On the spectrum of composite resonances

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*** Nicolas Bizot, MF, Marc Knecht, Jean-Loic Kneur** – 1610.09293, PRD95(2017)075006
Non-perturbative analysis of the spectrum of meson resonances in an ultraviolet-complete composite-Higgs model

*** Daniel Elander, MF, Marc Knecht, Jean-Loic Kneur** – in preparation
Holographic models of composite Higgs in the Veneziano limit

LFC19 @ ECT*, Trento, 9-16 September 2019

Motivations & Outline

- *No new physics signals below the TeV scale: little hierarchy problem for any extension of the Standard Model (m_h~ 0.1TeV)*

- *Large hierarchy problem (from TeV to Planck scale) still calls for an answer: the Higgs may be a composite object*

- *If the Higgs is composite, how heavy are the other resonances?*

- *Predictions require a definite ultraviolet completion: a new gauge theory of fermions, that confines at the TeV scale*

- *Estimate the spectrum of composite resonances in well-defined approximations: (I) non-perturbative QCD techniques*
  (II) gauge-gravity duality techniques

Scales in composite Higgs scenario

$m'_* \gg 10$ TeV

Composite sectors with a rich internal structure may develop several mass gaps (relevant for light fermions)

$m_* \sim 10$ TeV

The spectrum of composite resonances has typical mass gap
$m^* \sim g^* f$, with $1 < g^* < 4\pi$ the typical inter-resonance coupling

States with large coupling to the Higgs (top-quark partners) preferably light to reduce fine-tuning

$f \geq 1$ TeV

Spontaneous symmetry breaking of global symmetries: **$G_F \rightarrow H_F$**

The Higgs arises as a Nambu-Goldstone boson, with non-linear corrections to SM predictions **$\sim v^2 / f^2$**

$v = 246$ GeV

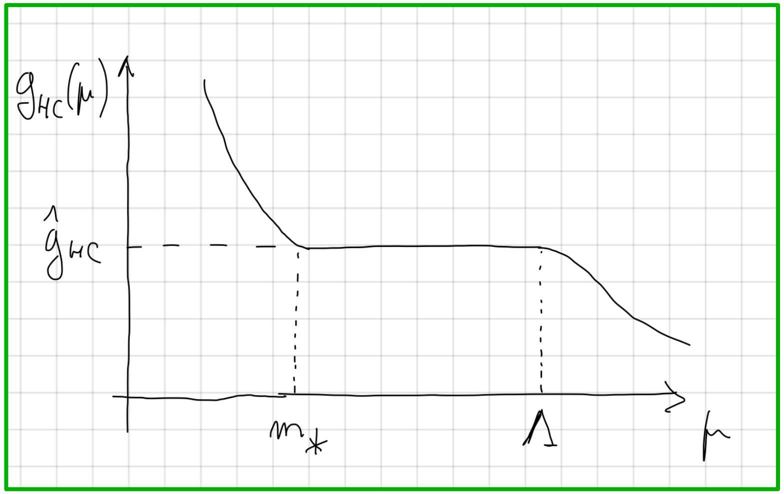
$m_h = 125$ GeV

SM couplings (top-quark Yukawa) break global symmetries **G_F**, therefore they induce radiatively the electroweak scale

review: Panico Wulzer 2015

From the UV to the IR

Prototype: asymptotically-free gauge theory (hyper-colour), that enters a strongly-coupled, walking regime (approximate scale-invariance), and eventually confines and develops a mass gap



- Partial Compositeness: mixing SM fermions with composite operators may induce hierarchy at IR scale m* from anarchy at UV scale Λ

D.B.Kaplan '91, Contino-Pomarol '04, ++

$$\mathcal{L}_{PC} = \lambda_i f_i \mathcal{O}_i + \ldots$$

$$\lambda_i(m_*) \underset{\Delta_i > 5/2}{\simeq} \lambda_i(\Lambda) \left(\frac{m_*}{\Lambda}\right)^{\Delta_i - 5/2} \equiv g^* \epsilon_i$$

- This explains Yukawa hierarchies & suppresses flavour / CP violation
- Large top-quark Yukawa requires $3/2 \leq \Delta_t \lesssim 5/2$

