A Holographic Description of the Strong Dynamics in Composite Higgs Models

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Work with Johanna Erdmenger, Kostas Rigatos and Werner Porod:

1907.09489 [hep-th]
2009.10737 [hep-ph]
2010.10279 [hep-ph]

Southampton Theory Astrophysics Gravity Research Centre

- A holographic description of chiral symmetry breaking by running γ and NJL operators
- "perfected QCD" & composite higgs models

Introduction

One of the most remarkable aspects of the Standard Model is that the ground state symmetries are less than those of the bare Lagrangian…

- Higgs potential is adhoc and not yet understood
- QCD provides a DYNAMICAL symmetry breaking mechanism

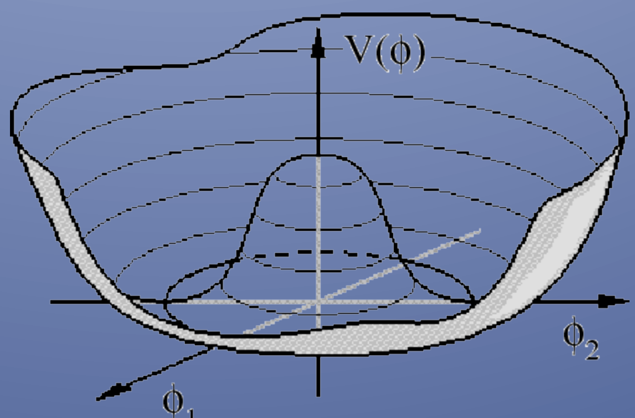
$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$$

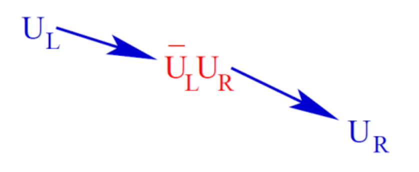
$$m\bar{\psi}\psi = m(\bar{\psi}_L\psi_R + h.c.)$$

$$\bar{u}\gamma^\mu u = \bar{u}_L\gamma^\mu u_L + \bar{u}_R\gamma^\mu u_R$$

Evidence: lack of parity doubling, proton mass, Goldstone pions

$$\langle \bar{u}_L u_R + \bar{d}_L d_R + h.c. \rangle \neq 0$$





Strongly Coupled BSM

A very long list of citations!

Technicolour

New techniquarks, and
strongly coupled gauge group

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

"Higgs" is the sigma meson.

Composite Higgs Models

New strong sector and symmetry breaking condensates lead to

4+ NGBs

whose SM interactions make them pNGB and 4 become the "Higgs"

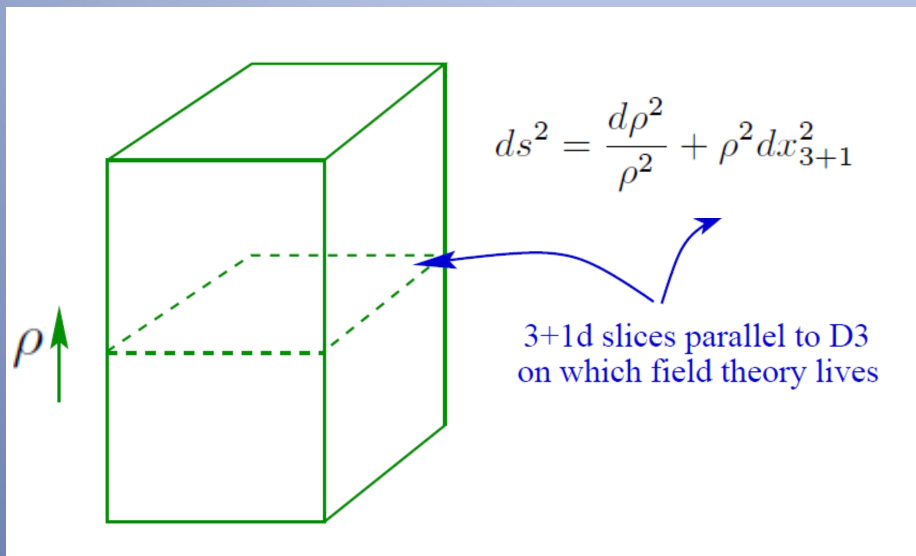
BOTH THEORIES TRY TO SOLVE THE SM FINE TUNING a la QCD

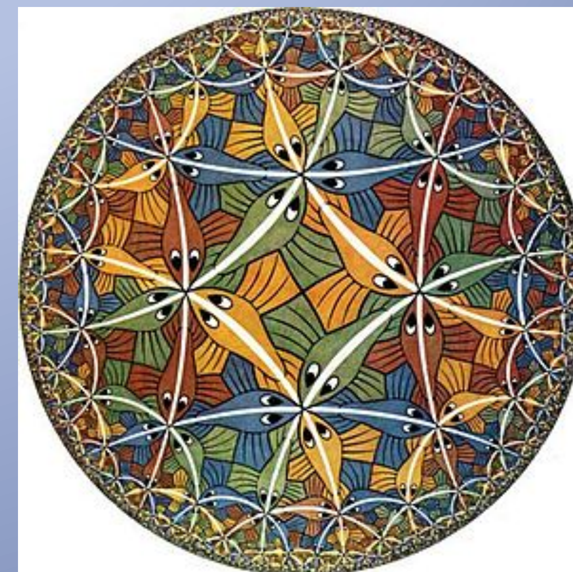
BUT HOW DO WE CALCULATE IF DYNAMICS DIFFERS FROM QCD?

NB: POST LHC I'M VERY AGNOSTIC ON WHAT GOD IS UP TO…
BUT THERE ARE MANY INTERESTING QFT PROBLEMS HERE…

The plan is to describe dynamical symmetry breaking scenarios holographically – they provide a weak coupling description of strongly coupled physics.

How Does AdS/CFT Work 1





Dilatations

$$\int d^4x \; \partial^\mu \phi \partial_\mu \phi, \qquad x \to e^{-\alpha} x, \qquad \phi \to e^{\alpha} \phi$$

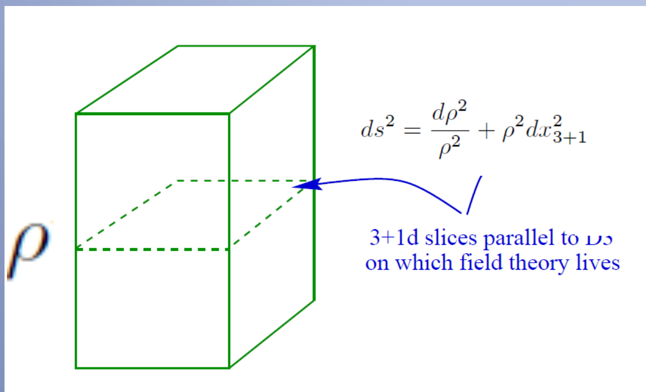
Become spacetime symmetry of AdS

$$\rho \to e^{\alpha} \rho$$

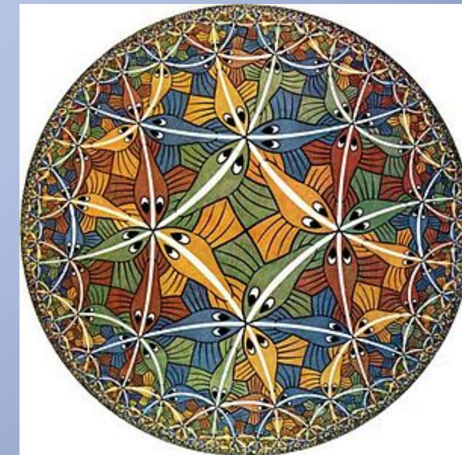
ρ is a continuous mass dimension

$\rightarrow$ RG Scale

How Does AdS/CFT Work 2



$$\sqrt{-Detg} = Det\left[-\begin{pmatrix} -\rho^2 & 0 & 0 & 0 & 0 \\ 0 & \rho^2 & 0 & 0 & 0 \\ 0 & 0 & \rho^2 & 0 & 0 \\ 0 & 0 & 0 & \rho^2 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\rho^2} \end{pmatrix}\right]^{1/2} = \rho^3$$



