LLNL2015

New results and open problems toward a minimal realization of the light composite Higgs

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

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University of California, San Diego

Lattice for Beyond the Standard Model Physics

April 23-25, 2015, LLNL workshop

What is our composite Higgs terminology?

the Higgs doublet field

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

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

The Higgs Lagrangian is

spontaneous symmetry breaking
Higgs mechanism

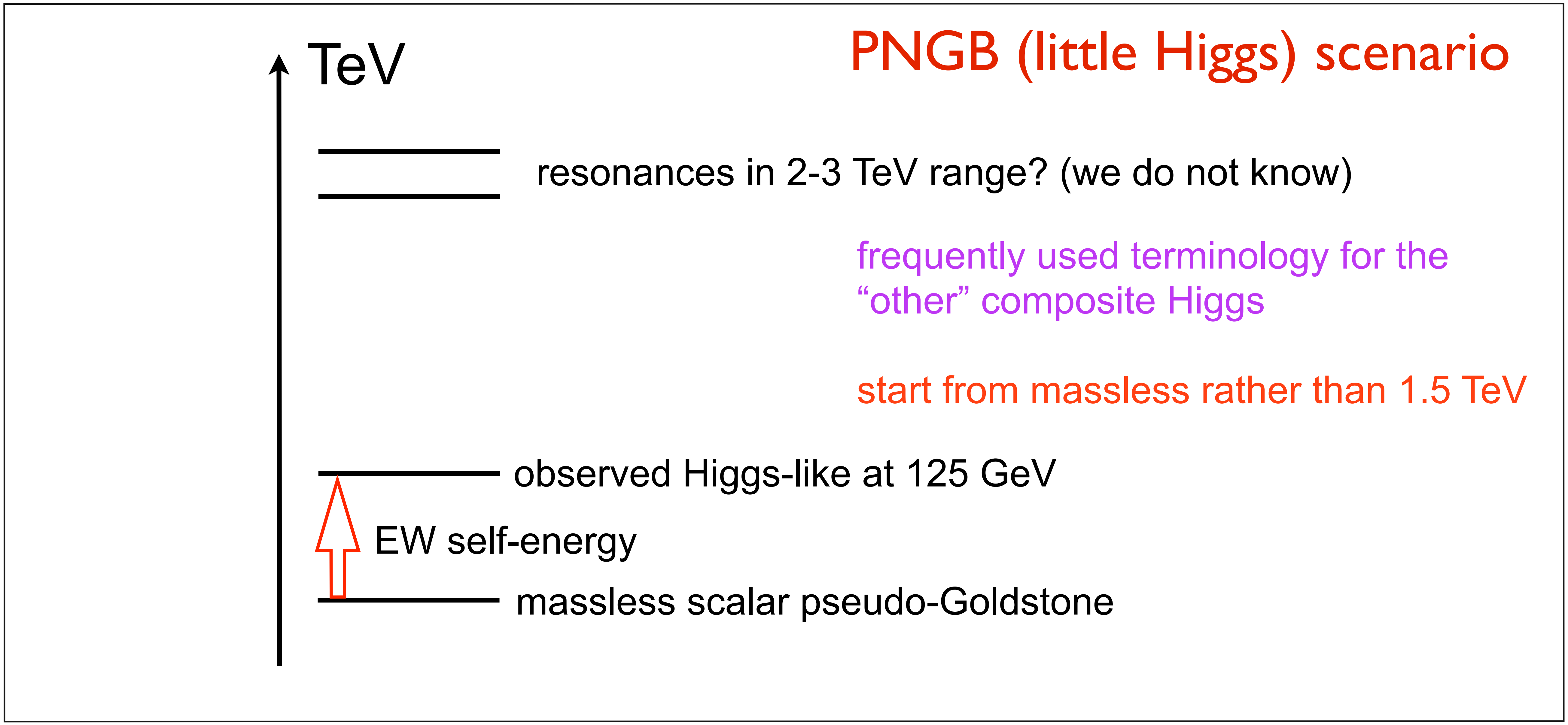
$$\mathcal{L} = \frac{1}{2}\mathrm{Tr}\left[D_\mu M^\dagger D^\mu M\right] - \frac{m_M^2}{2}\mathrm{Tr}\left[M^\dagger M\right] - \frac{\lambda}{4}\mathrm{Tr}\left[M^\dagger M\right]^2$$

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

strongly coupled gauge theory
fermions (Q) in gauge group reps

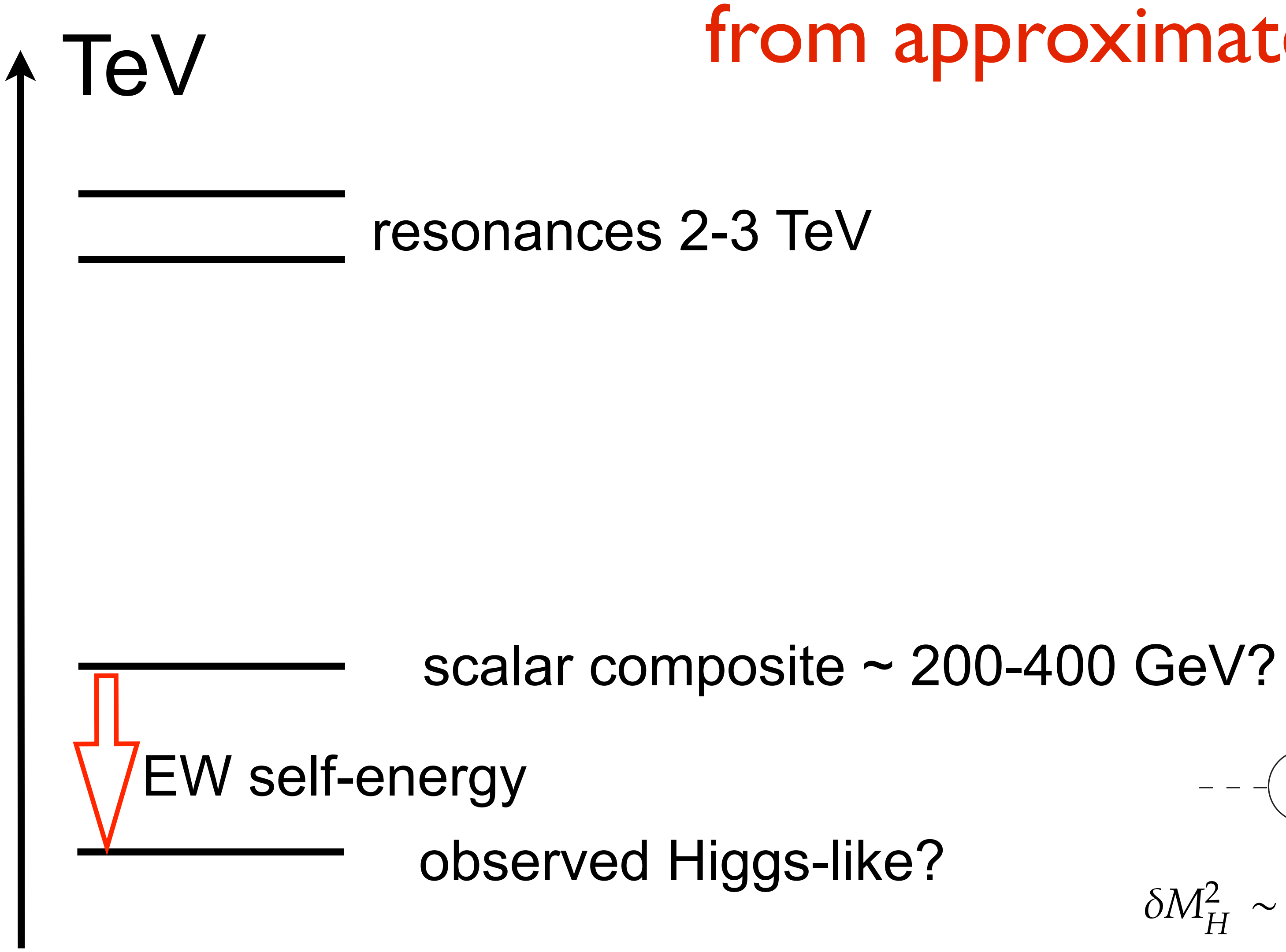
needle in the haystack?
or, just one of the haystacks?

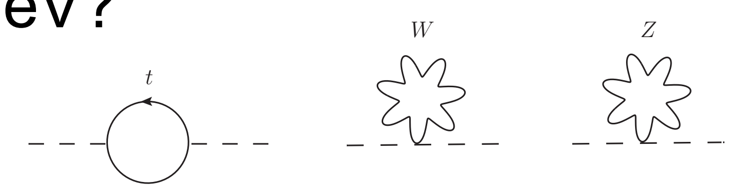
What is our composite Higgs terminology?



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, ...

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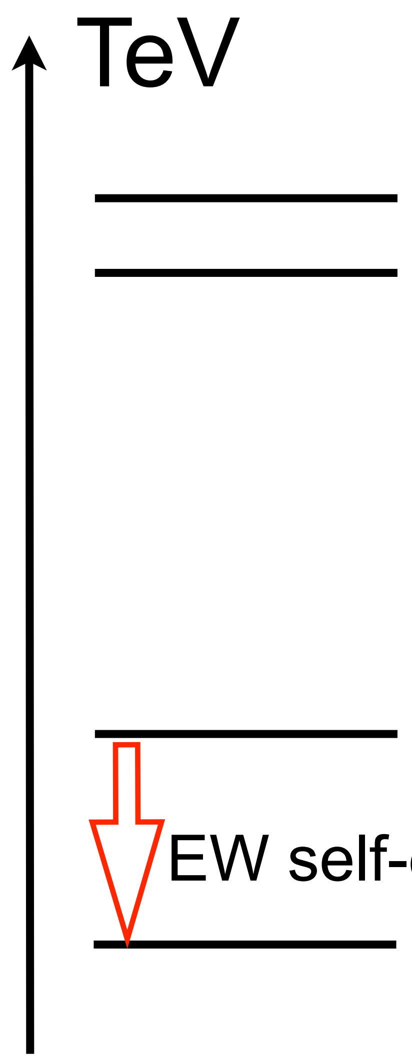
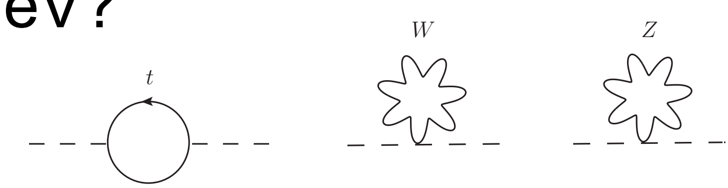


SCGT composite Higgs in this talk

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

both paradigms defer fermion mass generation issues



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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

Chiral Higgs condensate

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

Running coupling

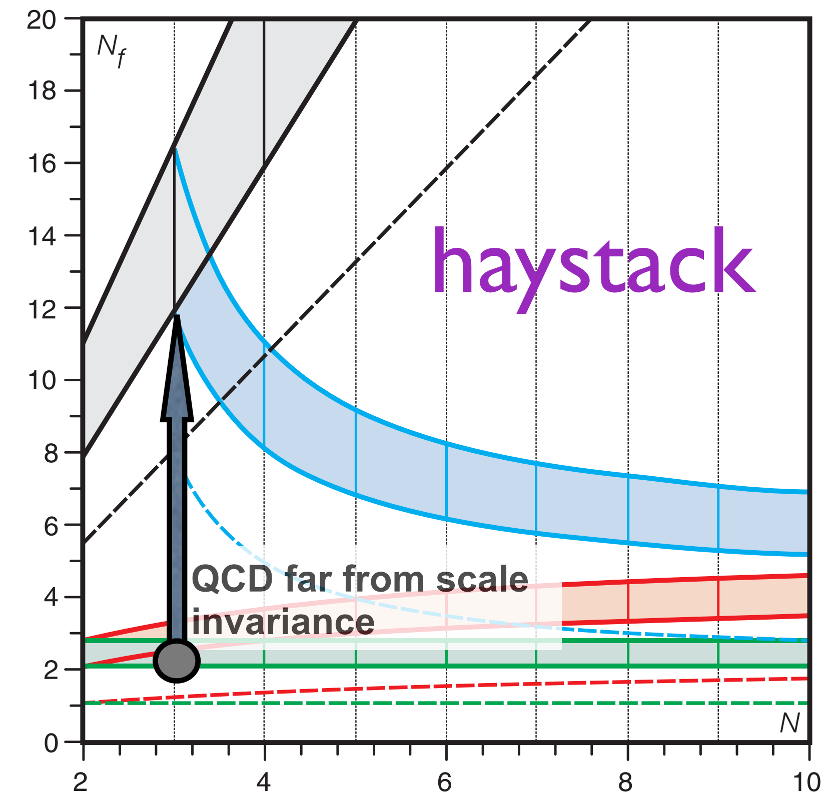
- scale dependent running coupling the R-word
- matching with mass anomalous dimension?

Early universe

- sextet EW phase transition
- sextet baryon and dark matter

Summary and Outlook

SCGT Theory Space © Sannino



close to scale invariance?

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

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

minimal EW embedding

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?

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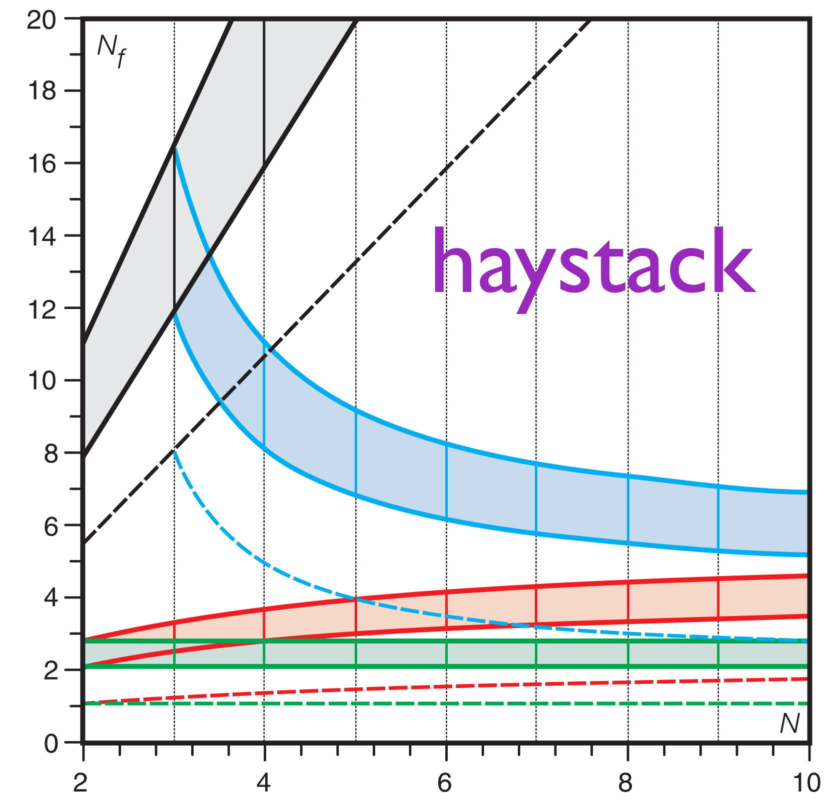

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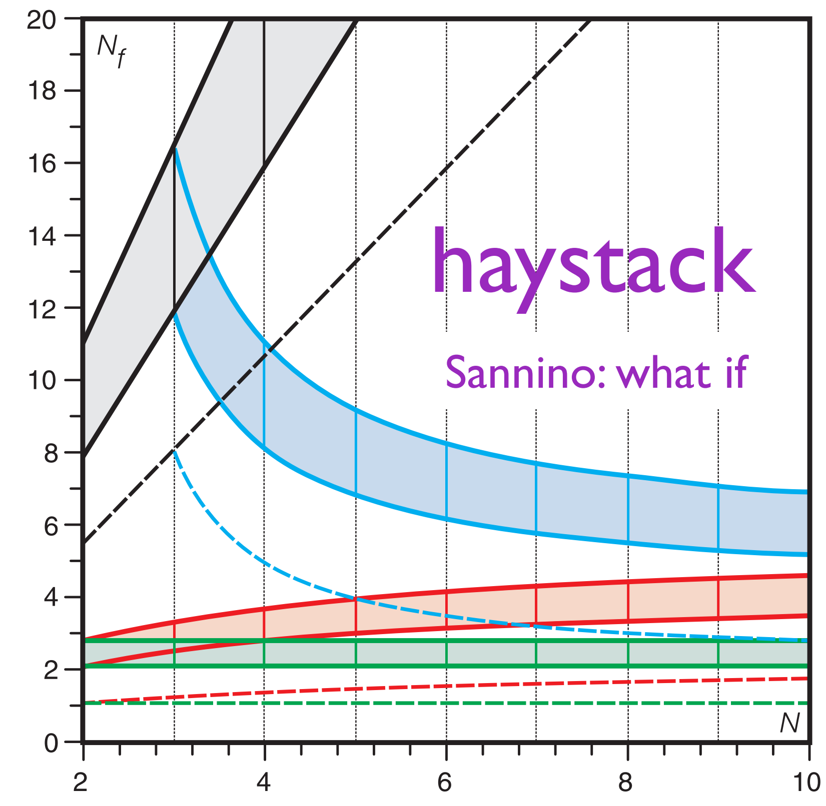

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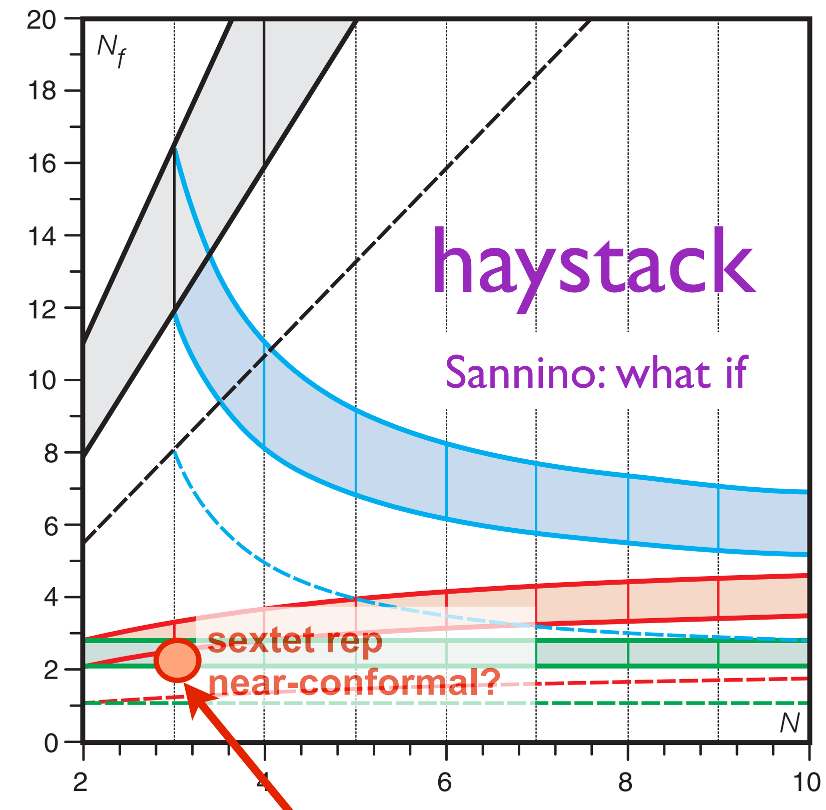

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The light 0++ scalar

QCD (aka old TC) 80ies,90ies

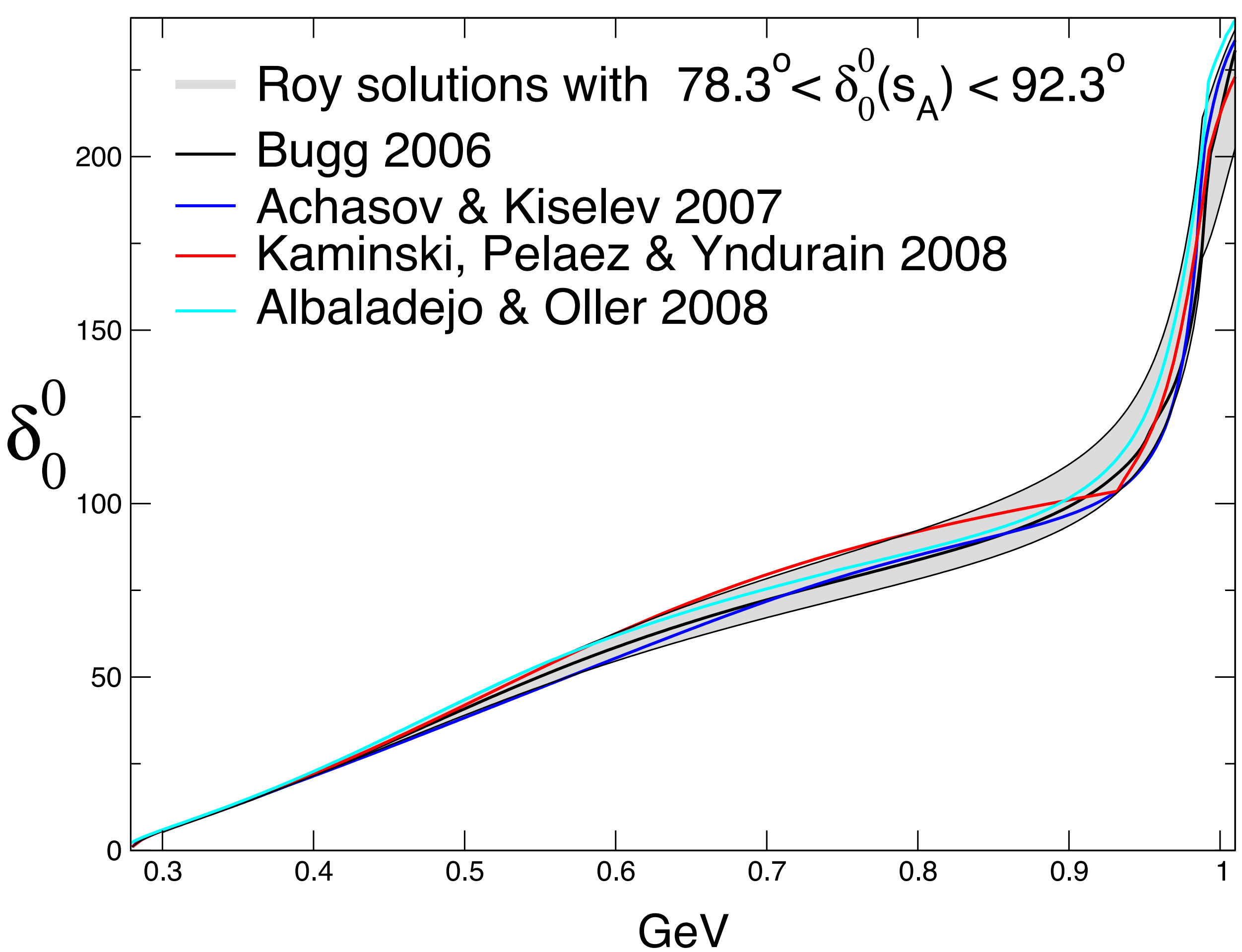
the failure of old Higgs-less technicolor:

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

$$\sqrt{s_\sigma} = (400 - 1200) - i\,(250 - 500)\ \mathrm{MeV}$$

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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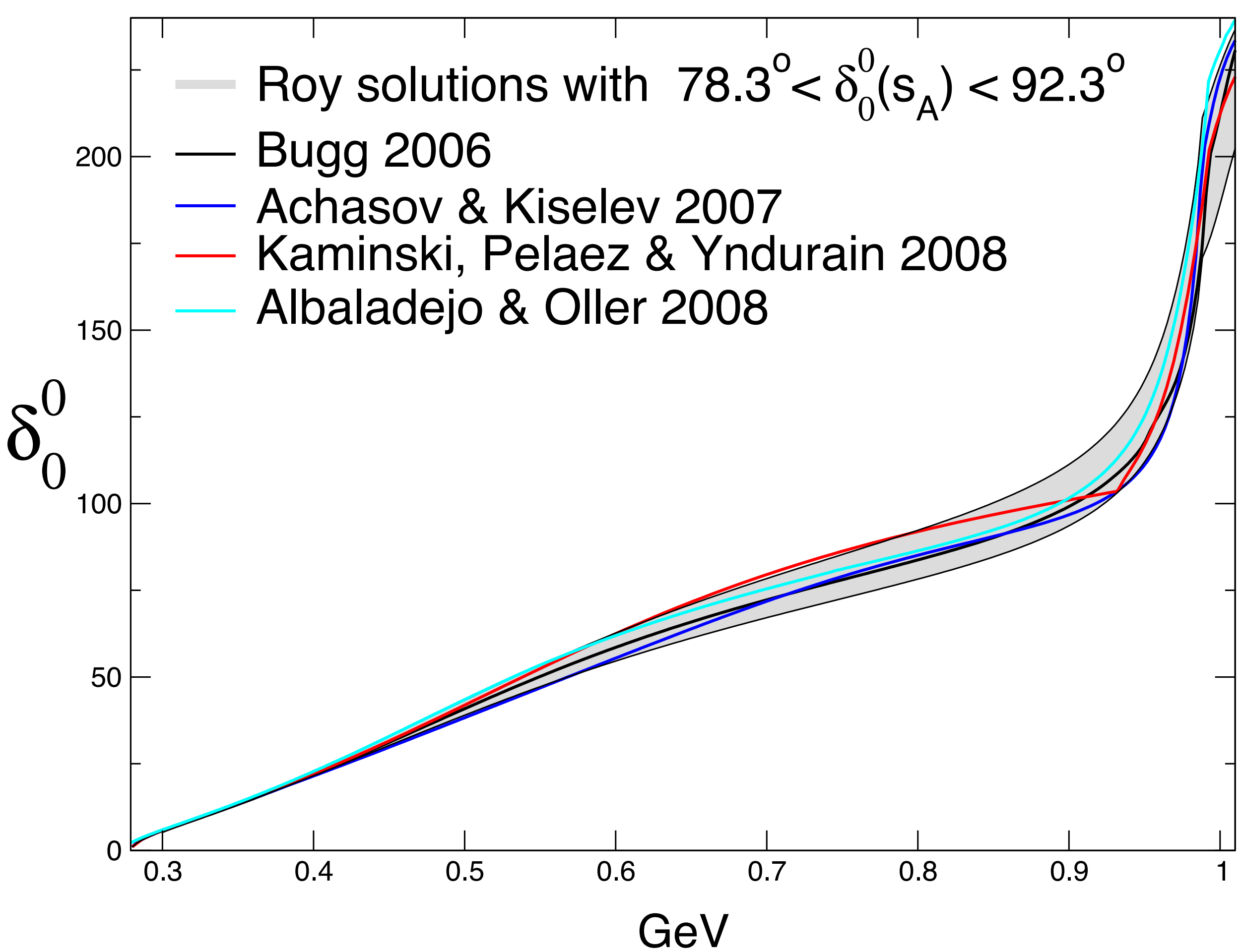


broad M_σ ~ 1.5 TeV in old technicolor, based on scaled up QCD, hence the tag "Higgs-less"

