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

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Motivations

- *TeV scale little hierarchy problems do not diminish big hierarchy solutions*
- *If the Higgs is composite, how heavy the other resonances are predicted to be?*
- *Definite answers require an ultraviolet complete theory*
- *Gauge theories of fermions that confine at the TeV scale can be studied with a plethora of QCD tools*
- *Analytic results, holding in well-defined approximations, may be very informative with little computational effort*

Barnard-Gherghetta-Sankar Ray, 1311.6562

Outline

- *Higgs as a composite Goldstone: the electroweak sector*
- *Tools to study the global symmetry breaking*
- *Tools to study the spectrum of meson resonances*
- *Cross-checks and limitations of the results*
- *Composite top-quark partners: the colour sector*
- *Non-trivial interplay of the two sectors: anomalies, coupled gap equations, mixing of singlet scalars, ...*
- *Some perspectives*

Note I will stick to ***the chiral limit*** : no new results (for now) on SM Yukawas, nor on electroweak symmetry breaking.

Some remarks ***beyond the chiral limit*** : constituent fermion masses, and SM gauging.

The electroweak sector

Requirements:

- The Higgs as a composite Goldstone boson (with custodial symmetry): $H_F \supset SU(2)_L x SU(2)_R$
- A minimal number of extra Goldstones: $G_F = SU(4)$ broken to $H_F = Sp(4)$ → the Higgs + a singlet

Katz-Nelson-Walker 05, Gripaios-Pomarol-Riva-Serra 09, Frigerio-Pomarol-Riva-Urbano 12

- An explicit ultraviolet completion, with no fundamental scalars: a gauge theory of fermions that confines
- Need for 4 fermions ψ, in a pseudo-real representation of the gauge group: the fundamental of $G_{HC} = Sp(2N)$

Minimal technicolour (N=1):
Ryttov-Sannino 08, Galloway-Evans-Luty-Tacchi 10, Cacciapaglia-Sannino 14

Other possible minimal models of this sort classified in Ferretti-Karateev '13, Vecchi '15

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Katz-Nelson-Walker 05, Gripaios ... 12

Compare with QCD:

$G_F = SU(3)_L \text{ x } SU(3)_R$ broken to $H_F = SU(3)_V$

$G_C = SU(3)_C$

- An explicit ultraviole... a gauge theory of fermio...
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Combining constituent fermions

		COLOUR	FLAVOUR	
	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-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 fermion bilinears have the quantum numbers of meson resonances

$$\text{scalars}: \ \sigma + S^{\hat{A}} \sim 1+5 \qquad \text{pseudoscalars}: \ \eta' + G^{\hat{A}} \sim 1+5$$

$$\text{vectors}: \ V^A_\mu \sim 10 \qquad \text{axialvectors}: \ a_\mu + A^{\hat{A}}_\mu \sim 1+5$$

The fate of the SU(4) symmetry
(without computations)

- The model is a vector-like gauge theory : all fermions ψ can be made massive, while preserving $G_C = Sp(2N)$: $m_\psi \psi\psi$
- Vafa-Witten theorem : the G_F subgroup preserved by m_ψ cannot be spontaneously broken → **Sp(4) unbroken**
- 't Hooft anomaly-matching : any global UV anomaly must be matched in the IR, either by massless spin-1/2 baryons or by Goldstone bosons → **SU(4) necessarily breaks** because ψ's cannot form any spin-1/2 baryon

$$d^{AB\hat{C}} = 2\mathrm{tr}(\{T^A, T^B\}T^{\hat{C}})$$

SU(4) broken and unbroken generators combine in non-zero anomaly coefficients

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

The unique invariant tensor of Sp(2N) Is two-index antisymmetric

The fate of the SU(4) symmetry
(effective potential from 4-fermion operators)

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

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

- Introduce an auxiliary scalar field M_{ab} whose equation of motion is

$$M^{ab} = -\frac{\kappa_A + \kappa_B}{2N}(\psi^a\psi^b)$$

- Compute the effective potential $V_{eff}(M_{ab})$ induced by fermion loops and minimise

$$\langle M_{ab}\rangle = \frac{M_\psi}{2}\Sigma_0 = \frac{M_\psi}{2}\begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

- Minimum is non-zero above four-fermion critical coupling

$$M_\psi \neq 0 \Rightarrow SU(4) \to Sp(4)$$

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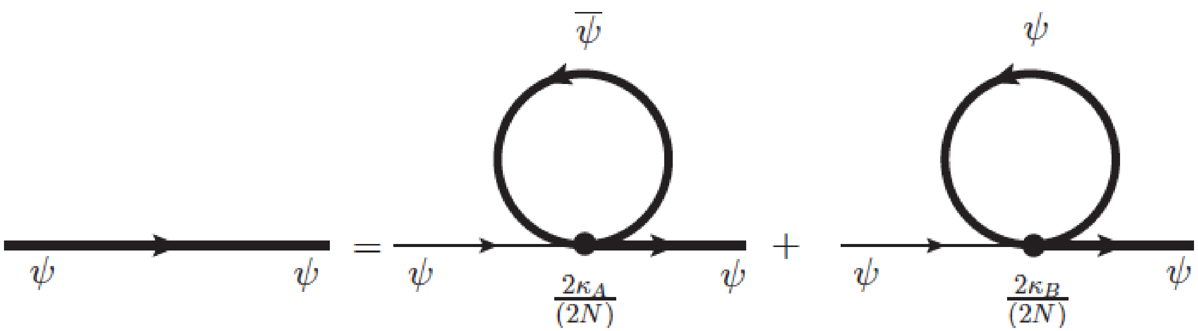
The fate of the SU(4) symmetry
(mass-gap from 4-fermion operators)

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

Mass-gap equation: self-consistent condition for **dynamical fermion mass M_ψ**



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

(this amounts to resum all massless-fermion diagrams leading in 1/N:
each additional tadpole come with a factor N for the loop and 1/N for the coupling)

Need for a cutoff Λ for the fermion loops, and for the whole NJL effective theory

