

# Applying gauge/gravity duality to Composite Higgs models

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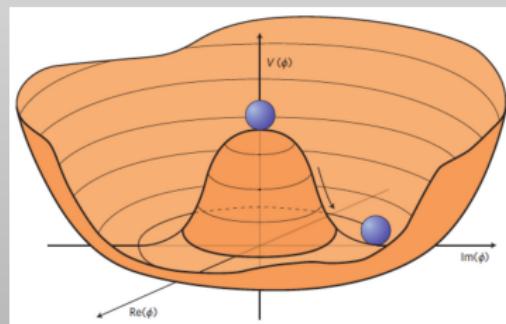
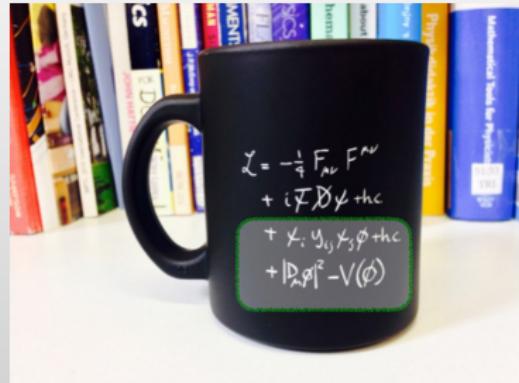
PRL **126** (2021), 071602, JHEP **02** (2021), 058

XVth Quark Confinement and the Hadron Spectrum conference  
4 August 2022

# Jobs of the SM-Higgs Multiplet

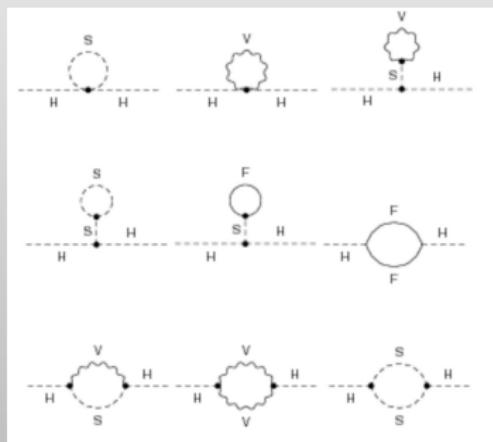
$$\phi(x) = \frac{1}{\sqrt{2}} e^{i\tau^a \chi^a(x)/v} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

- ▶ 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



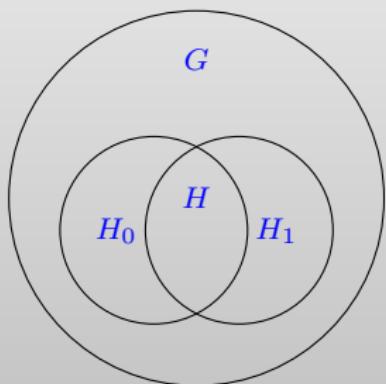
$$\frac{\delta v^2}{v^2} = \sum_i \pm \frac{g_i^2}{16\pi^2} \frac{M_i^2}{v^2} \gg 1$$

$M_i$ : 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

- $SO(5) \rightarrow SO(4)$  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  $G$ .

→ no Yukawa interaction if fermion are elementary (transform linearly).

Possible solution: mix elementary fermions with composite resonances.

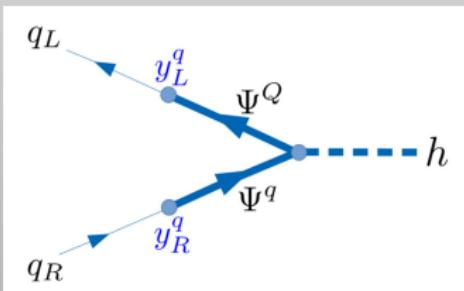
Elementary fermions (in  $SO(5)$ ) rep.)