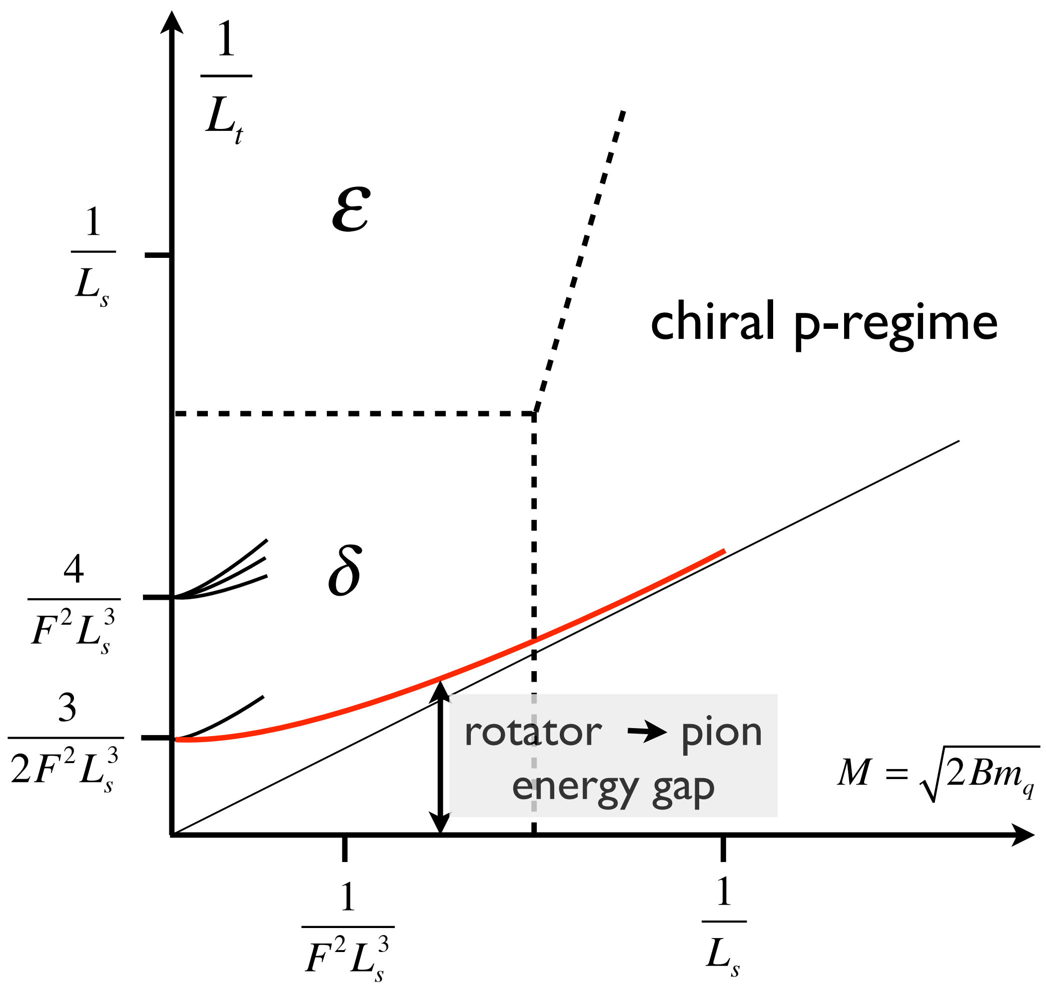
This is expected to be different in near-conformal strongly coupled gauge theories

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

Leutwyler:
dispersion theory combined with ChiPT

Spoiler alert: FL < √Nf/2 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 $l = 0,1,2,\ldots$ 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

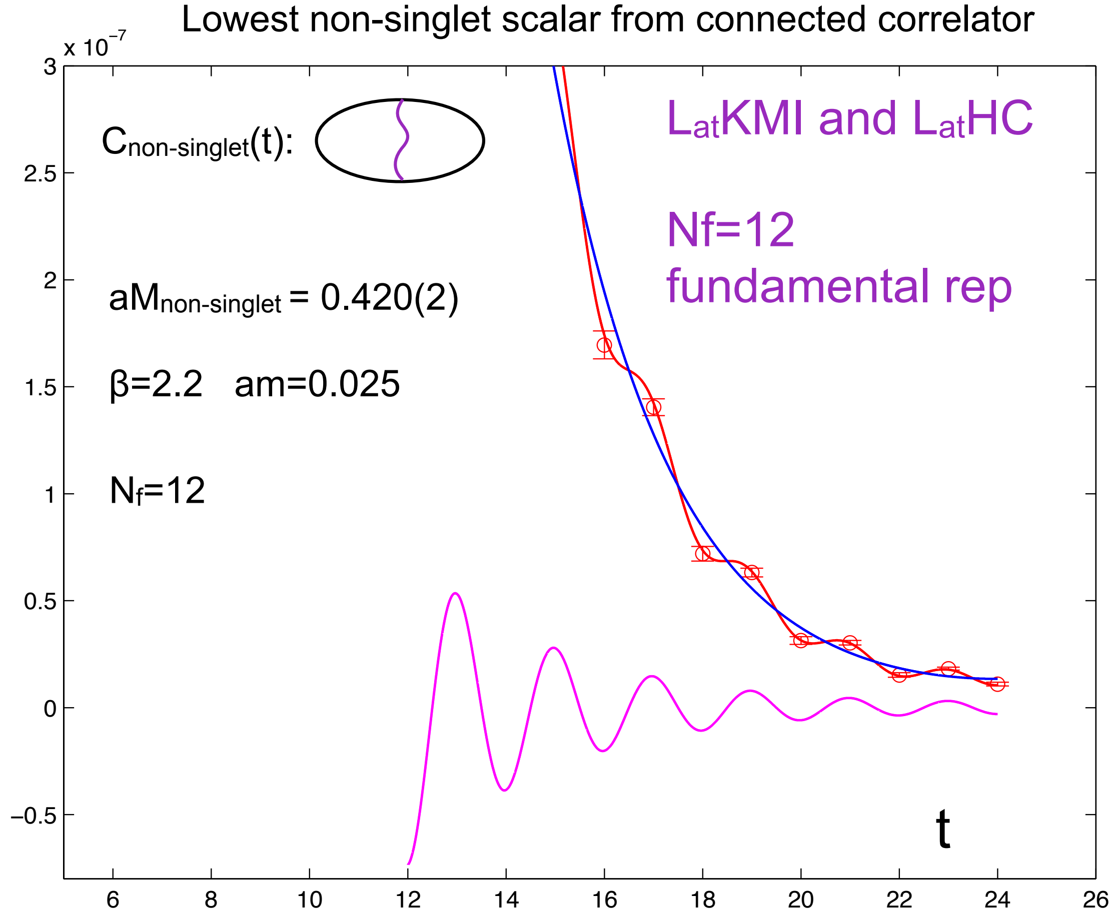
FL = 1 L= 2 fm in QCD and we crossed over to the χSB phase all 3 regimes (ε,δ,p) OK

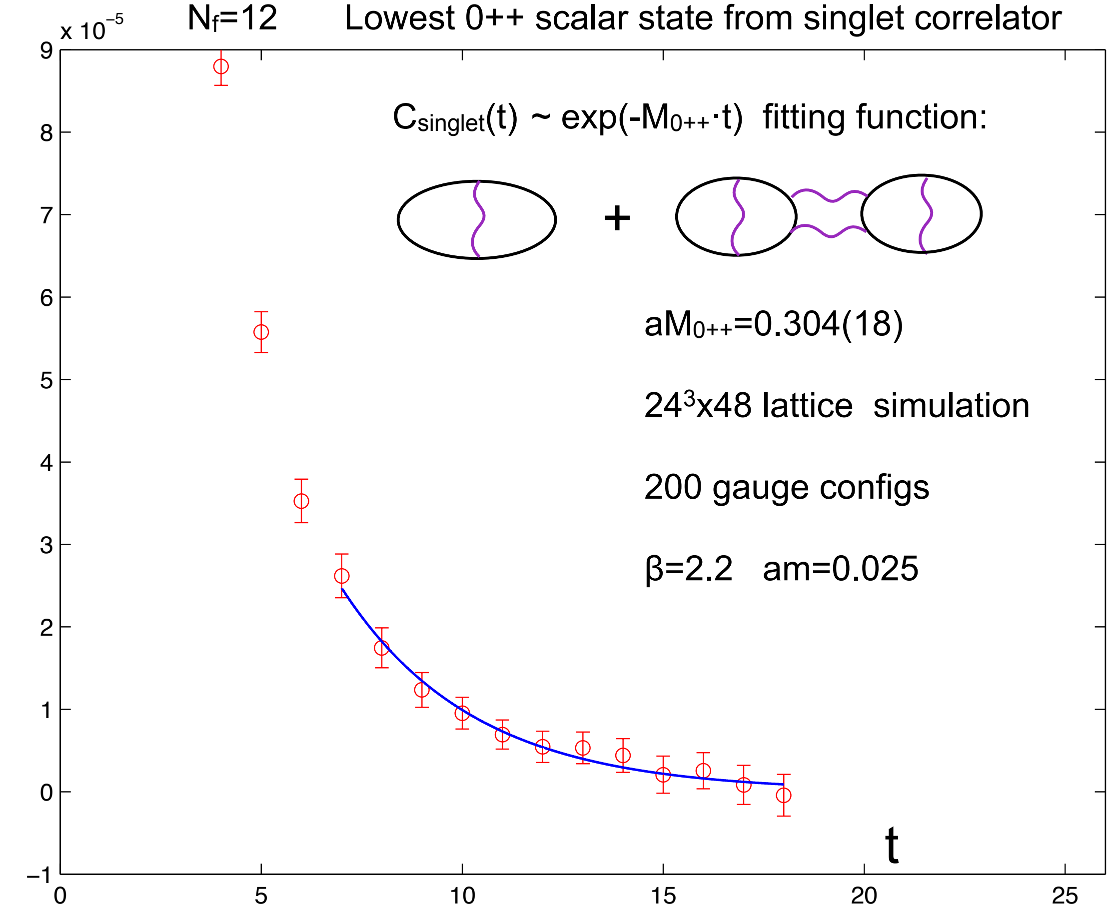
FL = 0.4 squeezed L= 0.8 fm, begins to look conformal not OK, misidentifies infinite volume phase

The light 0++ scalar

SCGT 2013-2015

test of scalar technology:



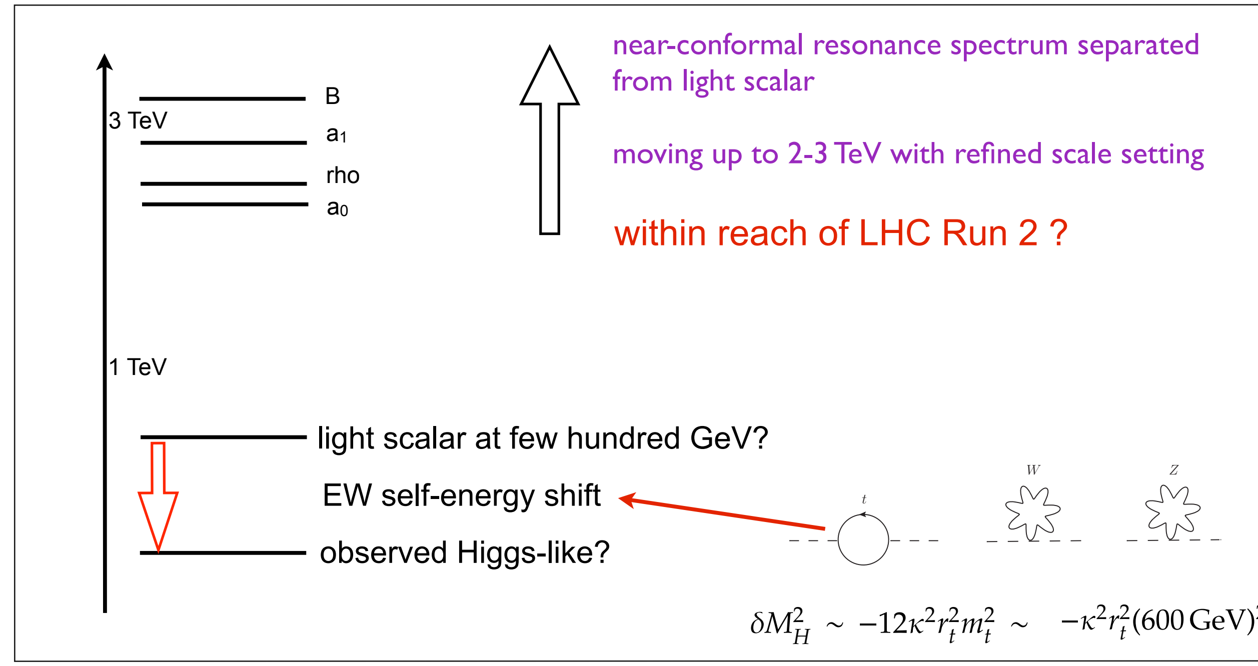


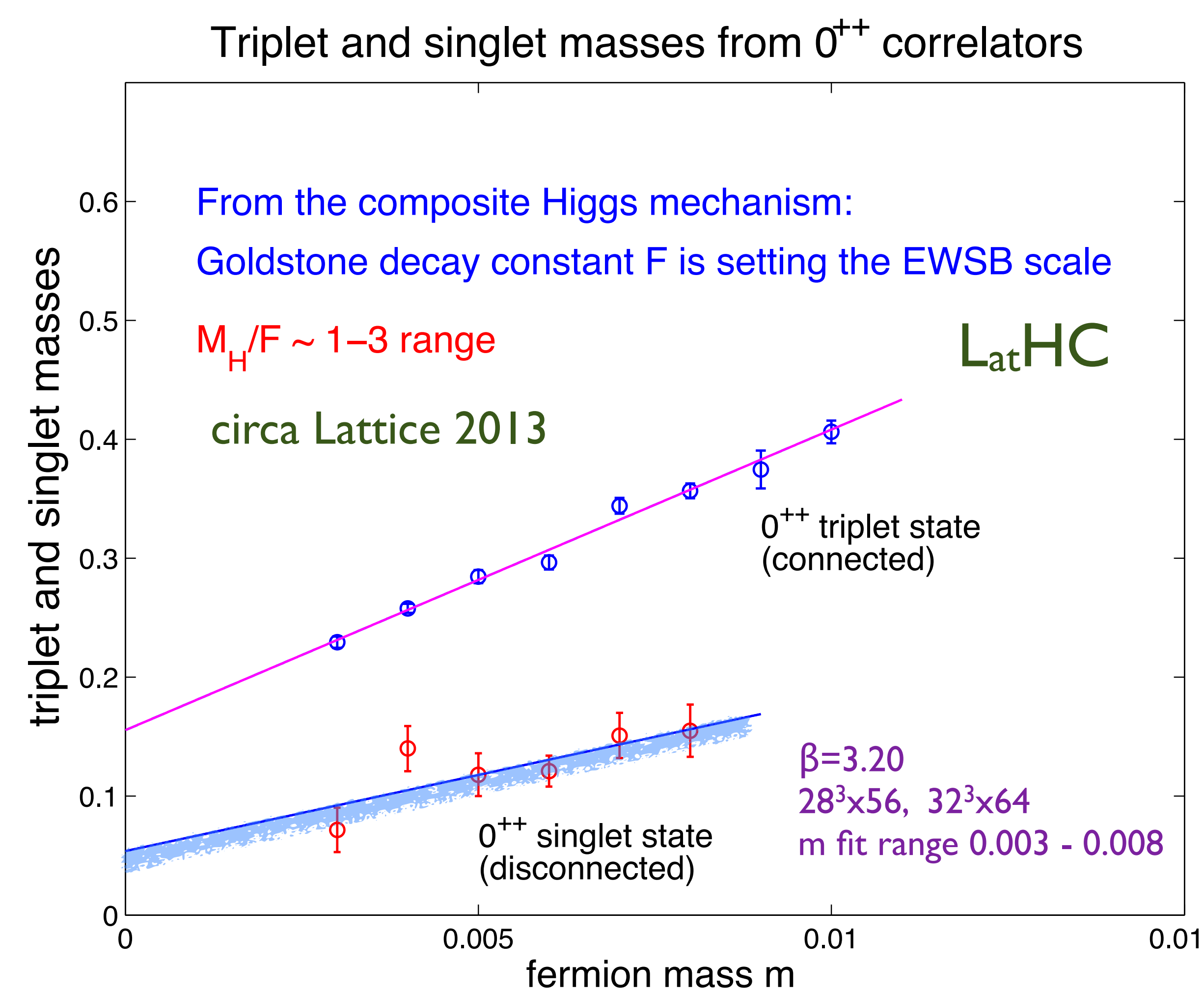
$$C(t) = \sum_n \left[A_n e^{-m_n(\Gamma_S \otimes \Gamma_T)t} + (-1)^t B_n e^{-m_n(\gamma_4\gamma_5\Gamma_S \otimes \gamma_4\gamma_5\Gamma_T)t}\right]$$

staggered correlator

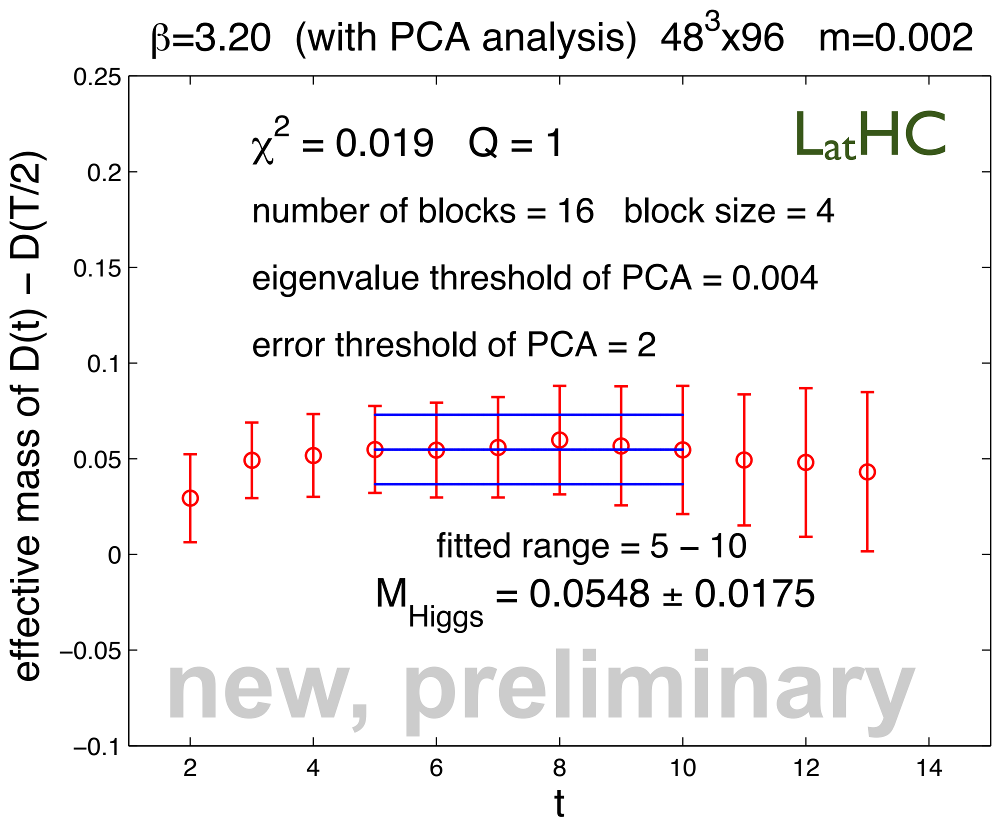
new results in N_f=2 sextet model (this talk) and N_f=4/8/12 models (LatKMI talks, A. Hasenfratz talk)

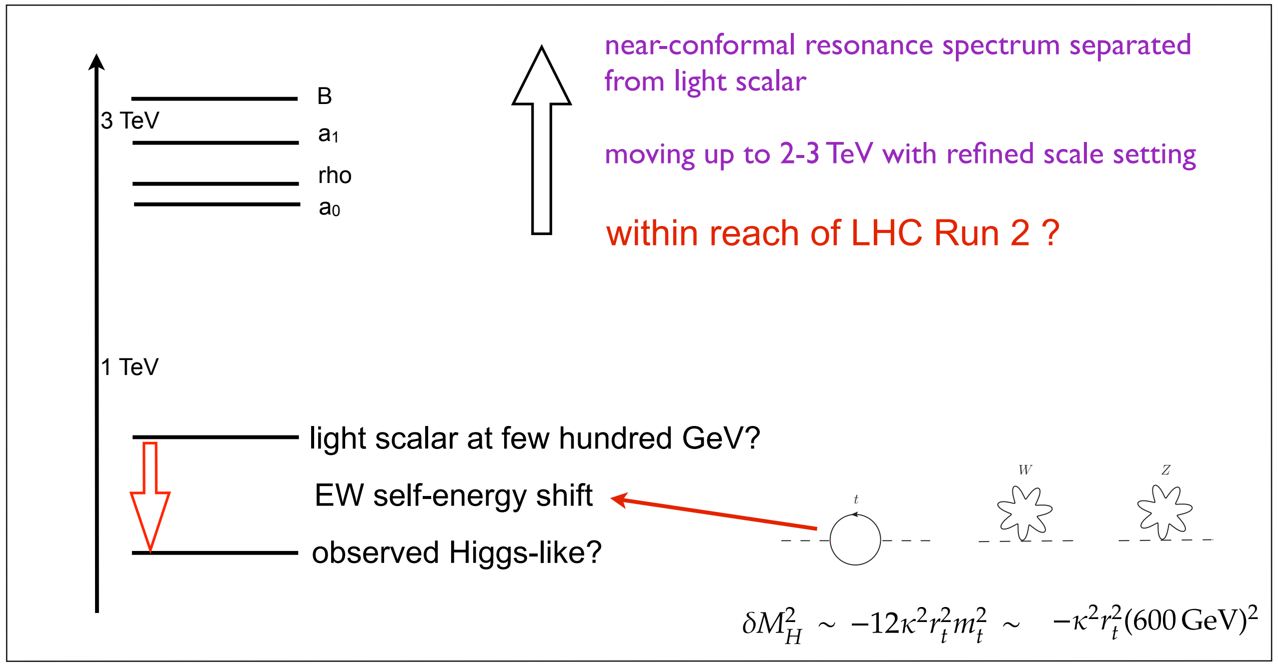
light 0++ scalar and spectrum   sextet model   LatHC

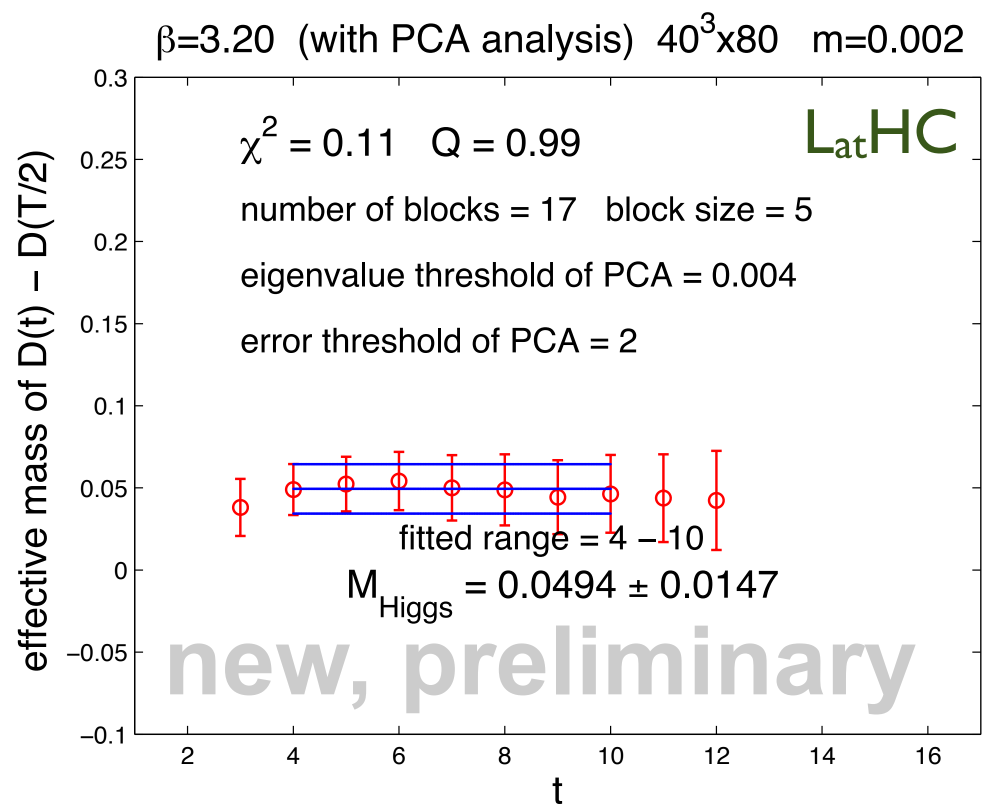


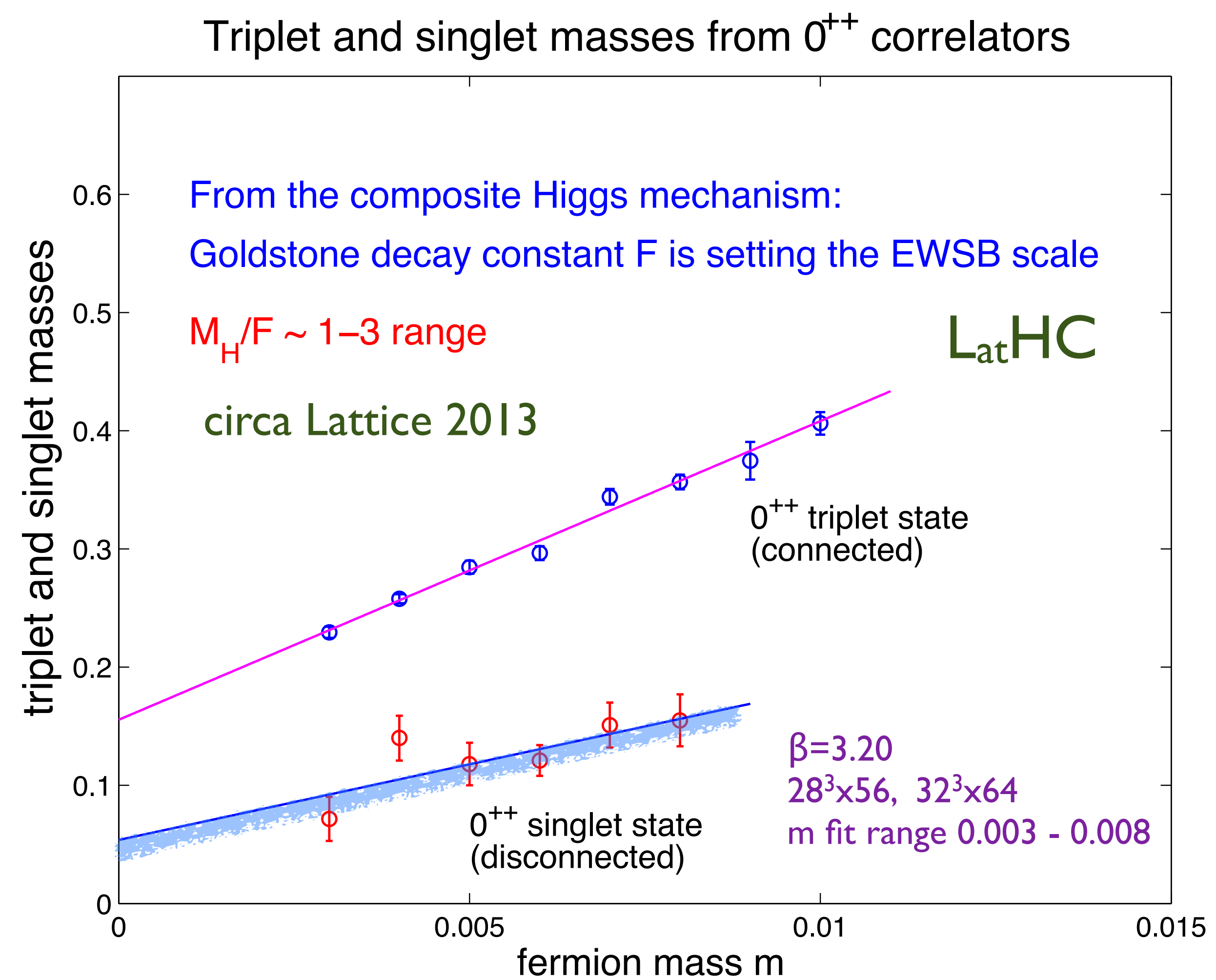


light 0++ scalar and spectrum sextet model LatHC









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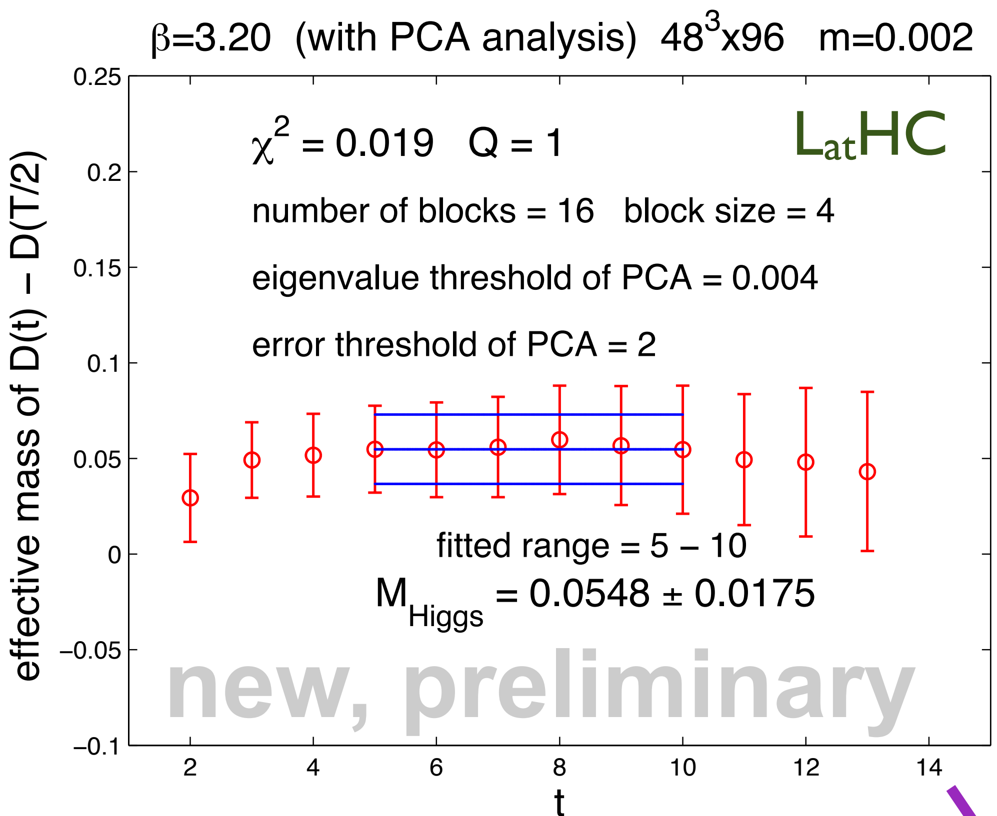

