Predictions for Composite Higgs models from gauge/gravity dualities

Werner Porod

(Uni. Würzburg)

in coll. with Johanna Erdmenger, Nick Evans, Yang Liu, Kostas Rigatos

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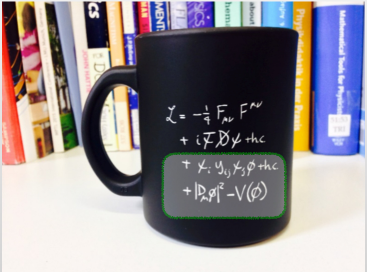
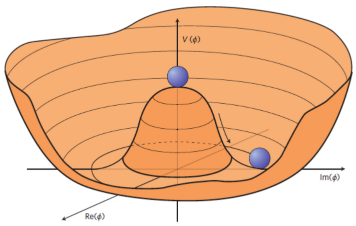
Jobs of the SM-Higgs Multiplet

$$\phi(x) = \frac{1}{\sqrt{2}} e^{i\tau^a \chi^a(x)/v} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

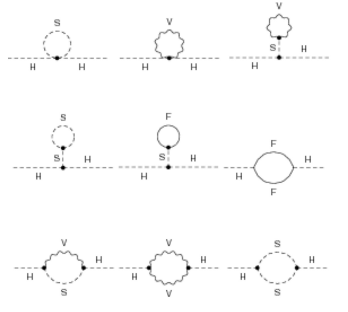
- its non-zero vacuum expectation value V spontaneously breaks the electroweak gauge group $SU(2)_L \times U(1)_Y$ to $U(1)_{em}$
- gives masses to $W^\pm$, Z
- gives masses to the fermions
- bonus: provides one physical scalar h ('the Higgs boson')





Hierarchy problem

In the absence of new symmetries/dynamics: Higgs condensate and Higgs mass are
unstable to quantum corrections & dragged-up to very large energy scales



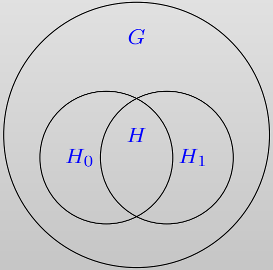
$$\frac{\delta v^2}{v^2} = \sum_i \pm \frac{g_i^2}{16\pi^2} \frac{M_i^2}{v^2} \gg 1$$

M_i: proxy for unknown heavy mass scales (flavour, GUTs, gravity, ...)

‘Minimal Composite Higgs framework’

K. Agashe, R. Contino and A. Pomarol, NPB **719** (2005), 165
R. Contino, TASI lectures 2009

Assumes there is an additional strong force, often called hyper-color, and new ‘quarks’



G: $SO(5) \times U(1)_X$, global symmetry of the strong sector above confinement scale

H_1: $SO(4) \times U(1)_X \sim SU(2)_L \times SU(2)_R \times U(1)_X$, global symmetry group in confined phase

H_0: $SU(2)_L \times U(1)_Y$, SM electroweak gauge group

H: $U(1)_{em}$, unbroken gauge group

- $SO(5) \to SO(4)$ breaking $\Rightarrow$ 4 Nambu-Goldstone bosons in $(2,2)$ of $SU(2)_L \times SU(2)_R$
- $Y = T^{3R} + X$, $U(1)_X$ needed to get correctly the hypercharges of the fermions

‘Minimal Composite Higgs framework’

Fermion masses and couplings: partial compositeness

Higgs transforms non-linearly under G.
$\Rightarrow$ no Yukawa interaction if fermion are elementary (transform linearly).
Possible solution: mix elementary fermions with composite resonances.

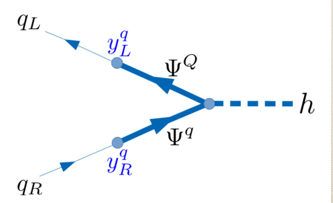
Elementary fermions (in $SO(5)$) rep.)

$$q_L = \frac{1}{\sqrt{2}}(\mathrm{i}\,d_L, d_L, \mathrm{i}\,u_L, -u_L, 0)^T$$

$$q_R = (0, 0, 0, 0, u_R)^T$$

Composite fermions (in $SO(5)$) rep.)

$$\Psi = \frac{1}{\sqrt{2}}\begin{pmatrix} \mathrm{i}B - \mathrm{i}X_{5/3} \\ B + X_{5/3} \\ \mathrm{i}T + \mathrm{i}X_{2/3} \\ -T + X_{2/3} \\ \sqrt{2}\tilde{T} \end{pmatrix}$$



Generic Composite Higgs set-up

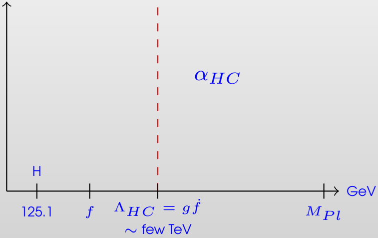
Possible solution to hierarchy problem

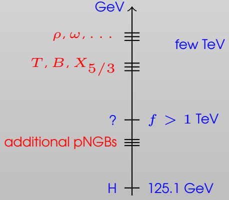
- Generate a scale $\Lambda_{HC} \ll M_{pl}$ through a new confining gauge group
- Interpret Higgs as a pseudo-Nambu-Goldstone boson (pNGB) of a spontaneously broken global symmetry of the new strong sector