Operators and sources appear as fields in the bulk

Eg

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

m is the quark mass
c is the quark condensate

A field for the mass/condensate:

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

$$\partial_\rho \left[\rho^3 \partial_\rho L\right] = 0$$

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

Running Dimensions in Holography

Raul Alvares, NE, Keun-Young arXiv:1204.2474 [hep-ph]; Matti Jarvinen, Elias Kiritsis arXiv:1112.1261 [hep-ph]

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

$$\partial_\rho[\rho^3\partial_\rho L] - \rho\Delta m^2 L = 0$$

$$L = \frac{m_{FP}}{\rho^\gamma} + \frac{c_{FP}}{\rho^{2-\gamma}}, \qquad \gamma(\gamma-2) = \Delta m^2$$

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

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

Top down derivation: many string constructions eg probe D7 branes in D3 backgrounds are examples of this…

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

Dynamic AdS/YM

Timo Alho, NE, KimmoTuominen
1307.4896

$$S = \int d^4x\, d\rho \,\mathrm{Tr}\, \rho^3 \left[\frac{1}{\rho^2 + |X|^2} |DX|^2 \quad + \frac{\Delta m^2}{\rho^2} |X|^2 \right.$$

$$X = L(\rho)\ e^{2i\pi^a T^a}.$$

$$ds^2 = \frac{d\rho^2}{(\rho^2 + |X|^2)} + (\rho^2 + |X|^2) dx^2,$$

|X| = L 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: X'(ρ=X) = 0

X enters into the AdS metric to cut off the radial scale at the value of m or the condensate – no hard wall

The gauge DYNAMICS is input through a guess for Δm

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

The only free parameters are Nc, Nf, m, Λ

The Meaning of X

QCD: we can treat the up quark as a probe in a background of glue + other quarks:

$$X = \bar{u}u$$

- γ Includes the running from the quarks so there is some by hand "backreaction"…. We can study mesons made of u quarks which by symmetry are degenerate with d states and mixed ud states..

Or we can promote X to a 2x2 matrix, Tr over the action… now we have a non-abelian DBI which can in principle include mass splitting – we won't do that here.

Real Representations: If quarks are in a real rep (eg adjoint) we form a Majorana spinor u = (ψ, $-$i σ ψ*) and again $X = \bar{u}u$

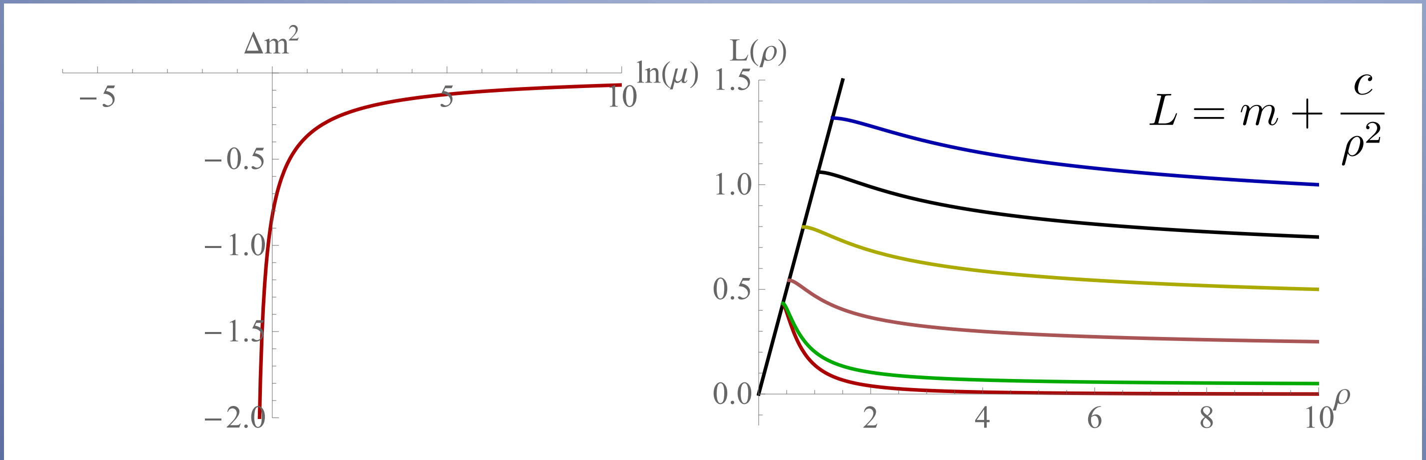
And bound states are X with γ–matrix structure inserted…

Assuming quarks are mass degenerate again we just look at one set of states, degenerate by symmetry to all the others….

Formation of the Chiral Condensate

We solve for the vacuum configuration of L

$$\partial_\rho[\rho^3 \partial_\rho L] - \rho \Delta m^2 L = 0\,.$$



Read off m and qq in the UV…

Δm^2 from QCD

Shoot out with

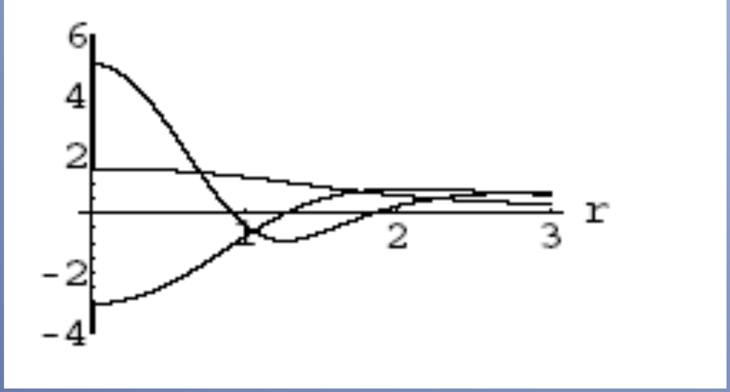
L’(ρ =L) = 0

Meson Fluctuations

$$S = \int d^4x \, d\rho \, \mathrm{Tr}\, \rho^3 \left[\frac{1}{\rho^2 + |X|^2} |DX|^2 + \frac{\Delta m^2}{\rho^2} |X|^2 + \frac{1}{2\kappa^2} (F_V^2 + F_A^2) \right]$$

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

$$\partial_\rho(\rho^3 \delta') - \Delta m^2 \rho \delta - \rho L_0 \delta \left. \frac{\partial \Delta m^2}{\partial L} \right|_{L_0} + M^2 R^4 \frac{\rho^3}{(L_0^2 + \rho^2)^2} \delta = 0 \, .$$



The source free solutions pick out particular mass states… the σ and its radial excited states…

