SCGT2015

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Thank you LatKMI for so quickly becoming a strong contributor!

SCGT2015

Toward the minimal realization of a light composite Higgs

Julius Kuti

University of California, San Diego

SCGT2015 KMI Workshop

March 2-6, 2015, Nagoya University, Japan

SCGT2015

Toward the minimal realization of a light composite Higgs

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

Zoltan Fodor, Kieran Holland, JK, Santanu Mondal, Daniel Nogradi, Chik Him Wong

Julius Kuti

University of California, San Diego

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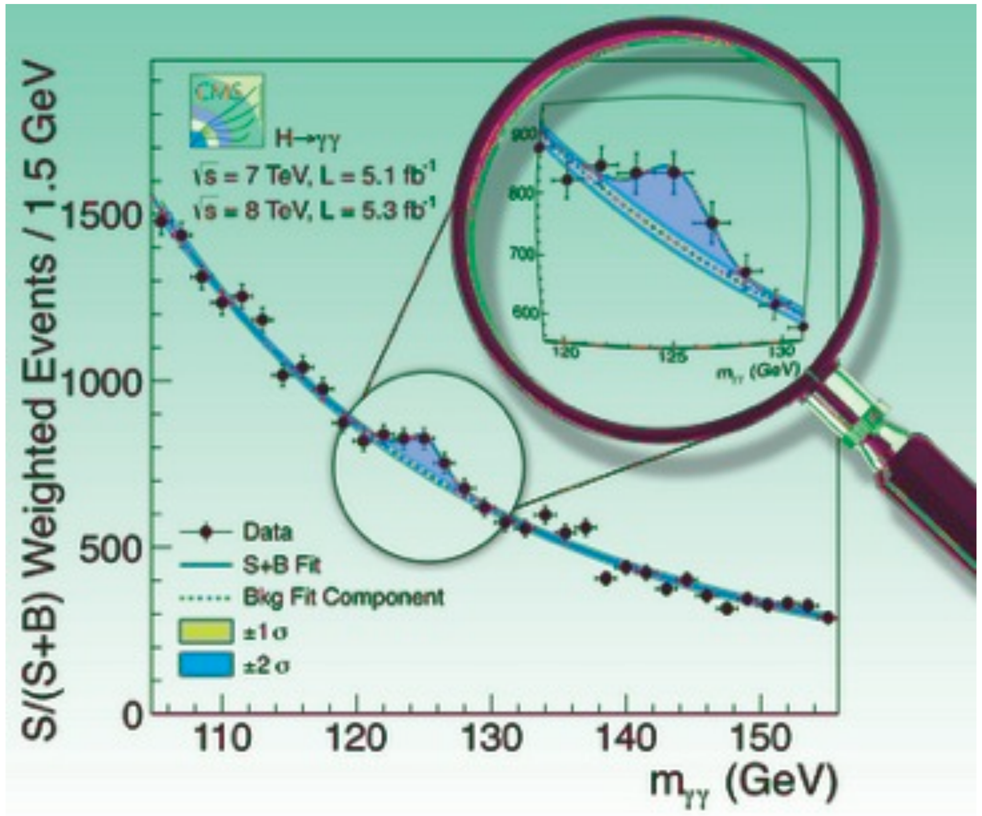
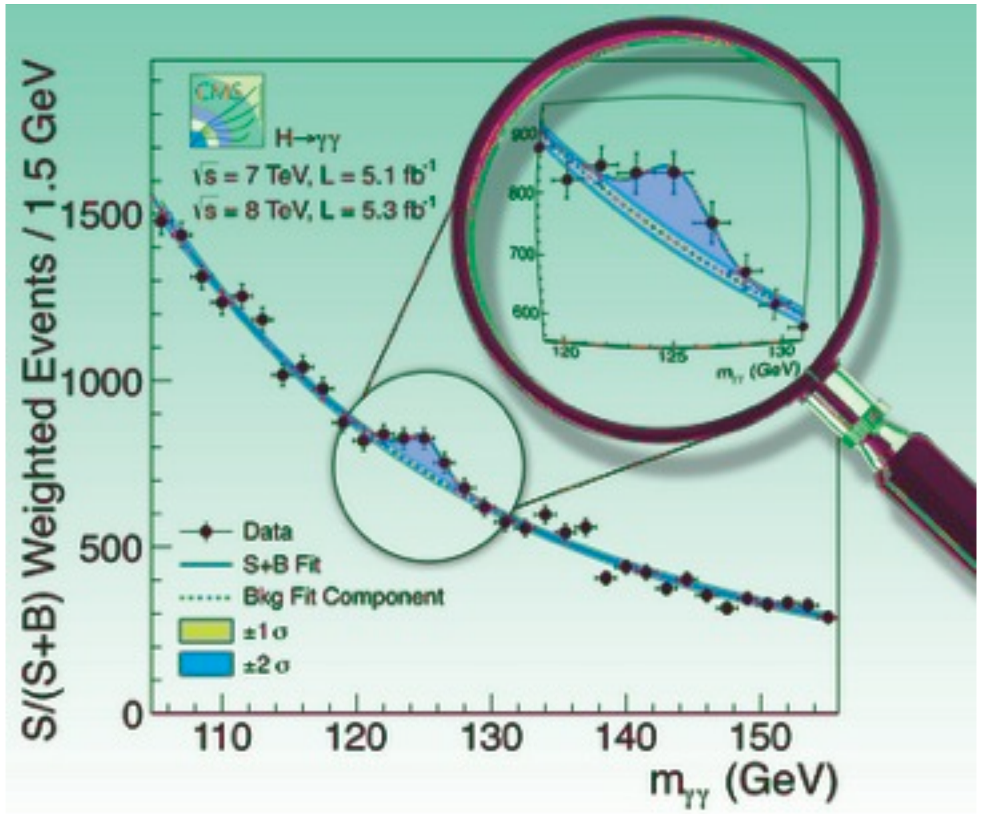
Any rational left for composite Higgs-like scalar on the lattice ?





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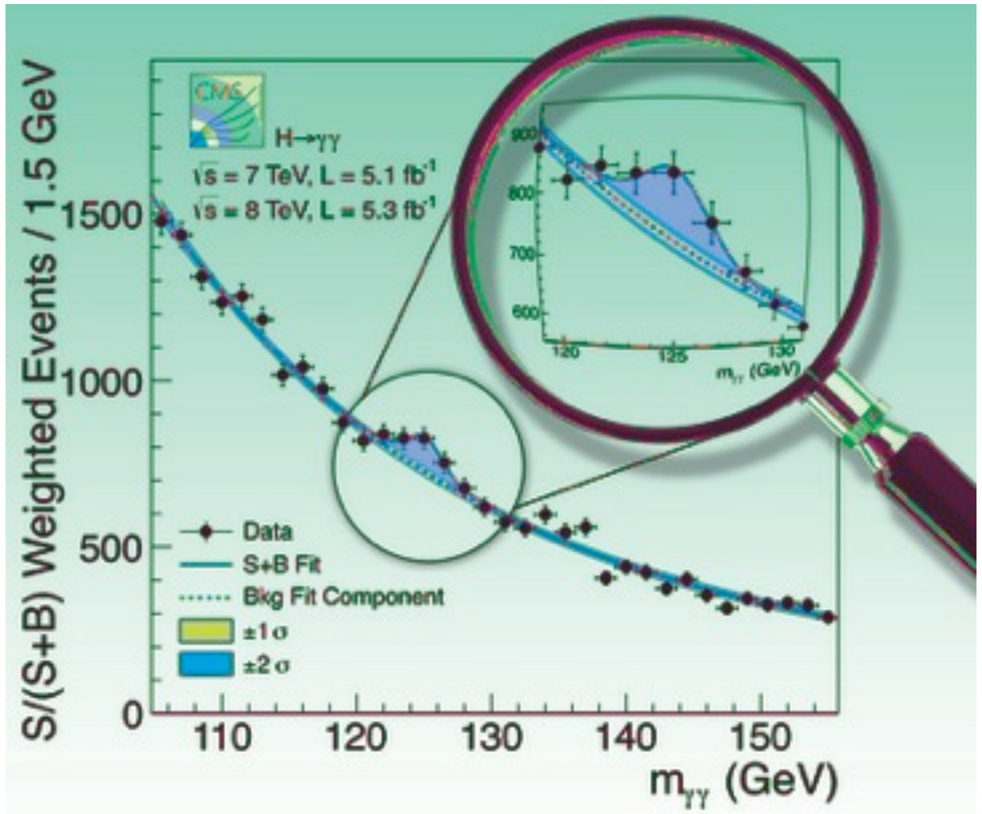
voices:

Strongly coupled BSM gauge theories are Higgs-less with resonances below 1 TeV

A light Higgs-like scalar was found, consistent with SM within errors, and composite states have not been seen below 1 TeV.



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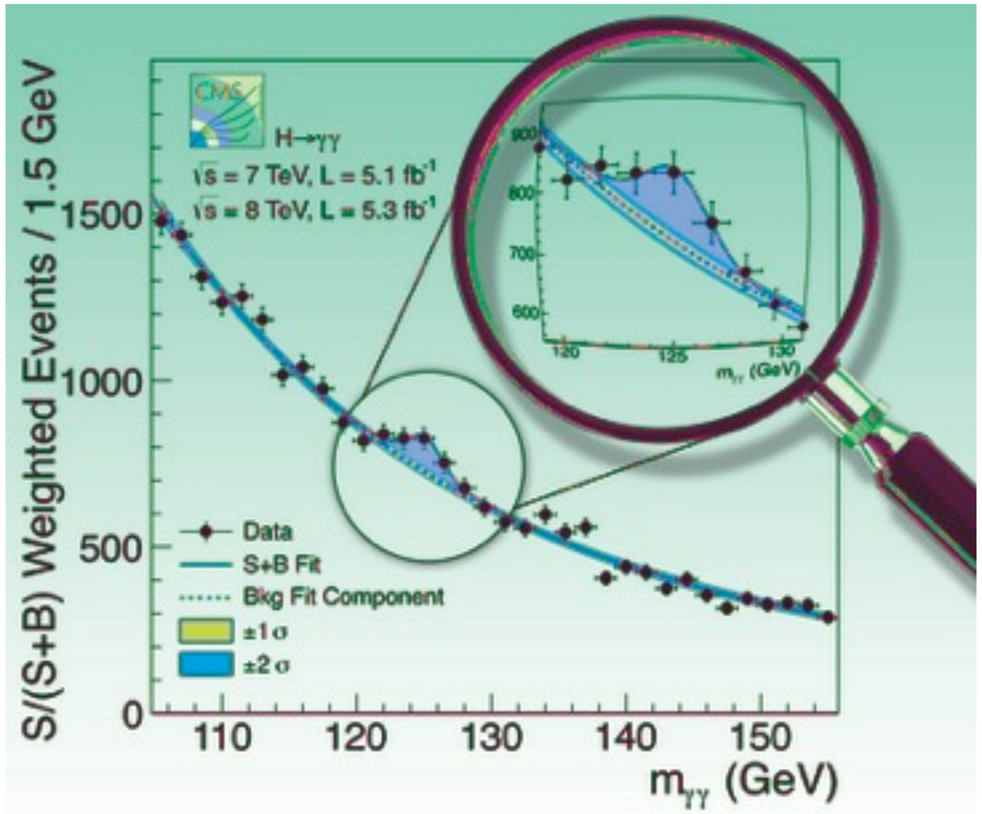

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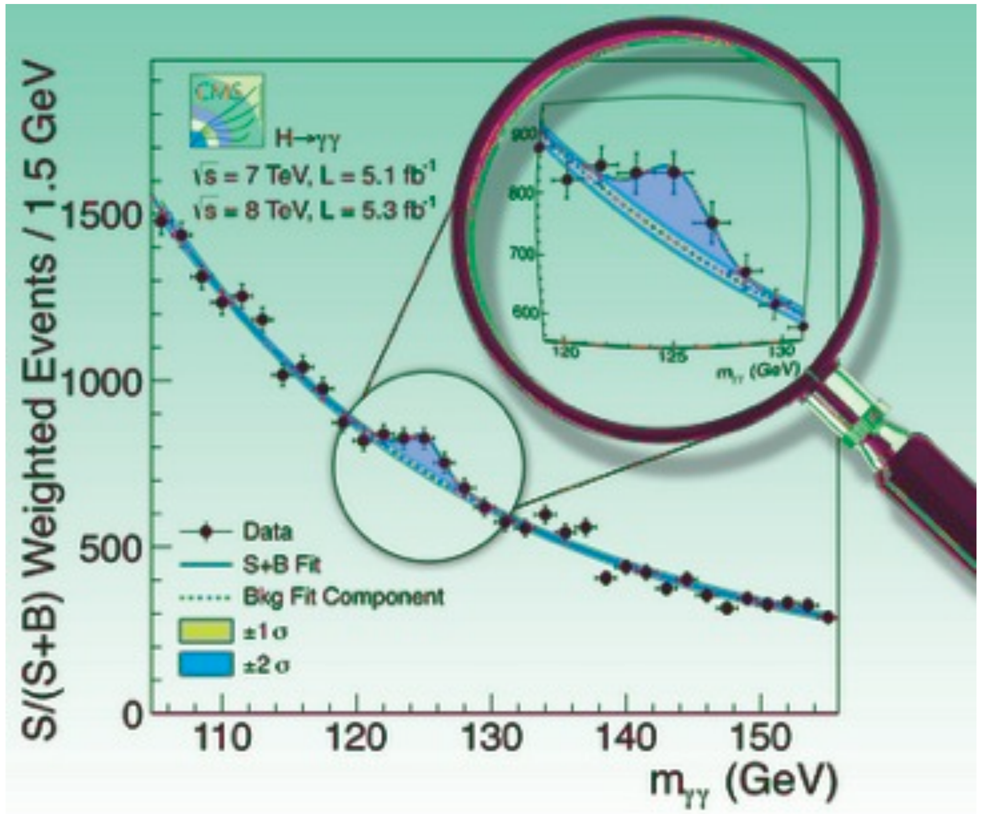

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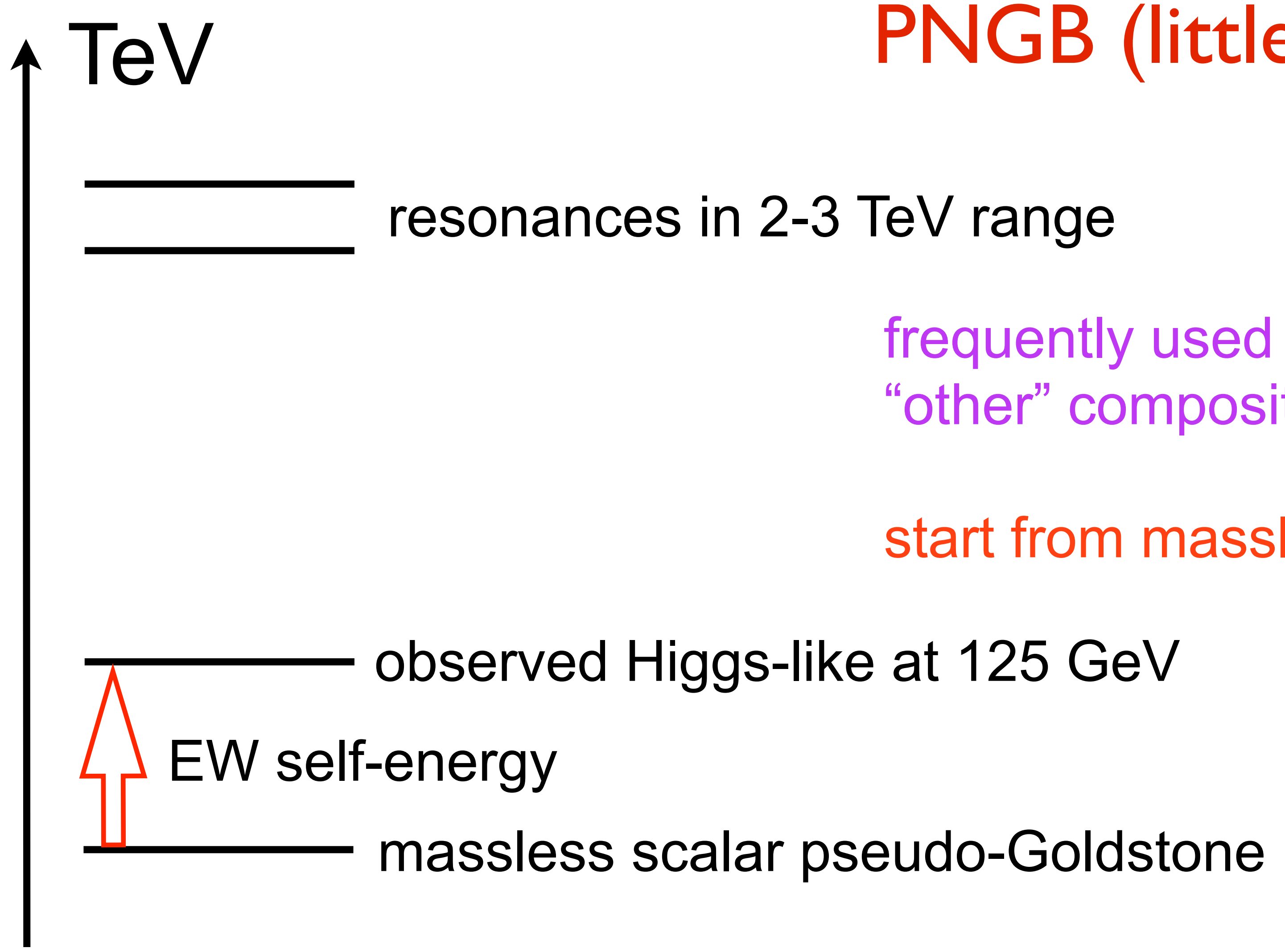
In near-conformal theories a light scalar seems to emerge with resonances in the 2-3 TeV range with tantalizing and unexplained scale separation (what tuning?)

Intriguing example: 2-index symmetric rep with two fermions

What is our composite Higgs terminology?

PNGB (little Higgs) scenario

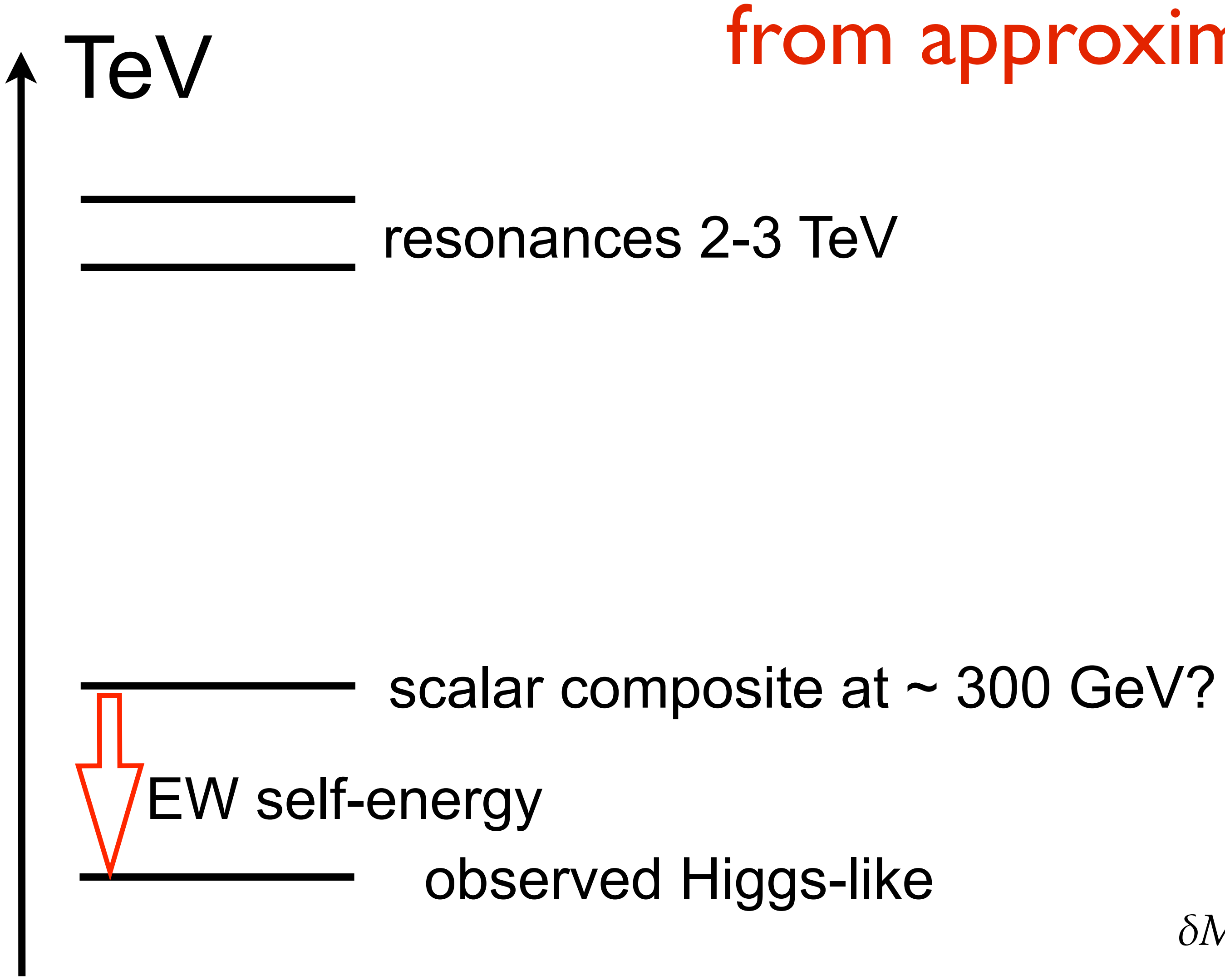


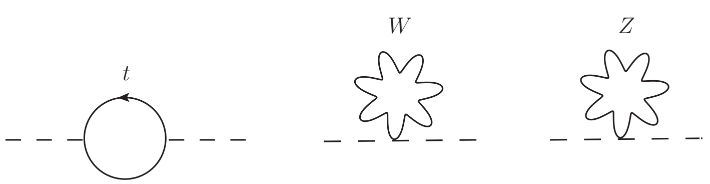
frequently used terminology for the "other" composite Higgs

start from massless rather than 1.5 TeV

What is our composite Higgs terminology?

from approximate scale invariance





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

Sannino, Foadi, Fransden, Tuominen, ...

What is our composite Higgs terminology?

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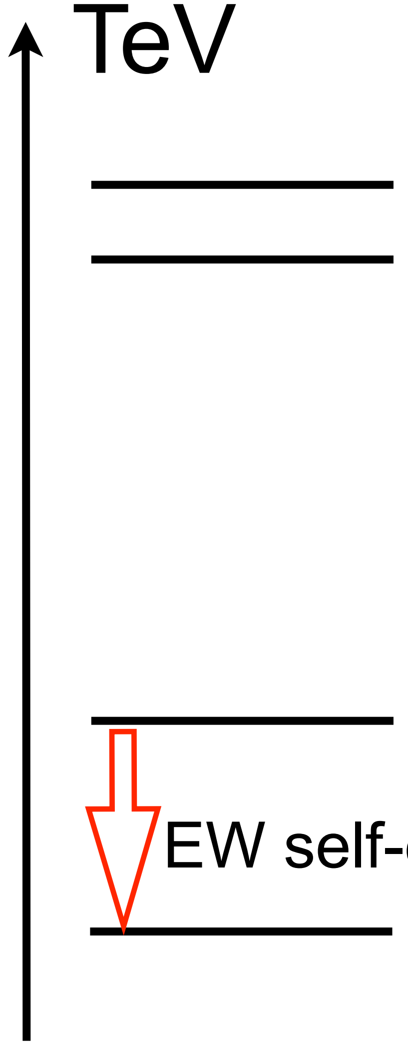
TeV



resonances 2-3 TeV

SCGT composite Higgs in this talk

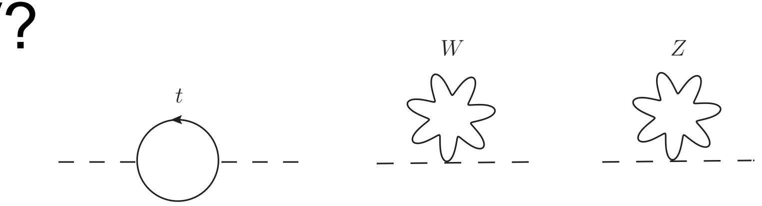
we start from a light scalar - but how light is light?

both paradigms defer mass generation issues   talks at SCGT15

scalar composite at ~ 300 GeV?

EW self-energy

observed Higgs-like



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What is our composite Higgs terminology?

the Higgs doublet field

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \pi_2 + i\,\pi_1 \\ \sigma - i\,\pi_3 \end{pmatrix} \qquad\qquad \frac{1}{\sqrt{2}}\left(\sigma + i\,\vec{\tau}\cdot\vec{\pi}\right) \equiv M$$

$$D_\mu M = \partial_\mu M - i\,g\,W_\mu M + i\,g' M\,B_\mu\,, \qquad \text{with} \qquad W_\mu = W_\mu^a \frac{\tau^a}{2}\,, \quad B_\mu = B_\mu \frac{\tau^3}{2}$$

The Higgs Lagrangian is

spontaneous symmetry breaking

Higgs mechanism

$$\mathcal{L} \;=\; \frac{1}{2}\mathrm{Tr}\left[D_\mu M^\dagger D^\mu M\right] - \frac{m_M^2}{2}\mathrm{Tr}\left[M^\dagger M\right] - \frac{\lambda}{4}\mathrm{Tr}\left[M^\dagger M\right]^2$$

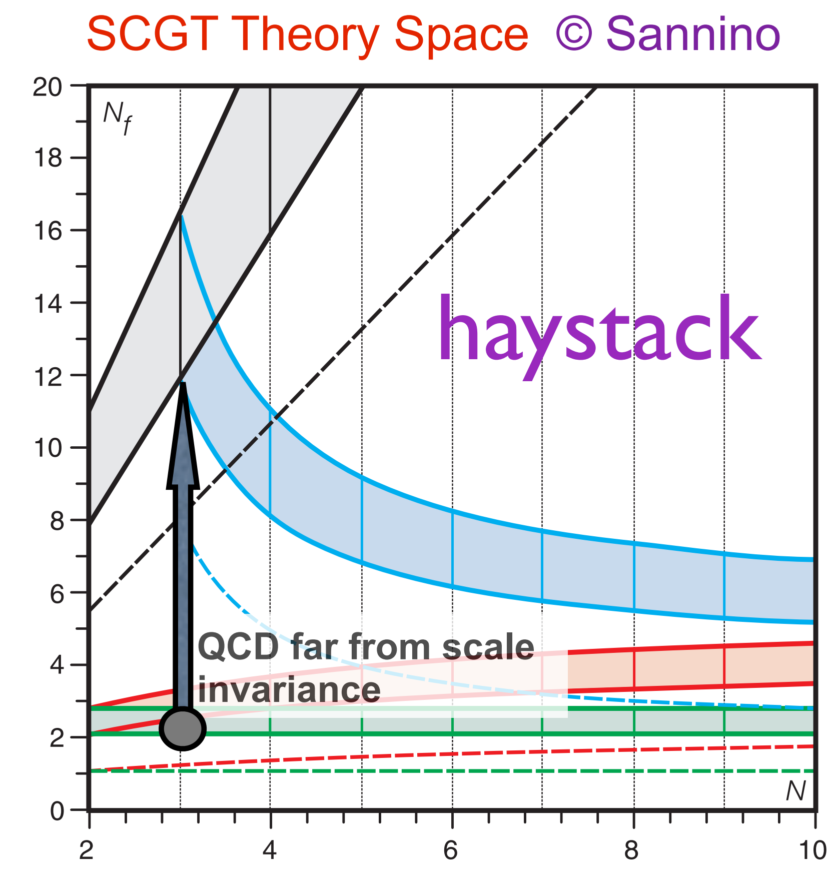
strongly coupled gauge theory

fermions (Q) in gauge group reps

$$\mathcal{L}_{Higgs} \rightarrow -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{Q}\gamma_\mu D^\mu Q + \ldots$$

needle in the haystack?

or, just one of the haystacks?


SCGT Theory Space © Sannino
haystack
QCD far from scale invariance
N_f
N
0
2
4
6
8
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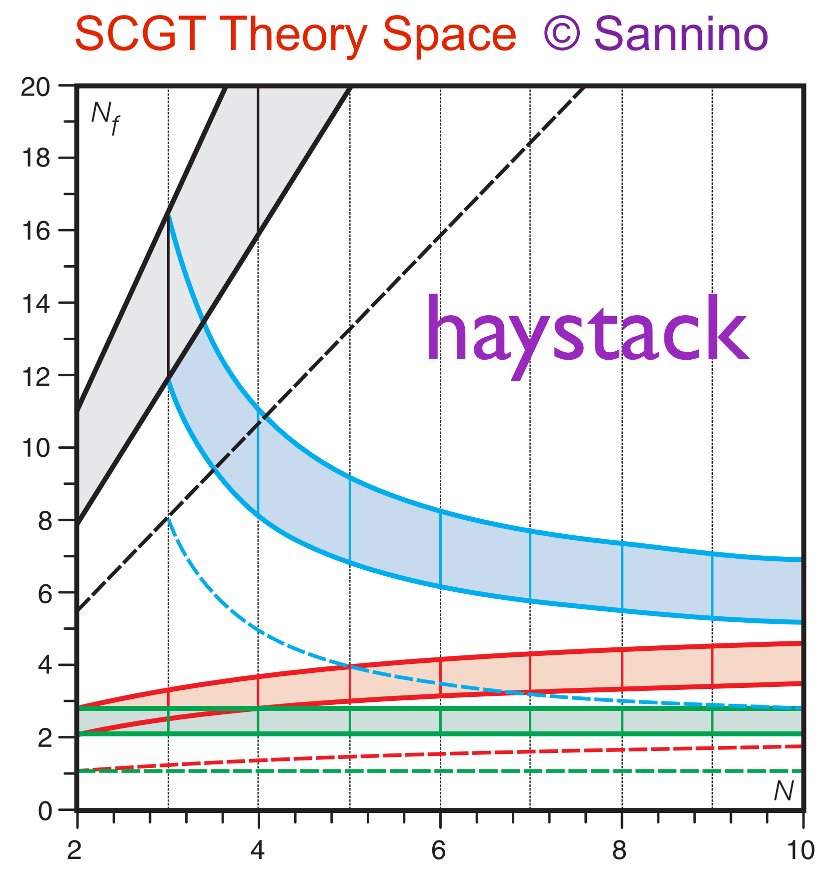
12
14
16
18
20
2
4
6
8
10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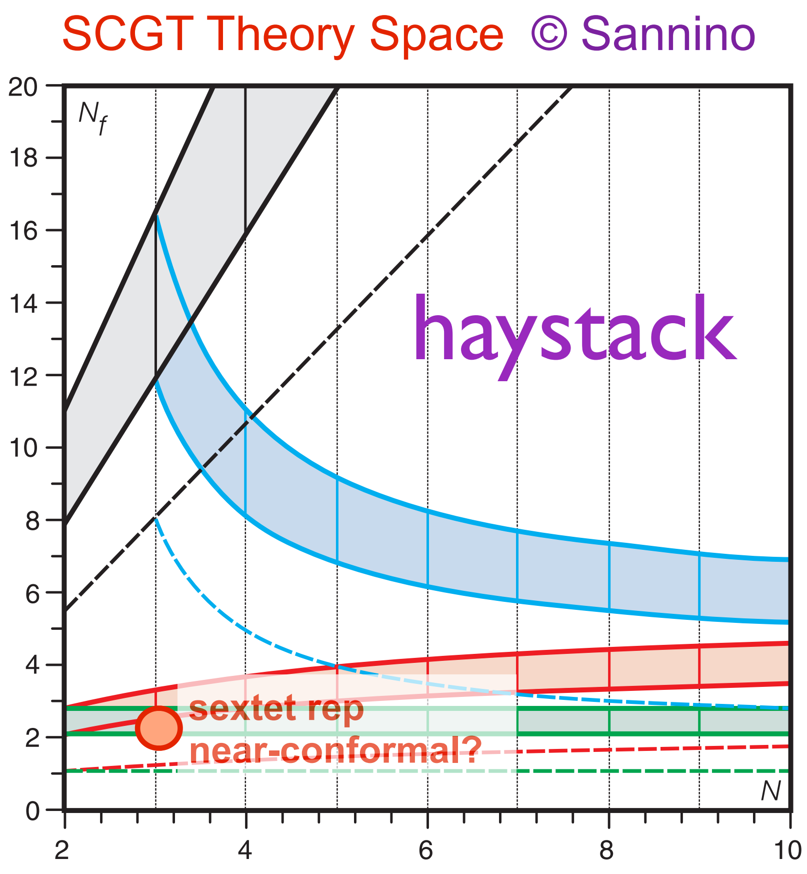

SCGT Theory Space © Sannino
N_f
haystack
sextet rep
near-conformal?
N
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6
4
2
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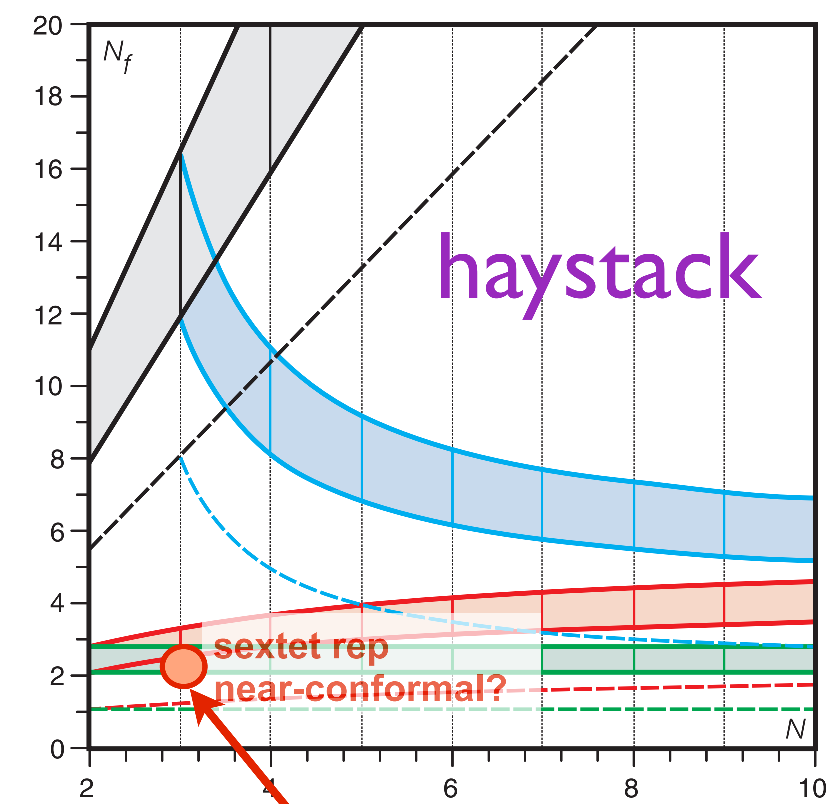
10

SCGT Theory Space © Sannino



close to scale invariance?

nf=2 sextet rep
massless fernions
SU(2) doublet

$$\begin{bmatrix} u(+e/2 \\ d(-e/2) \end{bmatrix}$$

minimal EW
embedding
Wong talk

3 Goldstones morph into weak bosons
minimal realization

QCD intuition for near-conformal
compositeness is just plain wrong

Technicolor thought to be scaled up QCD
theme of the talk:
composite Higgs-like scalar close to the
conformal window?

