Non-perturbative analysis of the spectrum of meson resonances in an ultraviolet-complete composite-Higgs model

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based on arXiV: 1610.09293 with M. Frigerio, M. Knecht and J.-L. Kneur

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- New strong dynamics condensates at scale Λ and spontaneously breaks a global symmetry G into H $\Rightarrow$ Higgs is naturally light as a pNGB leaving in G/H
- Potential and mass for the Higgs generated from linear coupling between SM fermions and composite spin 1/2 resonances (partial compositeness)

Effective models of composite Higgs

Full gauge theory (hypergluons, hyperfermions as d.o.f) hard to study below Λ because of its non-perturbative nature $\Rightarrow$ Effective models are useful

- Chiral Lagrangians: dictated only by global symmetries
  $\Rightarrow$ Little information on the details of the strong dynamics
  $\Rightarrow$ Not sure that an UV completion exists
- 4-fermion interactions approximate the strong dynamics
  (gauge bosons are froze-out)
  $\Rightarrow$ Definite UV completion and underlying gauge symmetry respected
  $\Rightarrow$ Possible to make calculation of non-perturbative quantities with Nambu Jona-Lasinio (NJL) techniques [Nambu and Jona-Lasinio '61]

UV completions: EW sector (Higgs as pNGB) + coloured sector (top partners)

Basic requirements for an UV completion

- Higgs as a composite Nambu-Goldstone boson leaving in coset G/H
- Custodial symmetry: $H \supset SU(2)_L \times SU(2)_R$
- No fundamental scalars

All possible minimal UV models classified in [Ferretti, Karateev, '14]

Minimal model: $SU(4)/Sp(4) \cong SO(6)/SO(5)$

- $SU(4)/Sp(4) \Rightarrow$ only 5 NGBs: Higgs doublet + singlet η
- 4 Weyl fermions $\psi \Rightarrow SU(4)$ global symmetry
- $Sp(4) \Rightarrow \psi$ belong to a pseudo-real hypercolour representation:
  the fundamental of $Sp(2N)$ [Barnard et al, '13]

		Lorentz	Colour: $Sp(2N)$	Flavour: $SU(4)$	Flavour: $Sp(4)$
Hypercolour fermions	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-zero bilinears	$M^{ab} \sim (\psi^a\psi^b)$	$(0,0)$	1	6^{ab}	$5+1$
	$\overline{M}_{ab} \sim (\overline{\psi}_a\overline{\psi}_b)$	$(0,0)$	1	$\overline{6}_{ab}$	$5+1$
Spin-one bilinears	$a^\mu \sim (\overline{\psi}_a\overline{\sigma}^\mu\psi^a)$	$(1/2,1/2)$	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	$10+5$

Hypercolour-invariant fermionic bilinears have the quantum numbers of the meson resonances

Lightest composite meson resonances

Scalars: $\sigma + S^{\hat{A}} \sim 1+5$

Pseudo-scalars: $\eta' + G^{\hat{A}} \sim 1+5$

Vectors: $V^A_\mu \sim 10$

Axial-vector: $a_\mu + A^{\hat{A}}_\mu \sim 1+5$

- The model is a vector-like gauge theory: all fermions ψ can be made massive ($m_\psi \psi\psi$), while preserving the gauge hypercolour symmetry $G_c = Sp(2N)$

- Vafa-Witten theorem: The flavour subgroup H of G preserved by m_ψ can not be spontaneously broken $\Rightarrow$ If $SU(4)$ broken, it is broken down to $Sp(4)$

- 't Hooft anomaly matching:
  Any global UV anomaly (generated by the hyperfermions ψ) must be matched in the IR, either by massless spin-1/2 baryons or Goldstone boson

  ψ's can not form baryons because they are in pseudo-real hypercolour irreps $\Rightarrow$ $SU(4)$ necessarily broken

$$d^{AB\hat{C}} = 2Tr[\{T^A, T^B\}T^{\hat{C}}]$$

$SU(4)$ broken ($T^{\hat{A}}$) and unbroken (T^A) generators combine in non-zero anomaly coefficients $\Rightarrow$ Global anomalies

$$(\psi^a \psi^b) \equiv \psi_i^a \Omega_{ij} \psi_j^b$$

The unique invariant tensor of $Sp(2N)$ is two-index antisymmetric
$\Rightarrow$ $SU(4)$-flavour contraction also antisymmetric ($4 \times 4 = 6_A + 10_S$)

