Holographic models of composite Higgs in the Veneziano limit

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LIO composite connections @ IP2I – Lyon

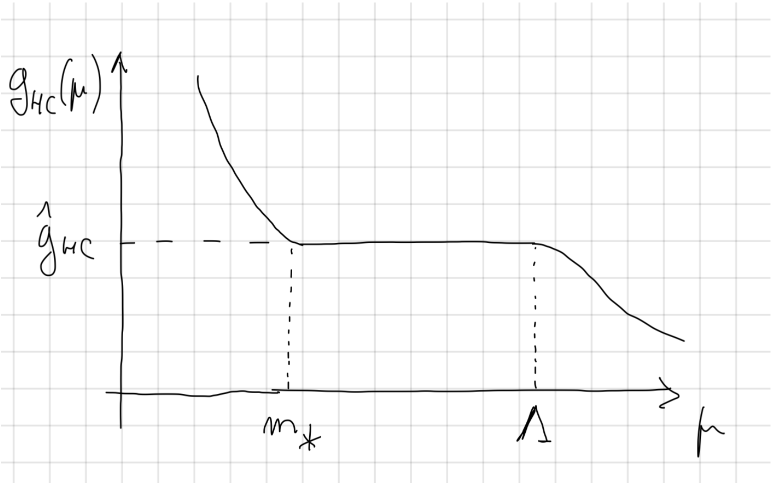
21-25 September 2020

Motivations & Outline

- *Strong dynamics at multi-TeV scale to address the hierarchy problem, with a composite pseudo-Goldstone Higgs,* $m_h \sim 0.1$ *TeV*
- *To estimate the spectrum of resonances, one needs a definite ultraviolet completion: a strongly-coupled gauge theory of fermions*
- *Reasons for a large number of flavours & (hyper)colours*
- *Holography: model the non-perturbative dynamics in 4D by a classical, weakly-coupled theory in 5D, via gauge-gravity duality*
- *Options to justify light composite bosons and/or fermions*

Relevant scales

Asymptotically-free gauge theory, Hyper-Colour, enters a strongly-coupled, walking regime, with approximate scale-invariance, and eventually confines and develops a mass gap m_*



Flavour symmetry breaking $\boxed{G_F \underset{m_*}{\to} H_F}$

Nambu-Goldstone boson decay constant $\boxed{f \simeq \frac{m_*}{g_*} \sim N_C^{1/2} \frac{m_*}{4\pi} \gtrsim 1 \text{ TeV}}$

Extra motivation is Partial Compositeness (PC): mixing SM fermions with composite operators

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

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

- Irrelevant operators to explain Yukawa hierarchies & suppress flavour/CP violation

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

- Relevant operators to explain large (top-quark) Higgs couplings: *$[O_i]$* < 5/2

The call for many flavours

TeV physics must respect SM gauge & global symmetries

$$G_F \xrightarrow{m_*} H_F \supset SU(2)_L \times SU(2)_R \times SU(3)_c \times U(1)_B \times U(1)_L$$

Higgs doublet, with custodial, coupled to quarks, respecting B & L

Hypercolour fermions in representations R_1 , … , R_k have symmetry

$$G_F = SU(N_1) \times \cdots \times SU(N_k) \times U(1)^{k-1}$$

Optimal choice of fermions: (see next slide)

$\psi_i^a \ (a = 1, \ldots, 2N_F)$ fundamental rep. of G_{HC}

χ_{ij} two-index rep. of G_{HC}

$$G_F = SU(2N_F) \times U(1) \xrightarrow{m_*} H_F = Sp(2N_F)$$

[case where fundamental is pseudoreal: $G_{HC} = Sp(2N_c)$]

Minimal realisation is *SU(10)* [rather than *SU(4) x SU(6)*]

Model in similar spirit: **Gertov, Nelson, Perko, Walker 2009**
Classification of other relevant cosets: **Ferretti, Karateev 2013, ++**

Motivations for $G_F = SU(2N_F) \times U(1)$

Highly preferable that **only ψ_i carry SM charges:**

- Preserve asymptotic freedom at large N_C

$$\boxed{11(N_C+1) - 2n_\chi(N_C \pm 1) - n_\psi > 0}$$

- Postpone Landau poles in SM gauge couplings

$$\boxed{\begin{array}{l} N_C = 5 : \Lambda_{SM} = \infty \\ N_C = 10 : \Lambda_{SM} \sim 10^{10}\ \mathrm{GeV} \end{array}}$$

- Preserve approximate gauge coupling unification

Agashe-Contino-Sundrum '05
Frigerio-Serra-Varagnolo '11

- Single χ_{ij} necessary and sufficient to implement PC via 'light' composite fermions

$$\boxed{F^{ab} = (\psi_i^a \psi_j^b \chi_{ij})}$$

In addition, **large N_F is theoretically intriguing:**

- Strongly coupled ($g_C^2 N_C \sim 4\pi$) IR fixed-point requires $x_F = N_F/N_C \sim few$
- Gravity dual: large flavour sector significantly backreacts on the AdS metric, inducing a mass gap m_* connected with the SSB scale f

Significant operators

As in QCD, a plethora of operators and a dense spectrum

Significant = hypercolour-invariant, most relevant, lower spins, …

$T^{(g)}_{\mu\nu} = F_{\mu\rho} F^{\rho}_{\nu}$ spin-0 (light dilaton?) and spin-2 glueballs

$S^{ab} \equiv (\psi^a \psi^b)$ $s \equiv (\chi\chi)$ spin-0 mesons (light dilaton and/or Goldstones?)

$J_{\mu a}{}^{b} \equiv (\overline{\psi}_a \overline{\sigma}_\mu \psi^b)$ $J_\mu \equiv (\overline{\chi}\, \overline{\sigma}_\mu \chi)$ spin-1 mesons

BOSONS

$F_1^{ab} = \psi^{[a} \chi \psi^{b]}$ $F_2^{ab} = \psi^{\{a} \chi \psi^{b\}}$

$\overline{F}^{ab} = \psi^{[a} \overline{\chi} \psi^{b]}$ $\overline{F}^{a}_{b} = \psi^a \chi \overline{\psi}_b$

spin-1/2 mesons with SM charges
(light top-quark partners?)

