SCGT14Mini

Higgs impostor, or just a light scalar on the lattice?

Julius Kuti

University of California, San Diego

SCGT14Mini KMI workshop, Nagoya, March 5, 2014

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Higgs impostor, or just a light scalar on the lattice?

Lattice Higgs Collaboration (L$_{at}$HC)

Zoltan Fodor, Kieran Holland, Santanu Mondal,
Daniel Nogradi, (Chris Schroeder), Chik Him Wong

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SCGT14Mini KMI workshop, Nagoya, March 5, 2014

This talk is dedicated to Keisuke Jimmy Juge to win his courageous fight at the Tsukuba University hospital

We also wish full and quick recovery to Yoichi Iwasaki from his serious injury

Keisuke Jimmy Juge

Lattice gauge theorist whom many of you know

On sabbatical at KEK from the University of the Pacific in California

Expert on hadron spectroscopy including the 0++ scalar spectrum from disconnected diagrams, so relevant to this workshop

Talk is based on 4 publications, with an overview and discussion of new developments since:

Can the nearly conformal sextet gauge model hide the Higgs impostor?
Zoltan Fodor (Wuppertal U. & IAS, Julich & Eotvos U.), Kieran Holland (U. Pacific, Stockton), Julius Kuti (UC, San Diego), Daniel Nogradi (Eotvos U.), Chris Schroeder (LLNL, Livermore), Chik Him Wong (UC, San Diego). Sep 2012. 10 pp.
Published in **Phys.Lett. B718 (2012) 657-666**
DOI: 10.1016/j.physletb.2012.10.079
e-Print: **arXiv:1209.0391 [hep-lat] | PDF**

The Yang-Mills gradient flow in finite volume
Zoltan Fodor (Wuppertal U. & IAS, Julich & Eotvos U.), Kieran Holland (U. Pacific, Stockton & Bern U.), Julius Kuti (UC, San Diego), Daniel Nogradi (Eotvos U.), Chik Him Wong (UC, San Diego). Aug 2012. 17 pp.
Published in **JHEP 1211 (2012) 007**
DOI: 10.1007/JHEP11(2012)007
e-Print: **arXiv:1208.1051 [hep-lat] | PDF**

Can a light Higgs impostor hide in composite gauge models?
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong. Jan 9, 2014. 7 pp.
Conference: C13-07-29.1 Proceedings
e-Print: **arXiv:1401.2176 [hep-lat] | PDF**

The chiral condensate from the Dirac spectrum in BSM gauge theories
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong. Feb 24, 2014. 7 pp.
Conference: C13-07-29.1 Proceedings
e-Print: **arXiv:1402.6029 [hep-lat] | PDF**

Outline

Lattice BSM after the Higgs discovery

Near-conformal light Higgs?

- light scalar (dilaton-like?) close to conformal window
- EW precision and S-parameter
- scale setting and spectroscopy

Running coupling

- running (walking?) coupling from gradient flow

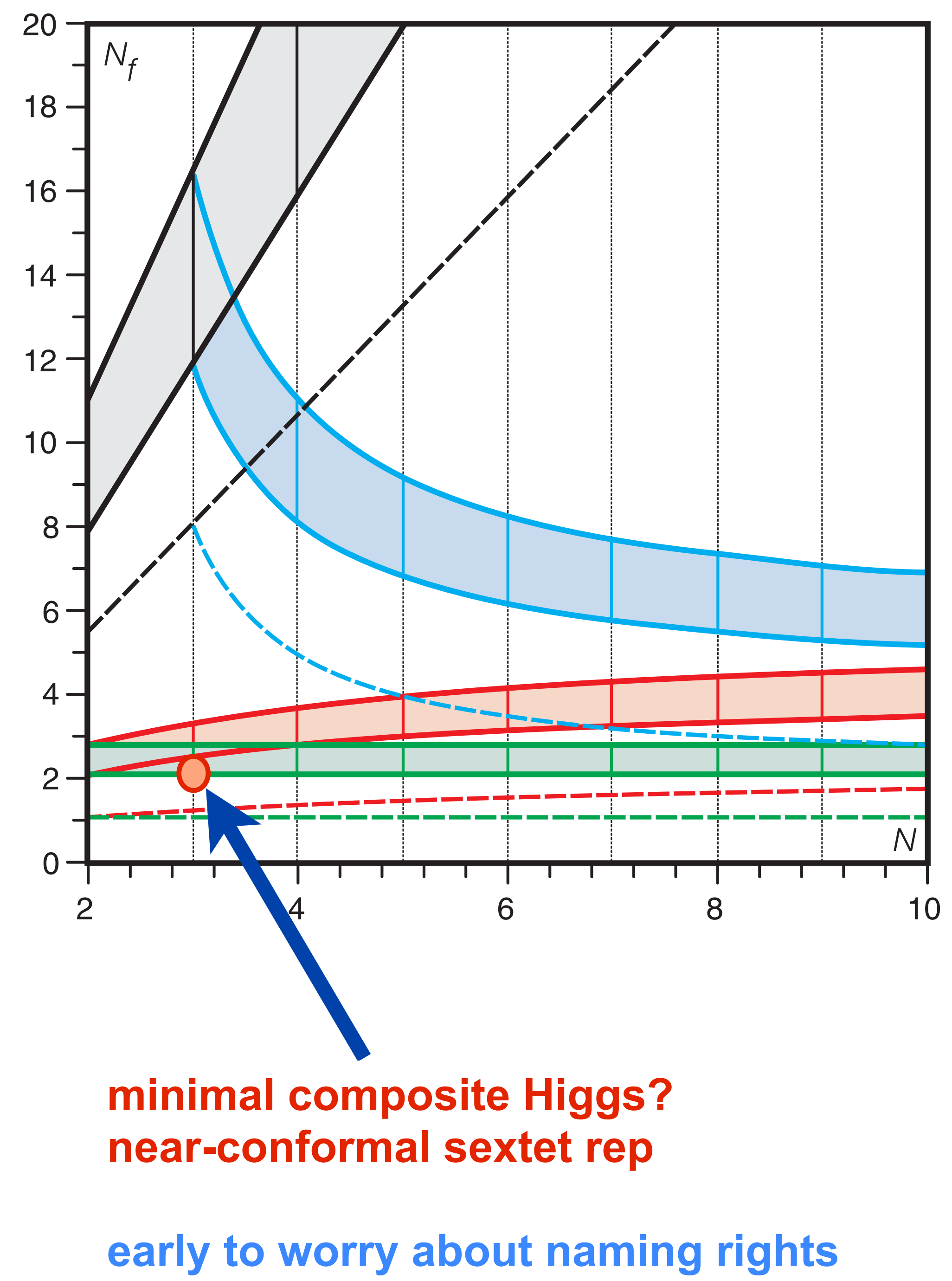
Chiral condensate

- new stochastic method for spectral density
- mode number
- large anomalous dimension?

Early universe

- EW phase transition
- dark matter

Summary and Outlook



Large Hadron Collider - CERN

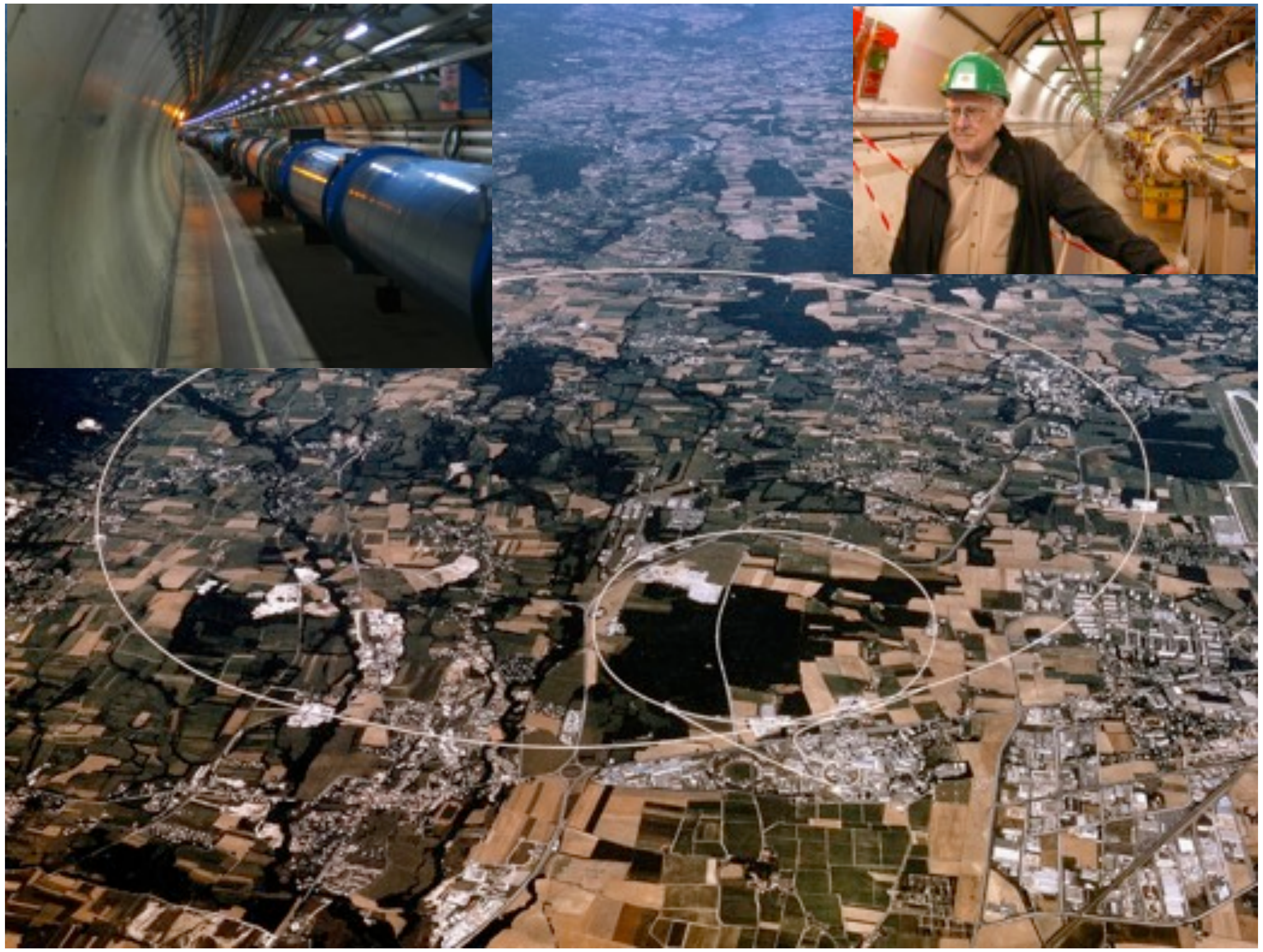
primary mission:

- Search for Higgs particle

- Origin of Electroweak symmetry breaking

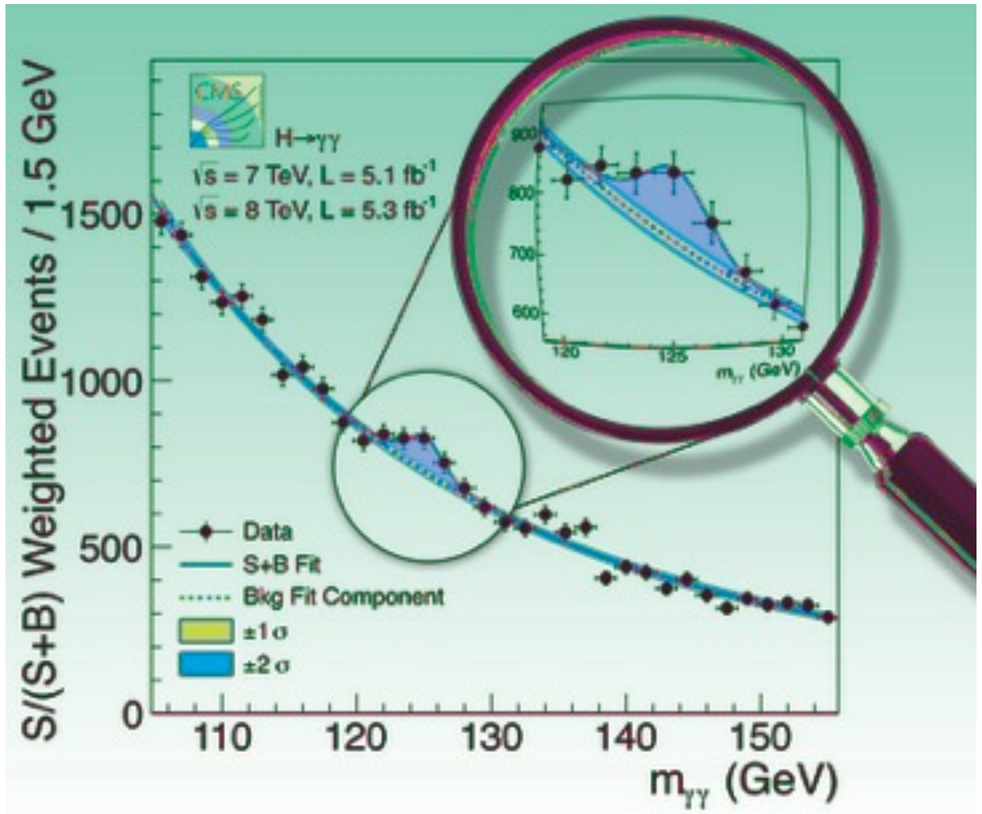
- **A Higgs-like particle is found**
  Is it the Standard Model Higgs? or
- Near-conformal strong dynamics?
- Composite PNGB-like Higgs?
- SUSY?
- 5 Dim?

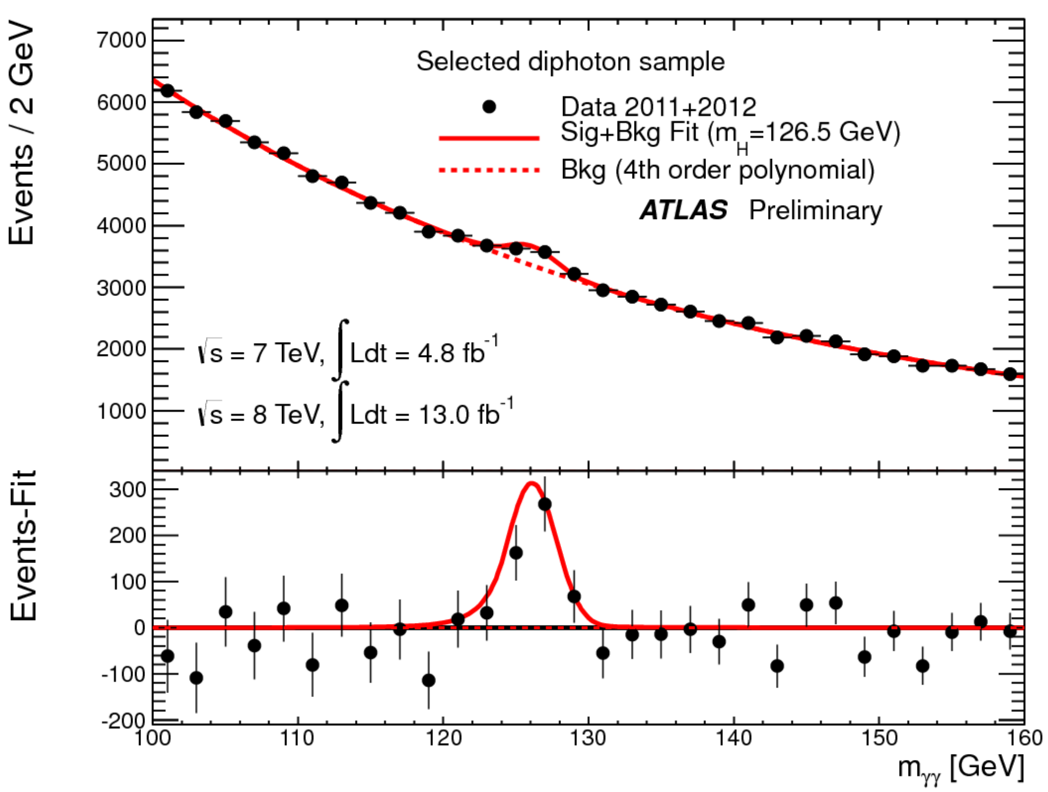
...



Primary focus of BSM lattice effort and this talk

Rational for lattice BSM:





voices: a light Higgs-like scalar was found, consistent with SM within errors, and composite states have not been seen below 1 TeV. Strongly coupled BSM gauge theories are Higgs-less with resonances below 1 TeV

facts: Compositeness has not been shown to be incompatible with the light Higgs scalar; earlier search for compositeness was based on naively scaled up QCD and unacceptable old technicolor guessing games. Resonances, out of first LHC run reach, are in the 2-3 TeV range in the theory I will discuss

lattice BSM plans: LHC14 run will search for new physics from compositeness and SUSY, and the lattice BSM community is preparing quantitative lattice based predictions to be ruled in or ruled out.
We better get this right !

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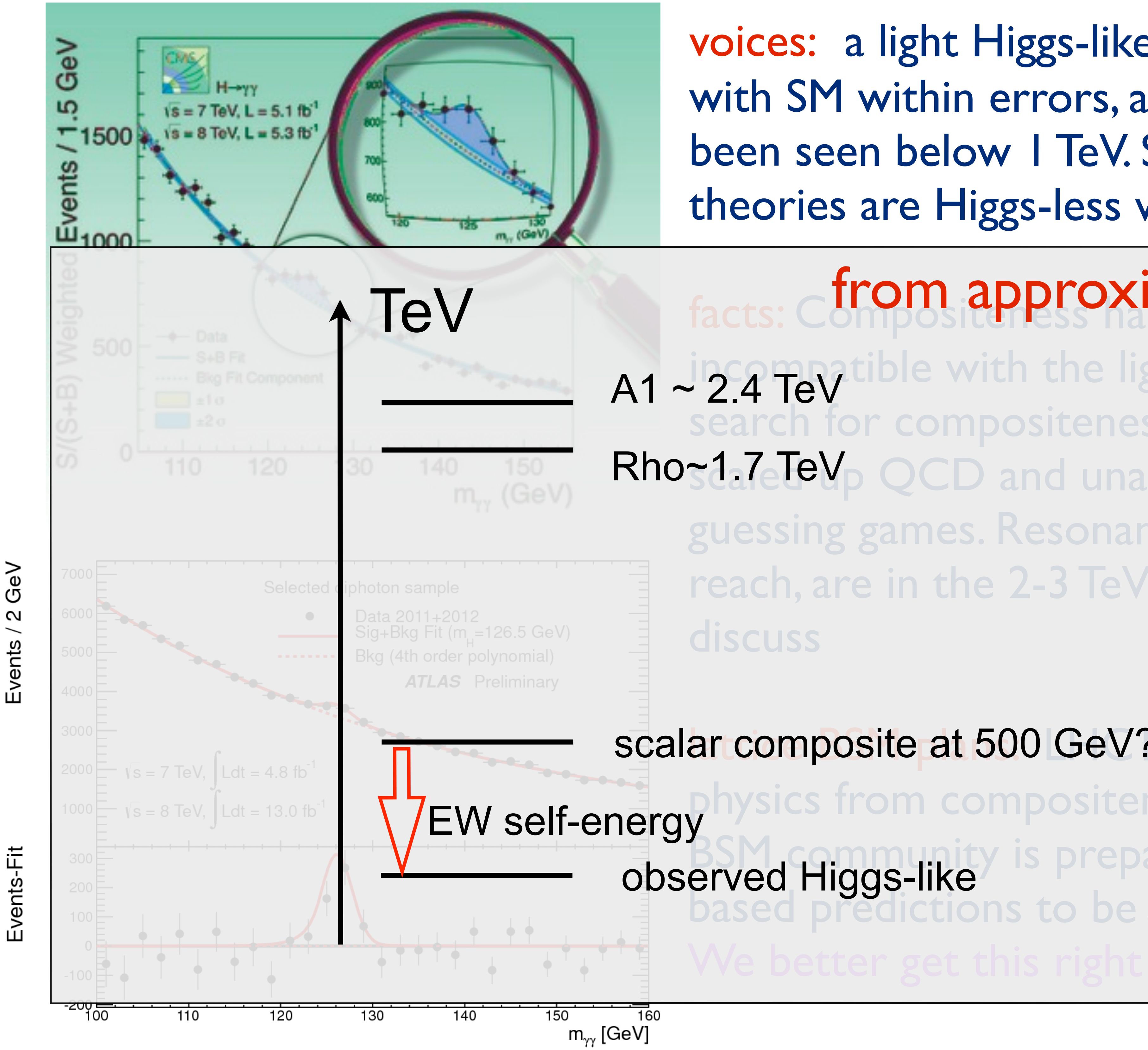
from approximate scale invariance



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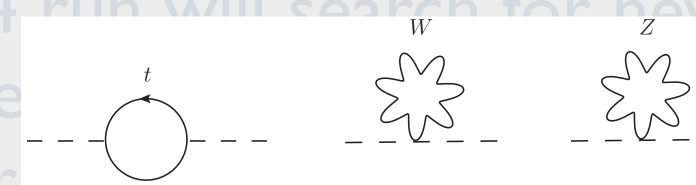

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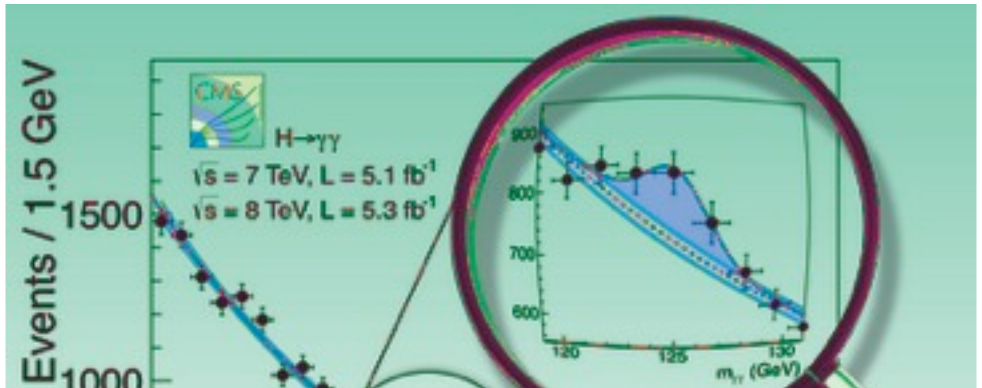

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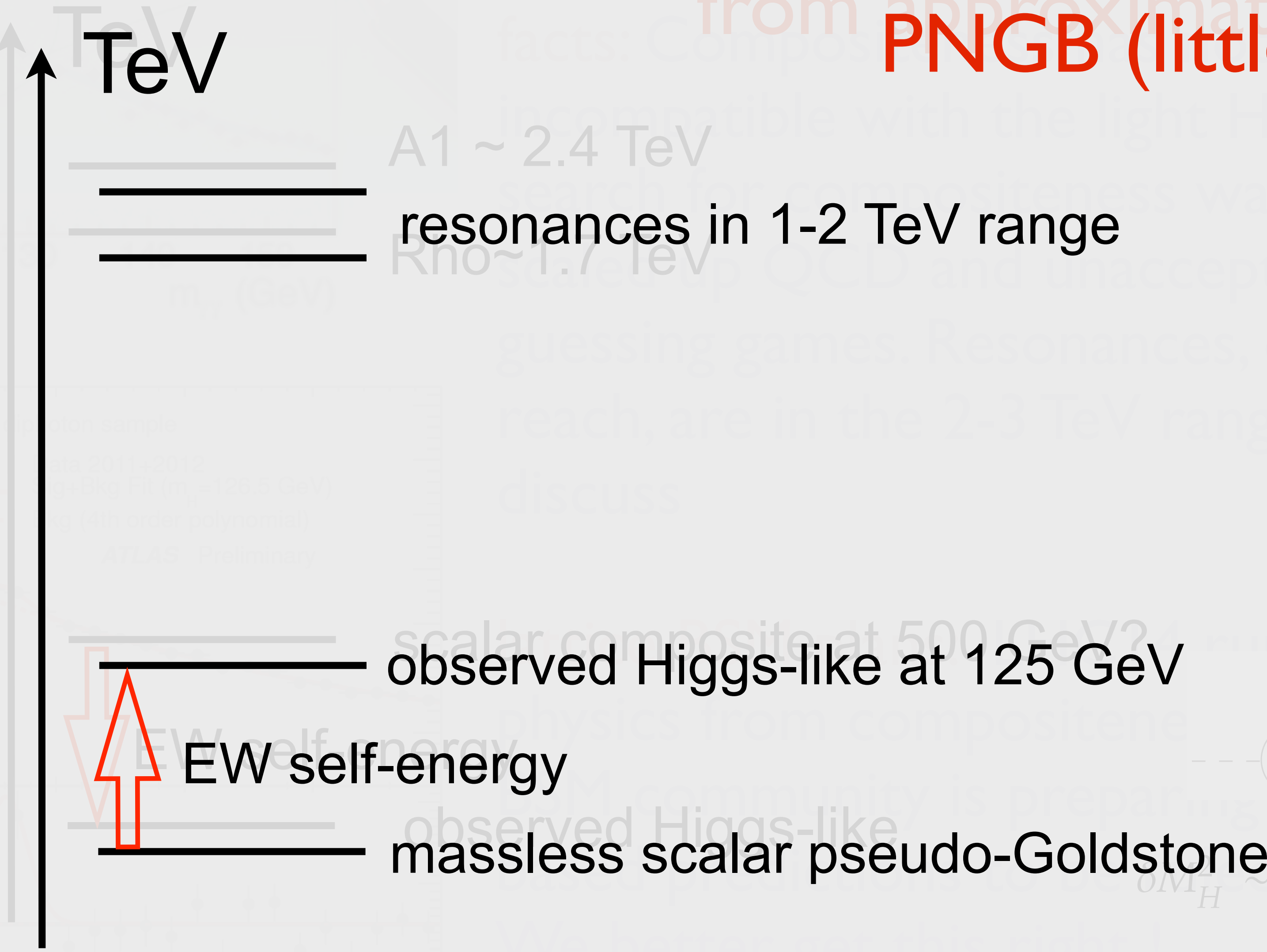
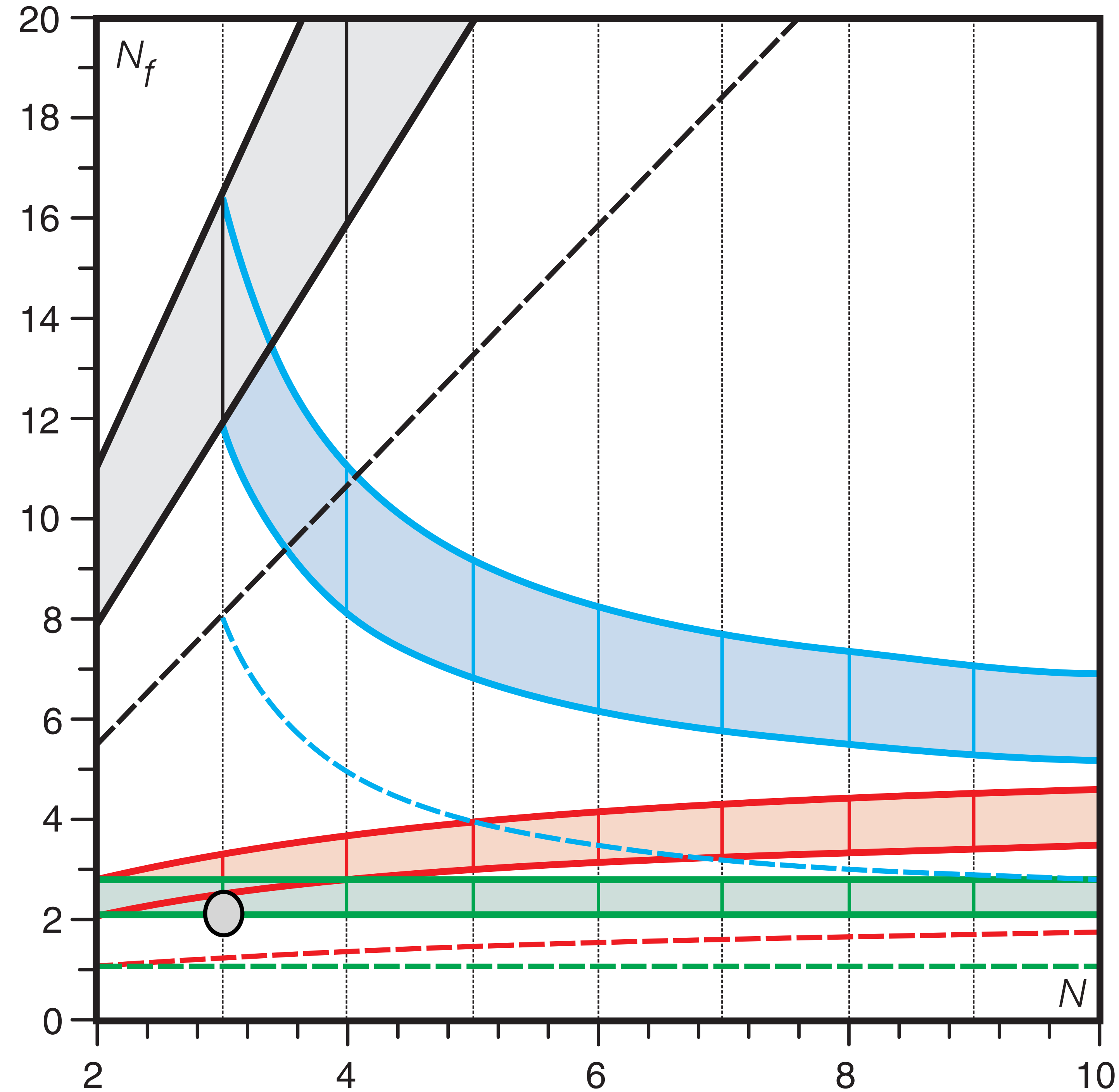
PNGB (little Higgs) scenario



near-conformal light Higgs (dilaton-like?) sextet rep



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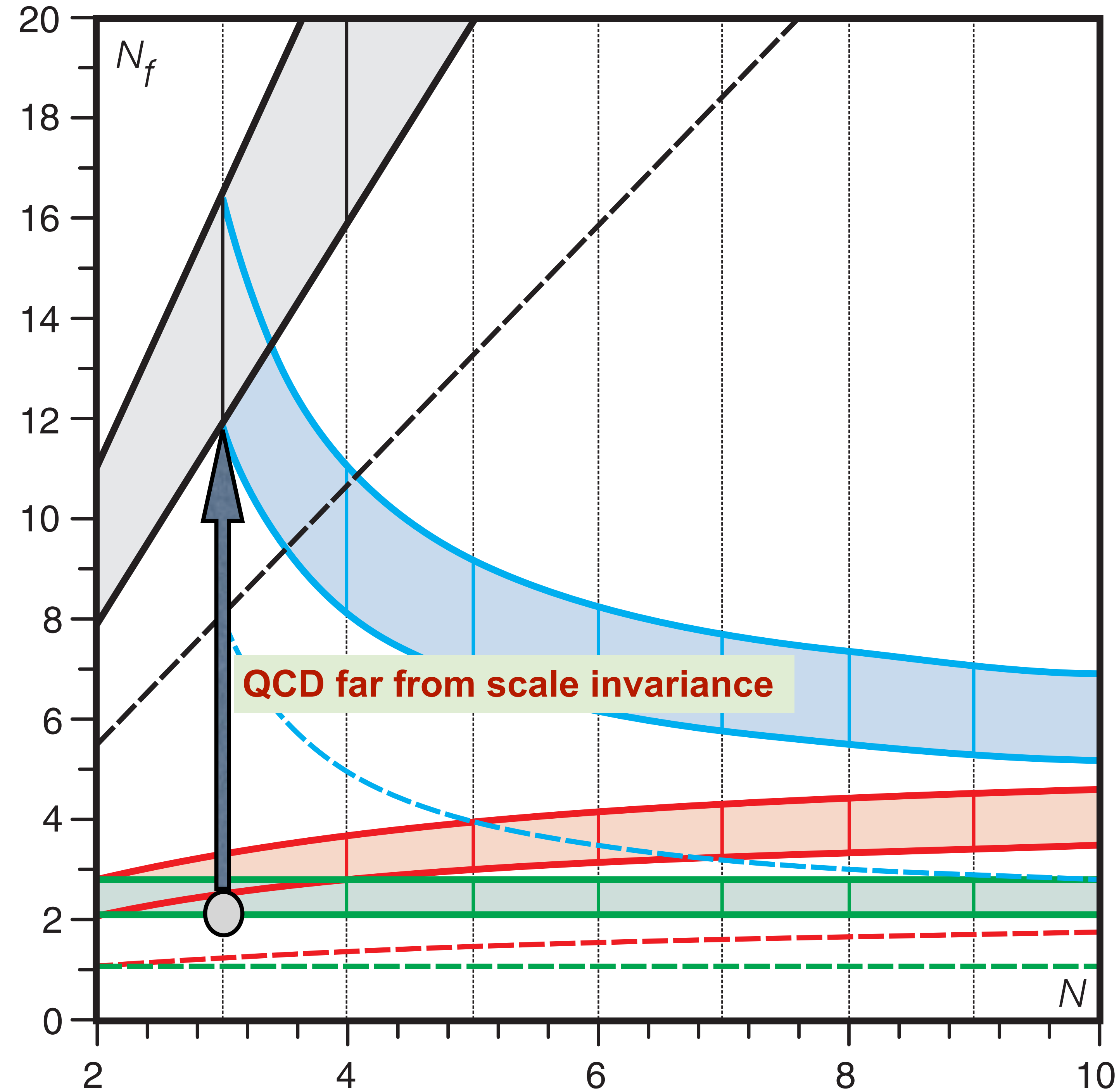