(Georgi, Kaplan, PLB **136** (1984), 136)

'Price' to pay

- additional resonances at the scale Λ_{HC} (vectors, vector-like fermions, scalars)
- additional light pNGBs/ extended scalar sector
- deviations of the Higgs couplings from their SM values of O(v/f)



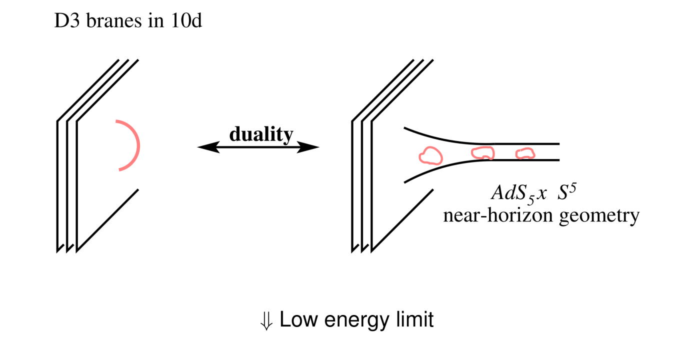


List of "minimal" CHM with fermion UV completions

$G_{\rm HC}$	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	Real	Real	SU(5)/SO(5) × SU(6)/SO(6)				
$SO(N_{\rm HC})$	$5\times\mathbf{S}_2$	$6\times\mathbf{F}$	$N_{\rm HC}\geq 55$	$\frac{5(N_{\rm HC}+2)}{6}$	1/3	/	
$SO(N_{\rm HC})$	$5\times\mathbf{Ad}$	$6\times\mathbf{F}$	$N_{\rm HC}\geq 15$	$\frac{5(N_{\rm HC}-2)}{6}$	1/3	/	
$SO(N_{\rm HC})$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$N_{\rm HC}=7,9$	$\frac{5}{6},\frac{5}{12}$	1/3	$N_{\rm HC}=7,9$	M1, M2
$SO(N_{\rm HC})$	$5\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\rm HC}=7,9$	$\frac{5}{6},\frac{5}{3}$	2/3	$N_{\rm HC}=7,9$	M3, M4
	Real	Pseudo-Real	SU(5)/SO(5) × SU(6)/Sp(6)				
$Sp(2N_{\rm HC})$	$5\times\mathbf{Ad}$	$6\times\mathbf{F}$	$2N_{\rm HC}\geq 12$	$\frac{5(N_{\rm HC}+1)}{3}$	1/3	/	
$Sp(2N_{\rm HC})$	$5\times\mathbf{A}_2$	$6\times\mathbf{F}$	$2N_{\rm HC}\geq 4$	$\frac{5(N_{\rm HC}-1)}{3}$	1/3	$2N_{\rm HC}=4$	M5
$SO(N_{\rm HC})$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$N_{\rm HC}=11,13$	$\frac{5}{24},\frac{5}{48}$	1/3	/	
	Real	Complex	SU(5)/SO(5) × SU(3)^2/SU(3)				
$SU(N_{\rm HC})$	$5\times\mathbf{A}_2$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$N_{\rm HC}=4$	$\frac{5}{3}$	1/3	$N_{\rm HC}=4$	M6
$SO(N_{\rm HC})$	$5\times\mathbf{F}$	$3\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$N_{\rm HC}=10,14$	$\frac{5}{12},\frac{5}{48}$	1/3	$N_{\rm HC}=10$	M7
	Pseudo-Real	Real	SU(4)/Sp(4) × SU(6)/SO(6)				
$Sp(2N_{\rm HC})$	$4\times\mathbf{F}$	$6\times\mathbf{A}_2$	$2N_{\rm HC}\leq 36$	$\frac{1}{3(N_{\rm HC}-1)}$	2/3	$2N_{\rm HC}=4$	M8
$SO(N_{\rm HC})$	$4\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\rm HC}=11,13$	$\frac{8}{3},\frac{16}{3}$	2/3	$N_{\rm HC}=11$	M9
	Complex	Real	SU(4)^2/SU(4) × SU(6)/SO(6)				
$SO(N_{\rm HC})$	$4\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$6\times\mathbf{F}$	$N_{\rm HC}=10$	$\frac{8}{3}$	2/3	$N_{\rm HC}=10$	M10
$SU(N_{\rm HC})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$6\times\mathbf{A}_2$	$N_{\rm HC}=4$	$\frac{2}{3}$	2/3	$N_{\rm HC}=4$	M11
	Complex	Complex	SU(4)^2/SU(4) × SU(3)^2/SU(3)				
$SU(N_{\rm HC})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$N_{\rm HC}\geq 5$	$\frac{4}{3(N_{\rm HC}-2)}$	2/3	$N_{\rm HC}=5$	M12
$SU(N_{\rm HC})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{S}_2,\overline{\mathbf{S}}_2)$	$N_{\rm HC}\geq 5$	$\frac{4}{3(N_{\rm HC}+2)}$	2/3	/	