$F = \chi\chi\chi$ $\overline{F} = \chi\overline{\chi}\chi$ $\hat{F} = F^{\mu\nu} \chi \sigma_{\mu\nu}$

SM-singlet spin-1/2 mesons
(light sterile neutrinos / dark matter?)

FERMIONS

Two-point correlators

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

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

$$\Pi_V(q^2) \underset{\text{large } N_C}{\simeq} \sum_n \frac{f_{Vn}^2}{q^2 - m_{Vn}^2}$$

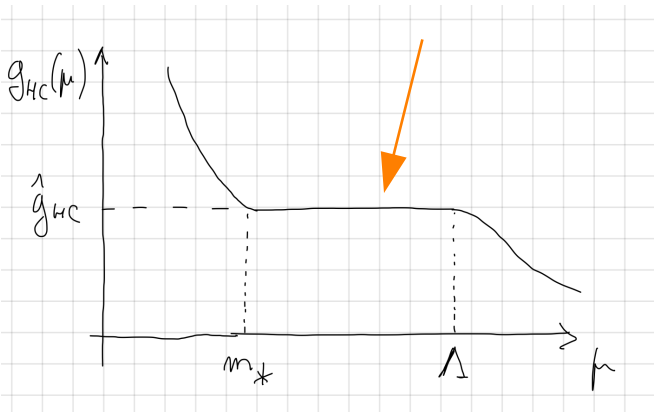
- The symmetry structure determines
(i) quantum numbers of the resonances
(ii) qualitative dependence of masses on symmetry-breaking parameters
(iii) spectral sum rules relating S-P and V-A masses and decay constants

- To be quantitative, either go numerically on the lattice,
or approximate non-perturbative dynamics by some analytic model:
- à la Nambu-Jona Lasinio
- via gauge-gravity duality

Bizot, Frigerio, Knecht, Kneur '16

Elander, Frigerio, Knecht, Kneur '20

Gauge-gravity duality



- The Hyper-Colour 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)

$$\mathrm{d}s^2 = e^{A(r)}\mathrm{d}^4x_{1,3} + \mathrm{d}r^2$$

$$AdS: \;\; A(r) = r \;, \quad \mu = \mu_0 e^r$$

Maldacena '97

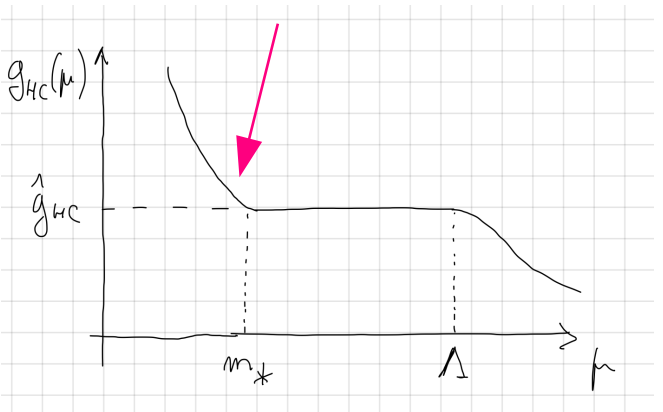
Operator O_Φ in given rep of global G_F	$\longleftrightarrow$	5-dim field Φ in same rep of gauged G_F
CFT correlator $\langle O_1 O_2 \rangle$	$\longleftrightarrow$	Bulk-action correlator $\langle \Phi_1 \Phi_2 \rangle$

GRAVITY SECTOR :

$$T_{\mu\nu} = F_{\mu\rho}F^{\rho}_{\nu} + \dots \quad \Leftrightarrow \quad g_{\mu\nu}(r)$$

$$\langle \mathrm{tr}(FF)\mathrm{tr}(FF)\rangle \sim N_C^2 \quad \Leftrightarrow \quad \mathcal{L}_{5D}[R] \sim N_C^2$$

Gauge-gravity duality



FLAVOUR SECTOR :

$$(\psi^a \psi^b) \quad \Leftrightarrow \quad \Phi^{ab}(r)$$

$$\langle(\psi^a\psi^a)(\psi^b\psi^b)\rangle \sim N_C N_F \quad \Leftrightarrow \quad \mathcal{L}_{5D}(\mathrm{tr}\Phi^{ab}) \sim N_C N_F$$

In the Veneziano limit, the flavour sector is of the same order as the gravity sector.

Thus, as the scalar Φ(r) develops a non-trivial profile, it strongly backreacts on the metric.

$$N_C \to \infty$$

$$x_F \equiv \frac{N_F}{N_C}$$
constant

CFT loses scale-invariance ⟷ Departure from AdS: warp factor A(r) ≠ r

Non-zero mass gap m_* ⟷ Geometry ends at some finite value r_0

Dynamical correlation !

Flavour SSB: non-zero Goldstone decay constant f ⟷ Φ(r) breaks spontaneously the gauge symmetry $SU(2N_F)$

An explicit model

Bulk fields:

$$g^{MN} = diag(-e^{2A}, e^{2A}, e^{2A}, e^{2A}, 1)^{MN}$$

$$\Phi_{ab} = \sigma \left[\Sigma_{ab}/2 + i\pi_{\hat{A}} (T^{\hat{A}} \Sigma)_{ab} \right] + \ldots$$

$$(A_M)_a^b = V_M^A (T^A)_a^b + A_M^{\hat{A}} (T^{\hat{A}})_a^b$$

Bulk action:

$$S = \int \mathrm{d}^5 x \sqrt{-g} \left[N_C^2 R/4 - N_C \left(|D\Phi|^2 + F^2/4 + V(\Phi) \right) \right]$$

Trace over flavour indexes: $|D\Phi|^2 + V(\Phi) = N_F \left[(\partial\sigma)^2/2 + \tilde{V}(\sigma) \right]$

Equations of motion:

$$\begin{array}{rcl} \partial_r^2 \sigma + 4\partial_r A \partial_r \sigma - \partial_\sigma \tilde{V}(\sigma) & = & 0 \\ 6(\partial_r A)^2 - x_F (\partial_r \sigma)^2 + 2x_F \tilde{V}(\sigma) & = & 0 \end{array}$$

