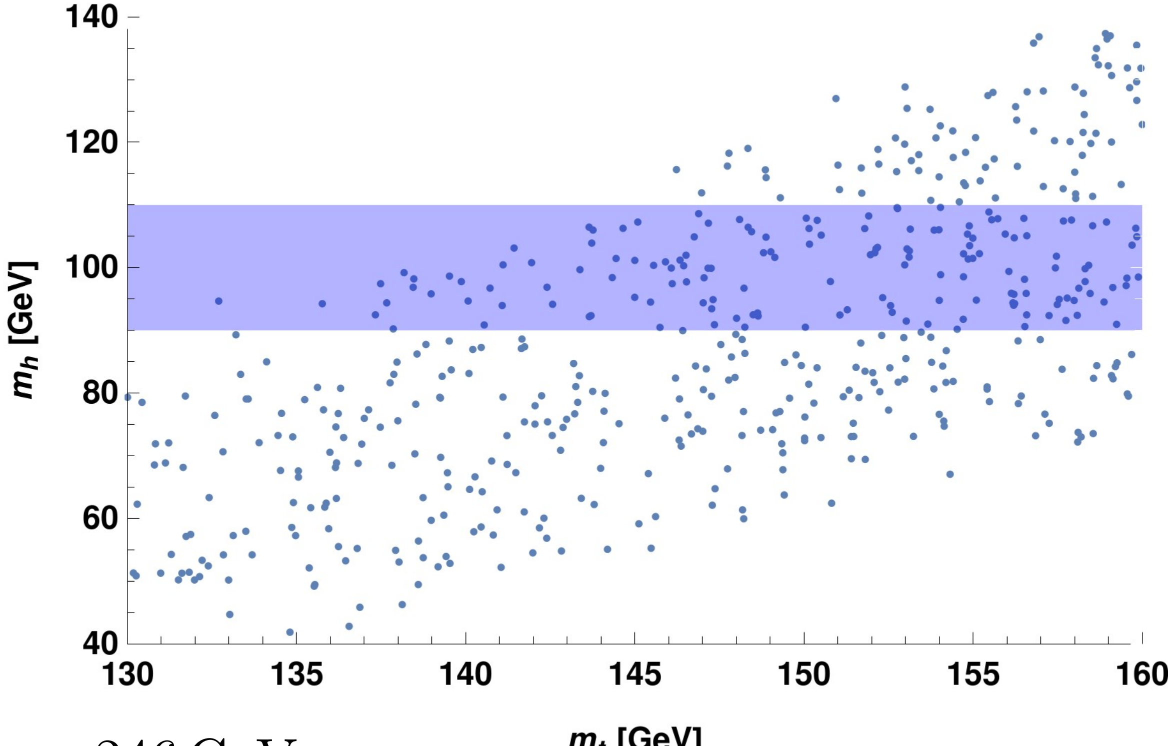
$$V_r(v,c,s) = \frac{N_r}{(4\pi)^2}\int_0^\infty dp\, p^3 \log(\rho_r(-p^2, v, c, s))$$

Higgs LQ singlet

Spectral function: $\rho_r(m^2_{n;r}, v, c, s) = 0$

Scalar Potential

Higgs + singlet + $(\mathbf{3},\mathbf{1})_{-1/3}$ LQ



$v = 246\,\mathrm{GeV}$

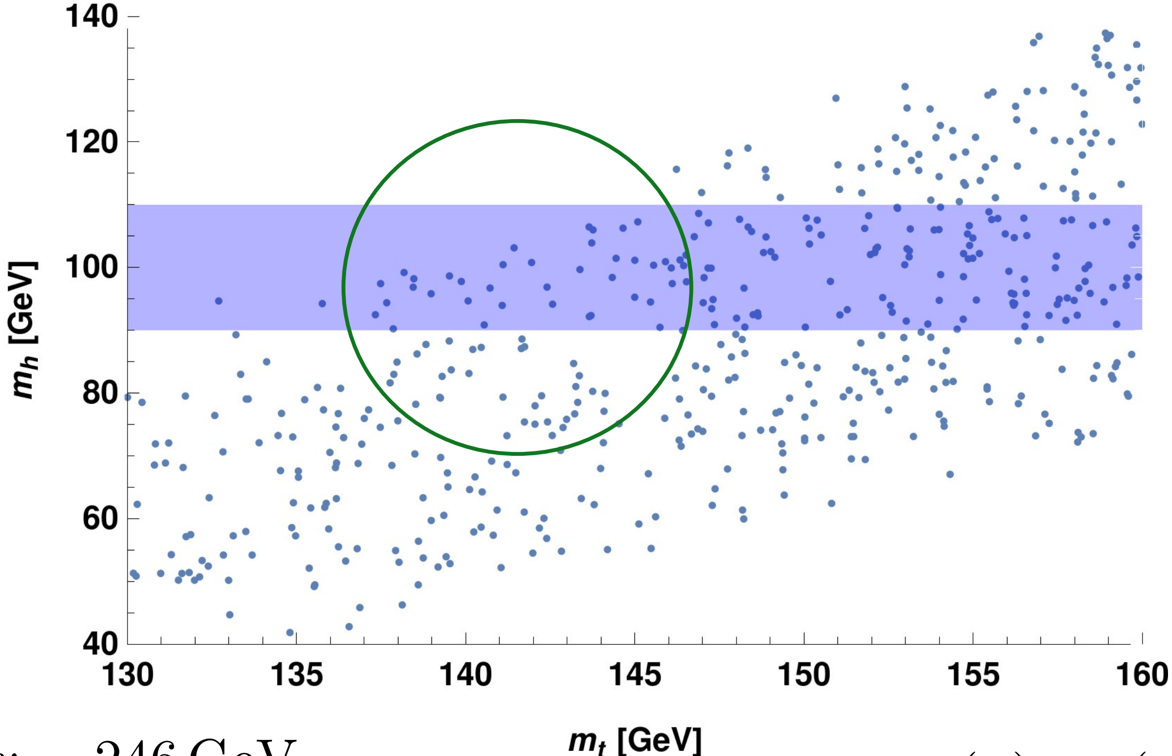
$m_h(\mu), m_t(\mu),$ with $\mu \sim f$

$M_{\tilde{u}} \neq 0$ *crucial*

$R'^{-1} = 10\,\mathrm{TeV}$
$\approx m_\rho/2$

Scalar Potential

$\text{Higgs} + \text{singlet} + (\mathbf{3},\mathbf{1})_{-1/3}\,\text{LQ}$



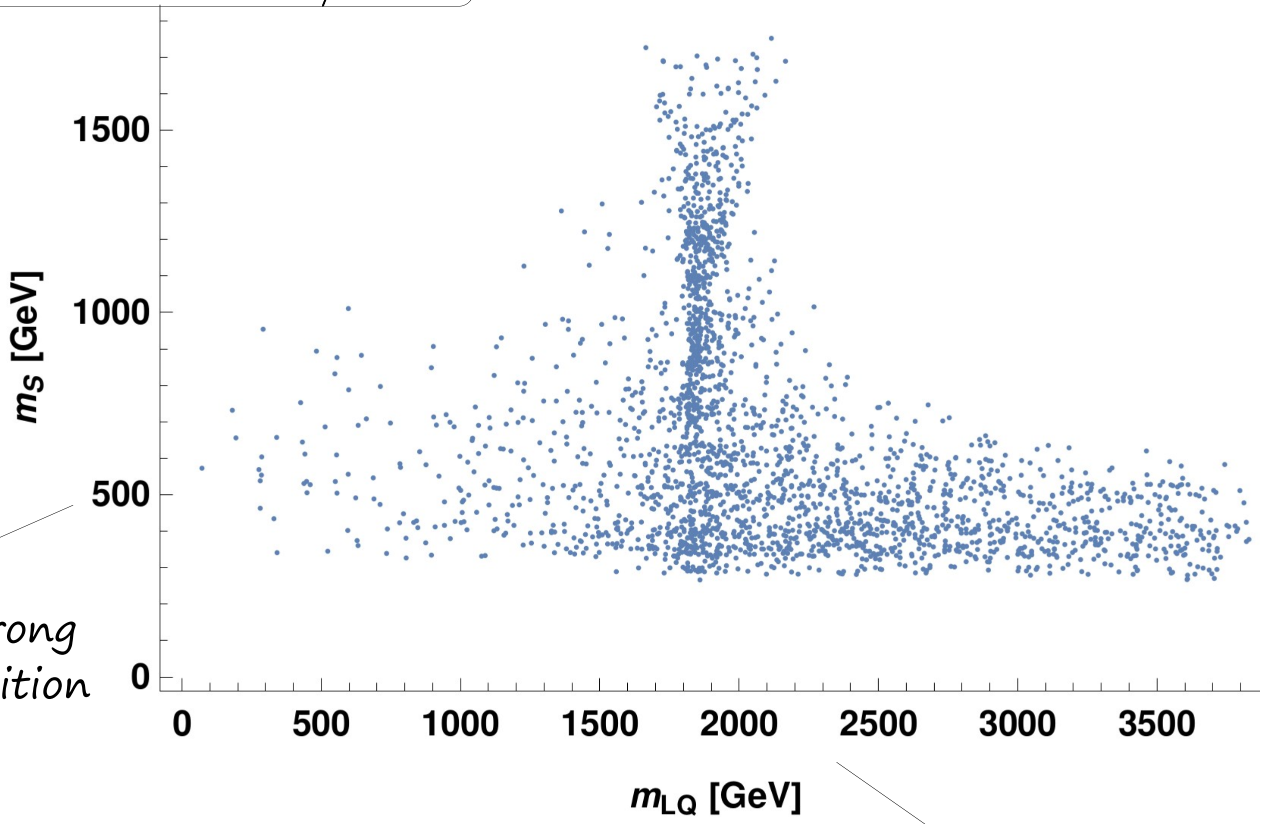
Correct quartic predicted!

$v = 246\,\text{GeV}$

$m_h(\mu), m_t(\mu), \text{ with } \mu \sim f$

Scalar Potential

Higgs + singlet + $(\mathbf{3},\mathbf{1})_{-1/3}$ LQ



Potentially induce strong
1st order Phase transition
→ Baryogenesis

address (CC) B anomalies

Vector Leptoquarks

$$A_\mu = \left(\begin{array}{cc|ccc|c}
(++) & (++) & (+-) & (+-) & (+-) & (--) \\
(++) & (++) & (+-) & (+-) & (+-) & (--) \\
\hline
(+-) & (+-) & (++) & (++) & (++) & (--) \\
(+-) & (+-) & (++) & (++) & (++) & (--) \\
(+-) & (+-) & (++) & (++) & (++) & (--) \\
\hline
(--) & (--) & (--) & (--) & (--) & (--)
\end{array}\right)$$

$$m_{(+,-)} = \frac{2}{R'\sqrt{2\log(\frac{R'}{R}) - 1}} \sim 0.25/R' \sim m_\rho/10 \ll m_\rho$$

$$\left(m_{(-,+)} \sim 2.5/R' \sim m_\rho\right)$$

Vector Leptoquarks

$$A_\mu = \left(\begin{array}{cc|ccc|c} (++) & (++) & (+-) & (+-) & (+-) & (--) \\ (++) & (++) & (+-) & (+-) & (+-) & (--) \\ \hline (+-) & (+-) & (++) & (++) & (++) & (--) \\ (+-) & (+-) & (++) & (++) & (++) & (--) \\ (+-) & (+-) & (++) & (++) & (++) & (--) \\ \hline (--) & (--) & (--) & (--) & (--) & (--) \end{array}\right)$$

$$m_{(+,-)} = \frac{2}{R'\sqrt{2\log(\frac{R'}{R}) - 1}} \sim 0.25/R' \sim m_\rho/10 \ll m_\rho$$

Di-lepton searches $\rightarrow$ $m_{(+,-)} \gtrsim 2.5\,\mathrm{TeV} \Rightarrow R'^{-1} \approx m_\rho/2 \gtrsim 10\,\mathrm{TeV}$

e.g. Crivellin, Müller, Schnell, 2101.07811

$\rightarrow$ same ballpark as EWPT and Flavor in GHU!