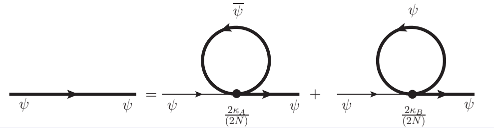
Mass gap from four-fermion interactions

Scalar 4-fermion operators relevant for the spontaneous breaking:

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

- κ_A controls spontaneous symmetry breaking $SU(4) \to Sp(4)$
- κ_B explicitly breaks the anomalous $U(1)$ symmetry
- 4-fermion vector operators with couplings $\kappa_{C,D}$

Schwinger Dyson equation determines dynamical fermion mass M_ψ



$$M_\psi = 4(\kappa_A + \kappa_B)M_\psi \tilde{A}_0(M_\psi^2)$$

Self-consistence implicitly ressums all diagrams leading in 1/N

$$\xi \equiv \frac{\Lambda^2(\kappa_A + \kappa_B)}{4\pi^2} = \left[1 - \frac{M_\psi^2}{\Lambda^2}\ln\left(\frac{\Lambda^2 + M_\psi^2}{M_\psi^2}\right)\right]^{-1}$$

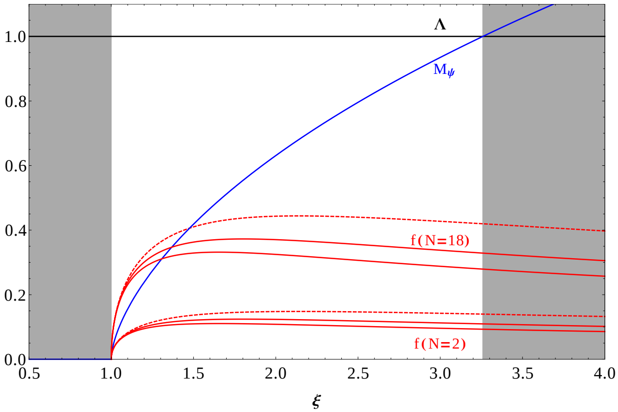
critical coupling $\quad 1 < \xi \lesssim 3.25 \quad$ maximal coupling

- Non trivial solution $M_\psi \neq 0$ ($SU(4)$ spontaneously broken) exists only if $\xi > 1$
- Consistent resummation: $0 < M_\psi/\Lambda \lesssim 1$

$$\langle vac|\mathcal{J}_\mu^{\hat{A}}(0)|G^{\hat{B}}(p)\rangle = ip_\mu \frac{f}{\sqrt{2}}\delta^{\hat{A}\hat{B}}$$

EW precision observables receive order v^2/f^2 corrections $\Rightarrow f \gtrsim 0.5-1$ TeV

$$\frac{f^2}{2} = \lim_{q^2\to 0}[-q^2\overline{\Pi}_A(q^2)] = \frac{\tilde{\Pi}_A(0)}{1+2\kappa_D\tilde{\Pi}_A(0)/N}, \qquad \tilde{\Pi}_A(0) = -2(2N)M_\psi^2\tilde{B}_0(0,M_\psi^2)$$

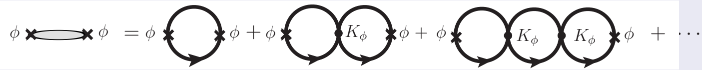


- f residue of the Goldstone boson pole in the resummed transverse axial correlator
- f sets the scale of the composite sector
- $f \propto 1/\sqrt{N}$
- f can be as small as $\Lambda/10$ ($\Lambda \equiv$ NJL cutoff)

$\Rightarrow$ possibly large hierarchy

Bethe-Salpether equation

Resummation (geometrical series) of an infinite number of constituent fermion loops at leading order in $1/N$ $\Rightarrow$ Two-point correlators develop a pole