Gravity-scalar background

Assume asymptotically AdS : $A(r) \underset{r\to\infty}{\simeq} r$

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

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

source for O_σ : ESB

VEV for O_σ : SSB

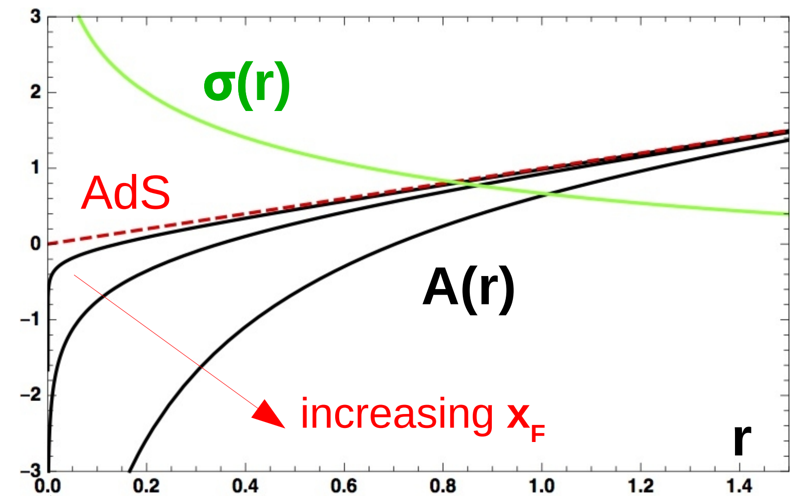
$$\boxed{O_\sigma \ \Leftrightarrow \sigma \qquad [O_\sigma] = \Delta_+}$$

Choose a specific form of V(σ)
inspired by some top-down models
(choice is relevant for IR behaviour)

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

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

Girardello, Petrini, Porrati, Zaffaroni '99



End of space

Poles of two-point functions

- Expand S_{bulk} around the background to quadratic order in the field fluctuations, for each 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

$\longleftrightarrow$

Fluctuations satisfy appropriate UV boundary conditions only for discrete values of q^2

$$\langle J^\mu(q) J^\nu(-q)\rangle = -\lim_{r\to\infty} \frac{\delta^2 S_{bulk}^{on-shell}}{\delta A_\mu(-q,r)\delta A_\nu(q,r)} \supset \lim_{r\to\infty}\left[\frac{N_C e^{2A(r)}}{g_5^2} P^{\mu\nu} \frac{\partial_r A_\rho(q,r)}{A_\rho(q,r)}\right]$$

- Axial-vector transverse correlator also defines SSB scale f^2 as the residue at $q^2 = 0$
  (precise **normalisation** sensitive to specific top-down model)

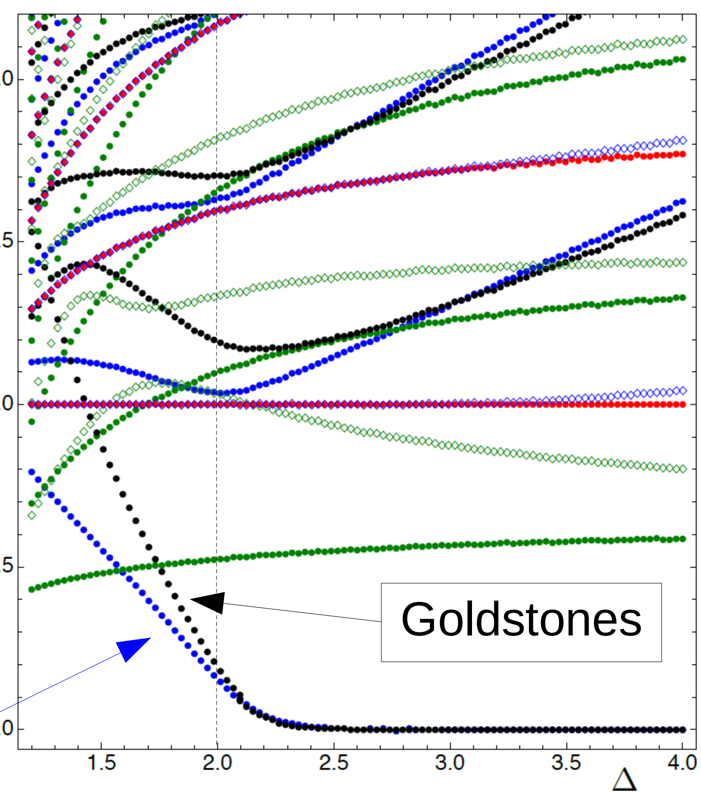
Boson spectrum as a function of Δ

Operator driving symmetry breaking scales as $[O_\sigma] = 4 - \Delta \quad \text{for } \Delta < 2\ (ESB)$
$[O_\sigma] = \Delta \quad \text{for } \Delta > 2\ (SSB)$

$x_F = 2 \quad g_5 = 5$

scalar singlets ●
scalar non-singlets ◊
pseudoscalars ●
vectors ●
axial vectors ◊
tensors ●