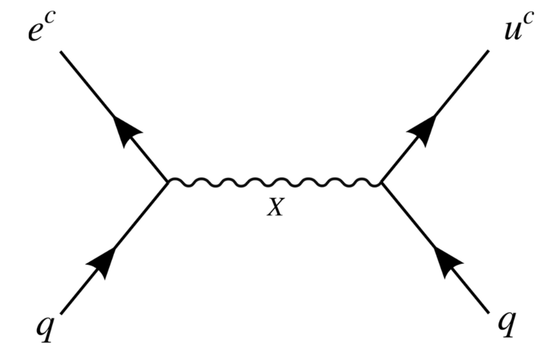
Proton Decay?

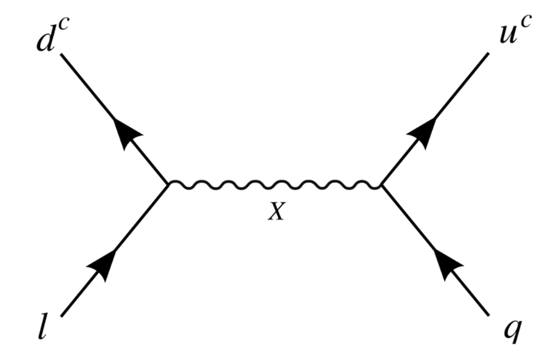
Fermion embeddings help: no $p \to \pi_0 + e^+$

$$\mathbf{20_L} \to (\mathbf{3},\mathbf{2})^{-,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{-,+}_{-2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{1}$$
$$(\mathbf{3}^*,\mathbf{2})^{-,+}_{-1/6} \oplus u_R(\mathbf{3},\mathbf{1})^{-,-}_{2/3} \oplus (\mathbf{1},\mathbf{1})^{-,+}_{-1}$$

$$\mathbf{15_L} \to q_L(\mathbf{3},\mathbf{2})^{+,+}_{1/6} \oplus (\mathbf{3}^*,\mathbf{1})^{+,-}_{-2/3} \oplus e^c_R(\mathbf{1},\mathbf{1})^{+,+}_{1}$$
$$\oplus (\mathbf{3},\mathbf{1})^{-,+}_{-1/3} \oplus (\mathbf{1},\mathbf{2})^{-,+}_{1/2}$$

$$\mathbf{6_L} \to d_R(\mathbf{3},\mathbf{1})^{-,-}_{-1/3} \oplus l^c_L(\mathbf{1},\mathbf{2})^{-,-}_{1/2} \oplus \nu^c_R(\mathbf{1},\mathbf{1})^{+,+}_{0}$$

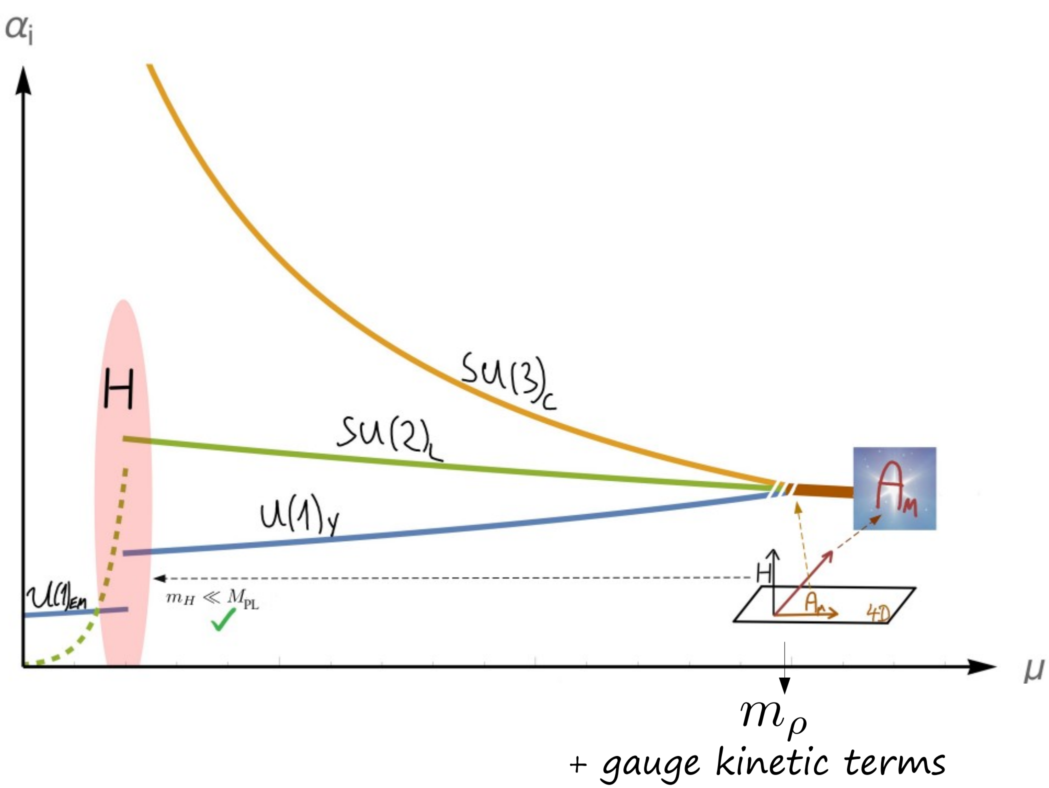


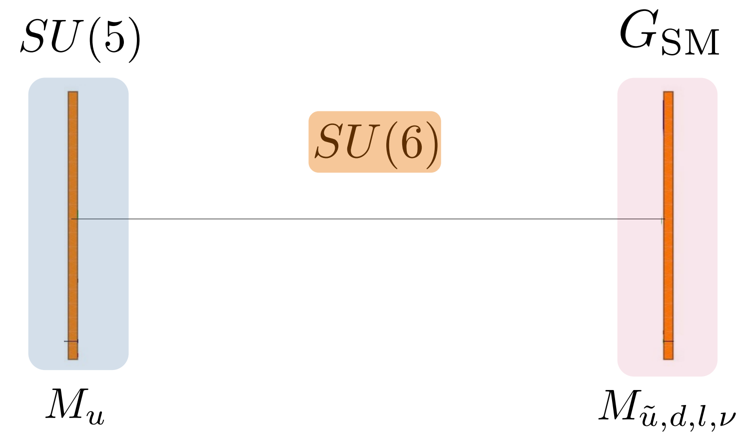


& secret baryon symmetry:

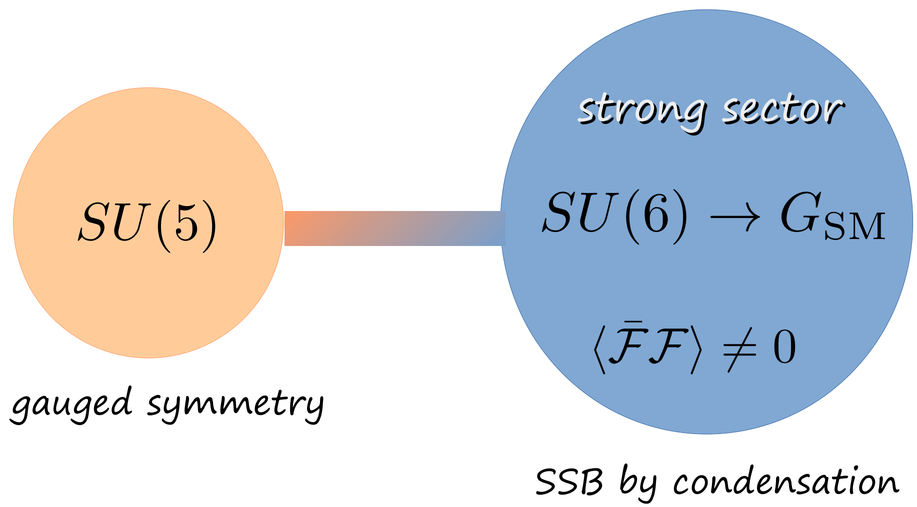
SM-fields with usual charges + charge new fermions and vector&scalar LQs