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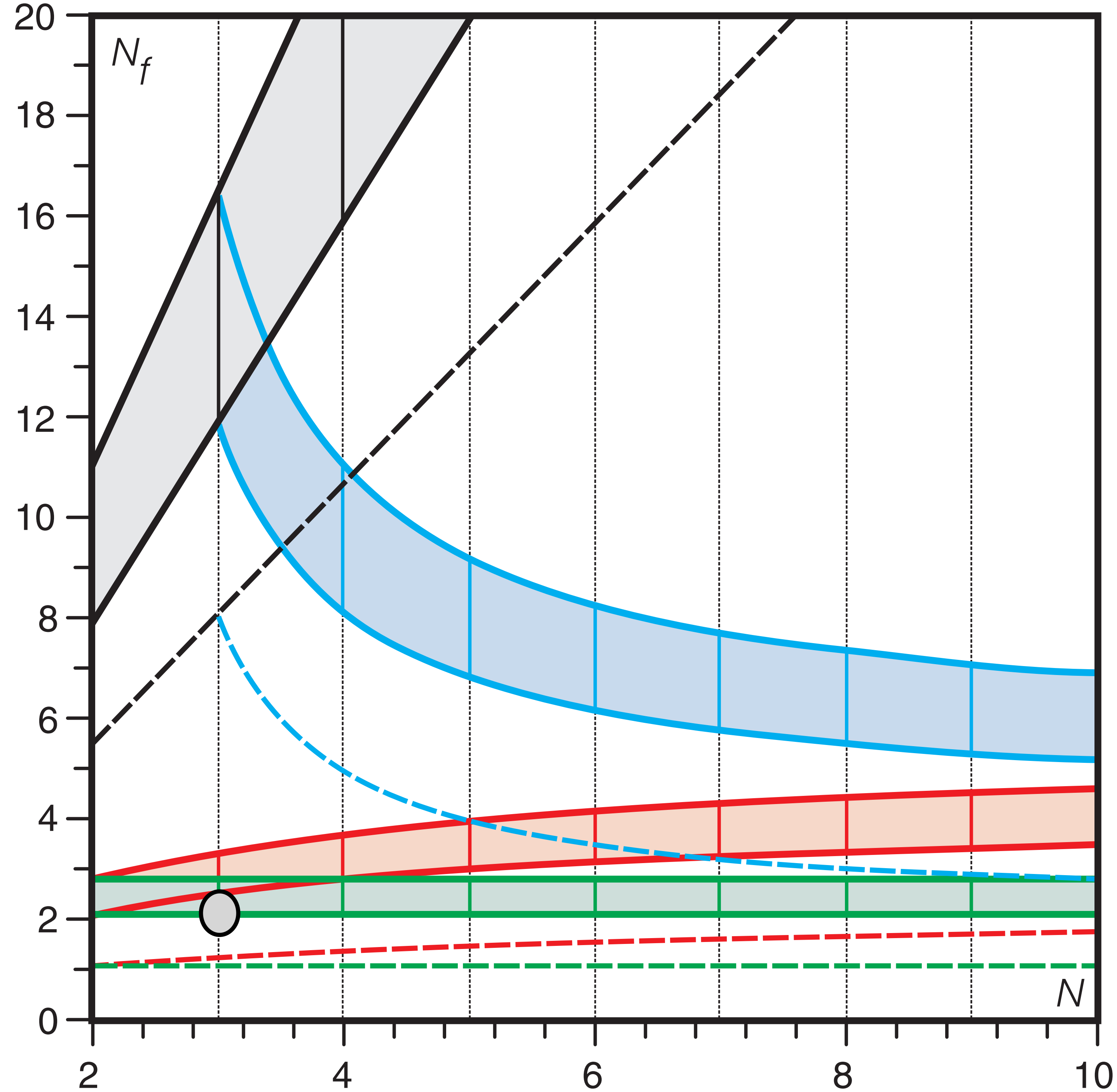


near-conformal light Higgs (dilaton-like?) sextet rep

to illustrate: sextet SU(3) color rep

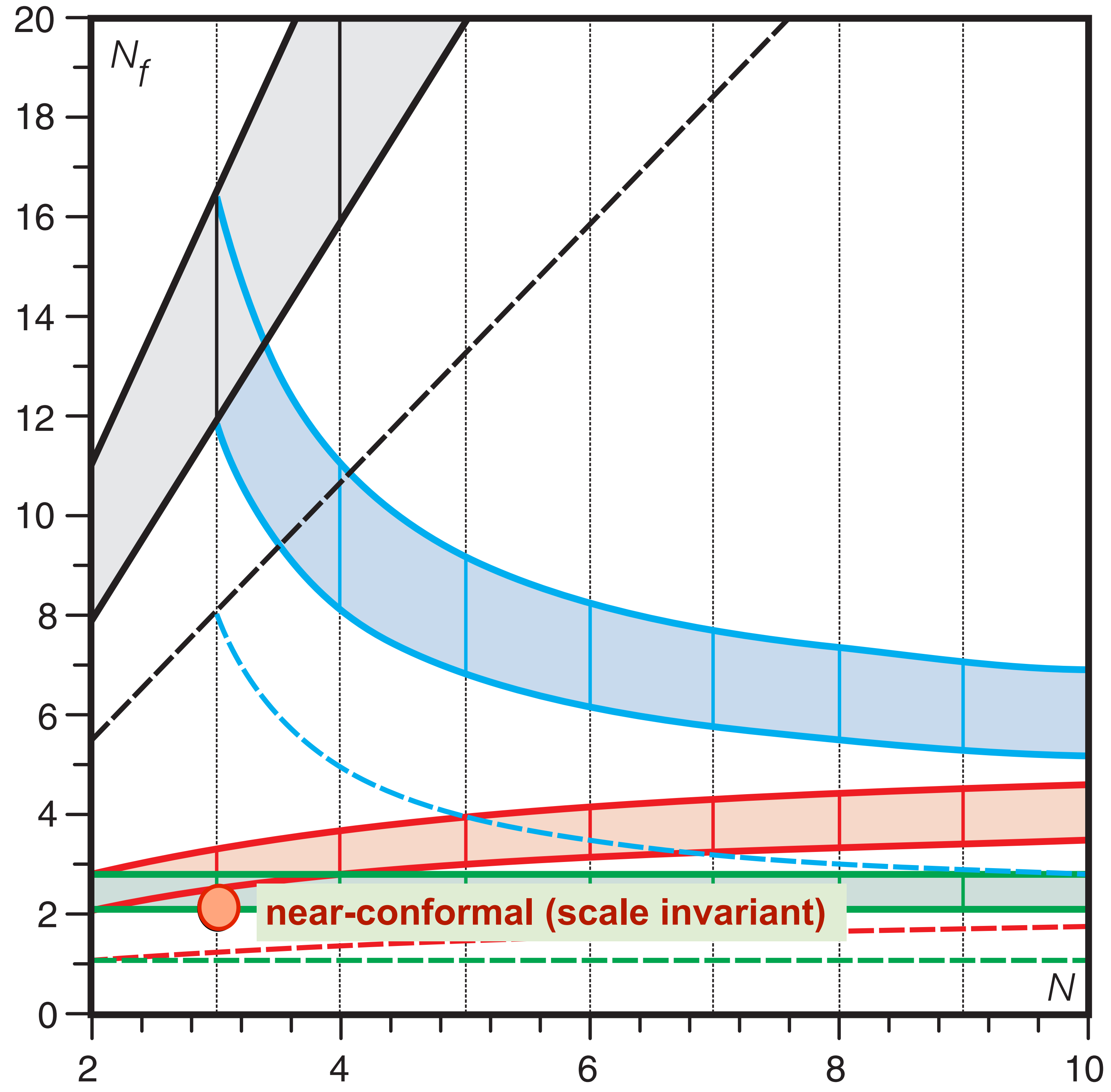
one massless fermion doublet $\begin{bmatrix} u \\ d \end{bmatrix}$

χSB on Λ~TeV scale

three Goldstone pions
become longitudinal
components of weak bosons

composite Higgs mechanism
scale of Higgs condensate
~ F=250 GeV

conflicts with EW constraints?



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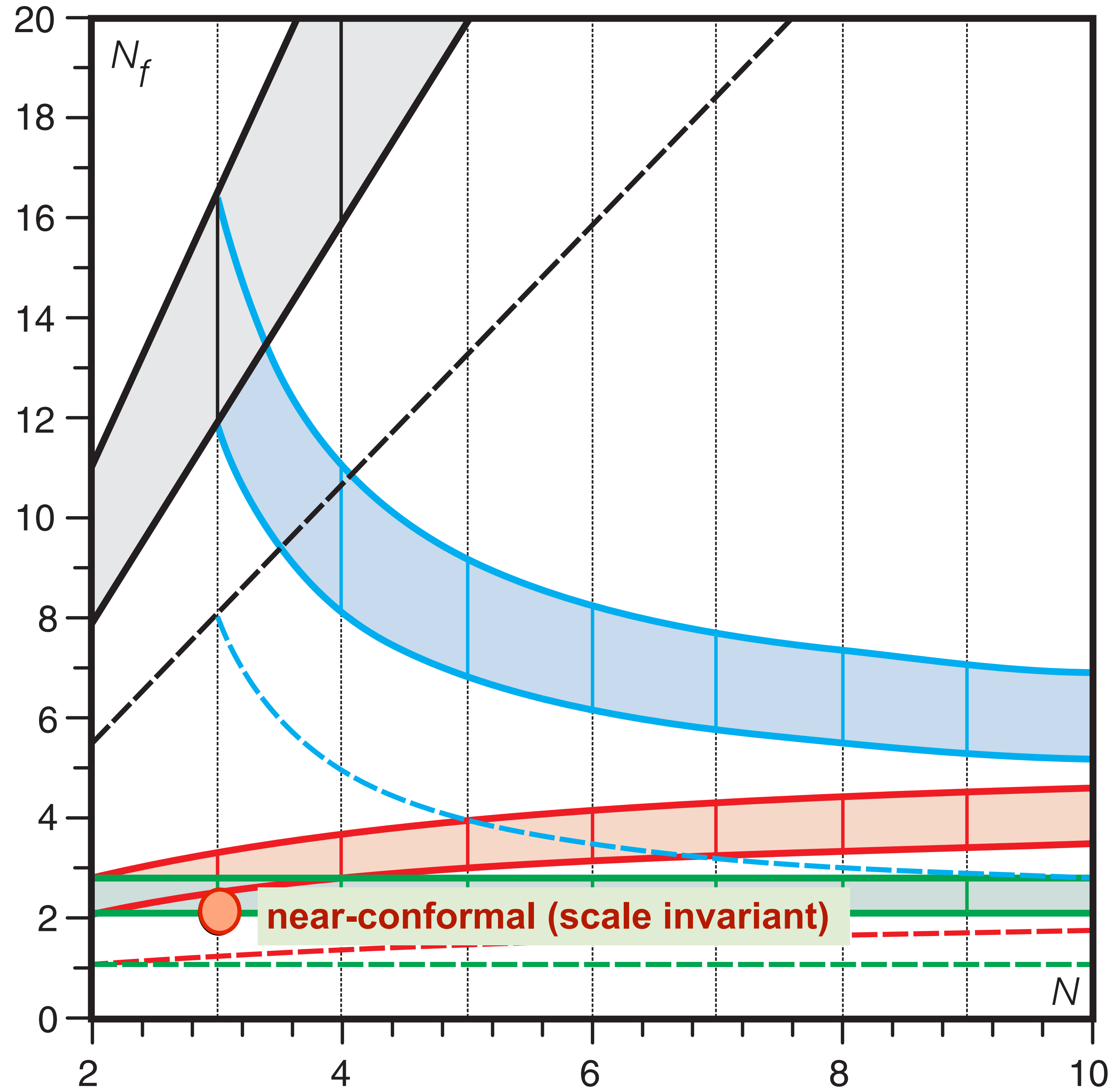
to apply QCD intuition to near-conformal compositeness is just plain wrong



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but too early to worry about
naming rights

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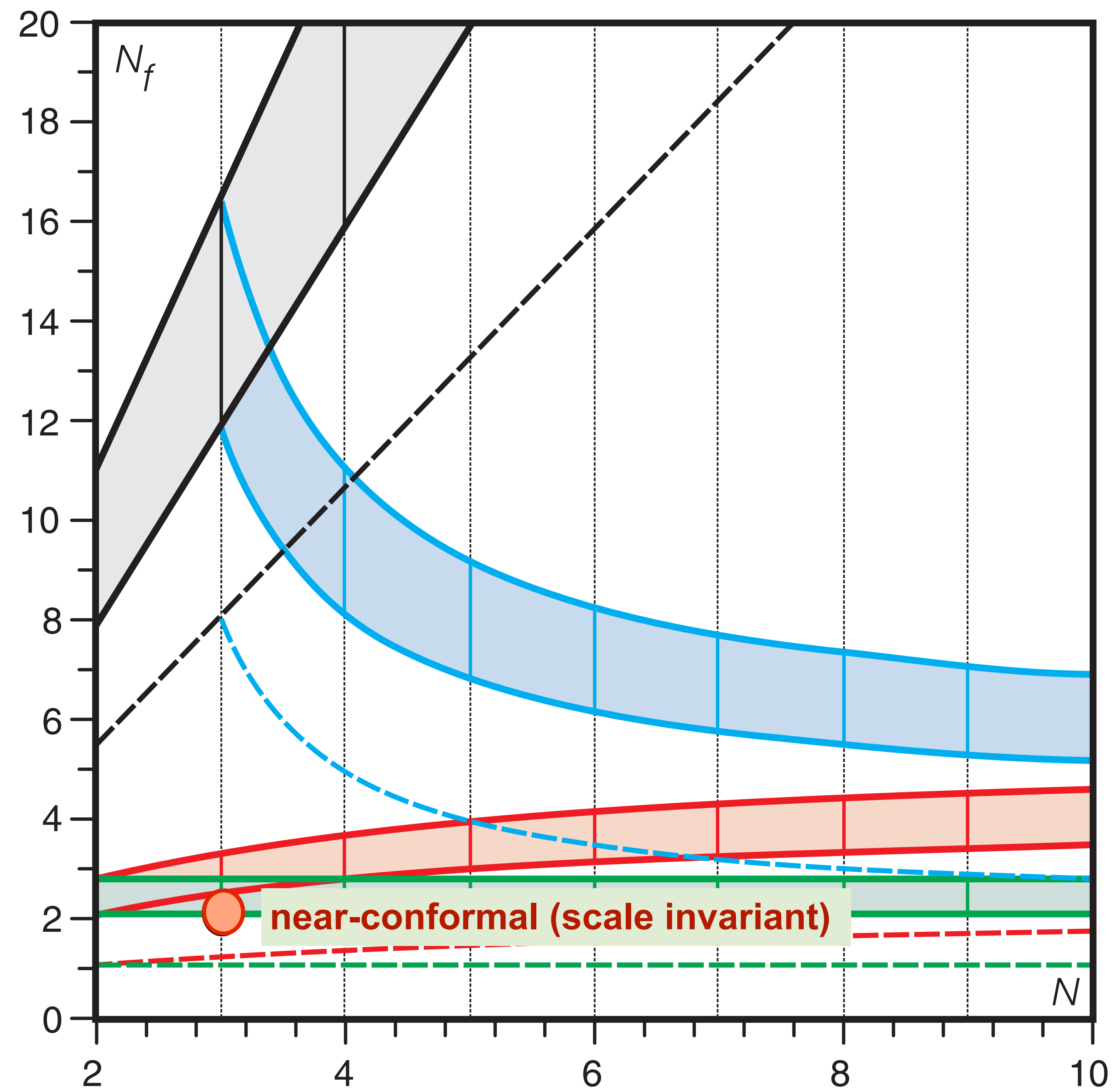

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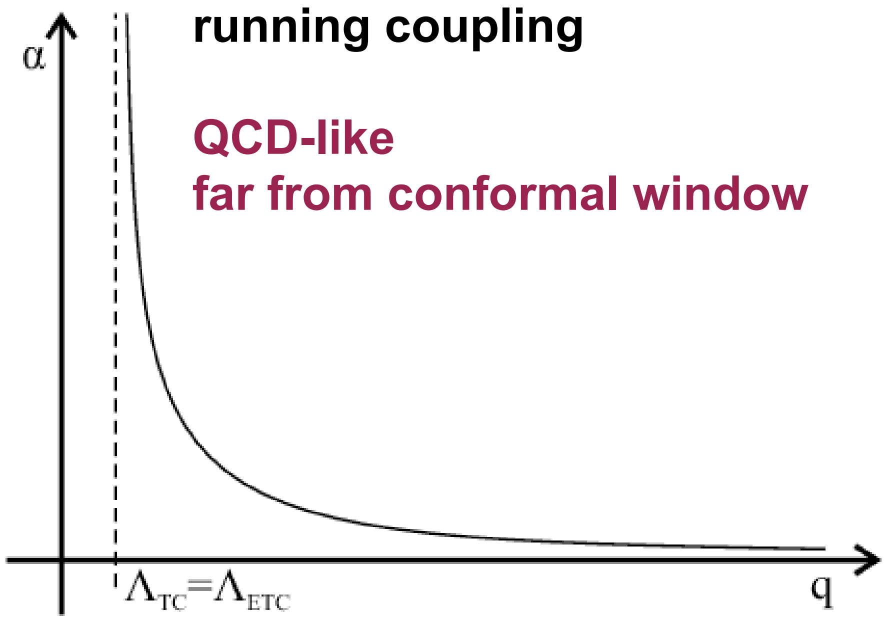

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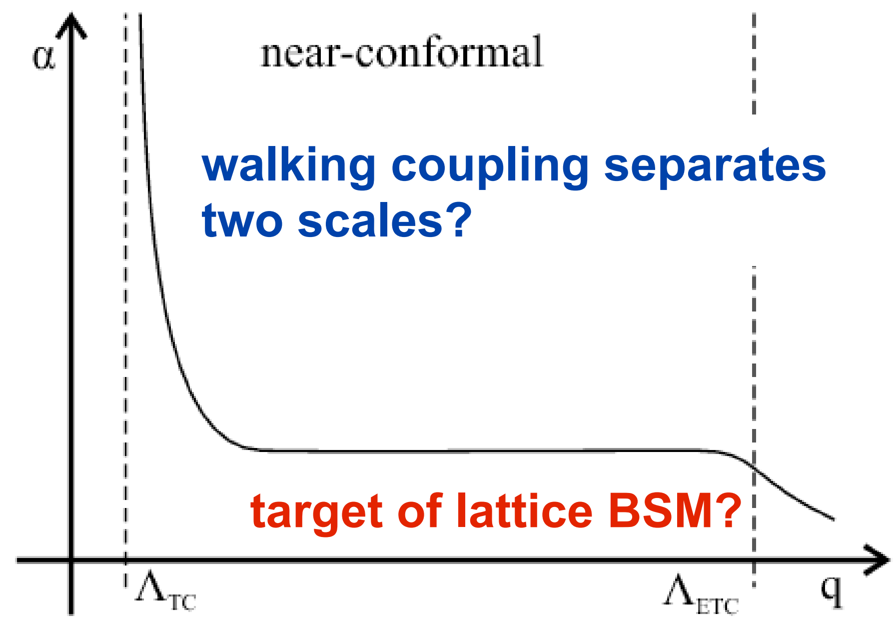

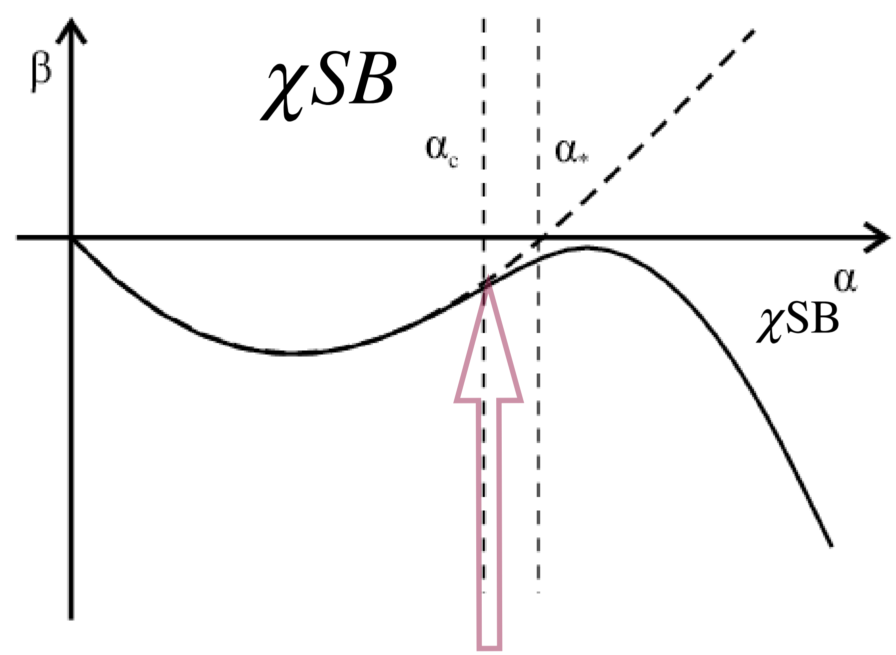

when chiral symmetry breaking
turns conformal FP into walking

χSB on Λ~TeV scale

walking gauge coupling?

fermion mass generation (effective EW int)

composite Higgs mechanism ?

broken scale invariance (dilaton) ?
or light non-SM composite Higgs
particle?

Early work using sextet rep:

Marciano (QCD paradigm, 1980)

Kogut,Shigemitsu,Sinclair
(quenched, 1984)

recent work:

Sannino and collaborators

DeGrand,Shamir,Svetitsky
IRFP or walking gauge coupling

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finite temperature

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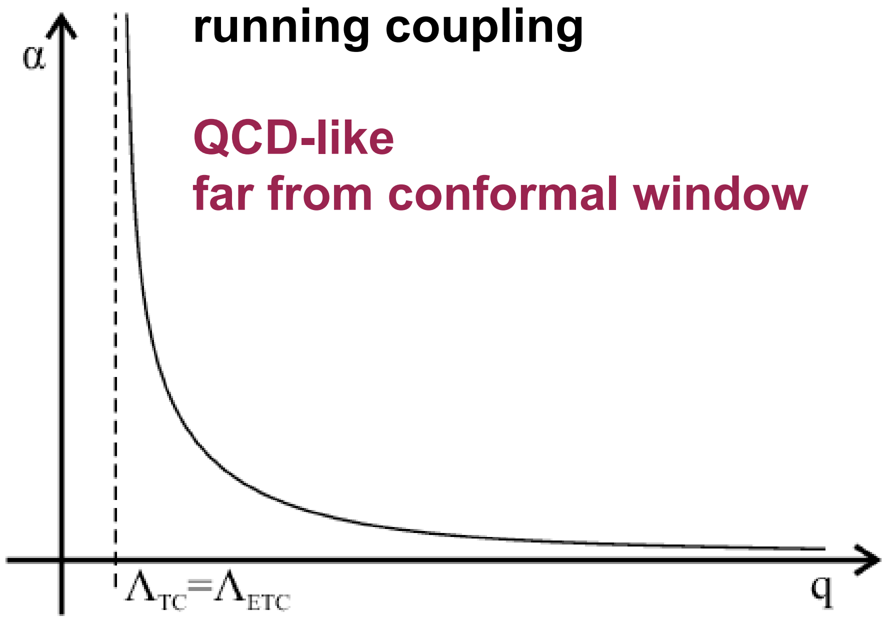

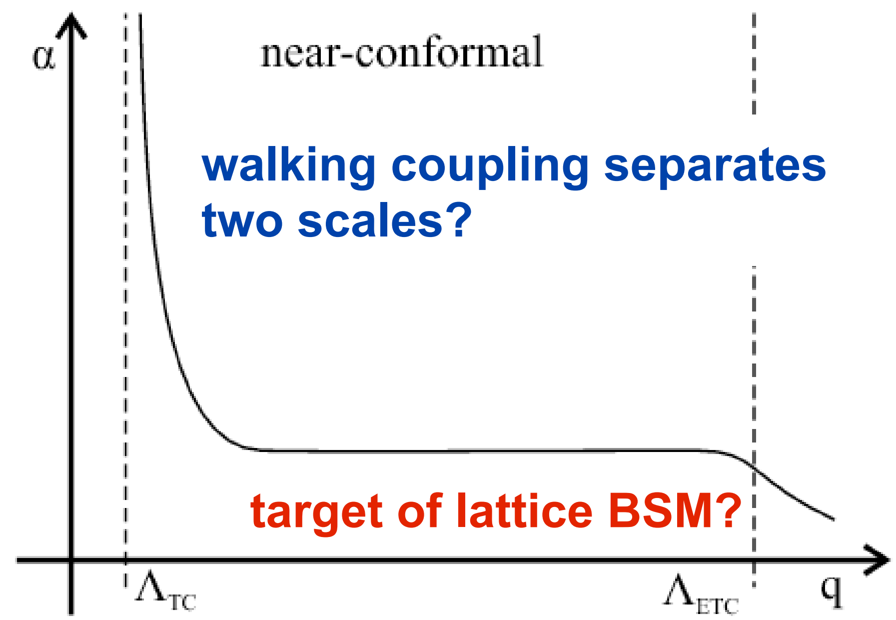

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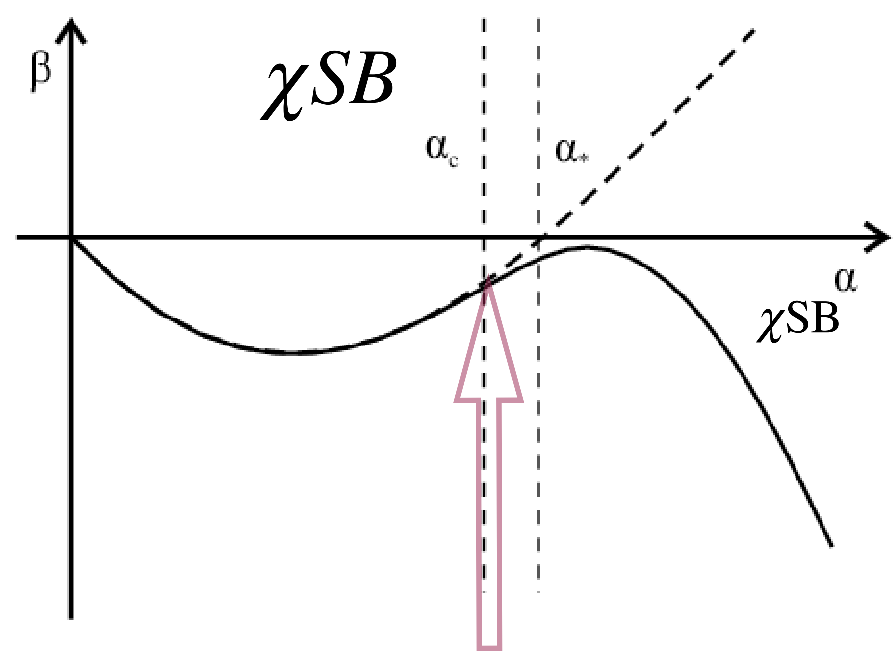

when chiral symmetry breaking
turns conformal FP into walking

two expectations:

(1) χSB and confinement

(2) light scalar close to CW (with walking) ?

near-conformal light Higgs (dilaton-like?) sextet rep

$$m_\sigma^2 \simeq -\frac{4}{f_\sigma^2}\langle 0|\left[\Theta_\mu^\mu(0)\right]_{NP}|0\rangle$$

Partially Conserved Dilatation Current (PCDC)

Will gradient flow based technology make the argument less slippery?

$$\partial_\mu \mathcal{D}^\mu = \Theta_\mu^\mu = \frac{\beta(\alpha)}{4\alpha} G_{\mu\nu}^a G^{a\mu\nu}$$

Dilatation current

Bardeen et al., Ellis, Yamawaki, Miransky, Appelquist, ...

$$\langle 0|\Theta^{\mu\nu}(x)|\sigma(p)\rangle = \frac{f_\sigma}{3}(p^\mu p^\nu - g^{\mu\nu}p^2)e^{-ipx}$$

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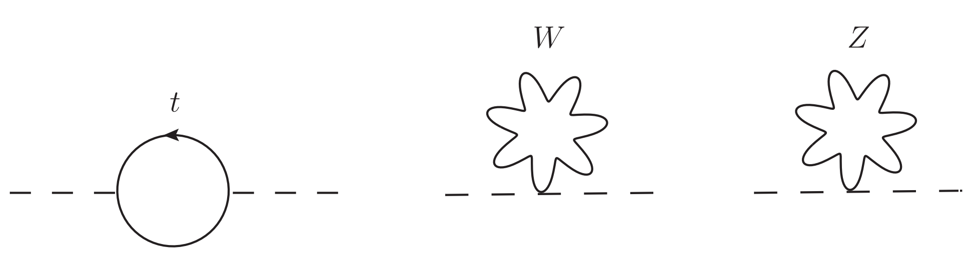
light composite scalar, but
how light is light ?

few hundred GeV Higgs impostor?