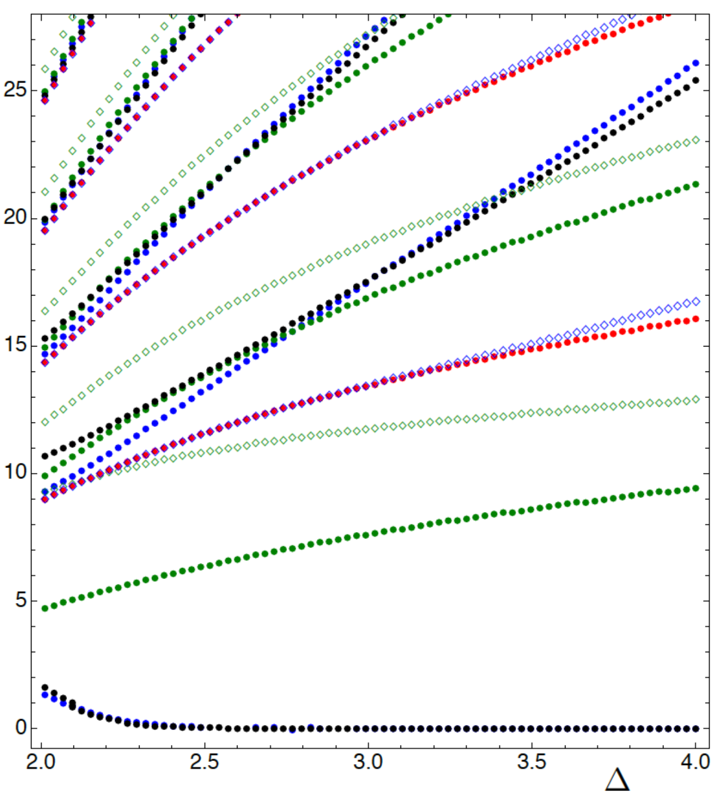
m/m_T lightest spin-2 glueball



Dilaton

---ESB---|--------SSB-------------|

$m/\tilde{f}$ Goldstone decay constant



$$\tilde{f} \equiv \frac{f}{\sqrt{N_C}} \gtrsim \frac{1\ \text{TeV}}{\sqrt{N_C}}$$

Sources of scale-symmetry breaking

Scalar invariance may be broken independently from the flavour sector !

This additional breaking can be described by a flavour-singlet bulk scalar :

$$S_\phi = -N_C^2 \int \mathrm{d}^5x \sqrt{-g}\,\left[|D\phi|^2 + V(\phi)\right]$$

$$\boxed{\phi \leftrightarrow O_\phi = (\chi\chi),\ (FF),\ \ldots \quad \Rightarrow \quad \langle O_\phi \overline{O_\phi}\rangle \sim N_C^2}$$

As usual, the profile depends on the choice of potential:

$$A) \quad \phi(r) = \phi_A\, e^{-\Delta_\phi r} \qquad\qquad B) \quad \phi(r) = \frac{1}{2}\sqrt{\frac{3}{\Delta_\phi}} \log \frac{1+\phi_B e^{-\Delta_\phi r}}{1-\phi_B e^{-\Delta_\phi r}}$$

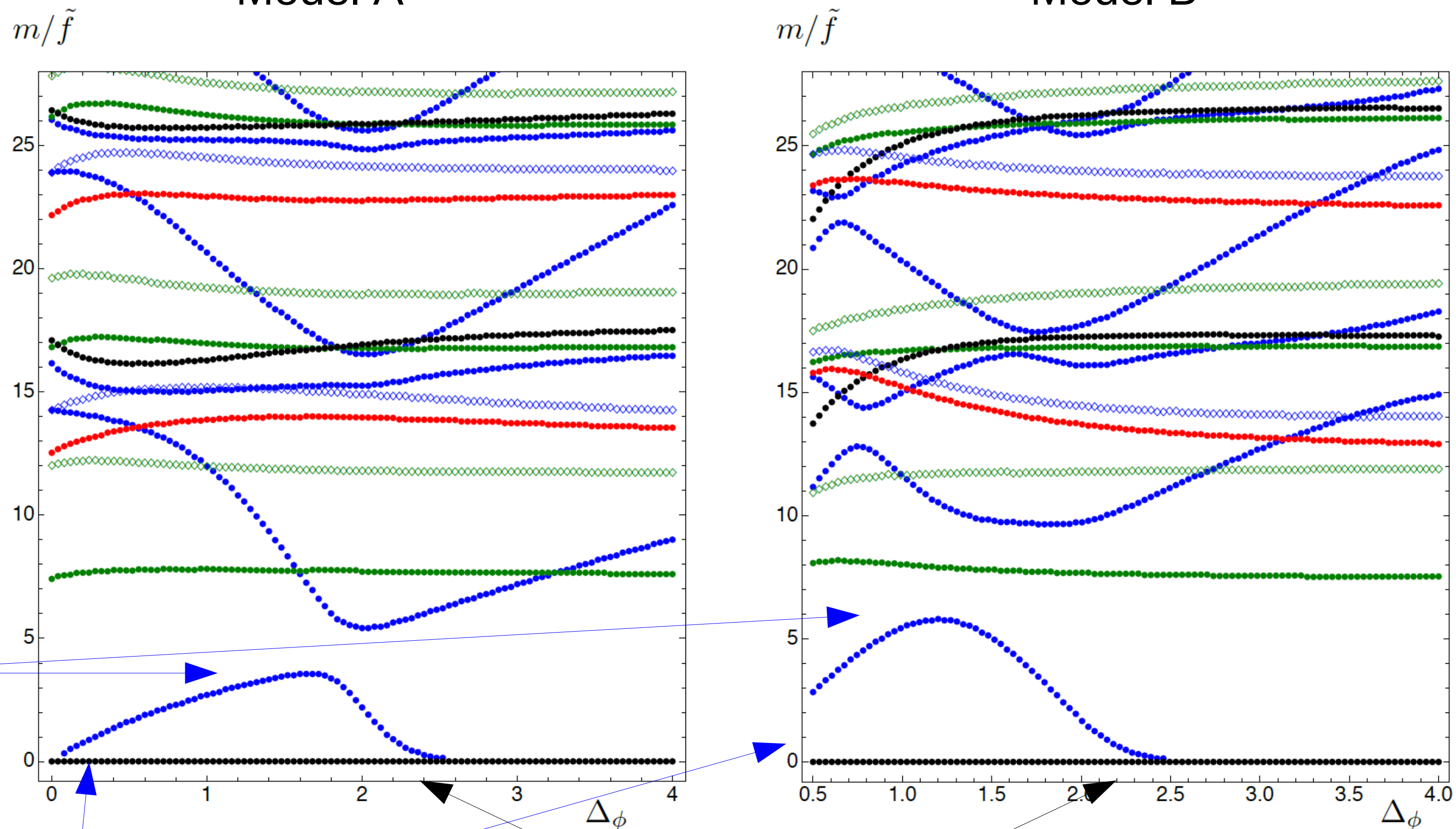
$$\boxed{\begin{array}{ll} 0 < \Delta_\phi < 2 \ : & \text{ESB by } \Delta\mathcal{L}_{CFT} \sim \mathcal{O}_\phi \phi_- \\ 2 < \Delta_\phi < 4 \ : & \text{SSB by } \langle O_\phi \rangle \sim \phi_+ \end{array}}$$