Unification: different options

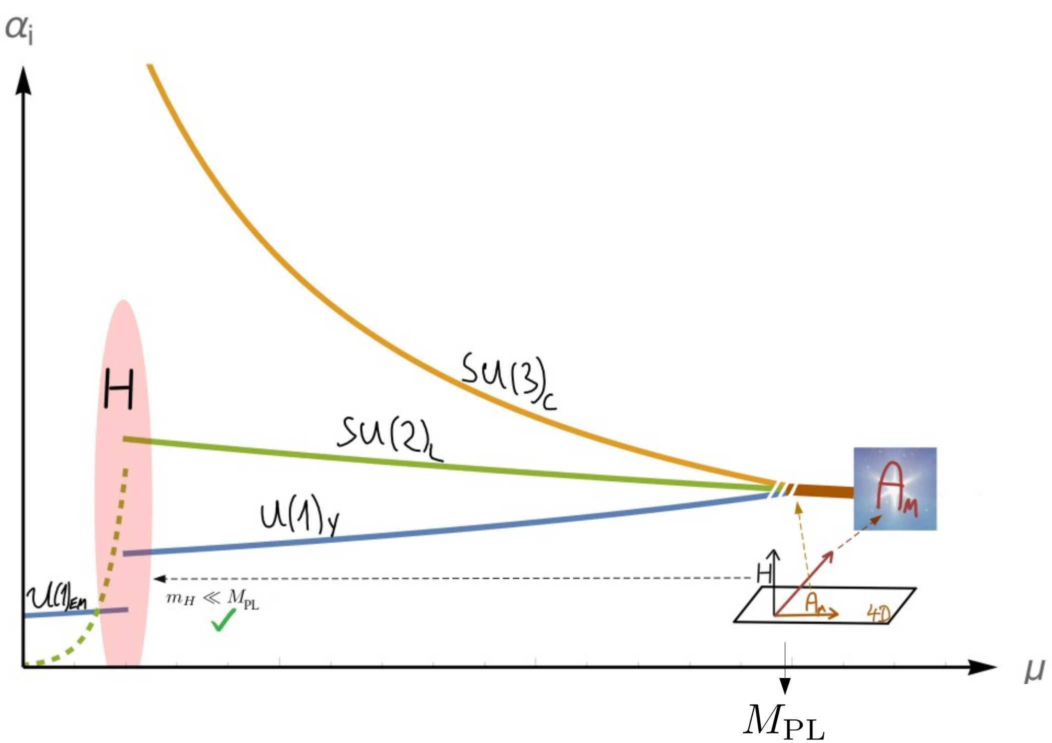




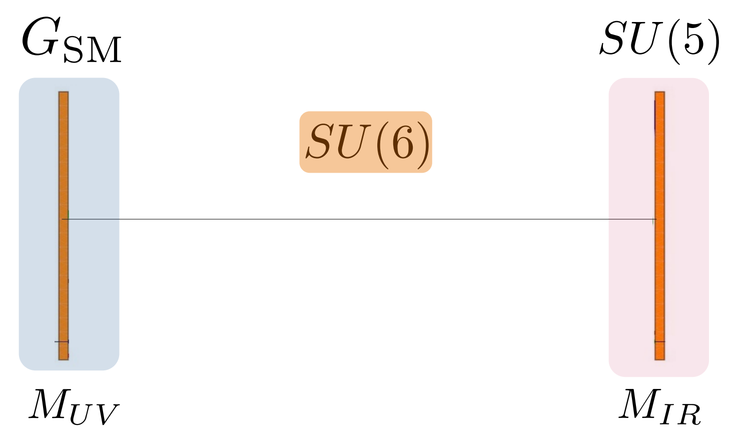
$m_\rho \sim 10\,\mathrm{TeV}$

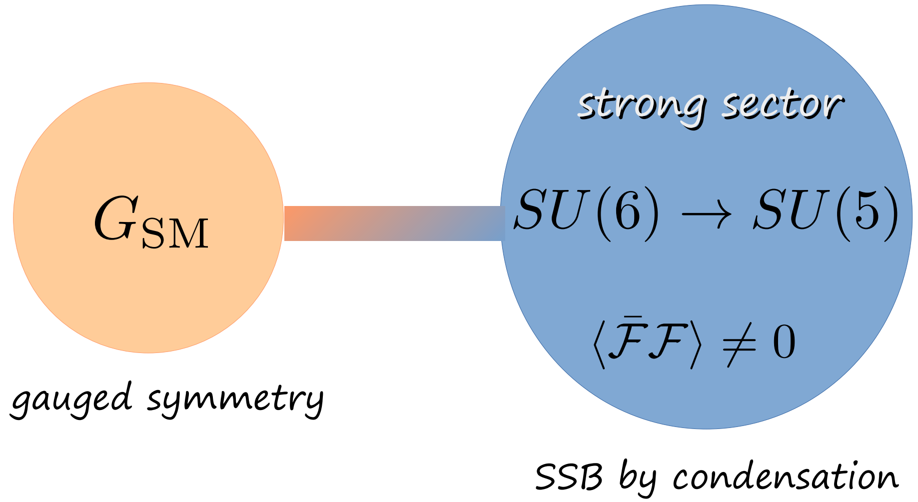


Unification: different options

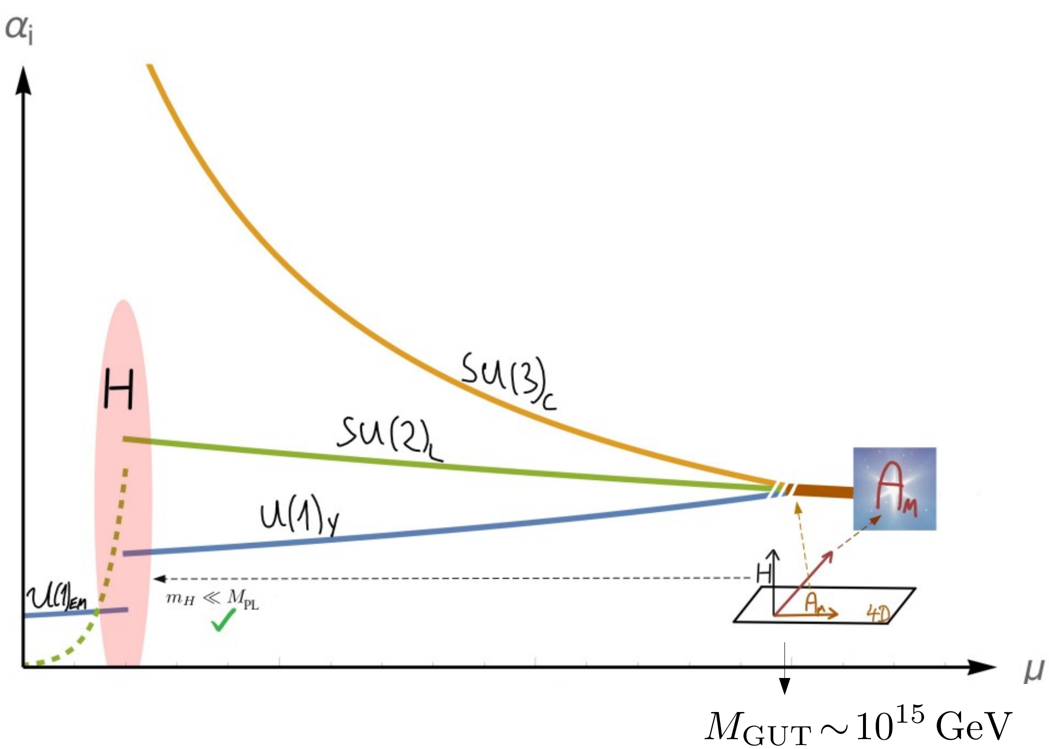


- KK modes of X,Y gauge bosons at TeV scale

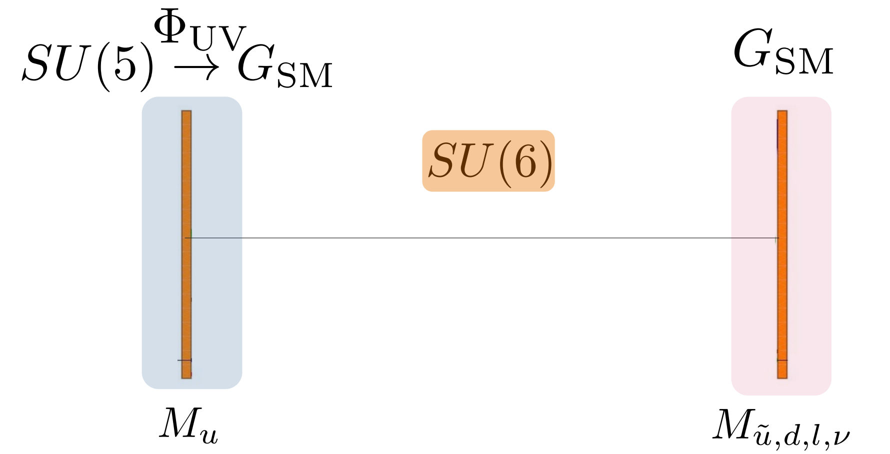


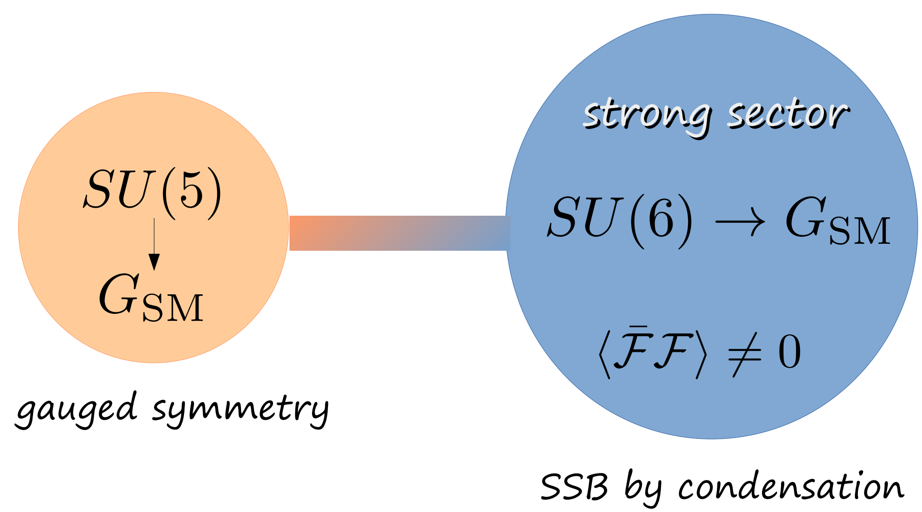


Unification: different options



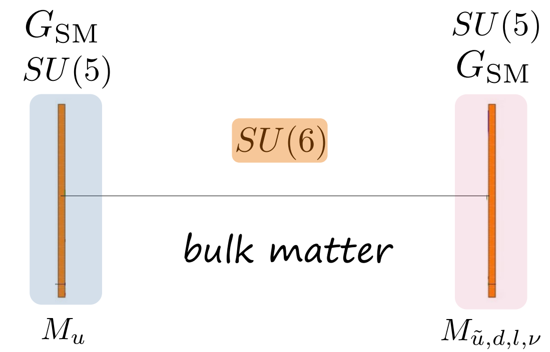
- KK modes of X,Y gauge bosons at TeV scale





Conclusions

- Embed GUT group in enhanced global symmetry of CH:
  Unification of all forces & EWSB (Higgs)!



- Modified symmetry breaking solves all problems of earlier models

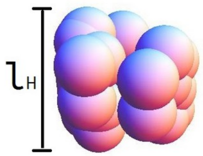
- Minimal fermion realization (cf. MCHM$_5$) leads to fully viable spectrum

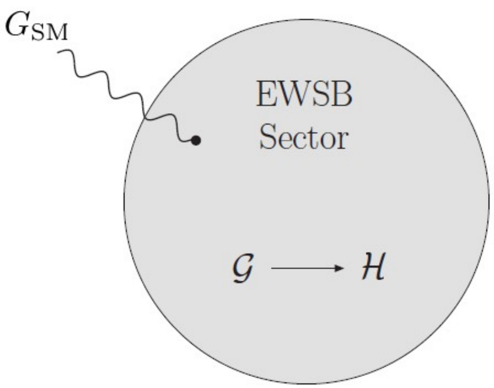
- Proton decay forbidden, KK modes of GUT gauge bosons at TeV scale

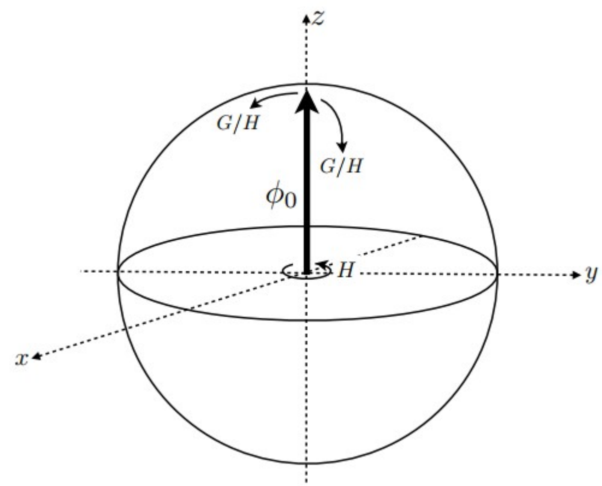
- Lots of directions to explore
  Top partners & tuning, Flavor anomalies, Unification, Baryogenesis, ...

