The scalar sector of SU(2) gauge theory with N_F=2 fundamental flavours

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in collaboration with
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based on
arXiv:1607.06654

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General interest

- Facts:
  - ★ Higgs-like state discovered
  - ★ Well described by the Standard Model !
  - ★ Higgs interaction is the only one not dictated by a gauge principle
- Gauge theories can feature scalar bound states
- Questions:
  - ★ Can strongly coupled extensions be used to describe a composite Higgs state ?
  - ★ Can the scalar or pseudoscalar sector be used in the context if Dark Matter ?
- Here:
  - ★ Benchmark for spin-0 states
  - ★ Spin-1 states : See T. Janowski talk

SU(2)$_C$ with N$_f$=2 fundamental Dirac flavours

- SU(2) gauge theory with N_f = 2 Dirac fermions in the fundamental representation.

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\overline{U}\gamma^\mu D_\mu U + i\overline{D}\gamma^\mu D_\mu D + \frac{m}{2}Q^T(-i\sigma^2)C\,EQ + \frac{m}{2}\left(Q^T(-i\sigma^2)C\,EQ\right)^\dagger$$

- Pseudo-real irrep of SU(2): **global flavour symmetry is upgraded to SU(4)** :

$$Q \equiv \begin{pmatrix} U_L \\ D_L \\ \widetilde{U}_L \\ \widetilde{D}_L \end{pmatrix} \equiv \begin{pmatrix} U_L \\ D_L \\ -i\sigma_2 C\bar{u}_R^T \\ -i\sigma_2 C\bar{d}_R^T \end{pmatrix}, \quad E = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

- Infinitesimal SU(4) transformation : $Q \longrightarrow \left(1 + i\sum_{n=1}^{15}\alpha^n T^n\right)$

- Generators that leaves the Lagrangian invariant satisfy : $ET^n + T^{nT}E = 0$

- Chiral symmetry breaking pattern : ***SU(4) -> Sp(4)*** ***(~ SO(6) -> SO(5))***

5 Goldtone bosons

EW embedding

[G. Cacciapaglia & F. Sannino, JHEP 1404,111 (2014)]

- $Q_L = (U_L, D_L)$: $SU(2)_L$ doublet with hypercharge 0
- $\tilde{U}_L, \tilde{D}_L$: $SU(2)_L$ singlet with hypercharge $\pm 1/2$

- Two interesting alignments of the condensate :

$$\Sigma_H \equiv E = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$: break EW symmetry

$$\Sigma_B \equiv \begin{pmatrix} i\sigma_2 & 0 \\ 0 & -i\sigma_2 \end{pmatrix}$$: does not break EW

- General case :

$$\Sigma_0 = \cos\theta \; \Sigma_B + \sin\theta \; \Sigma_H$$

- Two limit cases :
  - $\theta = 0$: EW does not break : composite Higgs limit
  - $\theta = \pi/2$: EW breaks + DM candidate : technicolor limit
- at LO : $m_W^2 = 2 g \; (F_{PS} \; \sin\theta)^2$

- The Higgs is a linear combination of a GB and of the 0^+ state

- Not excluded by experimental data [Arbey *et al*, arXiv:1502.0471]

General remarks

- QCD:
  - $m_\sigma/f_{PS} \sim 5$ and width is large
  - dependence on the quark mass ?
- SU(2) + 2 Fundamental:
  - σ is not light because of symmetry reasons
  - N_c dependence is not know
- Technical issues:
  - Rigorous treatment of resonances is challenging
  - Disconnected contributions are noisy
- after EW embedding:
  - physical Higgs is a mixture of a GB and of the σ
  - Scalar state receives large contributions from top loops.

