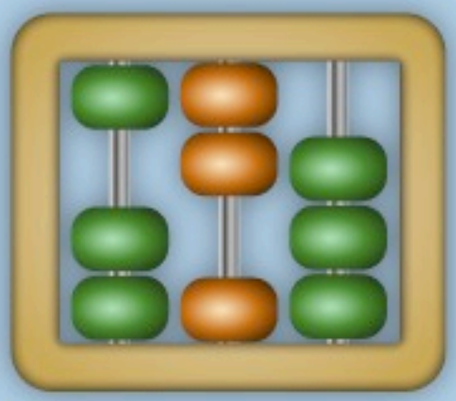

Higgs workshop
Edinburgh 2013

The sextet BSM model and the Higgs impostor

Lattice Higgs Collaboration (LHC) ->

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

Julius Kuti

University of California, San Diego

Strongly interacting dynamics beyond the Standard Model and the Higgs boson

Higgs Center workshop, University of Edinburgh, April 24-26, 2013

Outline

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- why the sextet model?

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- chiral symmetry breaking sextet model

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- dark matter, finite temperature

- summary and outlook

for more details of the discussions:

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

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

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

The sextet gauge model, light Higgs, and the dilaton

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

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

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

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

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

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

preliminary new results, published soon

why the sextet model?

LATTICE GAUGE THEORIES AT THE ENERGY FRONTIER

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

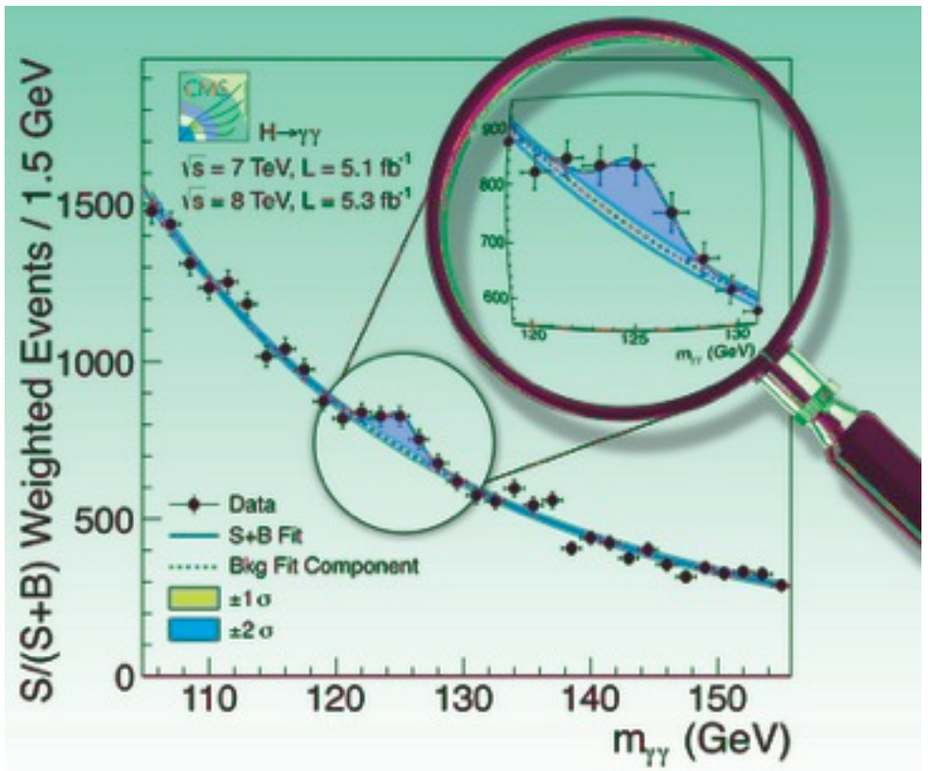
(USQCD Collaboration)

(Dated: March 10, 2013)

White paper - USQCD BSM community based effort :

- identify most significant accomplishments of last few years
- identify our three major research directions for planning
- describe the toolset and its phenomenological applications
- estimate resources needed for the plan