Foadi, Fransden, Sannino
open for spirited theory discussions



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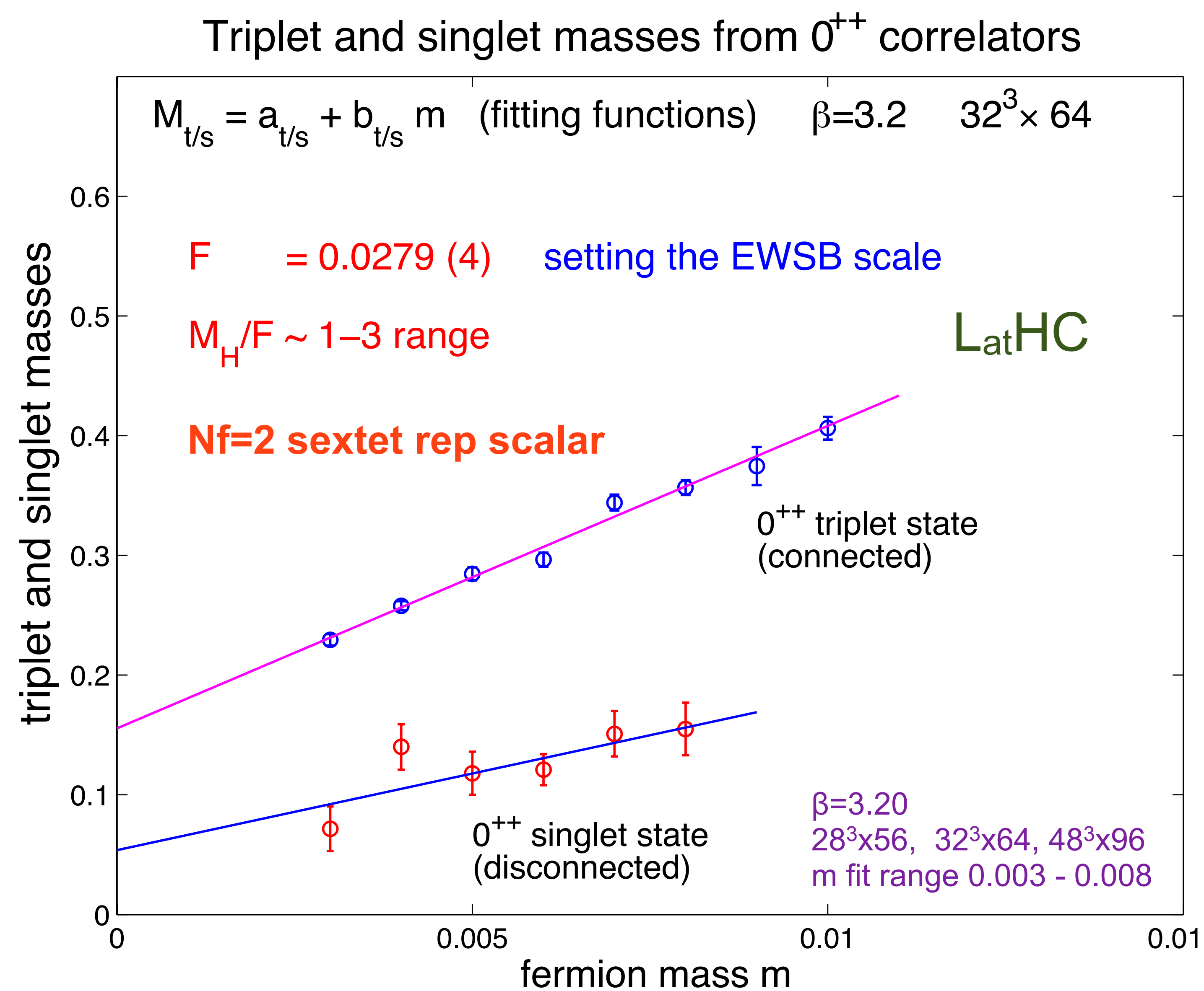

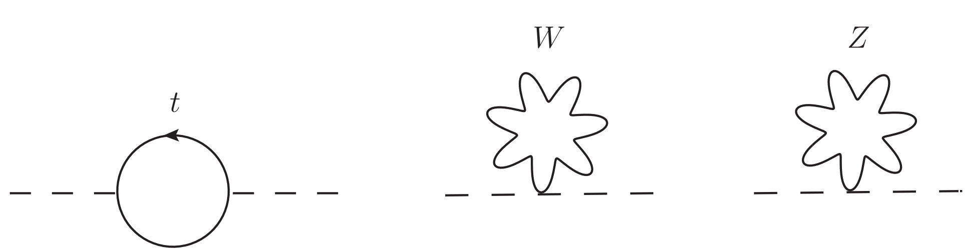

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Bardeen et al., Ellis, Yamawaki, Miransky, Appelquist, ...

Higgs impostor of SCGT(perhaps dilaton-like) or “just a light scalar on the lattice” ?

what is missing?

how light is light ?

few hundred GeV Higgs impostor?

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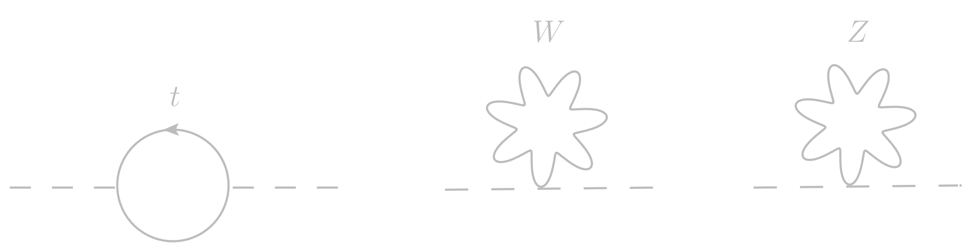

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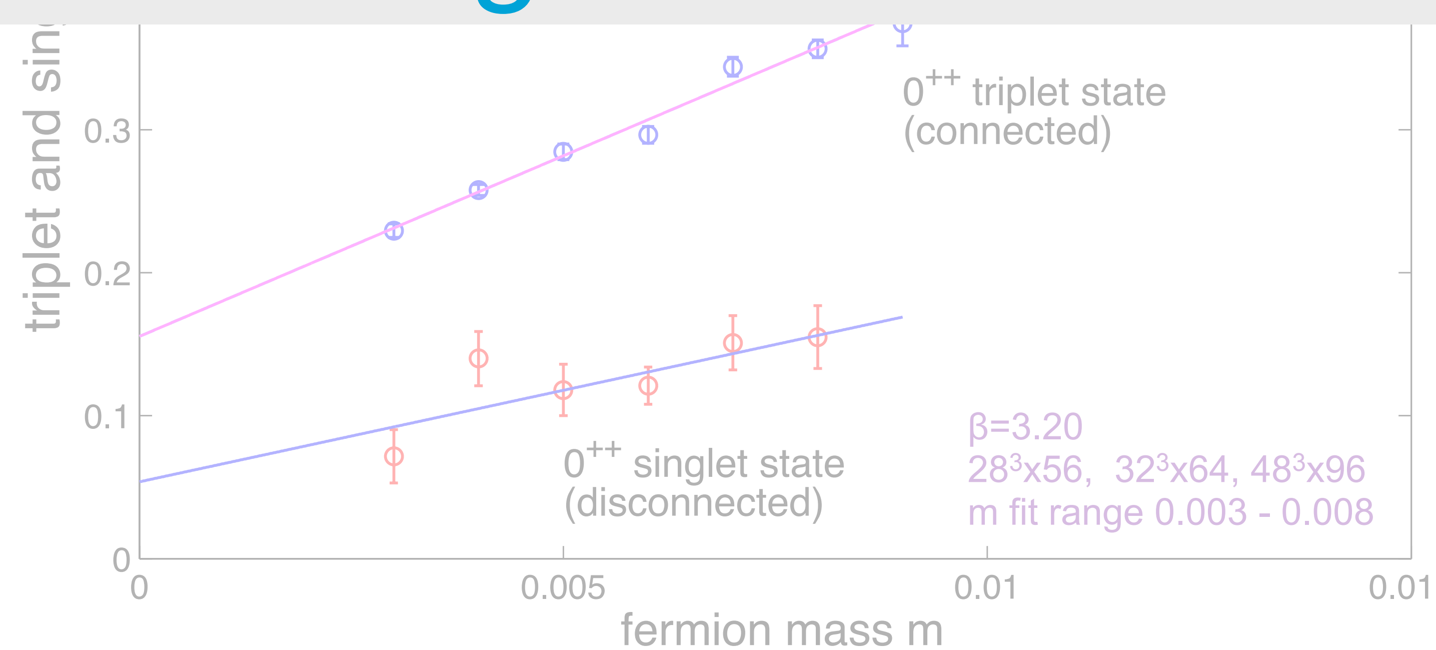

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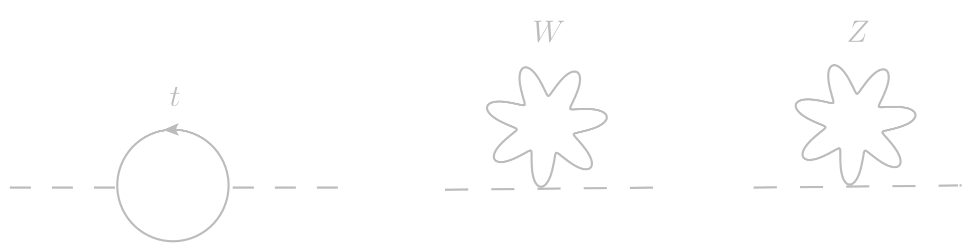

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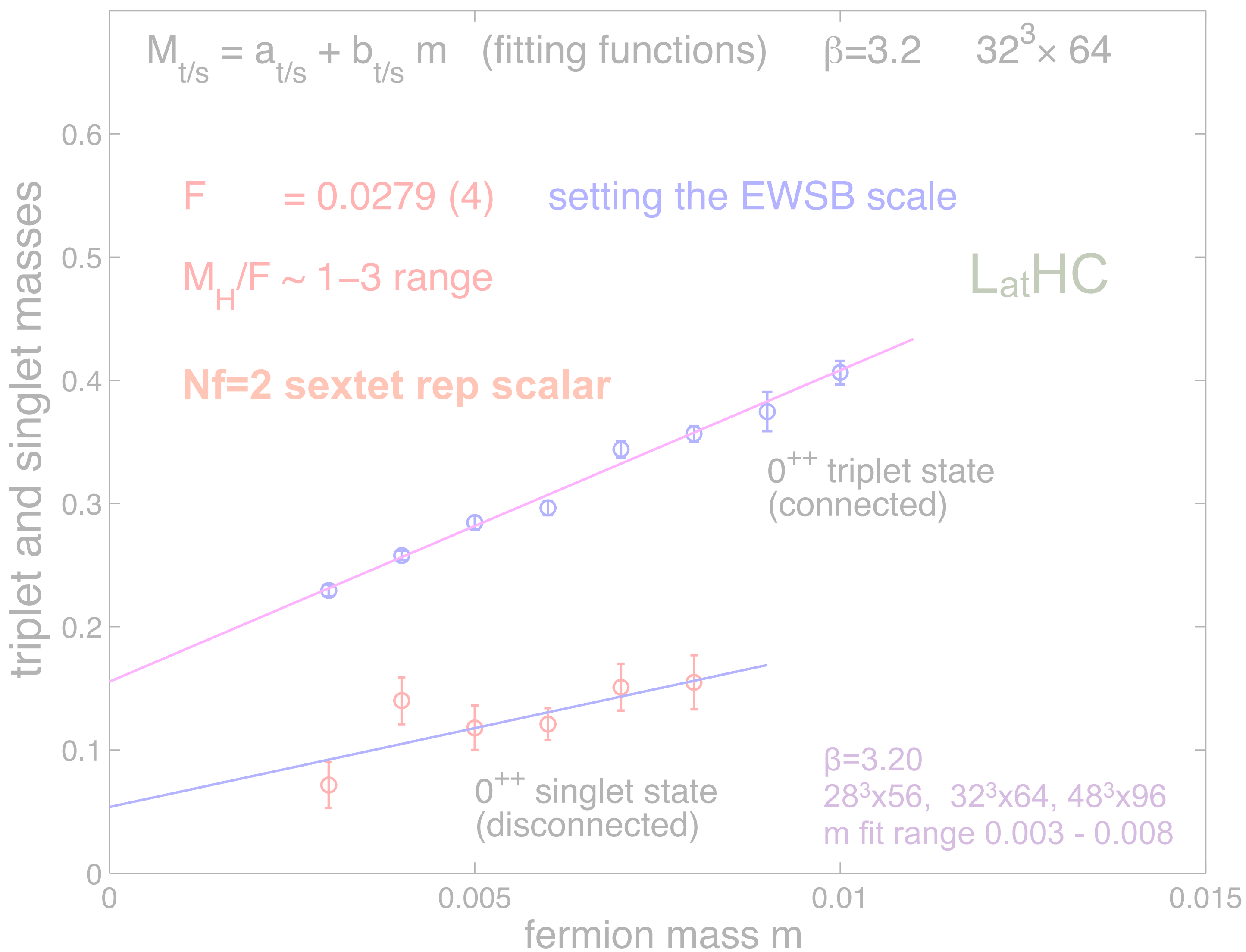
Triplet and singlet masses from 0^{++} correlators



our new code (sextet Janos) is highly optimized impressive Borsanyi/Wong effort
in production now to answer questions in second generation run set:

We are in a second generation run set

β=3.15, 3.20, 3.25, 3.30 gauge couplings

$48\text{x}96^3$, $40\text{x}80^3$, $32\text{x}64^3$ volumes

3 fermion masses in each run

this is expensive

our new code (sextet Janos) is highly optimized **impressive Borsanyi/Wong effort**
in production now to answer questions in second generation run set:

1. Test of chiral perturbation theory below the scale of low mass scalar?
   - how to test if light scalar is dilaton-like — close to CW?
   - both require new low energy effective action — like Matsuzaki/Yamawaki proposal?
   - is there an f_σ / f_π crisis?

2. Needs precise scale setting and resonance spectrum
   - S and T parameters of Electroweak precision tests
   - large volumes **F · L ~ 1, or larger!**
   - slow topology

3. Running (walking?) coupling
   - volume-dependent running coupling
   - scale-dependent L= ∞ coupling in chiral limit

4. Consistent chiral condensate
   - GMOR relation is still not quite consistent
   - new method for spectral density and mode number
   - anomalous dimension of chiral condensate

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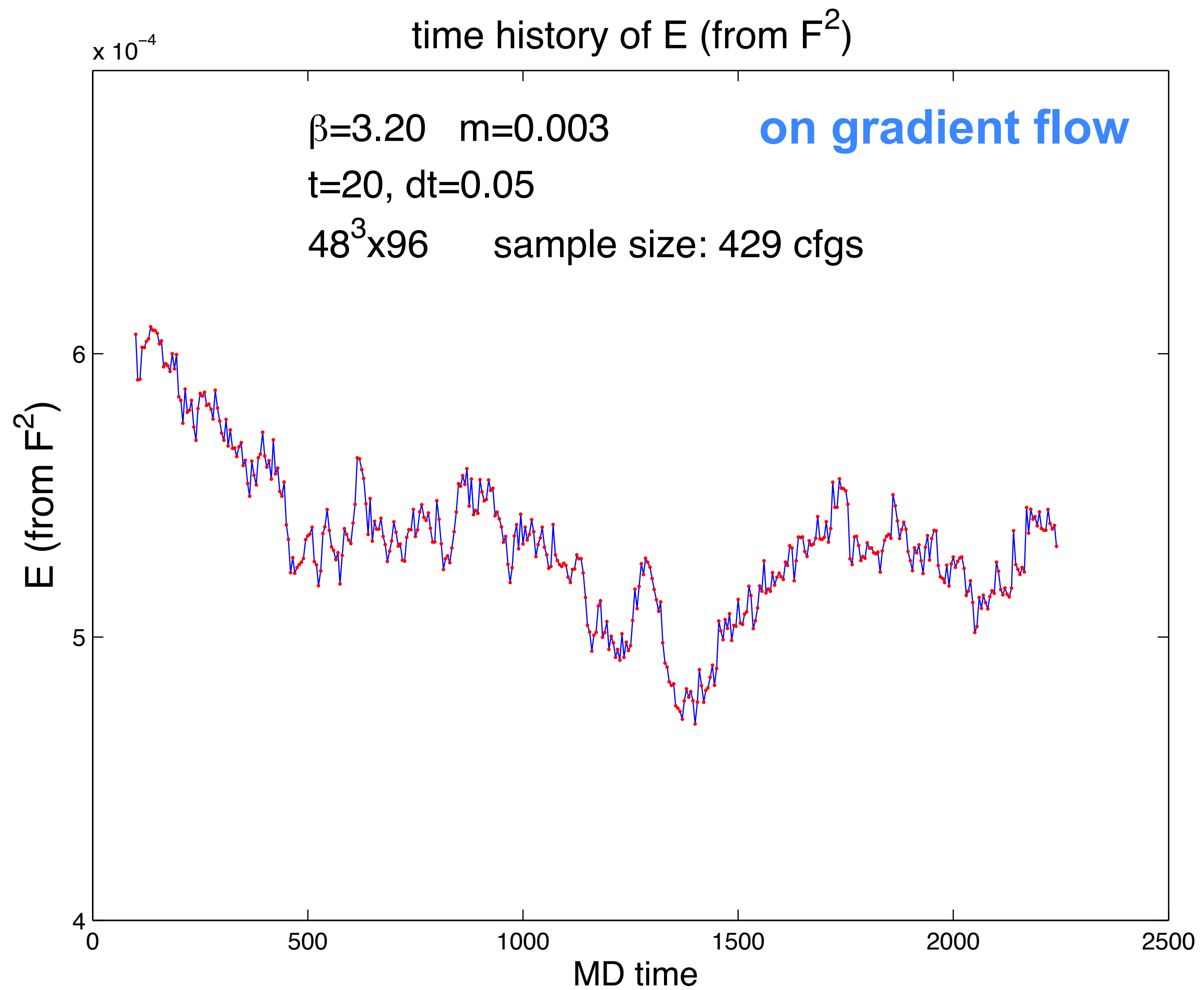
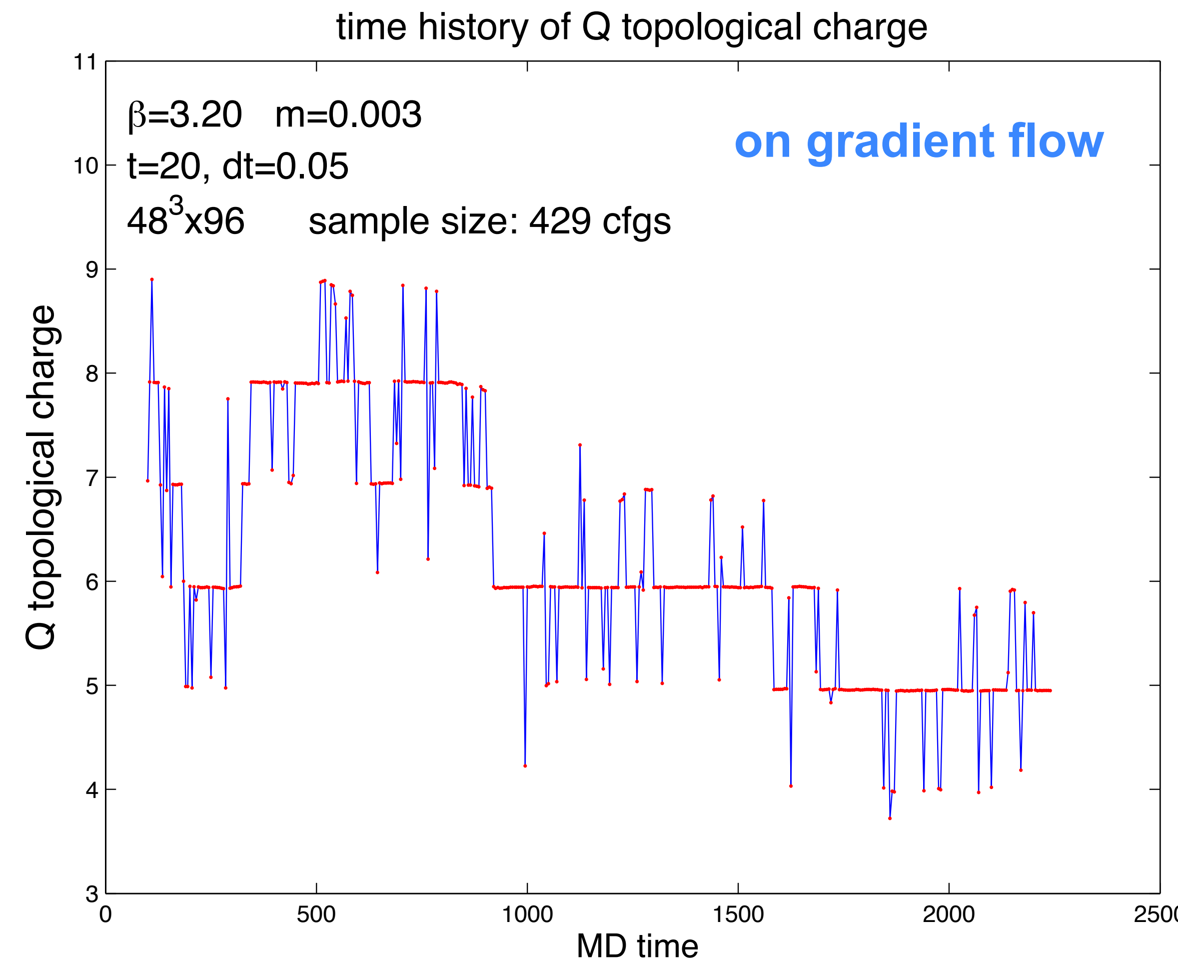

time history of E (from F^2)
x 10^{-4}
β=3.20 m=0.003
t=20, dt=0.05
48^3x96 sample size: 429 cfgs
on gradient flow
E (from F^2)
MD time
0
500
1000
1500
2000
2500
4
5
6


time history of Q topological charge
β=3.20 m=0.003
t=20, dt=0.05
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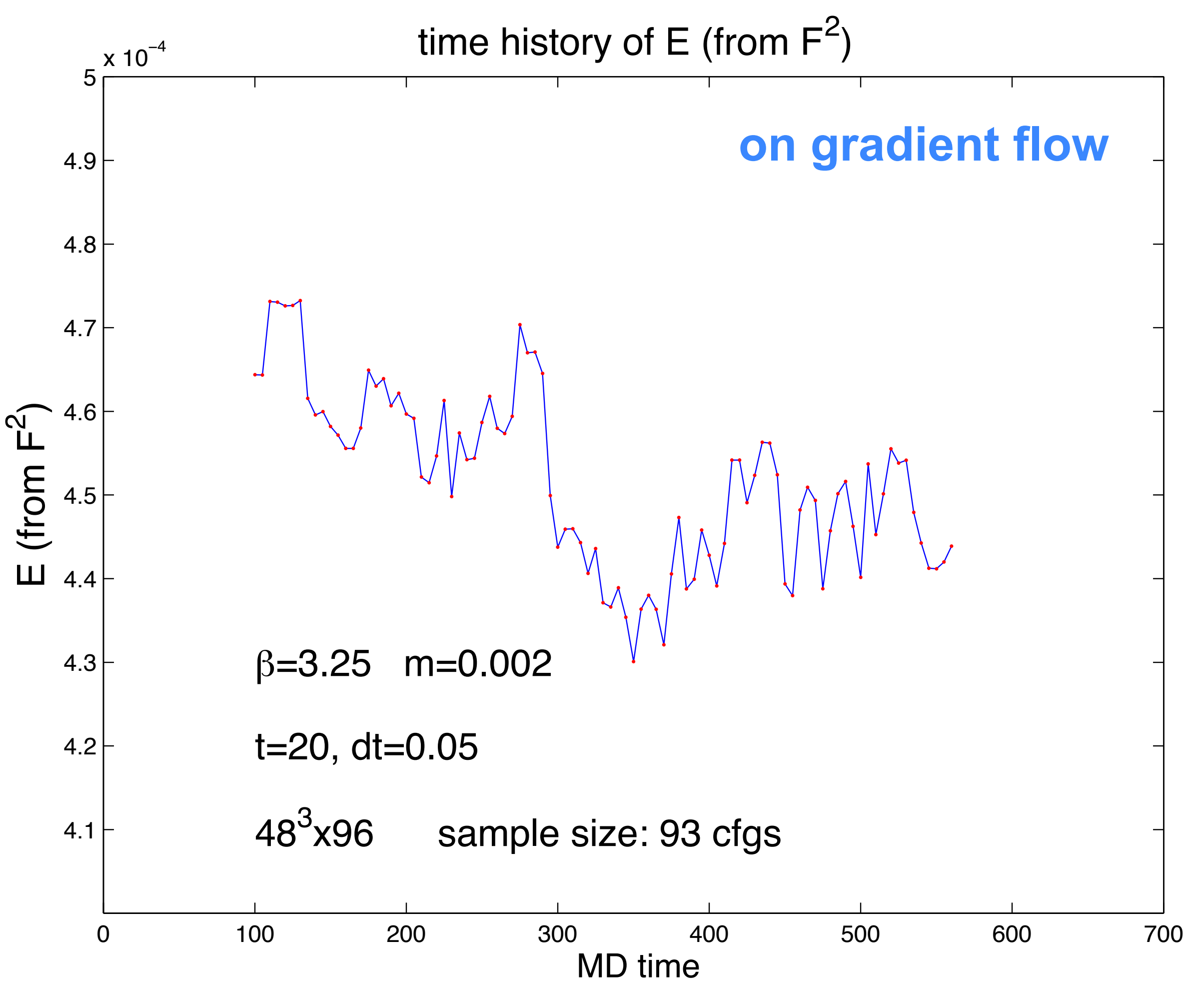
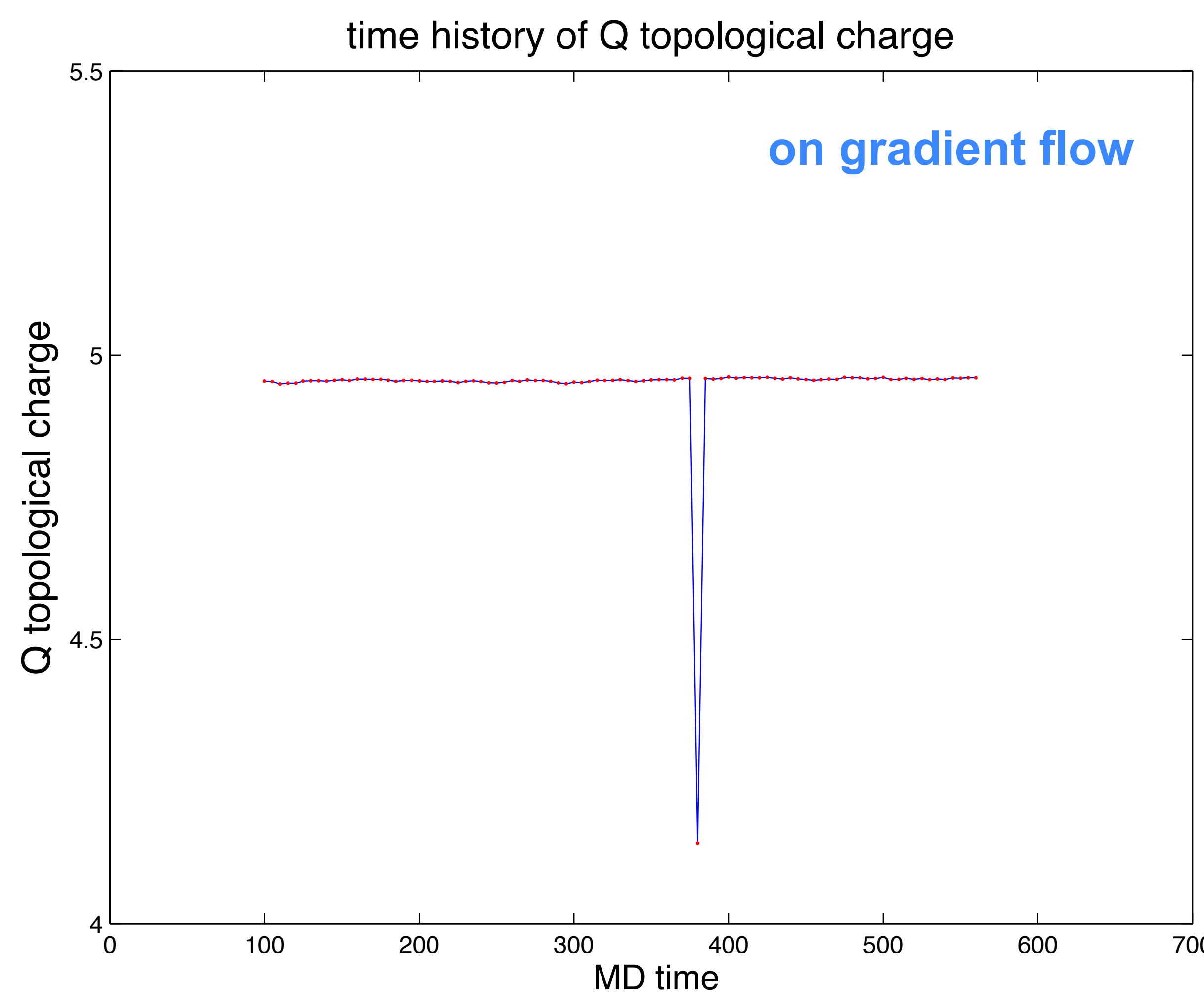
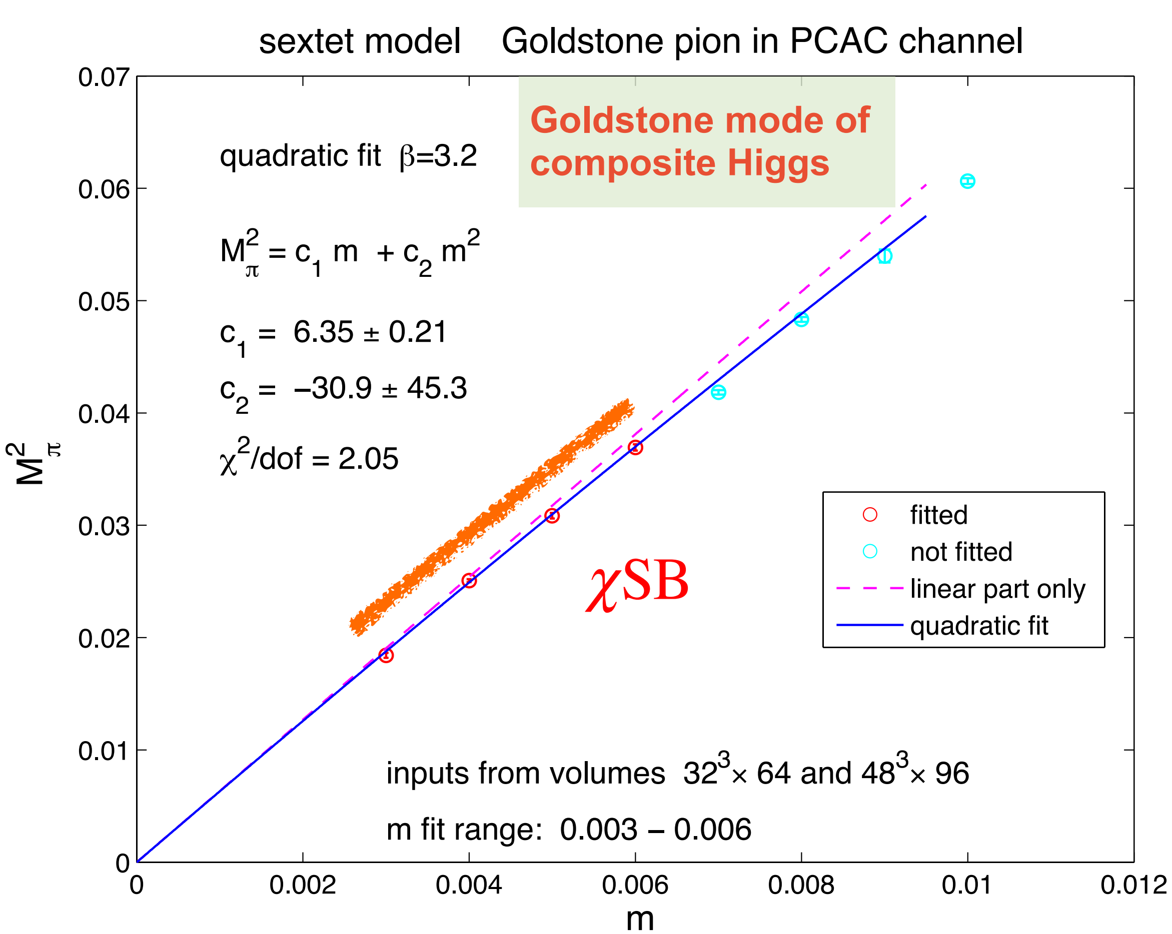
Q topological charge
MD time
0
500
1000
1500
2000
2500
3
4
5
6
7
8
9
10
11

