Large N estimates of resonance masses in a composite Higgs model

Nicolas Bizot

In collaboration with M. Frigerio, M. Knecht and J-L. Kneur

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Composite Higgs models

New strong dynamics condensates at scale Λ and spontaneously breaks a global symmetry G into H

$\Rightarrow$ Higgs is naturally light as a pNGB of the coset G/H

Effective models of the gauge theory

The gauge theory in term of hypergluons and fundamental fermions is difficult to study below Λ because of its non-perturbative nature

$\Rightarrow$ Useful to consider effective models

- Low scale effective models:
  Lagrangian is dictated by global symmetries only, model includes Goldstone bosons and light resonances
  $\Rightarrow$ Little information on the details of the strong dynamics

- Intermediate scale effective models:
  Lagrangian in term of 4-fermion operators respects explicitly the underlying gauge symmetry (gauge bosons are froze-out)
  $\Rightarrow$ Possible to make calculation of non-perturbative quantities with Nambu Jona-Lasinio (NJL) techniques [Nambu and Jona-Lasinio '61]

gauge theory

(fundamental fermions, techni-gluons)

$$\mathcal{L}_{\text{gauge}} = \overline{\Psi} i \not{D} \Psi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

Λ

Intermediate scale effective models

(fermionic bilinears)

$$\mathcal{L}_{\text{NJL}} = \overline{\Psi} i \not{\partial} \Psi + \sum_{\alpha} \left(\overline{\Psi} \Gamma^{\alpha} \Psi \right) \left(\overline{\Psi} \Gamma_{\alpha} \Psi \right)$$

NJL techniques (Large N), ...

f

Low scale effective models

(Goldstone bosons, ...)

$$\mathcal{L}_{\chi PT} = \frac{f^2}{2} \partial_{\mu} \Pi \partial^{\mu} \Pi + \cdots$$

Chiral perturbation theory

A composite model based on SU(4)/Sp(4)

The spontaneous global symmetry breaking $SU(4)/Sp(4) \cong SO(6)/SO(5)$ contains the Higgs doublet as a Goldstone ($Sp(4) \supset SU(2)_L$)

Realization of $SU(4)/Sp(4)$ in term of 4-fermion operators

- 4 Weyl fermions $\psi \to$ global $SU(4)$ symmetry

  [Barnard, Gherghetta and Ray, 1311.6562]

$$\mathcal{L}^S_\psi = \frac{\kappa_A}{2N}(\psi^a\psi^b)(\overline{\psi_a}\ \overline{\psi_b}) + \frac{\kappa_B}{8N}\left[\epsilon_{abcd}(\psi^a\psi^b)(\psi^c\psi^d) + h.c.\right]$$

- Gauge symmetry $Sp(2N)$: $\psi \sim \square \longrightarrow (2N)$ hypercolours

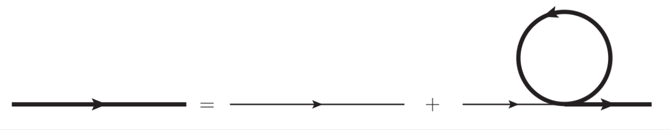
  $\Rightarrow$ A condensate $\langle\psi\psi\rangle \neq 0$ would breaks $SU(4)$ down to $Sp(4)$

  [Peskin '80]

$(\psi^a\psi^b) \sim 1_{Sp(2N)} \to$ fermionic bilinears are hypercolour singlets

Dynamical mass of the fermions

Mass gap (Schwinger-Dyson equation)



$\Rightarrow$ Non-perturbative calculation which sums an infinite number of diagrams at leading order in $1/N$ expansion

Critical coupling and dynamical mass

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

[Barnard et al '13]

Non trivial solution $M_\psi \neq 0$ exists only if $(\kappa_A+\kappa_B) > 4\pi^2/\Lambda^2$

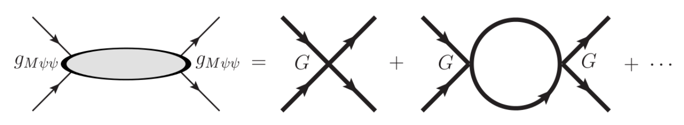
$\Rightarrow$ The global symmetry is broken above a critical coupling where a dynamical mass for the fermions M_ψ is generated ($\langle\psi\psi\rangle = M_\psi/(\kappa_A+\kappa_B)$)

Mesons masses and couplings

Physical mesons are present in the spectrum after condensation

Bethe-Salpeter equation

Geometrical series re-sums an infinite number of diagrams at leading order in $1/N$



$\Rightarrow$ Pole of the series is interpreted as the mass m_M of the physical meson M and the residue as the coupling $g_{M\psi\psi}$

$$iD_M^{\alpha\beta}(p^2) = \frac{iG\ \delta^{\alpha\beta}}{1 - G\ \Pi_M(p^2)} \equiv \frac{-ig^2_{M\psi\psi}\ \delta^{\alpha\beta}}{p^2 - m_M^2}$$