Backup

Composite Higgs: Some Details







EWSB due to QCD

- Global symmetry breaking

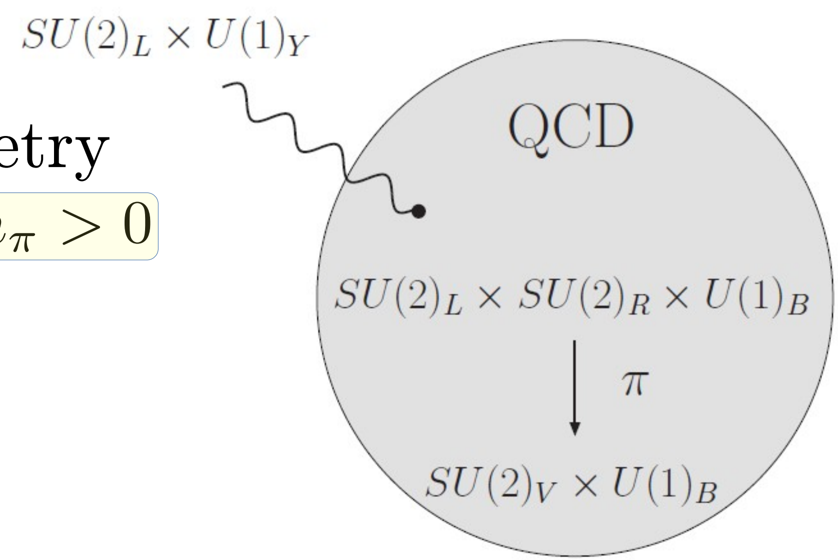
$\boxed{SU(2)_L \times SU(2)_R} \times U(1)_B \to \boxed{SU(2)_V} \times U(1)_B \quad \to 3\,\mathrm{GB}\,\pi^a$

- Only subgroup weakly gauged:

$G_{\mathrm{EW}} = SU(2)_L \times U(1)_Y$

→ *explicit* breaking of global symmetry

$\boxed{m_\pi > 0}$

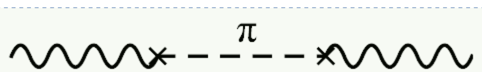


- $\boxed{\mathrm{G}_{\mathrm{EW}}}$ broken by $\langle \bar{q}q \rangle \neq 0$:

$\boxed{SU(2)_L \times U(1)_Y \to U(1)_{\mathrm{EM}}}$

→ W,Z become massive, absorb π^a

so far no Higgs...



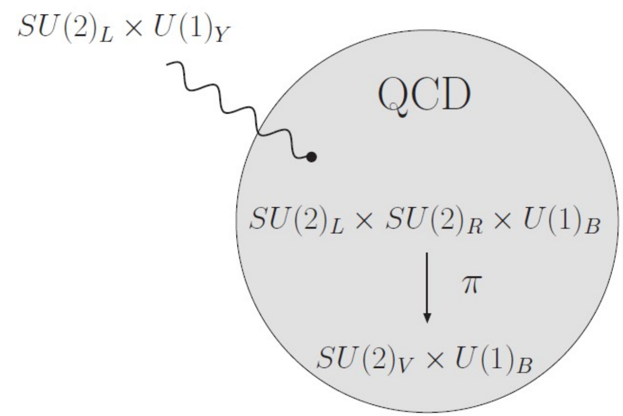
$$\Rightarrow m_W = \frac{g f_\pi}{2} \simeq 29\,\mathrm{MeV}$$

EWSB due to QCD

- $\mathrm{G_{EW}}$ broken by $\langle \bar{q}q \rangle \neq 0$:

$$SU(2)_L \times U(1)_Y \to U(1)_{\mathrm{EM}}$$

→ W,Z become massive, absorb π^a

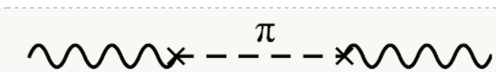


$$W \text{ propagator } G_{\mu\nu}(q) = \frac{-i(P_T)_{\mu\nu}}{q^2 - g^2\Pi(q^2)/2} \qquad (P_T)_{\mu\nu} \equiv \eta_{\mu\nu} - q_\mu q_\nu / q^2$$

$$(\xi = 0)$$

$$\Pi_{\mu\nu}(q) = (P_T)_{\mu\nu}\Pi(q^2)$$

$$i\Pi_{\mu\nu}(q) = -i\int d^4x e^{iq\cdot x}\langle 0|T(J^+_\mu(x)J^-_\nu(0))|0\rangle$$



$$\langle 0|J^+_\mu|\pi^-(p)\rangle = i\frac{f_\pi}{\sqrt{2}}p_\mu \Rightarrow \boxed{\Pi(q^2) = \frac{f_\pi^2}{2}} \Rightarrow m_W = \frac{g f_\pi}{2} \simeq 29\,\mathrm{MeV}$$

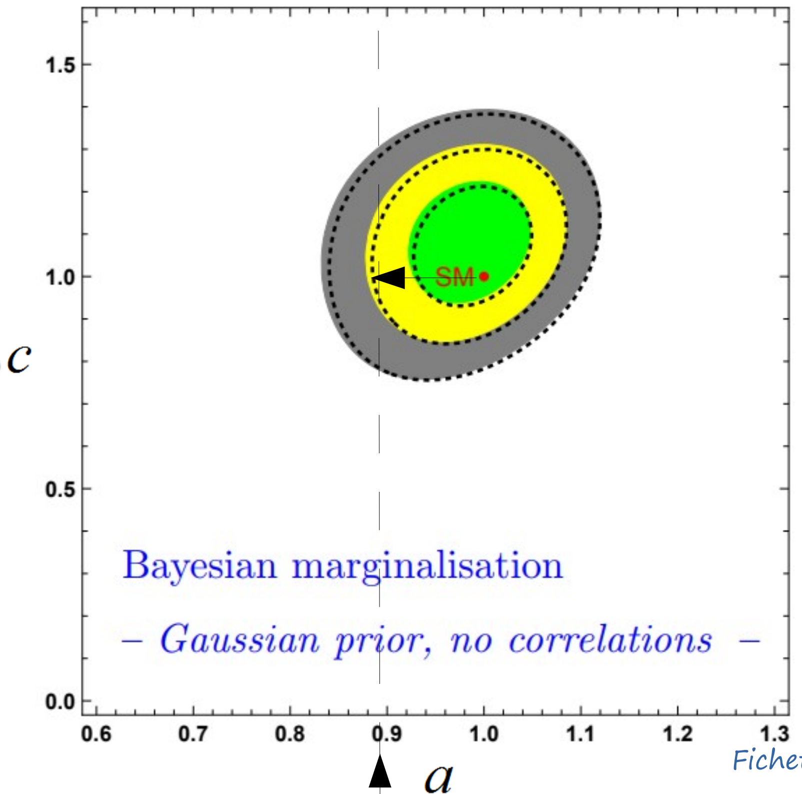
Higgs Couplings

$$\mathcal{L}_H = \frac{1}{2}\partial_\mu h \partial^\mu h + V(h) + \frac{v^2}{4}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)\right]\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right)$$

$$-\frac{v}{\sqrt{2}}(\bar{u}_L^{(i)}\ \bar{d}_L^{(i)})\Sigma(1 + c\frac{h}{v} + \cdots)\begin{pmatrix} Y_{ij}^u u_R^{(j)} \\ Y_{ij}^d d_R^{(j)} \end{pmatrix} + \mathrm{h.c.}$$

depends on fermion embedding

$\longrightarrow$ $a = \sqrt{1-\xi}\,,$ $\quad b = (1-2\xi)$



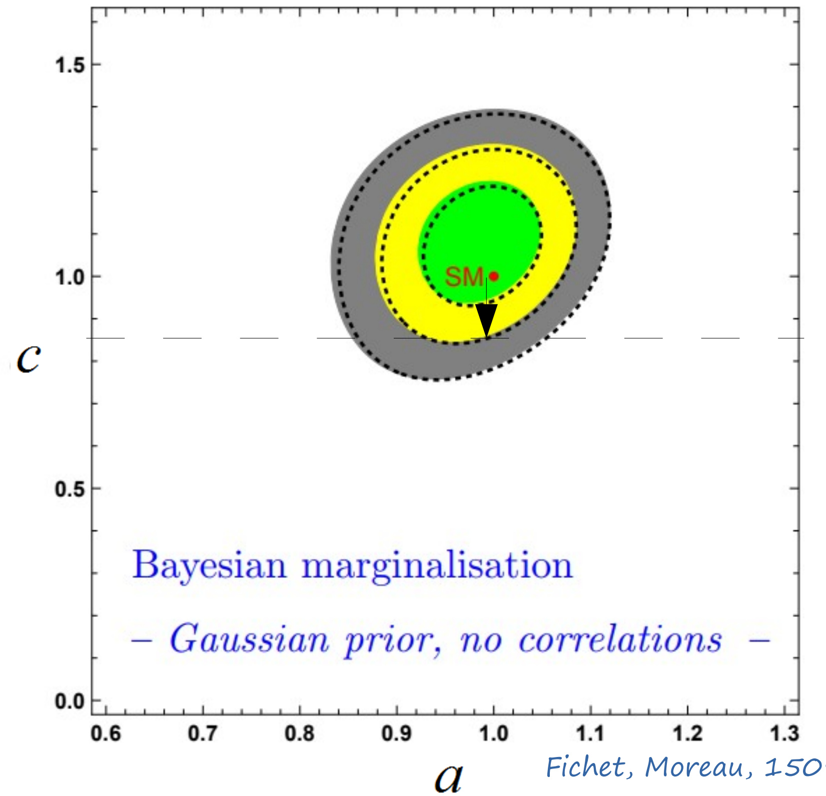
Fichet, Moreau, 1509.00472

$\xi \approx 0.2 \rightarrow f \approx 550\,\mathrm{GeV}$

Higgs-Fermion Couplings

$$\mathcal{L}_H = \frac{1}{2}\partial_\mu h \partial^\mu h + V(h) + \frac{v^2}{4}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)\right]\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right)$$
$$-\frac{v}{\sqrt{2}}(\bar{u}_L^{(i)}\ \bar{d}_L^{(i)})\Sigma(1 + c\frac{h}{v} + \cdots)\begin{pmatrix} Y_{ij}^u u_R^{(j)} \\ Y_{ij}^d d_R^{(j)} \end{pmatrix} + \mathrm{h.c.}$$

depends on fermion embedding



Fichet, Moreau, 1509.00472

Rather model dependent:
Representations of $\Psi^{Q,q}$ under SO(5)

$c = \sqrt{1-\xi}$: MCHM_4 (spinorial)

$c = \frac{1-2\xi}{\sqrt{1-\xi}}$: MCHM_5 (fundamental)

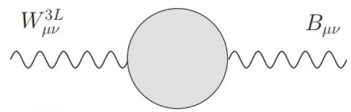
...