Outline

Near-conformal SCGT?

- light scalar close to conformal window? the D-word
- navigating mine fields of p, ε, and δ regimes in chiPT
- scale setting and spectroscopy
- mixed action strategy the R-word

Chiral Higgs condensate

- new stochastic method for spectral density
- GMOR and mode number
- epsilon regime and RMT
- large mass anomalous dimension?

Running coupling

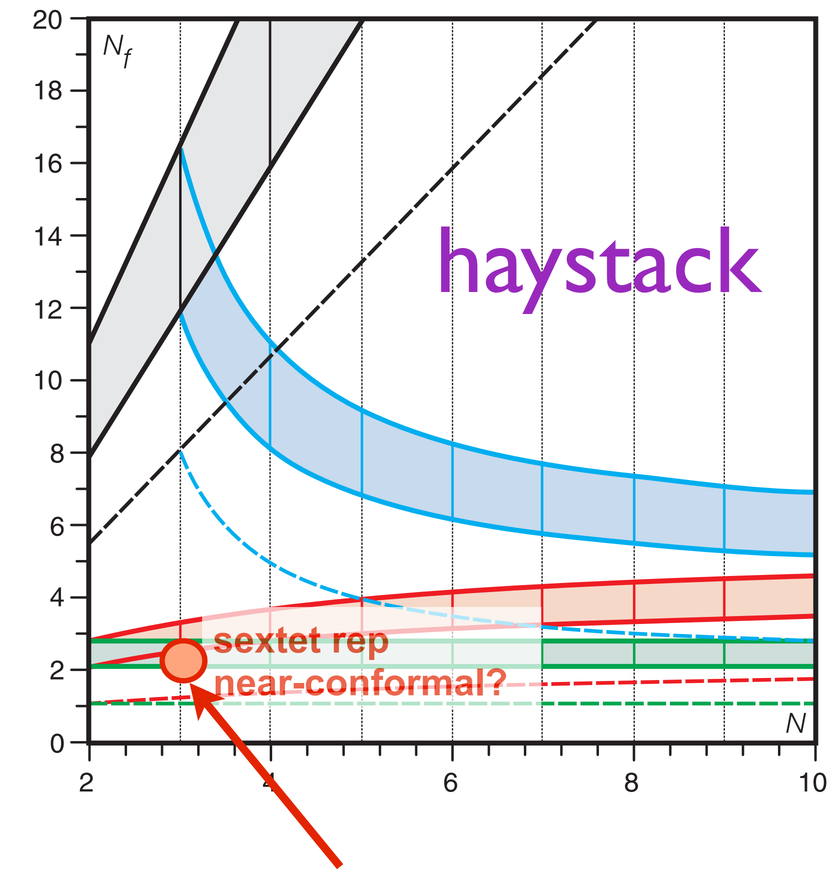
- scale dependent running coupling
- matching with mass anomalous dimension?

Early universe

- sextet EW phase transition
- sextet baryon and dark matter Wong talk

Summary and Outlook

SCGT Theory Space © Sannino



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The light 0++ scalar

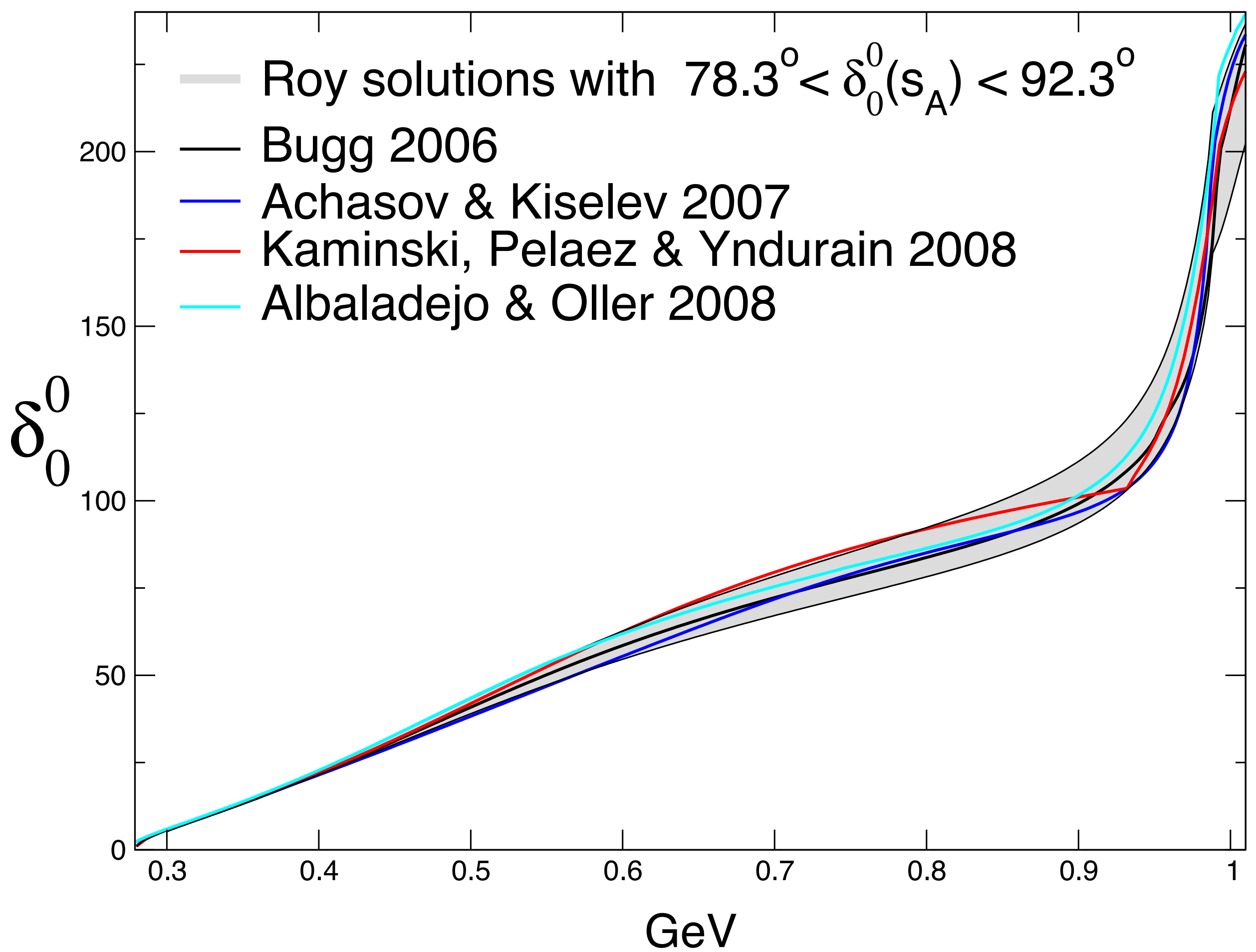
QCD (aka old TC) 80ies, 90ies

the failure of old Higgs-less technicolor:

0^{++} scalar in QCD (bad Higgs impostor)

$\sqrt{s_\sigma}$ = (400 - 1200) - i (250 - 500) MeV estimate in Particle Data Book

π-π phase shift in 0^{++} "Higgs" channel



$$\sqrt{s_\sigma} = 441\,^{+16}_{-8} - i\,272\,^{+9}_{-12.5}\ \mathrm{MeV}$$

Leutwyler:
dispersion theory combined with ChiPT

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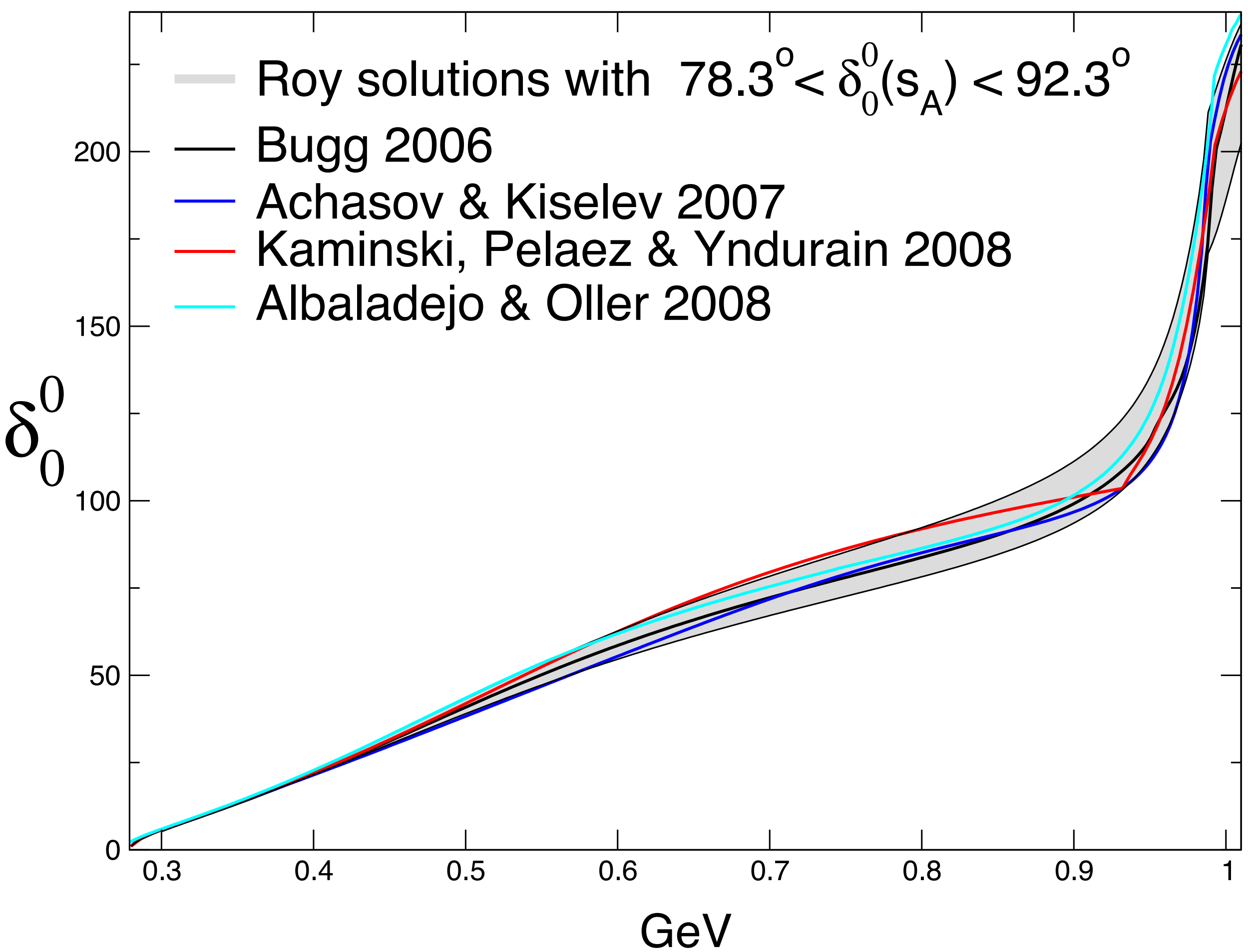


broad M_σ ~ 1.5 TeV in old technicolor, based on scaled up QCD, hence the tag "Higgs-less"

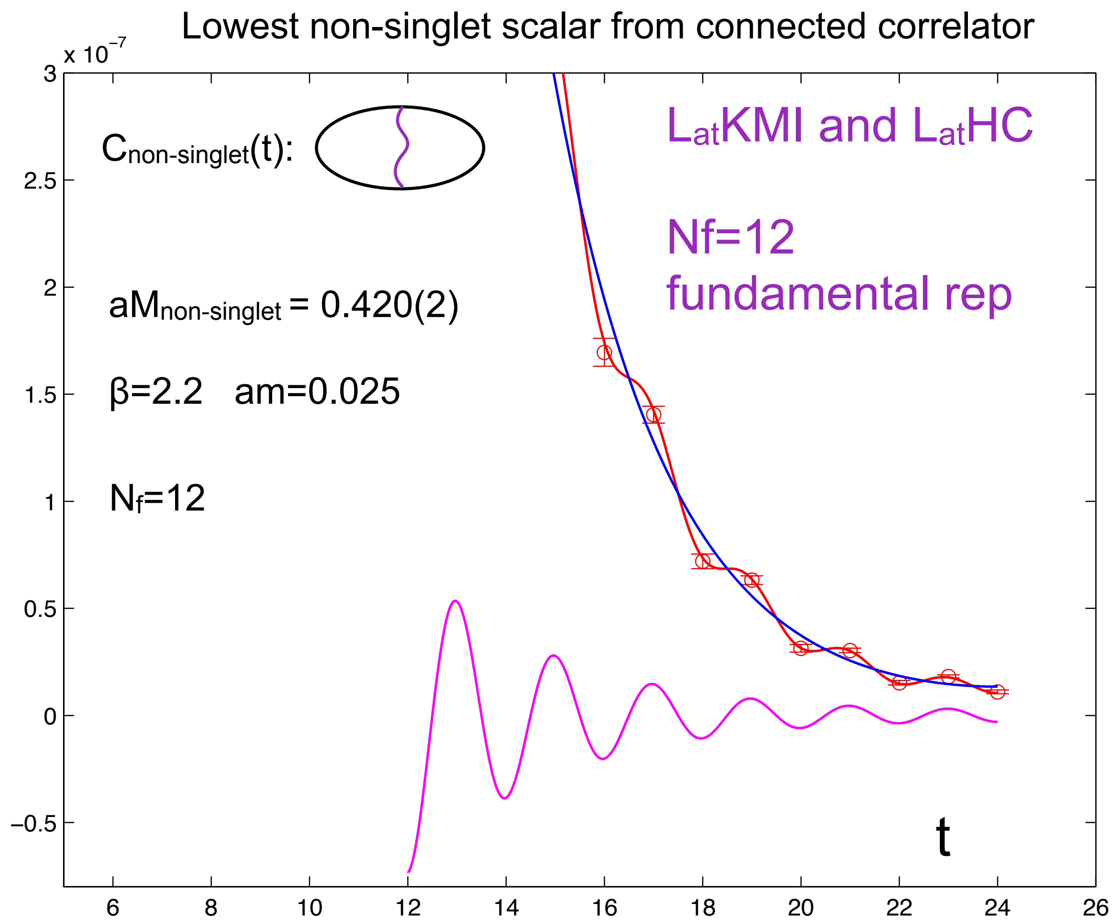
This is expected to be different in near-conformal strongly coupled gauge theories

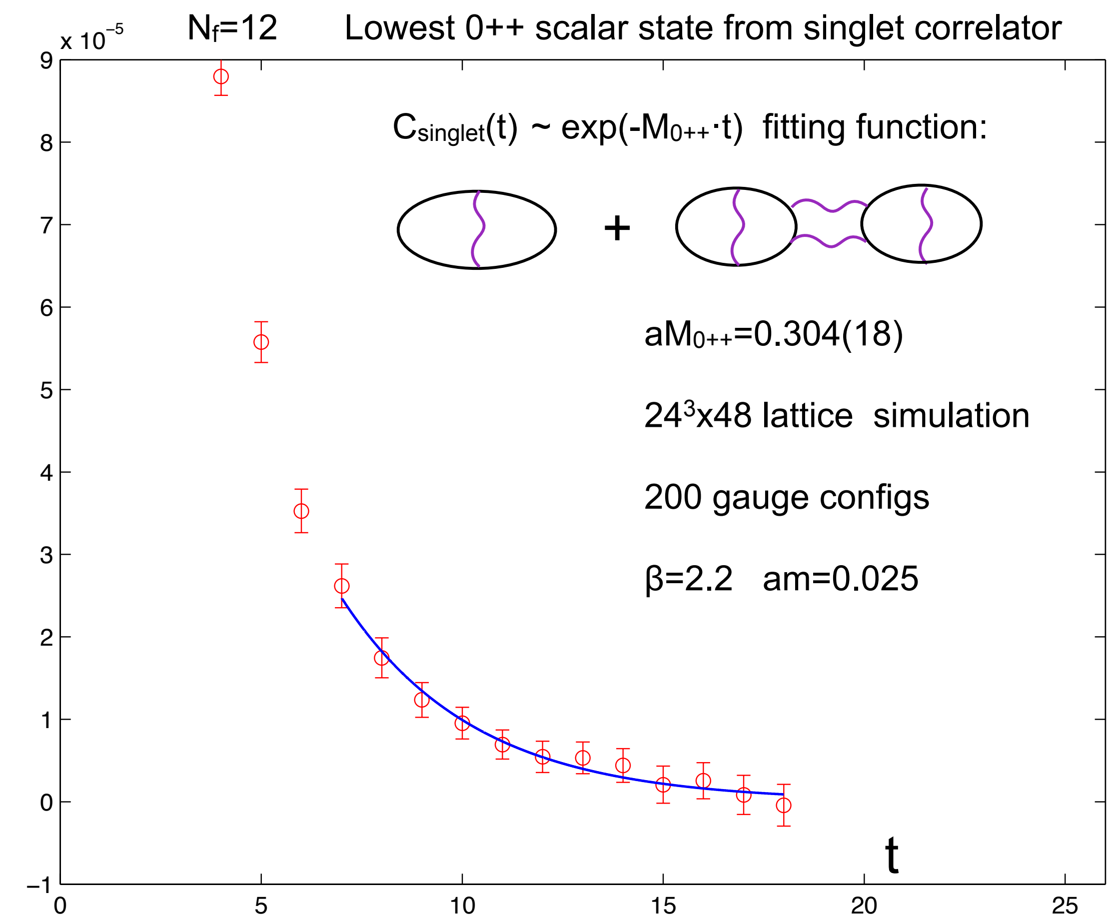
$$\sqrt{s_\sigma} = 441\,^{+16}_{-8} - i\,272\,^{+9}_{-12.5}\ \mathrm{MeV}$$

Leutwyler:
dispersion theory combined with ChiPT

The light 0++ scalar SCGT 2013-2015

test of scalar technology:





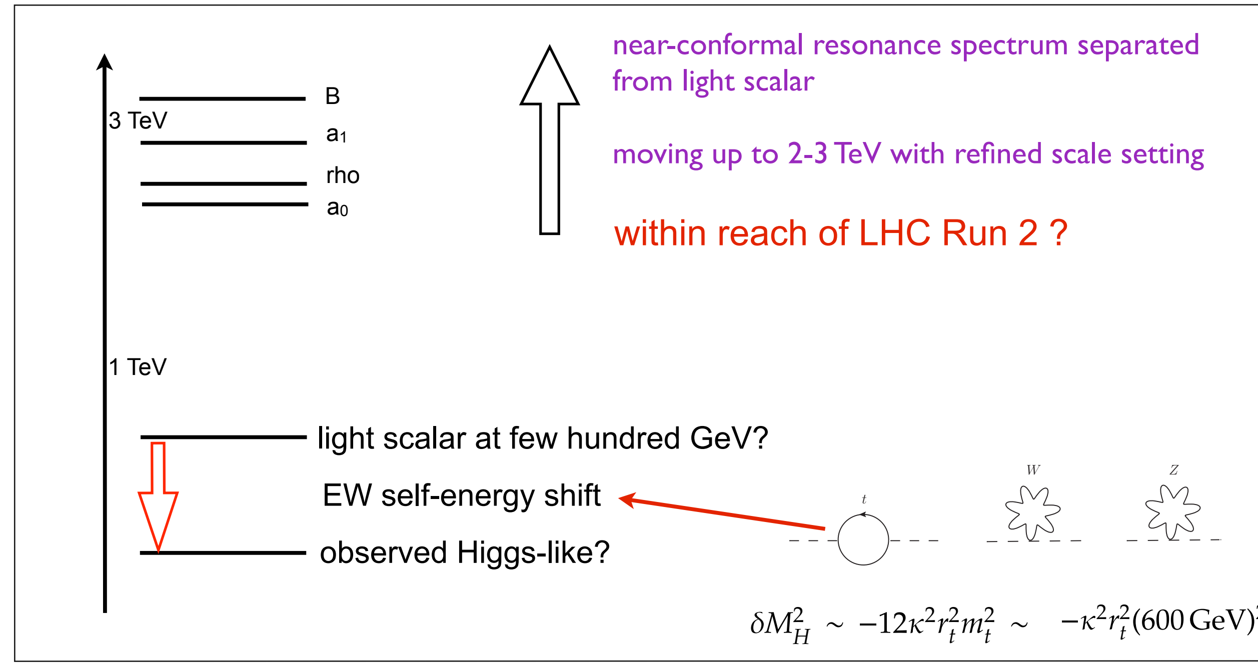
$$C(t) = \sum_n \left[A_n e^{-m_n(\Gamma_S \otimes \Gamma_T)t} + (-1)^t B_n e^{-m_n(\gamma_4\gamma_5\Gamma_S \otimes \gamma_4\gamma_5\Gamma_T)t}\right]$$

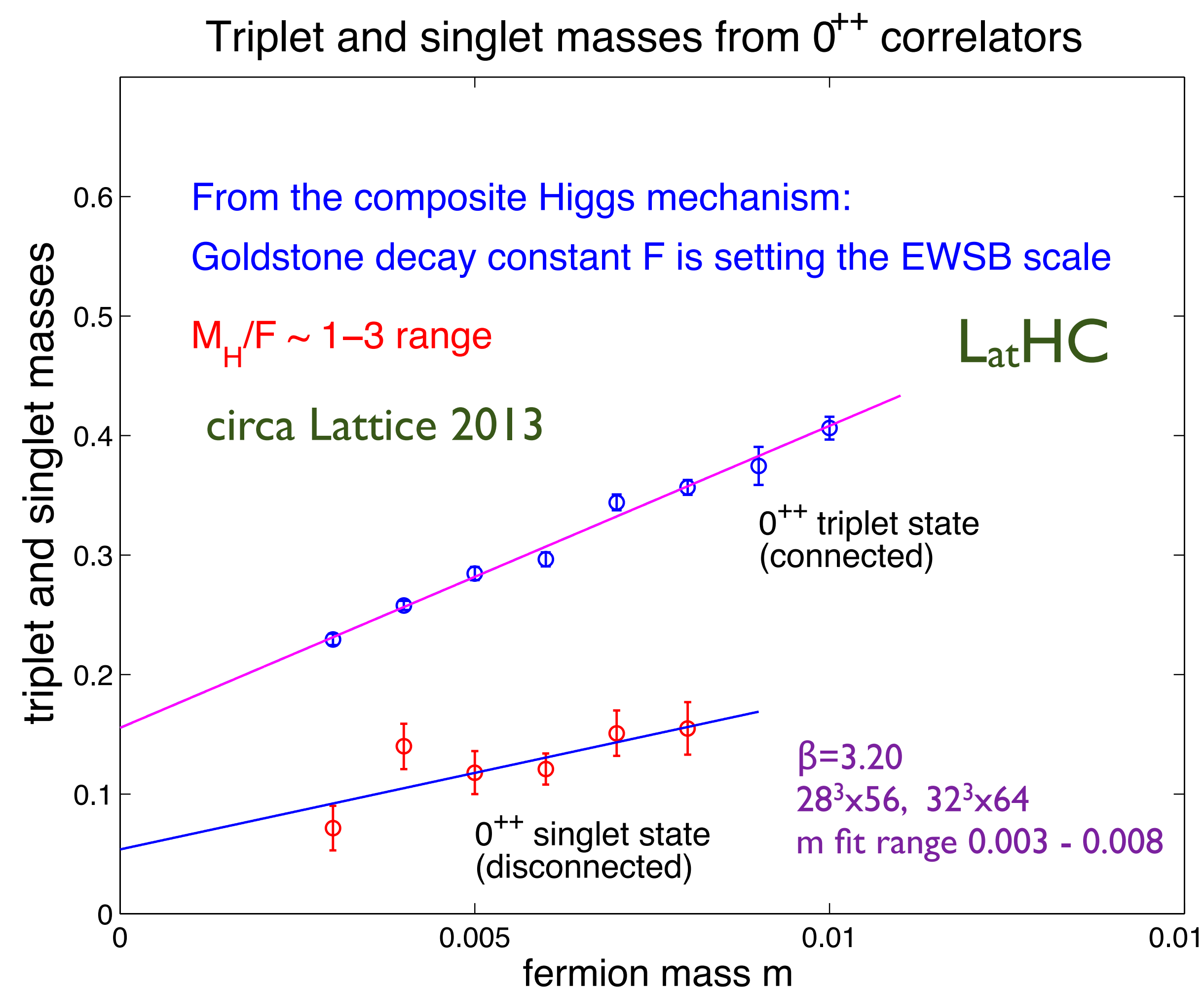
staggered correlator

new results in N_f=2 sextet model (this talk) and N_f=4/8/12 models (LatKMI talks, A. Hasenfratz talk)

