$SU(2)$ with fundamental fermions and scalars

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Composite Higgs Models

The Higgs sector of the SM is replaced by a new strongly interacting sector $\Rightarrow$ dynamical breaking of EW symmetry

Two classes of models

- Technicolor [a]: Higgs $\Leftrightarrow$ Lightest resonance
- Composite Goldstone-Higgs [b]: Larger global symmetry than what strictly needed to break EW symmetry. Higgs $\Leftrightarrow$ Goldstone boson

[a] S. Weinberg, Phys. Rev. D13 (1976); L. Susskind, Phys. Rev. D20 (1979)

[b] D. B. Kaplan, H. Georgi, Phys. Lett. B136 (1984); D. B. Kaplan, H. Georgi, S. Dimopoulos, Phys. Lett. B136 (1984)

SM fermion masses

Partial compositeness [a]

[a] D. B. Kaplan, Nucl. Phys. B365 (1991)

Linear coupling between SM fermions and a composite state of the new strong sector : $\boxed{\mathcal{L}_{int} \propto f\mathcal{F}\mathcal{F}\mathcal{F}}$

- Need for large anomalous dimensions (not measured so far)

$$\boxed{\begin{array}{c}\frac{\lambda_f(\Lambda_{UV})}{\Lambda_{UV}^{d-4}} f\mathcal{F}\mathcal{F}\mathcal{F} \\ \downarrow \\ \frac{\lambda_f(\Lambda_{EW})}{\Lambda_{EW}^{d-4}} f\mathcal{F}\mathcal{F}\mathcal{F}\end{array}} \qquad \Rightarrow \lambda_f(\Lambda_{EW}) = \lambda_f(\Lambda_{UV})\left(\frac{\Lambda_{EW}}{\Lambda_{UV}}\right)^{d-4}$$

  - $d - 4 \approx 0$
  - $d = \frac{3}{2} + d_{\mathcal{F}\mathcal{F}\mathcal{F}} = \frac{3}{2} + 3 \times \frac{3}{2} - \gamma \Rightarrow \boxed{\gamma \approx 2}$

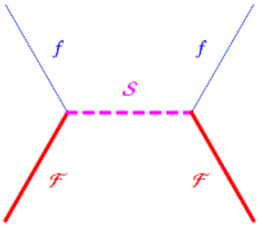
- $\mathcal{F}\mathcal{F}\mathcal{F}$ must have the same scaling dimension as a scalar plus a fermion

Fundamental partial compositeness [a]

[a] F. Sannino, A. Strumia, A. Tesi, E.Vigiani, JHEP 1611 (2016) 029

- A composite Goldstone-Higgs model
  - Gauge group: $SU(N_C)$, $SO(N_C)$, $Sp(N_C)$
  - N_f fundamental fermions ($\mathcal{F}$)
  - N_S fundamental scalars ($\mathcal{S}$)
- Masses of all the SM fermions are generated via partial compositeness:

$$\boxed{\mathcal{L}_{int} \propto f\mathcal{F}\mathcal{S}}$$



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Minimal fundamental partial compositeness [a]

[a] G. Cacciapaglia, H. Gertov, F. Sannino, A. E. Thomsen, arXiv:1704.07845

- Gauge group in a pseudoreal representation ($\rightarrow$ enhanced global symmetry)
- $N_f = 2$
- $N_S = 12 \Rightarrow$ provide mass for all the SM fermion fields

Scalar quartic couplings

Scalar quartic potential

- Example: $SU(N_C)$, N_f fermions, N_S scalars
- Scalar quartic potential:

$$\boxed{V = \lambda^{(1)}\mathrm{Tr}(\mathcal{S}^\dagger\mathcal{S})^2 + \lambda^{(2)}\mathrm{Tr}(\mathcal{S}^\dagger\mathcal{S}\mathcal{S}^\dagger\mathcal{S})}$$

- If $N_S = 1 \Rightarrow \mathrm{Tr}(\mathcal{S}^\dagger\mathcal{S}\mathcal{S}^\dagger\mathcal{S}) = \mathrm{Tr}(\mathcal{S}^\dagger\mathcal{S})^2 \Rightarrow$ 1 quartic coupling ($\lambda = \lambda^{(1)} + \lambda^{(2)}$)

