BSM workshop
BNL 2013

Simplest near-conformal composite Higgs

Lattice Higgs Collaboration (LHC)

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

Julius Kuti
University of California, San Diego

BSM workshop December 5-6, 2013
Brookhaven National Laboratory

Outline

After the Higgs discovery

Light Higgs near conformality

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

Running coupling and past controversies

running (walking?) coupling from gradient flow

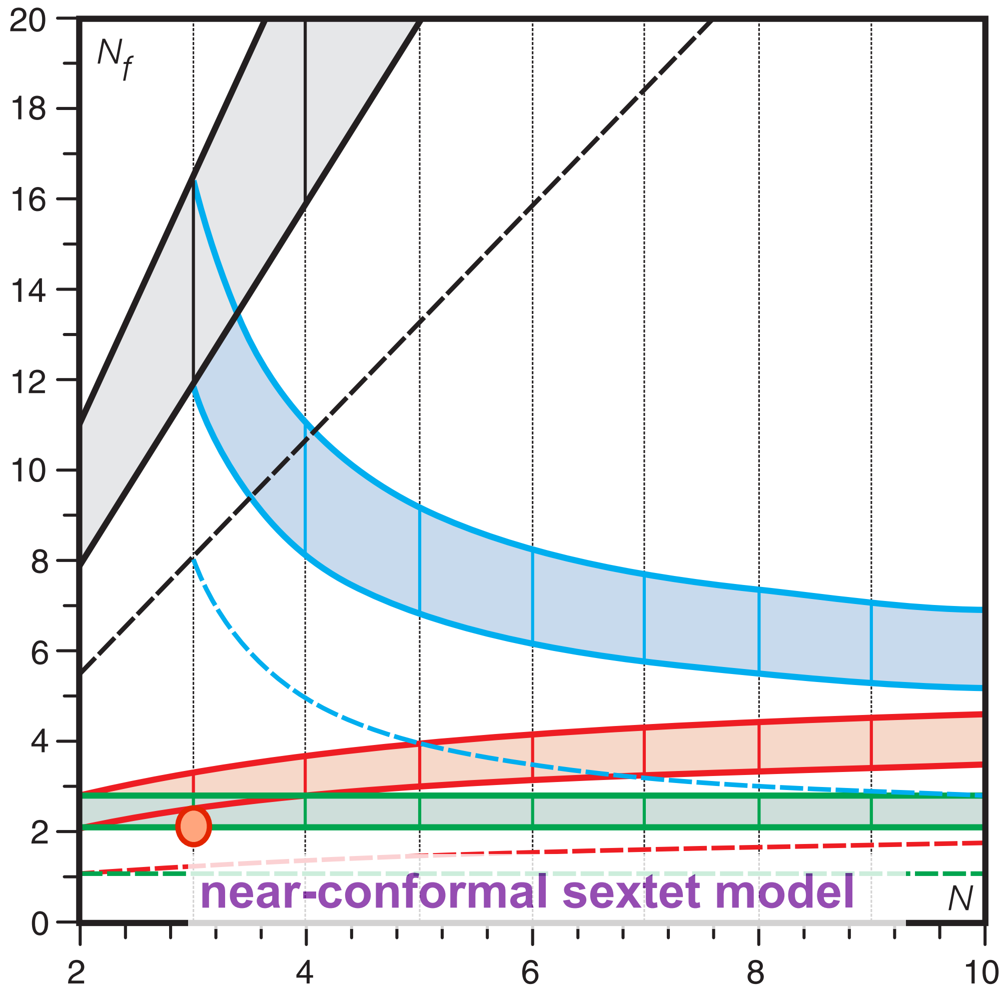
Chiral condensate

new stochastic method for spectral density
large anomalous dimension

Early universe

EW phase transition
dark matter

Summary and Outlook



for more details of recent results from LHC BSM group :

Can the nearly conformal sextet gauge model hide the Higgs impostor?

Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chris Schroeder, Chik Him Wong

Published in **Phys.Lett. B718 (2012) 657-666**

The sextet gauge model, light Higgs, and the dilaton

Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chris Schroeder, Chik Him Wong

Published in **PoS LATTICE2012 (2012) 024**

Confining force and running coupling with twelve fundamental and two sextet fermions

Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chris Schroeder, Chik Him Wong

Published in **PoS LATTICE2012 (2012) 025**

Can a light Higgs impostor hide in composite gauge models?

Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong

Published in **PoS LATTICE2013 (2013) 062**

The chiral condensate from the Dirac spectrum in BSM gauge theories

Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong

Published in **PoS LATTICE2013 (2013) 089**

Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chik Him Wong

new papers in the pipeline, soon to be published

Large Hadron Collider - CERN

primary mission:

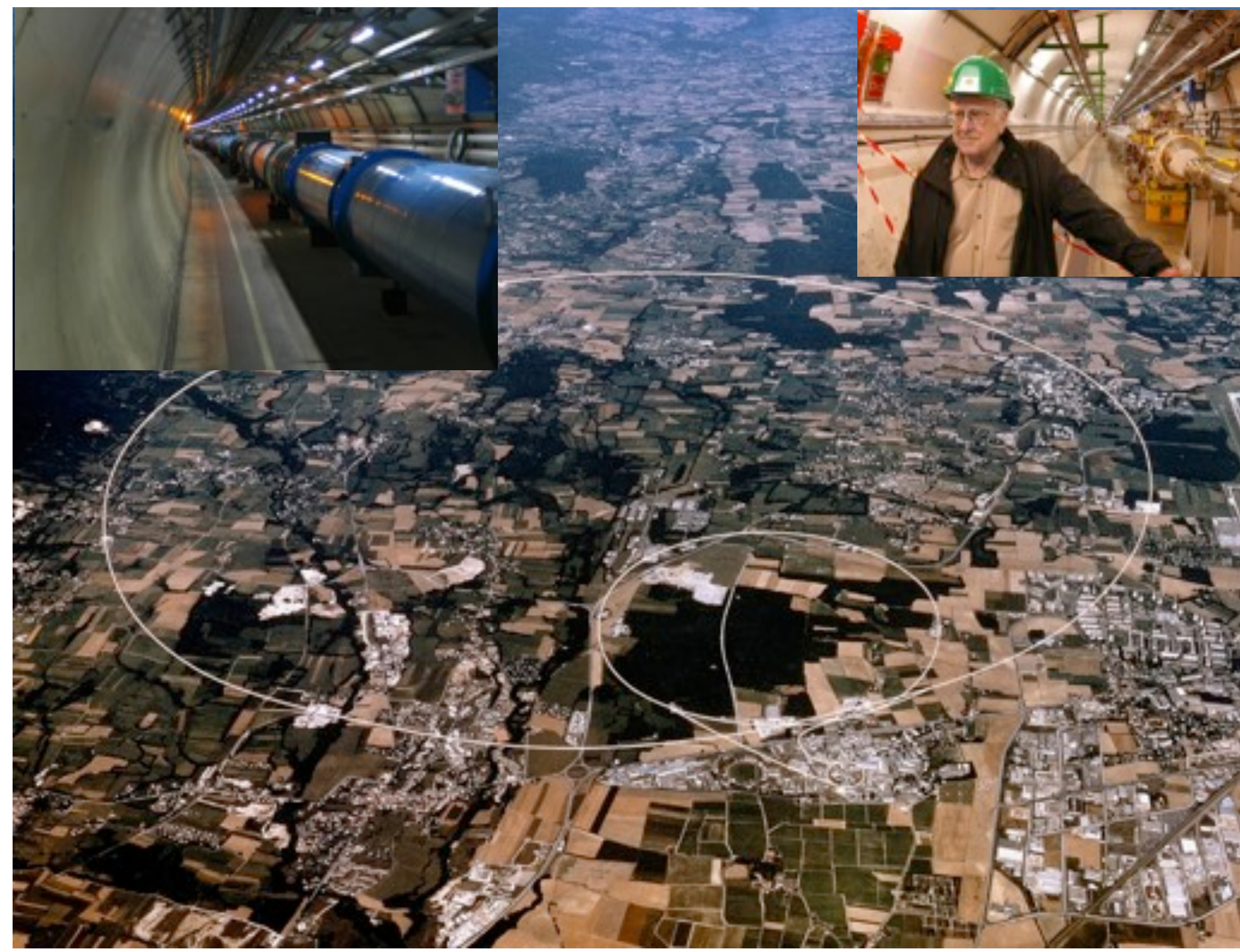
- Search for Higgs particle

- 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 work



LATTICE GAUGE THEORIES AT THE ENERGY FRONTIER

Thomas Appelquist, Richard Brower, Simon Catterall, George Fleming, Joel Giedt, Anna Hasenfratz, Julius Kuti, Ethan Neil, and David Schaich

(USQCD Collaboration)

(Dated: March 10, 2013)

USQCD BSM White Paper - community based effort input into US Snowmass 2013 planning:

USQCD and the composite Higgs at the Energy Frontier

The recent discovery of the Higgs-like particle at 126 GeV is the beginning of the experimental search for a deeper dynamical explanation of electroweak symmetry breaking beyond the Standard Model (BSM). The USQCD collaboration has developed an important BSM research direction with the primary focus on the composite Higgs mechanism as outlined in our recent USQCD BSM white paper [1] and in this short report. Deploying advanced lattice field theory technology, we are investigating new strong gauge dynamics to explore consistency with a composite Higgs particle at 126 GeV which will require new non-perturbative insight into this fundamental problem. The organizing principle of our program is to explore the dynamical implications of approximate scale invariance and chiral symmetries with dynamical symmetry breaking patterns that may lead to the composite Higgs mechanism with protection of the light scalar mass, well separated from predicted new resonances, which maybe on the 1-2 TeV scale. Based on an underlying strongly-coupled theory, lattice calculations provide the masses and decay constants of these new particles, enabling concrete predictions for future experimental results at colliders and in dark matter searches.

On the other hand, if the higher resonances are too heavy to be directly probed at the LHC, indirect evidence for Higgs compositeness may appear for example as altered rates for electroweak gauge boson scattering, changes to the Higgs coupling constants, or the presence of additional light Higgs-like resonances. Here lattice calculations are used to derive the low energy constants in an Effective Field Theory description to predict departures of a composite Higgs dynamics from the standard model predictions. Of course as new experimental evidence from the LHC is forthcoming, BSM lattice simulations will be focused on an increasingly narrower class of candidate theories, consistent with experimental constraints, increasing its power as a theoretical tool in the search for BSM physics. Two major components of our BSM lattice program are carefully planned and coordinated, as summarized below.

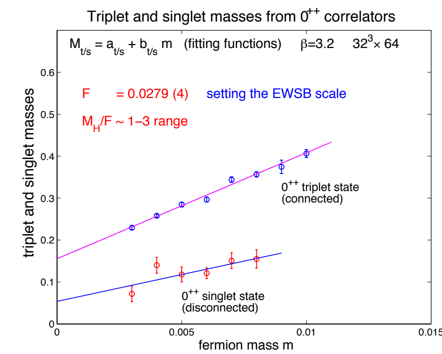


FIG. 1. This plot is unpublished and for illustration only. Some of the flavor singlet scalar data points are expected to remain in flux before final analysis and publication [3]. The ongoing work indicates the emergence of a light flavor singlet scalar state (red) with 0^{++} quantum numbers in the sextet rep of a fermion doublet with the minimal realization of the composite Higgs mechanism. Annihilation diagrams driven by strong gauge dynamics downshift the mass of the flavor singlet state close to the EWSB scale. Turning on a third massive EW singlet in the model might bring the β-function even closer to zero with minimal tuning. The fermion mass dependence of the isotriplet meson (blue) is also shown, not effected by disconnected annihilation diagram. In the chiral limit it is a heavy resonance above 1 TeV. The model predicts several resonances in the 1-2 TeV range.

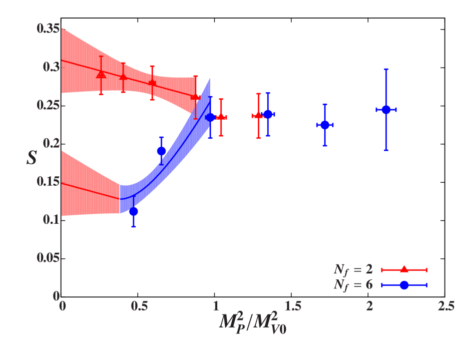
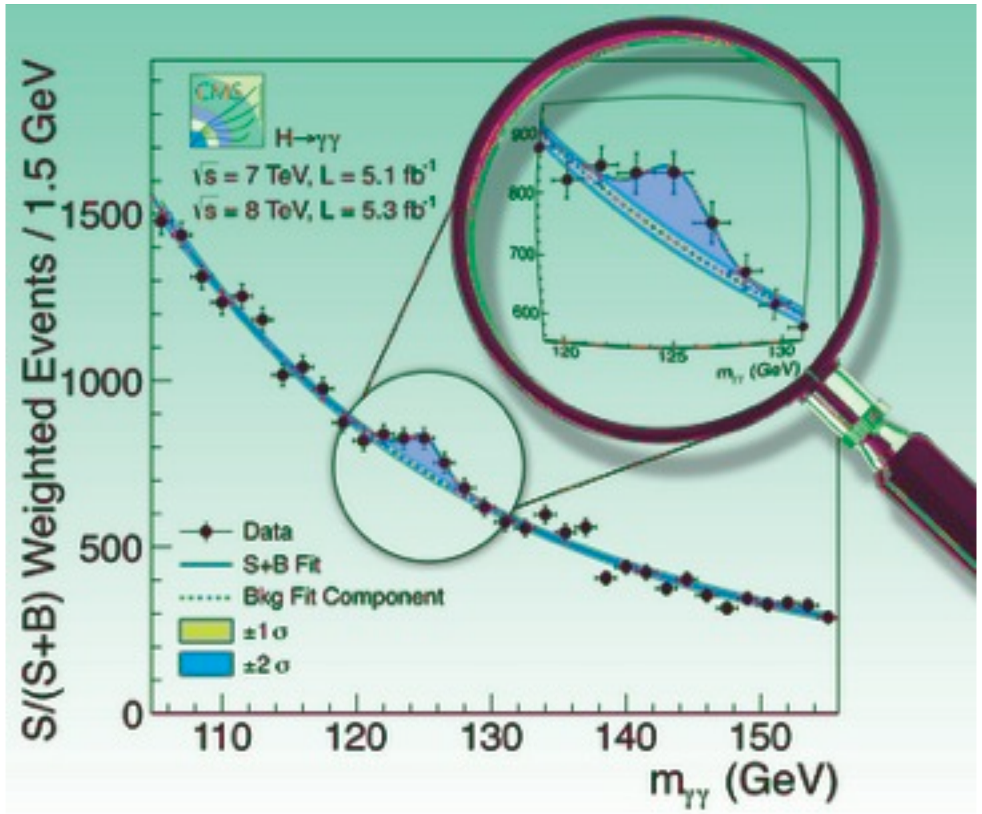
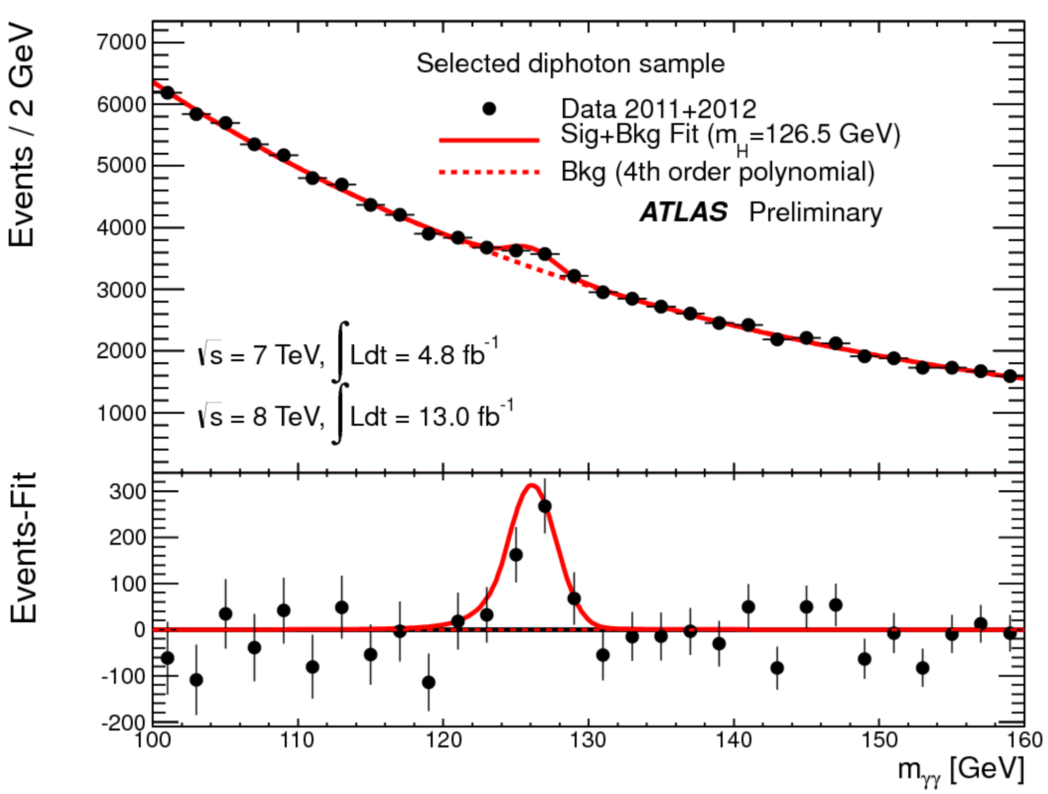


FIG. 2. From [11], lattice simulation results for the S-parameter per electroweak doublet, comparing SU(3) gauge theories with $N_f = 2$ (red triangles) and $N_f = 6$ (blue circles) degenerate strongly-coupled fermions in the fundamental representation. The horizontal axis is proportional to the pseudoscalar Goldstone boson mass squared, or equivalently the input fermion mass m. The $N_f = 2$ value of S is in conflict with electroweak precision measurements, but the reduction at $N_f = 6$ indicates that the value of S in many-fermion theories can be acceptably small, in contrast to more naïve scaling estimates [13].