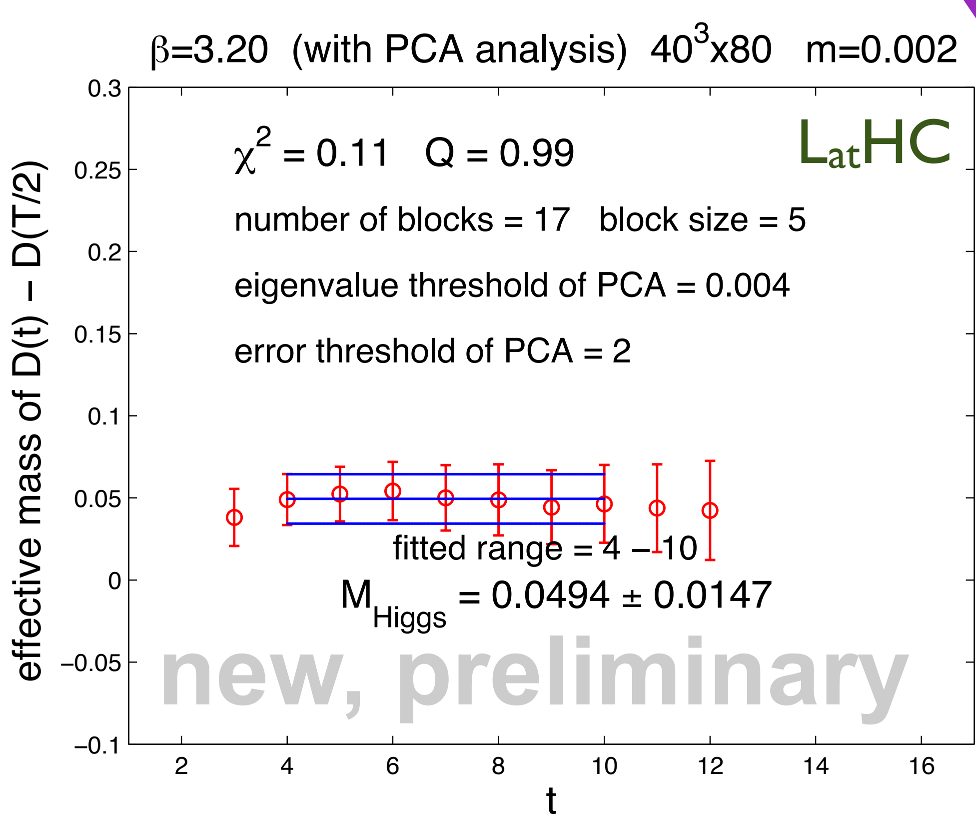

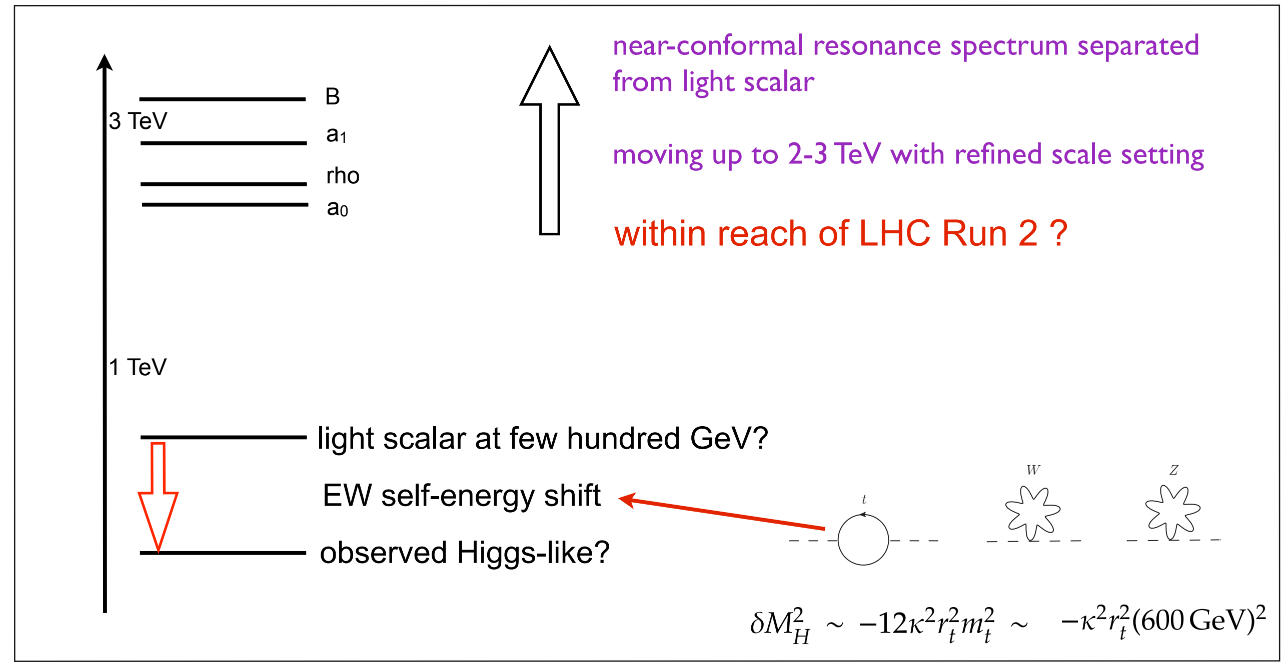

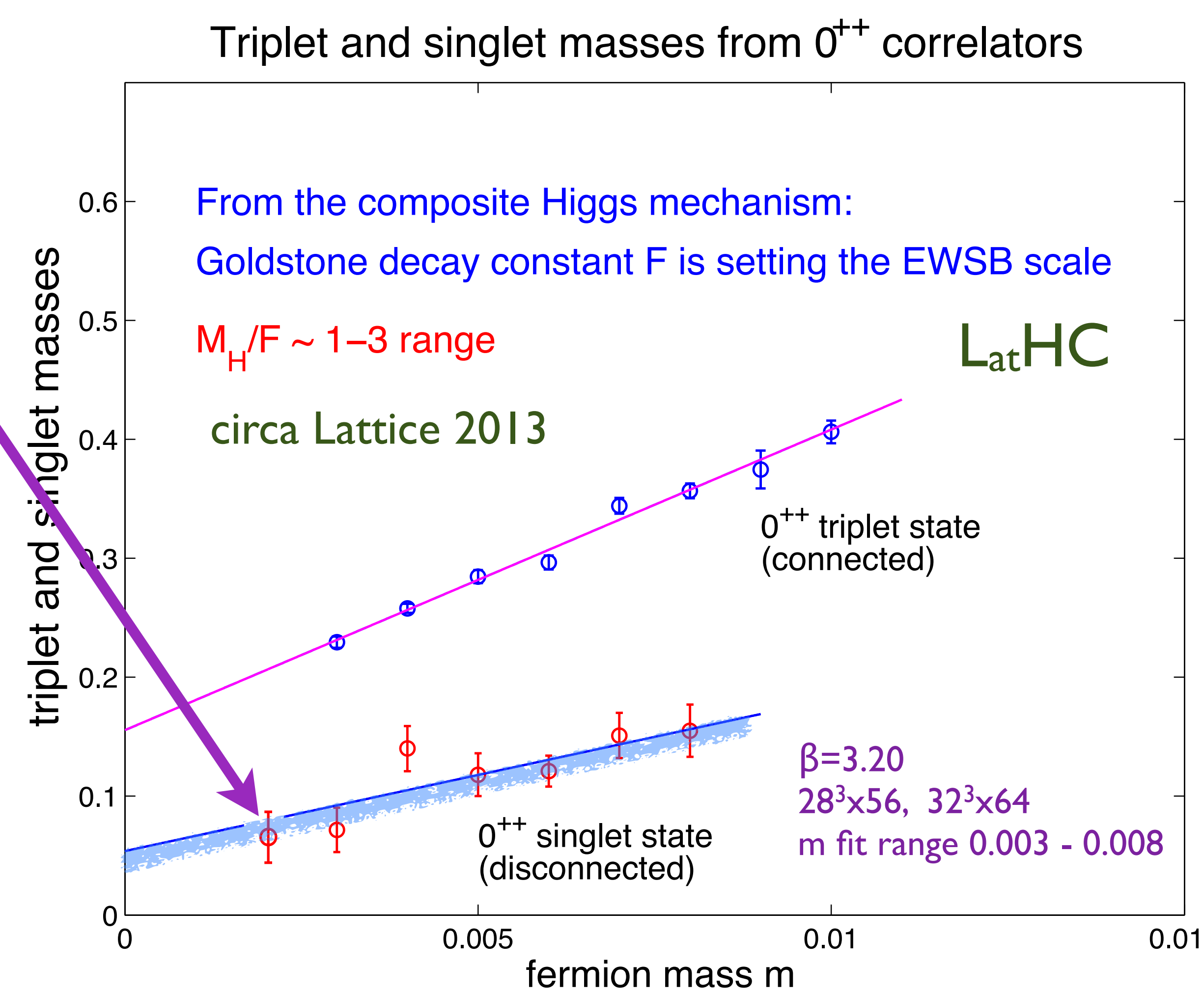

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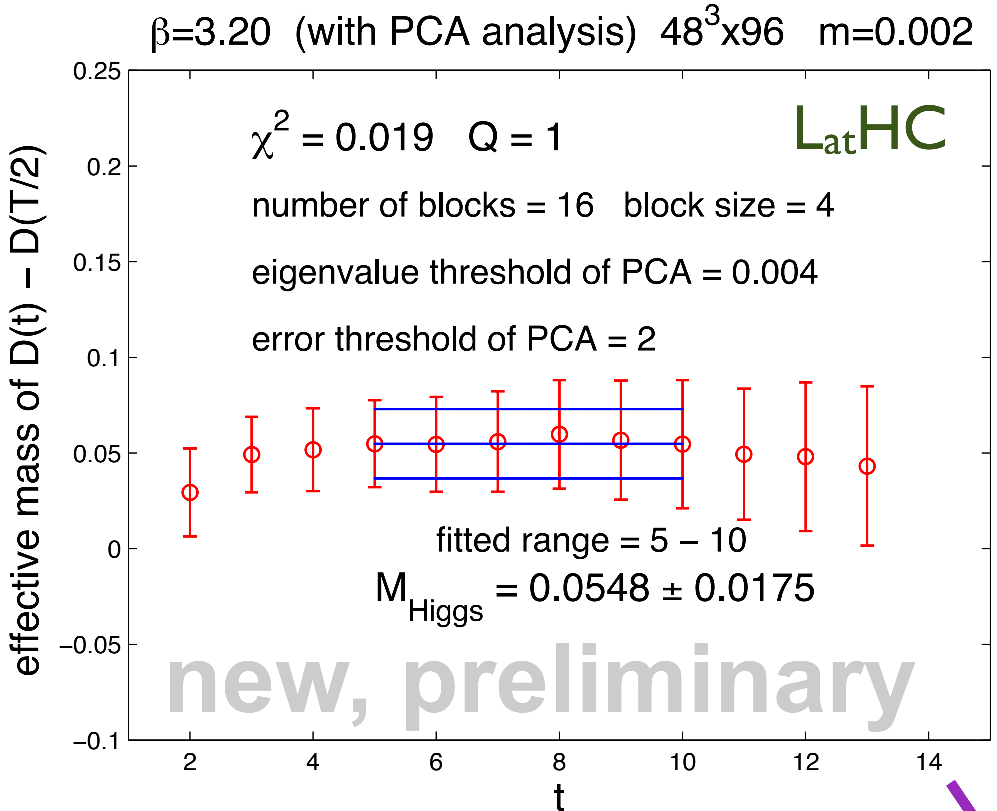
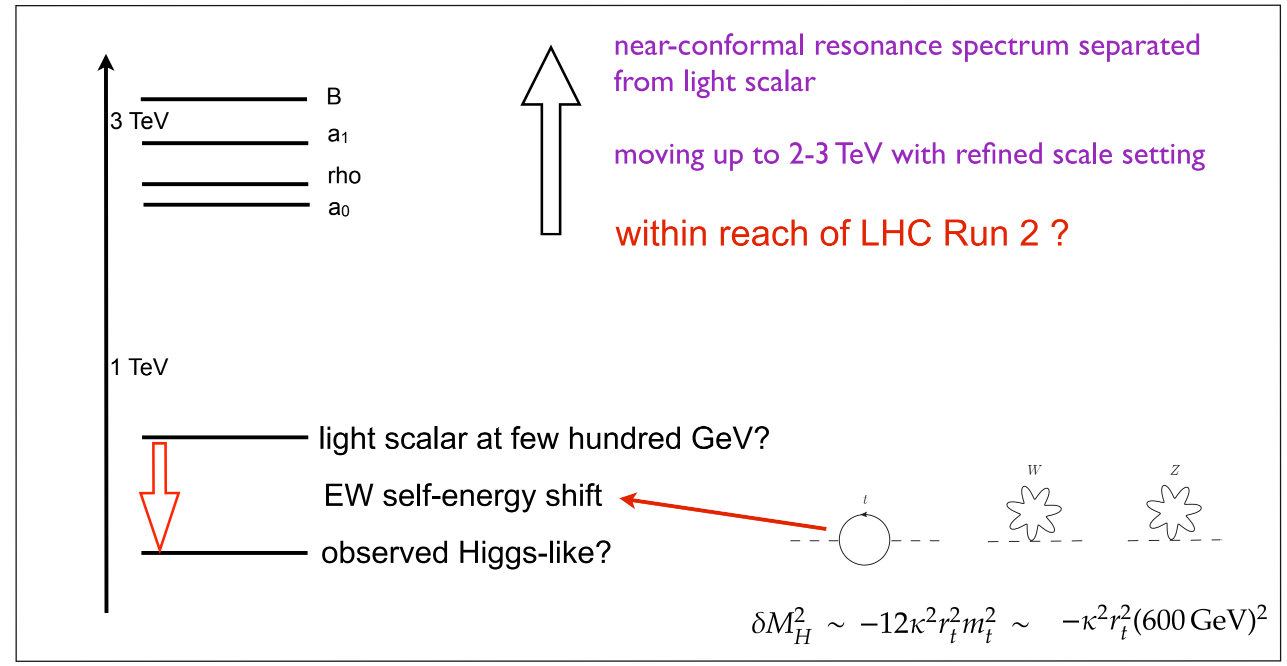
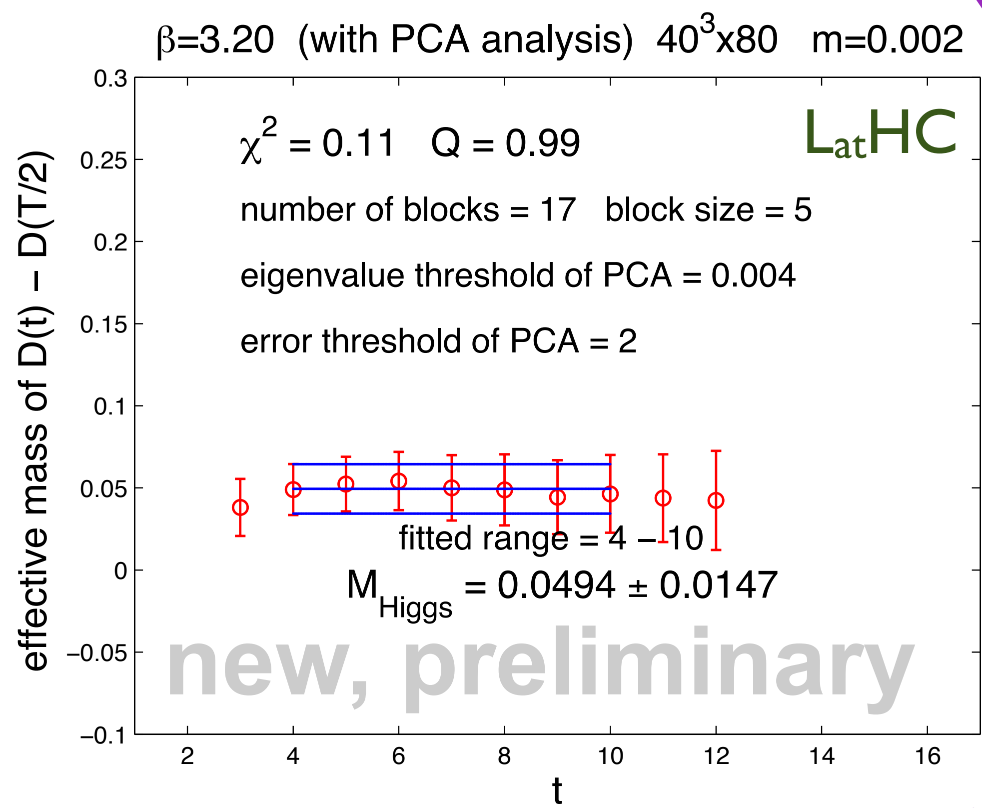
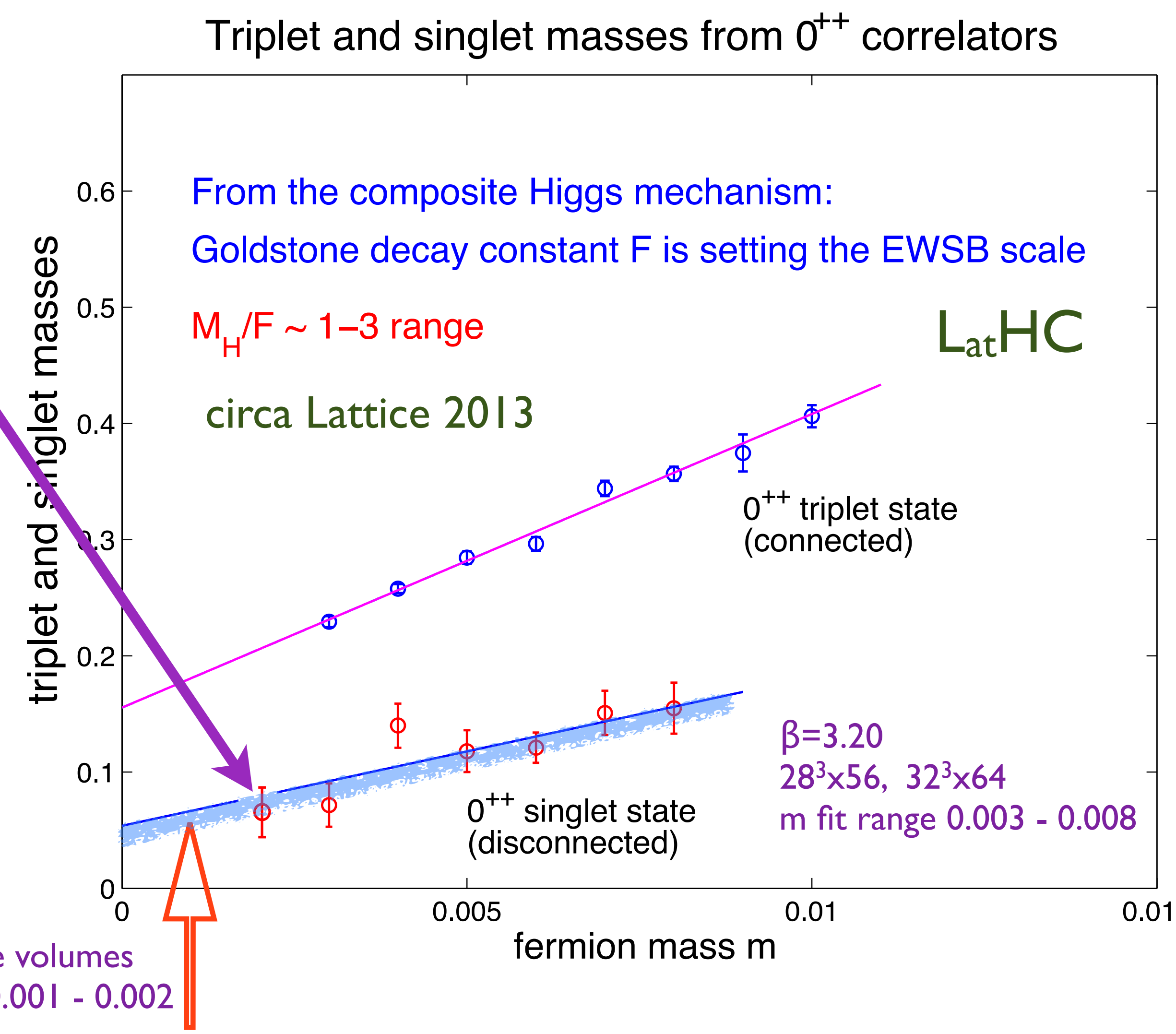