Boson spectrum as a function of Δ_ϕ

Two scalars in the bulk: **a flavourful $\boldsymbol{\Phi_{ab}}$ and a flavour-singlet ϕ**

$\Delta = 3$
$x_F = 1$
$g_5 = 5$

scalar singlets ●
scalar non-singlets ◊
pseudoscalars ●
vectors ●
axial vectors ◊
tensors ●



Dilaton never decouples

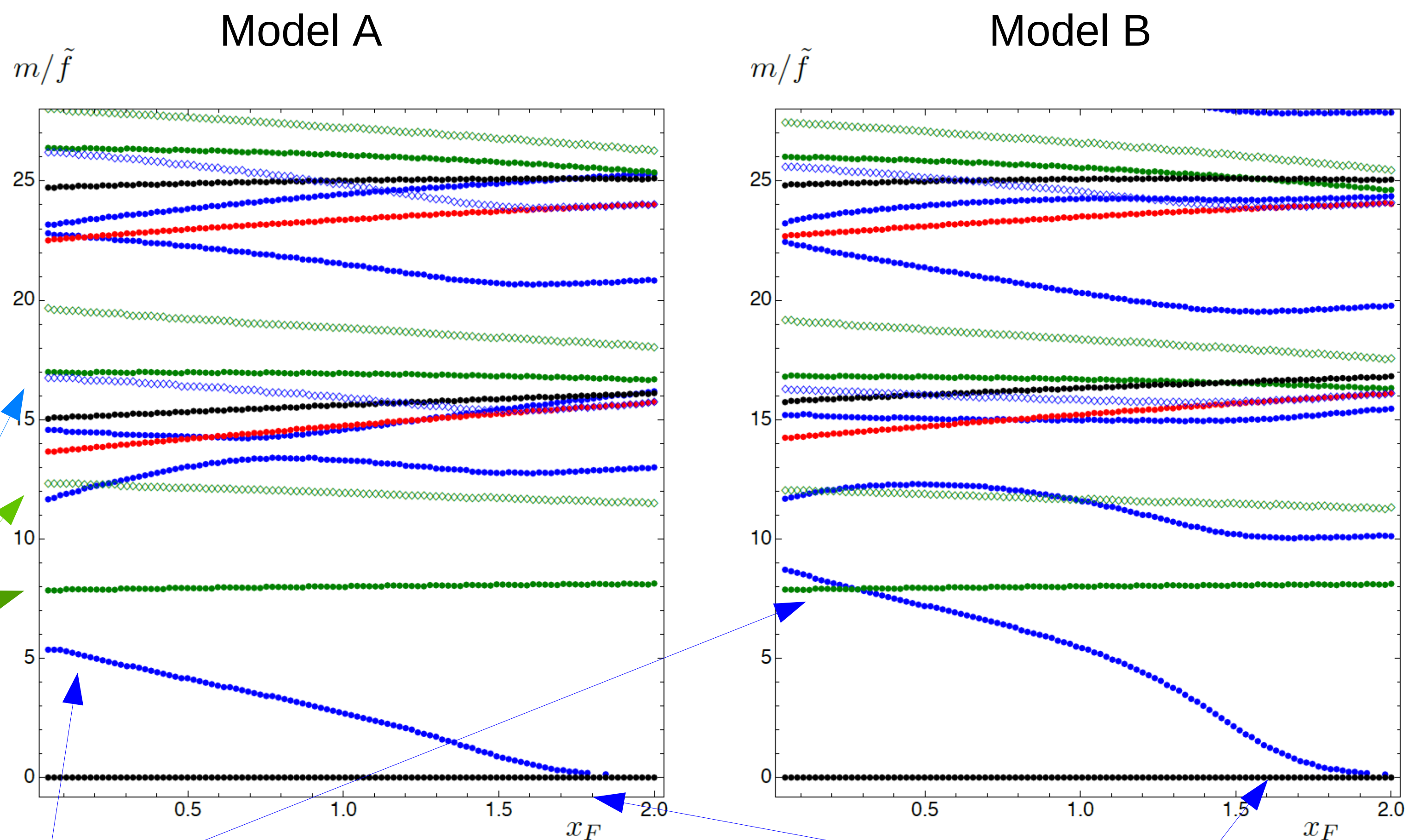
Dilaton remains light if deformation close to marginal: $[O_\phi] = 4 - \Delta_\phi$

Dilaton mass can be lifted as the NGBs remain light

Boson spectrum as a function of x_F

$\Delta = 3$
$\Delta_\phi = 1$
$g_5 = 5$

Scalar masses significantly depend on the number of flavours



scalar singlets ●
scalar non-singlets ◊
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tensors ●

Sp(4) on lattice with quenched fermions, **Bennett, Hong, Lee, Lin, Lucini, Mesiti, Piai, Rantaharju, Vadacchino, 2019**

For x_F << 1 the ESB in the singlet sector becomes order-one effect

For x_F >> 1 the flavoured SSB dominates over singlet ESB: dilaton light again !