[R. Foadi, M. Frandsen & F. Sannino:Phys.Rev. D87 (2013) no.9, 095001]

Lattice techniques & results

The setup

R. Lewis, C. Pica, F. Sannino, Phys.Rev. D85 (2012) 014504 [arXiv:1109.3513]

A. Hietanen, C. Pica, R. Lewis, F. Sannino, JHEP 1407 (2014) 116 [arXiv:1404.2794]

A. Hietanen, C. Pica, R. Lewis, F. Sannino [arXiv:1308.4130]

R. Arthur, V.D, A. Hietanen, M. Hansen, C. Pica, F. Sannino [arXiv:1602.06559]

R. Arthur, V.D, A. Hietanen,, C. Pica, F. Sannino [arXiv:1607.06654]

- Plaquette action + Wilson Fermions
- Several volumes $V=L^3xT$
- 4 lattice spacings : a
- Several fermion masses m_f
- Intermediate scale setting w_0 from the Gradient flow

S. Borsanyi et. al., JHEP 09 (2012) 010, [arXiv:1203.4469]

- Non-perturbative renormalization
- Scale setting : $F_{PS} \sin \Theta = 246$ GeV
- HiRep code

L. Del Debbio, A. Patella, C. Pica, Phys.Rev. D81 (2010) 094503

Correlators

R. Arthur, VD, A. Hietanen, C. Pica, F. Sannino [arXiv:1607.06654]

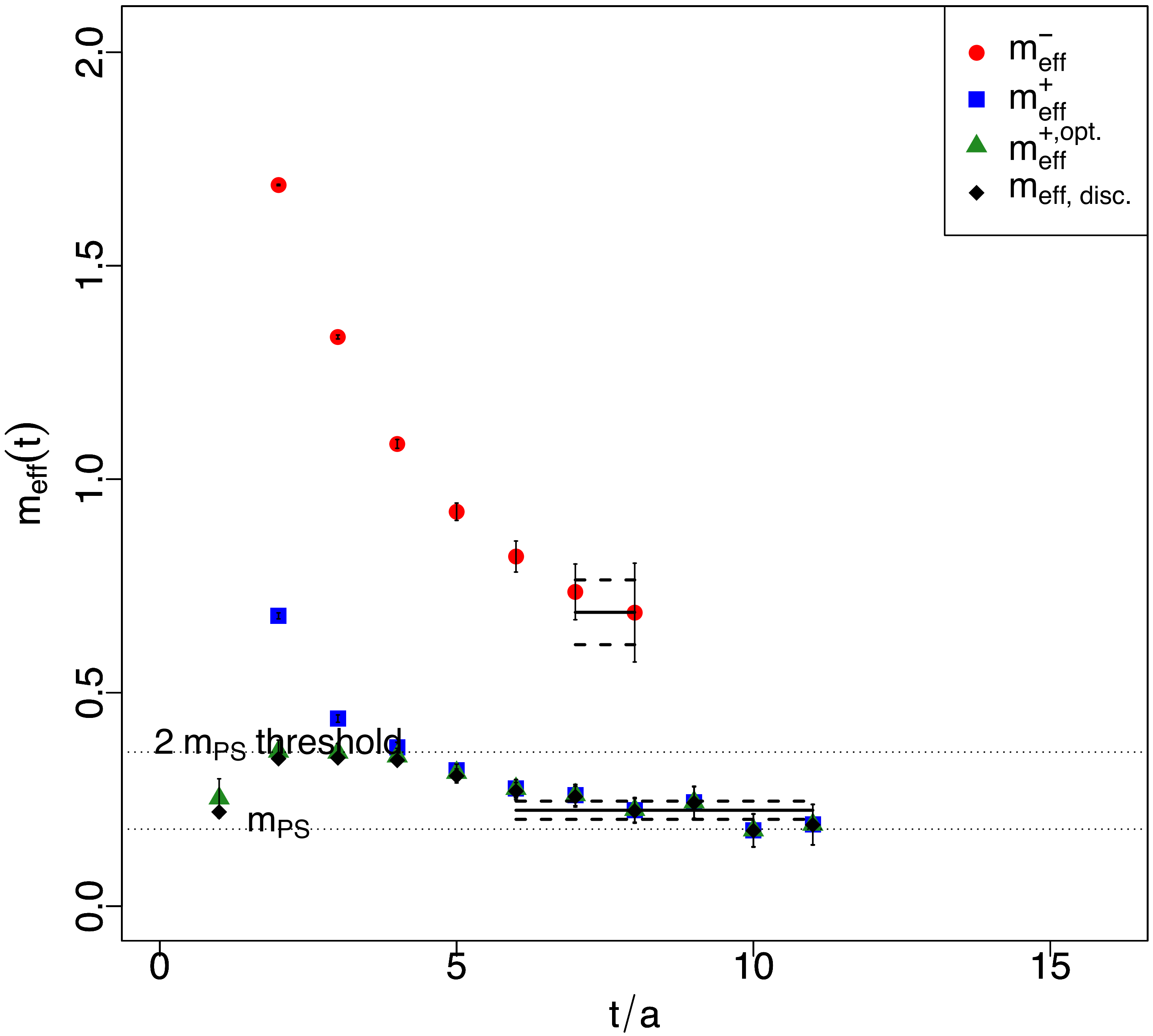
- Interpolating fields :
  - ★ scalar iso-singlet, σ $J = \bar{u}u + \bar{d}d$
  - ★ scalar iso-vector, a_0 $J = \bar{u}u - \bar{d}d$
  - ★ pseudoscalar, η' $J = \bar{u}\gamma_5 u + \bar{d}\gamma_5 d$
- Correlator : $C_{2\mathrm{pts}}(t) = \sum_{\vec{x}} \langle J(t,\vec{x})\bar{J}(0)\rangle$
- After integration over the fermions (σ case):

