USQCD 2015

objective: minimal realization of light composite Higgs

Lattice Higgs Collaboration ($\mathrm{L_{at}HC}$)

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USQCD Collaboration Meeting

May 1-2, 2015, Fermilab

What is our composite Higgs terminology?

the Higgs doublet field

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

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

The Higgs Lagrangian is

spontaneous symmetry breaking

Higgs mechanism

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

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

strongly coupled gauge theory

N_f fermions in gauge group reps

needle in the haystack?

or, just one of the haystacks?

Outline

Near-conformal SCGT?

light scalar close to conformal window effective theory?
scale setting and spectroscopy
systematics and mixed action

Chiral Higgs condensate

GMOR and mode number
epsilon regime and RMT
large mass anomalous dimension?

Scale dependent renormalized coupling

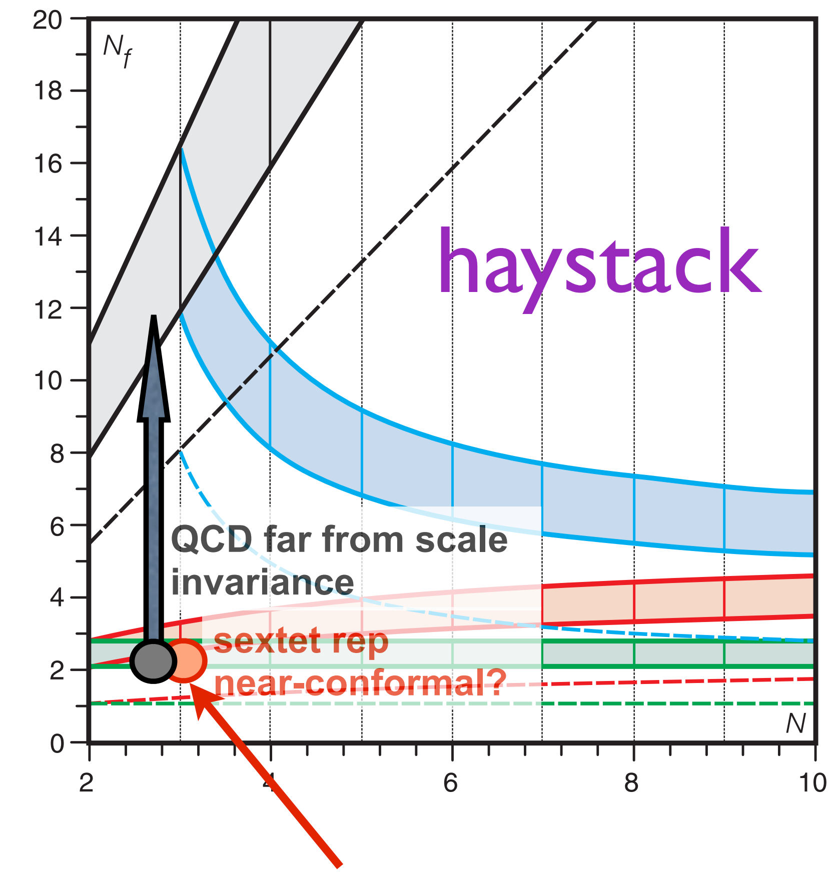
matching scale dependent coupling from
form UV to IR with chiSB

Early universe

EW phase transition, sextet baryon, and dark matter

Summary

SCGT Theory Space



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

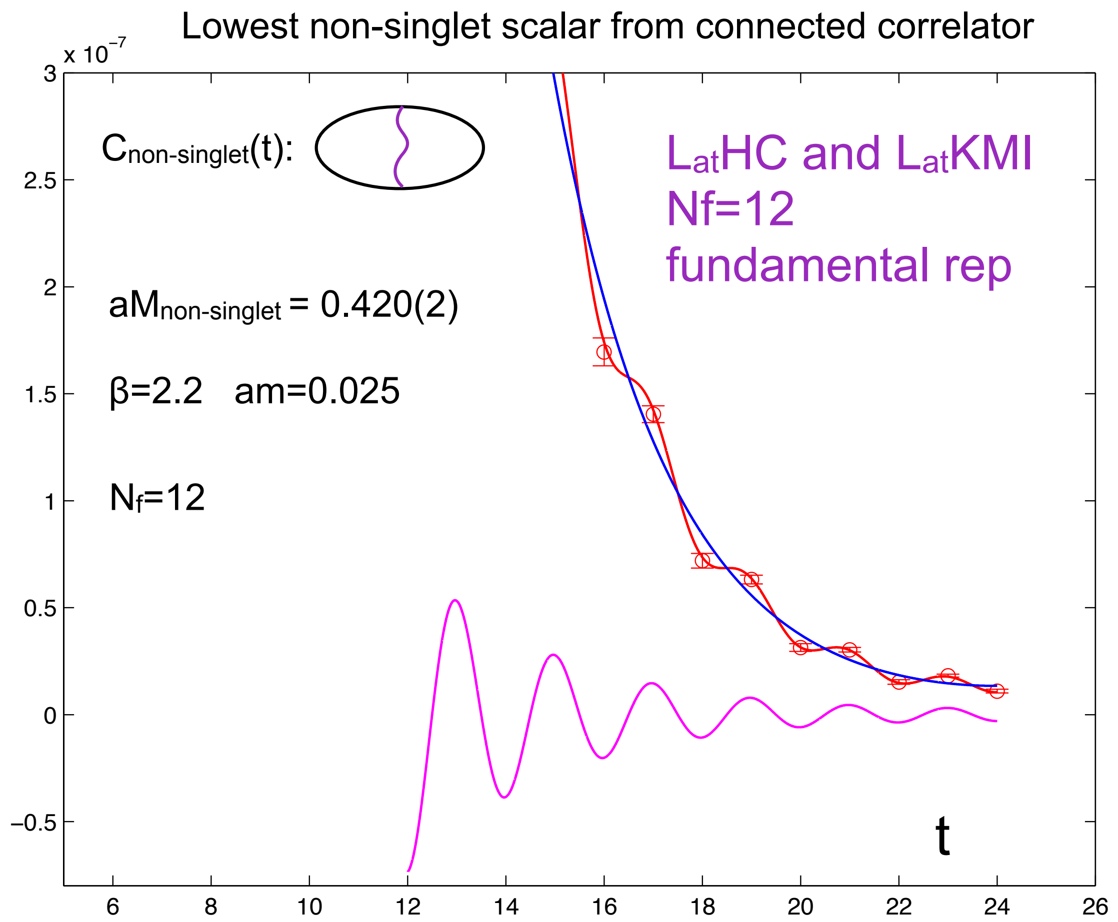
QCD intuition for near-conformal compositeness is just plain wrong

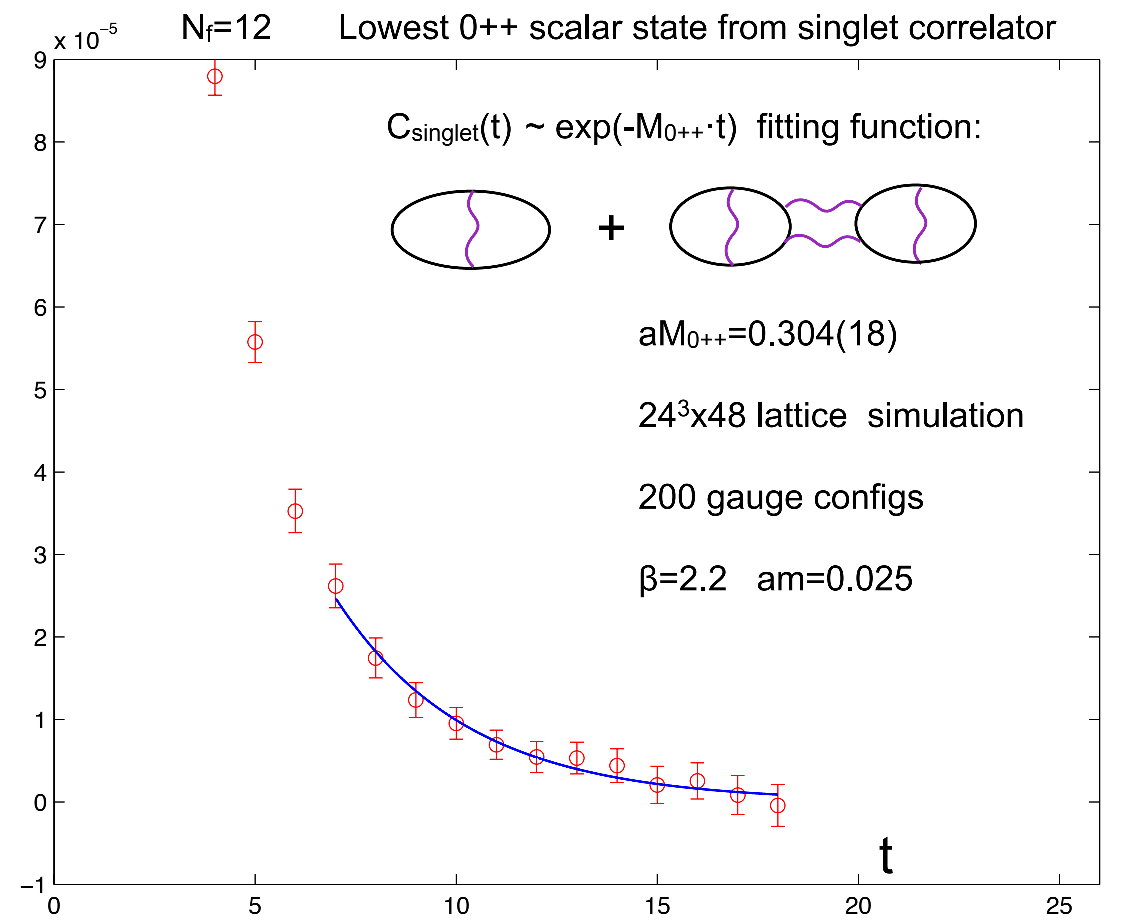
Technicolor thought to be scaled up QCD
motivation of the project:
composite Higgs-like scalar close to the conformal window

light 0++ scalar and spectrum

2013-14 testing

test of scalar technology:

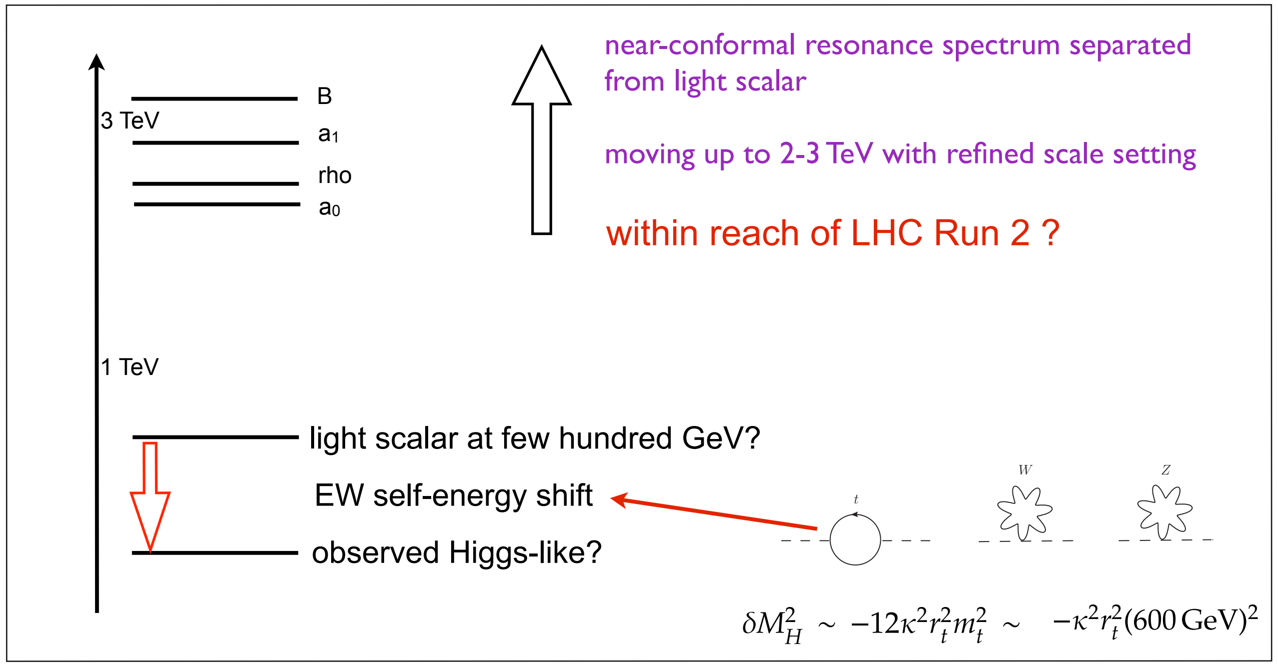


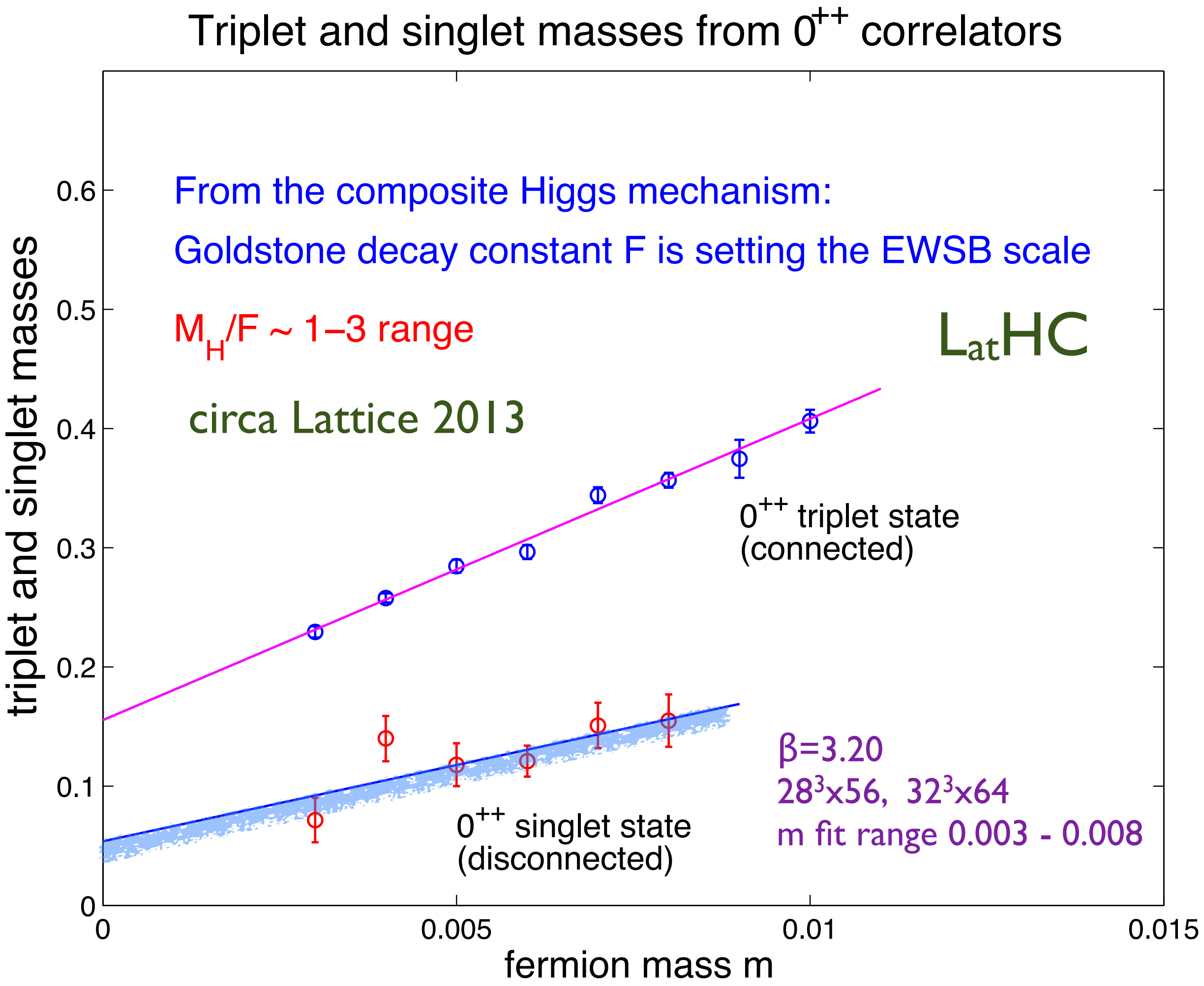


$$C(t) = \sum_n \left[A_n e^{-m_n(\Gamma_S \otimes \Gamma_T)t} + (-1)^t B_n e^{-m_n(\gamma_4\gamma_5\Gamma_S \otimes \gamma_4\gamma_5\Gamma_T)t}\right]$$

staggered correlator

light 0++ scalar and spectrum sextet model LatHC





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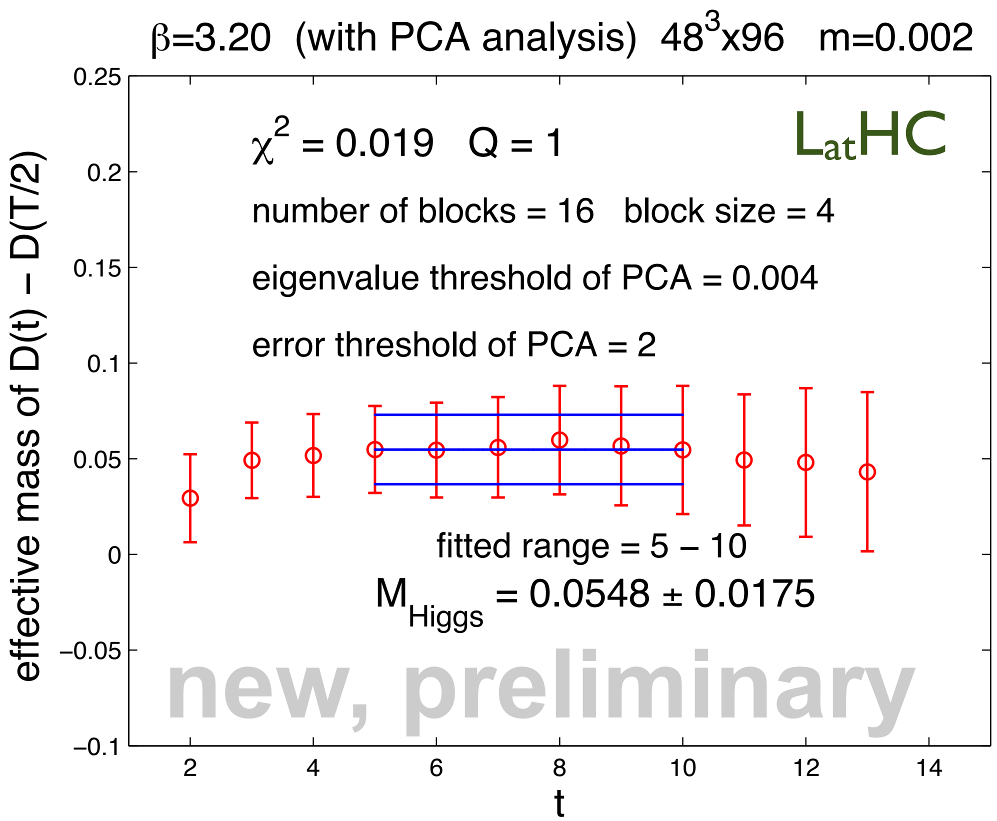