Rational for BSM:



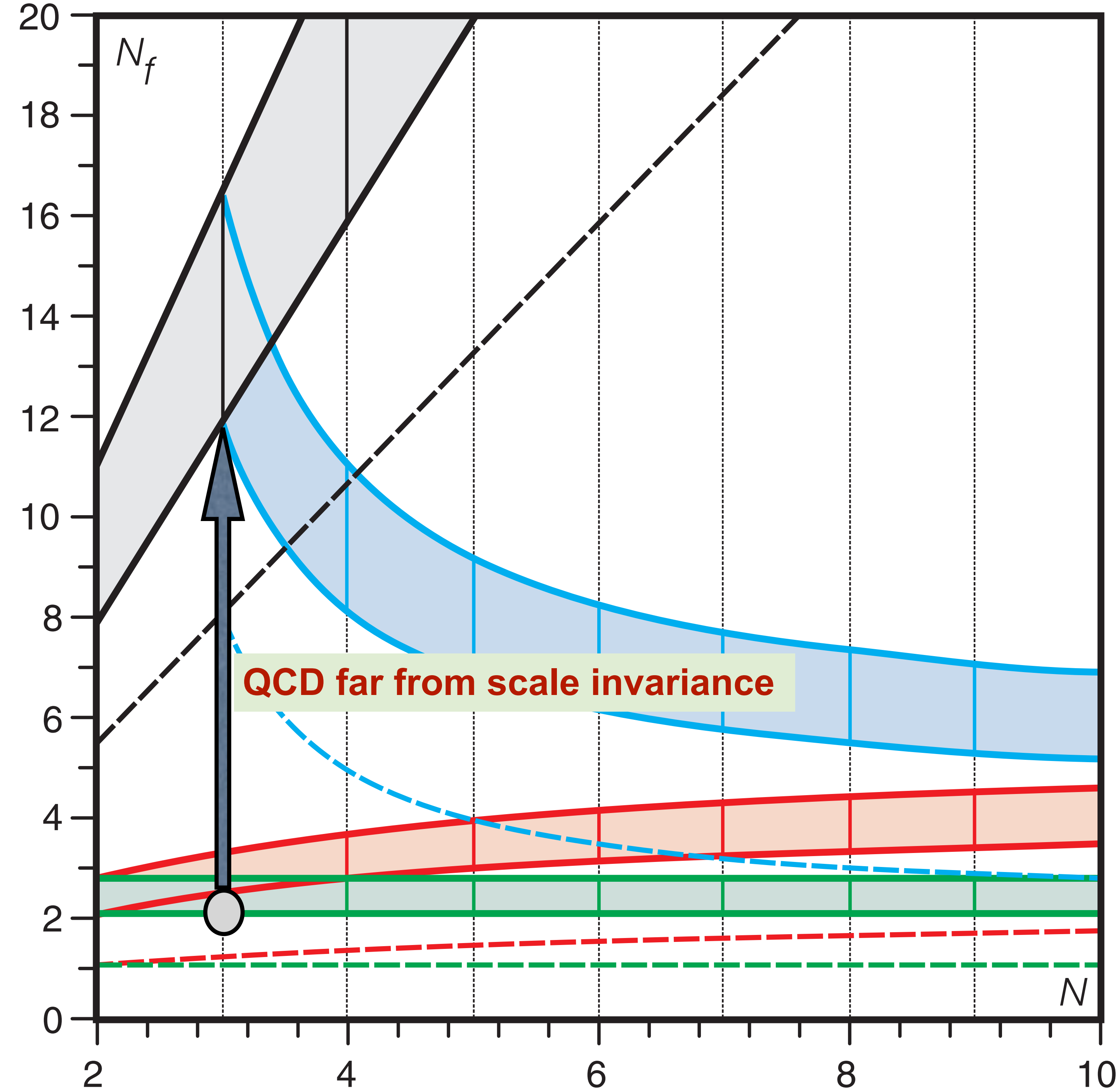


voices: a light Higgs-like scalar was found, consistent with SM within errors, and composite states have not been seen below 1 TeV. Strongly coupled BSM gauge theories are Higgs-less with resonances below 1 TeV
>> Nima and the tombstone

facts: Compositeness and a light Higgs scalar are not incompatible; search for composite states was not based on solid predictions but on naively scaled up QCD and unacceptable old technicolor guessing games. Resonances, out of LHC run1 reach, are in the 2-3 TeV range in the theory I will discuss

lattice BSM plans: LHC run2 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 !

light Higgs near conformality (dilaton-like?) sextet



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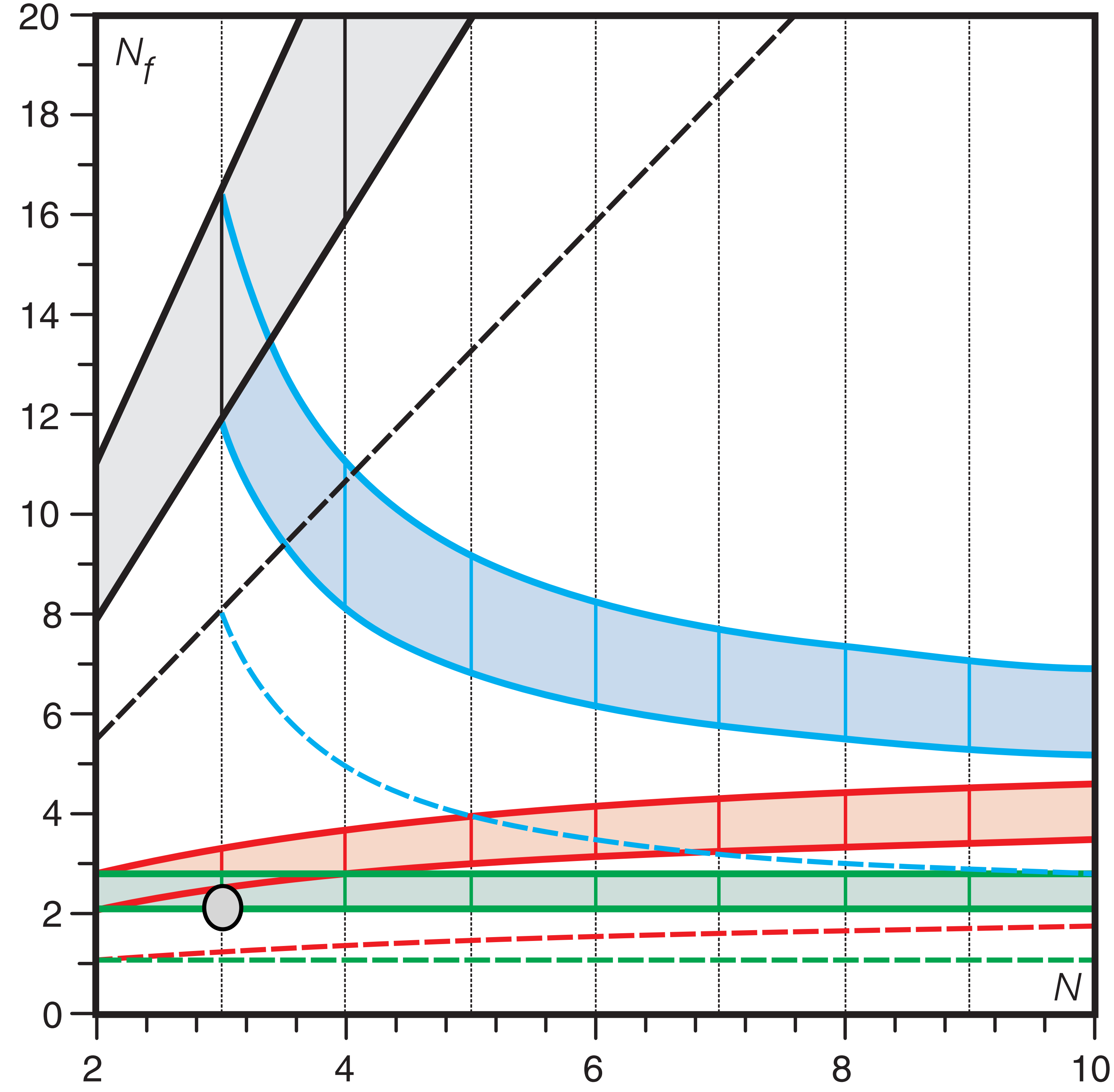


light Higgs near conformality (dilaton-like?) sextet

to illustrate: sextet SU(3) color rep

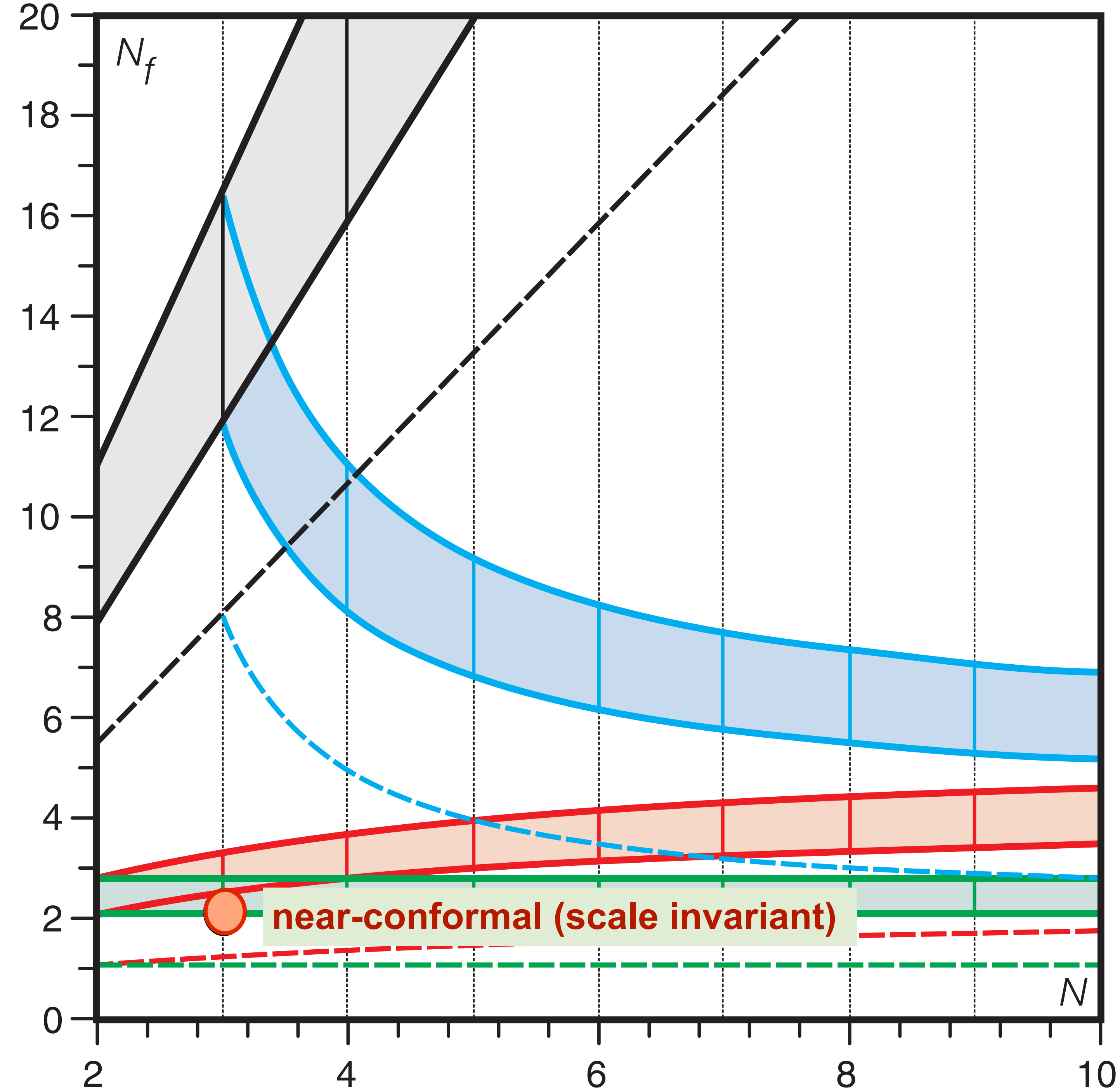
one massless fermion doublet $\begin{bmatrix} u \\ d \end{bmatrix}$

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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auction for naming rights?

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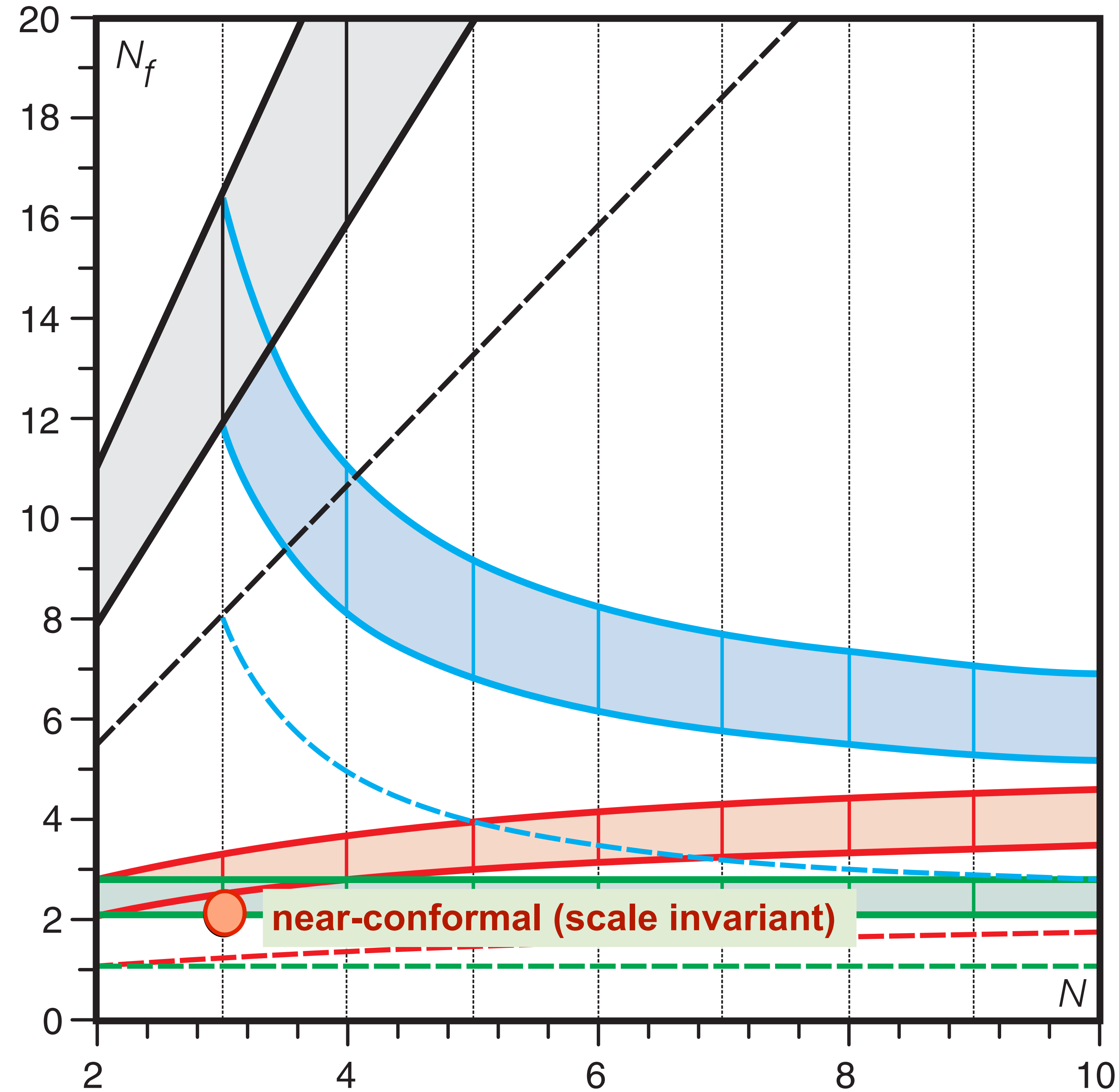

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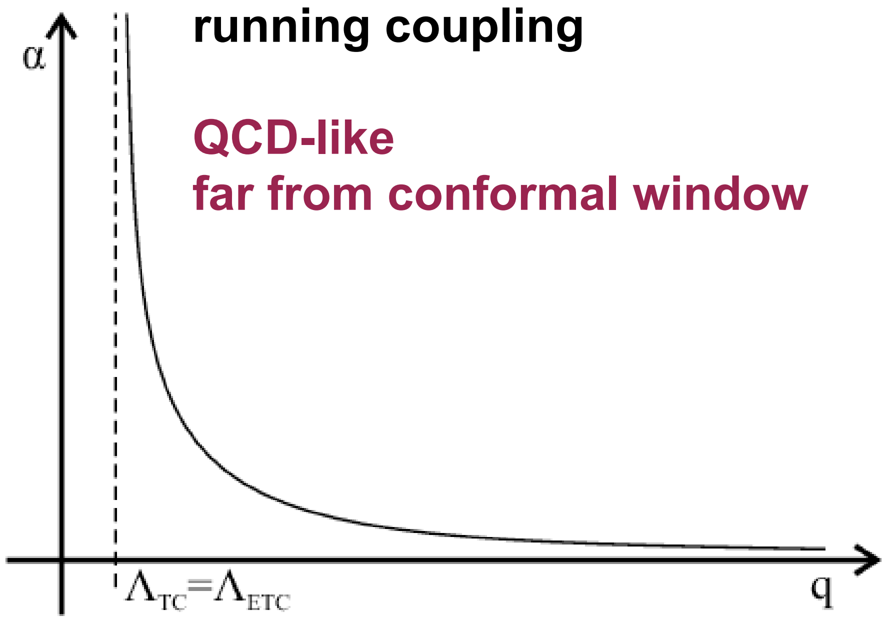

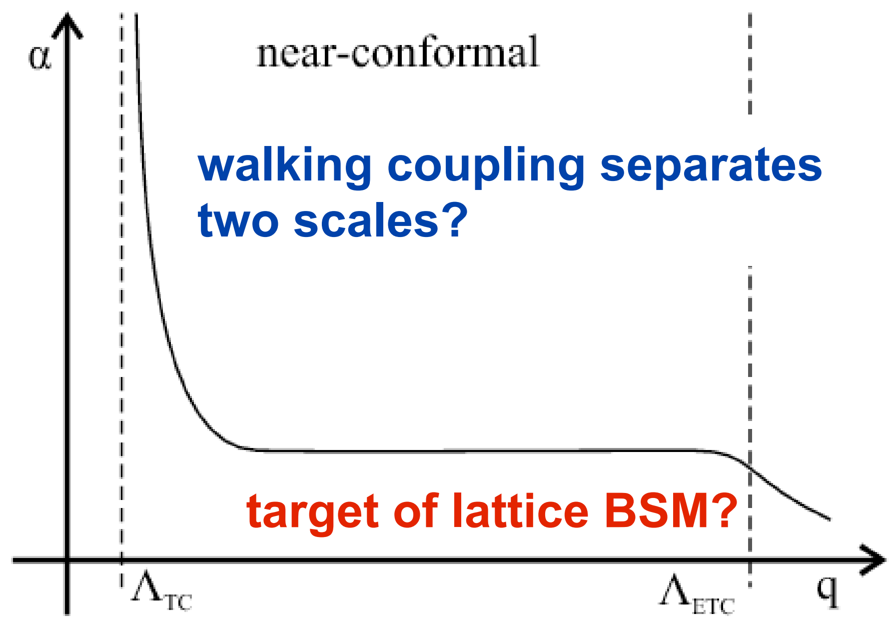

χSB on Λ~TeV scale

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

Lattice Higgs Collaboration

Kogut,Sinclair
finite temperature

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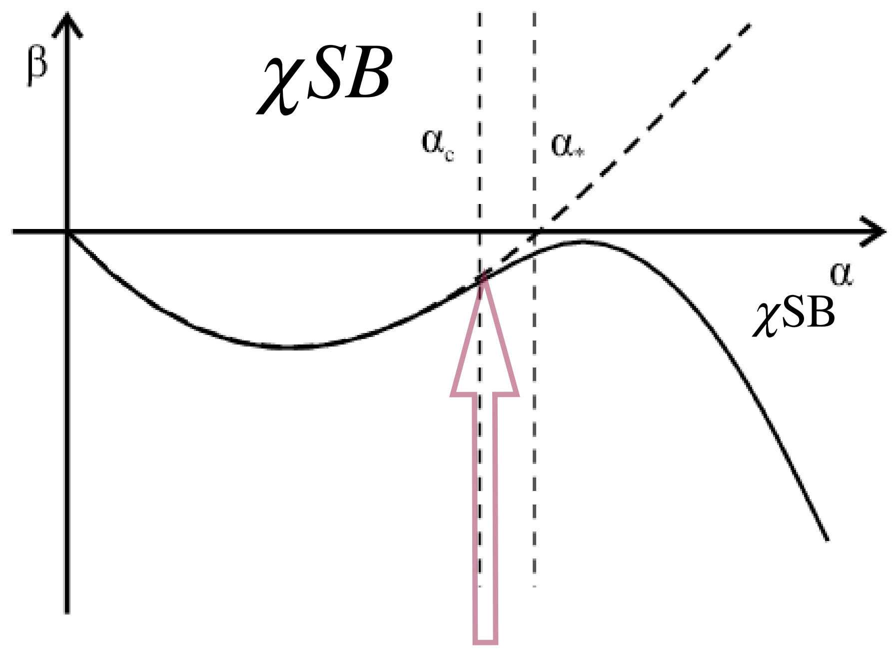
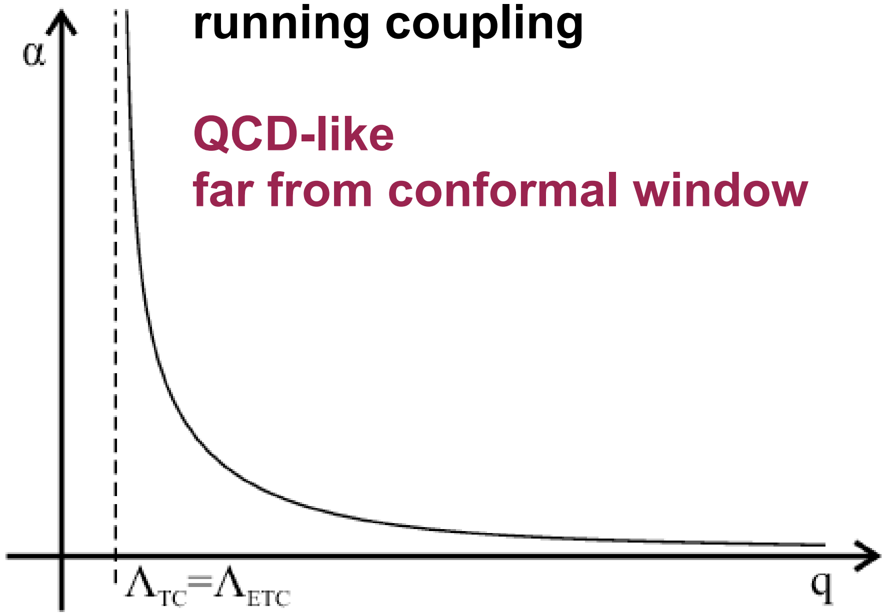
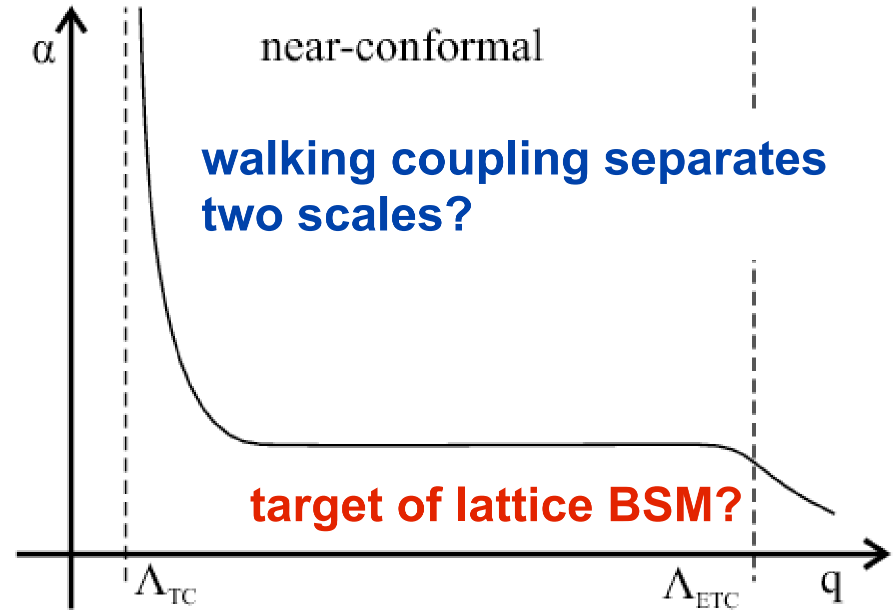


