Composite Higgs Dynamics on the Lattice

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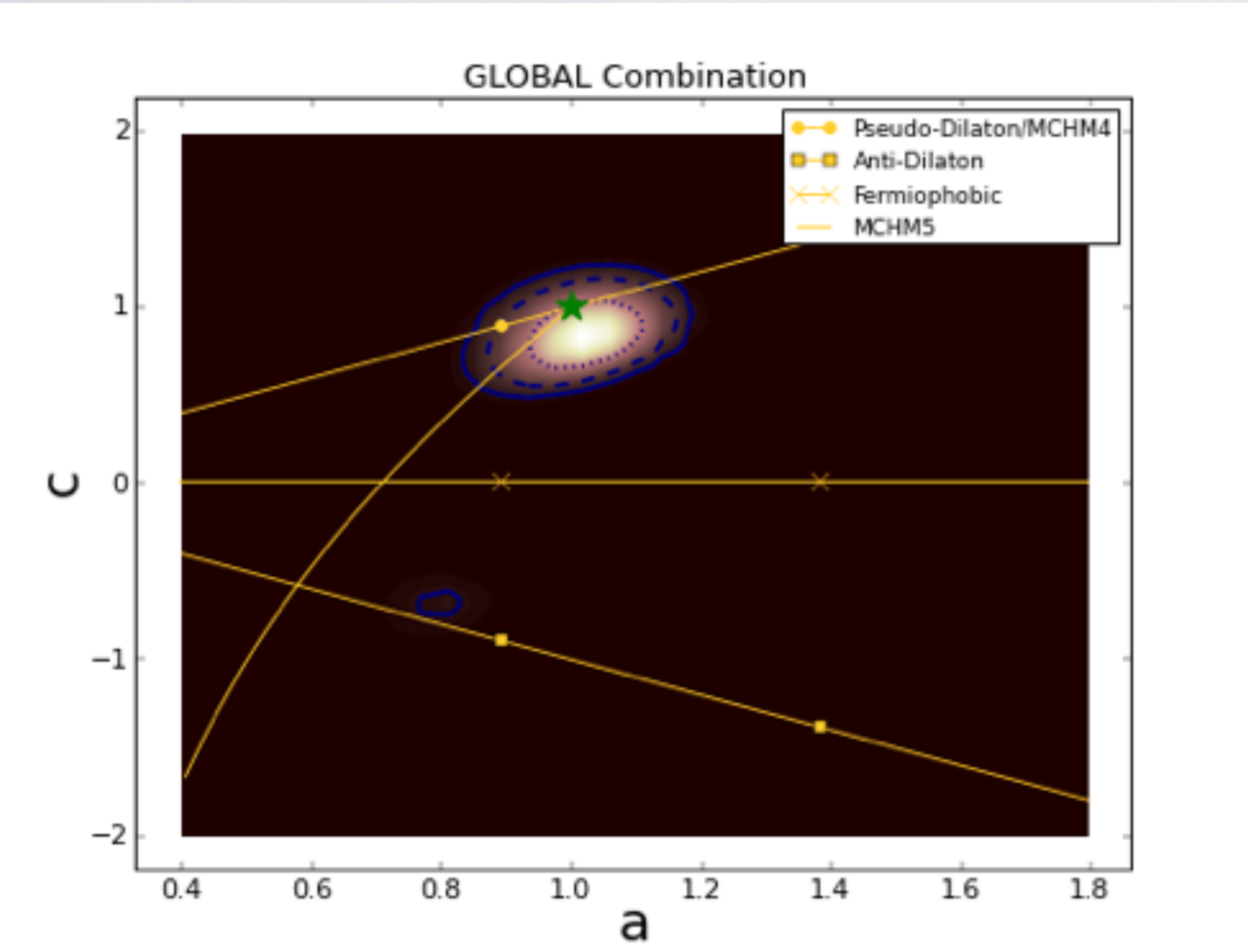
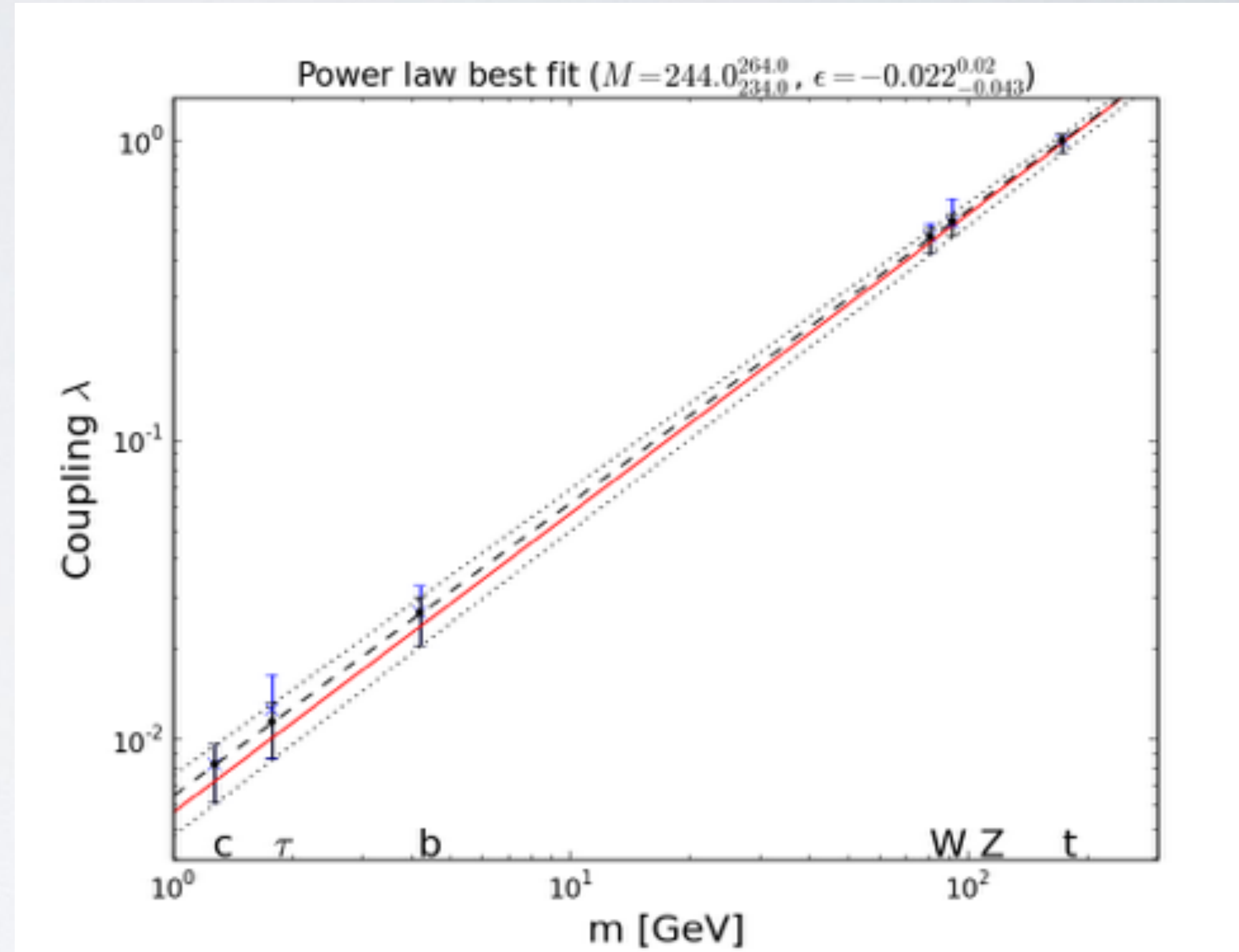
CP3 Origins
Cosmology & Particle Physics

Standard Model Higgs

$$m_H = 125.09 \pm 0.24\,\mathrm{GeV}$$





$$\mathscr{L} = \frac{v^2}{4}\mathrm{Tr} D_\mu \Sigma^\dagger D^\mu \Sigma \left(1 + 2a\frac{H}{v} + \ldots\right) - \bar{\psi}^i_L \Sigma \psi_R \left(1 + c\frac{H}{v} + \ldots\right)$$

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon},\ g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

J. Ellis and T. You, JHEP 1306 (2013) 103

Can the Higgs be composite?

- If EWSB is due to a condensate of strongly-interacting fermions, one would expect, in general, composite scalar particles
- To not be excluded by experiments, this scalar states should mimic a SM-like Higgs boson.
- This could happen if the composite scalar is a light pseudo-Goldstone boson of some (higher scale) broken symmetry, e.g:
  - approximate scale invariance symmetry (dilaton)
  - larger chiral symmetry (composite Goldstone boson Higgs)

Technicolor

S. Weinberg & L. Susskind, '79

Higgs is the lightest scalar excitation of the condensate

Plus

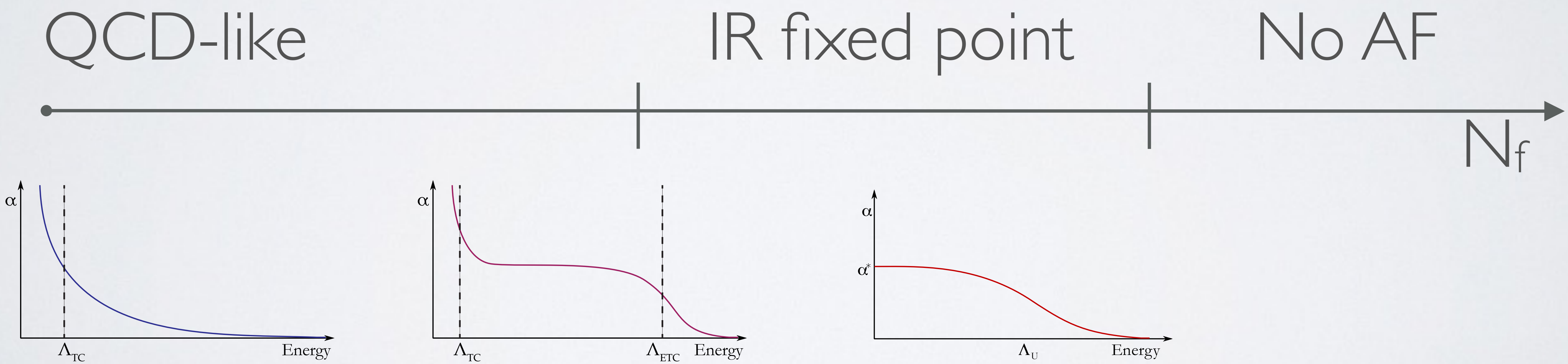
- Break EW
- UV complete theories available to explore
- Natural