$c \approx 0.85 \rightarrow f \approx 500\,(780)\,\mathrm{GeV}$ for $\mathrm{MCHM}_4(\mathrm{MCHM}_5)$

Electroweak Precision Tests

- Tree Level (SO5/SO(4)) :

$$S = 2\pi\xi\, \Pi_1'(0)$$

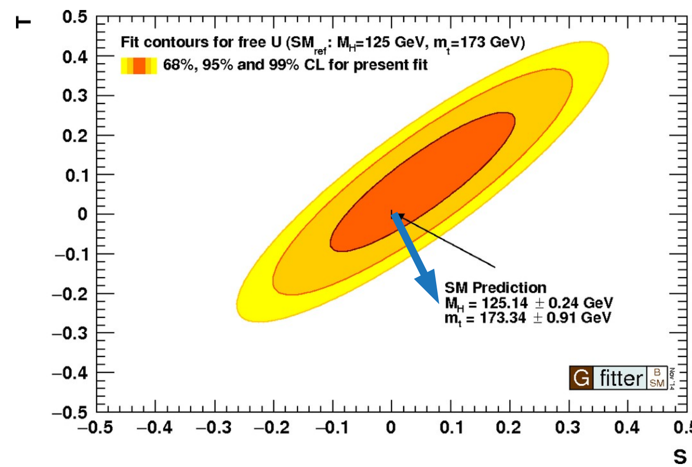


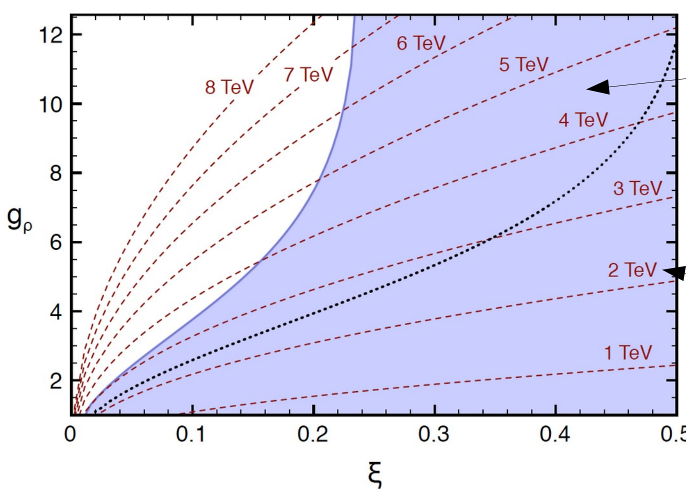
$$T = 0 \text{ (custodial)}$$

$$\approx 4\pi\,(1.36)\left(\frac{v}{m_\rho}\right)^2 \to 0 \text{ for } \xi \to 0$$

- 1-loop: modified Higgs-Gauge couplings

$$\sim \cos(\langle h\rangle/f) = \sqrt{1-\xi} \qquad \to \Delta S > 0,\ \Delta T < 0$$





excluded (99% CL)

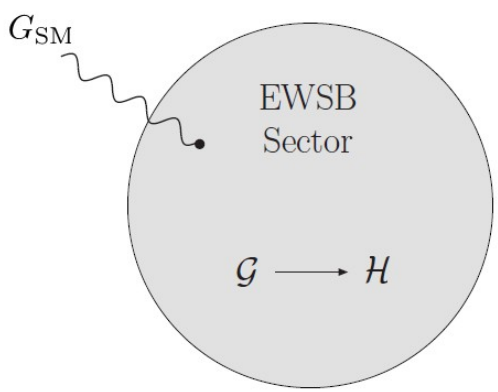
m_ρ

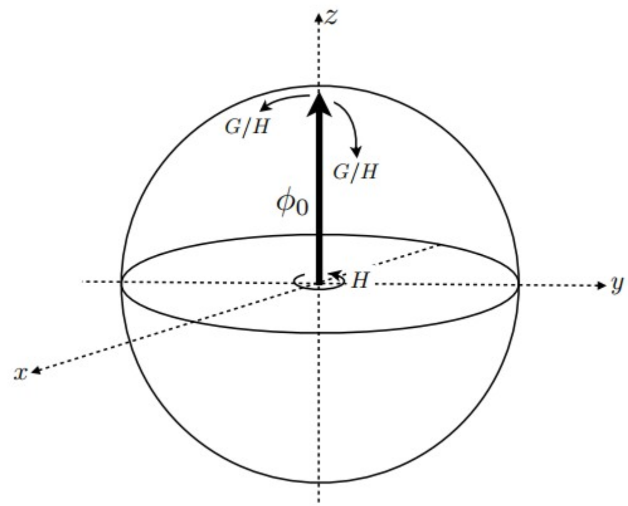
Contino, 1005.4269

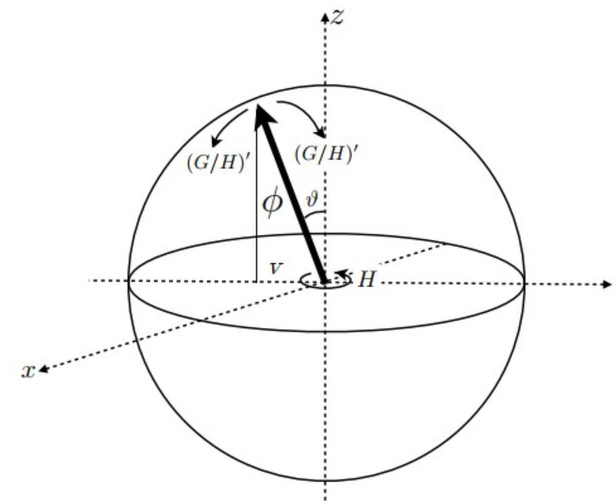
$$\xi \lesssim 0.1 \to f \gtrsim 800\,\text{GeV} @ 95\%\text{CL}$$

Thamm, Torre, Wulzer, 1502.01701
Ghosh, Salvarezza, Senia, 1511.08235

Vacuum Misalignment: Geometric Picture







- $\mathcal{G} \to \overset{\equiv \mathcal{H}_1}{\mathcal{H}} \supseteq G_{\mathrm{SM}}$, Generators $\{T^A\} = \{T^a, T^{\hat{a}}\}$, $\quad T^a : \mathcal{H},\ T^{\hat{a}} : \mathcal{G}/\mathcal{H}$

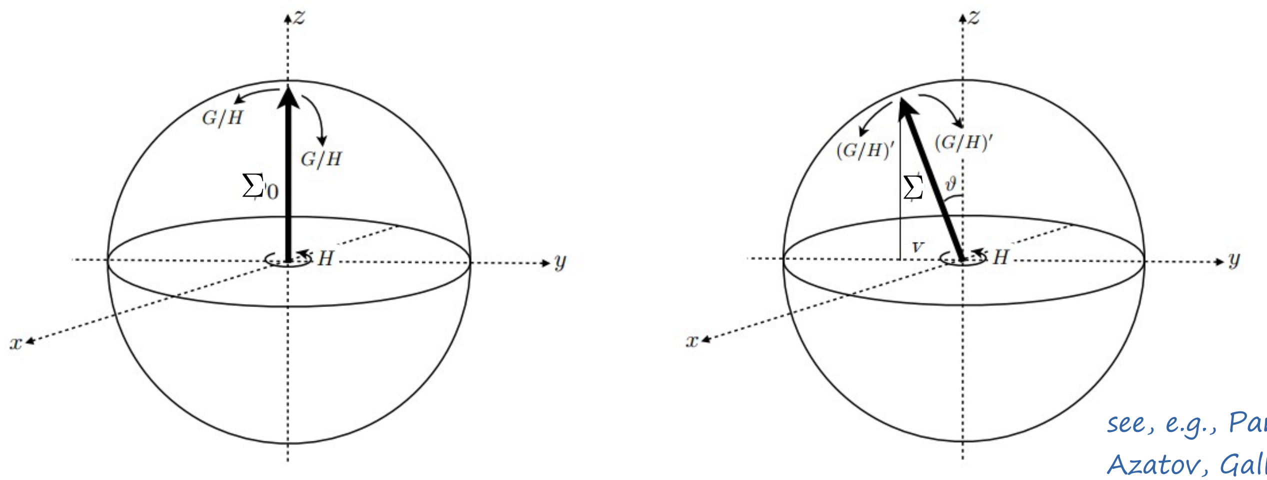
- Reference vacuum configuration ϕ_0 : $\ T^a \phi_0 = 0\,,\ T^{\hat{a}} \phi_0 \neq 0$

  $\rightarrow$ NGB fields $\ \phi(x) = e^{i\theta_{\hat{a}}(x) T^{\hat{a}}} \phi_0$: local transformations in $T^{\hat{a}}$ directions

- Explicit $\mathcal{G}$ breaking $\rightarrow$ non-vanishing $\langle \theta_{\hat{a}} \rangle$, breaks G_{EW}:
  misalignment of true vacuum $\langle \phi \rangle$ vs. $\mathcal{H}$-preserving ϕ_0, anlge $\vartheta \equiv \langle \theta \rangle$

EW breaking: $\ v = f \sin\vartheta\,,\ \ f = |\phi_0|$

Vacuum Misalignment



see, e.g., Panico, Wulzer, 1506.01961, Azatov, Galloway, 1212.1380

Explicit $\mathcal{G}$ breaking $\rightarrow \langle h \rangle > 0 \Rightarrow$ breaks $G_{\rm EW} \subset \mathcal{H}$:
misalignment of true $\langle \Sigma \rangle$ vs. $\mathcal{H}$-preserving Σ_0, anlge $\vartheta \equiv \langle h \rangle / f$

EW breaking: $v = f \sin\vartheta\,, \;\; f = |\Sigma_0|$

Challenge: $\xi \equiv v^2/f^2 = \sin^2\vartheta \ll 1$
without excessive tuning

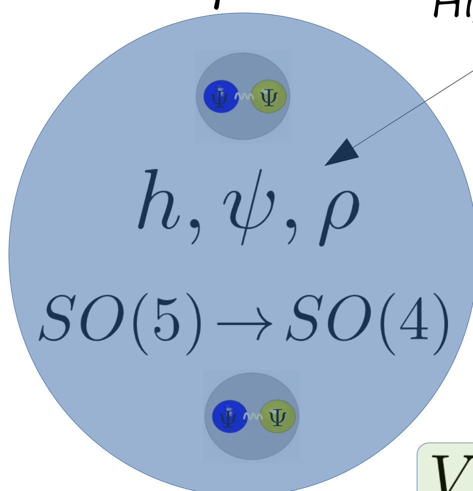
$$\Sigma(x) = \Sigma_0\, e^{-i\frac{\sqrt{2}}{f} h_a(x) T^a}$$

$$\Sigma_0 = (0,0,0,0,1) : SO(5) \rightarrow SO(4)$$

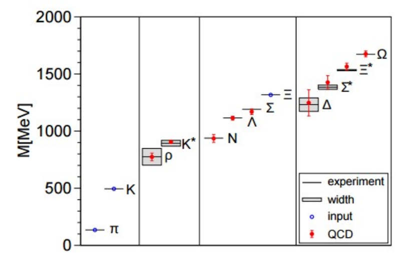
$$\mathcal{L}_\Sigma = \frac{f^2}{2} (D_\mu \Sigma)^T (D^\mu \Sigma)$$

SO(5) → SO(4) *Composite* Higgs

composite



Higgs + fermionic & bosonic
resonances of
strong sector



$$V(h) \propto 0$$

Below condensation scale : effective description of Higgs sector via NLσM

$$\Sigma = U\,\Sigma_0\,, \quad U = e^{i\frac{\sqrt{2}}{f} h_{\hat{a}} T^{\hat{a}}}$$

$\Sigma_0 = (0,0,0,0,1)$

$T^{\hat{a}} : SO(5)/SO(4)$

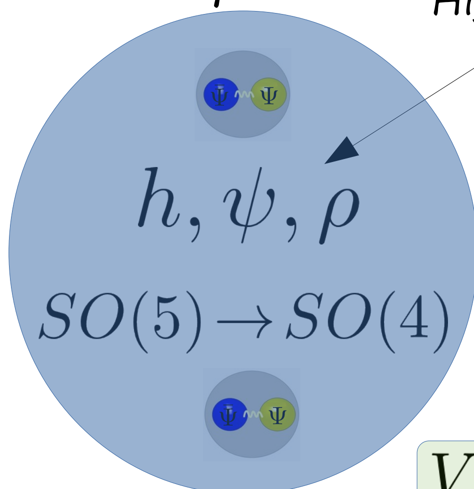
h transforms as fundamental of $SO(4)$ or

complex bi-doublet (h, h^c) of $SU(2)_L \times SU(2)_R \cong SO(4)$

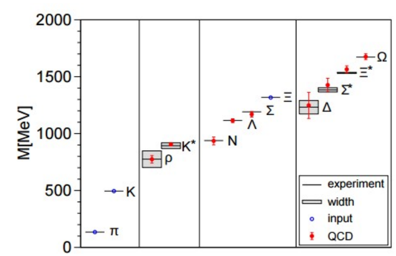
gauge

SO(5) → SO(4) Composite Higgs

composite



Higgs + fermionic & bosonic resonances of strong sector



$$V(h) \propto 0$$

Below condensation scale Λ_c: effective description of Higgs sector via NLσM

$$\Sigma = U\,\Sigma_0\,,\ \ U = e^{i\frac{\sqrt{2}}{f} h_{\hat{a}} T^{\hat{a}}}$$

$$\Sigma_0 = (0,0,0,0,1)$$
$$T^{\hat{a}} : SO(5)/SO(4)$$

$$SO(5): \ \ \boxed{\Sigma = \frac{\sin(h/f)}{h}\left(h^1, h^2, h^3, h^4, h\cot(h/f)\right)}\,, \qquad h \equiv \sqrt{(h^{\hat{a}})^2}$$