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

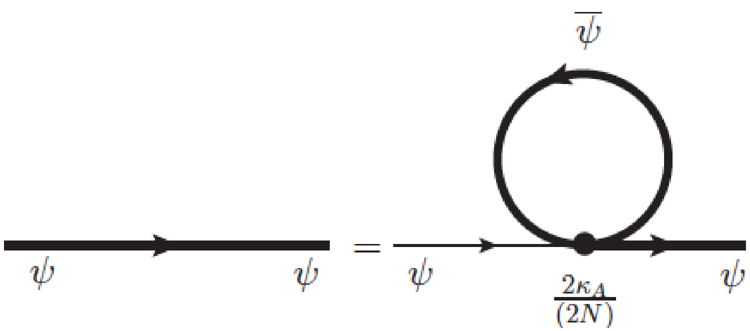
$$0 < M_\psi/\Lambda \lesssim 1$$

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

The fate of the SU(4) symmetry
(mass-gap from 4-fermion operators)

$$\mathcal{L}^{\psi}_{scal} = \frac{\kappa_A}{2N}(\psi^a \psi^b)$$

Mass-gap equation: self-con



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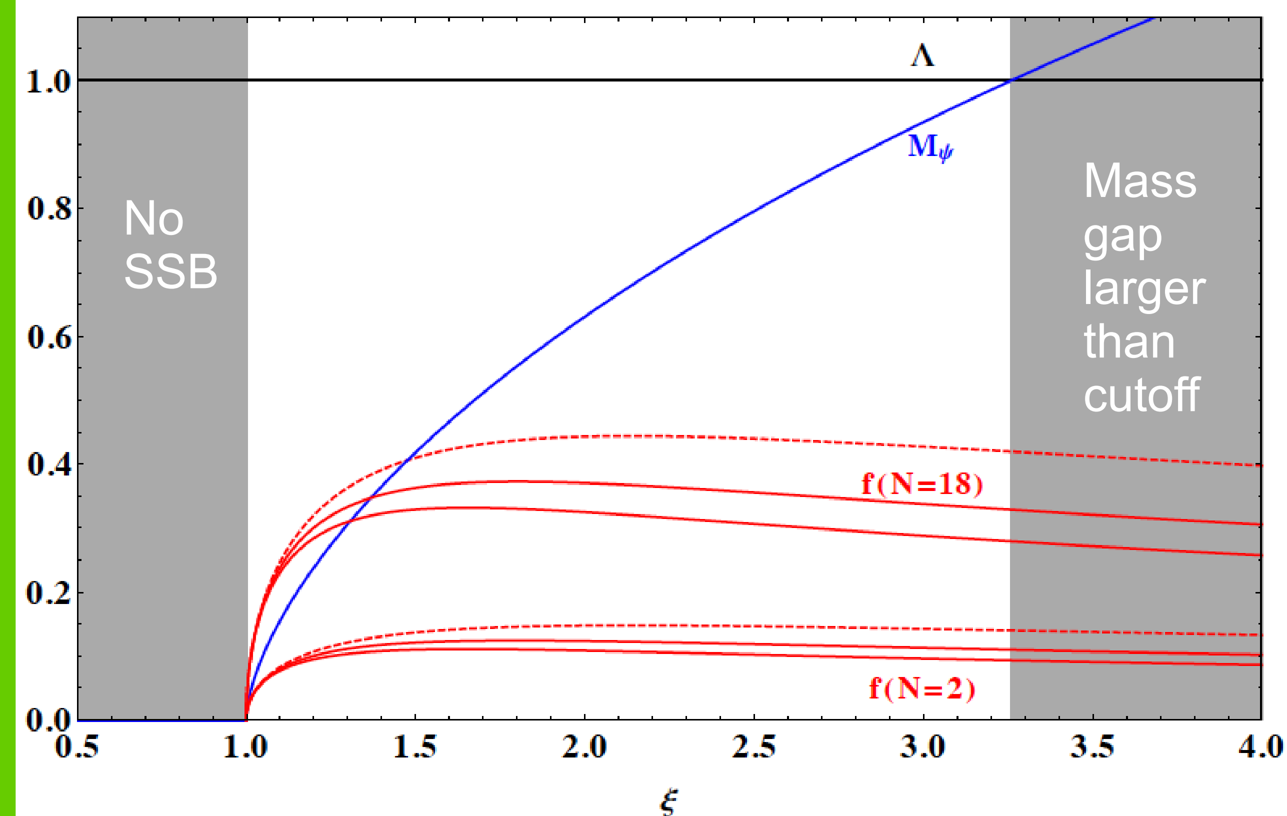

Need for a cutoff Λ for the fermion loops, and for the whole NJL effective theory

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

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The spectrum of mesons
(before computations)

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

- Chiral limit: G's are massless; for vanishing κ_B also η' massless
  [κ_B induced by the $U(1)_\psi$ anomaly, that vanishes for large N]

- Super-convergent spectral sum rules: some V-A and S-P two-point correlators are order parameters for SU(4)/Sp(4)
  → they must vanish rapidly in the UV
  → associated spectral densities converge fast

$$\mathcal{J}_\mu^A = \Omega_{ij}\overline{\psi}_i \overline{\sigma}_\mu T^A \psi_j \qquad \Pi_V(q^2)\delta^{AB}(q_\mu q_\nu - \eta_{\mu\nu} q^2) = i\int d^4x\, e^{iq\cdot x}\langle \text{vac}|T\{\mathcal{J}_\mu^A(x)\mathcal{J}_\nu^B(0)\}|\text{vac}\rangle$$

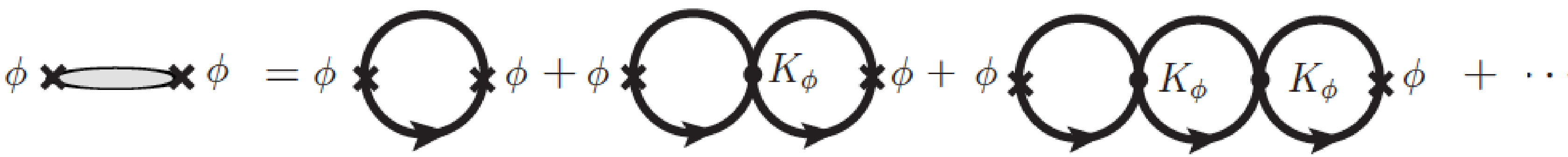
$$\lim_{q^2\to-\infty}(q^2)^2 \times (\Pi_V - \Pi_A)(q^2) = 0 \qquad \int_0^\infty dt\, \text{Im}\Pi_{V\text{-}A}(t) = 0 \qquad \int_0^\infty dt\, t\, \text{Im}\Pi_{V\text{-}A}(t) = 0$$

$$\langle 0|\mathcal{J}_\mu^A(0)|V^B(p)\rangle \equiv f_V M_V\, \epsilon_\mu(p)\delta^{AB} \qquad f_V^2 M_V^2 - f_A^2 M_A^2 - F_G^2 = 0, \qquad f_V^2 M_V^4 - f_A^2 M_A^4 = 0$$

(narrow-width single-resonance approximation)

The spectrum of mesons
(from four-fermion operators)

Resummation of constituent fermion loops at leading order in 1/N
$\longrightarrow$ two-point correlators develop a pole



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

The pole defines the meson mass

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

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

The spectrum of mesons
(from four-fermion operators)

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

Inserting the gap-equation, one recovers consistently the Goldstone pole: $M_G = 0$

