

Composite Higgs model on the lattice

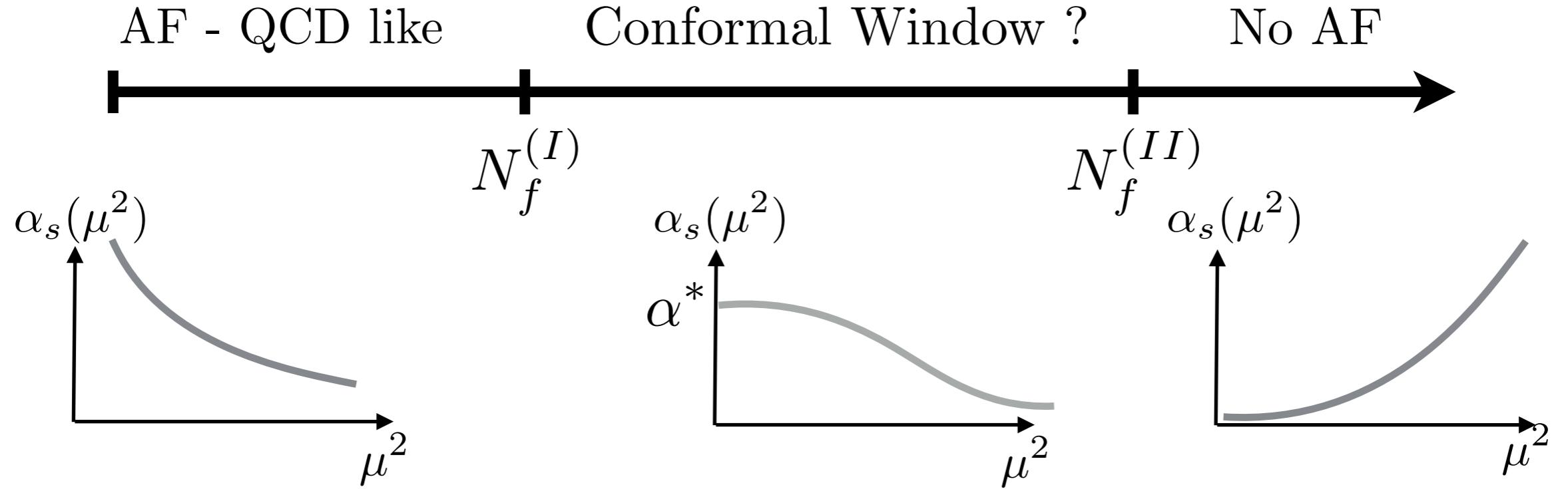
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in collaboration with
R. Arthur, M. Hansen, A. Hietanen, C. Pica and F. Sannino
CP³ Origins

Rencontre de Physique des Particules 2016, Annecy, 27 Janvier 2016

Phase diagram



Parameters :

- Gauge group : SU, SO, SP, E
- Matter representation : R
- # of flavors : N_f

Why and how ?

- Charting the phase diagram requires non-perturbative calculations.
Kuti, Fodor, Nogradi *et al*
- Can the rich variety of behavior be used for BSM ?
 - * Dynamical EW symmetry breaking (« Technicolor », ...) S. Weinberg '79, L. Susskind '79
 - * Composite Higgs model (Higgs is a pseudo GB, ...) Kaplan & Georgi '84
 - * Composite Dark Matter
- Lattice observables :
 - * low-lying spectrum (SSB chiral symmetry, spin 0, spin 1,...)
 - * Running coupling constant
 - * Scattering properties (widths of resonances, scattering lengths)
 - * Matrix element (form factors)

$SU(2)_c$ with $N_f=2$ Dirac flavours

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

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu} + i \bar{U} \gamma^\mu D_\mu U + i \bar{D} \gamma^\mu D_\mu D + \frac{m}{2} Q^T (-i\sigma^2) C E Q + \frac{m}{2} (Q^T (-i\sigma^2) C E Q)^\dagger$$

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

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

- Infinitesimal $SU(4)$ transformation : $Q \rightarrow \left(1 + i \sum_{n=1}^{15} \alpha^n T^n \right)$
- Generators that leaves the Lagrangian invariant satisfy : $E T^n + T^{nT} E = 0$
- Chiral symmetry breaking pattern : **$SU(4)$ breaks to $SP(4)$** \Rightarrow 5 Goldstone 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 :

$$\Sigma_H \equiv E = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} : \text{break EW symmetry} \quad \Sigma_B \equiv \begin{pmatrix} i\sigma_2 & 0 \\ 0 & -i\sigma_2 \end{pmatrix} : \text{does not break EW}$$