The light 0++ scalar

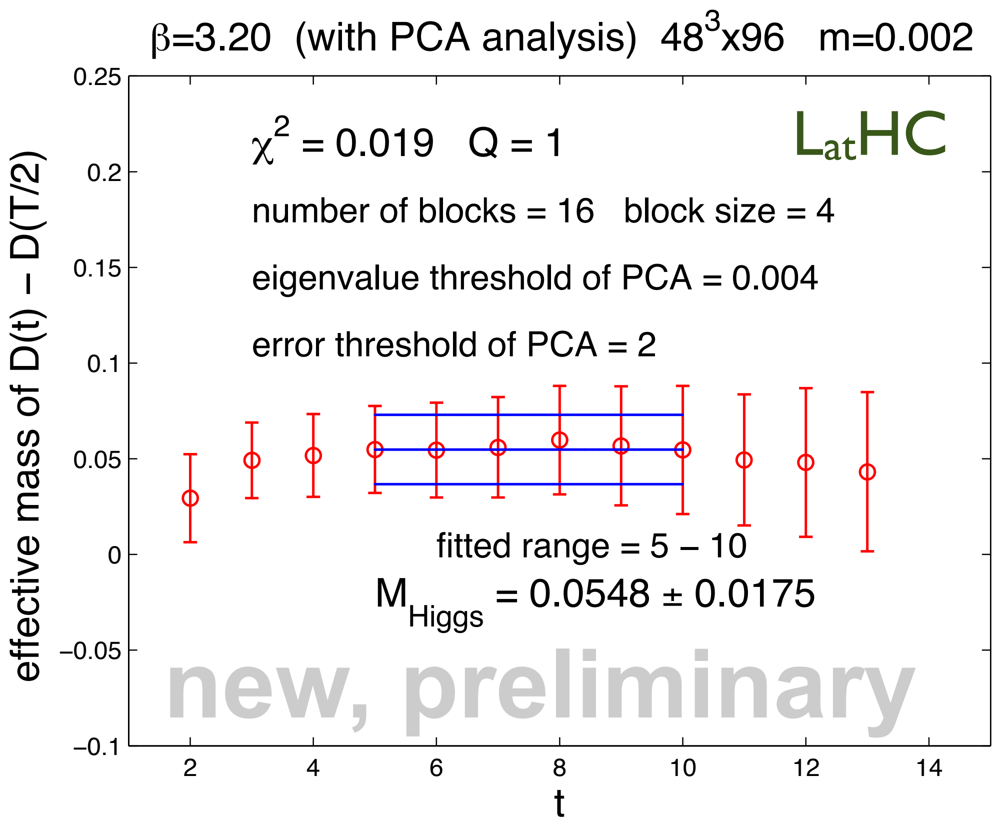
sextet model $L_{at}HC$

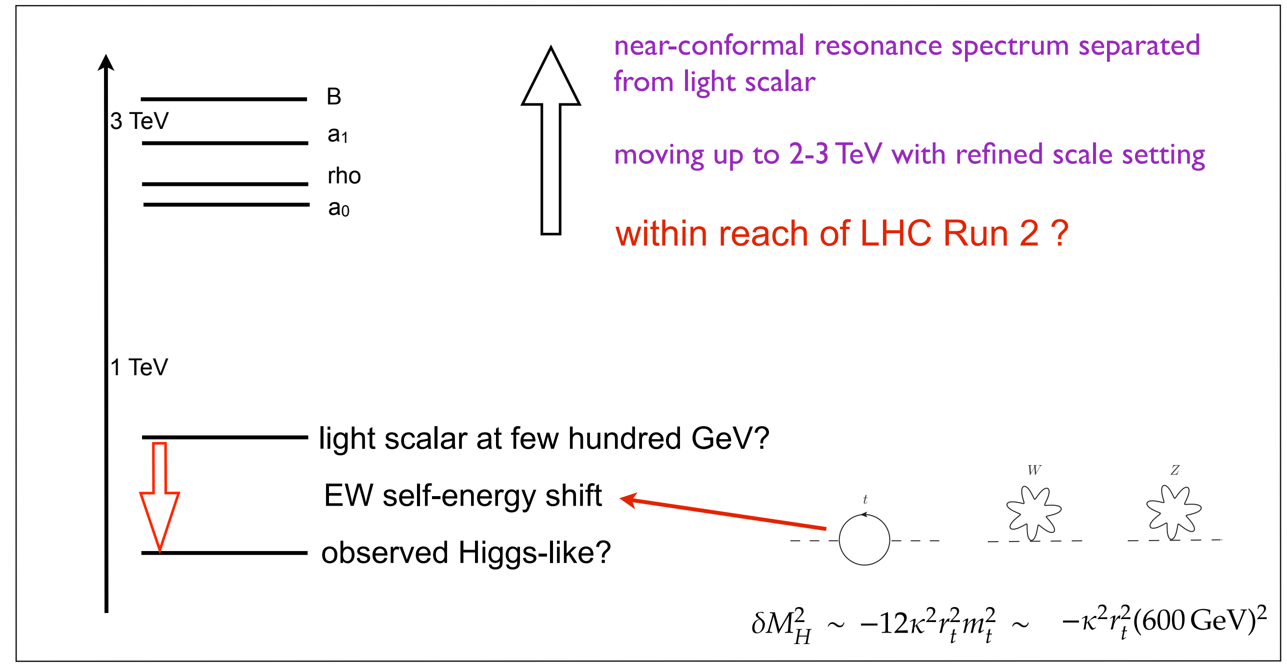


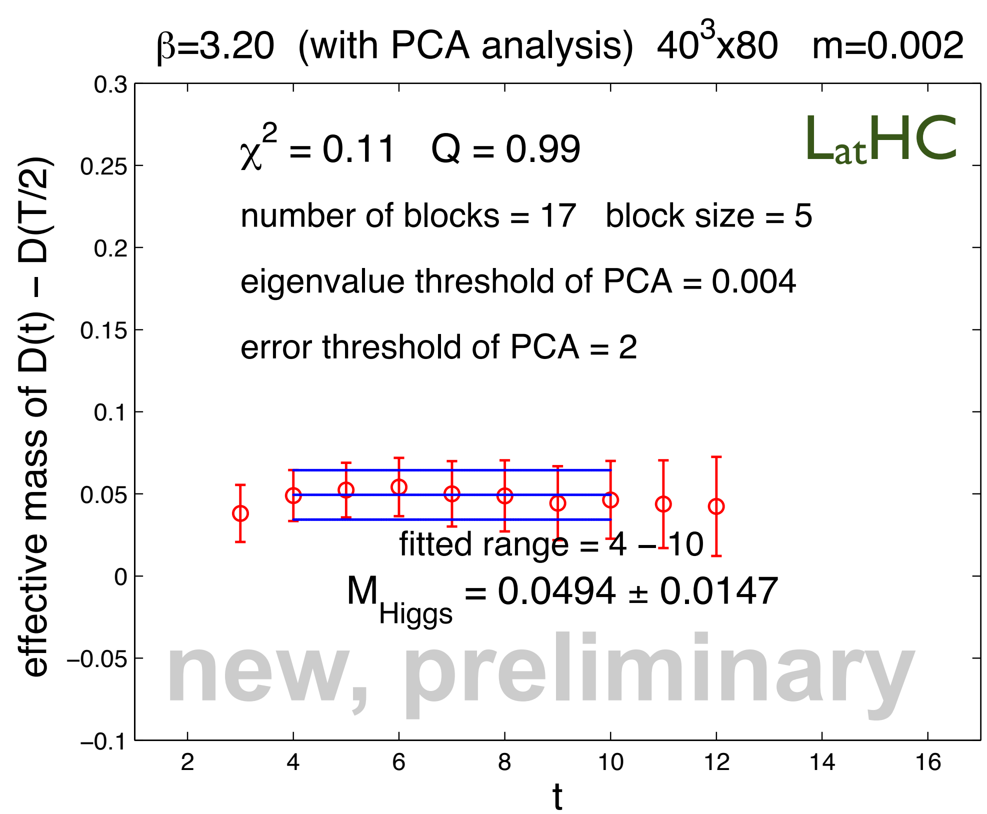


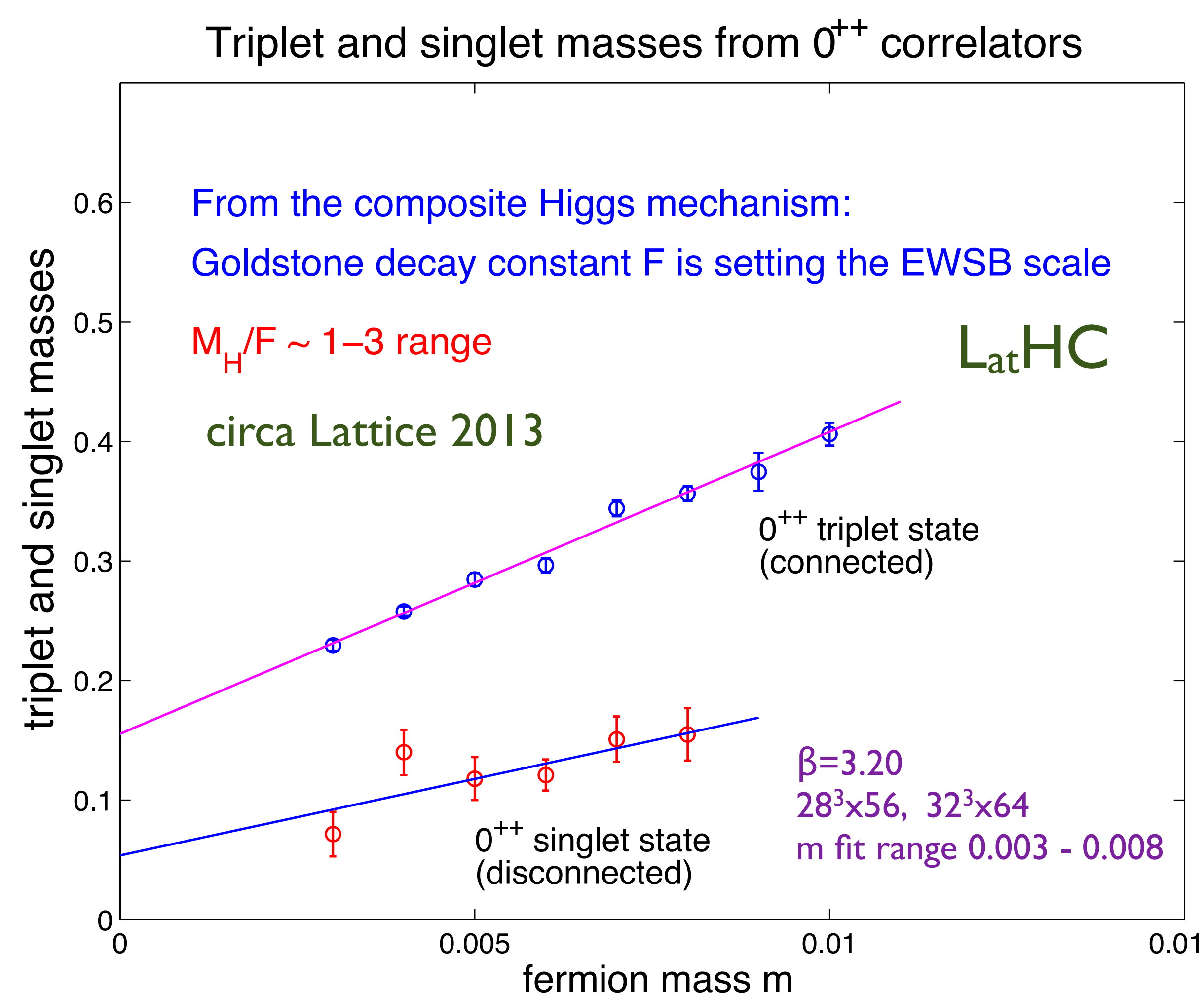
The light 0++ scalar

sextet model LatHC









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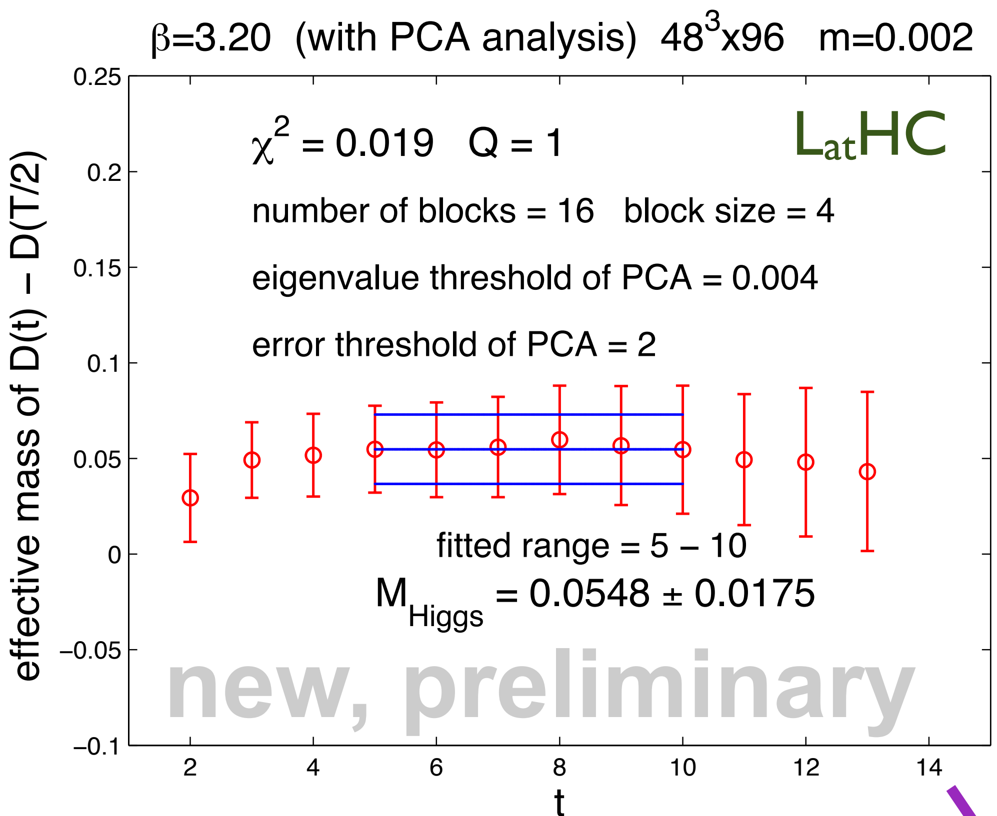
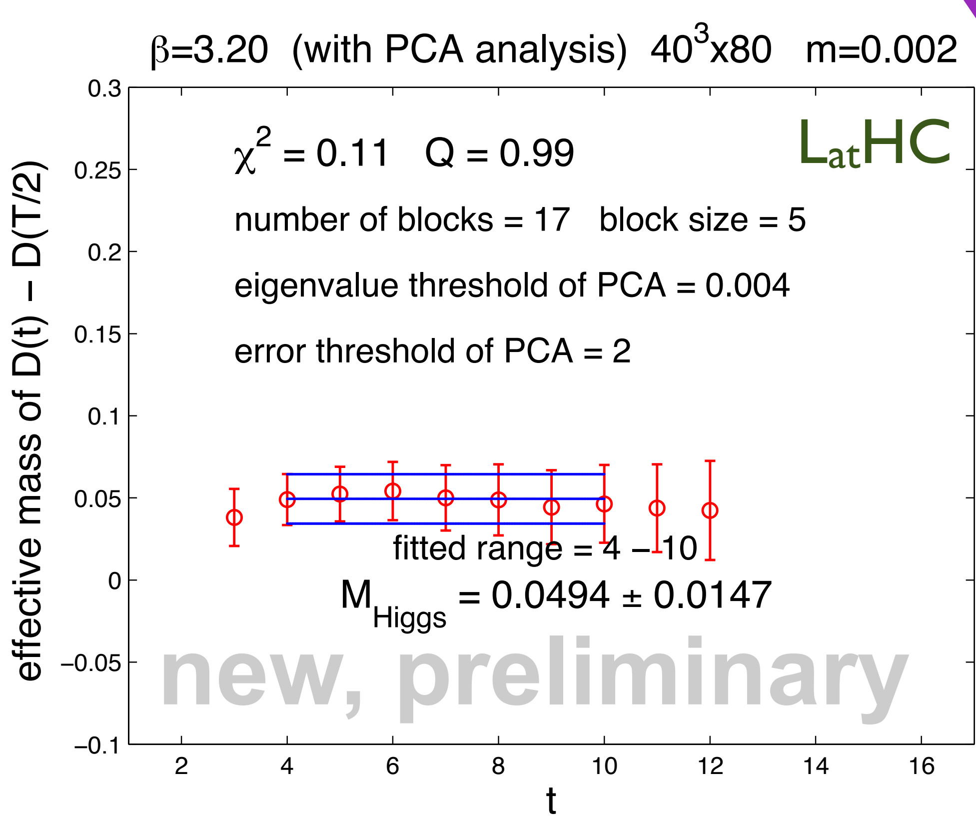
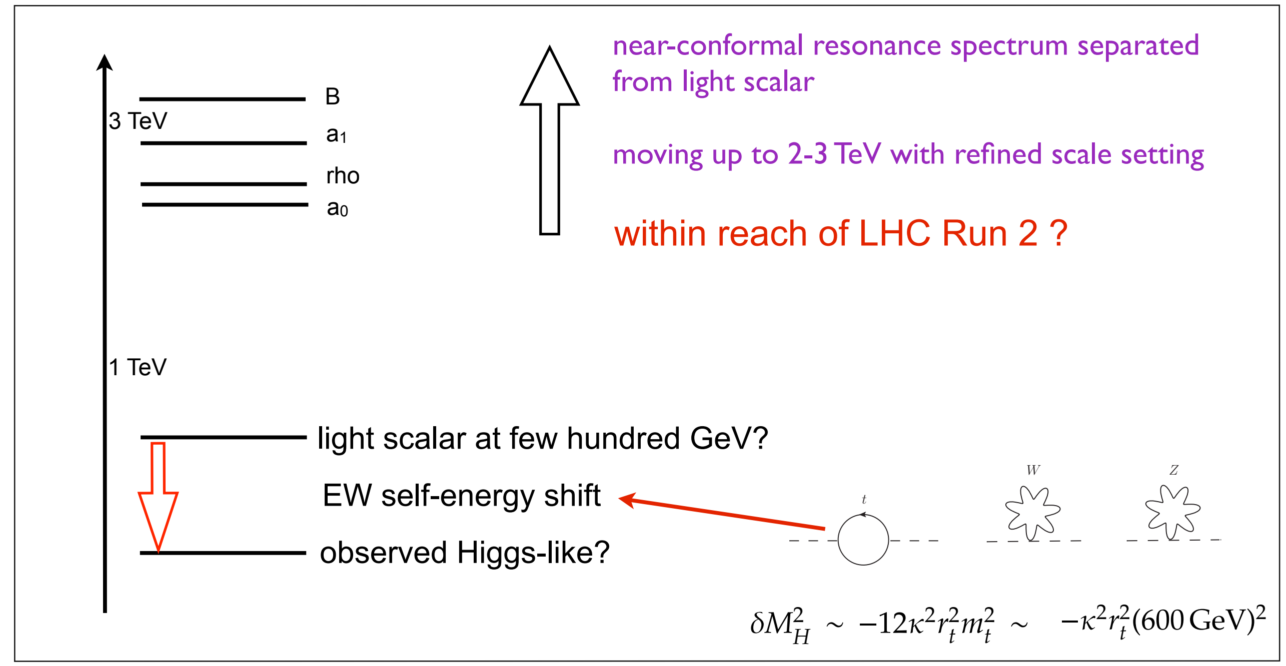
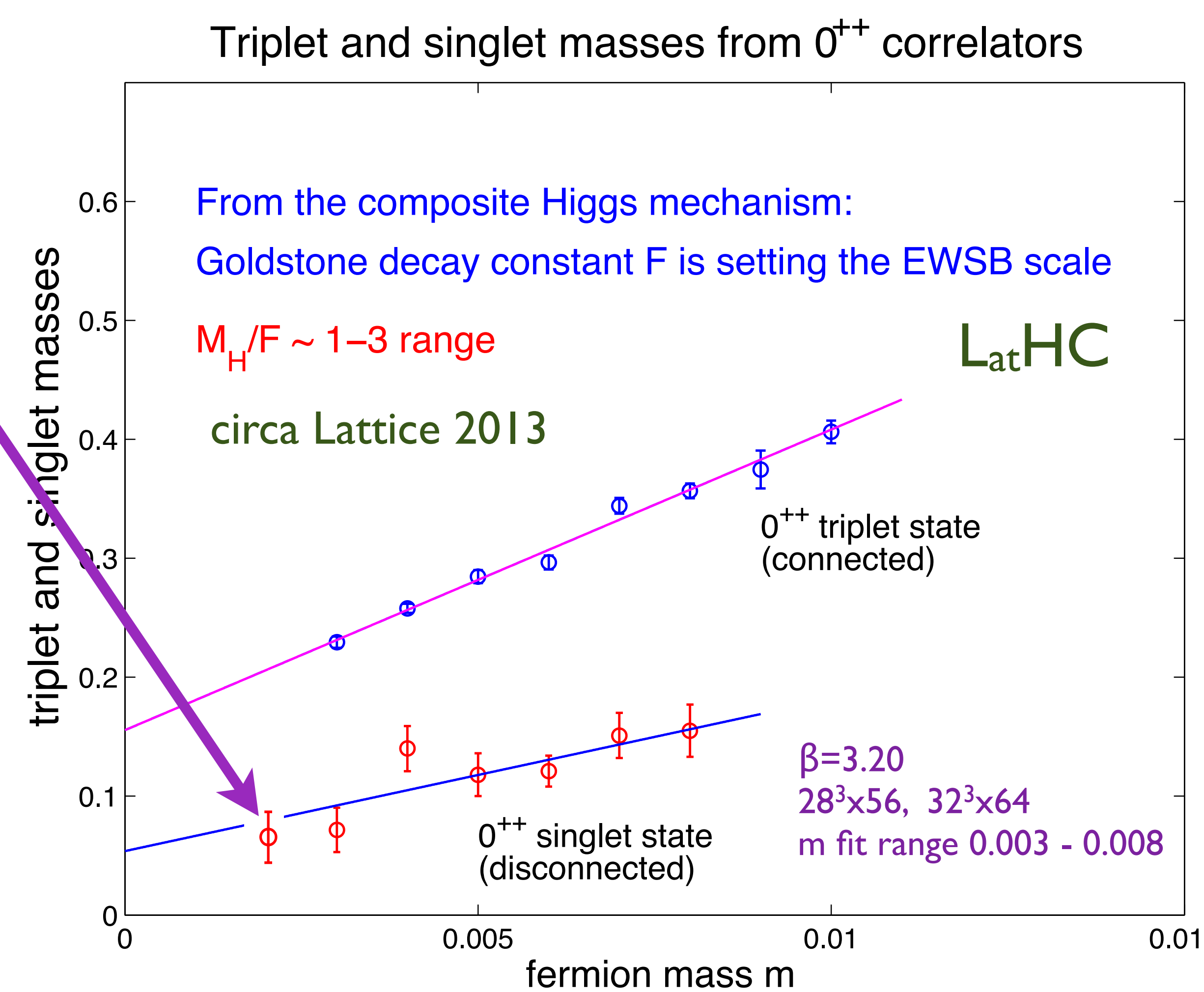
sextet model LatHC









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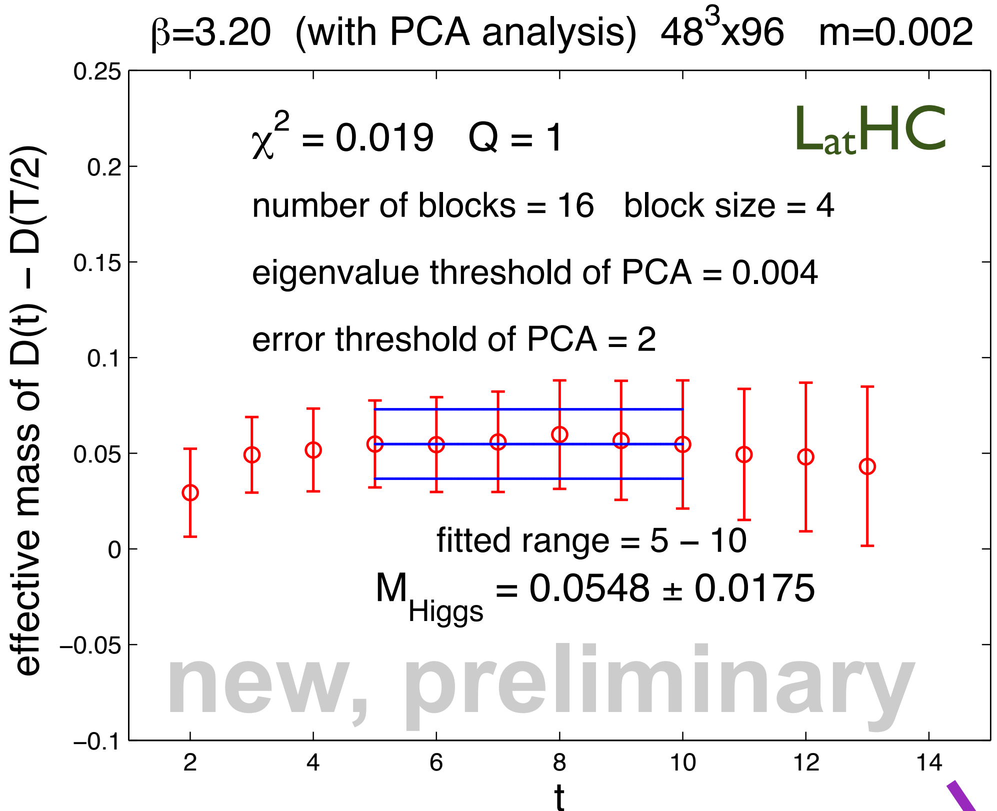
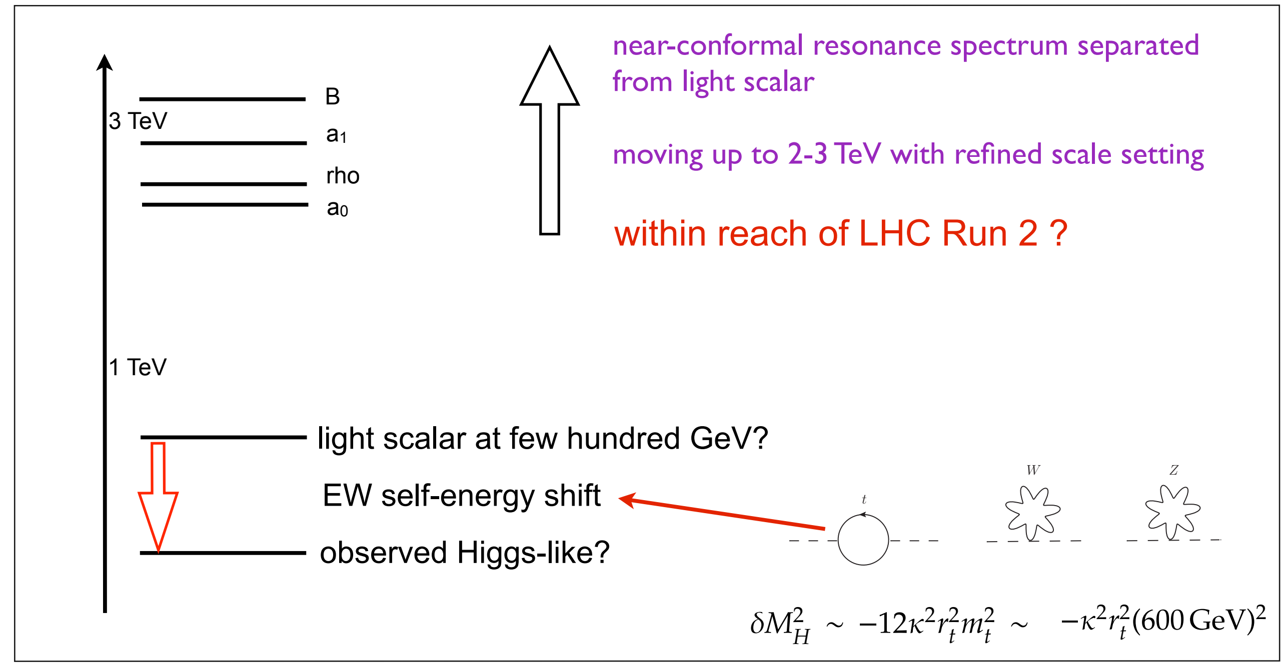
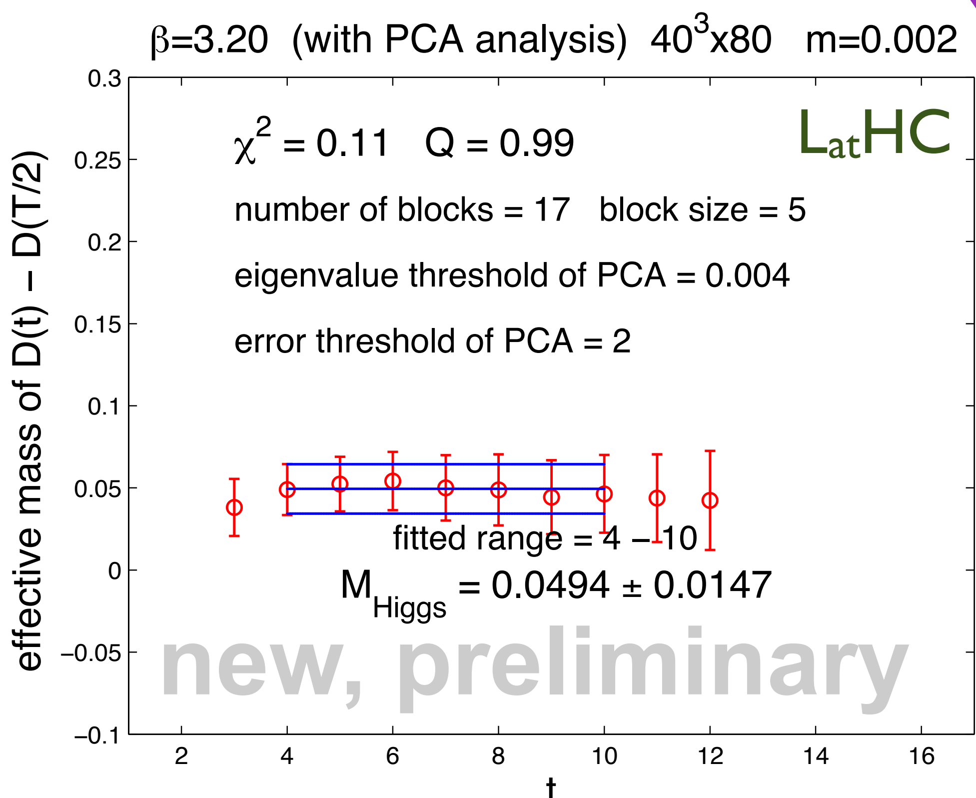
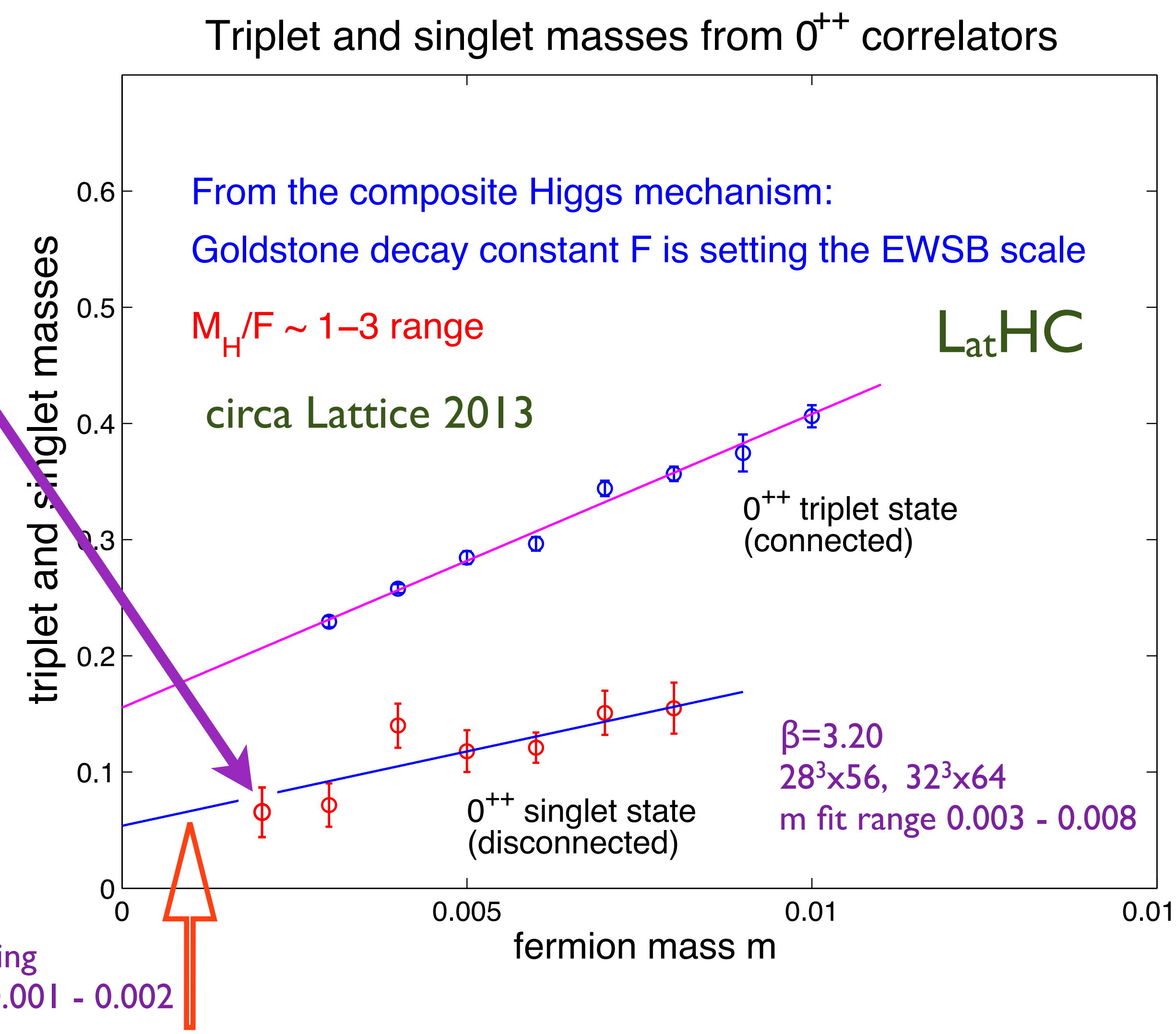
sextet model LatHC





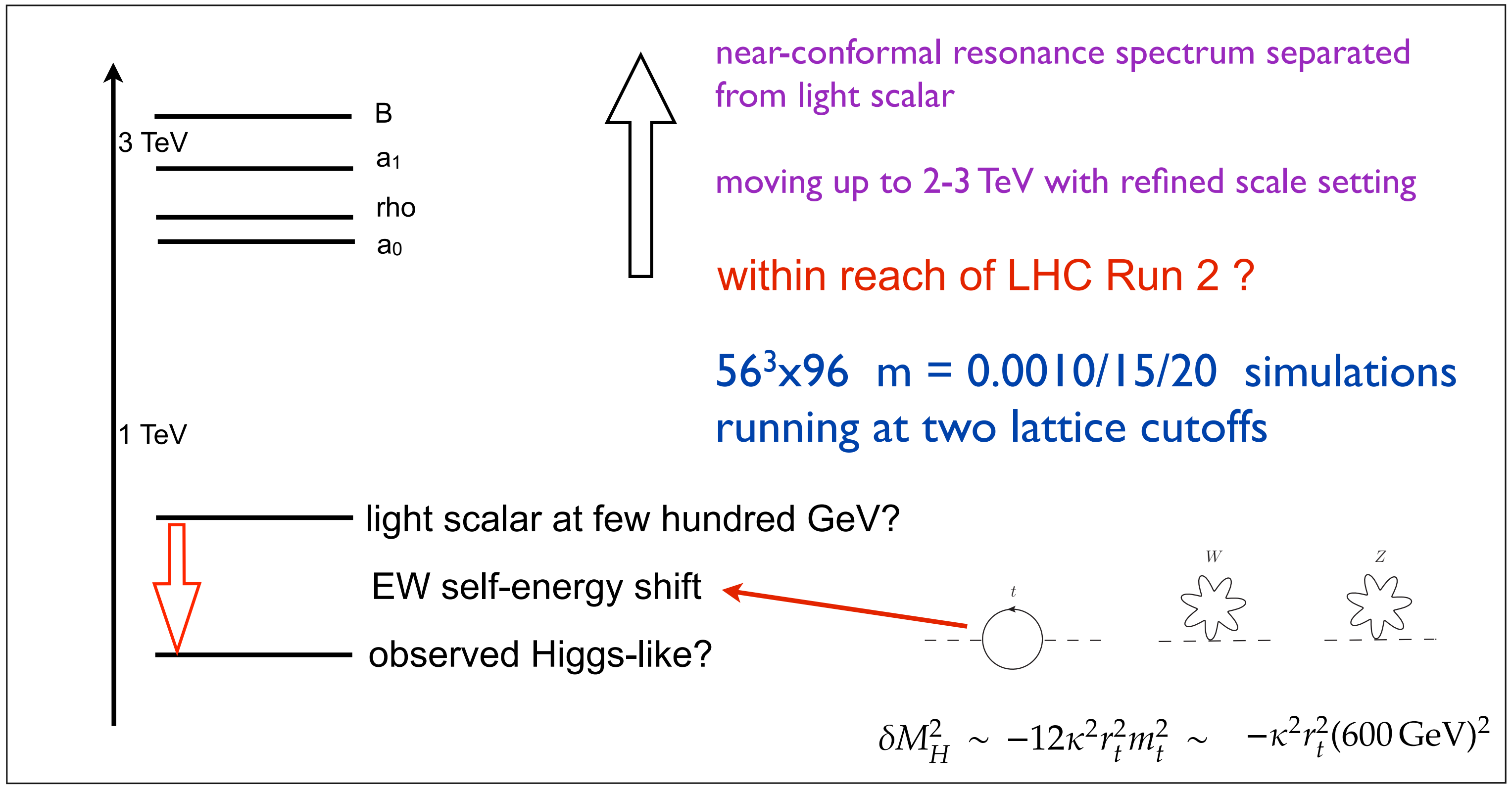




56³x96 running
m fit range 0.001 - 0.002

The light 0++ scalar

challenges on two tracks



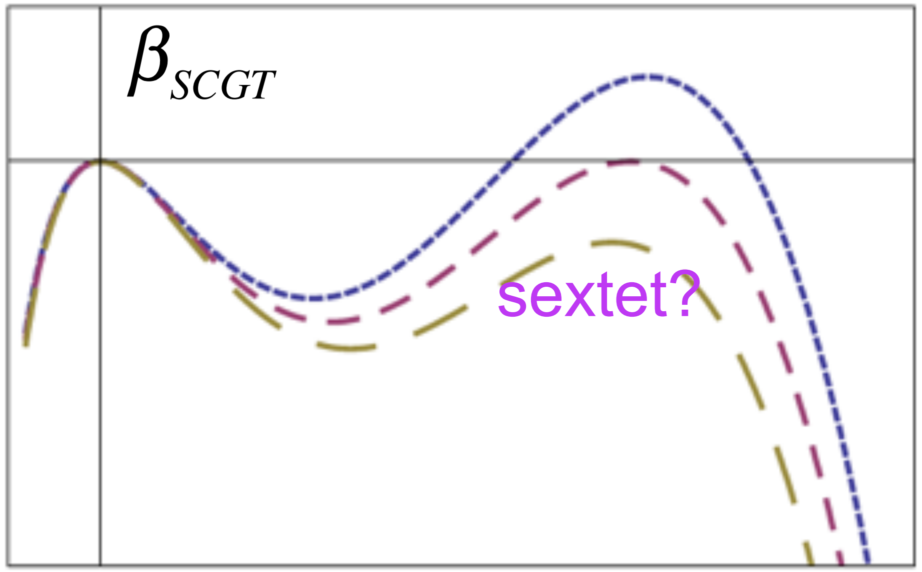
Theory track:

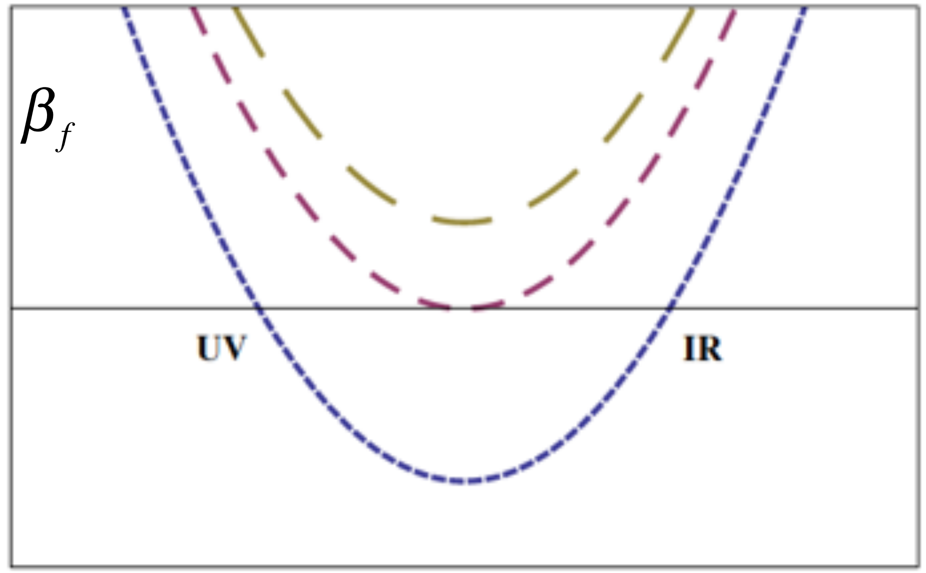
- is there a natural explanation for scale separation close to CW?
- is there testable meaning to dilaton interpretation?
- how to do mass deformed χPT when scalar is not decoupled from Goldstones?
- how the low mass scalar is effecting the RMT analysis in m → 0 limit?