when chiral symmetry breaking
turns conformal FP into walking

light Higgs near conformality (dilaton-like?) sextet





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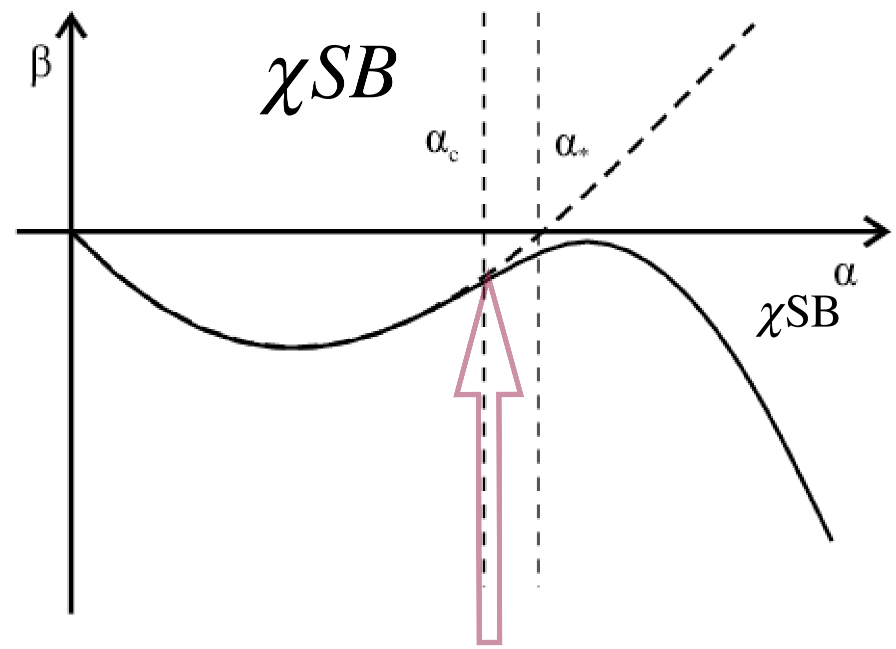

when chiral symmetry breaking
turns conformal FP into walking

two expectations:

(1) χSB and confinement

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

light Higgs near conformality (dilaton-like?) sextet

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

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

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

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$$\left[\Theta_\mu^\mu\right]_{NP} = \frac{\beta(\alpha)}{4\alpha}\left[G_{\mu\nu}^a G^{a\mu\nu}\right]_{NP} \qquad \frac{m_\sigma}{f_\sigma} \to ?$$

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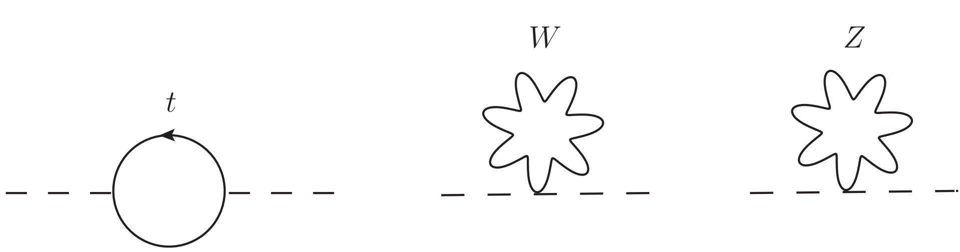
but how light is light ?
few hundred GeV Higgs impostor?

Foadi, Fransden, Sannino
open for spirited theory discussions



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

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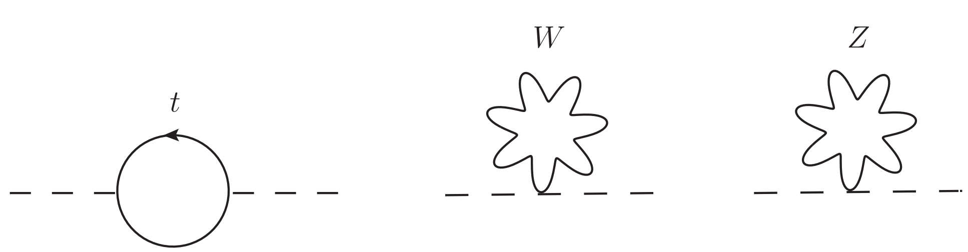

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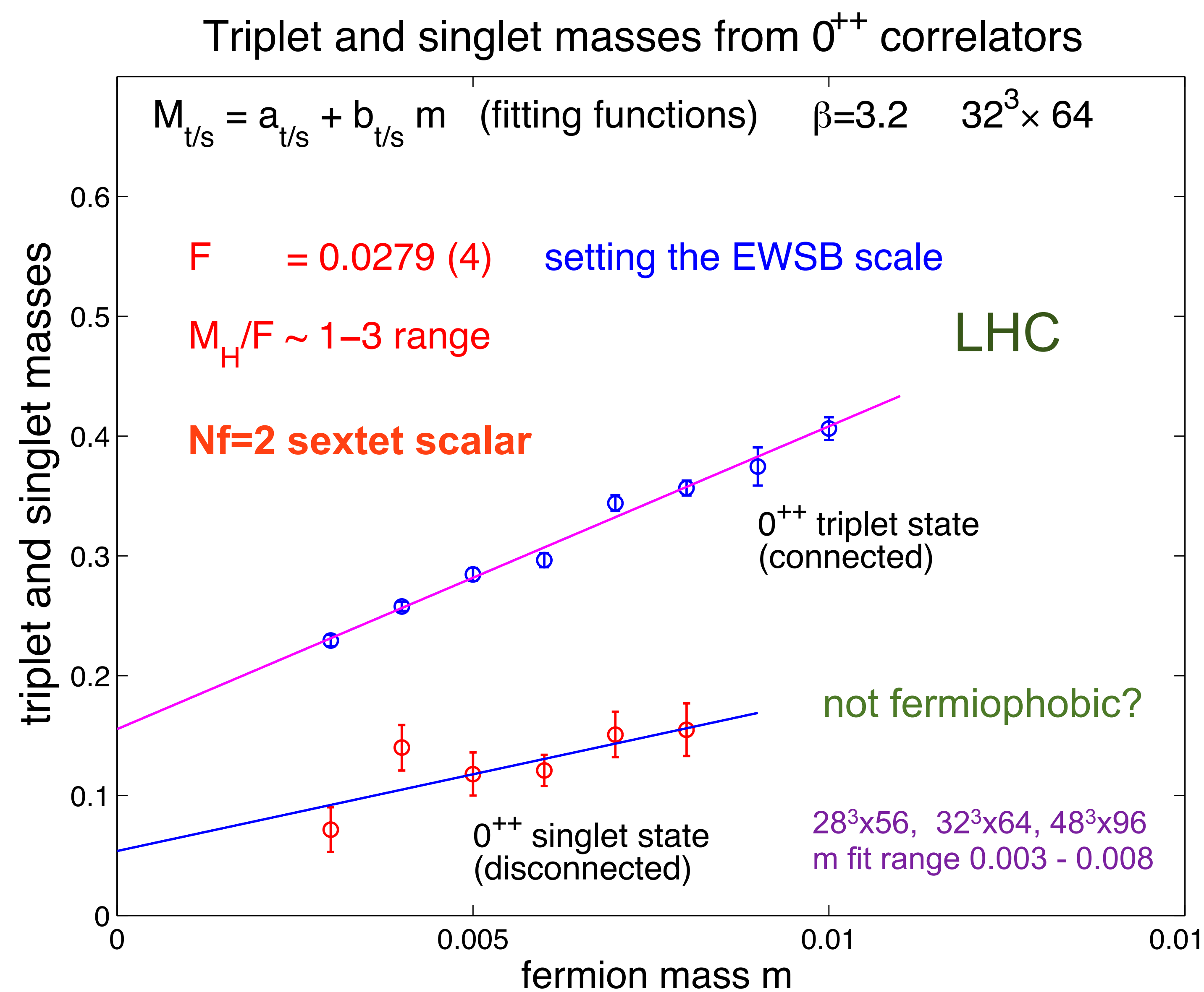

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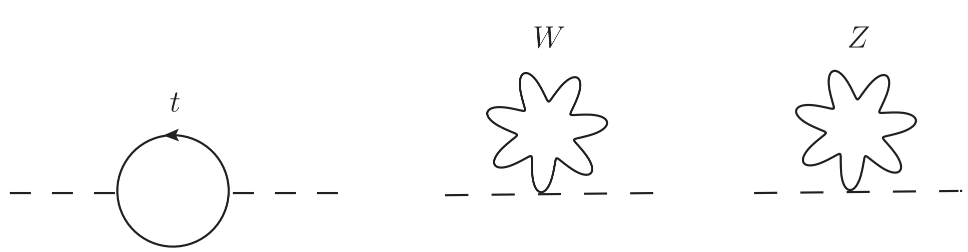
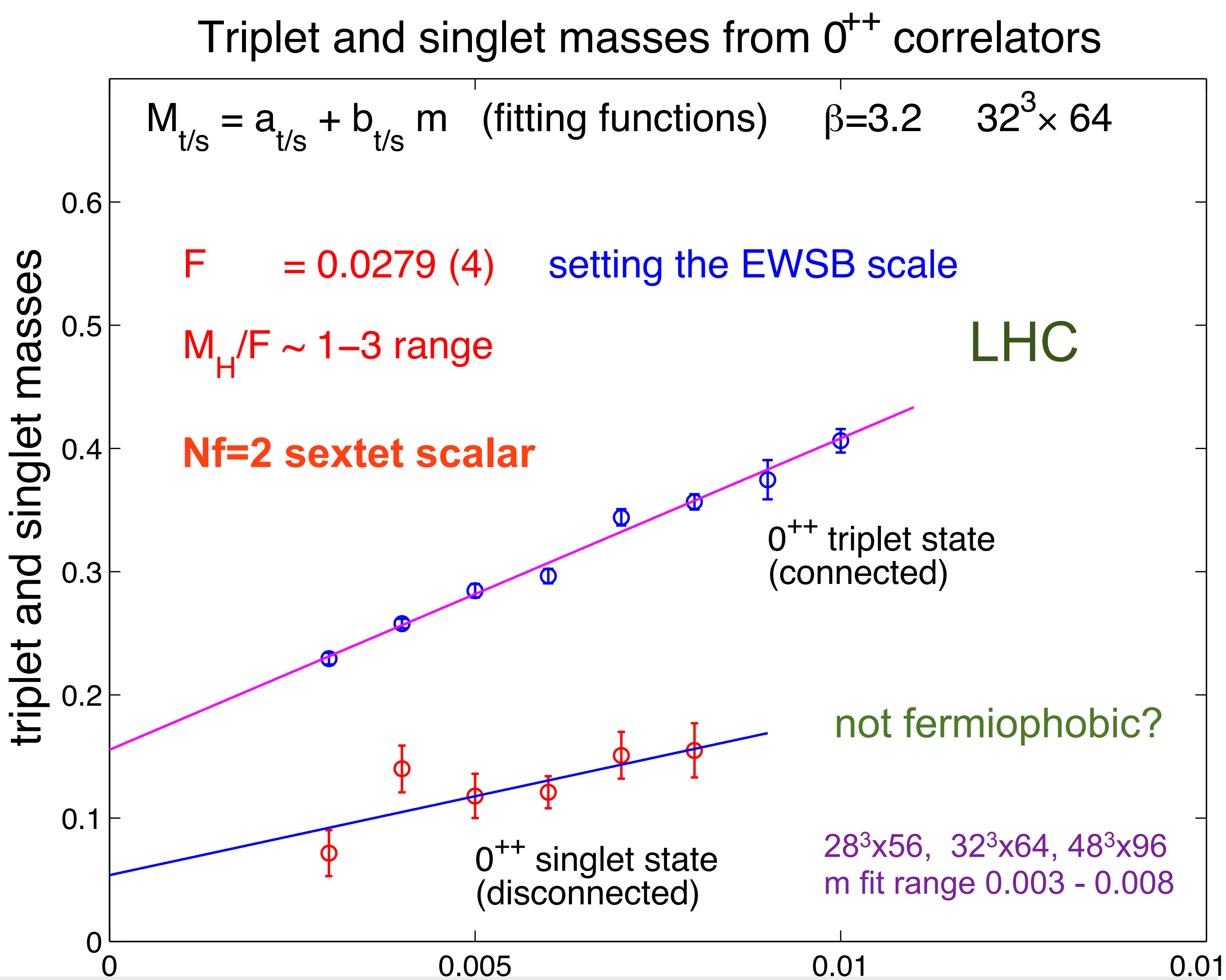




dilaton-like scalar states in SCGT, or “just a light Higgs” ?

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_{Pl}

observed Higgs -> Metastable vacuum

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

effective theory of strongly coupled composite Higgs scenario

$$\omega \sim 1$$

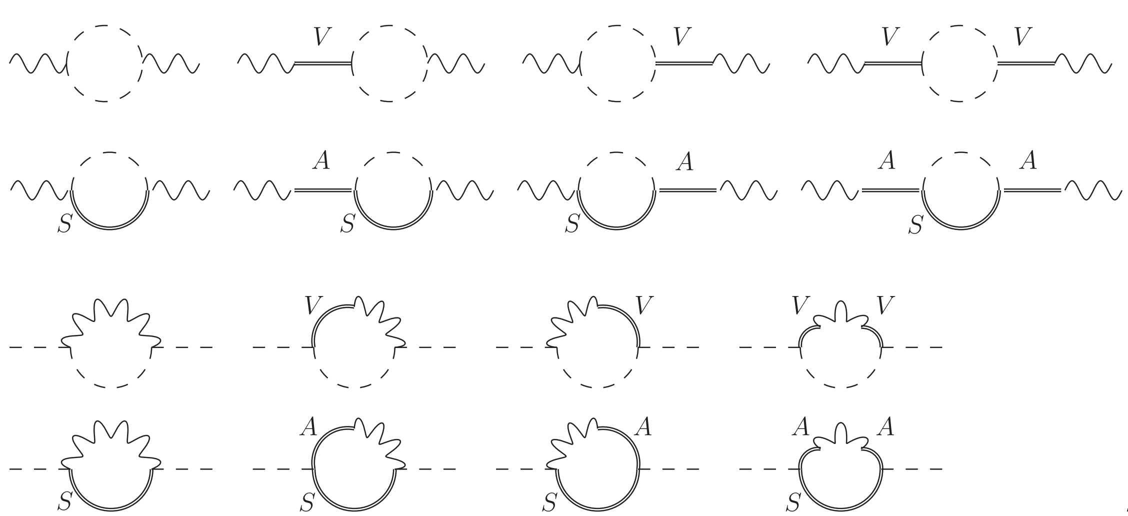
u: Goldstone

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

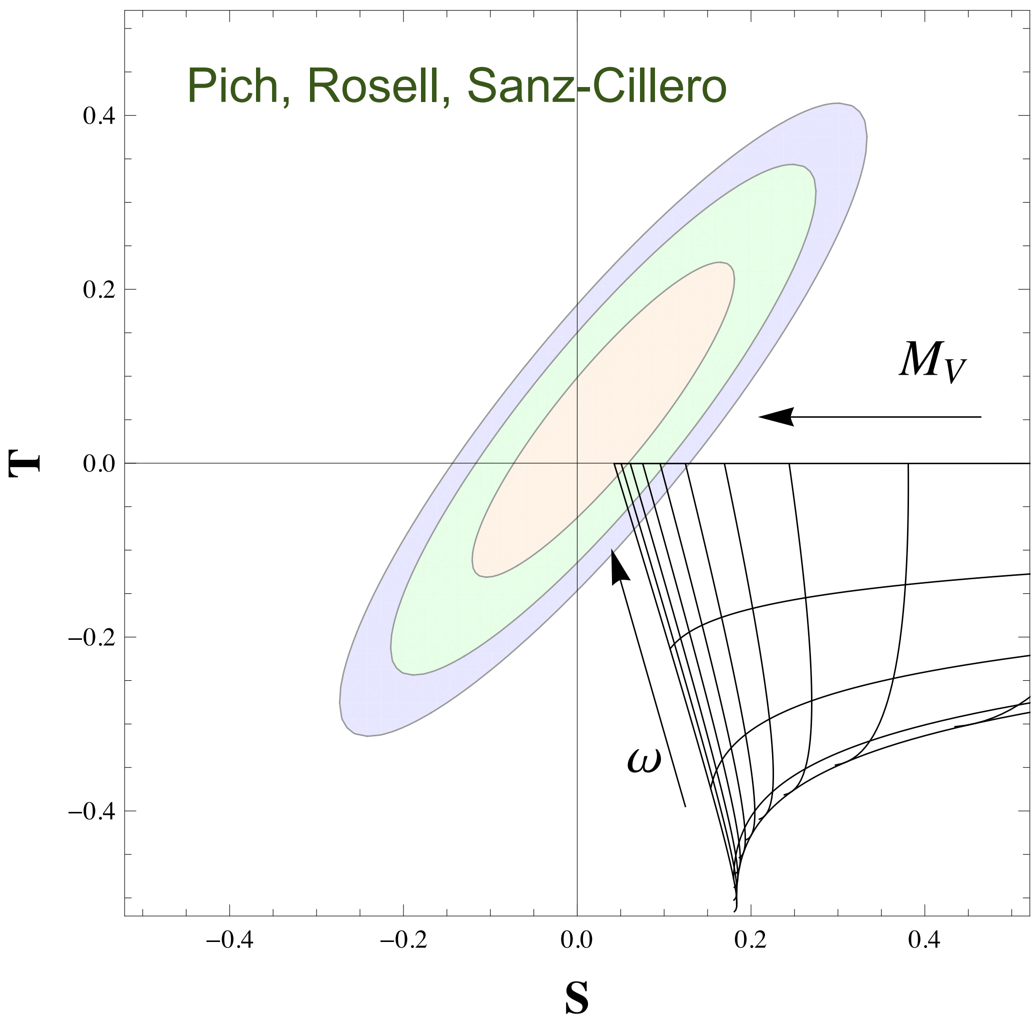


FIG. 2. NLO determinations of S and T, imposing the two WSRs. The approximately vertical curves correspond to constant values of M_V, from 1.5 to 6.0 TeV at intervals of 0.5 TeV. The approximately horizontal curves have constant values of ω: 0.00, 0.25, 0.50, 0.75, 1.00. The arrows indicate the directions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