Minus

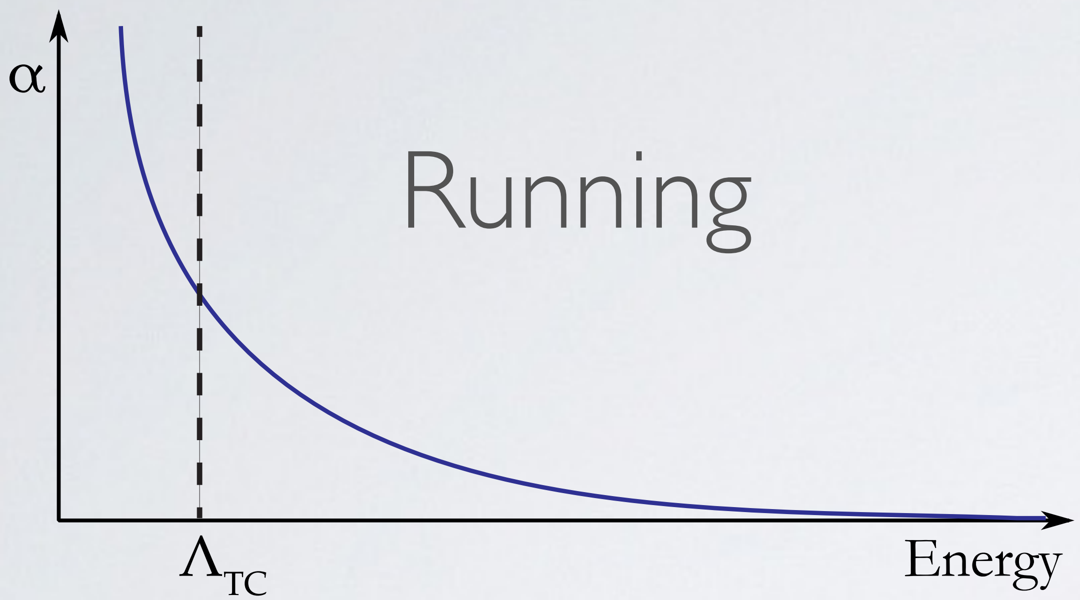
- Fermion masses vs FCNC
- Electroweak precision data
- Light Higgs
- Higgs couplings

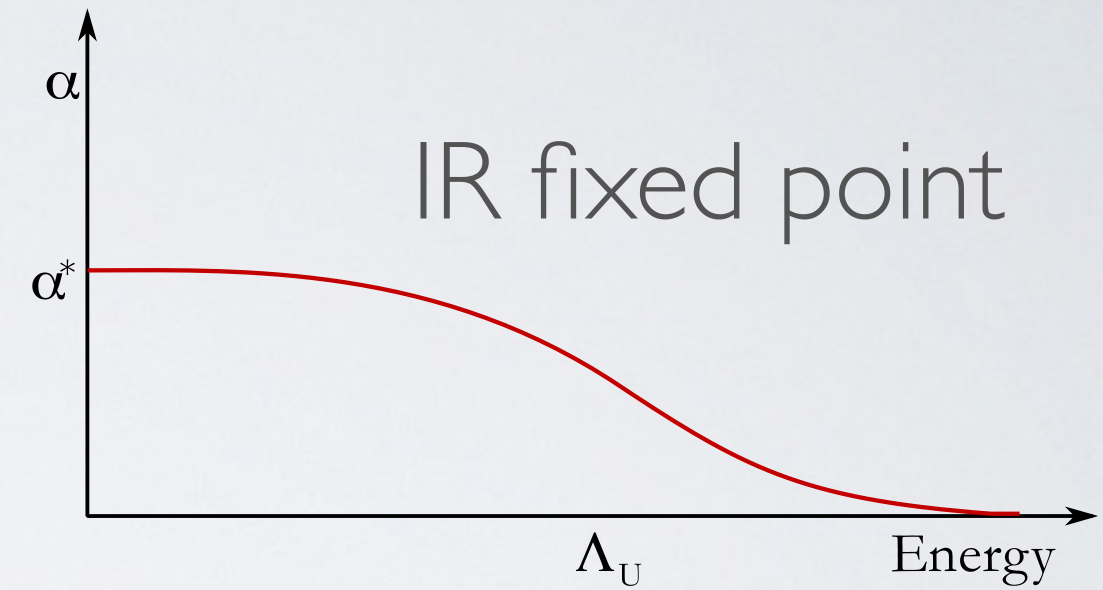
Parameters

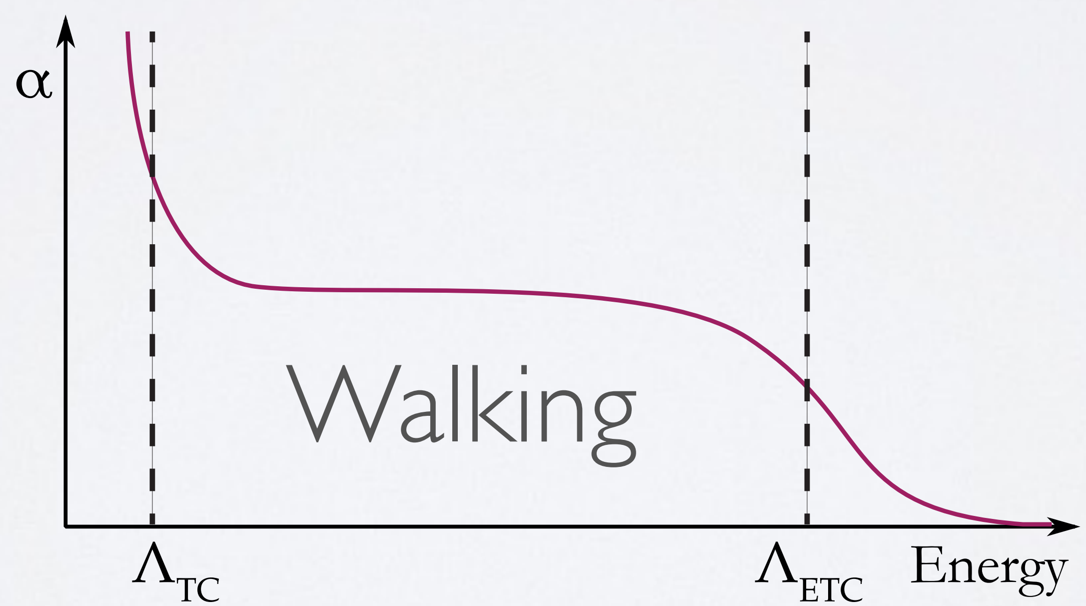
- Gauge Group: SU, SO, SP, Exceptional
- Matter Representation
- # of Flavors per Representation



Walking

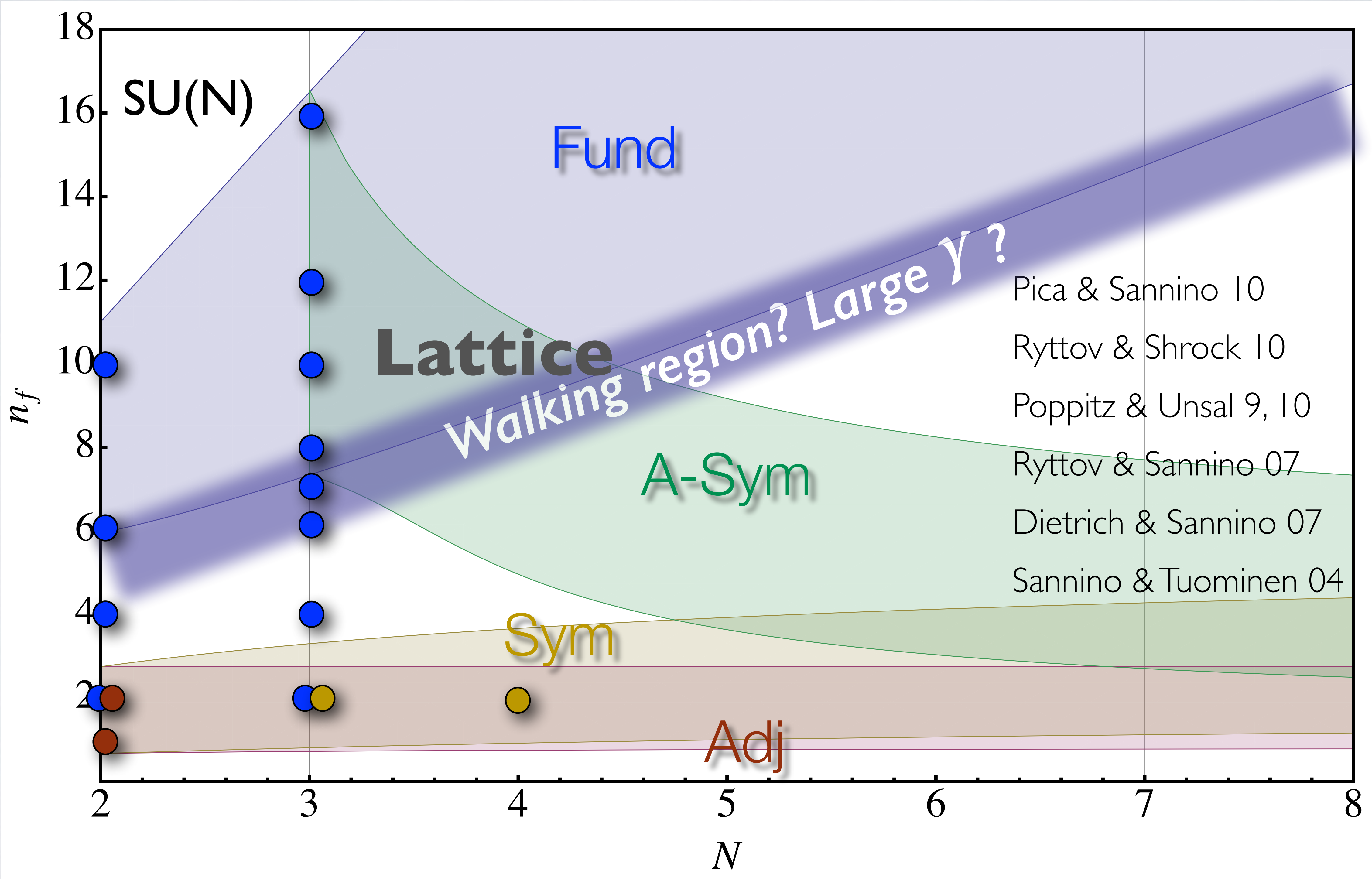






Holdom, Appelquist, Miranski, Yamawaki, Wijewardhana

SU(N) phase diagram



Other groups: SO(n), SP(n), exceptional

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Minimal (Walking) Models

- Use the Lattice to investigate quantitatively models which can feature the right dynamics:
- SU(2) + 2 Dirac Adjoint **$SU(2)_a$ - MWT**
- SU(3) + 2 Dirac Symmetric **$SU(3)_s$ - MWT**
- SO(4) + 2 Dirac Vector **$SO(4)_v$ - MWT**
- SU(3) + 2 Dirac Fund. + Ungauged **$SU(3)_f$ - pMWT**
- SU(2) +2 Dirac Fund. + … (U - MWT) **$SU(2)_f$ - MWT**