Simulation track:

- new mixed action strategy
- more accurate scale setting in continuum limit FL >1!
- analysis of slowly changing topology
- glueball mixing
- to reach decoupling of low mass scalar in RMT limit?

Theory track: BKT (Miransky) conformal phase transition?





tunable deformation of IRFP?

four-fermion operator with large anomalous dim?

$$L_{SCGT} \Rightarrow L_{SCGT} + \frac{f}{\Lambda^2}(\bar{\psi}\psi)^2$$

Miransky, Yamawaki
Kaplan, Son, Stephanov
Gies,.. RG flow
large-N double trace limit
(Witten, Rastelli, Vecchi)
Kutasov, ... (holographic)

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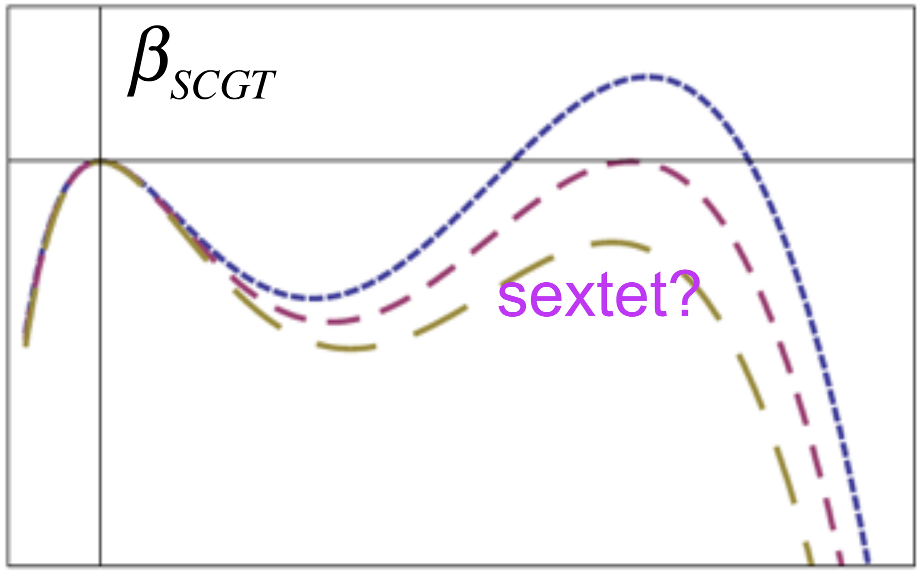

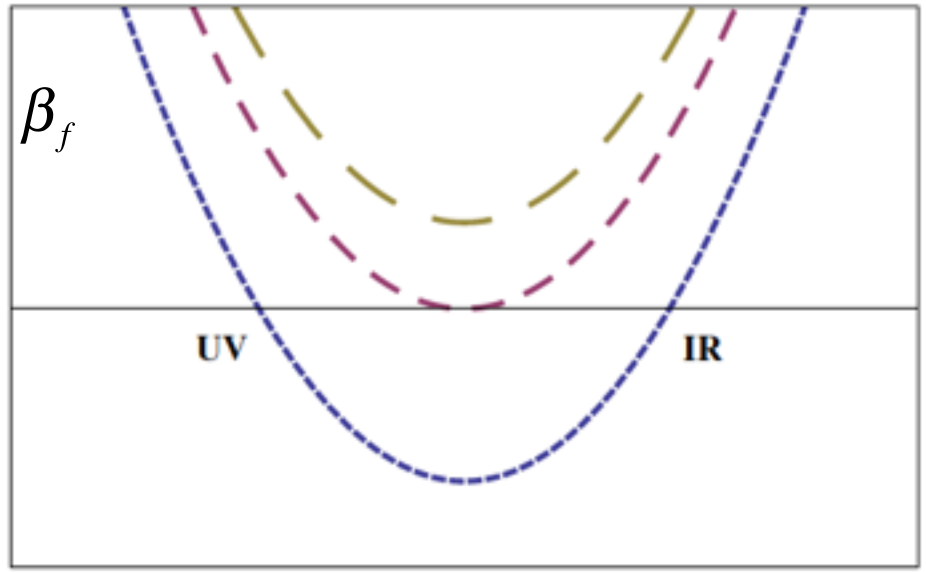

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If anomalous dimension of $(\bar{\psi}\psi)^2$ becomes marginal,

the beta function $\beta(g^2, f)$ can lead to collapse of the pair of the IR FP and the UV FP (created by the NJL term) $\Rightarrow$ asymptotic safety.

Only if x is tuned to x_c critical of the BKT (conformal) phase transition.

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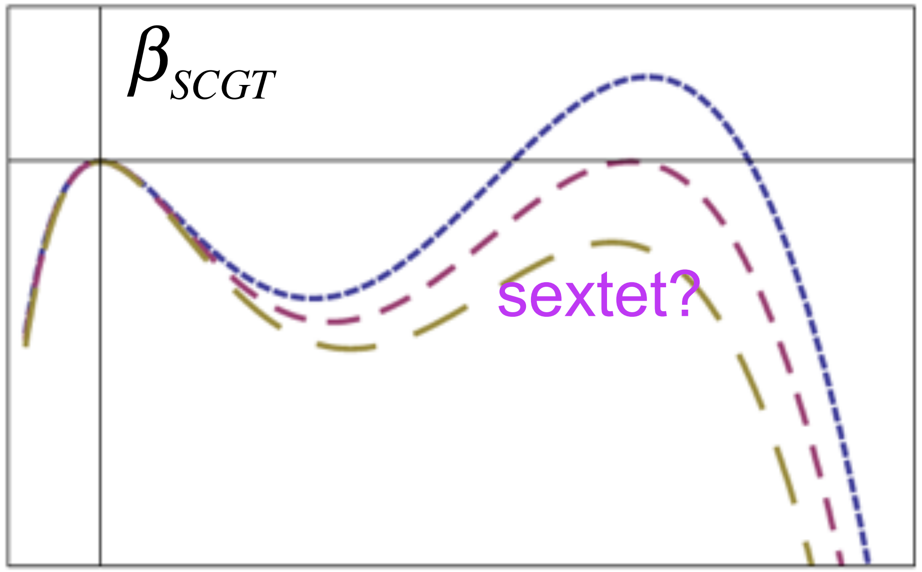

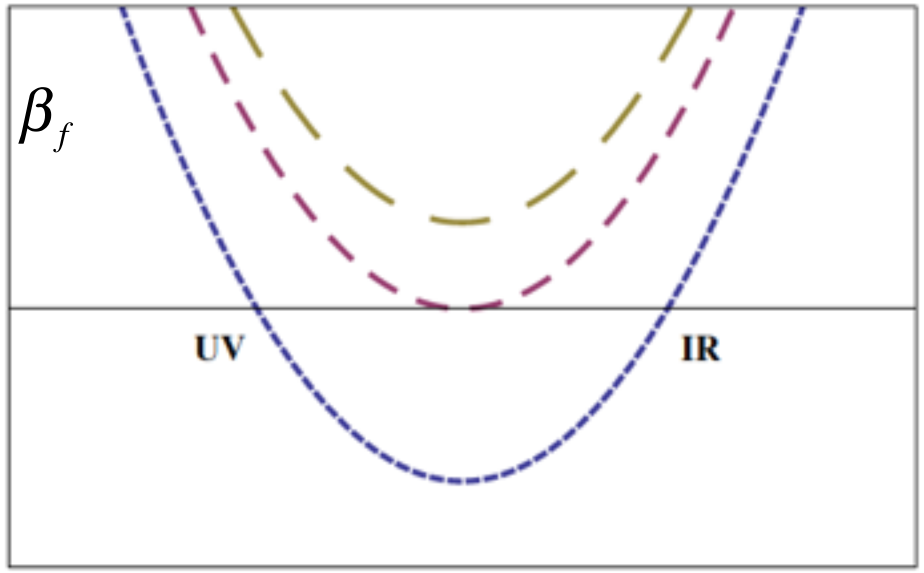

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On the lattice all terms are present on the cutoff scale in the Wilsonian sense and the model will decide what it wants to do with them.
Depending on anomalous dimension of $(\bar{\psi}\psi)^2$ any of the scenarios can play out at any given point in the SCGT theory space.

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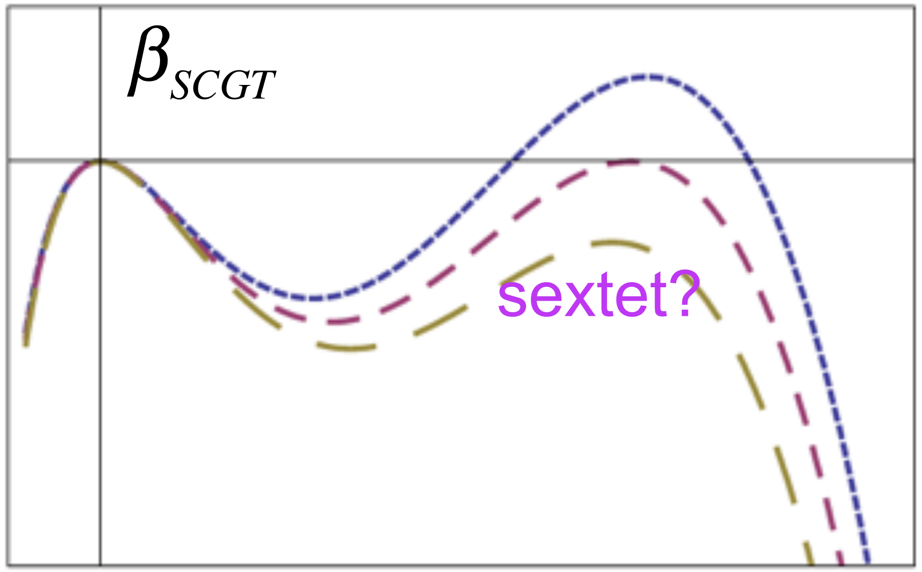

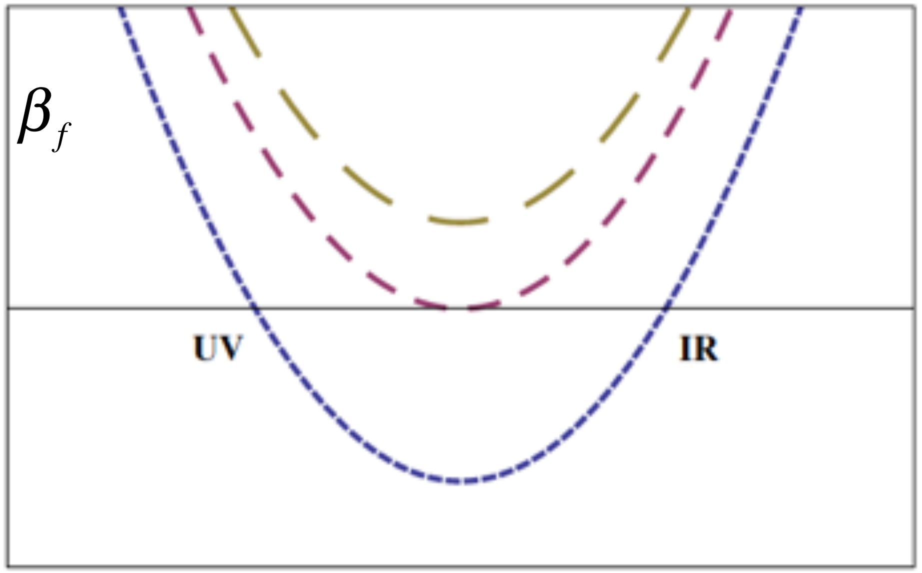

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NJL is misinterpreted but the general idea is attractive, does not need NJL:

Four-fermion interaction near four dimensions

J. Zinn-Justin *

THE EQUIVALENCE OF THE TOP QUARK CONDENSATE AND THE ELEMENTARY HIGGS FIELD

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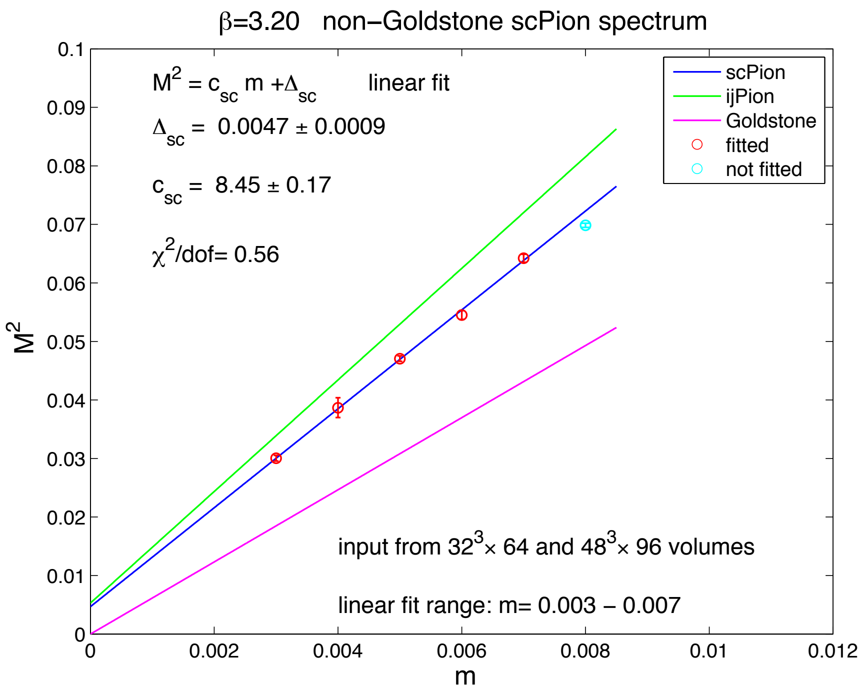
Simulation track: mixed action



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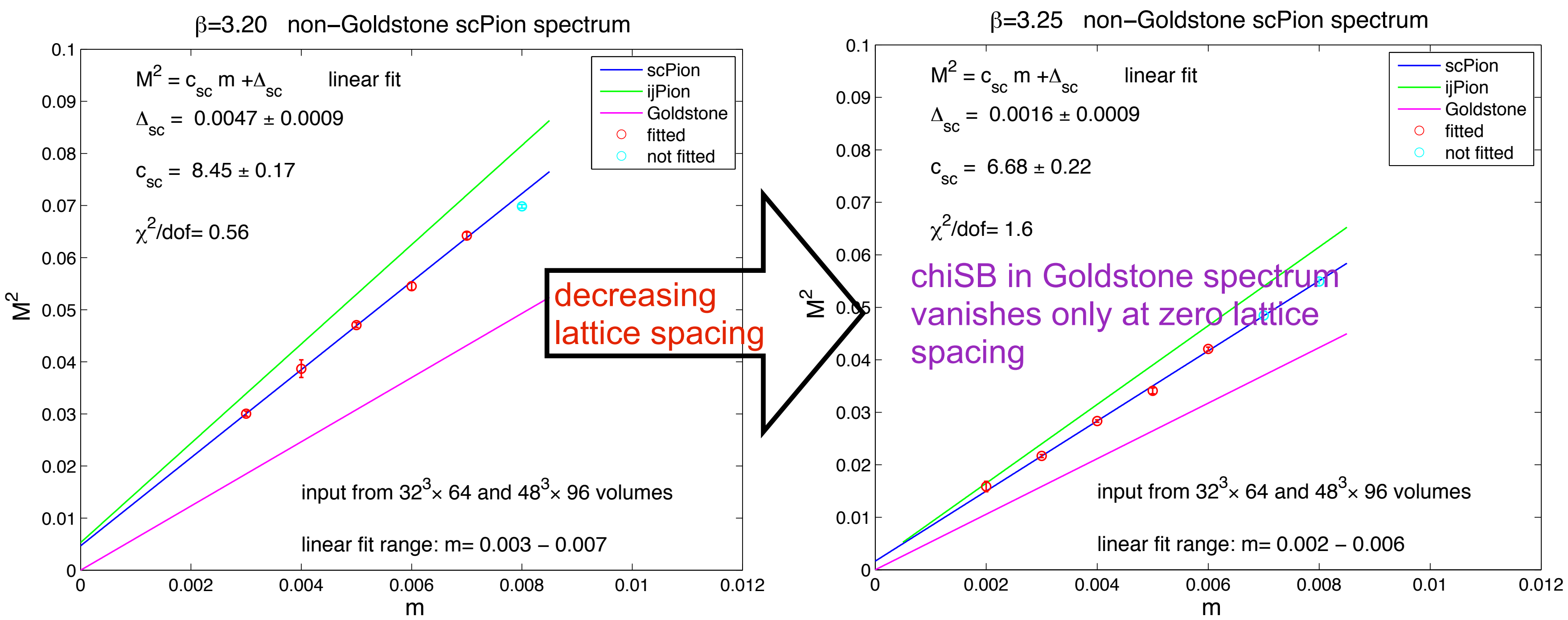

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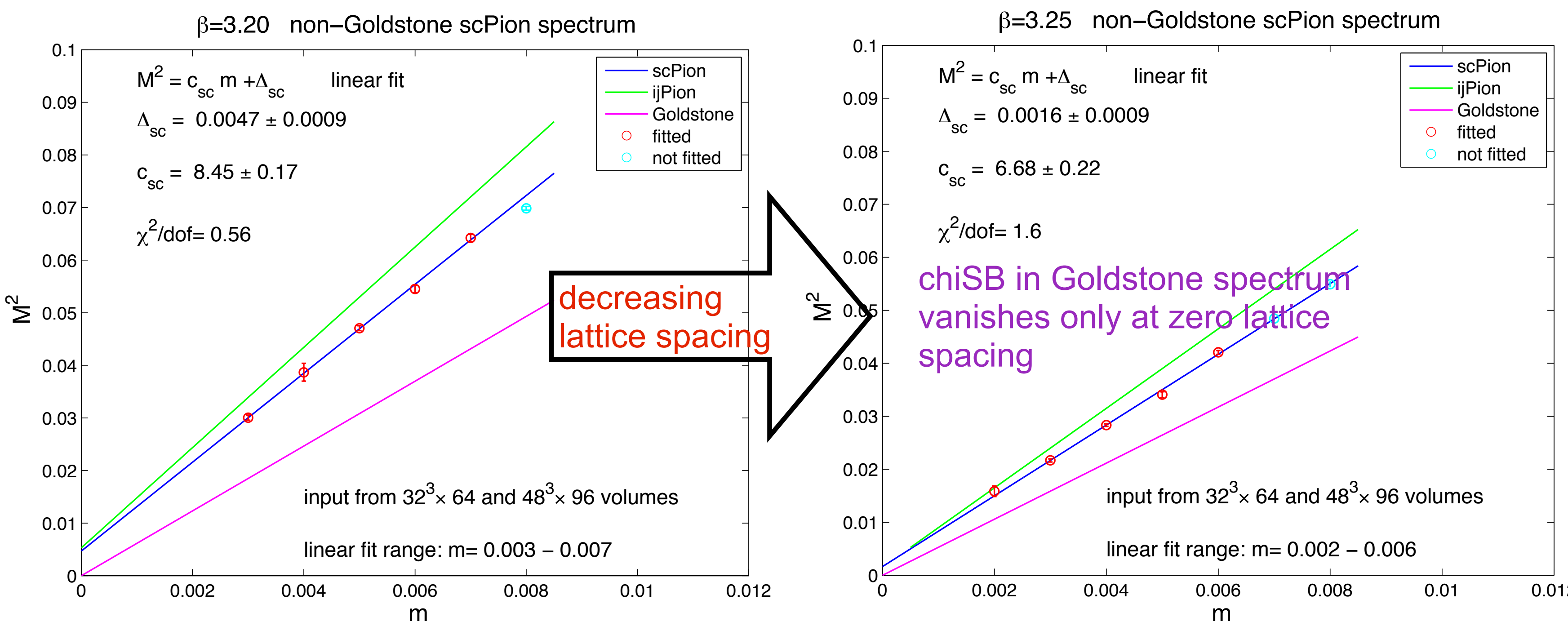

idea:

- use the gauge configurations generated with sea fermions
- taste breaking makes chiPT analysis complicated
- in the analysis use valence Dirac operator with gauge links on the gradient flow
- taste symmetry is restored in valence spectrum
- Mixed Action analysis should agree with original standard analysis when cutoff is removed: this is OK!

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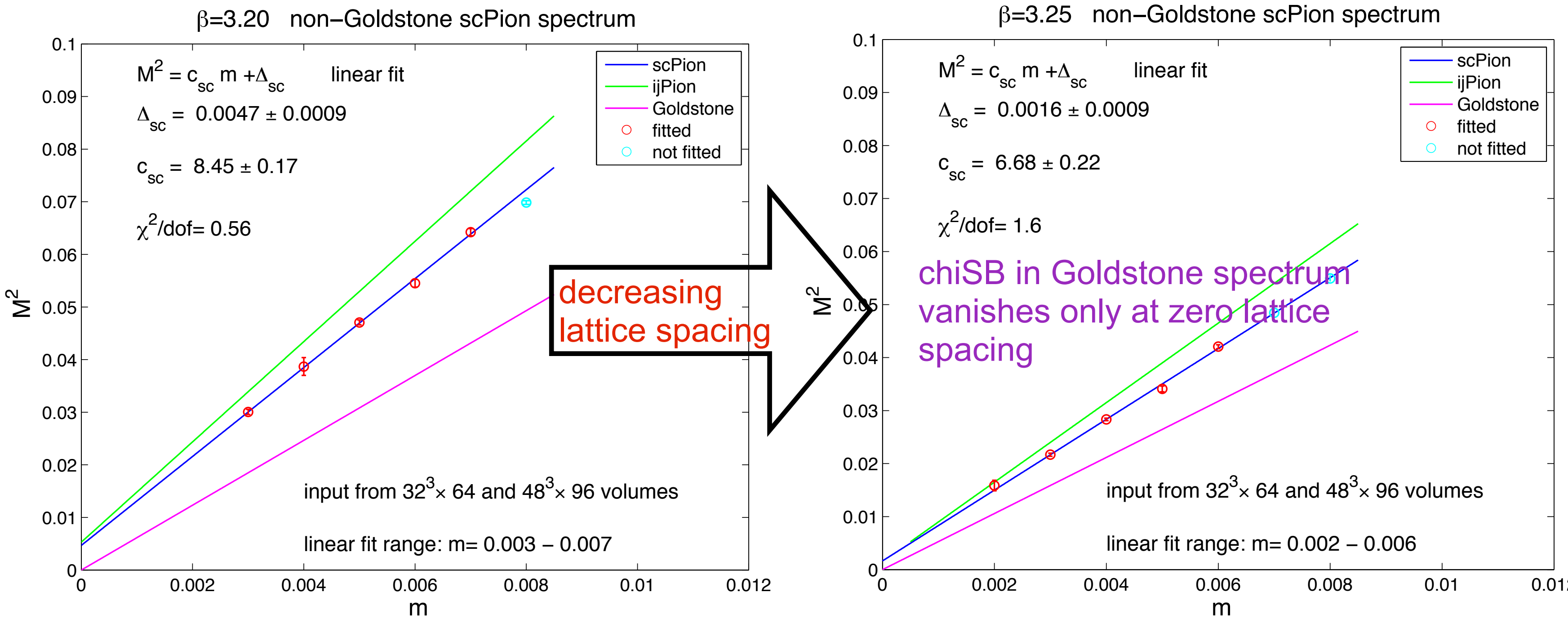

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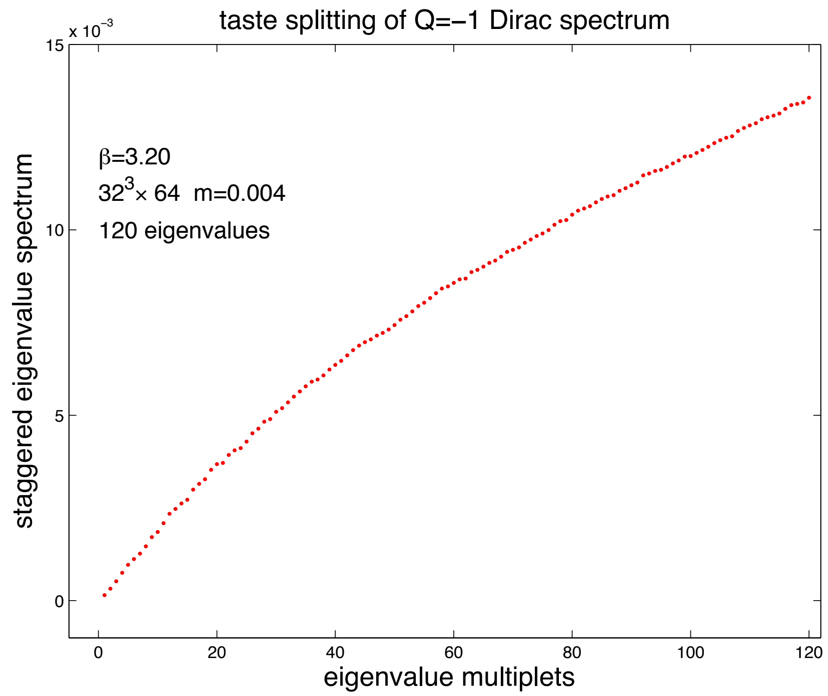

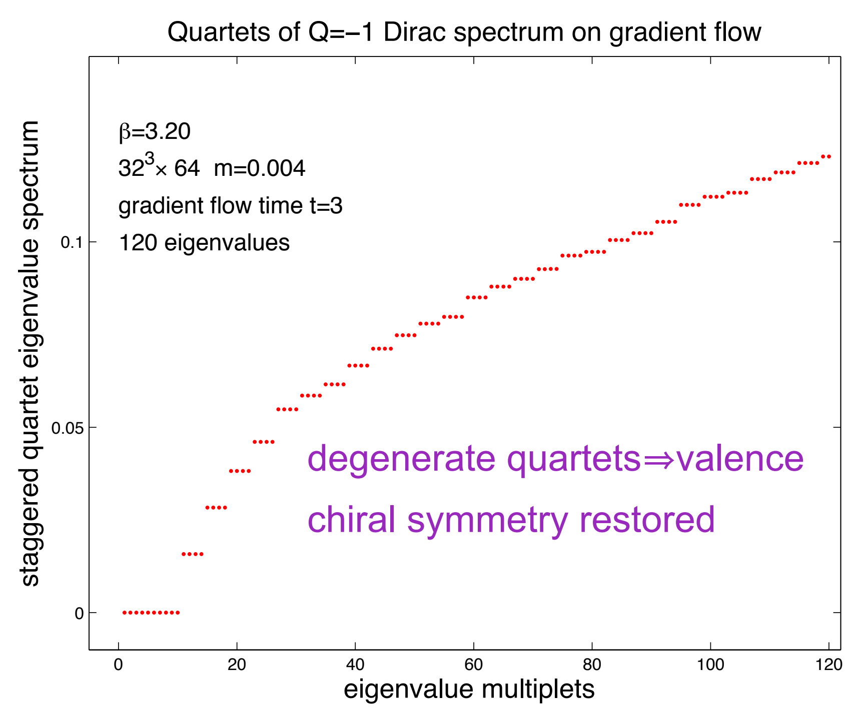

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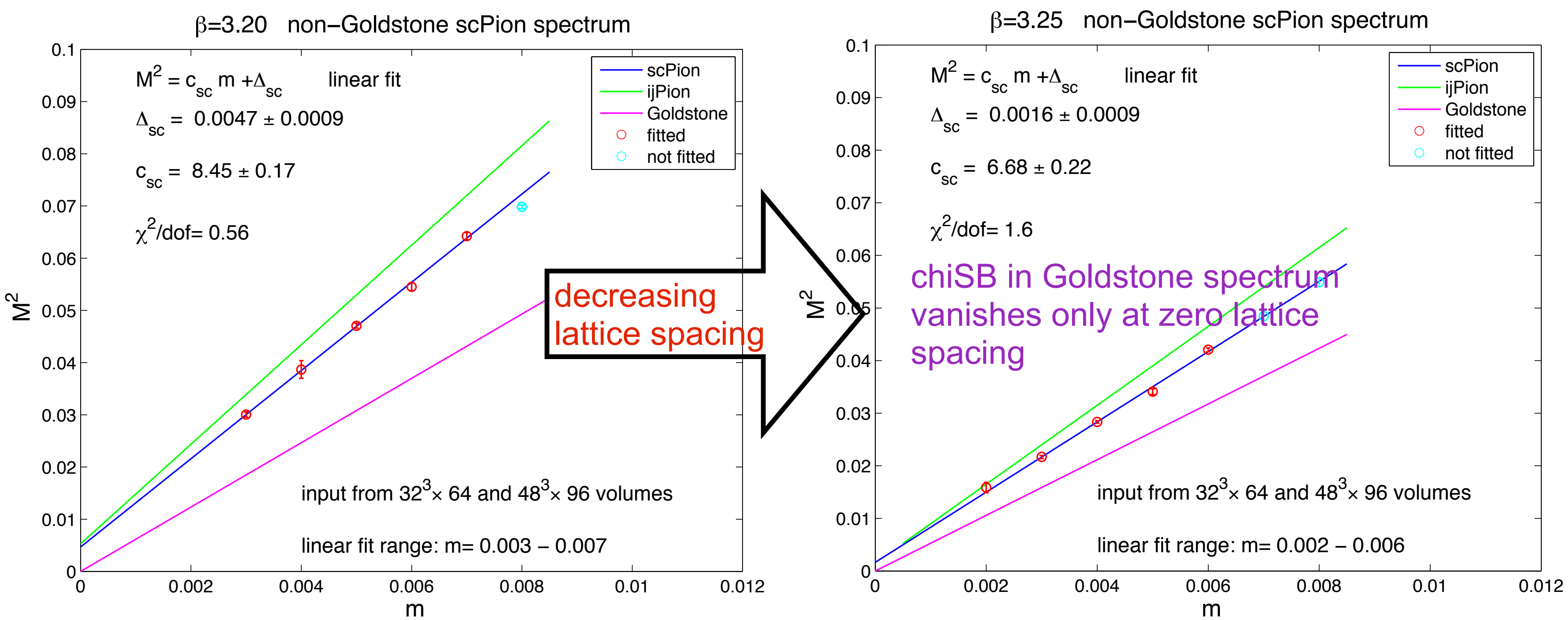

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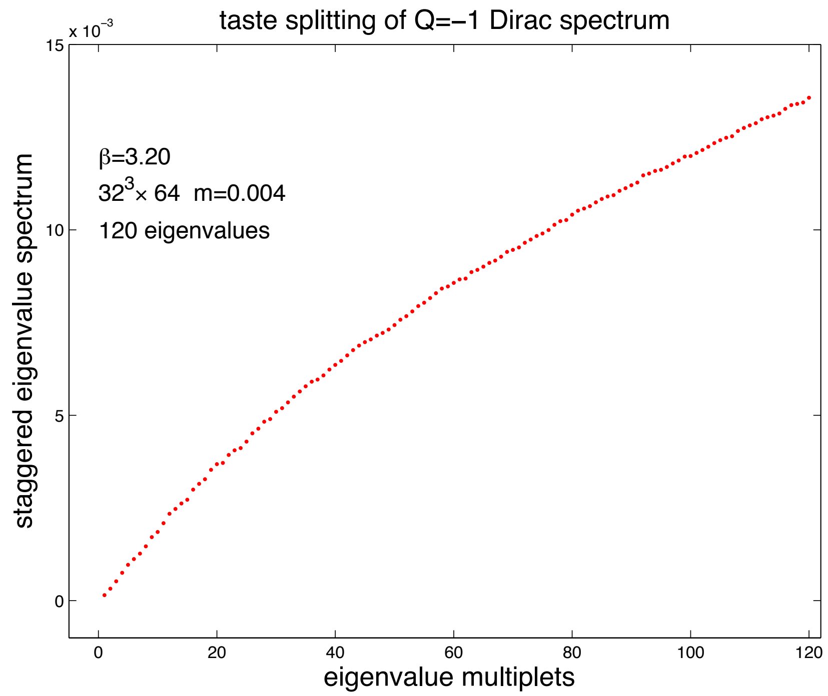