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

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

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

From two Weinberg sum rules and from NLO loop expansion:

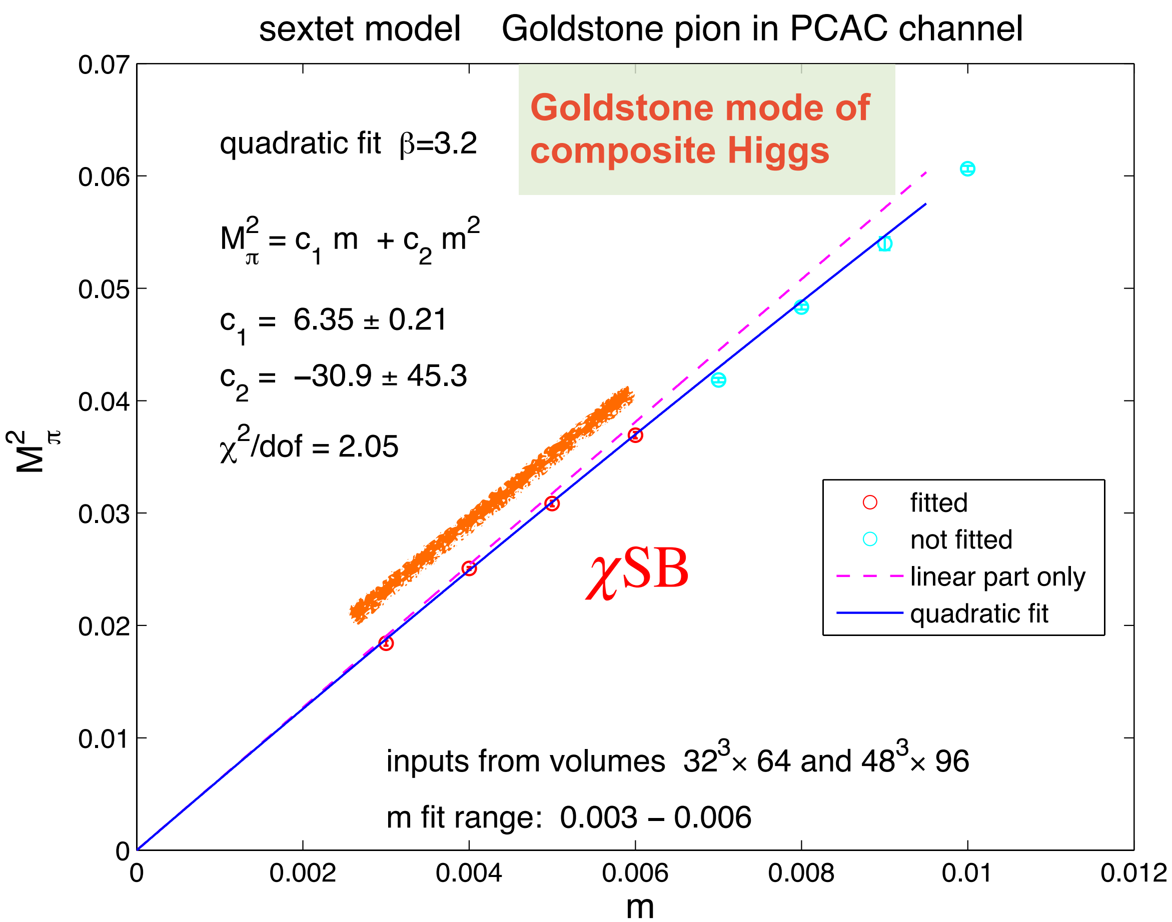
M_V, M_A ~ 2 TeV or higher is compatible with S,T constraints (it is tight and arguably ambiguous)

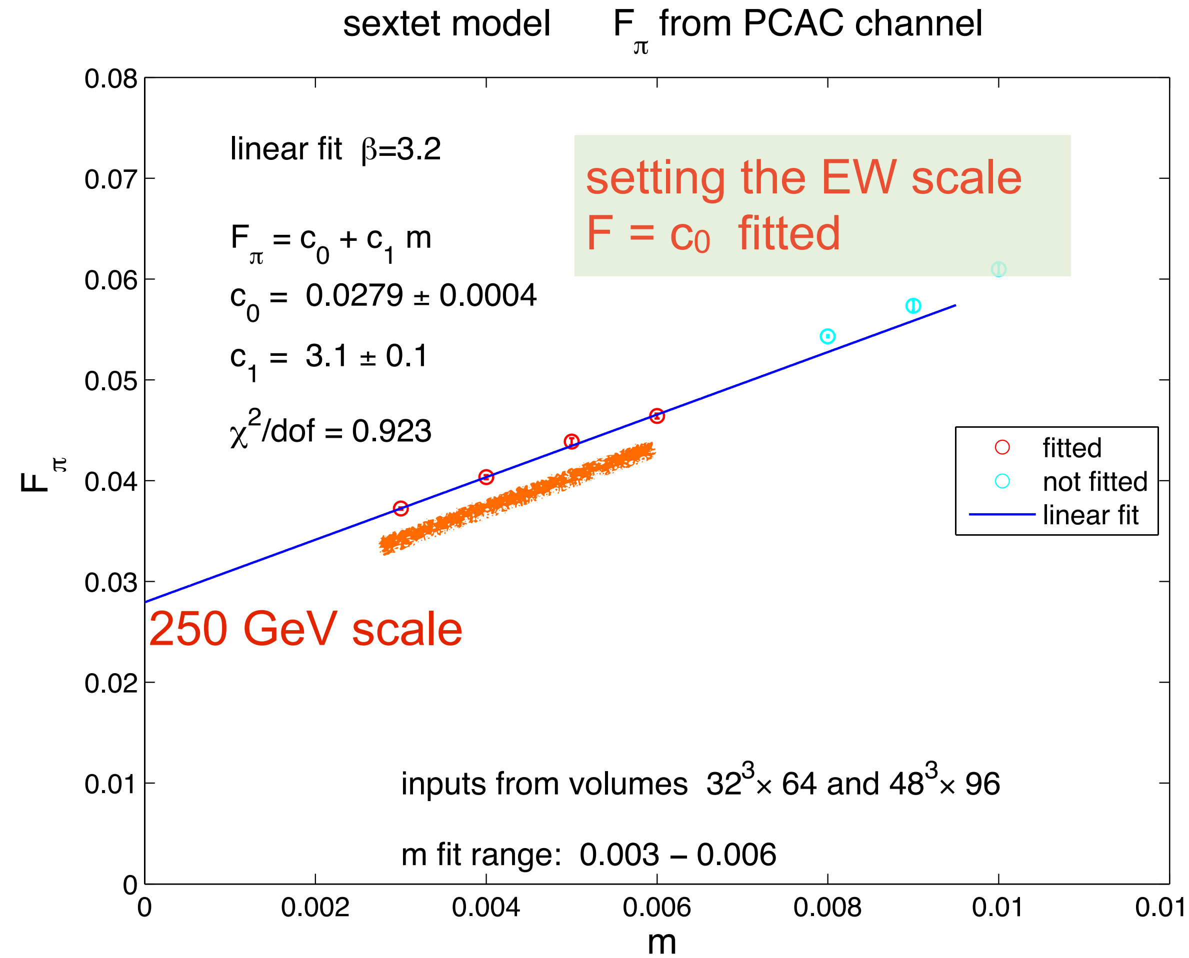
more work needed

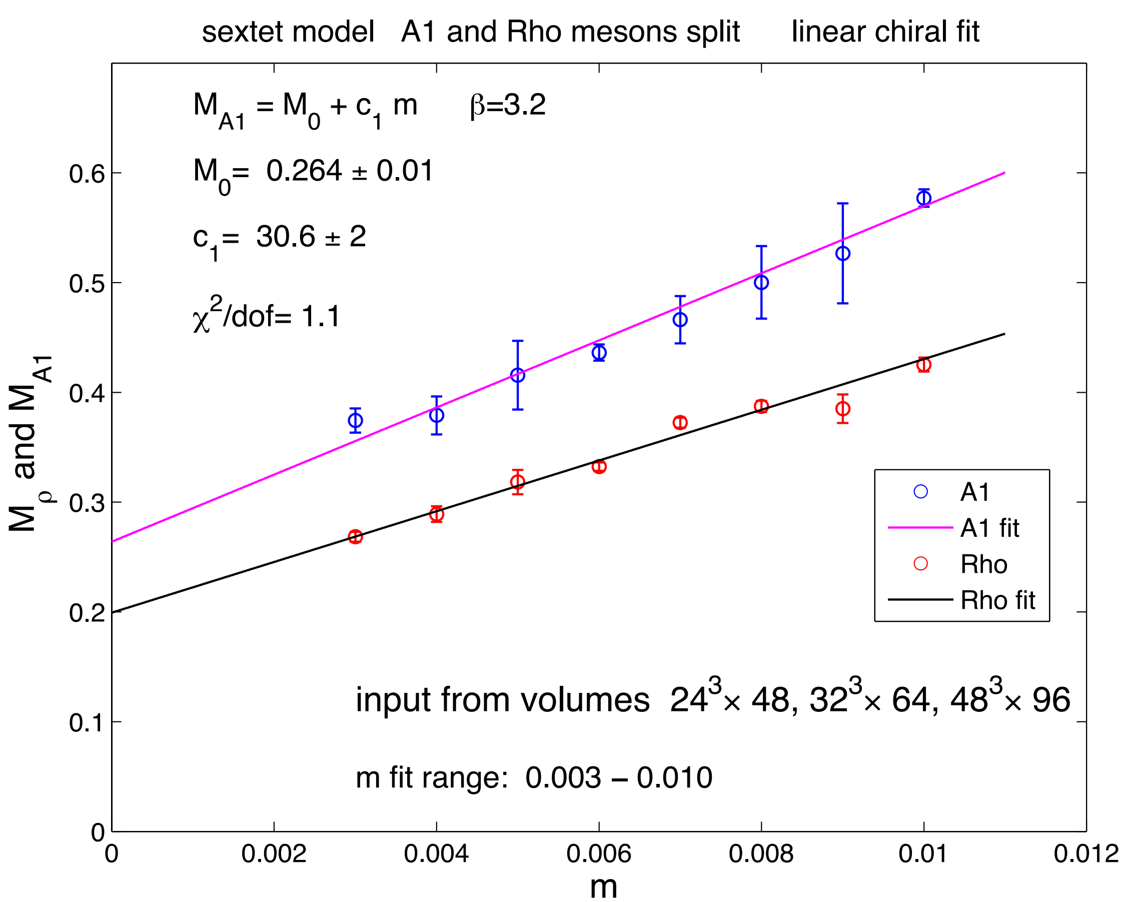
related body of work by Sannino and collaborators

Spectroscopy and scale setting

sextet N_f=2







A1/F ~ 9.5

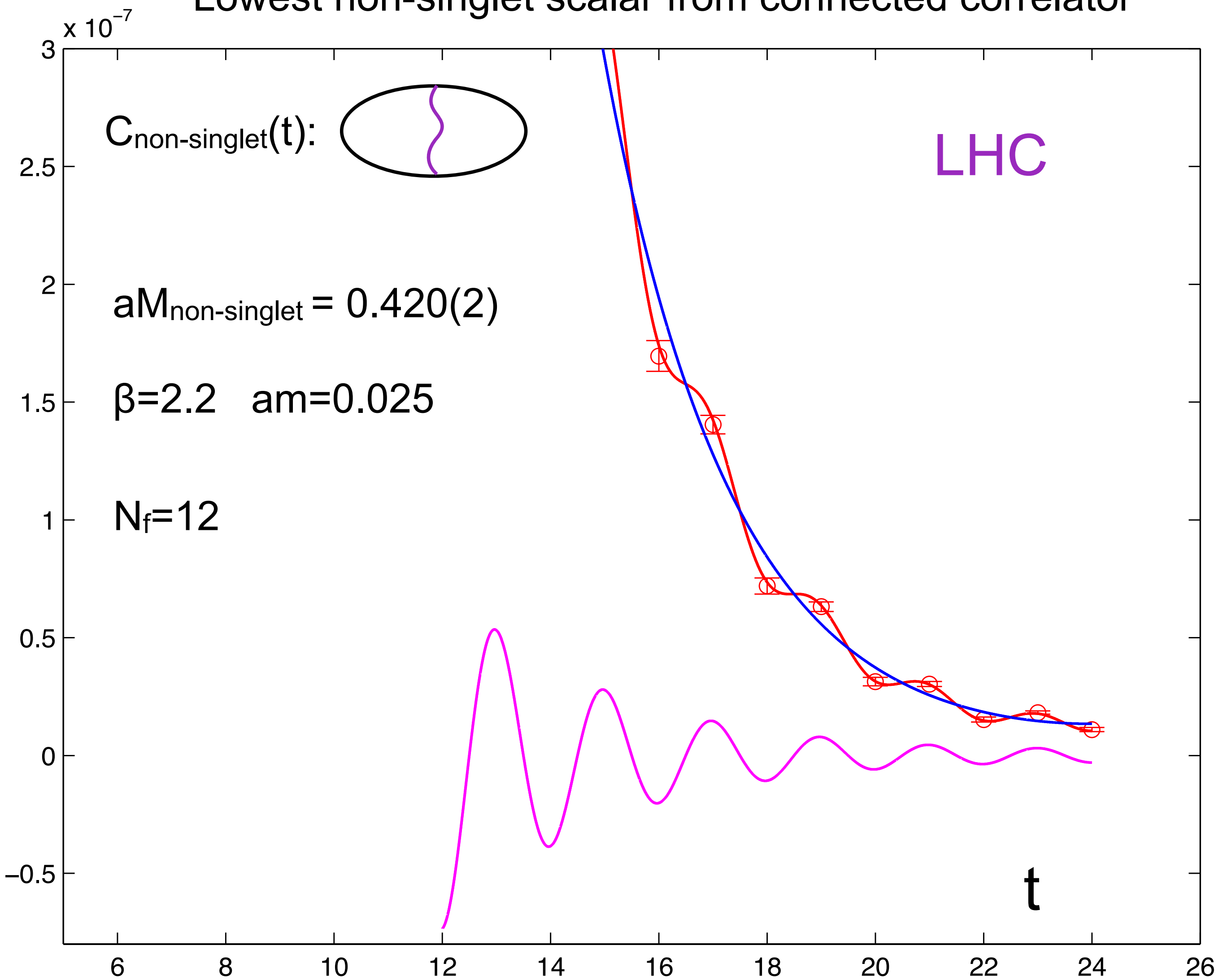
M_{A1}~ 2.37 TeV

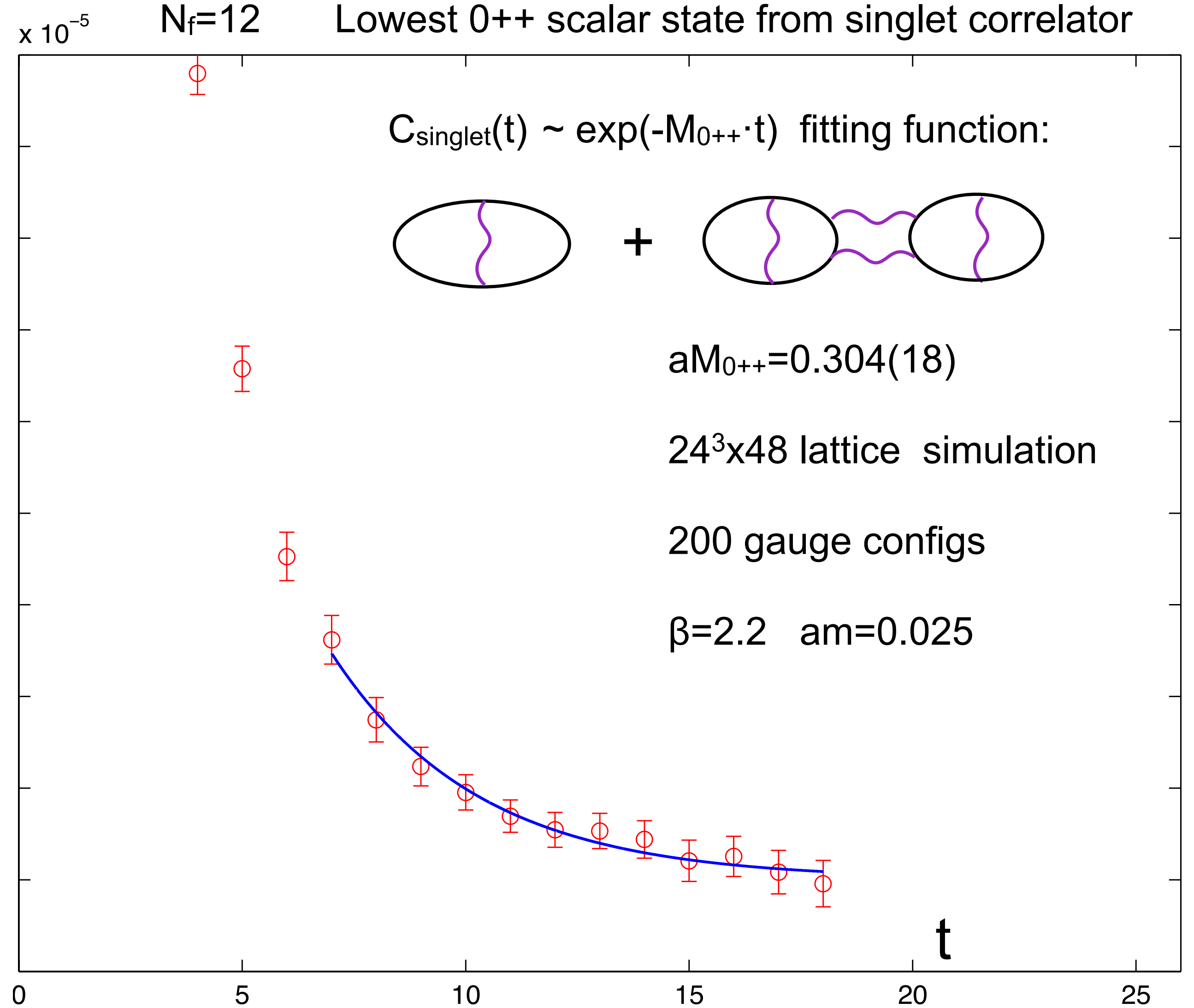
LHC14?