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

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

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

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



# Generic Composite Higgs set-up

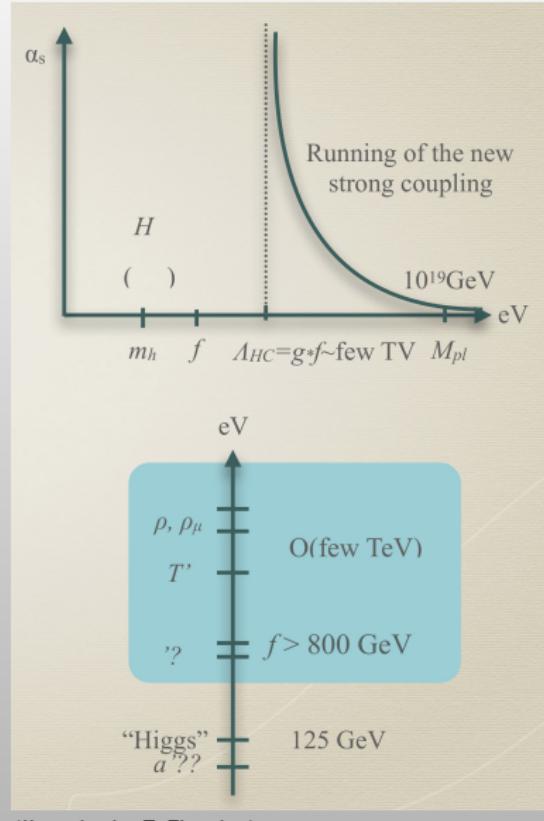
Possible solution to hierarchy problem

- ▶ 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)

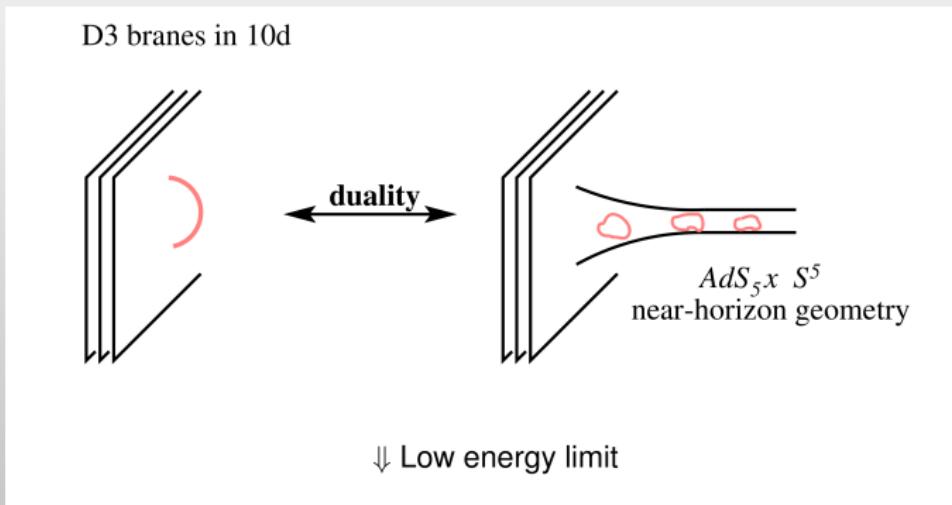
'Price' to pay

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



(thanks to T. Flacke)

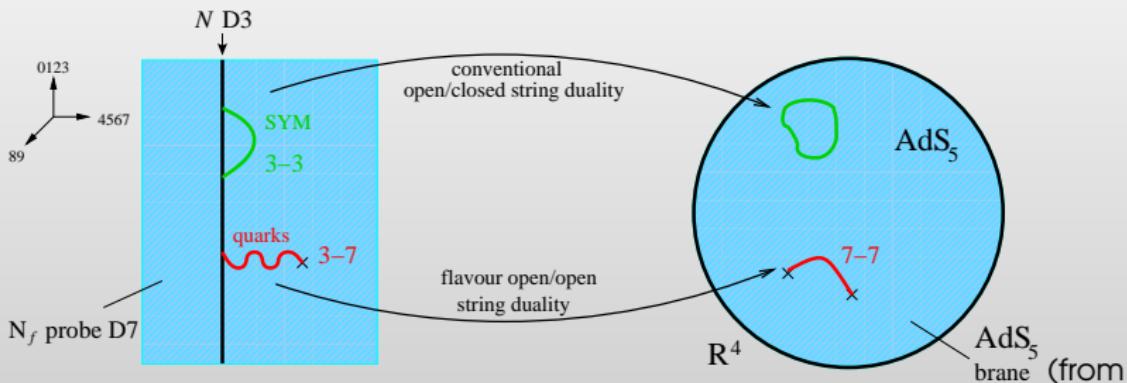
# String theory origin of the AdS/CFT correspondence