Minimal UV-complete composite Higgs

- Hyper-Colour gauge theory: $G_{HC} = Sp(2N_C)$
- 4 Weyl fermions ψ^a in the fundamental of G_{HC}: flavour symmetry $G_F = SU(4)$
- Strong dynamics breaks spontaneously G_F to a subgroup $H_F = Sp(4) \supset SU(2)_W$
  → the Higgs emerges as a composite Goldstone
- **Unavoidably, the Higgs is not alone:** e.g. several fermion-bilinear operators

		Lorentz	$Sp(2N)$	$SU(4)$	$Sp(4)$
	ψ_i^a	$(1/2,0)$	$\square_i$	4^a	4
	$\overline{\psi}_{ai} \equiv \psi^\dagger_{aj}\Omega_{ji}$	$(0,1/2)$	$\square_i$	$\overline{4}_a$	4^*
Spin-0 mesons	$M^{ab} \sim (\psi^a\psi^b)$	$(0,0)$	1	6^{ab}	$5+1$
	$\overline{M}_{ab} \sim (\overline{\psi}_a\overline{\psi}_b)$	$(0,0)$	1	$\overline{6}_{ab}$	$5+1$
Spin-1 mesons	$a^\mu \sim (\overline{\psi}_a\overline{\sigma}^\mu\psi^a)$	$(1/2,1/2)$	1	1	1
	$(V^\mu, A^\mu)^b_a \sim (\overline{\psi}_a\overline{\sigma}^\mu\psi^b)$	$(1/2,1/2)$	1	15^a_b	$10+5$

Two-point correlators

- The mass spectrum for each composite operator is determined by the poles of the associated two-point function

$$\Pi_V(q^2)\delta^{AB}(q_\mu q_\nu - \eta_{\mu\nu}q^2) = i\int d^4x\, e^{iq\cdot x}\langle \mathrm{vac}|T\{\mathcal{J}^A_\mu(x)\mathcal{J}^B_\nu(0)\}|\mathrm{vac}\rangle$$

$$\mathcal{J}^A_\mu = \Omega_{ij}\overline{\psi}_i\overline{\sigma}_\mu T^A\psi_j \qquad \Pi_V(q^2) \underset{\text{large } N_C}{\simeq} \sum_n \frac{f^2_{Vn}}{q^2 - m^2_{Vn}}$$

- The symmetry structure determines
  (i) quantum numbers of the resonances
  (ii) qualitative dependence of masses on symmetry-breaking parameters
  (iii) spectral sum rules relating S-P and V-A masses and decay constant

$$\text{scalars}: \ \sigma + S^{\hat{A}} \sim 1+5 \qquad \text{pseudoscalars}: \ \eta' + G^{\hat{A}} \sim 1+5$$
$$\text{vectors}: \ V^A_\mu \sim 10 \qquad \text{axialvectors}: \ a_\mu + A^{\hat{A}}_\mu \sim 1+5$$

- To be quantitative, need to model the non-perturbative dynamics

Spectrum of mesons à la NJL

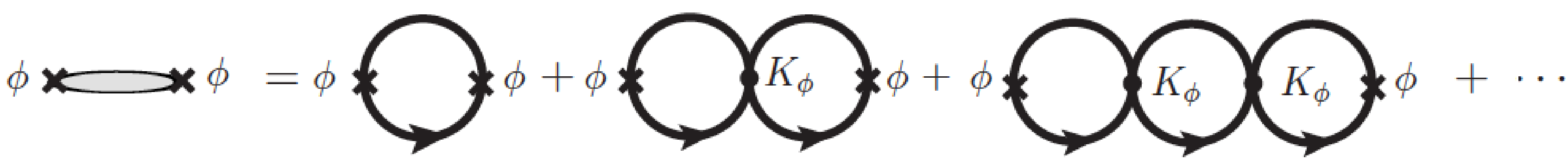
Bizot, Frigerio, Knecht, Kneur '16

- Nambu-Jona Lasinio approximation of strong dynamics:
  'decouple' hypergluons to induce effective 4-fermion interactions

$$\mathcal{L}^{\psi}_{scal} = \frac{\kappa_A}{2N}(\psi^a\psi^b)(\overline{\psi}_a\,\overline{\psi}_b) - \frac{\kappa_B}{8N}\left[\epsilon_{abcd}(\psi^a\psi^b)(\psi^c\psi^d) + h.c.\right]$$

Barnard-Gherghetta -Sankar Ray '13

- A non-zero mass-gap is induced $\langle\psi^a\psi^b\rangle \neq 0 \;\Rightarrow\; SU(4) \to Sp(4)$
- One can resum constituent fermion loops (at leading order in $1/N_c$) that contribute to the two-point correlators