AdS/CFT correspondence:

Theory of gravity in D+1 dimensions
dual to gauge theory in D dimensions

- Most famous example:

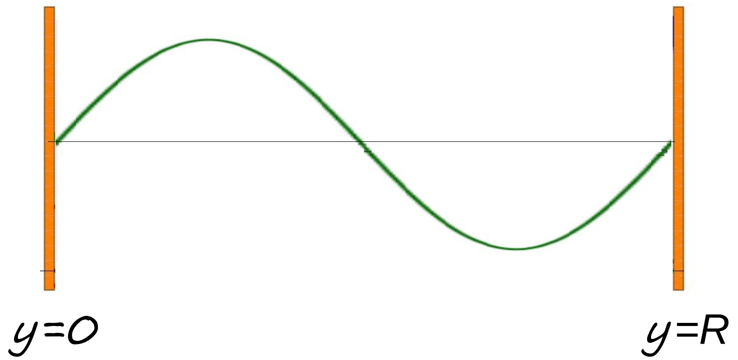
  Type IIB string theory in $AdS_5 \times S^5$ dual to N=4 SYM on boundary of AdS space

'Maldacena conjecture'
Adv. Theor. Math. Phys. 2,231(1998)
Int. J. Theor. Phys. 38,1113(1999)

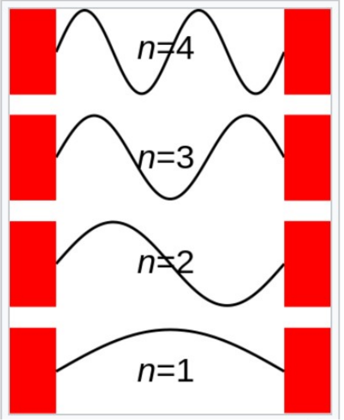
Gubser, Klebanov, Polyakov, PLB 428,105(1998)
Witten, Adv. Theor. Math. Phys. 2, 253 (1998)

Kaluza-Klein Decomposition

T. Kaluza, Sitzungsber. Preuss. Akad. Wiss. Berlin, 966 (1921)
O. Klein, Z. Phys.37, 895 (1926)



Original Idea:
unify gravity and electromagnetism, by merging the photon vector field together with the 4D Minkowski metric into a 5×5 metric



Simple Example: Scalar field in 5D

$$S_5 = \frac{1}{2}\int d^4x \int_0^R dy\ \partial_M \Phi(x,y)\partial^M \Phi(x,y) - m_5^2 \Phi^2(x,y)$$

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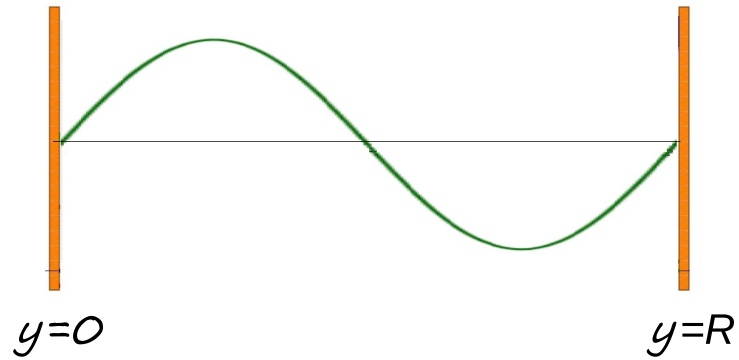

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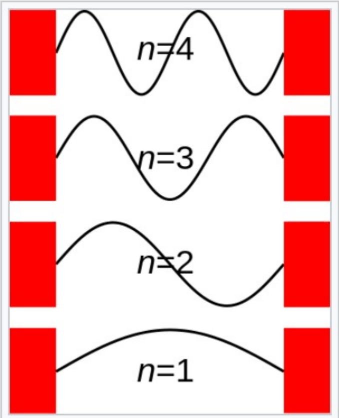

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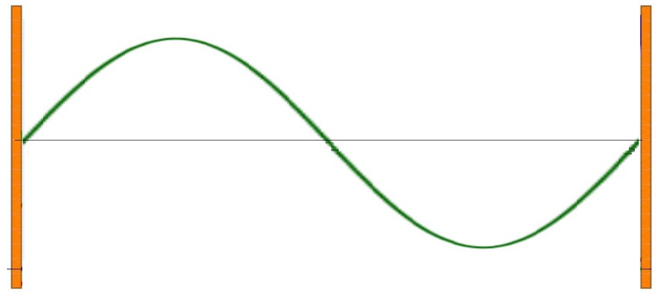
KK decomposition into complete set of orthonormal functions $f_n(y)$ on interval

$$\Phi(x,y) = \sum_n \phi_n(x) f_n(y)\,, \qquad \int_0^R dy\ f_n(y) f_m(y) = \delta_{nm}$$

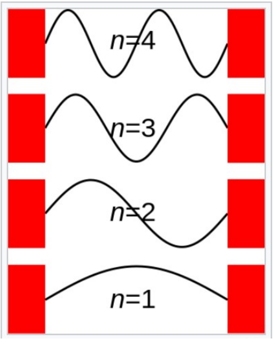
4D scalars

Kaluza-Klein Decomposition



T. Kaluza, Sitzungsber. Preuss. Akad. Wiss. Berlin, 966 (1921)
O. Klein, Z. Phys.37, 895 (1926)

$$M = \overbrace{0,1,2,3,}^{x^\mu} \overset{y}{\mathbf{4}}$$



$$\boxed{S_5 = \frac{1}{2}\int d^4x \int_0^R dy\ \partial_M \Phi(x,y)\partial^M \Phi(x,y) - m_5^2 \Phi^2(x,y)}$$

$$\eta_{MN} = \mathrm{diag}(1,-1,-1,-1,-1)$$

$$\Phi(x,y) = \sum_n \phi_n(x) f_n(y)$$

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$$S_5 = \frac{1}{2}\int d^4x \sum_n \{\partial_\mu \phi_n(x)\partial^\mu \phi_n(x) - m_5^2 \phi_n^2(x)\}$$

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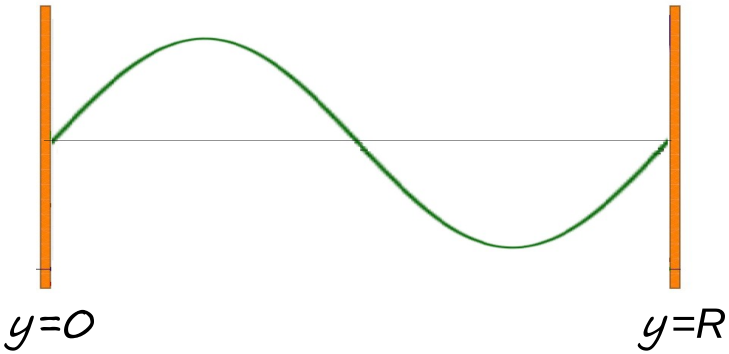

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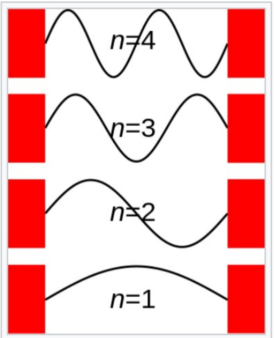

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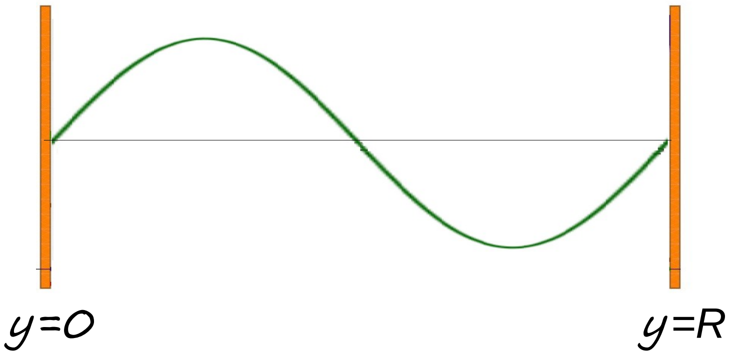
Kaluza-Klein Decomposition



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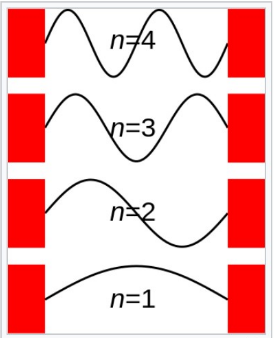

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IBP

$$-\frac{1}{2}\int d^4x \sum_{m,n} \phi_m(x)\phi_n(x)\ (f_m(R)f_n'(R) - f_m(0)f_n'(0))$$

Kaluza-Klein Decomposition

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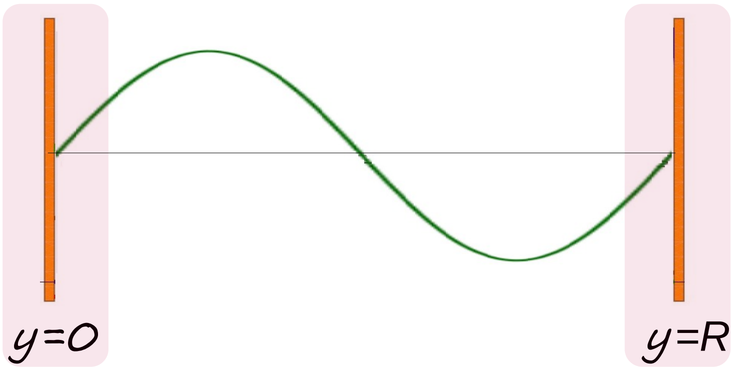

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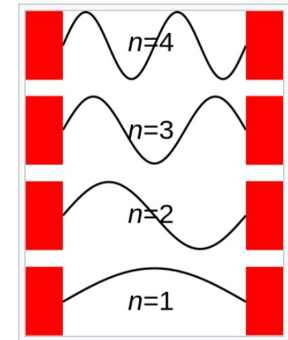

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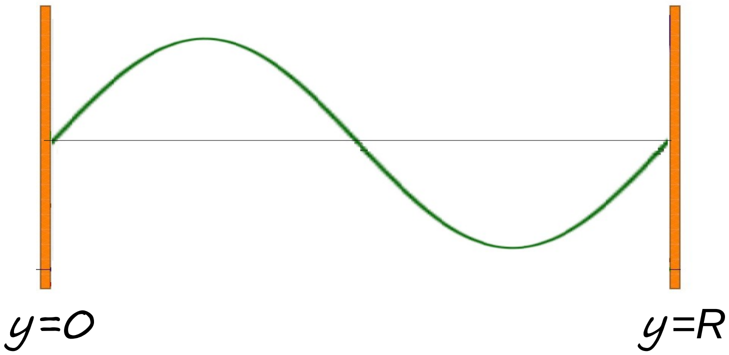
Kaluza-Klein Decomposition