The pole defines the meson mass M_ϕ

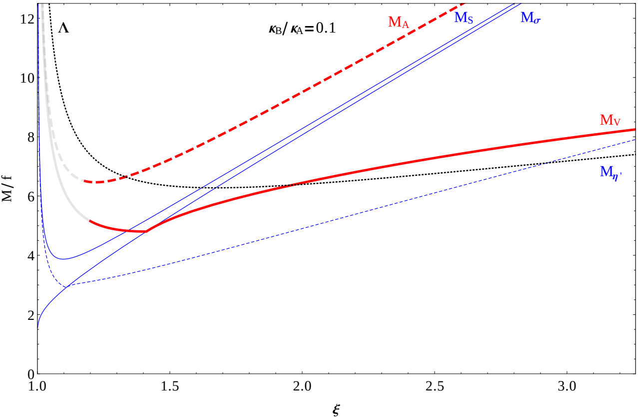
$$\overline{\Pi}_\phi(q^2) = \frac{\tilde{\Pi}_\phi(q^2)}{1 - 2K_\phi \tilde{\Pi}_\phi(q^2)} \longrightarrow 1 - 2K_\phi \tilde{\Pi}_\phi(q^2 = M_\phi^2) = 0$$

ϕ	K_ϕ	$\tilde{\Pi}_\phi(q^2)$
$G^{\hat{A}}$	$2(\kappa_A + \kappa_B)/(2N)$	$\tilde{\Pi}_P(q^2) = (2N)\left[\tilde{A}_0(M_\psi^2) - \frac{q^2}{2}\tilde{B}_0(q^2, M_\psi^2)\right]$
η'	$2(\kappa_A - \kappa_B)/(2N)$	
$S^{\hat{A}}$	$2(\kappa_A - \kappa_B)/(2N)$	$\tilde{\Pi}_S(q^2) = (2N)\left[\tilde{A}_0(M_\psi^2) - \frac{1}{2}(q^2 - 4M_\psi^2)\tilde{B}_0(q^2, M_\psi^2)\right]$
σ	$2(\kappa_A + \kappa_B)/(2N)$	

and similarly for the spin one channels V and A

Current-current hypothesis

- Large-N relation among 4-fermion operators dominated by single hypergluon exchange $\rightarrow \kappa_A = \kappa_C = \kappa_D$ $\quad (M_a = M_A)$



- $M_\phi / f \sim 1/\sqrt{N}$ ($N = 4$ here)
- Free parameters: $\xi = \Lambda^2(\kappa_A + \kappa_B)/(4\pi^2)$, κ_B/κ_A
- EW splitting neglected (e.g. $5_{Sp(4)} = 2_{\pm 1/2} 1_0$) $\Rightarrow$ Full $Sp(4)$ multiplets
- Consistently recover NGBs: $M_G = 0$

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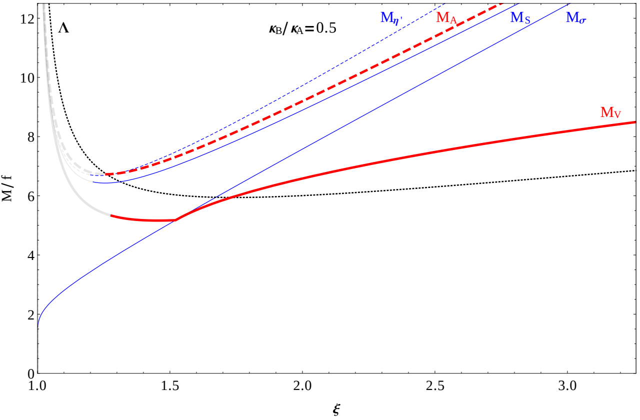

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Adding the coloured sector

Coloured fundamental fermions

Introduce constituent coloured fermions X^f that can form spin-1/2 baryons mixing with SM top quark

- VL embedding of $SU(3)_c$ inside coloured sector implies 6 Weyl fermions X^f
$\Rightarrow SU(6) \to SO(6) \supset SU(3)_c$

- Need to go beyond $Sp(2N)$ fundamental representation (real rep.)
$\Rightarrow$ 2-index traceless antisymmetric ($N \geqslant 2$): $X^f_{ij} = -X^f_{ji} \sim \boxed{}$ $X^f_{ij}\Omega_{ji} = 0$