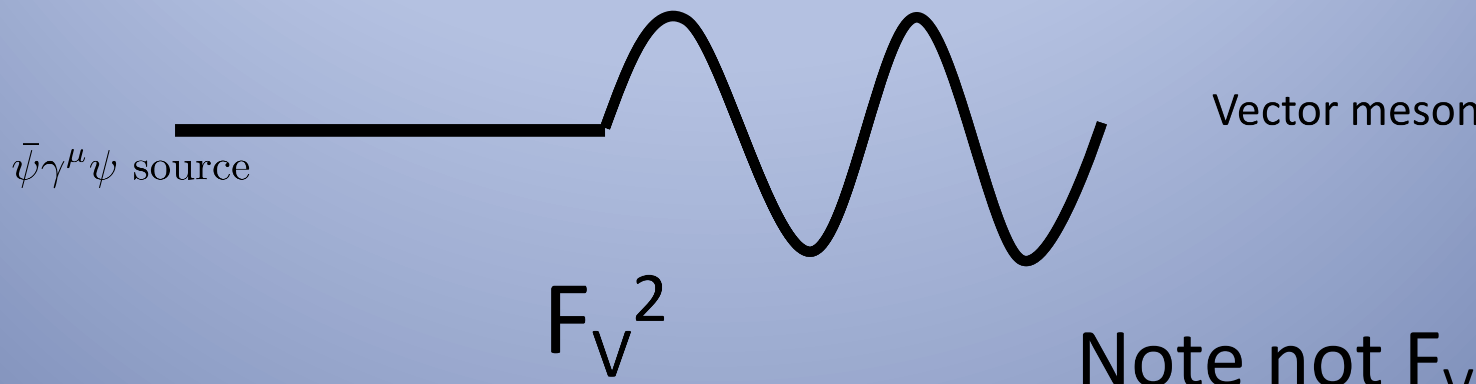
The gauge fields let us also study the operators and states

$$\bar{q} \gamma^\mu q \rightarrow \rho \text{ meson}$$

$$\bar{q} \gamma^\mu \gamma^5 q \rightarrow \text{a meson}$$

Decay Constants (a la. AdS/QCD - hep-ph/0501128 [hep-ph])

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



Note not $F_V\, m_V$

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 eg Π_{VV} in the UV…

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

Baryons

cf Brodsky, de Teramond hep-th/0501022 [hep-th]

Plus our 1907.09489 [hep-th]

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.

$$S_{1/2} = \int d^5x\ \rho^3\ \bar{\Psi}\left(\not{D}_{\rm AAdS} - m\right)\Psi\,.$$

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 the pre-factors are given by

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

$$\psi_+ \sim \mathcal{J}\sqrt{\rho} + \mathcal{O}\frac{M_B}{6}\rho^{-11/2}\,,$$
$$\psi_- \sim \mathcal{J}\frac{M_B}{4}\frac{1}{\sqrt{\rho}} + \mathcal{O}\rho^{-9/2}\,.$$

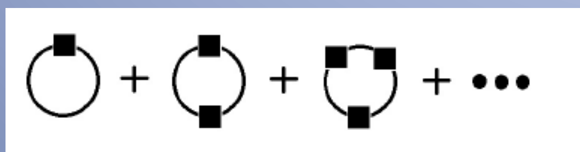
IR boundary conditions

$$\psi_+(\rho = L_{IR}) = 1, \qquad \partial_\rho\psi_+(\rho = L_{IR}) = 0\,,$$
$$\psi_-(\rho = L_{IR}) = 0, \qquad \partial_\rho\psi_-(\rho = L_{IR}) = \frac{1}{L_{IR}}\,.$$

Higher Dimension/Nambu Jona-Lasinio Operators

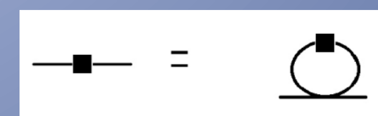
$$\mathcal{L} = \bar{\psi}_L \partial\!\!\!/ \psi_L + \bar{\psi}_R \partial\!\!\!/ \psi_R + \frac{g^2}{\Lambda_{UV}^2} \bar{\psi}_L \psi_R \bar{\psi}_R \psi_L$$

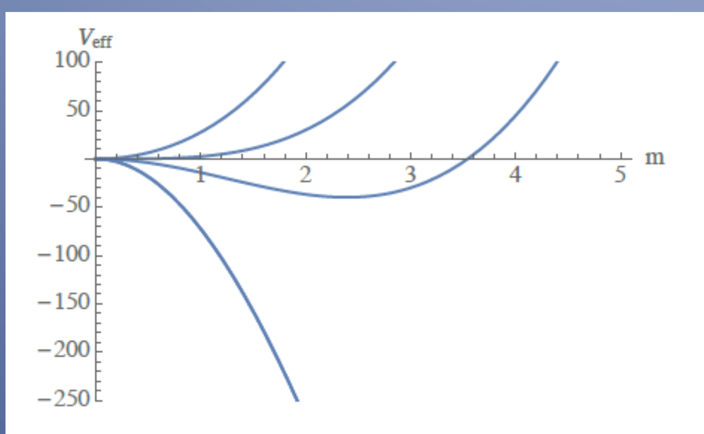
Calculate effective potential

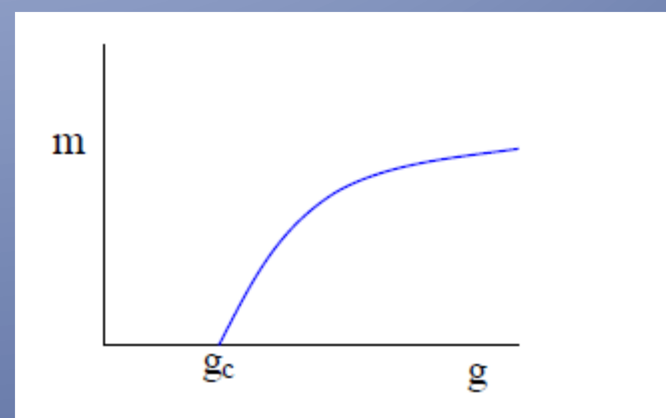


$$\Delta V_{\text{eff}} = -\int_0^{\Lambda_{UV}} \frac{d^4 k}{(2\pi)^4} \text{Tr} \log(k^2 + m^2)$$

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







Witten's Multi-Trace Operator Prescription

Witten hep-th/0112258; NE + K Kim 1601.02824 [hep-th]

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

so add

$$S = \int d\rho \mathcal{L} + \left.\frac{L^2\rho^2}{g^2}\right|_{\Lambda_{UV}}$$

On variation…

$$0 = EL\ eqn\ + \frac{\partial\mathcal{L}}{\partial L'}\delta L|_{UV,IR} + \frac{2L\Lambda_{UV}^2}{g^2}\delta L|_{UV}$$

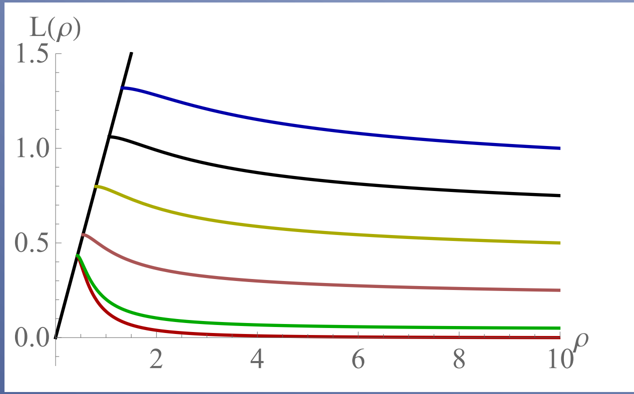
$$L = m + \frac{c}{\rho^2}$$

$$\frac{\partial\mathcal{L}}{\partial L'} = \rho^3\partial_\rho L = -2c$$

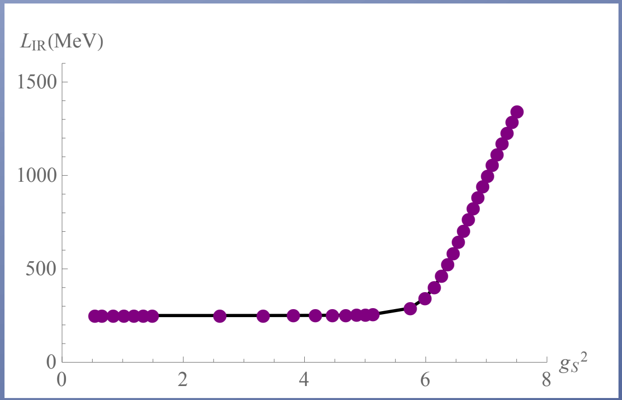
Now we let the mass vary in the UV and need…

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

The Euler Lagrange equation solutions are left unchanged but we pick those that satisfy the UV and IR boundary conditions..