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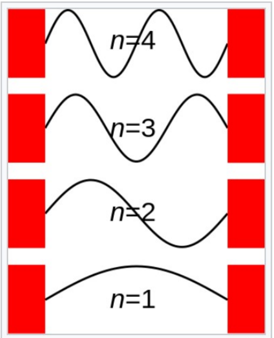

'Matching' or variation of S

$$S_5 = \frac{1}{2}\int d^4x \sum_n \{\partial_\mu \phi_n(x) \partial^\mu \phi_n(x) - m_5^2 \phi_n^2(x)\}$$
$$+\frac{1}{2}\int d^4x \int_0^R dy \sum_{m,n} \phi_m(x)\phi_n(x)\ f_m(y)\partial_y^2 f_n(y) \quad \Rightarrow \quad \partial_y^2 f_n(y) = -a_n^2 f_n(y)$$
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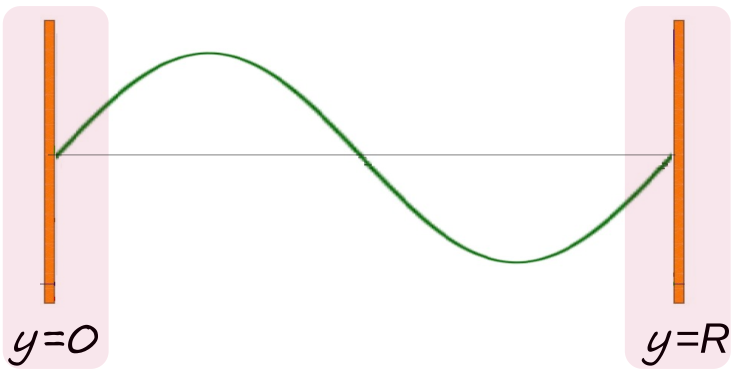
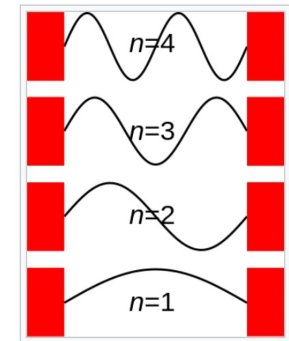
Boundary Conditions



$$\Phi(x,y) = \textstyle\sum_n \phi_n(x) f_n(y)$$

$$\int_0^R dy \; f_n(y) f_m(y) = \delta_{nm}$$



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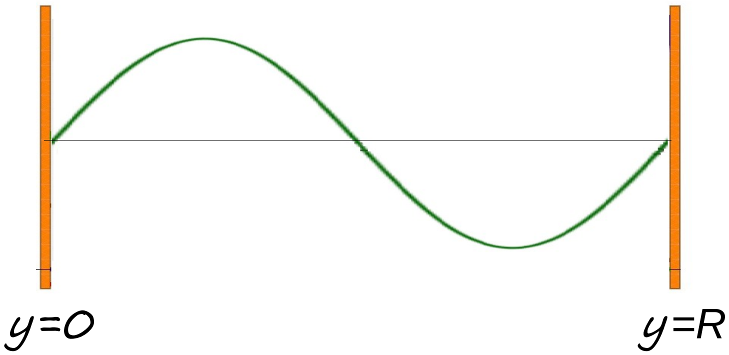
$$y = 0, R$$

Kaluza-Klein Decomposition



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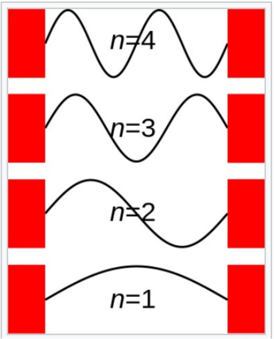

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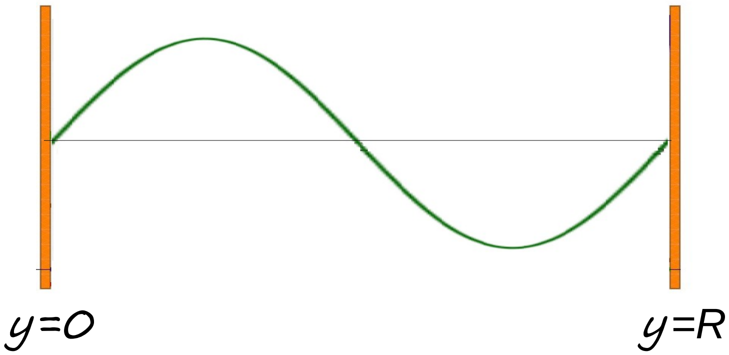

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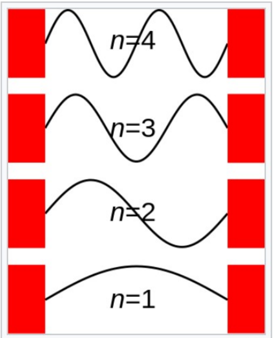

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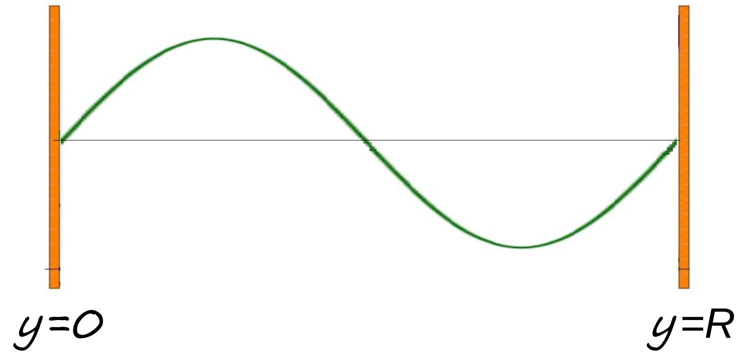
$$S = \frac{1}{2}\int d^4x \sum_n \{\partial_\mu \phi_n(x)\partial^\mu \phi_n(x) - m_n^2 \phi_n^2(x)\}$$

$$\boxed{m_n^2 = m_5^2 + a_n^2}$$

Kaluza-Klein Decomposition



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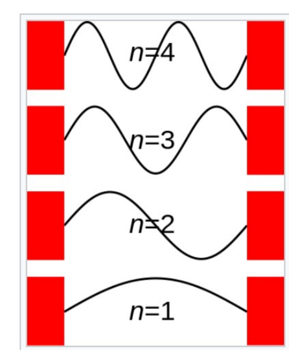
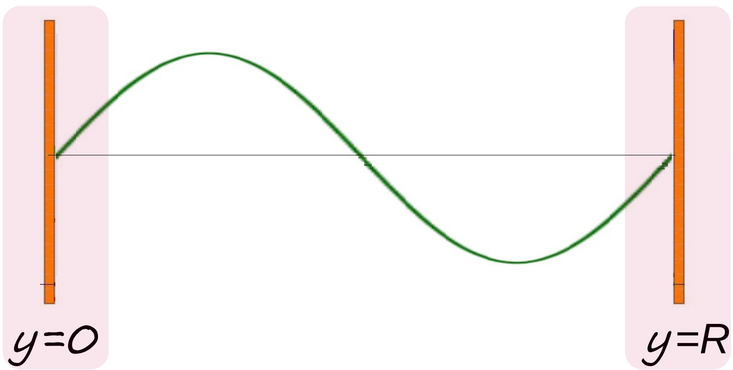


$$S = \frac{1}{2}\int d^4x \sum_n \{\partial_\mu \phi_n(x)\partial^\mu \phi_n(x) - m_n^2 \phi_n^2(x)\}$$

$$m_n^2 = m_5^2 + a_n^2$$

Scalar in compact. XD = infinite tower of 4D scalars with different masses

Kaluza-Klein Profiles



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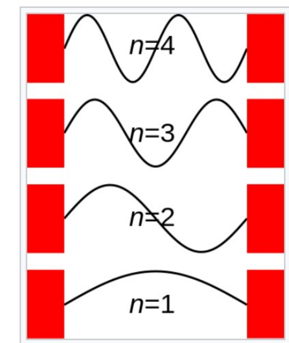


$$S = \frac{1}{2} \int d^4x \sum_n \{\partial_\mu \phi_n(x) \partial^\mu \phi_n(x) - m_n^2 \phi_n^2(x)\}$$

$$m_n^2 = m_5^2 + a_n^2$$

$$\partial_y^2 f_n(y) = -a_n^2 f_n(y)$$

$$f_n(y) = c_n \cos(a_n y) + d_n \sin(a_n y)$$

$$f_n(y) = 0 \vee f_n'(y) = 0$$
$$y = 0, R$$

Mass spectrum from boundary conditions (BCs)

Solution → Randall-Sundrum Scenario

Randall, Sundrum, hep-ph/9905221

- Non-trivial metric such that (4D) length scales get contracted differently along fifth dimension → '**warp factor**'

$$\boxed{ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2}$$

$$S_{\mathrm{IR}} \supset \int d^4x\, r \int_{-\pi}^{\pi} d\phi\, \frac{\sqrt{G}}{r^2}\left[G^{\mu\nu}(D_\mu\Phi)^\dagger(D_\nu\Phi) - V(\Phi)\right]\delta(|\phi|-\pi)$$

$$V(\Phi) = \frac{\lambda_5}{2}\left(\Phi^\dagger\Phi - \frac{v_5^2}{2}\right)^2$$

$$v_5 = \sqrt{2\mu_5^2/\lambda_5} \sim M_{\mathrm{Pl}}$$

$$= \int d^4x\sqrt{-\bar{g}}\, e^{-4kr\pi}\left\{e^{2kr\pi}\bar{g}^{\mu\nu}(D_\mu\Phi)^\dagger(D_\nu\Phi) - \frac{\lambda_5}{2}\left(\Phi^\dagger\Phi - \frac{v_5^2}{2}\right)^2\right\}$$

$$\bar{g}_{\mu\nu}(x) \equiv \eta_{\mu\nu} + \bar{h}_{\mu\nu}(x)$$

$$\Phi \to e^{kr\pi}\Phi$$

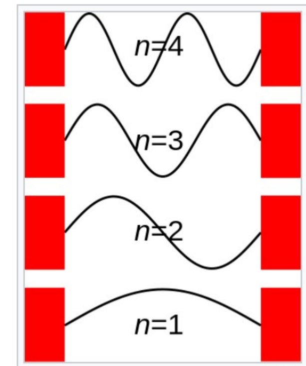
$$= \int d^4x\sqrt{-\bar{g}}\left\{\bar{g}^{\mu\nu}(D_\mu\Phi)^\dagger(D_\nu\Phi) - \frac{\lambda_5}{2}\left(\Phi^\dagger\Phi - e^{-2kr\pi}\frac{v_5^2}{2}\right)^2\right\}$$

$$v = e^{-kr\pi}v_5 \sim \mathrm{TeV}$$

→ **HP solved** (gravitational redshifting)

Kaluza-Klein Decomposition

T. Kaluza, Sitzungsber. Preuss. Akad. Wiss. Berlin, 966 (1921)
O. Klein, Z. Phys.37, 895 (1926)



- In complete analogy to flat case → 5D SM
  (just different metric)
- Light Fermion fields can be localized differently along XD