Main changes with in presence of the two sectors

- 't Hooft anomaly matching: $SU(4)$ must be broken to $Sp(4)$ (except for $N = 8n$)
No such argument for $SU(6)/SO(6)$

- New conserved $U(1)$ current $\mathcal{J}^\mu_0$: Generalise κ_B-term, Extra NGB η_0

- Coupling between EW and coloured sectors:
$\Rightarrow$ Mass gap M_ψ and M_X are coupled (novel feature w.r.t QCD)
$\Rightarrow$ Mixing in scalar and pseudo-scalar singlet sectors

- Coloured pNGBs receive mass from gluon loops: Enough to comply with direct searches even for $f = 1$ TeV

UV completion of composite Higgs model in term of 4-fermion interactions
First application of NJL techniques in composite Higgs models

- NJL well describes SSB: non-perturbative computation of $M_{\psi,X}$ and f
$\Rightarrow$ f can be as small as $\Lambda/10$ $\rightarrow$ large hierarchy could explain that no new states have been observed so far at LHC

- Computation of the composite masses (consistent with lattice results)
$\Rightarrow$ spectrum belong to multi-TeV range but few states can be relatively light (e.g. EW and coloured pNGBs including η_0, η' for small κ_B/κ_A, vectors for intermediate ξ, σ for small ξ)

- Only few parameters (ξ, κ_{A6}/κ_A, κ_B/κ_A, N, m_X) if current-current hypothesis is assumed $\Rightarrow$ Phenomenologically simple

Outlooks

- Calculation of top partners masses within NJL framework
- Generate Higgs potential by realizing partial compositeness
- Consider other UV completions (other cosets and/or hyperfermions)

$\Rightarrow$ Completions with $f \sim N^2$ imply lighter composite resonances in EW sector

Thanks for your attention!

Vector-like gauge theories

Vector-like $\equiv$ An even number of Weyl fermions can be made all massive in a gauge invariant way

Vafa-Witten theorem

In any vector-like gauge theory with massless fermions and vanishing vacuum angles, the subgroup H_m of the flavour group G that corresponds to the remaining global symmetry when all fermion flavours are given identical gauge invariant masses, cannot be spontaneously broken

$\Rightarrow$ If H_m corresponds to a maximal subgroup of G: either G is not spontaneously broken at all, or G is spontaneously broken towards H_m

Three cases in vector-like theories: [Peskin, '80]

- $G = SU(N_f)_L \times SU(N_f)_R$ and $H_m = SU(N_f)_V$ (complex rep. of $\mathcal{G}$)
- $G = SU(2N_f)$ and $H_m = SO(2N_f)$ (real rep.)
  $H_m = Sp(2N_f)$ (pseudo-real rep.)

No confinement in the NJL $\Rightarrow$ Prescription for the unphysical imaginary parts

$$1 - 2K_\phi \tilde{\Pi}_\phi(q^2) = c_0^\phi(q^2) + c_1^\phi(q^2) q^2 \quad \longrightarrow \quad M_\phi^2 = Re\left[-\frac{c_0^\phi(M_\phi^2)}{c_1^\phi(M_\phi^2)} \right]$$

$K_\phi \equiv$ four-fermion couplings $\qquad \tilde{\Pi}_\phi(q^2) \equiv$ Polarisation amplitudes

- Inserting the gap-equation, one recovers consistently the Goldstone pole: $M_G = 0$
- Singlet pseudo-scalar proportional to $U(1)$ anomaly and mixes with axial vector: $$M_{\eta'}^2 = -\frac{\kappa_B}{\kappa_A^2 - \kappa_B^2} \frac{[1 - 2K_a \tilde{\Pi}_A^L(M_{\eta'}^2)]}{\tilde{B}_0(M_{\eta'}^2, M_\psi^2)}$$
- Scalars proportional to the mass gap M_ψ: $$M_\sigma^2 = 4M_\psi^2, \qquad M_S^2 = 4M_\psi^2 + M_{\eta'}^2 \frac{\tilde{B}_0(M_{\eta'}^2, M_\psi^2)}{\tilde{B}_0(M_S^2, M_\psi^2)} \simeq M_\sigma^2 + M_{\eta'}^2$$
- Vector heavy even for vanishing mass gap: $$M_V^2 = \frac{-3}{4\kappa_D \tilde{B}_0(M_V^2, M_\psi^2)} + 2M_\psi^2 \frac{\tilde{B}_0(0, M_\psi^2)}{\tilde{B}_0(M_V^2, M_\psi^2)} - 2M_\psi^2$$
- Axial-vector generally the heaviest: $$M_A^2 = \frac{-3}{4\kappa_D \tilde{B}_0(M_A^2, M_\psi^2)} + 2M_\psi^2 \frac{\tilde{B}_0(0, M_\psi^2)}{\tilde{B}_0(M_V A2, M_\psi^2)} + 4M_\psi^2 \simeq M_V^2 + 6M_\psi^2$$