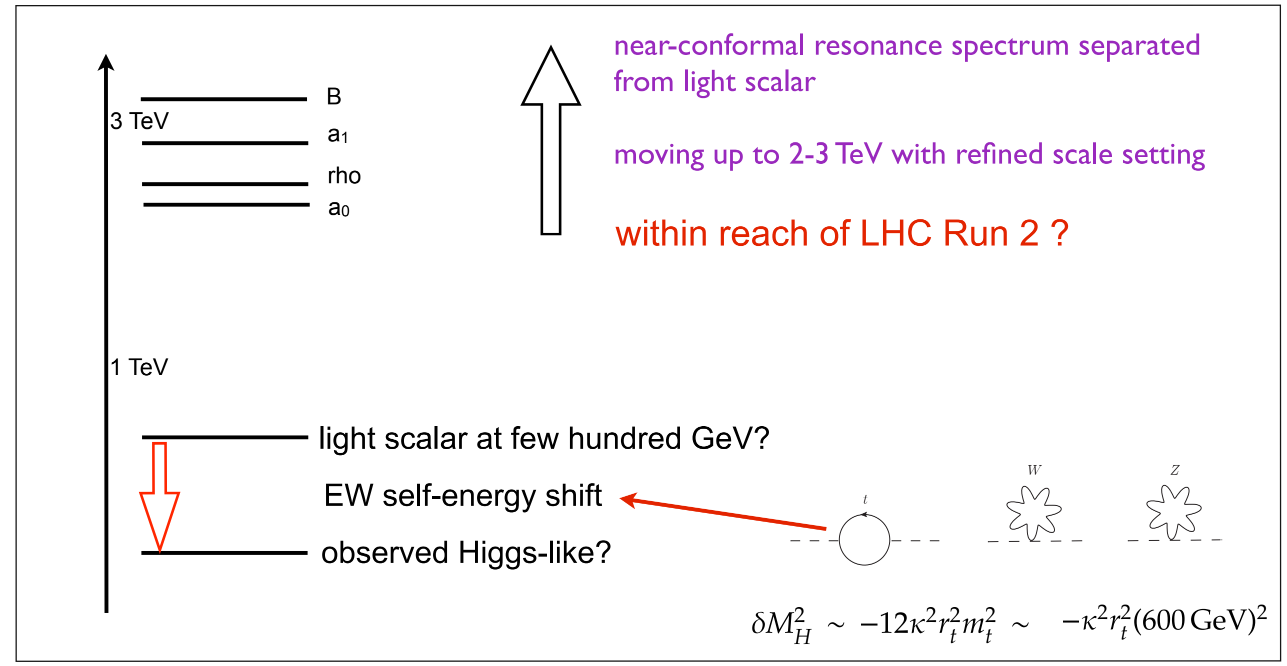

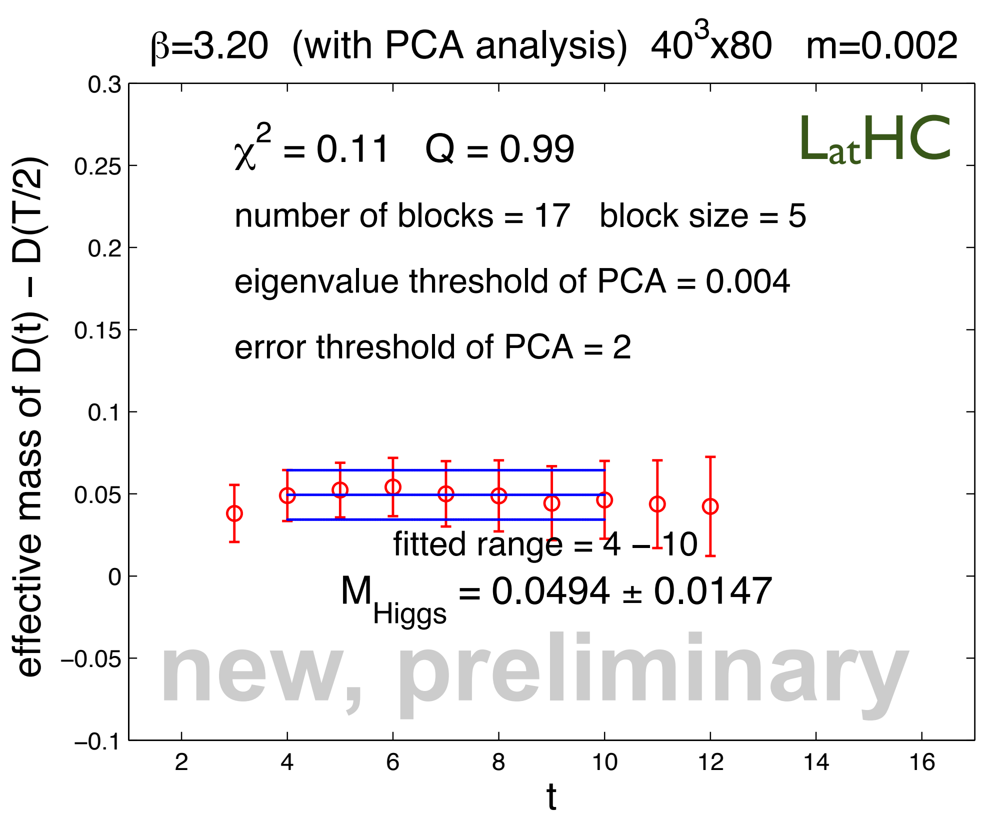

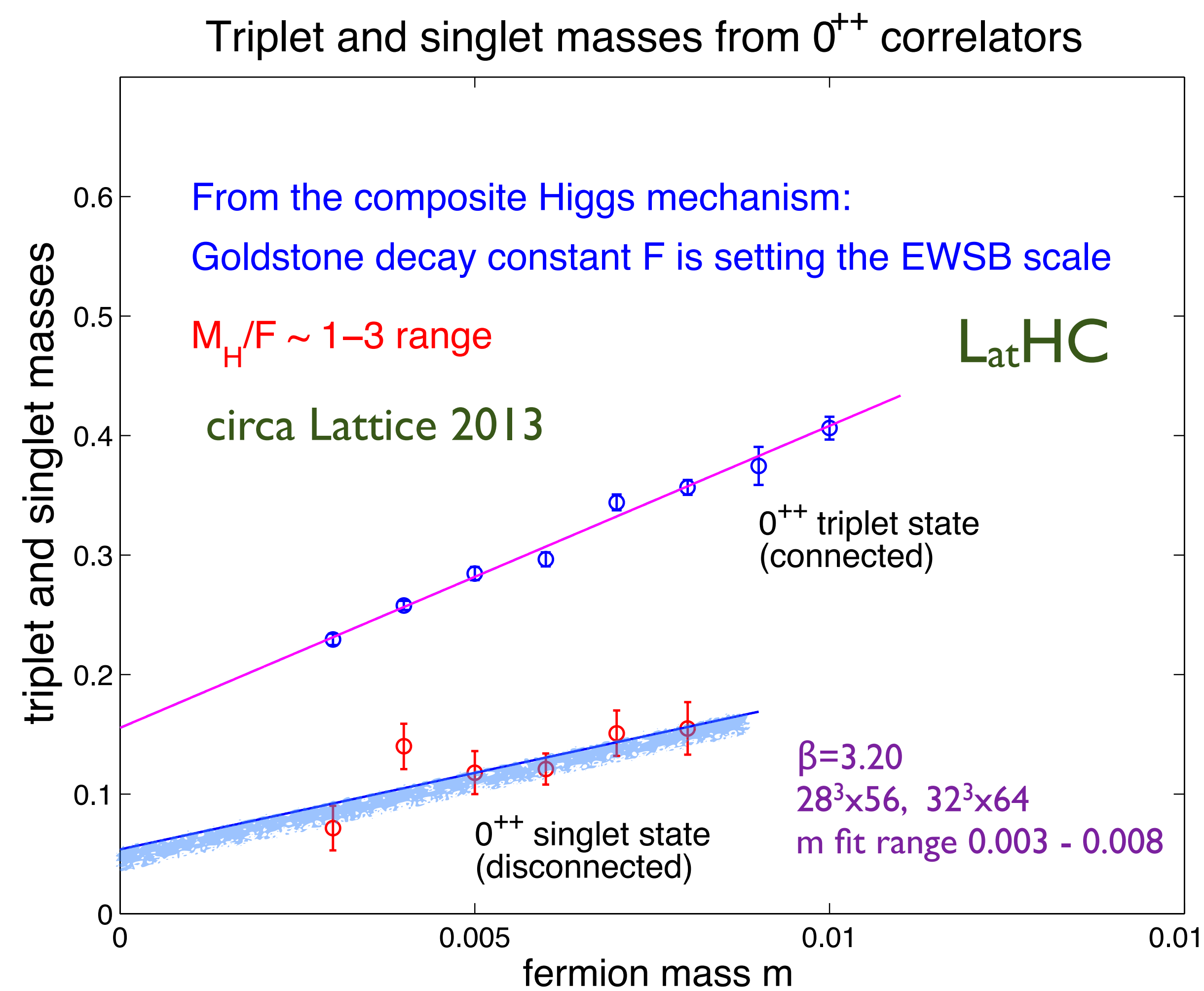

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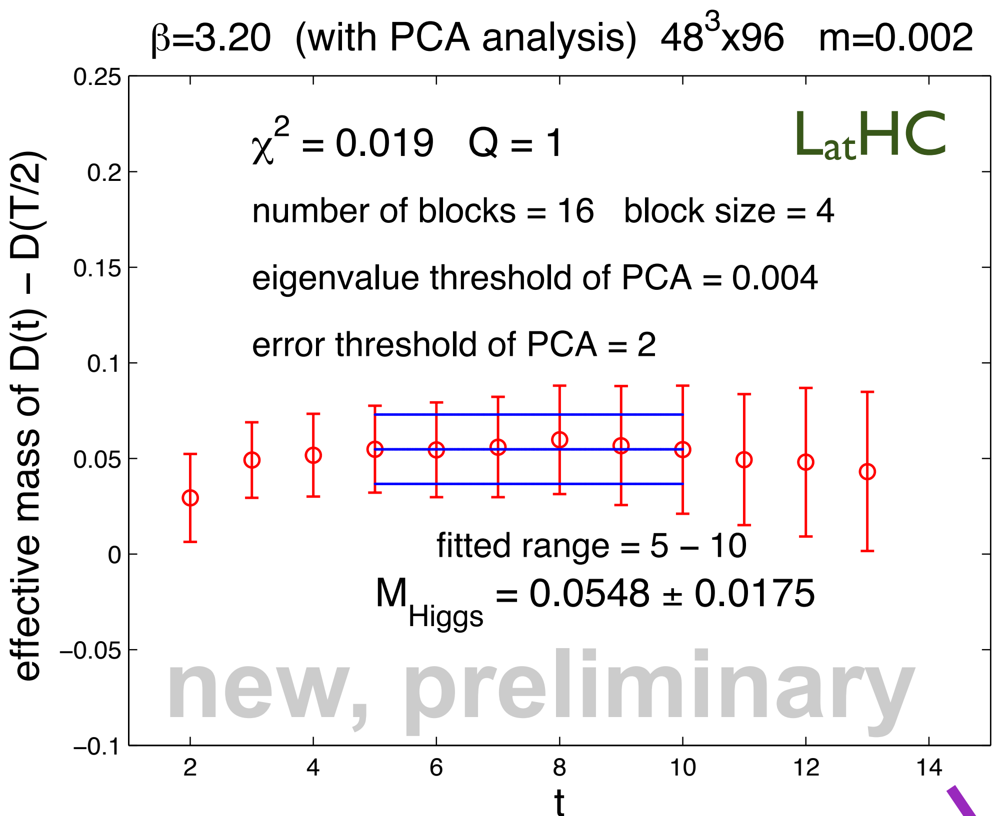
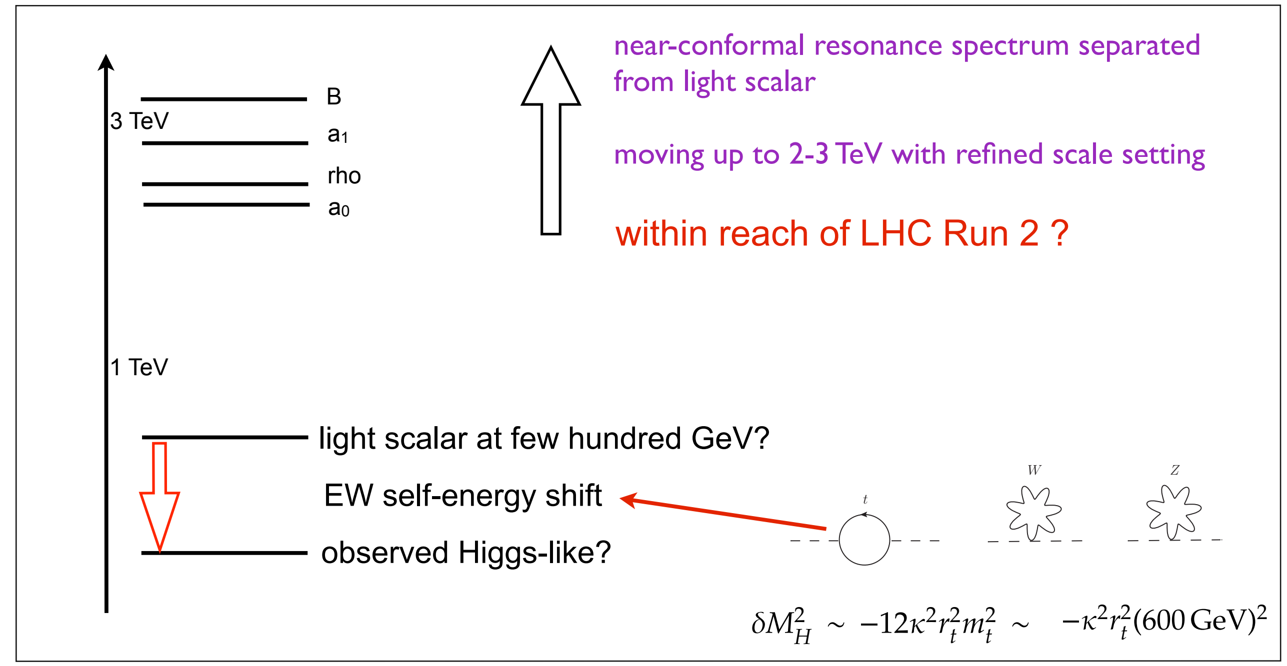
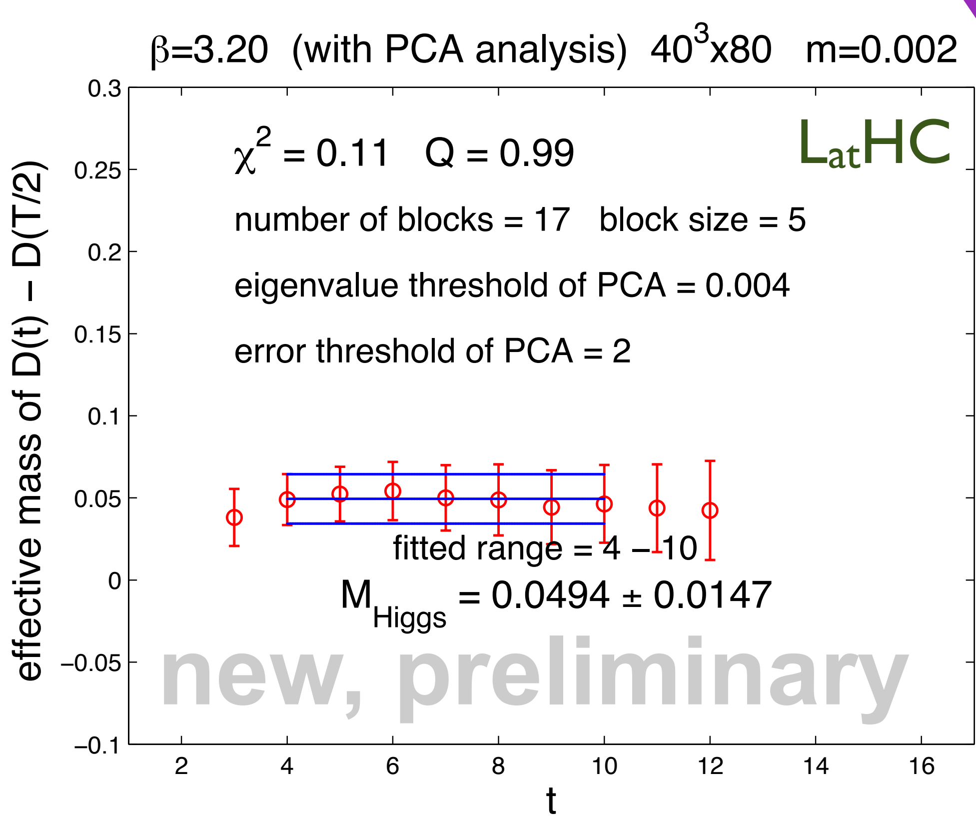
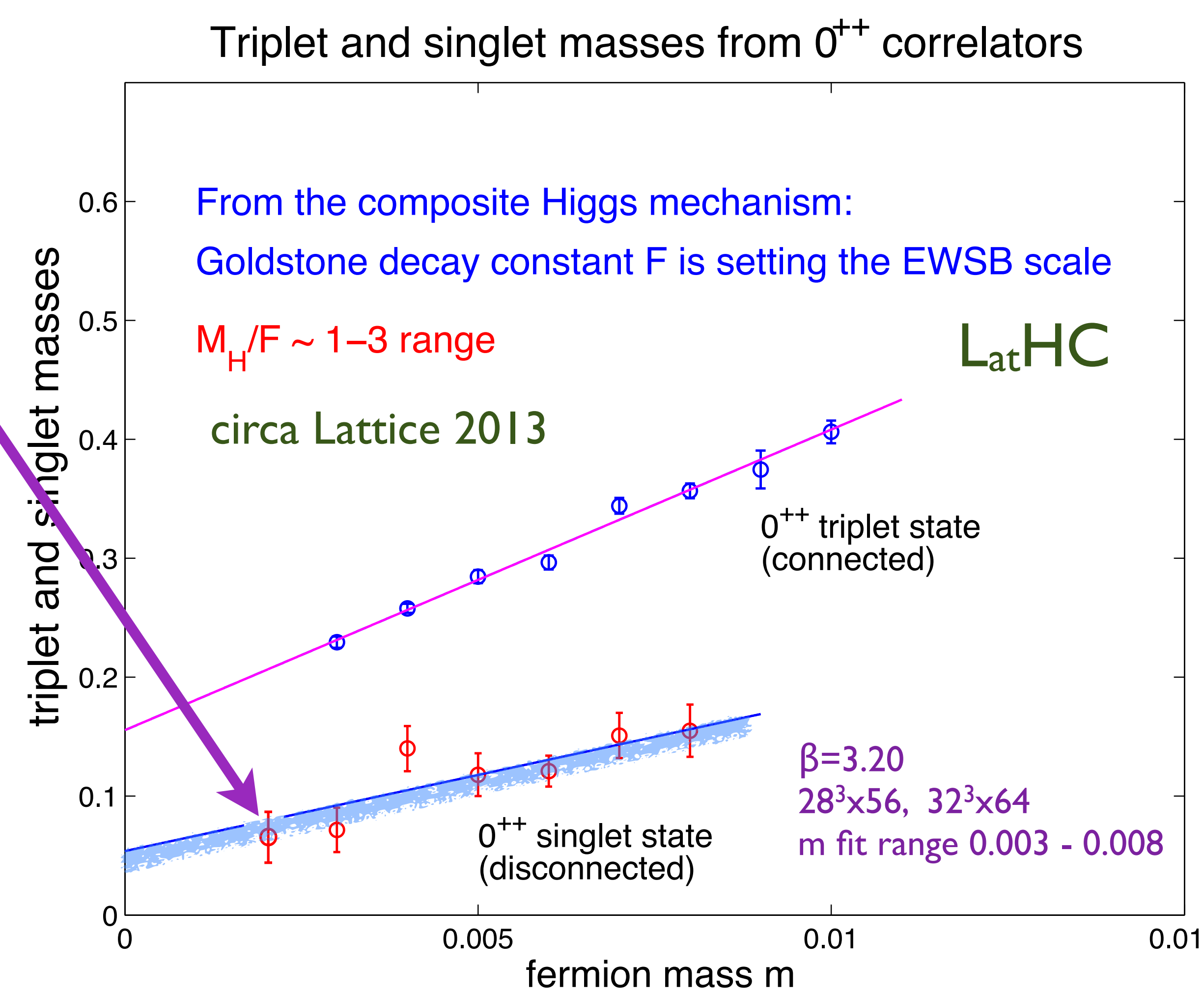
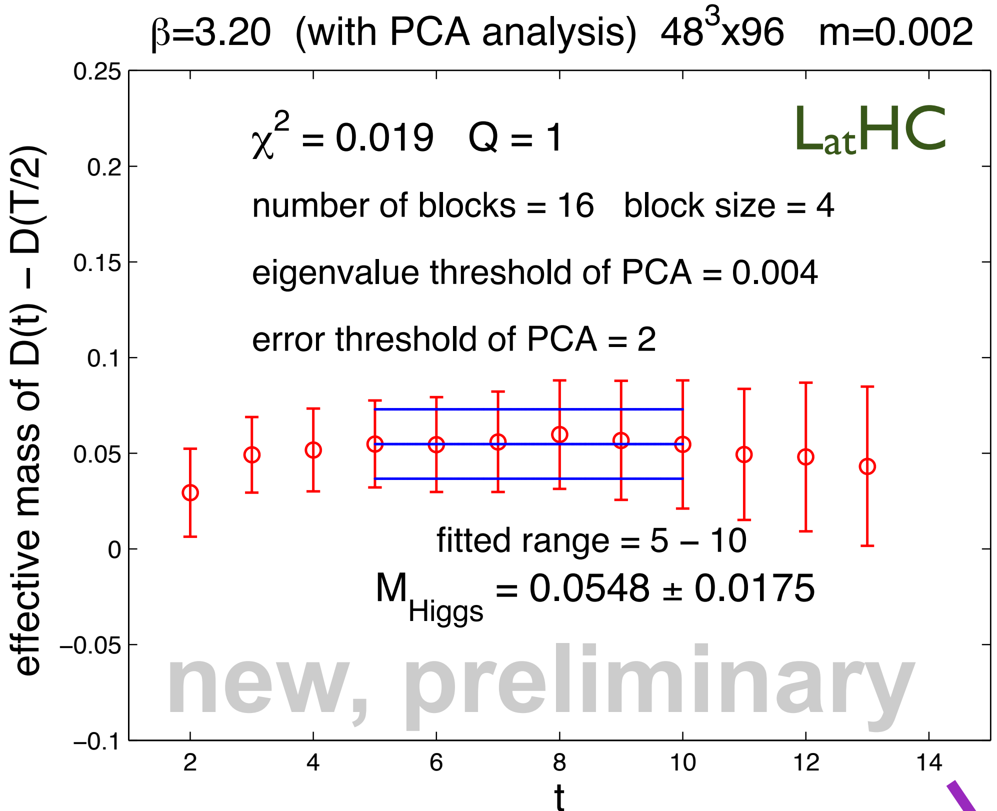