Singlet pseudoscalar proportional to anomaly and mixes with axial vector:

$$M_{\eta'}^2 = -\frac{\kappa_B}{\kappa_A^2 - \kappa_B^2} \frac{1}{\tilde{B}_0(M_{\eta'}^2, M_\psi^2)} \left[1 - 2K_a \tilde{\Pi}_A^L(M_{\eta'}^2)\right]$$

Scalars proportional to the mass gap:

$$M_\sigma^2 = 4M_\psi^2 \qquad M_S^2 = 4M_\psi^2 + M_\eta^2 \frac{\tilde{B}_0(M_\eta^2, M_\psi^2)}{\tilde{B}_0(M_S^2, M_\psi^2)} \simeq M_\sigma^2 + M_\eta^2$$

Vector heavy even for a 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:

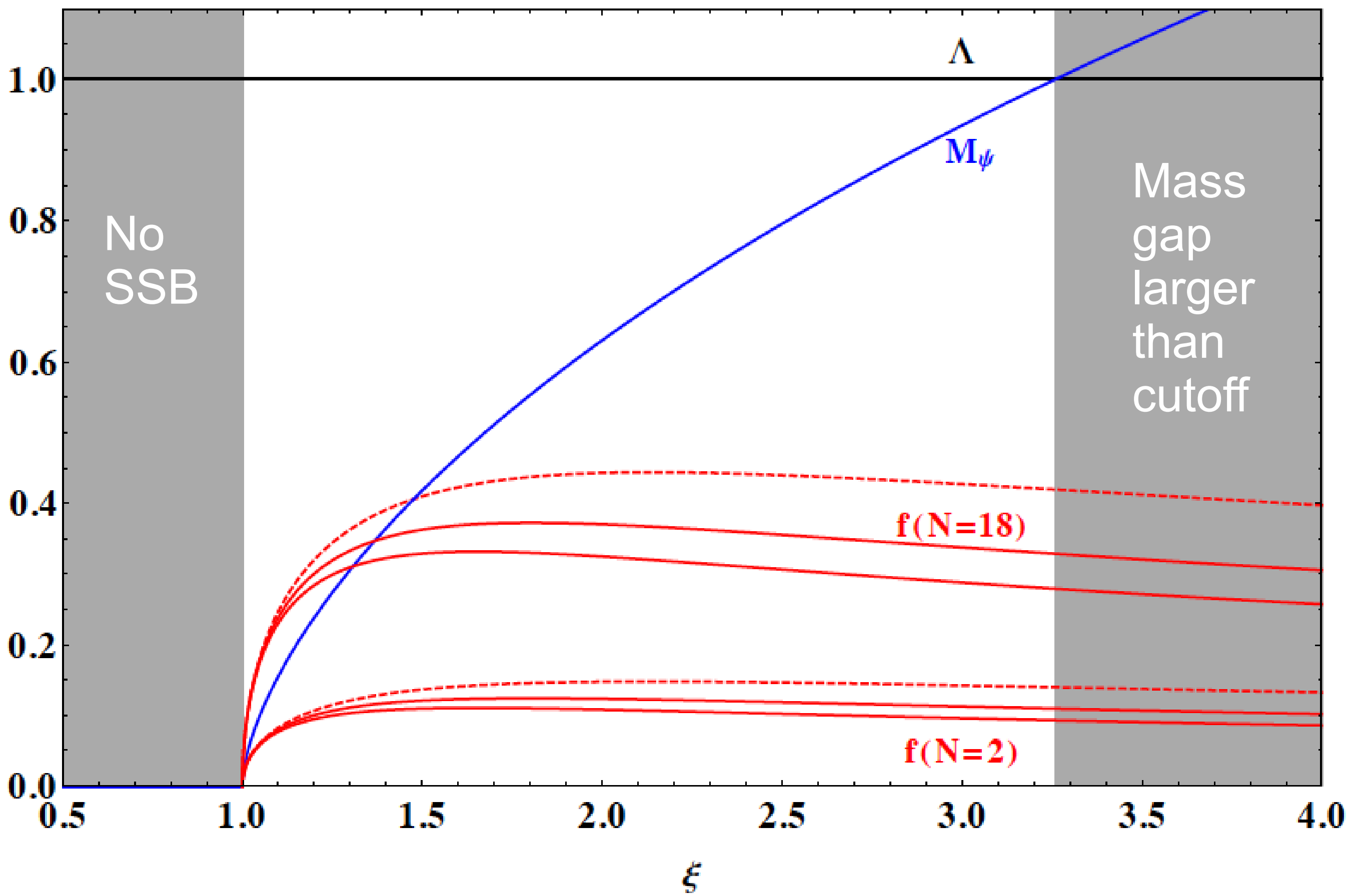
$$M_A^2 = -\frac{3}{4\kappa_D \tilde{B}_0(M_A^2, M_\psi^2)} + 2M_\psi^2 \frac{\tilde{B}_0(0, M_\psi^2)}{\tilde{B}_0(M_A^2, M_\psi^2)} + 4M_\psi^2 \simeq M_V^2 + 6M_\psi^2$$

The Goldstone decay constant

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

Electroweak precision observables receive order v^2 / f^2 corrections → f > (0.5-1)TeV

$$\frac{f^2}{2} = \lim_{q^2\to 0}\left(-q^2\overline{\Pi}_A(q^2)\right) = \frac{\tilde{\Pi}_A(0)}{1-2K_D\tilde{\Pi}_A(0)}\,, \quad \tilde{\Pi}_A(0) = -2\,(2N)\,M_\psi^2\tilde{B}_0(0,M_\psi^2)$$



f is the residue of the Goldstone boson pole in the resummed, transverse, axial-vector correlator