- A quartic self coupling for the scalar fields is always generated via the gauge interaction
- The scalar quartic couplings do not necessarily have a Landau pole

Renormalization group flow

- $N_S = 1 \Rightarrow$ couplings: $\boxed{g,\ \lambda}$
- Renormalization group equations: $\frac{d\alpha}{d\ln\frac{\mu}{\mu_0}} = \beta_\alpha$

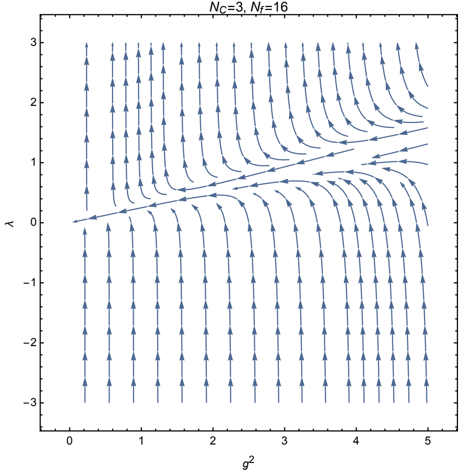
1-loop β-functions

$$(4\pi)^2\beta_g = -\left(\frac{11}{3}N_C - \frac{2}{3}N_f - \frac{N_S}{6}\right)g^3$$

$$(4\pi)^2\beta_\lambda = 4(N_C+4)\lambda^2 - \frac{6(N_C^2-1)}{N_C}g^2\lambda + \frac{3N_C^3+3N_C^2-12N_C+6}{4N_C^2}g^4$$

Complete asymptotic freedom

$N_S = 1$



N_C	N_f
2	No solutions
3	$15.93 < N_f < 16.25$
4	$19.8 < N_f < 21.75$
5	$23.56 < N_f < 27.25$
6	$27.27 < N_f < 32.75$
7	$30.94 < N_f < 38.25$
8	$34.6 < N_f < 43.75$
9	$38.24 < N_f < 49.25$
10	$41.88 < N_f < 54.75$

The need for lattice simulations

The global symmetry breaking must happen in the same way as in a model with only gauge bosons and fermions $\Rightarrow$ the scalars must be a small perturbation to the gauge-fermion model

$SU(2)$ + 2 fermions and 1 scalar

- $SU(2)$ + 2 fundamental fermions, minimal model of composite Goldstone-Higgs, has been extensively studied [a]
- $N_S = 1 \Rightarrow$ one scalar quartic coupling
- Not completely asymptotically free
  - We cannot take the continuum limit
  - Landau pole at a high energy scale $\Rightarrow$ matching to an effective theory

[a] R. Arthur, V. Drach, M. Hansen, A. Hietanen, C. Pica, Phys.Rev. D94 (2016)

Lattice action

$$\mathcal{S} = \beta \sum_{x} \sum_{\mu<\nu} \left(1 - \frac{1}{N_C} \mathrm{Re\ tr} P_{\mu\nu}(x)\right) + \sum_{i=1}^{N_F=2} \sum_{x,y\in\Lambda} \bar{\psi}(x) D(x,y) \psi(y) +$$
$$\sum_{x} \Big[- \sum_{\mu} \Big(S^{\dagger}(x) U(x,\mu) S(x+\mu) + S^{\dagger}(x) U(x-\mu,\mu)^{\dagger} S(x-\mu) \Big) +$$
$$(m_S^2 + 8) S^{\dagger}(x) S(x) + \lambda (S^{\dagger}(x) S(x))^2 \Big]$$

- $P_{\mu\nu}(x) = U(x,\mu) U(x+\mu,\nu) U(x+\nu,\mu)^{\dagger} U(x,\nu)^{\dagger}$
- $D(x,y) = \delta_{x,y} - \frac{\kappa}{2} \Big[(1-\gamma_\mu) U(x,\mu) \delta_{y,x+\mu} + (1+\gamma_\mu) U(x-\mu,\mu)^{\dagger} \delta_{y,x-\mu} \Big]$
- $\kappa = \frac{2}{8+2m_F}$