G. Ferretti, JHEP **06** (2016), 107; A. Belyaev et al. JHEP **01** (2017), 094

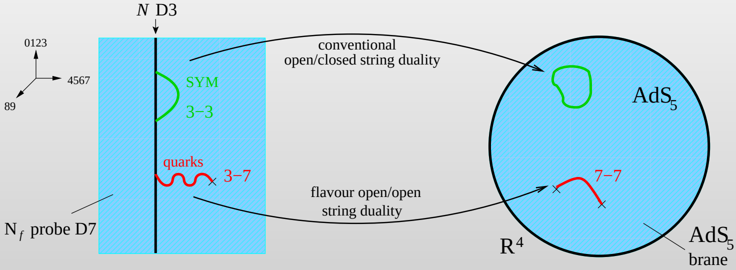
String theory origin of the AdS/CFT correspondence



Supersymmetric $SU(N)$ gauge theory in four dimensions ($N \to \infty$ limit) $\Leftrightarrow$ Supergravity on the space $\text{AdS}_5 \times S^5$

J. M. Maldacena, Adv. Theor. Math. Phys. **2** (1998), 231

Quarks in the AdS/CFT correspondence



(from J. Erdmenger et al, Eur. Phys. J. A **35** (2008), 81)

$N \to \infty$ (standard Maldacena limit), N_f small (probe approximation)

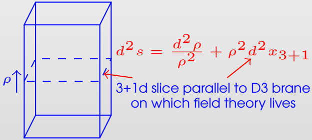
duality acts twice

$\mathcal{N} = 4$ $SU(N)$ Super Yang-Mills theory coupled to $\mathcal{N} = 2$ fundamental hypermultiplet	$\Leftrightarrow$	IIB supergravity on $AdS_5 \times S^5$ + Probe brane DBI on $AdS_5 \times S^3$

A. Karch and E. Katz, JHEP **06** (2002), 043

(DBI: Dirac-Born-Infeld)

How does AdS/CFT work?



$$\sqrt{-\det g} = \left| \begin{pmatrix} -\rho^2 & 0 & 0 & 0 & 0 \\ 0 & \rho^2 & 0 & 0 & 0 \\ 0 & 0 & \rho^2 & 0 & 0 \\ 0 & 0 & 0 & \rho^2 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\rho^2} \end{pmatrix} \right|^{1/2} = \rho^3$$

Field theory side

Operators and sources appear as fields in the bulk, e.g.

$$\int d^4x \, m \, \bar{\psi}\psi$$

m is the quark mass and c the condensate

$$c = \langle \bar{\psi}\psi \rangle$$

AdS side

A field for the mass/condensate

$$\int d^4x \int d\rho \frac{1}{2} \rho^3 (\partial_\rho L)^2$$

$$\Rightarrow \quad \partial_\rho \left(\rho^3 \partial_\rho L \right) = 0$$

$$\Rightarrow L = m + \frac{c}{\rho^2}$$

Running Dimensions in Holography

Holographically we can change the dimension of our operator by adding a mass term

$$\partial_\rho \left(\rho^3 \partial_\rho L\right) - \rho\, \Delta m^2 L = 0 \quad , \quad \gamma(\gamma-2) = \Delta m^2$$
$$\Rightarrow L = \frac{m}{\rho^\gamma} + \frac{c}{\rho^{2-\gamma}}$$

$\Delta m^2 = -1$ corresponds to $\gamma = 1$ and is special – the Breitenlohner Freedman bound instability . . .

So we can include a running coupling by a running mass squared for the scalar.

Top down derivation: many string constructions e.g. probe D7 branes in D3 backgrounds are examples of this . . .

R. Alvares, N. Evans, K.-Young arXiv:1204.2474 (hep-ph); M. Jarvinen, E. Kiritsis arXiv:1112.1261 (hep-ph)

Dynamic AdS/YM

$$S = \int d^4x \int d\rho \, \mathrm{Tr} \left[\frac{1}{\rho^2 + |X|^2} |DX| + \frac{\Delta m^2}{\rho^2} |X|^2 \right]$$

$$X = L(\rho) \mathrm{e}^{2 \mathrm{i} \pi \xi^a(x) T^a} , \qquad d^2 s = \frac{d^2 \rho}{\rho^2 + |X|^2} + (\rho^2 + |X|^2) d^2 x$$

$L = |X|$ is now the dynamical field whose solution will determine the condensate as a function of m - the phase is the pion.

We use the top-down IR boundary condition on mass-shell: $L'(\rho = L) = 0$

X enters into the AdS metric to cut off the radial scale at the value of m or the condensate - no hard wall.
gauge/gravity duality: $X \Leftrightarrow \bar{q} q$

The gauge dynamics is input through a guess for $\Delta m = \gamma(\gamma - 2)$ with

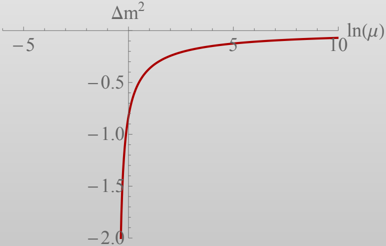
$$\gamma = \frac{3(N_c^2 - 1)}{4 \pi N_c} \alpha$$

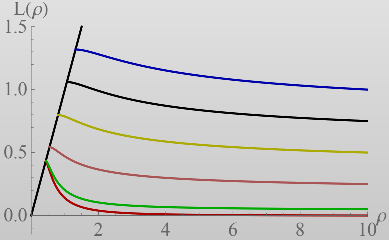
in case of $SU(N_c)$. The only free parameters are $N_c, N_f, m, \Lambda_{UV}$
T. Alho, N. Evans, K. Tuominen arXiv:1307.4896 (hep-ph)

Formation of the Chiral Condensate

We solve for the vacuum configuration of $L = |X| \quad (\equiv v = |\langle H \rangle|)$

$$\partial_\rho \left(\rho^3 \partial_\rho L(\rho)\right) - \rho\, \Delta m^2(\rho) L(\rho) = 0\,, \quad L'(\rho = L) = 0 \quad \text{and} \quad L(\rho) = \rho$$





$N_c = 3, N_f = 2, \mu = \sqrt{\rho^2 + L^2}$; the $L(\rho)$ with a massless UV quark has $L_{IR} = 0.43$; quark masses from top to bottom: 1, 0.75, 0.5, 0.25, 0.05, 0. Here units are set by $\alpha(\rho = 1) = 0.65$.