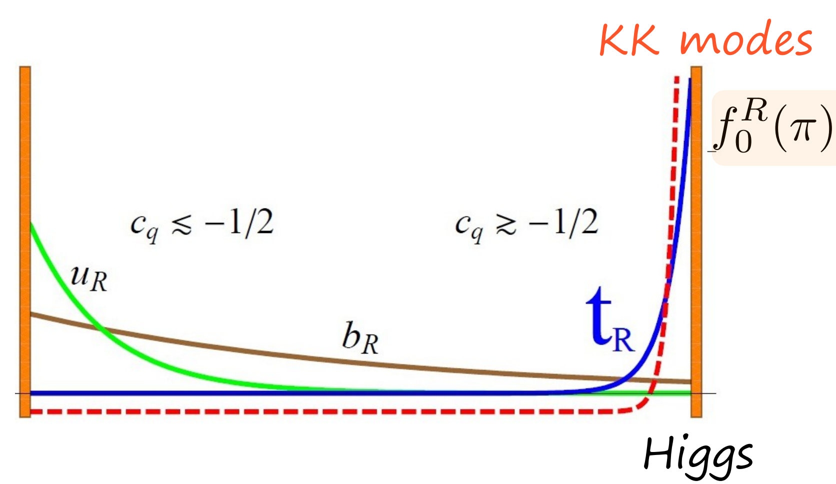
$$S = \int \mathrm{d}^4x \int \mathrm{d}\phi \, \sqrt{G} \left\{ E_a^A \left[\frac{i}{2} \, \bar{\Psi} \gamma^a (\partial_A - \overleftarrow{\partial_A}) \Psi + \frac{\omega_{bcA}}{8} \, \bar{\Psi} \{ \gamma^a, \sigma^{bc} \} \Psi \right] - m \, \mathrm{sgn}(\phi) \, \bar{\Psi} \Psi \right\}$$

- Profiles $f_0^R(\phi) \propto e^{ckr|\phi|}$
  (RH)

$c \equiv -m/k$

$$f_0^R(\pi) \propto \sqrt{\frac{1+2c}{1-\epsilon^{1+2c}}}$$

$\epsilon \equiv e^{-kr\pi} \approx 10^{-16}$



Kaluza-Klein Decomposition

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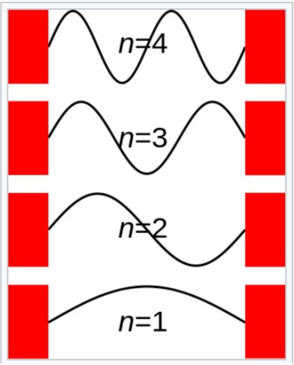

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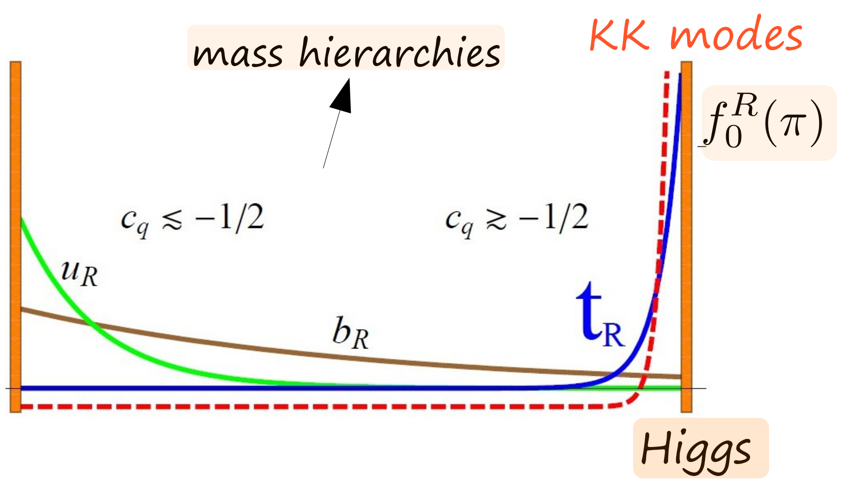
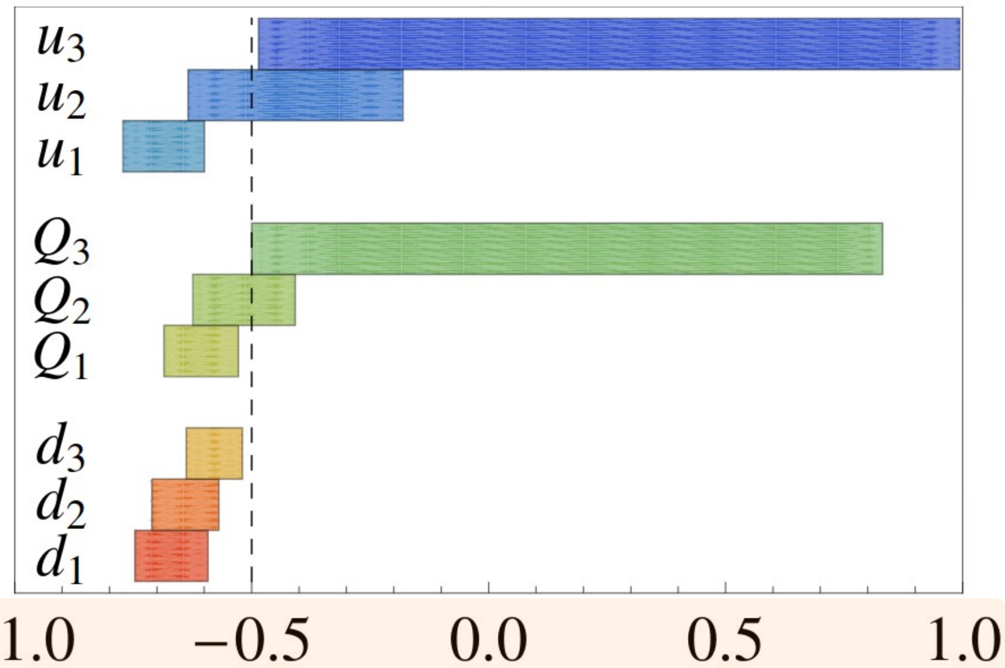


Solution to Flavor Puzzle



Goertz, 1112.6387

$c_{u_i,Q_i,d_i} \sim \mathcal{O}(1)$

- Profiles $f_0^R(\phi) \propto e^{ckr|\phi|}$
  (RH)

$$c \equiv -m/k$$

$$f_0^R(\pi) \propto \sqrt{\frac{1+2c}{1-\epsilon^{1+2c}}}$$

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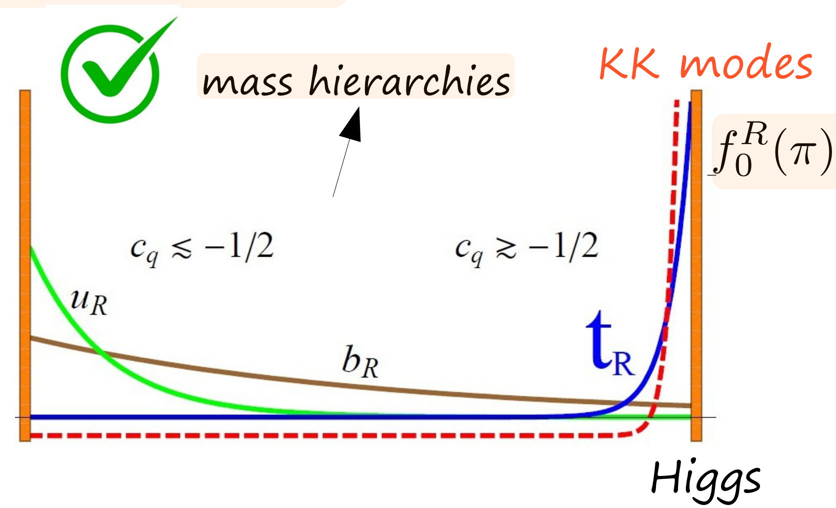
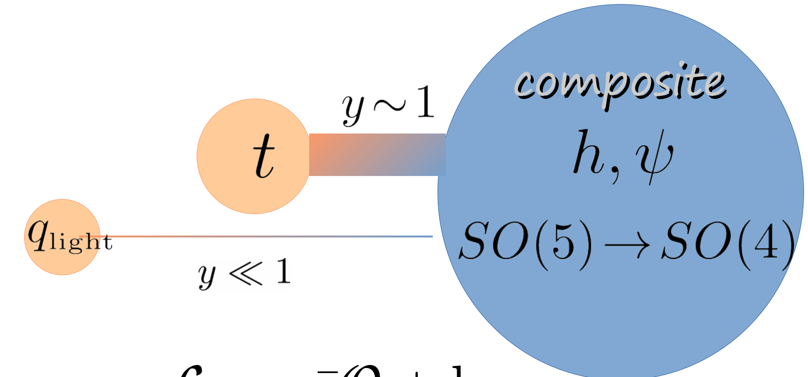


RS - Partial Compositeness

- Addresses the flavor puzzle:

$y^q_{L,R} \sim (\Lambda/\Lambda_{UV})^{\gamma_{L,R}}\,, \qquad \gamma_{L,R} = [\mathcal{O}_{L,R}] - 5/2$

→ Hierarchies generated naturally



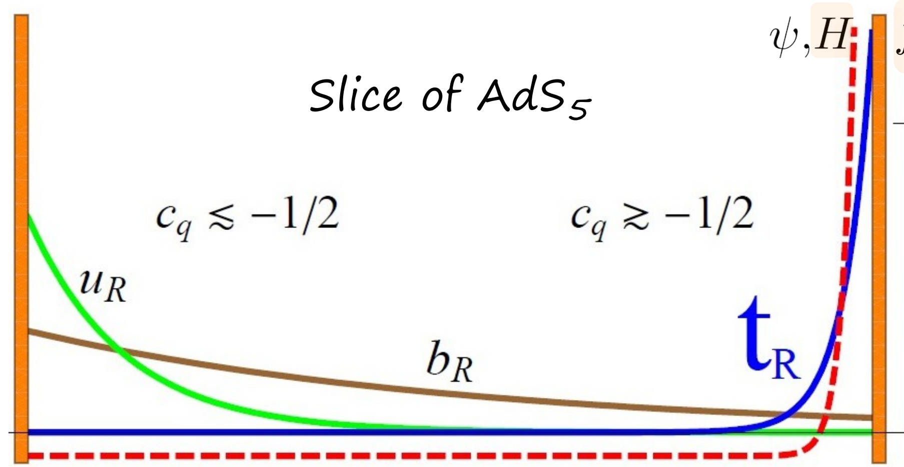
$$\mathcal{L} = y\bar{q}\mathcal{O} + \mathrm{h.c.}$$

$$\gamma_R = |c_R - 1/2| - 1$$

Overlap with Higgs → mass

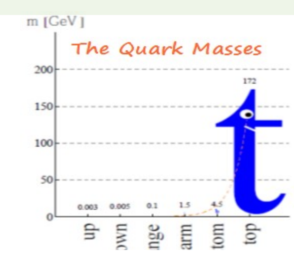
$f^R_0(\pi) \sim (1-\epsilon^{1+2c})^{-1/2}$

Dual picture: Extra Dimension



UV brane: elementary sector

Froggatt-Nielsen-like mass matrices



$$V_{\rm CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

Anomalous Dimensions γ ↔ XD Localization c ↔ FN U(1) charge