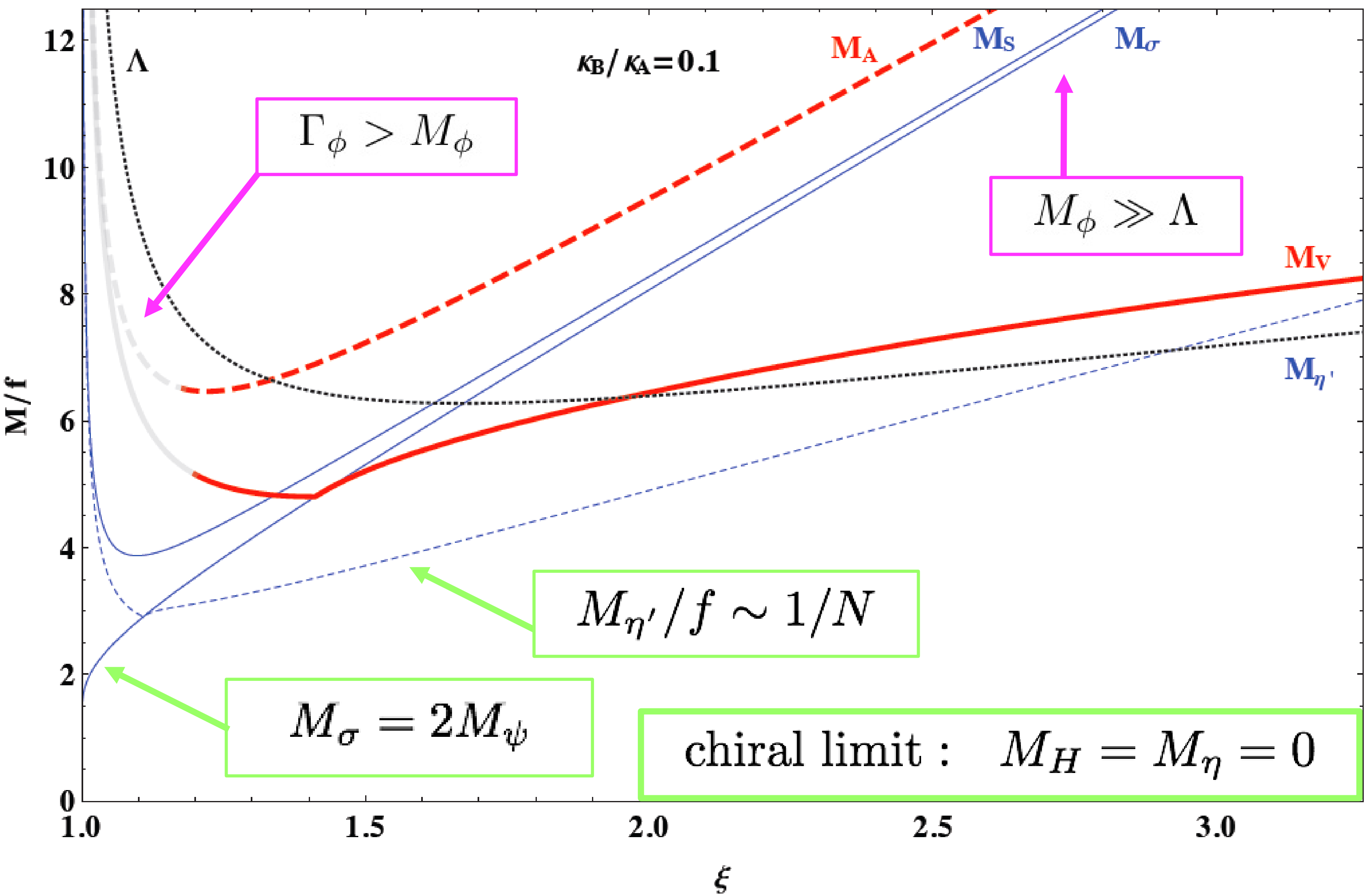
$$f \propto \sqrt{N}$$

f can be as small as a tenth of the NJL cutoff

Meson masses in units of f

$M_\phi / f \sim \sqrt{1/N}$ here $N = 4$

Spin-zero and spin-one 4-fermion operators have the same coupling strength, if single-hypergluon exchange dominates (expected when N is large)



$\kappa_C = \kappa_A$
$\kappa_D = \kappa_A$

$\kappa_A + \kappa_B \sim \xi$
κ_B / κ_A free

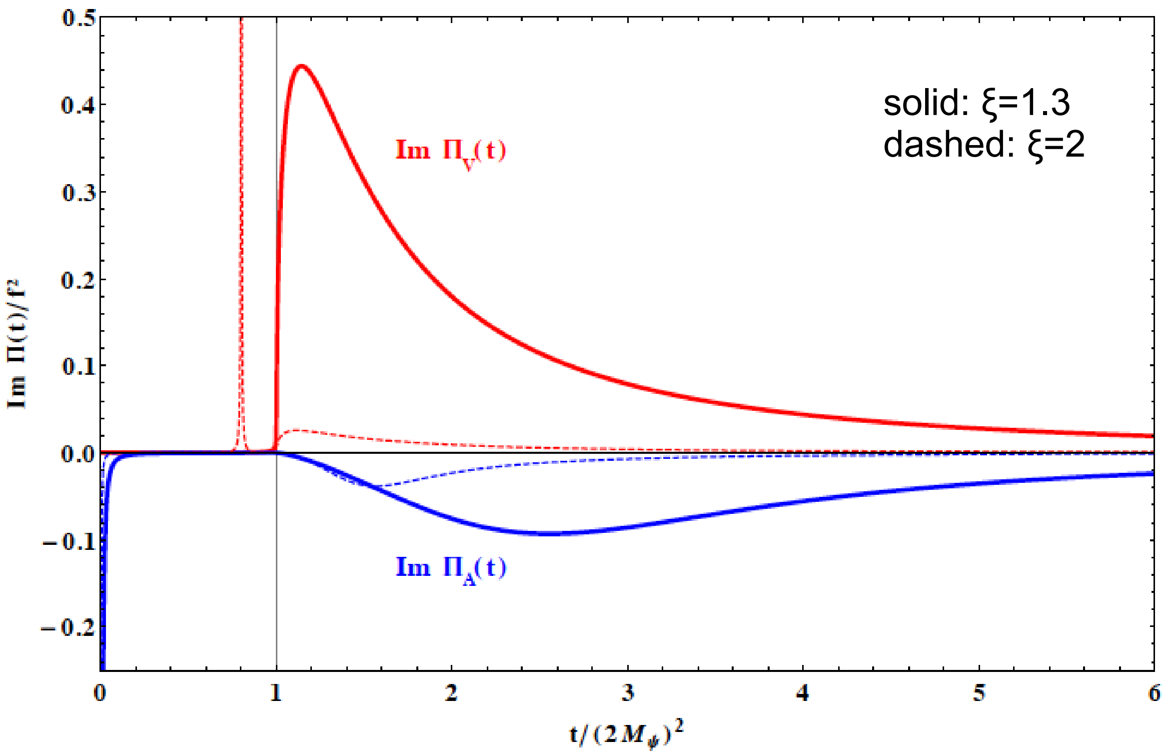
Degenerate Sp(4) multiplets (electroweak splitting neglected)