New hardware proposal of USQCD submitted to DOE
with three main directions

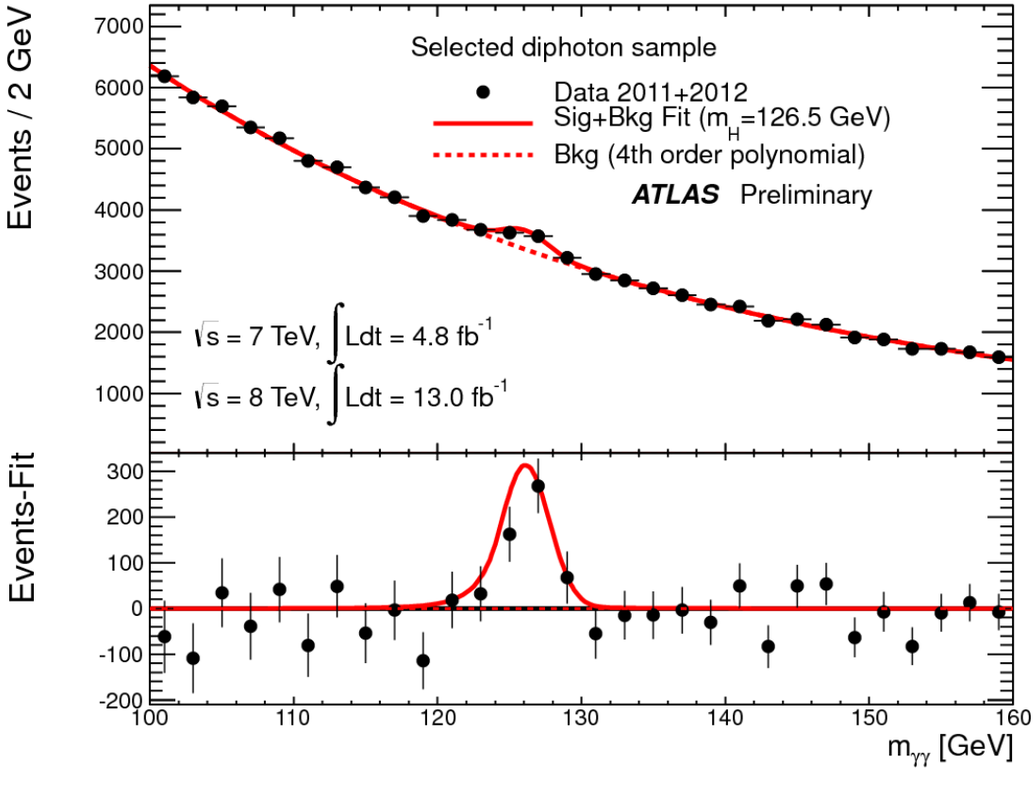


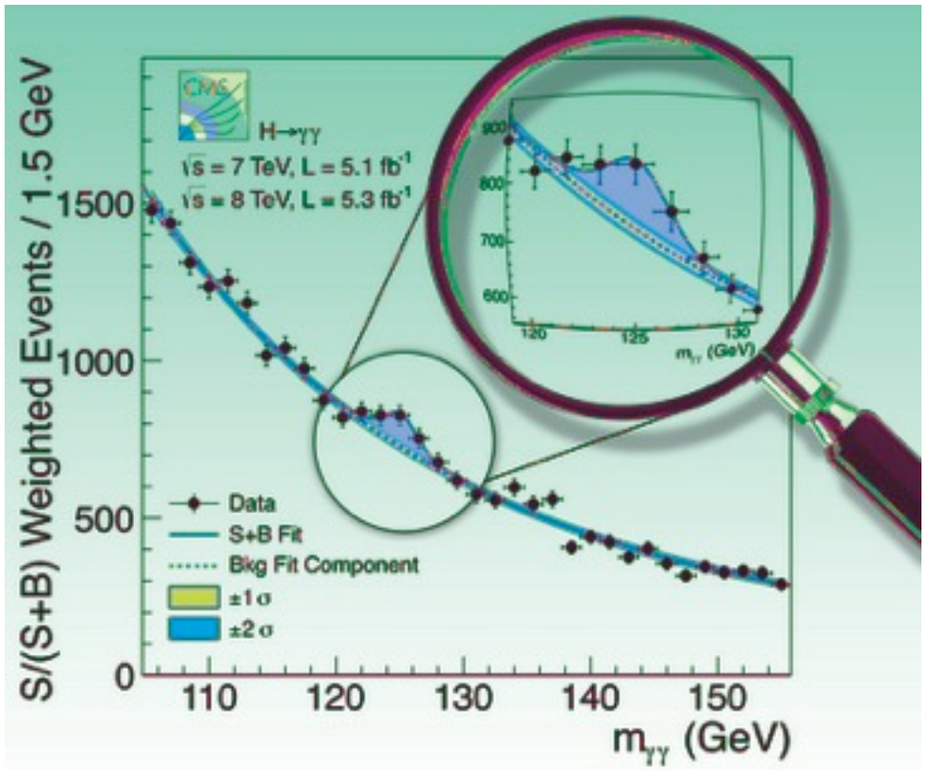
- two plots effected our planning no kidding :)

  where is the Higgs? no more asked
  what is it made of? asked now all the time

- "Mexican hat" solution parametrization rather than dynamical explanation?

- has fine tuning and hierarchy problems





A malicious choice!