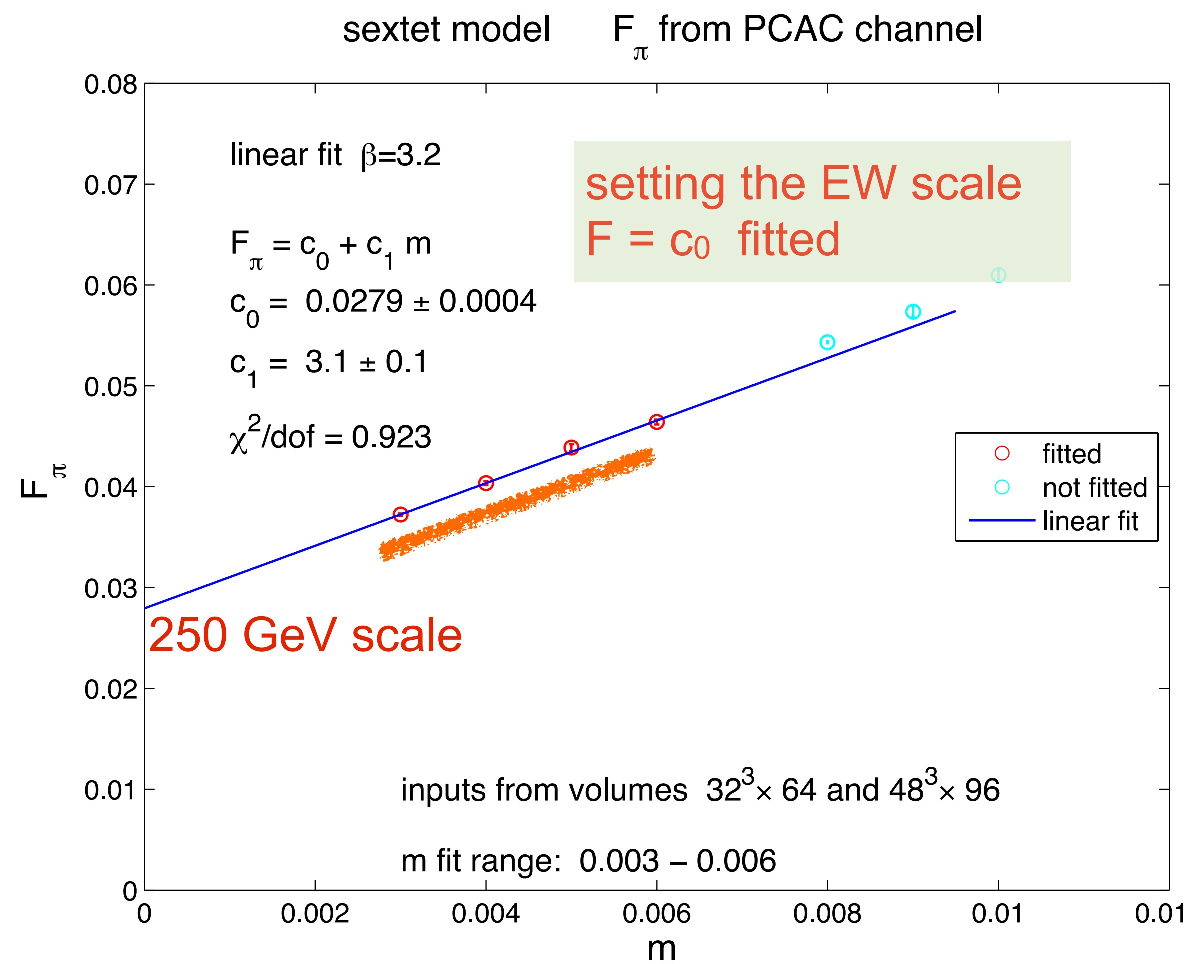

time history of E (from F^2)
x 10^{-4}
on gradient flow
β=3.25 m=0.002
t=20, dt=0.05
48^3x96 sample size: 93 cfgs
E (from F^2)
MD time
0
100
200
300
400
500
600
700
4.1
4.2
4.3
4.4
4.5
4.6
4.7
4.8
4.9
5

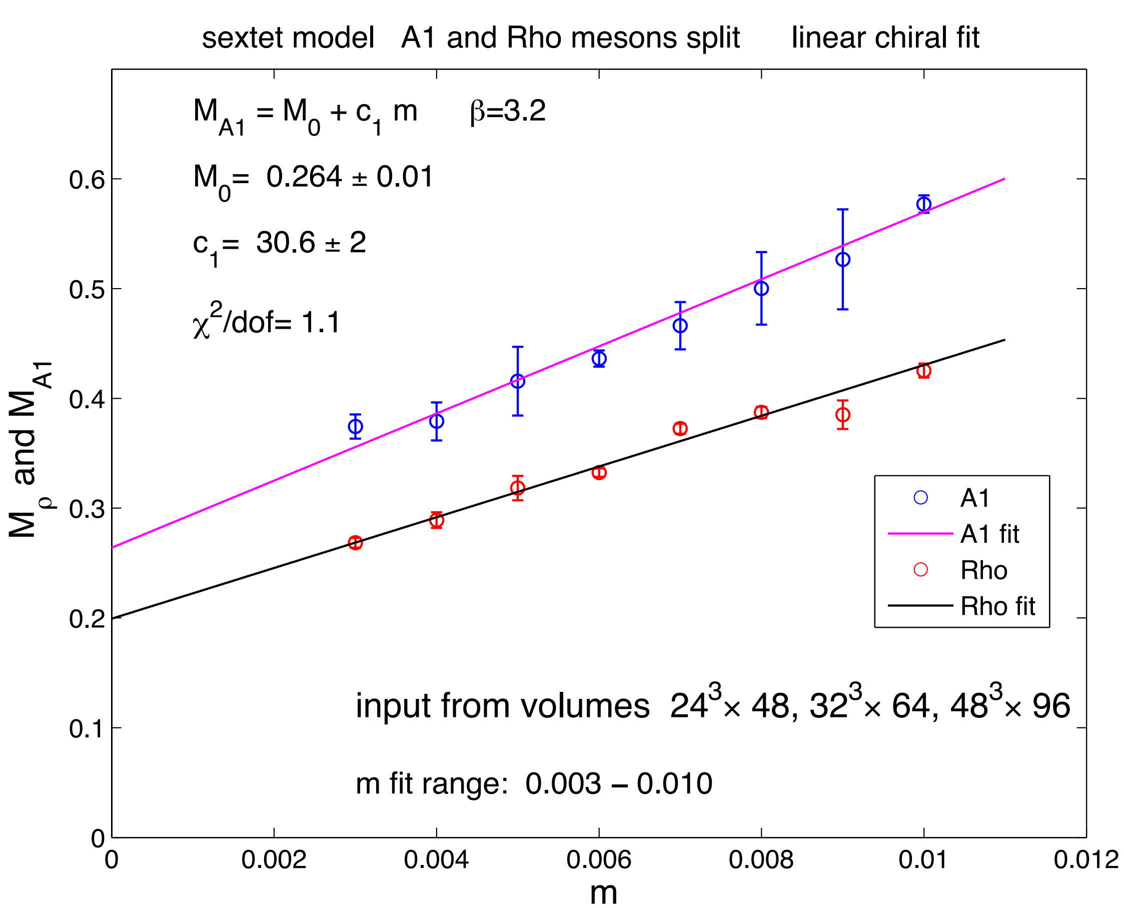

time history of Q topological charge
on gradient flow
Q topological charge
MD time
0
100
200
300
400
500
600
700
4
4.5
5
5.5

Spectroscopy and scale setting

sextet N_f=2







A1/F ~ 9.5

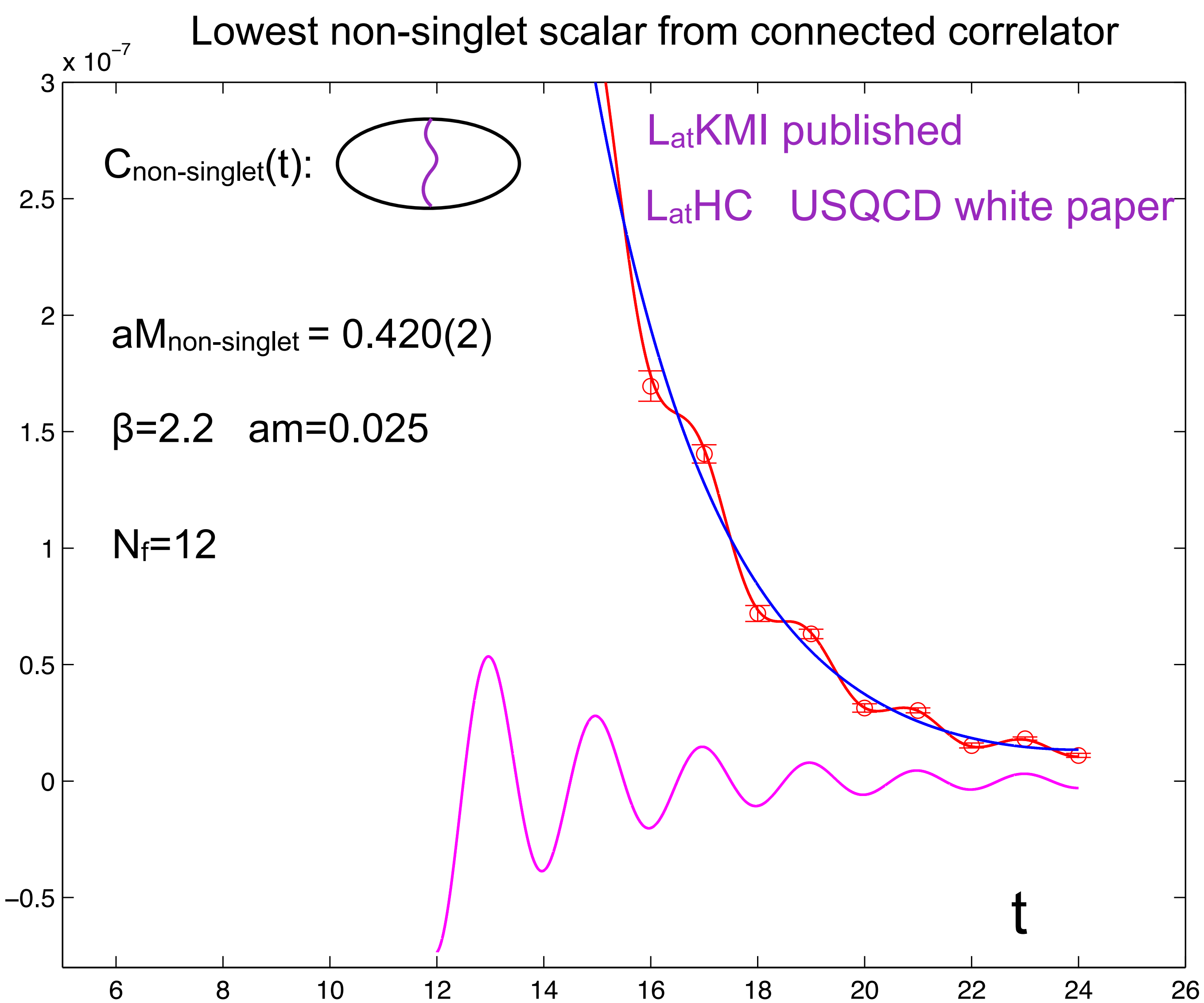
M_{A1}~ 2.37 TeV

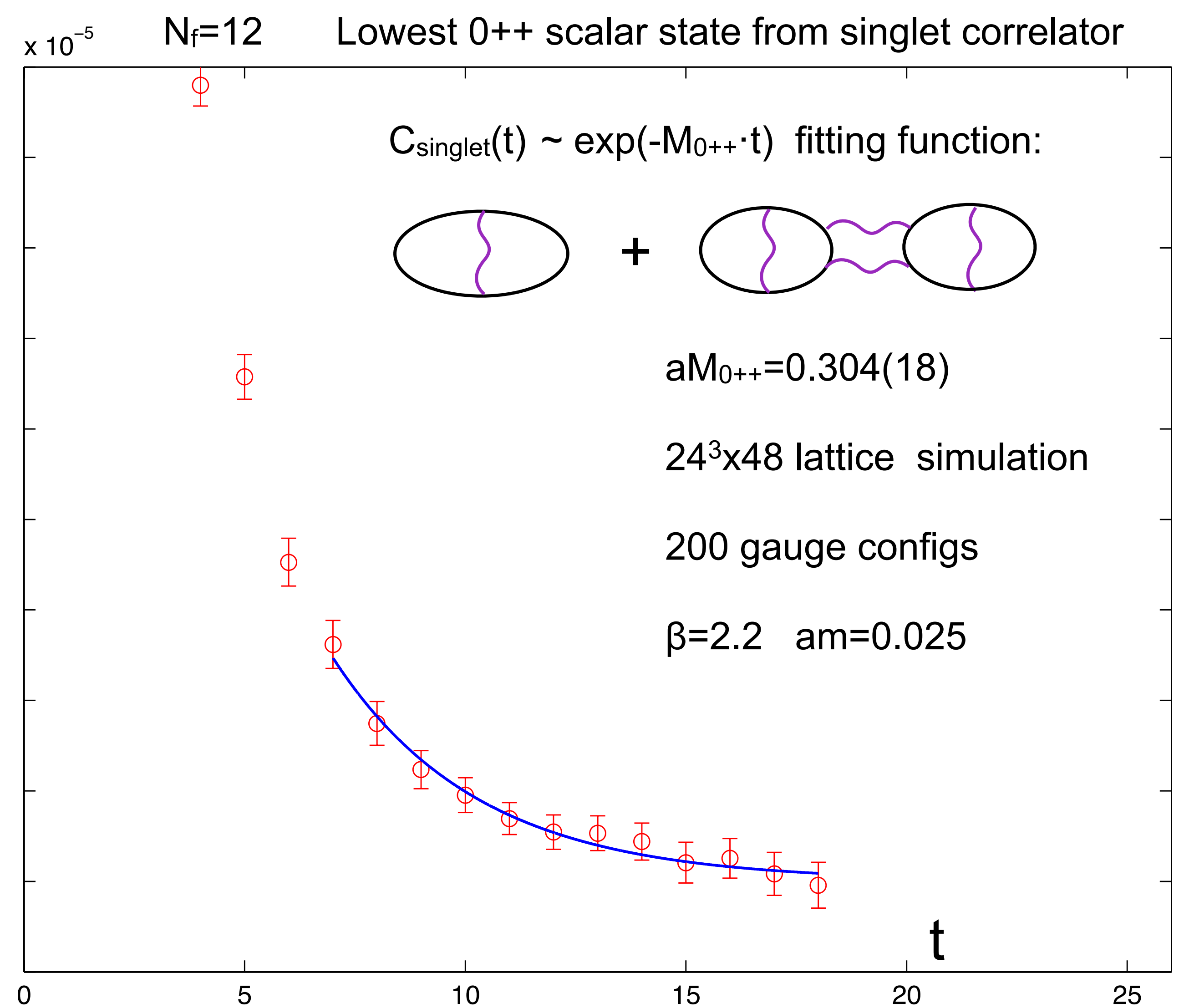
LHC14?

- Nf=2 SU(3) sextet M_{a0}, M_ρ, and M_{A1}
- three lowest states above light scalar “Higgs state”

Spectroscopy and scale setting (scalar) $N_f=12$

test of technology:





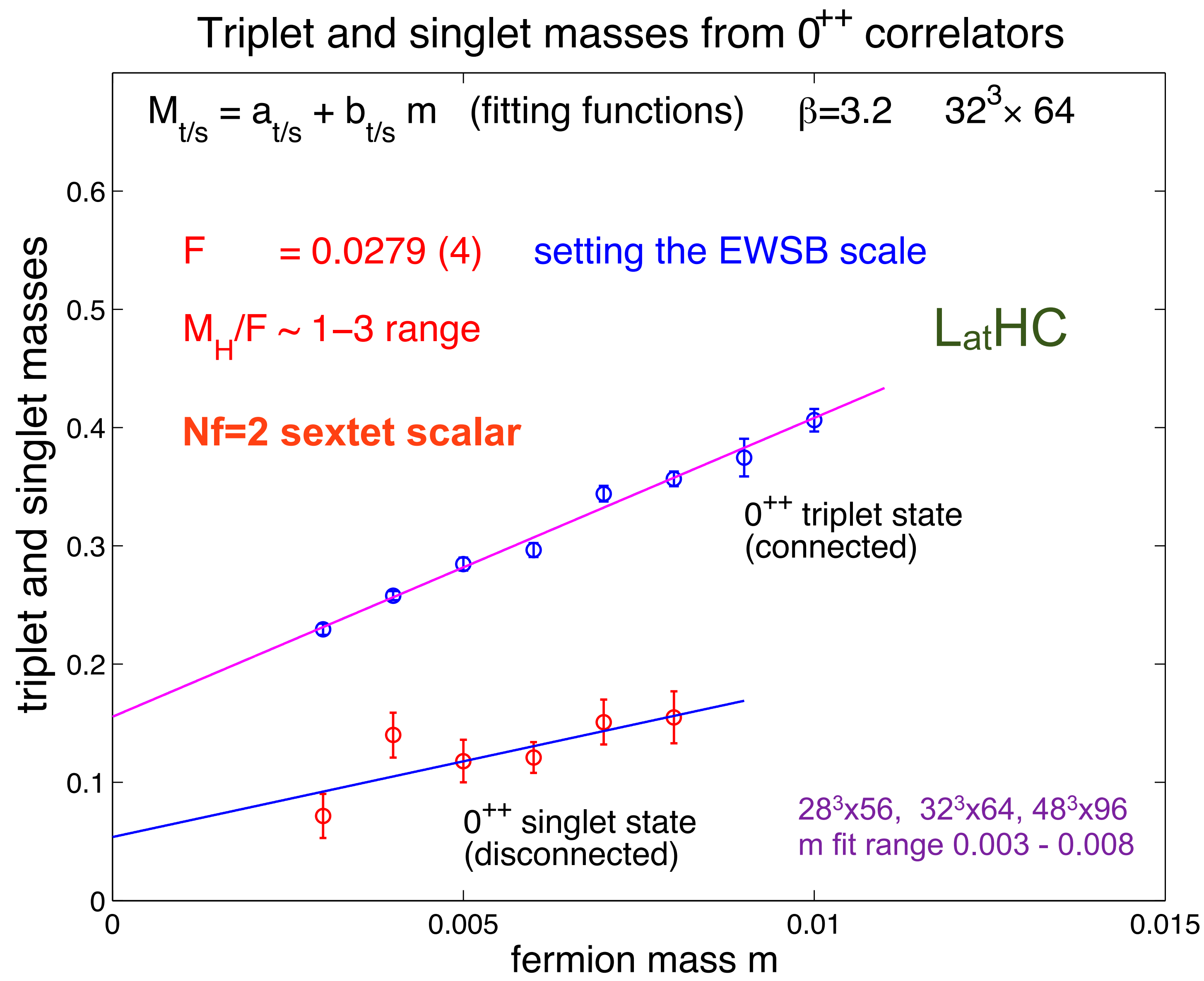
$$C(t) = \sum_n \left[A_n e^{-m_n(\Gamma_S\otimes\Gamma_T)t} + (-1)^t B_n e^{-m_n(\gamma_4\gamma_5\Gamma_S\otimes\gamma_4\gamma_5\Gamma_T)t}\right]$$

staggered correlator

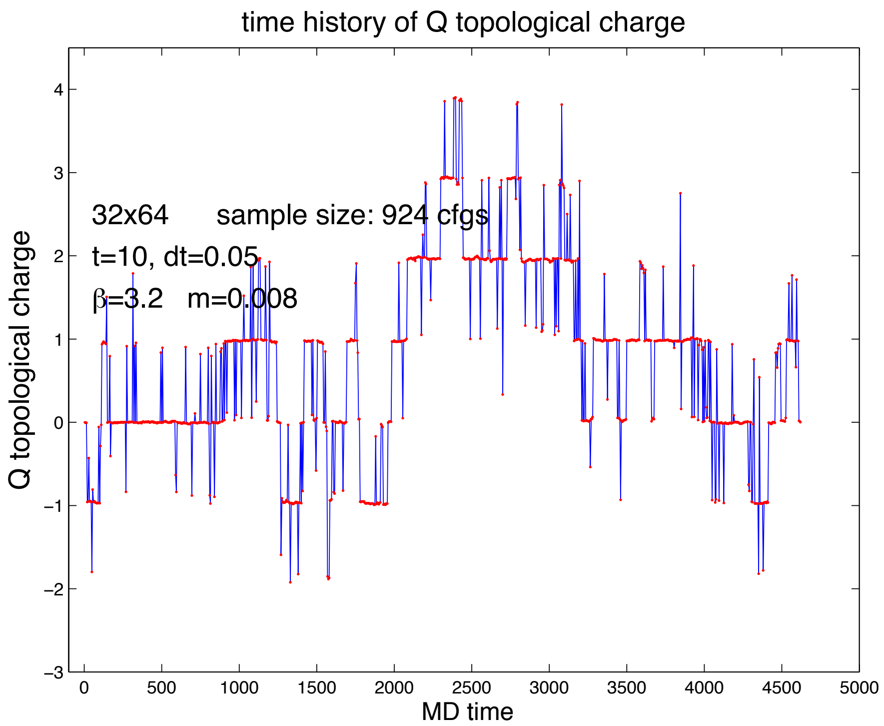
similar analysis in sextet model with $N_f=2$

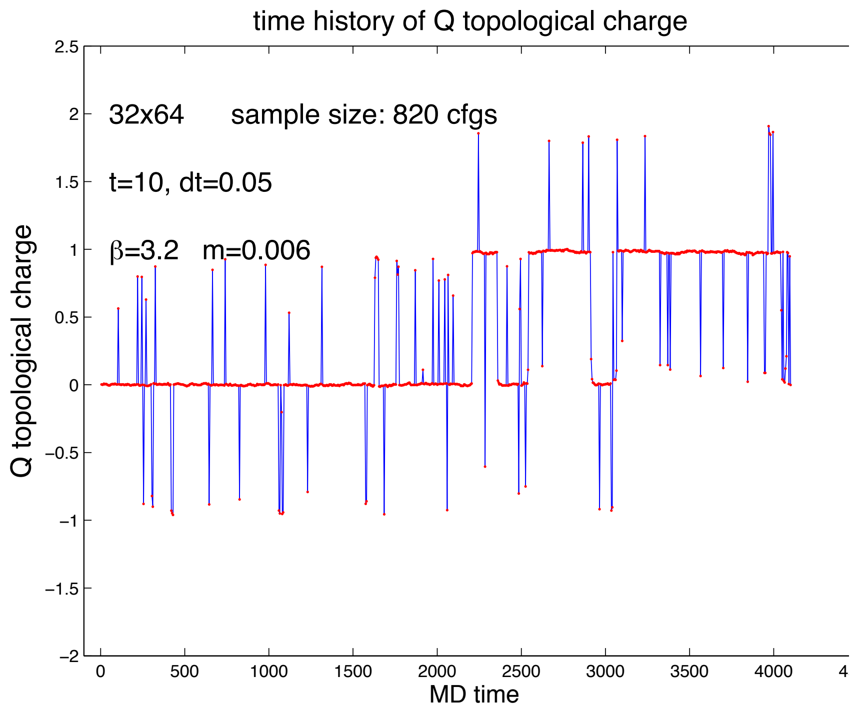
Spectroscopy (scalar)

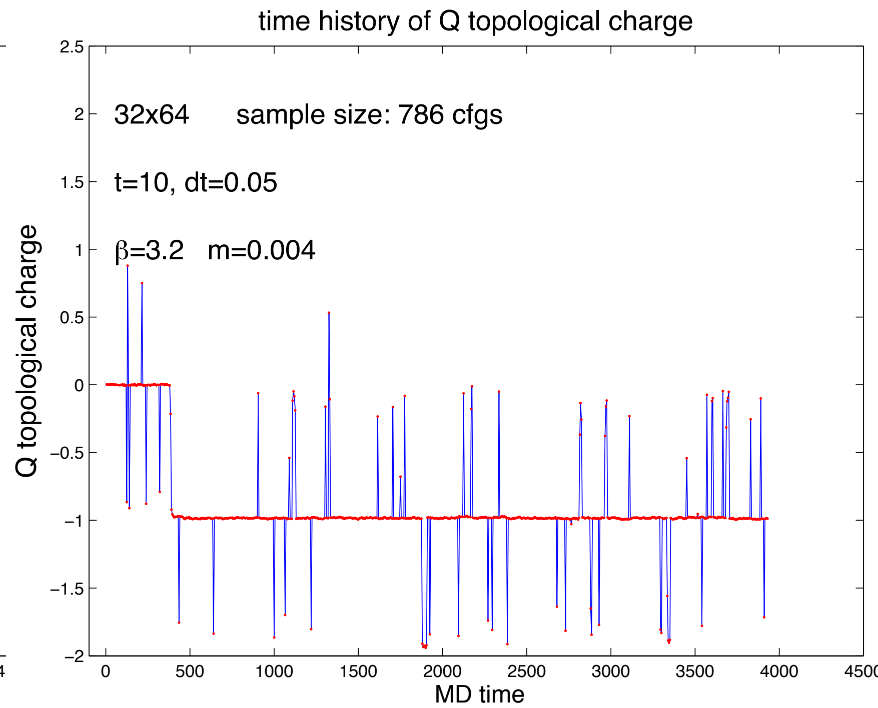
sextet rep N_f=2



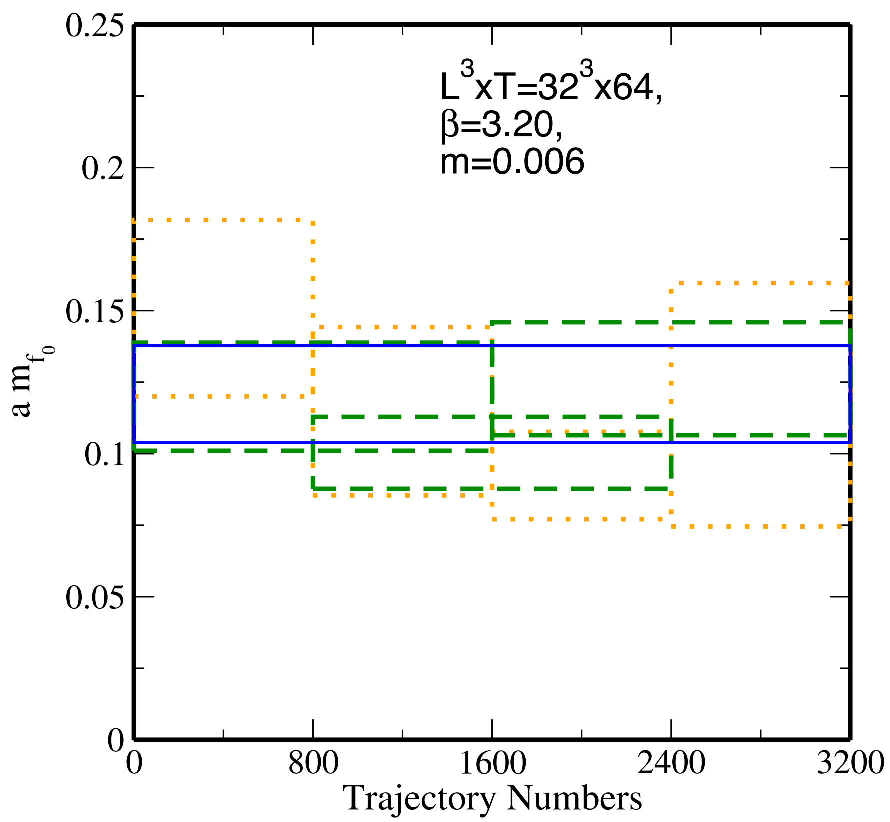
slowly changing topology complicates the analysis:





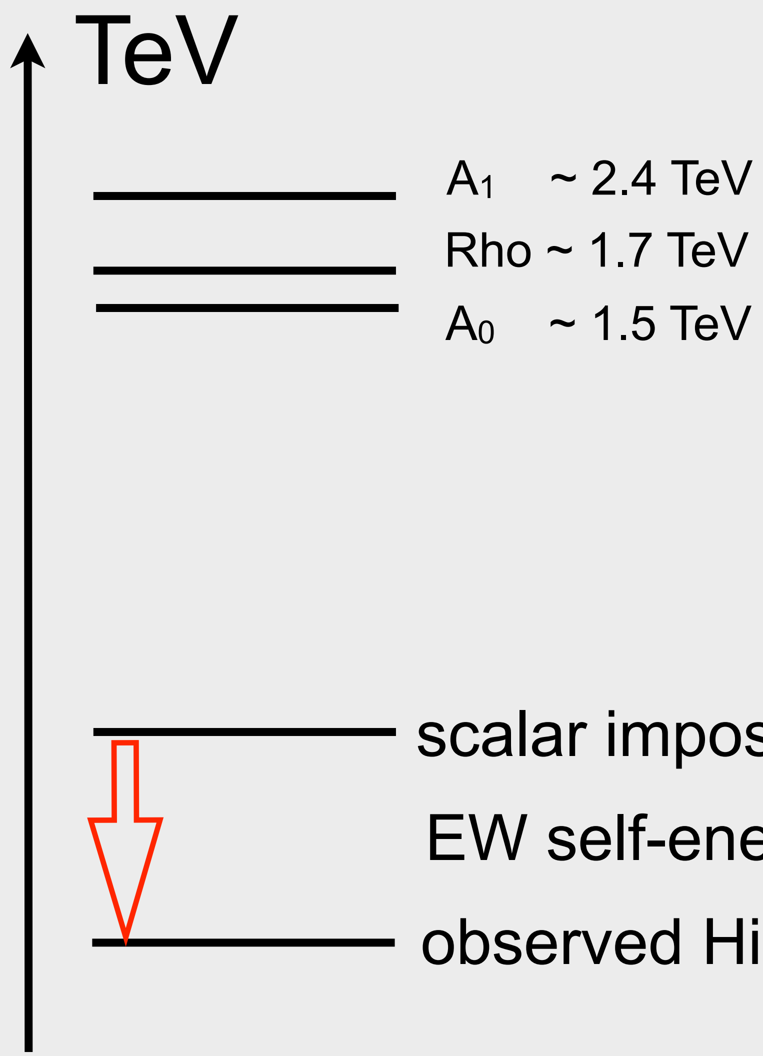


- challenging to deal with it
- effect on scalar spectrum is hardly detectable
- slow topology can be synthesized by stochastic algorithms but its practical utilization is unclear
- slowly changing topology perhaps can be accelerated in open segments of very long lattices in time direction?
- or take the bullet and analyze at fixed topology



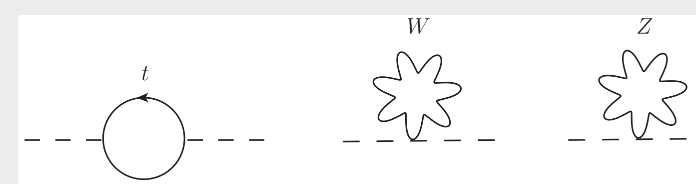
Spectroscopy for LHC14 run

sextet N_f=2



not ruled out from first LHC run
within reach of LHC14 run

LatHC is working on second generation precision



$$\delta M_H^2 \sim -12\kappa^2 r_t^2 m_t^2 \sim -\kappa^2 r_t^2 (600\,\mathrm{GeV})^2$$

light composite Higgs and EW constraints

Decay Mode	ATLAS	CMS	Tevatron
$H \to bb$	$0.2^{+0.7}_{-0.6}$	1.15 ± 0.62	$1.59^{+0.69}_{-0.72}$
$H \to \tau\tau$	$0.7^{+0.7}_{-0.6}$	1.10 ± 0.41	$1.68^{+2.28}_{-1.68}$
$H \to \gamma\gamma$	$1.55^{+0.33}_{-0.28}$	0.77 ± 0.27	$5.97^{+3.39}_{-3.12}$
$H \to WW^*$	$0.99^{+0.31}_{-0.28}$	0.68 ± 0.20	$0.94^{+0.85}_{-0.83}$
$H \to ZZ^*$	$1.43^{+0.40}_{-0.35}$	0.92 ± 0.28	
Combined	1.23 ± 0.18	0.80 ± 0.14	$1.44^{+0.59}_{-0.56}$

$$\mu \equiv \sigma \cdot \mathrm{Br}/(\sigma_{\mathrm{SM}} \cdot \mathrm{Br}_{\mathrm{SM}})$$

$$\mu = 0.96 \pm 0.11$$

From Higgs potential and Top coupling:

M_H > 130 GeV absolute stable vacuum below M_{Planck}

observed Higgs -> Metastable vacuum?