- 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:



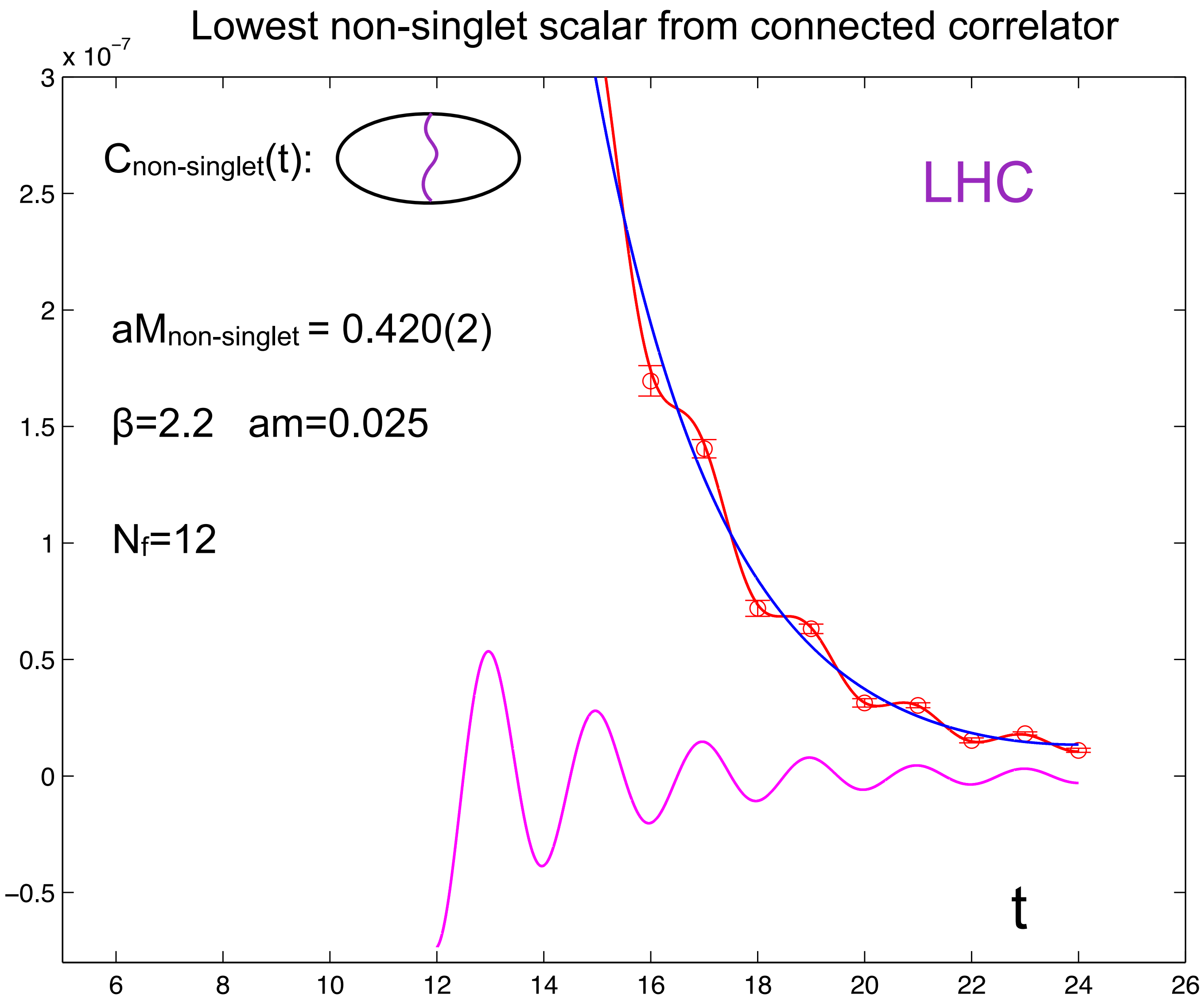


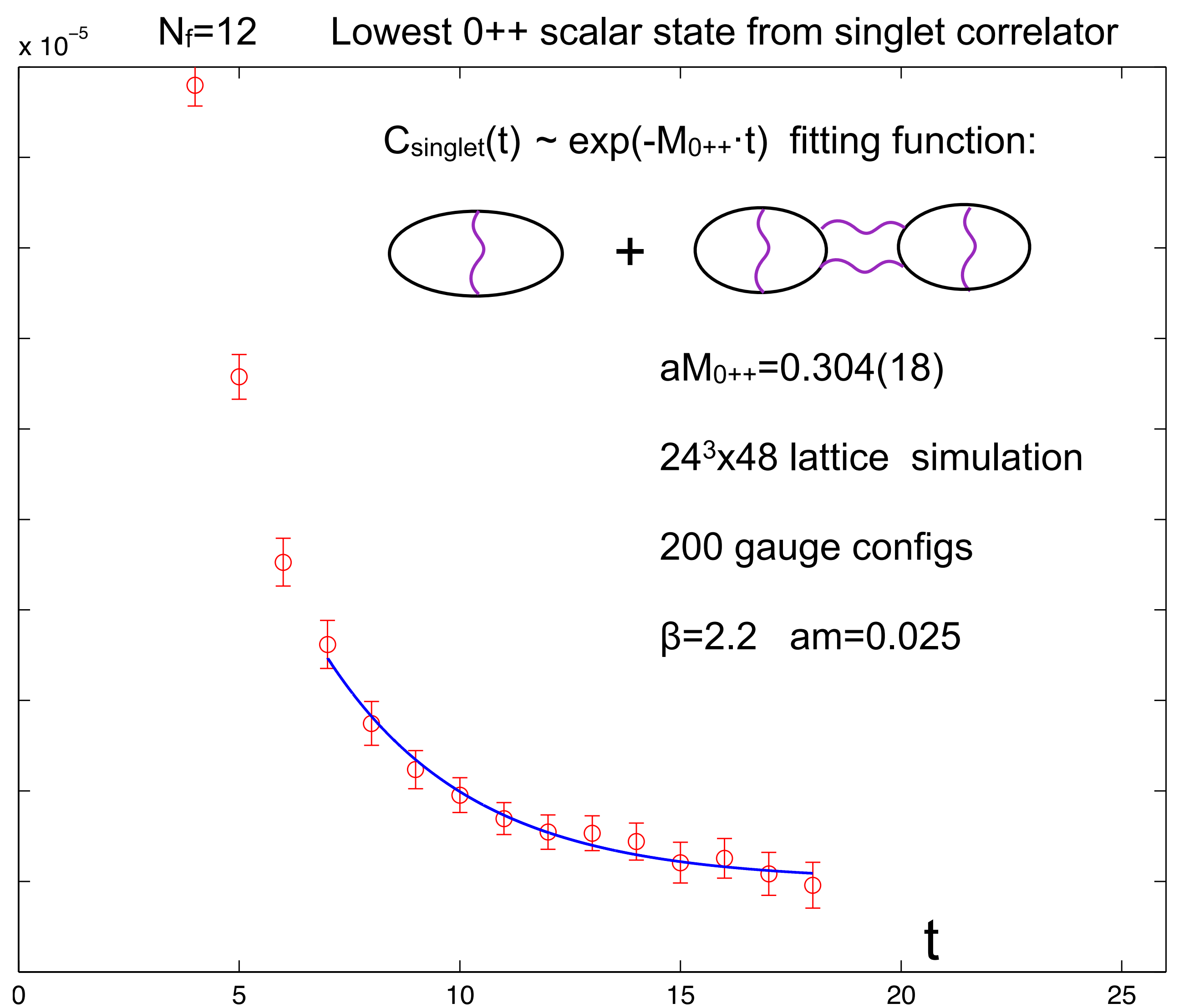
$$C(t) = \sum_n \left[A_n e^{-m_n(\Gamma_S\otimes\Gamma_T)t} + (-1)^t B_n e^{-m_n(\gamma_4\gamma_5\Gamma_S\otimes\gamma_4\gamma_5\Gamma_T)t}\right]$$

staggered correlator

Spectroscopy and scale setting (scalar) N_f=12

test of technology:



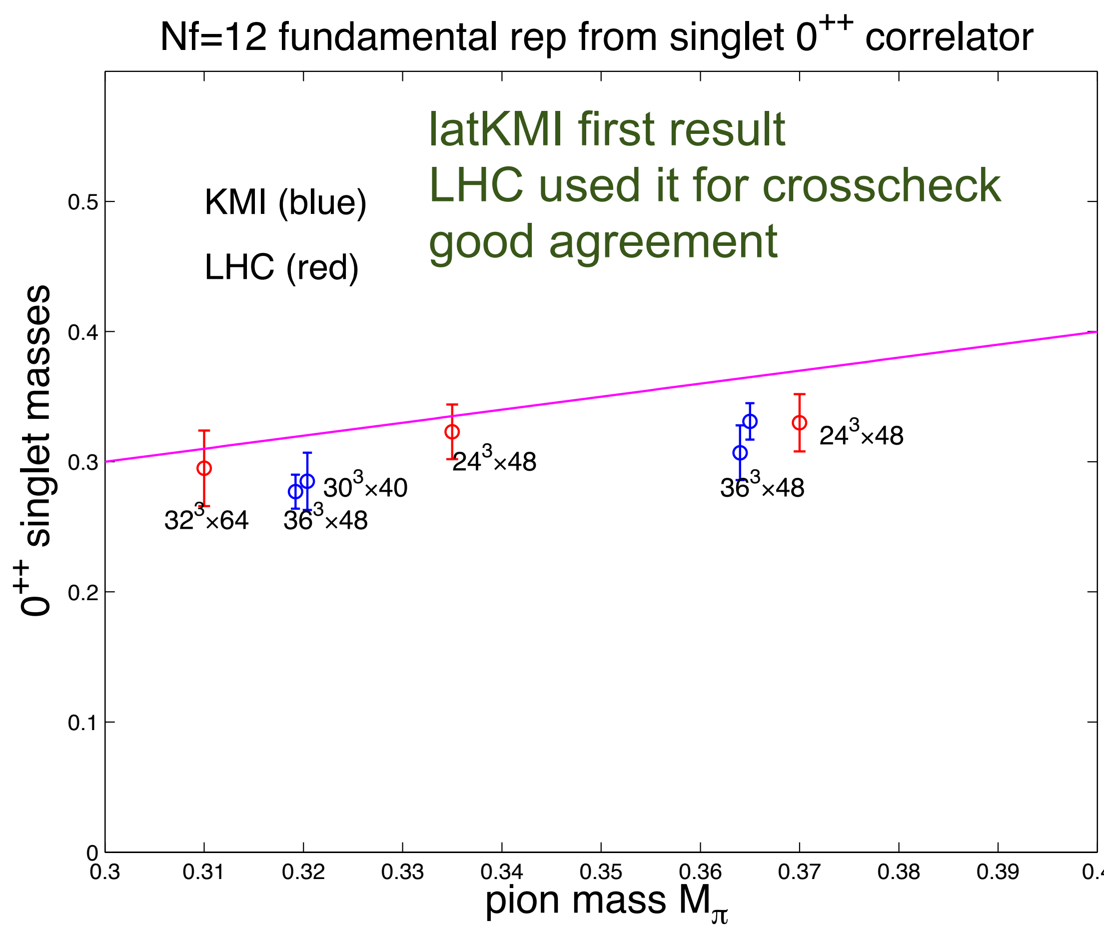


$$C(t) = \sum_n \left[A_n e^{-m_n(\Gamma_S \otimes \Gamma_T)t} + (-1)^t B_n e^{-m_n(\gamma_4\gamma_5\Gamma_S \otimes \gamma_4\gamma_5\Gamma_T)t}\right]$$

staggered correlator

similar analysis in sextet model with N_f=2

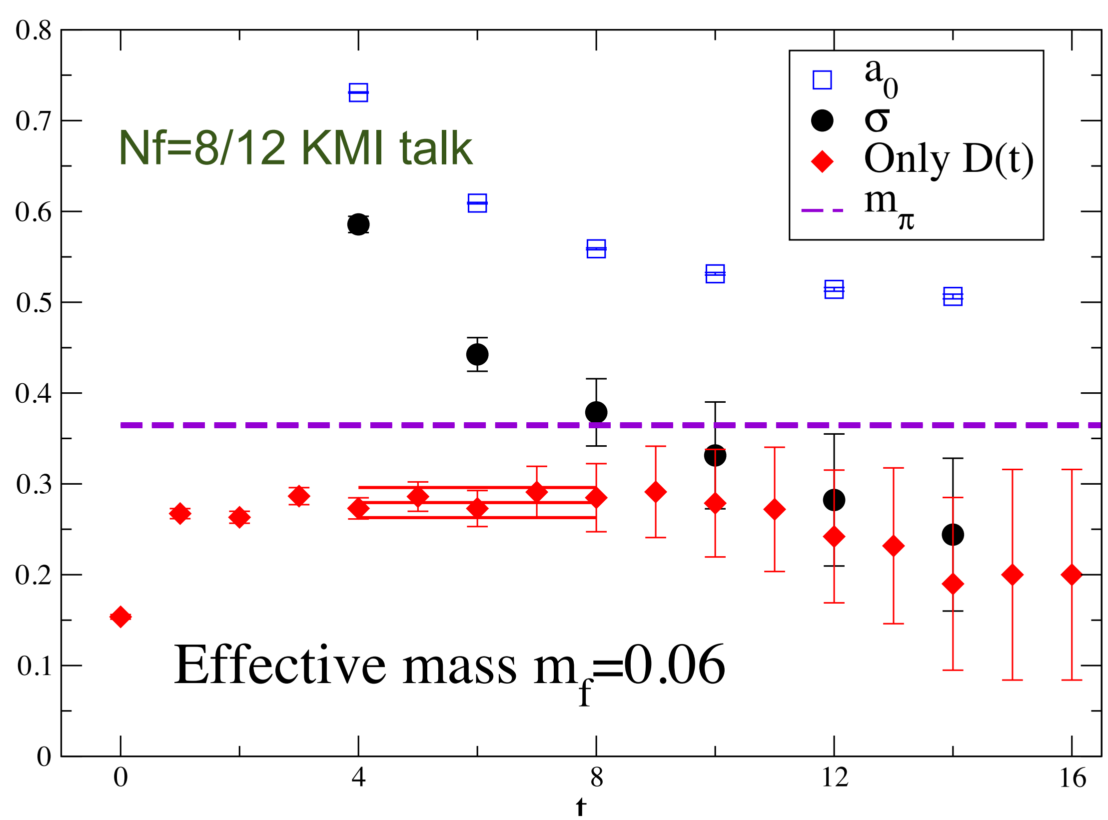
Spectroscopy and scale setting (scalar) N_f=12



LHC group was holding back on Nf=8 (USBSM incite)

It has always been a low-hanging fruit

New development: LHC is doing Nf=8 now
second generation rerun of earlier published work



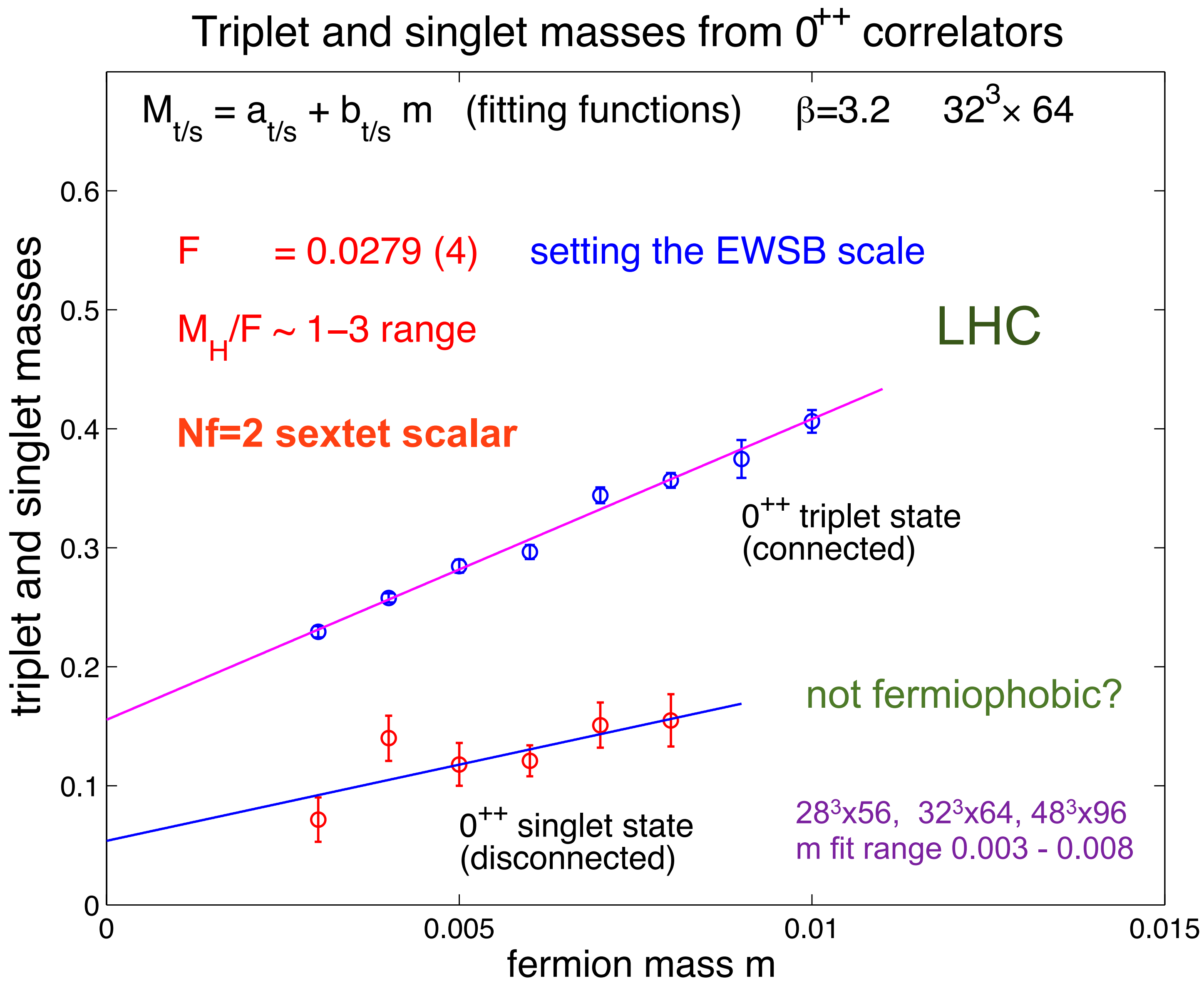
Non-singlet scalar
a_0: $-C_+(t)$

Singlet scalar
σ: $3D_+(t) - C_+(t)$
σ: $D(t)$ i.e. $m_\sigma < m_{a_0}$
Consistent m_σ
with smaller error
also Jin and Mawhinney
$m_\sigma < m_\pi$ at $m_f = 0.06$

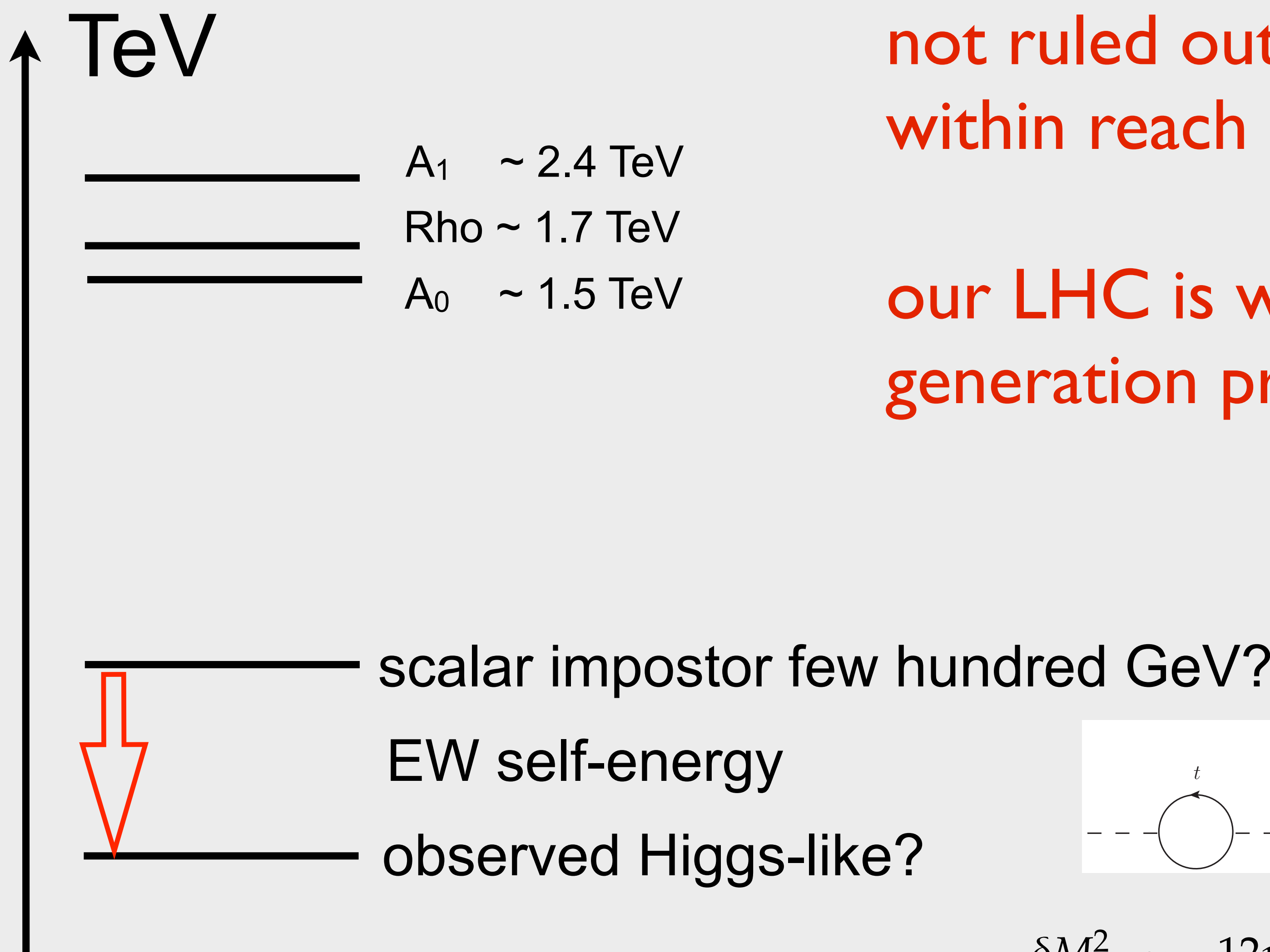
Spectroscopy (scalar)