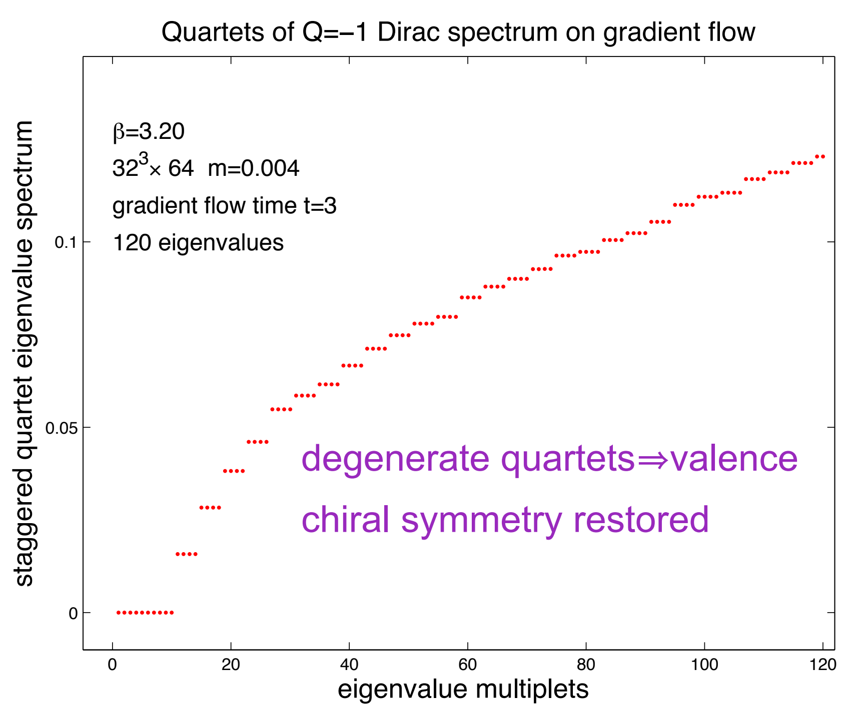

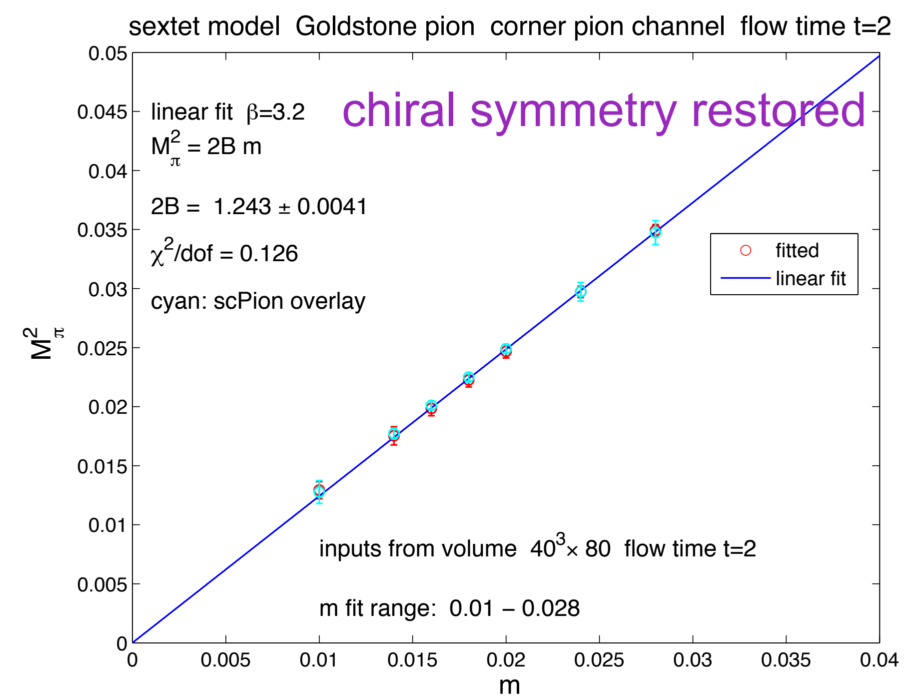

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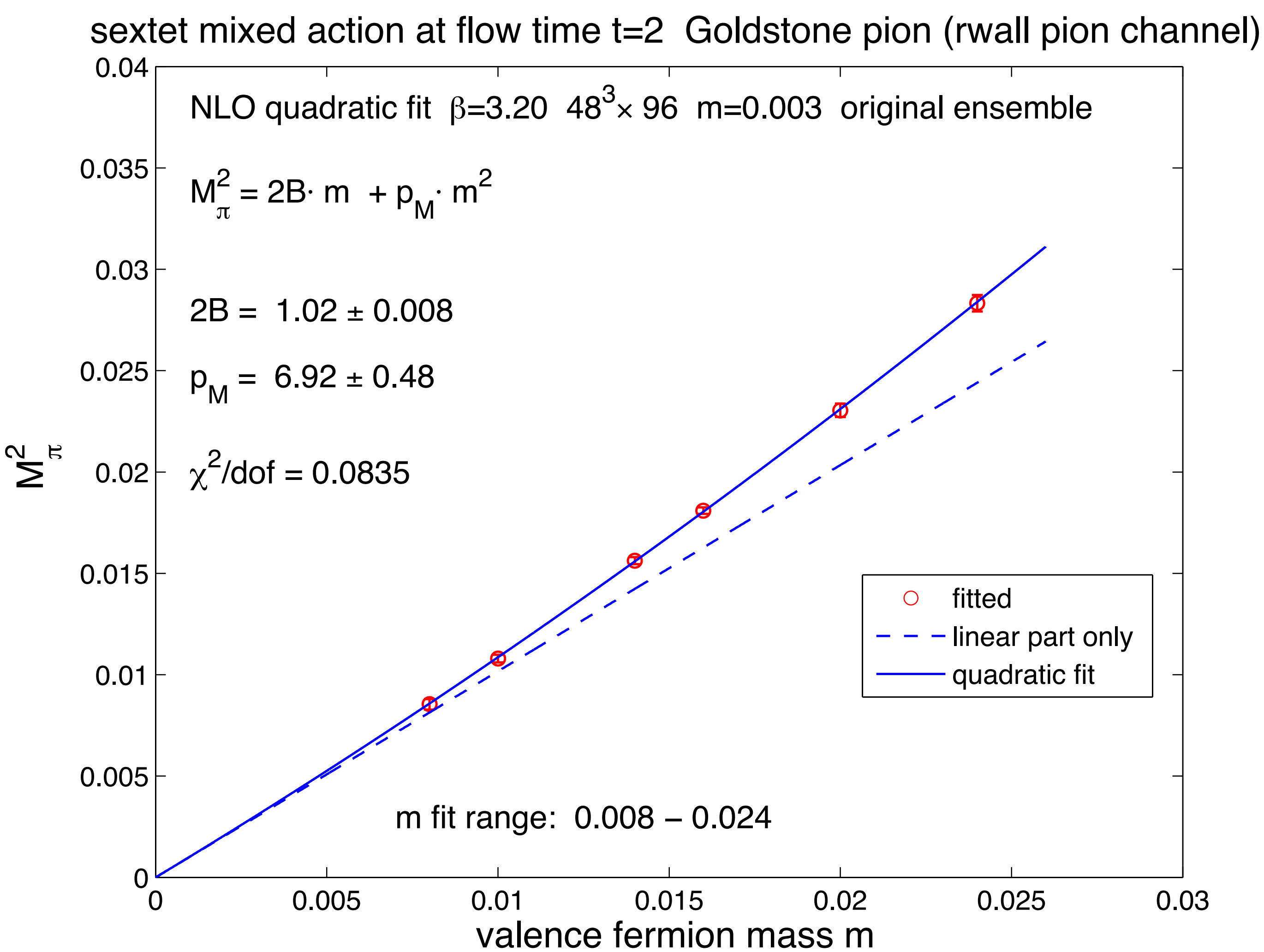
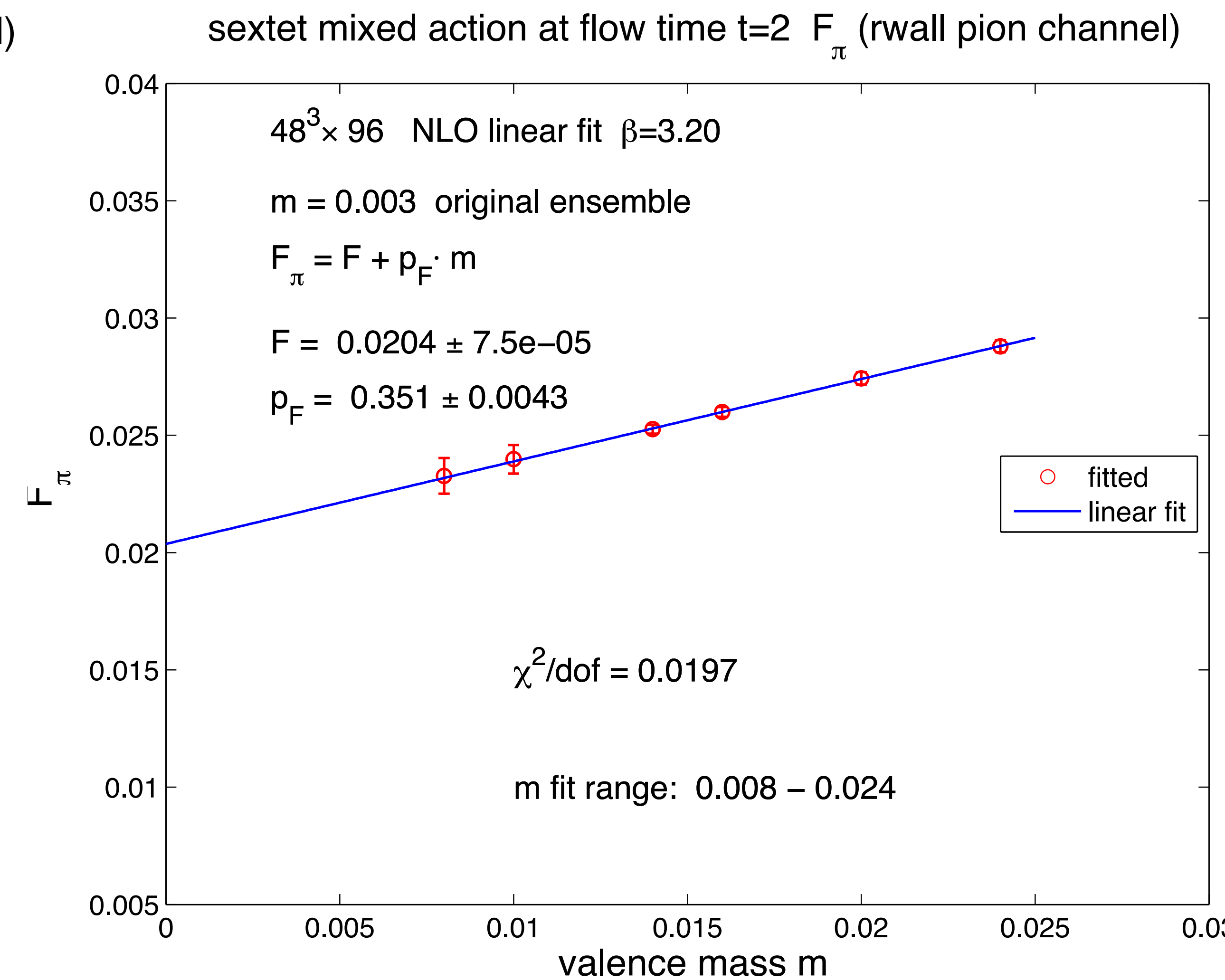
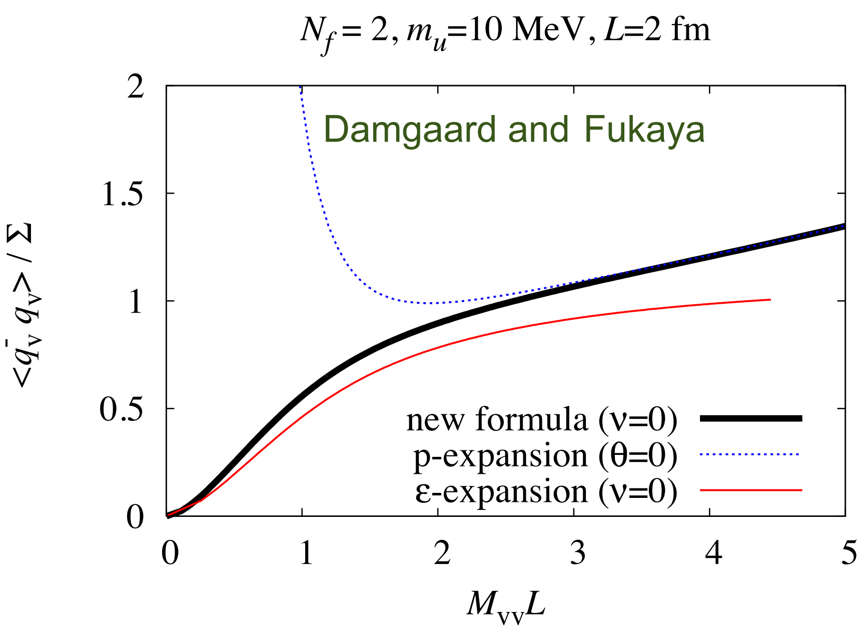


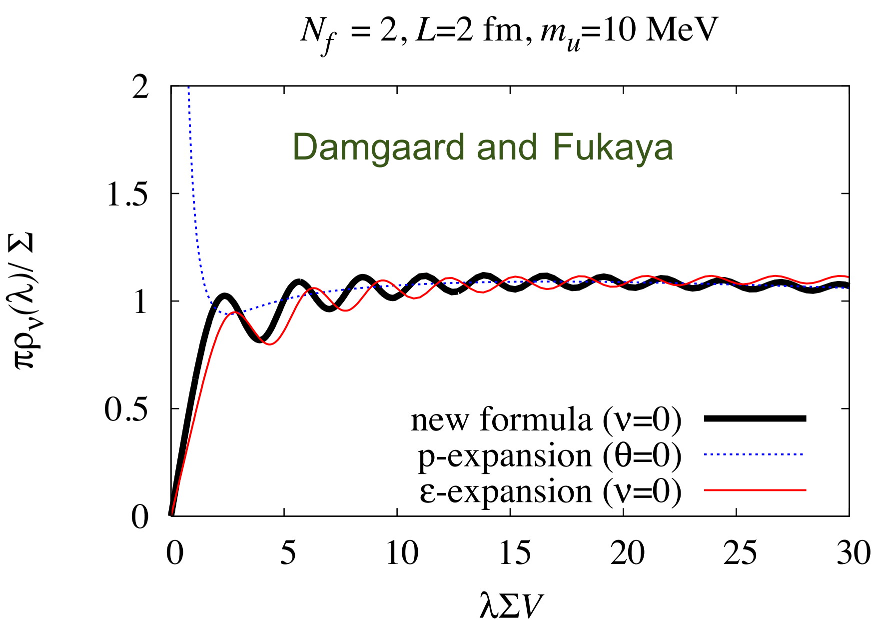


- B dropped about a factor of 5 after matching valence fermion mass   B is not RG invariant
- very small change in F after matching (B/F ratio dropped substantially)   F physical, RG invariant
- Mixed Action analysis is better ChiPT fitting procedure for staggered fermions
- cutoff effects remain but analysis is freed from taste breaking cutoff problems
  gives new perspective on rooting!

Simulation track: mixed action

epsilon regime, p regime to epsilon regime crossover, valence pqChiPT with Mixed Action:





new analysis in crossover and RMT regime opens up with mixed action on gradient flow

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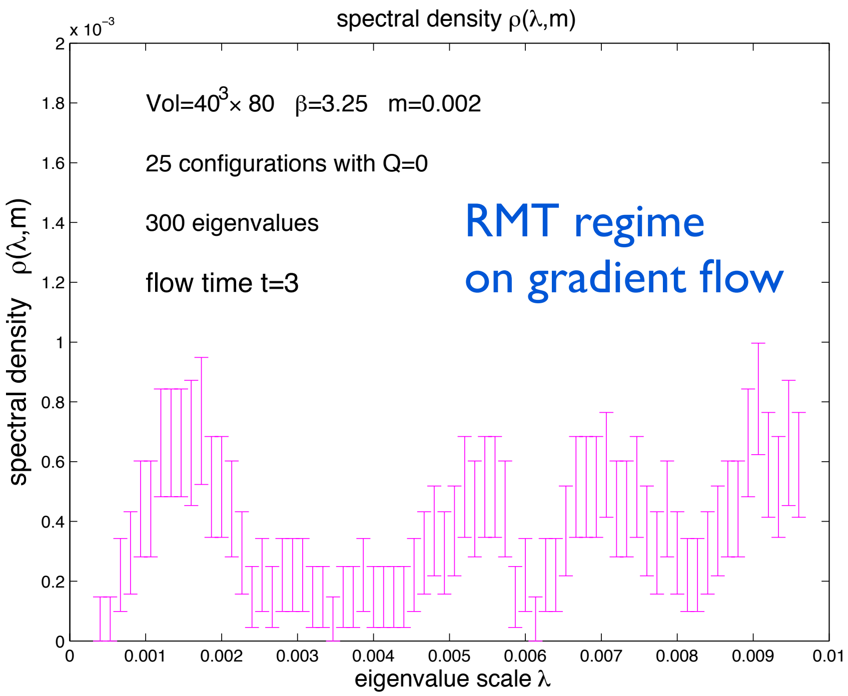

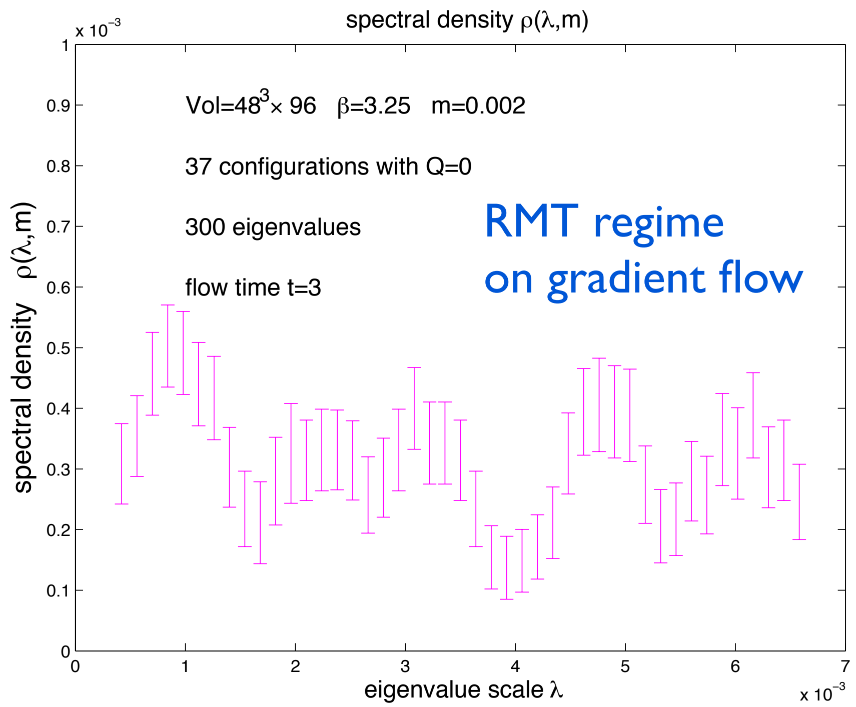

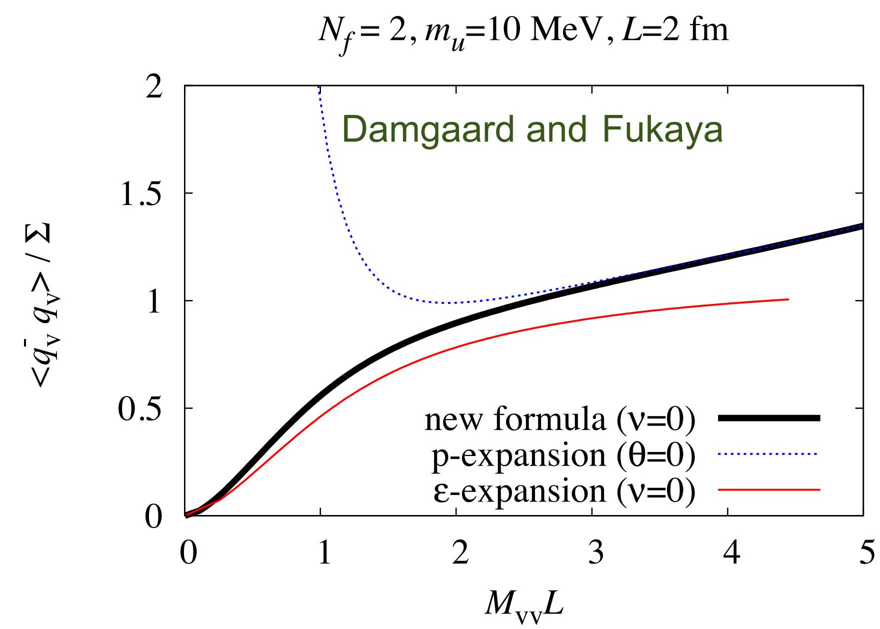

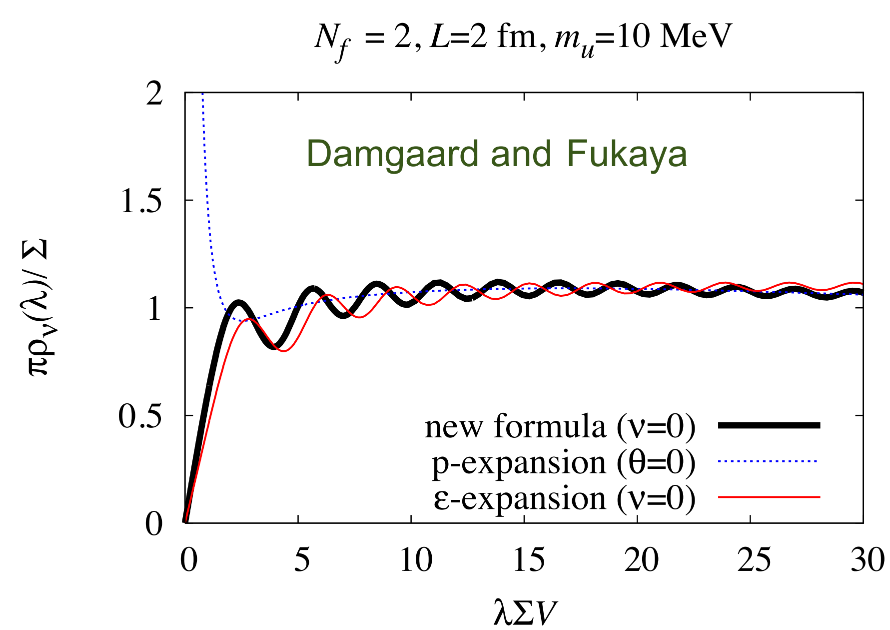

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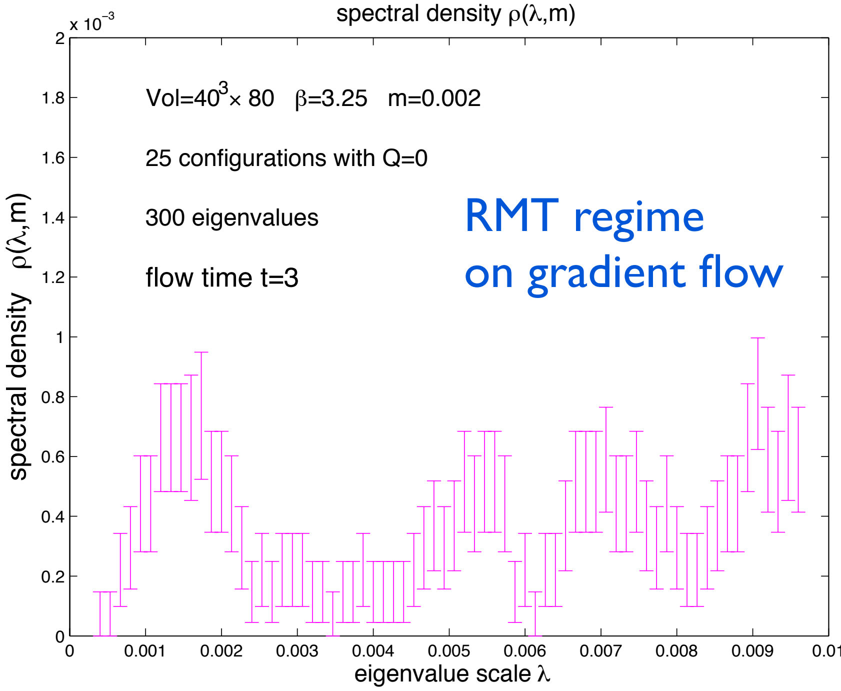
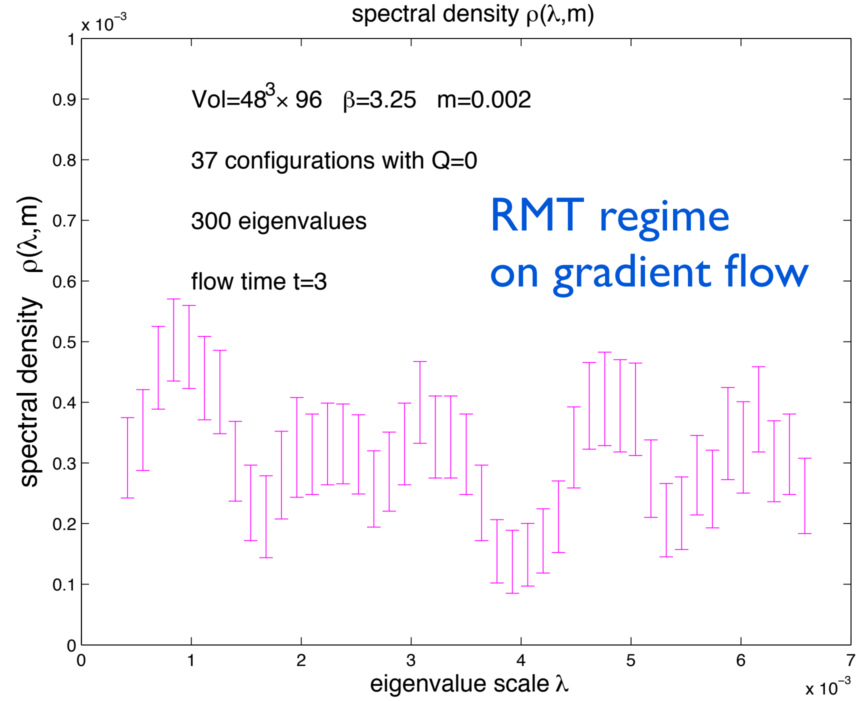
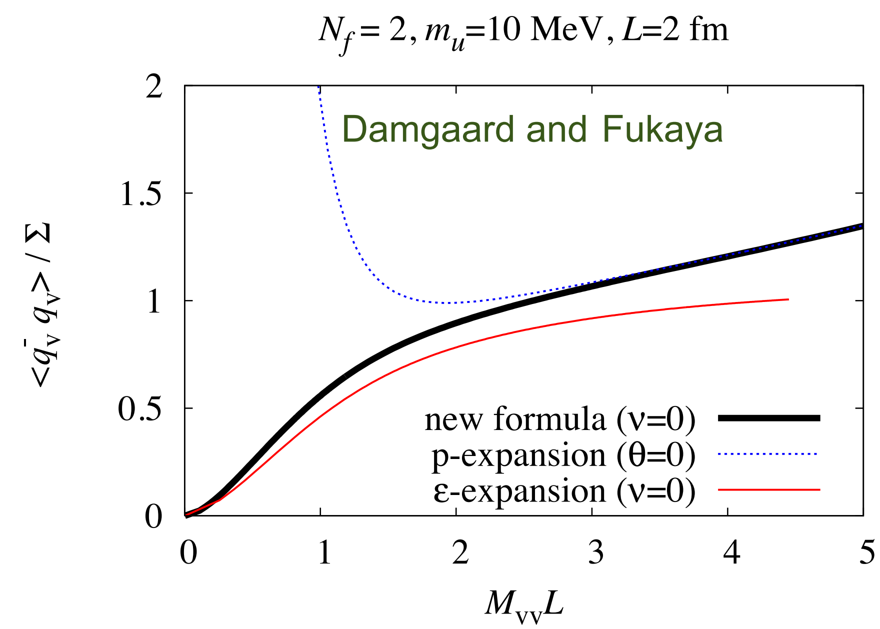
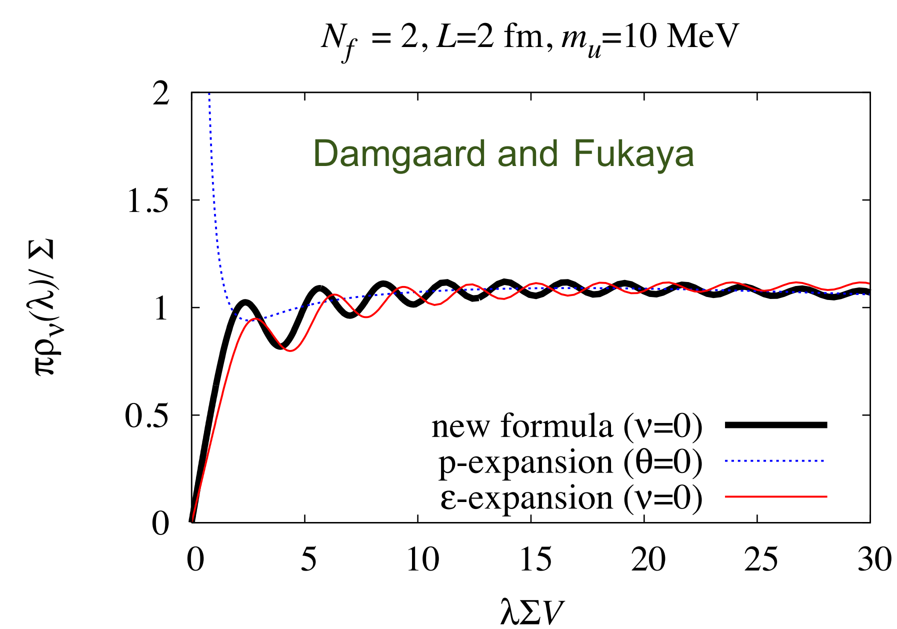






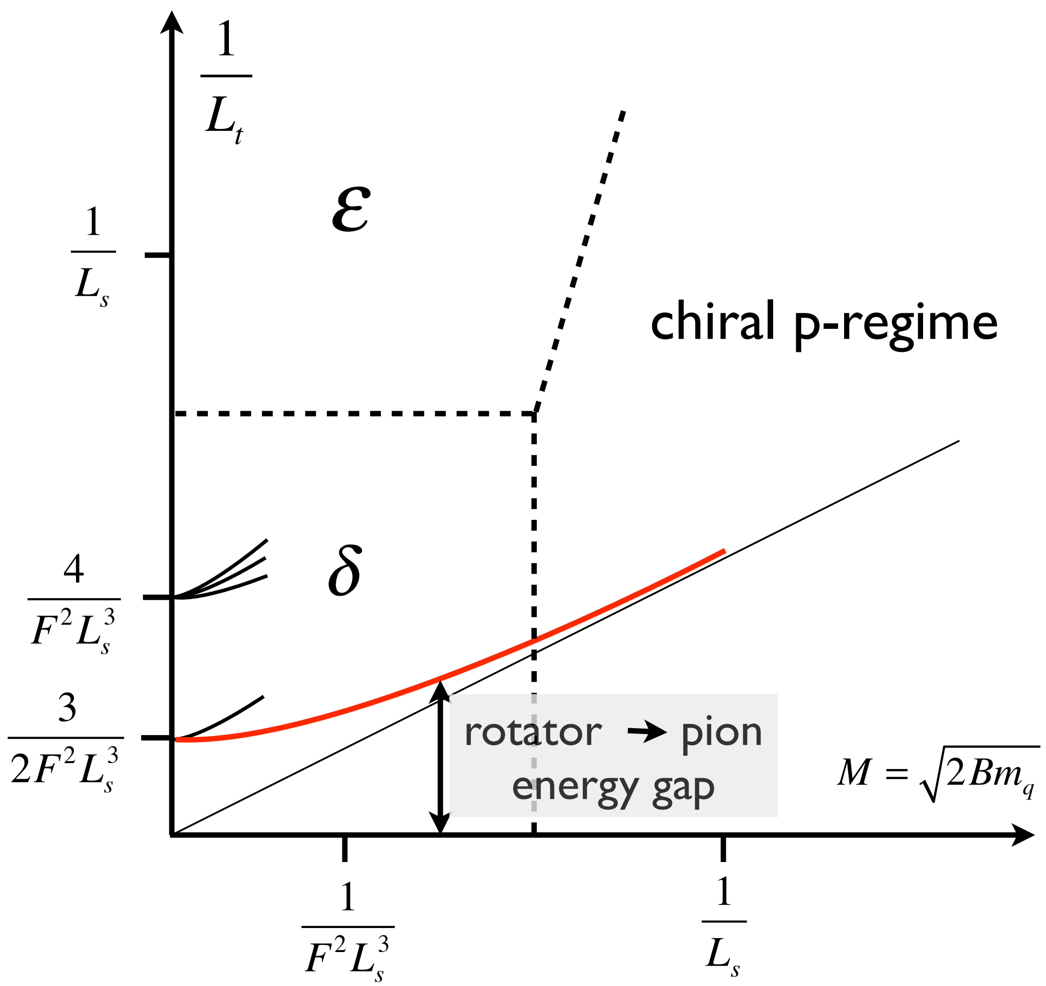


- B drops by large factor after matching, with some small decrease in F
- GMOR implies large drop of order O(10) in the chiral condensate Σ
  Σ is not RG invariant, requires renormalization
- in original analysis mΣV ~ O(100-200)
  to reach RMT regime close to CW would require enormous resources
- in Mixed Action analysis λΣV ~ O(10-20) RMT regime can be reached

new analysis in crossover and RMT regime opens up with mixed action on gradient flow

Simulation track: FL < 1 simulations ⇒ no theory

when in finite volume, it is always an expansion in 1/FL !



Condition of reaching the chiral expansion regime can be estimated from rotator spectrum ⇒

$E_l = \frac{1}{2\theta} l(l+2)$ with $l = 0,1,2,...$ rotator spectrum for $SU(2)_f \times SU(2)_f$

direct application to sextet model

$\theta = F^2 L_s^3 (1 + \frac{C(N_f = 2)}{F^2 L_s^2} + O(1/F^4 L_s^4))$ (P. Hasenfratz and F. Niedermayer)

expansion in $1/F^2 L_s^2$!