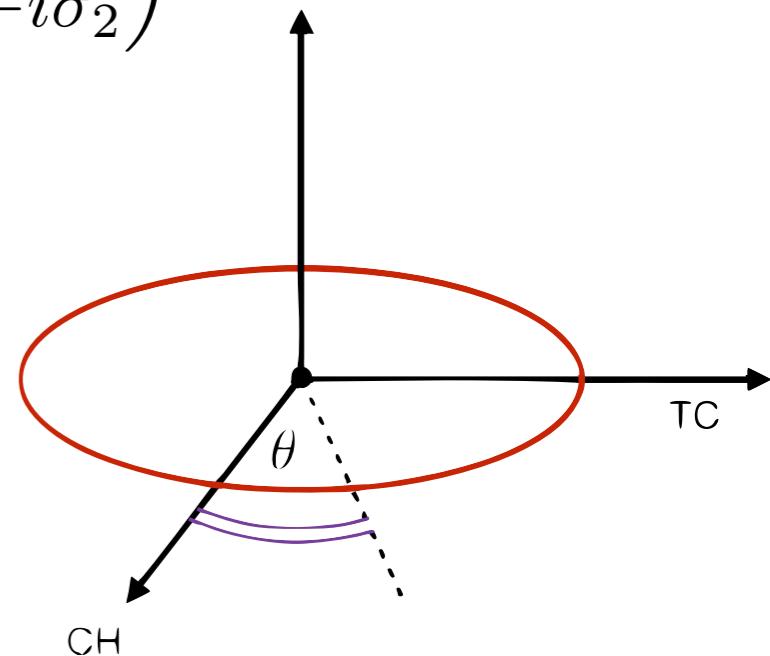
- ♦ General superposition : $\Sigma_0 = \cos \theta \Sigma_B + \sin \theta \Sigma_H$

- ♦ Two limit cases :

- * $\theta = 0$: EW does not break : composite Higgs limit
- * $\theta = \pi/2$: EW breaks + DM candidate : technicolor limit

- ♦ For instance at LO : $m_W^2 = 2 g (F_{PS} \sin \Theta)^2$

- ♦ Mixed case is natural : $0 < \theta < \pi/2 \Rightarrow$ the model interpolate between TC and CH



The setup

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- 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, C. Pica, F. Sannino [arXiv:1602.XXXXX]

- ♦ Plaquette action + Wilson Fermions
- ♦ Several volumes $V=L^3 \times T$ \Rightarrow extrapolate to infinite volume
- ♦ 4 lattice spacings : a \Rightarrow extrapolate to the continuum limit
- ♦ Several fermion masses $m_f \longleftrightarrow m_{PS}^2$ \Rightarrow extrapolate to the chiral limit
- ♦ 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
- ♦ Mass of stable states obtained by computing :