$$\mathcal{L} = \frac{v^2}{4}\langle u_\mu u^\mu \rangle \left(1 + \frac{2\omega}{v} S_1\right) + \frac{F_A}{2\sqrt{2}}\langle A_{\mu\nu} f_-^{\mu\nu} \rangle + \frac{F_V}{2\sqrt{2}}\langle V_{\mu\nu} f_+^{\mu\nu} \rangle + \frac{iG_V}{2\sqrt{2}}\langle V_{\mu\nu}[u^\mu, u^\nu] \rangle + \sqrt{2}\lambda_1^{SA}\partial_\mu S_1 \langle A^{\mu\nu} u_\nu \rangle ,$$

effective theory of strongly coupled composite Higgs scenario

$$\omega \sim 1$$

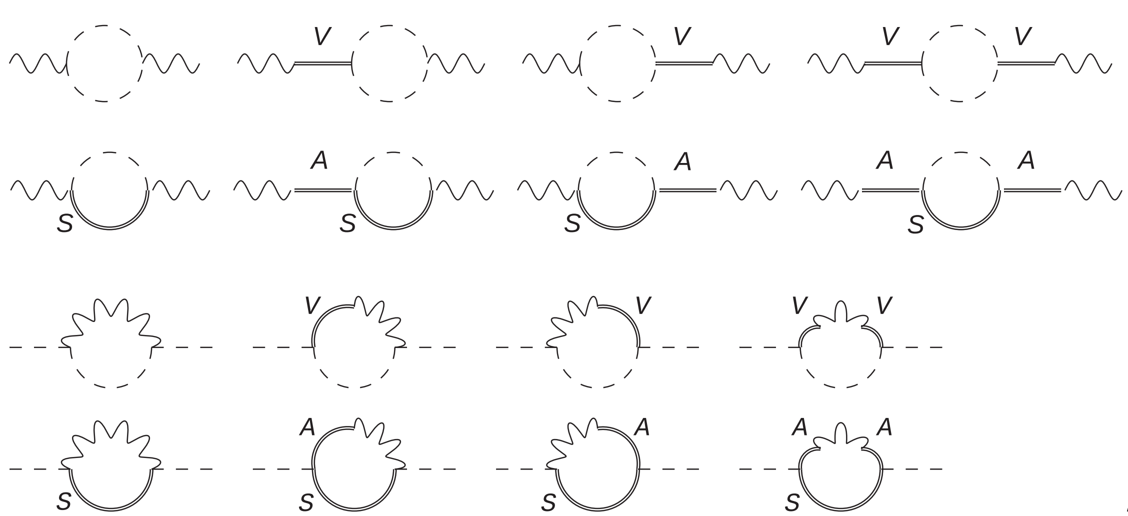
u: Goldstone

S: scalar (Higgs)

f: gauge field

A: axial resonances

V: vector resonance



NLO S-param

$$S = 0.03 \pm 0.10$$

global fits

NLO T-param

$$T = 0.05 \pm 0.12$$

light composite Higgs and EW constraints

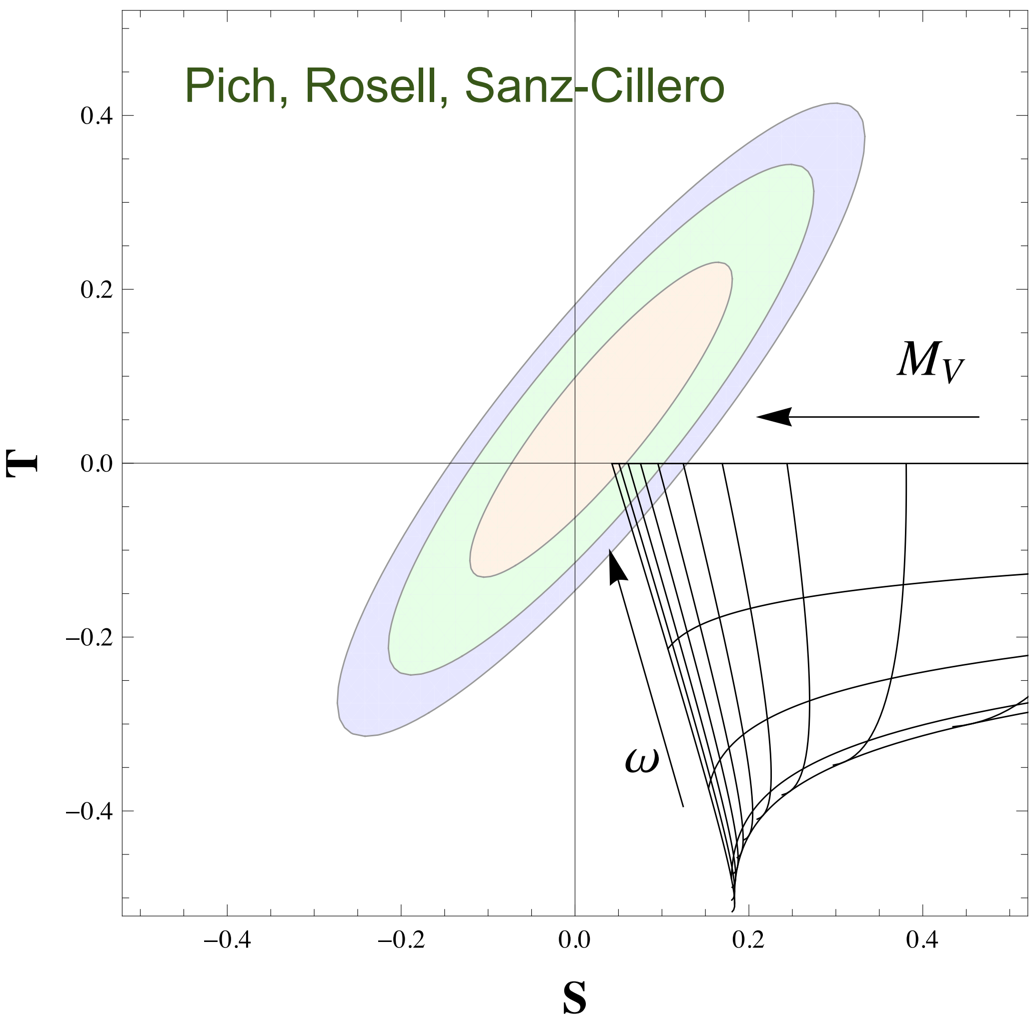


FIG. 2. NLO determinations of S and T, imposing the two WSRs. The approximately vertical curves correspond to constant values of M_V, from 1.5 to 6.0 TeV at intervals of 0.5 TeV. The approximately horizontal curves have constant values of ω: 0.00, 0.25, 0.50, 0.75, 1.00. The arrows indicate the directions of growing M_V and ω. The ellipses give the experimentally allowed regions at 68% (orange), 95% (green) and 99% (blue) CL.

$$S = \frac{16\pi}{g^2 \tan\theta_W} \int_0^\infty \frac{\mathrm{dt}}{t} \left[\rho_S(t) - \rho_S(t)^{\mathrm{SM}} \right]$$

$$S_{\mathrm{LO}} = 4\pi \left(\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2} \right)$$

$$T = \frac{4\pi}{g'^2 \cos^2\theta_W} \int_0^\infty \frac{\mathrm{dt}}{t^2} \left[\rho_T(t) - \rho_T(t)^{\mathrm{SM}} \right]$$

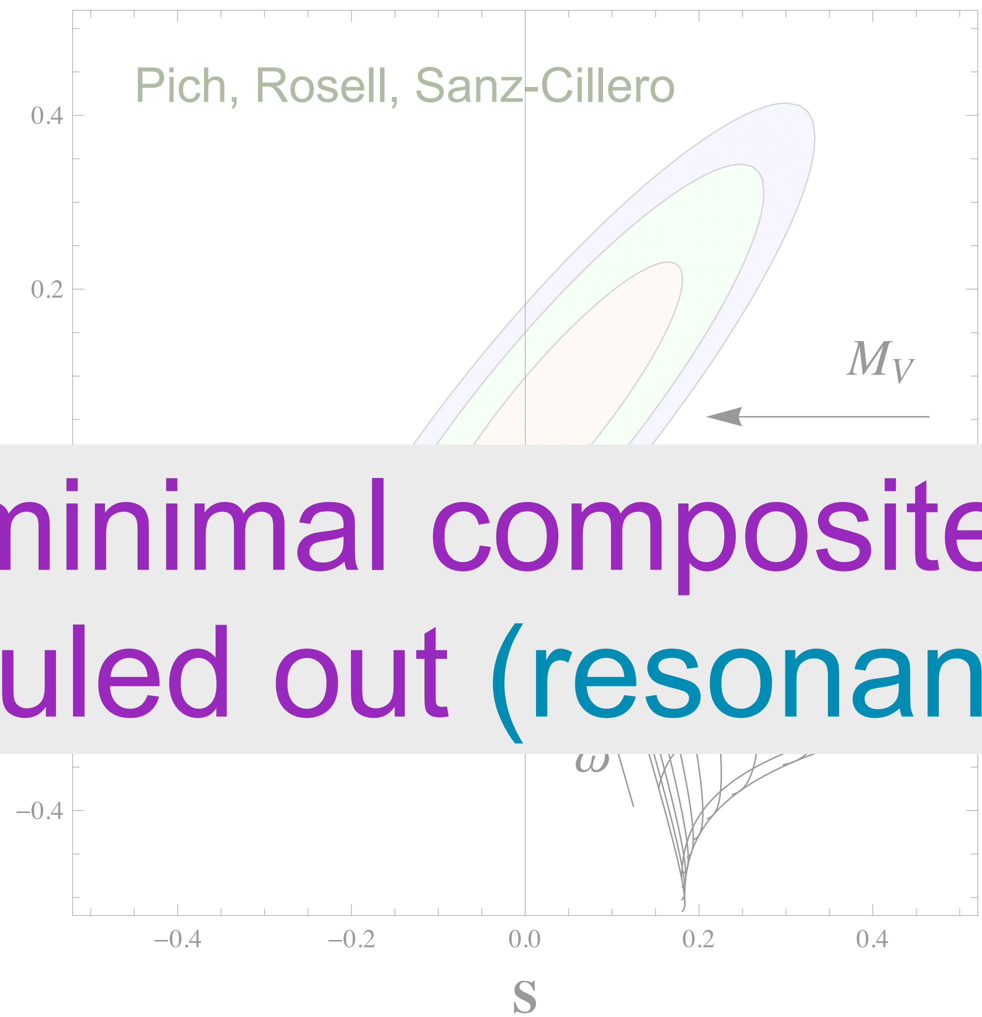
From two Weinberg sum rules and from NLO loop expansion:

M_V, M_A ~ 2 TeV or higher is compatible with S,T constraints (it is tight and arguably ambiguous)

more work needed

related body of work by Sannino and collaborators

light composite Higgs and EW constraints



$$S = \frac{16\pi}{g^2 \tan\theta_W} \int_0^\infty \frac{dt}{t} \left[\rho_S(t) - \rho_S(t)^{SM} \right]$$

$$S_{LO} = 4\pi \left(\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2} \right)$$

minimal composite Higgs in sextet rep is not ruled out (resonance spectrum in 2 TeV range)

FIG. 2. NLO determinations of S and T, imposing the two WSRs. The approximately vertical curves correspond to constant values of M_V, from 1.5 to 6.0 TeV at intervals of 0.5 TeV. The approximately horizontal curves have constant values of ω: 0.00, 0.25, 0.50, 0.75, 1.00. The arrows indicate the directions of growing M_V and ω. The ellipses give the experimentally allowed regions at 68% (orange), 95% (green) and 99% (blue) CL.

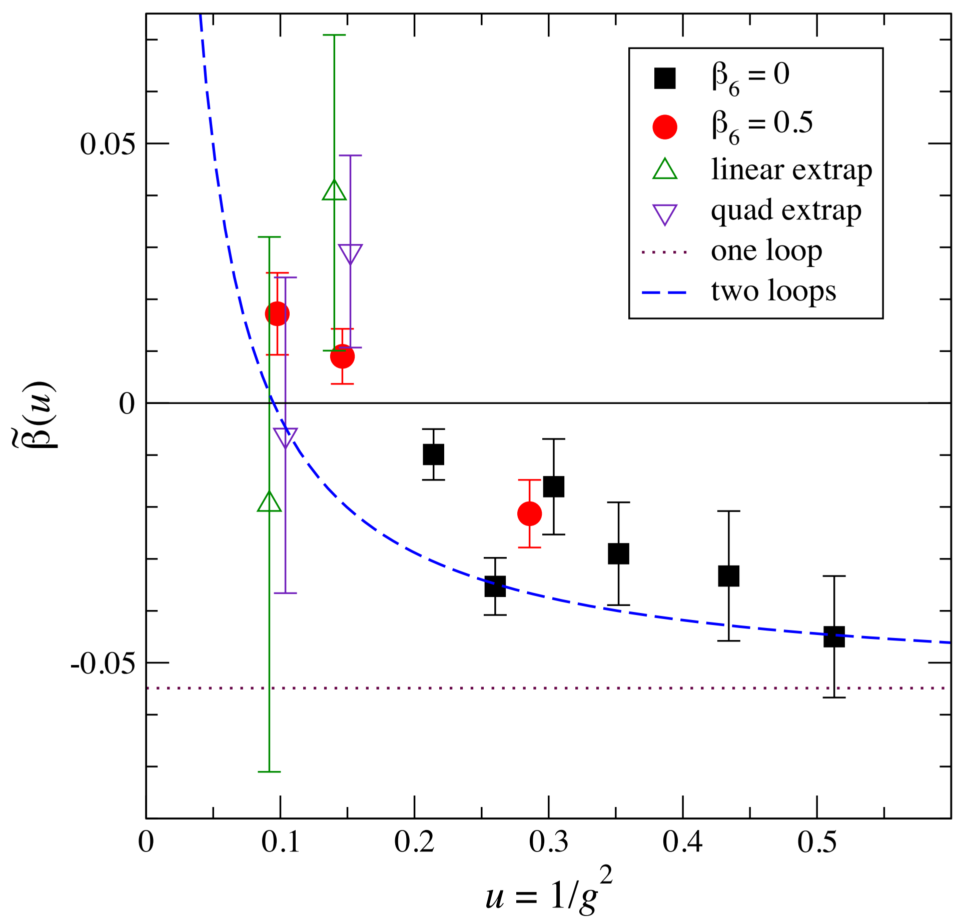
From two Weinberg sum rules and from NLO loop expansion:

M_V, M_A ~ 2 TeV or higher is compatible with S,T constraints (it is tight and arguably ambiguous)

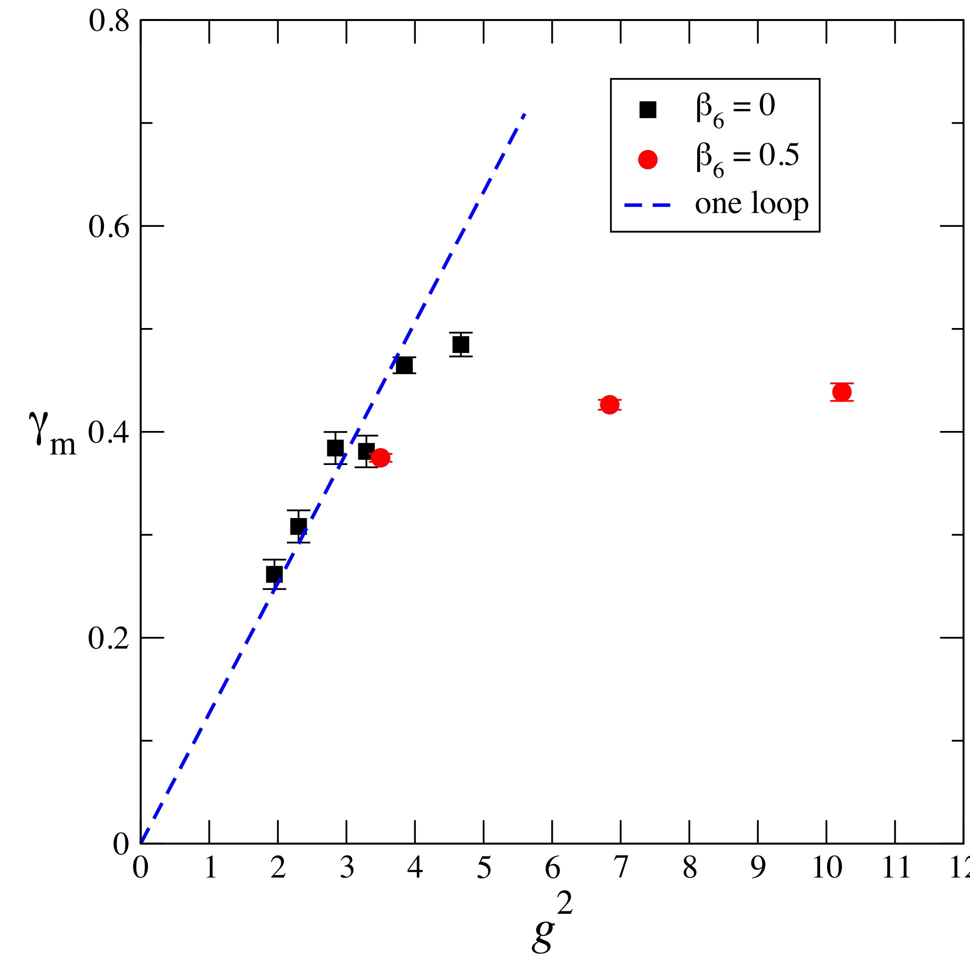
more work needed

related body of work by Sannino and collaborators

running coupling and beta function from gradient flow   sextet rep



DeGrand
Shamir
Svetitsky



authors: We cannot confirm the existence of an infrared fixed point

in authors' final analysis anomalous dimension remains ~ 0.4 at large renormalized couplings

LHC group has the gradient flow beta function (no zero) and the anomalous dimension growing far above 0.4 (from Dirac spectrum) - incomplete analysis
consistent with chiral SB

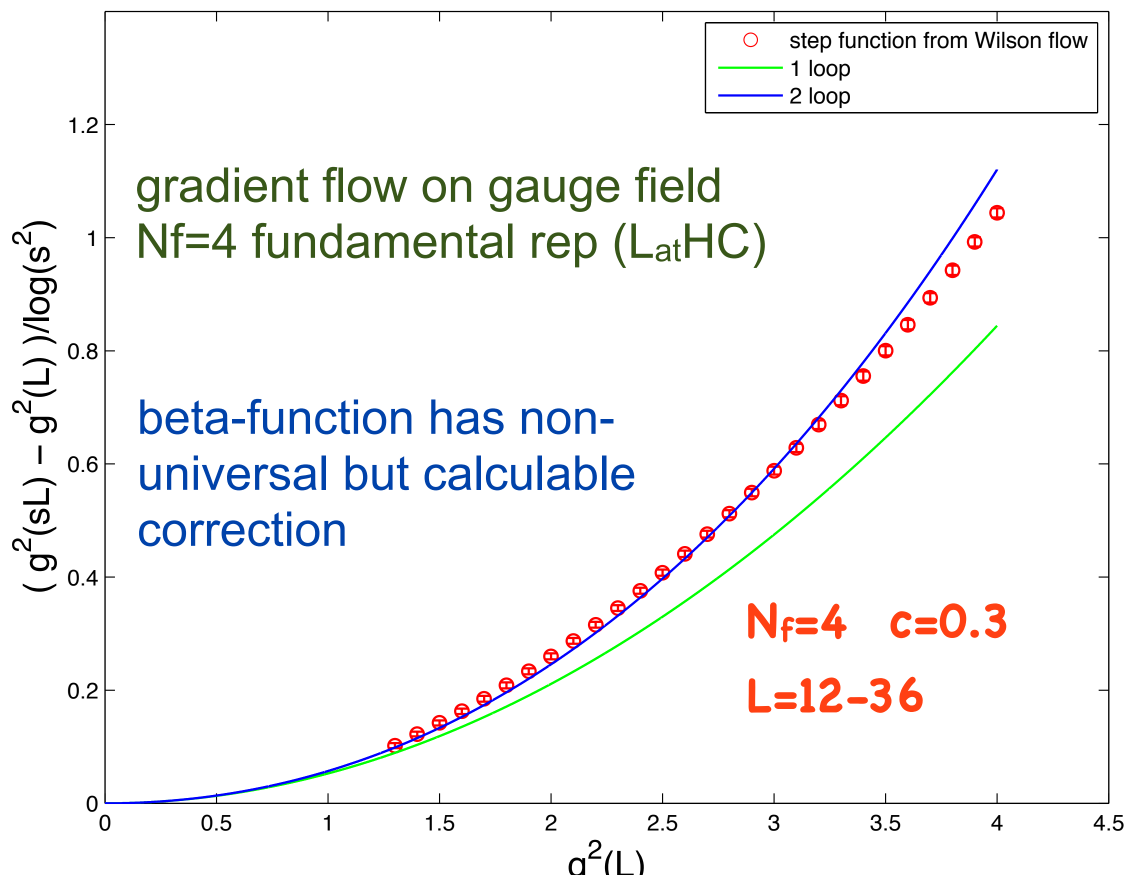
running coupling and beta function from gradient flow sextet rep

L-dependent running coupling definition from gauge field gradient flow

$$\langle E(t)\rangle = \frac{3}{4\pi t^2}\alpha(q)\{1+k_1\alpha(q)+O(\alpha^2)\}, \quad q=\frac{1}{\sqrt{8t}}, \quad k_1 = 1.0978 + 0.0075\times N_f$$

while holding $c=(8t)^{1/2}/L$ fixed: $\quad \alpha_c(L) = \frac{4\pi}{3}\frac{\langle t^2 E(t)\rangle}{1+\delta(c)}$

$$\delta(c) = \vartheta_3^4(e^{-1/c^2}) - 1 - \frac{c^4\pi^2}{3}$$

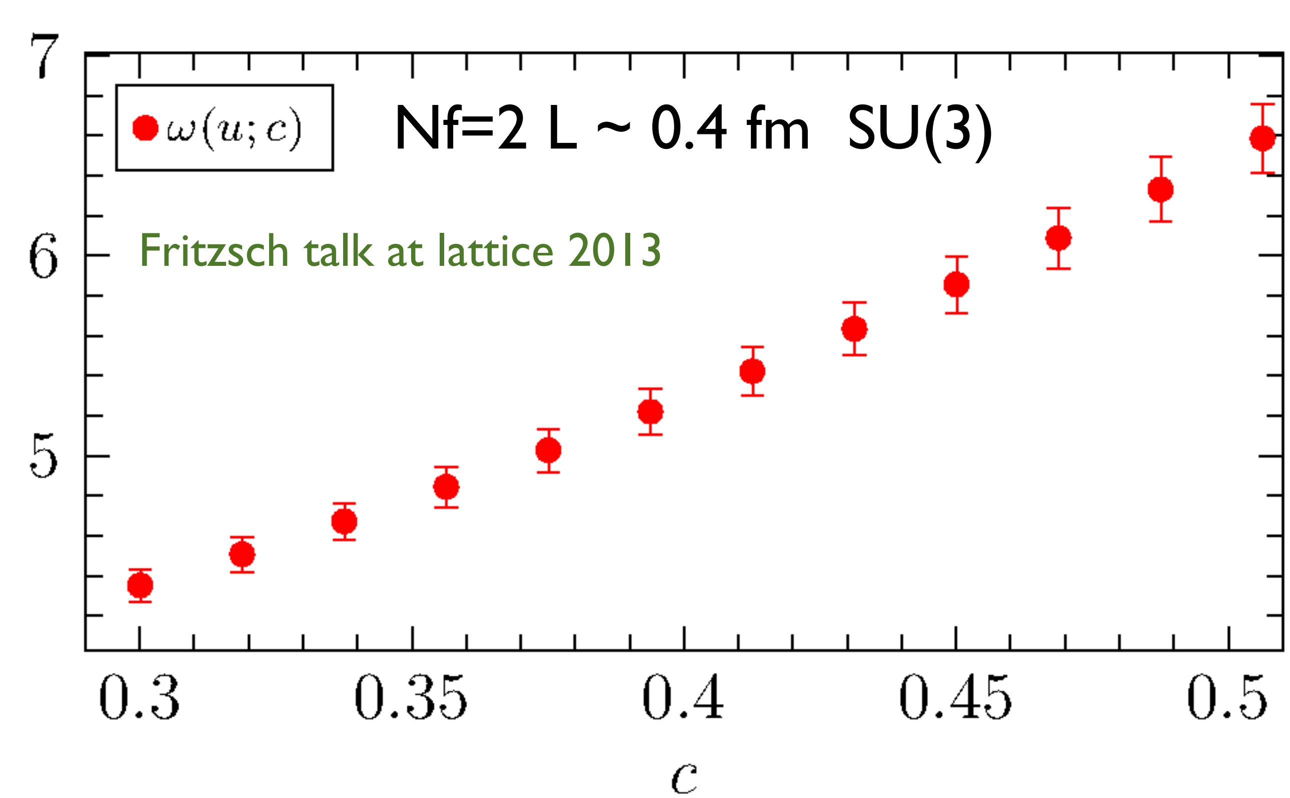


massless fermions; antiperiodic all directions

s=1.5 step N_f=4 staggered fermions; 4-stout; L=12-36

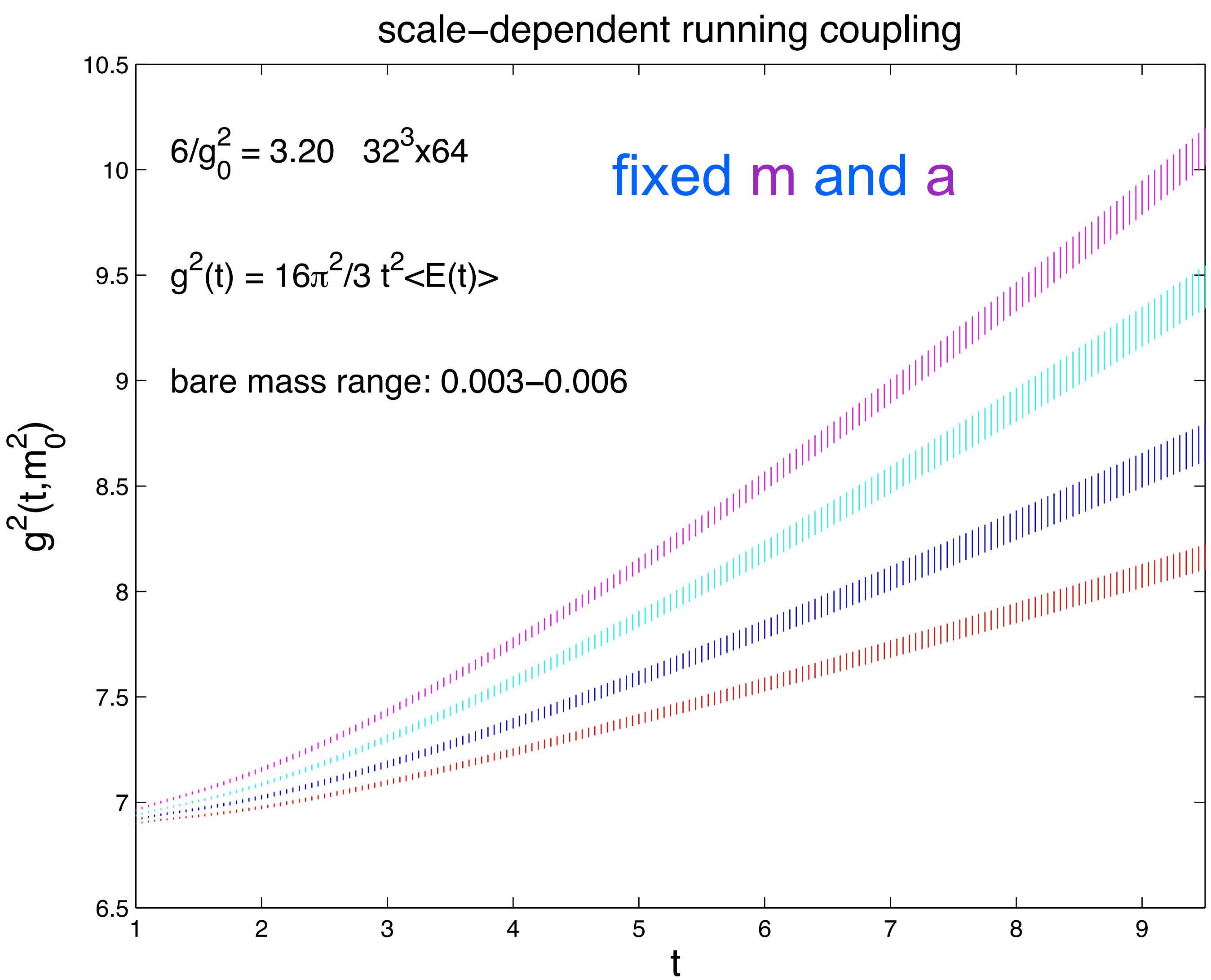
we have results for Nf=8,12 and Nf=2 sextet

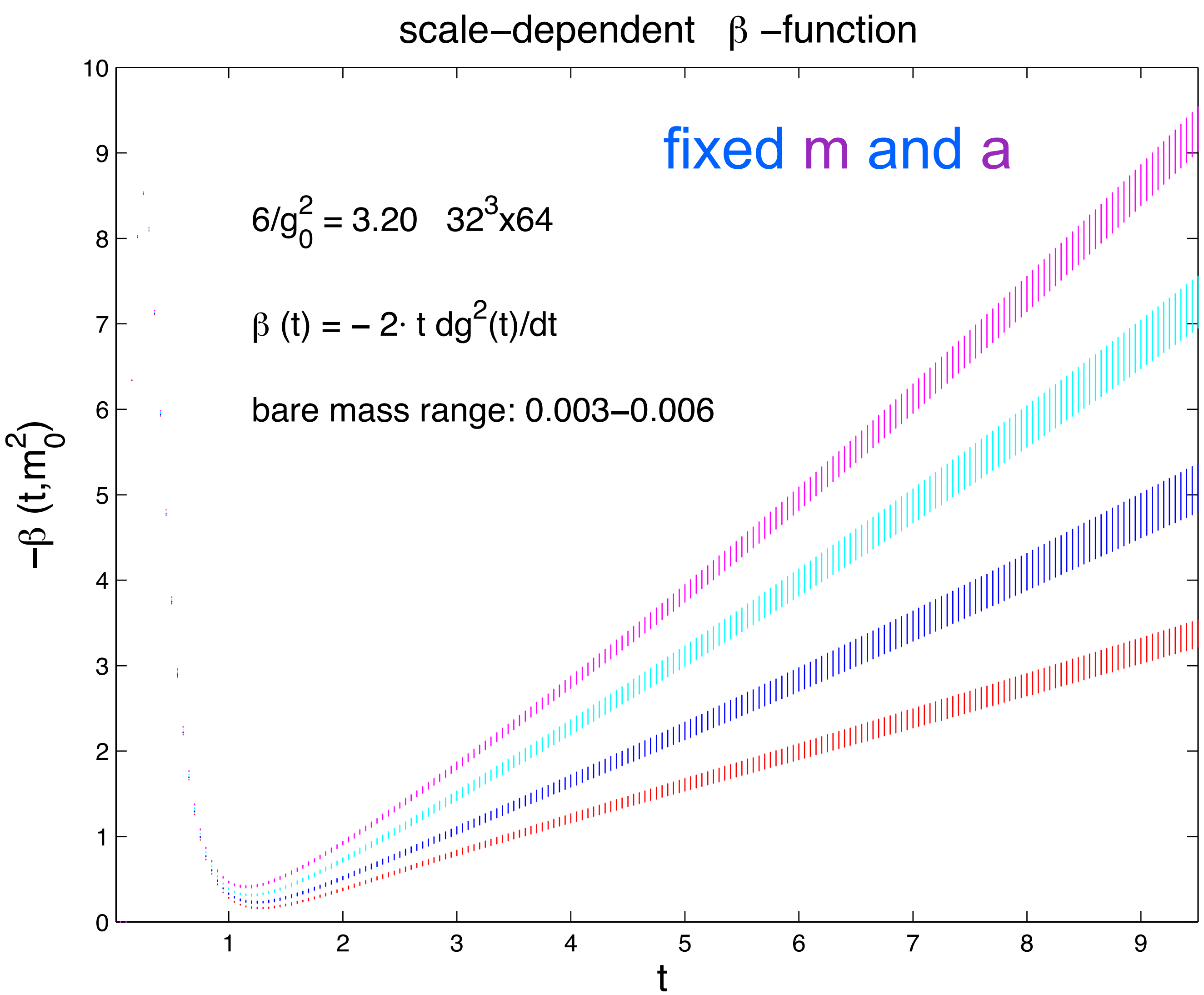
gradient flow coupling with SF boundary conditions



beta-function has conventional loop expansion

scale-dependent running coupling from gauge field gradient flow





freeze-out from N_f=3 to N_f=2 inside conformal window
mass-dependent beta-function of sextet model
MOM scheme