Only one doublet gauged → small S parameter

TC Higgs

- TC Higgs is the lightest isospin-0 scalar made of TC-fermions

$$H \sim c_1 \bar{Q}Q + c_2 \bar{Q}Q\bar{Q}Q + \cdots$$

- will contain also a TC-glue component

- analogue to QCD lightest scalar:
  $f_0(500)$ with mass ~ 400-550 MeV

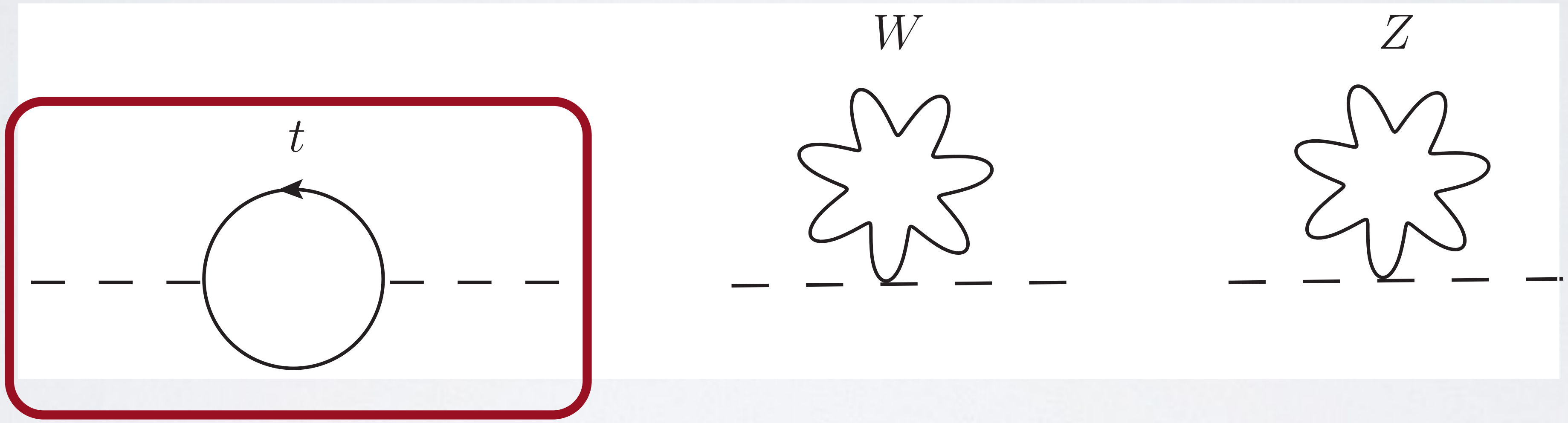
Sannino & Schechter 95 PRD; Harada, Sannino & Schechter 95 PRD, 96PRL;
see also: Pelaez - Confinement X

TC Higgs mass

R. Foadi, M. Frandsen, F. Sannino, Phys.Rev. D 87, 095001

- Can it be light?

- SM radiative corrections shift the TC Higss mass

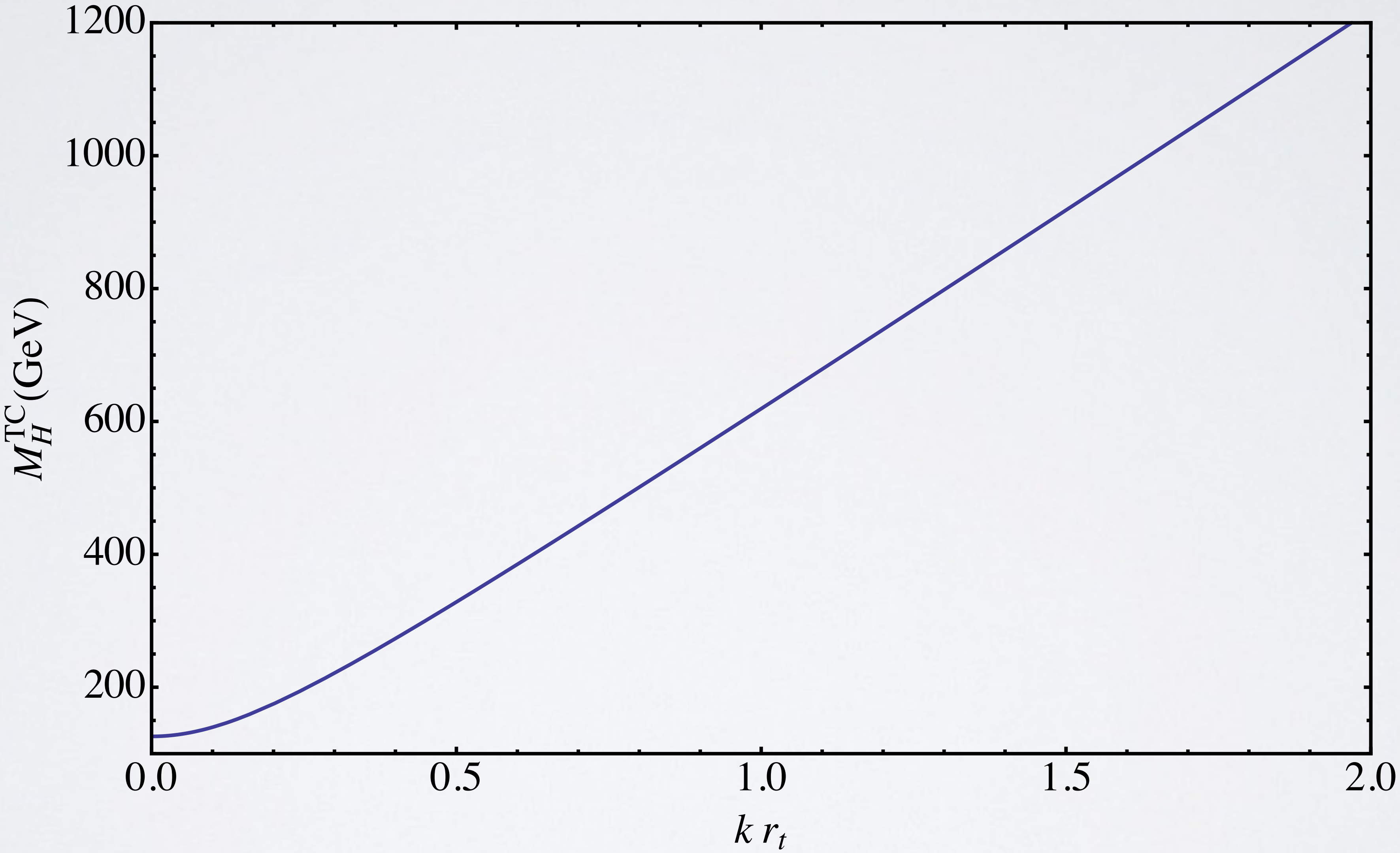


$$M_H^2 = (M_H^{\rm TC})^2 + \frac{3(4\pi\kappa F_\Pi)^2}{16\pi^2 v^2}\left[-4r_t^2 m_t^2 + 2s_\pi\left(m_W^2 + \frac{m_Z^2}{2}\right)\right] + \Delta_{M_H^2}(4\pi\kappa F_\Pi)$$

TC Higgs mass

R. Foadi, M. Frandsen, F. Sannino, Phys.Rev. D 87, 095001

- Can it be light? $(M_H^{\rm TC})^2 \simeq M_H^2 + 12\ \kappa^2 r_t^2 m_t^2$



- Narrow due to kinematics [Similar to $f_0(980)$ in QCD]

TC Higgs couplings?

A. Belyaev, M.S. Brown, R. Foadi, M. Frandsen, PhysRevD.90.035012

- The leading order interaction of the TC Higgs with EW goldstone bosons can be described by:

$$\mathscr{L}_{H\Pi\Pi} = \frac{c_\Pi}{v} H \partial_\mu \Pi^a \partial^\mu \Pi^a \quad \text{with} \quad c_\Pi = 1$$

- One can estimate the analogue coupling in QCD

$$\mathscr{L}_{\sigma\pi\pi} = \frac{c_\pi}{f_\pi} \sigma \partial_\mu \pi^a \partial^\mu \pi^a$$

from elastic pi-pi scattering data

m_σ (MeV)	$\lvert g_{\sigma\pi\pi}\rvert$ (GeV)	$\lvert c_\pi^{QCD}\rvert$
$457^{+14}_{-13} - i(279^{+11}_{-7})$, [35]	$3.59^{+0.11}_{-0.13}$	1.0169 ± 0.06
$445 \pm 25 - i(278^{+22}_{-18})$, [35]	3.4 ± 0.5	1.0013 ± 0.17
$441^{+16}_{-8} - i(272^{+9}_{-12.5})$ [36]	$3.31^{+0.35}_{-0.15}$	1.0035 ± 0.12
$474 \pm 6 - i(254 \pm 4)$, [37]	3.58 ± 0.03	1.0264 ± 0.024
$443 \pm 2 - i(216 \pm 4)$ [38]	2.97 ± 0.04	1.0479 ± 0.020
$452 \pm 12 - i(260 \pm 15)$ [39]	2.65 ± 0.01	0.8026 ± 0.053
$453 - i271$, [40]	3.5	1.0255

Composite Goldstone Higgs

D.B. Kaplan & H. Georgi, '84

Higgs is a pseudo Goldstone boson

Plus

- Higgs is massless
- Gauge boson couplings

Minus

- Underlying UV complete theory
- Higgs mass
- Fermion masses/couplings
- EW vacuum alignment