$C(N_f = 2) = 0.45$ (FL=1 is ~ 2fm in lite QCD) C will grow with ~ N_f

the constraints are the same in the ε-regime and p-regime

FL = 0.1 L=0.2 fm in QCD femto world OK to study volume dependent PT coupling running with V

FL = 1 L= 2 fm in QCD and we crossed over to the χSB phase all 3 regimes (ε,δ,p) OK

FL = 0.4 squeezed L= 0.8 fm, begins to look conformal not OK, misidentifies infinite volume phase

The chiral condensate new method

novel algorithm of the project:

- stochastic determination of the scale dependent continuous spectral density function and mode number distribution function
- from the Chebyshev approximation to the spectrum of the Dirac operator averaged over the ensemble of lattice gauge configurations

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- chiral limit of the renormalized chiral condensate
- scale-dependent anomalous dimension of chiral condensate
- consistency check of GMOR relation
- Random Matrix Theory spectra
- topological susceptibility, and more ...

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spectral density function and mode number function:

chiral condensate and RG:

mode number distribution of Dirac spectrum

$$\rho(\lambda,m) = \frac{1}{V}\sum_{k=1}^{\infty}\langle\delta(\lambda-\lambda_k)\rangle$$

$$\lim_{\lambda\to 0}\lim_{m\to 0}\lim_{V\to\infty}\rho(\lambda,m) = \frac{\Sigma}{\pi}$$

spectral density (Banks-Casher)

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

mode number function

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

renormalized and RG invariant

(Giusti and Luscher)

The chiral condensate   new method

The eigenvalues λ_i^2 of the D$^+$D operator are rescaled to the [0,1] interval

D is the staggered Dirac operator in our applications (method is general)

in rescaling $\lambda_{\min}^2 = 0$ is set and $\lambda_{\max}^2$ is estimated by power iteration

spectral density ρ(t) from ensemble averages

over the D†D matrix with dimension N

$$\rho(t) = \left\langle \frac{1}{N} \sum_{i=1}^{N} \delta(t - \lambda_i) \right\rangle_{\substack{gauge \\ ensemble}}$$

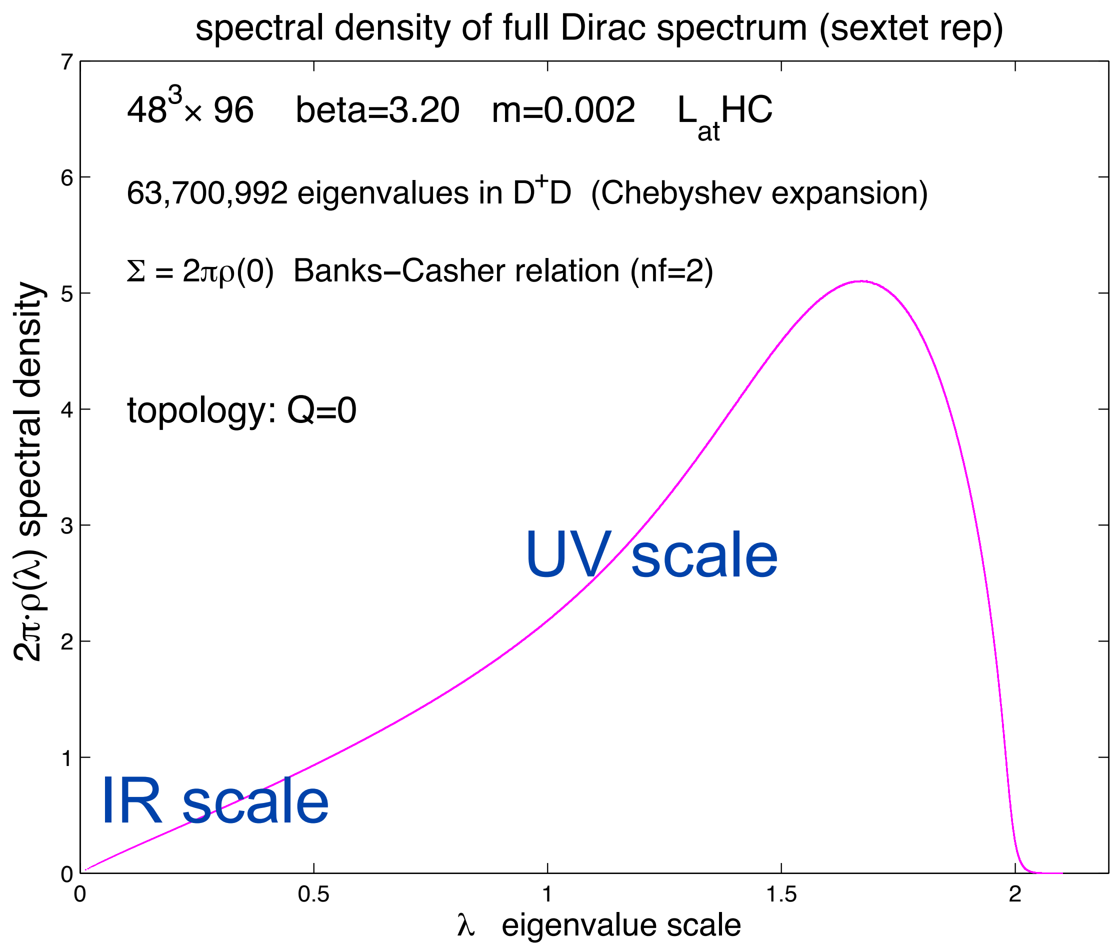
$$\rho(t) = \frac{1}{\sqrt{1-t^2}} \sum_{k=0}^{\infty} c_k T_k(t)$$ expansion in Cebyshev polynomials

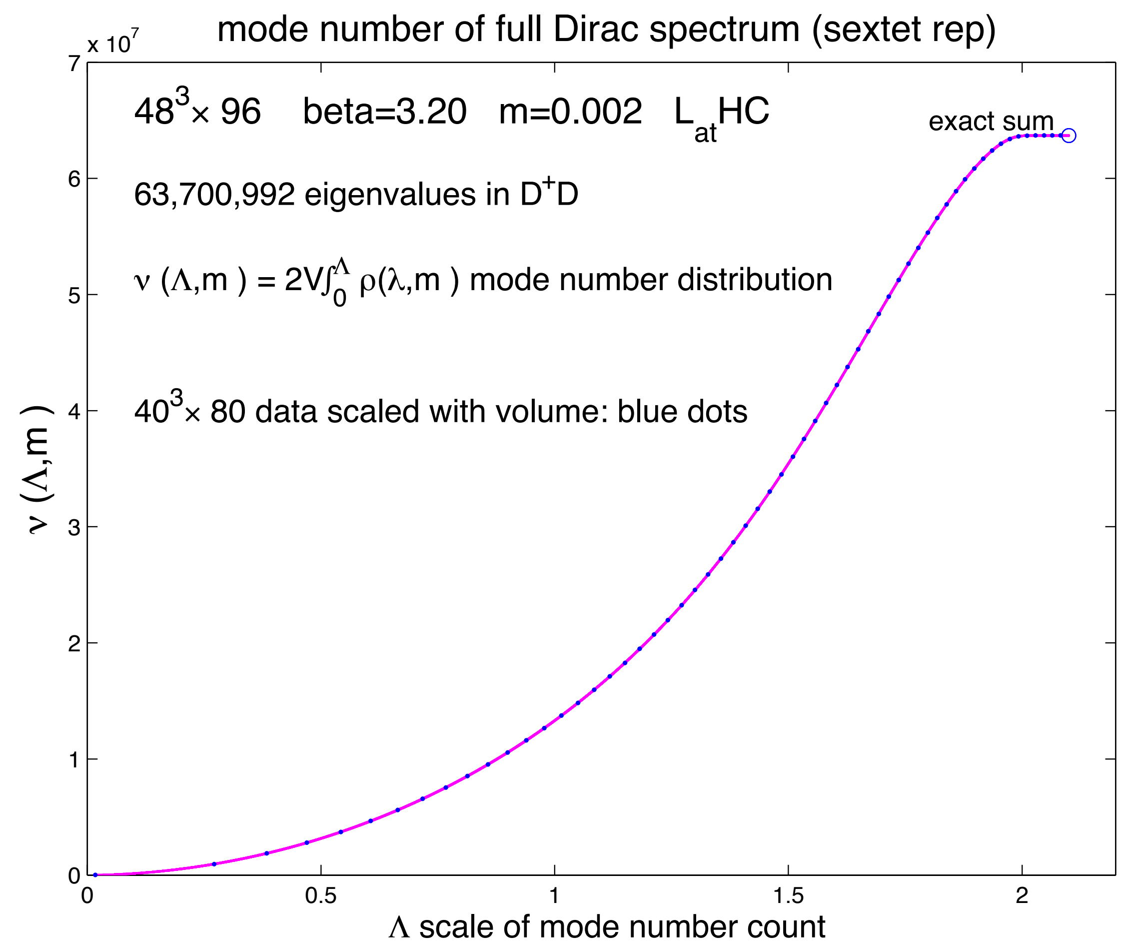
$$c_k = \begin{cases} \dfrac{2}{\pi} \displaystyle\int_{-1}^{1} T_k(t)\rho(t) & \mathrm{k} = 0 \\ \dfrac{1}{\pi} \displaystyle\int_{-1}^{1} T_k(t)\rho(t) & \mathrm{k} \neq 0 \end{cases} \Rightarrow c_k = \begin{cases} \dfrac{2}{N\pi} \displaystyle\sum_{i=1}^{N} T_k(\lambda_i^2) & \mathrm{k} = 0 \\ \dfrac{1}{N\pi} \displaystyle\sum_{i=1}^{N} T_k(\lambda_i^2) & \mathrm{k} \neq 0 \end{cases}$$

more details on the poster!

$\sum_{i=1}^{N} T_k(\lambda_i^2)$ is given by trace of $T_k(D^+D)$ operator

The chiral condensate full spectrum





- nf=2 sextet example illustrates results from the Chebyshev expansion
- full spectrum with 6,000 Chebyshev polynomials in the expansion
- the integrated spectral density counts the sum of all eigenmodes correctly
- Jackknife errors are so small that they are not visible in the plots.

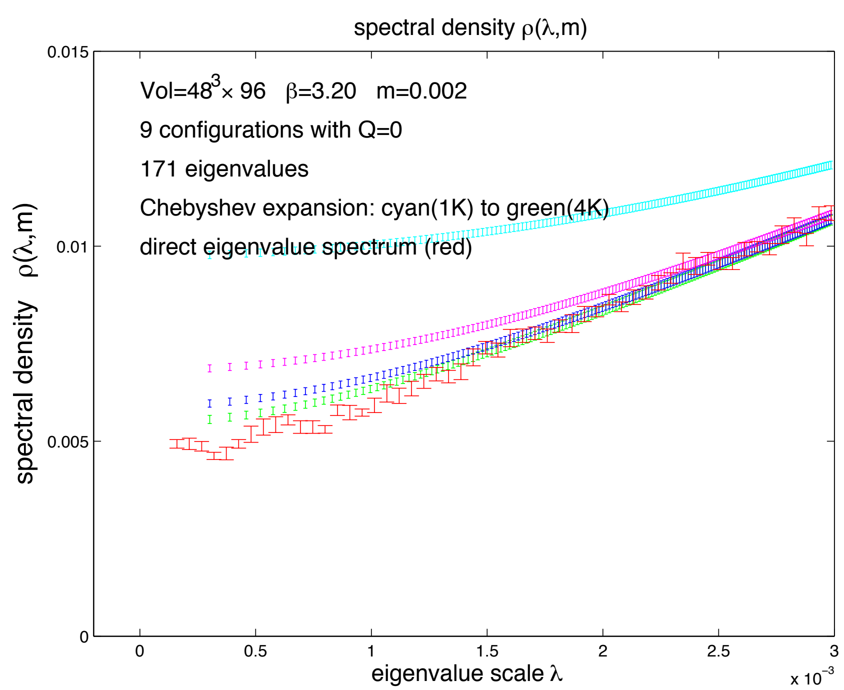
The chiral condensate   GMOR test in far IR

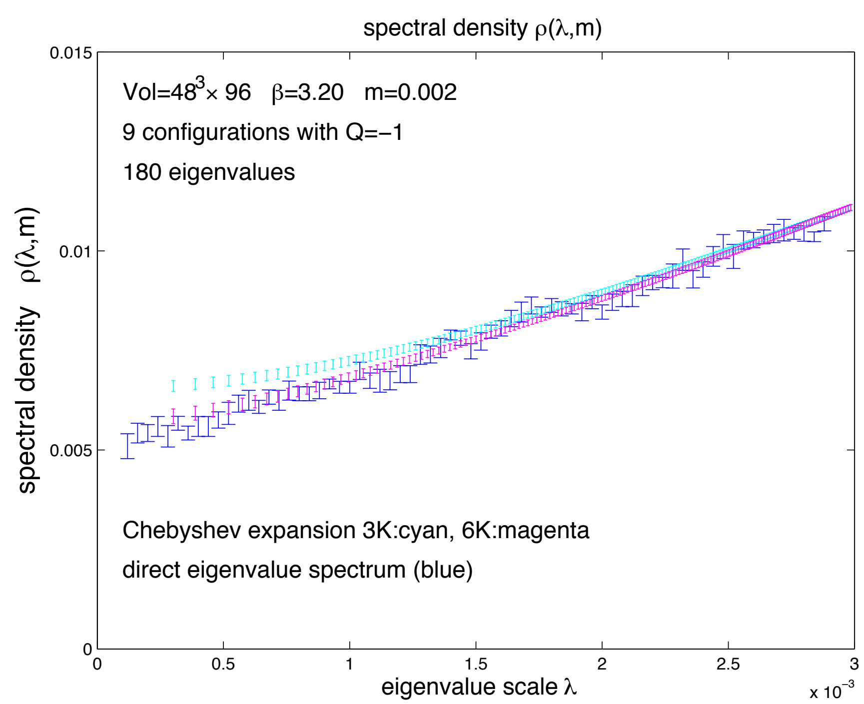
GMOR relation (nf=2): $2BF^2 = \Sigma$ (Σ is the chiral condensate)

F: decay constant of Goldstone pion $M_\pi^2 = 2B \cdot m$ in LO χPT

from chiral perturbation theory of the condensate in the p-regime:

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





Improved determination of the chiral condensate Σ compared from Dirac spectra and the Chebyshev expansion.
With the additive NLO cutoff term separated from B and new fit to F, the improved result on Σ eliminates previous discrepancies in the GMOR relation.

The chiral condensate mass anomalous dimension

Boulder group pioneered fitting procedure

$$\nu_R(M_R, m_R) = \nu(M, m) \approx const \cdot M^{\frac{4}{1+\gamma_m(M)}},$$

or equivalently, $\nu(M, m) \approx const \cdot \lambda^{\frac{4}{1+\gamma_m(\lambda)}}$, with $\gamma_m(\lambda)$ fitted

How to match λ scale and g^2 ?

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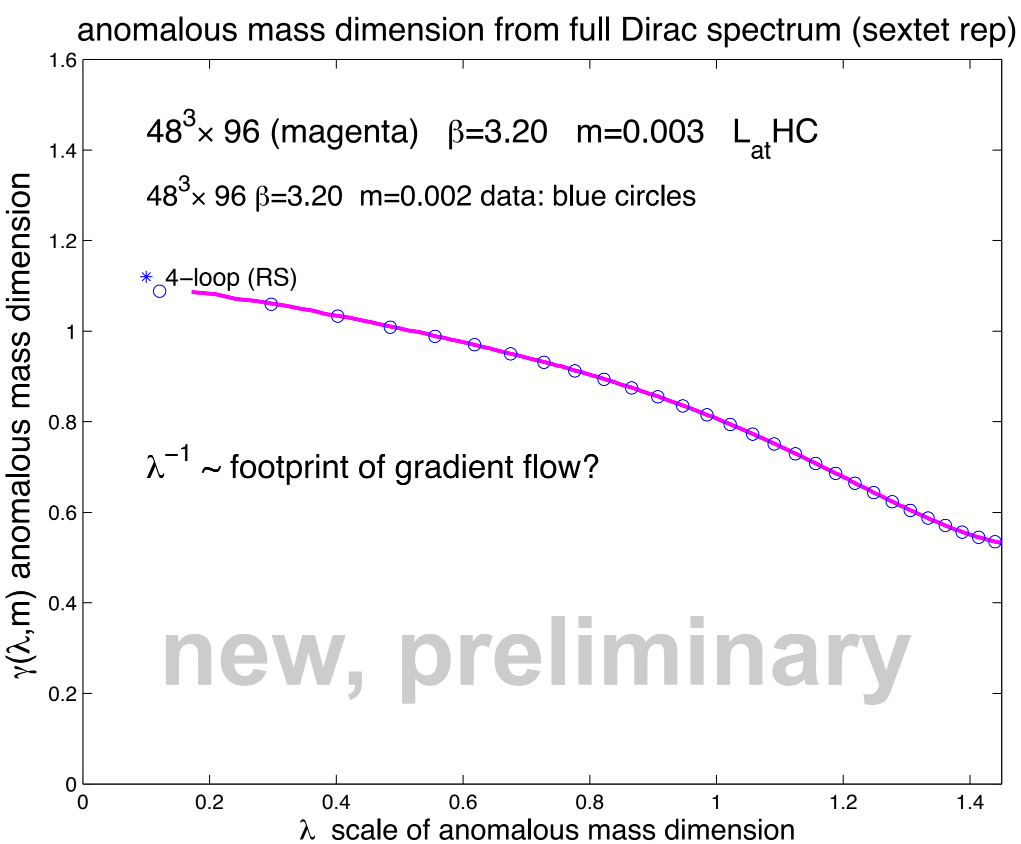

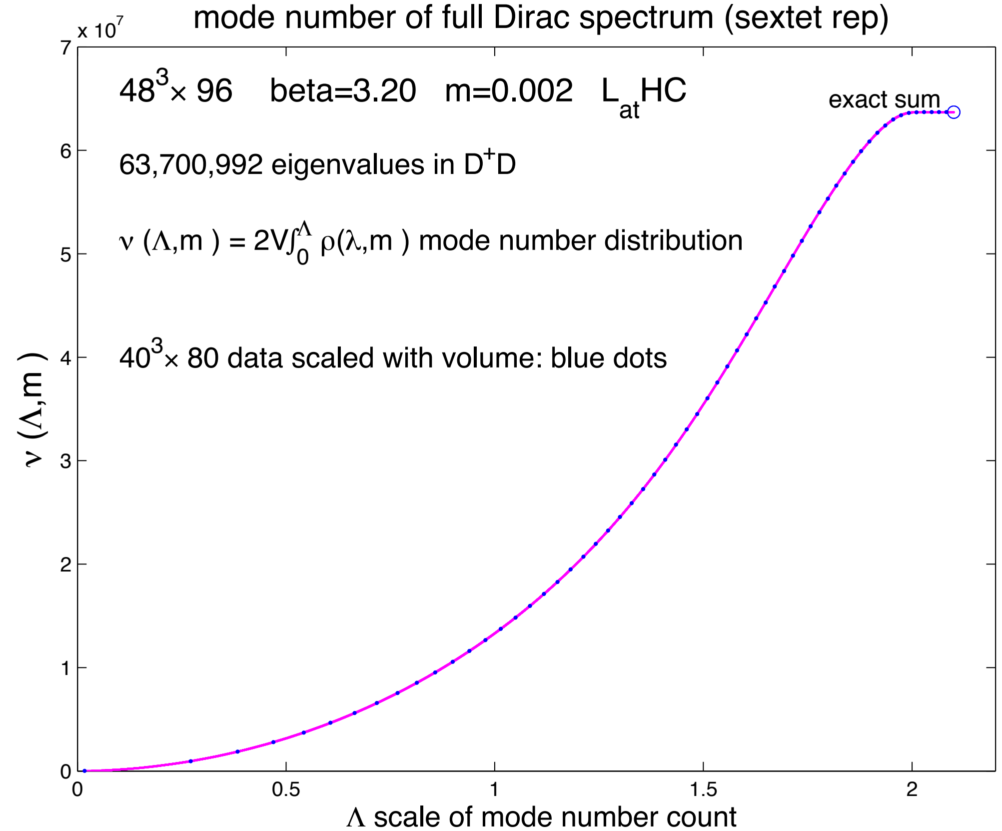

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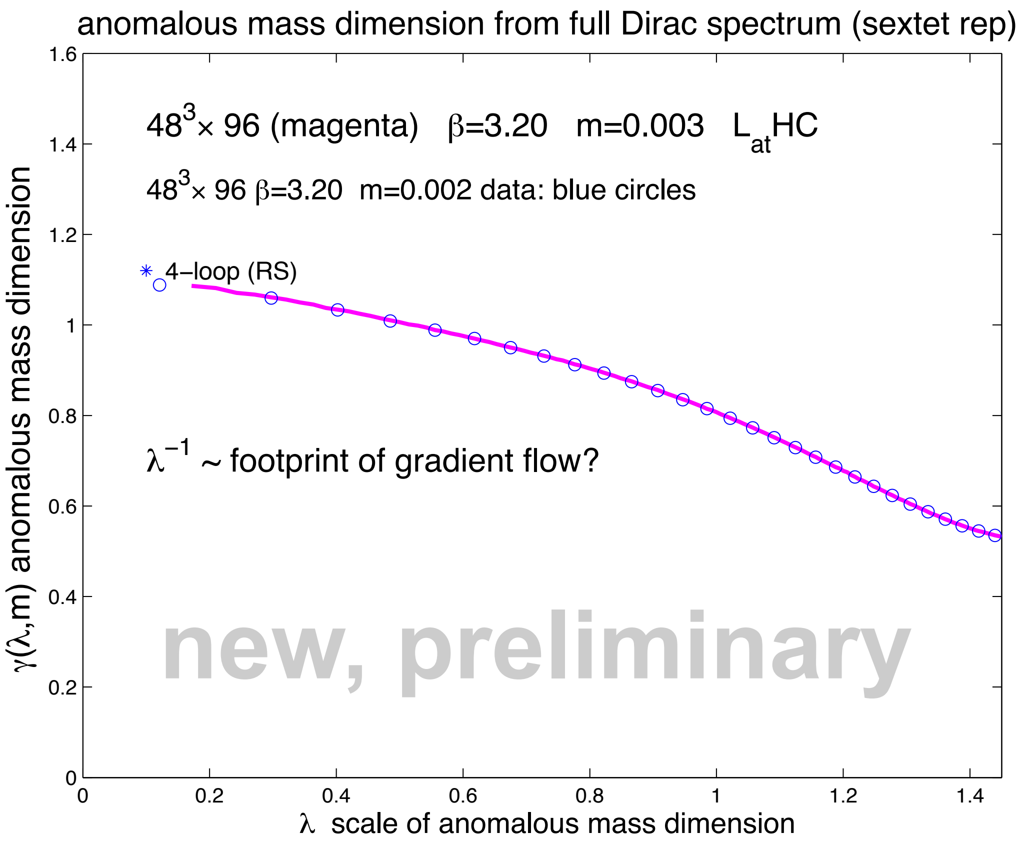
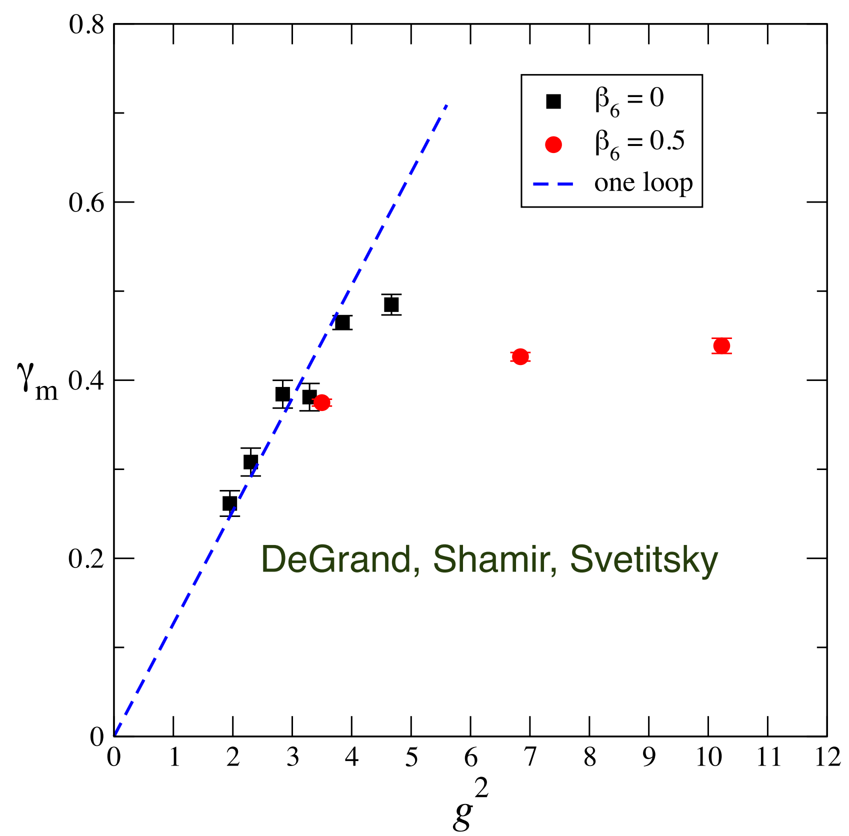




more details on the poster!

How to match λ scale and g^2 ?

the running coupling and the β function   finite volume

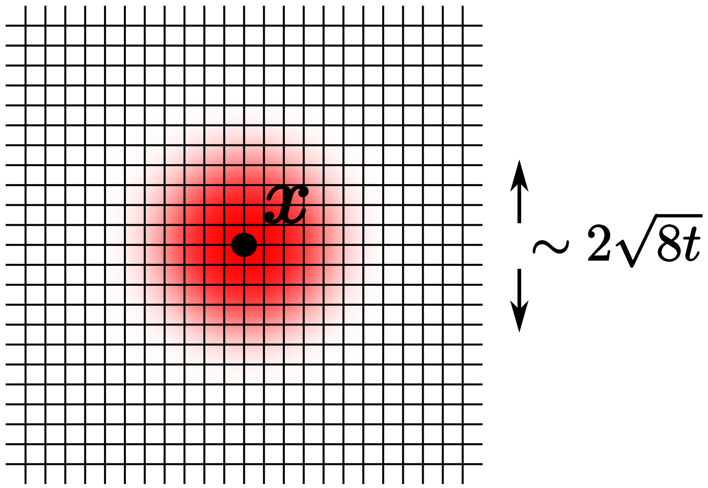
LatHC group introduced the running coupling and its β function from the gauge field gradient flow with the scale set by the finite volume
variations of it are becoming the standard approach

$$\dot{B}_\mu = D_\nu G_{\nu\mu} + \lambda D_\mu \partial_\nu B_\nu$$

Martin Lüscher

$$B_{\mu,1}(t,x) = \int \mathrm{d}^D y \, K_t(x-y) A_\mu(y),$$

earlier work by Neuberger



$$K_t(z) = \int \frac{\mathrm{d}^D p}{(2\pi)^D} \mathrm{e}^{ipz} \mathrm{e}^{-tp^2} = \frac{\mathrm{e}^{-z^2/4t}}{(4\pi t)^{D/2}}$$

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

t is the gradient flow time
Running coupling definition (range is $(8t)^{1/2}$) :

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

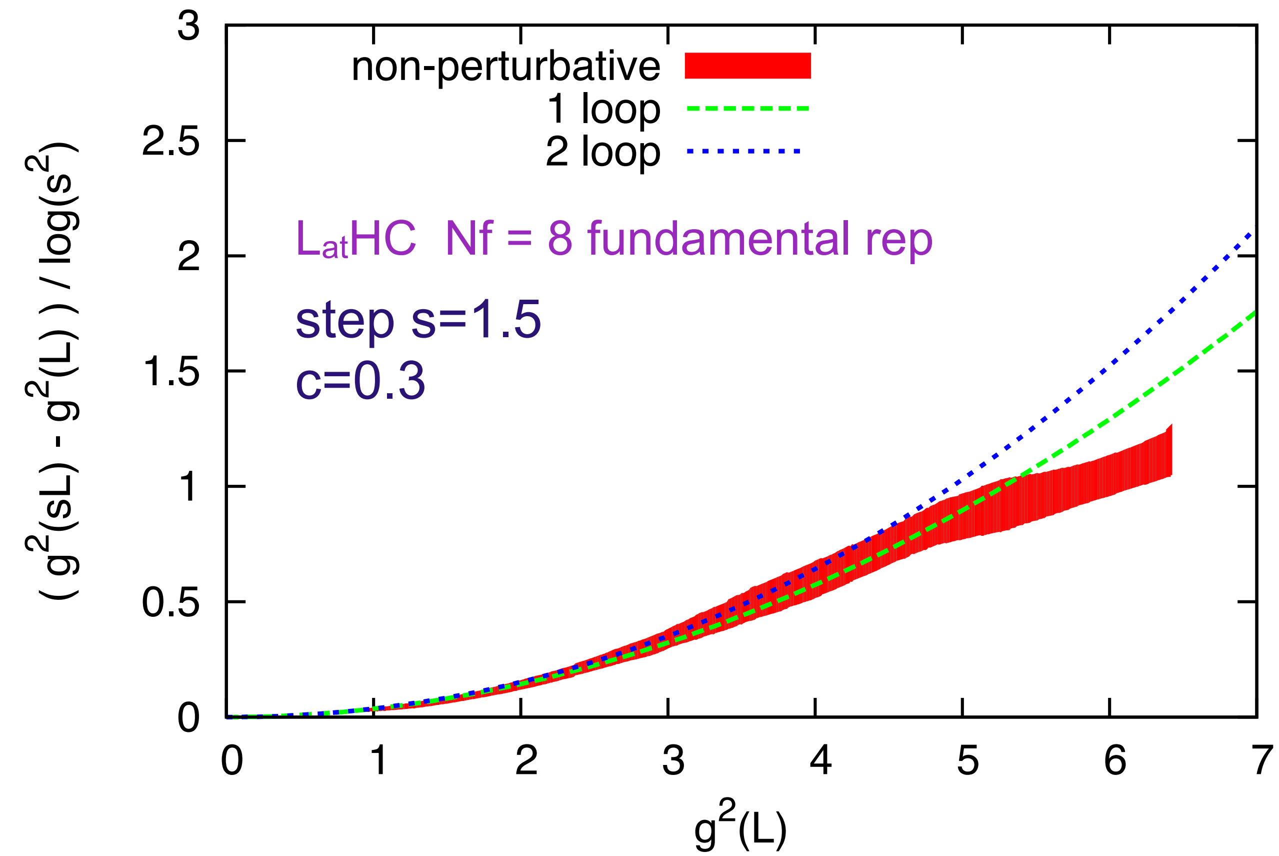
$$\delta(c) = \vartheta_3^4(e^{-1/c^2}) - 1 - \frac{c^4 \pi^2}{3}$$

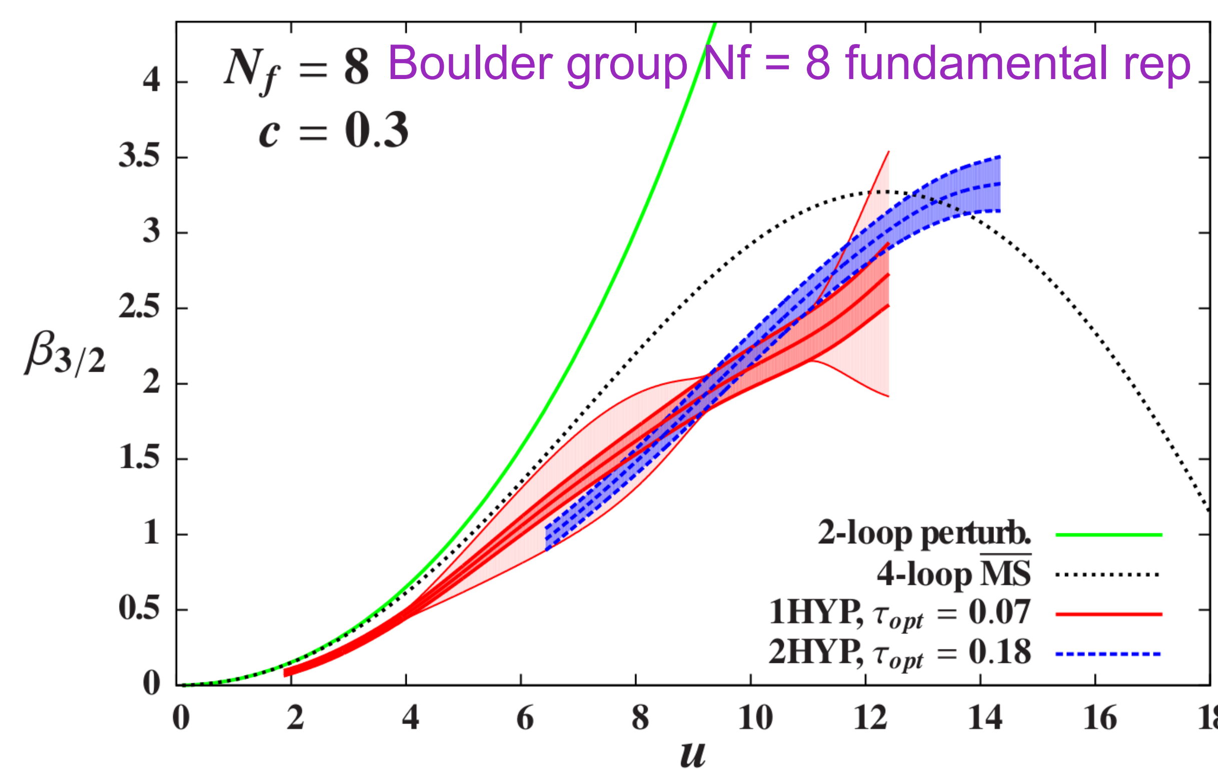
3rd Jacobi function

three different boundary conditions are used in practice:
anti-periodic fermion fields
Schrödinger functional
twisted gauge fields and fermion fields

fundamental rep: Nf=8 Boulder group and LatHC Nf=12 Boulder group and Taiwan group sextet rep: Nf=2 LatHC

the running coupling and the β function   finite volume





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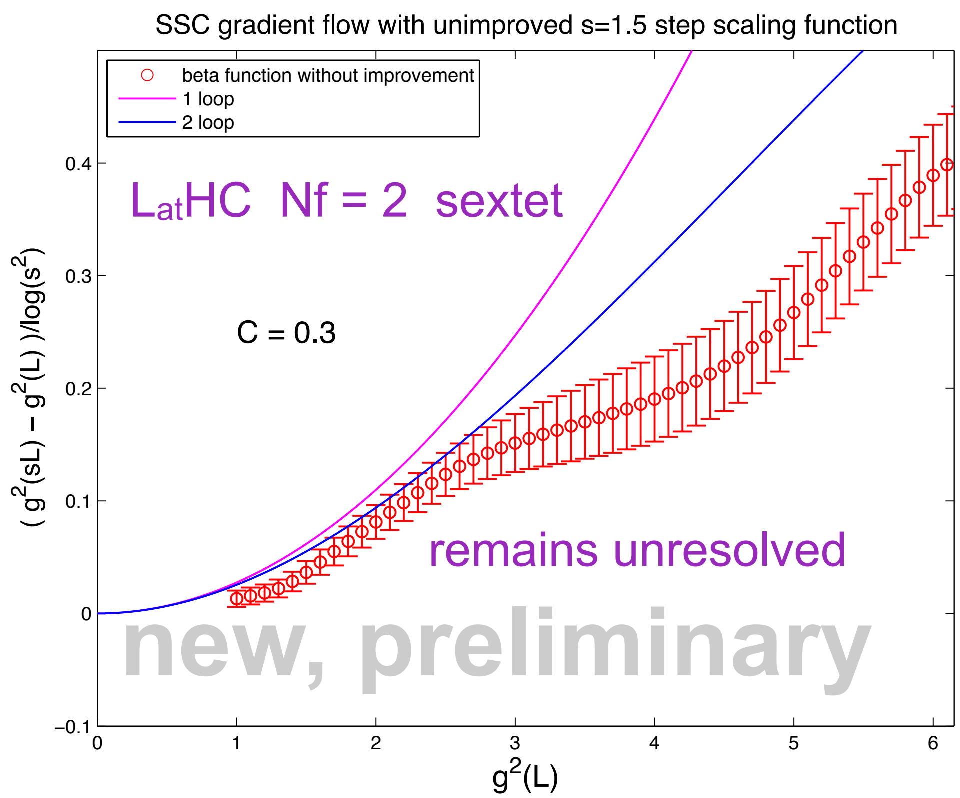