Read off m,c and compute g



For operators that are zero in the vacuum one can still include the effect of HDOs at the level of the perturbations that give the spectrum.

QCD Dynamics – Nc=3, Nf=2, m_q=0

$$\mu \frac{d\alpha}{d\mu} = -b_0 \alpha^2, \qquad b_0 = \frac{1}{6\pi}(11N_c - 2N_F),$$

$$\gamma = \frac{3C_2}{2\pi}\alpha = \frac{3(N_c^2-1)}{4N_c\pi}\alpha\,.$$

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%

Table 1: 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

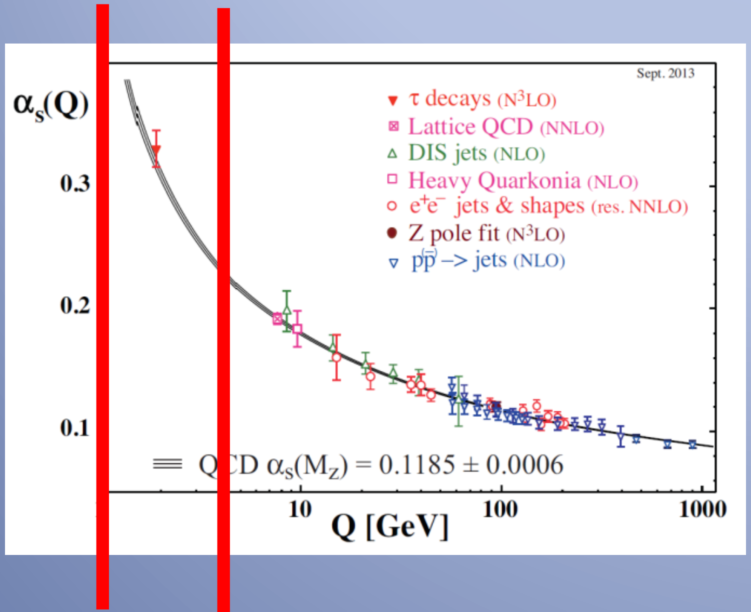
Pattern sensible

Pion decay constant needs a mass term

Baryon mass high

Radial excitations scale wrongly – 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 effects… and stringy effects in the gravity model….

$$\frac{g_S^2}{\Lambda_{UV}^2}|\bar{q}q|^2\,, \qquad \frac{g_V^2}{\Lambda_{UV}^2}|\bar{q}\gamma^\mu q|^2\,, \qquad \frac{g_A^2}{\Lambda_{UV}^2}|\bar{q}\gamma^\mu\gamma_5 q|^2\,, \qquad \frac{g_B^2}{\Lambda_{UV}^5}|qqq|^2\,,$$

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%

Table 2: The spectum and the decay constants for two-flavour QCD with HDOs from fig. 7 used to improve the spectrum.

Pretty good… but we've lost some predictivity….

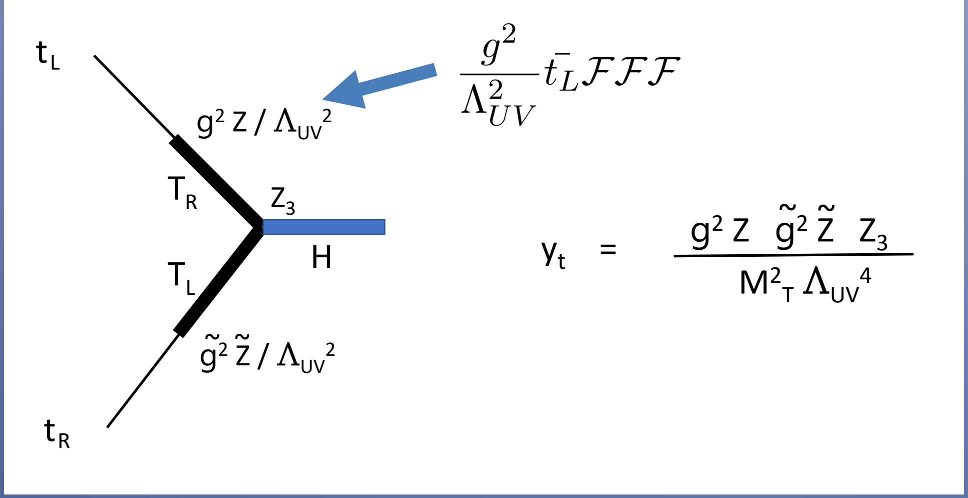
Composite Higgs Models

THE BASICS: a model must have “quark” condensates that break a global symmetry to give 4+ Goldstones that can be made the SM Higgs… one then hopes gauge loops and top quark loops generate the SM higgs potential…. eg Golterman, Shamir arXiv:1502.00390 [hep-ph].

The potential is of the form [47]

$$V_h = -C_{LR}(3g_2^2 + g_Y^2)\cos^2\left(\frac{h}{f}\right) + \frac{y_t^2}{2} C_t \sin^2\left(\frac{2h}{f}\right)$$

To form the top mass without FCNCs people use “partial top compositeness” (D Kaplan 1991)



We are now assuming there are baryons that have the same quantum numbers as the left and right handed top quarks.

Their mass must be anomalously low relative to the rho mass to make mt

Ferretti and Karateev have catalogued 26 classes of composite Higgs models with top partners (we have computed the spectrum for all of them!) .. Let's concentrate on 2 with lattice results…

Sp(4) 4F $6A_2$

J. Barnard, T. Gherghetta, and T. S. Ray, "UV descriptions of composite Higgs models without elementary scalars," JHEP **02** (2014) 002, arXiv:1311.6562 [hep-ph].

The sextet quarks are expected to condense first and break SU(6) -> SO(6). These guys are just here to form F A_2 F baryon top partners.

Then the fundamentals break SU(4) -> Sp(4) – this is where the Higgs is generated. [It's the same condensation as in QCD but because there is a real rep here the symmetry is enhanced]

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

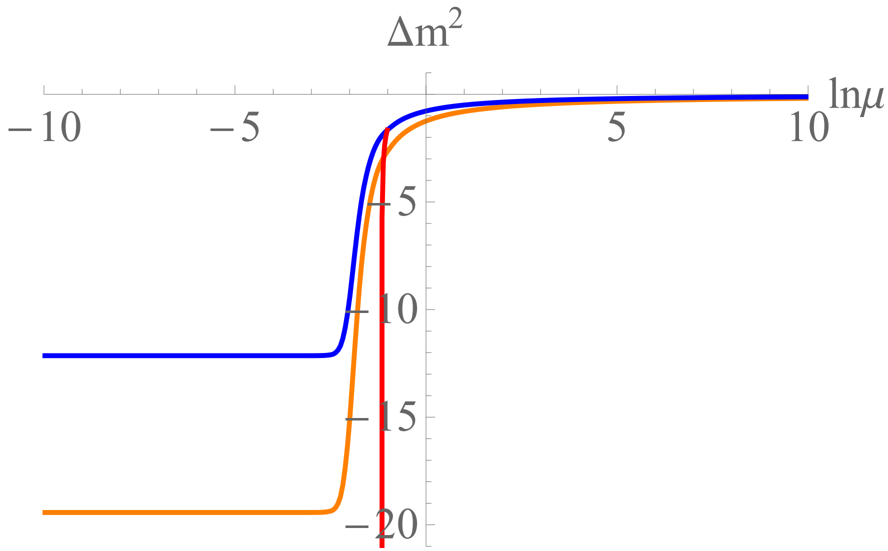
$$b_1 = \frac{1}{24\pi^2}\left(34(N+1)^2 - 5(N+1)N_{f_1} - \frac{3}{4}(2N+1)N_{f_1} - 10(N+1)(N-1)N_{f_2} - 6N(N-1)N_{f_2}\right)$$