$G \equiv$ any scalar couplings
$\Pi_M \equiv$ 2-point function

Scalar and vector mesons spectrum

Scalar spectrum

Physical mesons have the same quantum numbers as the fermionic bilinears $(\psi^a \psi^b) \sim (1+5)_{Sp(4)}$

$\Rightarrow$ Spectrum contains scalar and pseudo-scalar singlets and quintuplets $M = \{\sigma,\ G^{\hat{A}},\ a,\ \mathcal{S}^{\hat{A}}\}$

$$M_G^2 = 0\ , \quad M_a^2 = -\frac{\kappa_B}{\kappa_A^2 - \kappa_B^2}\,\frac{1}{B_0(M_a^2, M_\psi^2)}, \quad M_{\sigma,\mathcal{S}}^2 = M_{G,a}^2 + 4M_\psi^2$$

$\Rightarrow$ 5 Goldstone bosons $G^{\hat{A}}$

Vector and Axial-vector resonances

$(\psi^a \sigma^\mu \overline{\psi}_b) \sim (1+5+10)_{Sp(4)} \Rightarrow V^\mu = \{a_1^\mu,\ A^{\mu\hat{A}},\ \rho^{\mu,A}\}$

NJL techniques can be applied to Spin 1 resonances as well starting from

$$\mathcal{L}_\psi^V = -\frac{\kappa_C}{2N}\,\frac{(\psi^a \sigma^\mu \overline{\psi_a}\,)}{2\sqrt{2}}\,\frac{(\psi^b \sigma_\mu \overline{\psi_b}\,)}{2\sqrt{2}} - \frac{\kappa_D}{2N}\,(\psi^a \sigma^\mu \overline{\psi_b}\,)\,(\psi^b \sigma_\mu \overline{\psi_a}\,)$$

Phenomenological model

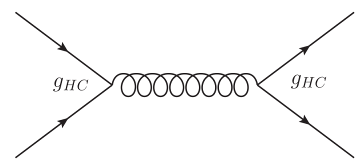
At least 6 free parameters: $\kappa_{A,B,C,D}$, N and Λ

Current-current interaction

Inspired by the gauge theory it is natural to start from a current-current interaction (work well in QCD [Klimt et al '90])

$$\mathcal{L}_{\psi}^{UV} = \frac{\kappa_{\psi}}{2N} \frac{\left(\psi\sigma^{\mu} T^{I} \overline{\psi}\right)}{2\sqrt{2}} \frac{\left(\psi\sigma_{\mu} T^{I} \overline{\psi}\right)}{2\sqrt{2}}$$

$T^{I} \equiv$ generators of Sp(2N)



Fierz transformations

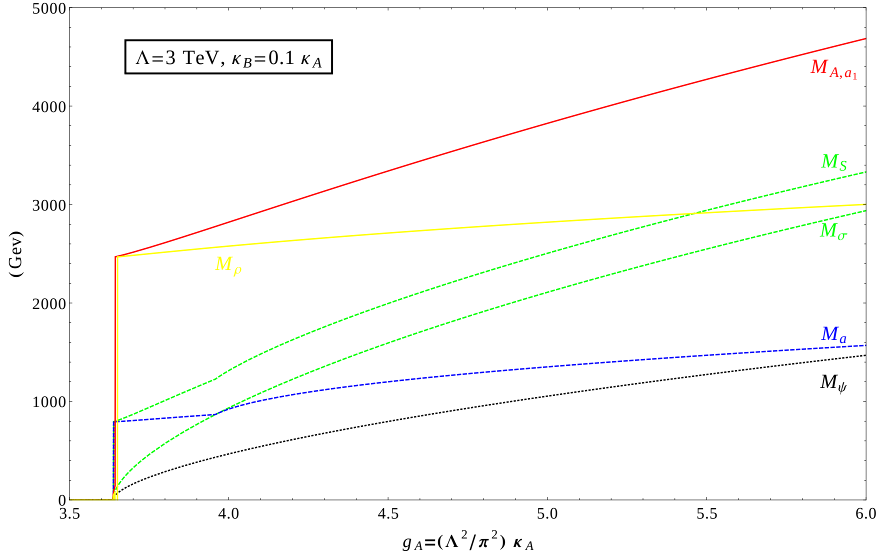
All of the operators are generated by Fierz transformations from the current-current interaction

$$\kappa_A = 2\kappa_C = 2\kappa_D = \kappa_{\psi}/8 + O(1/N)$$

$\Rightarrow$ Reduced set of free parameters

κ_B is separately induced from the U(1) anomaly

Spectrum


5000
4000
3000
2000
1000
0
3.5
4.0
4.5
5.0
5.5
6.0
(Gev)
$g_A=(\Lambda^2/\pi^2)\ \kappa_A$
Λ=3 TeV, κ_B=0.1 κ_A
M_{A,a_1}
M_S
M_σ
M_ρ
M_a
M_ψ

A coloured sector based on SU(6)/SO(6)

Composite models contain top partners ie coloured resonances
$\Rightarrow$ additional sector with coloured (under $SU(3)_c$) fermions is needed