SU(2) Composite Higgs

G. Cacciapaglia & F. Sannino, JHEP04(2014)111

- $SU(2)_{TC}$ with N_f=2 fund
- SO(6)/SO(5) chiral symmetry breaking

Appelquist, Sannino, 98, 99
Ryttov, Sannino, 2008
Katz, Nelson Walker, 2005
Gripaios, Pomarol, Riva, Serra, 2009
Galloway, Evans, Luty, Tacchi, 2010

- Common framework for TC and CH
- Fundamental 4D underlying theory,
  Spectrum can be obtained via lattice simulations

The SU(2) model

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \overline{U}(i\gamma^\mu D_\mu - m)U + \overline{D}(i\gamma^\mu D_\mu - m)D$$

$$Q = \begin{pmatrix} U_L \\ D_L \\ \widetilde{U}_L \\ \widetilde{D}_L \end{pmatrix} \qquad E = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

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

The model

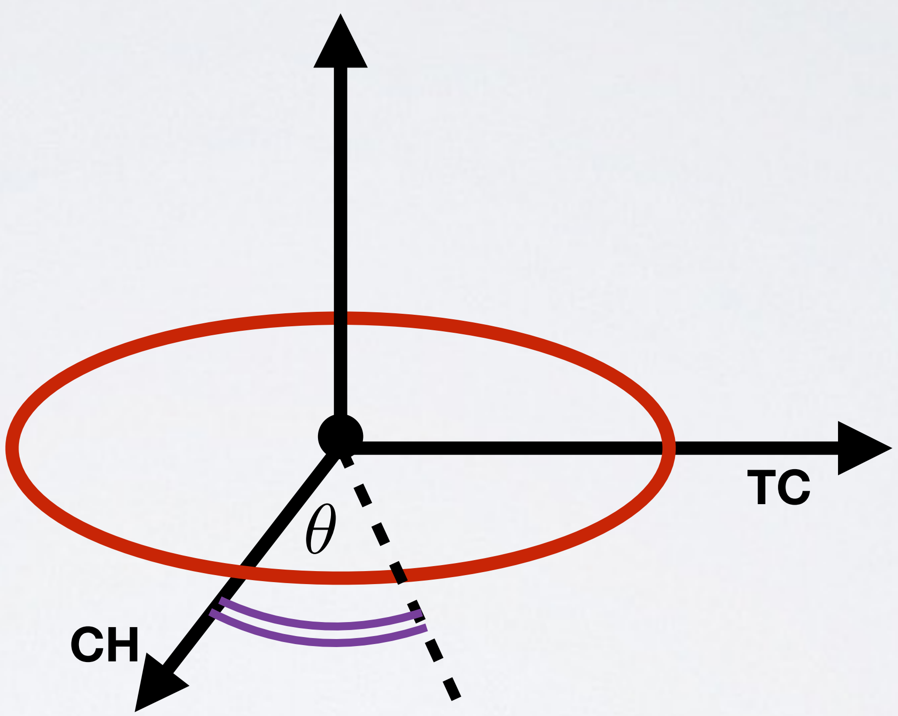
- $Q_L = (U_L, D_L)$: $SU(2)_L$ doublet with zero hypercharge
- other two fields: $SU(2)_L$ singlets with hypercharge $\pm 1/2$
- two interesting alignments of the condensate:

1. $\langle QQ \rangle \propto \begin{pmatrix} i\sigma_2 & 0 \\ 0 & -i\sigma_2 \end{pmatrix} \equiv \Sigma_B$ does not break EW
2. $\langle QQ \rangle \propto = -i\,E = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \equiv \Sigma_H$ does break EW symmetry

- general superposition: $\Sigma_0 = \cos\theta\,\Sigma_B + \sin\theta\,\Sigma_H$

SO(6)~SU(4) → Sp(4)~SO(5)

- Fundamental 4d underlying dynamics
- 5 Goldstone bosons
- 3 eaten by $W^{\pm}$,Z

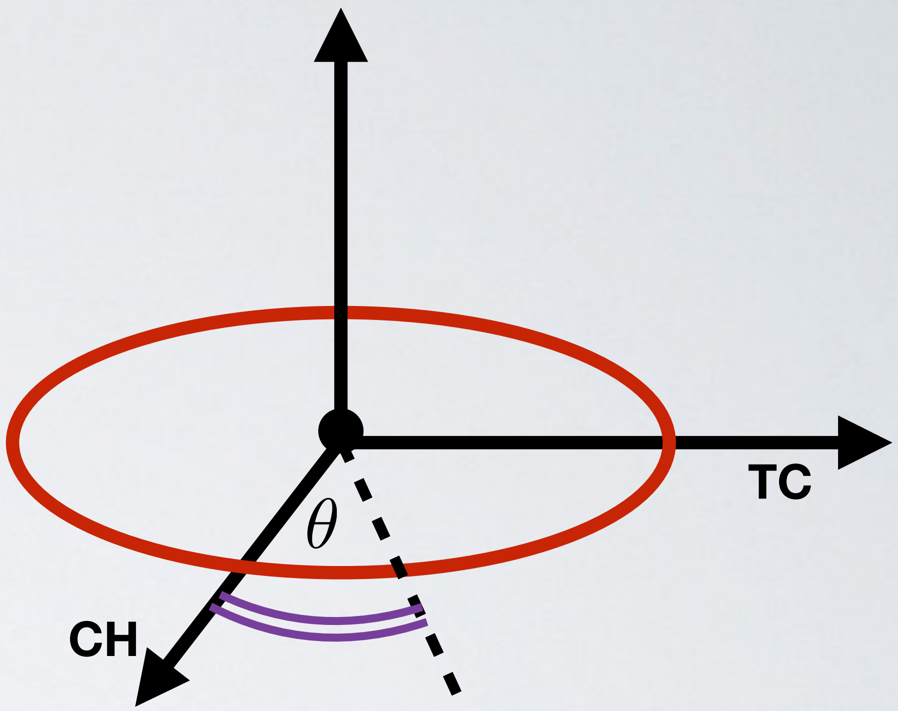


θ~0
- I GB is Higgs-like
- other GB is SM neutral

θ~π/2
- GB complex doublet
- SM neutral
- Natural DM candidate

Generic properties

- TC-Higgs and PGB Higgs mix
- Top reduces TC-Higgs mass
- Top contributes to PGB Higgs mass



Couplings: for θ near zero:

$$\frac{g_{WWh_1}}{g^{SM}_{WWh}} = 1 + C\theta + \mathcal{O}(\theta^2)$$

$$\frac{g_{tth_1}}{g^{SM}_{tth}} = 1 + D\theta + \mathcal{O}(\theta^2)$$

- Modified Higgs phenomenology
- a new TeV scalar lighter than vectors?

Spin one resonances

- Rescale TC limit: $f_{\mathrm{PS}} \sin\theta = 246\mathrm{GeV}$

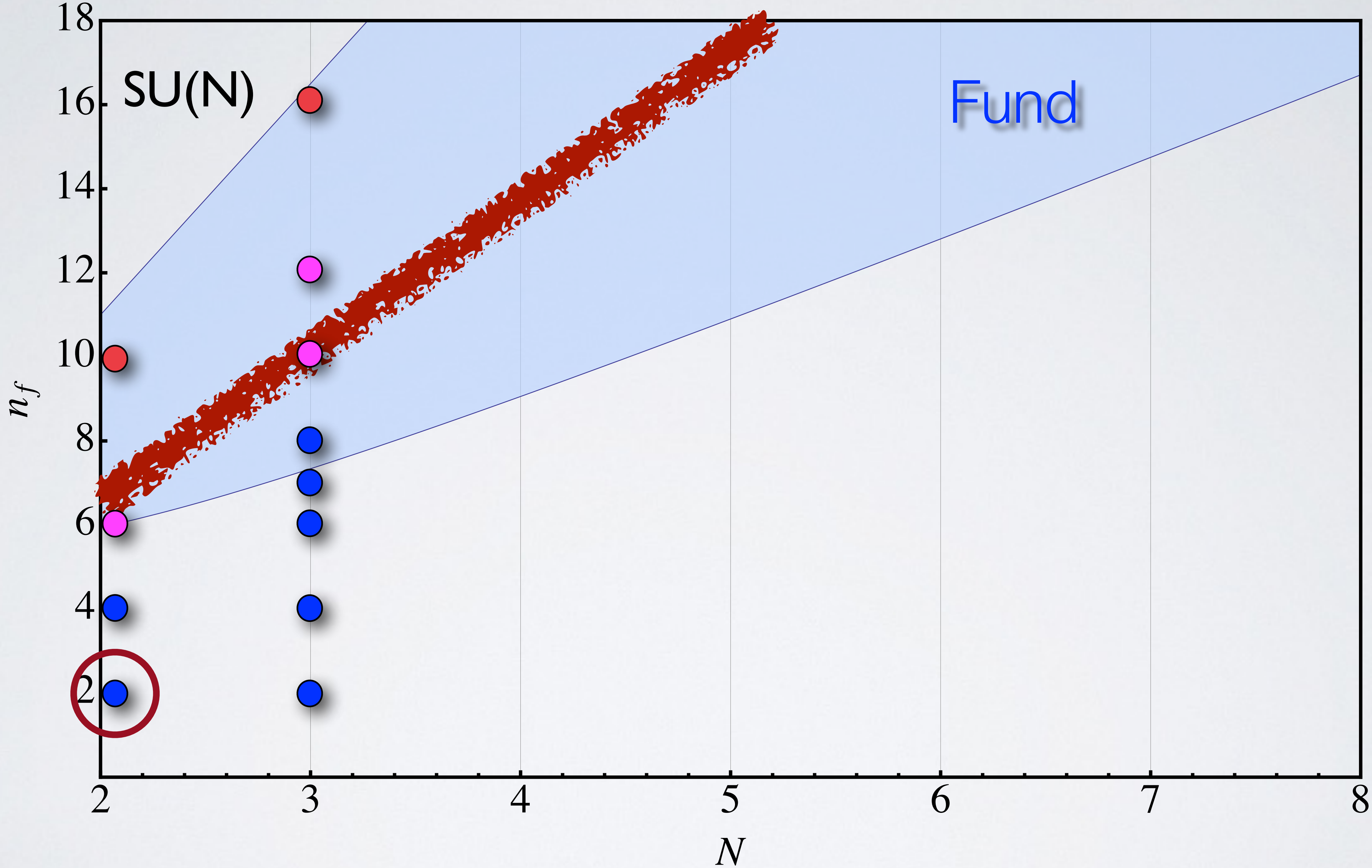
$$m_\rho = \frac{m_\rho^{TC}}{\sin\theta} \qquad m_A = \frac{m_A^{TC}}{\sin\theta}$$