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

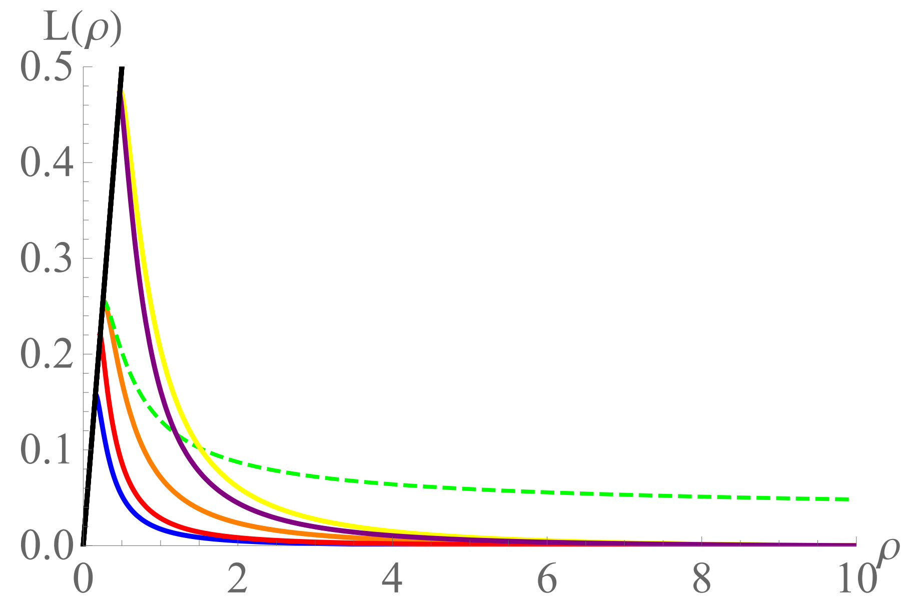
$$\gamma_F = \frac{3}{2\pi}\frac{2N+1}{4}\alpha$$

These fix Δm^2 and hence the model….

The running AdS mass



The RG mass profiles of the quarks



How you decouple the quarks is important and unknown – I'll concentrate on when they are removed below their IR mass scale. Quench = pure glue running.

The gap between F and A2 grows the less you decouple the quarks – the slower the running the more conformal the theory is around the chiral symmetry breaking point – this will lead to a lighter scalar meson…

	AdS/$Sp(4)$ no decouple	AdS/Sp(4) A2 decouple	AdS/Sp(4) quench	lattice [78] quench	lattice [79] 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		

Consider our quenched model against the lattice quenched results of

[78] E. Bennett, D. K. Hong, J.-W. Lee, C.-J. D. Lin, B. Lucini, M. Mesiti, M. Piai, J. Rantaharju, and D. Vadacchino, "Sp(4) gauge theories on the lattice: quenched fundamental and antisymmetric fermions," arXiv:1912.06505 [hep-lat].

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M_{BA_2}	1.85	1.85	1.86		
M_{BF}	1.13	1.53	1.79		

We set the scale in the A2 sector… the pattern of mass scales is right…. $f\pi$, A, σ meson sectors are a little light….

	AdS/$Sp(4)$ no decouple	AdS/Sp(4) A2 decouple	AdS/Sp(4) quench	lattice [78] quench	lattice [79] unquench
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$f_{\pi F}$	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		

The F sector is lighter than the A2s and then also in the right pattern

	AdS/$Sp(4)$ no decouple	AdS/Sp(4) A2 decouple	AdS/Sp(4) quench	lattice [78] quench	lattice [79] 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)	
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M_{BF}	1.13	1.53	1.79		

Unquenching done for the Fs only on the lattice and there are no big changes – no info on interplay with A2 though…

E. Bennett, D. K. Hong, J.-W. Lee, C.-J. D. Lin, B. Lucini, M. Piai, and D. Vadacchino, "Sp(4) gauge theories on the lattice: $N_f = 2$ dynamical fundamental fermions," JHEP **12** (2019) 053, arXiv:1909.12662 [hep-lat].

The holographic model is most useful to see how changes in the running change the spectrum… the gap between the F and A2 sector grows. (even more if you don't decouple the heavy A2s)

	AdS/$Sp(4)$ no decouple	AdS/Sp(4) A2 decouple	AdS/Sp(4) quench	lattice [78] quench	lattice [79] unquench
$f_{\pi A_2}$	0.120	0.120	0.103	0.1453(12)	
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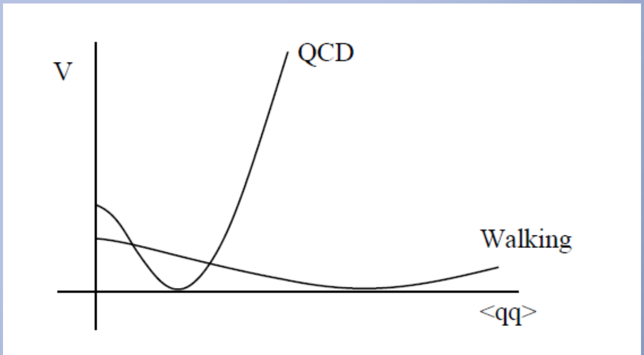
M_{BF}	1.13	1.53	1.79		

And the slower the running the lighter the scalar mass becomes – this is the biggest change… note it makes a big difference which scale sees the slower running…



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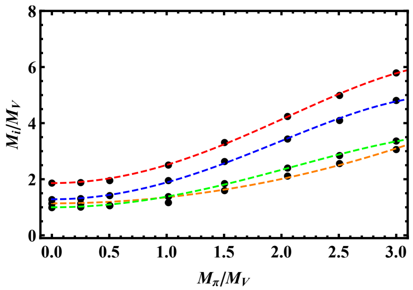
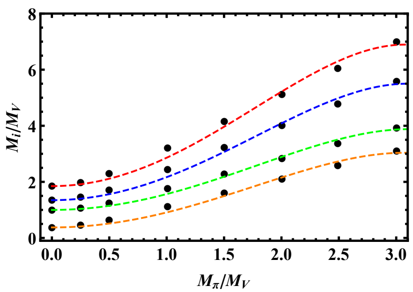
And the mass dependence...