- SM fermions may mix with composite resonances (partial compositeness: Linear couplings between the SM fermions and coloured spin 1/2 composite resonances)

$\Rightarrow$ Generates couplings between SM and composite Higgs and SM fermion masses

$\Rightarrow$ Source of explicit breaking: generates a potential and a mass for the Higgs (potential generated mainly by the heavy top quark)

- Introduce constituent coloured fermions X^f that can form spin-1/2 baryons

$\Rightarrow$ Need to go beyond $Sp(2N)$ fundamental representation (real rep.) $\rightarrow N \geqslant 2$

	Lorentz	$Sp(2N)$	$SU(6)$	$SO(6)$
X^f_{ij}	$(1/2,0)$	$\boxminus_{ij}$	6^f	6
$\overline{X}_{fij} \equiv \Omega_{ik} X^{\dagger}_{fkl} \Omega_{lj}$	$(0,1/2)$	$\boxminus_{ij}$	$\overline{6}_f$	6
$M_c^{fg} \sim (X^f X^g)$	$(0,0)$	1	21^{fg}	$20' + 1$
$\overline{M}_{cfg} \sim (\overline{X}_f \overline{X}_g)$	$(0,0)$	1	$\overline{21}_{fg}$	$20' + 1$
$a^{\mu}_X \sim (\overline{X}^f \overline{\sigma}^{\mu} X_f)$	$(1/2,1/2)$	1	1	1
$(V^{\mu}_c, A^{\mu}_c)^g_f \sim (\overline{X}_f \overline{\sigma}^{\mu} X^g)$	$(1/2,1/2)$	1	35^f_g	$15 + 20'$

- 6 Weyl fermions
  $X^f \sim 6_{SU(6)} = (3 + \overline{3})_{SU(3)_c}$
- $SU(6) \supset SU(3)_c \rightarrow SO(6)$
- $X_{ij} \sim \boxminus$
  $X^f_{ij} = -X^f_{ji}, \quad X^f_{ij}\Omega_{ji} = 0$

Spin-zero coloured mesons

Spin-one coloured mesons

$U(1)$ (anomalous) symmetries

Lot of changes appears when theory includes both EW and coloured sectors

- Important to consider global fermion numbers $U(1)_\psi$ and $U(1)_X$
- Currents $\mathcal{J}^0_{\mu\psi,X}$ both anomalous w.r.t $Sp(2N)$ (like $U(1)_A$ in QCD)
- However, one linear combination is anomaly free and thus conserved:

$$\mathcal{J}^0_\mu = \mathcal{J}^0_{\mu X} - 3(N-1)\mathcal{J}^0_{\mu\psi}$$

$\Rightarrow$ New Goldstone boson η_0 appears while η' receive a mass from the anomaly

Construct the minimal operator that preserves all exact symmetries but explicitly breaks the anomalous $U(1)$

- EW sector: $Sp(2N)$ anomaly breaks $U(1)_\psi \to \mathcal{O}_\psi = -\frac{1}{4}\epsilon_{abcd}(\psi^a\psi^b)(\psi^c\psi^d)$
- Colour sector: anomaly breaks $U(1)_X \to \mathcal{O}_X = -\frac{1}{6!}\epsilon_{f_1\cdots f_6}\epsilon_{g_1\cdots g_6}(X^{f_1}X^{g_1})\cdots(X^{f_6}X^{g_6})$
- Full theory preserves $U(1)_{X-3(N-1)\psi}$: $\to \mathcal{L}_{\psi X} = A_{\psi X}\frac{\mathcal{O}_\psi}{(2N)^2}\left[\frac{\mathcal{O}_X}{[(2N+1)(N-1)]^6}\right]^{(N-1)}$