Lattice results

SU(2)$_f$ N_f=2

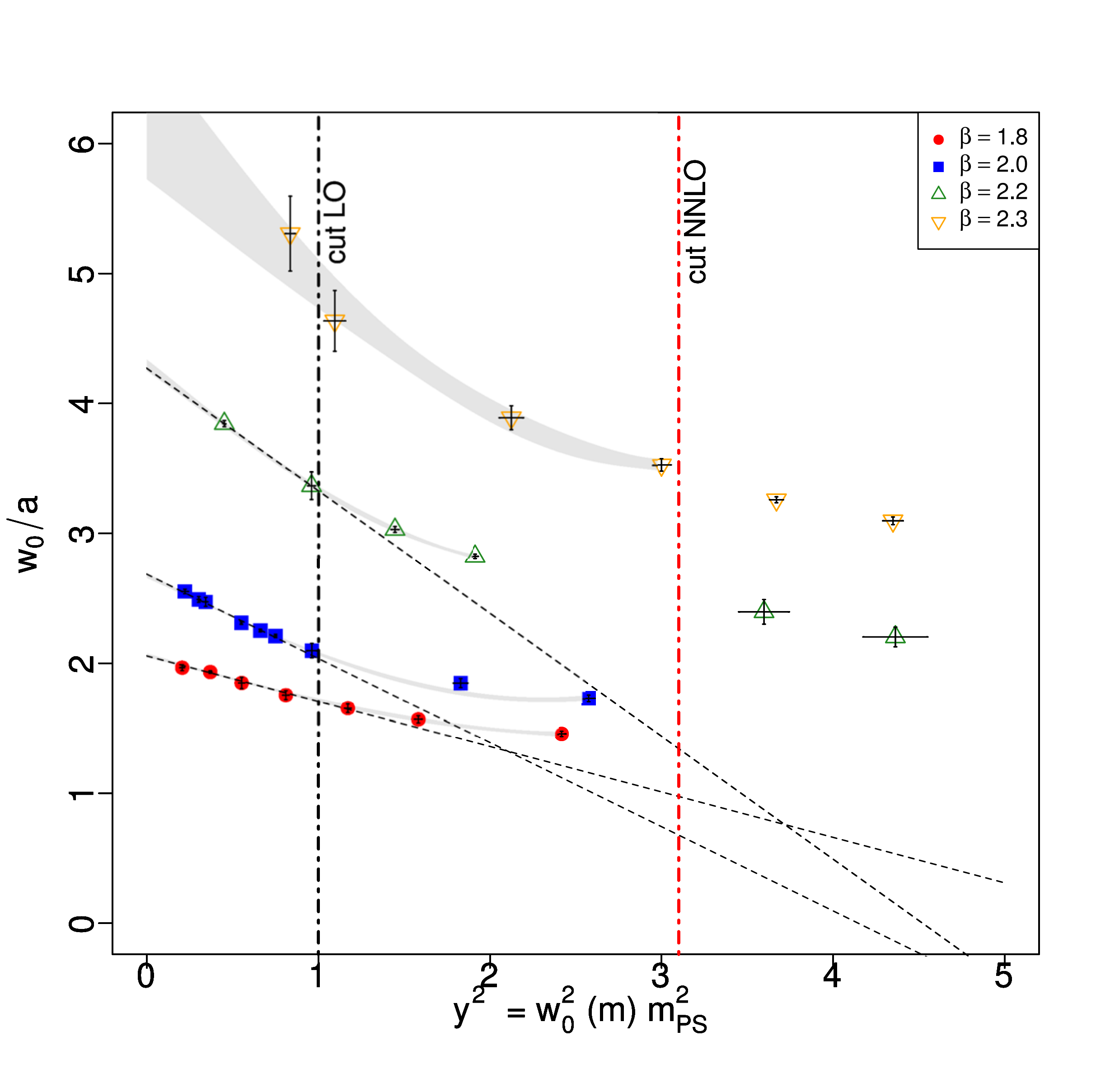
Ref:
R. Lewis, C. Pica, F. Sannino, Phys.Rev. D85 (2012) 014504 [arXiv:1109.3513]
A. Hietanen, R. Lewis, C. Pica, F. Sannino, [arXiv:1308.4130 [hep-ph]]
A. Hietanen, R. Lewis, C. Pica, F. Sannino, JHEP 1407 (2014) 116 [arXiv:1404.2794 [hep-lat]]
R. Arthur, A. Hietanen, V. Drach, M. Hansen, C.P., F. Sannino, arXiv:1602.06559
R. Arthur, A. Hietanen, V. Drach, M. Hansen, C.P., F. Sannino, *in preparation*