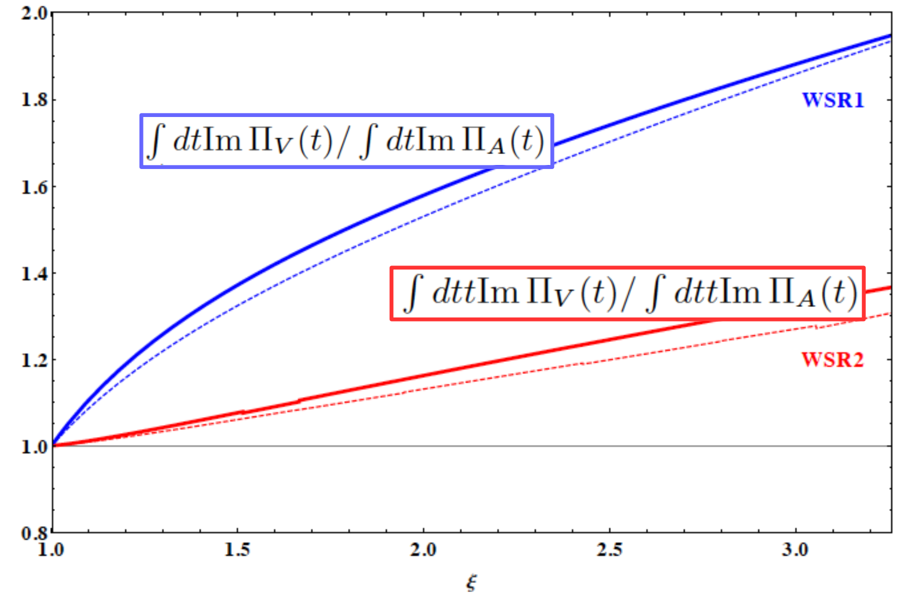
$M_a = M_A$

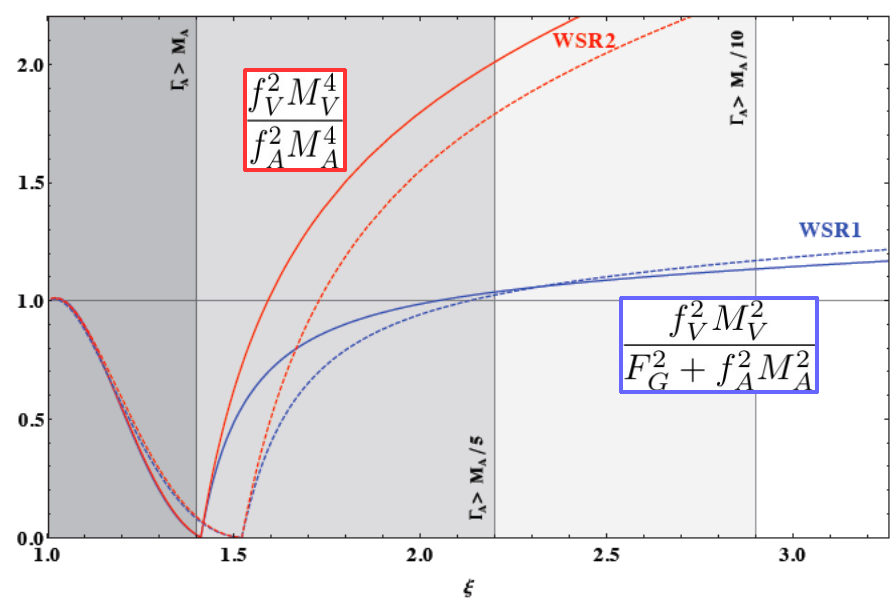
Comparison with sum rules

$$\int_0^\infty dt\, \mathrm{Im}\Pi_{V-A}(t) = 0 \qquad \int_0^\infty dt\, t\, \mathrm{Im}\Pi_{V-A}(t) = 0$$

NJL effective theory ceases to be valid for $t > \Lambda^2$: this region Is negligible only for small ξ







Narrow-width & single-resonance approximation (masses and decay constants extracted from the resummed two-point correlators)

$$f_V^2 M_V^2 - f_A^2 M_A^2 - F_G^2 = 0, \qquad f_V^2 M_V^4 - f_A^2 M_A^4 = 0$$

Comparison with lattice

Arthur-Drach-Hansen-Hietanen-Pica-Sannino, 1602.06559 & 1607.06654

Recent lattice study for N=1: $G_{HC} = Sp(2) \approx SU(2)$

$$M_V = 13.1(2.2)f \qquad M_A = 14.5(3.6)f$$

$$M_\sigma = 19.2(10.8)f \qquad M_S = 16.7(4.9)f \qquad M_{\eta'} = 12.8(4.7)f$$

*possible √2 issue with the normalisation of *f*

Meson masses computed à la NJL scale as 1/√N, and they are expected to be more precise at large N...

Matching lattice and NJL predictions, one can roughly identify the preferred values for 4-fermion couplings:

- Small A-V splitting prefers ξ close to one, but then σ is too light: intermediate values ξ ~ (1.5 - 2) seem to provide a better global agreement
- The heavy pseudoscalar requires $\kappa_B/\kappa_A > 0.2$

Introducing the colour sector

- To couple to the composite Higgs, the **SM fermions may mix linearly with composite resonances** (partial compositeness)
  → especially suitable to induce the large **top quark Yukawa coupling**
- Need to introduce **constituent fermions *X*** ^{f} *that (i) are coloured and (ii) can form spin-1/2 baryons*
  → need to go beyond the Sp(2N)-fundamental representation & to have N≥2

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		HYPER COLOUR	FLAVOUR	
	Lorentz	$Sp(2N)$	$SU(6)$	$SO(6)$
X^f_{ij}	$(1/2,0)$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}_{ij}$	6^f	6
$\overline{X}_{fij} \equiv \Omega_{ik} X^\dagger_{fkl} \Omega_{lj}$	$(0,1/2)$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}_{ij}$	$\overline{6}_f$	6
$M^{fg}_c \sim (X^f X^g)$	$(0,0)$	1	21^{fg}	$20'+1$
$\overline{M}_{cfg} \sim (\overline{X}_f \overline{X}_g)$	$(0,0)$	1	$\overline{21}_{fg}$	$20'+1$
$a^\mu_c \sim (\overline{X}^f \overline{\sigma}^\mu X_f)$	$(1/2,1/2)$	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	$15+20'$

$$X^f \sim 6_{SU(6)} = (3+\overline{3})_{SU(3)_c}$$

$$X^f_{ij} = -X^f_{ji} \qquad X^f_{ij}\Omega_{ji} = 0$$

$$X^f \sim \overline{X}_f : \quad SU(6) \to SO(6)$$

} spin-zero mesons (M, $\overline{M}$ rows)

} spin-one mesons (a, (V,A) rows)

U(1) (anomalous) symmetries

Besides SU(4)$_\psi$ and SU(6)$_X$, it is important to consider global fermion numbers U(1)$_\psi$ and U(1)$_X$ with currents

$$\mathcal{J}^0_{\psi\mu} = -\overline{\psi}\overline{\sigma}_\mu\psi \qquad \mathcal{J}^0_{X\mu} = \overline{X}\overline{\sigma}_\mu X$$

They are both anomalous w.r.t. to Sp(2N) [like U(1)$_A$ w.r.t. QCD]

$$\partial^\mu \mathcal{J}^0_{\psi,X\mu} \propto \frac{g^2_{HC}}{32\pi^2} \sum_{I=1}^{N(2N+1)} \epsilon_{\mu\nu\rho\sigma} G^{I,\mu\nu}_{HC} G^{I,\rho\sigma}_{HC}$$

However a linear combination U(1) is anomaly-free and thus conserved

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

When either <ψψ> or <XX> condense, a new Goldstone η_0 appears, while one unique η' receives a mass from the anomaly

An operator for the Sp(2N) anomaly

The analog of 't Hooft determinant in QCD : $2N_F$ - fermion operator, that breaks the anomalous $U(1)_A$ and explains the large η' mass

Let us build the minimal fermion operator that breaks the anomalous U(1)'s but preserves all exact symmetries. It incorporates the effect of the Sp(2N) anomaly!