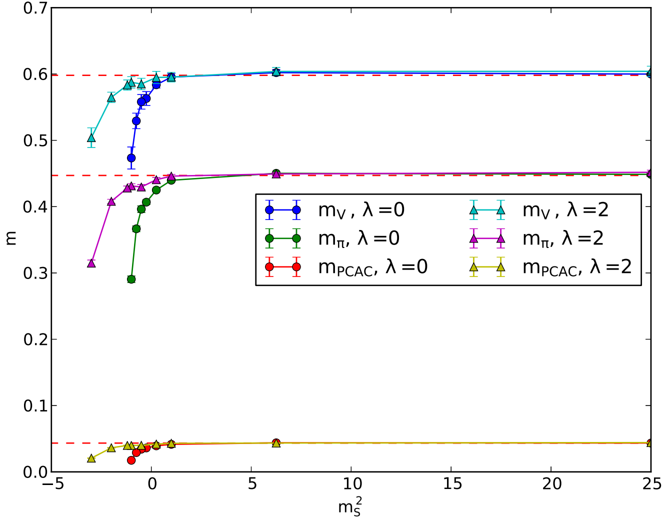
Choice of bare parameters

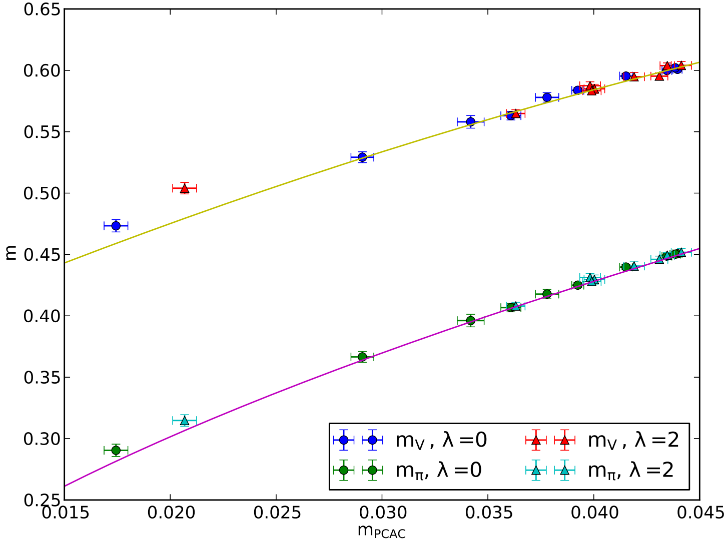
- Lattice size: $T = 32$, $V = 16^3$
- Fixed $\boxed{\beta = 2.0}$, $\boxed{m_f = -0.94}$
- Different values of m_s and λ

λ	m_S^2
0	25
0	6.25
0	1
0	0.25
0	0
0	-0.25
0	-0.5
0	-0.75
0	-1

λ	m_S^2
2	25
2	6.25
2	1
2	0.25
2	-0.5
2	-1
2	-1.2
2	-2
2	-3

Meson spectrum

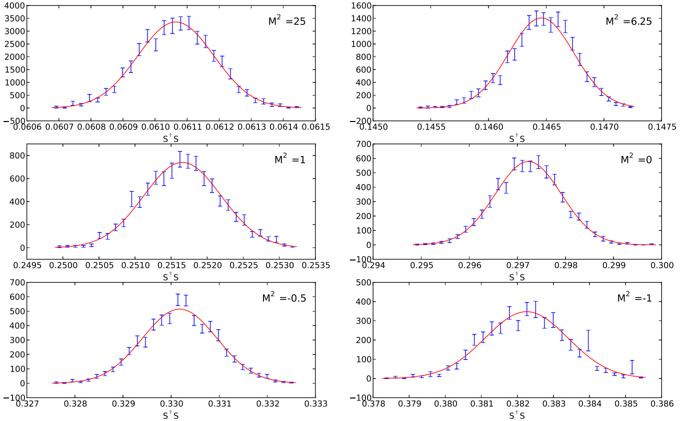



0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
m
0.015
0.020
0.025
0.030
0.035
0.040
0.045
m_PCAC
m_V, λ=0
m_V, λ=2
m_π, λ=0
m_π, λ=2