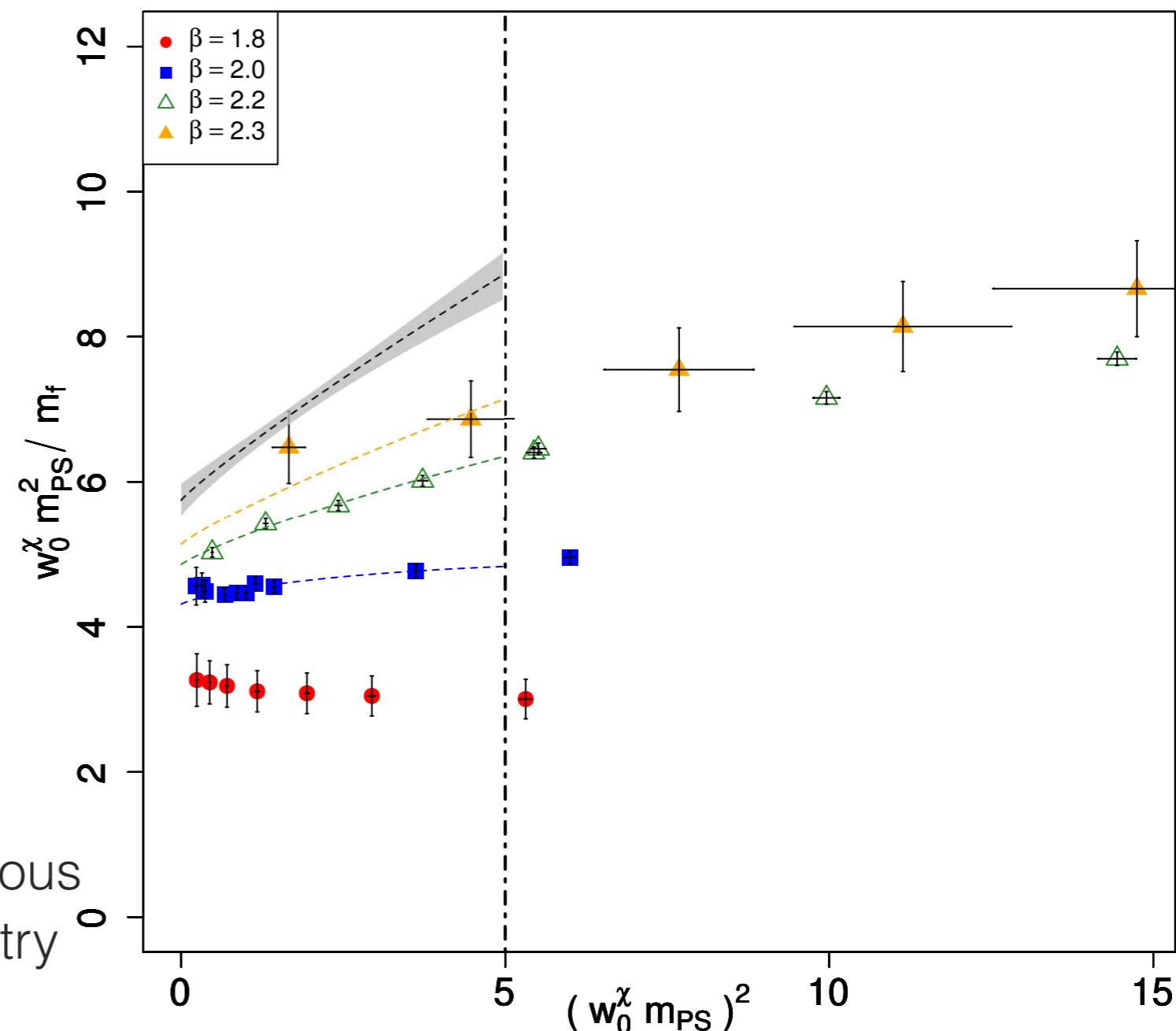
$$\sum_{\vec{x}} \langle \bar{\psi} \gamma_5 \tau^3 \psi(x) \bar{\psi} \gamma_5 \tau^3 \psi(0) \rangle \underset{t \rightarrow \infty}{=} e^{-m_{PS} t} + \text{subleading exponentials}$$

Goldstone bosons

R. Arthur, VD, A. Hietanen, C. Pica, F. Sannino [arXiv:1602.XXXXX]

- M_{PS}/m_f versus m_{PS}^2
- Global fit of 4 lattice spacings
- continuum curve : grey band