Electroweak sector: Sp(2N) anomaly breaks $U(1)_\psi$

$$\mathcal{O}_\psi = -\frac{1}{4}\epsilon_{abcd}(\psi^a\psi^b)(\psi^c\psi^d)$$

Colour sector: Sp(2N) anomaly breaks $U(1)_X$

$$\mathcal{O}_X = -\frac{1}{6!}\epsilon_{f_1\cdots f_6}\epsilon_{g_1\cdots g_6}(X^{f_1}X^{g_1})\cdots(X^{f_6}X^{g_6})$$

But, full theory preserves $U(1)_{X - 3(N-1)\psi}$

$$\mathcal{L}_{\psi X} = A_{\psi X}\frac{\mathcal{O}_\psi}{(2N)^2}\left[\frac{\mathcal{O}_X}{[(2N+1)(N-1)]^6}\right]^{(N-1)} + h.c.$$

Four-fermion operators are recovered after spontaneous symmetry breaking

$$\langle\Psi\Psi\rangle \equiv -2(2N)M_\psi\tilde{A}_0(M_\psi^2) \qquad \langle XX\rangle = -2(2N+1)(N-1)M_X\tilde{A}_0(M_X^2)$$

Non-standard large-N behaviour of the anomaly : $\dim_X \sim N^2 \;\Rightarrow\; M^2_{\eta'} \sim A_{\psi X} \sim N^0$

The fate of SU(4) x SU(6) x U(1)

('t Hooft anomaly matching with baryons)

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

$$2\mathrm{tr}(T^{\hat{A}}(r)\{T^B(r), T^C(r)\}) = A(r) d^{\hat{A}BC}$$

$$\sum_{i=\psi,X} n_i A(r_i) = \sum_{i=baryon} n'_i A(r_i)$$

$SU(4)^3$: matching impossible for N ≠ 8n → SU(4) breaks to Sp(4)
→ one expects a non-zero condensate <ψψ> ≠ 0

$SU(6)^3$: matching always possible → SU(6) may not break to SO(6)
→ the condensate <XX> may vanish or not

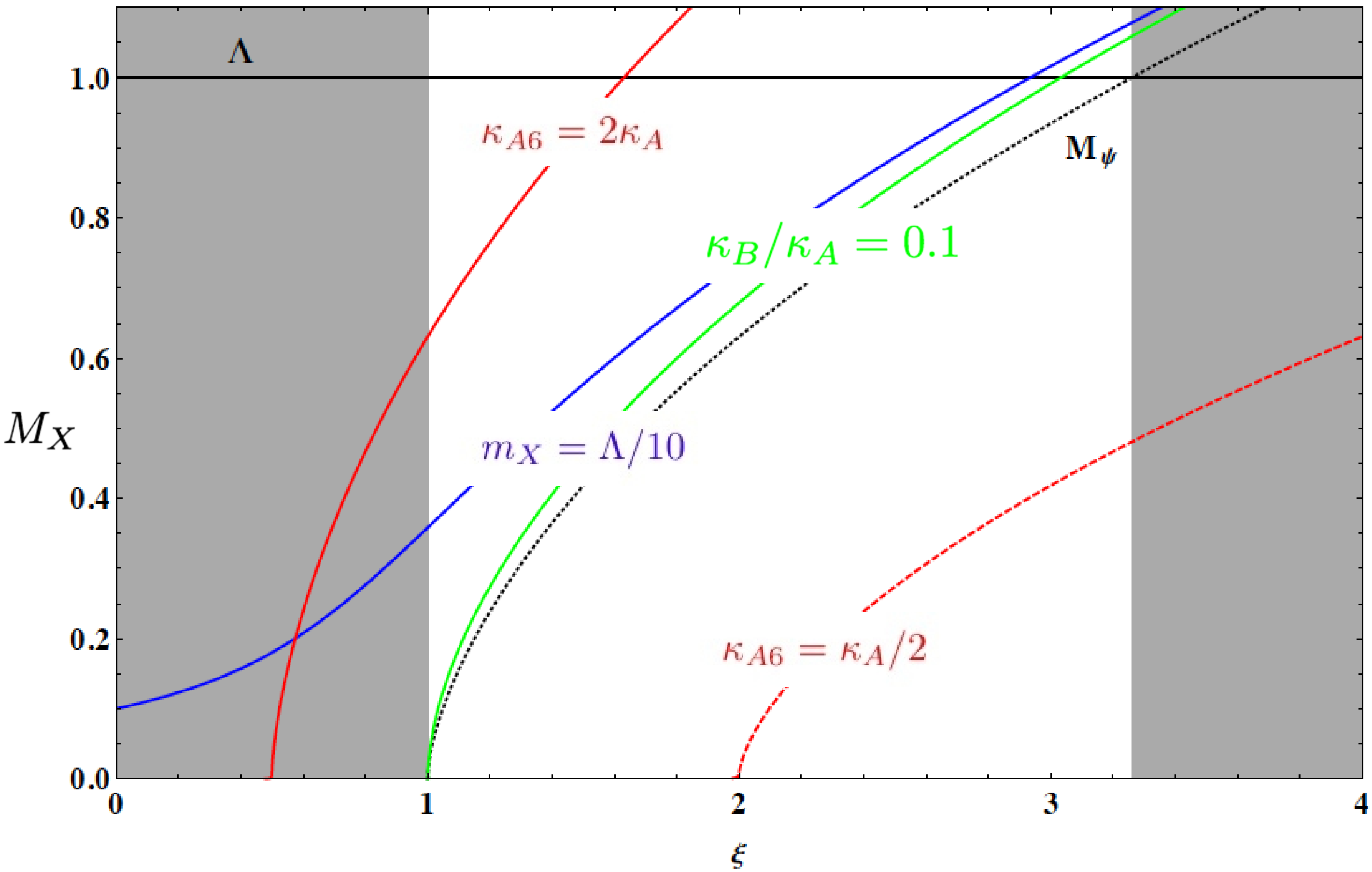
If it vanishes, light baryons may be top partners: Cacciapaglia-Parolini'15

$SU(6)^2$ x U(1), $SU(4)^2$ x U(1), $U(1)^3$: hard to match all by a common set of baryons; in any case, U(1) is broken when <ψψ> ≠ 0