Fermionic sector

Consider first composite fermions in isolation: no mixing with elementary SM fermions

Source for fermion operators: $O_R^{ab} = \psi^a \bar{\chi} \psi^b \quad \leftrightarrow \quad \Psi_L^{ab}|_{r\to\infty}$

$$\mathcal{S}_\Psi = -N_C^2 \int \mathrm{d}^5 x \sqrt{-g}\, \mathrm{Tr}\left[\frac{1}{2}(\overline{\Psi}\Gamma^M D_M \Psi - \overline{D_M \Psi}\Gamma^M \Psi) + M_\Psi \overline{\Psi}\Psi\right]$$

Spectrum given by the poles of $i\langle O_R(q)\overline{O_R}(-q)\rangle = \lim_{r\to\infty} \frac{\delta^2 S_\Psi^{on-shell}}{\delta\bar{\psi}_L(-q)\delta\psi_L(q)}$

UV behaviour is dual to scaling dimension

$$\Psi_L(q,r) = e^{-2A(r)+M_\Psi r}\psi_L(q,r) \underset{r\to\infty}{\sim} e^{-(2-M_\Psi)r}$$

$$[O_R] = 4 - [\psi_L] = 2 + M_\Psi \quad \underset{unitarity}{\Rightarrow} \quad M_\Psi \geq -1/2$$

Equation of motion $\left[\partial_r^2 + (\partial_r A + 2M_\Psi)\partial_r - q^2 e^{-2A}\right]\psi_L = 0$

Two consistent IR boundary conditions

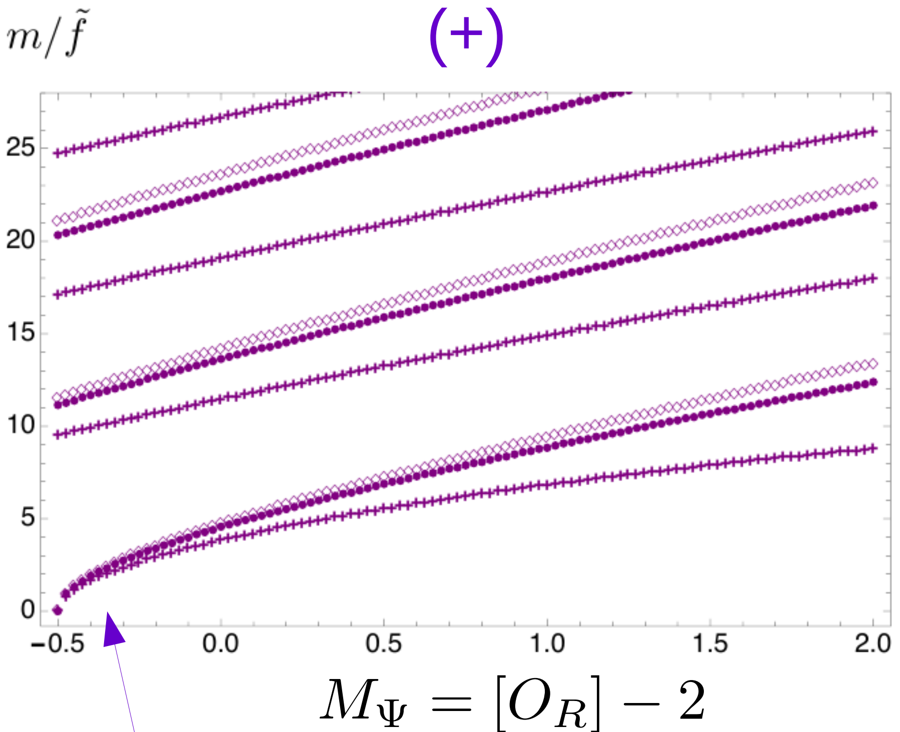
$$\psi_L|_{r_{IR}} = 0 \qquad (-)$$
$$\partial_r \psi_L|_{r_{IR}} = 0 \quad (+)$$

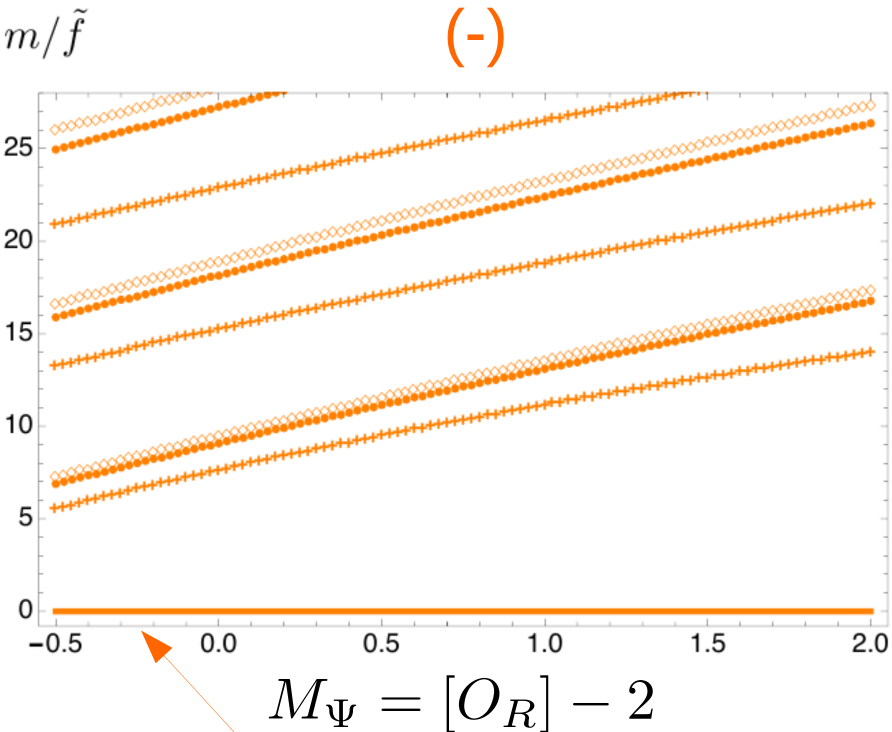
Contino Pomarol 2004

Fermion spectrum as function of M_ψ

$\Delta = 3 \qquad g_5 = 5$

x_F = 0.5: ◊ x_F = 2: ● x_F = 4: +





As $[O_R] \to 3/2$, one chiral fermion decouples from the composite sector

There is always a chiral fermion, for any value of M_ψ and x_F

(possible even in vector-like gauge theories !)