⇒ consistent with expected spontaneous symmetry breaking of chiral symmetry

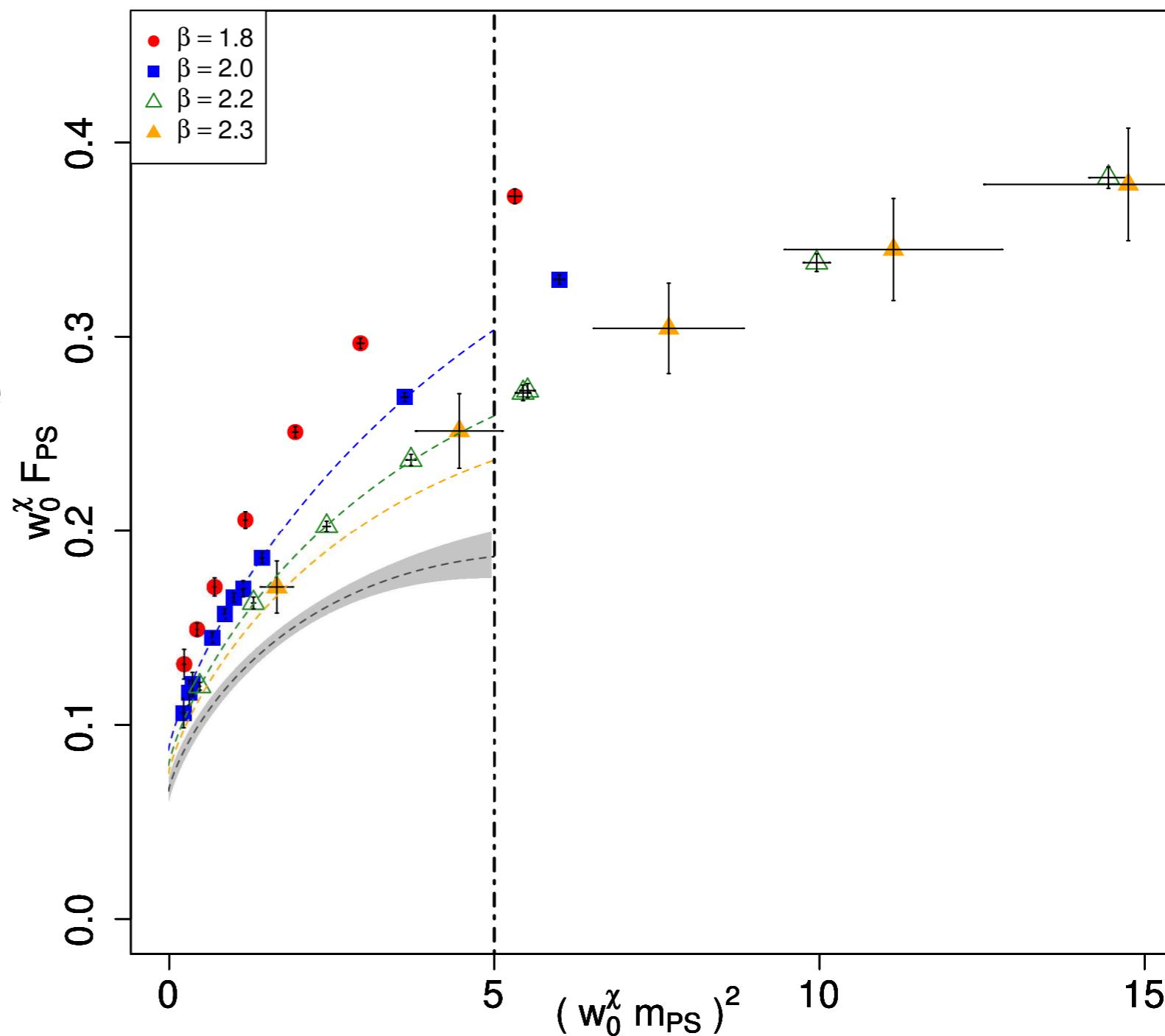


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