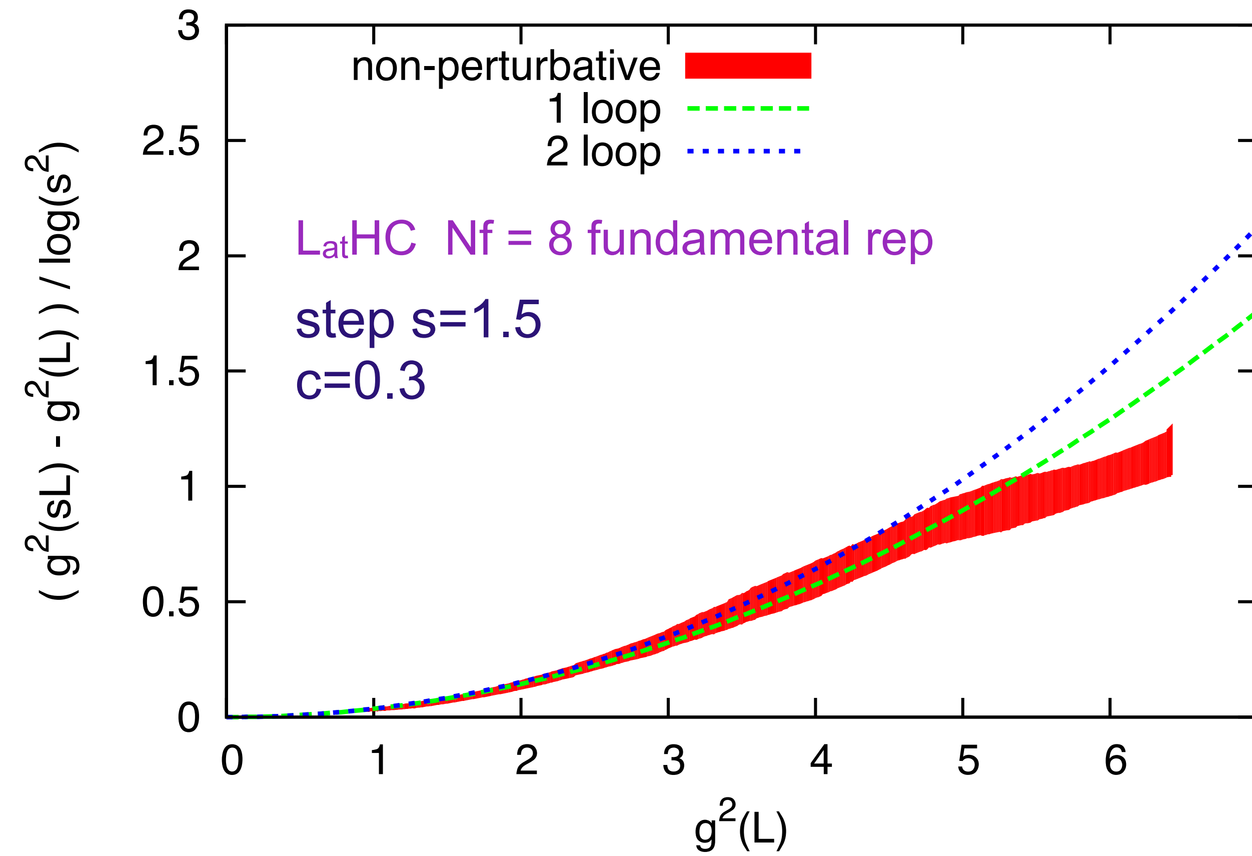

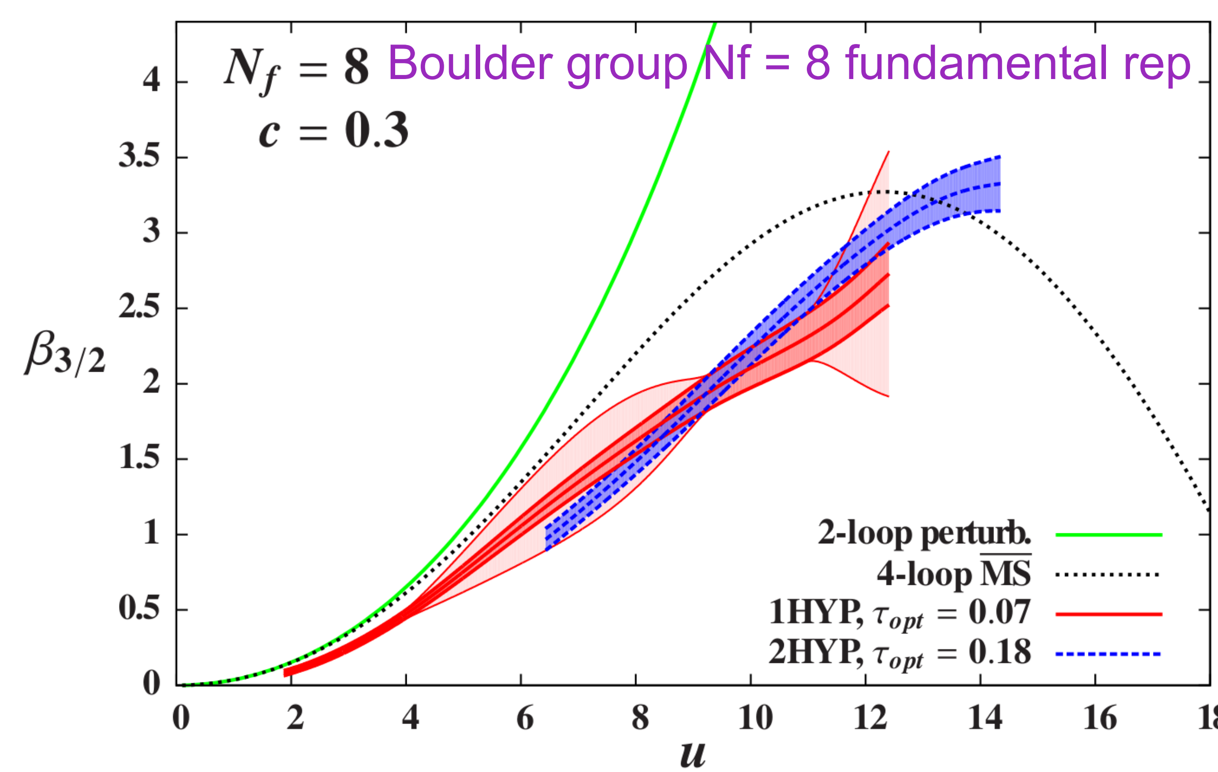

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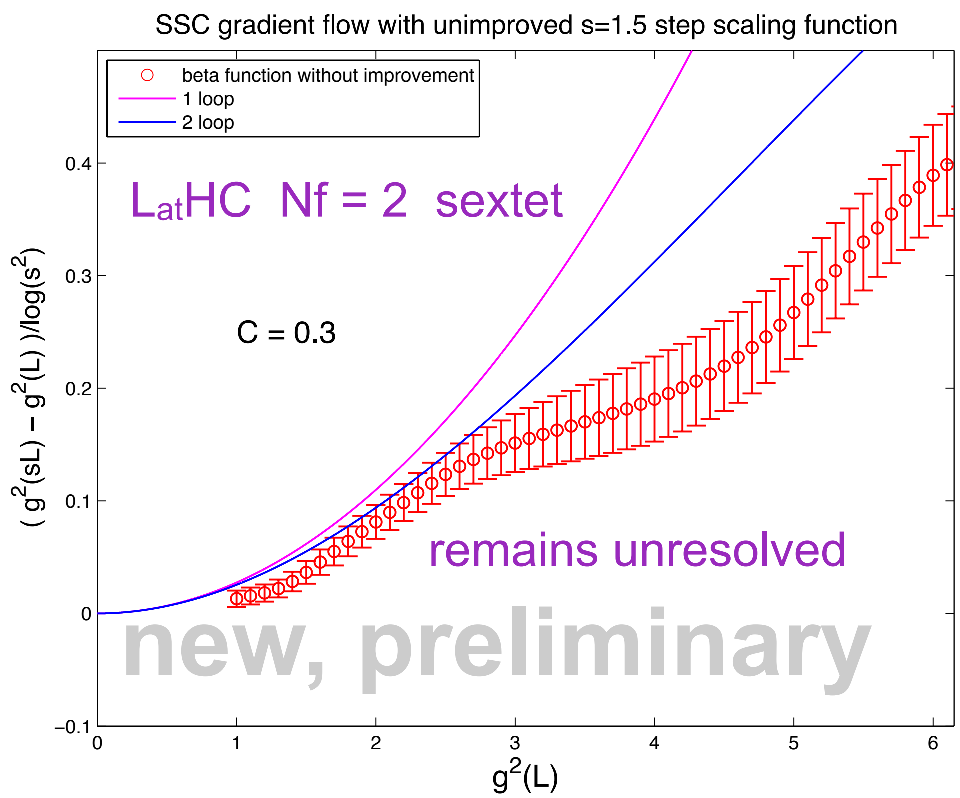
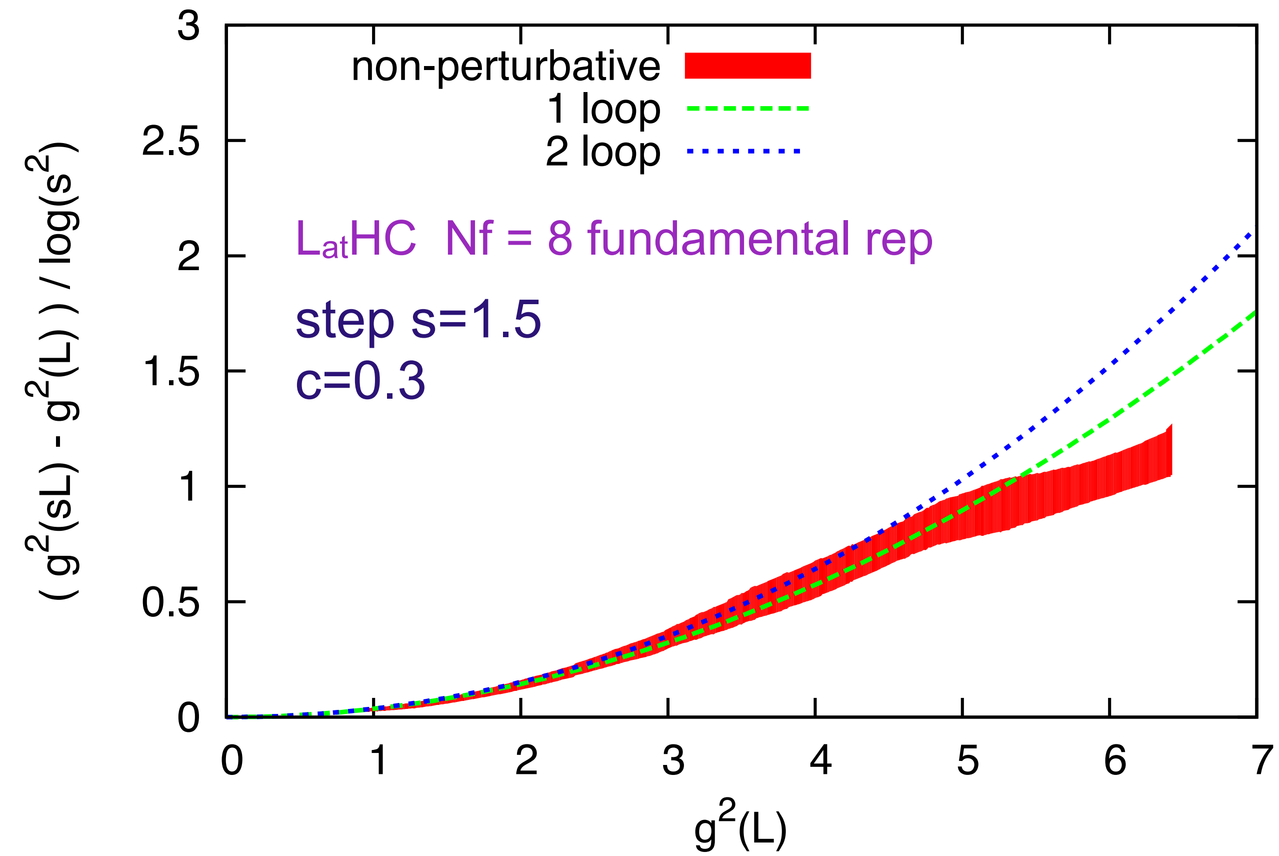
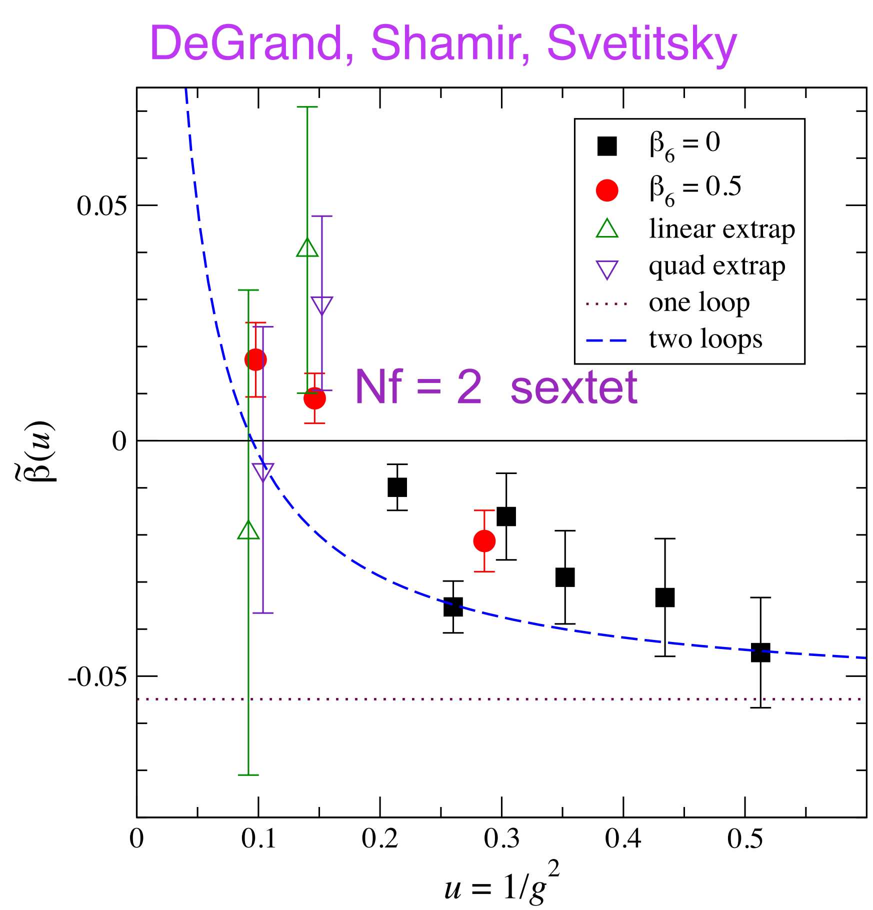
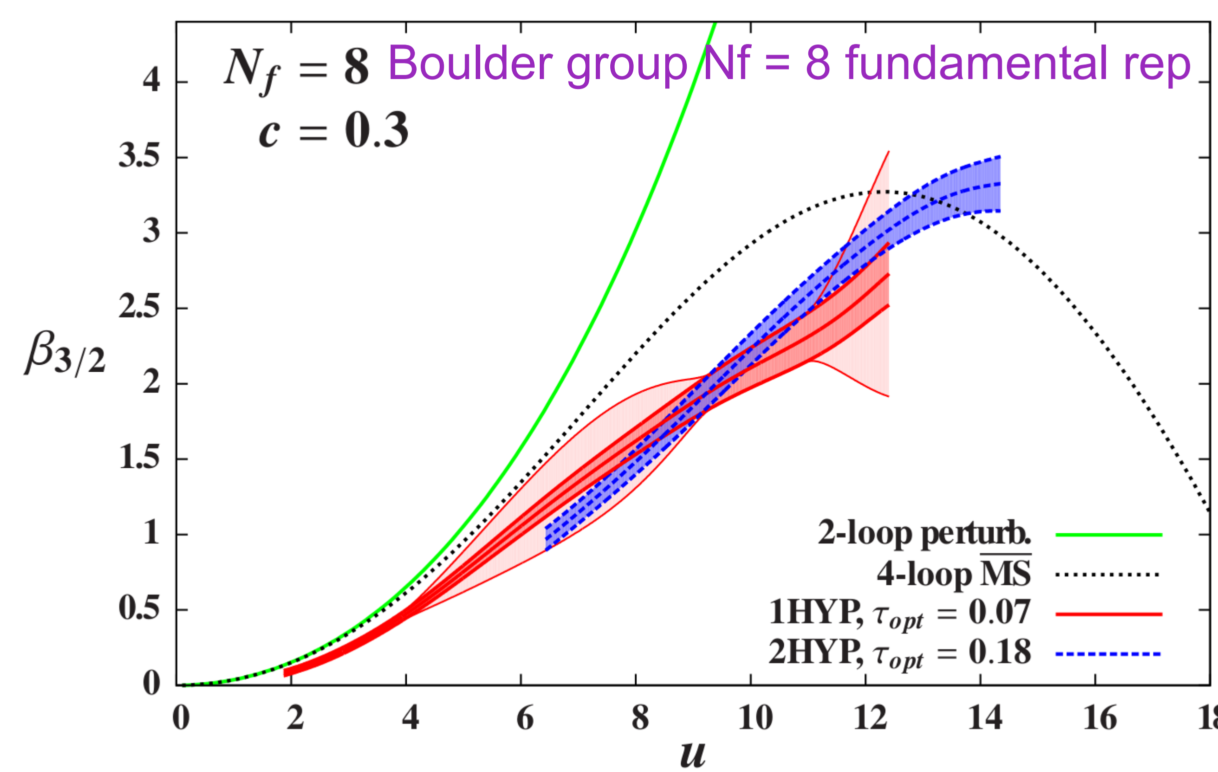
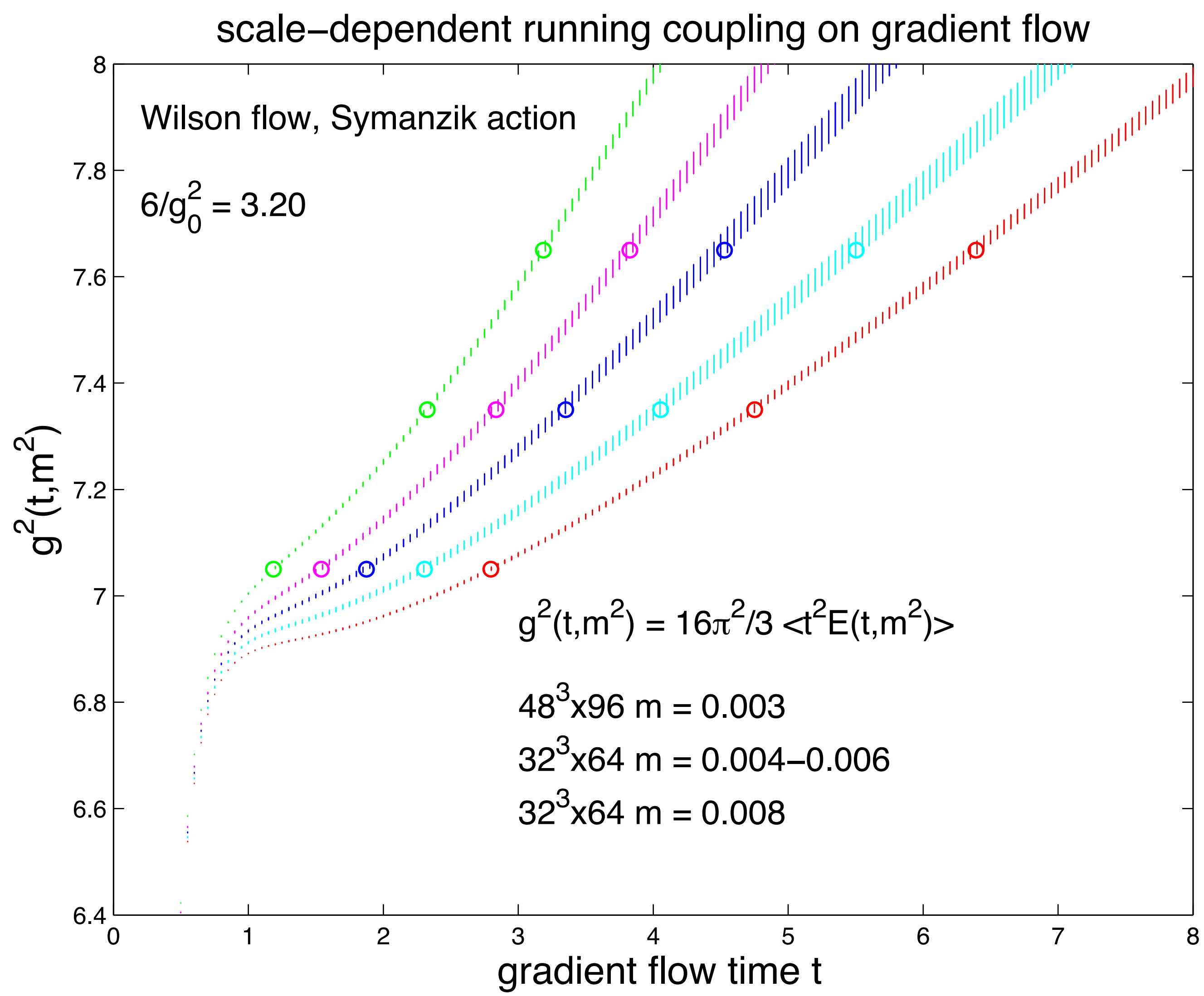


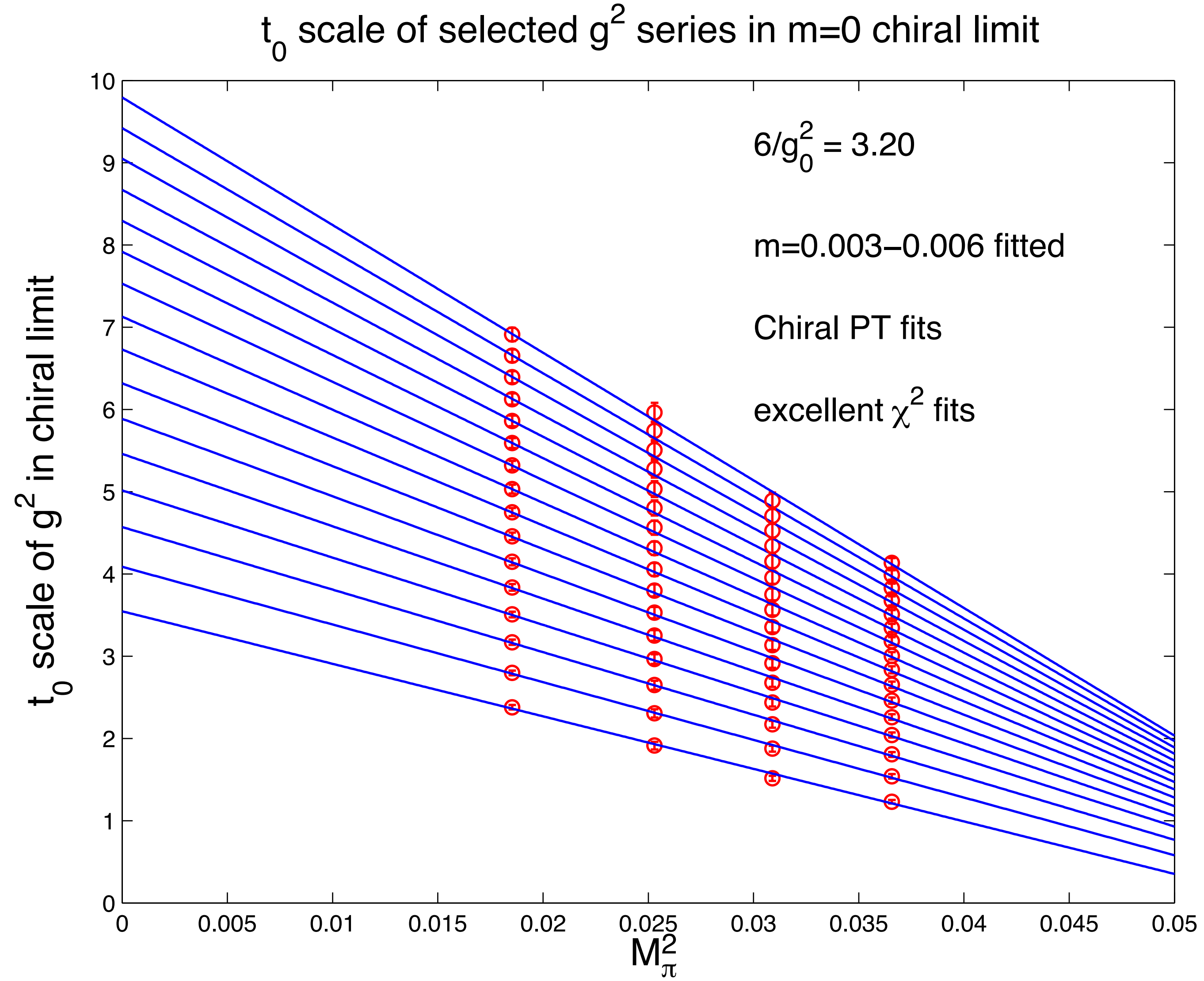


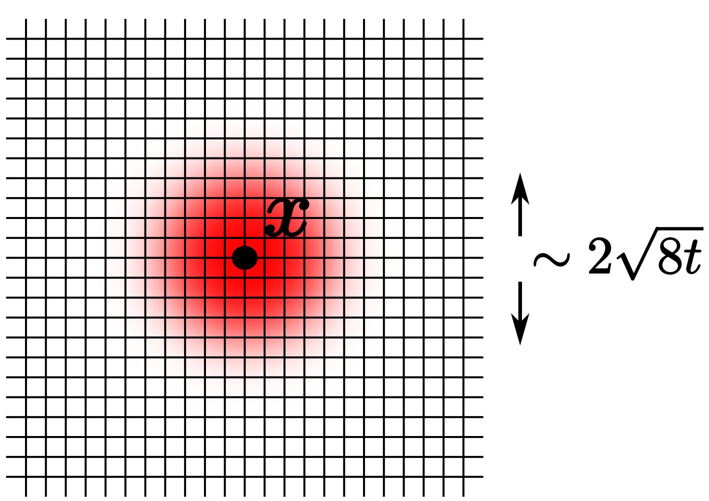




the running coupling and the β function infinite volume







leading dependence of $g^2(t,m)$ on M_π^2 is linear

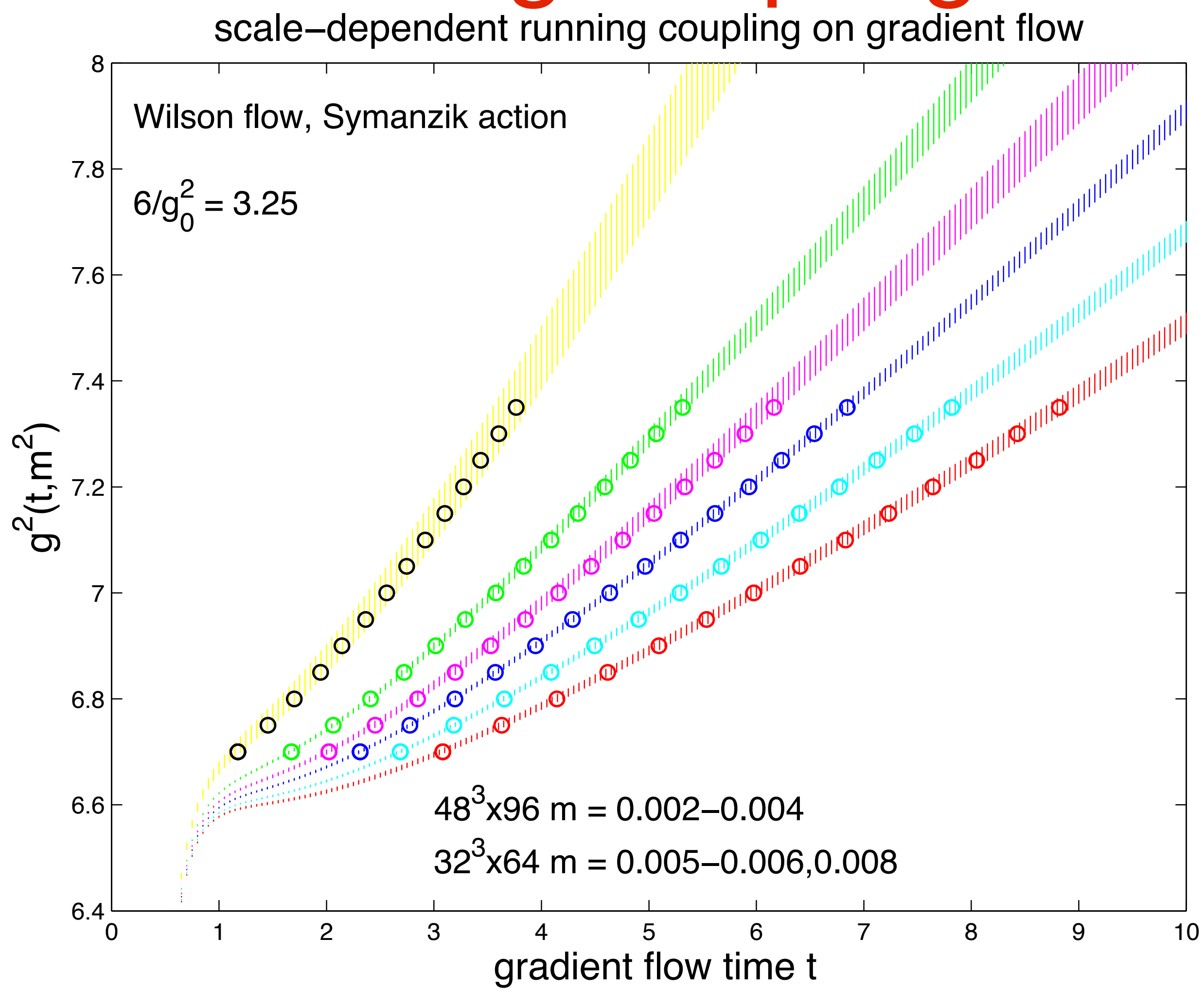
based on gradient flow chiPT Bär and Golterman