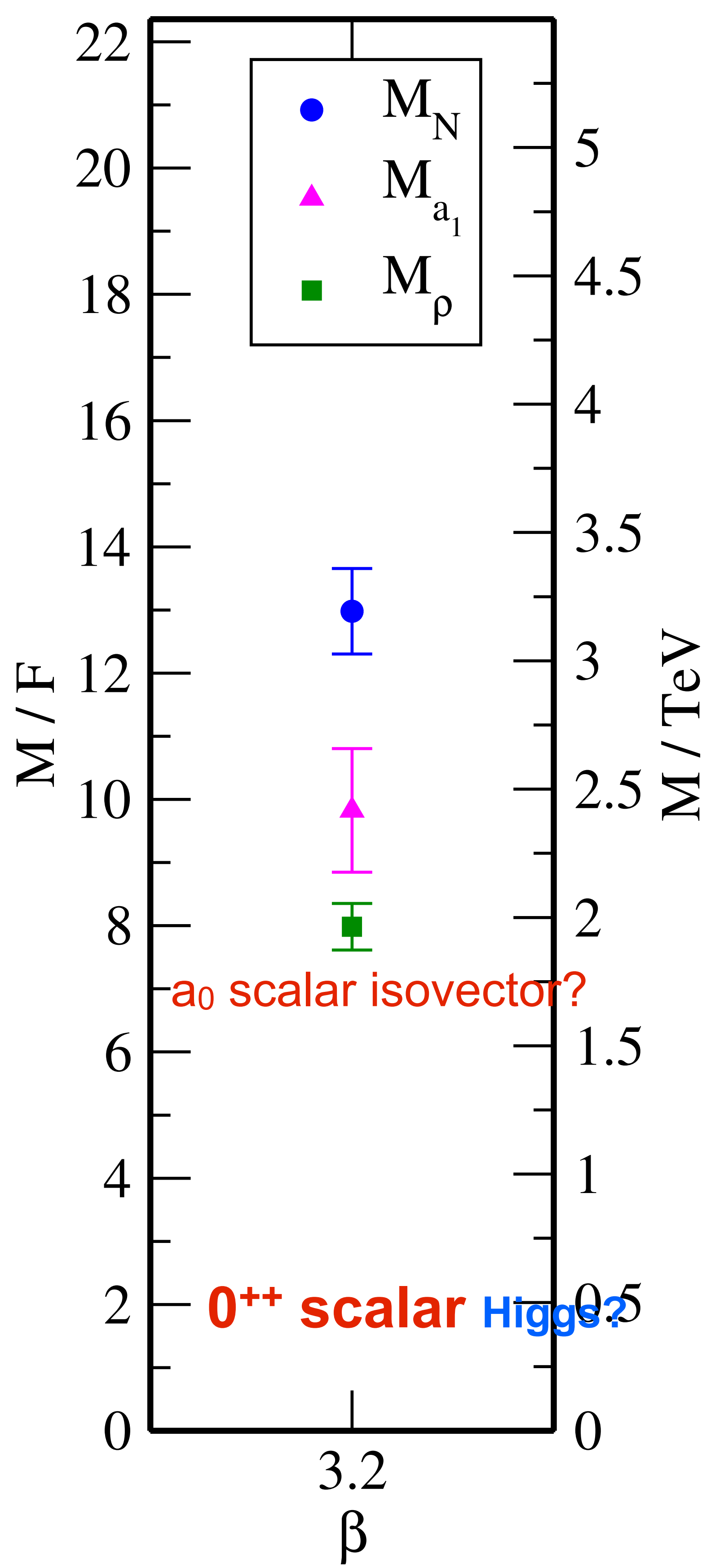




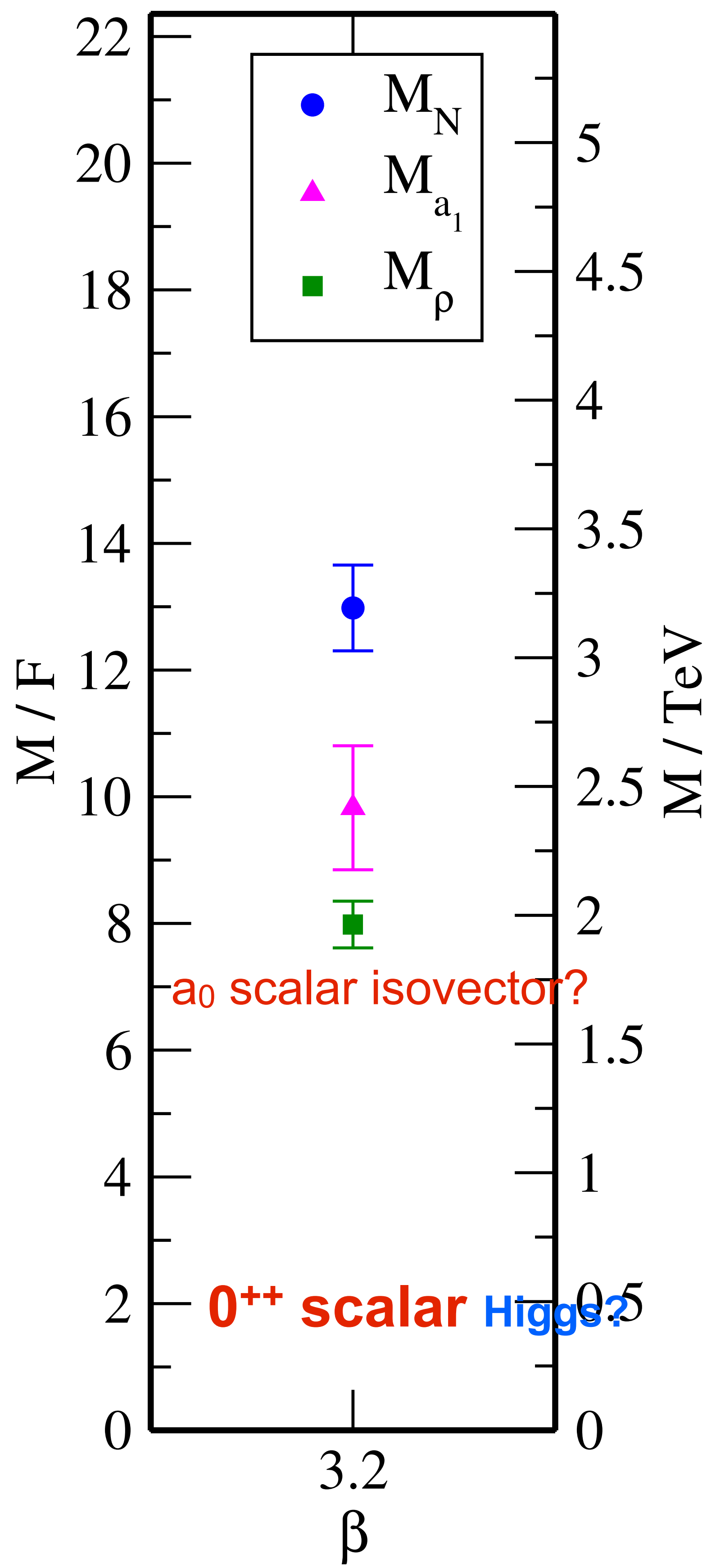


running large volumes
m fit range 0.001 - 0.002

light 0++ scalar and spectrum   sextet model   LatHC



light 0++ scalar and spectrum sextet model $L_{at}HC$



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Eur. Phys. J. C.

CERN-PH-EP-2015-052
30th March 2015

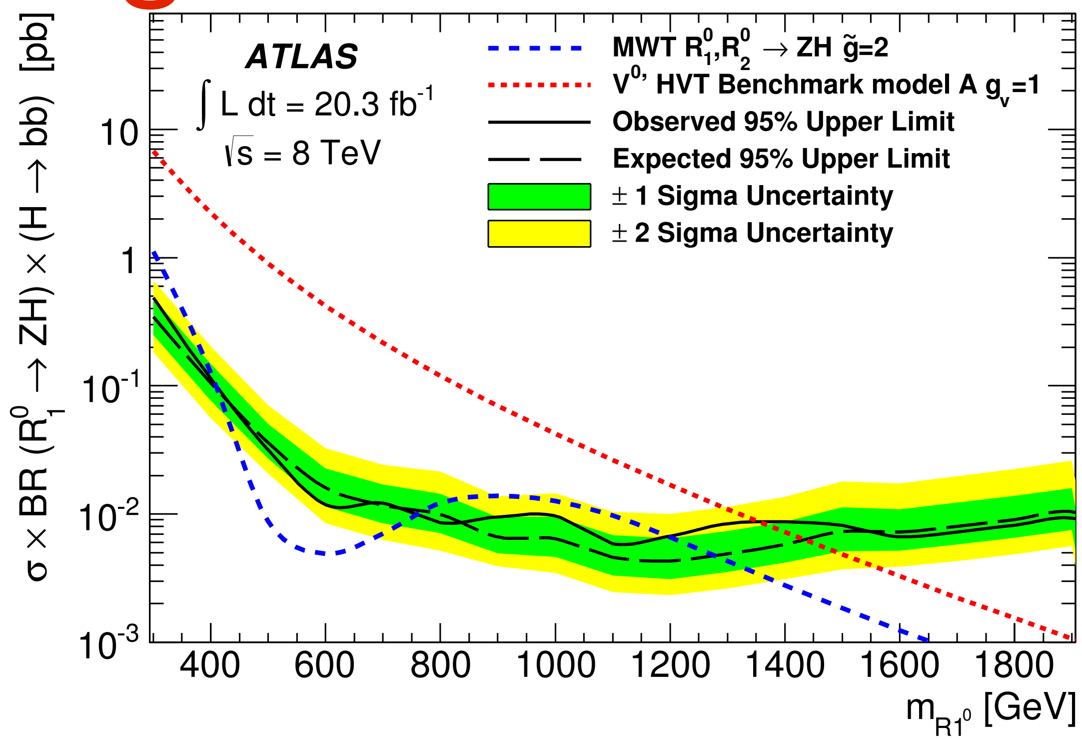
Search for a new resonance decaying to a W or Z boson and a Higgs boson in the $\ell\ell/\ell\nu/\nu\nu + b\bar{b}$ final states with the ATLAS Detector

The ATLAS Collaboration with Sannino

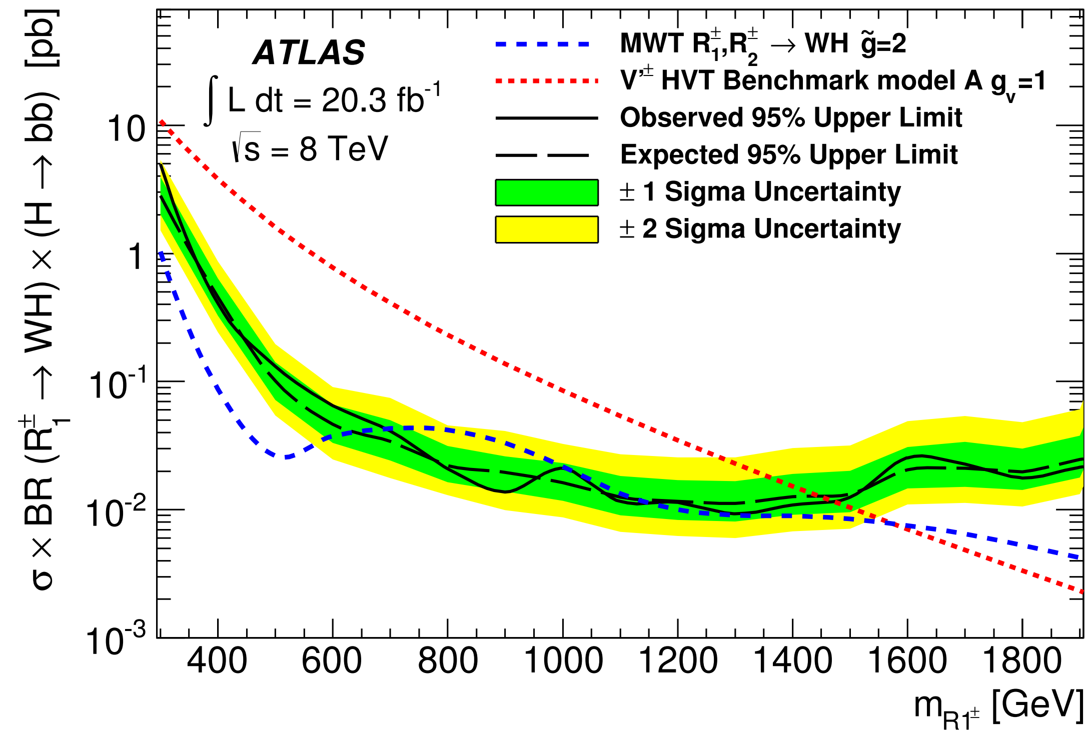
Abstract

A search for a new resonance decaying to a W or Z boson and a Higgs boson in the $\ell\ell/\ell\nu/\nu\nu+b\bar{b}$ final states is performed using 20.3 fb^{-1} of pp collision data recorded at $\sqrt{s}$ = 8 TeV with the ATLAS detector at the Large Hadron Collider. The search is conducted by examining the WH/ZH invariant mass distribution for a localized excess. No significant deviation from the Standard Model background prediction is observed. The results are interpreted in terms of constraints on the Minimal Walking Technicolor model and on a simplified approach based on a phenomenological Lagrangian of Heavy Vector Triplets.

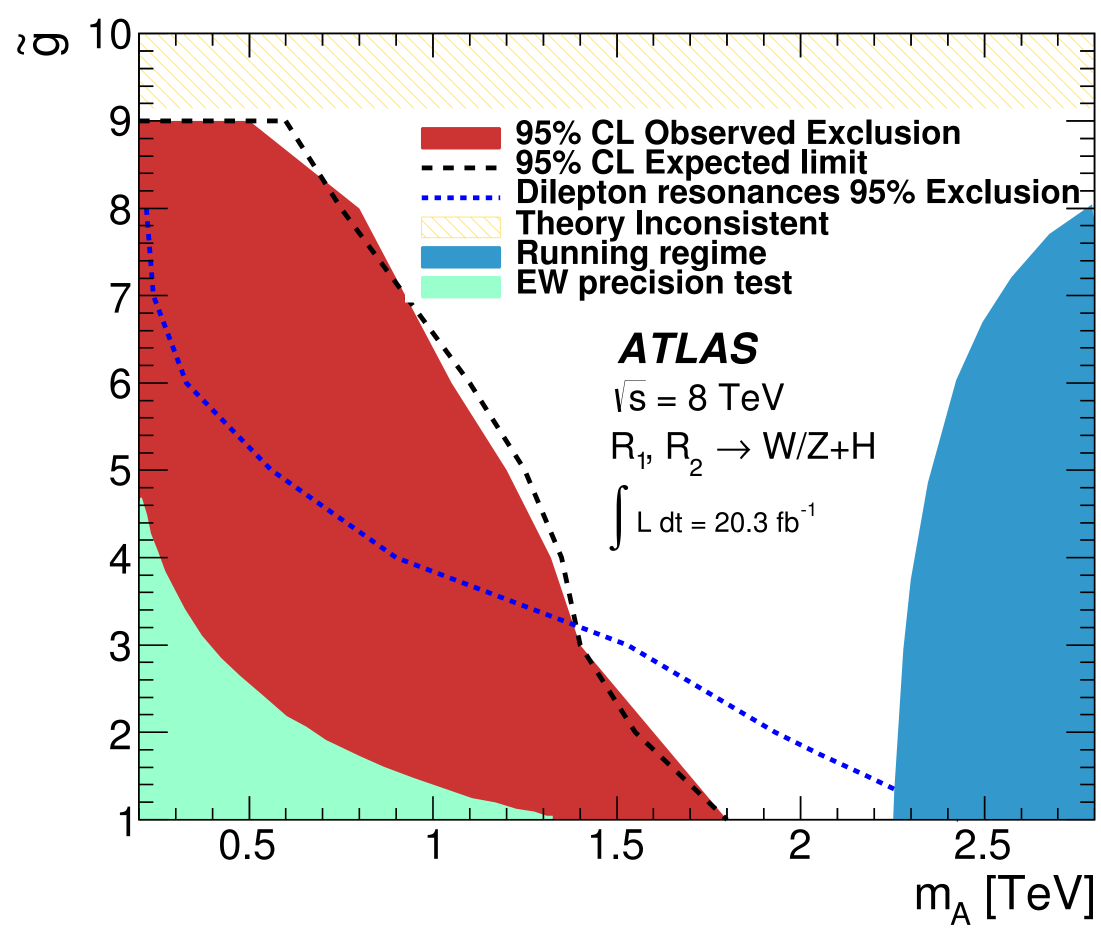
light 0++ scalar and spectrum sextet model $L_{at}HC$

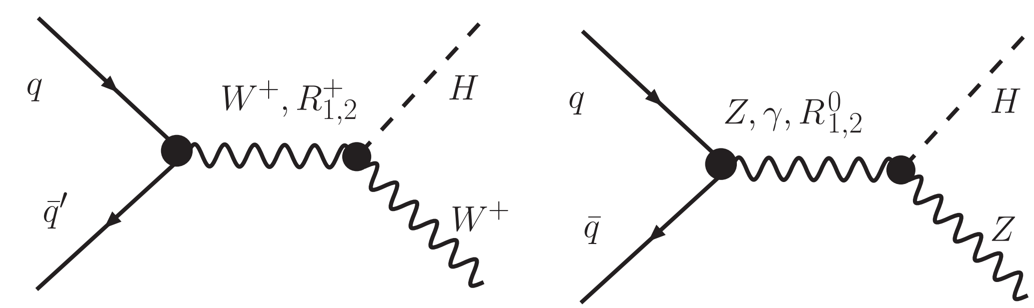


(a) $R_1^0(V'^0) \rightarrow ZH,\, H \rightarrow b\bar{b}$



(b) $R_1^{\pm}(V'^{\pm}) \rightarrow WH,\, H \rightarrow b\bar{b}$





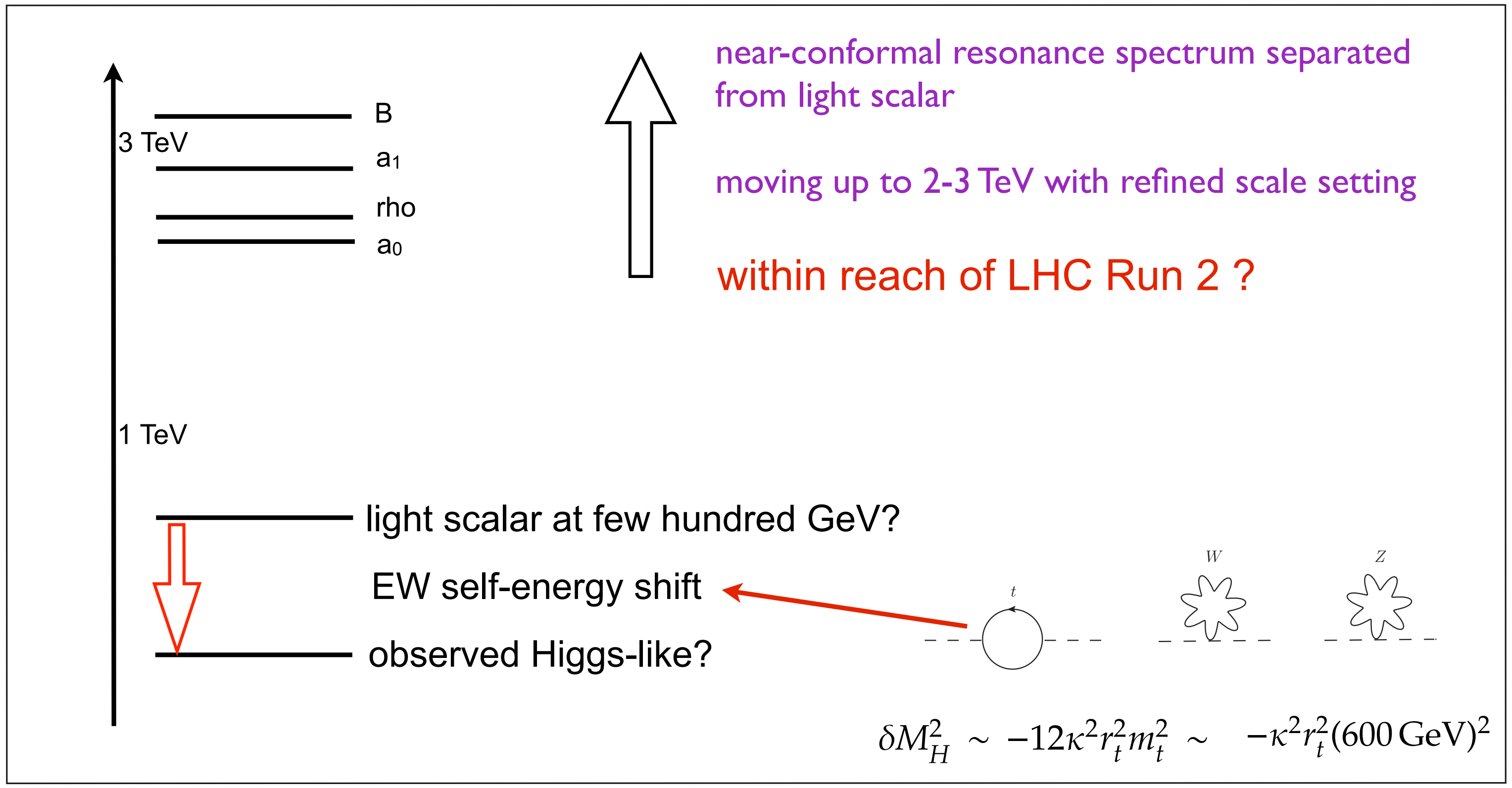
R_1 and R_2 couplings:

ĝ is the coupling in SU(4) vector boson

g/ĝ is the coupling to fermions

light 0++ scalar and spectrum

two tracks of challenges



Theory track:

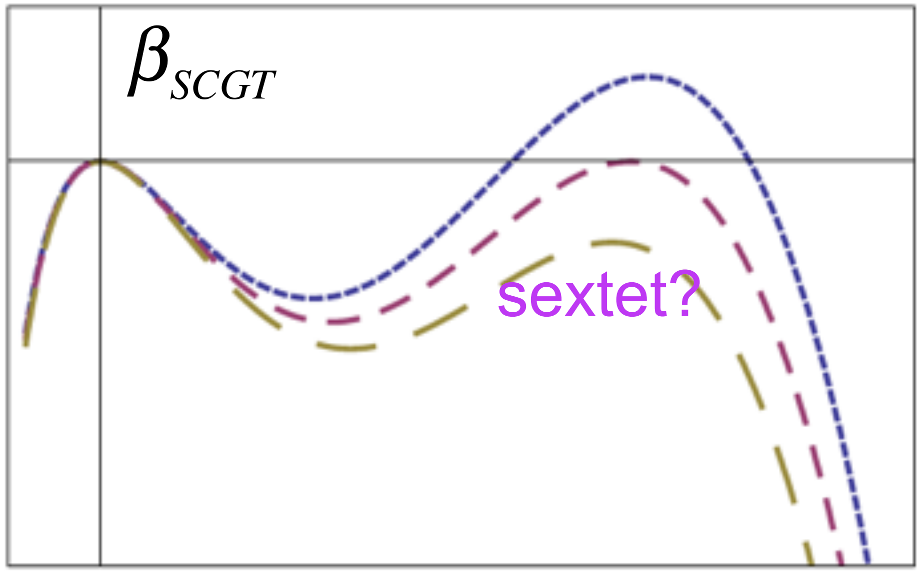
- is there a natural explanation for scale separation close to CW?
- testable meaning to dilaton interpretation?
- how to do mass deformed χPT when scalar is not decoupled from Goldstones?
- how the low mass scalar is effecting the RMT analysis in m → 0 limit ?

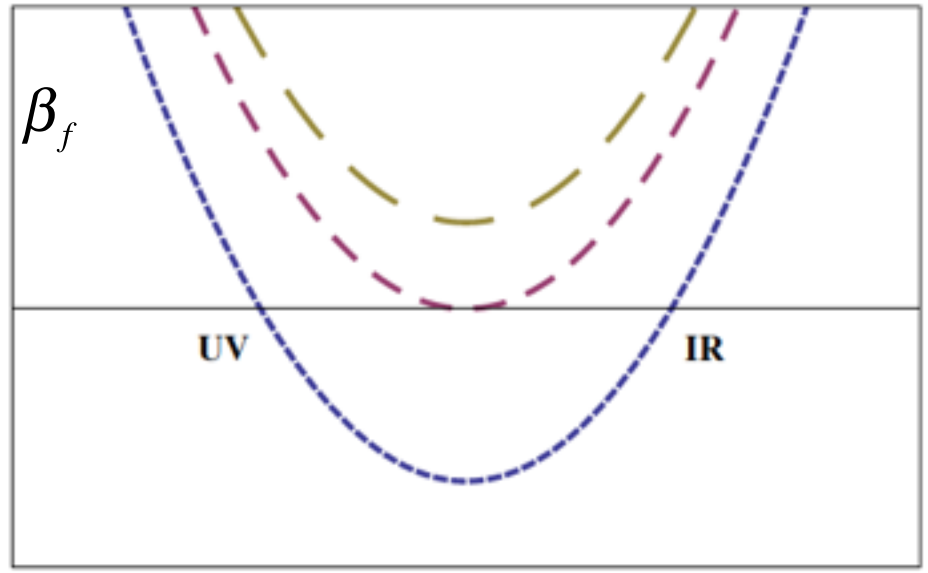
Simulation track:

- 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?

an idea to work on?

BKT (Miransky) conformal phase transition?





tunable deformation of IRFP?

four-fermion operator with large anomalous dim?

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

In the ivory tower we tune $x = N_f / N_c$ in and out of CW starting from L_{SCGT} at IRFP and adding NJL term.

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.

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.