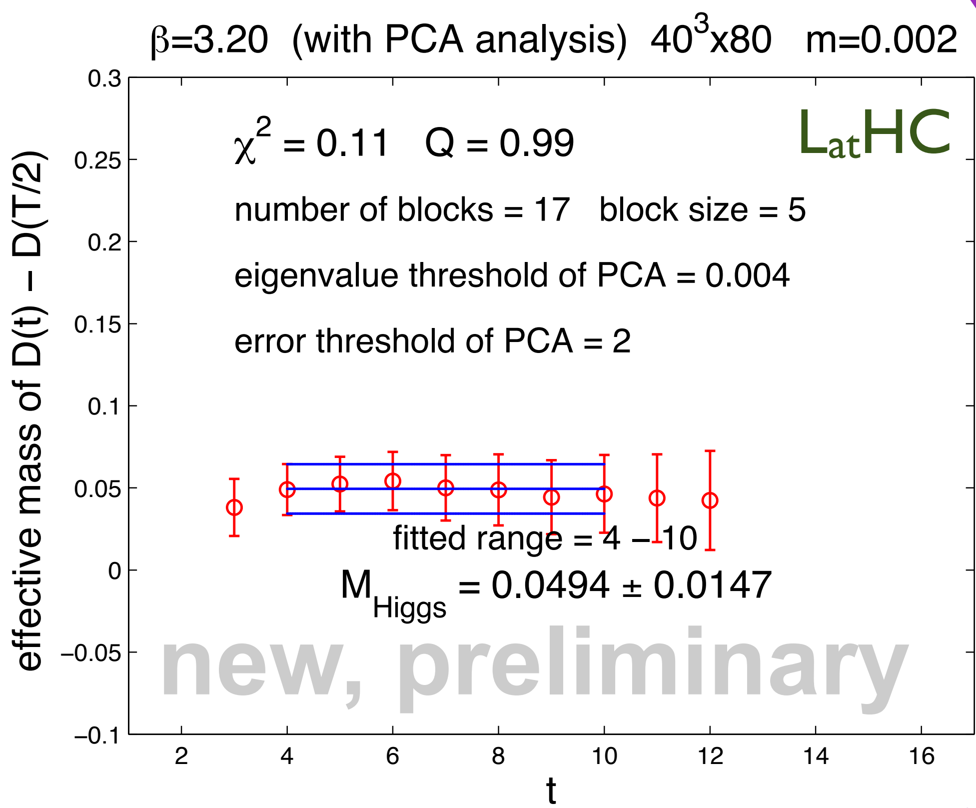


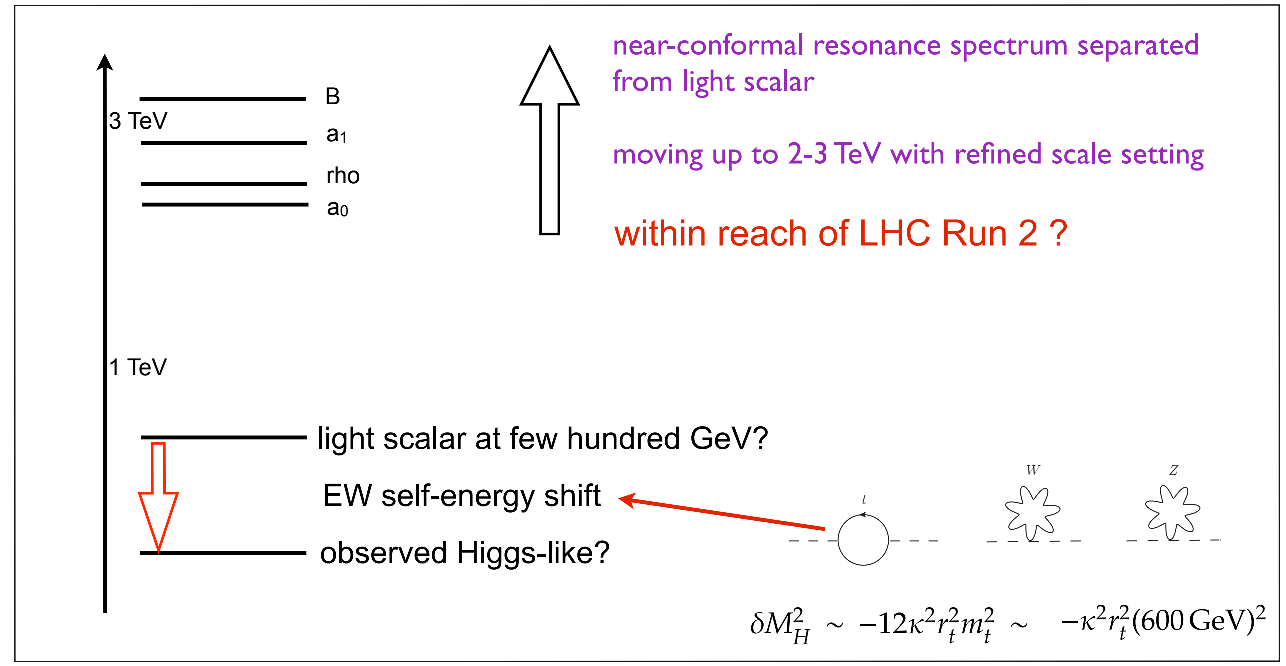


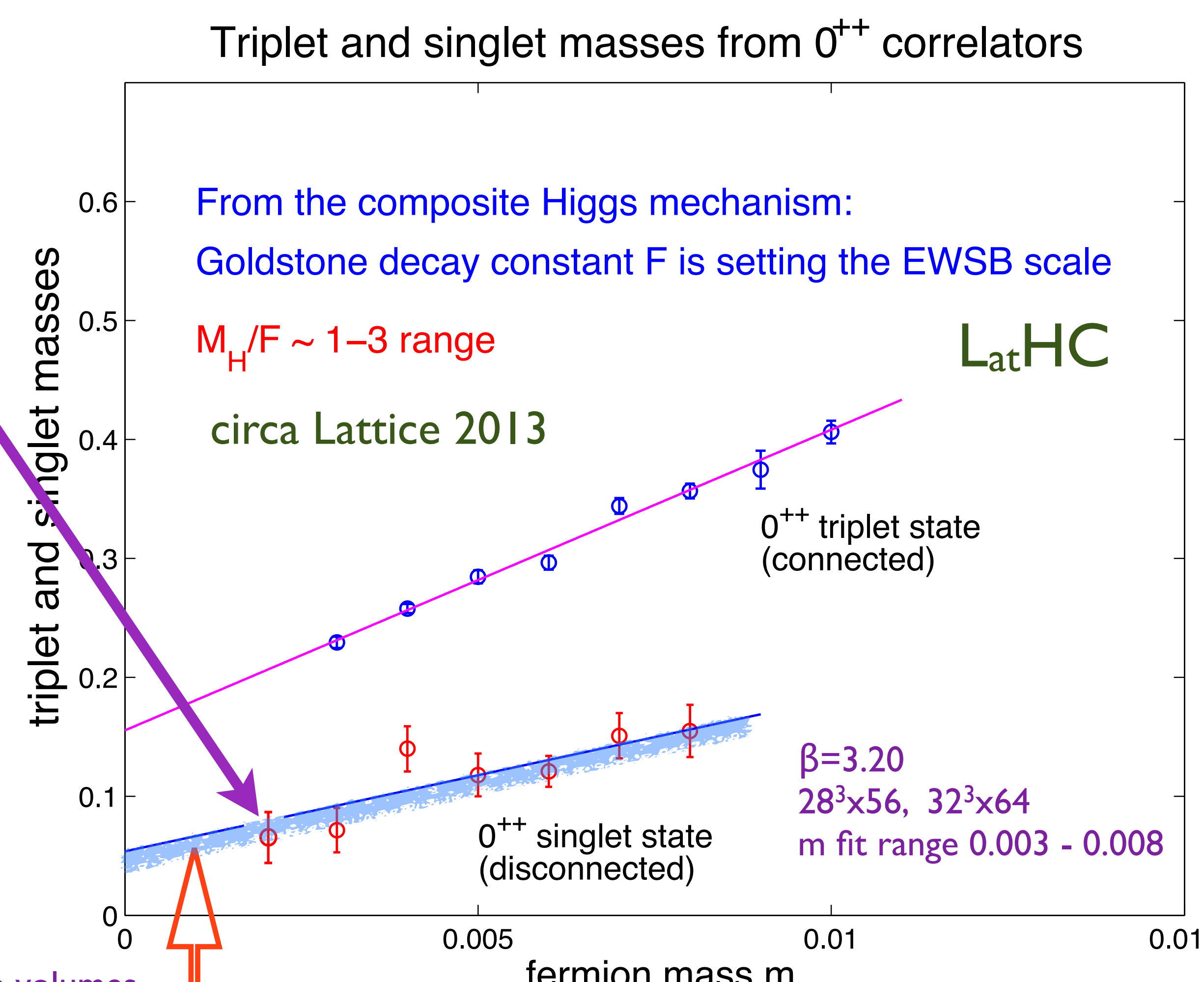


light 0++ scalar and spectrum   sextet model   LatHC



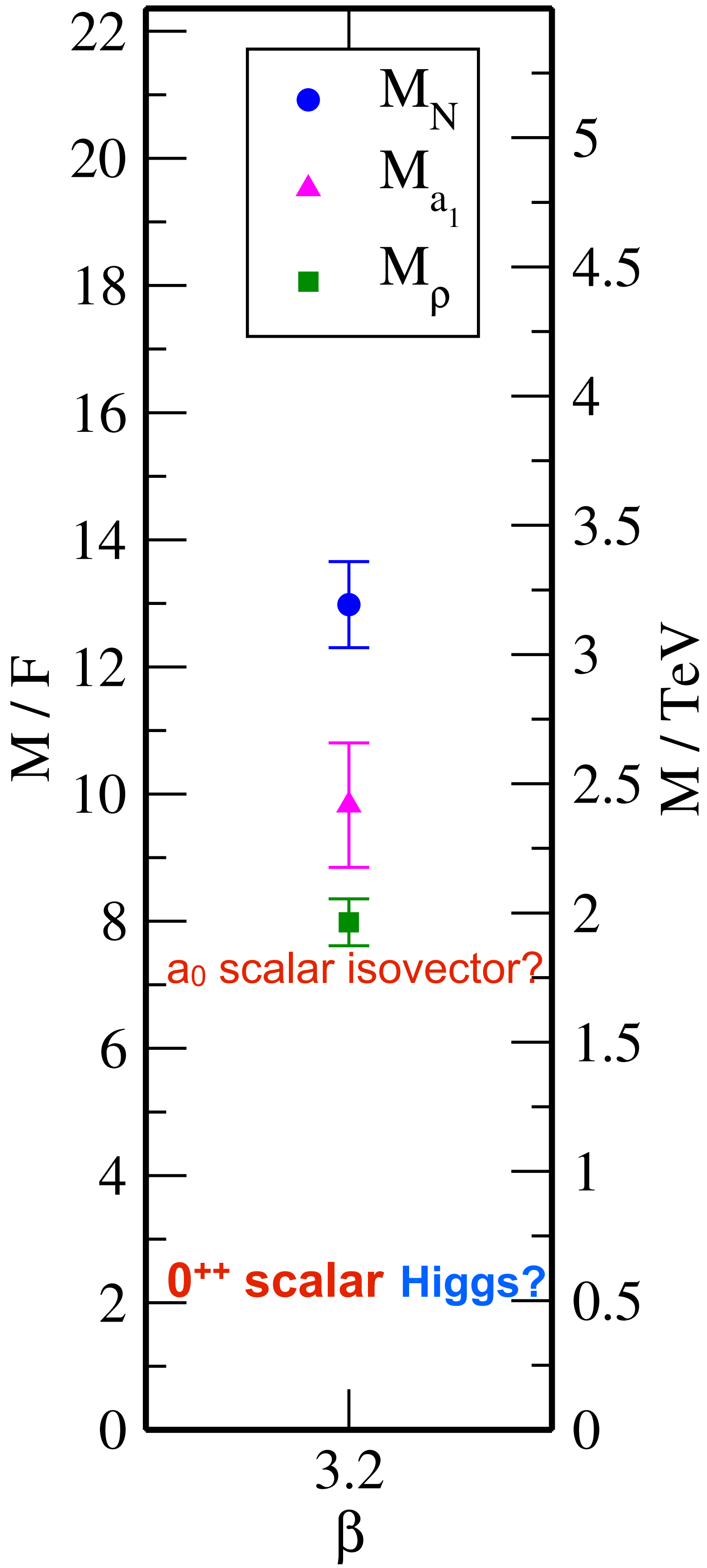






running large volumes
m fit range 0.001 - 0.002

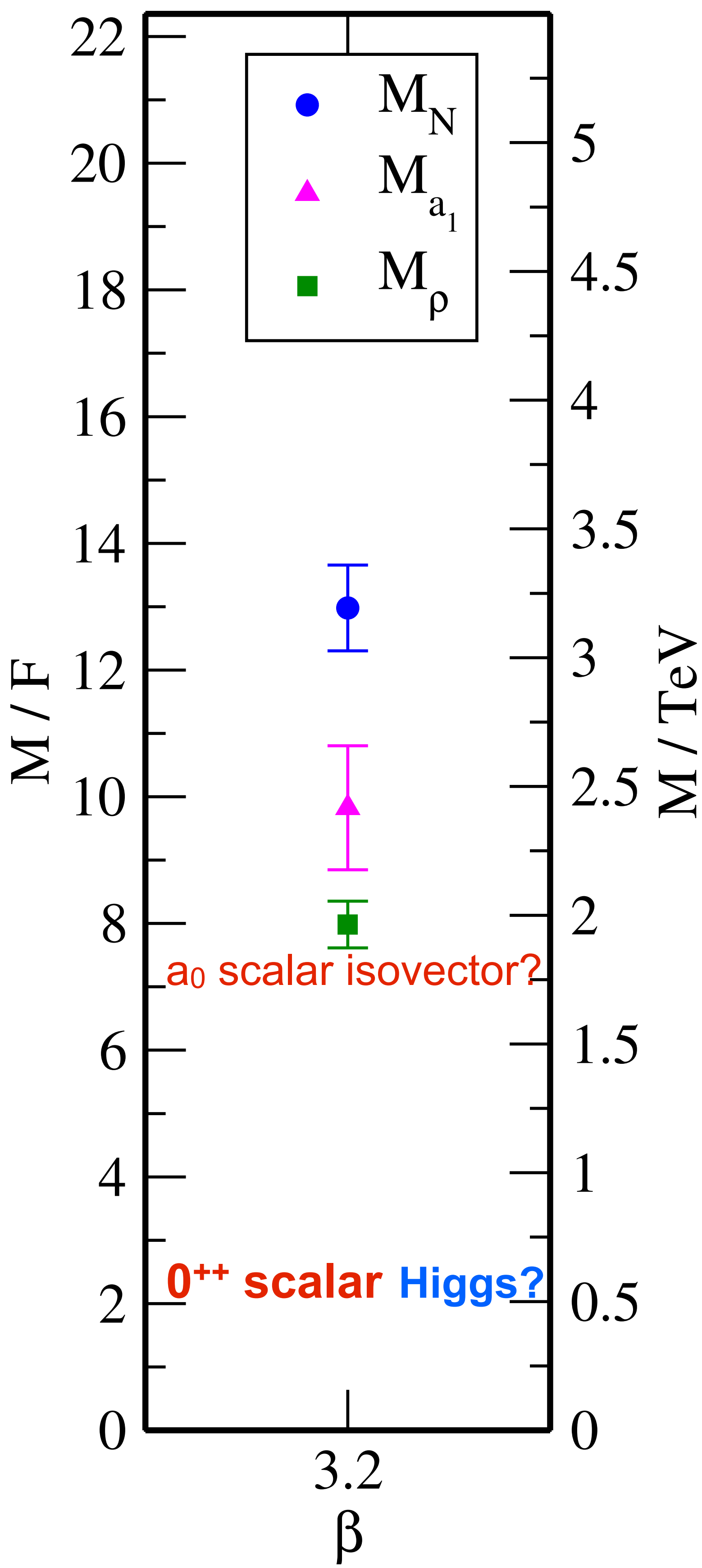
light 0++ scalar and spectrum   sextet model   LatHC

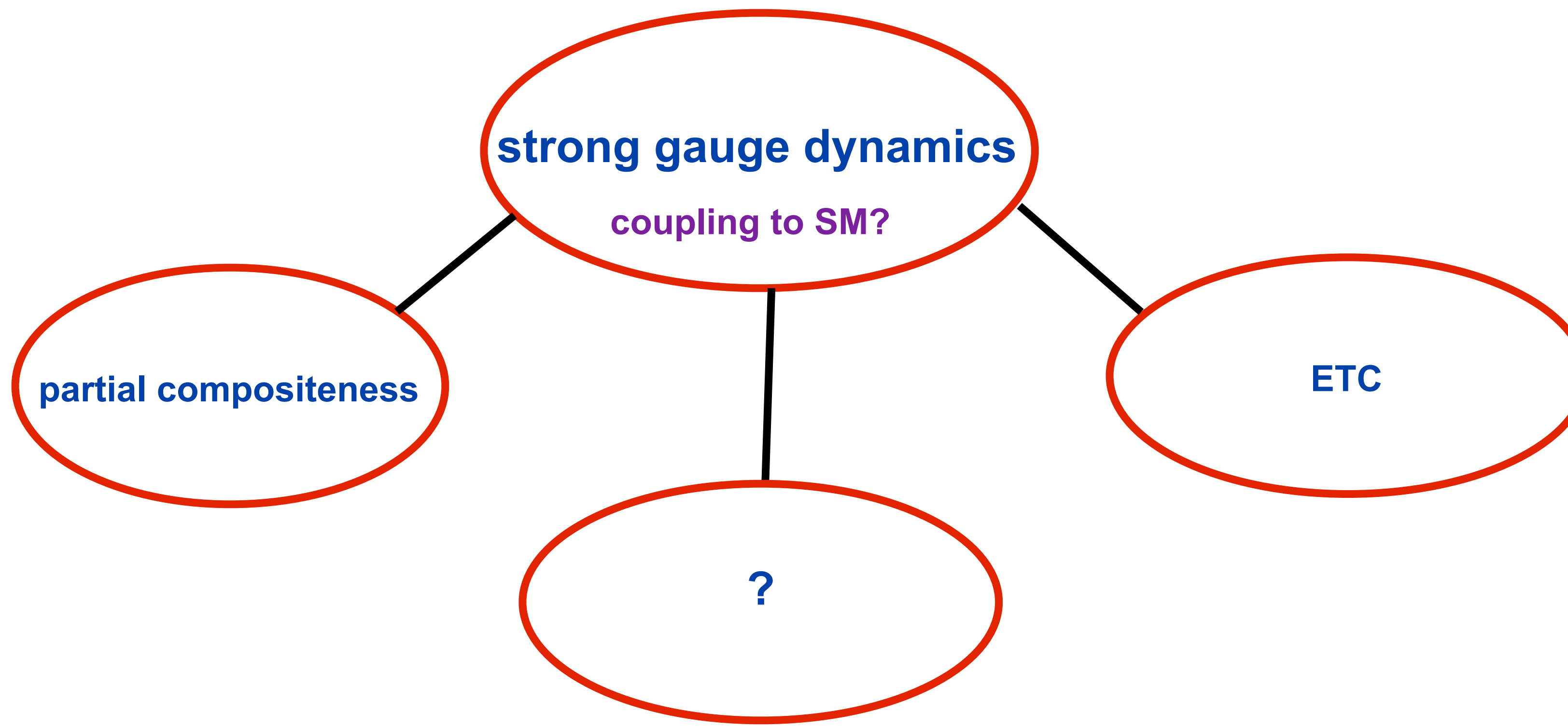


strong gauge dynamics

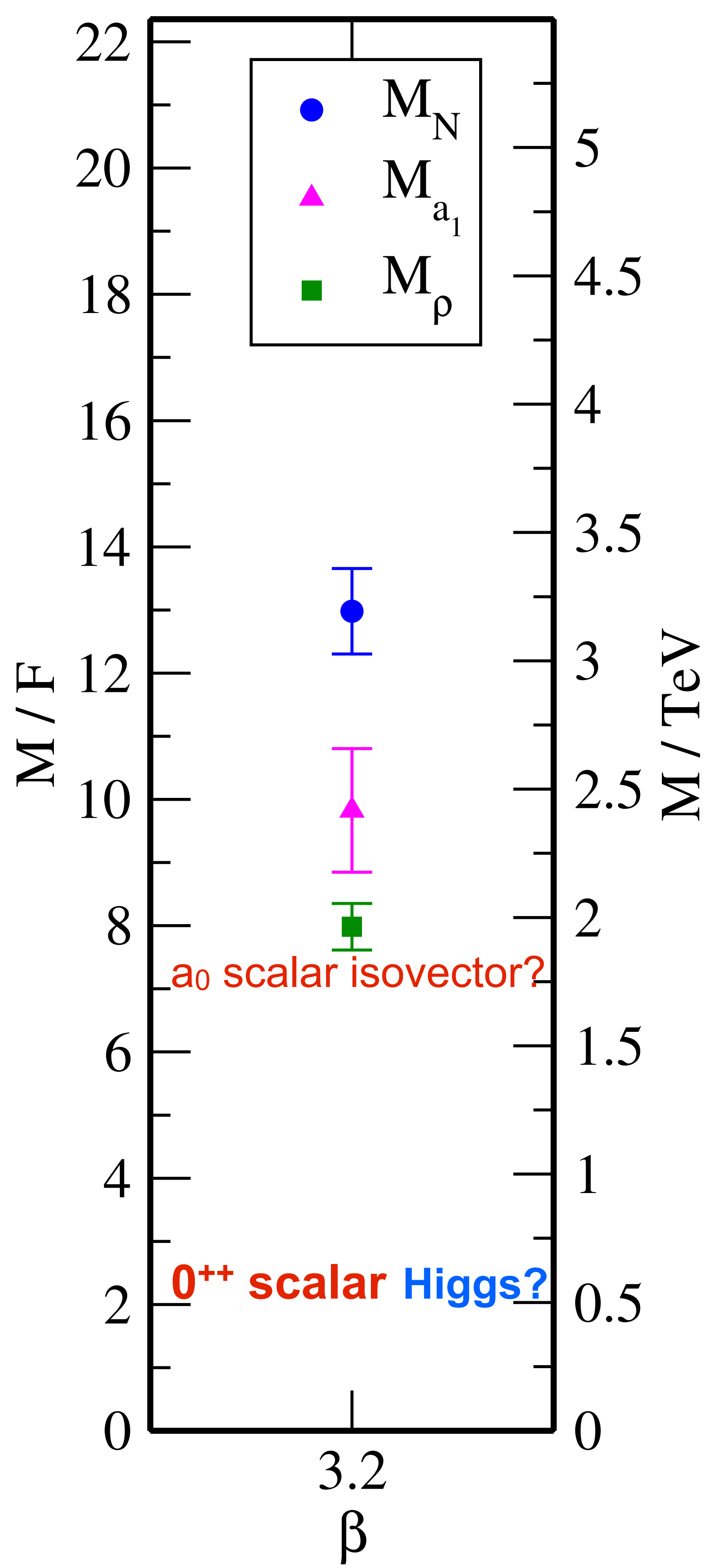
coupling to SM?