Spectroscopy (scalar)

sextet N_f=2

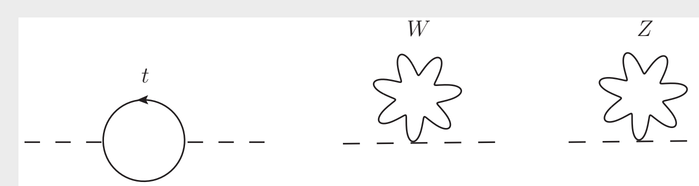


Spectroscopy for LHC run2 sextet $N_f=2$



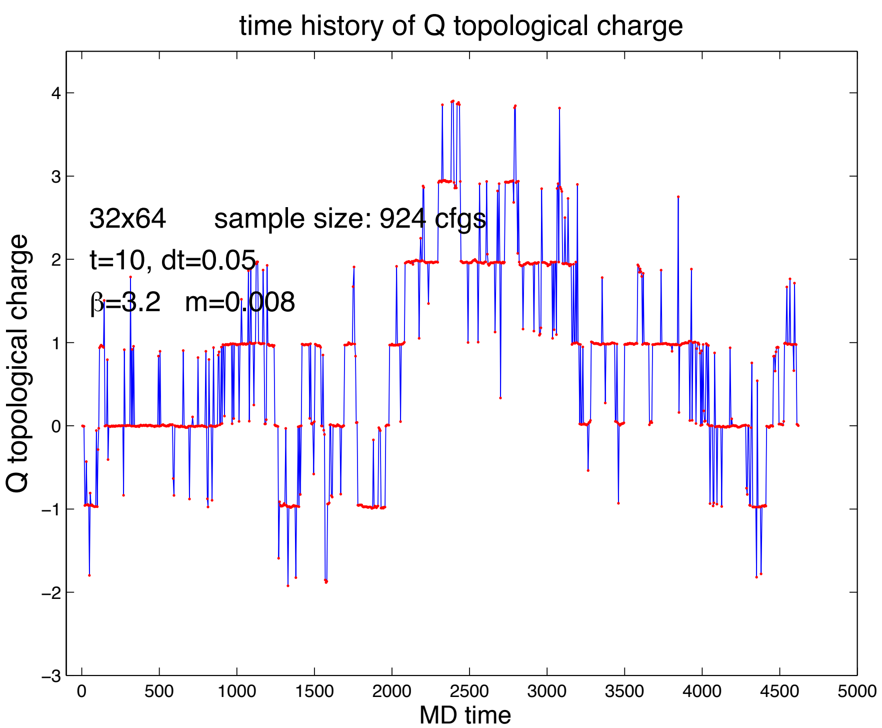
not ruled out from LHC run1
within reach of LHC run2

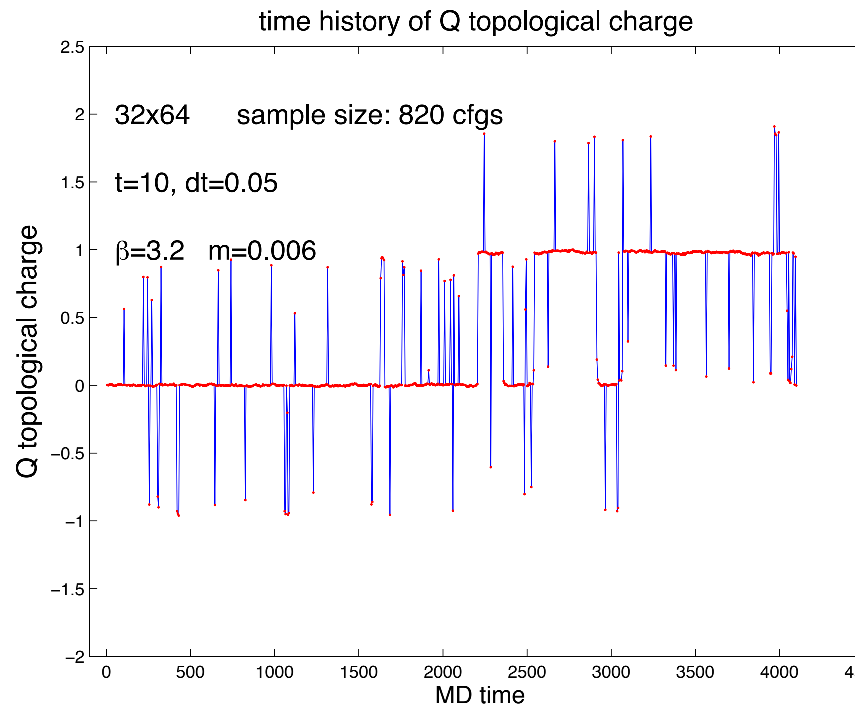
our LHC is working on second generation precision now

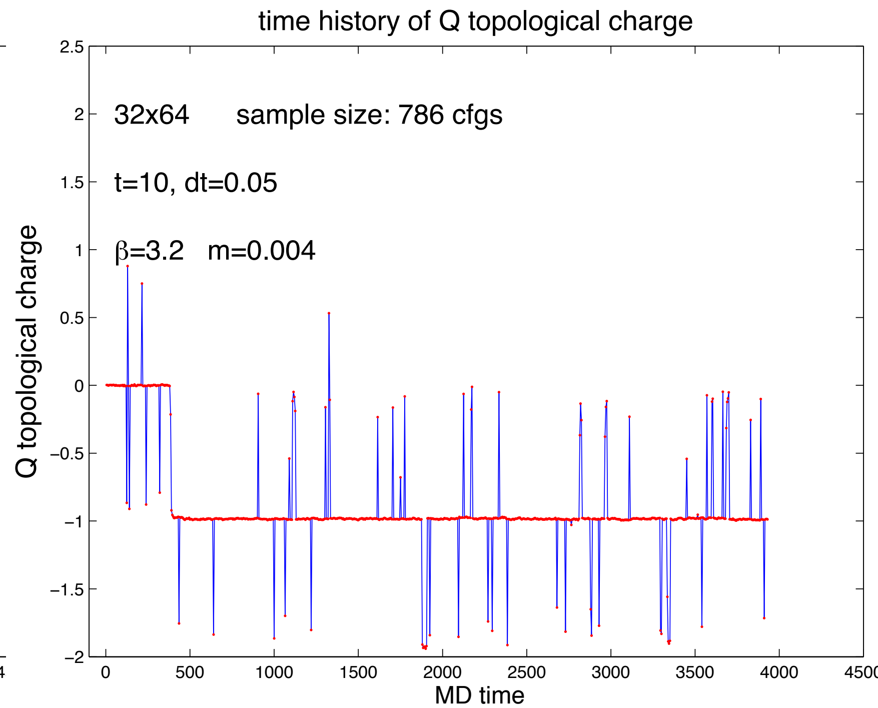


$$\delta M_H^2 \sim -12\kappa^2 r_t^2 m_t^2 \sim -\kappa^2 r_t^2 (600\,\mathrm{GeV})^2$$

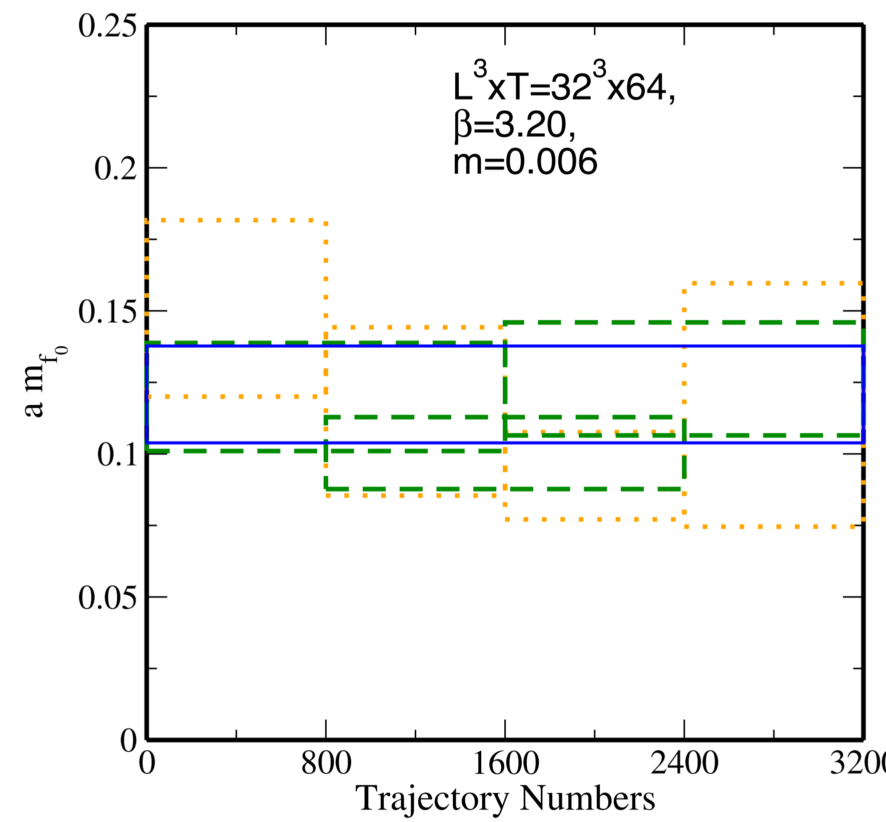
slowly changing topology complicates the analysis:







- it is 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



running coupling from gradient flow

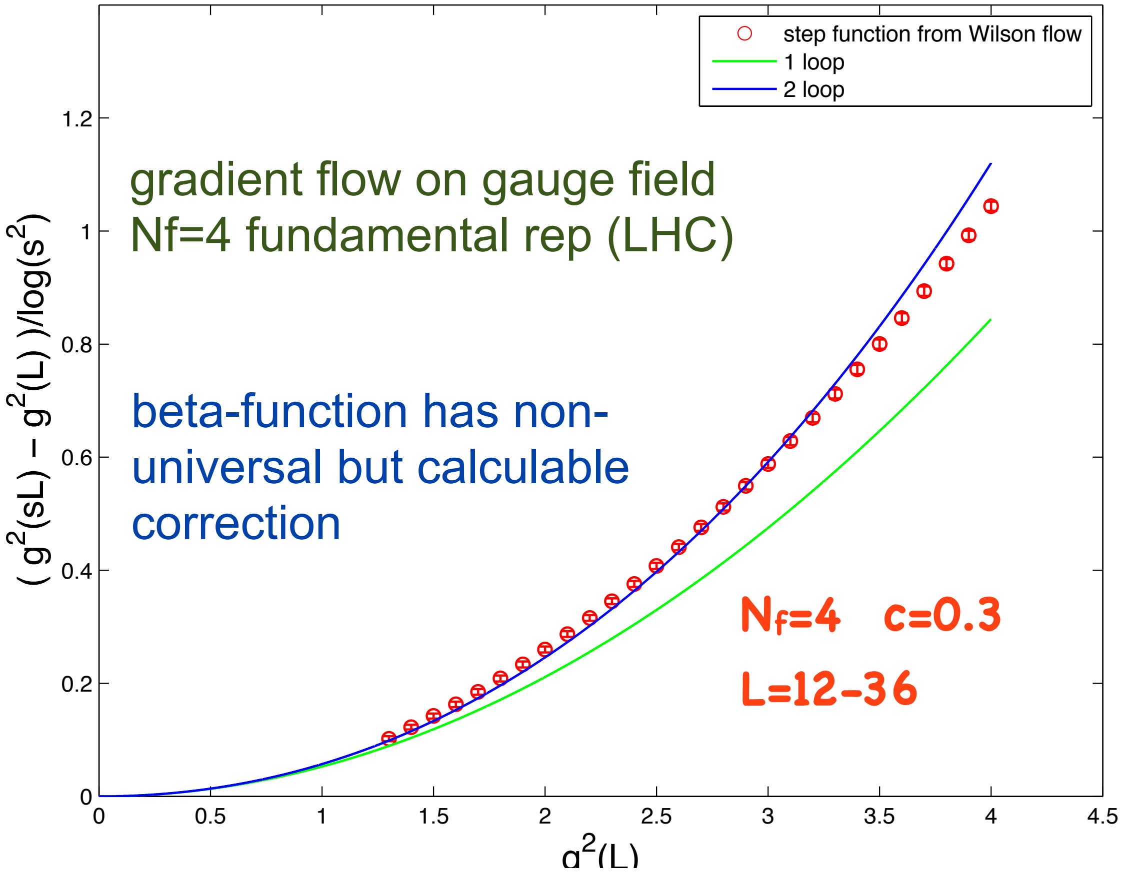
sextet

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

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

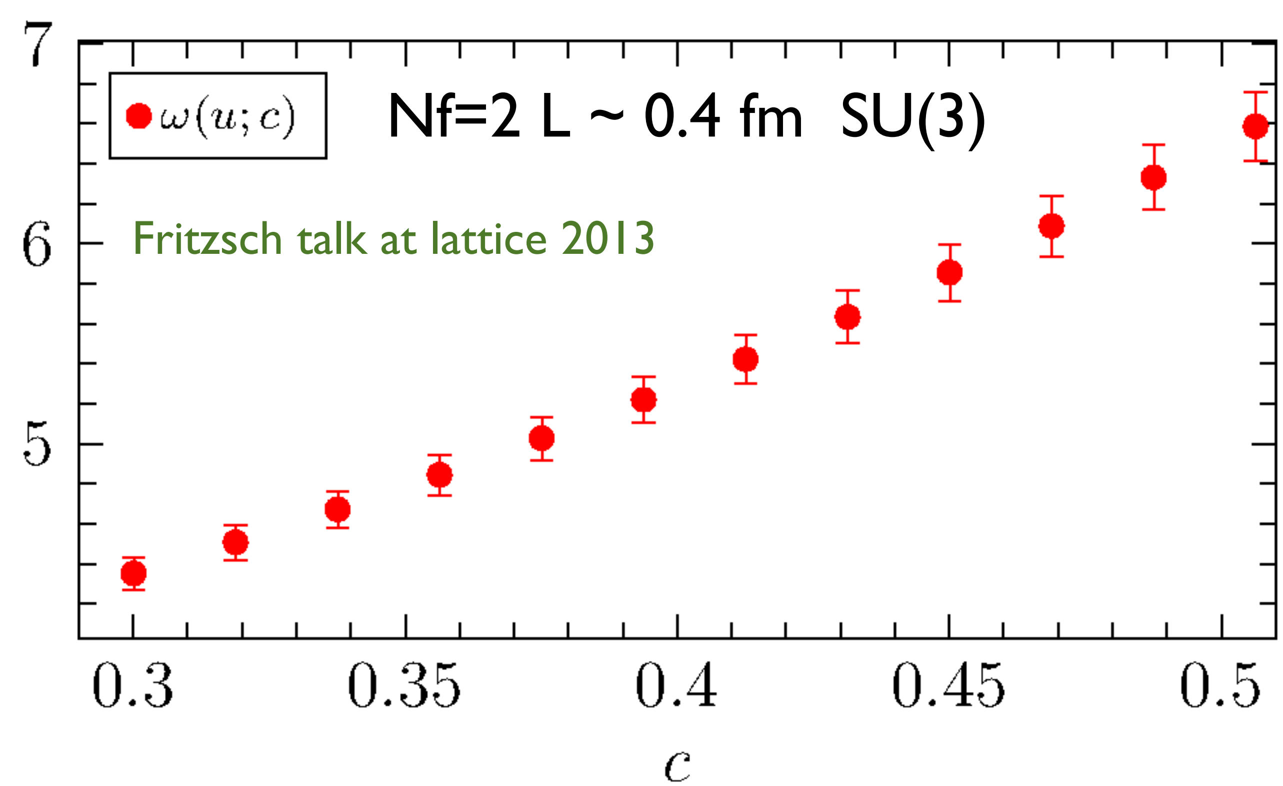


massless fermions; antiperiodic all directions

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

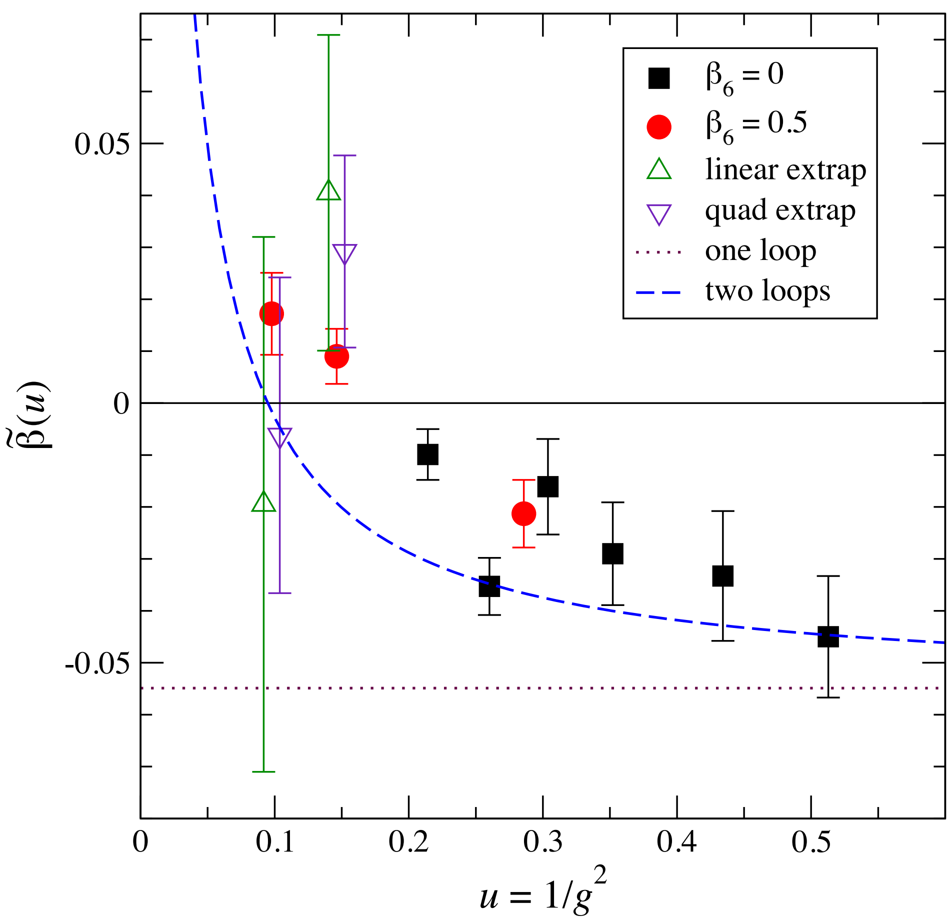
gradient flow coupling with SF boundary conditions