A_2 Sector - quenched



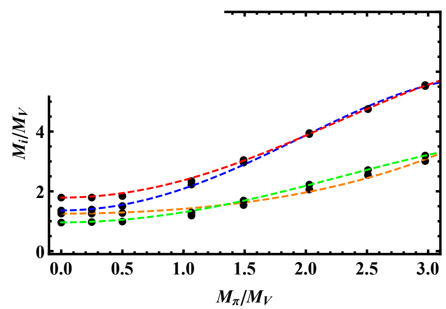
$$
\begin{aligned}
M_S &= 1.14 + 0.217\ M_\pi^2\,,\\
M_{S\text{lat}} &= 1.65(15) + 0.17(5) M_\pi^2\,,\\
M_V &= 1 + 0.392\ M_\pi^2\,,\\
M_{V\text{lat}} &= 1.000(32) + 0.45(26)\ M_\pi^2\,,\\
M_A &= 1.28 + 0.627\ M_\pi^2\,,\\
M_{A\text{lat}} &= 1.75(13) + 0.40(12)\ M_\pi^2\,,\\
M_B &= 1.86 + 0.673\ M_\pi^2\,.
\end{aligned}
$$

A_2 Sector - no decoupling



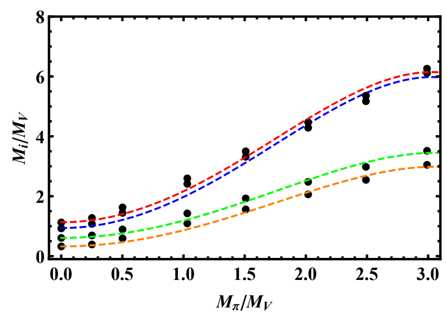
$$
\begin{aligned}
M_S &= 0.375 + 0.564\ M_\pi^2 - 0.0299\ M_\pi^4\,,\\
M_V &= 1 + 0.595\ M_\pi^2 - 0.0307\ M_\pi^4\,,\\
M_A &= 1.35 + 0.865\ M_\pi^2 - 0.0450\ M_\pi^4\,,\\
M_B &= 1.85 + 1.07\ M_\pi^2 - 0.0564\ M_\pi^4\,.
\end{aligned}
$$

F Sector - quenched



$$
\begin{aligned}
M_S &= 1.25 + 0.154\ M_\pi^2\,,\\
M_{S\text{lat}} &= 1.52(1) + 0.09(10)\ M_\pi^2\,,\\
M_V &= 0.962 + 0.349\ M_\pi^2\,,\\
M_{V\text{lat}} &= 0.83(19) + 0.50(16)\ M_\pi^2\,,\\
M_A &= 1.36 + 0.758\ M_\pi^2\,,\\
M_{A\text{lat}} &= 1.32(18) + 0.42(0.20)\ M_\pi^2\,,\\
M_B &= 1.79 + 0.599\ M_\pi^2\,.
\end{aligned}
$$

F Sector - no decoupling



$$
\begin{aligned}
M_S &= 0.325 + 0.57\ M_\pi^2 - 0.031\ M_\pi^4\,,\\
M_V &= 0.61 + 0.61\ M_\pi^2 - 0.033\ M_\pi^4\,,\\
M_A &= 0.938 + 1.1\ M_\pi^2 - 0.06\ M_\pi^4\,,\\
M_B &= 1.13 + 1.09\ M_\pi^2 - 0.059\ M_\pi^4\,.
\end{aligned}
$$

Finally we can predict the F A2 F top partner mass… we bound it as lying between a F F F and an A2 A2 A2 state…

	AdS/$Sp(4)$ no decouple	AdS/Sp(4) A2 decouple	AdS/Sp(4) quench	lattice [78] quench	lattice [79] unquench
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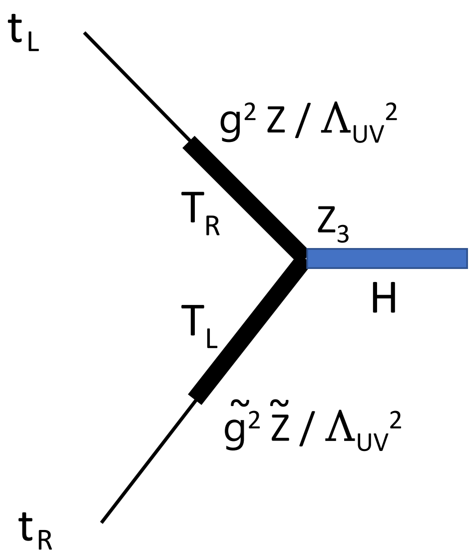
M_{BF}	1.13	1.53	1.79		

The Top Mass



$$y_t = \frac{g^2 Z \;\; \tilde{g}^2 \tilde{Z} \;\; Z_3}{M^2_T \, \Lambda_{UV}^4}$$

Plausible forms for the Z factors upto order one couplings (this is beyond quadratic order in the holographic model)

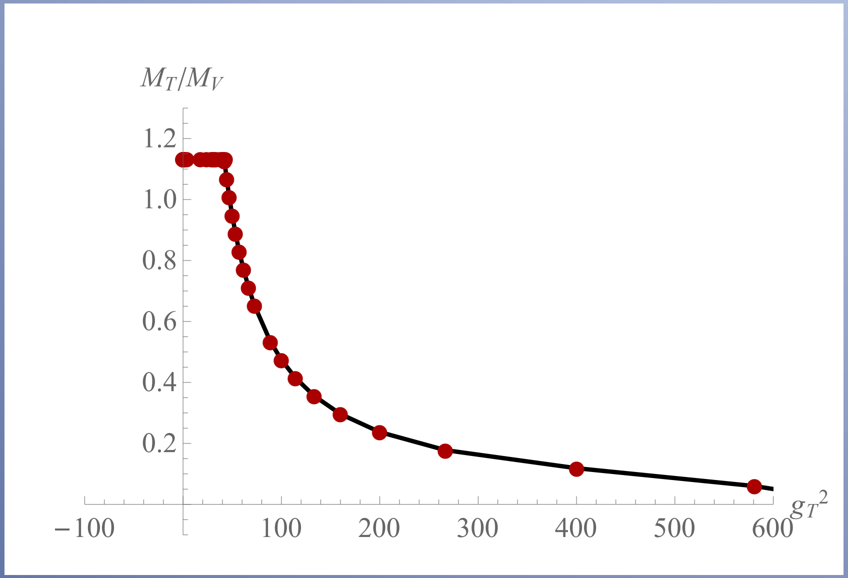
$$Z_3 \simeq \int d\rho \; \rho^3 \; \frac{\partial_\rho \pi(\rho) \;\; \psi_B(\rho)^2}{(\rho^2 + L^2)^2} \, ,$$

$$Z = \tilde{Z} \simeq \int d\rho \; \rho^3 \partial_\rho \psi_B(\rho) \, .$$

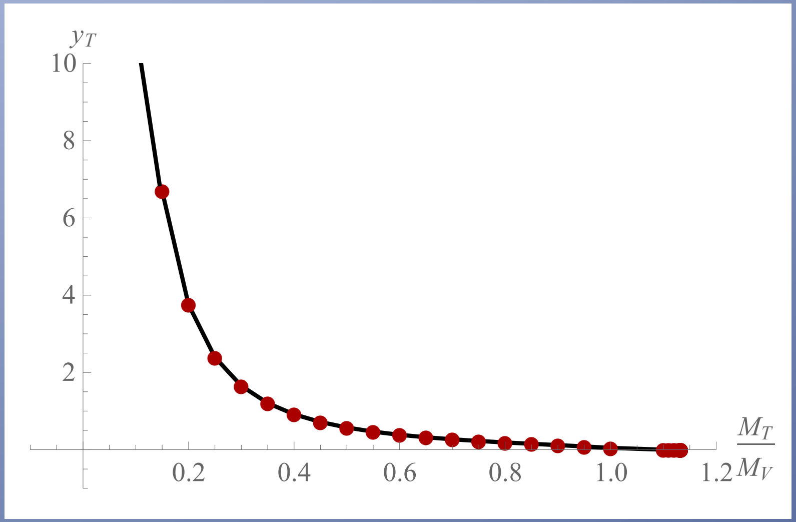
$y_t = 0.01$ naturally… $\Lambda = 5$ TeV

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 – we drive the top partner baryon mass to half the vector meson mass…

SU(4) 3 F 3 $\bar{F}$ 5 A_2

G. Ferretti, "UV Completions of Partial Compositeness: The Case for a SU(4) Gauge Group," JHEP **06** (2014) 142, arXiv:1404.7137 [hep-ph].