- **position of IRFP inside CW not tunable with m**
- **plateau length tunable, its position is not (in or out)**

$$\mu \frac{d}{d\mu}\alpha(\mu) = -\alpha(\mu)^2 \pi^{-1}\left[\beta_0 + \beta_1 \cdot \alpha(\mu)\right]$$

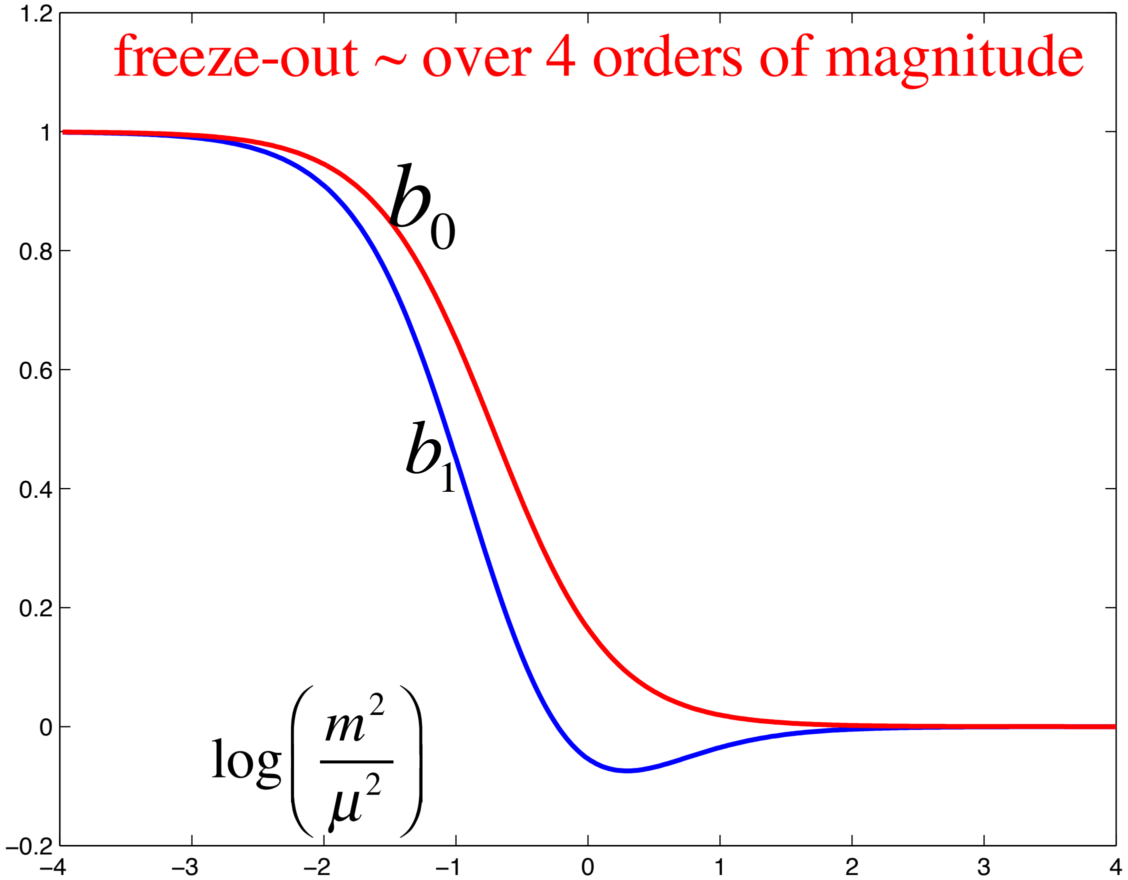
$$\beta_0 = \frac{11}{6}C_A - \frac{2}{3}T_F\sum_f b_0(x), \qquad x = \frac{m_f^2}{\mu^2}$$

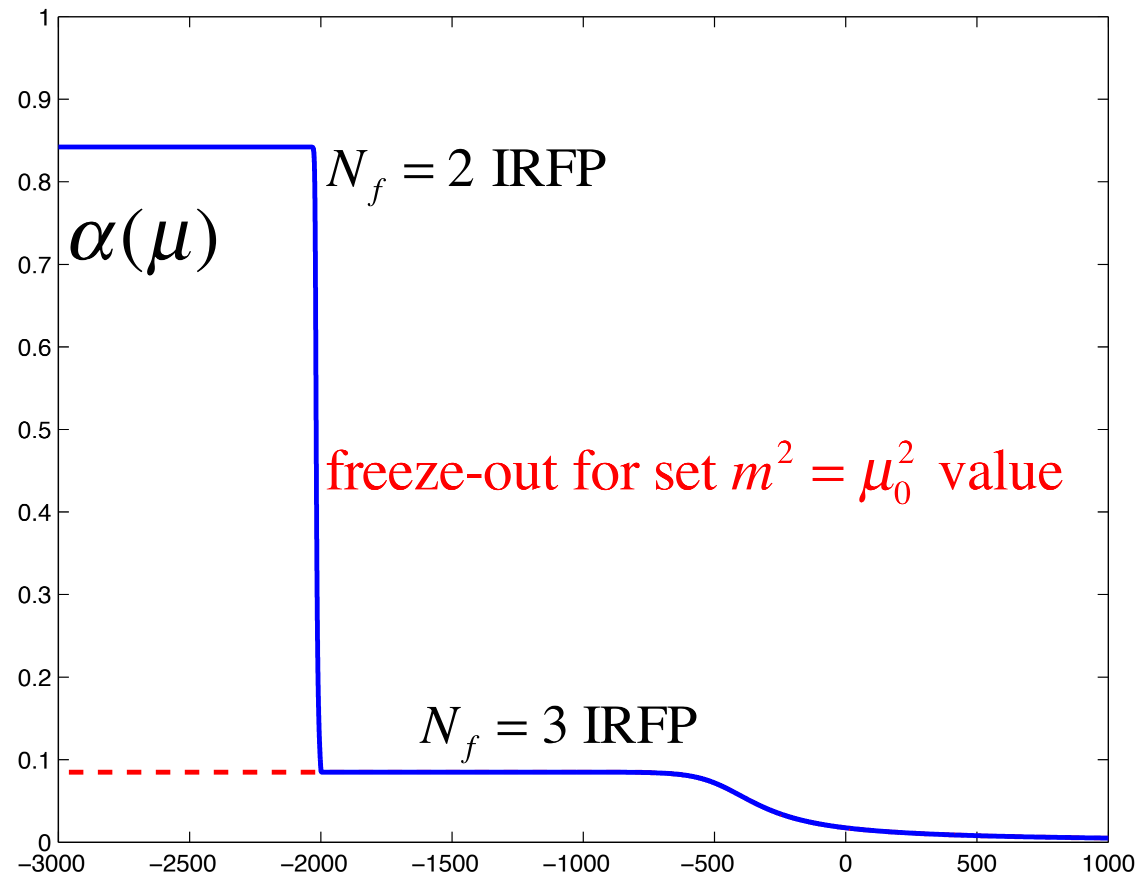
$$b_0(x) = 1 - 6x + \frac{12x^2}{\sqrt{1+4x}}\ln\frac{\sqrt{1+4x}+1}{\sqrt{1+4x}-1}$$

$$\beta_1(x) = \frac{17}{12}C_A^2 - (\frac{5}{6}C_A + \frac{1}{2}C_F)\cdot T_F\sum_f b_1(x)$$

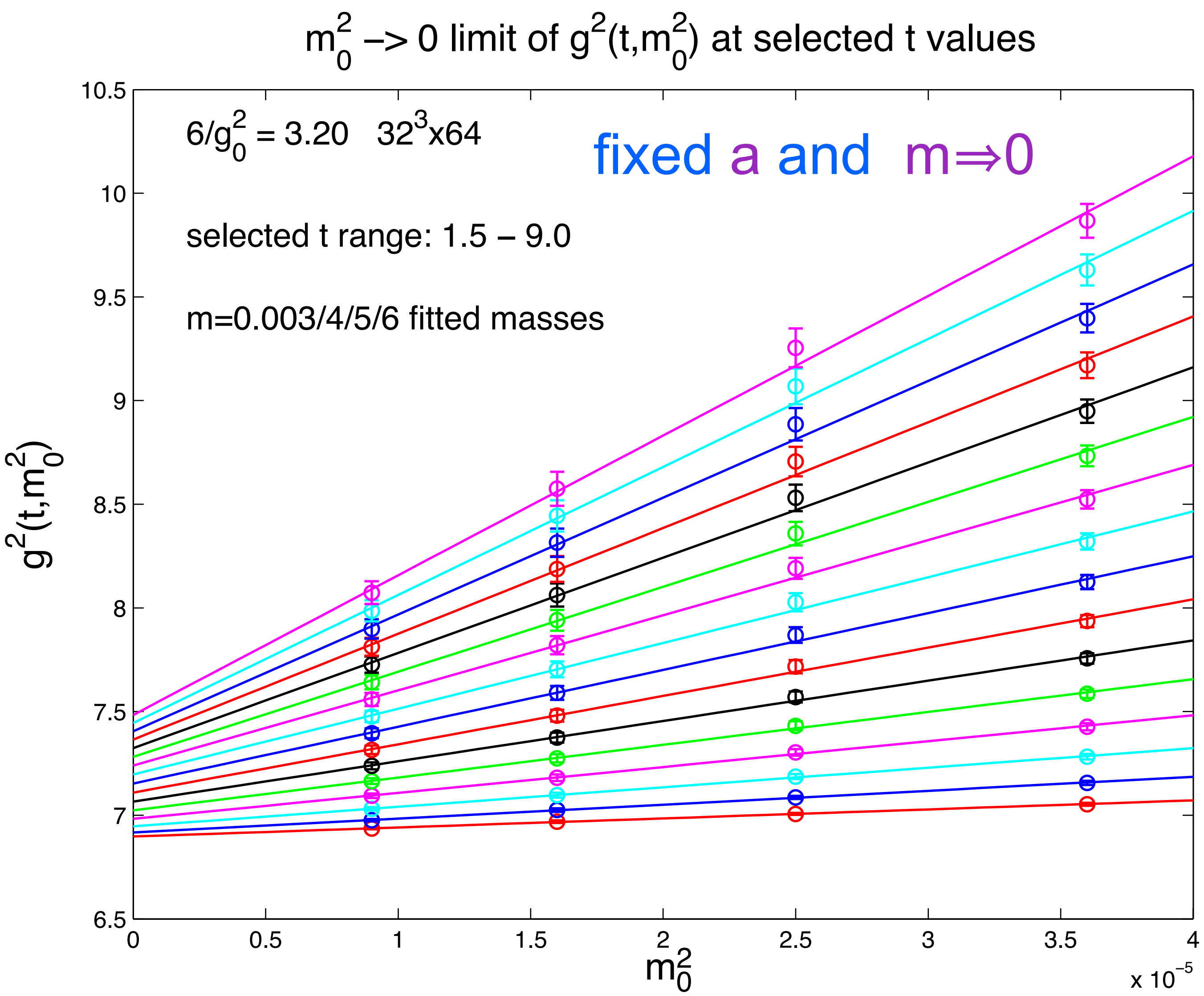
$$b_1(x) = \frac{-0.45577x + 0.26995}{x^2 + 2.1742x + 0.26995}$$

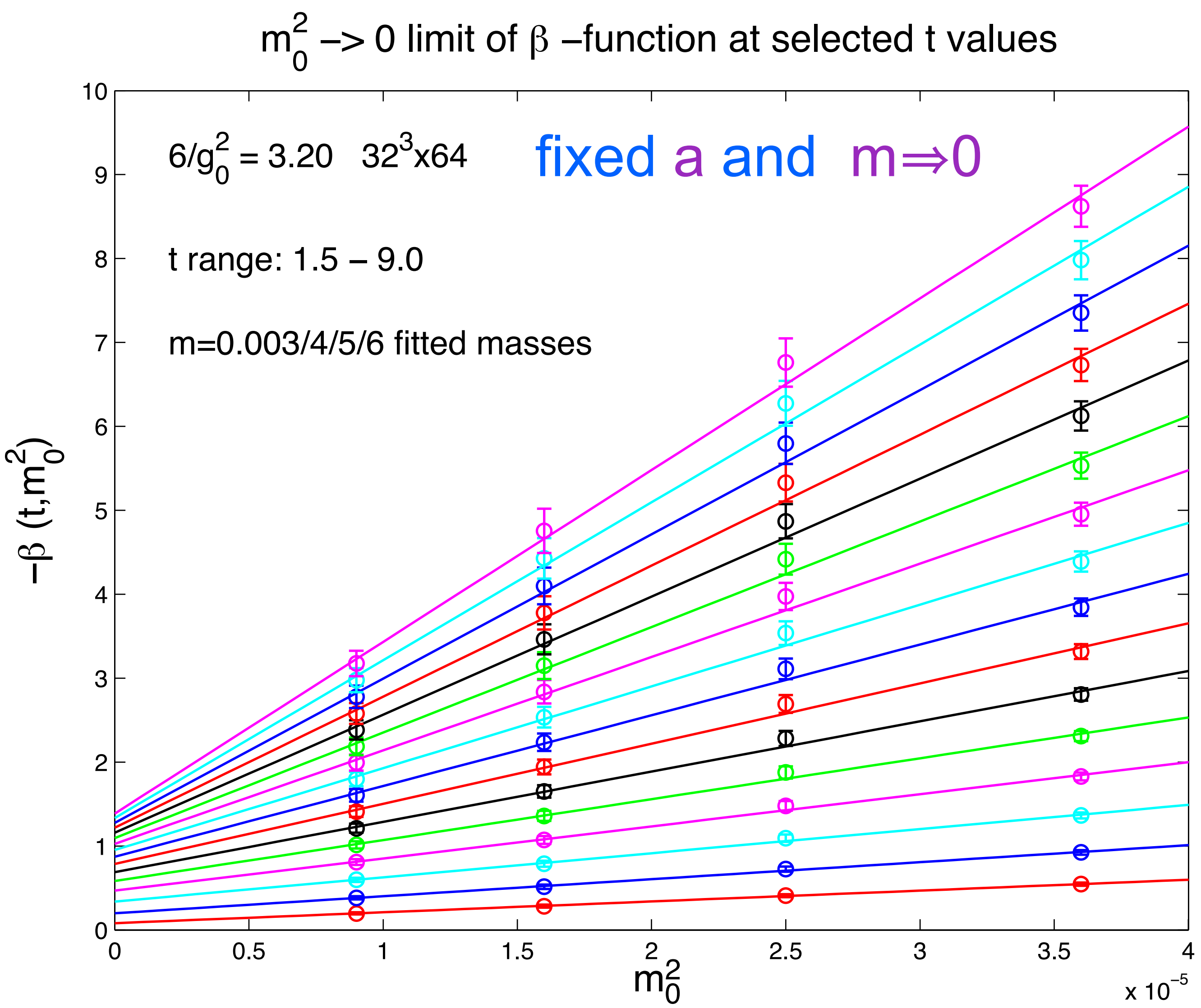
sextet parameters: $C_A = 3$; $C_F = \frac{10}{3}$; $T_F = \frac{5}{2}$



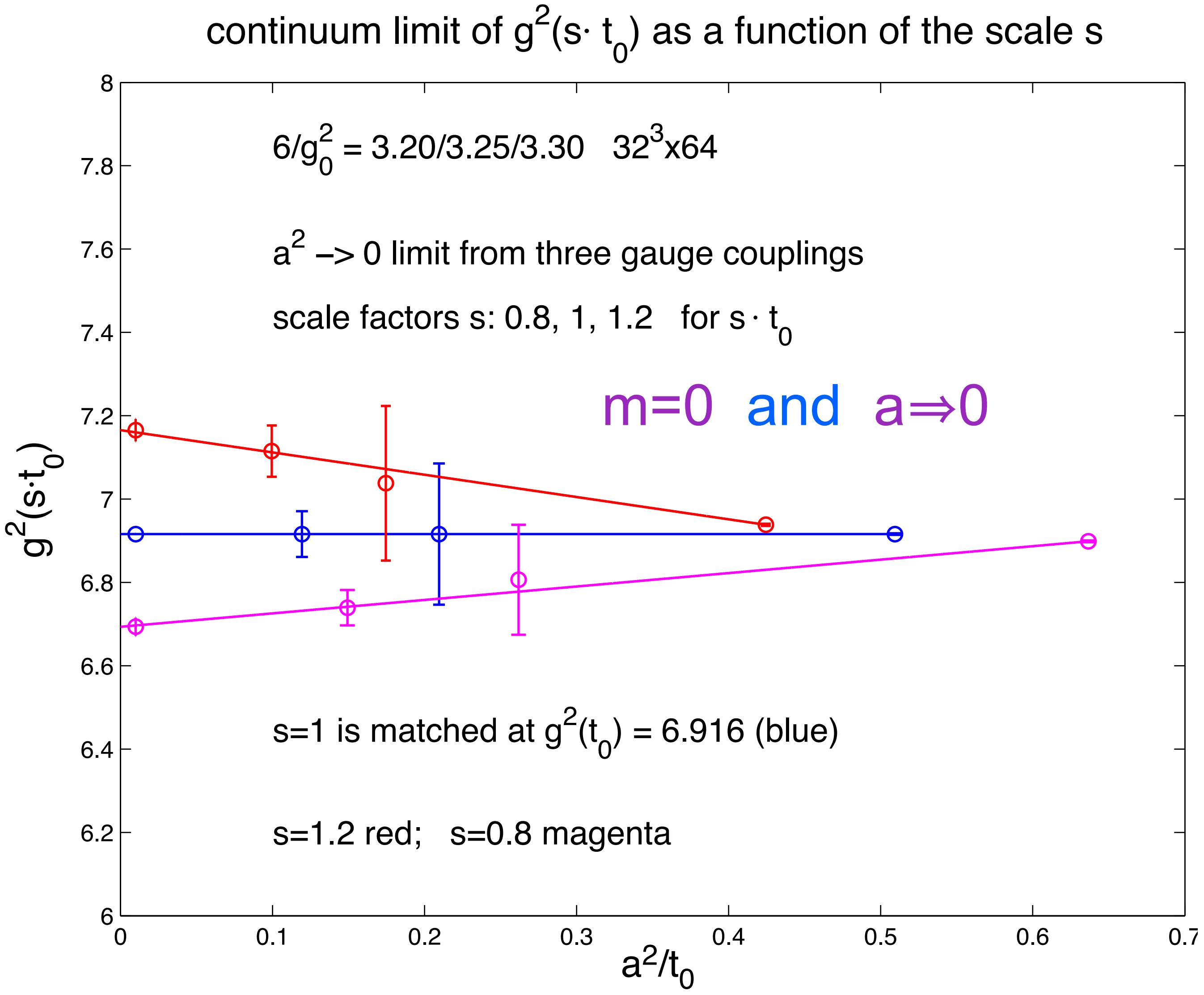


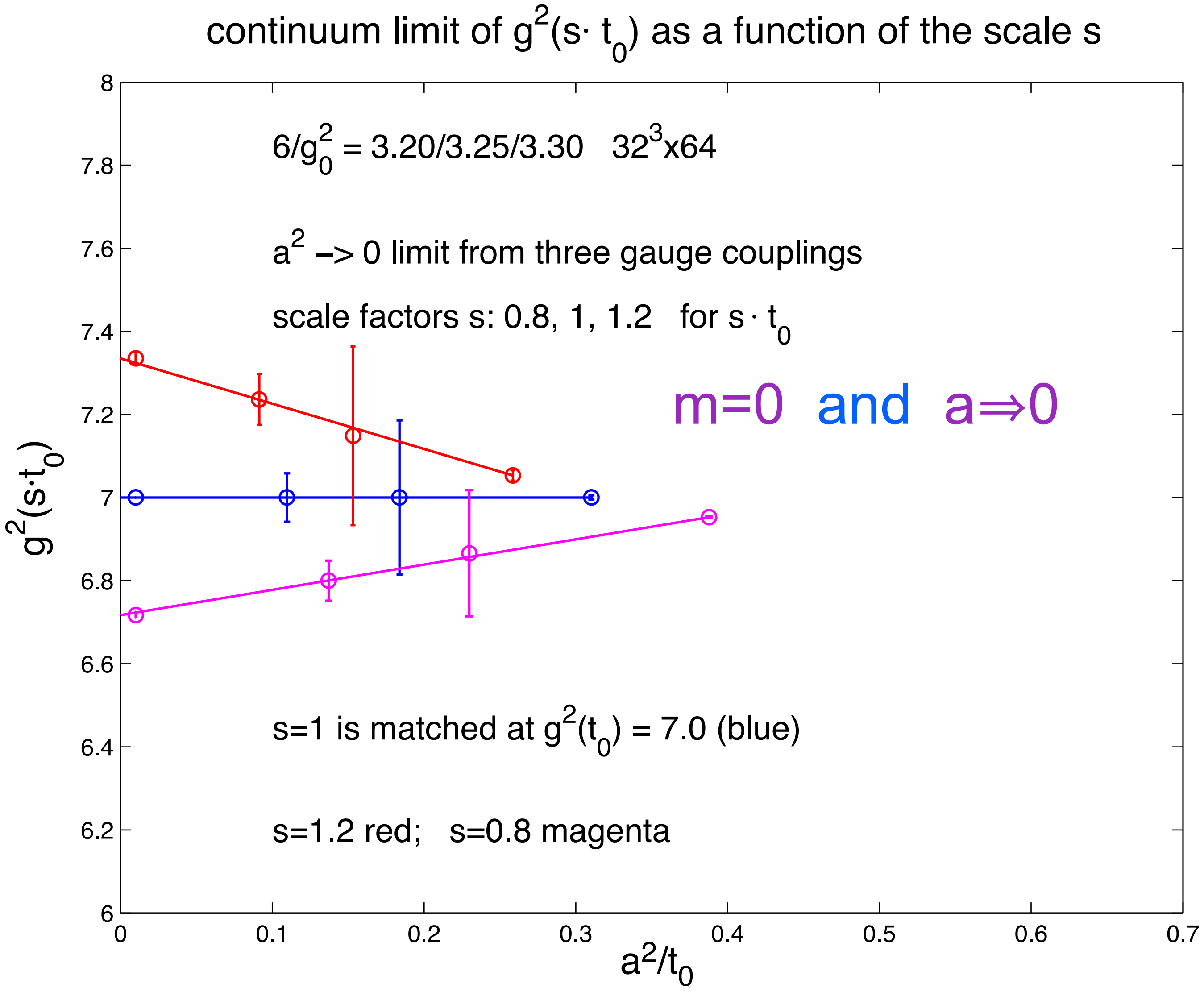
scale-dependent running coupling from gauge field gradient flow





scale-dependent running coupling from gauge field gradient flow





The chiral (Higgs) condensate

- New stochastic method

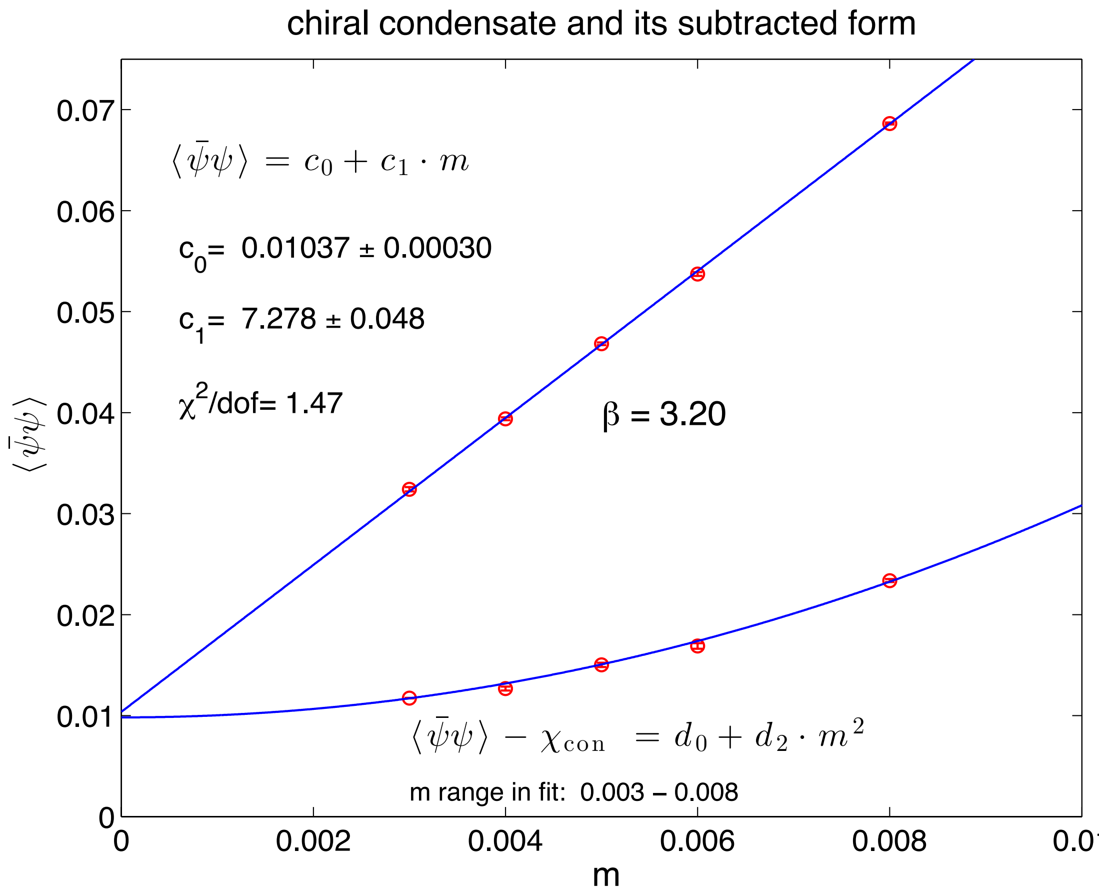
- Direct determination of full spectral density and mode number distribution on gauge configurations

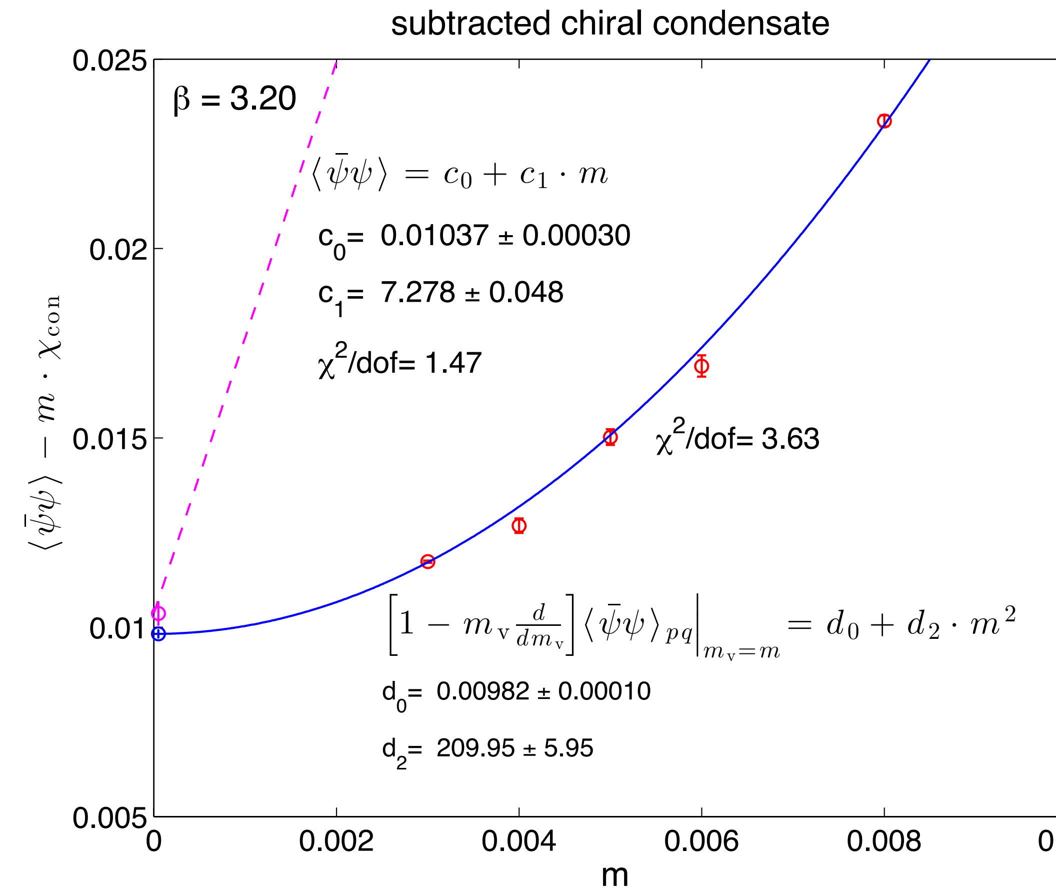
- To remove UV divergences at finite fermion mass

- To investigate internal (in)consistencies with GMOR relation

- To determine anomalous dimension of the chiral condensate

The chiral condensate in the sextet theory





control on UV divergences: mode number density of chiral condensate

$$\rho(\lambda, m) = \frac{1}{V}\sum_{k=1}^{\infty}\langle\delta(\lambda-\lambda_k)\rangle \qquad \lim_{\lambda\to 0}\lim_{m\to 0}\lim_{V\to\infty}\rho(\lambda, m) = \frac{\Sigma}{\pi}$$

spectral density

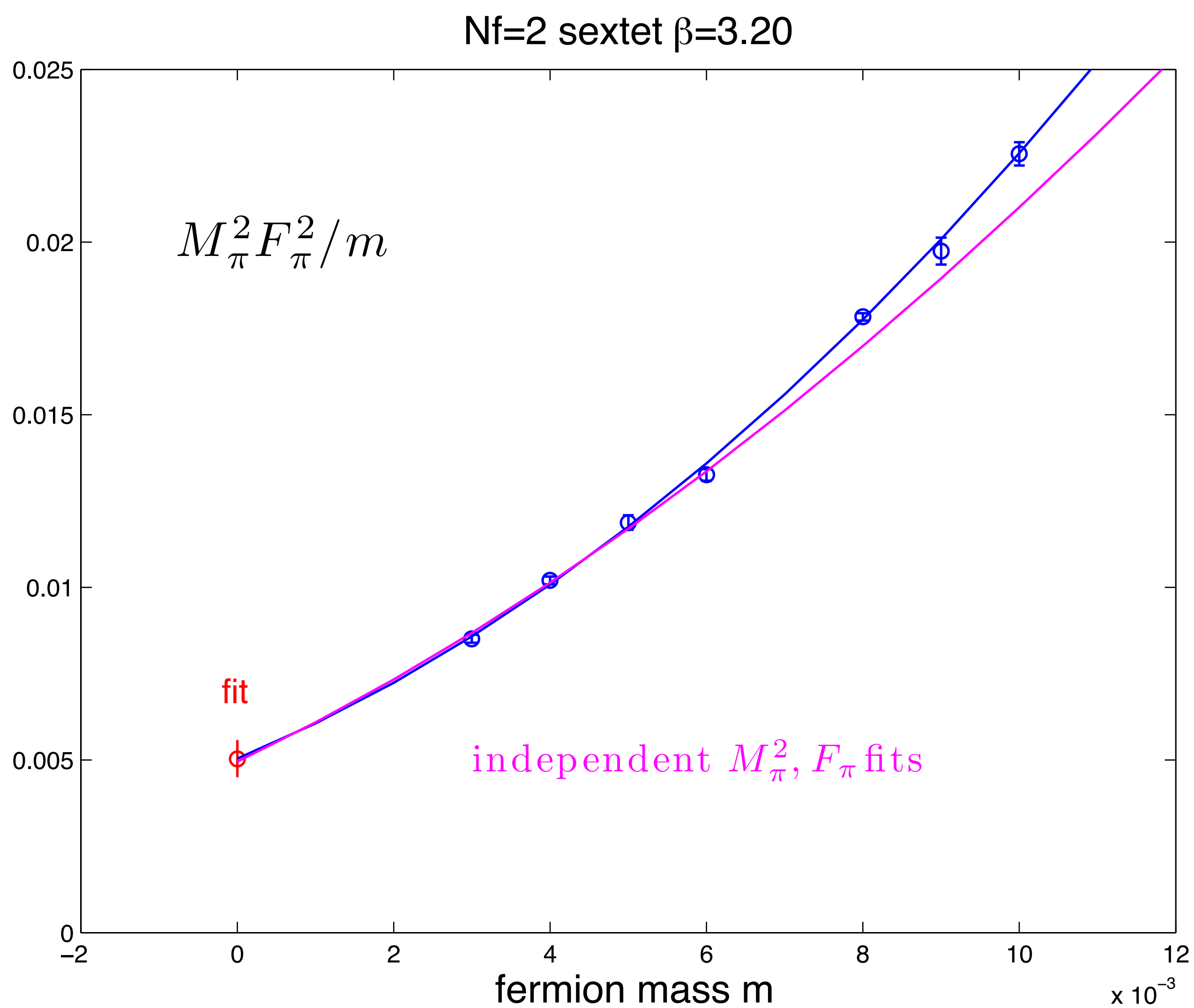
$$\nu(M, m) = V\int_{-\Lambda}^{\Lambda} \mathrm{d}\lambda\,\rho(\lambda, m), \qquad \Lambda = \sqrt{M^2 - m^2}$$