Histograms $S^\dagger S$

$$S^\dagger S = \frac{1}{VT}\sum_{x\in\Lambda} S^\dagger(x)S(x)$$

$\boxed{\lambda = 0}$



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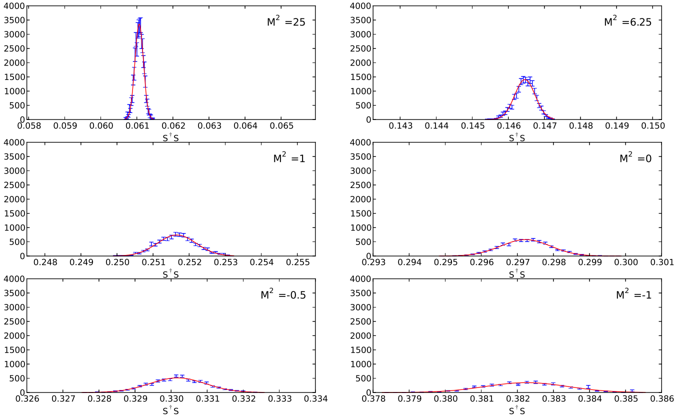


Conclusions and outlook

Conclusions

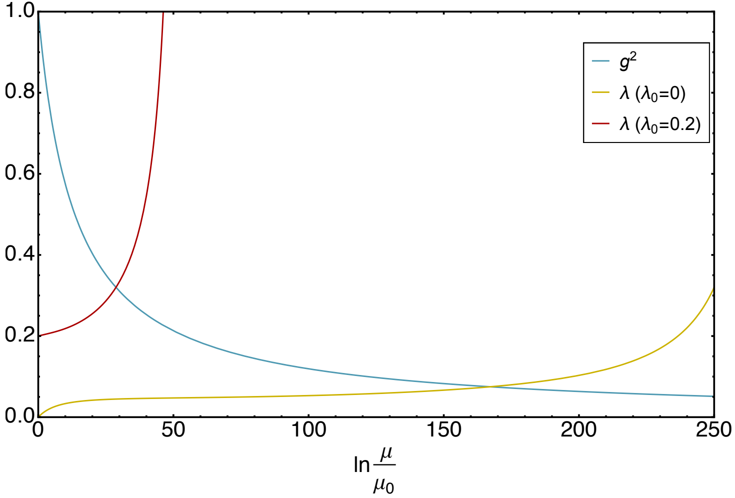
- First study of Fundamental Partial Compositeness on the lattice
- For large m_S^2 the spectrum of the gauge-fermion theory is recovered
- For smaller m_S^2, the deviation in the spectrum can be explained by a shift in m_{PCAC}
- No symmetry breaking is observed in the scalar sector

Future analysis

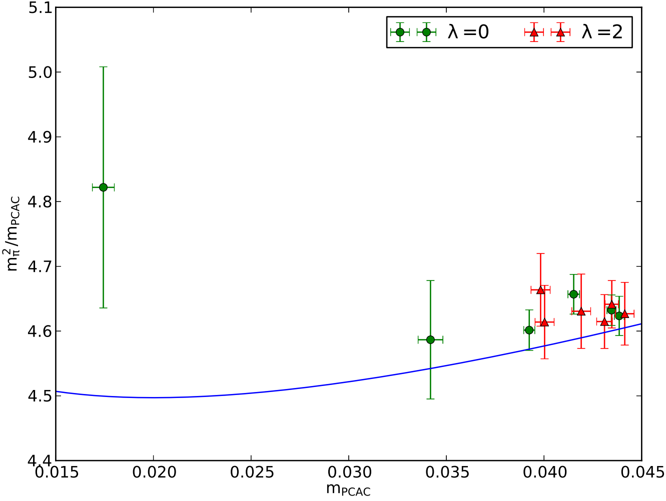
- More values of m_f and λ; different lattice spacings β
- Outline the phase structure
- Spectrum of $\psi^\dagger S$ and $S^\dagger S$ states

Running of the couplings ($SU(2)$, $N_f = 2$, $N_S = 1$)

$$\mu \sim \frac{1}{a}$$



m_π^2 / m_{PCAC}



λ =0
λ =2
5.1
5.0
4.9
4.8
4.7
4.6
4.5
4.4
0.015
0.020
0.025
0.030
0.035
0.040
0.045
m_π^2/m_{PCAC}
m_{PCAC}