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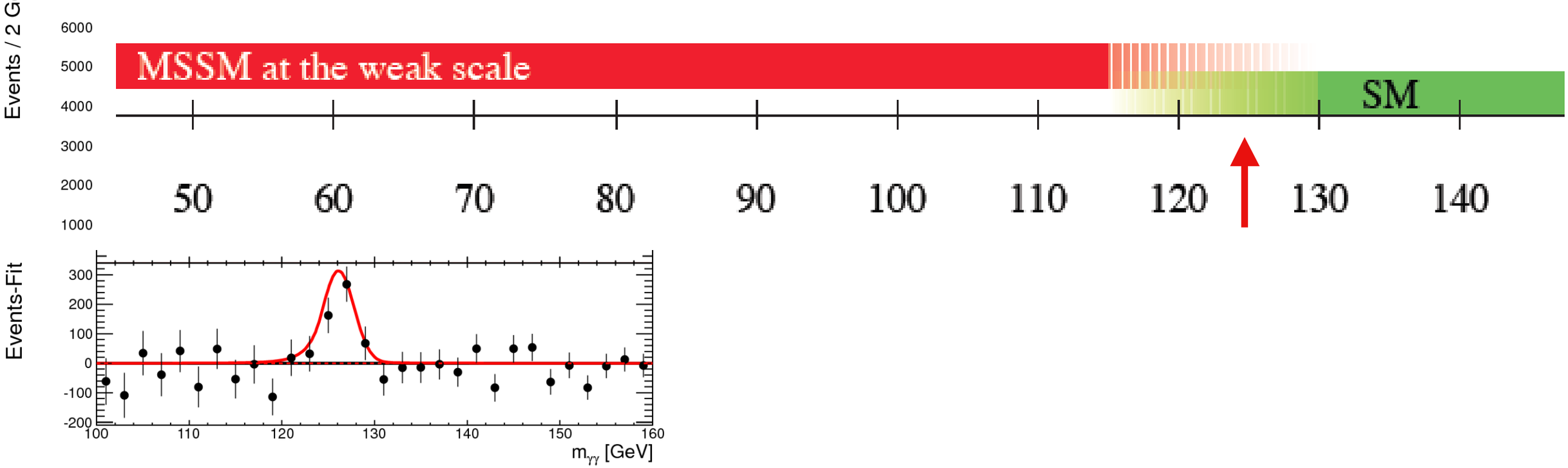
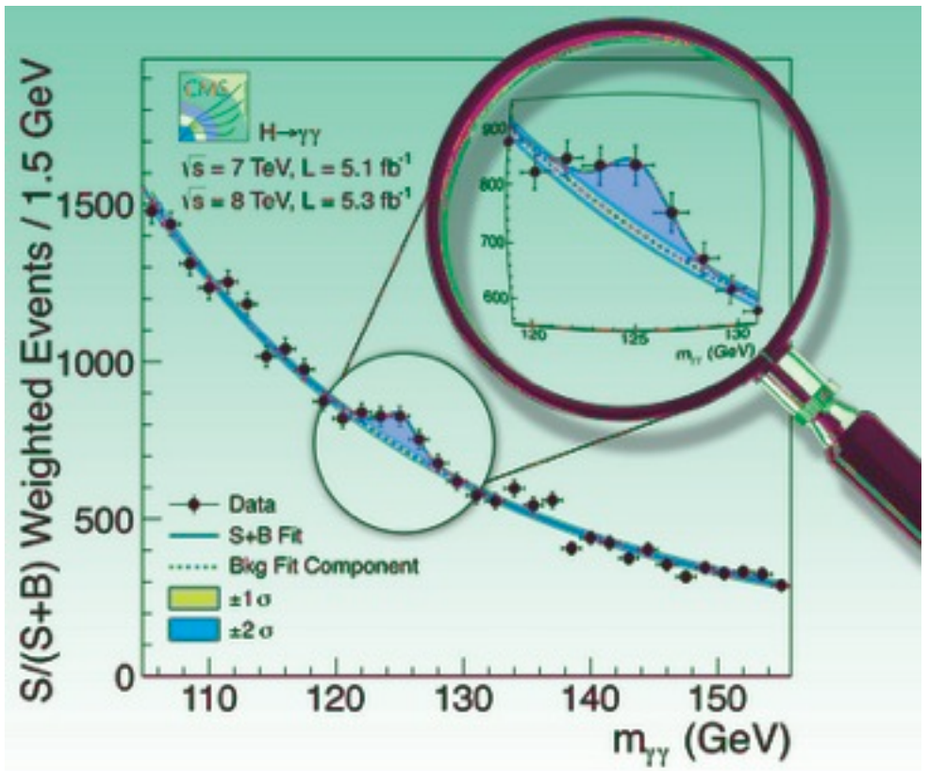
Strumia





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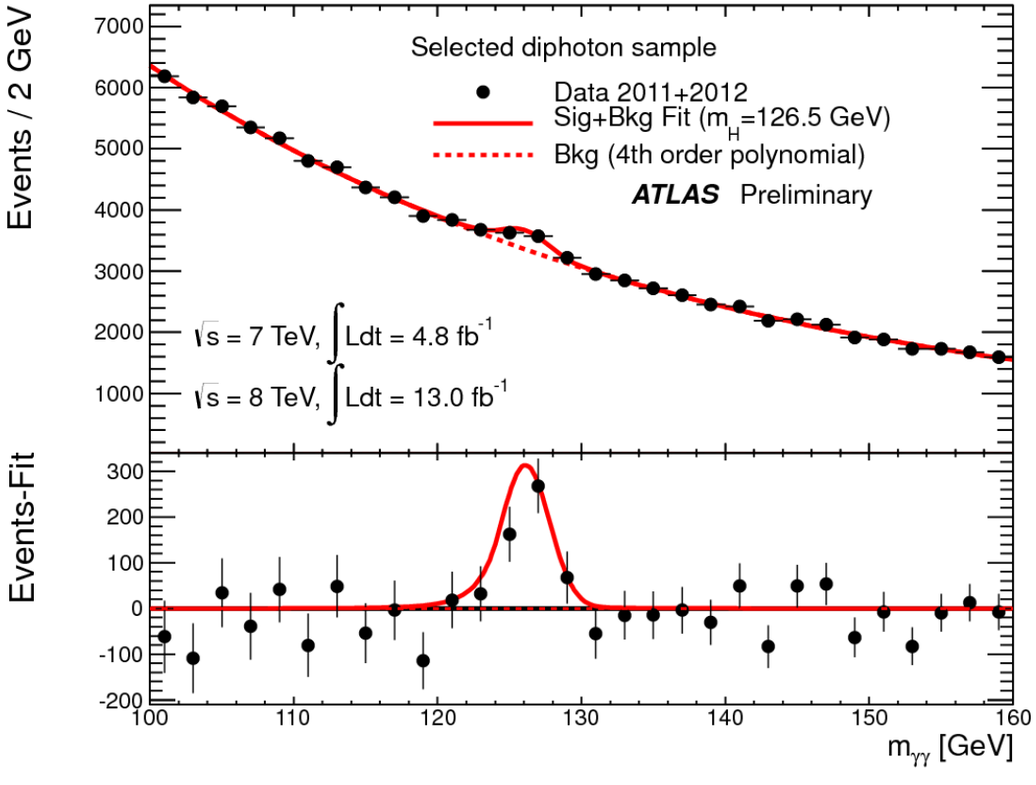