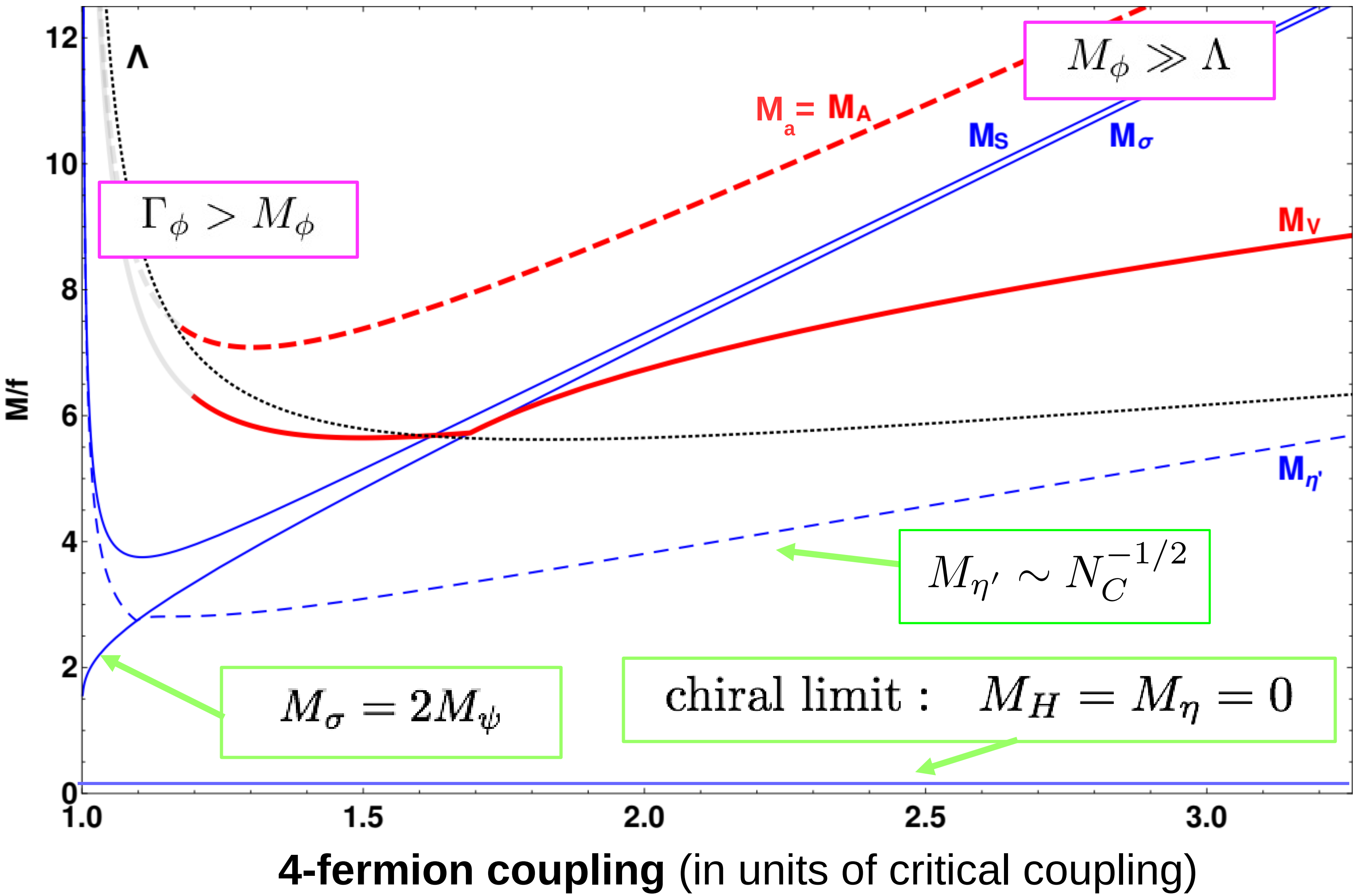


$$\overline{\Pi}_\phi(q^2) \equiv \frac{\tilde{\Pi}_\phi(q^2)}{1 - 2K_\phi\tilde{\Pi}_\phi(q^2)}$$