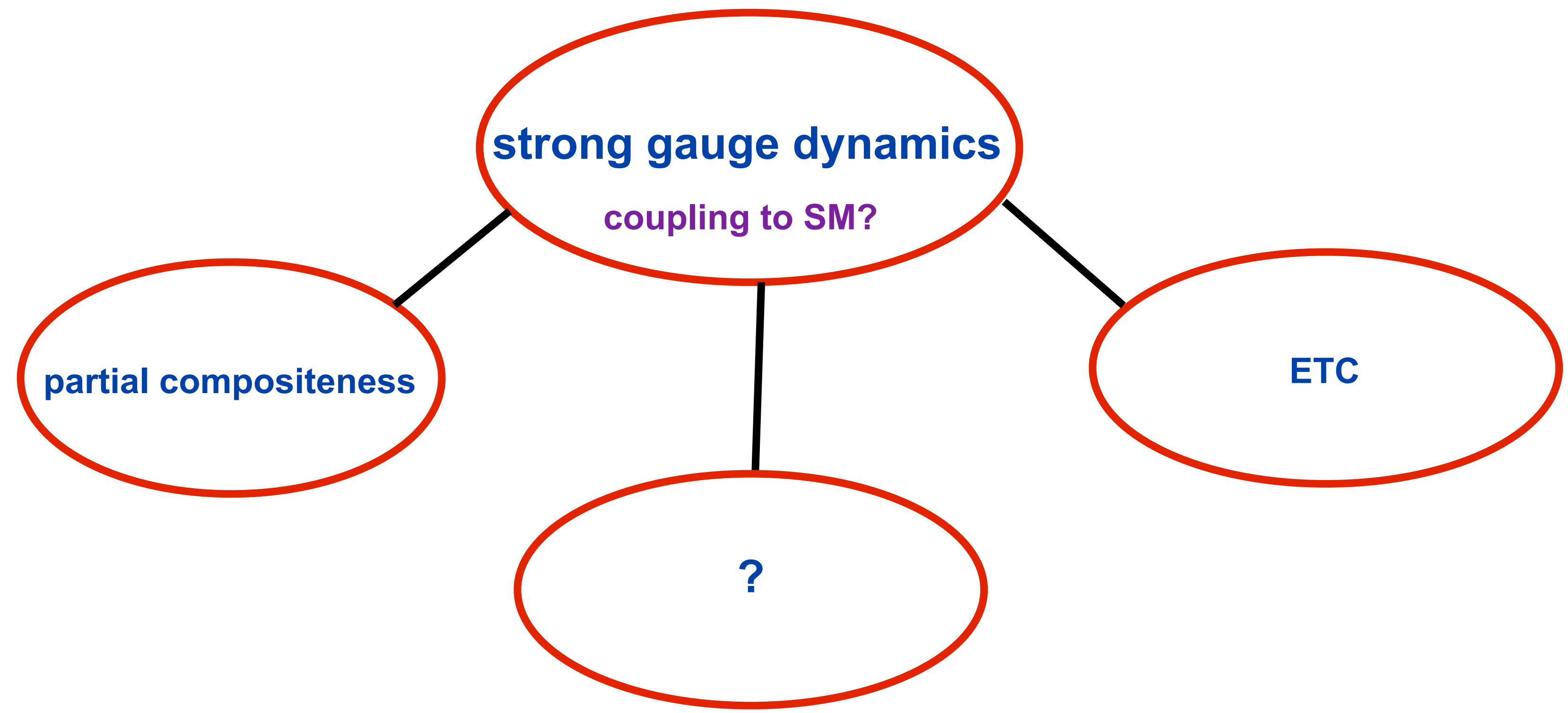
light 0++ scalar and spectrum   sextet model   LatHC





light 0++ scalar and spectrum sextet model LatHC



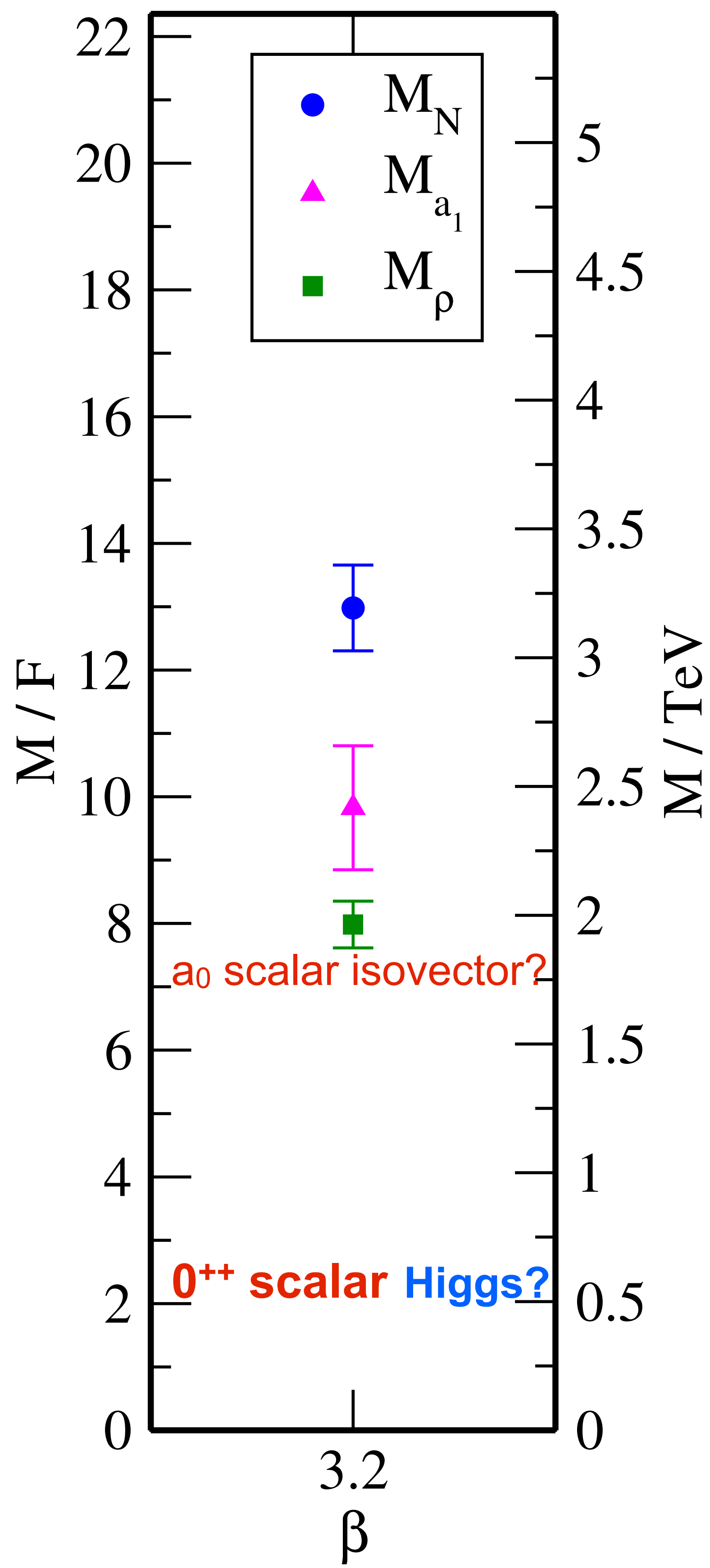


extended linear sigma model

dilaton

} **effective theories**

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

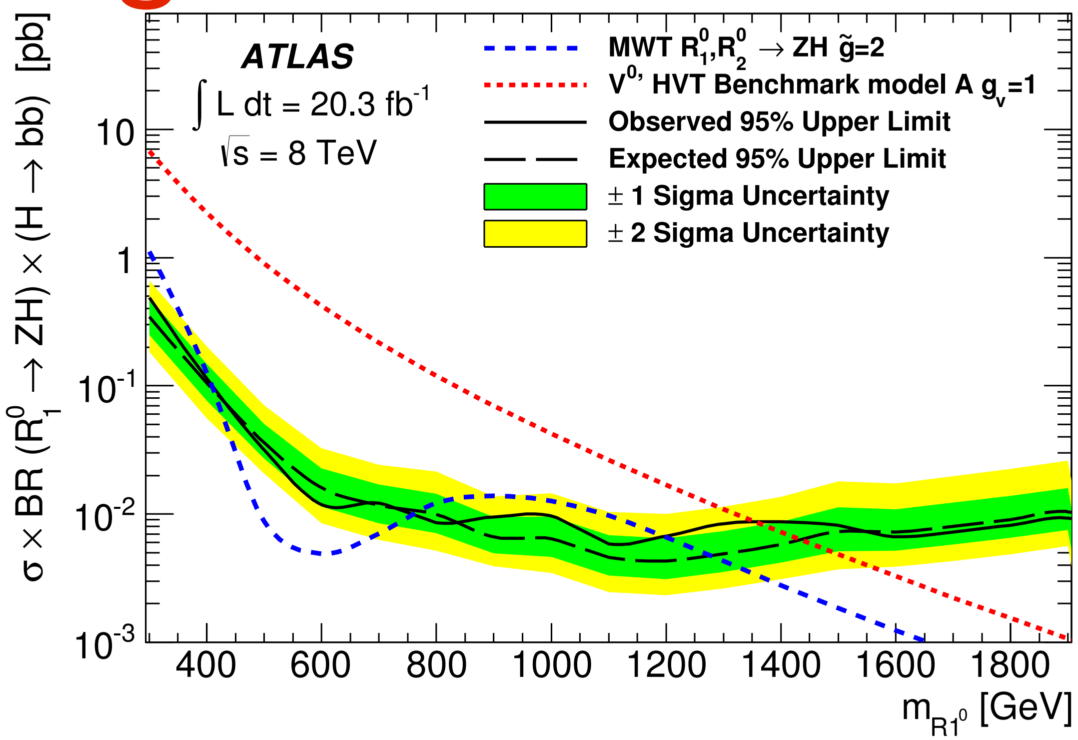
The ATLAS Collaboration

Abstract

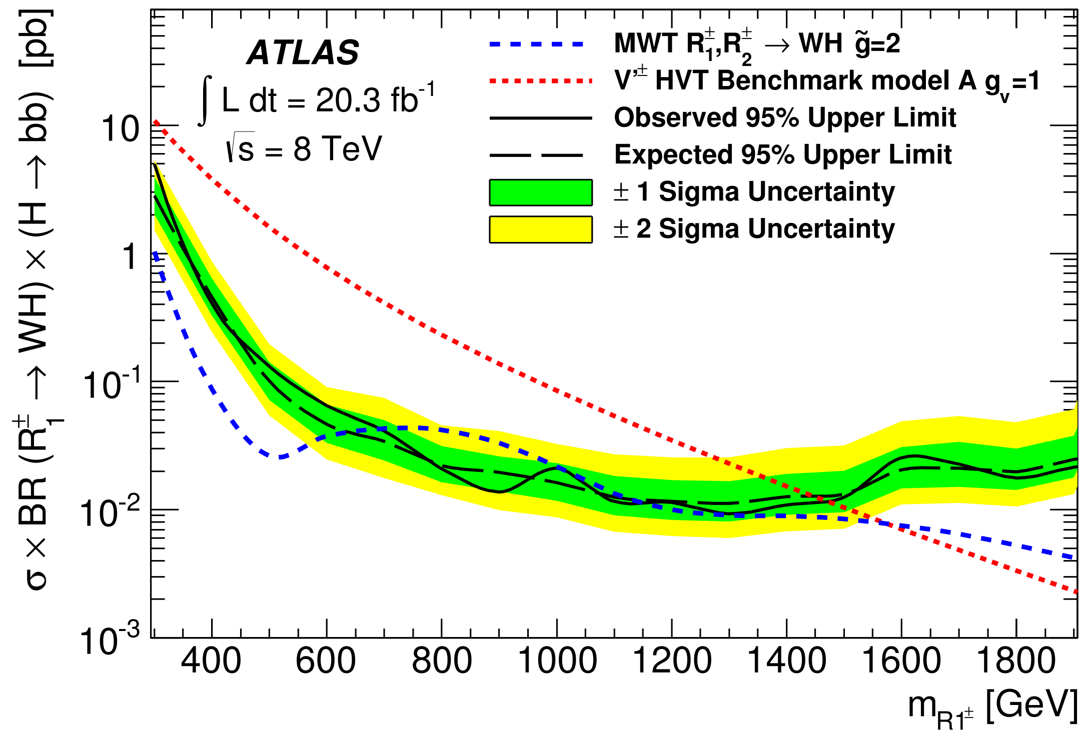
A search for a new resonance decaying to a W or Z boson and a Higgs boson in the $\ell\ell/\ell\nu/\nu\nu+ b\bar{b}$ final states is performed using 20.3 fb^{-1} of pp collision data recorded at $\sqrt{s}$ = 8 TeV with the ATLAS detector at the Large Hadron Collider. The search is conducted by examining 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

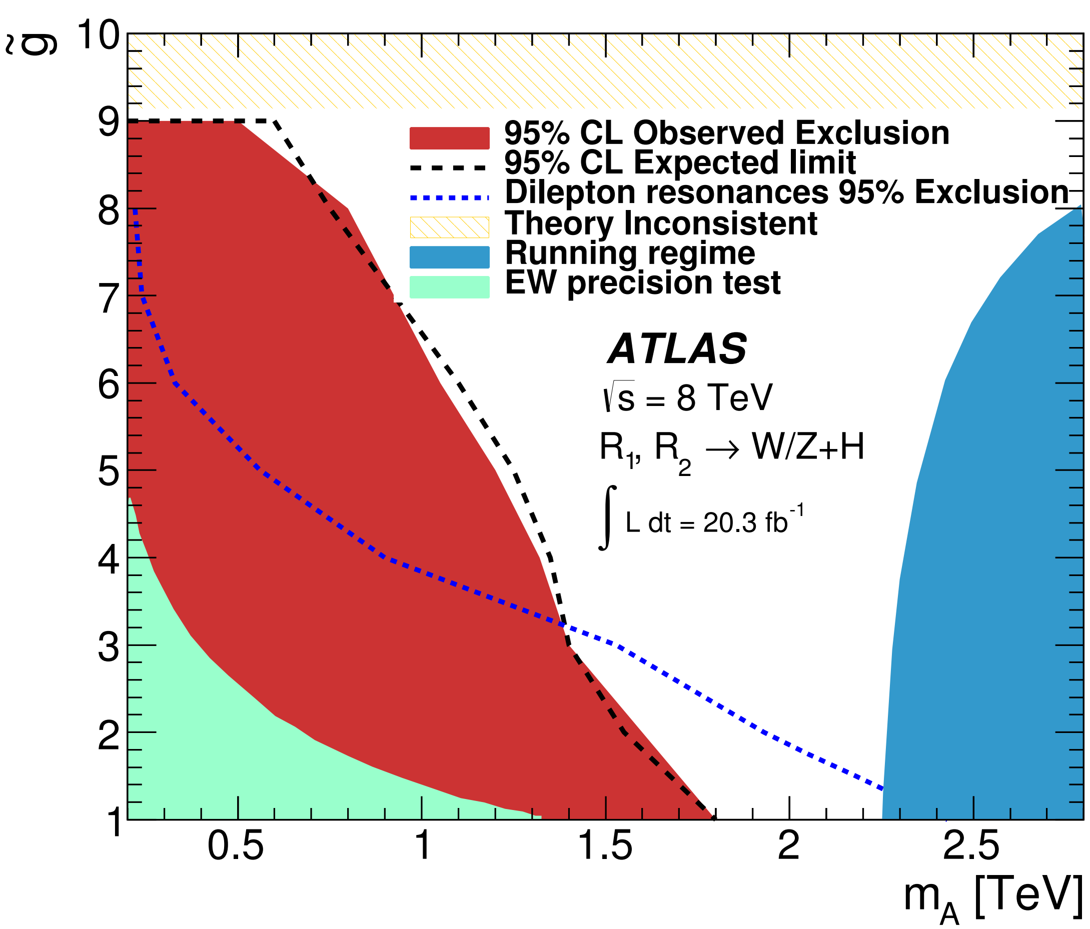
sextet model $L_{at}HC$

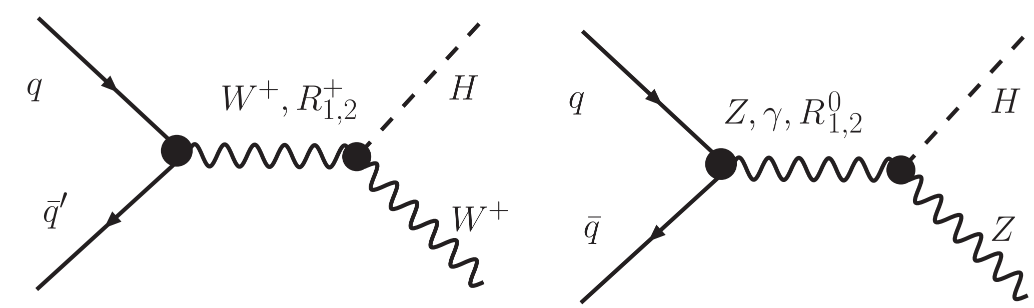


(a) $R_1^0(V'^0) \to ZH,\, H \to b\bar{b}$



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





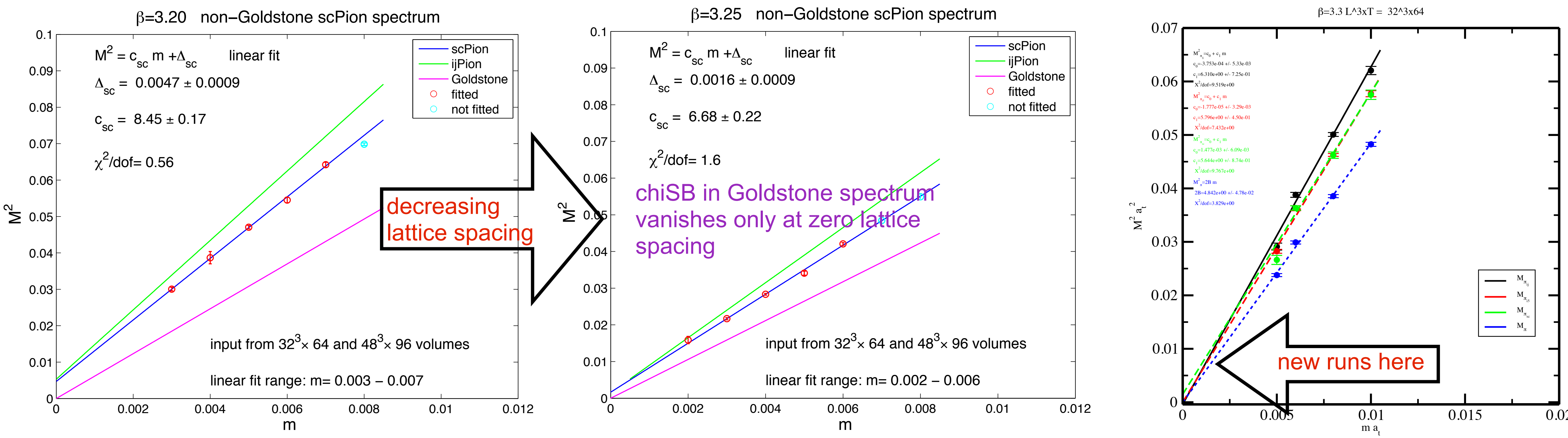
R_1 and R_2 couplings:

ĝ is the coupling in SU(4) vector boson

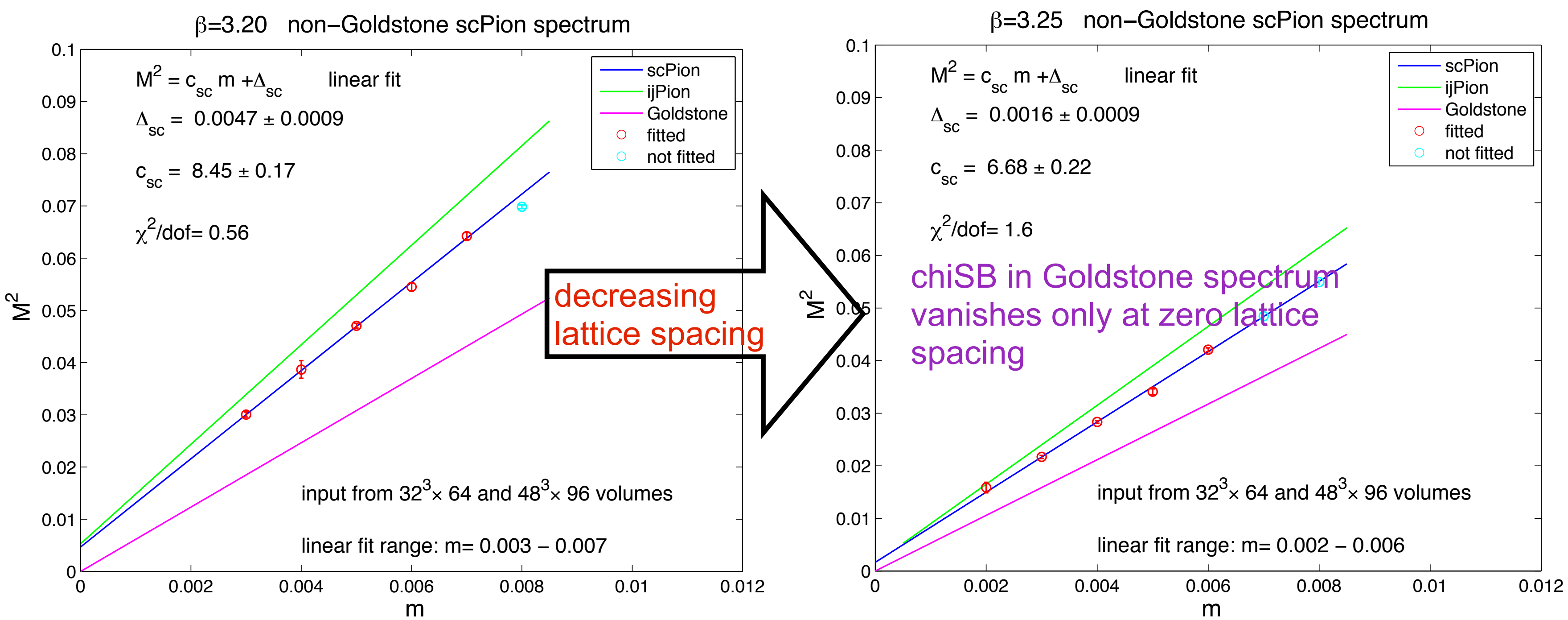
g/ĝ is the coupling to fermions

systematics and mixed action

taste breaking to improve



systematics and mixed action   taste breaking to improve



idea:

- use the gauge configurations generated with sea fermions
- taste breaking makes chiPT analysis unnecessarily 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: cross check

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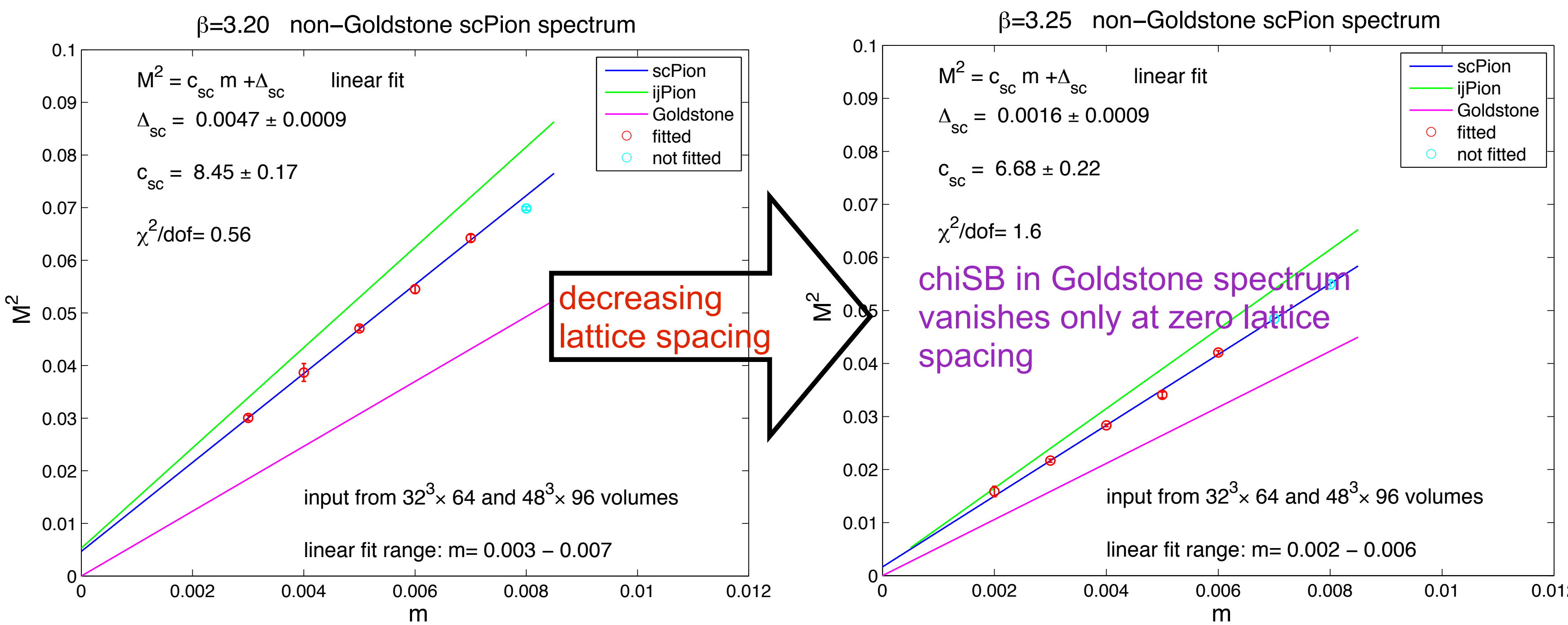
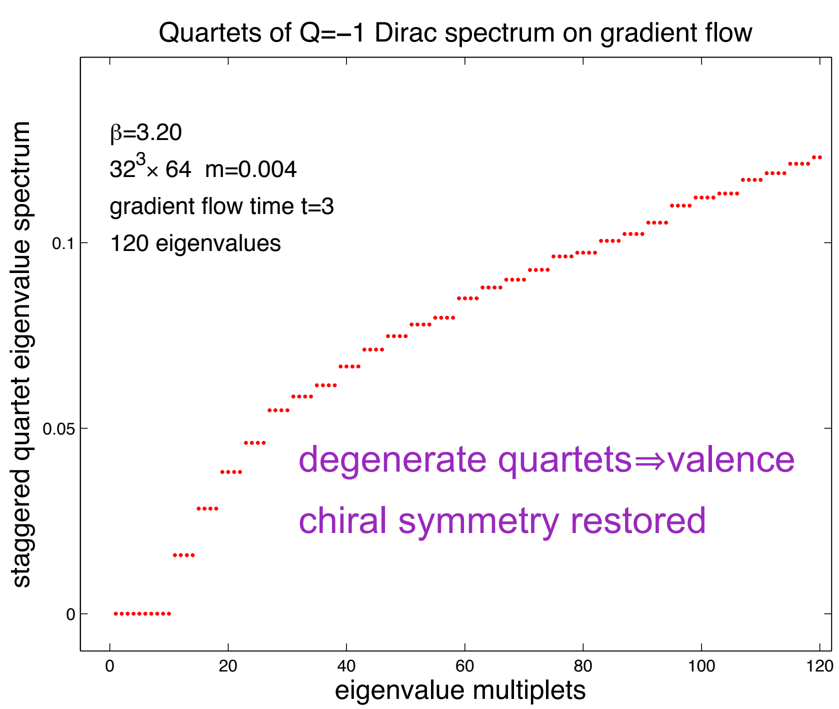
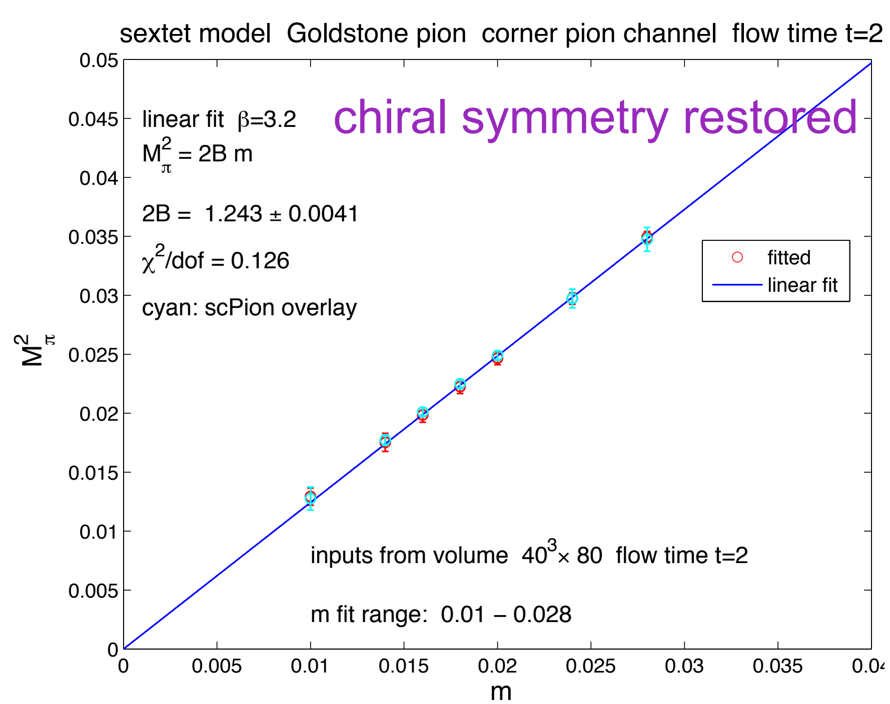
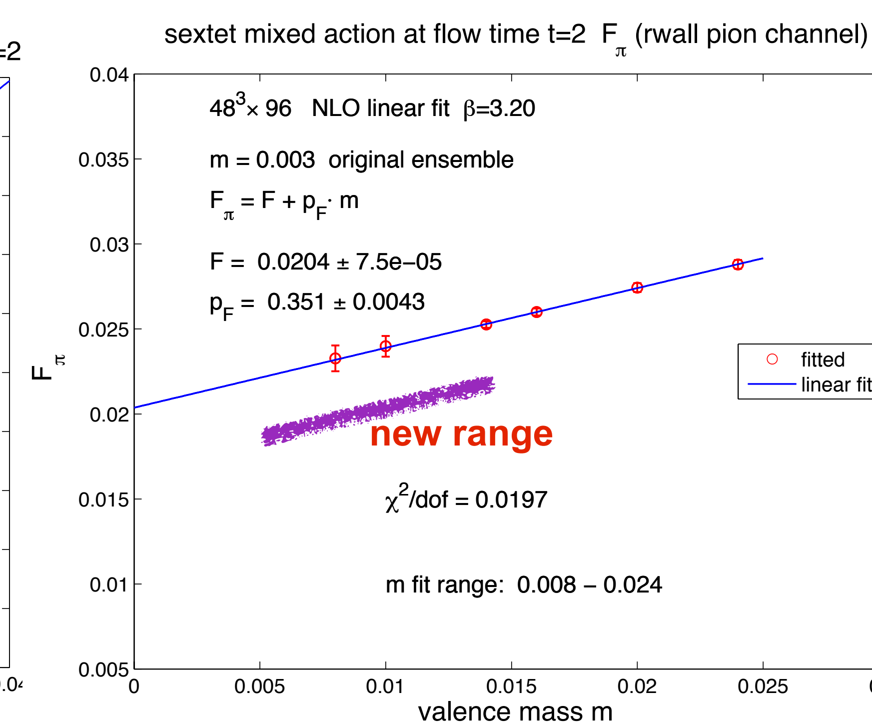


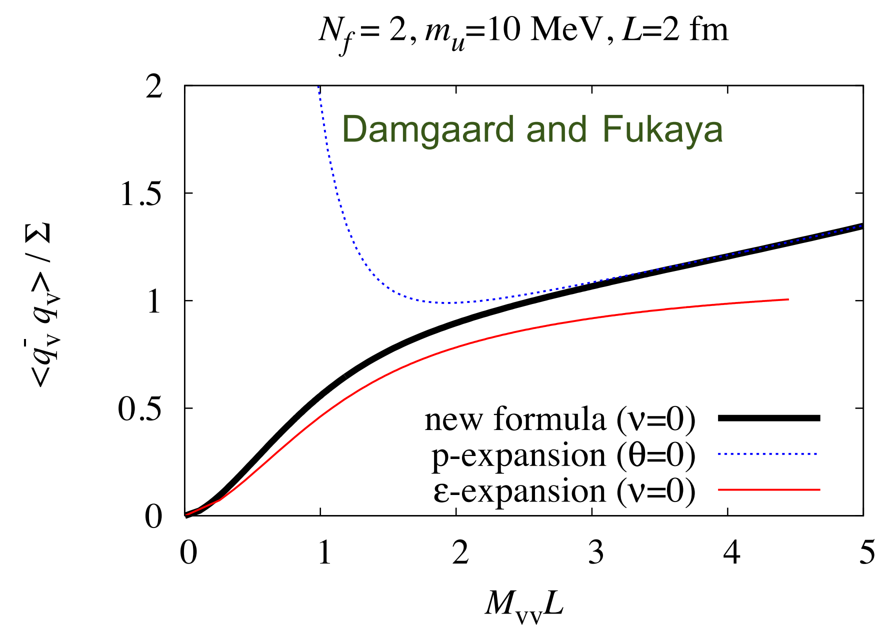


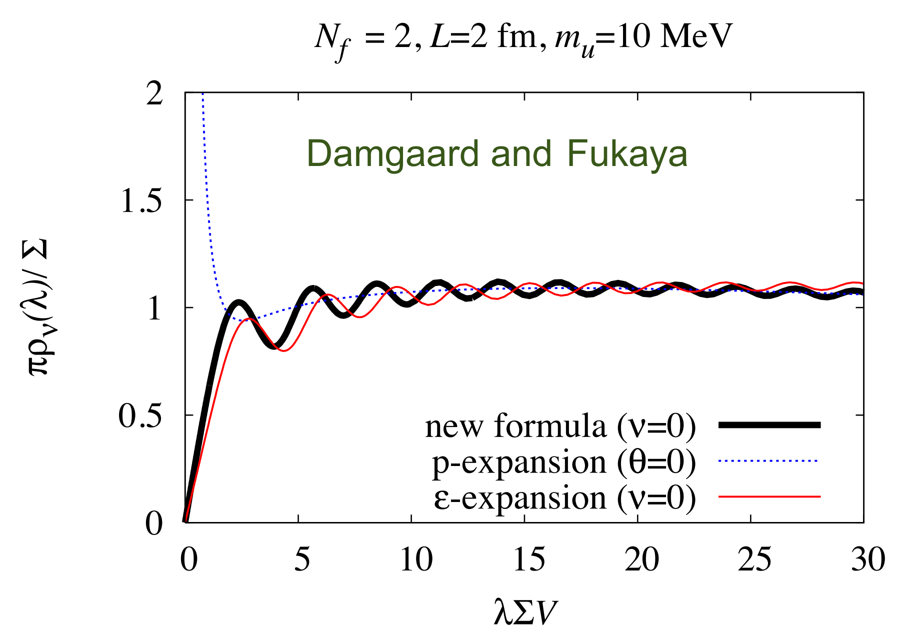




taste breaking and mixed action

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

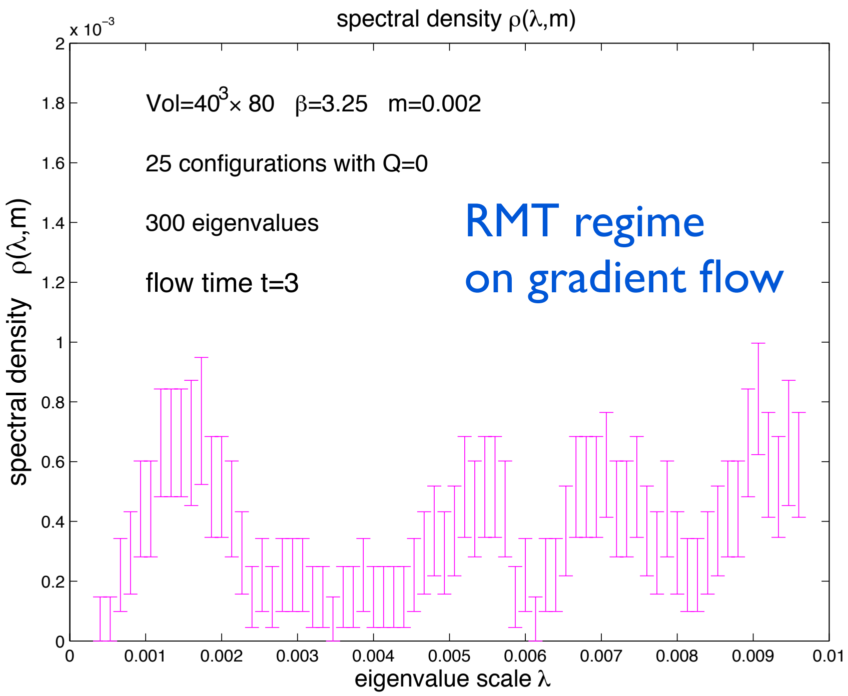


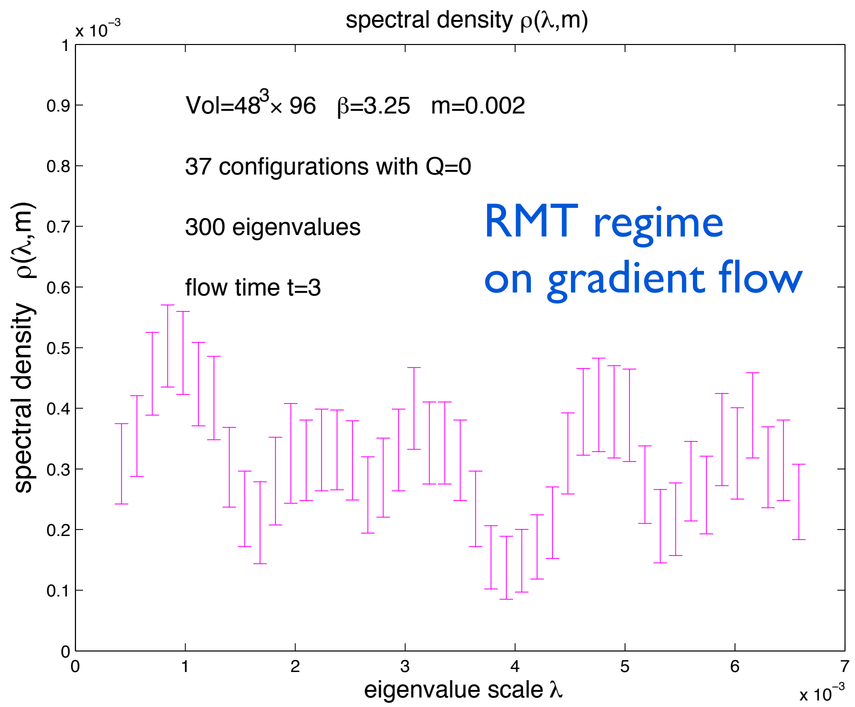


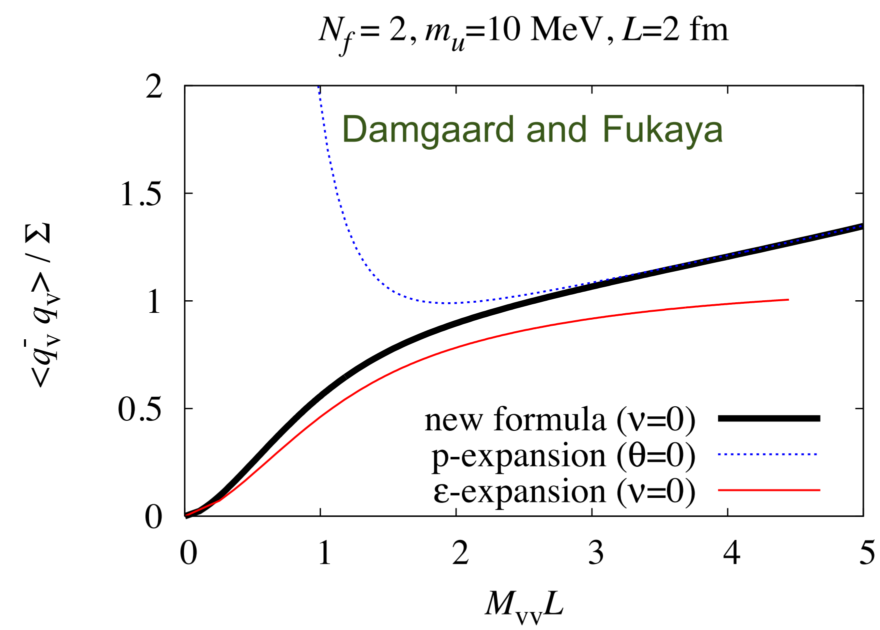
new analysis in crossover and RMT regime opens up with mixed action on gradient flow