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

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

Four-fermion interaction near four dimensions

J. Zinn-Justin *

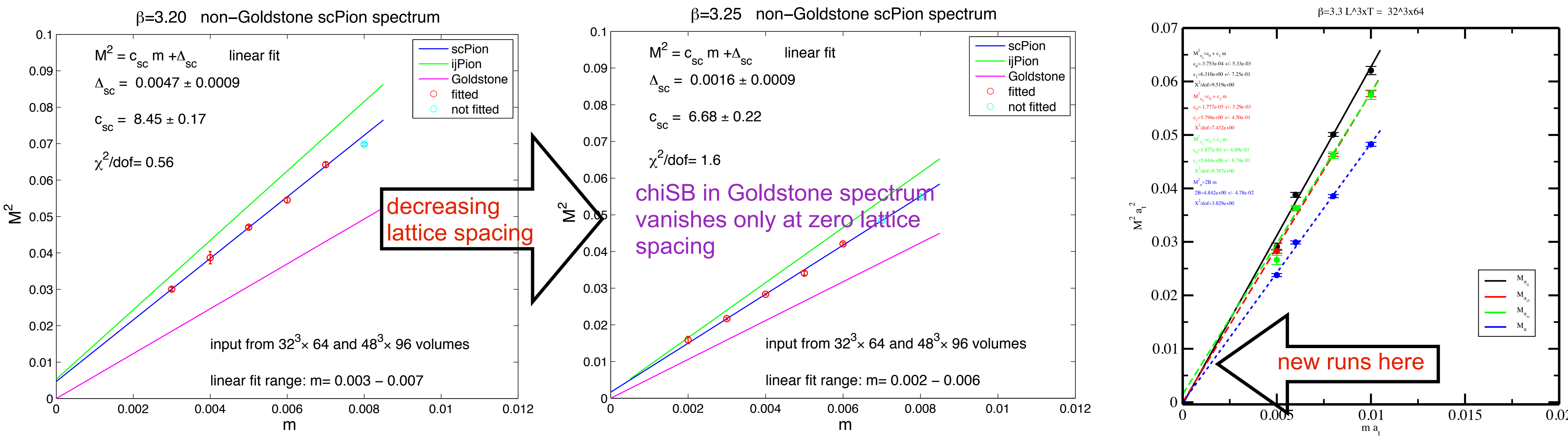
THE EQUIVALENCE OF THE TOP QUARK CONDENSATE AND THE ELEMENTARY HIGGS FIELD

Anna HASENFRATZ

University of Arizona at Tucson, Department of Physics, Tucson, AZ 85721, USA

Peter HASENFRATZ*, Karl JANSEN, Julius KUTI and Yue SHEN**

taste breaking and mixed action



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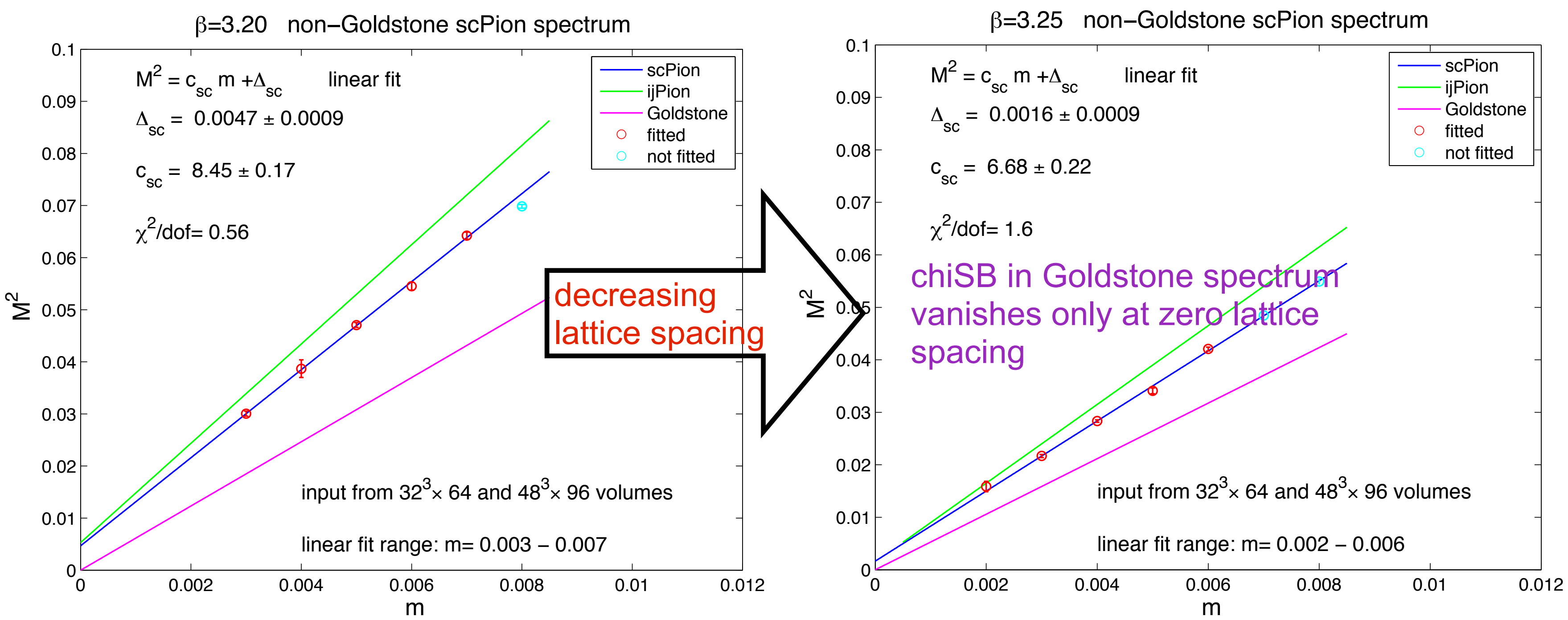
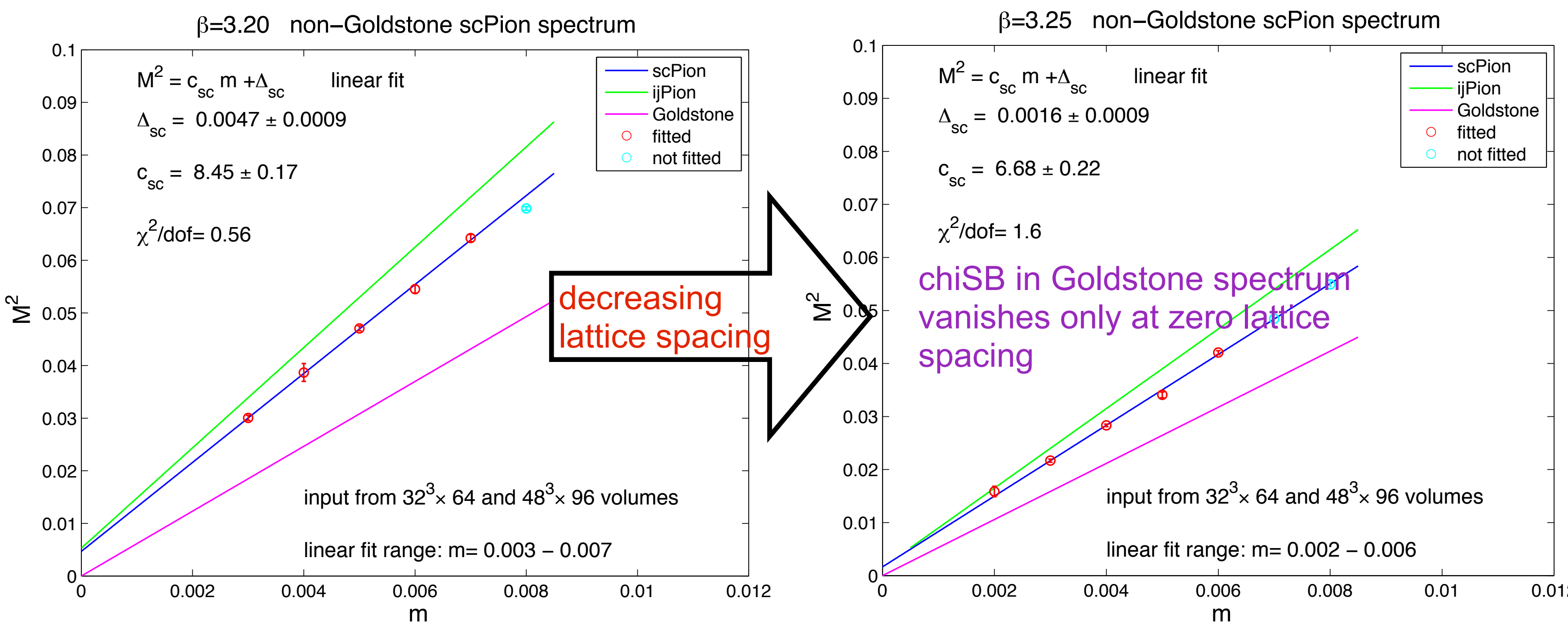
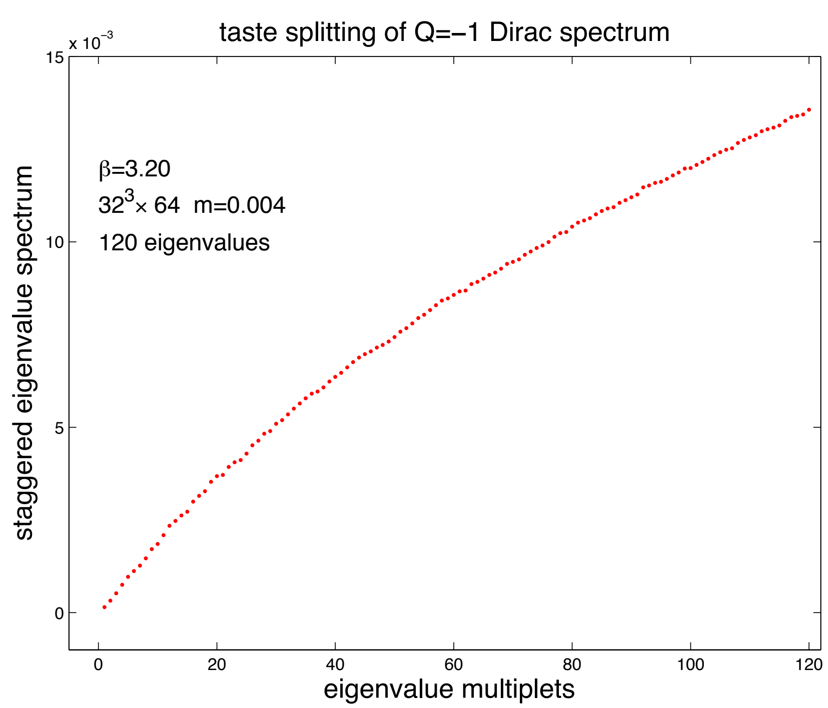


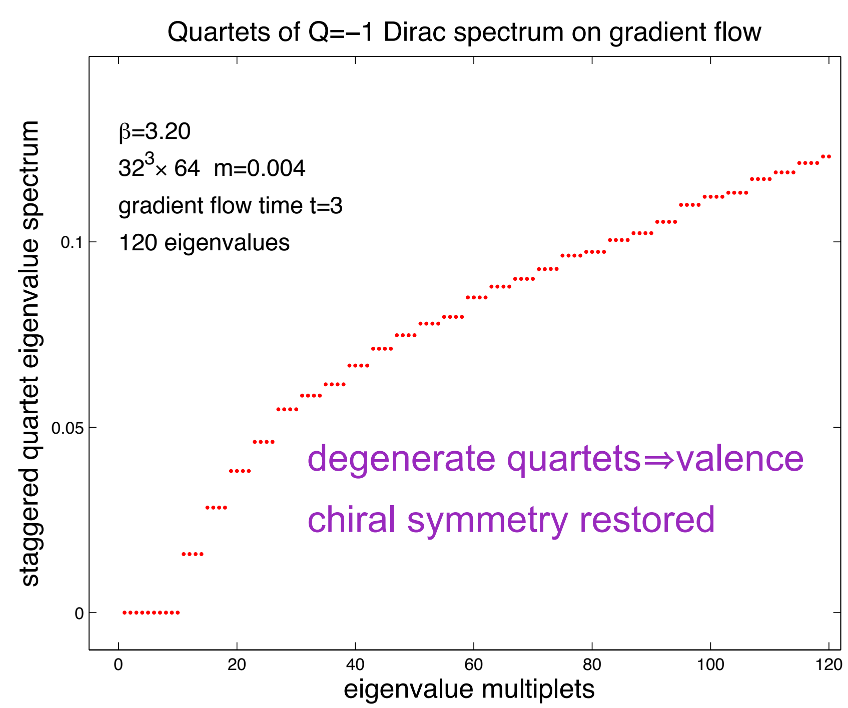
idea:

- 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!

taste breaking and mixed action







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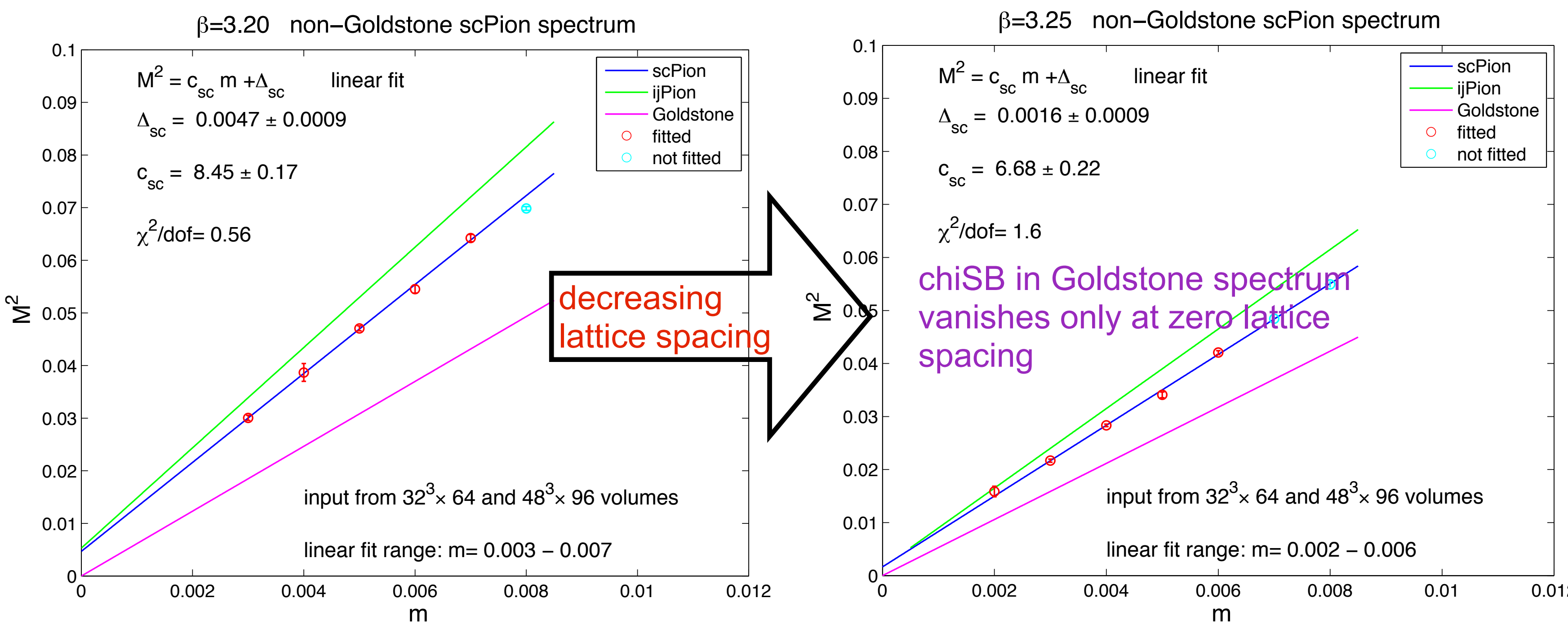
- taste symmetry is restored in valence spectrum
- Mixed Action analysis should agree with original standard analysis when cutoff is removed: this is OK!

taste breaking and mixed action



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
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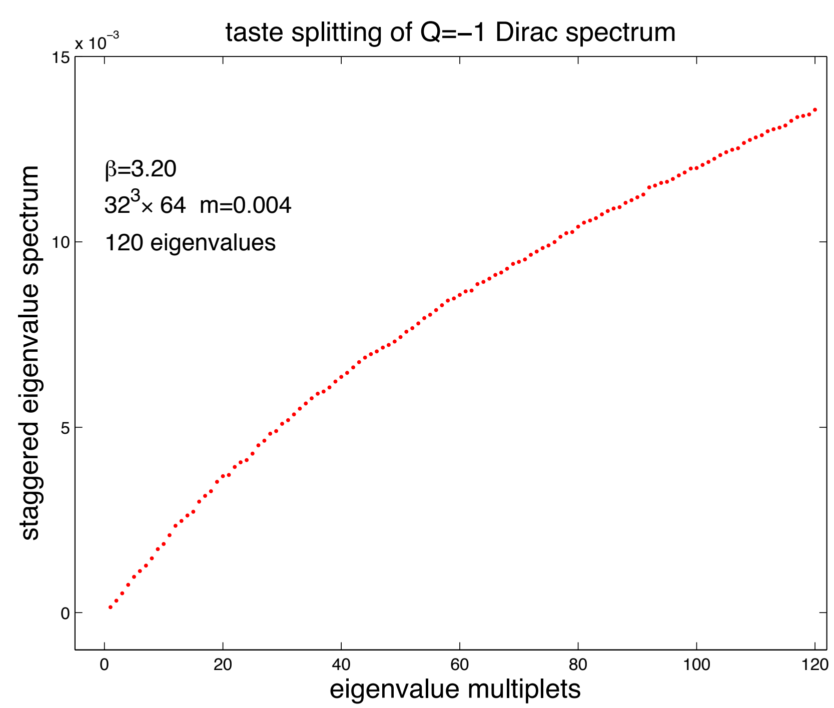

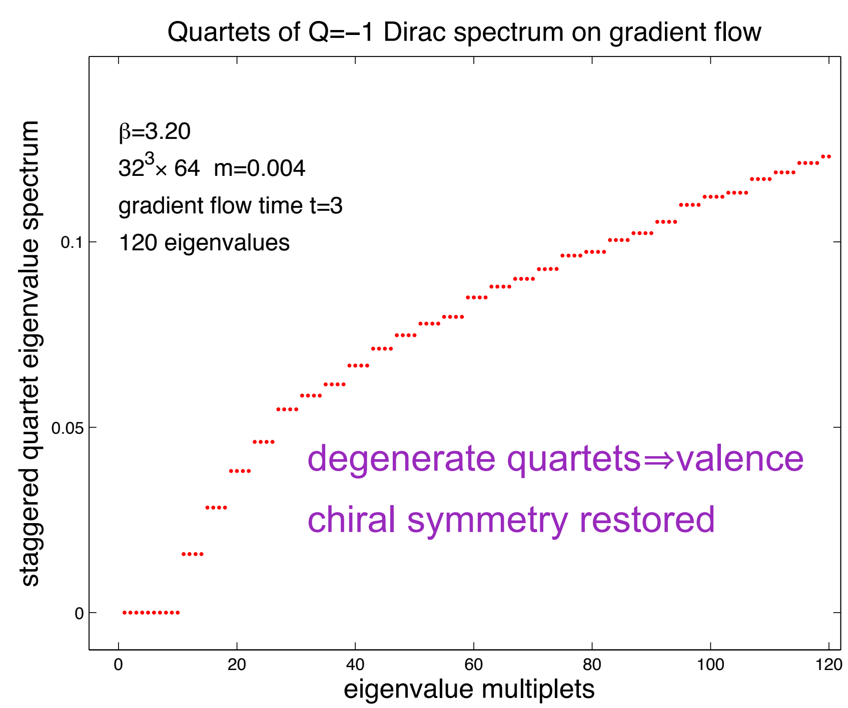

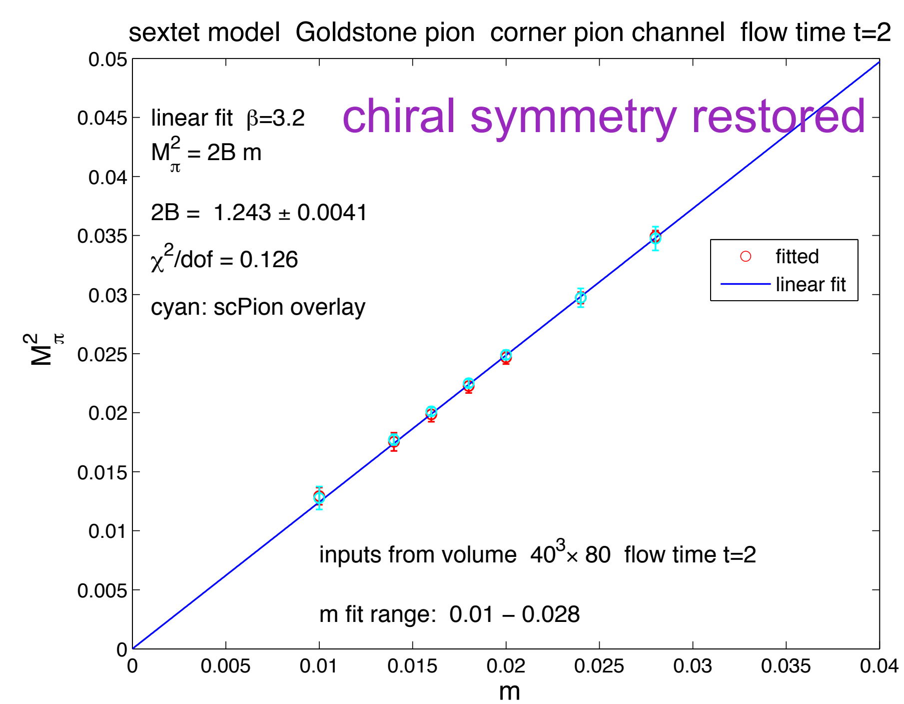

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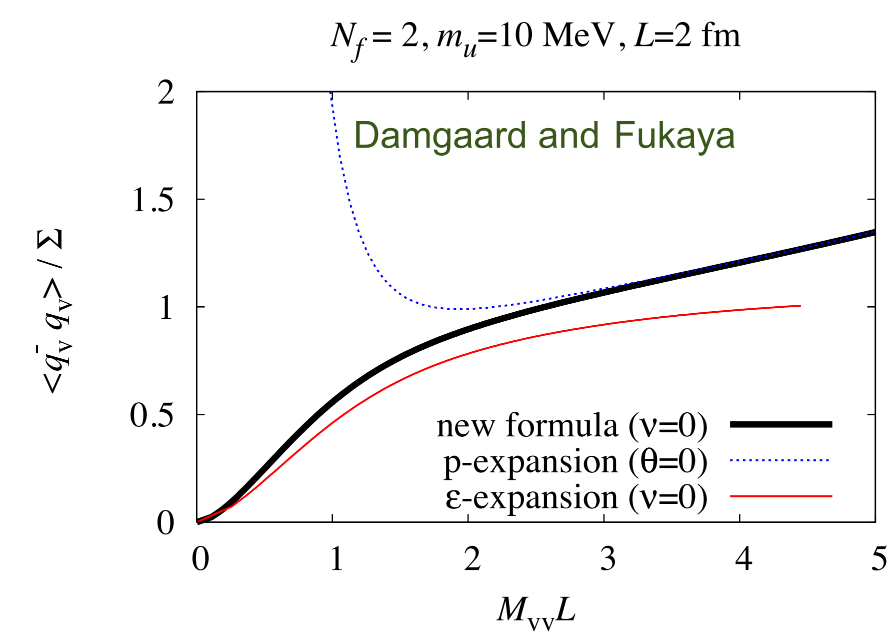
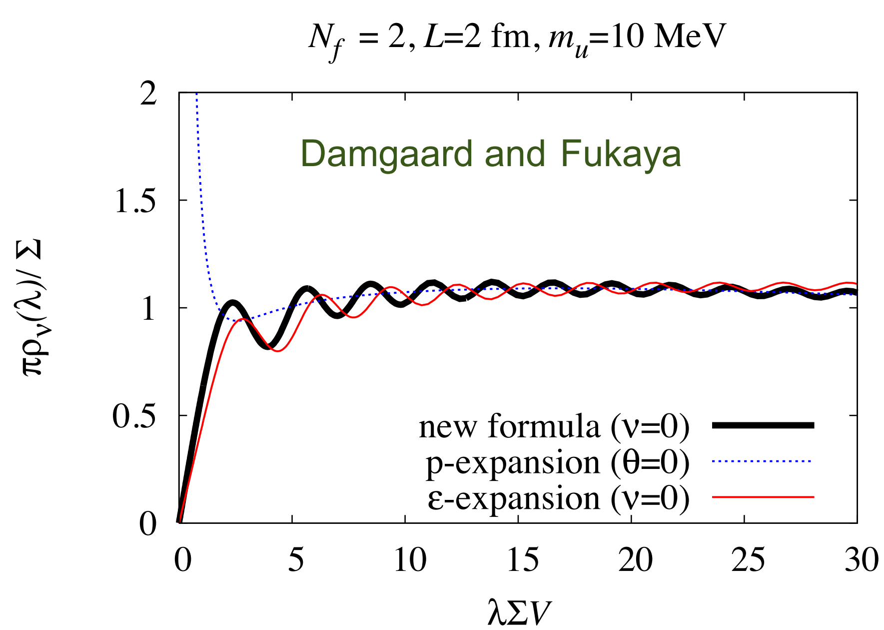
epsilon regime, p regime to epsilon regime crossover, valence pqChiPT with Mixed Action:





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

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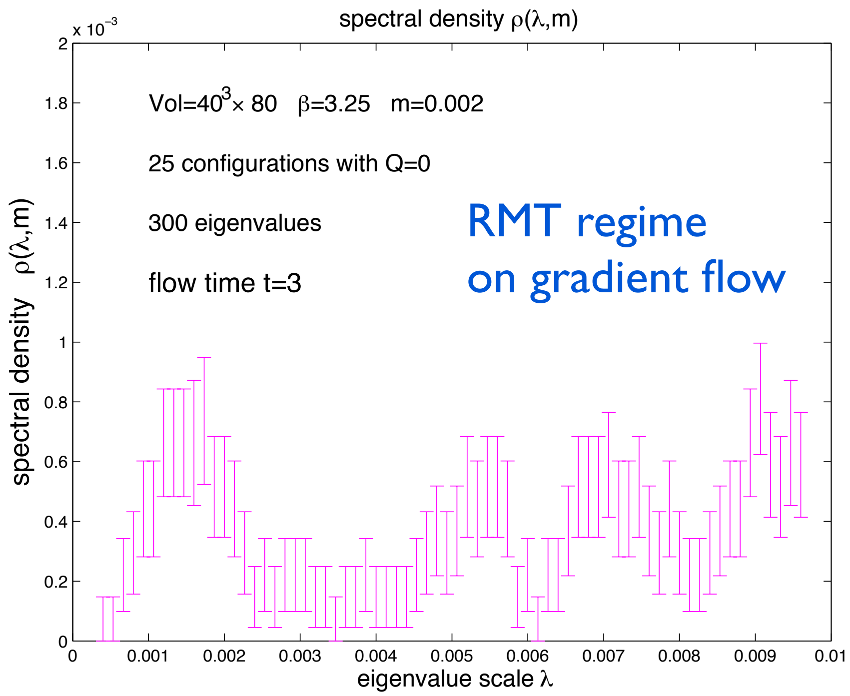