A pole develops, thus defining the meson mass

Meson masses in units of f

Bizot, Frigerio, Knecht, Kneur '16



spin-0 & spin-1 operators can be related in the NJL approximation

$f \sim N_C^{1/2}$

$M \sim N_C^0$

Here $N_C = 4$

Looking for top partners

- Top-quark Partial Compositeness:
  need coloured, spin-1/2 composite resonances
- In $Sp(2N_C)$ theories ($\psi_i\psi_j\psi_k$) cannot be contracted into a hypercolour-singlet (the only invariant tensor is $\Omega_{ij} = -\Omega_{ji}$)
- Need to introduce **new constituent fermions X** to allow for ($\psi\psi X$)

$$X^f \sim \begin{array}{|c|}\hline \\ \hline \\ \hline \end{array} \qquad X^f_{ij} = -X^f_{ji} \qquad X^f_{ij}\Omega_{ji} = 0$$

Barnard, Gherghetta, Sankar Ray, '13

- **Flavour group must also contain colour:**

$$G_F \to H_F \supset SU(3)_c \times SU(2)_w \times U(1)_y$$

- **Asymptotic freedom** prefers a single X and many flavours for ψ :

$$\boxed{\psi_i, \quad i = 1, \ldots, 2N_F \quad : \quad G_F = SU(2N_F) \to Sp(2N_F), \quad N_F \geq 4}$$

Characterising spin-1/2 resonances

Painful group theory (generalisation of QCD)...

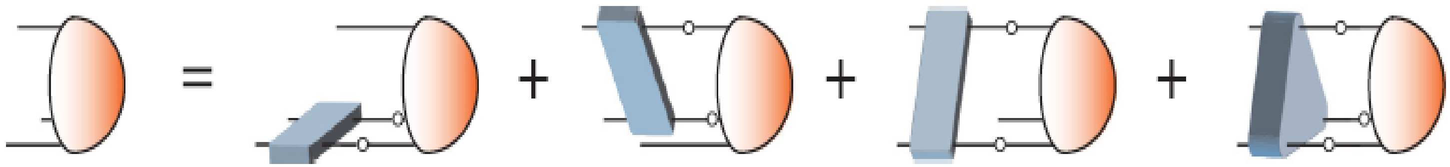
$$\mathcal{B}_1^{ab} = (\psi^a \psi^b X) \ , \qquad \mathcal{B}_2^{ab} = (\psi^a \psi^b \overline{X}) \ , \qquad \mathcal{B}_b^{a} = (\psi^a \overline{\psi}_b X)$$

Easy to identify flavour-components with the top-quark quantum numbers.

As for mesons, mass spectrum is given by poles of two-point functions:

$$\langle \mathcal{B}(q) \overline{\mathcal{B}}(-q) \rangle$$

Computation of the mass spectrum à la Nambu-Jona Lasinio is possible, via a laborious resummation in two steps: (diquark+quark)

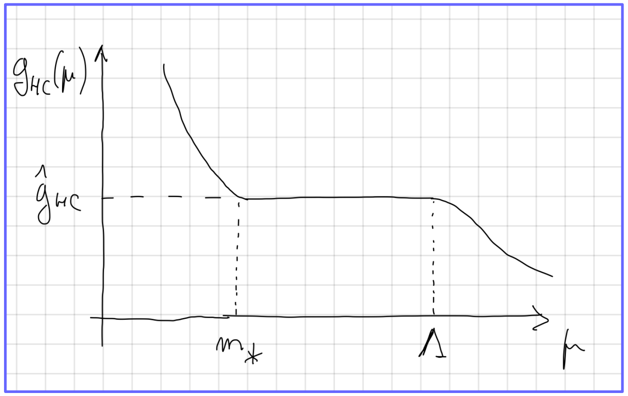


Eichmann et al., PPNP 91 (2016) 1

Preliminary results [Bizot,Kneur] are reasonable,
but several approximations hard to control...

Gauge-gravity duality

à la Daniel Elander



- The HC sector close to a fixed point : an approximate CFT
- The CFT (with N_C and $\lambda = g^2_C N_C$ large) has a holographic description as gravity in 5-dim AdS (in the classical & weakly-coupled limit)

Maldacena '97

$$\mathrm{d}s^2 = \mathrm{d}r^2 + e^{2r}\mathrm{d}x^2_{1,3}$$

- Operator O_Φ in given rep of global G_F ↔
  ↔ 5-dim field Φ in same rep of gauged G_F (and also same spin)
- Bulk scalar Φ(r) with non-flat profile back-reacts on the metric:
  CFT loses scale-invariance and may develop a mass gap m_* ↔
  ↔ Gravity loses AdS geometry, acquiring a warp factor $A(r) \neq r$
- Spontaneous SB by $\langle O_\Phi \rangle \neq 0$: massless dilaton & goldstones
- Explicit SB by $\Phi(r \to \infty) \neq 0$: non-zero β-functions, no light scalars