Meson Fluctuations

$$S = \int d^4x \int d\rho \, \mathrm{Tr} \left[\frac{1}{\rho^2 + |X|^2} |DX| + \frac{\Delta m^2}{\rho^2} |X|^2 \right] + \frac{1}{2\kappa^2} (F_V^2 + F_A^2)$$

$$L = L_0 + \delta(x) e^{ikx} \quad k^2 = -M^2$$

$$\partial_\rho(\rho^3 \partial_\rho \delta) - \Delta m^2 \, \rho \, \delta - \rho \, L_0 \, \delta \frac{\partial \Delta m^2}{\partial L} \Big|_{L_0} + M^2 \frac{\rho^3}{(L_0^2 + \rho^2)^2} \delta = 0$$

The source free solutions pick out particular mass states, the σ (or f_0) and its radial excited states

The gauge fields let us also study the operators and states

$\bar{u}\gamma_\mu u \to \rho$ meson , $\bar{u}\gamma_\mu\gamma_5 u \to a$ meson

QCD Dynamics – $N_c = 3, N_f = 2, m_q = 0$

$$\mu \frac{d\alpha}{d\mu} = -b_0 \alpha^2 \qquad b_0 = \frac{1}{6\pi}\left(11N_c - (N_f + \bar{N}_f)\right), \qquad \gamma = \frac{3({N_c}^2 - 1)}{4N_c \pi}\alpha\,.$$

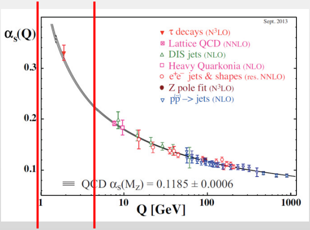
Two-loop contributions included as well

Observables (MeV)	QCD	AdS/SU(3) 2 F 2 $\bar{F}$	Deviation
M_ρ	775	775*	fitted
M_A	1230	1183	- 4%
M_S	500/990	973	+64%/-2%
M_B	938	1451	+43%
f_π	93	55.6	-50%
f_ρ	345	321	- 7%
f_A	433	368	-16%
$M_{\rho,n=1}$	1465	1678	+14%
$M_{A,n=1}$	1655	1922	+19%
$M_{S,n=1}$	990 /1200-1500	2009	+64%/+35%
$M_{B,n=1}$	1440	2406	+50%

The predictions for masses and decay constants (in MeV) for $N_f = 2$ massless QCD. The ρ-meson mass has been used to set the scale (indicated by the *).

- scale fixed by V-meson
- f_π needs a mass term
- baryon mass high
- radial exitations wrong – no string physics included

Perfecting with HDOs



The weakly coupled gravity dual should only live between the red lines
probably we need HDOs at the UV scale to include matching effect and stringy effects in the gravity model

$$\frac{g_S^2}{\Lambda_{UV}^2}|\bar{q}q|^2 \quad \frac{g_V^2}{\Lambda_{UV}^2}|\bar{q}\gamma^\mu q|^2 \quad \frac{g_A^2}{\Lambda_{UV}^2}|\bar{q}\gamma^\mu\gamma_5 q|^2$$

$$\frac{g_B^2}{\Lambda_{UV}^5}|qqq|^2$$

Observables (MeV)	QCD	Dynamic AdS/QCD	HDO coupling
M_V	775	775	sets scale
M_A	1230	1230	fitted by $g_A^2 = 5.76149$
M_S	500/990	597	prediction $+20\%/-40\%$
M_B	938	938	fitted by $g_B^2 = 25.1558$
f_π	93	93	fitted by $g_S^2 = 4.58981$
f_V	345	345	fitted by $g_V^2 = 4.64807$
f_A	433	444	prediction $+2.5\%$
$M_{V,n=1}$	1465	1532	prediction $+4.5\%$
$M_{A,n=1}$	1655	1789	prediction $+8\%$
$M_{S,n=1}$	990/1200-1500	1449	prediction $+46\%/0\%$
$M_{B,n=1}$	1440	1529	prediction $+6\%$

The spectrum and the decay constants for two-flavour QCD with HDOs used to improve the spectrum.