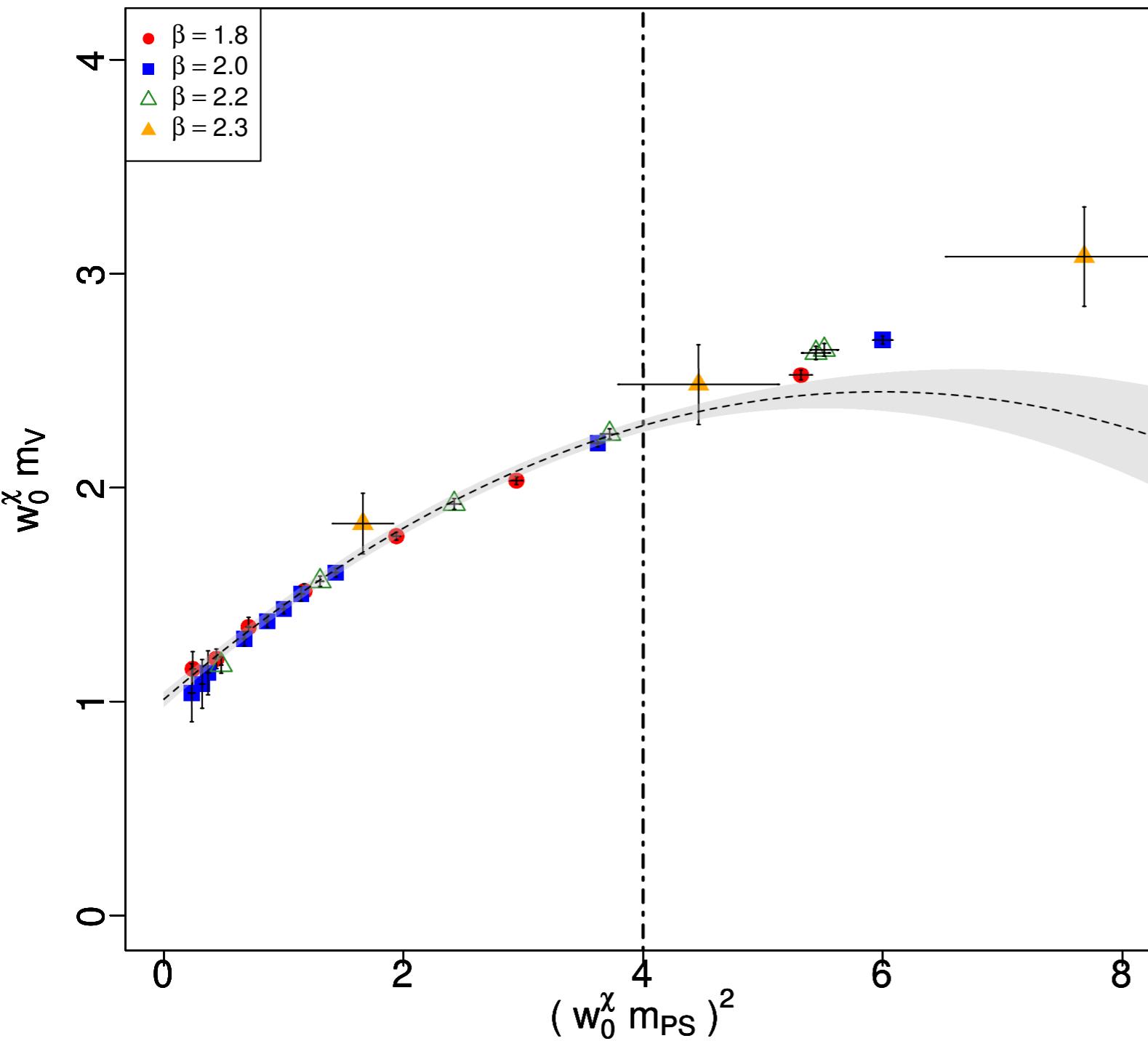
- F_{PS} versus m_{PS}^2
- Global fit of 4 lattice spacings
- continuum curve : grey band