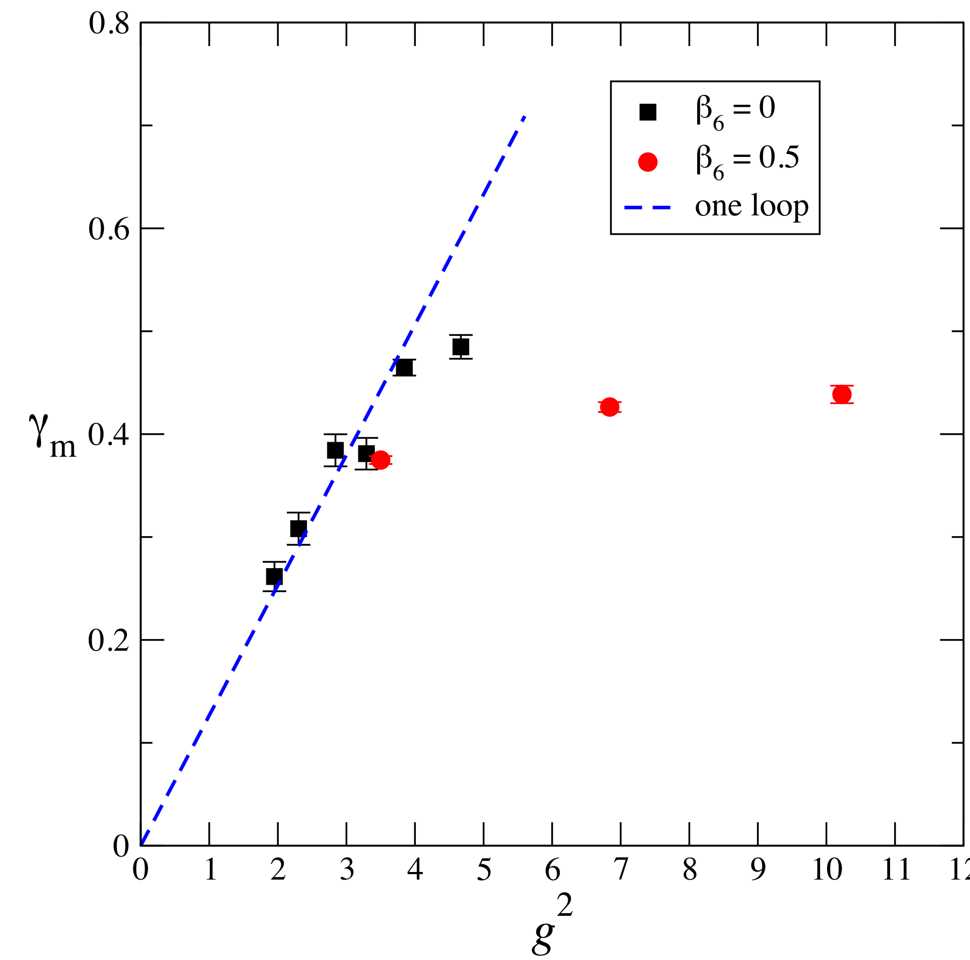
beta-function has conventional loop expansion

running coupling from gradient flow

sextet



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

The chiral condensate in the sextet model

- New stochastic method sextet Nf=2

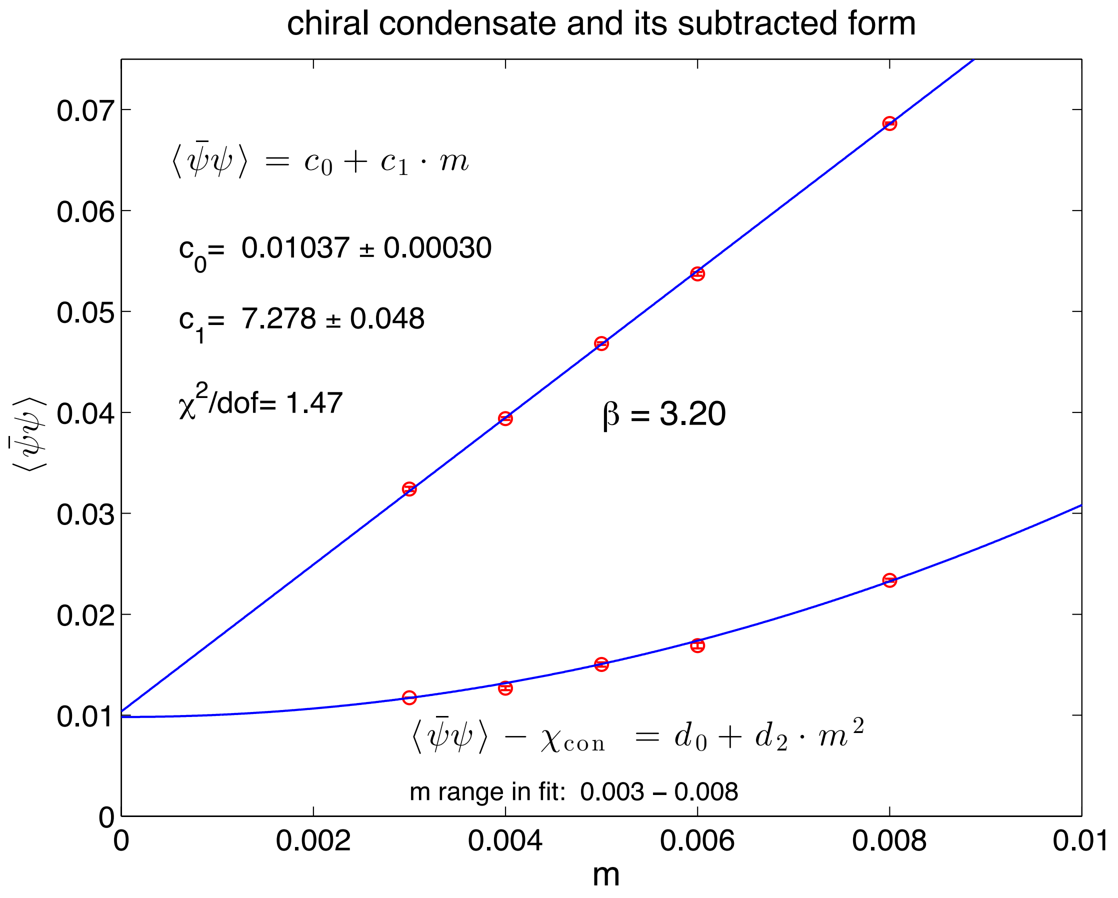
- Direct determination of full spectral density and mode number distribution on gauge configurations

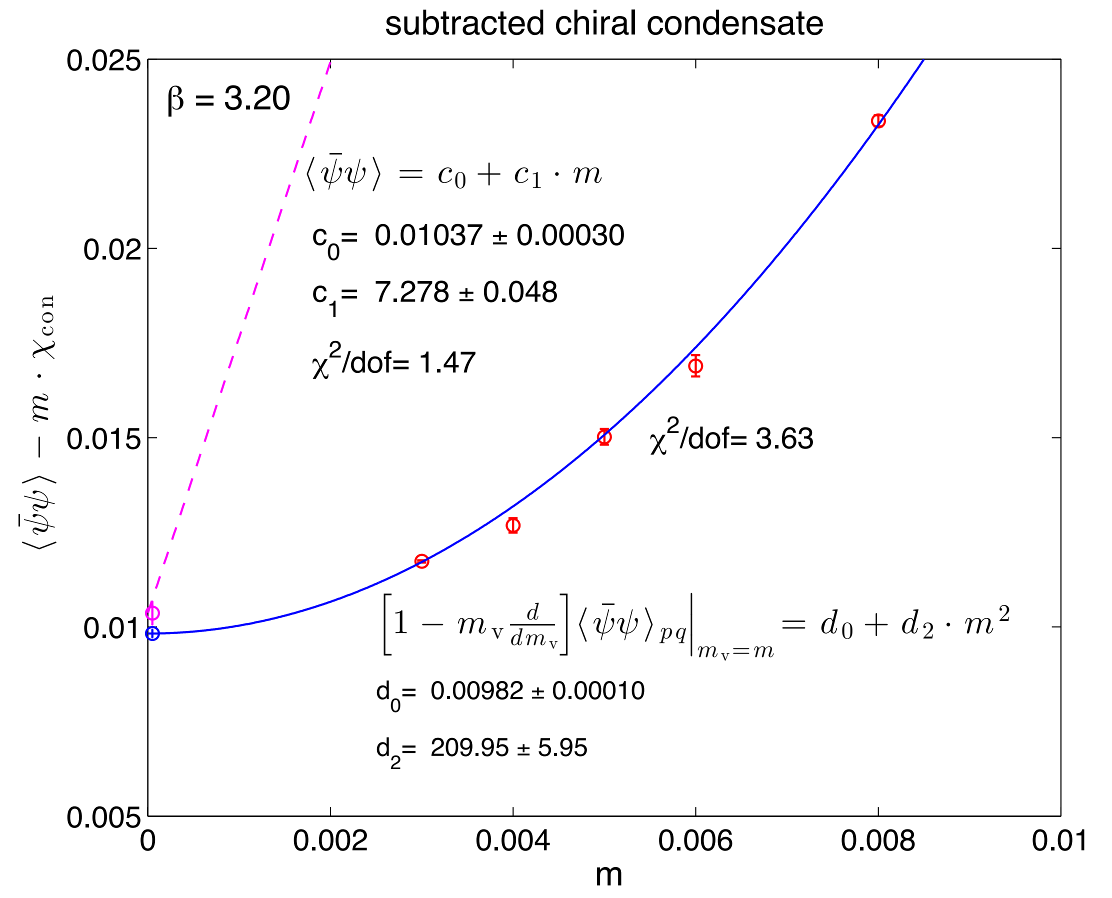
- To remove UV divergences at finite fermion mass

- To investigate internal (in)consistencies with GMOR relation

- To determine anomalous dimension of the chiral condensate

The chiral condensate in the sextet model





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

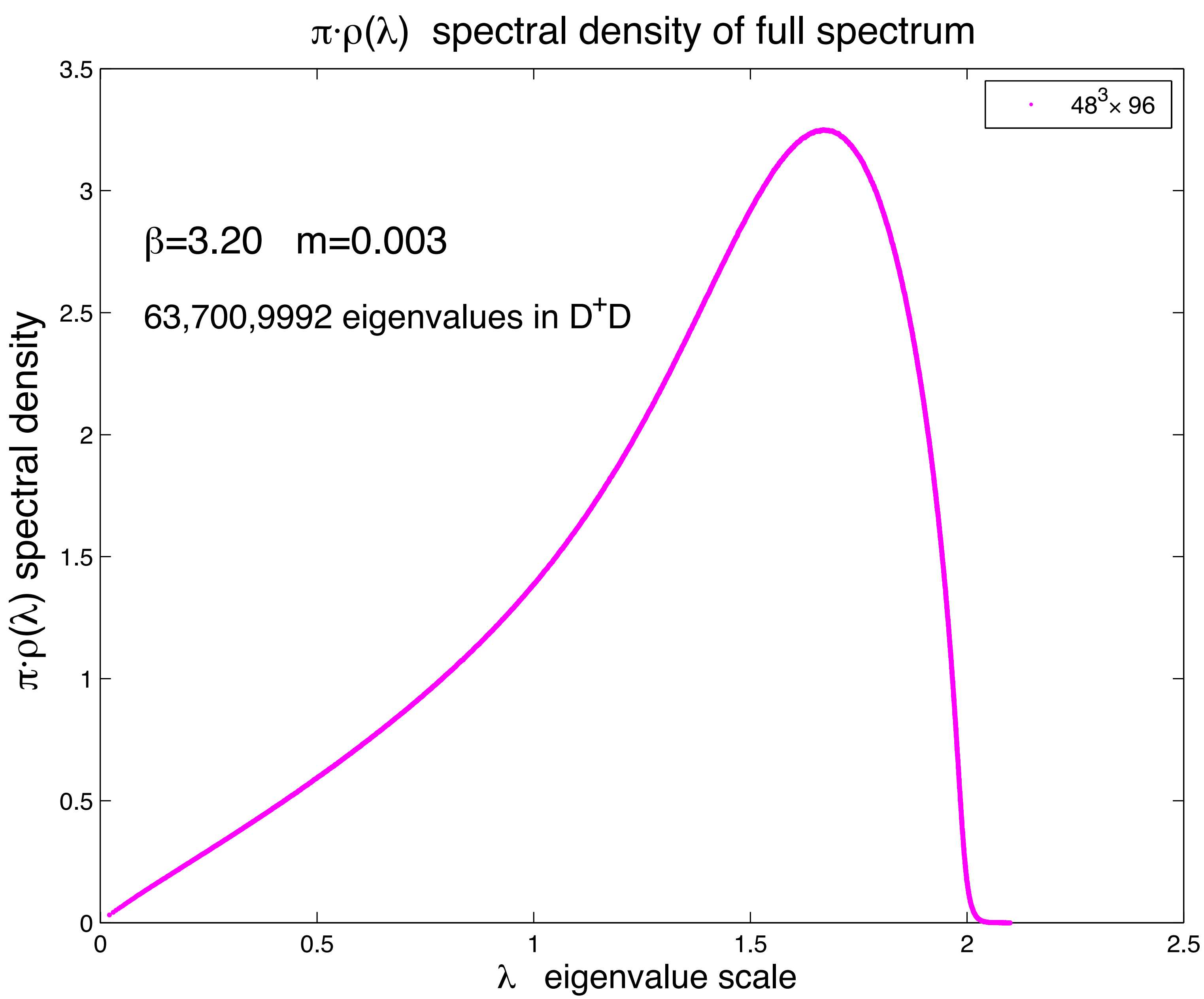
$$\nu(M,m) = V\int_{-\Lambda}^{\Lambda} \mathrm{d}\lambda\,\rho(\lambda,m), \qquad \Lambda = \sqrt{M^2 - m^2}$$ mode number density

$$\nu_{\rm R}(M_{\rm R}, m_{\rm R}) = \nu(M, m_{\rm q})$$ renormalized and RG invariant (Giusti and Luscher)

The chiral condensate in the sextet model

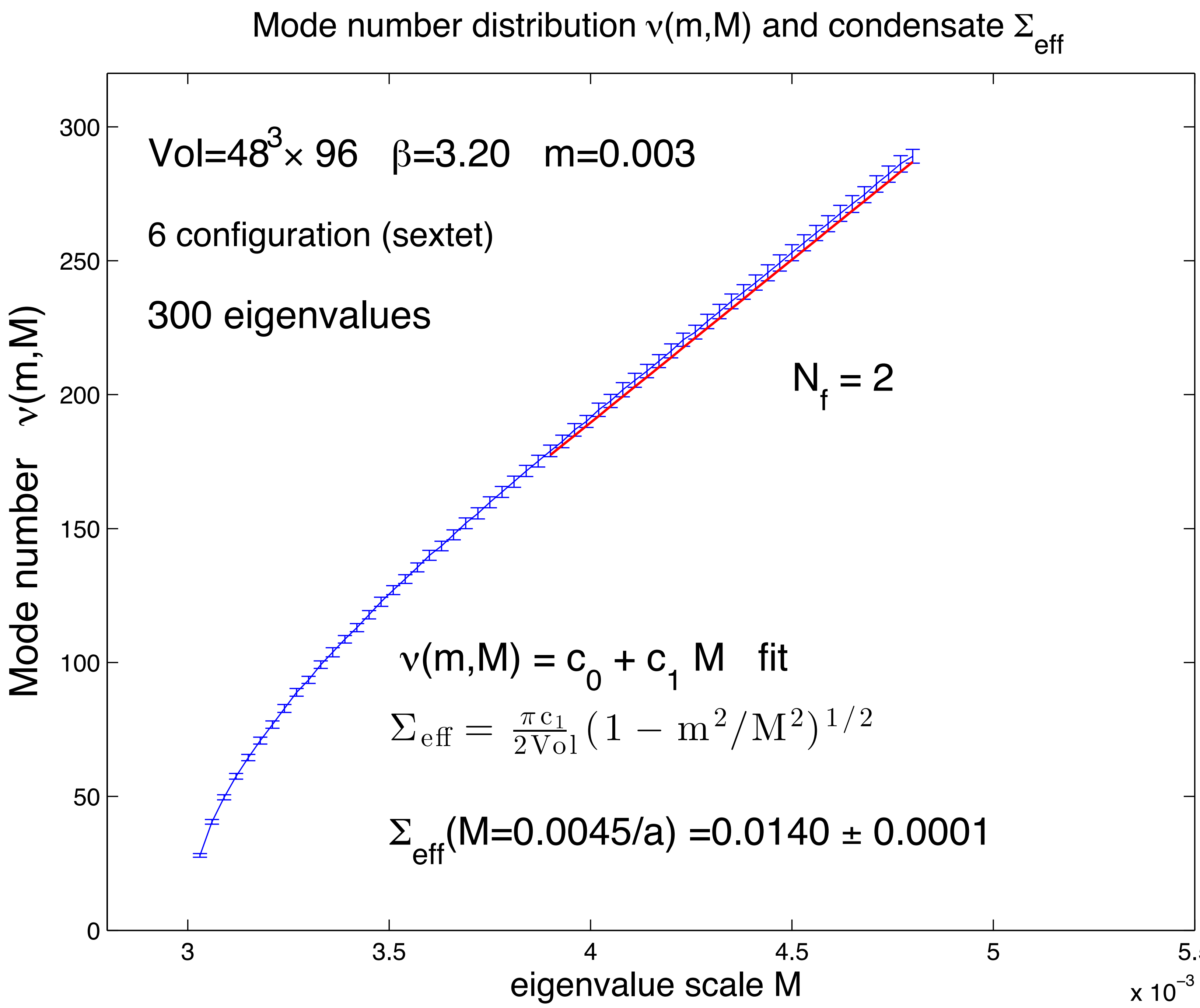
new stochastic method sextet Nf=2

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



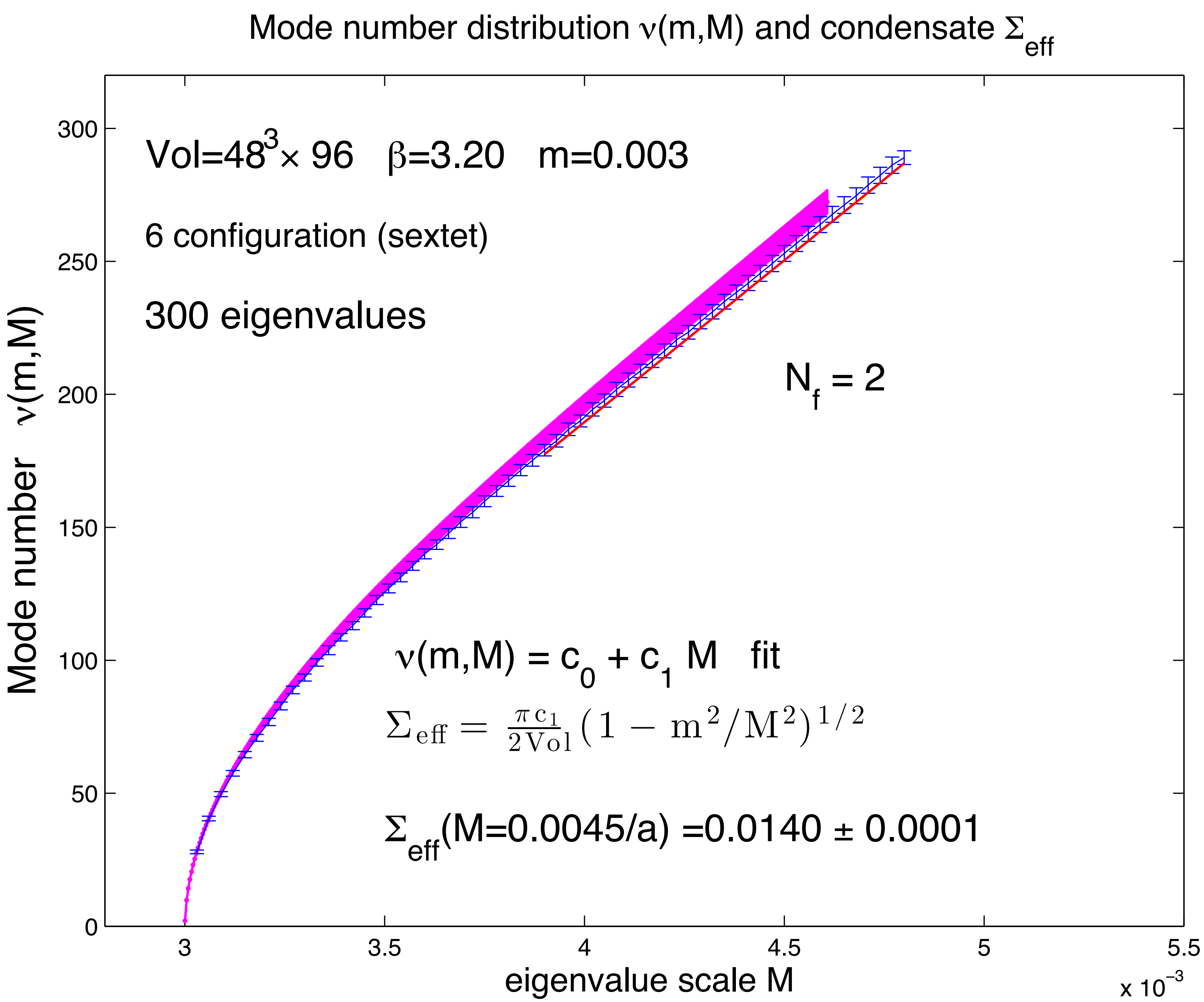
- Passed all tests so far
- example is from 48^3x96 lattices
- allows the scale-dependent determination of the anomalous dimension of the chiral condensate