Pretty good
but we've lost some
predictivity

Gauge group $Sp(4)$, 4F, $6A_2$, global: $SU(4) \times SU(6)/Sp(4) \times SO(6)$

M8 model of previous list

- The sextet quarks A_2 are expected to condense first and break $SU(6) \to SO(6)$. Their main job: form FA_2F baryon top partners.
- Then the fundamentals F break $SU(4) \to Sp(4)$ – this is where the Higgs is generated. (It's the same condensation as in QCD)

$$b_0 = \frac{1}{6\pi}\left(11(N+1) - N_{f_1} - 2(N-1)N_{f_2}\right)$$

$$\gamma_{A_2} = \frac{3}{2\pi} N\alpha\,,$$

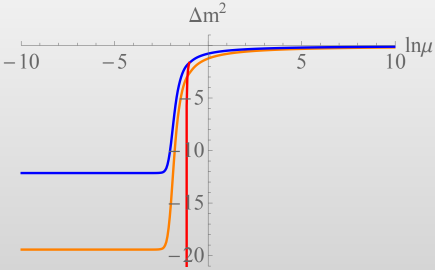
$$\gamma_F = \frac{3}{2\pi}\frac{2N+1}{4}\alpha\,,$$

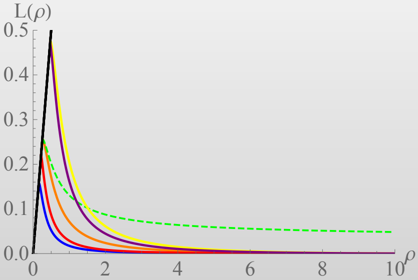
with $N = 4$, $N_{f_1} = 4$ and $N_{f_2} = 6$ (two-loop contributions included as well)

These fix Δm^2 and hence the model

Quenching: set $N_{f_1} = N_{f_2} = 0$ in b_i

Gauge group $Sp(4)$, 4F, $6A_2$, global: $SU(4) \times SU(6)/Sp(4) \times SO(6)$





- blue line: F
- orange line: A_2
- red line: F but A_2 integrated out when it condensates
- dashed green: F + additional NJL-terms such that it matches in the IR the A_2 representation.
- yellow line: quenched models for the A_2
- purple line: quenched models for the F

How to decouple the quarks is important and unknown

Gauge group $Sp(4)$, 4F, $6A_2$, global: $SU(4) \times SU(6)/Sp(4) \times SO(6)$

	AdS/$Sp(4)$ no decouple	AdS/$Sp(4)$ A2 decouple	AdS/$Sp(4)$ quench	lattice[a] quench	lattice[b] unquench
$f_{\pi A_2}$	0.120	0.120	0.103	0.1453(12)	
$f_{\pi F}$	0.0569	0.0701	0.0756	0.1079(52)	0.1018(83)
$M_{V A_2}$	1*	1*	1*	1.000(32)	
$f_{V A_2}$	0.517	0.517	0.518	0.508(18)	
$M_{V F}$	0.61	0.814	0.962	0.83(19)	0.83(27)
$f_{V F}$	0.271	0.364	0.428	0.411(58)	0.430(86)
$M_{A A_2}$	1.35	1.35	1.28	1.75 (13)	
$f_{A A_2}$	0.520	0.520	0.524	0.794(70)	
$M_{A F}$	0.938	1.19	1.36	1.32(18)	1.34(14)
$f_{A F}$	0.303	0.399	0.462	0.54(11)	0.559(76)
$M_{S A_2}$	0.375	0.375	1.14	1.65(15)	
$M_{S F}$	0.325	0.902	1.25	1.52 (11)	1.40(19)
$M_{B A_2}$	1.85	1.85	1.86		
$M_{B F}$	1.13	1.53	1.79		

[a] Ed Bennett et al., PRD **101** (2020), 074516; [b] Ed Bennett et al., JHEP **12** (2019), 053

Gauge group $Sp(4)$, 4F, $6A_2$, global: $SU(4) \times SU(6)/Sp(4) \times SO(6)$

	AdS/$Sp(4)$ no decouple	AdS/$Sp(4)$ A2 decouple	AdS/$Sp(4)$ quench	lattice[a] quench	lattice[b] unquench
$f_{\pi A_2}$	0.120	0.120	0.103	0.1453(12)	
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$M_{V A_2}$	1*	1*	1*	1.000(32)	
$f_{V A_2}$	0.517	0.517	0.518	0.508(18)	
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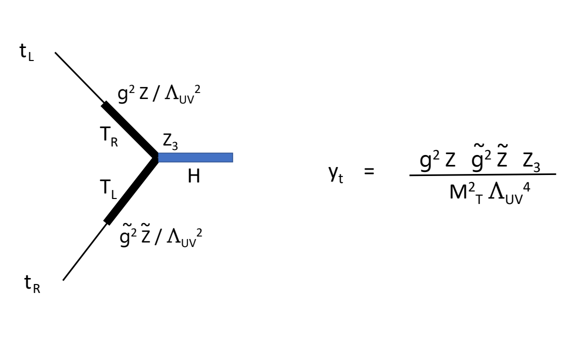
$M_{B A_2}$	1.85	1.85	1.86		
$M_{B F}$	1.13	1.53	1.79		

[a] Ed Bennett et al., PRD **101** (2020), 074516; [b] Ed Bennett et al., JHEP **12** (2019), 053

Gauge group $Sp(4)$, 4F, $6A_2$, global: $SU(4) \times SU(6)/Sp(4) \times SO(6)$

Top Yukawa coupling:



Plausible forms for the Z factors up to O(1) couplings
(this is beyond quadratic order in the holographic model)

$$Z_3 \simeq \int d\rho\, \rho^3 \frac{\partial_\rho \pi(\rho)\, \psi_B(\rho)^2}{(\rho^2 + L^2)^2}\,, \qquad Z = \tilde{Z} \simeq \int d\rho\, \rho^3 \partial_\rho \psi_B(\rho)$$