⇒ Set the scale



Vector resonance

R. Arthur, VD, A. Hietanen, C. Pica, F Sannino [arXiv:1602.XXXXX]

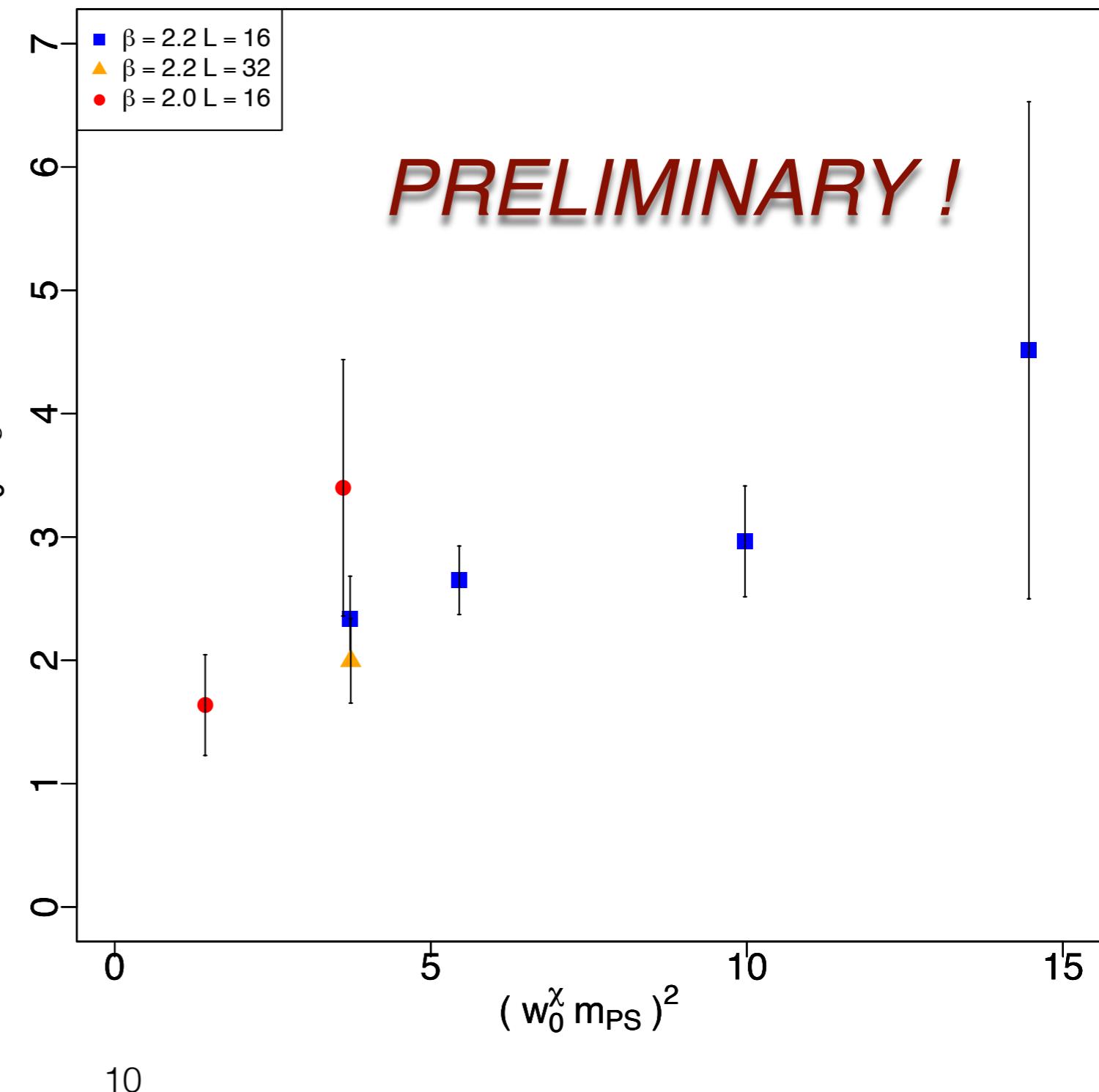


- Vector meson stable in the regime of our simulations ($m_V < 2 m_{PS}$)
- All 4 lattice spacings are consistent.
- $m_V = 12.9(2.2) F_{PS}$
- Fairly heavy : $m_V = 3.2 \text{ TeV}/\sin \Theta$
- Scalar sector ?

σ resonance

R. Arthur, VD, A. Hietanen, C. Pica, F. Sannino [arXiv:16XX.XXXXX]

- Extremely challenging : disconnected contributions
- Stable in our regime
- consistent results but relatively heavy ?



Summary & Conclusions

- Lattice as a laboratory to explore non-perturbative dynamics of gauge theories
- Prediction for $SU(2)_c + N_f = 2$ (Fund. representation)
 - ★ $m_V/F_{PS} \sim 12.9(2.2)$; $m_A/F_{PS} \sim 14.3(3.4)$
- Unified CH model :
 - ★ $m_V = 3.2 \text{ TeV} / \sin \Theta$ & $m_A = 3.5 \text{ TeV} / \sin \Theta$;
 - ★ *Beyond current LHC constraints even for $\Theta = \pi/2$*
 - ★ *Scalar sector would be the signature at LHC Run ?*
 - ★ *More on LHC phenomenology :*

A. Arbey, G. Cacciapaglia, H. Cai, A. Deandrea, S. Le Corre, F. Sannino, 1502.04718

Backup

Scattering length

R. Arthur, VD, A. Hietanen, C. Pica, Sandino [arXiv:16XX.XXXXX]

- Definition :

$$\text{Re } T_{l=0}^{(\pi^+ \pi^+ \rightarrow \pi^+ \pi^+)}(q) = a_0 + \mathcal{O}(q^2)$$

- LO prediction :

$$m_\pi a_{0,\text{LO}}^{\text{MS}} = -\frac{m_\pi^2}{32\pi f_\pi^2}$$

- Lattice can constraints low energy constant appearing at NLO