The role of large N_F

- G_F must contain SM symmetries : need for $N_F >> 1$
  Light resonances require N_C not too large (f ≥ 1 TeV and $m_*^2 \sim f^2 / N_C$)

- CFT correlators ↔ S_{bulk} correlators : same scaling with N_C and N_F

$$\begin{array}{lcl} \langle G_{ij} G_{ij} \rangle \sim N_C^2 & \leftrightarrow & S_{bulk}[R] \propto N_C^2 \\ \langle \psi_i^a \psi_i^a \rangle \sim N_C N_F & \leftrightarrow & S_{bulk}[\mathrm{Tr}\ \Phi_\psi^{ab}] \propto N_C N_F \end{array}$$

- If $x_F = N_F/N_C \sim 1$, one cannot treat the flavour sector as a probe on top of a fixed background (e.g. AdS) :
  back-reaction important in the Veneziano limit (large N_C , x_F constant)

- The profile $\sigma(r) = \mathrm{Tr}[\Phi(r)]/N_F$ may relate the two IR scales:
  - the end of geometry r_{IR} corresponds to the mass gap m_*
  - the vev $\langle O_\sigma \rangle$ controls the decay constant f of Goldstones
  Potentially more predictive than AdS models with an IR brane !

Gravity-scalar background

Elander, Frigerio, Knecht, Kneur, preliminary

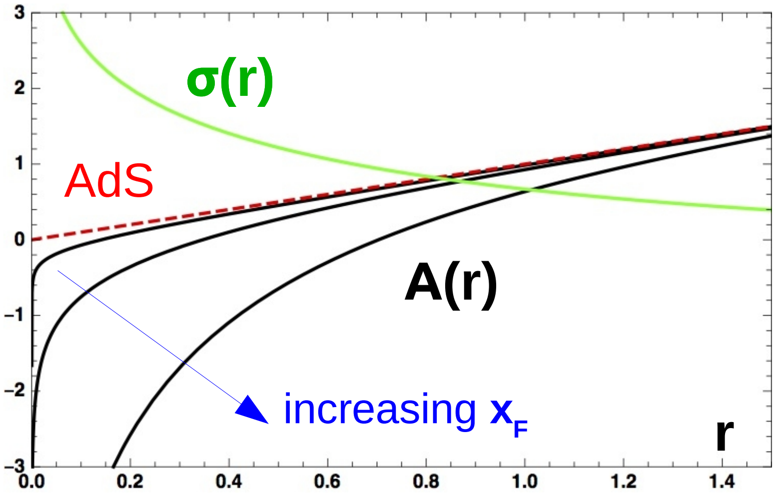
$$ds^2 = g_{MN} dx^M dx^N = dr^2 + e^{2A(r)} dx_{1,3}^2$$

$$S_{bulk} = N_C^2 \int d^5x \sqrt{-g} \left[\frac{R}{4} - \frac{\Lambda}{2} - x_F \left(\frac{1}{2} g^{MN} \partial_M \sigma \partial_N \sigma + V(\sigma) \right) \right]$$

Girardello, Petrini, Porrati, Zaffaroni '99

Choose a specific form of V inspired by some top-down models (relevant for the detailed behaviour in the IR)

$$\begin{cases} \sigma(r) = \frac{1}{2}\sqrt{\frac{3}{\Delta}} \log \frac{1+e^{-\Delta r}}{1-e^{-\Delta r}} \underset{r\to\infty}{\sim} \sqrt{\frac{3}{\Delta}} e^{-\Delta r} \\ A(r) = r + \frac{x_F}{2\Delta} \log(1-e^{-2\Delta r}) \underset{r\to\infty}{\sim} r \end{cases}$$



The UV behaviour of the scalar controls the deformation of the CFT

$$\sigma(r) \underset{r\to\infty}{\simeq} \left(\sigma_- e^{-\Delta_- r} + \sigma_+ e^{-\Delta_+ r} \right) \qquad \Delta_\pm = 2 \pm \sqrt{4 + m_\sigma^2}$$

$$V(\sigma) \underset{r\to\infty}{\simeq} -\frac{1}{2}\Delta(4-\Delta)\sigma^2 + \dots$$

$$\begin{array}{ll} 0 < \Delta < 2 : & \text{ESB by } \Delta\mathcal{L}_{CFT} \sim \mathcal{O}_\sigma \sigma_- \\ 2 < \Delta < 4 : & \text{SSB by } \langle O_\sigma \rangle \sim \sigma_+ \end{array}$$