After spontaneous breaking $\mathcal{L}_{\psi X}$ generates effective 4-fermion operators ψ^4, X^4 and ψ^2X^2

Possible trilinear baryons:

$$\Psi^{abf} = (\psi^a \psi^b X^f), \quad \Psi^{ab}_{f} = (\psi^a \psi^b \overline{X}_f), \quad \Psi^{af}_{b} = (\psi^a \overline{\psi}_b X^f),$$
$$\Psi^{fgh} = (X^f X^g X^h), \quad \Psi^{fg}_{h} = (X^f X^g \overline{X}_h)$$

Anomaly matching condition:

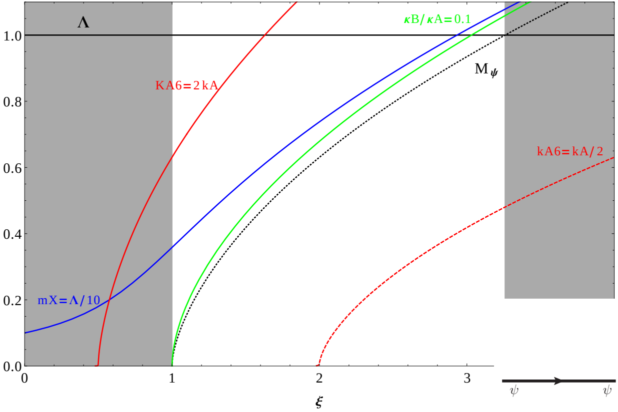
$$\sum_{i=\psi,X} n_i A(r_i) = \sum_{i=baryon} n_{i'} A(r_i), \qquad 2Tr[T_r^{\hat{A}}\{T_r^B, T_r^C\}] = A(r) d^{\hat{A}BC}$$

- $SU(4)^3$: Matching impossible for $N \neq 8n \Rightarrow SU(4)$ breaks to $Sp(4)$ and one expects non-zero condensate $\langle\psi\psi\rangle \neq 0$
- $SU(6)^3$: Matching always possible $\Rightarrow SU(6)$ may not break to $SO(6)$ and the condensate $\langle XX \rangle$ may vanish or not
- $SU(4)^2 \times U(1), SU(6)^2 \times U(1), U(1)^3$: $U(1)$ most likely broken by $\langle\psi\psi\rangle$

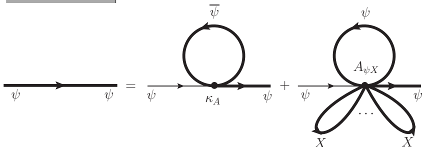
Two coupled mass gap equations:

$$\begin{cases} M_\psi = 4\left[\kappa_A + \kappa_B(M_X^2)\right] M_\psi \tilde{A}_0(M_\psi^2) \\ M_X = 4\left[\kappa_{A6} + \kappa_{B6}(M_\psi^2, M_X^2)\right] M_X \tilde{A}_0(M_X^2) + m_X \end{cases}$$

$$\begin{cases} \kappa_B = \kappa_{B6} = 0 \\ \kappa_A = \kappa_{A6},\, m_X = 0 \end{cases} \Rightarrow M_\psi = M_X$$



- Coloured sector window [between critical coupling ($M_X = 0$) and maximal coupling ($M_X = \Lambda$)] shifts respect to the EW sector window
- $m_X \neq 0$: No critical coupling as $M_X \geqslant m_X$

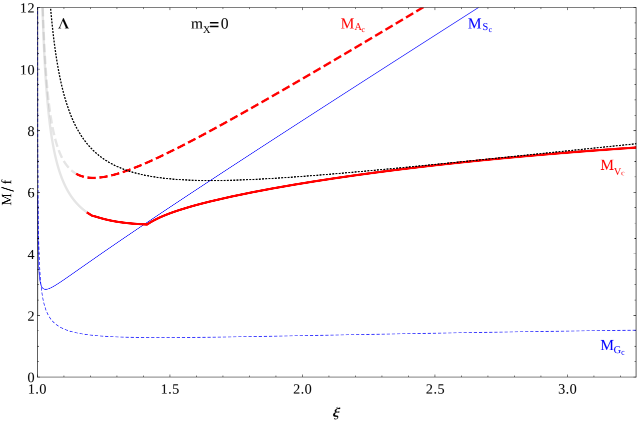


Current-current hypothesis

The ratio EW masses/ coloured masses strongly depends on the ratio κ_{A6}/κ_A

Unfortunately the large-N approximation does not determine this ratio uniquely (but still determines $\kappa_{A6} = \kappa_{C6} = \kappa_{D6}$)