In this model the A2 symmetry breaking generates the SM higgs and the Fs are to give F A_2 F top partners

V. Ayyar, T. DeGrand, M. Golterman, D. C. Hackett, W. I. Jay, E. T. Neil, Y. Shamir, and B. Svetitsky, "Spectroscopy of SU(4) composite Higgs theory with two distinct fermion representations," Phys. Rev. D **97** no. 7, (2018) 074505, arXiv:1710.00806 [hep-lat].

The lattice has simulated (unquenched) SU(4) 2 F 2 F 4 A_2

	Lattice [80] $4A_2, 2F, 2\bar{F}$ 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

The pattern is right…

The A2-F gap is very well described…

Adding extra flavours is not a huge change…

Scalar masses get lighter as add extra flavours

SU(4) 3 F 3 $\bar{F}$ 5 A_2

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The lattice has simulated (unquenched) SU(4) 2 F 2 F 6 A_2

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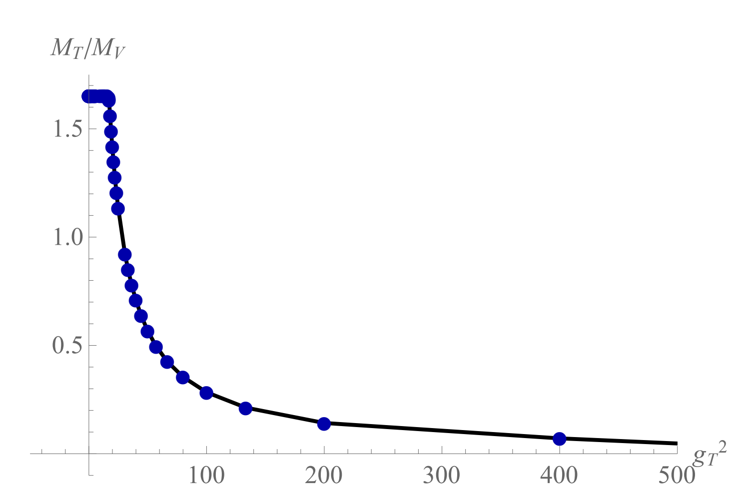
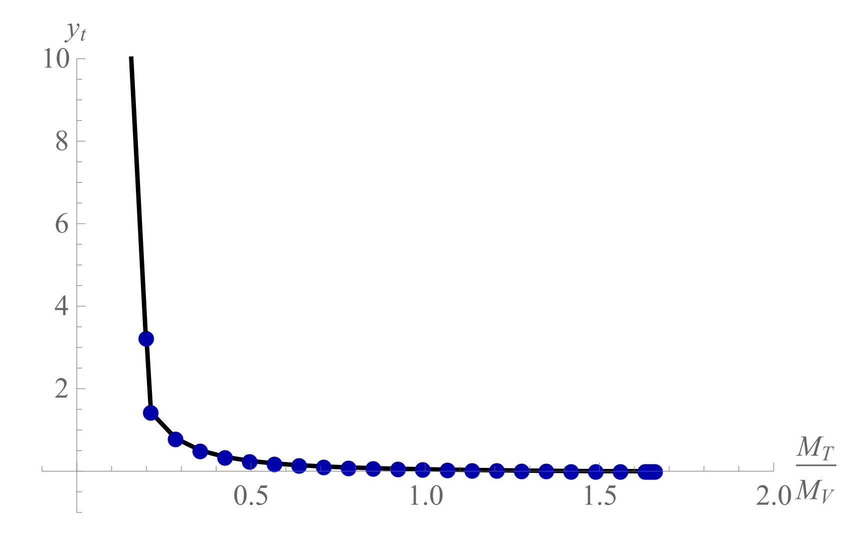


which raises y_t



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

We've also computed for

These are the sub-set of theories that do not lie in the conformal window at the level of our parametrizations of the runnings.

AdS/G_2 $11F$	AdS/G_2 $15F$	AdS/F_4 $11F$	AdS/F_4 $12F$

$\mathrm{AdS}/Sp(4)$ $5A_2, 6F$	$\mathrm{AdS}/Sp(14)$ $5A_2, 6F$	$\mathrm{AdS}/Sp(4)$ $4F, 6A_2$	$\mathrm{AdS}/Sp(8)$ $4F, 6A_2$

$\mathrm{AdS}/SO(7)$ $5F, 6s$	$\mathrm{AdS}/SO(7)$ $5s, 6F$	$\mathrm{AdS}/SO(9)$ $5F, 6s$	$\mathrm{AdS}/SO(9)$ $5s, 6F$

$\mathrm{AdS}/SO(10)$ $5F, 6s$	$\mathrm{AdS}/SO(11)$ $5F, 6s$	$\mathrm{AdS}/SO(11)$ $4s, 6F$	$\mathrm{AdS}/SO(13)$ $4s, 6F$

$\mathrm{AdS}/SO(8)$ $5F, 3s, 3\tilde{s}$	$\mathrm{AdS}/SO(10)$ $5F, 3s, 3\tilde{s}$	$\mathrm{AdS}/SO(12)$ $5F, 3s, 3\tilde{s}$

$\mathrm{AdS}/SO(10)$ $4s, 4\tilde{s}, 6F$	$\mathrm{AdS}/SU(4)$ $4F, 4\bar{F}, 6A_2$

$\mathrm{AdS}/SU(5)$ $4F, 4\bar{F}, 3A_2, 3\bar{A}_2$	$\mathrm{AdS}/SU(5)$ $4A_2, 4\bar{A}_2, 3F, 3\bar{F}$	$\mathrm{AdS}/SU(7)$ $4F, 4\bar{F}, 3A_3, 3\bar{A}_3$	$\mathrm{AdS}/SU(10)$ $4F, 4\bar{F}, 3S_2, 3\bar{S}_2$	$\mathrm{AdS}/SU(71)$ $3F, 3\bar{F}, 4S_2, 4\bar{S}_2$

which shows the simplicity of the method to get decent stabs at the spectrum….

Conclusions

- We have holographic models that describe chiral symmetry breaking due to the running of γ and NJL interactions

- Pretty much any theory is game…

- We've applied this to technicolour models previously… now Composite Higgs Models where we can quickly compare to lattice results and look for changes as we UNQUENCH, and ADD EXTRA FLAVOURS BEYOND THE LATTICE

- Clearly there needs to be interplay with more rigorous lattice but eg if they understand decoupling we can improve the model.. Or better knowledge of γ…

- We can quickly do a lot of theories!

- We've proposed a new HDO method to raise the top Yukawa coupling in these models….

- What next? Specific model issues after this broad brush survey eg mass splittings, competing NJL and mass term vacuum alignment… Strongly coupled dark matter sectors?