Holography for two-point functions

- Expand S_{bulk} around the background to quadratic order in the field fluctuations, for any bulk field (spin-0, 1/2, 1, 2)
- E.o.m. linear in the fluctuations can be solved, to determine $S_{bulk}^{on\text{-}shell}$

$$\langle \mathcal{O}_1 \mathcal{O}_2 \rangle \quad \leftrightarrow \quad \lim_{r\to\infty} \frac{\delta^2 S_{bulk}^{on-shell}[\phi_i(r)]}{\delta\phi_1(r)\delta\phi_2(r)}$$

Deformed-CFT: poles of two-point functions are the resonance masses

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Fluctuations satisfy appropriate UV boundary conditions only for discrete values of q^2
(equivalently: select KK mode masses)

- The SSB scale f is defined by the residue, at $q^2=0$, of the axial-vector transverse correlator

Elander, Frigerio, Knecht, Kneur, preliminary

$$\langle J^\mu(q) J^\nu(-q) \rangle = -\lim_{r\to\infty} \frac{\delta^2 S_{bulk}^{on-shell}}{\delta A_\mu(-q,r)\delta A_\nu(q,r)} \supset \lim_{r\to\infty} \left[e^{2A(r)} P^{\mu\nu} \frac{\partial_r A_\rho(q,r)}{A_\rho(q,r)} \right]$$