$\Rightarrow$ Choose $\kappa_A = \kappa_{A6}$



- $M_\phi/f \sim 1/\sqrt{N}$ ($N = 4$, $\kappa_B/\kappa_A = 1/100$ here)
- Goldstone bosons receive a mass from gluon loops that evade bounds for $f \gtrsim 1$ TeV
- Goldstone (and coloured resonances) mass increase with f

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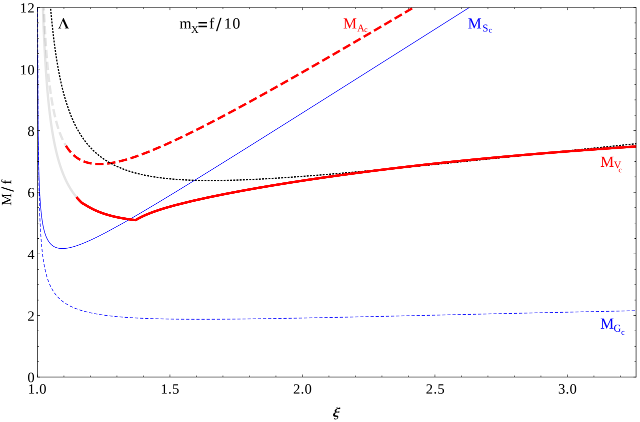

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The $Sp(4)$ singlet mesons σ, η', a^μ may mix with the $SO(6)$ singlet ones σ_c, η'_c, a^μ_c (all SM singlets)

If on ignores mixing: $\begin{cases} M_\sigma = 2M_\psi \\ M_{\sigma_c} = 2M_X \end{cases}$ $\begin{cases} M^2_{\eta'} \sim \kappa_B \\ M^2_{\eta'_c} \sim (\kappa_{B6}, m_X) \end{cases}$ $\begin{cases} M_a = M_A \\ M_{a_c} = M_{A_c} \end{cases}$

▶ Axial-vectors: $Sp(2N)$ current-current operators do not induce singlet-singlet mixing operators

⇒ Axial singlet mixing is subleading in $1/N$

▶ (Pseudo-)scalars: Anomalous operator $A_{\psi X}$ induces a coupling $\psi^2 X^2$ of the same order as the couplings ψ^4, X^4

⇒ The mixing is a leading effect for (pseudo-)scalars

⇒ One linear combination of eta', η'_c is massless for $m_X = 0$: $U(1)$ Goldstone

$$\mathbf{K}_{\eta_\psi \eta_X} = \begin{pmatrix} K_{\eta_\psi} & -K_{\psi X} & 0 & 0 \\ -K_{\psi X} & K_{\eta_X} & 0 & 0 \\ 0 & 0 & K_a & 0 \\ 0 & 0 & 0 & K_{a_c} \end{pmatrix}, \quad \mathbf{\Pi}_{\eta_\psi \eta_X} = \begin{pmatrix} \tilde{\Pi}^\psi_P & 0 & \sqrt{p^2}\tilde{\Pi}^\psi_{AP} & 0 \\ 0 & \tilde{\Pi}^X_P & 0 & \sqrt{p^2}\tilde{\Pi}^X_{AP} \\ \sqrt{p^2}\tilde{\Pi}^\psi_{AP} & 0 & \tilde{\Pi}^{L\psi}_A & 0 \\ 0 & \sqrt{p^2}\tilde{\Pi}^X_{AP} & 0 & \tilde{\Pi}^{LX}_A \end{pmatrix}$$

Mixed states may couple both to EW gauge boson ($\phi \to \gamma\gamma$) and gluons ($gg \to \phi$)

⇒ Potential discovery channel