Supersymmetric  $SU(N)$  gauge theory in four dimensions ( $N \rightarrow \infty$  limit)  $\Leftrightarrow$  Supergravity on the space  $AdS_5 \times S^5$

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

# Quarks in the AdS/CFT correspondence



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

$N \rightarrow \infty$  (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

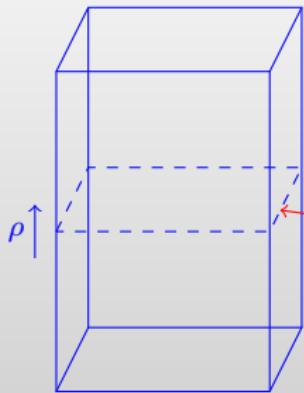
↔

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?



$$d^2 s = \frac{d^2 \rho}{\rho^2} + \rho^2 d^2 x_{3+1}$$

3+1d slice parallel to D3 brane  
on which field theory lives



dilation  $\Leftrightarrow$  running of gauge couplings

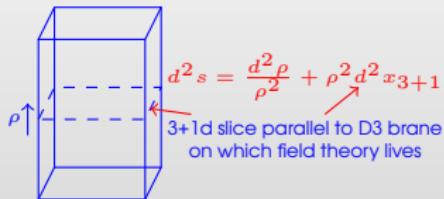
$$\int d^4 x \partial_\mu \phi \partial^\mu \phi, \quad x \rightarrow e^{-\alpha} x \quad \phi \rightarrow e^\alpha \phi$$

dilaton become spacetime symmetry of AdS

$$\rho \rightarrow e^\alpha \rho$$

$\rho$  is a continuous mass dimension  $\rightarrow$  RG scale

# How does AdS/CFT work?



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

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

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

AdS side

A field for the mass/condensate

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

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

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



# Running Dimensions in Holography

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

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

$\Delta m^2 = -1$  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 ...

Very complex geometries describe the gauge theory glue-dynamic ... a single quark in that background is described by a field such as this with the running of the mass determined by the gluon-dynamics ...

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

# Dynamic AdS/YM

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

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

$L = |X|$  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

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

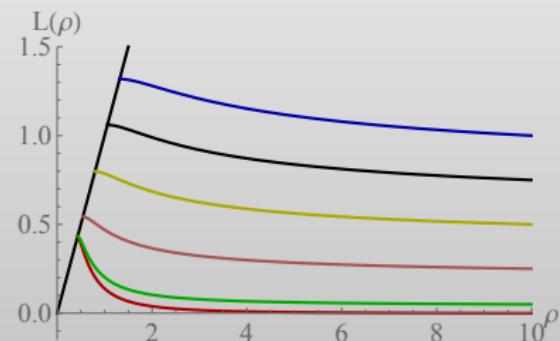
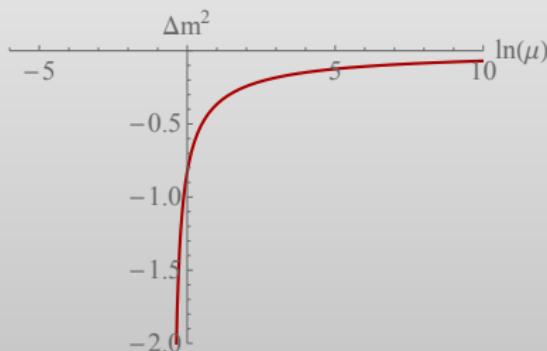
in case of  $SU(N_c)$ . The only free parameters are  $N_c, N_f, m, \Lambda_{UV}$

T. Alho, N. Evans, K. Tuominen arXiv:1307.4896 (hep-ph)

# Formation of the Chiral Condensate

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

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



$N_c = 3, N_f = 2, \mu = \sqrt{\rho^2 + L^2}$ ; 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

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

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

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

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

The gauge fields let us also study the operators and states

$$\bar{u} \gamma_\mu u \rightarrow \rho \text{ meson} , \quad \bar{u} \gamma_\mu \gamma_5 u \rightarrow a \text{ meson}$$