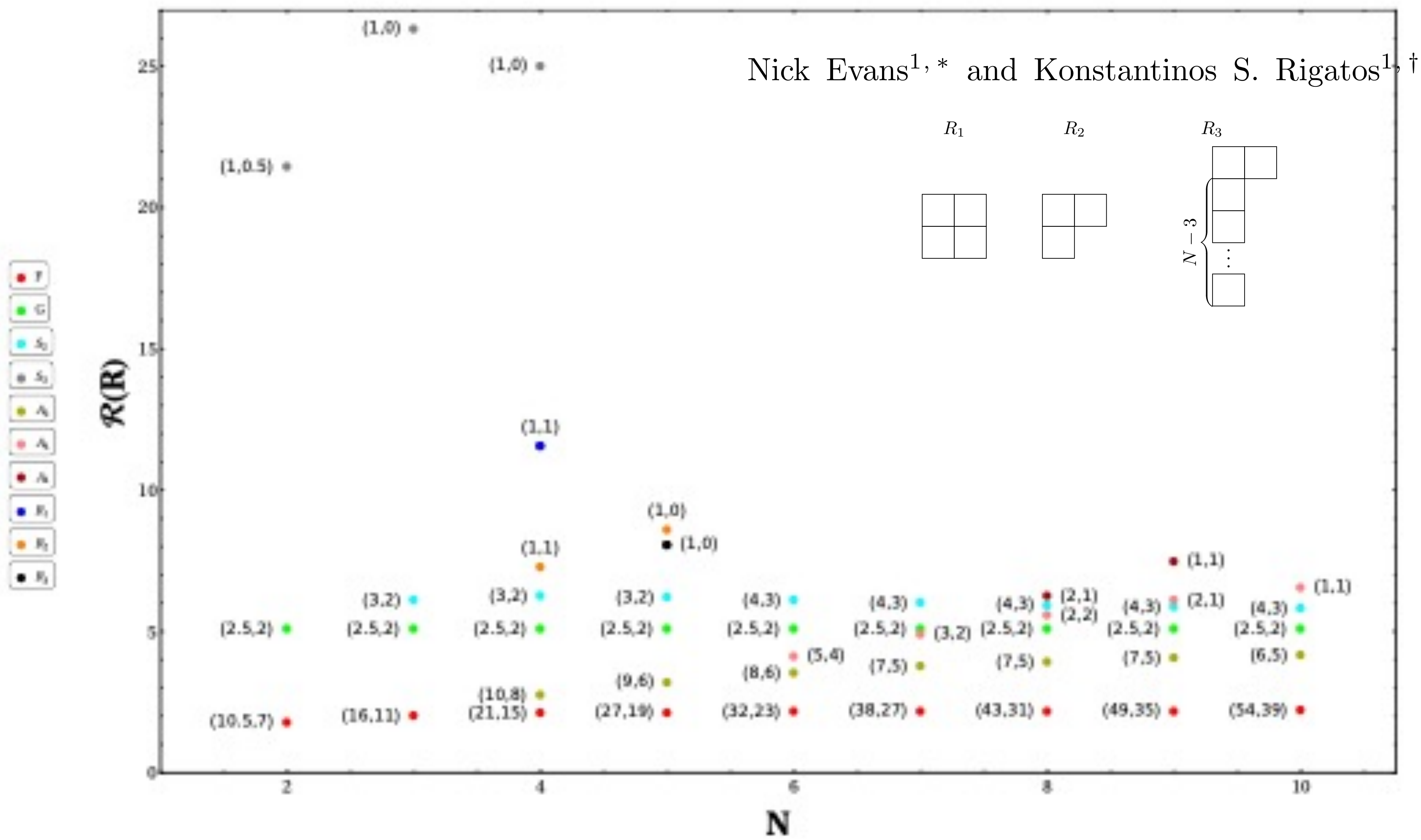
- A parallel programme is using these techniques to study dense QCD matter and making contact with LIGO data on the equation of state…

Hot off the press….

Confinement vs Chiral Symmetry breaking…

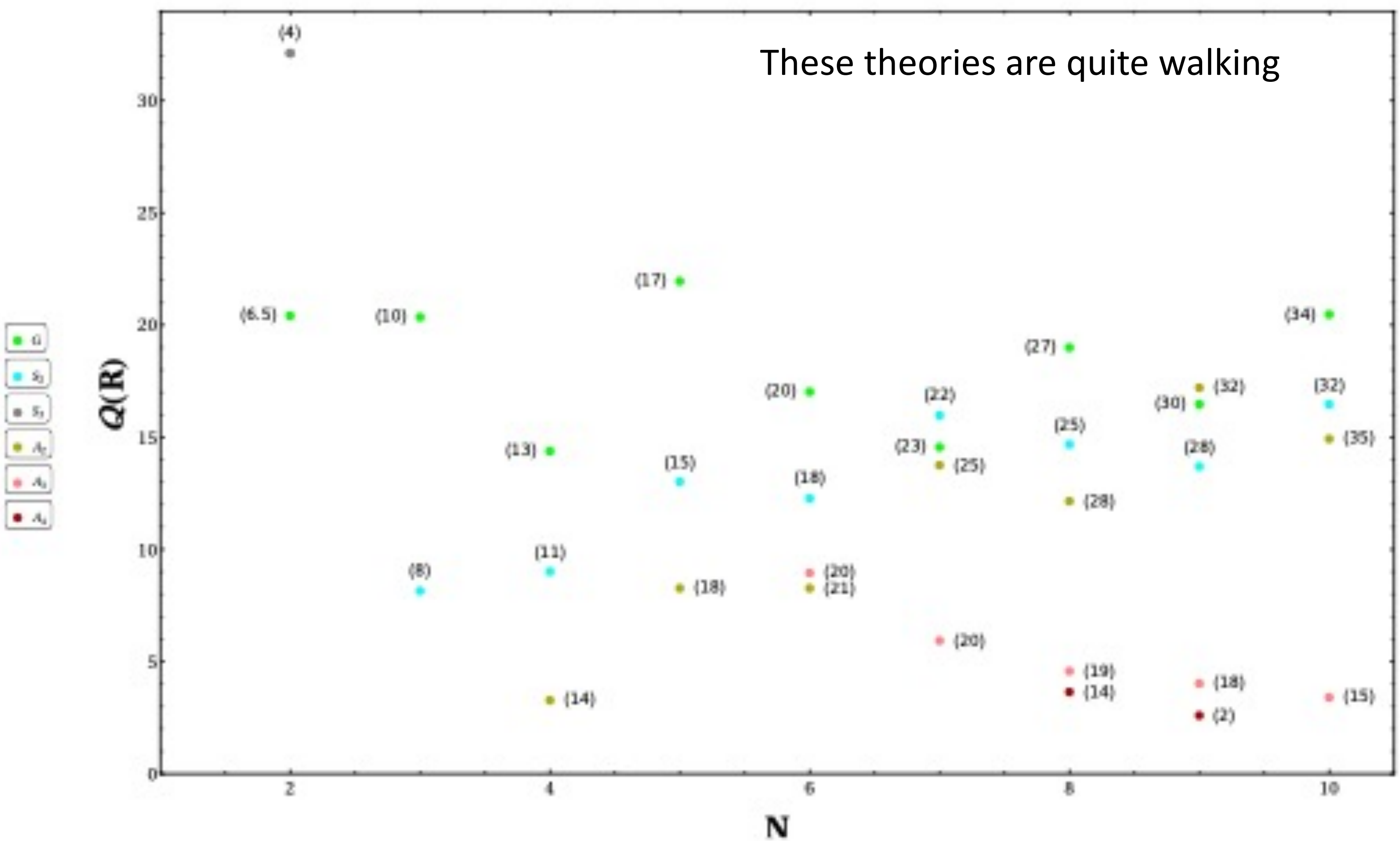
We've seen multi-rep theories with gaps between chiral symmetry breaking scales…. How big can they be?

This would be a measure of the gap to confinement also…



$$\mathcal{R}(R) = \frac{\Lambda_{\chi SB}}{\Lambda_{\text{pole}}}$$

[49] F. Karsch and M. Lutgemeier, Nucl. Phys. B **550**, 449 (1999), arXiv:hep-lat/9812023.



$$\mathcal{Q}(R) = \frac{\Lambda_{\chi SB\ R}}{\Lambda_{\chi SB\ F}}$$