$$C_{2\mathrm{pts}}(t) = \sum_{\vec{x}} \mathrm{tr}\{\mathrm{S}(\mathrm{x},0)\mathrm{S}(0,\mathrm{x})\} + \mathrm{N_f} \sum_{\tilde{\mathrm{x}}} \mathrm{tr}\{\mathrm{S}(\mathrm{x},\mathrm{x})\}\mathrm{tr}\{\mathrm{S}(0,0)\}$$

- Effective mass $\frac{C(t-a)}{C(t)} = \frac{e^{-m_{\mathrm{eff}}(t)(t-a)} + e^{-m_{\mathrm{eff}}(t)(T-(t-a))}}{e^{-m_{\mathrm{eff}}(t)t} + e^{-m_{\mathrm{eff}}(t)(T-t)}}$
- Stochastic estimation based on 4-volume sources
- N_{src}=64 is enough for all our ensembles.

results on 3 new states of the theory : σ,a_0,η'

Effective mass: scalar channel



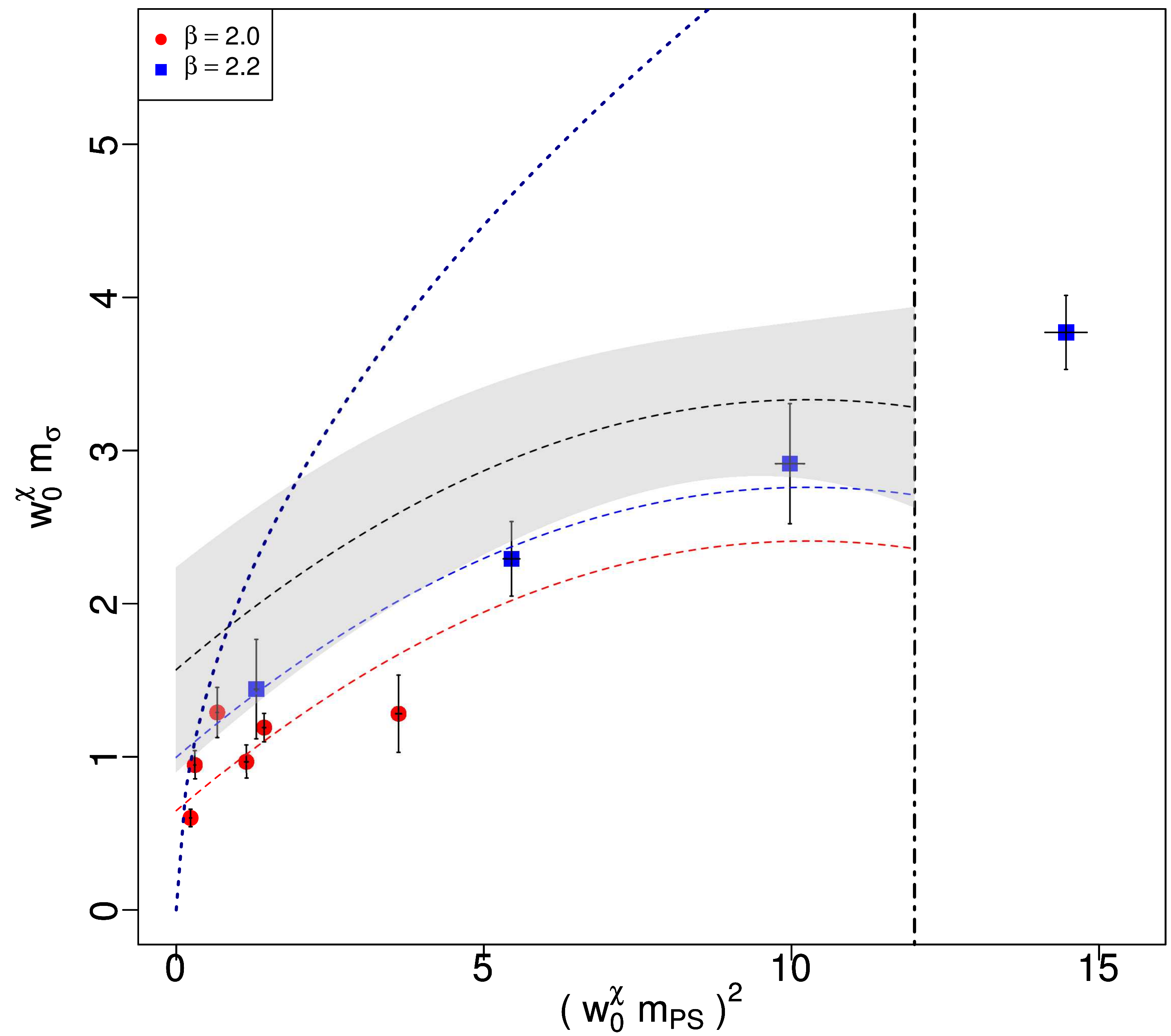
- Most chiral run: β=2.0, m=-0.958, V=32^4
- Clear plateau
- σ is stable in our setup !
- a_0 above 3 GBs threshold
- 2200 configurations
- $m_\sigma \sim m_{PS}$!

No need to consider yet the resonance analysis for the σ

σ resonance: 0(0+)

Extrapolating from stable regime is not justified …

- σ stable in our simulation
- cut-off effects negligible
- Global fit
- $m_\sigma = 19.2(10.8)\ F_{PS}$