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

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

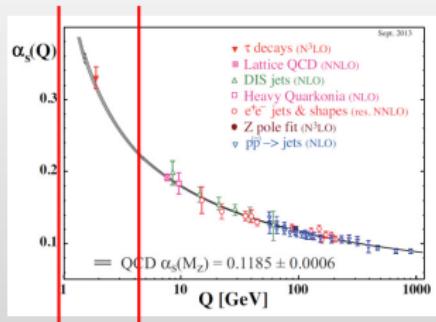
Two-loop contribution included as well

Observables (MeV)	QCD	AdS/SU(3) 2 F 2 $\bar{F}$	Deviation
$M_\rho$	775	775*	fitted
$M_A$	1230	1183	- 4%
$M_S$	500/990	973	+64%/-2%
$M_B$	938	1451	+43%
$f_\pi$	93	55.6	-50%
$f_\rho$	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%

- ▶ scale fixed by  $V$ -meson
- ▶  $f_\pi$  needs a mass term
- ▶ baryon mass high
- ▶ radial excitations wrong – no string physics included

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

# 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

$$\begin{aligned} & \frac{g_S^2}{\Lambda_{UV}^2} |\bar{q}q|^2 \quad \frac{g_V^2}{\Lambda_{UV}^2} |\bar{q}\gamma^\mu q|^2 \quad \frac{g_A^2}{\Lambda_{UV}^2} |\bar{q}\gamma^\mu \gamma_5 q|^2 \\ & \frac{g_B^2}{\Lambda_{UV}^5} |qqq|^2 \end{aligned}$$

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 $g_B^2 = 25.1558$
$f_\pi$	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 $+6\%$

Pretty good  
but we've lost some  
predictivity

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

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

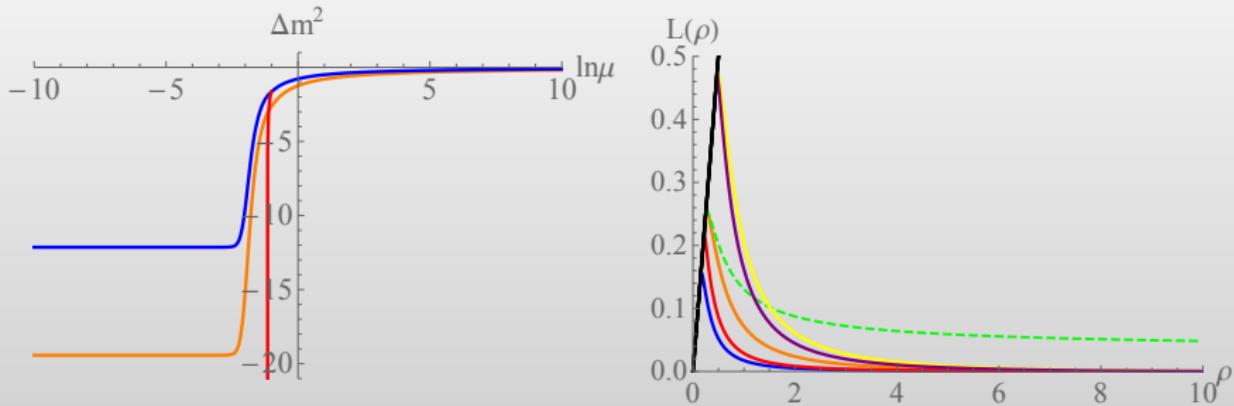
- ▶ The sextet quarks  $A_2$  are expected to condense first and break  $SU(6) \rightarrow SO(6)$ . Their main job: form  $FA_2F$  baryon top partners.
- ▶ Then the fundamentals  $F$  break  $SU(4) \rightarrow Sp(4)$  – this is where the Higgs is generated. (It's the same condensation as in QCD)

$$\begin{aligned}b_0 &= \frac{1}{6\pi} \left( 11(N+1) - N_{f_1} - 2(N-1)N_{f_2} \right) \\ \gamma_{A_2} &= \frac{3}{2\pi} N \alpha, \\ \gamma_F &= \frac{3}{2\pi} \frac{2N+1}{4} \alpha,\end{aligned}$$