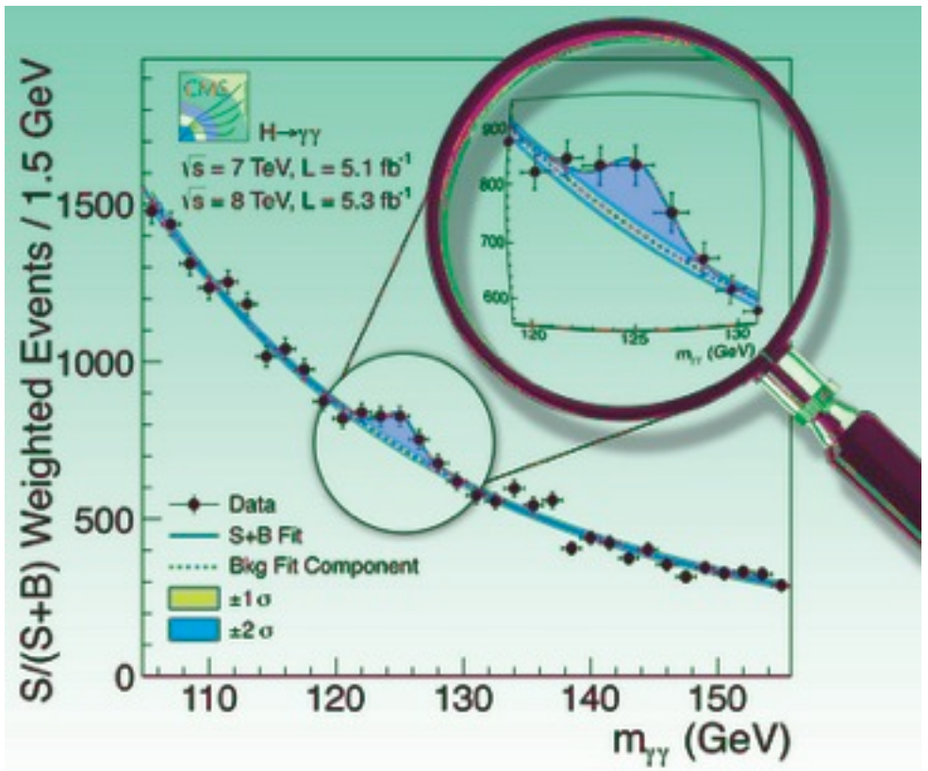

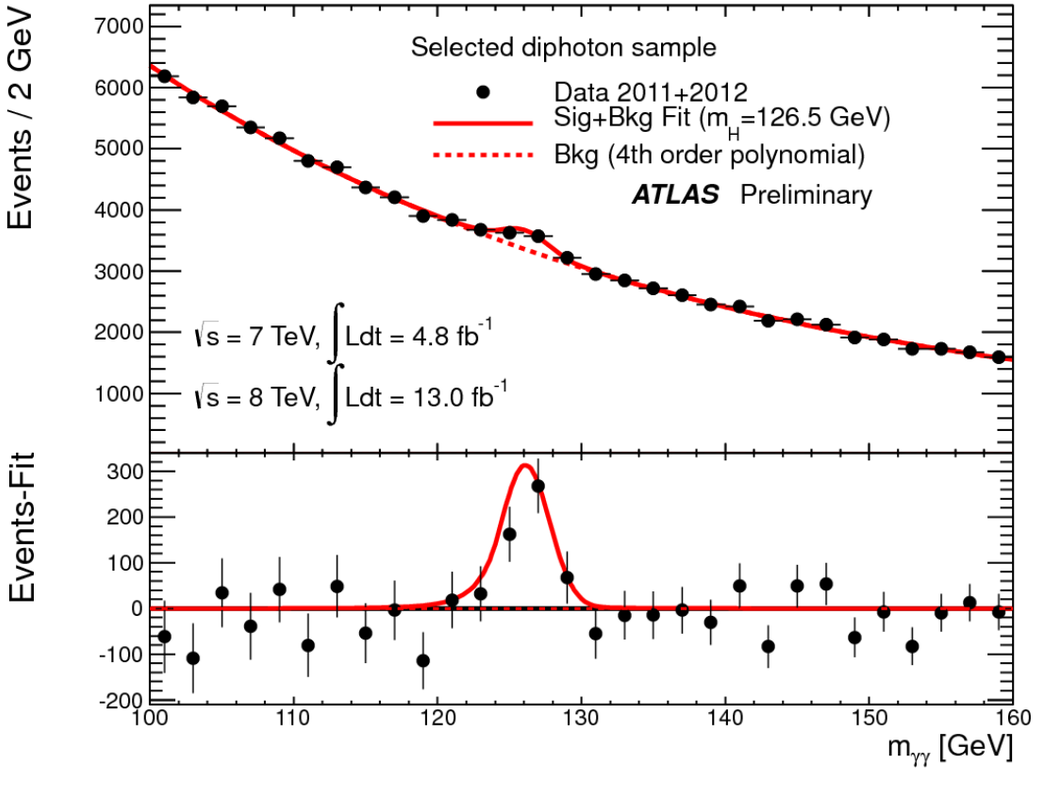

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- three BSM directions to do better:

  sextet model

  - strongly coupled near-conformal gauge theories

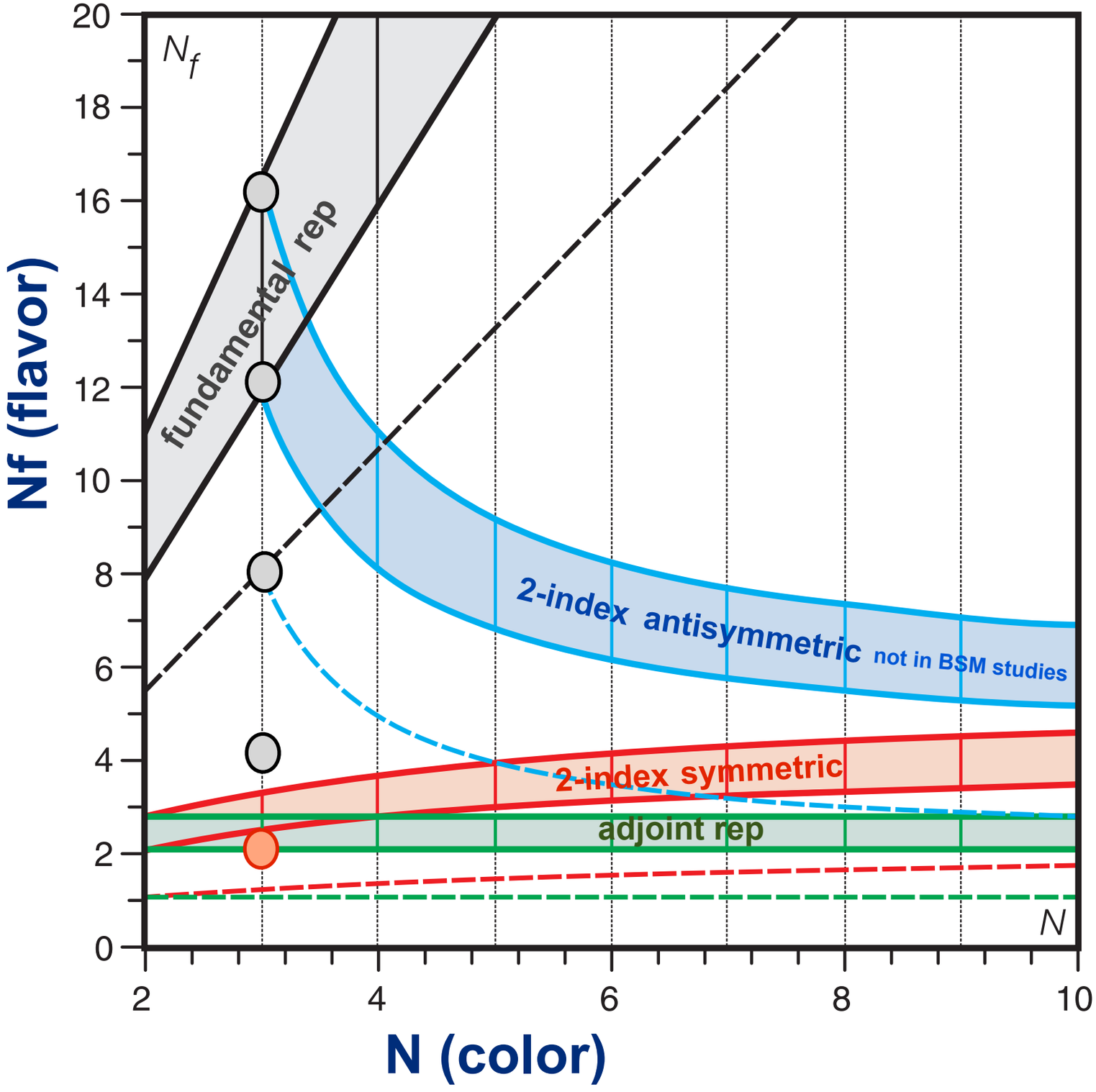
  - light pseudo-Goldstone boson (like little Higgs)

  - SUSY

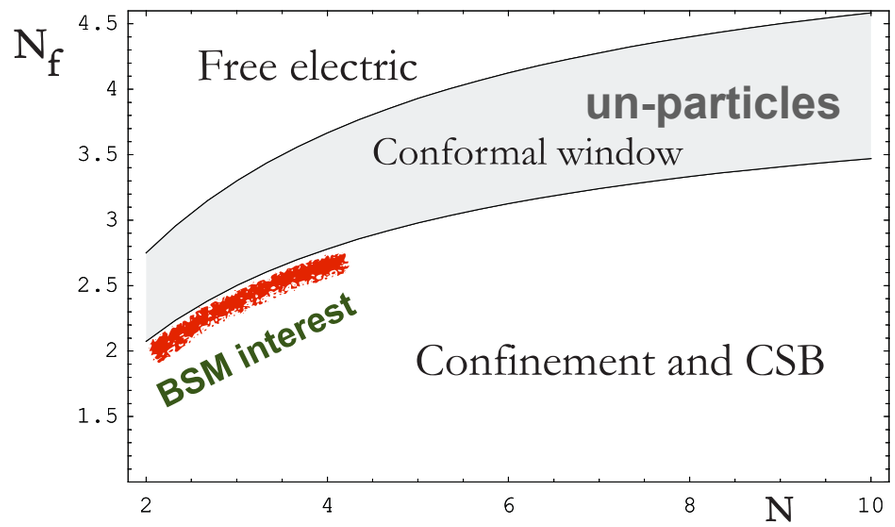
- new physics with little or no tuning within LHC reach, or hiding just above LHC reach?

theory space and conformal window

color, flavor, and massless fermion representation



for each rep BSM interest is below conformal window but close to it:



physics prospects of sextet look promising ?