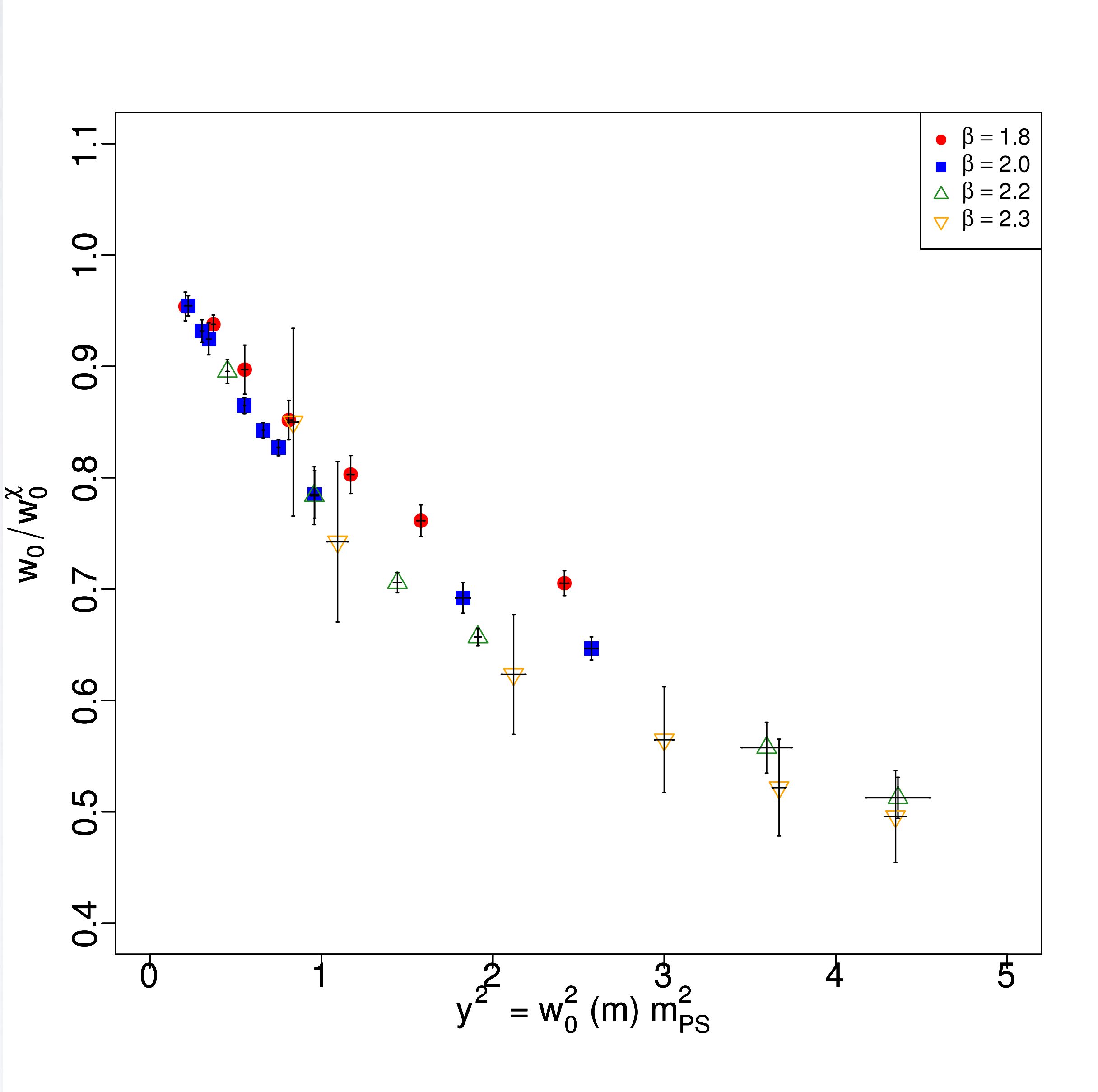
Lattice conformal window



Scale Setting

$$W(t) = t\frac{d}{dt}[t^2 E(t)]\,,\; W(w_0^2) \equiv 1$$





$$w_0(m_{ps}^2) = w_0^\chi\left(1 + Ay^2 + By^4\log y^2\right)$$

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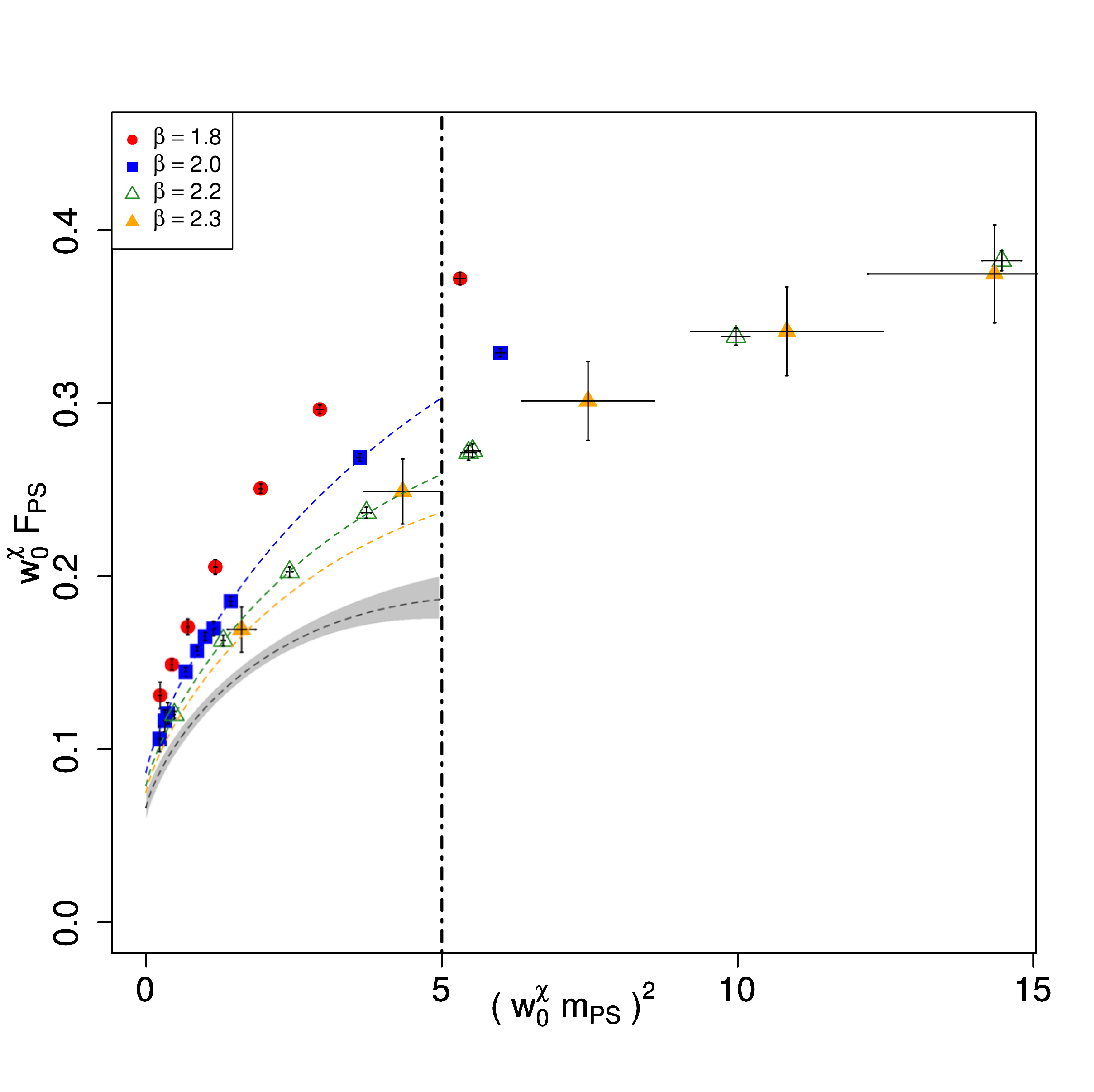
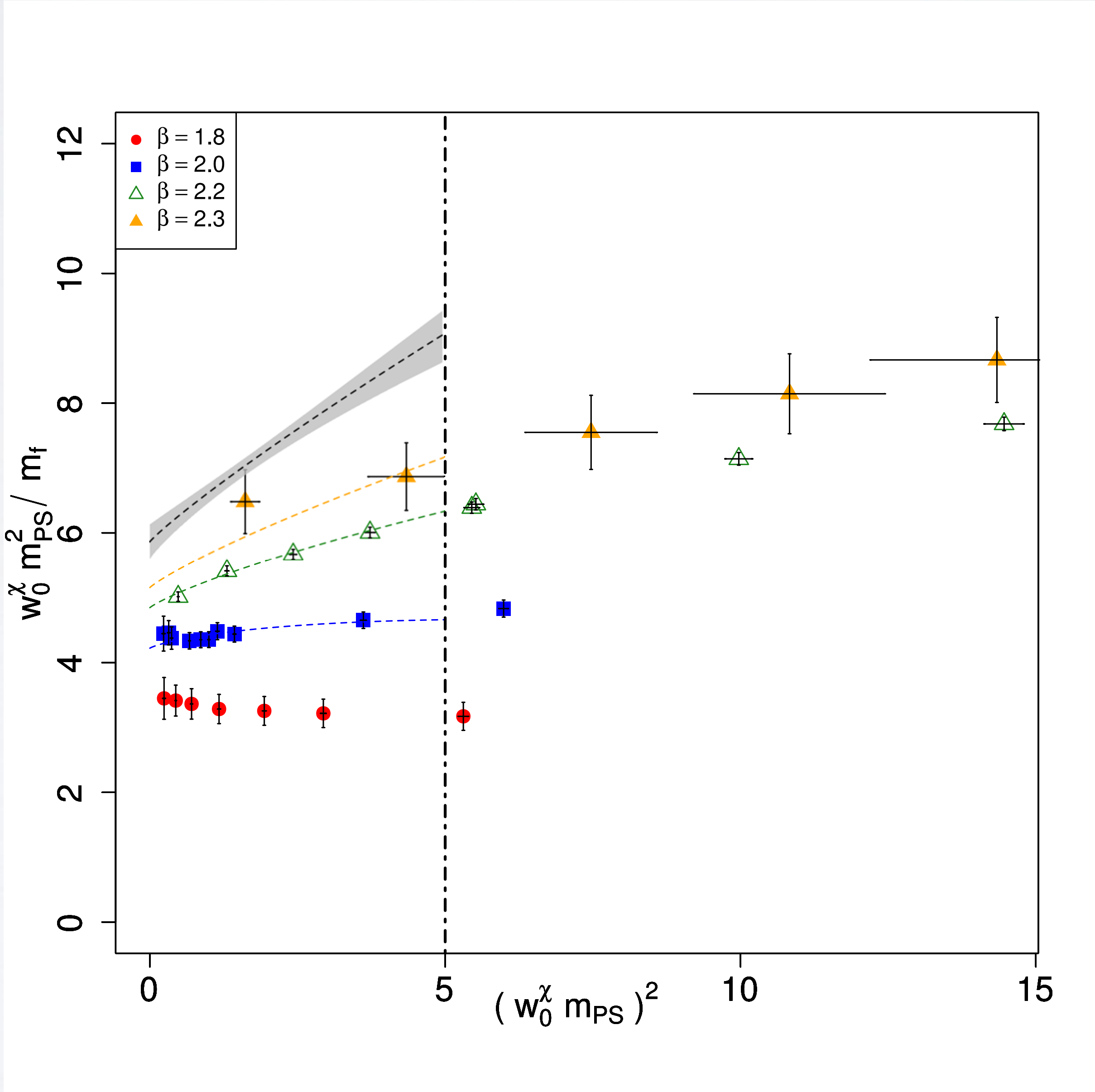
Goldstone bosons

$$f_{PS} = F\left[1 - a_F \tilde{x} \log\frac{m_{PS}^2}{\mu^2} + b_F \tilde{x} + \delta_F \frac{a}{w_0^\chi} + \gamma_F m_{PS}^2 \frac{a}{w_0^\chi}\right] \qquad \frac{m_{PS}^2}{m_f} = 2B\left[1 - a_M \tilde{x} \log\frac{m_{ps}^2}{\mu^2} + b_M \tilde{x} + \delta_M \frac{a}{w_0^\chi} + \gamma_M m_{ps}^2 \frac{a}{w_0^\chi}\right]$$