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

These fix  $\Delta m^2$  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 condenses
- ▶ 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 you 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 <sup>a</sup> quench	lattice <sup>b</sup> 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)
$M_{VA_2}$	1*	1*	1*	1.000(32)	
$f_{VA_2}$	0.517	0.517	0.518	0.508(18)	
$M_{VF}$	0.61	0.814	0.962	0.83(19)	0.83(27)
$f_{VF}$	0.271	0.364	0.428	0.411(58)	0.430(86)
$M_{AA_2}$	1.35	1.35	1.28	1.75 (13)	
$f_{AA_2}$	0.520	0.520	0.524	0.794(70)	
$M_{AF}$	0.938	1.19	1.36	1.32(18)	1.34(14)
$f_{AF}$	0.303	0.399	0.462	0.54(11)	0.559(76)
$M_{SA_2}$	0.375	0.375	1.14	1.65(15)	
$M_{SF}$	0.325	0.902	1.25	1.52 (11)	1.40(19)
$M_{BA_2}$	1.85	1.85	1.86		
$M_{BF}$	1.13	1.53	1.79		

<sup>a</sup> Ed Bennett et al., PRD **101** (2020), 074516; <sup>b</sup> Ed Bennett et al., JHEP **12** (2019), 053

- ▶ We set the scale in the  $A_2$  sector  
the pattern of mass scales is right  
 $A, S$  meson sectors are a little light
- ▶ The  $F$  sector is lighter than the  $A_2$ s and then also in the right pattern

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

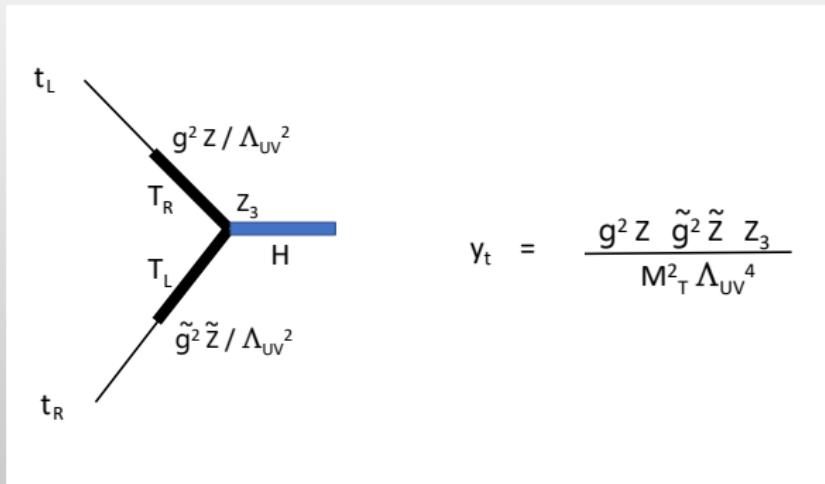
	AdS/ $Sp(4)$ no decouple	AdS/ $Sp(4)$ A2 decouple	AdS/ $Sp(4)$ quench	lattice <sup>a</sup> quench	lattice <sup>b</sup> unquench
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<sup>a</sup> Ed Bennett et al., PRD **101** (2020), 074516; <sup>b</sup> Ed Bennett et al., JHEP **12** (2019), 053

- ▶ holographic modeling useful to study effect of changes in the running
- ▶ the gap between the  $F$  and  $A_2$  sector grows (in particular if  $A_2$  not decoupled)
- ▶ the slower the running the lighter the scalar mass becomes – is the biggest change
- ▶ prediction for baryons: between  $FFF$  and  $A_2 A_2 A_2$  values

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)

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

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

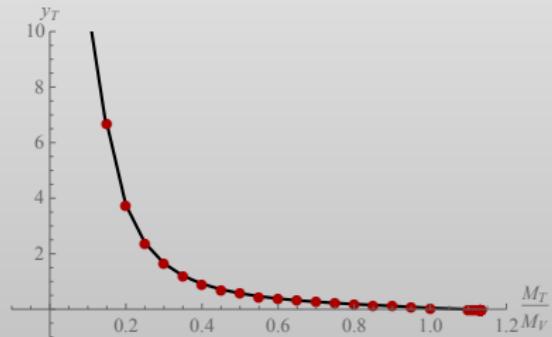
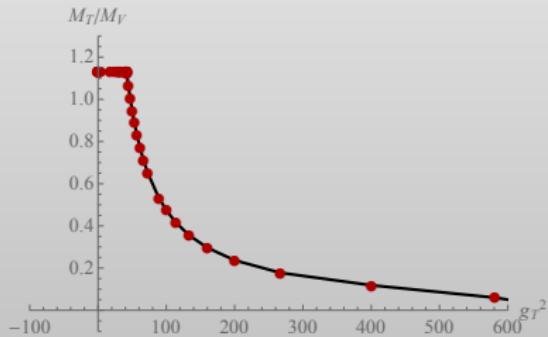
Confirmed on the lattice