$\Rightarrow Y_t \simeq 0.01 - 0.1$ naturally if $\Lambda_{UV} \simeq$ few TeV

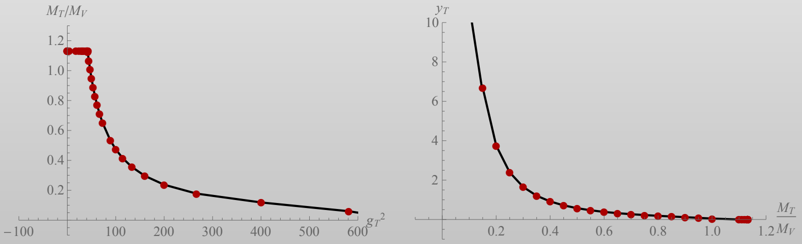
Confirmed on the lattice

Gauge group $Sp(4)$, 4F, $6A_2$, global: $SU(4) \times SU(6)/Sp(4) \times SO(6)$

Important: We can lower the top partner mass using a HDO

$$\mathcal{L}_{HDO} = \frac{g_T^2}{\Lambda_{UV}^5} |F A_2 F|^2 \,.$$

which raises Y_t:



This is a new mechanism to generate the large top mass in these models – drives the top partner baryon mass to half the vector meson mass

- We have holographic models that describe chiral symmetry breaking due to the running of γ and NJL interactions
- compare to lattice results and look for changes as we unquench, and extra flavours beyond the lattice
- We have proposed a new HDO method to raise the top Yukawa coupling in these models
- What next:
  - exploration of effect on top-partner bounds taking obtained mass ratios as guide-line
  - non-Abelian DBI to get mass splitting between different representations of unbroken flavour sub-group, first step done by considering QCD with 3 flavours

non-abelian DBI action, $m_u = m_d = 2.3$ MeV, $m_s = 95$ MeV

Observables	QCD (MeV)	$N_f = 3$ Numerics (MeV)	Deviation
$\rho(770), \omega(782)$	775.26 ± 0.23	775*	fitted
$K^*(892)$	891.67 ± 0.26	966	8%
$\phi(1020)$	1019.461 ± 0.016	1120	9%
$a_1(1260), f_1(1260)$	1230 ± 40	1103	11%
$K_1(1400)$	1403 ± 7	1432	2%
$f_1(1420)$	1426.3 ± 0.9	1847	26%
$a_0(980), f_0(980)$	980 ± 20	930	5%
$K_0^*(700)$	845 ± 17	987	16%
$f_0(1370)$ (?)	1370	1031	28%
$\pi^{0,\pm}$	139.57039 ± 0.00017	128	9%
$K^{0,\pm}$	497.611 ± 0.013	497	O(0.1) %

J. Erdmenger, N. Evans, Y. Liu, WP, arXiv:2304.09190

Towards underlying models

A wish list to construct and classify candidate models:
Gerghetta et al (2015), Ferretti et al. PLB (2014), PRD 94 (2016), JHEP 1701.094

Underlying models of a composite Higgs should

- contain no elementary scalars (otherwise there would be again a hierarchy problem)
- have a simple hyper-color group
- have a Higgs candidate amongst the pNGBs of the bound states
- have a top-partner amongst its bound states
  (for top mass via partial compositeness)
- satisfy further 'standard' consistency conditions (asymptotic freedom, no gauge anomalies)

The resulting models have several common features:

- All models predict pNGBs beyond the Higgs multiplet
- All models contain several top partner multiplets

Example: HC = $Sp(2N_c)$, electroweak coset $SU(4)/Sp(4)$, strong coset $SU(6)/SO(6)$

Field content of the underlying model

	$Sp(2N_c)$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$SU(4)$	$SU(6)$	$U(1)_X$
ψ_1 ψ_2	$\square$	$\mathbf{1}$	$\mathbf{2}$	0	**4**	**1**	$-3(N_c-1)q_\chi$
ψ_3	$\square$	$\mathbf{1}$	$\mathbf{1}$	$1/2$			
ψ_4	$\square$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$			
χ_1 χ_2 χ_3	$\begin{array}{c}\square\\\square\end{array}$	$\mathbf{3}$	$\mathbf{1}$	x	**1**	**6**	q_χ
χ_4 χ_5 χ_6	$\begin{array}{c}\square\\\square\end{array}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-x$			

Bound states of the model

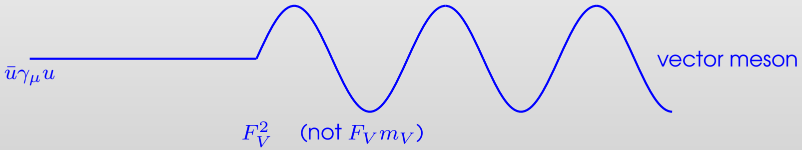
	spin	$SU(4)\times SU(6)$	$Sp(4)\times SO(6)$	names
$\psi\psi$	0	$(\mathbf{6},\mathbf{1})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{5},\mathbf{1})$	σ π
$\chi\chi$	0	$(\mathbf{1},\mathbf{21})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{1},\mathbf{20})$	σ_c π_c
$\chi\psi\psi$	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_1^1 ψ_1^5
$\chi\bar\psi\bar\psi$	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_2^1 ψ_2^5
$\psi\bar\chi\bar\psi$	1/2	$(\mathbf{1},\bar{\mathbf{6}})$	$(\mathbf{1},\mathbf{6})$	ψ_3
$\psi\bar\chi\bar\psi$	1/2	$(\mathbf{15},\bar{\mathbf{6}})$	$(\mathbf{5},\mathbf{6})$ $(\mathbf{10},\mathbf{6})$	ψ_4^5 ψ_4^{10}
$\bar\psi\sigma^\mu\psi$	1	$(\mathbf{15},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$ $(\mathbf{10},\mathbf{1})$	a ρ
$\bar\chi\sigma^\mu\chi$	1	$(\mathbf{1},\mathbf{35})$	$(\mathbf{1},\mathbf{20})$ $(\mathbf{1},\mathbf{15})$	a_c ρ_c