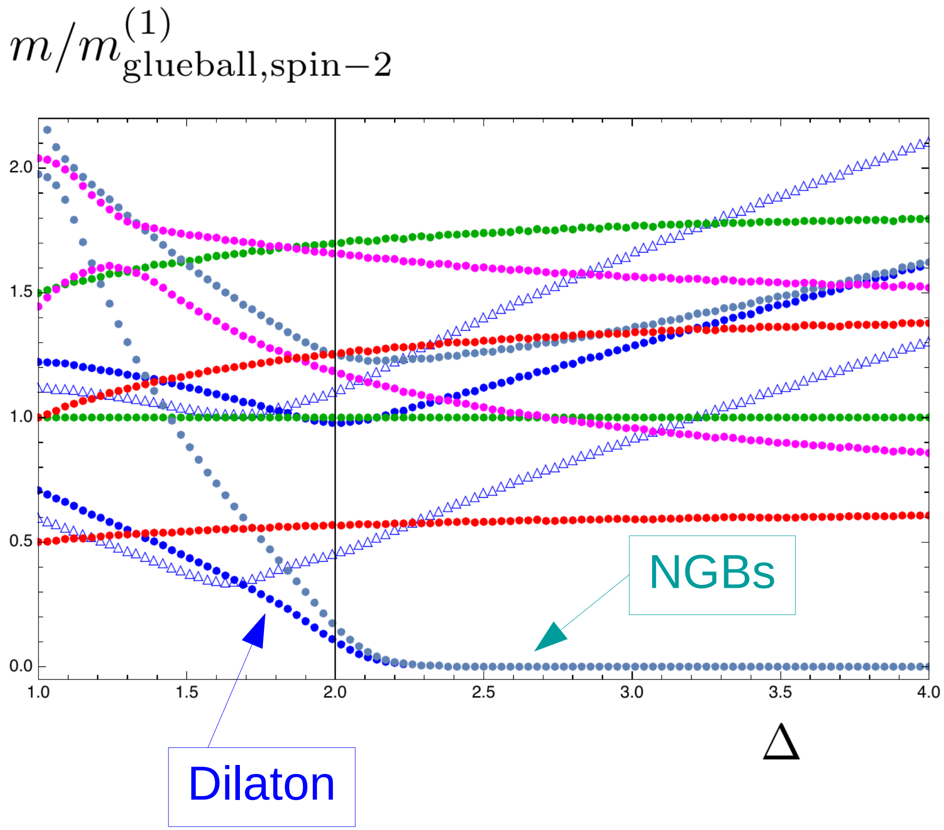
Spectrum of resonances - Bosons

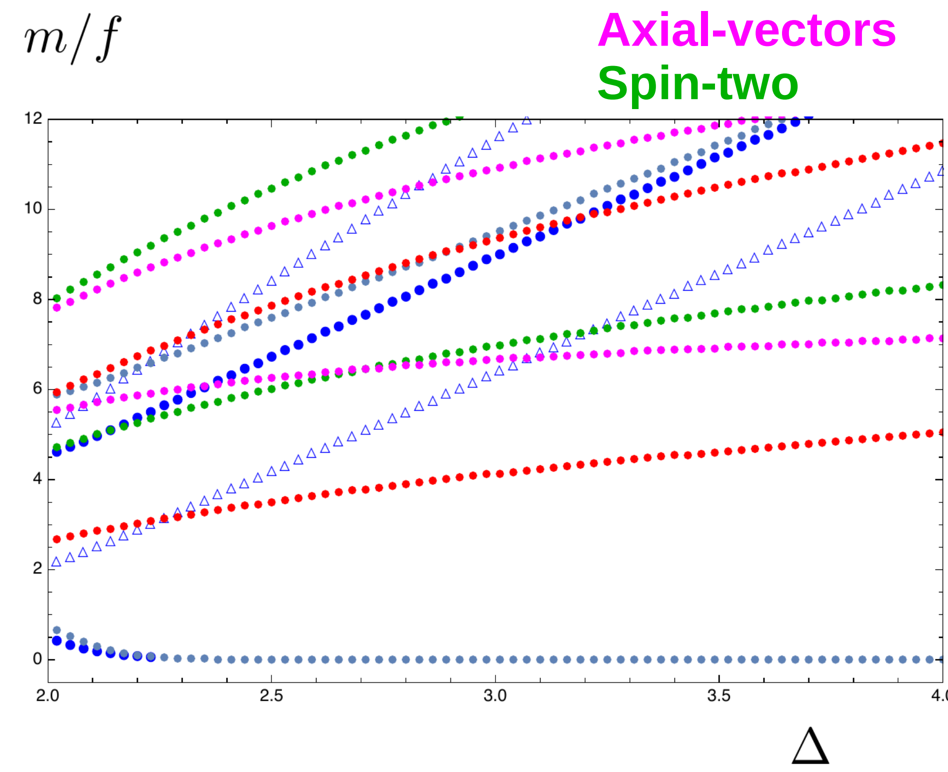
Elander, Frigerio, Knecht, Kneur, preliminary

The masses of spin-0,1,2 resonances crucially depend on the **operator anomalous dimension Δ**

Other parameters are fixed to g_5 = 5 [the 5-dim gauge coupling] and x_F = 1 [number of flavours / number of colours]

Scalars
Pseudo-scalars
Vectors
Axial-vectors
Spin-two





- **Dilaton mass may be lifted** by flavour-singlet breaking of scale-invariance, e.g. XX operator
- Scaling of f with N_C and N_F known, but **f normalisation** depends on specific top-down model

Spectrum of resonances - Fermions

Elander, Frigerio, Knecht, Kneur, preliminary

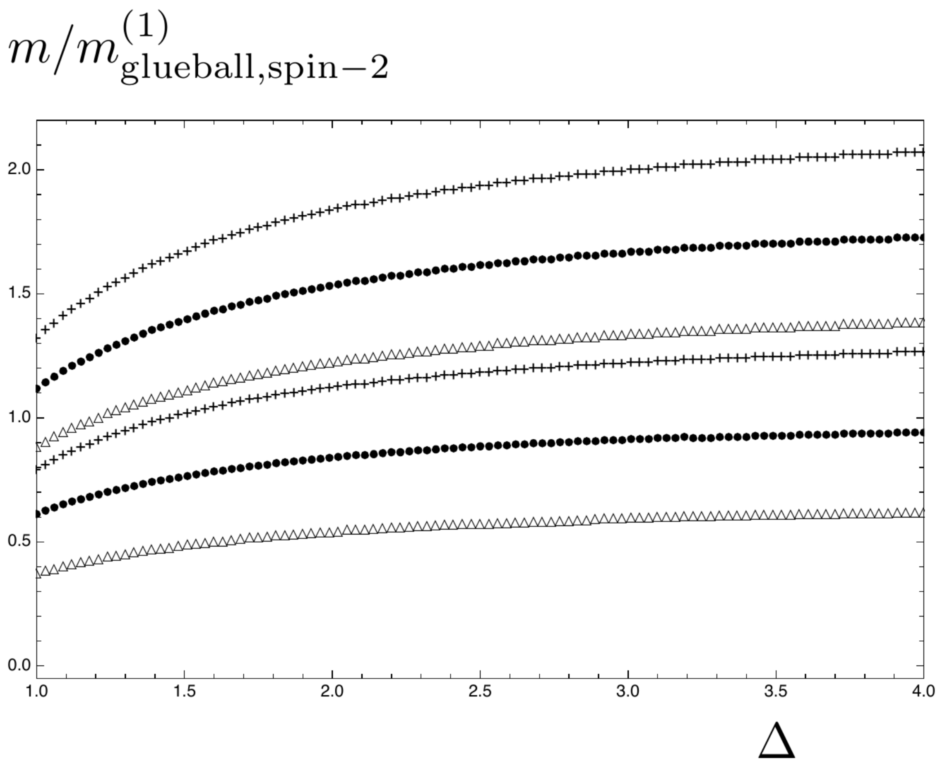
Fermionic operator B (top partner) ↔ Dirac fermion Ψ in the bulk