The fate of SU(4) x SU(6) x U(1)
(coupled mass-gap equations)

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

$$\left.\begin{array}{l} \kappa_{B6} = \kappa_B = 0 \\ m_X = 0 \\ \kappa_{A6} = \kappa_A \end{array}\right\} \Rightarrow M_X = M_\psi$$



The colour sector window, between critical coupling, where $M_X = 0$, and maximal coupling, where $M_X = \Lambda$, shifts respect to the electroweak sector window

Strong dependence on the ratio κ_{A6} / κ_A

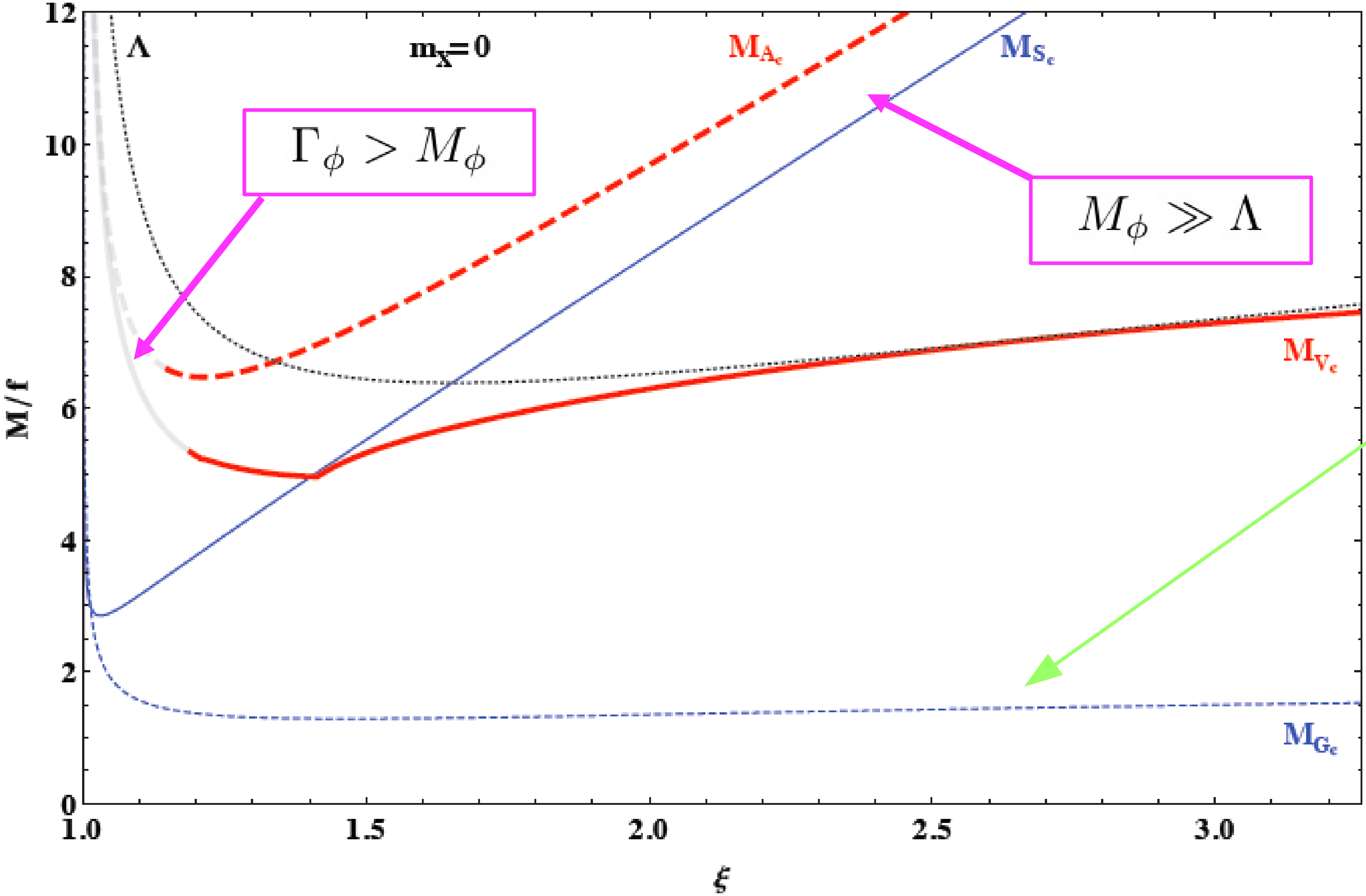
The large-N approximation does not determine this ratio uniquely

Coloured meson masses

$M_\phi / f \sim \sqrt{1/N}$ here $N = 4$

The ratio EW masses / coloured masses strongly depends on the ratio κ_{A6} / κ_A that unfortunately is a free parameter

$\kappa_{A6} = \kappa_A$
$\kappa_B = \kappa_A / 100$



Coloured Goldstone bosons receive **a mass from gluon loops: M_{Gc} > 1.3 f**
Behind the corner at the LHC?

Goldstone mass may be raised by **a non-zero m_X** (confront with pions)

Singlet meson masses with mixing

The Sp(4) singlet mesons σ_ψ, η_ψ, a^μ_ψ may mix with the SO(6) singlet ones σ_X, η_X, a^μ_X as they are all SM singlets

- **Axial-vectors:** Sp(2N) current-current operators (leading in 1/N) do not mix Ψ and X sectors → the mixing is subleading.
- **(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 η_ψ and η_X is massless (for m_X=0): the U(1) Goldstone η_0

$$\mathbf{\Pi}_{\sigma_\psi \sigma_X} = \begin{pmatrix} \tilde{\Pi}_S^\psi & 0 \\ 0 & \tilde{\Pi}_S^X \end{pmatrix} , \qquad \mathbf{K}_{\sigma_\psi \sigma_X} = \begin{pmatrix} K_{\sigma_\psi} & K_{\psi X} \\ K_{\psi X} & K_{\sigma_X}, \end{pmatrix}$$