G. Cacciapaglia et al, JHEP **11** (2015) 201

Decay Constants

a la AdS/QCd, see J. Erlich, E. Katz, D. T. Son and M. A. Stephanov, PRL **95** (2005), 261602

Decay constants are determined by allowing a source to couple to a physical state



Now we need to fix the normalizations of the holographic linear perturbations . . .

For the physical states we canonically normalize the kinetic terms. . .

For the source solutions we fix κ and the norms so that we match perturbative results for e.g. Π_{VV} in the UV

$$N_V^2 = N_A^2 = \frac{g_5^2 d(R)\, N_f(R)}{48\pi^2}$$

Baryons

In D3/D7 system some quark-gaugino-quark tri-fermion states are described by world volume fermions on the D7 – it does not seem unreasonable to include three quark states in this way therefore

$$S_{1/2} = \int d^4x \int \rho\, \rho^3 \bar{\Psi}(\not{D}_{AdS} - m)\Psi$$

The four component fermion satisfies the second order equation

$$\left(\partial_\rho^2 + \mathcal{P}_1 \partial_\rho + \frac{M_B^2}{r^4} + \mathcal{P}_2 \frac{1}{r^4} - \frac{m^2}{r^2} - \mathcal{P}_3 \frac{m}{r^3}\, \gamma^\rho \right) \psi = 0\,,$$

where M_B is the baryon mass and

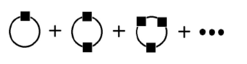
$$\mathcal{P}_1 = \frac{6}{r^2}\left(\rho + L_0\, \partial_\rho L_0\right)\,,$$
$$\mathcal{P}_2 = 2\left((\rho^2 + L_0^2) L \partial_\rho^2 L_0 + (\rho^2 + 3L_0^2)(\partial_\rho L_0)^2 + 4\rho L_0 \partial_\rho L_0 + 3\rho^2 + L_0^2 \right)\,,$$
$$\mathcal{P}_3 = \left(\rho + L_0\, \partial_\rho L_0\right)\,.$$

G. F. de Teramond and S. J. Brodsky, PRL **94** (2005), 201601; R. Abt, J. Erdmenger, N. Evans and K. S. Rigatos, JHEP **11** (2019), 160

Higher Dimension/Nambu Jona-Lasinio Operators

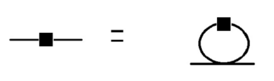
$$\mathcal{L} = \bar{\psi}_L \partial\!\!\!/ \psi_L + \bar{\psi}_R \partial\!\!\!/ \psi_R + \frac{g^2}{\Lambda_{UV}} \bar{\psi}_L \psi_R \bar{\psi}_R \psi_L$$

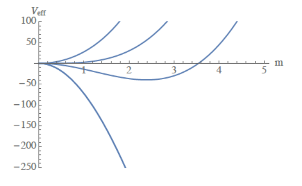
Calculate effective potential

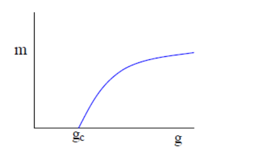


$$\Delta V_{eff} = -\int_0^{\{} \Lambda_{UV} \frac{d^4k}{(2\pi)^4} \mathrm{Tr} \log(k^2 + m^2)$$

$$\frac{g^2}{\Lambda_{UV}} \bar{\psi}_L \psi_R \bar{\psi}_R \psi_L \to \frac{g^2}{\Lambda_{UV}} \langle \bar{\psi}_L \psi_R \rangle \bar{\psi}_R \psi_L \to \frac{m^2 \Lambda_{UV}}{g^2}$$







Witten's Multi-Trace Operator Prescription

E. Witten hep-th/0112258; N. Evans + K. Kim arXiv:1601.02824 (hep-th)

$$\frac{g^2}{\Lambda_{UV}} \bar{\psi}_L \psi_R \bar{\psi}_R \psi_L \to \frac{g^2}{\Lambda_{UV}} \langle \bar{\psi}_L \psi_R \rangle \bar{\psi}_R \psi_L \to \frac{m^2 \Lambda_{UV}}{g^2}$$

so add

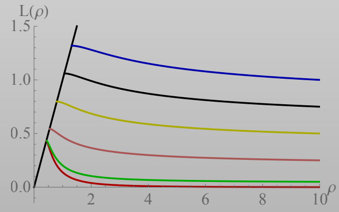
$$S = \int \mathcal{L} + \frac{L^2 \rho^2}{g^2}\Big|_{\Lambda_{UV}}$$