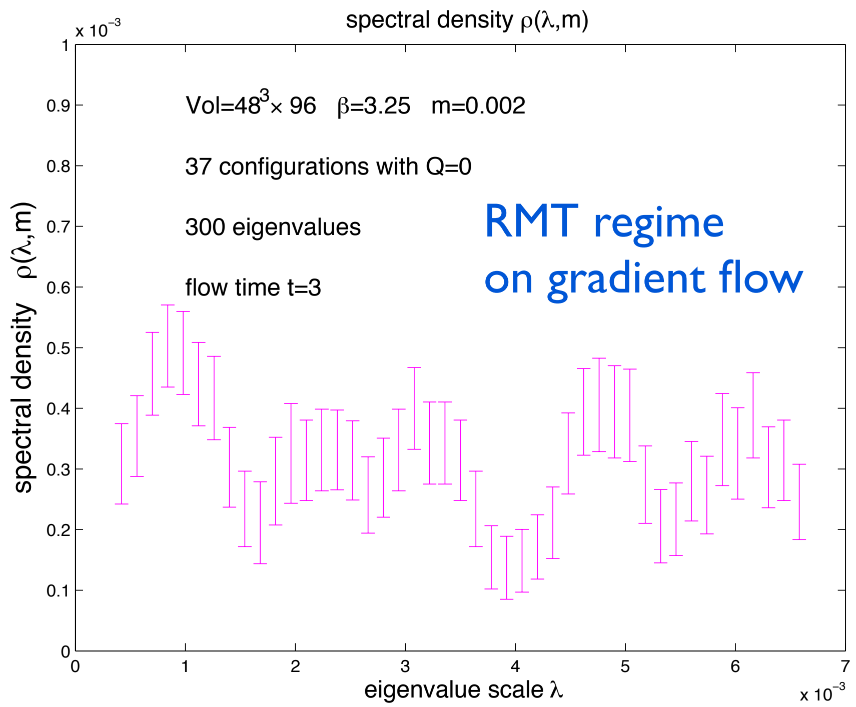

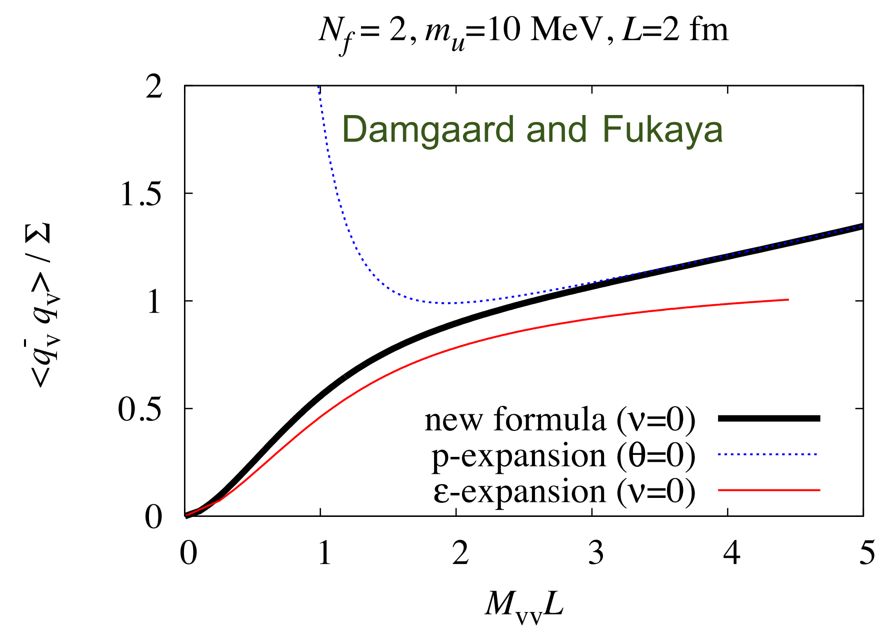

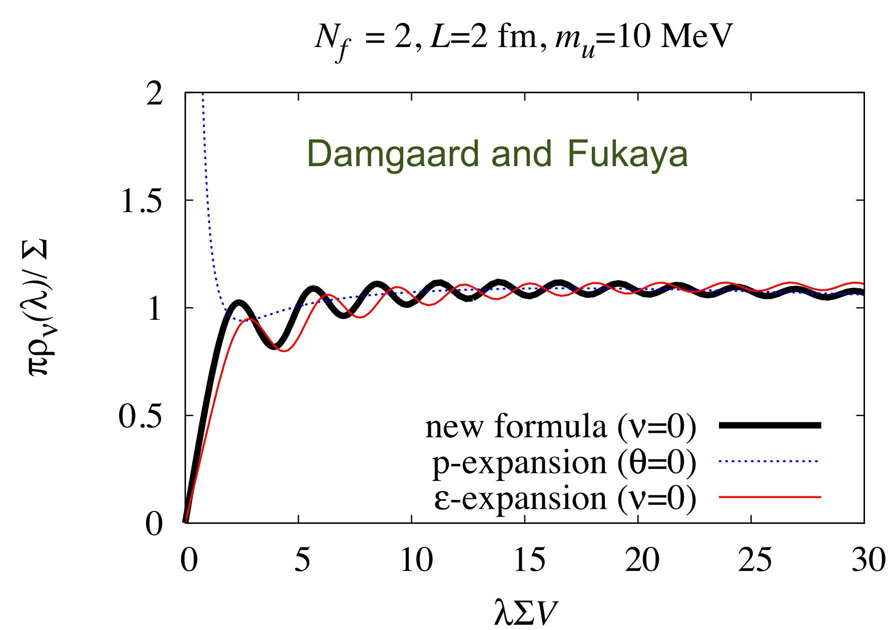

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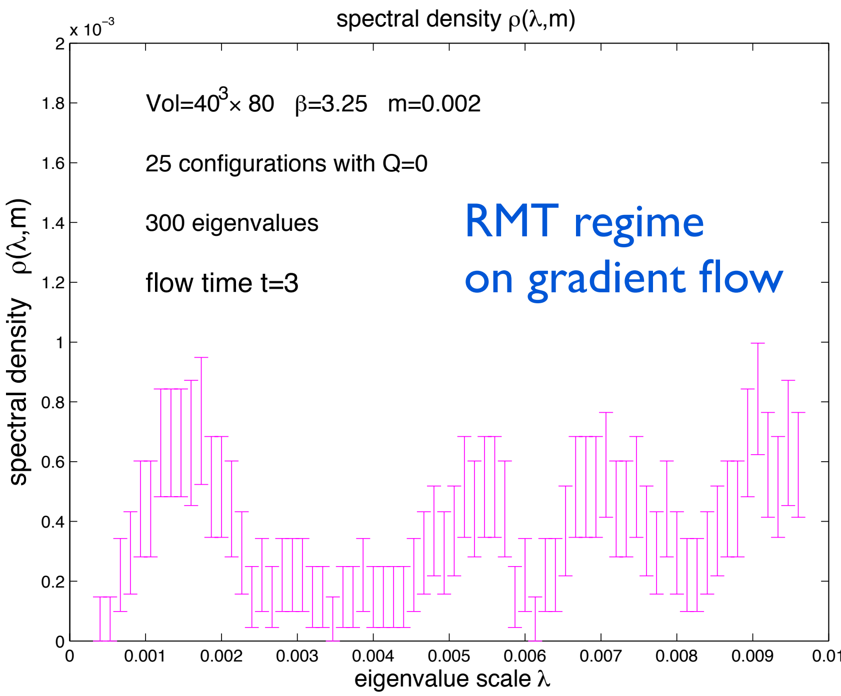
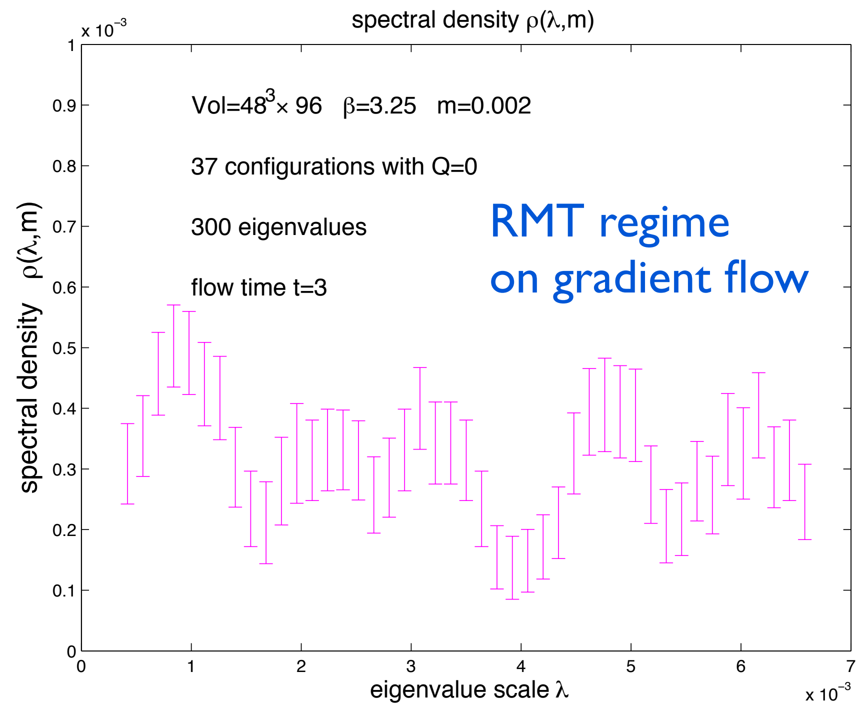
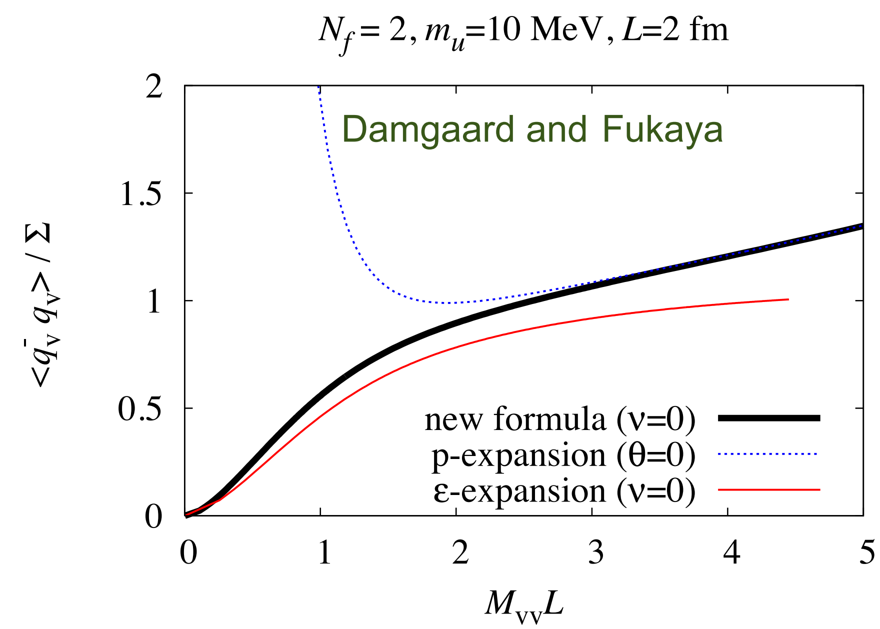
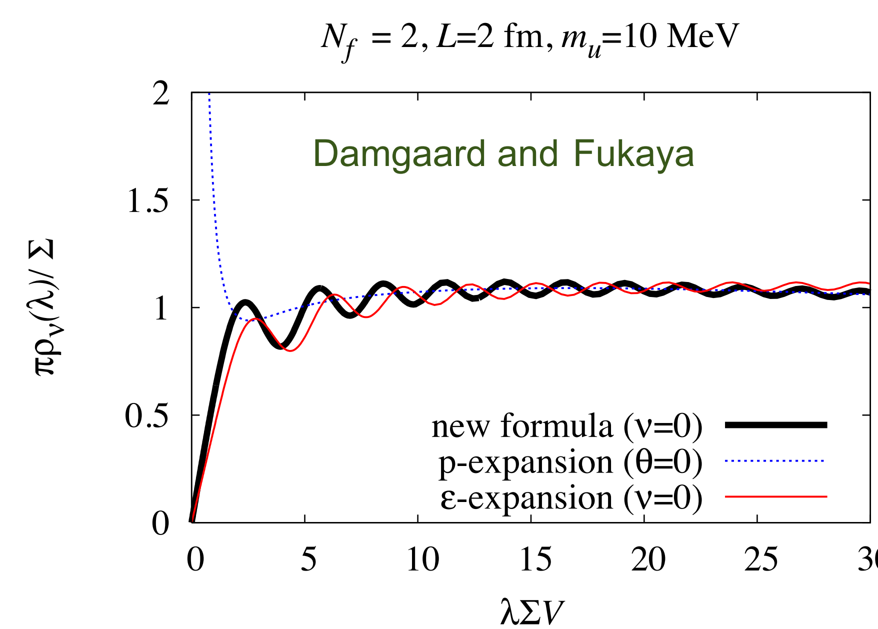








- B drops by large factor after matching, with some small decrease in F
- GMOR implies large drop of order O(10) in the chiral condensate Σ
  Σ is not RG invariant, requires renormalization
- in original analysis mΣV ~ O(100-200)
  to reach RMT regime close to CW would require enormous resources
- in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

The chiral condensate new method

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)

spectral density ρ(t) from ensemble averages over the $D^{\dagger}D$ matrix with dimension N

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

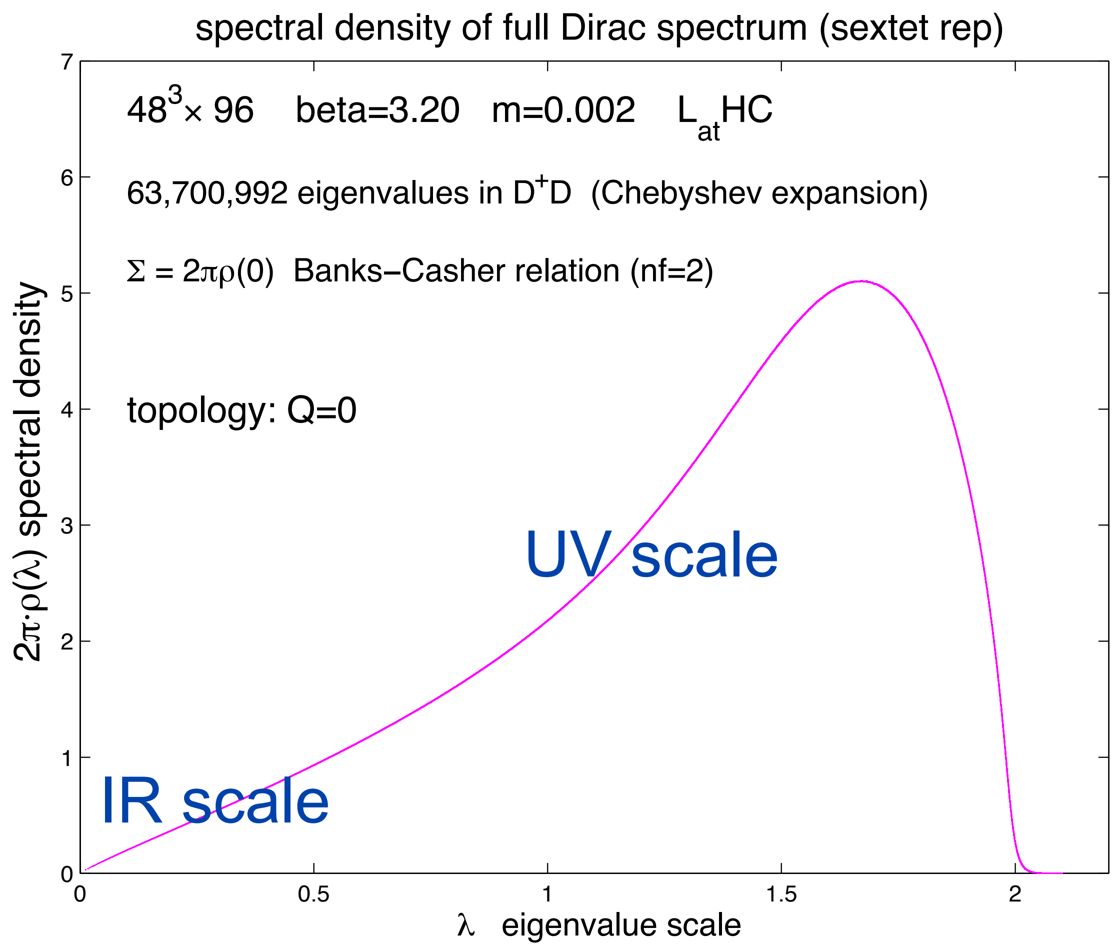
$$\rho(t) = \frac{1}{\sqrt{1-t^2}}\sum_{k=0}^{\infty}c_k T_k(t)$$

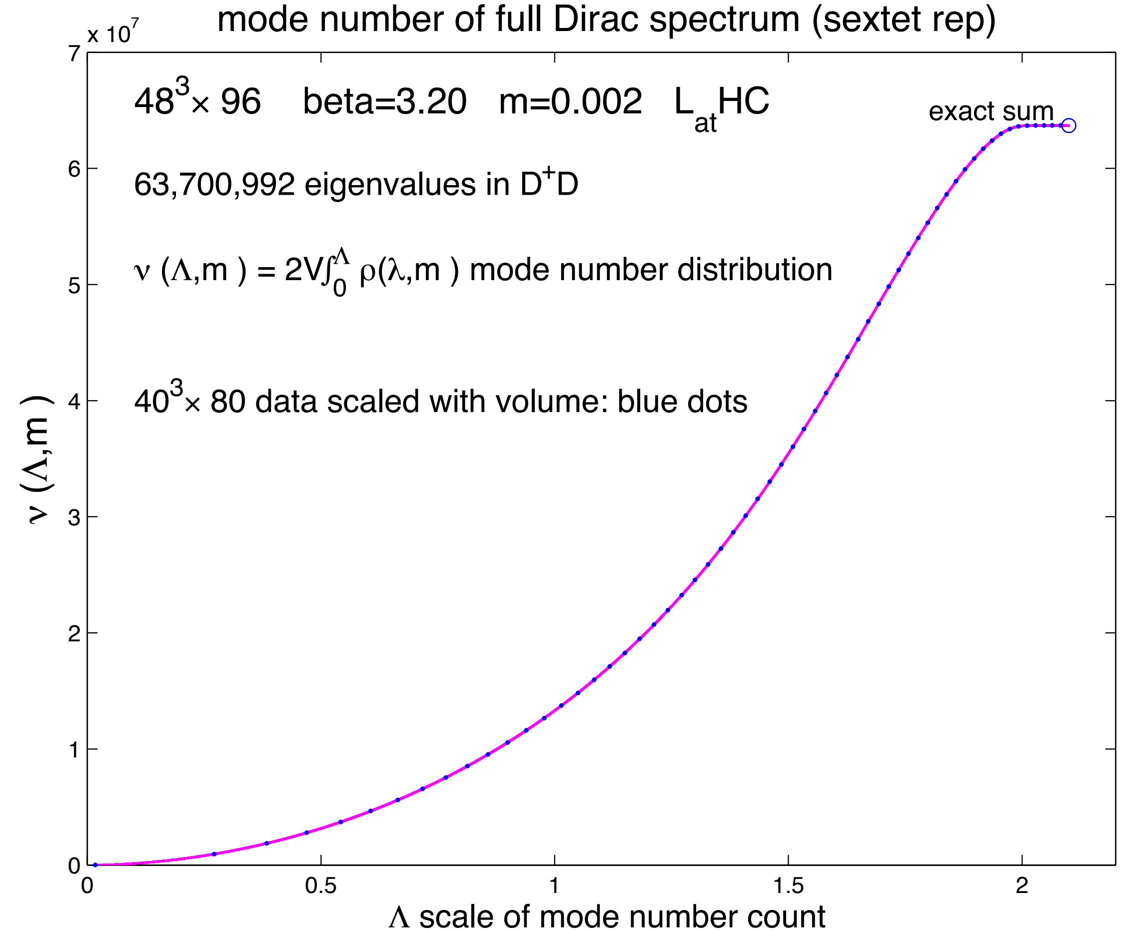
expansion in Cebyshev polynomials

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

$\sum_{i=1}^{N} T_k(\lambda^2{}_i)$ 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.

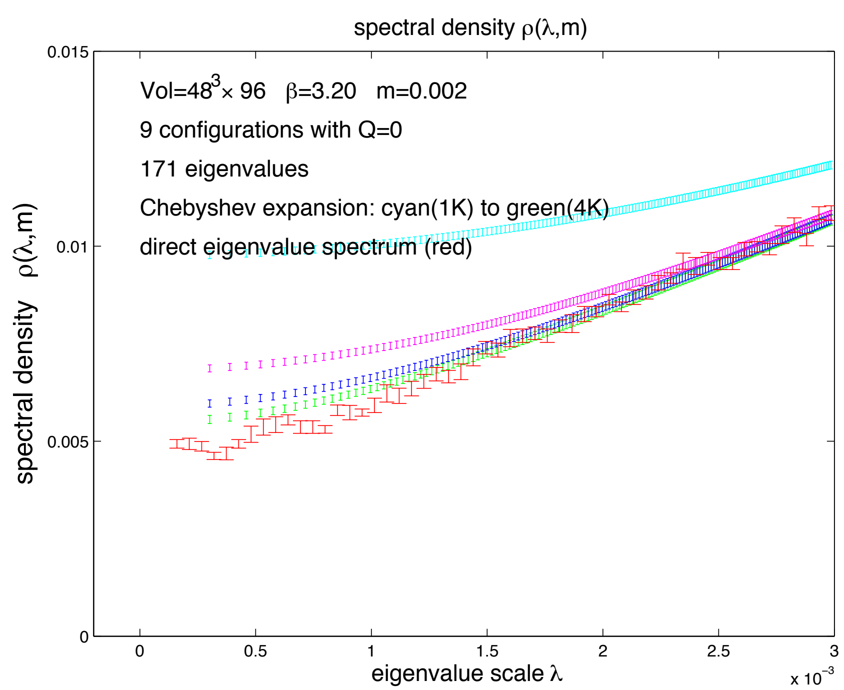
The chiral condensate GMOR test in far IR

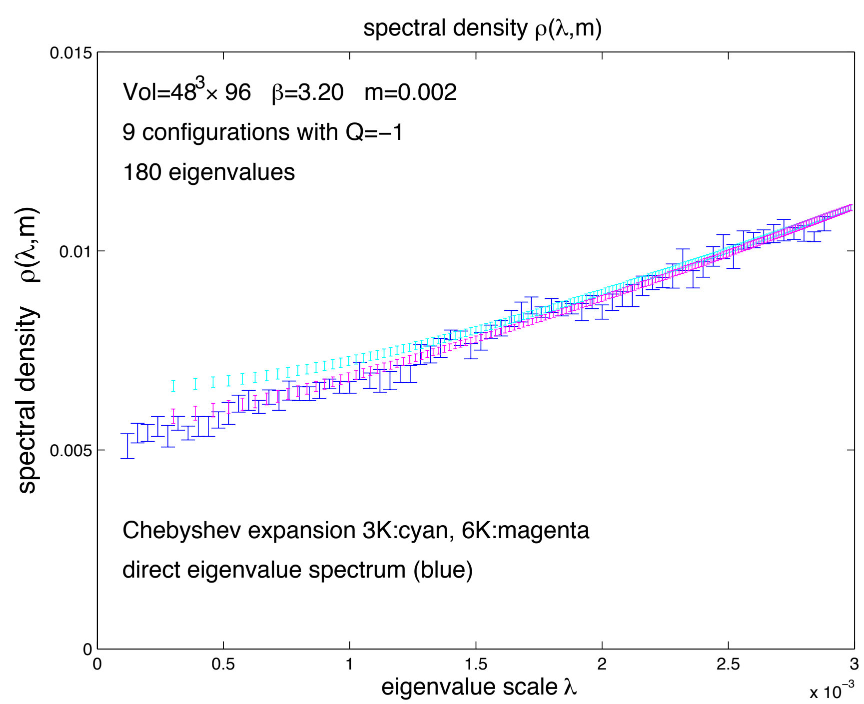
GMOR relation (nf=2): $2BF^2 = \Sigma$ (Σ is the chiral condensate)

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:

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





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

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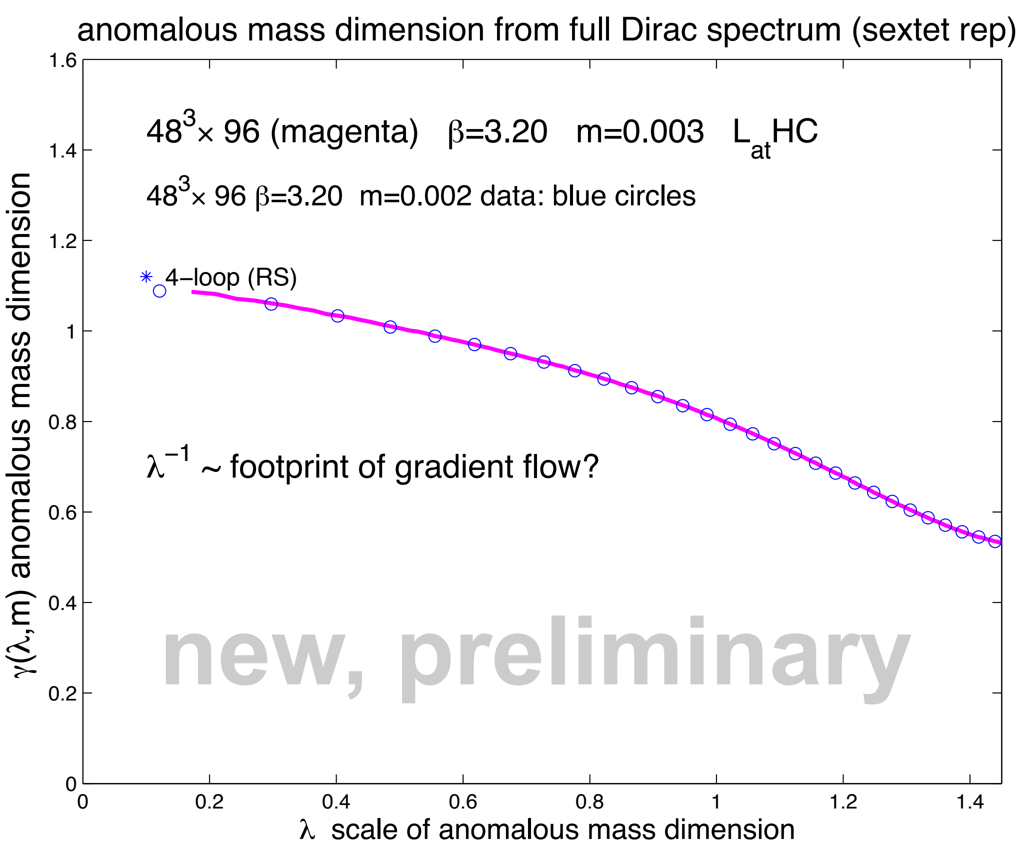

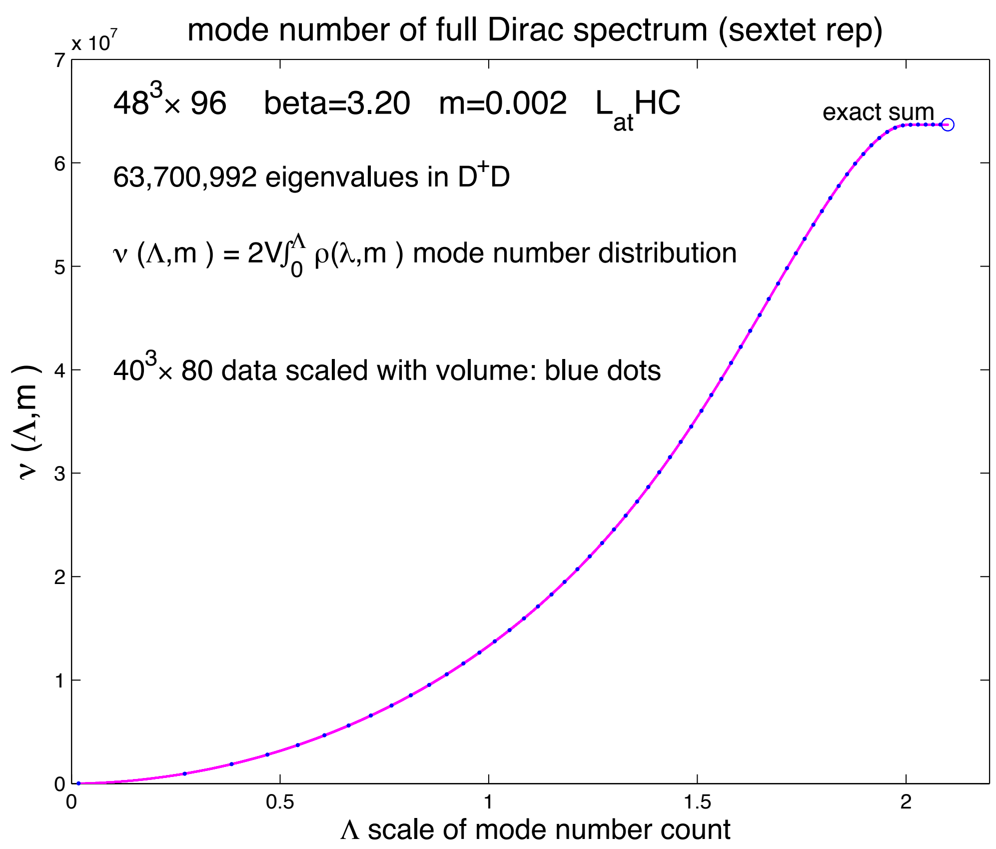

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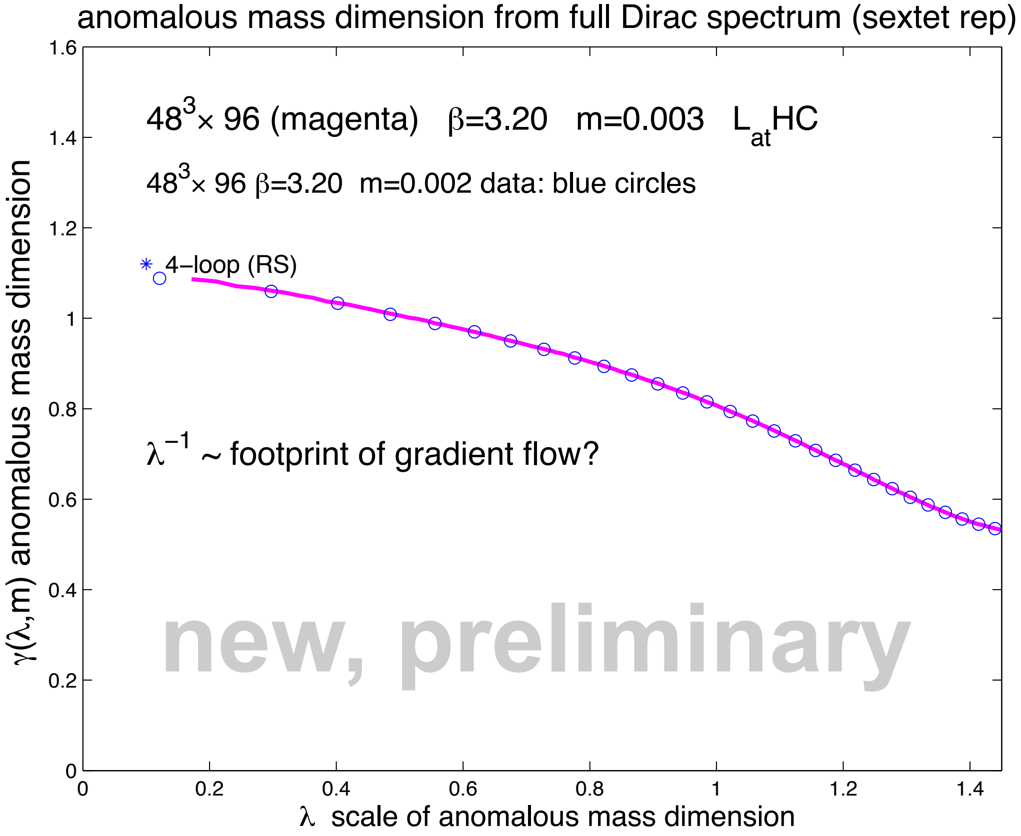

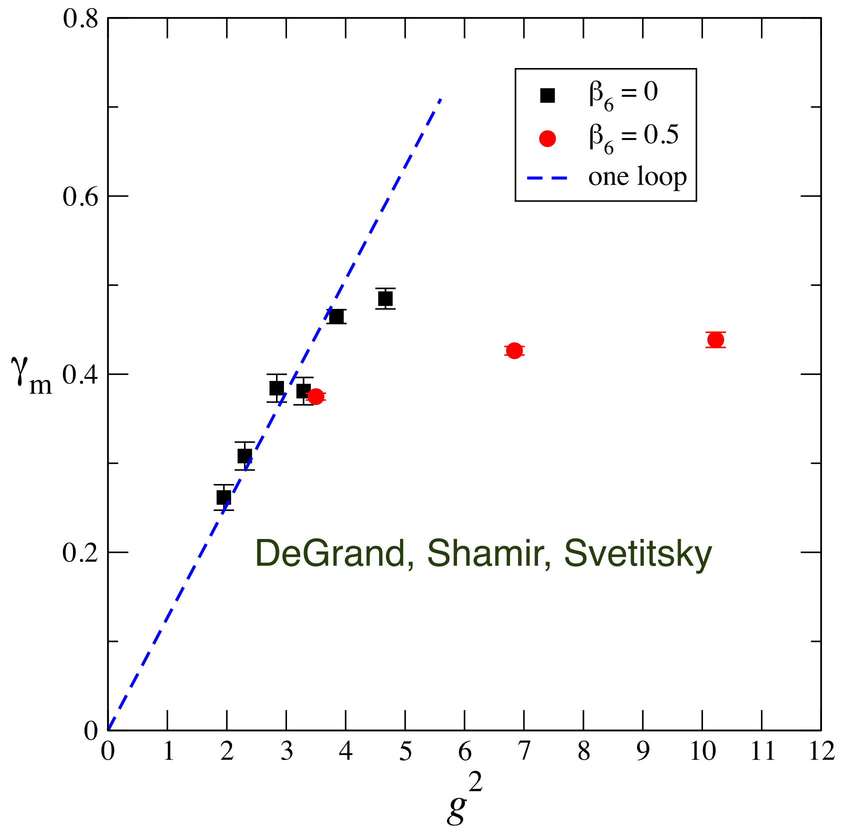

more details on the Nagoya poster!