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

$$\mathcal{L}_{HDO} = \frac{g_T^2}{\Lambda_{UV}^5} |FA_2F|^2.$$

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  $\gamma$  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,  $m_u = m_d = 2.3 \text{ MeV}$ ,  $m_s = 95 \text{ MeV}$

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

J. Erdmenger, N. Evans, Y. Liu, WP, arXiv:2208:xxxxx



# 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

## List of "minimal" CHM UV embeddings

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

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

Field content of the underlying model

	$Sp(2N_c)$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$SU(4)$	$SU(6)$	$U(1)_X$
$\psi_1$	□	1	2	0	4	1	$-3(N_c - 1)q_\chi$
$\psi_2$	□	1	1	1/2			
$\psi_3$	□	1	1	-1/2			
$\psi_4$	□	1	1				
$\chi_1$	□□	3	1	x	1	6	$q_\chi$
$\chi_2$	□□						
$\chi_3$	□□						
$\chi_4$	□	̄3	1	-x	1	6	$q_\chi$
$\chi_5$	□						
$\chi_6$	□						

Bound states of the model

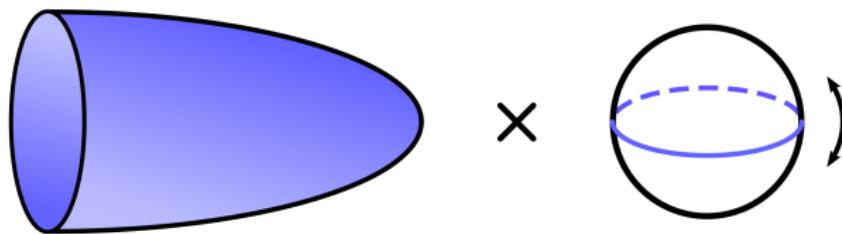
	spin	$SU(4) \times SU(6)$	$Sp(4) \times SO(6)$	names
$\psi\psi$	0	(6, 1)	(1, 1) (5, 1)	$\sigma$ $\pi$
			(1, 1) (1, 20)	$\sigma_c$ $\pi_c$
$\chi\chi$	1/2	(6, 6)	(1, 6) (5, 6)	$\psi_1^1$ $\psi_5^1$
			(1, 6) (5, 6)	$\psi_2^1$ $\psi_5^2$
$\chi\bar{\psi}\psi$	1/2	(6, 6)	(1, 6)	$\psi_3$
			(5, 6)	$\psi_4^5$
$\psi\bar{\chi}\bar{\psi}$	1/2	(1, 6)	(1, 6)	$\psi_4^1$
			(10, 6)	$\psi_4^{10}$
$\psi\sigma^\mu\psi$	1	(15, 1)	(5, 1) (10, 1)	$a$ $\rho$
			(1, 20) (1, 15)	$a_c$ $\rho_c$
$\bar{\chi}\sigma^\mu\chi$	1	(1, 35)		

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

# Quarks in the AdS/CFT correspondence

Add D7-Branes (eight-dimensional surfaces) to ten-dimensional space

	0	1	2	3	4	5	6	7	8	9
N D3	X	X	X	X						
1,2 D7	X	X	X	X	X	X	X	X		



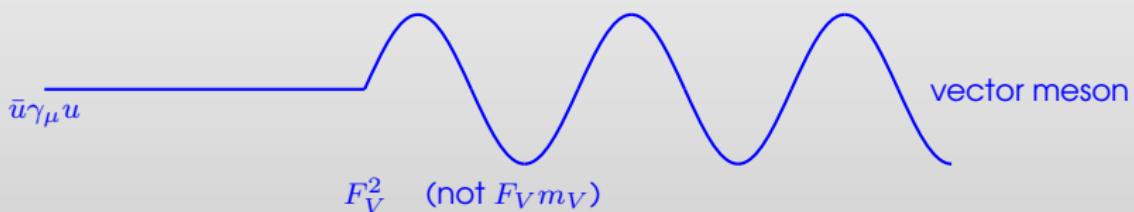
(thanks to J. Erdmenger)