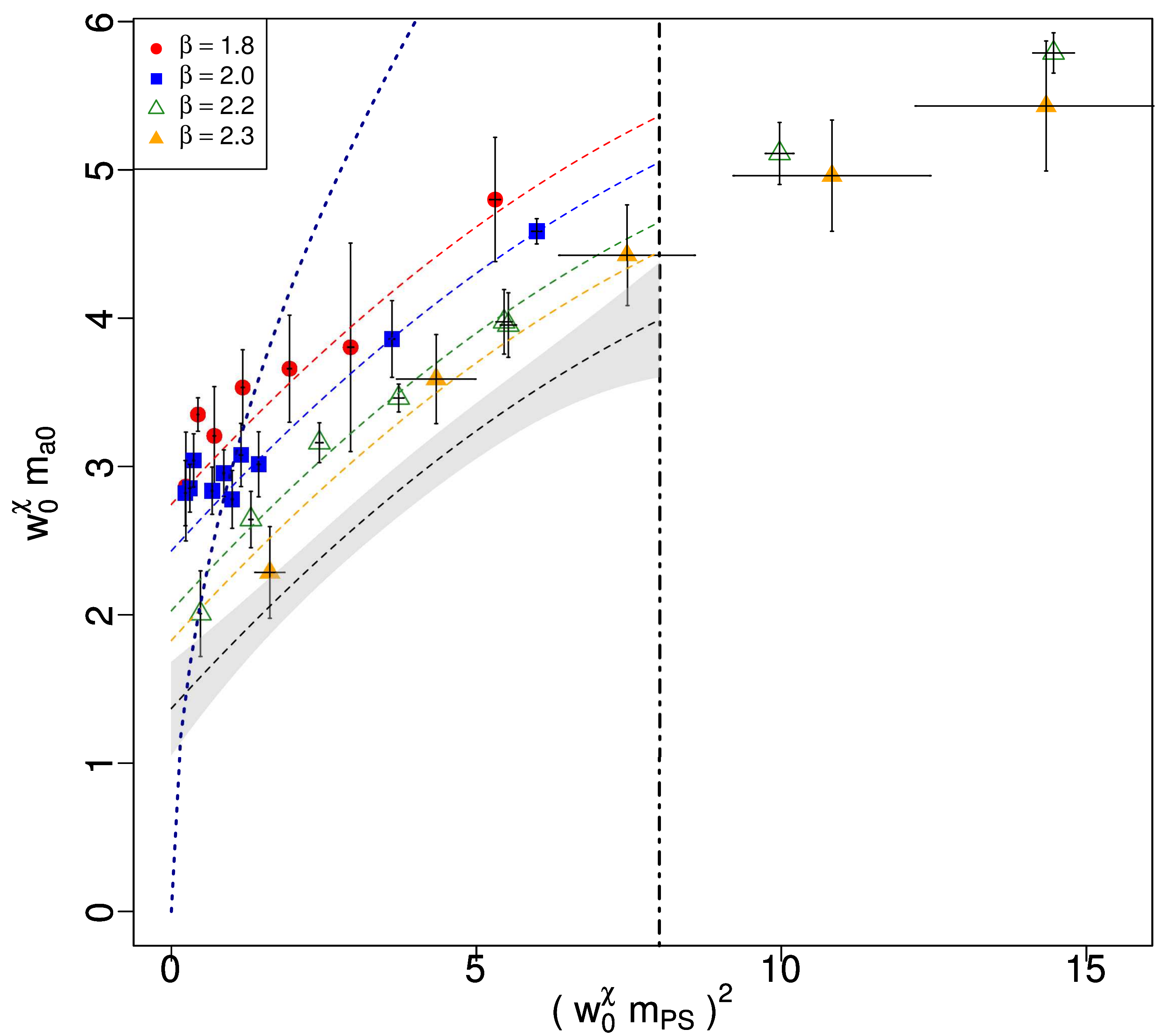


$$w_0^\chi m_X = w_0^\chi m_X^\chi + A(w_0^\chi m_{\rm ps})^2 + B(w_0^\chi m_{\rm ps})^4 + C\frac{a}{w_0}$$