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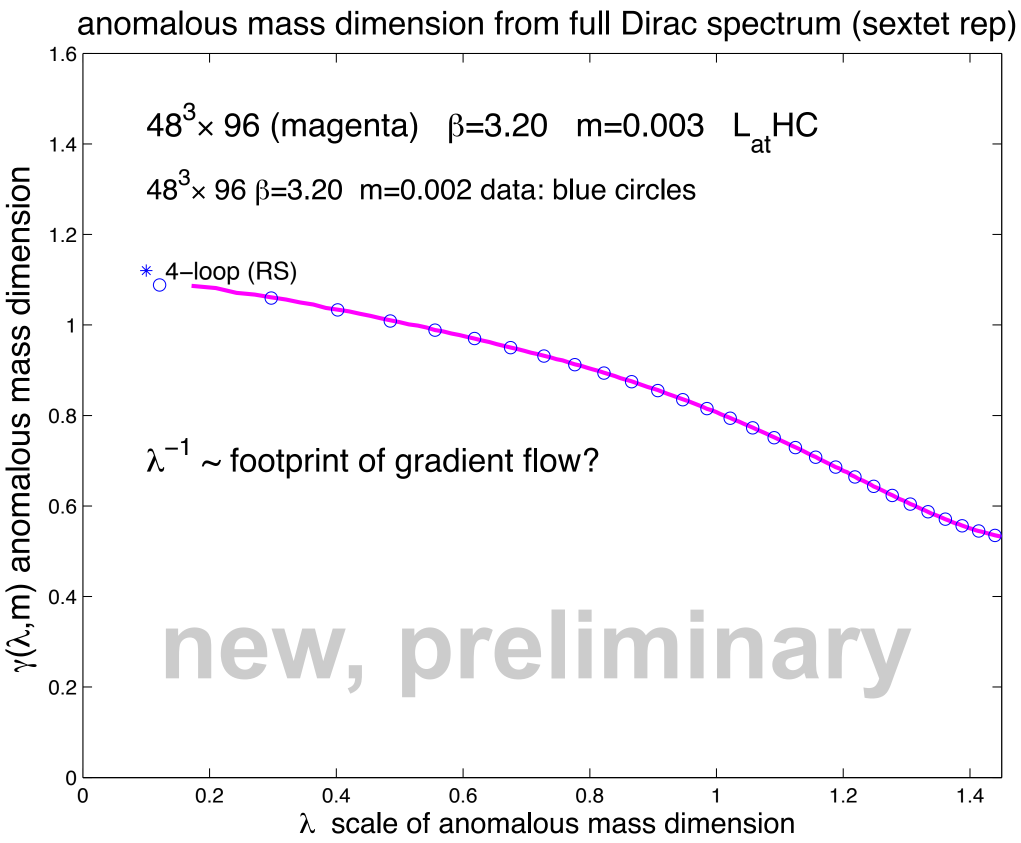

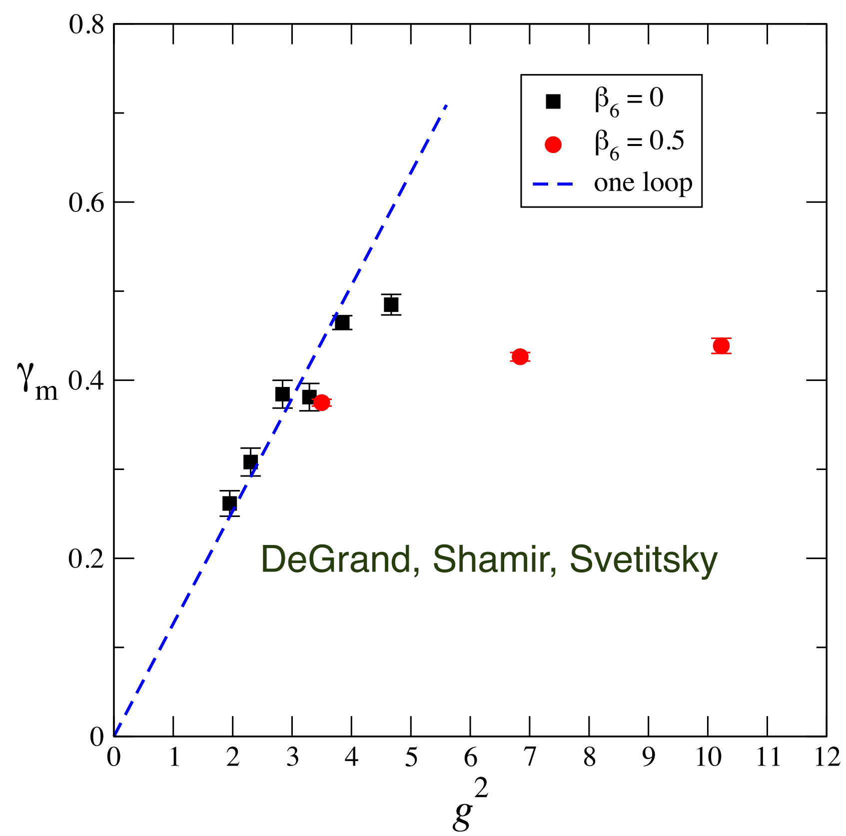

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How to match λ scale and g^2 ?

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

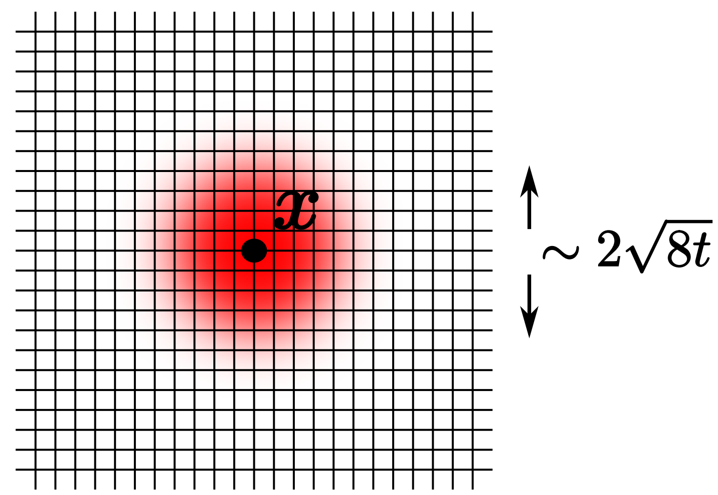
$$\dot{B}_\mu = D_\nu G_{\nu\mu} + \lambda D_\mu \partial_\nu B_\nu$$

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

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

Martin Lüscher

earlier work by Neuberger



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

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

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

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

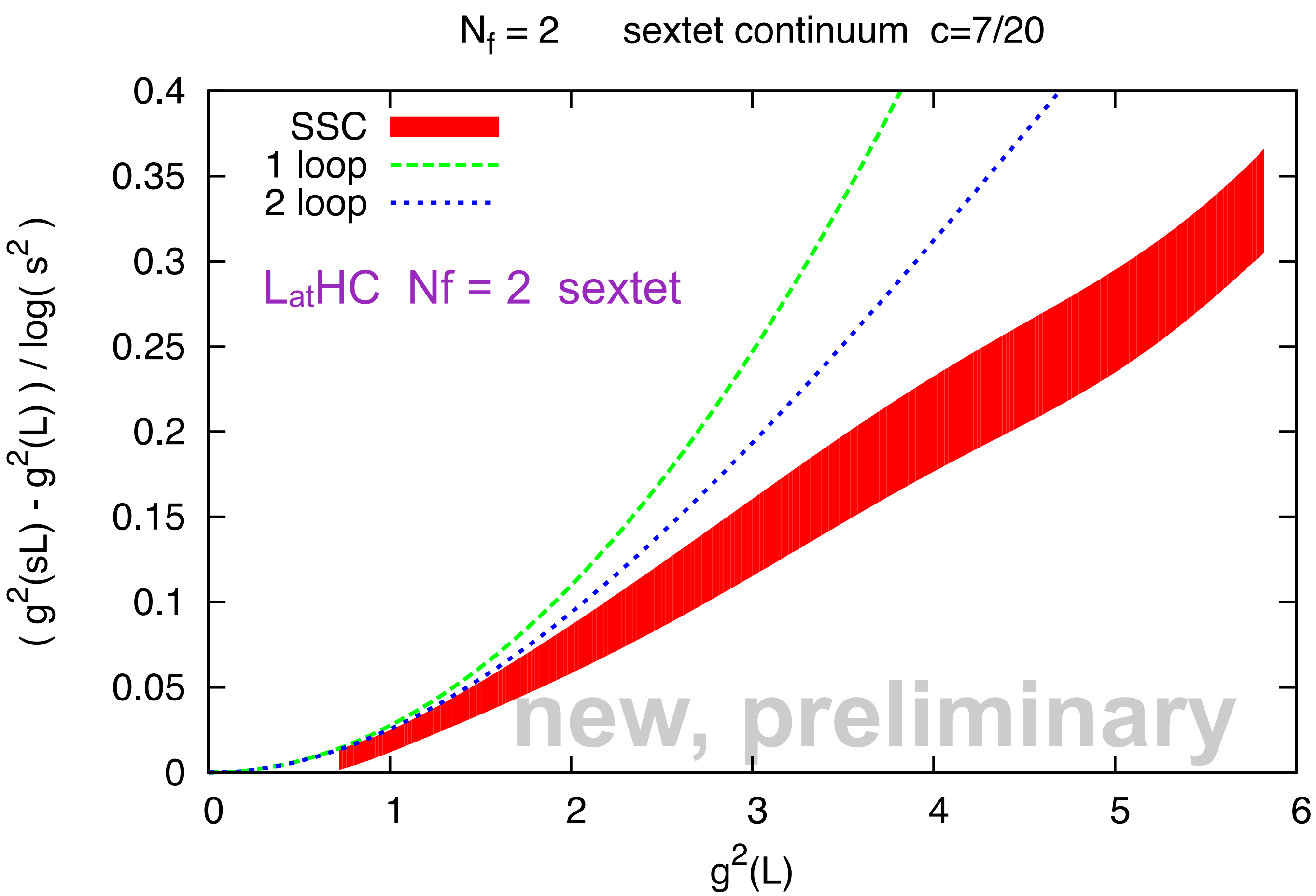
3rd Jacobi function

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

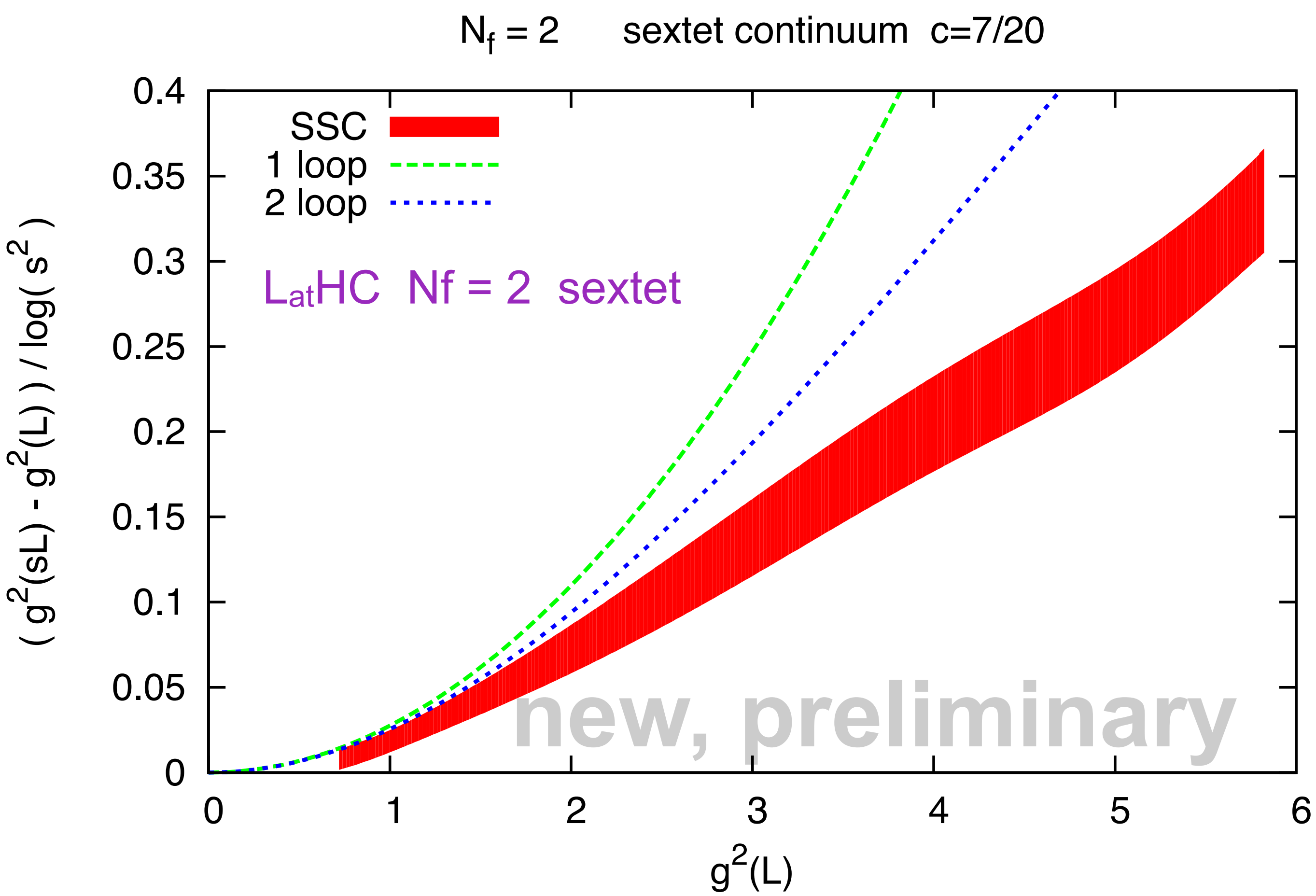


monotonic increase of beta function consistent with:

- mass deformed spectroscopy at low fermion mass
- chiral condensate
- GMOR
- mass anomalous dimension
- connection with $g^2(t,m)$ in bulk with chiSB

lattice step functions: 12→18, 16→24, 20→30, 24→36
last two step functions are critical in the analysis:
SSC vs. WSC are consistent at large flow times which requires the large volumes

the running coupling and the β function   finite volume



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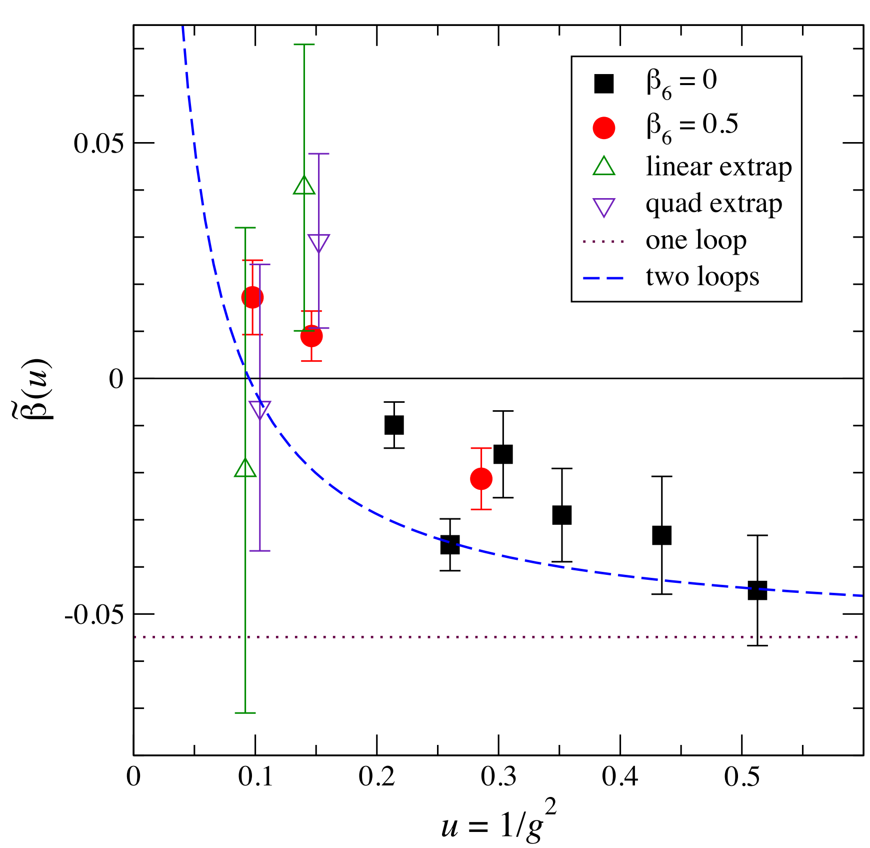
DeGrand, Shamir, Svetitsky



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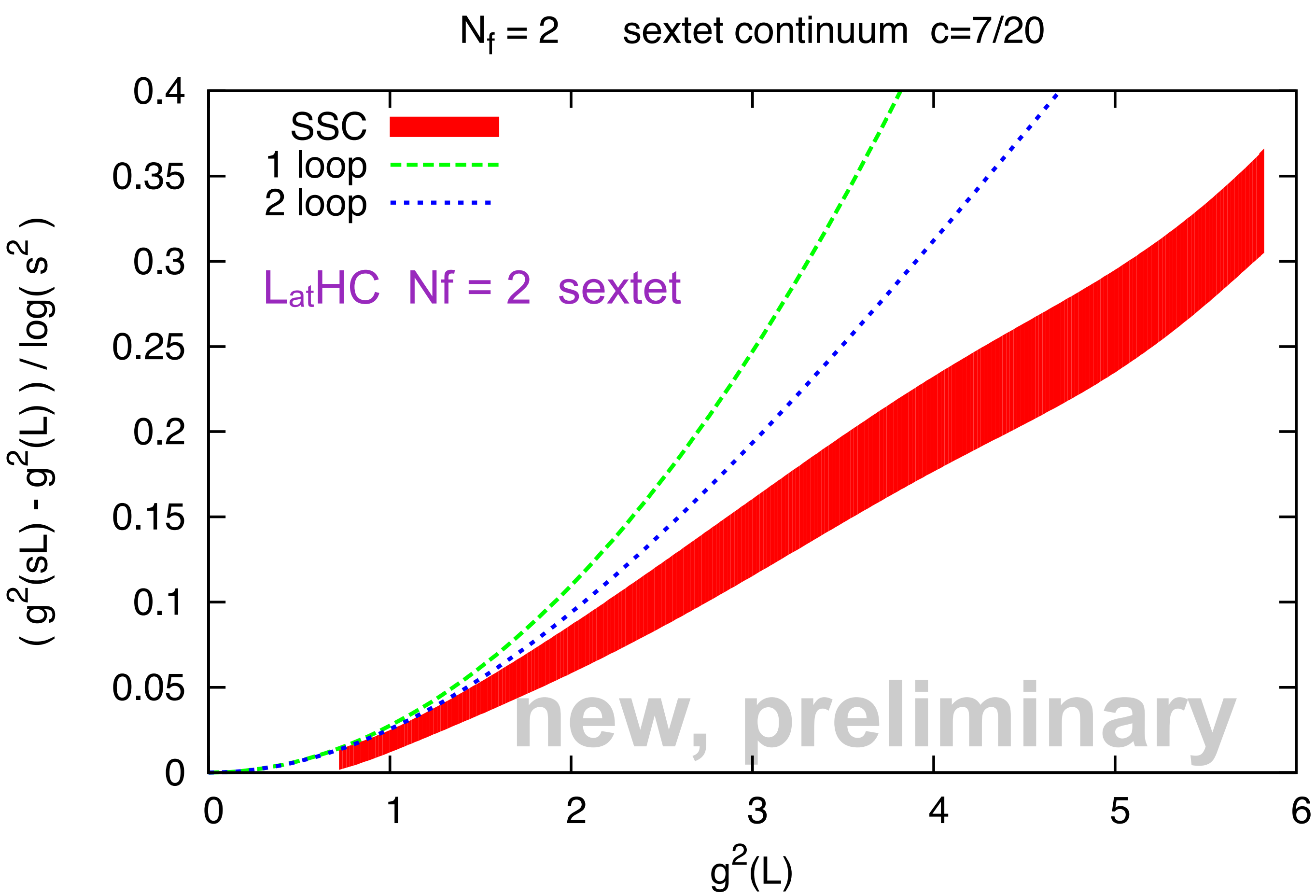

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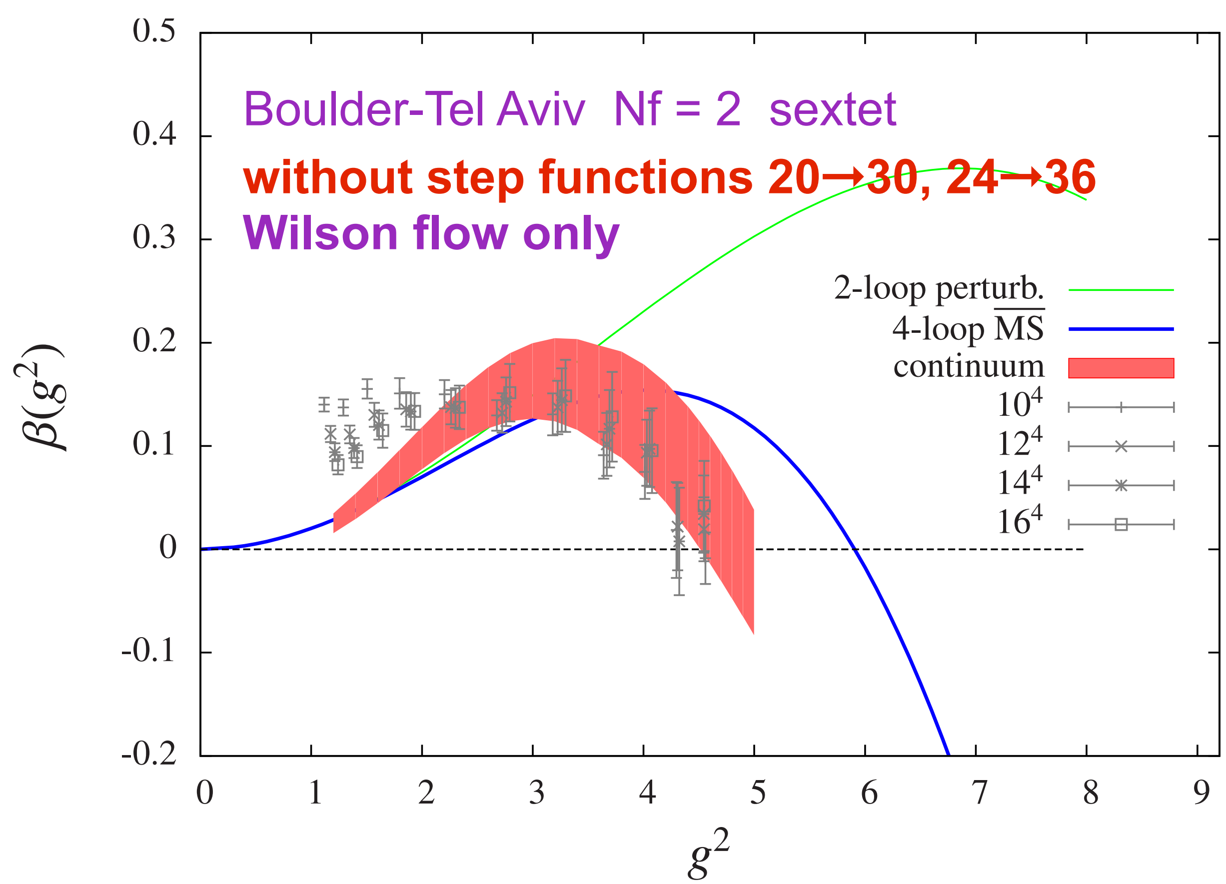