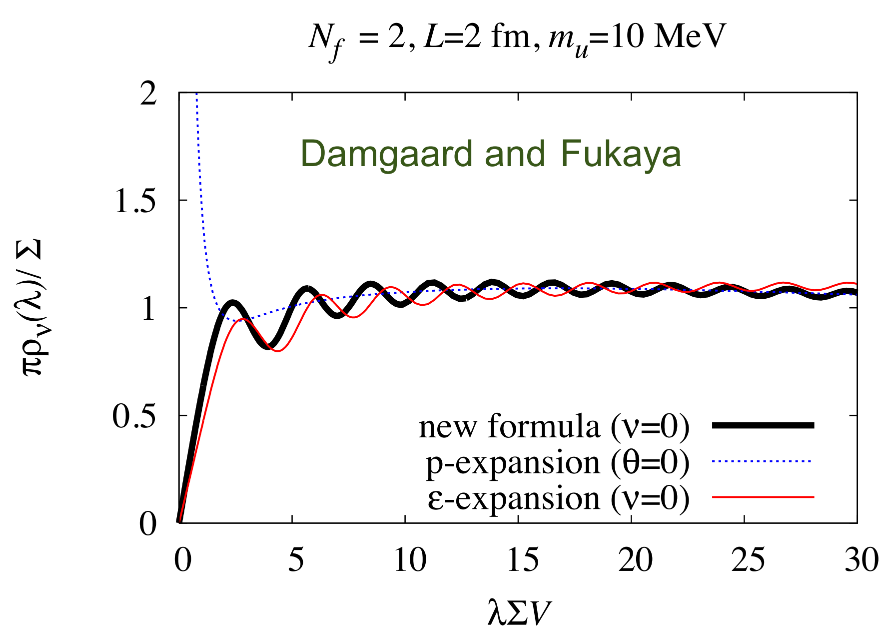
taste breaking and mixed action

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





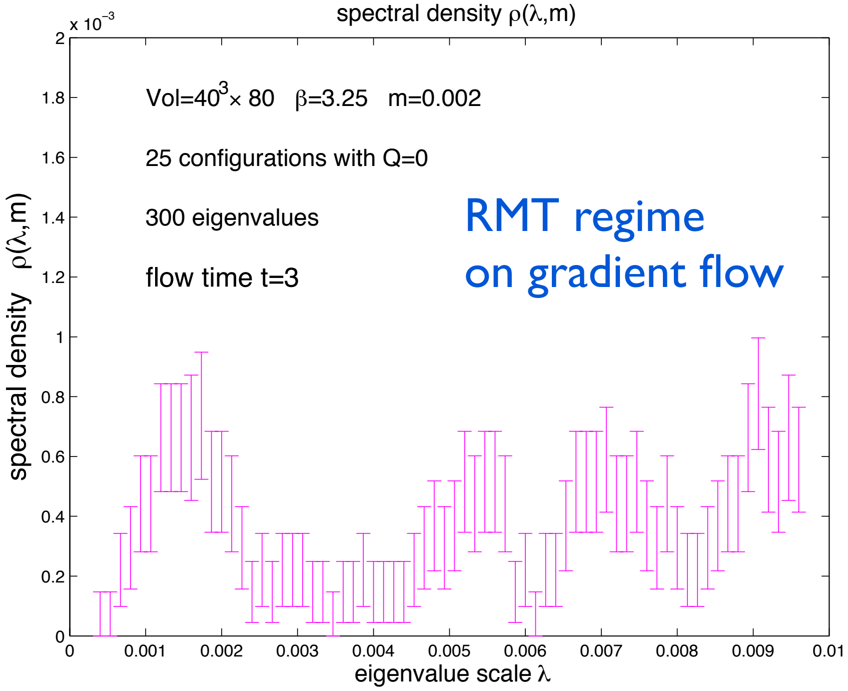


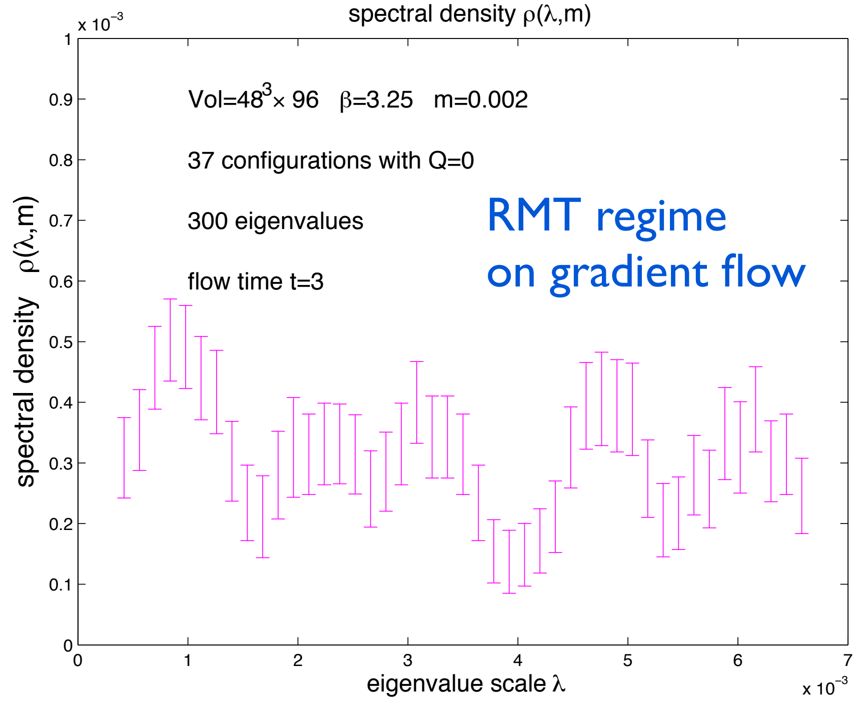


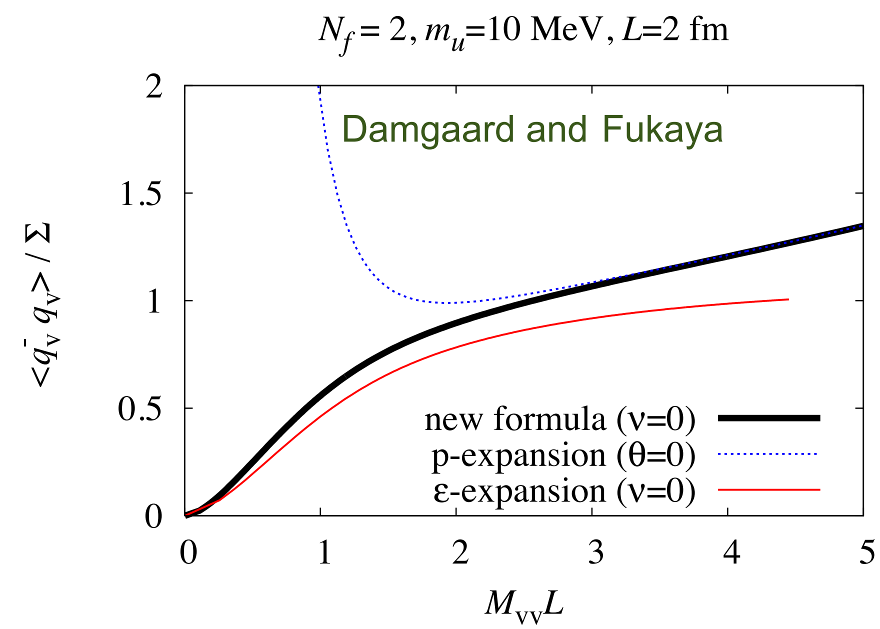
new analysis in crossover and RMT regime opens up with mixed action on gradient flow

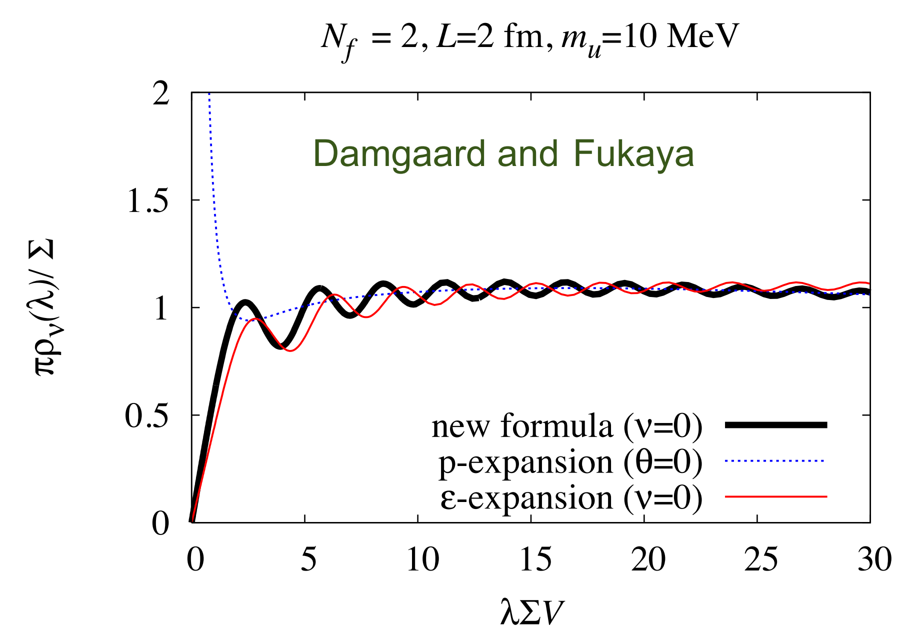
taste breaking and mixed action

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





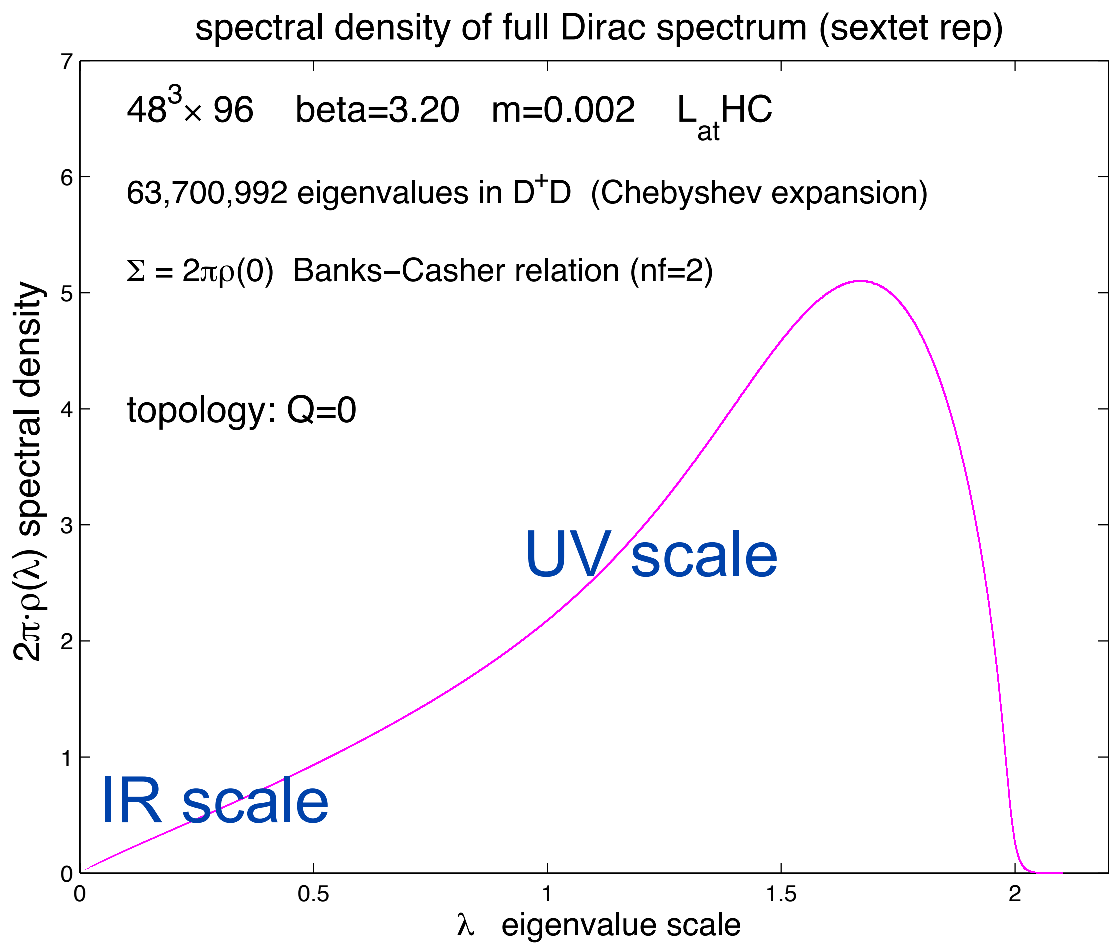


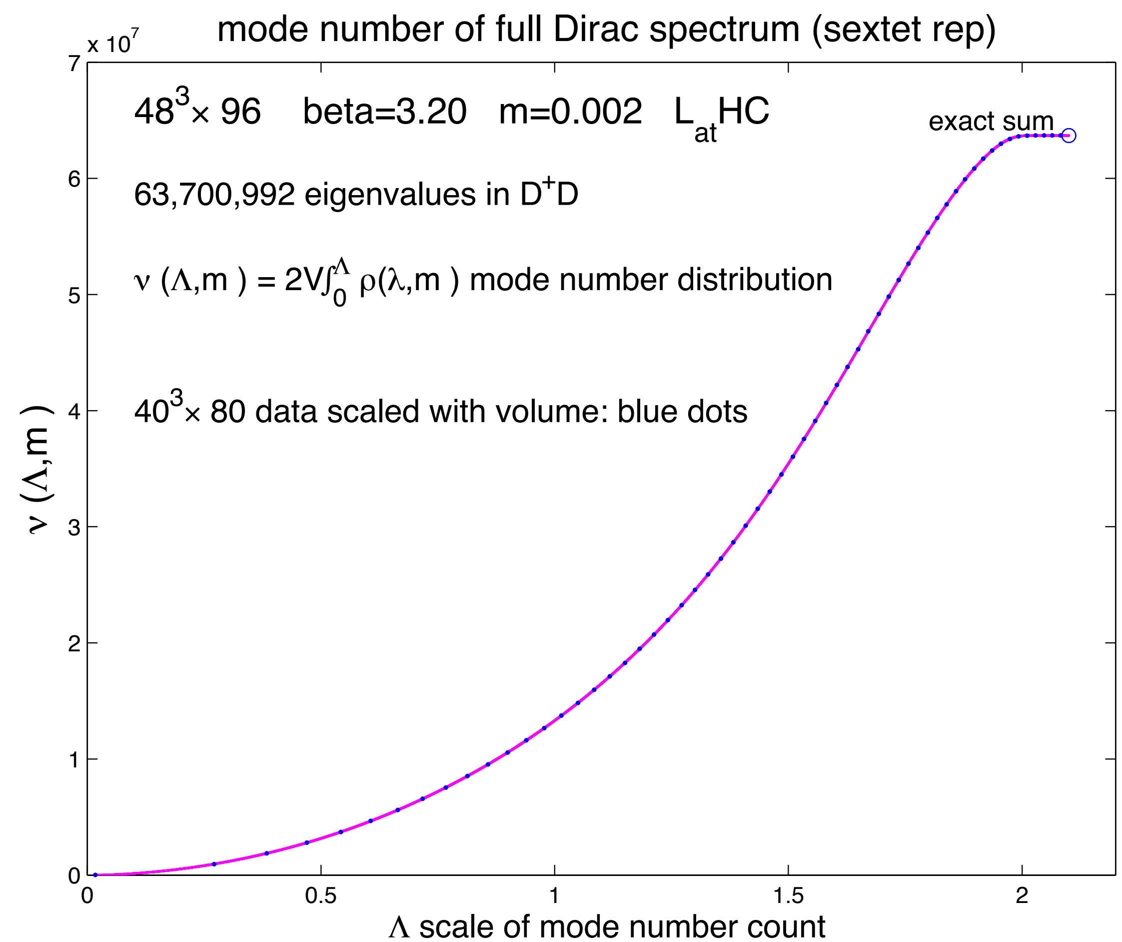


- B drops by large factor after matching, with some small decrease in F
- GMOR implies large drop of order O(10) in the chiral condensate Σ
  Σ is not RG invariant, requires rescaling
- in original analysis mΣV ~ O(100-200)
  to reach RMT regime close to CW requires large resources
- in Mixed Action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





- 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.

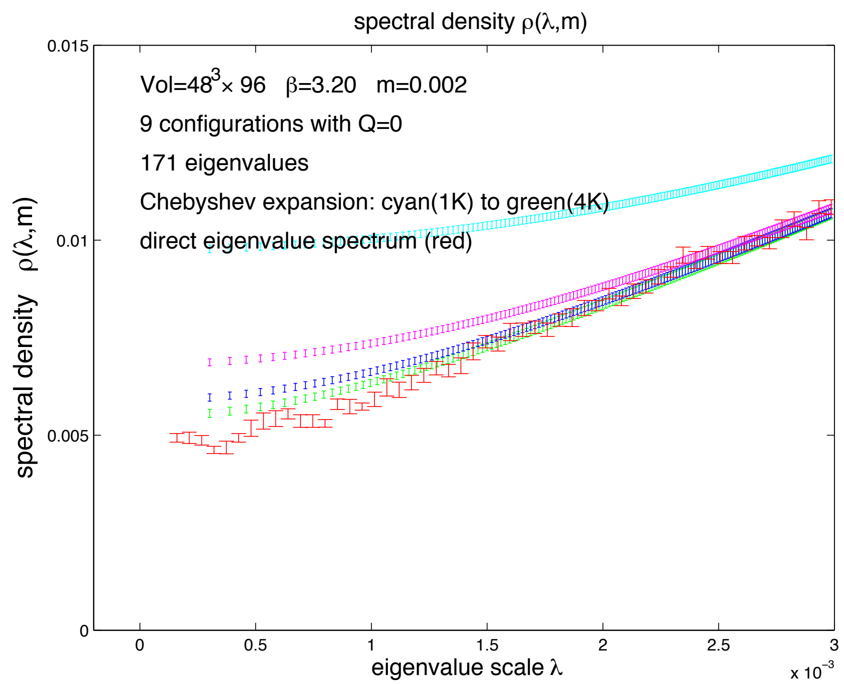
The chiral condensate   GMOR test in far IR

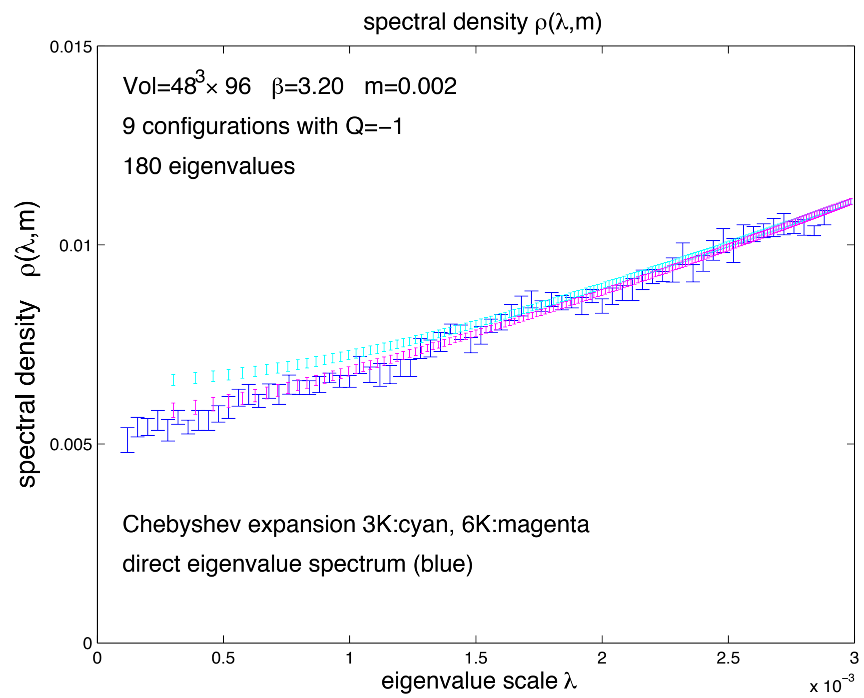
GMOR relation (nf=2): $2BF^2 = \Sigma$ (Σ is the chiral condensate)

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:

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





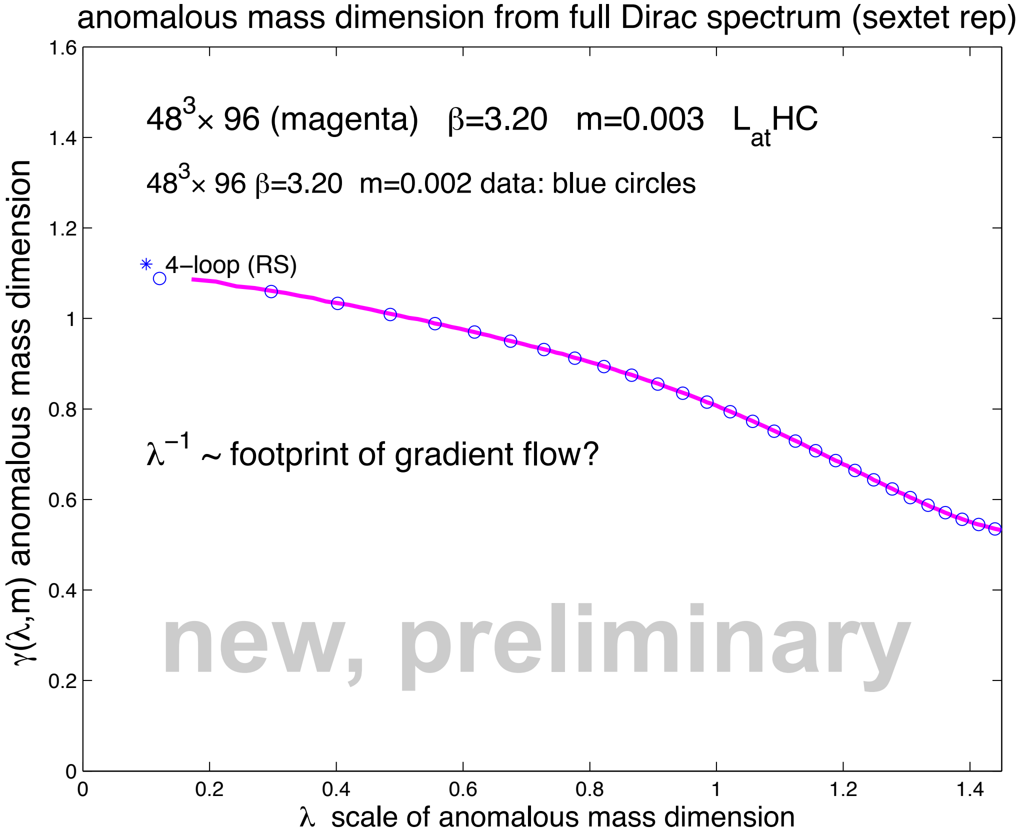
Improved determination of the chiral condensate Σ compared from Dirac spectra and the Chebyshev expansion.
With the additive NLO cutoff term separated from B and new fit to F, the improved result on Σ eliminates previous discrepancies in the GMOR relation.

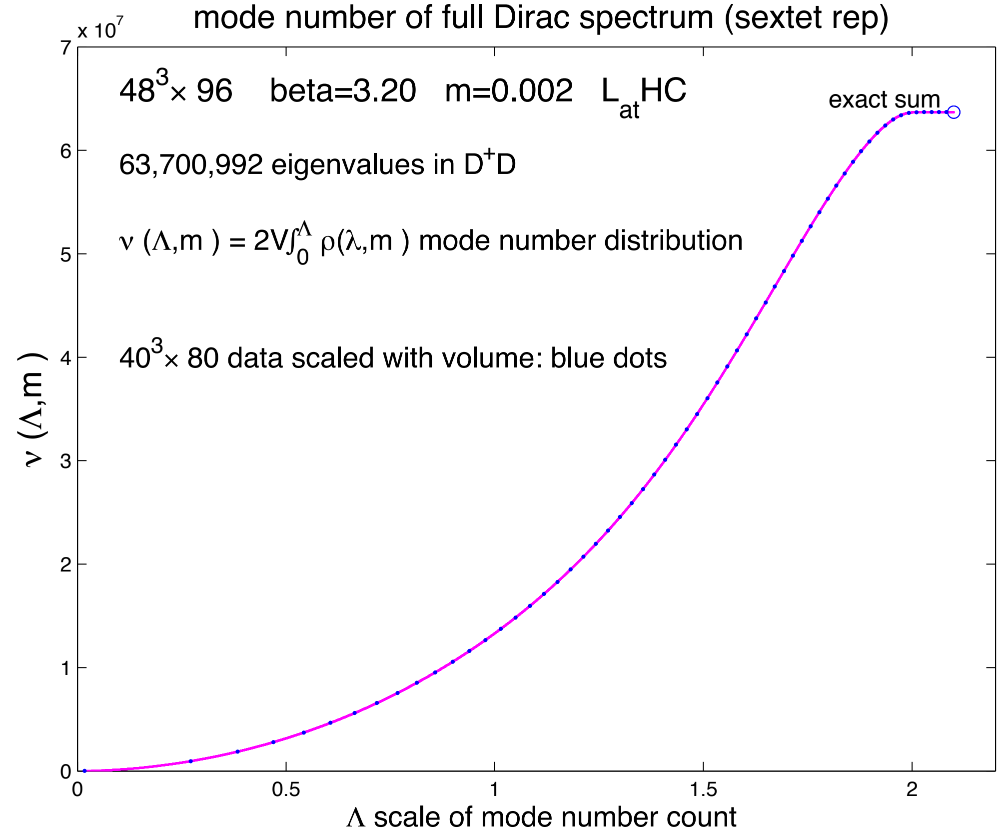
The chiral condensate mass anomalous dimension

Boulder group pioneered fitting procedure

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

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





How to match λ scale and g^2 ?