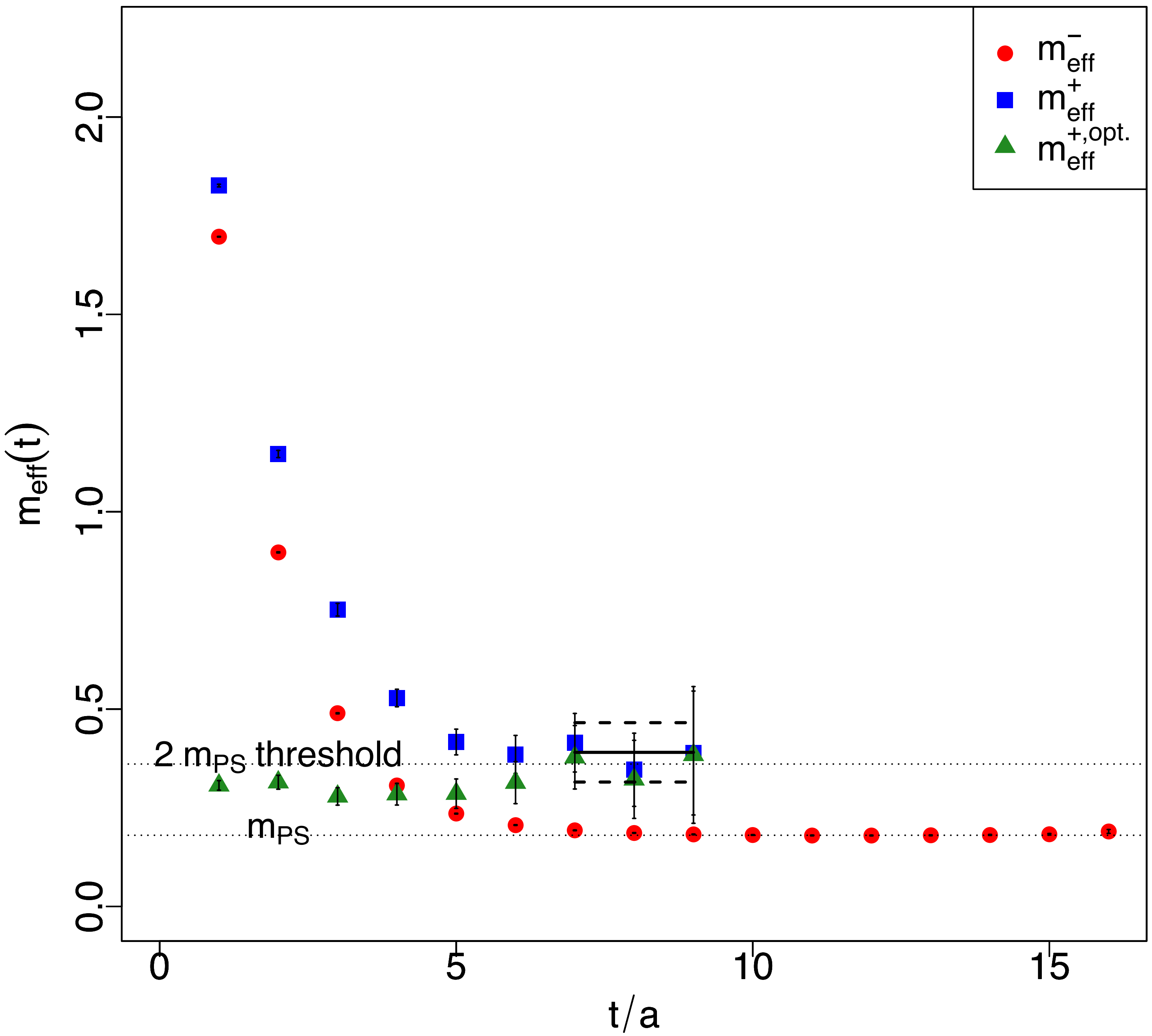
a_0 resonance: $1(0^+)$

Extrapolating from stable regime is not justified …

- Global fit including 4 lattice spacings
- Only data below 3 x m_{PS} threshold included
- *large* cut-off effects ?
- $m=16.7(4.9)\ F_{PS}$