On variation

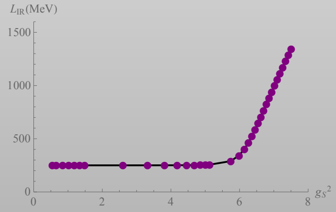
$$0 = \text{E.-L. eqn} + \frac{\partial \mathcal{L}}{\partial L'} \delta L \Big|_{\Lambda_{IR,UV}} + \frac{2L\rho^2}{g^2} \delta L \Big|_{\Lambda_{UV}}$$

The Euler Lagrange equation solutions are left unchanged but we pick those that satisfy the UV and IR boundary conditions. Now we let the mass vary in the UV and need

$$m = \frac{g^2}{\Lambda_{UV}} c$$



Read off m, c and compute g



$SU(4), 3F, 3\,\bar{F}, 5A_2$; $SU(5) \times SU(3)_L \times SU(3)_R / SO(5) \times SU(3)$

(G. Ferretti, JHEP **06** (2014), 142)

Here the A_2 symmetry breaking generates the SM Higgs; FA_2F top partners

	Lattice[a] $4A_2, 2F, 2\bar{F}$ unquench	AdS/$SU(4)$ $4A_2, 2F, 2\bar{F}$ no decouple	AdS/$SU(4)$ $4A_2, 2F, 2\bar{F}$ decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ no decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ quench
$f_{\pi A_2}$	0.15(4)	0.0997	0.0997	0.111	0.111	0.102
$f_{\pi F}$	0.11(2)	0.0949	0.0953	0.0844	0.109	0.892
$M_{V A_2}$	1.00(4)	1*	1*	1*	1*	1*
$f_{V A_2}$	0.68(5)	0.489	0.489	0.516	0.516	0.517
$M_{V F}$	0.93(7)	0.933	0.939	0.890	0.904	0.976
$f_{V F}$	0.49(7)	0.458	0.461	0.437	0.491	0.479
$M_{A A_2}$		1.37	1.37	1.32	1.32	1.28
$f_{A A_2}$		0.505	0.505	0.521	0.521	0.522
$M_{A F}$		1.37	1.37	1.21	1.23	1.28
$f_{A F}$		0.501	0.504	0.453	0.509	0.492
$M_{S A_2}$		0.873	0.873	0.684	0.684	1.18
$M_{S F}$		1.03	1.02	0.811	0.798	1.25
$M_{J A_2}$	3.9(3)	2.21	2.21	2.21	2.21	2.22
$M_{J F}$	2.0(2)	2.07	2.08	1.97	2.00	2.17
$M_{B A_2}$	1.4(1)	1.85	1.85	1.85	1.85	1.86
$M_{B F}$	1.4(1)	1.74	1.75	1.65	1.68	1.81

[a] V. Ayyar et al., PRD **97** (2018), 074505: (unquenched) $SU(4)\ 2F, 2\bar{F}, 4A_2$

- pattern agree quite well in particular M_{VF} and M_{JF}
- M_{JA_2} off and also M_{BF} on the lattice below our estimate

$SU(4), 3F, 3\ \bar{F}, 5A_2$; $SU(5) \times SU(3)_L \times SU(3)_R/SO(5) \times SU(3)$

	Lattice[a] $4A_2, 2F, 2\bar{F}$ unquench	AdS/$SU(4)$ $4A_2, 2F, 2\bar{F}$ no decouple	AdS/$SU(4)$ $4A_2, 2F, 2\bar{F}$ decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ no decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ decouple	AdS/$SU(4)$ $5A_2, 3F, 3\bar{F}$ quench
$f_{\pi A_2}$	0.15(4)	0.0997	0.0997	0.111	0.111	0.102
$f_{\pi F}$	0.11(2)	0.0949	0.0953	0.0844	0.109	0.892
$M_{V A_2}$	1.00(4)	1*	1*	1*	1*	1*
$f_{V A_2}$	0.68(5)	0.489	0.489	0.516	0.516	0.517
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$M_{J F}$	2.0(2)	2.07	2.08	1.97	2.00	2.17
$M_{B A_2}$	1.4(1)	1.85	1.85	1.85	1.85	1.86
$M_{B F}$	1.4(1)	1.74	1.75	1.65	1.68	1.81

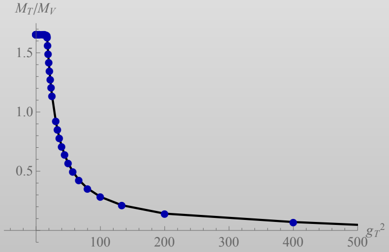
- Adding extra flavours is not a huge change
- Scalar masses get lighter by adding extra flavours

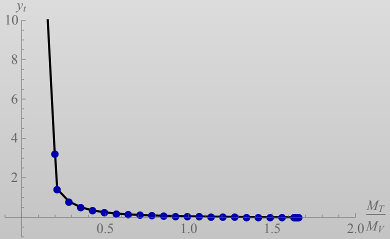
$SU(4), 3F, 3\,\bar{F}, 5A_2;\ SU(5) \times SU(3)_L \times SU(3)_R/SO(5) \times SU(3)$

Top Yukawa coupling: similar as before, need additional HDO

$$\mathcal{L}_{HDO} = \frac{g_T^2}{\Lambda_{UV}^5} |F A_2 F|^2 \,.$$

which raises Y_t:





This is a new mechanism to generate the large top mass in these models – we drive the top partner baryon mass to about $1/3$ the vector meson mass