Bulk Yukawa coupling

The scaling-dimension of a fermion operator $[O_R]$ may be scale-dependent

A bulk-fermion mass M_ψ may be radial-dependent, if coupled to the scalar $\phi(r)$

$$\boxed{S_{\mathrm{Y}} = -N_C^2 \int \mathrm{d}^5 x \sqrt{-g}\, \left[y_5 \phi \overline{\Psi} \Psi\right] \quad \Rightarrow \quad M_\Psi(r) = M_\Psi + y_5 \phi(r)}$$

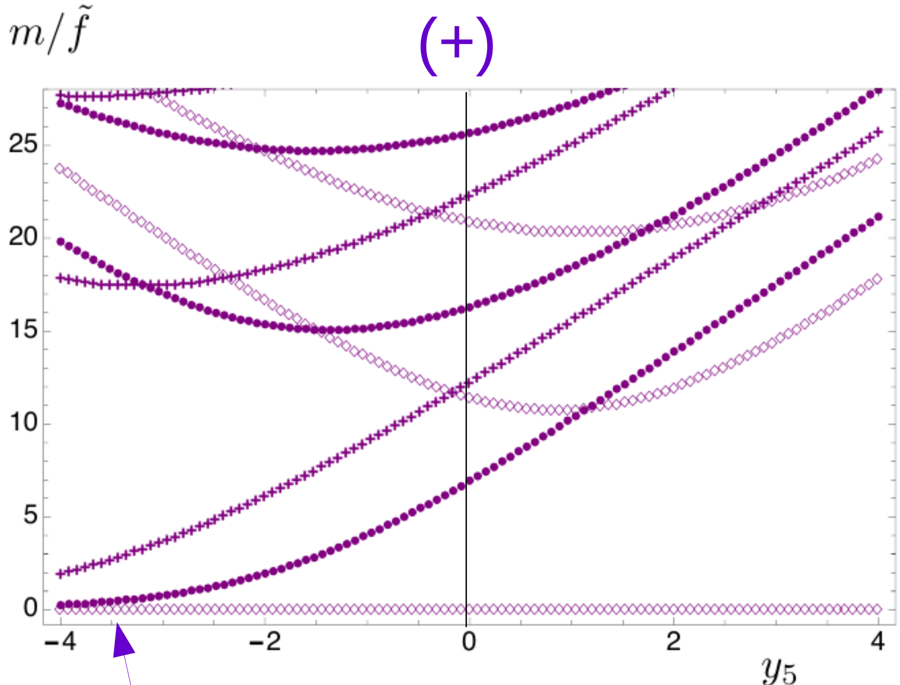
As $\phi(r)$ grows in the IR, the lightest fermion modes can be strongly affected

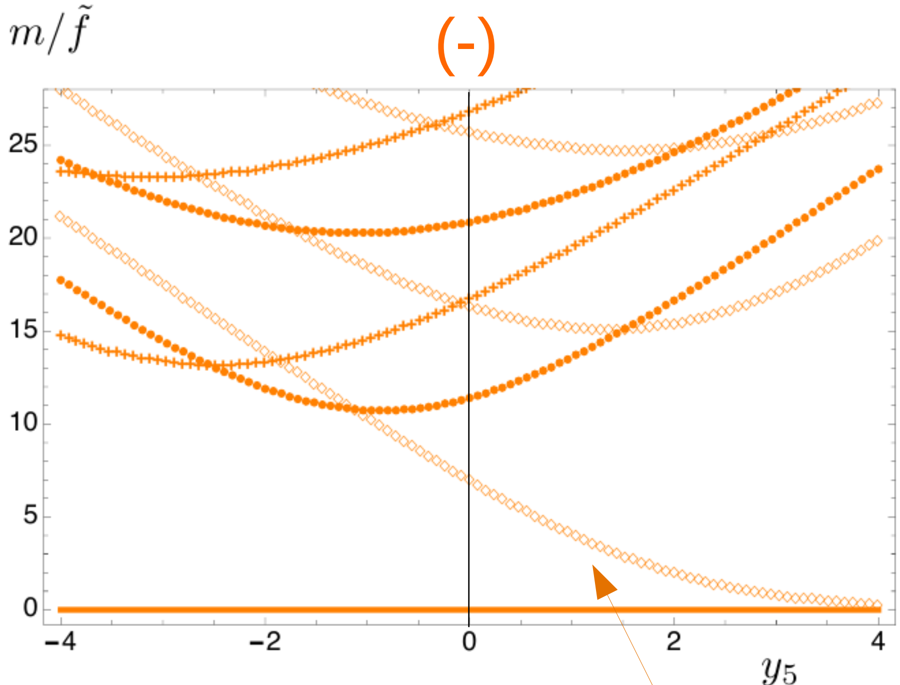
Depending on the sign of y_5, the IR behaviour of $\Psi(r)$ changes significantly

Fermion spectrum as function of y_5

$\Delta = 3 \quad \Delta_\phi = 1$
$g_5 = 5 \quad x_F = 1$

M_ψ = -0.5: ◊ M_ψ = +0.5: ● M_ψ = +2: +





Large negative y_5 suppresses ψ_L in the IR, roughly "turning (+) into (-)":
The zero-mode becomes light for any value of M_ψ
Light fermion possible even for $[O_R]$ >> 3/2 !

First massive mode for $[O_R]$ = 3/2 becomes light for large positive y_5 ?!?

PC: holographic RG flow

Partial Compositeness amounts to mix elementary fermion χ_L with composite operator O_R

$$S_\chi[\mu] = \int \mathrm{d}^4 q \left[\overline{\chi_L}(-i\gamma^\mu q_\mu)\chi_L + \overline{O_R}\,\tilde{\lambda}(\mu)\chi_L\right] \qquad \tilde{\lambda}(\mu) = N_C^{-1}\mu^{[O_R]-5/2}\lambda(\mu)$$

renormalisation scale μ

Holographic Wilsonian Renormalisation Group

UV cutoff μ corresponds to finite radial coordinate *r:*

Duality is assumed to hold along the flow:

$$\boxed{\mu^{-1}(r) = \int_r^\infty \mathrm{d}\tilde{r} e^{-A(\tilde{r})}}$$

$$Z_{4D}[\mu] \equiv \int D\chi|_{q\leq\mu} e^{iS_\chi} = Z_{5D}[r] \equiv \int D\Psi|_{\tilde{r}\leq r} e^{iS_\Psi} e^{\int \mathrm{d}^4 q \overline{\psi_L} \frac{\gamma^\mu q_\mu}{\tilde{\lambda}^2}\psi_L \big|_r}$$

Elander, Isono, Mandal 2011

RG flow equation can be derived as r varies, for an arbitrary background geometry