The chiral condensate in the sextet model



- 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 model



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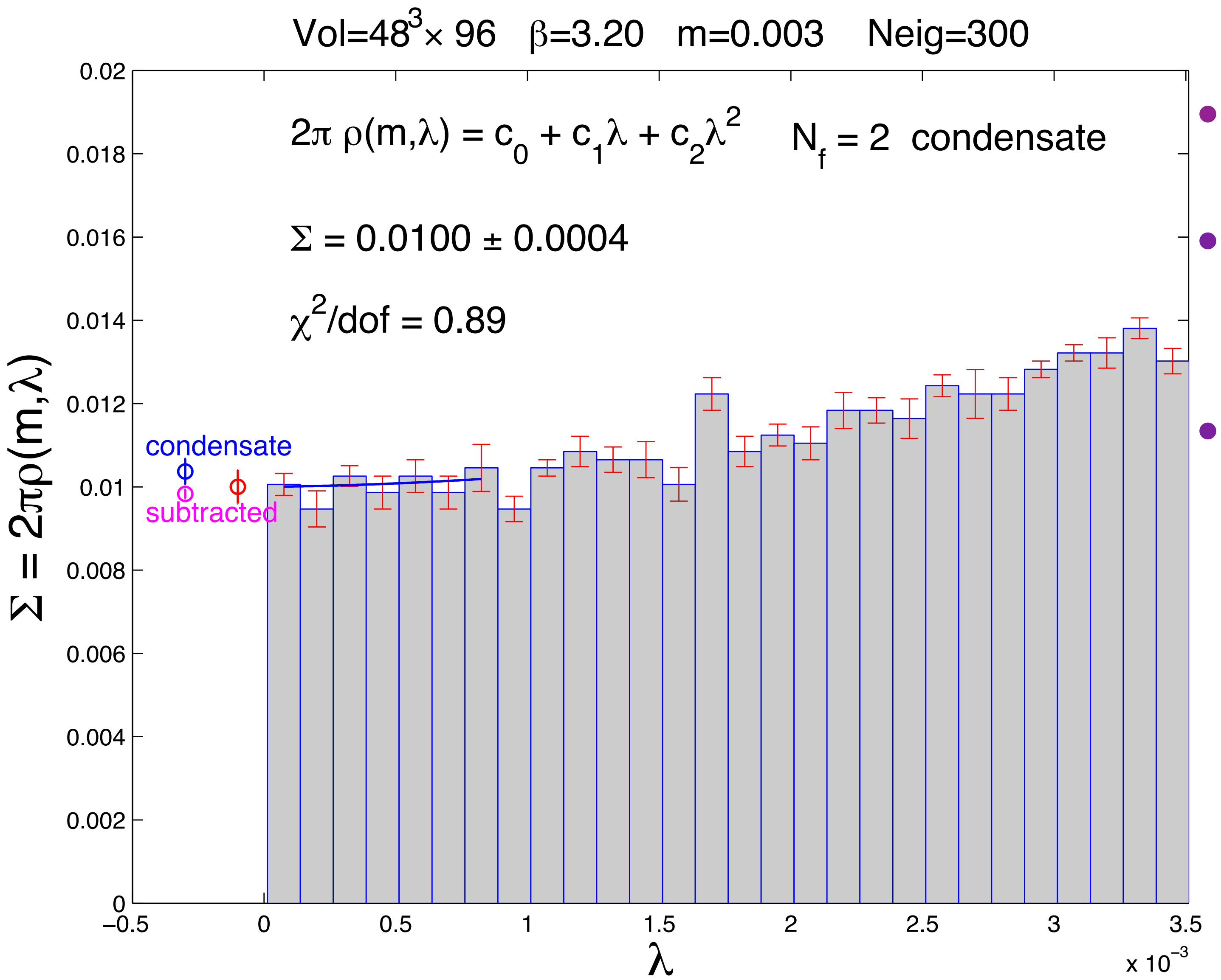
The chiral condensate in the sextet model

new stochastic method sextet Nf=2

comparison with direct determination of spectral density from eigenvalue spectrum



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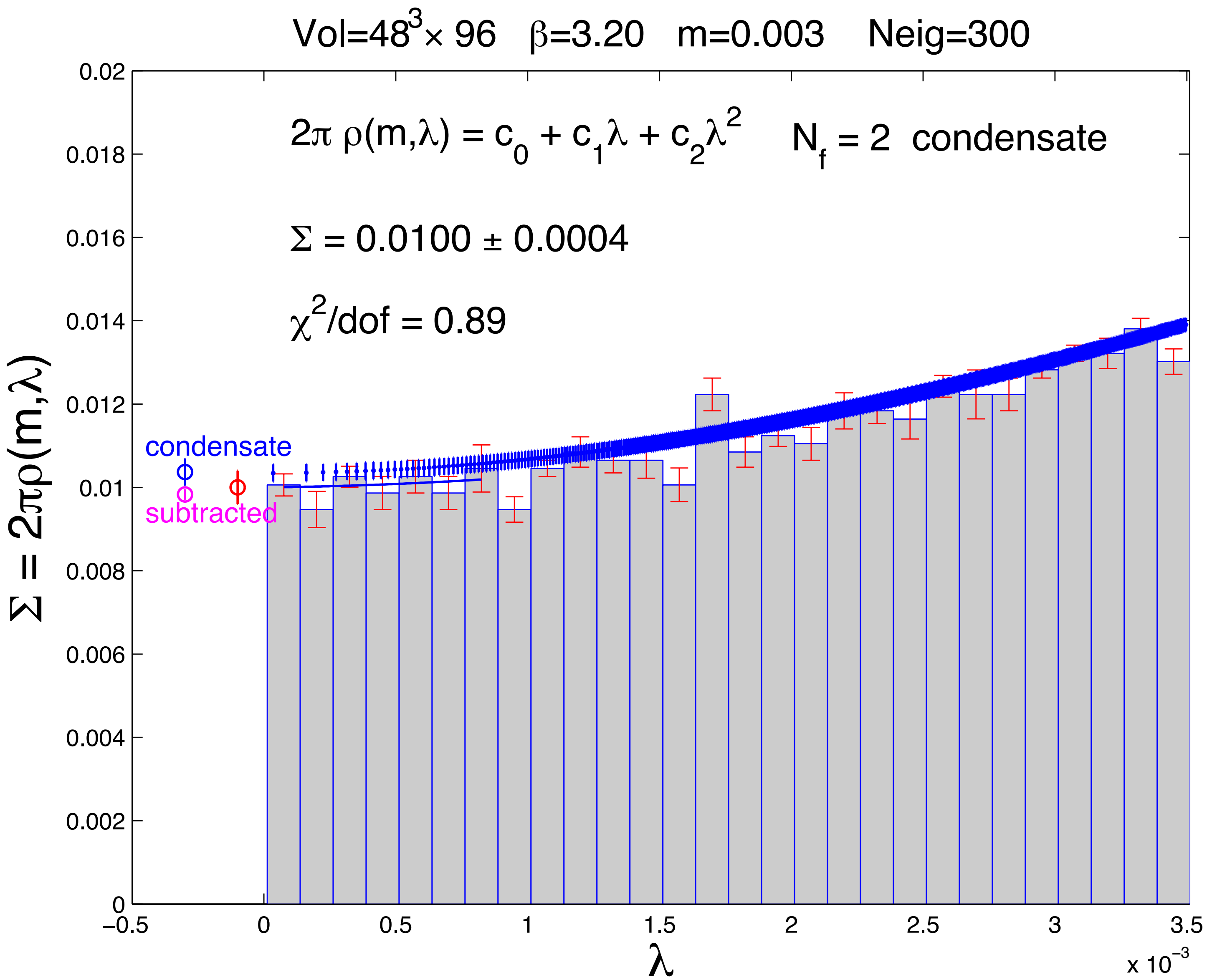
The chiral condensate in the sextet model

new stochastic method sextet Nf=2

comparison with direct determination of spectral density from eigenvalue spectrum

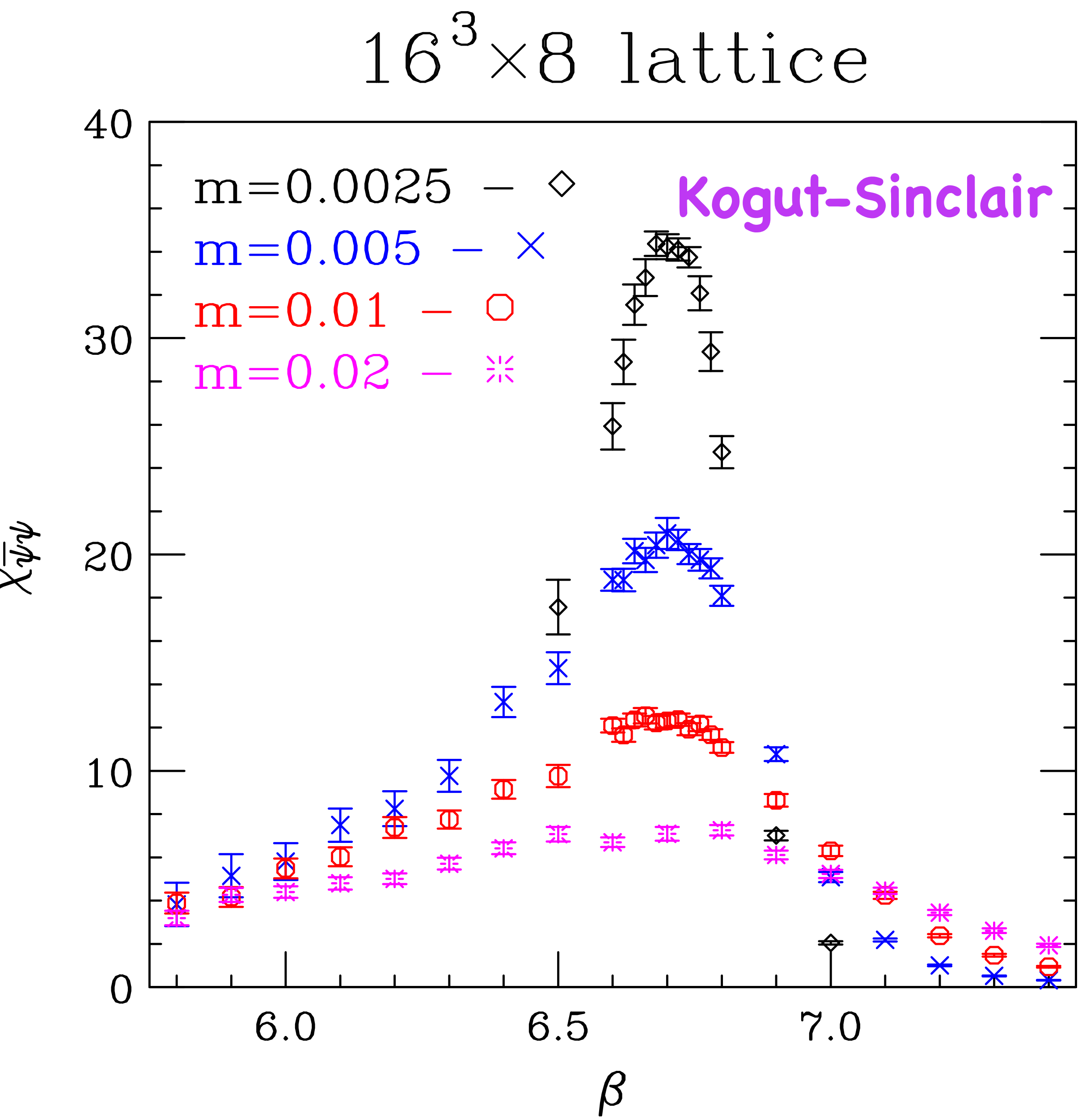


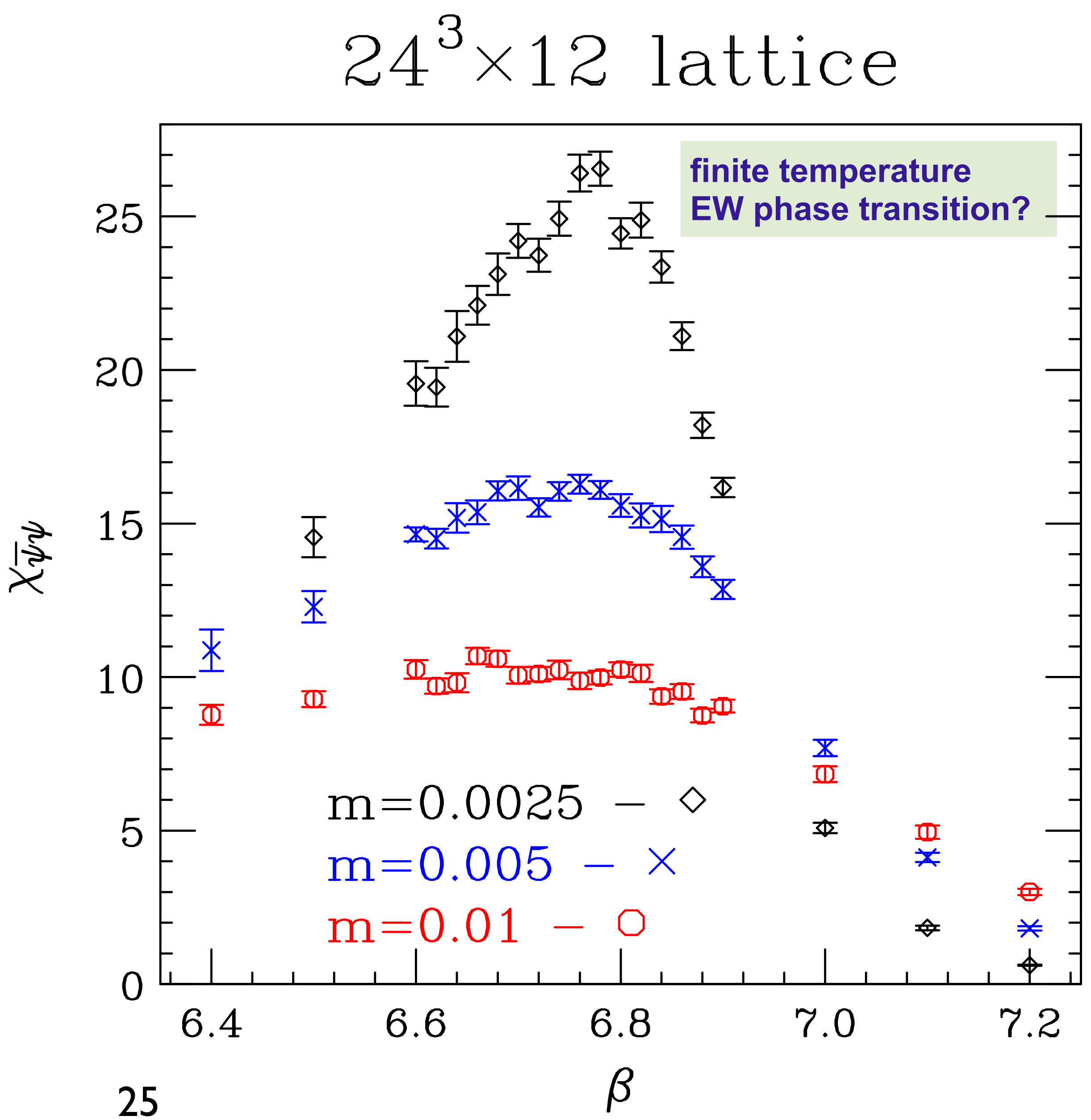
- new stochastic method sextet Nf=2
- comparison with direct determination of spectral density from eigenvalue spectrum
- stringent test

Early universe and the sextet model

Kogut-Sinclair work consistent with χSB phase transition

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





Early universe and the sextet model

The Total Energy of the Universe:

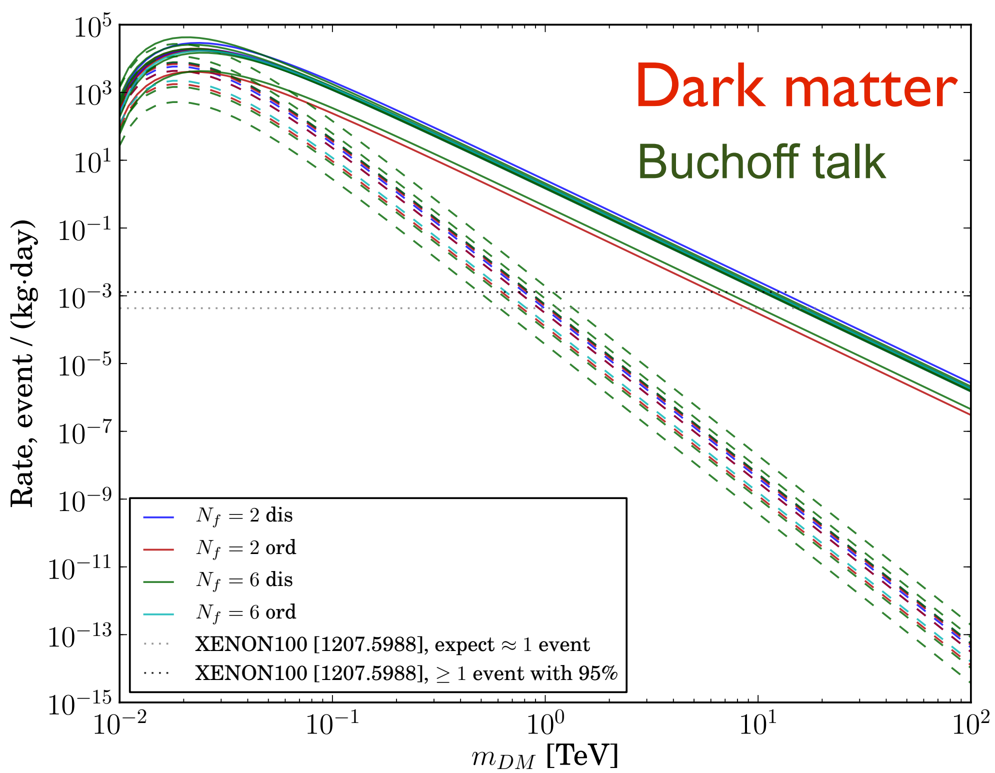
Vacuum Energy (Dark Energy)	~	67 %
Dark Matter	~	29 %
Visible Baryonic Matter	~	4 %

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 Higgs is light near conformality

light scalar (dilaton-like) emerging	close to conformal window
running (walking) coupling in progress	really challenging to do
chiral condensate	new method
spectroscopy	emerging resonance spectrum
dark matter	implications are intriguing strong self-interactions?

We have the simplest Higgs impostor candidate (but it can fail)

more work and resources needed to investigate viability