theory space and conformal window

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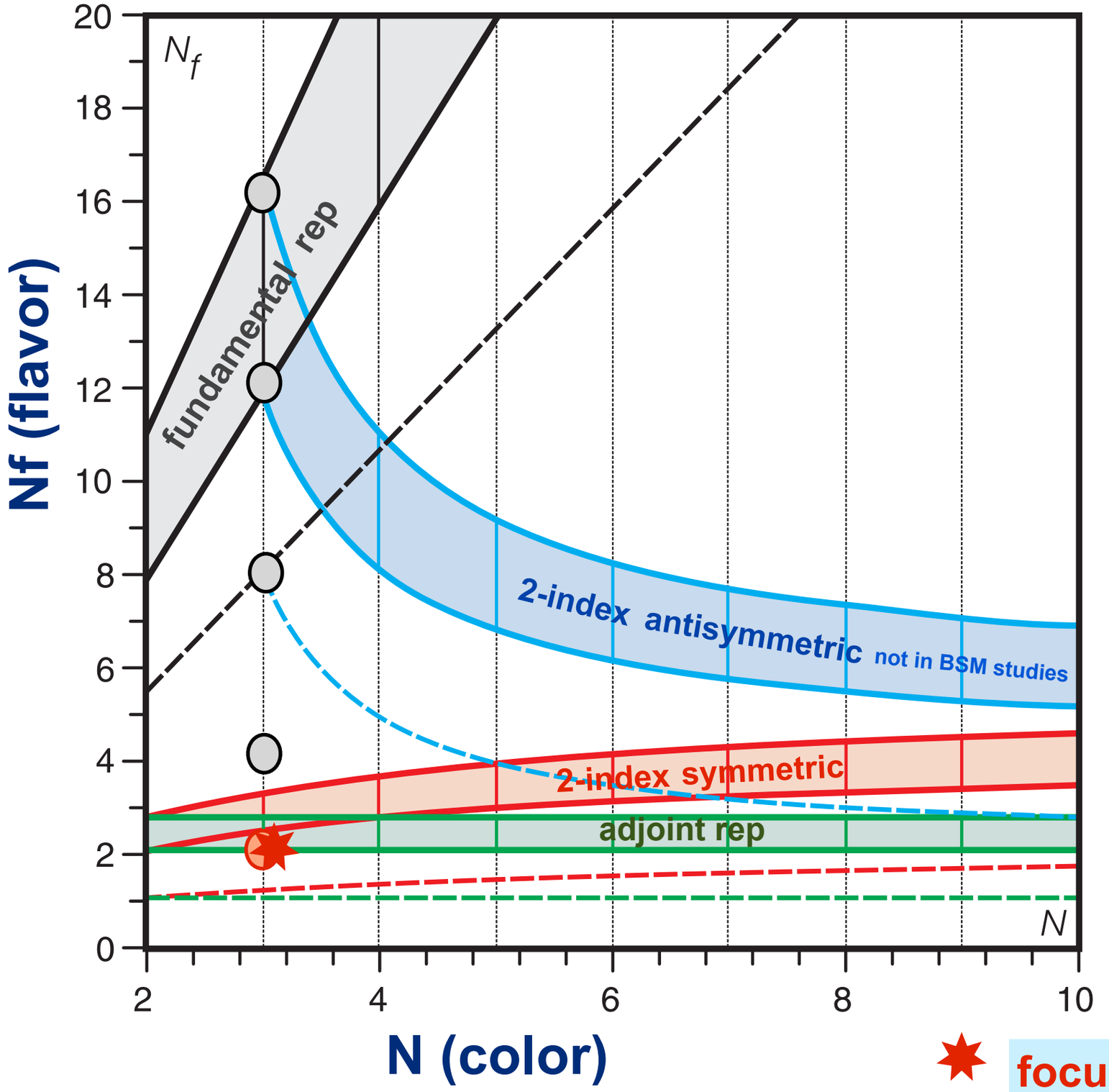

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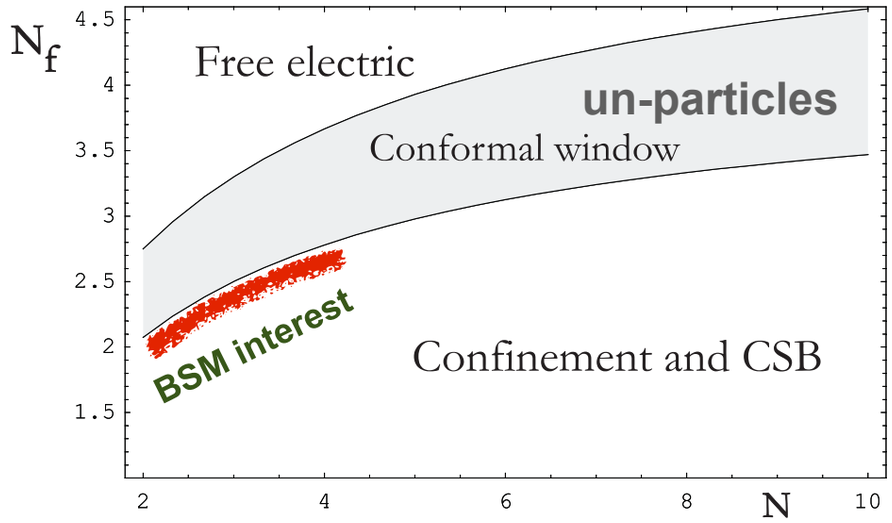
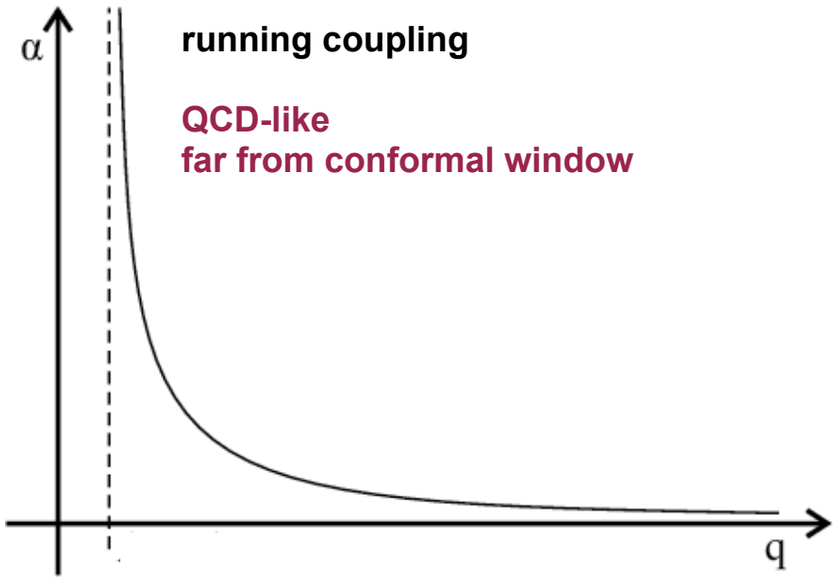


physics prospects of sextet look promising ?