E.g. AdS metric, low-energy limit :

$$\mu\partial_\mu \lambda^2 = (2[O_R]-5)\lambda^2 + \lambda^4$$

Non-trivial IR fixed point, if the deformation is relevant: $\lambda^2_{IRFP} = 5 - 2[O_R]$

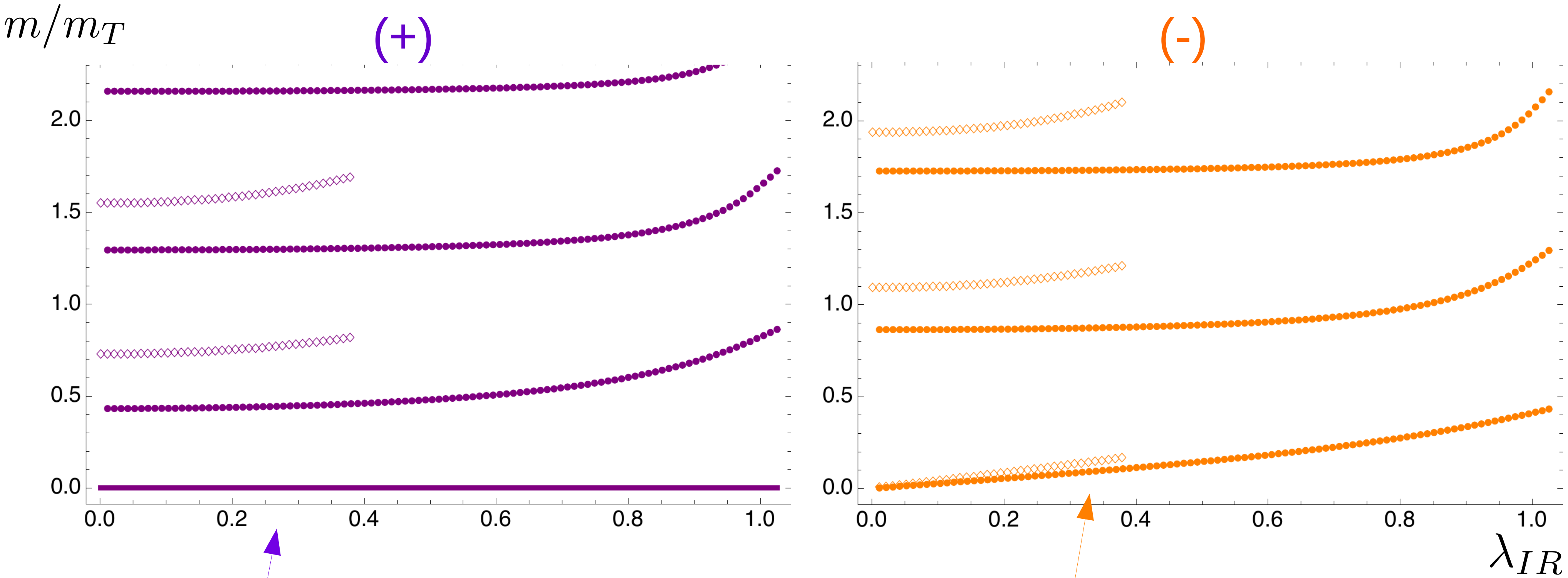
Fermion spectrum as function of λ

$$\langle \chi_L(q)\overline{\chi}_L(-q)\rangle_\mu = \frac{-1}{\gamma^\nu q_\nu - \tilde{\lambda}^2(\mu)\langle \mathcal{O}_R(q)\overline{\mathcal{O}}_R(-q)\rangle_\mu^{\lambda=0}}$$

Poles are RG-invariant, as they should

AdS case ($x_F \to 0$)

irrelevant $[O_R] = 2.75$: ◊ *relevant $[O_R] = 2$: ●*



λ pairs a chiral composite fermion with the chiral elementary fermion

λ describes composite-elementary mixing: degree of compositeness of the chiral mode varies

General case ($x_F \neq 0$) in progress

Summary

- A composite Higgs requires a **rich new physics spectrum**
- **Many flavours** are needed to comply with the SM structure
- **Many colours** allow to model non-perturbative dynamics by using holography
- **A self-consistent gravity-scalar background** describes dynamically the mass gap & flavour symmetry-breaking
- **Higgs partners may be light** when SSB scale >> ESB scale: several other Goldstones & a dilaton
- **SM fermion partners may be light,** in various interesting limits

H_F-to-SM decomposition (N_F=5)

$$H_F = Sp(10) \supset SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_B \qquad Y = \pm T_3^R + \frac{B}{2}$$

$$\psi^a \sim 10_{Sp(10)} = \left[(3,1,1)_{1/3} + (\overline{3},1,1)_{-1/3} + (1,2,1)_0 + (1,1,2)_0\right]_{SU_{3221}}$$

$$(\psi^a \psi^b) \sim (10 \times 10)_{Sp(10)} = (1_A + 44_A + 55_S)_{Sp(10)}$$

$$\begin{aligned}
(1_A)_{Sp(10)} &= \left[(1,1,1)_0\right]_{SU_{3221}} \\
(44_A)_{Sp(10)} &= \big[2 \times (1,1,1)_0 + (1,2,2)_0 + (8,1,1)_0 + (3,1,1)_{-2/3} + (\overline{3},1,1)_{2/3} \\
&\quad + (3,2,1)_{1/3} + (\overline{3},2,1)_{-1/3} + (3,1,2)_{1/3} + (\overline{3},1,2)_{-1/3}\big]_{SU_{3221}} \\
(55_S)_{Sp(10)} &= \big[(1,1,1)_0 + (1,2,2)_0 + (1,1,3)_0 + (1,3,1)_0 + (8,1,1)_0 + (6,1,1)_{2/3} + (\overline{6},1,1)_{-2/3} \\
&\quad + (3,2,1)_{1/3} + (\overline{3},2,1)_{-1/3} + (3,1,2)_{1/3} + (\overline{3},1,2)_{-1/3}\big]_{SU_{3221}}
\end{aligned}$$

Enjoy phenomenology!