The chiral condensate   mass anomalous dimension

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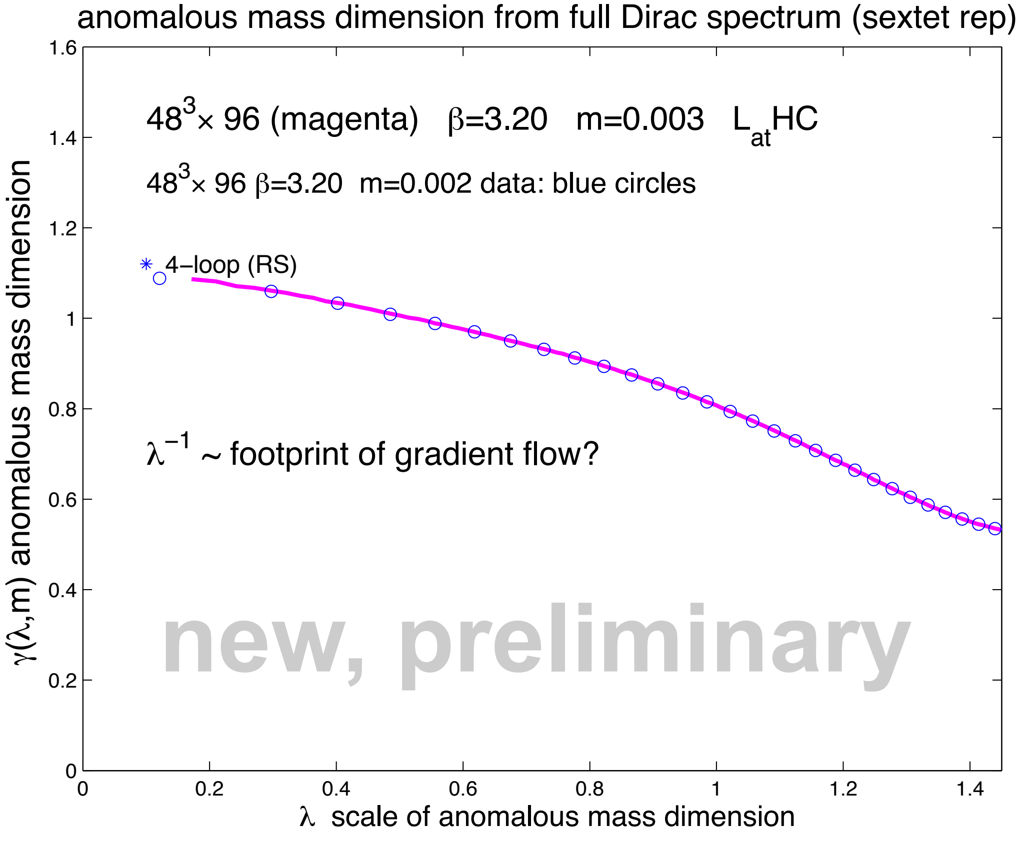
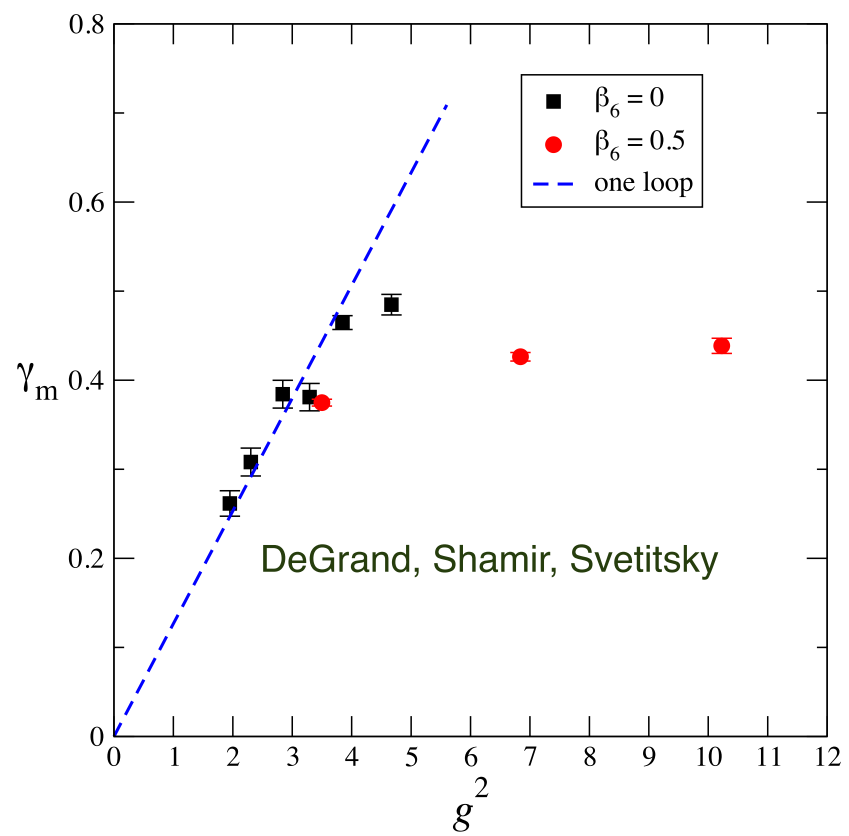
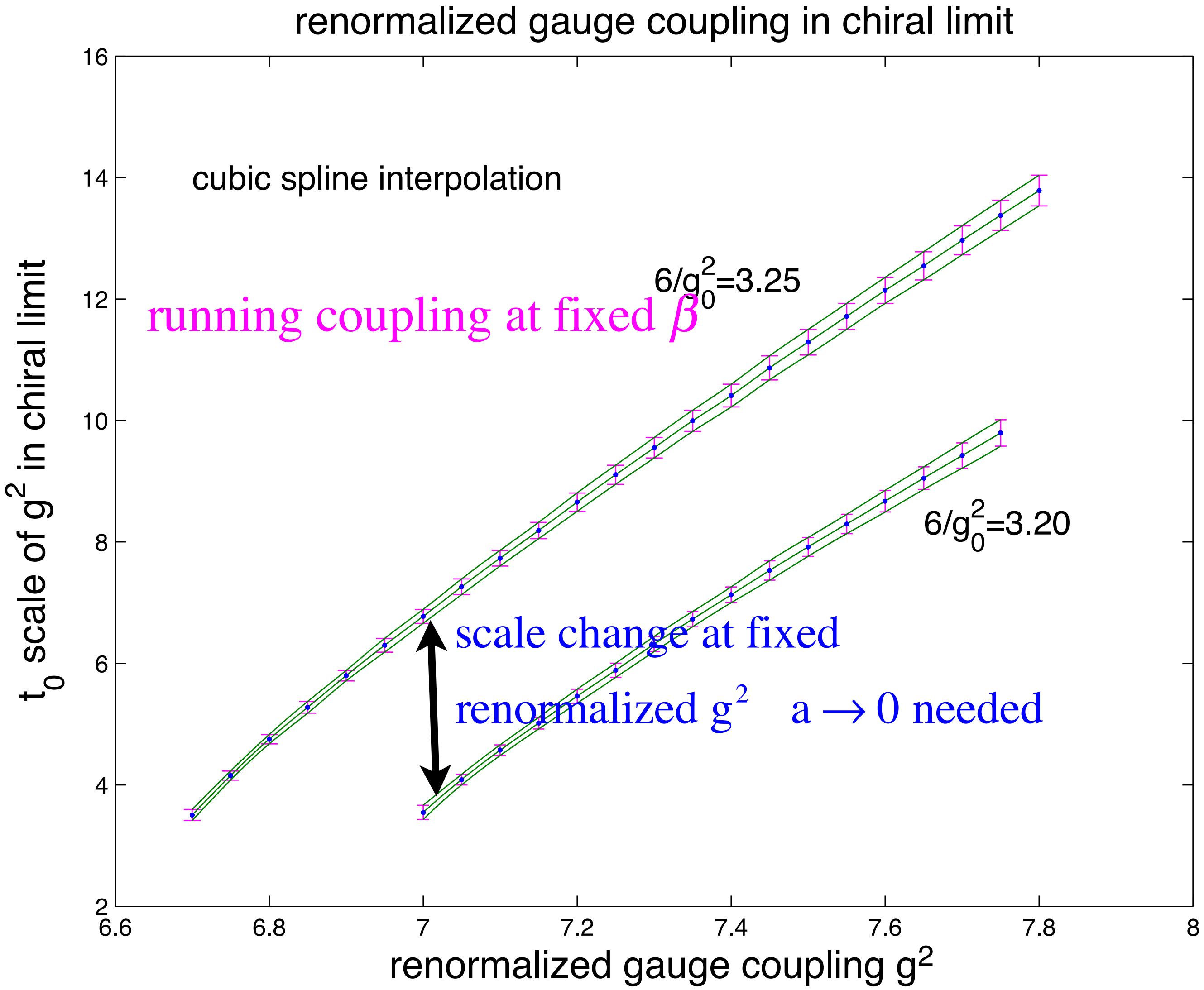
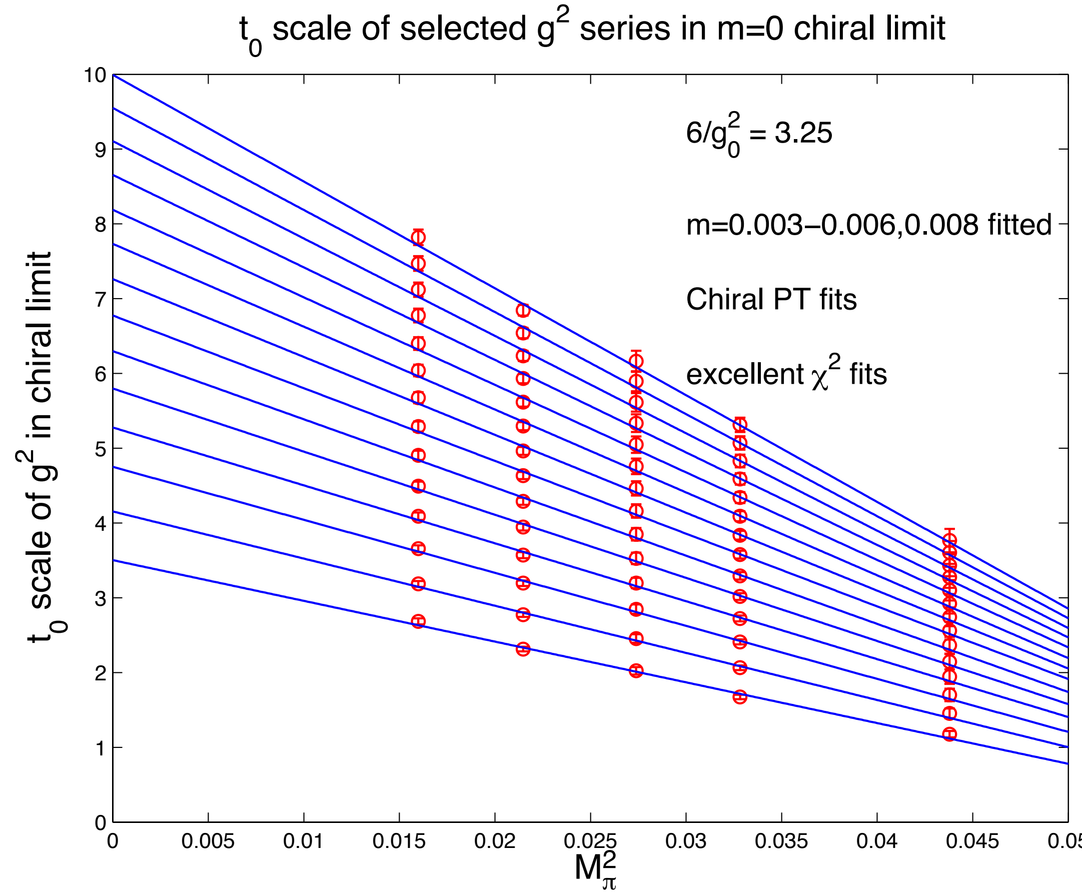


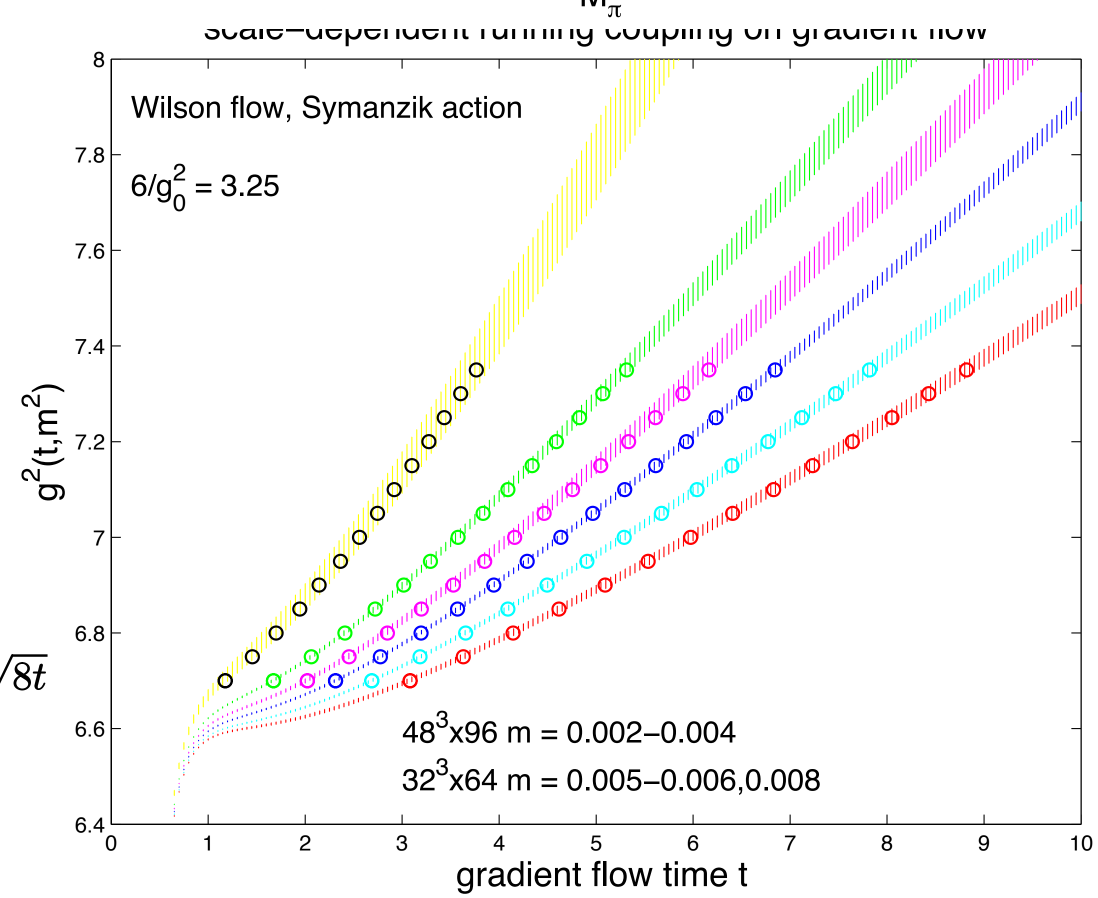


How to match λ scale and g^2 ?

scale-dependent coupling matching IR to UV





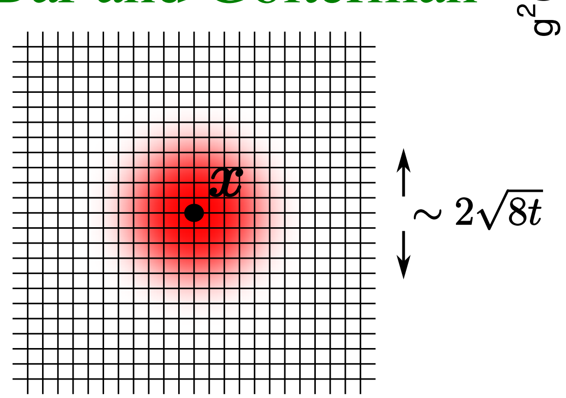


leading dependence of $g^2(t,m)$ on M_π^2 is linear

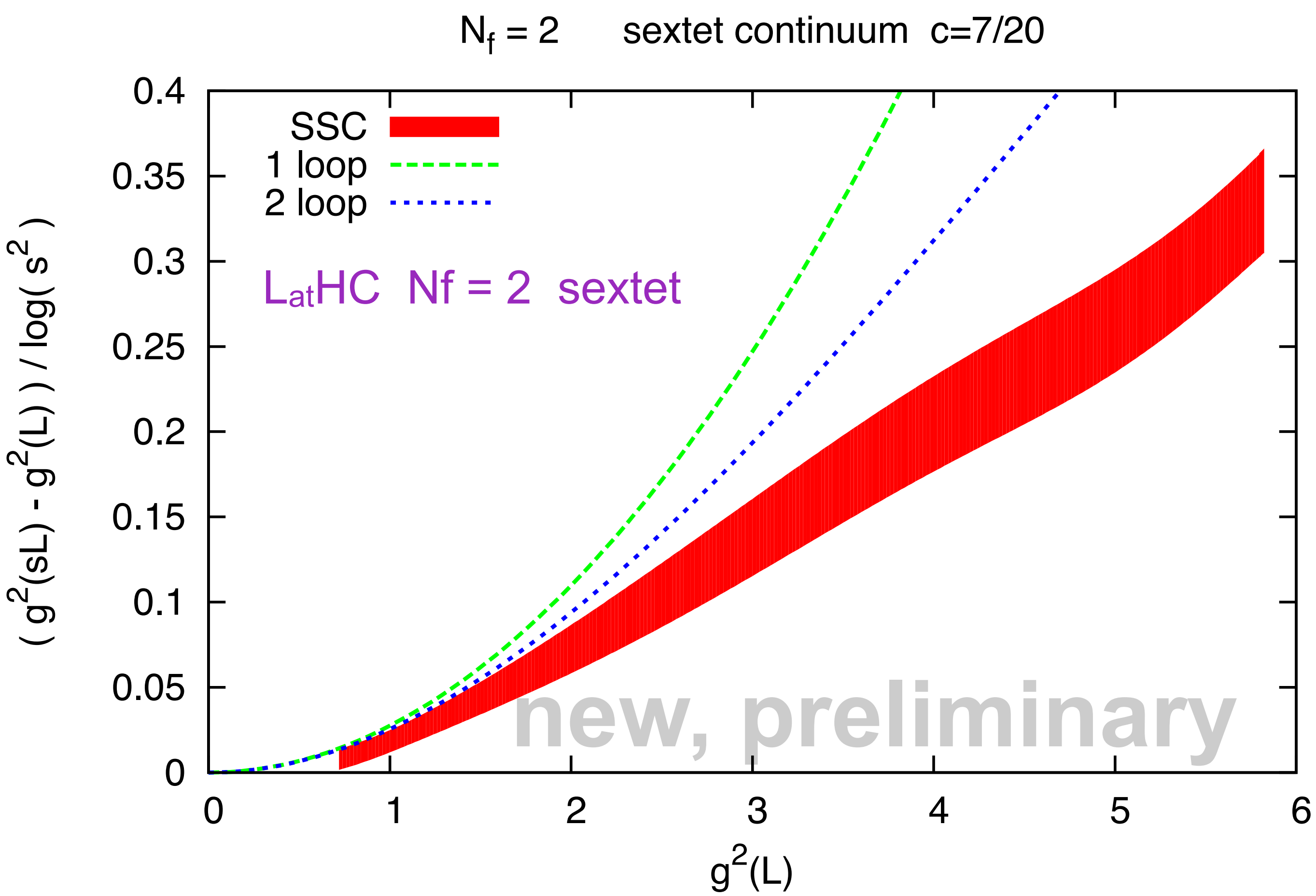
based on gradient flow chiPT Bär and Golterman

works better than expected

chiral logs are not detectable



the running coupling and the β function   finite volume



monotonic increase of g^2 with scale is 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