Quarks: Low energy limit of open strings between D3- and D7-Branes

# 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  $\kappa$  and the norms so that we match perturbative results for e.g.  $\Pi_{VV}$  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

$$\mathcal{P}_1 = \frac{6}{r^2} (\rho + L_0 \partial_\rho L_0),$$

$$\mathcal{P}_2 = 2 ((\rho^2 + L_0^2)L \partial_\rho^2 L_0 + (\rho^2 + 3L_0^2)(\partial_\rho L_0)^2 + 4\rho L_0 \partial_\rho L_0 + 3\rho^2 + L_0^2),$$

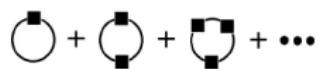
$$\mathcal{P}_3 = (\rho + L_0 \partial_\rho L_0).$$

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

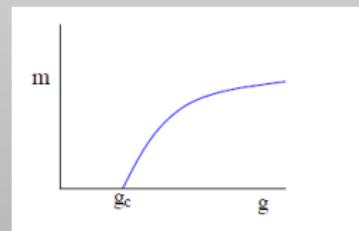
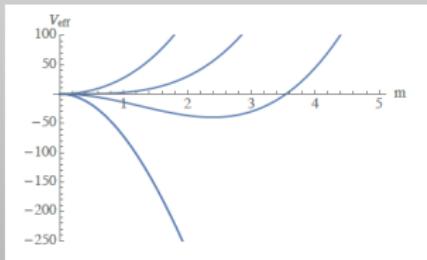
$$\mathcal{L} = \bar{\psi}_L \partial \psi_L + \bar{\psi}_R \partial \psi_R + \frac{g^2}{\Lambda_{UV}} \bar{\psi}_L \psi_R \bar{\psi}_R \psi_L$$

Calculate effective potential



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

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



# Witten's Multi-Trace Operator Prescription

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

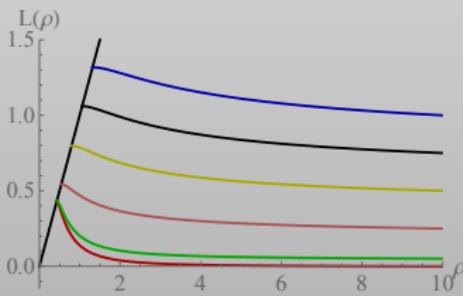
$$\frac{g^2}{\Lambda_{UV}} \bar{\psi}_L \psi_R \bar{\psi}_R \psi_L \rightarrow \frac{g^2}{\Lambda_{UV}} \langle \bar{\psi}_L \psi_R \rangle \bar{\psi}_R \psi_L \rightarrow \frac{m^2 \Lambda_{UV}}{g^2} \quad \text{so add} \quad S = \int \mathcal{L} + \frac{L^2 \rho^2}{g^2} \Big|_{\Lambda_{UV}}$$

On variation

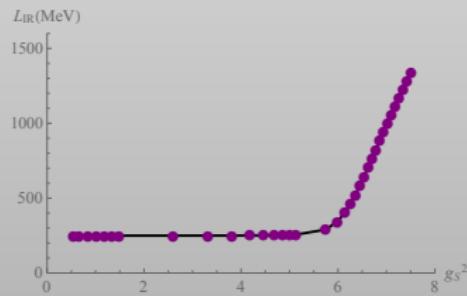
$$0 = \text{E.-L. eqn} + \frac{\partial \mathcal{L}}{\partial L'} \delta L \Big|_{\Lambda_{IR,UV}} + \frac{2L\rho^2}{g^2} \delta L \Big|_{\Lambda_{UV}}$$