Effective mass: pseudoscalar channel

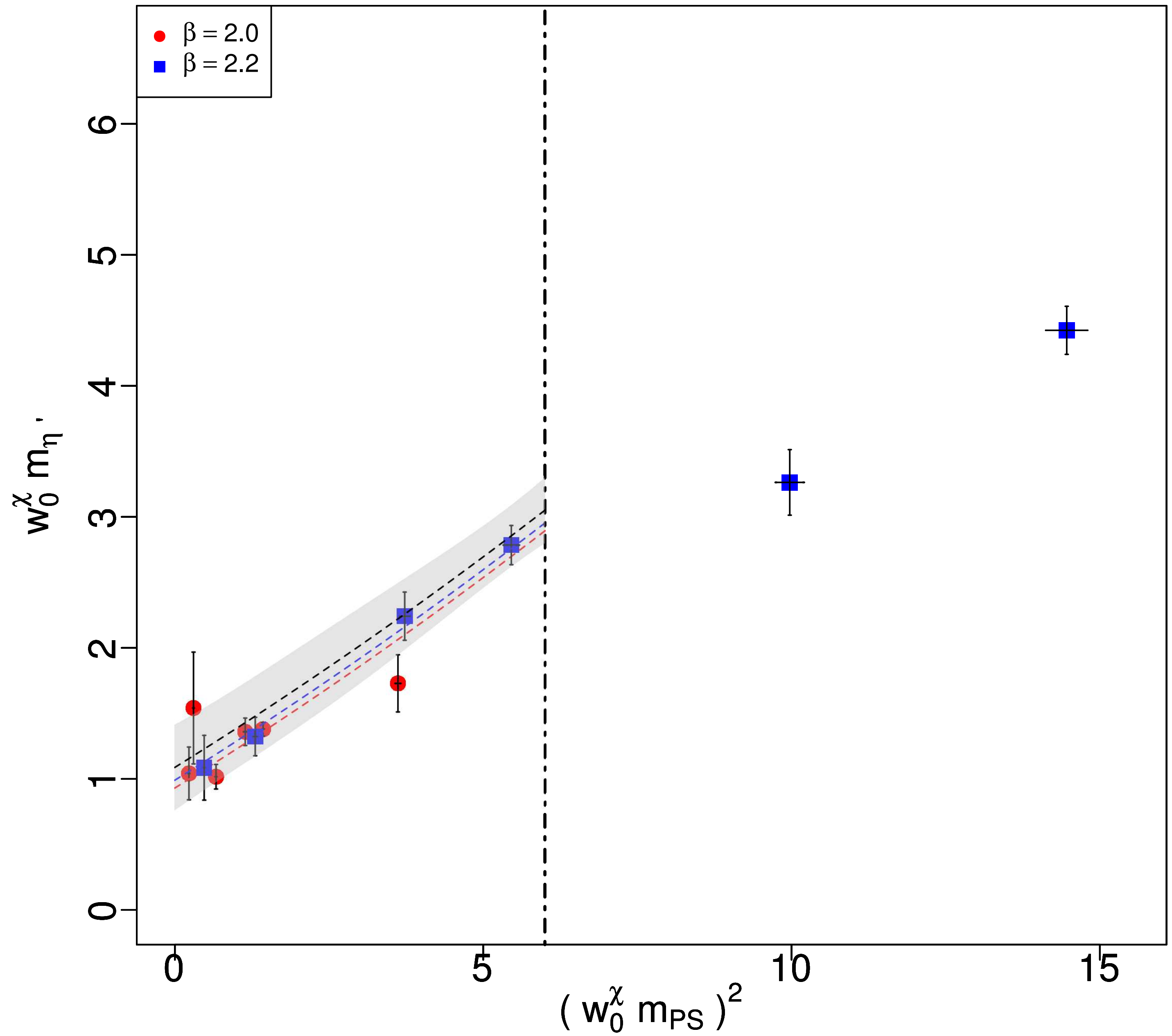


- Most chiral run: β=2.0, m=-0.958, $V=32^4$
- η' signal
- 2200 configurations
- Reasonable plateau

Contribution from the disconnected diagrams is sizable only for our lightest masses

η’: 0(0⁻)

- 2 lattice spacings
- $m_\eta > m_{ps}$ only at our lightest fermion masses.
- cut-off effect negligible
- m_η=12.8(4.7) F_{PS}



$$w_0^\chi m_X = w_0^\chi m_X^\chi + A(w_0^\chi m_{\text{ps}})^2 + B(w_0^\chi m_{\text{ps}})^4 + C\frac{a}{w_0}$$

Conclusions

- Non-perturbative dynamics of gauge theories is explored
- $SU(2)_c + N_f=2$: UV completion for a CH/TC scenario
- Signals are observed
- σ is stable in our range of mass
- Extrapolation: decay threshold effects are neglected
- Benchmark results in the spin-0 sector :
  - ★ $m_{a0}/F_{PS} = 16.7(4.9)$
  - ★ $m_{\sigma}/F_{PS} = 19.2(10.8)$
  - ★ $m_{\eta}/F_{PS} = 12.8(4.7)$
- Surprise : $m_{\sigma} \sim m_{PS}$ on a large range of mass