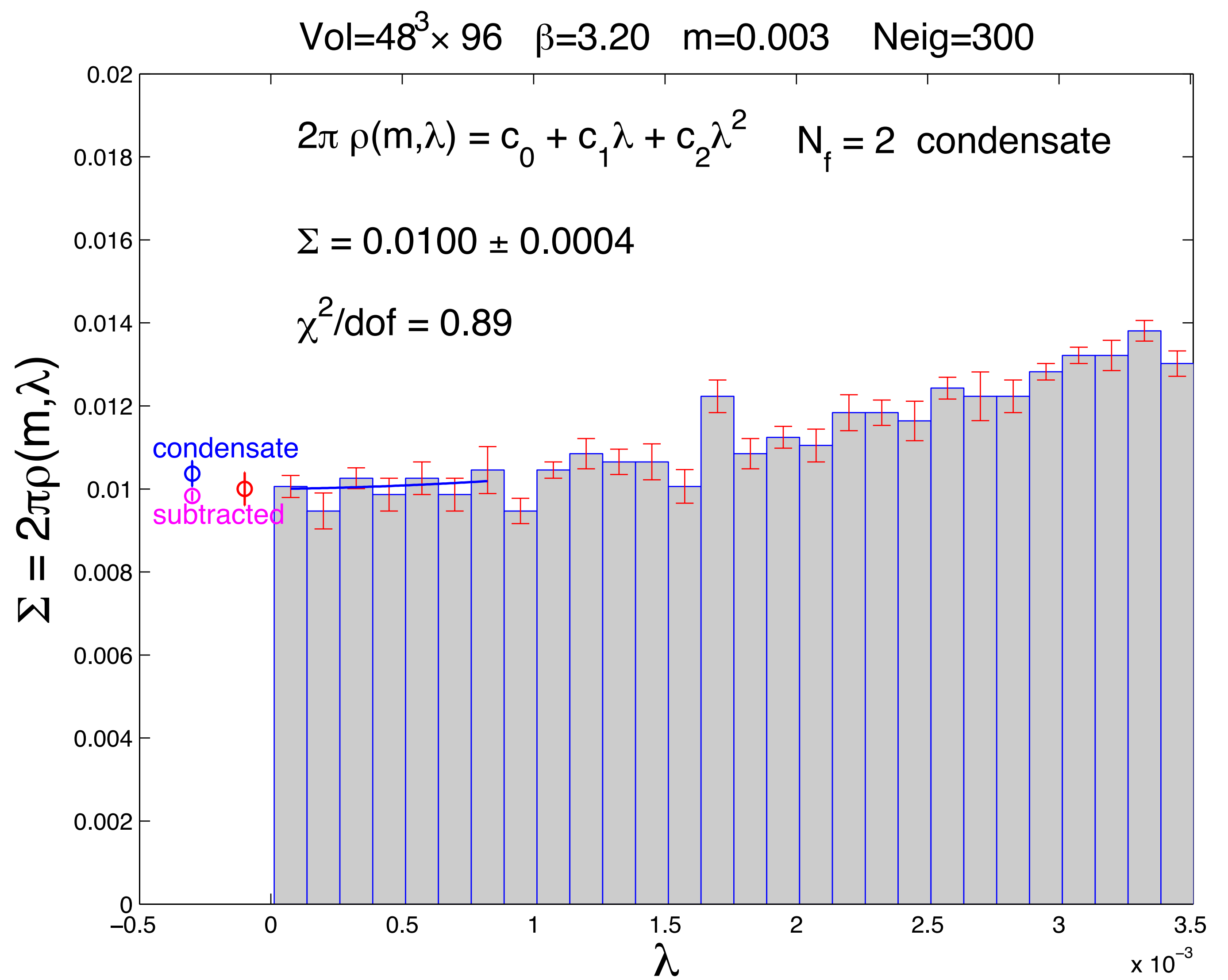
mode number density

$$\nu_{\mathrm{R}}(M_{\mathrm{R}}, m_{\mathrm{R}}) = \nu(M, m_{\mathrm{q}})$$

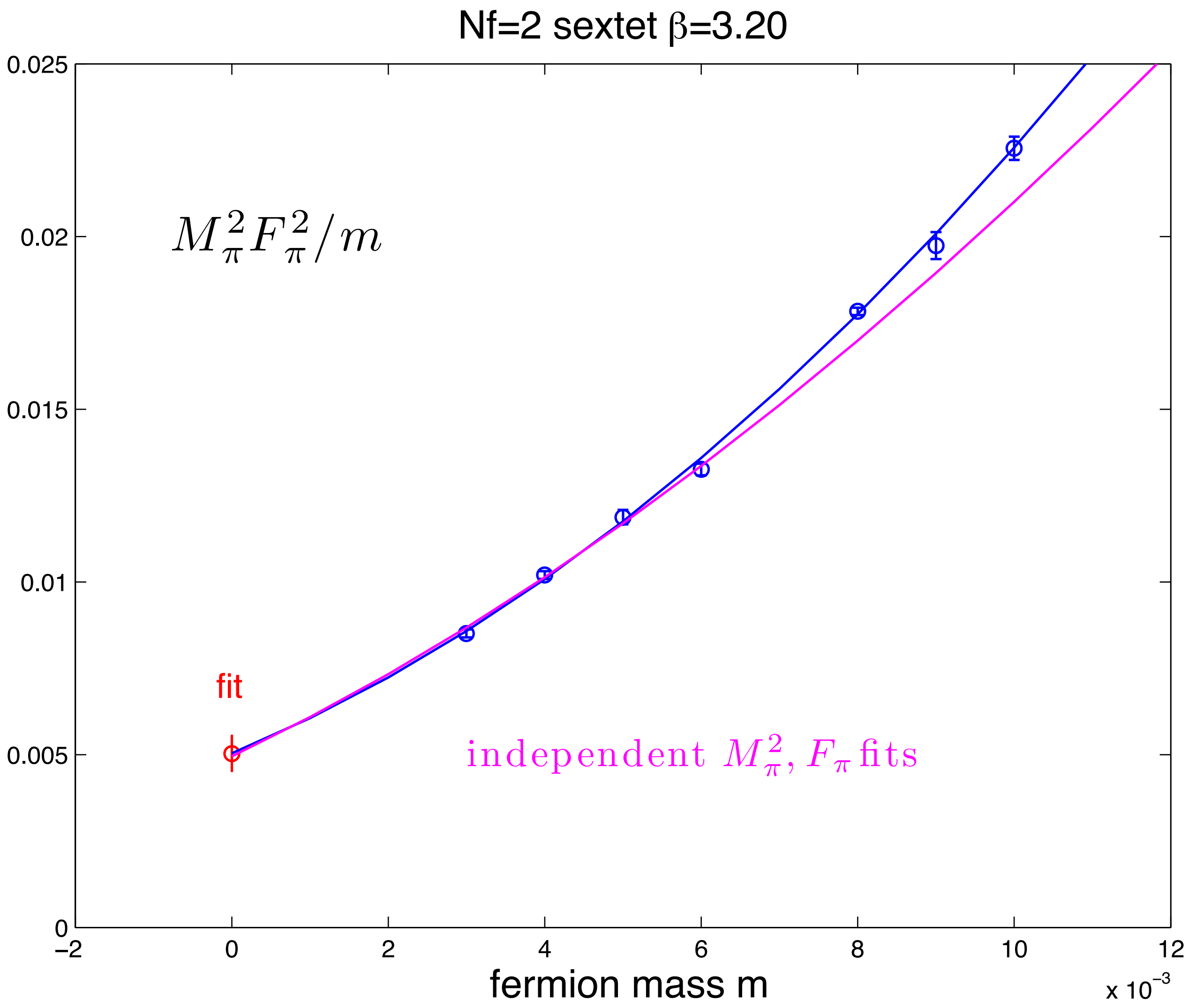
renormalized and RG invariant (Giusti and Luscher)

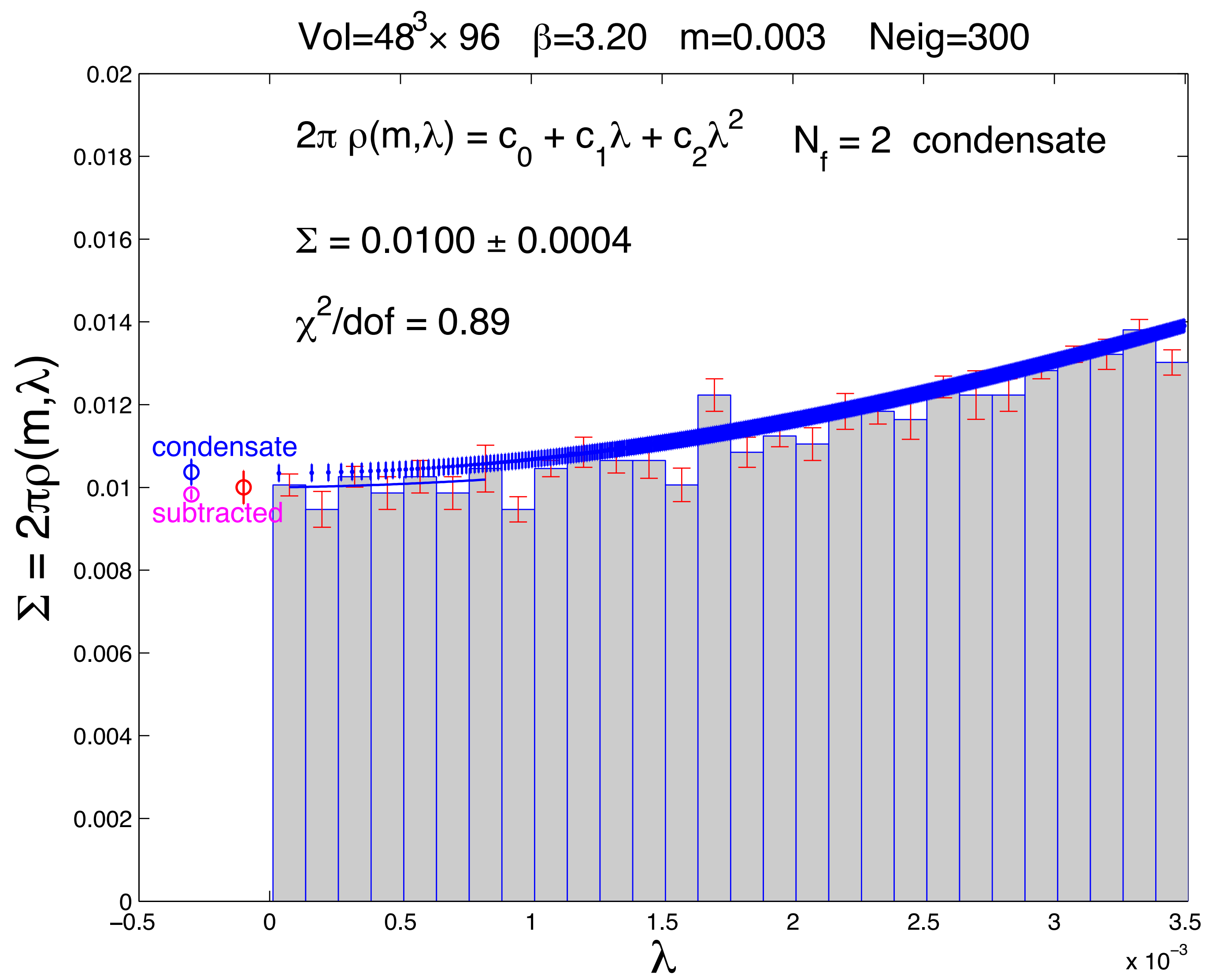
The chiral condensate in the sextet theory



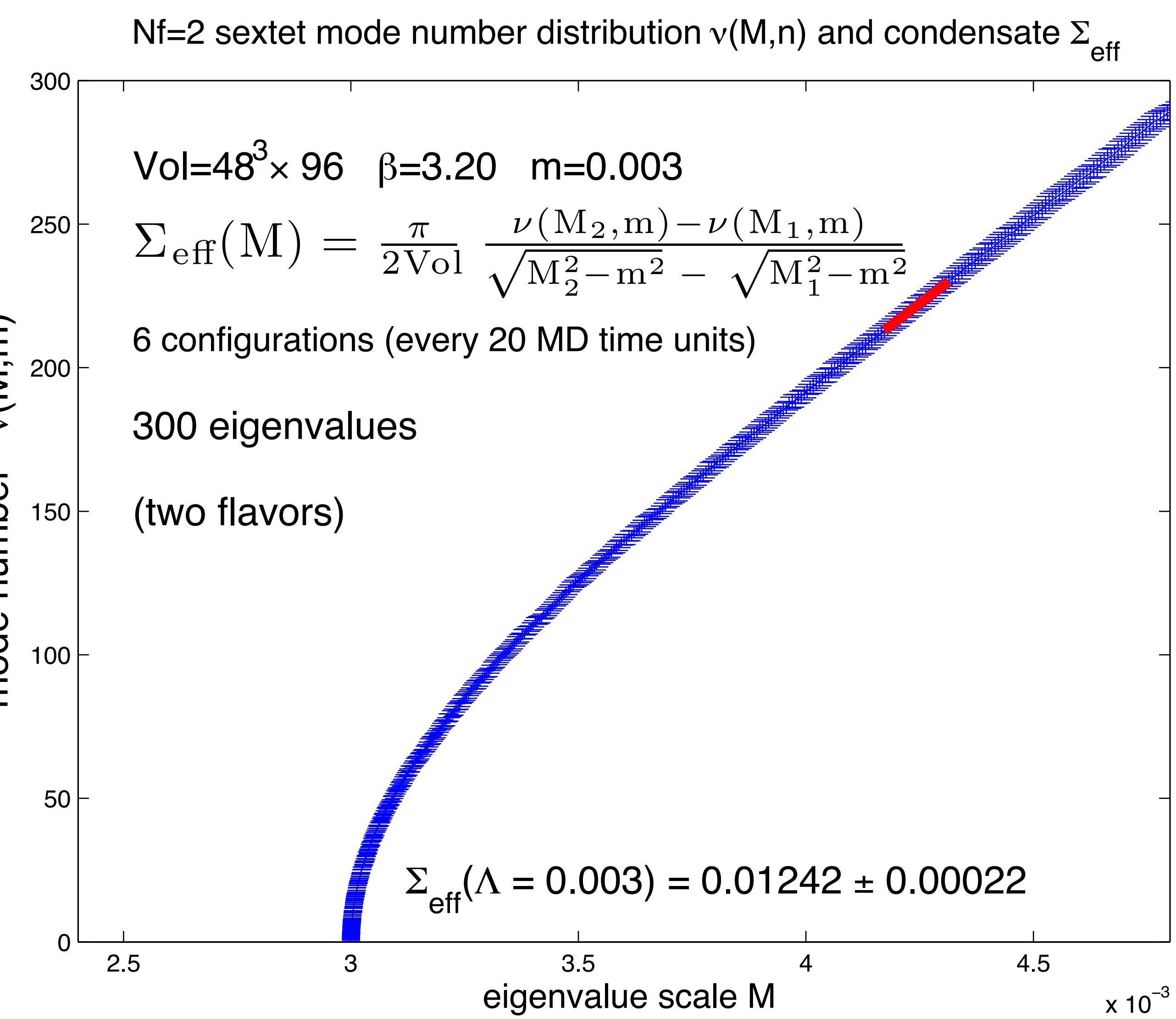


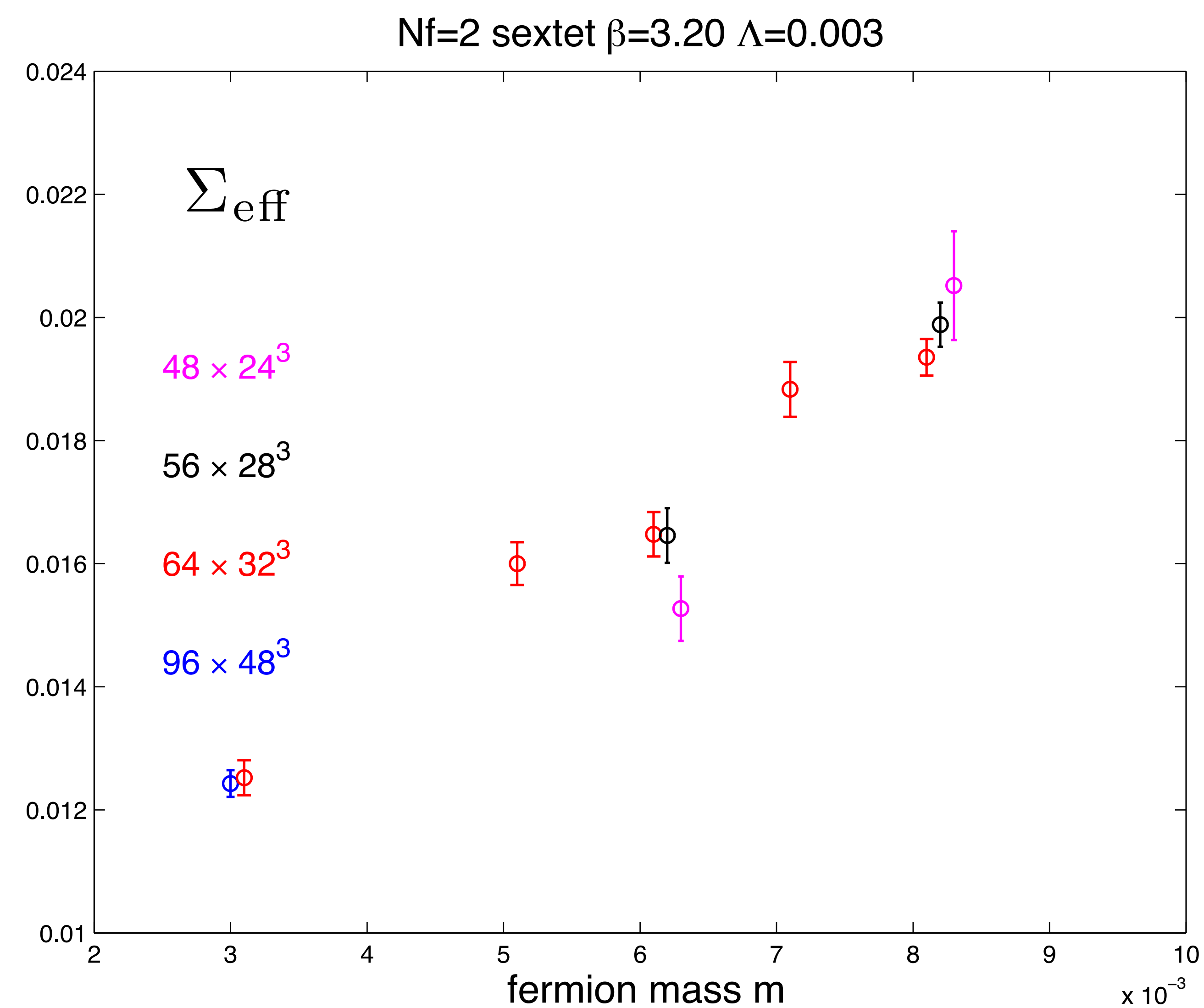
The chiral condensate in the sextet theory





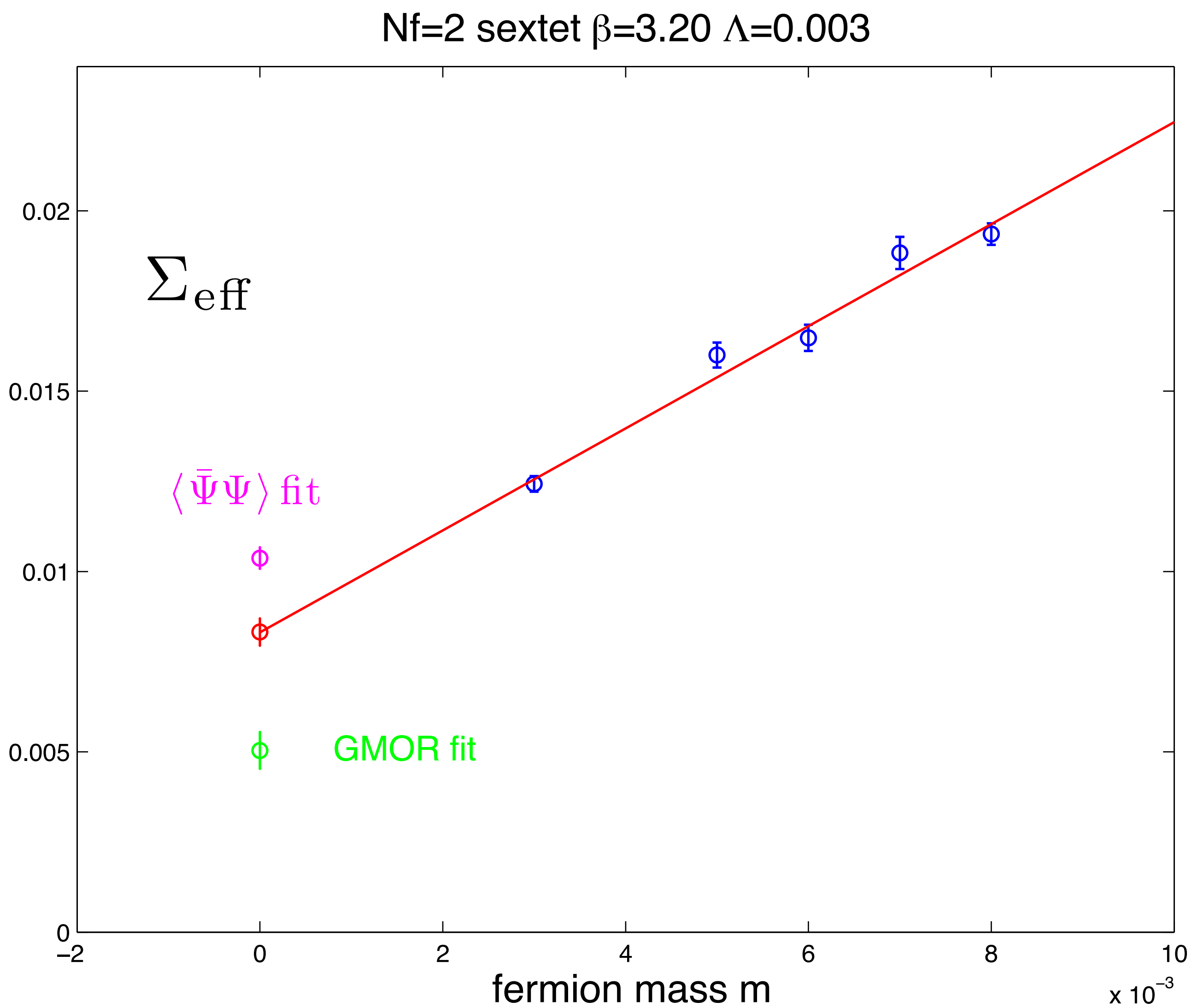
The chiral condensate in the sextet theory

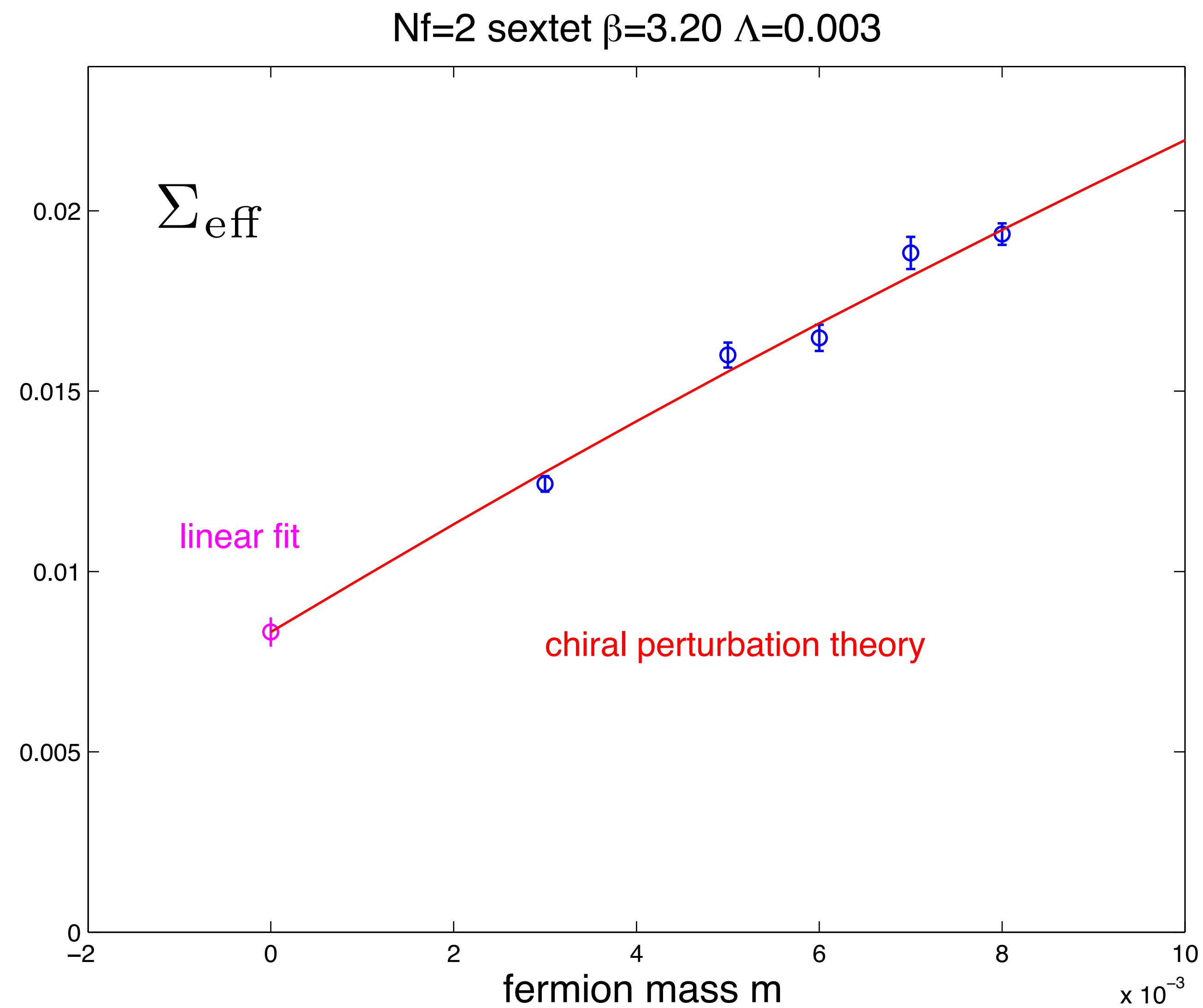




$$\frac{\Sigma_{\rm eff}}{\Sigma} = 1 + \frac{\Sigma}{32\pi^3 N_F F^4}\left[2N_F^2|\Lambda|\arctan\frac{|\Lambda|}{m} - 4\pi|\Lambda| - N_F^2 m\log\frac{\Lambda^2+m^2}{\mu^2} - 4m\log\frac{|\Lambda|}{\mu}\right]$$