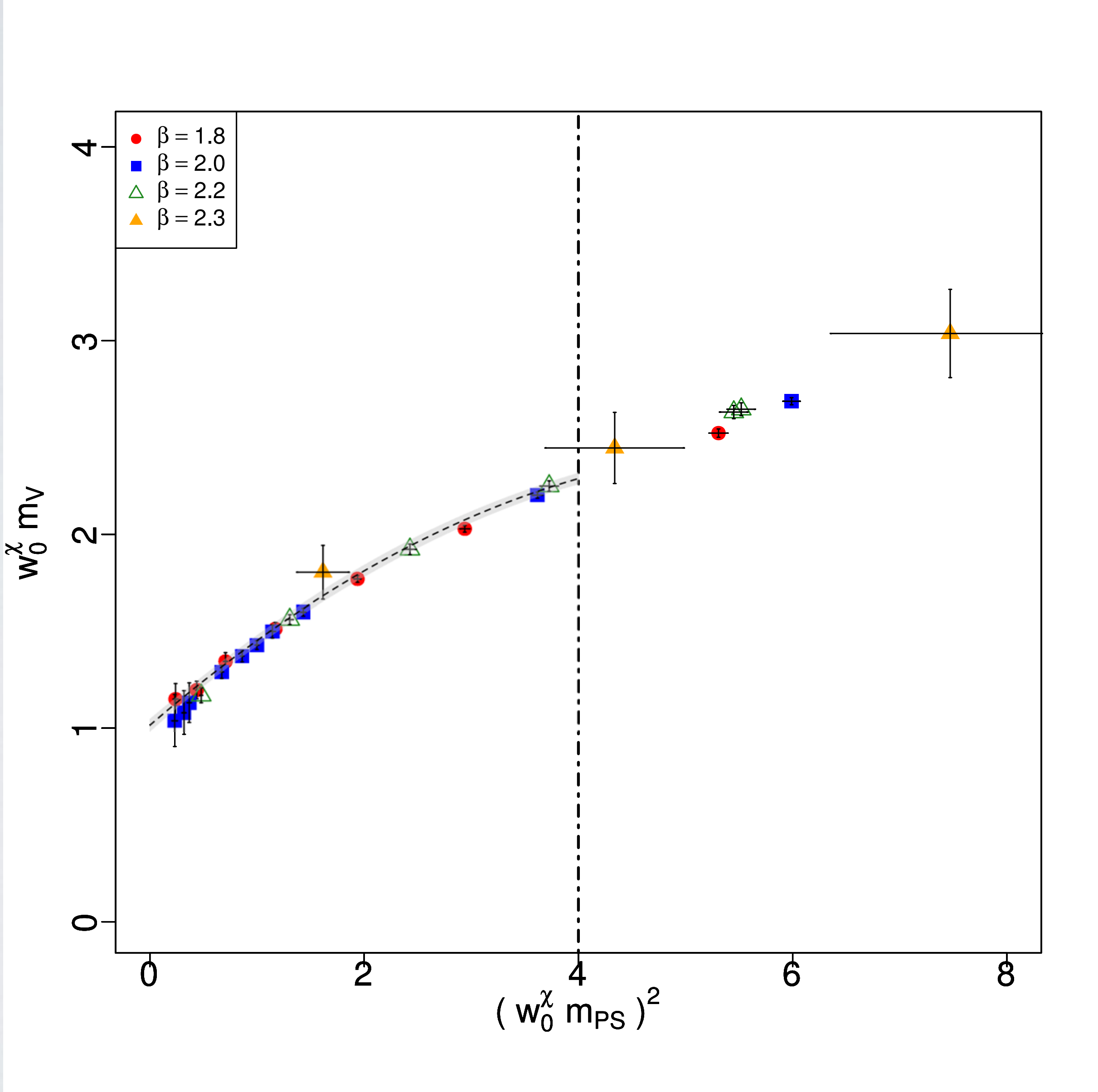


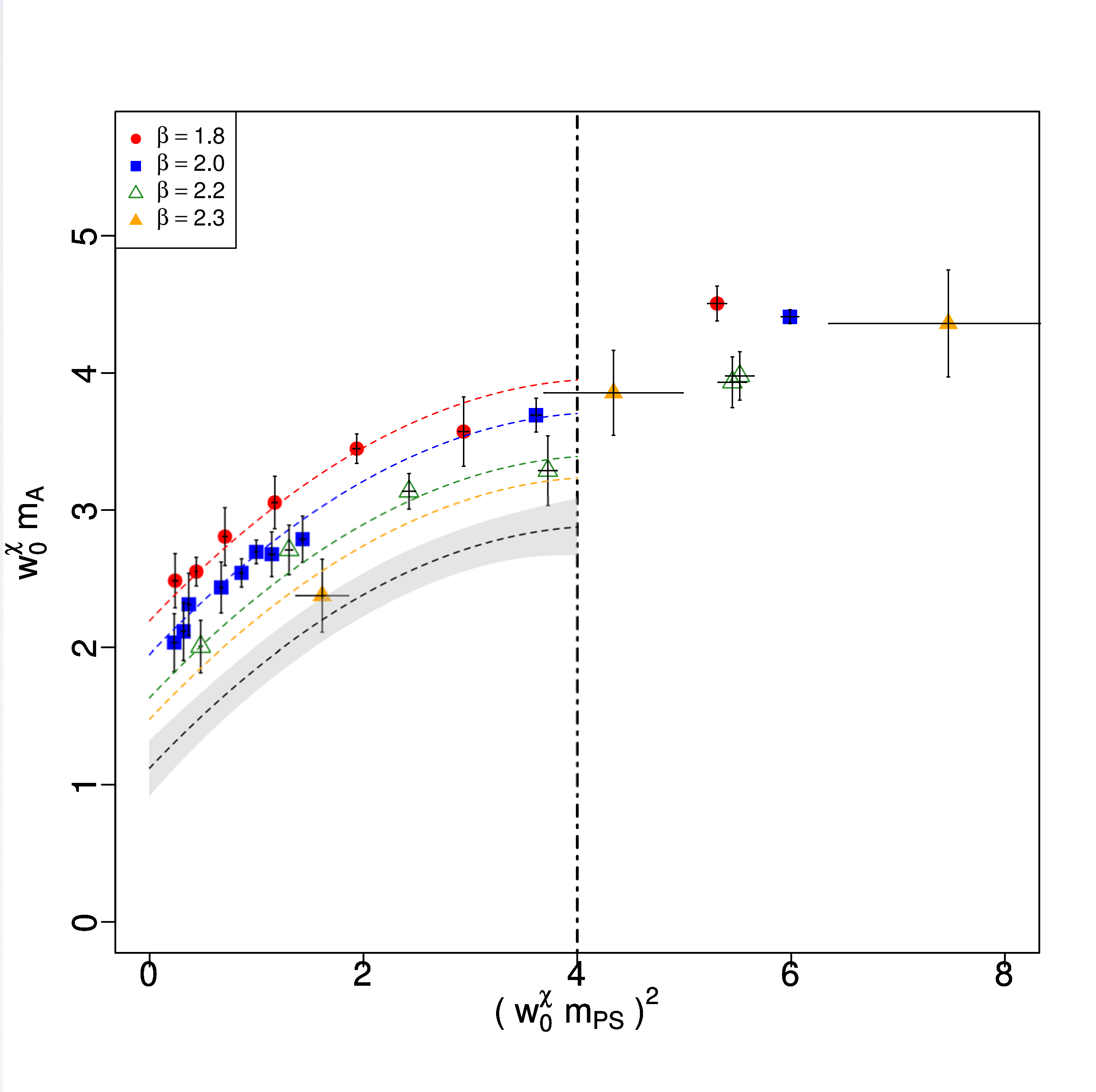


$$w_0^\chi F = 0.078(4)(12) \quad w_0^\chi B = 2.88(15)(17) \quad \Sigma^{1/3}/F = 4.19(26)$$

Spin-1 Resonances

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





$$m_V / f_{PS} = 13.1(2.2)$$

$$m_A / f_{PS} = 14.5(3.6)$$

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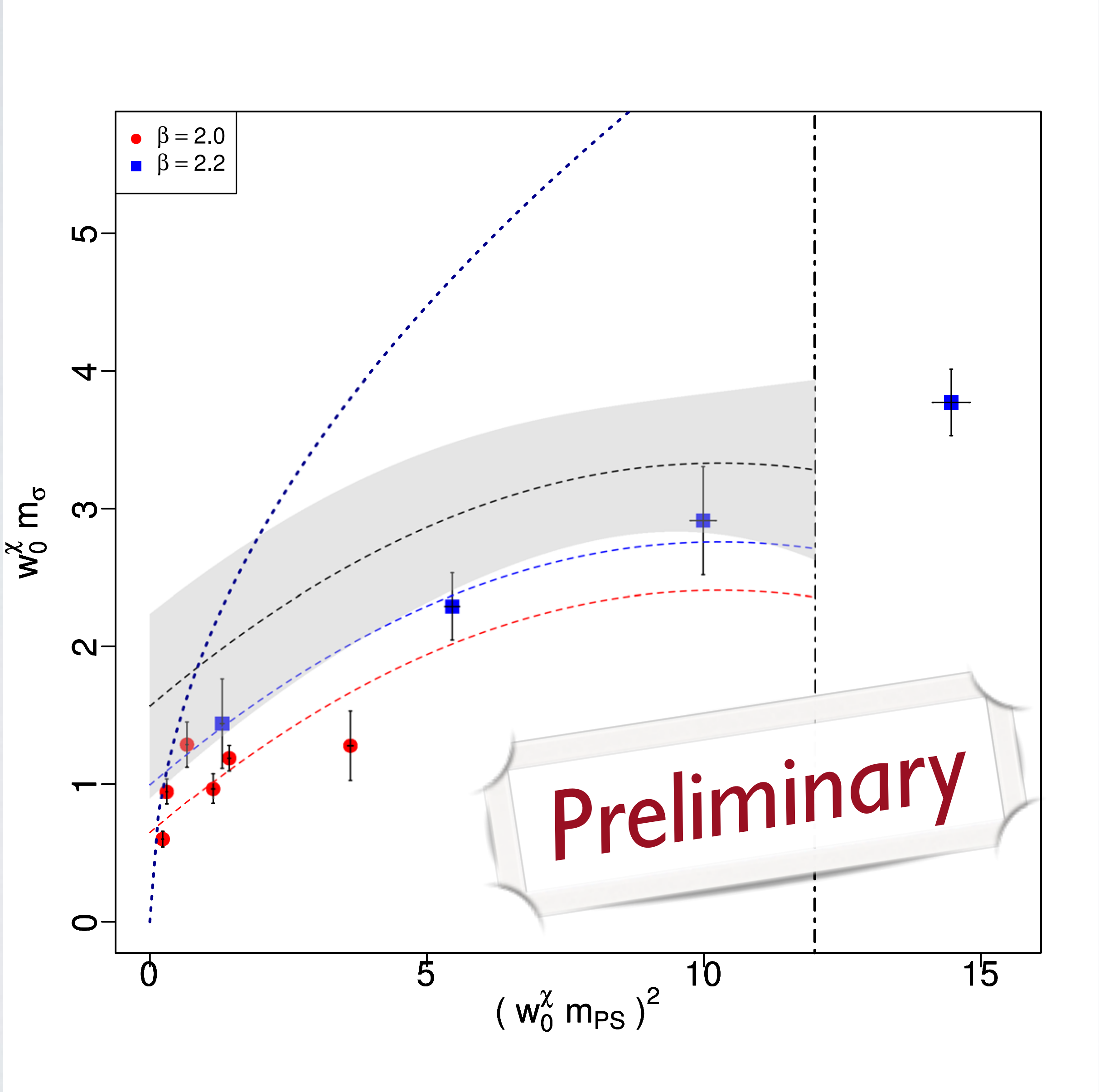
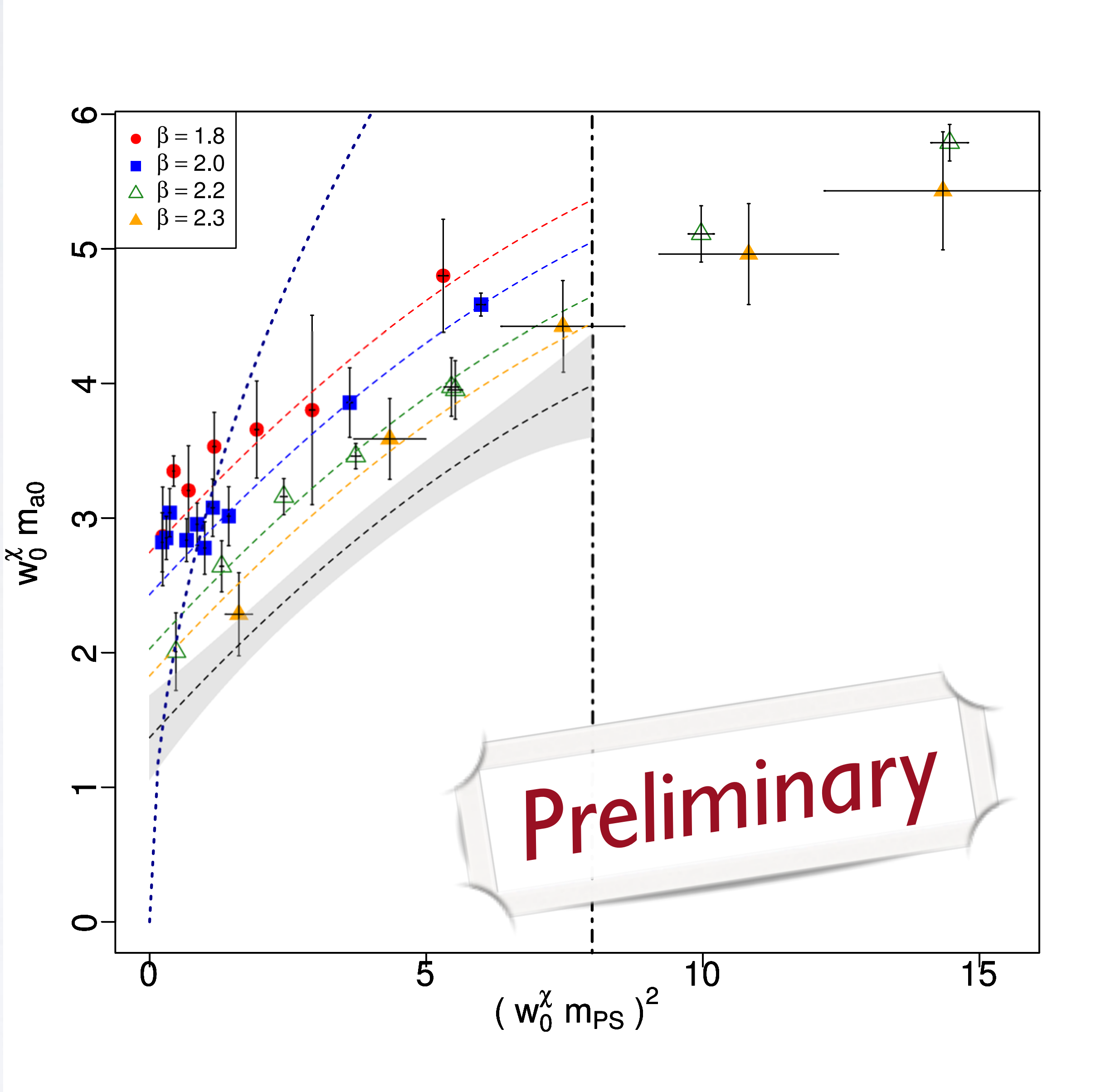
Spin-0 Resonances