Coloured SU(6)/SO(6) sector

6 Weyl fermions X $\rightarrow$ global SU(6) symmetry [Barnard et al '13]

$$\mathcal{L}_X^S = \frac{1}{2} m_\chi \left(X^f X^g \right) + \frac{\kappa_S}{(2N)^2} (X^f X^g)(\overline{X_f}\ \overline{X_g})$$

- $X \sim \boxminus$ under $Sp(2N)$ $\rightarrow$ less trivial Fierz transformations
- $\langle XX \rangle$ spontaneously breaks $SU(6)$ down to $SO(6)$ [Peskin '80]
- $SO(6) \supset SU(3)_c$: $6_{SO(6)} = (3 + \overline{3})_{SU(3)_c} \rightarrow$ No $SU(3)_c$ anomalies
- m_χ explicitly breaks $SU(6)$ and induces a mass for coloured pNGB which are more constrained by collider searches [Cacciapaglia et al '15]

Calculations are similar to the uncoloured sector with different resonances:

$$(X^f X^g) \sim (1 + 20)_{SO(6)} \sim (1 + 8 + 6 + \overline{6})_{SU(3)_c}$$
$$(X^f \sigma^\mu \overline{X}_g) \sim (1+20+15)_{SO(6)} \sim (1+8+6+\overline{6}+1+8+3+\overline{3})_{SU(3)_c}$$

Conclusions

We have considered a model with 4-fermion interactions and used NJL techniques to make non-perturbative calculations (masses, couplings, decay constants $\cdots$)

- The model predicts a particular pattern in the spectrum of the scalar and vector in the colourless and coloured sectors
  $\Rightarrow$ can be tested at collider
- The model depends only on few parameters if we start from the current-current operator.
  $\Rightarrow$ simple from phenomenological point of view

NJL model with 4-fermion interactions should be view as an approximation of the full gauge theory but:

- it well describes the spontaneous breaking of the global symmetries.
- it gives an easy way (complementary to the lattice) to make approximate non-perturbative calculations.
- it is fruitful in the case of QCD (the only known strongly coupled theory) $\Rightarrow$ Natural to apply NJL to composite Higgs models.

Outlooks

- Calculation of top partners masses
- Generate the Higgs potential by gauging the SM group and realizing the partial compositeness for the top quark (add explicit breaking terms) $\Rightarrow$ Small corrections to the masses of the resonances $\sim \mathcal{O}\left(m_h^2/M_M^2\right)$
- Apply NJL techniques to other UV completions (other cosets or other field contents)

Thanks for your attention

Backup

Diquarks and Baryons

Top partners quantum numbers

Under the global symmetry $SU(4) \times SU(6)$ the top partners (coloured triplets) transform as [Cacciapaglia et al '15]

$(X\psi\psi) \sim (6,6)$ $\quad$ $(X\overline{\psi}\ \overline{\psi}) \sim (\overline{6},6)$ $\quad$ $(X\overline{\psi}\psi) \sim (1,6) + (15,6)$

$6_{SU(6)} = (3 + \overline{3})_{SU(3)_c}$ $\quad$ $(\square \times \begin{smallmatrix}\square\\\square\end{smallmatrix}) \times \square = \square \times \square + \cdots = \bullet + \cdots$

Diquarks

Maximal attractive channel: $V(\square \times \begin{smallmatrix}\square\\\square\end{smallmatrix}) \sim -N/2$ $\quad V(\square \times \square) \sim -1/4$

$\Rightarrow$ $(X\psi)$ diquark more likely than $(\psi\psi)$

Baryon masses

Effective 4-fermion interaction between "quarks" and "di-quarks" (integrating out X fermion) in the Bethe-Salpeter equation leads to the propagators of physicals baryons.

$\Rightarrow$ Static approximation $\equiv$ baryon is mainly built from a "quark" and a "diquark"

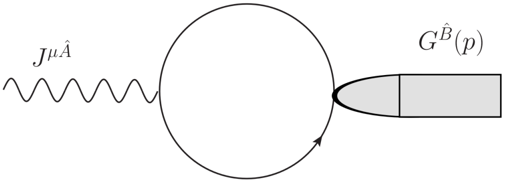
Decay constants

The calculation of decay constants is possible with NJL techniques

Pseudo-scalar (F_G) decay constant

F_G ($\equiv f_\pi$ in QCD) describes the strength of the decay into SM particles
$\Rightarrow$ measure of the coupling to the broken currents

$$\langle 0|J^{\mu\hat{A}}|G^{\hat{B}}(p)\rangle = ip^\mu F_G \delta^{\hat{A}\hat{B}}$$



Vector (F_ρ) and Axial (F_A) decay constants

$$\langle 0|J^{\mu A}|\rho^B(p)\rangle = F_\rho M_\rho\, \varepsilon^\mu(p)\, \delta^{AB}, \qquad \langle 0|J^{\mu\hat{A}}|A^{\hat{B}}(p)\rangle = F_A M_A\, \varepsilon^\mu(p)\, \delta^{\hat{A}\hat{B}}$$