The chiral condensate in the sextet theory

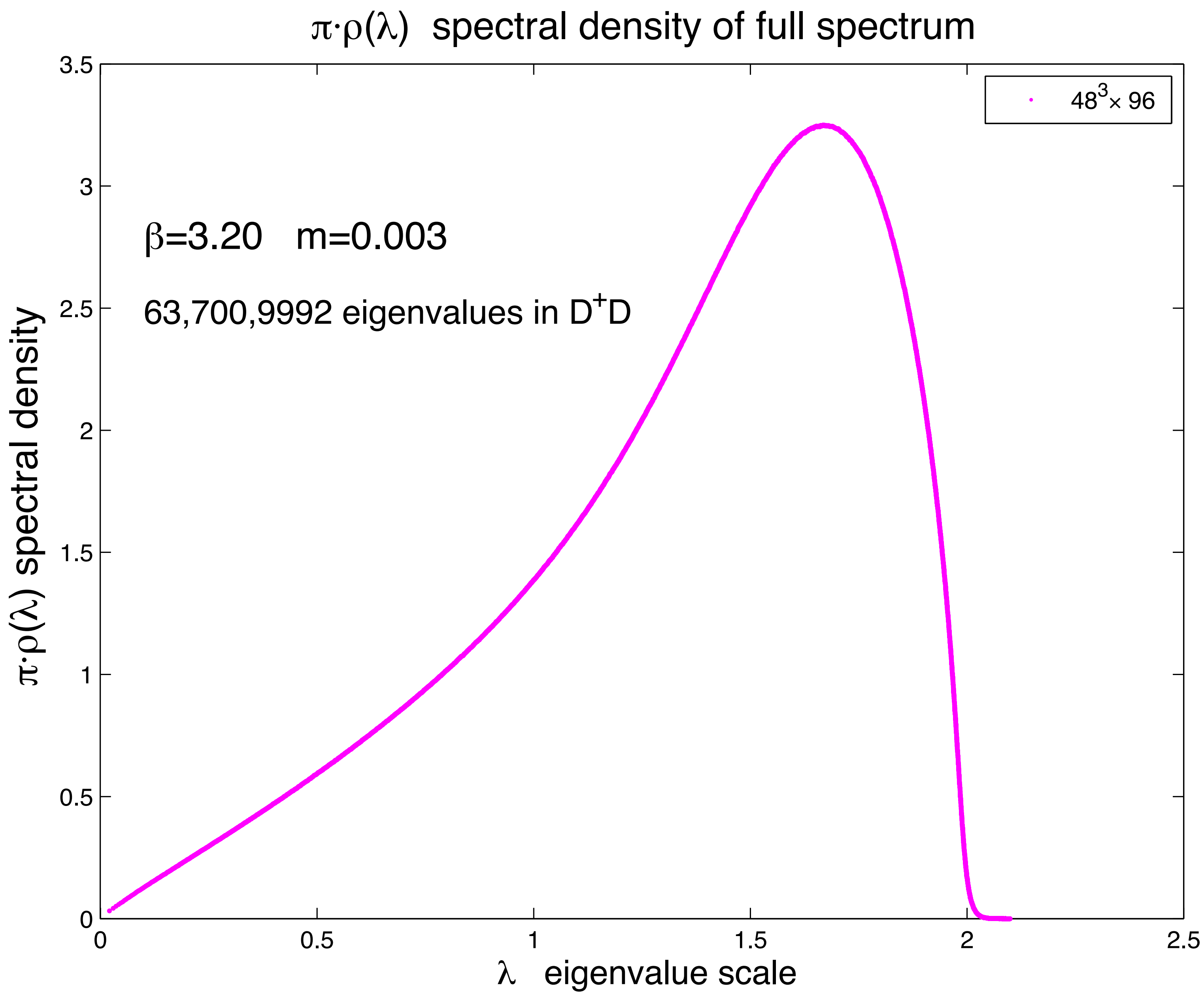




The chiral condensate in the sextet theory

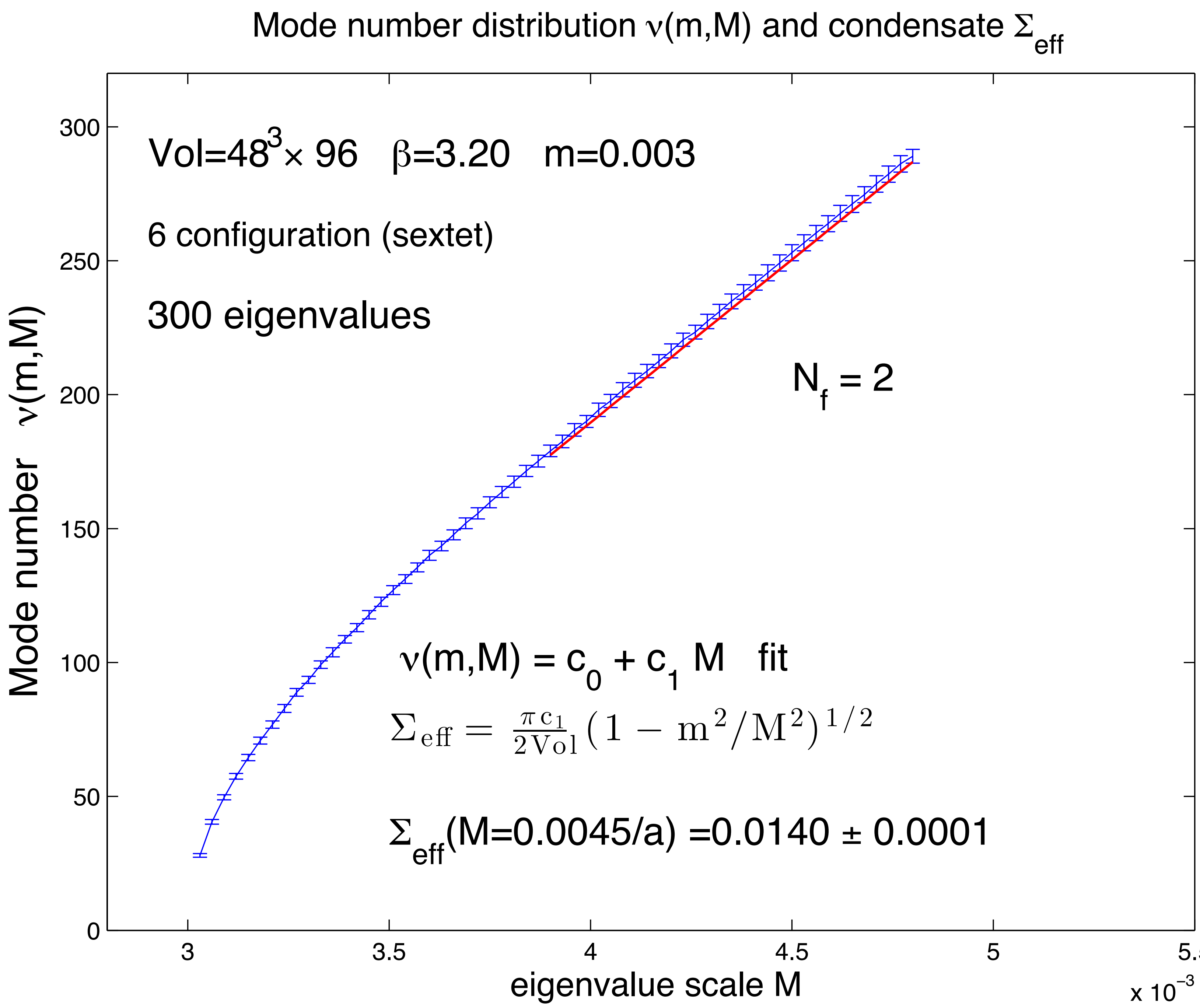
new stochastic method sextet Nf=2   code by Ricky Wong

direct determination of full spectral density and mode number distribution on gauge configurations



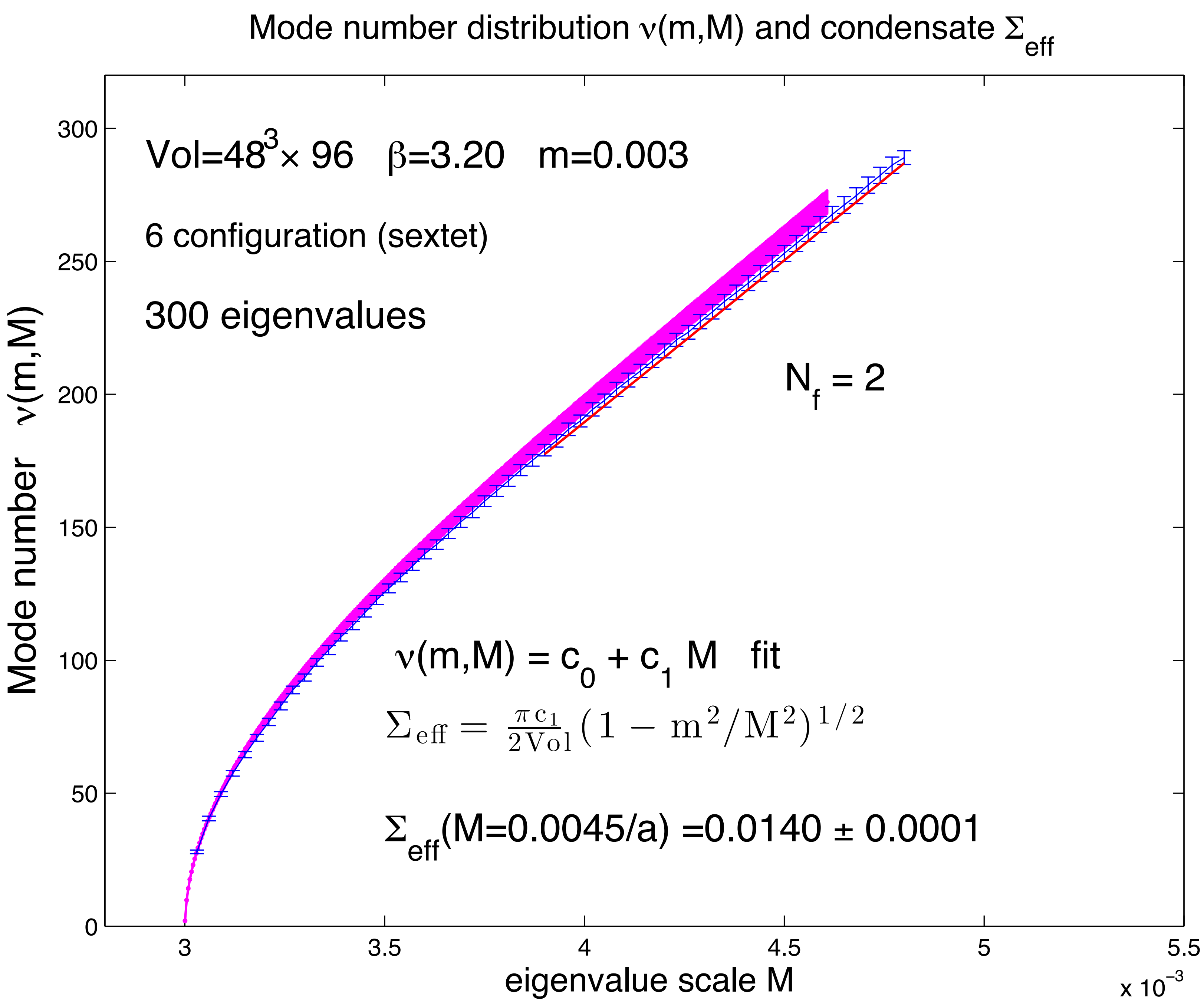
- Passed all tests so far
- example is from 48^3x96 lattices
- allows the scale-dependent determination of the anomalous dimension of the chiral condensate

The chiral condensate in the sextet theory



- new stochastic method sextet Nf=2
- comparison with direct calculation of mode number distribution from eigenvalue spectrum
- stringent test
- details in forthcoming publication

The chiral condensate in the sextet theory

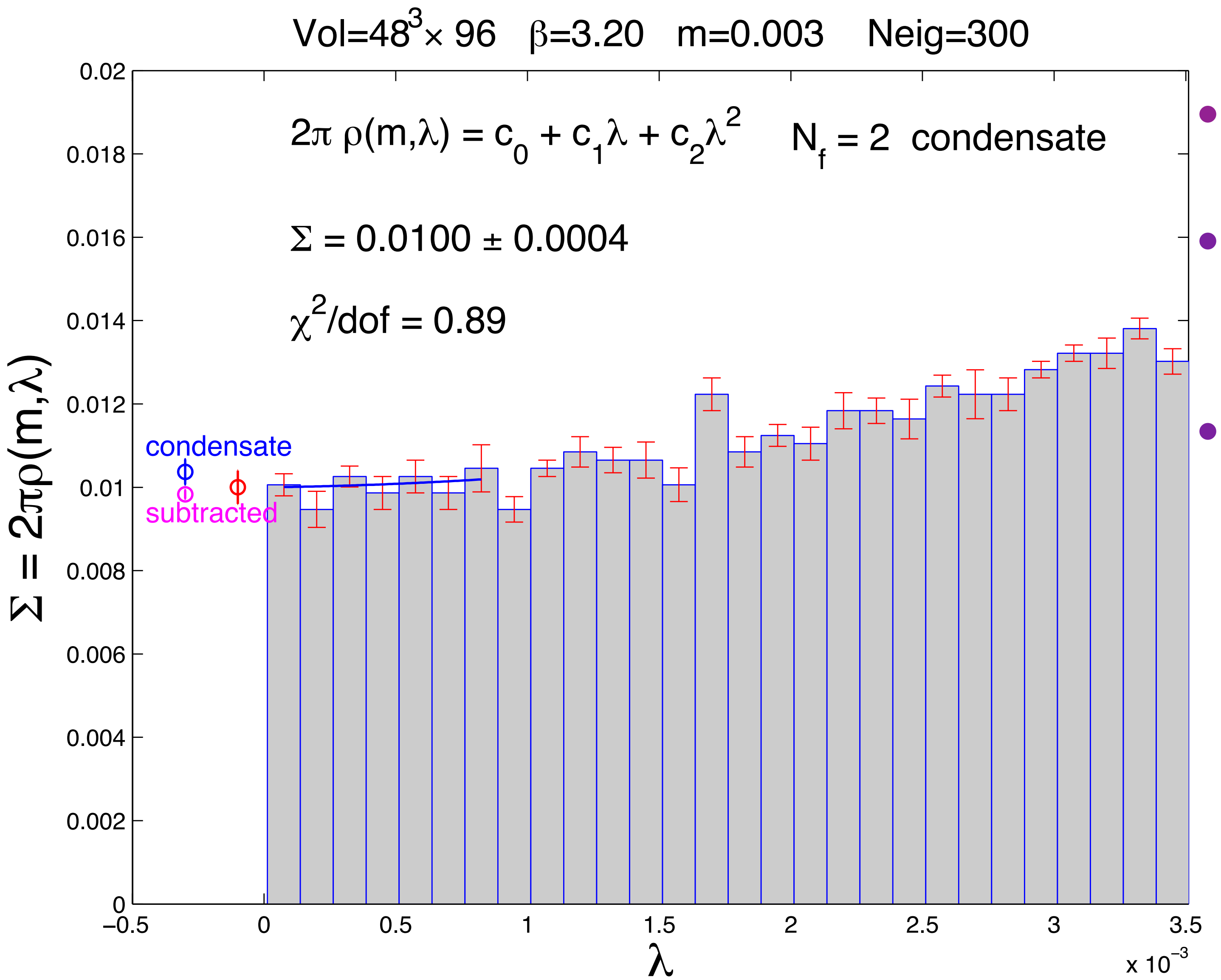


- new stochastic method sextet Nf=2
- comparison with direct calculation of mode number distribution from eigenvalue spectrum
- stringent test
- details in forthcoming publication

The chiral condensate in the sextet theory

new stochastic method sextet rep Nf=2

comparison with direct determination of spectral density from eigenvalue spectrum



- new stochastic method sextet Nf=2
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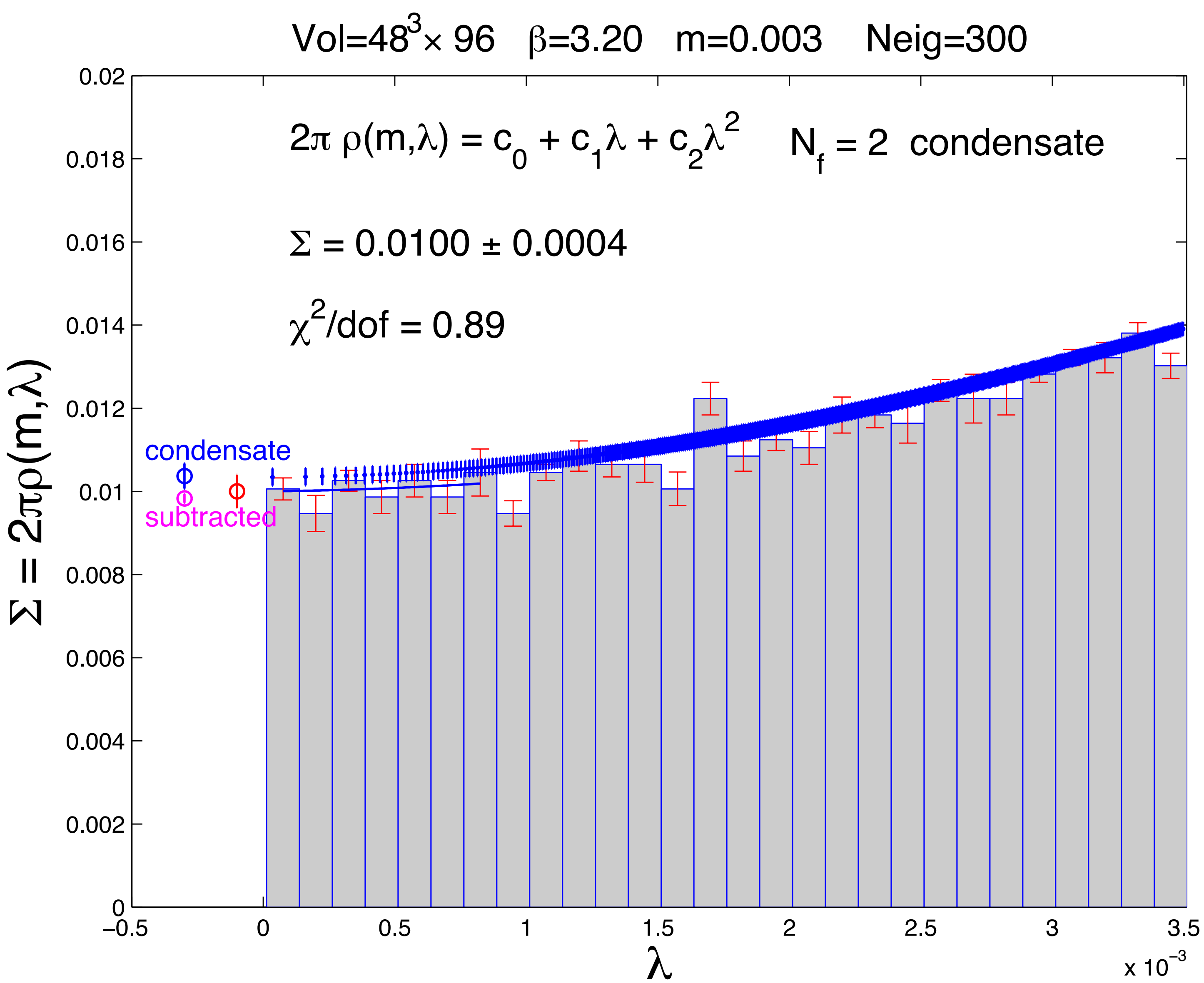
The chiral condensate in the sextet theory

new stochastic method sextet rep Nf=2

comparison with direct determination of spectral density from eigenvalue spectrum

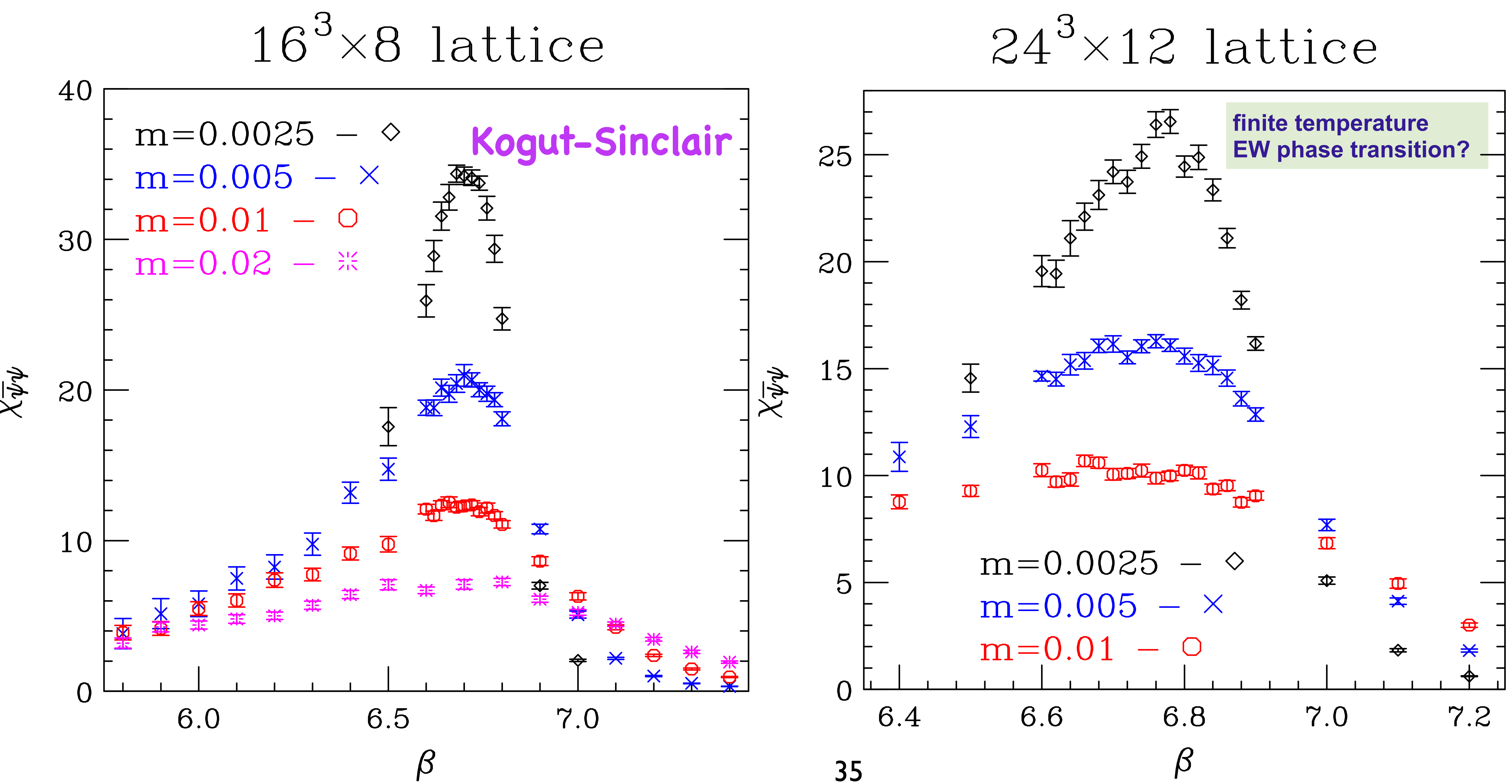


- new stochastic method sextet Nf=2
- comparison with direct determination of spectral density from eigenvalue spectrum
- stringent test

Early universe

Kogut-Sinclair work consistent with χSB phase transition

Relevance in early cosmology (order of the phase transition?)



Early universe

The Total Energy of the Universe:

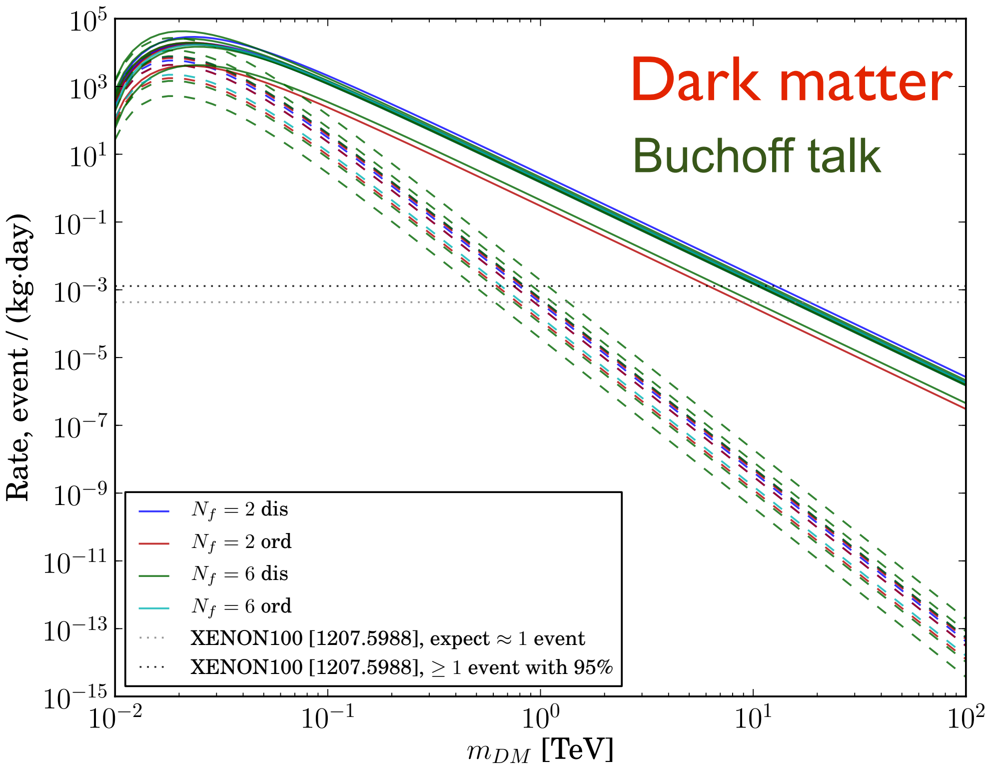
Vacuum Energy (Dark Energy)	~	67 %
Dark Matter	~	29 %
Visible Baryonic Matter	~	4 %

Dark matter

self-interacting?

O(barn) cross section would be challenging

T. Appelquist, R. C. Brower, M. I. Buchoff, M. Cheng, S. D. Cohen, G. T. Fleming, J. Kiskis, M. F. Lin, E. T. Neil, J. C. Osborn, C. Rebbi, D. Schaich, C. Schroeder, S. Syritsyn, G. Voronov, P. Vranas, and J. Wasem (Lattice Strong Dynamics (LSD) Collaboration)



- lattice BSM phenomenology of dark matter
  pioneering LSD work
- Nf=2 Qu=2/3 Qd = -1/3
  udd neutral dark matter candidate
- dark matter candidate sextet Nf=2
  electroweak active in the application
- there is room for third heavy fermion
  flavor as electroweak singlet
- rather subtle sextet baryon
  construction (symmetric in color)

Summary and Outlook

Simplest composite scalar is light near conformality

light scalar (dilaton-like?) emerging	close to conformal window?
running (walking) coupling in progress	difficult, Gradient Flow is huge improvement
chiral condensate	new method is very promising
spectroscopy	emerging resonance spectrum ~ 2 TeV
dark matter	implications are intriguing strong self-interactions?

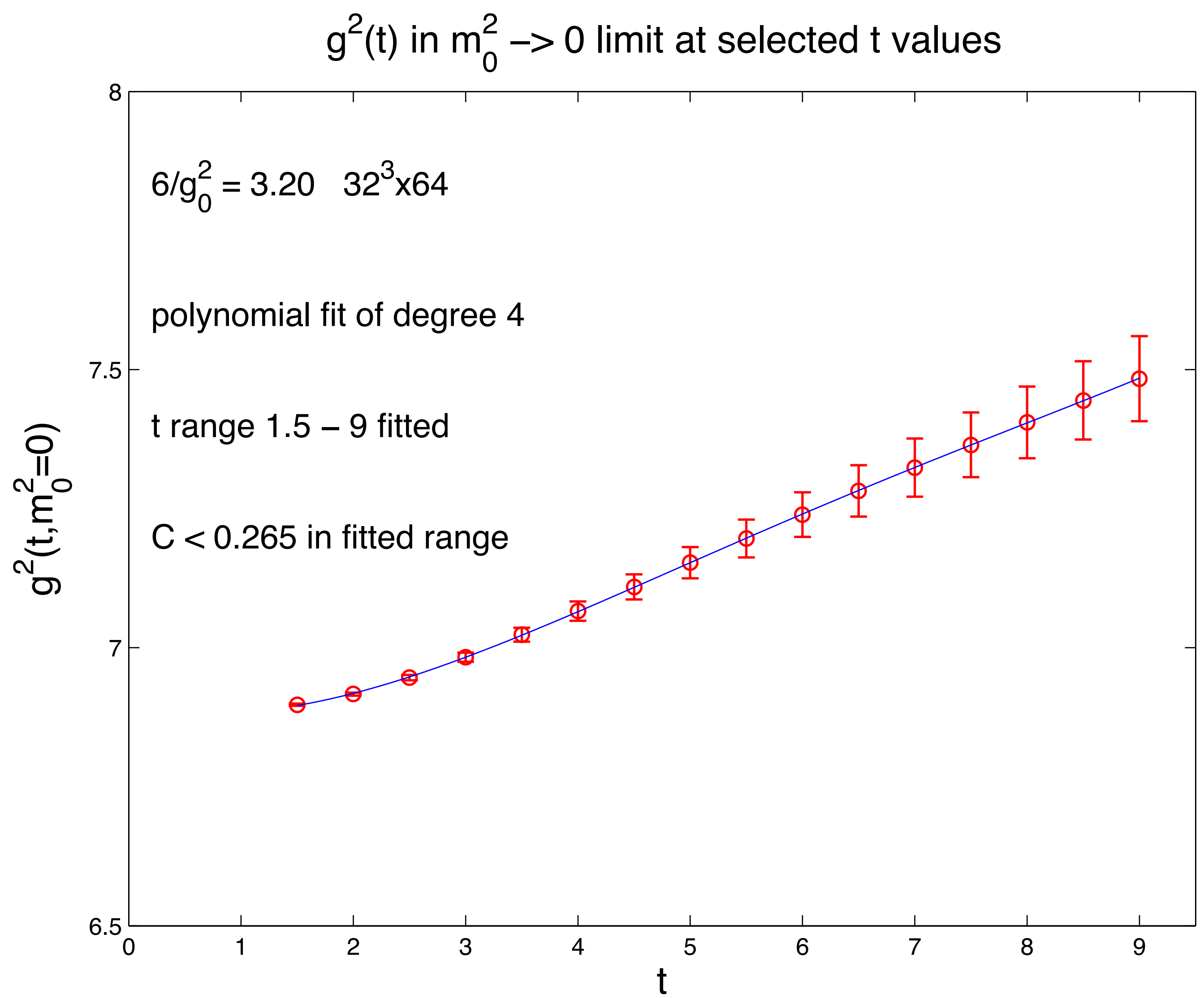
Tuning with third flavor ?

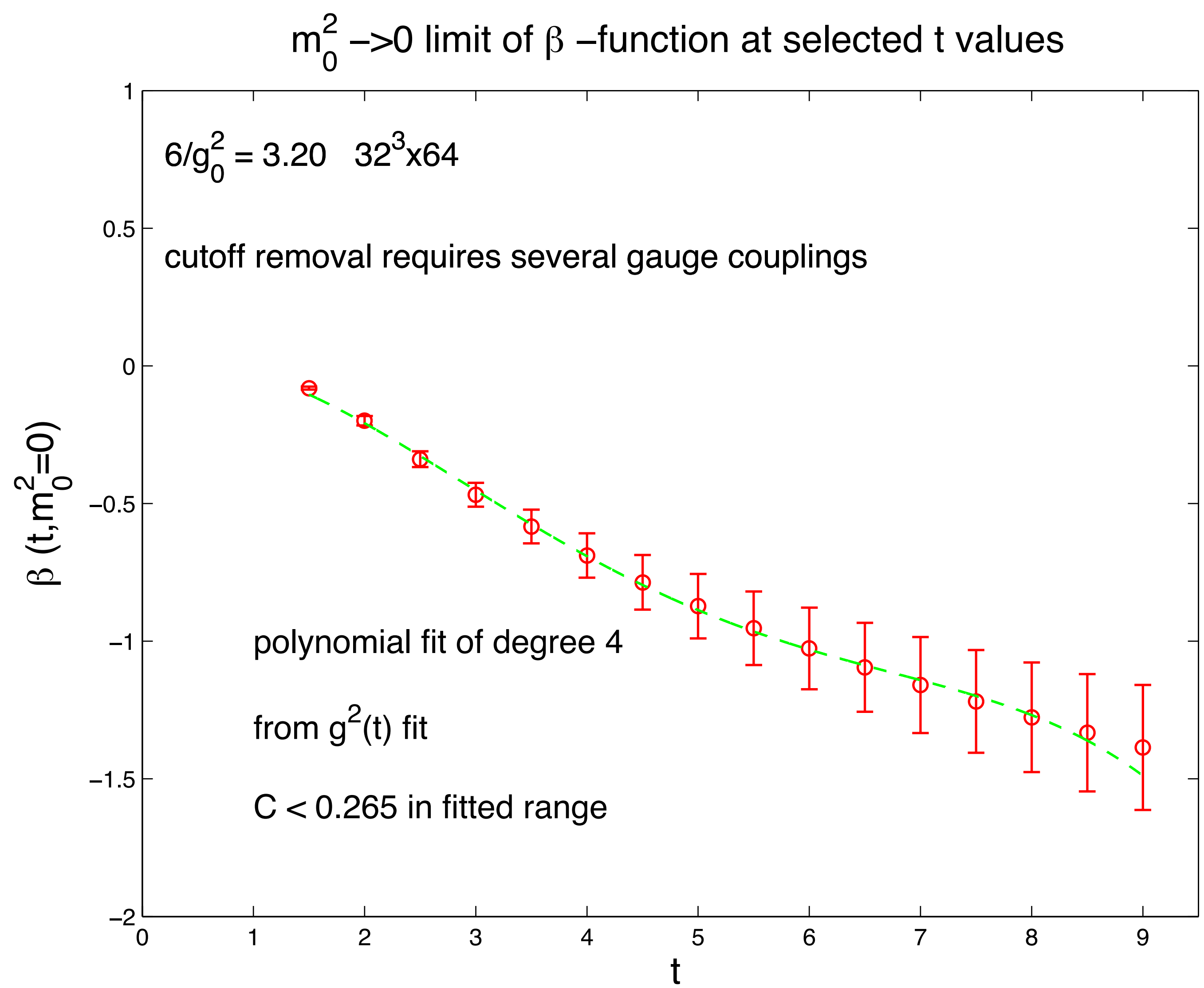
We have a candidate for minimal Higgs impostor to make it fail !

Our job is not to oversell, but do everything we can to kill the model !

If we fail to kill, the model will speak for itself

backup slides


g^2(t) in m_0^2 –> 0 limit at selected t values
6/g_0^2 = 3.20 32^3x64
polynomial fit of degree 4
t range 1.5 – 9 fitted
C < 0.265 in fitted range
g^2(t,m_0^2=0)
t


m_0^2 –>0 limit of β –function at selected t values
6/g_0^2 = 3.20 32^3x64
cutoff removal requires several gauge couplings
polynomial fit of degree 4
from g^2(t) fit
C < 0.265 in fitted range
β (t,m_0^2=0)
t