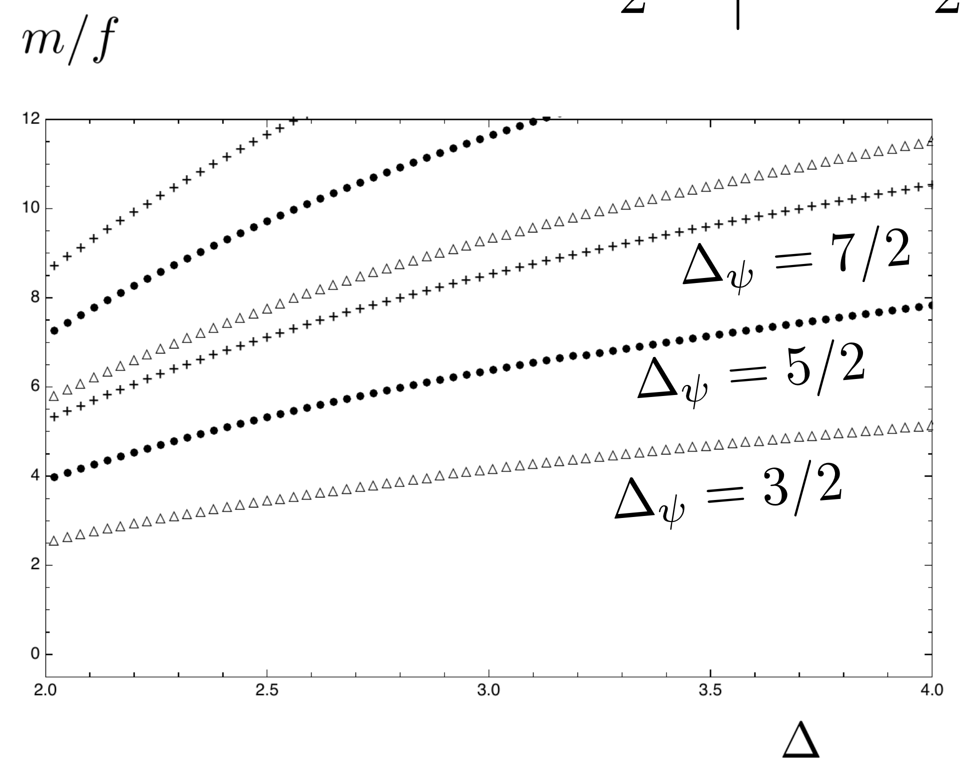
The bulk mass m_ψ is related to the operator scaling dimension Δ_ψ

Large top Yukawa requires marginal / relevant operator: $\Delta_\psi \leq 5/2$

$$\mathcal{L} \supset \lambda_{t_L} \overline{\Psi_{t_L}} \mathcal{B}_{t_L}$$

$$\Delta_{t_L} = \frac{3}{2} + \left| m_{t_L} + \frac{1}{2} \right|$$





Searching for scenarios with a fermion resonance parametrically light ...

Summary

- A composite Higgs does not come alone
- Higgs & top composite partners may well be within reach
- Modeling non-perturbative dynamics requires radical assumptions, but it appears to be very instructive
- A few rationales for lightness:
  - *SSB scale >> ESB scale: light Goldstones, dilaton, ...*
  - *Anomaly-matching : light η' , composite chiral fermions, ...*
  - *Others ?*
- Quantitative estimates are model-dependent