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





$m_\sigma / f_{\rm PS} = 19.2(10.8)$

$m_{a_0} / f_{\rm PS} = 16.7(4.9)$

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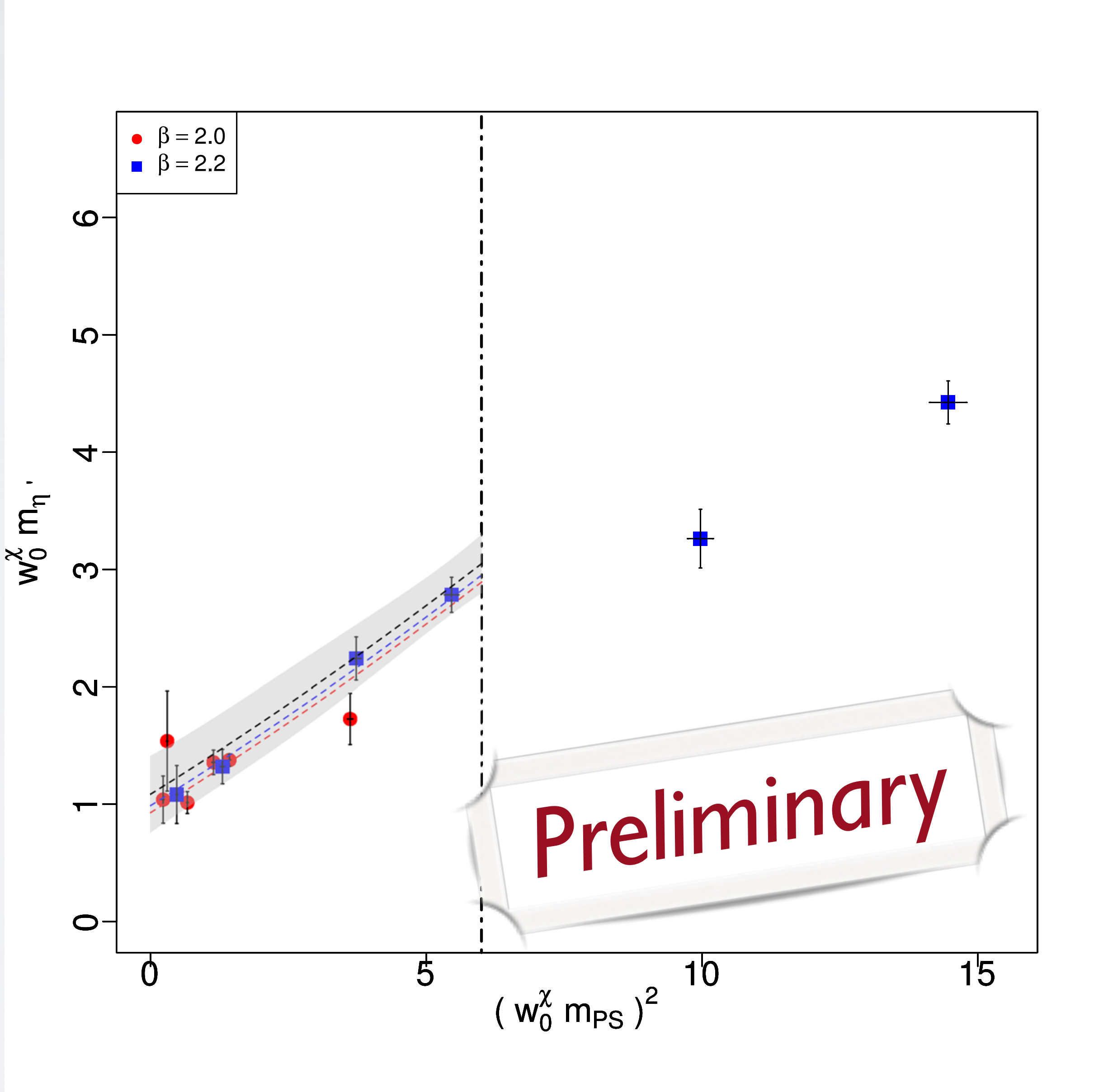
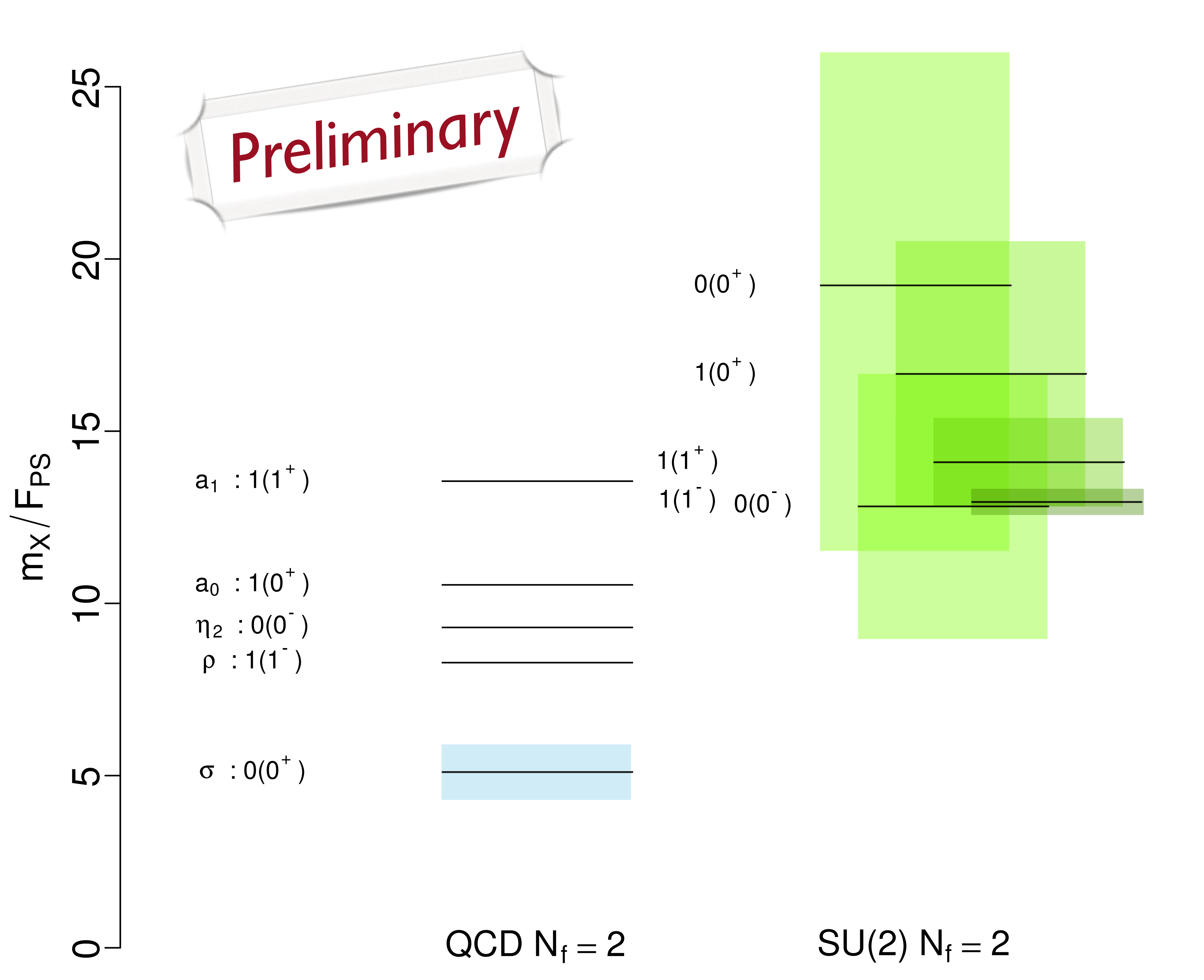
Spin-0 Resonances

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



$$m_{\eta'} / f_{\rm PS} = 12.8(4.7)$$

Resonances - Summary



Conclusions

- Lattice simulations yield first principle results for the NP dynamics and can provide trustable quantitative results on the spectrum are possible and available
- Several interesting models are being investigated, which include examples of strongly coupled models with light scalars
- The study of scalar sector of strongly coupled model is challenging, but seems within reach
- SU(2) model viable might be viable as composite goldstone Higgs model, but spin 1 and 0 resonances in the 30-50 TeV region for $\sin\theta \simeq 0.1$

Thank you!