Spectrum is very sensitive even to a small anomaly coefficient $A_{\psi X}$

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

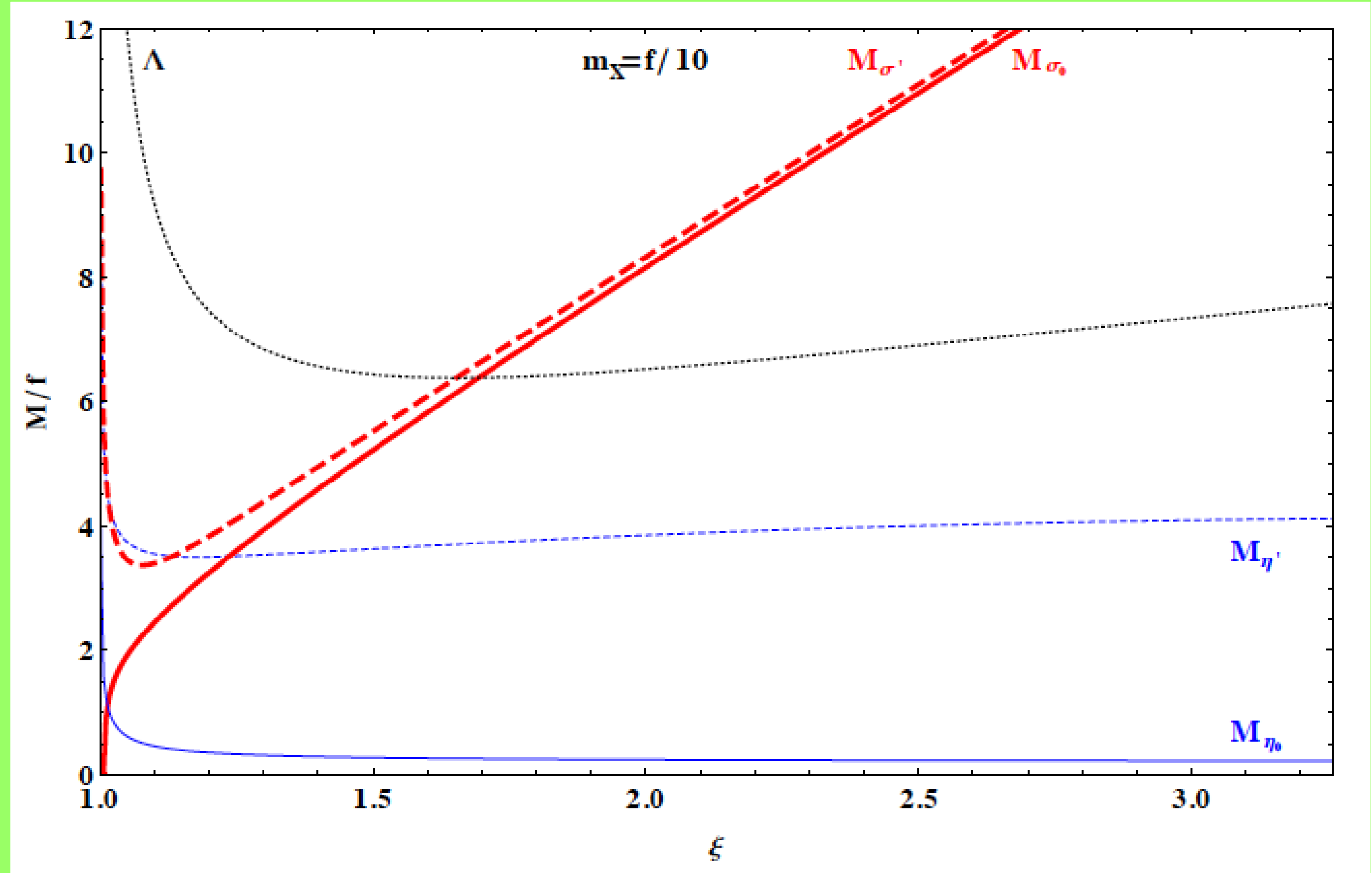
Mixed states may couple both to electroweak bosons and gluons!

Singlet me

The Sp(4) singlet mesons σ

as they are all SM singlets

- **Axial-vectors:** Sp(2N) cu
X sectors → the mixing is
- **(Pseudo-)scalars:** anoma
order as the couplings Ψ^4,
one linear combination of



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Mixed states may couple both to electroweak bosons and gluons!

Couplings to SM gauge bosons

The $SU(3)_c xSU(2)_w xU(1)_Y$ currents within SO(6)xSp(4) are weakly coupled to the SM gauge bosons

$$\mathcal{L}_{\rm int} = -i g_W \mathcal{W}^\mu \mathcal{J}^W_\mu$$

This explicit symmetry breaking, when acting on the Goldstone-boson states, induces non-zero matrix elements, that can be computed perturbatively

Goldstones with SM charges acquire a positive mass from gauge boson loops

$$\Delta M^2_{\hat{A}} = -\frac{3}{4\pi} \times \frac{1}{F_G^2} \times \frac{g_W^2}{4\pi} \times \int_0^\infty dQ^2\, Q^2\, \Pi_{V\text{-}A}(Q^2) \times C_2^{(H_W)}(R_W)$$

For our estimates, we integrated the V-A correlator, resummed à la NJL, up to $Q^2=\Lambda^2$

Goldstones with SM anomalies decay into two SM gauge bosons with definite strength

$$\mathcal{L}^{\rm WZW}_{\rm eff} = -\frac{g_W^2 d_{HC}}{64\pi^2 F_G} \epsilon_{\mu\nu\rho\sigma} \mathcal{W}^{\mu\nu}(x) \mathcal{W}^{\rho\sigma}(x) \sum_{\hat{A}} d^{WW\hat{A}} G^{\hat{A}}(x)$$

This is relevant for the two singlet Goldstones, η and η_0, and for the color octet O_0:

Waiting for true resonances in di-photons, di-W/Z, di-jets ...

e.g. Cai-Flacke-Lespinasse'15, Belyaev-Cacciapaglia-Cai-Ferretti-Flacke-Parolini-Serodio'16

To-do list

- Study couplings among resonances: widths, decay chains, ...
- The Goldstone (Higgs) potential (mass) receives contributions from
  - SM gauging (determined up to a form factor)
  - SM Yukawas (dependent on the mixing of SM fermions with baryons)
  - non-SM parameters such as $m_{\psi,X}$ (arbitrary)
- Need to compute mass and interactions of the top partners

$$\Psi^{abf} = (\psi^a \psi^b X^f)$$

  - resummation of leading-1/N diagrams is possible, by generalising the meson procedure to baryons (baryon masses reasonably reproduced by the NJL model for QCD): in progress...
- With an improved control on the top-partner parameters, the top contribution to the Goldstone potential should be more predictable
  - study EWSB, determine the tuning needed for m_h=125 GeV, ...

e.g. Matsedonskyi-Panico-Wulzer '13,'14,'15

Summary

- Higgs bound state of a strongly-coupled gauge theory → accompanied by a set of mesons with electroweak (and likely colour) quantum numbers
- Non-perturbative QCD artillery allows to characterise the meson spectrum
- Large-N, Nambu-Jona Lasinio techniques: a crude approximation of real dynamics → predictions may carry a large (a few over N) uncertainty, but:
  - The model is clearly defined and precisely computable
  - The detailed symmetry structure is correctly accounted for → a number of self-consistency relations hold
- In the minimal model, the meson masses lie above (4-5)f > 4TeV, with a few significant exceptions: two singlet Goldstones η and η_0, possibly the σ_0 and/or the η', and the coloured Goldstones
- Need to estimate the top partner spectrum to quantify the little hierarchy