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 <sup>a</sup> $4A_2, 2F, 2\bar{F}$ 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
$f_{\pi F}$	0.11(2)	0.0949	0.0953	0.0844	0.109
$MVA_2$	1.00(4)	1*	1*	1*	1*
$fVA_2$	0.68(5)	0.489	0.489	0.516	0.516
$MVF$	0.93(7)	0.933	0.939	0.890	0.904
$fVF$	0.49(7)	0.458	0.461	0.437	0.491
$MAA_2$		1.37	1.37	1.32	1.28
$fAA_2$		0.505	0.505	0.521	0.522
$MAF$		1.37	1.37	1.21	1.28
$fAF$		0.501	0.504	0.453	0.509
$MSA_2$		0.873	0.873	0.684	1.18
$MSF$		1.03	1.02	0.811	0.798
$MJA_2$	3.9(3)	2.21	2.21	2.21	2.22
$MJF$	2.0(2)	2.07	2.08	1.97	2.00
$MBA_2$	1.4(1)	1.85	1.85	1.85	1.86
$MBF$	1.4(1)	1.74	1.75	1.65	1.81

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

- ▶ pattern agree quite well in particular  $MVF$  and  $MJF$
- ▶  $MJA_2$  off and also  $MBF$  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 <sup>a</sup> $4A_2, 2F, 2\bar{F}$ 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	<b>0.0997</b>	0.1111	<b>0.1111</b>	0.102
$f_{\pi} F$	0.11(2)	0.0949	<b>0.0953</b>	0.0844	<b>0.109</b>	0.892
$M_{VA_2}$	1.00(4)	1*	<b>1*</b>	1*	<b>1*</b>	1*
$f_{VA_2}$	0.68(5)	0.489	<b>0.489</b>	0.516	<b>0.516</b>	0.517
$M_{VF}$	0.93(7)	0.933	<b>0.939</b>	0.890	<b>0.904</b>	0.976
$f_{VF}$	0.49(7)	0.458	<b>0.461</b>	0.437	<b>0.491</b>	0.479
$M_{AA_2}$		1.37	<b>1.37</b>	1.32	<b>1.32</b>	1.28
$f_{AA_2}$		0.505	<b>0.505</b>	0.521	<b>0.521</b>	0.522
$M_{AF}$		1.37	<b>1.37</b>	1.21	<b>1.23</b>	1.28
$f_{AF}$		0.501	<b>0.504</b>	0.453	<b>0.509</b>	0.492
$M_{SA_2}$		0.873	<b>0.873</b>	0.684	<b>0.684</b>	1.18
$M_{SF}$		1.03	<b>1.02</b>	0.811	<b>0.798</b>	1.25
$M_{JA_2}$	3.9(3)	2.21	<b>2.21</b>	2.21	<b>2.21</b>	2.22
$M_{JF}$	2.0(2)	2.07	<b>2.08</b>	1.97	<b>2.00</b>	2.17
$M_{BA_2}$	1.4(1)	1.85	<b>1.85</b>	1.85	<b>1.85</b>	1.86
$M_{BF}$	1.4(1)	1.74	<b>1.75</b>	1.65	<b>1.68</b>	1.81

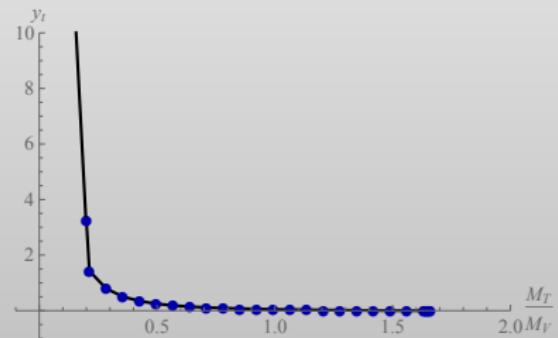
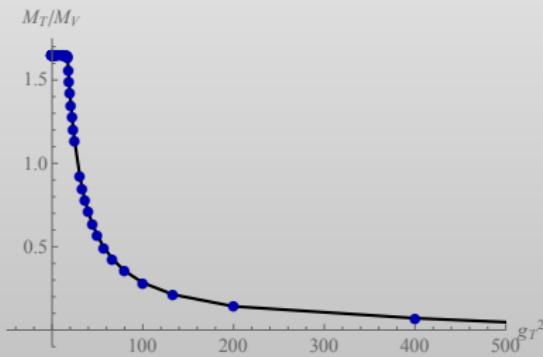
- ▶ Adding extra flavours is not a huge change
- ▶ Scalar masses get lighter by adding extra flavours

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

Top Yukawa coupling: similar as before, need additional HDO

$$\mathcal{L}_{HDO} = \frac{g_T^2}{\Lambda_{UV}^5} |FA_2F|^2.$$

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