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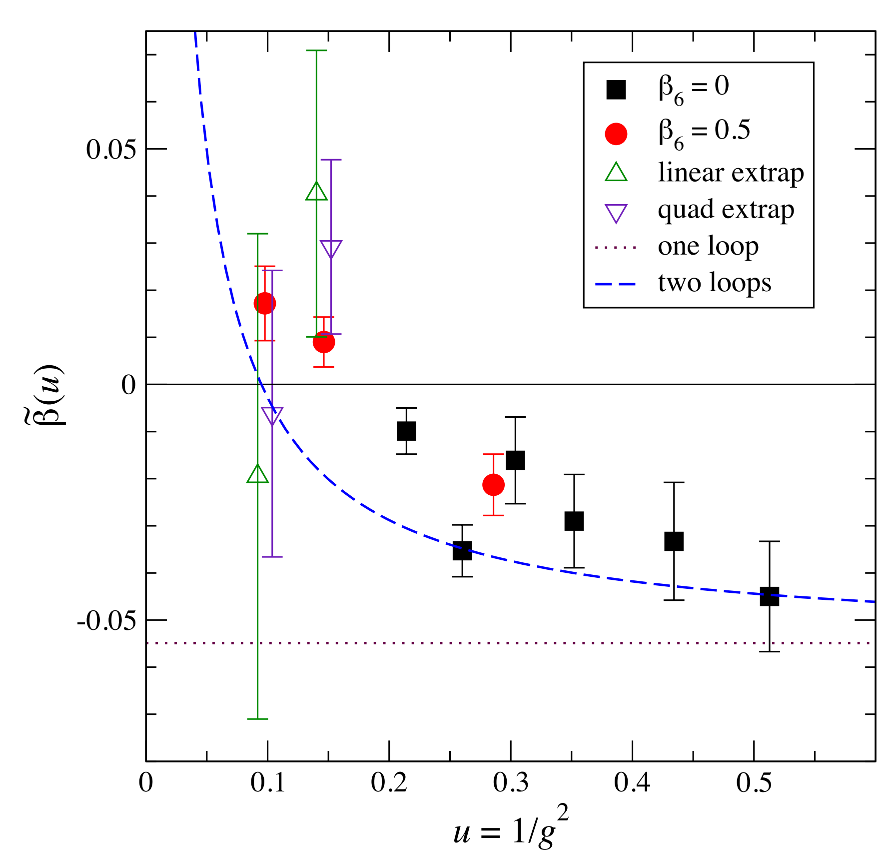

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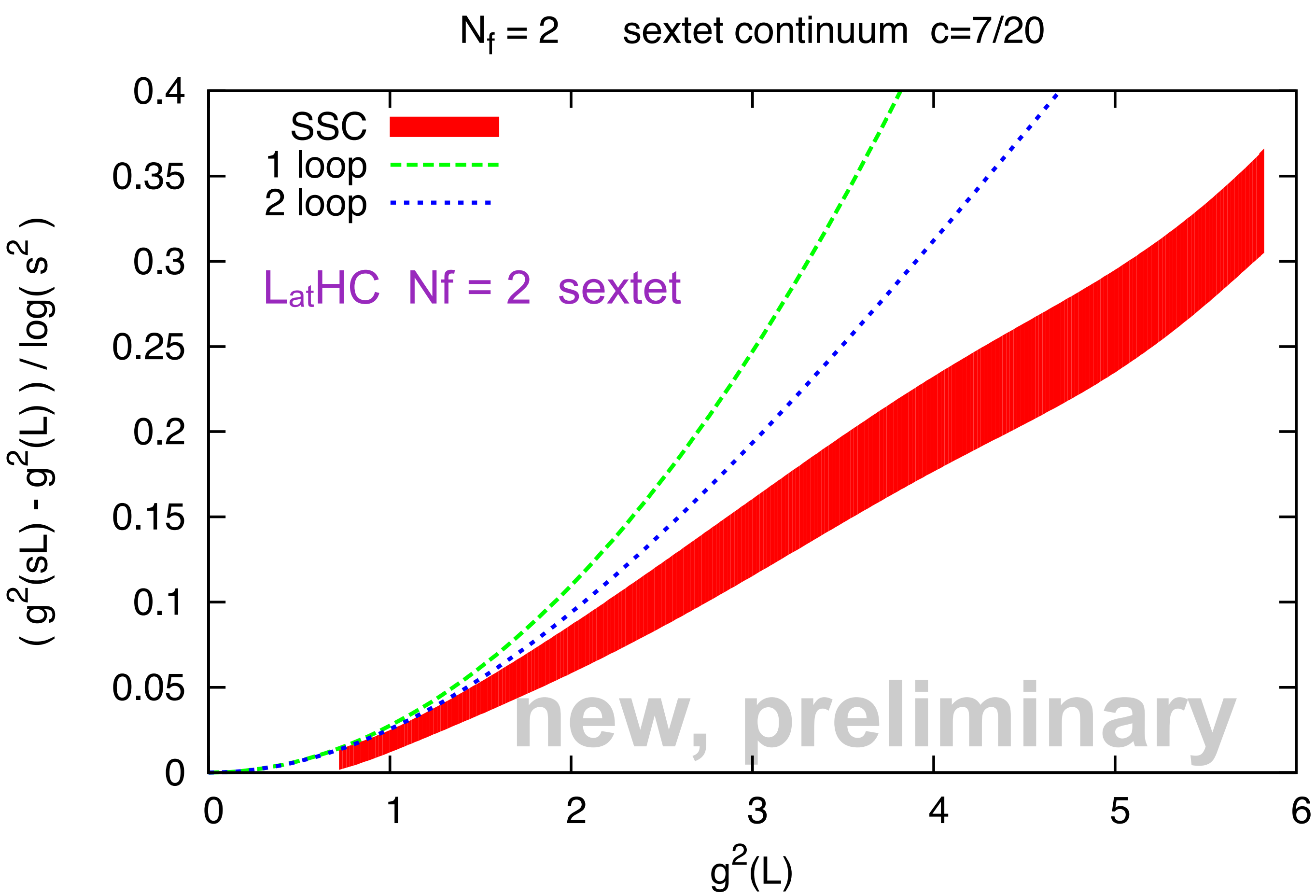

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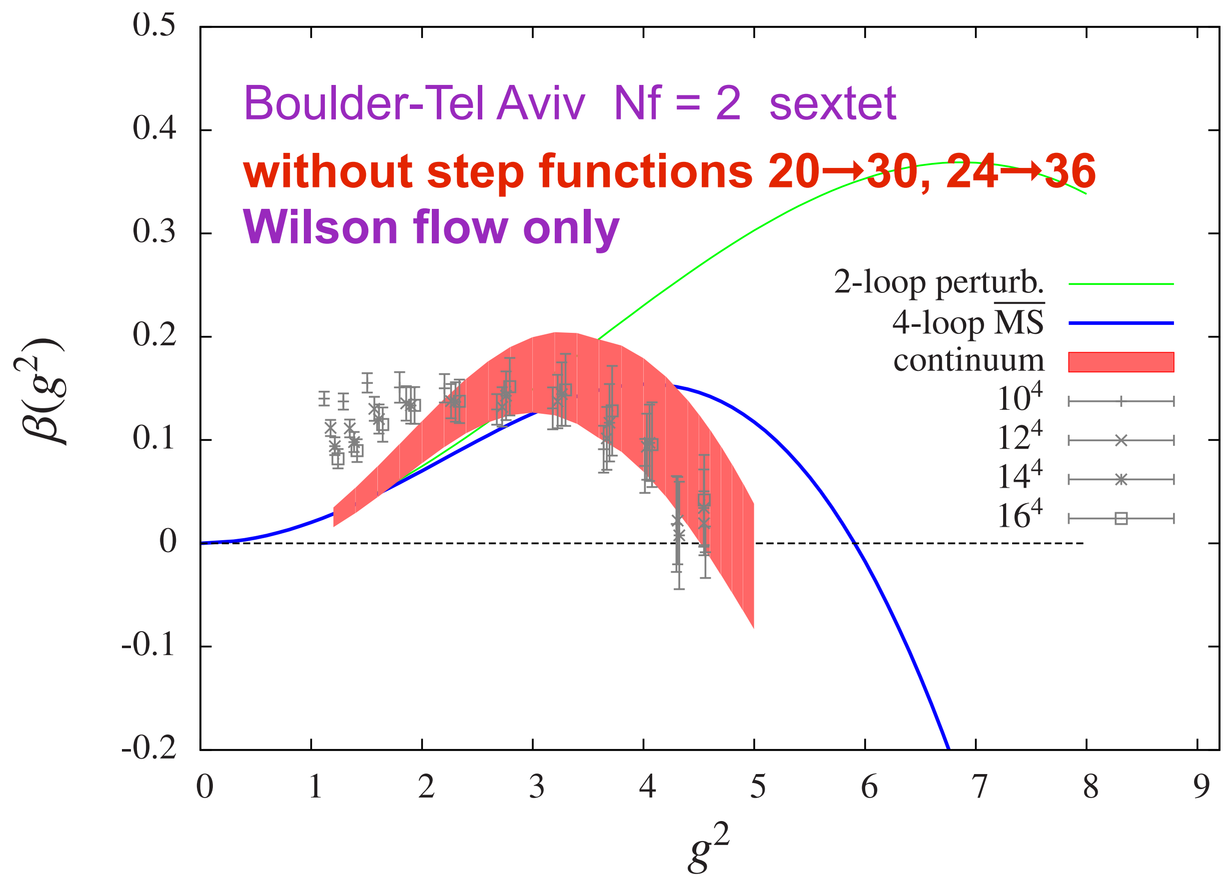
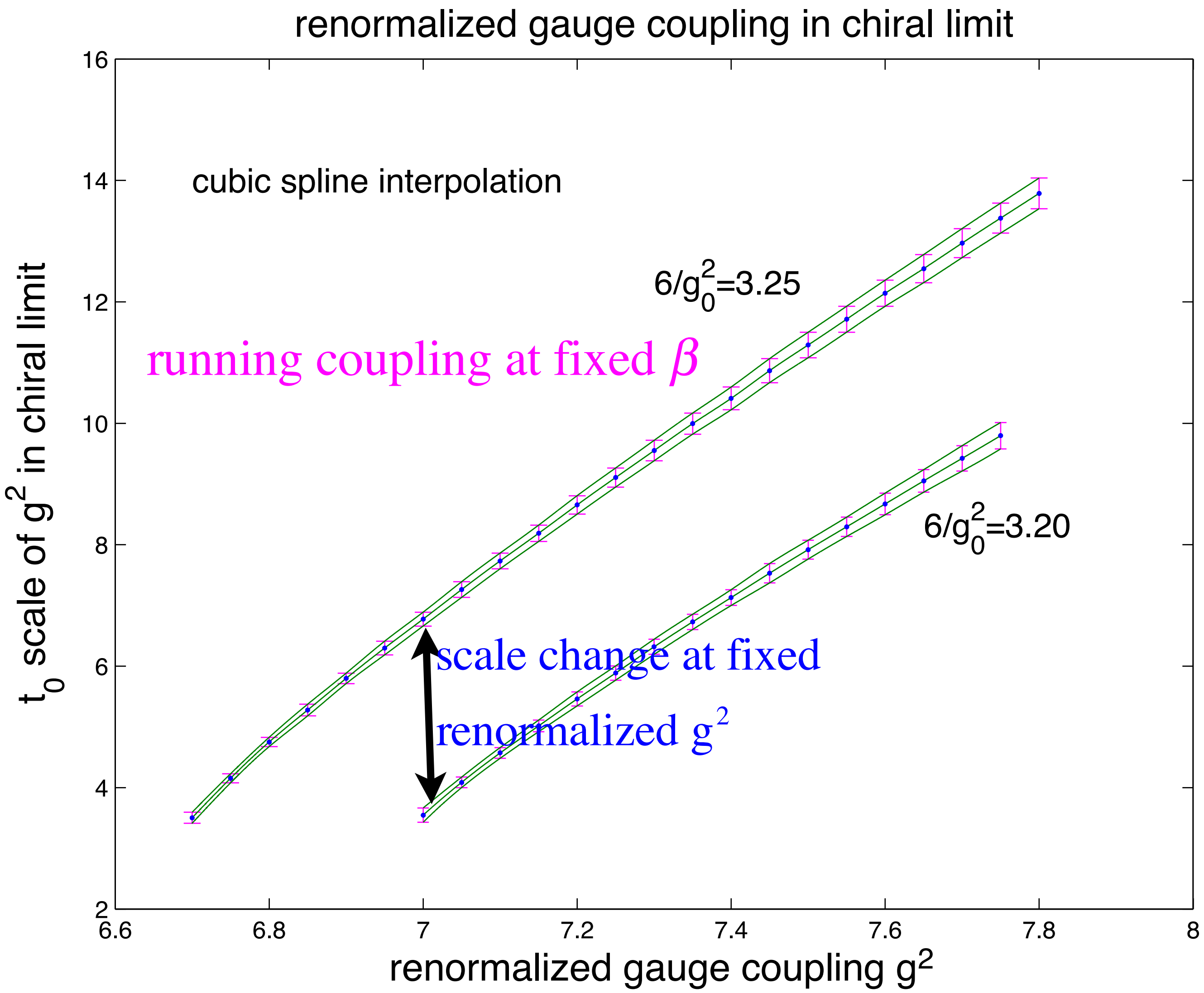
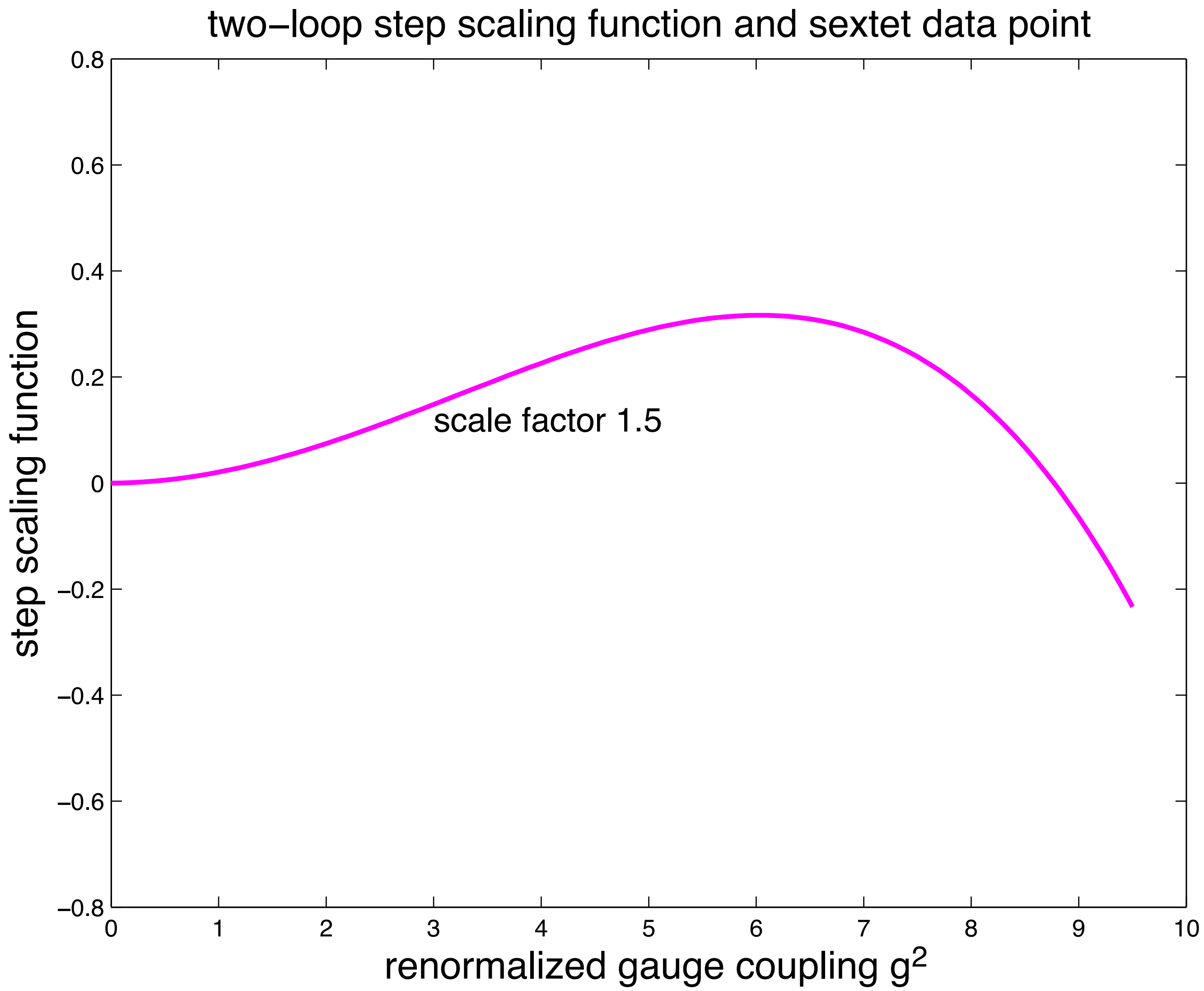


This disagreement is between two groups and not about criticizing the staggered formulation

besides: promoting a beta function zero to conformal IRFP would require to remove the cutoff with the ω scaling exponent

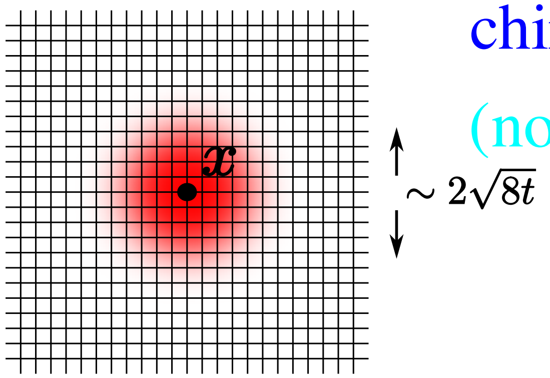
the running coupling and the β function infinite volume





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



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

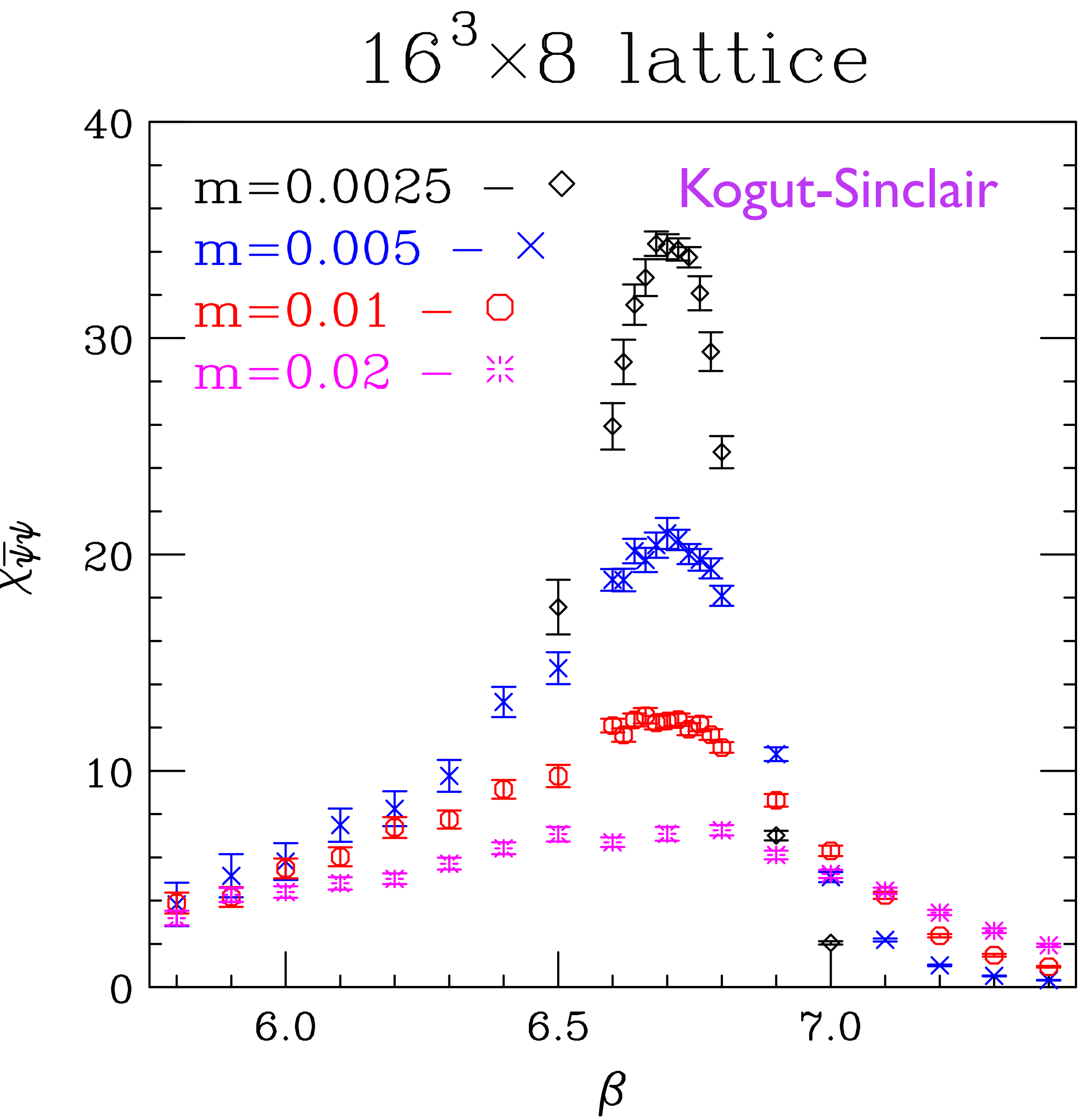
(not deep enough in leading log chiPT regime)

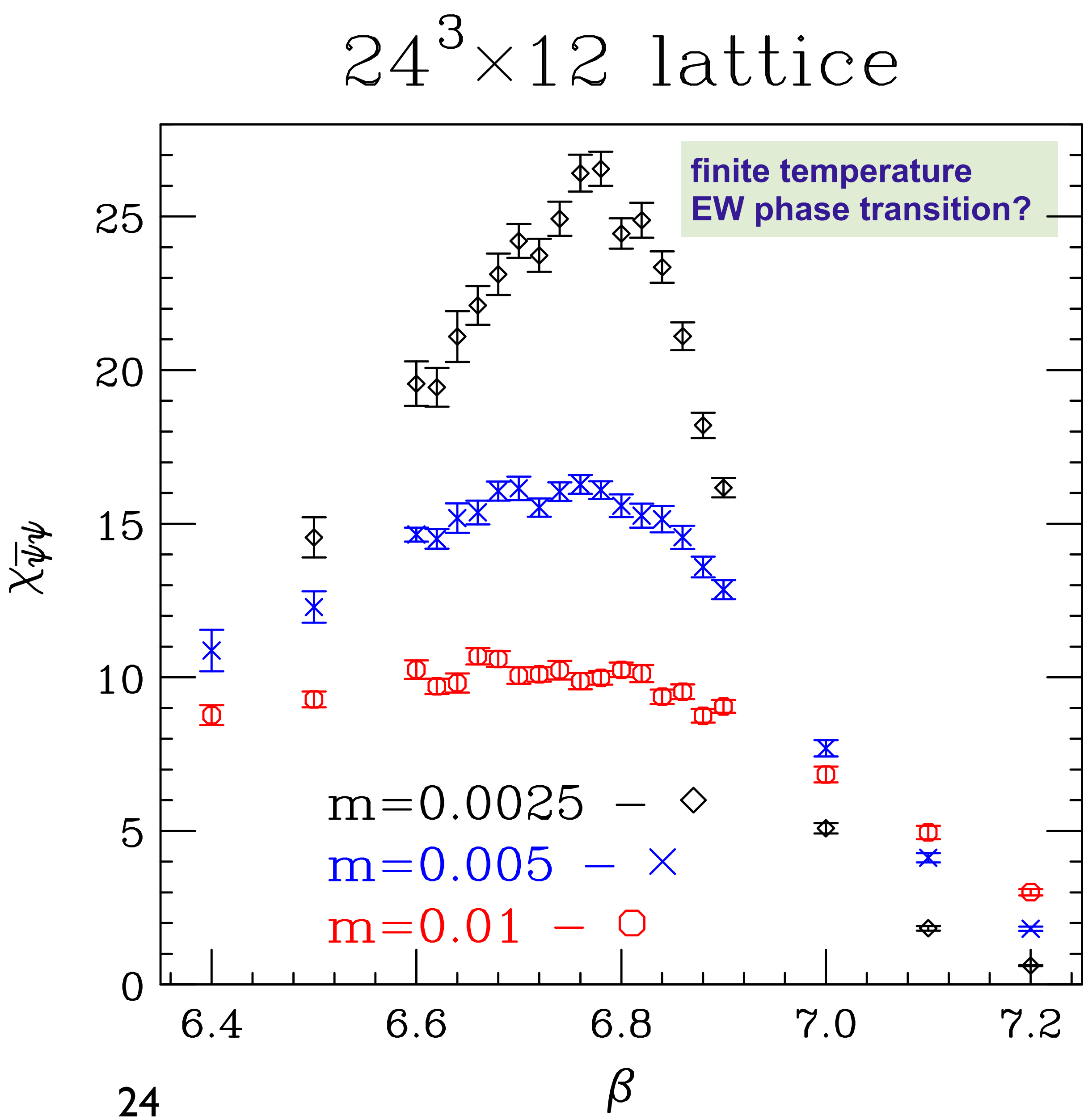
Early universe

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

- 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?

Three $SU(3)$ sextet fermions can give rise to a color singlet. The tensor product $6 \otimes 6 \otimes 6$ can be decomposed into irreducible representations of $SU(3)$ as,

$$6 \otimes 6 \otimes 6 = 1 \oplus 2 \times 8 \oplus 10 \oplus \overline{10} \oplus 3 \times 27 \oplus 28 \oplus 2 \times 35$$

where irreps are denoted by their dimensions and $\overline{10}$ is the complex conjugate of 10.

Fermions in the 6-representation carry 2 indices, ψ_{ab}, and transform as

$$\psi_{aa'} \longrightarrow U_{ab}\ U_{a'b'}\ \psi_{bb'}$$

and the singlet can be constructed explicitly as

$$\varepsilon_{abc}\ \varepsilon_{a'b'c'}\ \psi_{aa'}\ \psi_{bb'}\ \psi_{cc'}.$$

Summary: simplest composite scalar is probably very light (near conformality?)

• light scalar (dilaton-like?) emerging	close to conformal window?
• spectroscopy	emerging resonance spectrum ~ 2-3 TeV
• chiral condensate, large $\gamma(\lambda)$	new method is very promising
• running (walking) coupling in progress	difficult, Gradient Flow is huge improvement
• Electroweak phase transition and baryon	intriguing