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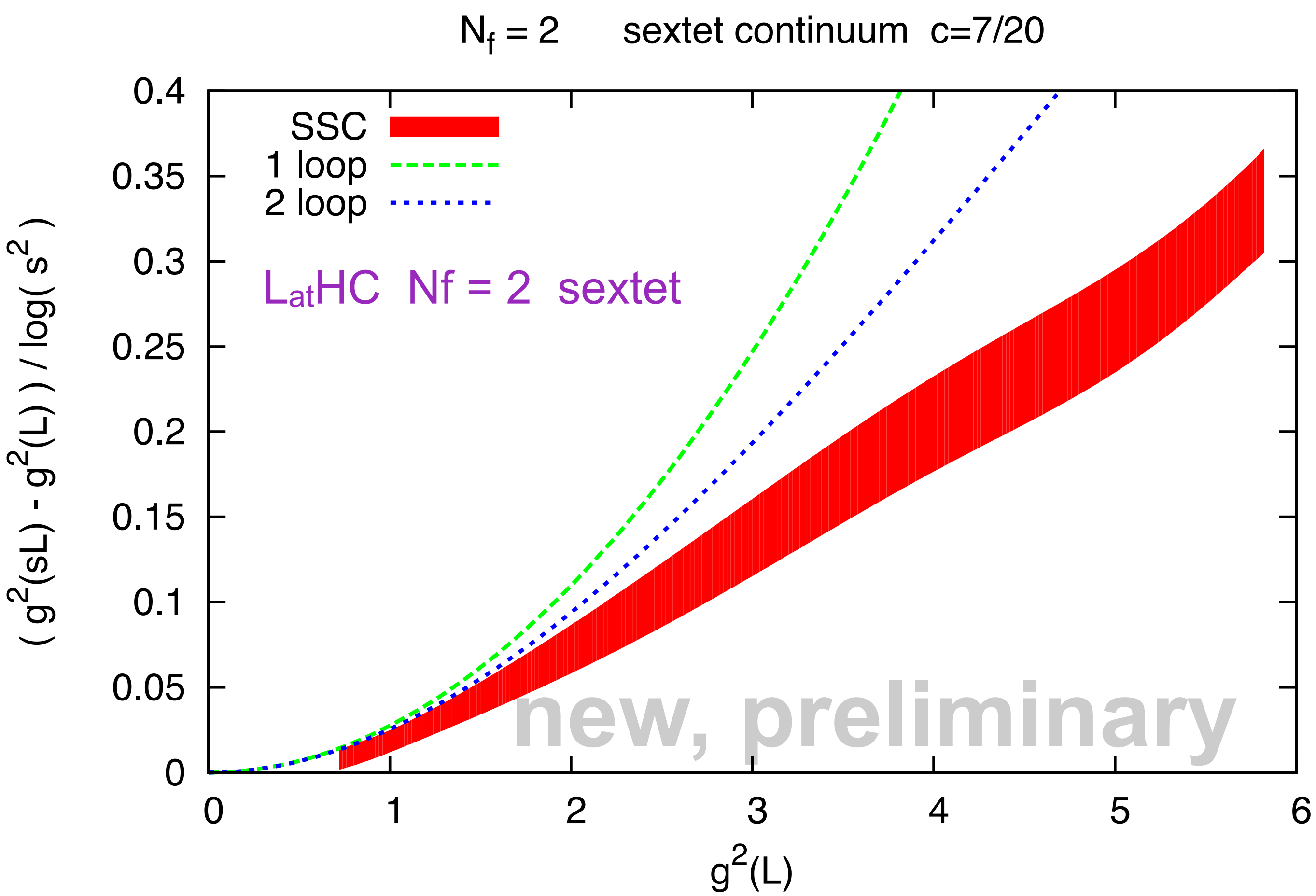

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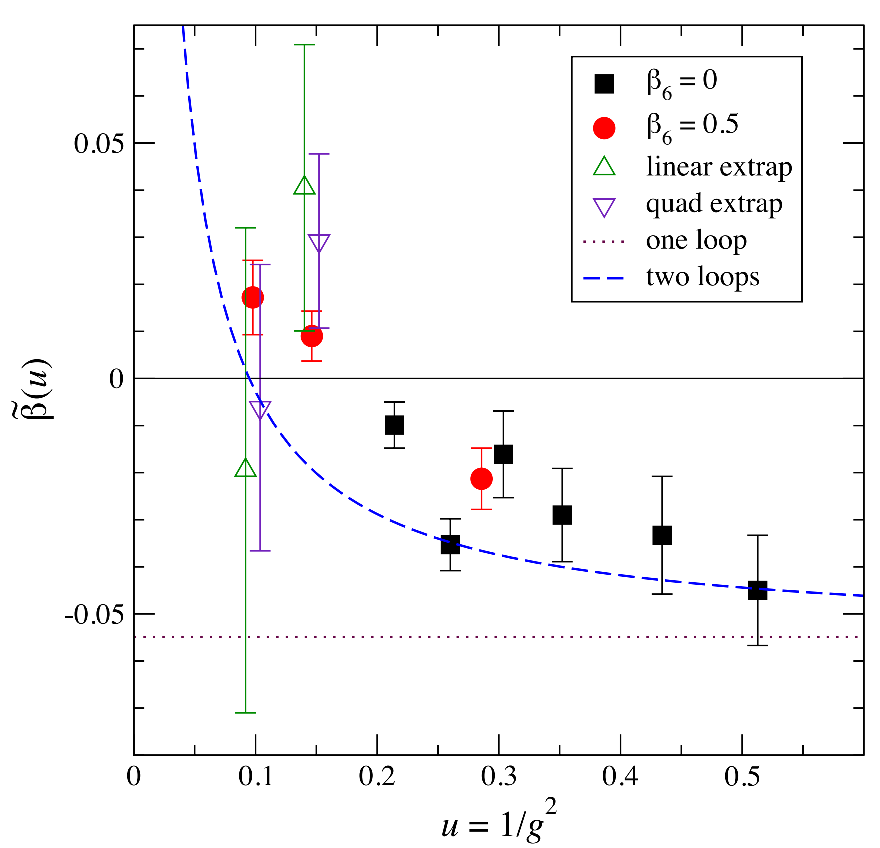
DeGrand, Shamir, Svetitsky



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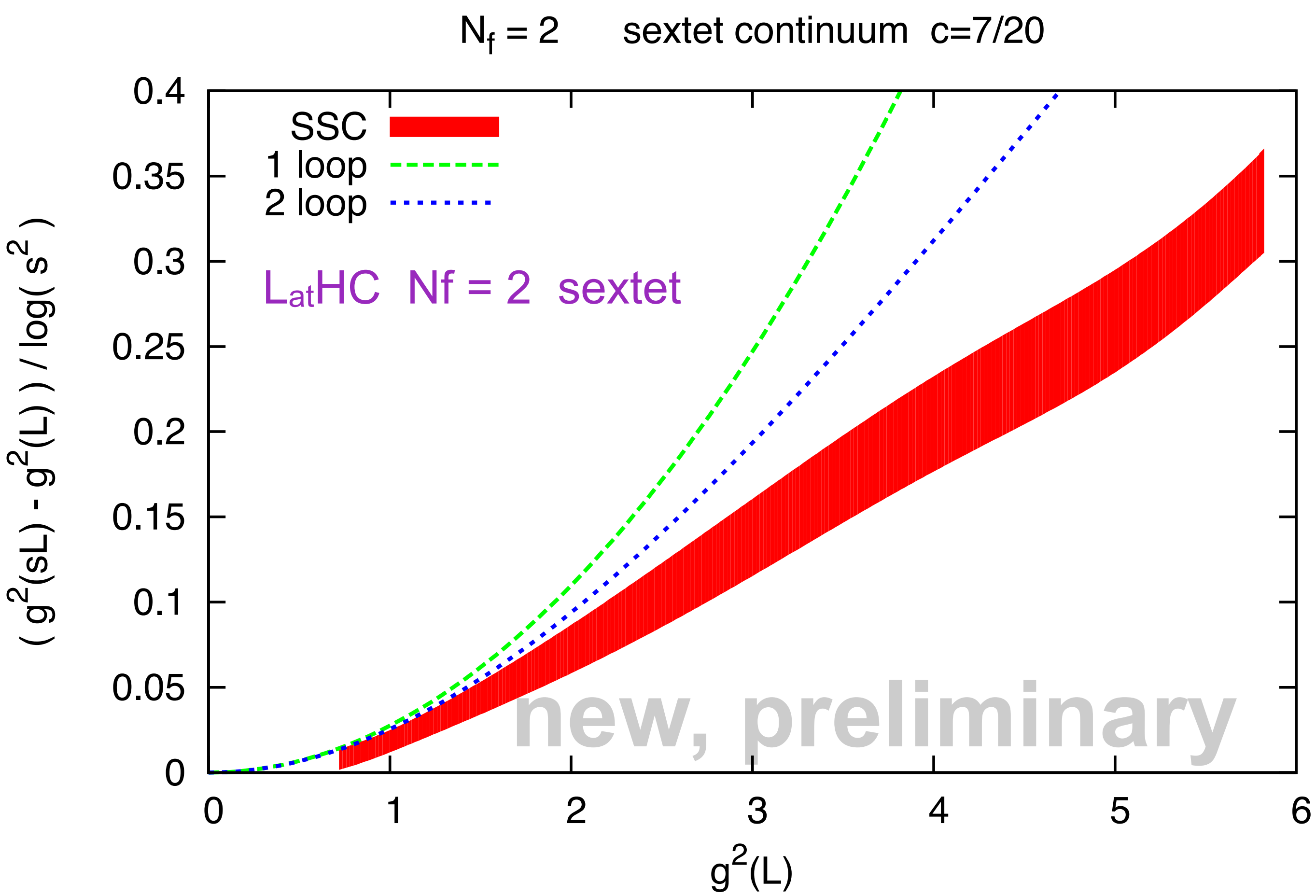

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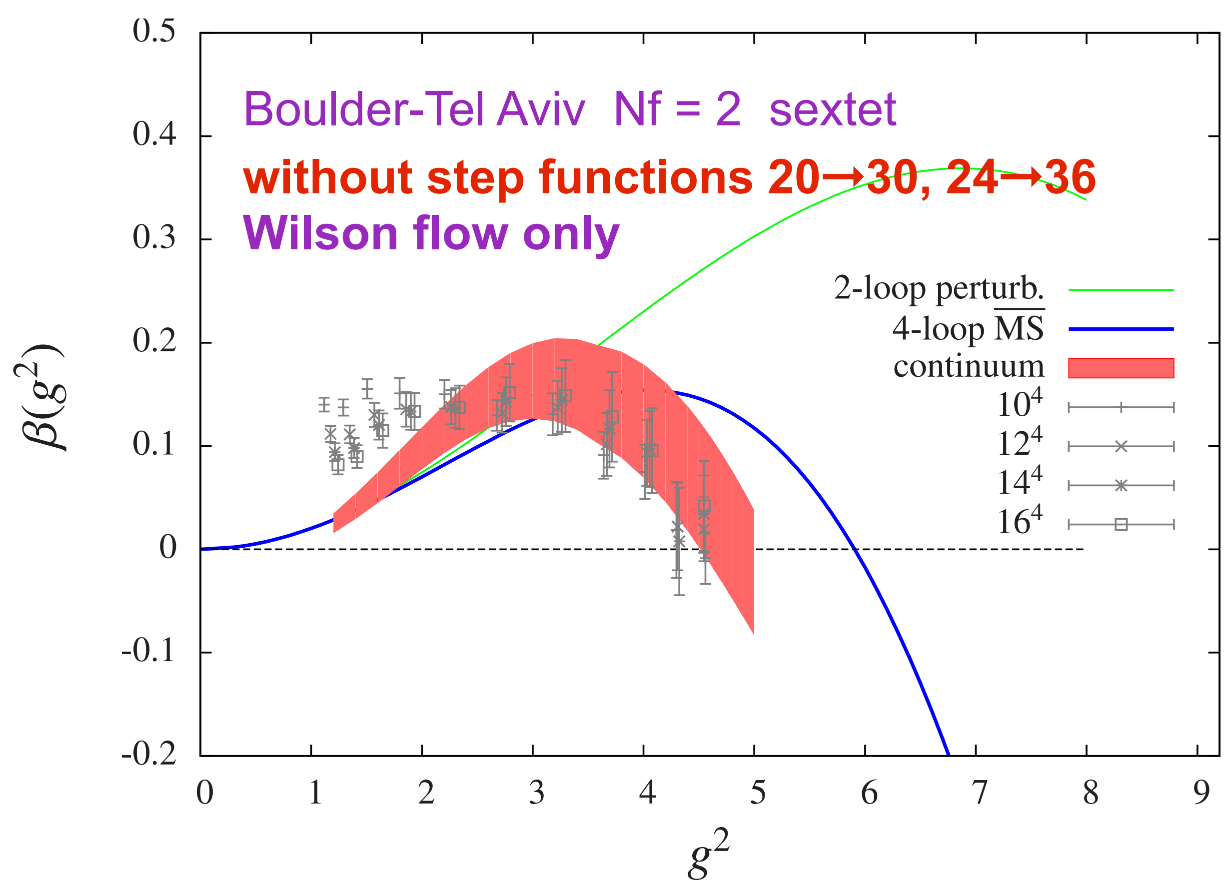

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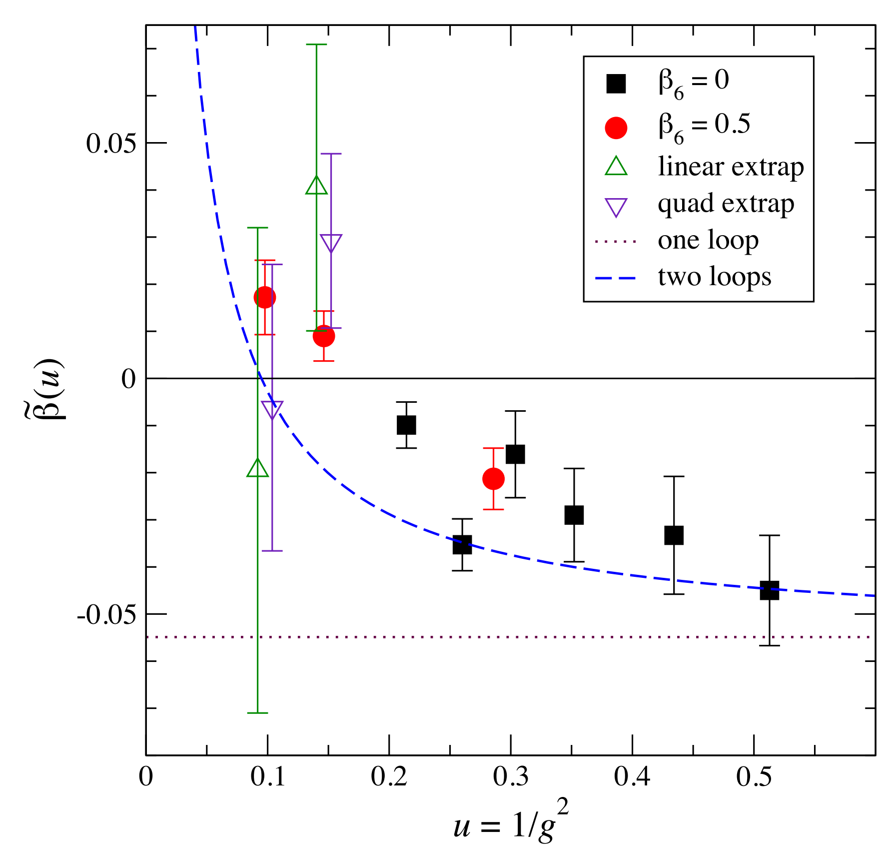

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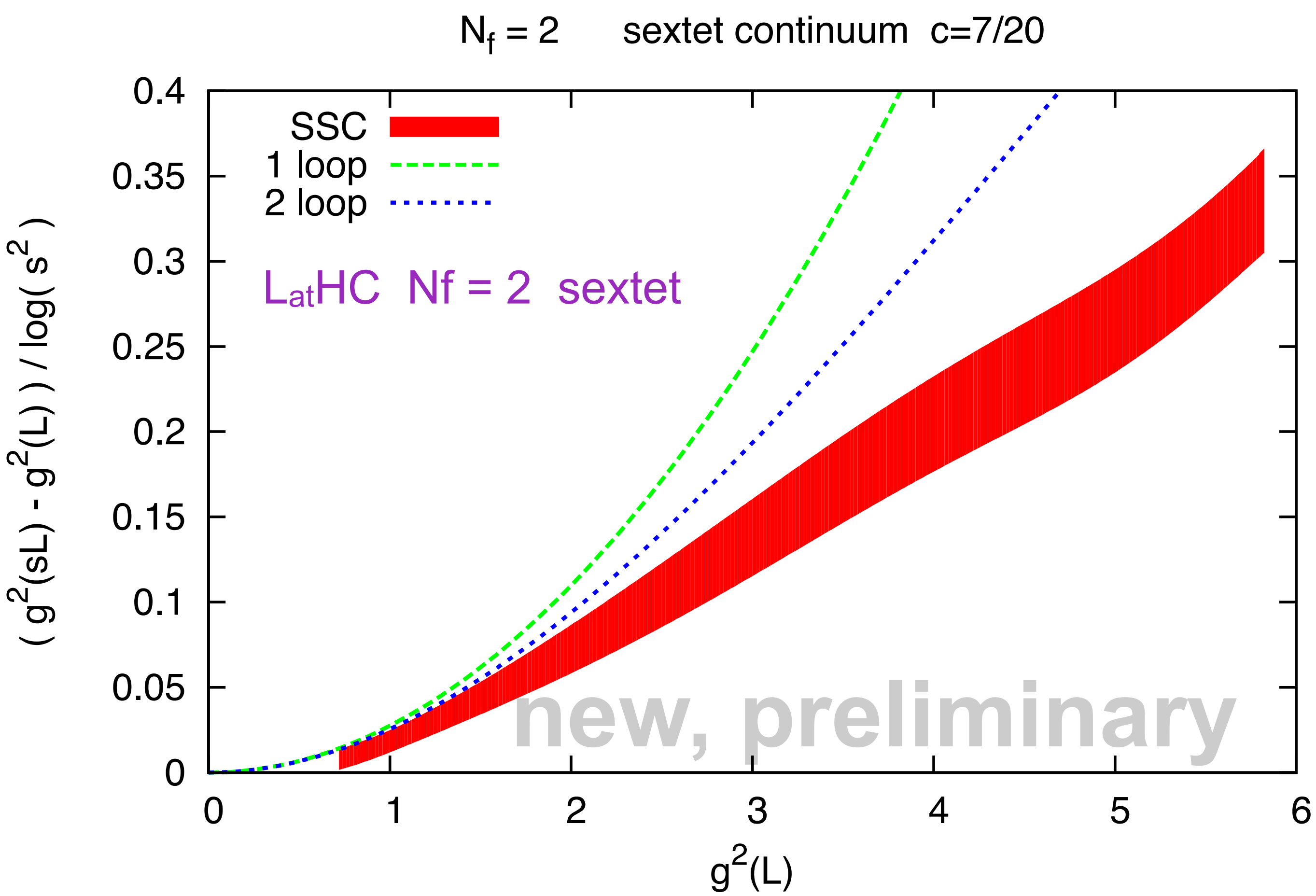

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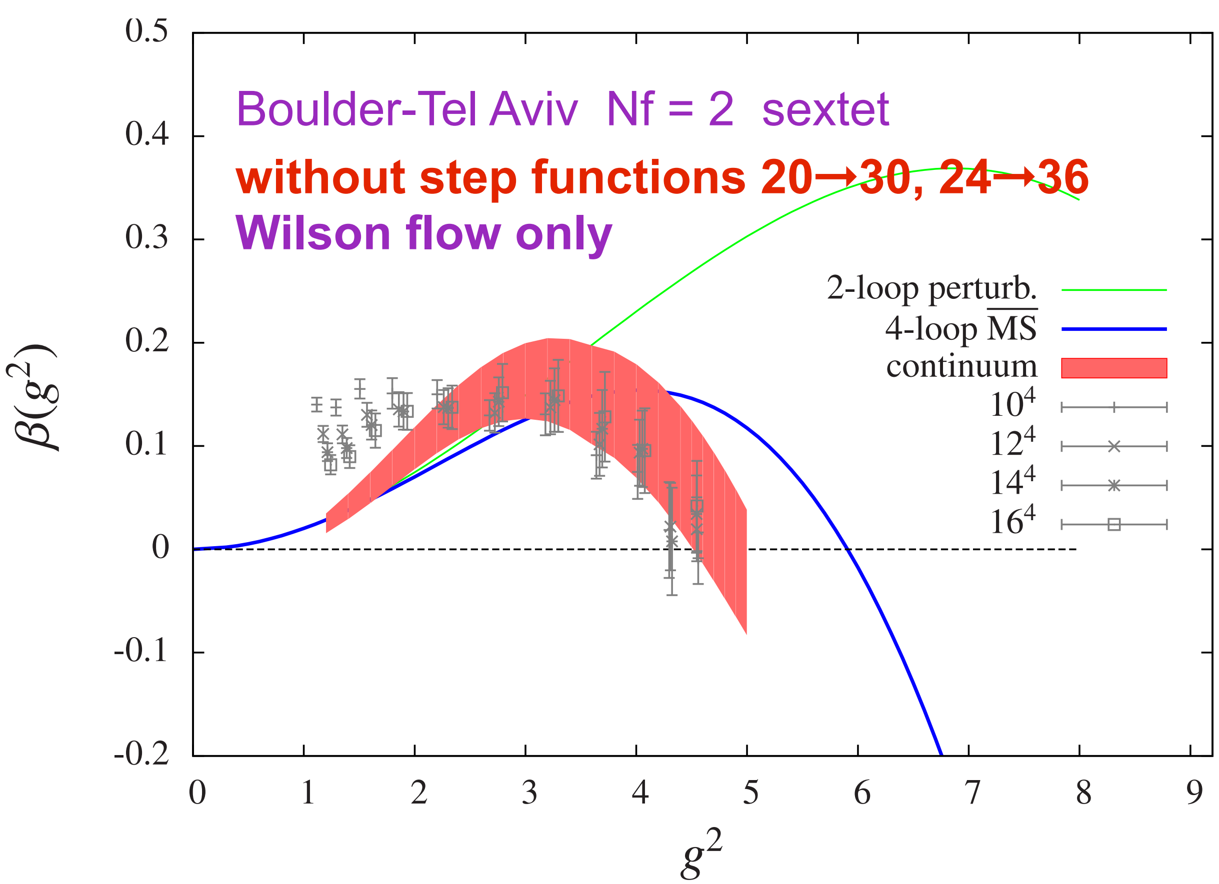

This is disagreement is between two analyses nothing to do with staggered formulation

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

Early universe

Kogut-Sinclair work consistent with χSB EW phase transition
Relevance in early cosmology (order of the phase transition?)
L_{at}HC is doing a new analysis using different methods

- 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)

• successful knock on LHC door	ATLAS analysis and CMS plan
• very efficient staggered BG/Q code	30-40 percent CG efficiency sextet Janos
• 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
• scale-dependent coupling	difficult, Gradient Flow is huge improvement
• Electroweak phase transition and baryon	intriguing