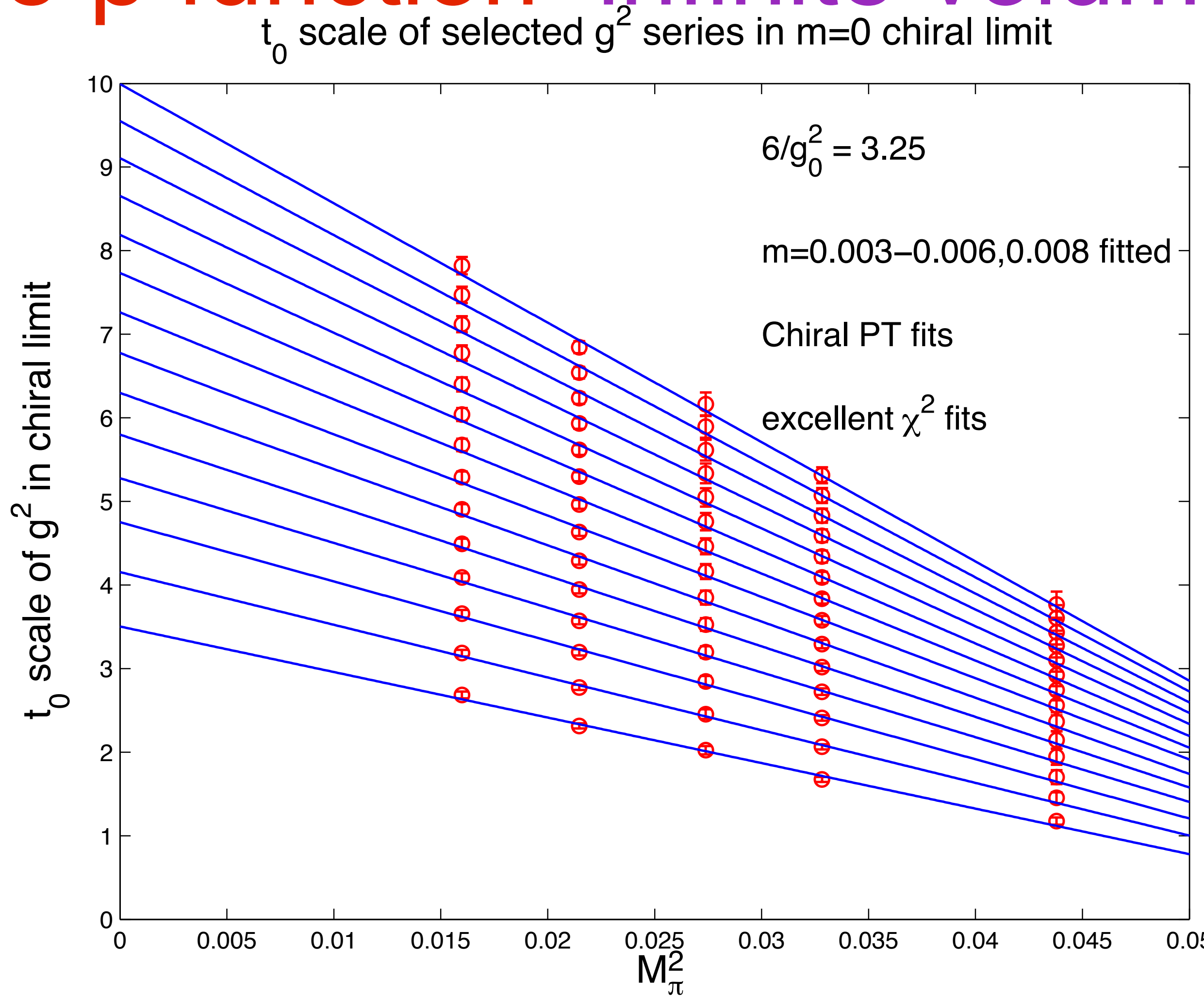
works better than expected

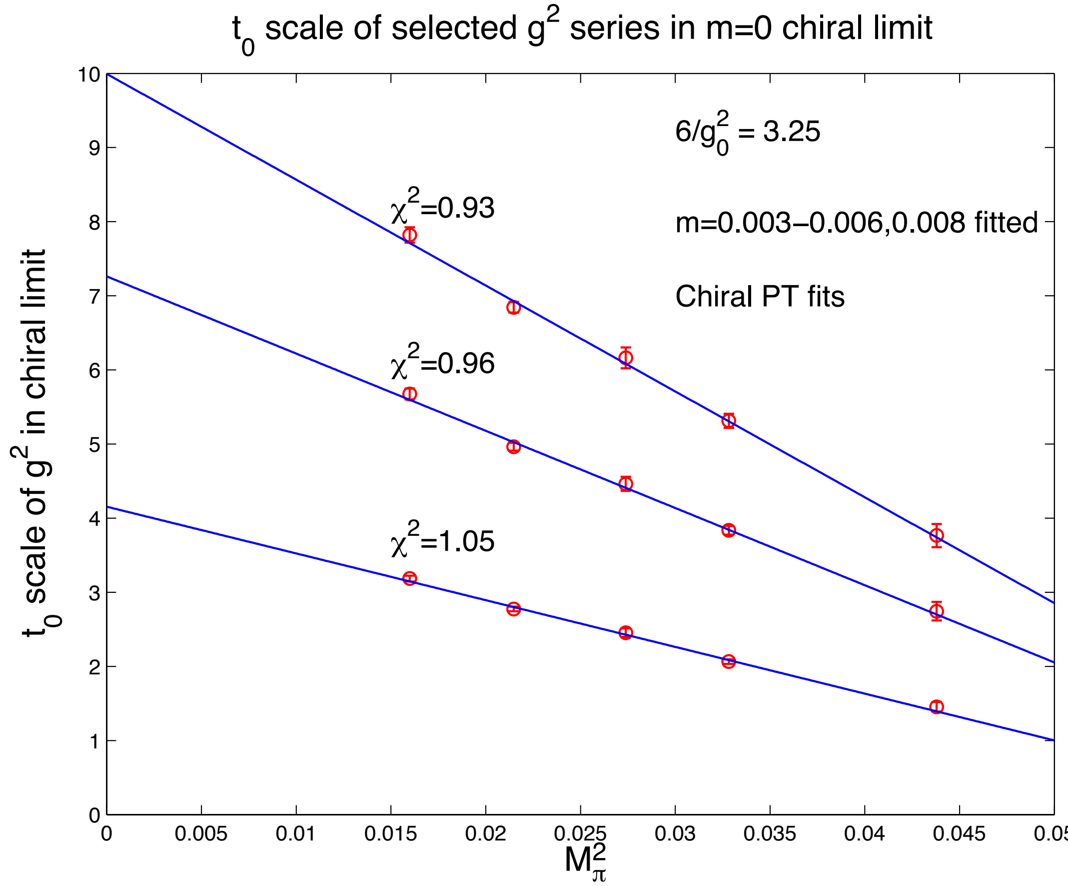
chiral logs are not detectable

(not deep enough in leading log chiPT regime)

the running coupling and the β function infinite volume







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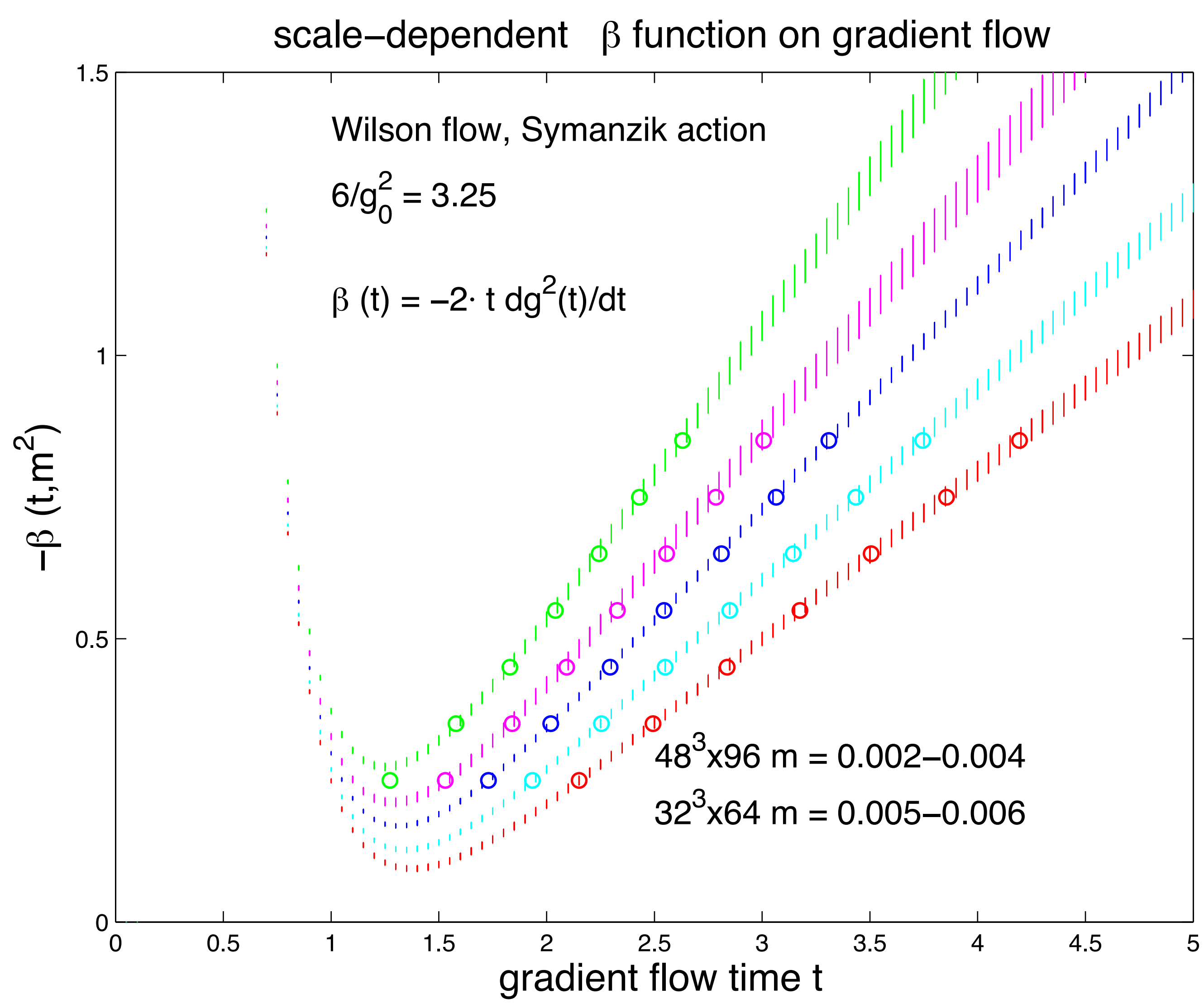
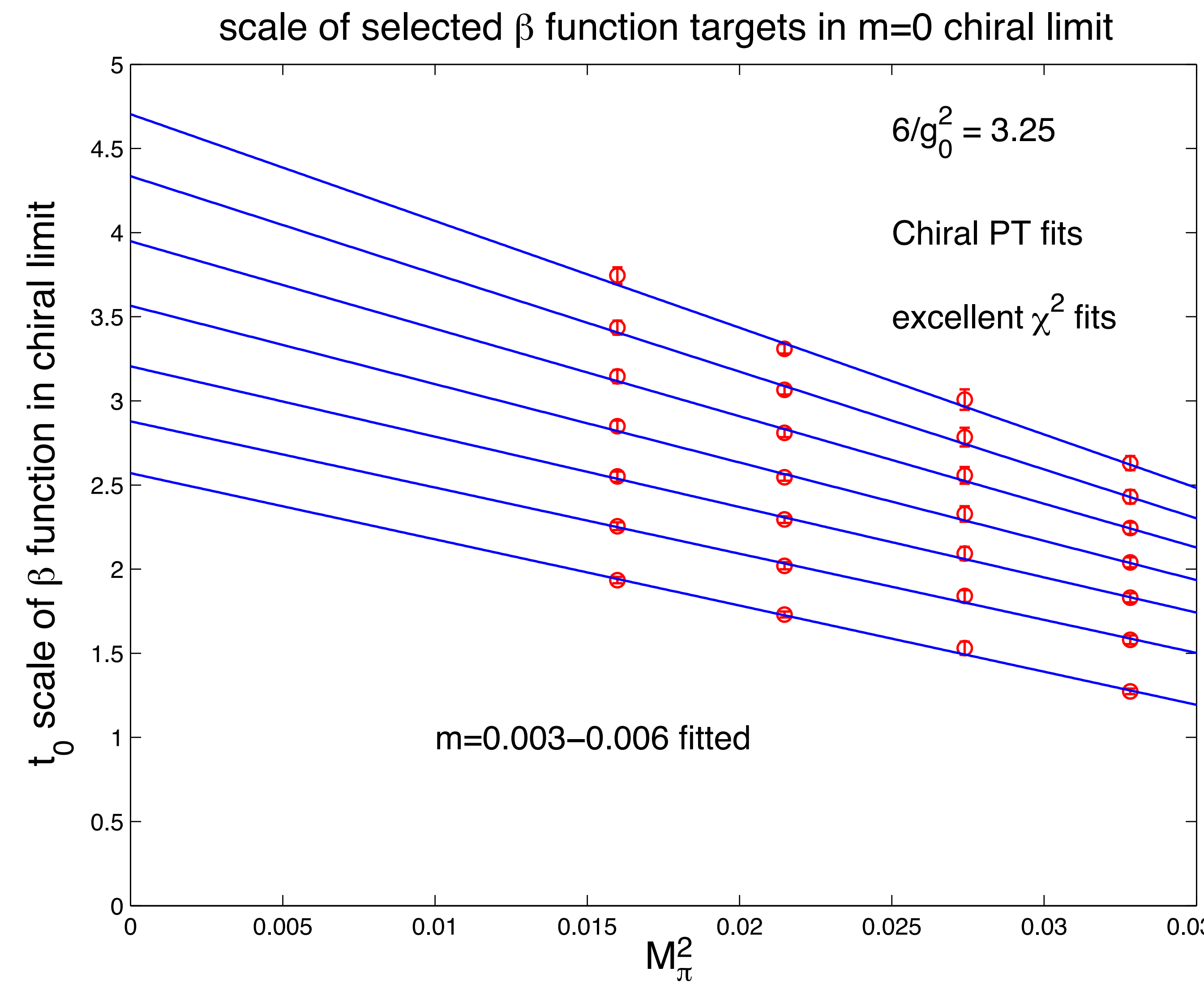
(not deep enough in leading log chiPT regime)

the running coupling and the β function infinite volume





direct numerical determination of

$$\beta(t) = -2t\frac{dg^2(t,m)}{dt}$$ on the gradient flow

leading dependence of $g^2(t,m)$ on M_π^2 is linear

based on gradient flow chiPT Bär and Golterman

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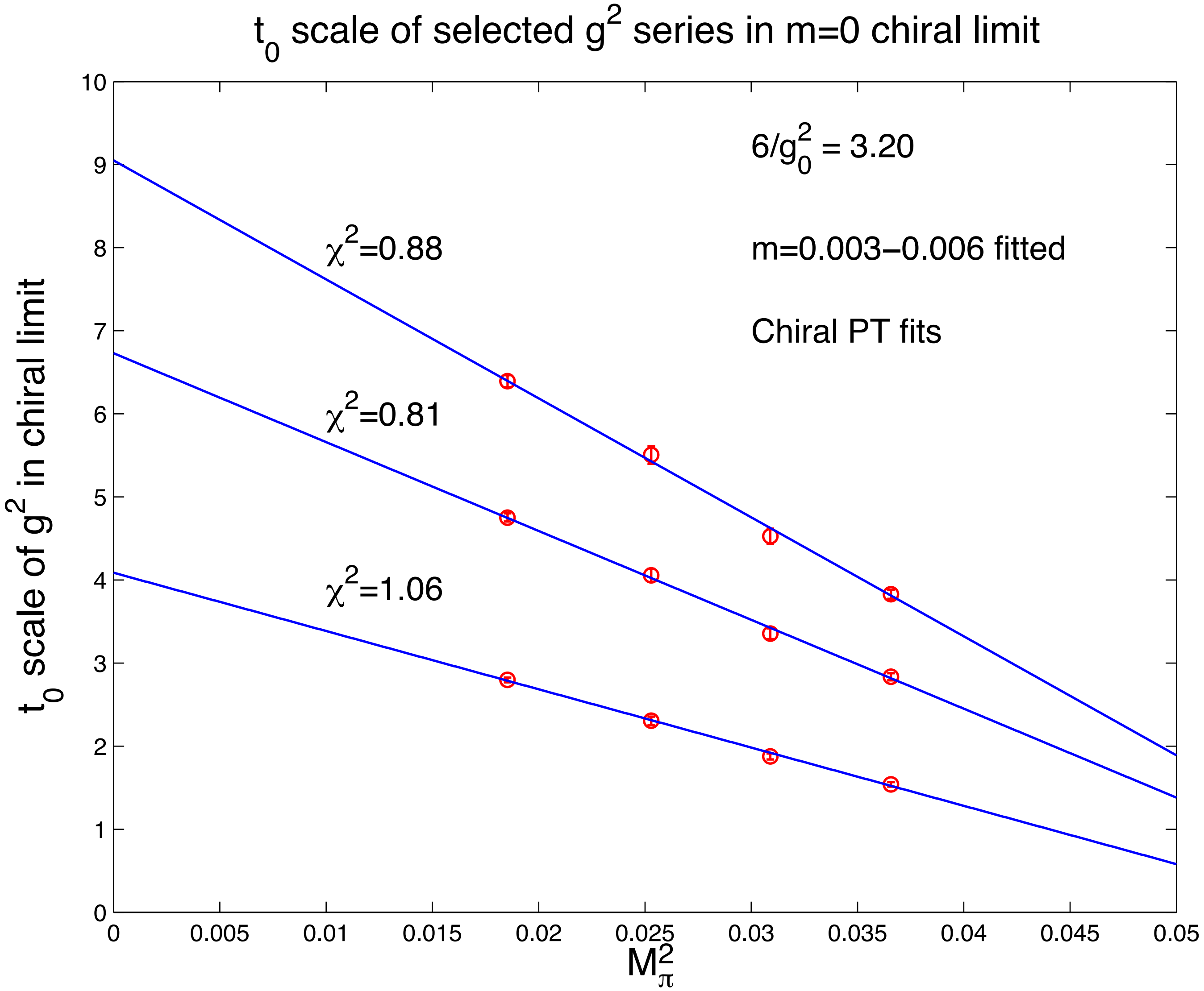

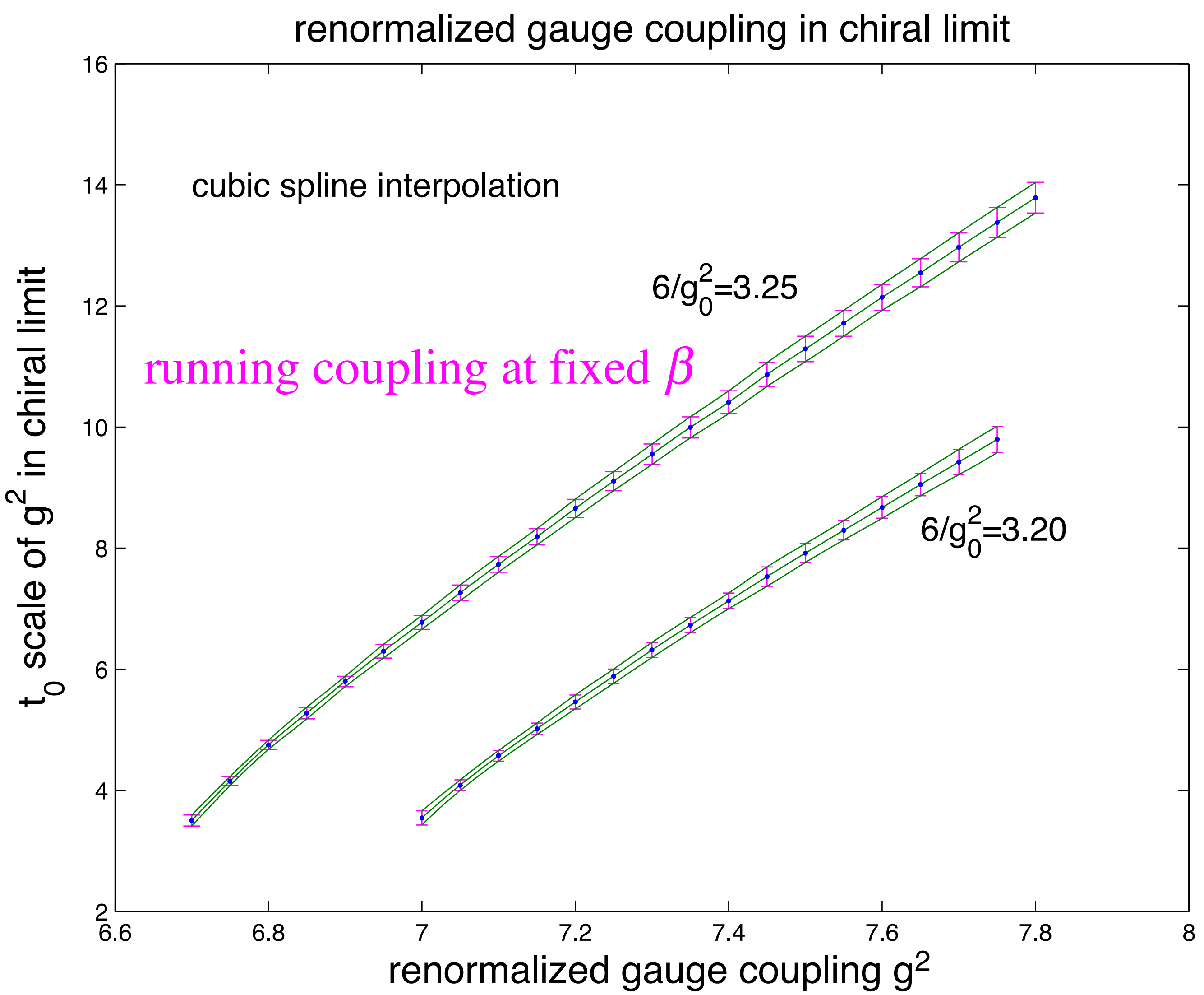

running coupling, calculated at several bare g_0^2, allowes to determine the scale-dependent β function

This is in infinite volume, the opposite of running with a scale set by the finite volume

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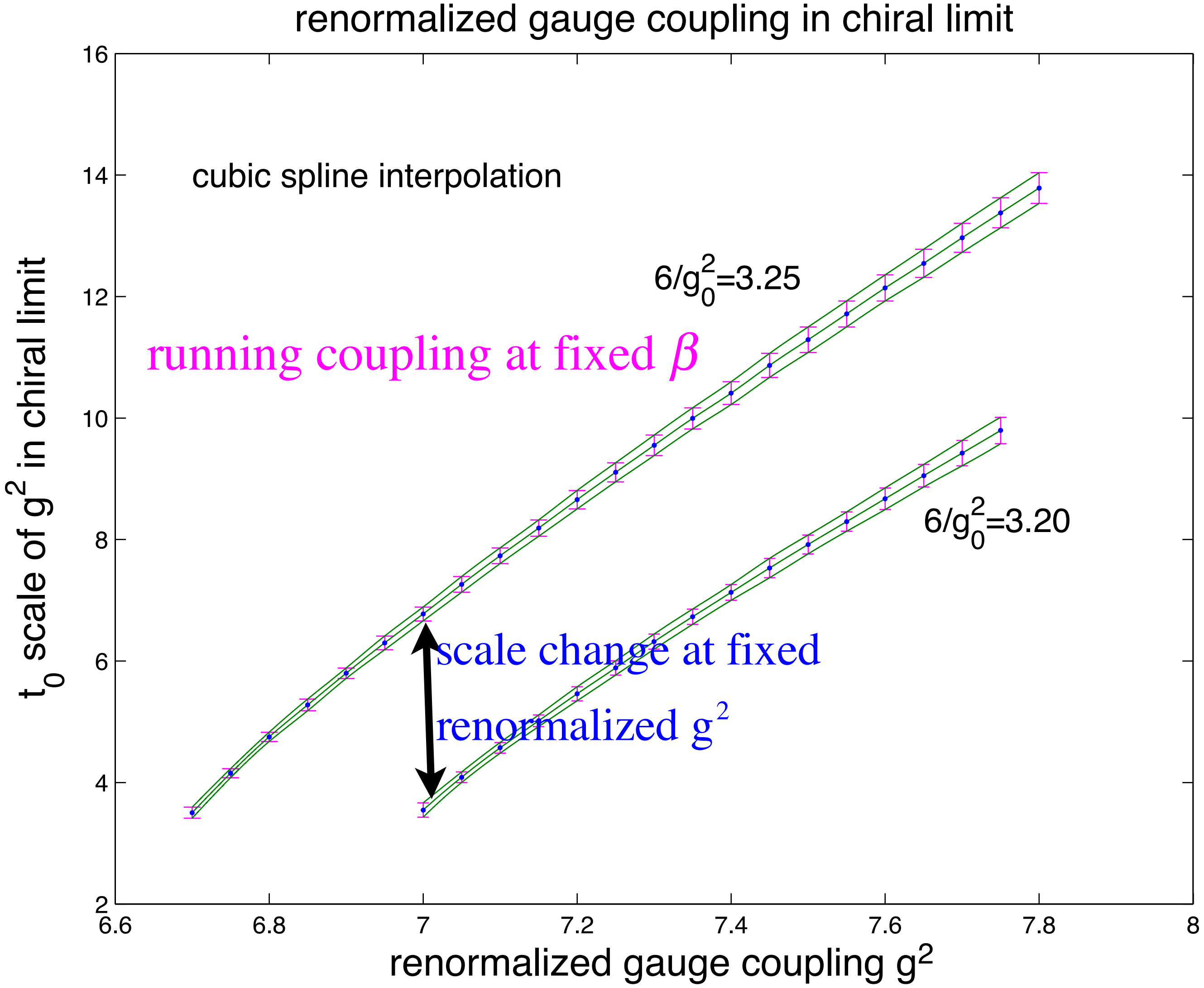

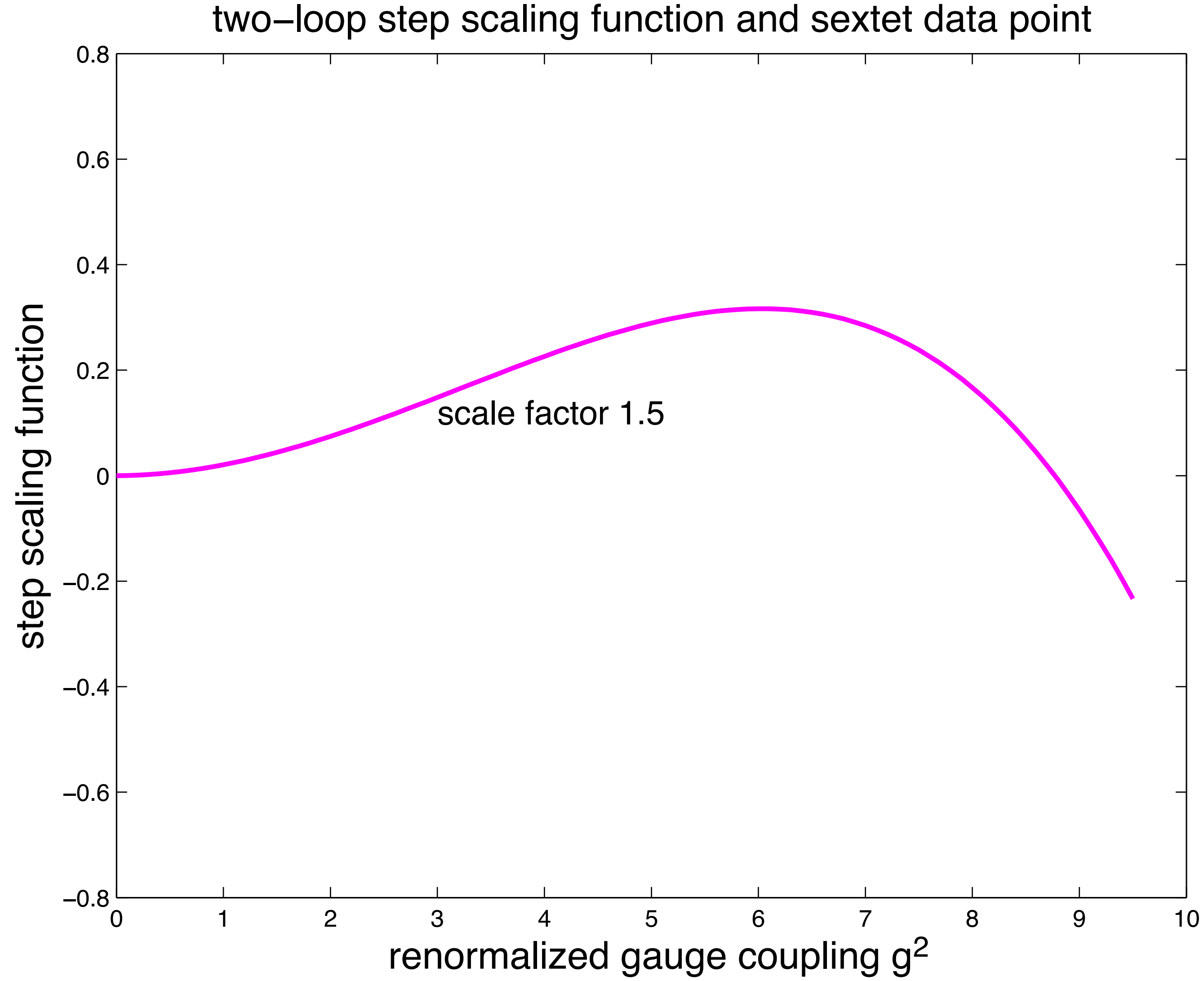

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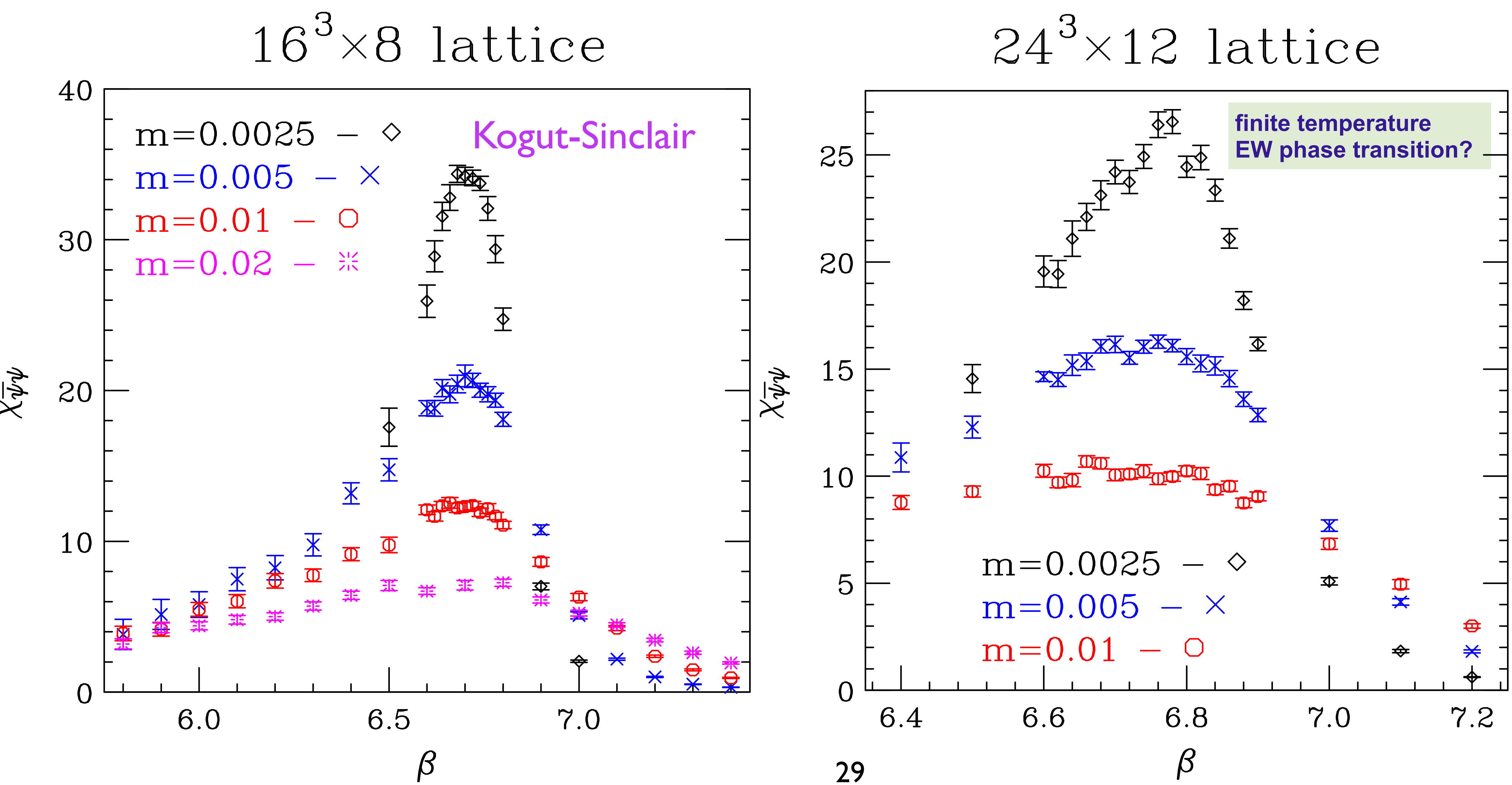
Early universe

Kogut-Sinclair work consistent with χSB phase transition

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

L_{at}HC is doing a new analysis using different methods



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

- lattice BSM phenomenology of dark matter
  Sannino and collaborators - fundamental and adjoint rep
  LSD collaboration - fundamental rep
- Nf=2 Qu=2/3 Qd = -1/3 fundamental rep
  udd neutral dark matter candidate

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- dark matter candidate sextet Nf=2
  electroweak active in the application
- 1/2 unit of electric charge (anomalies)
- rather subtle sextet baryon
  construction (symmetric in color)
- charged relics not expected?

Wong talk/poster

Summary and Outlook

Summary: simplest composite scalar is probably very 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, large $\gamma(\lambda)$ — new method is very promising   poster
- spectroscopy — emerging resonance spectrum ~ 2-3 TeV
- dark matter — implications are intriguing
- we are investigating tuning with third flavor (massive EW singlet)

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Outlook: is it worth the big effort?

chances of sextet model ~ ε
would be significance ~ $1/\varepsilon$
it makes sense to work on it ~ $O(\varepsilon/\varepsilon = 1)$
and we learn more about SCGT!

backup