★ **focus of talk**

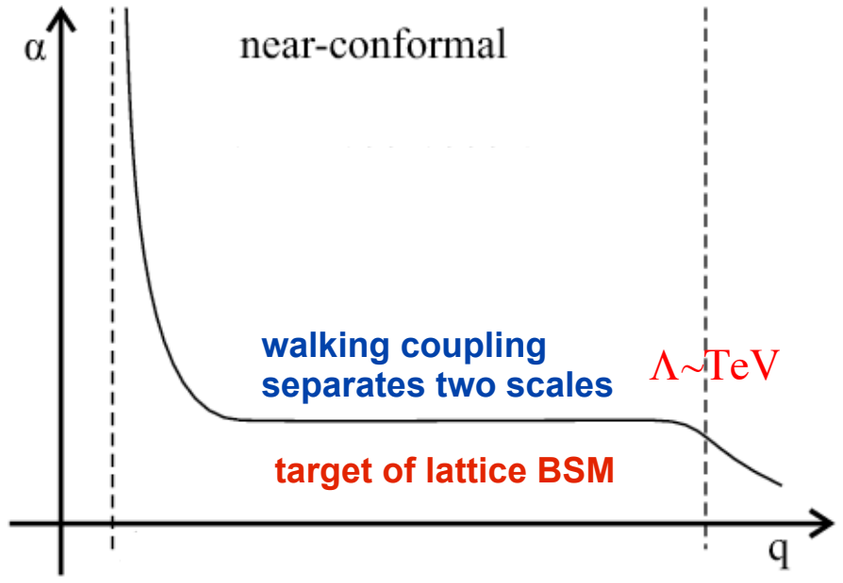
New extended data set and analysis

simplest realization of composite Higgs: Nf=2 SU(3) sextet representation



running coupling

QCD-like
far from conformal window



χSB on Λ~TeV scale

walking gauge coupling

fermion mass generation not addressed

what composite Higgs mechanism ?

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

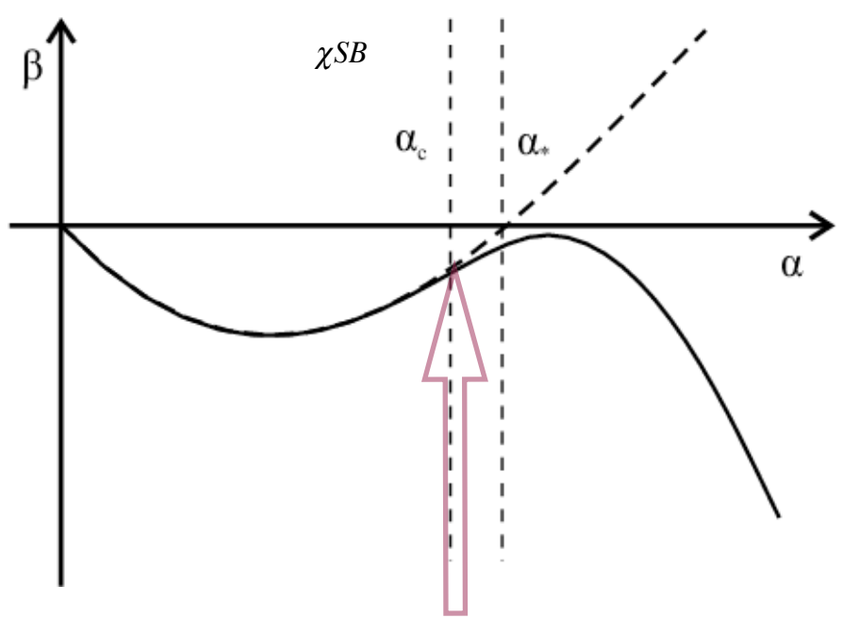
original Technicolor paradigm replaced with sextet SU(3) color rep:

one massless fermion doublet $\begin{bmatrix} u \\ d \end{bmatrix}$
χSB on Λ~TeV scale

three Goldstone pions
become longitudinal
components of weak bosons

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

conflicts with EW precision constraints?



when chiral symmetry breaking
turns conformal FP into walking

Early work using sextet rep:

Marciano (QCD paradigm, 1980)

Kogut,Shigemitsu,Sinclair
(quenched, 1984)

recent work:

DeGrand,Shamir,Svetitsky
IRFP or walking gauge coupling

Lattice Higgs Collaboration
χSB

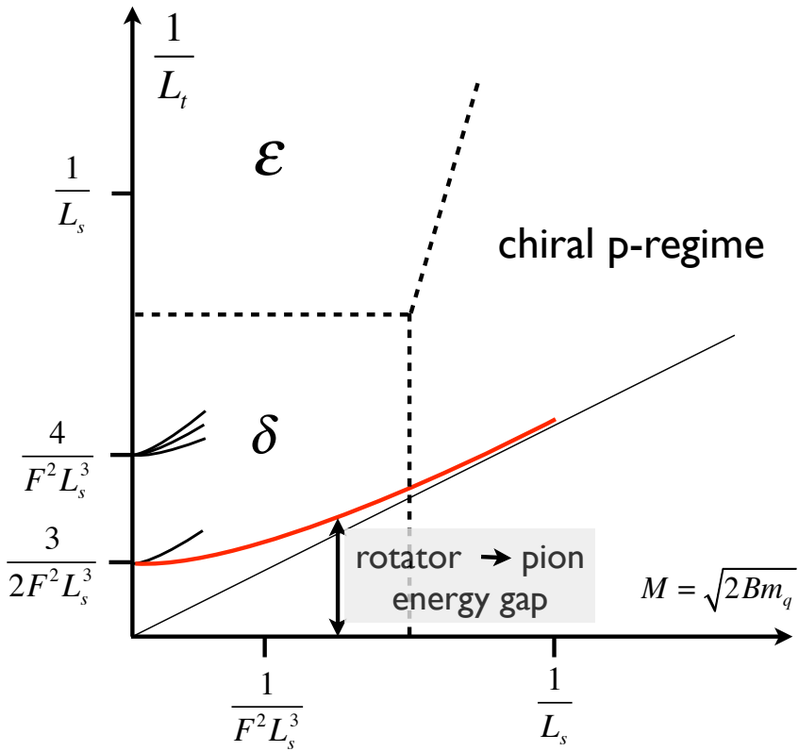
Kogut,Sinclair
finite temperature

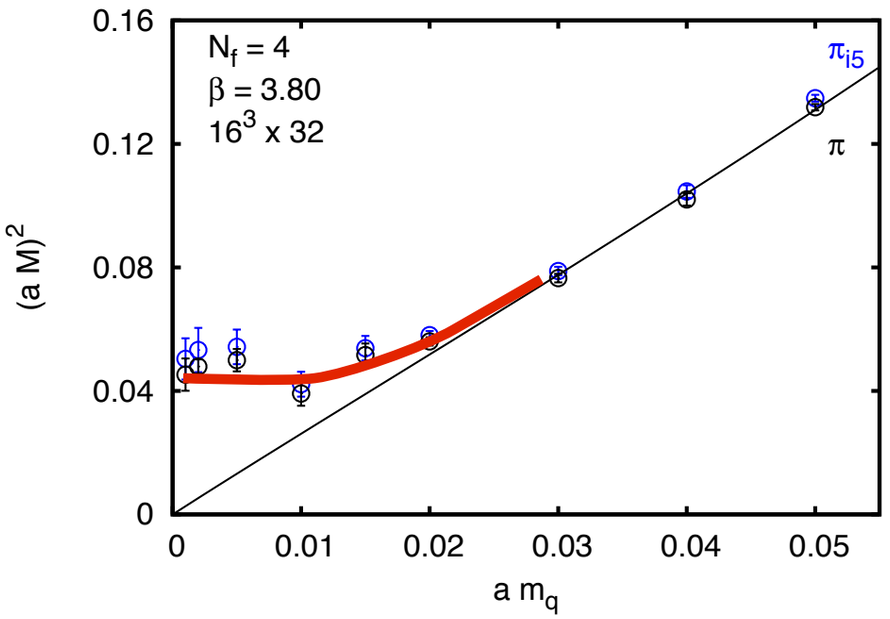
sextet model with two critical requirements:
(1) χSB
(2) walking gauge coupling?

role of the third fermion flavor?

chiral symmetry breaking in the sextet model

mass deformed chiral SB in finite volume below conformal window:





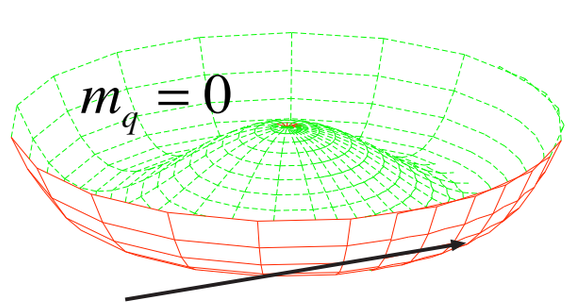
Goldstone dynamics is different in each regime

We study δ and ε-regimes (RMT)

and p-regime (probing chiral loops)

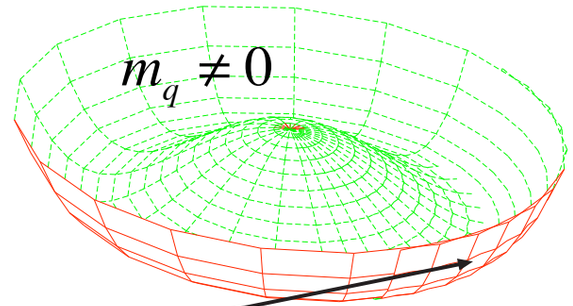
complement each other

interpretation of rotator levels in $m_q \to 0$ limit:

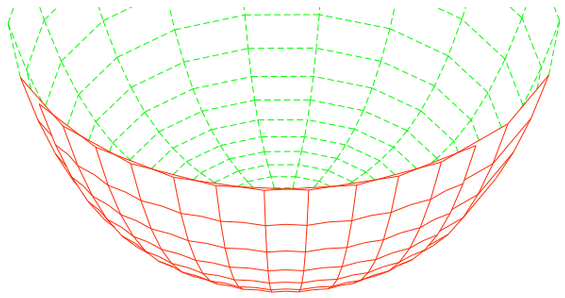


Veff: chiral condensate in flavor space

arbitrary orientation of condensate



tilted condensate



Not to misidentify rotator gaps

as evidence of chirally symmetric

phase !

Our sextet simulations are in the p-regime β=3.2 and β=3.25

simulation details:

tree level improved Symanzik gauge action; $\beta = 6/g^2$ normalization

smearing in staggered fermions: 2 stout steps

rooting with two flavors (follow-up work without rooting if model will pass first tests)

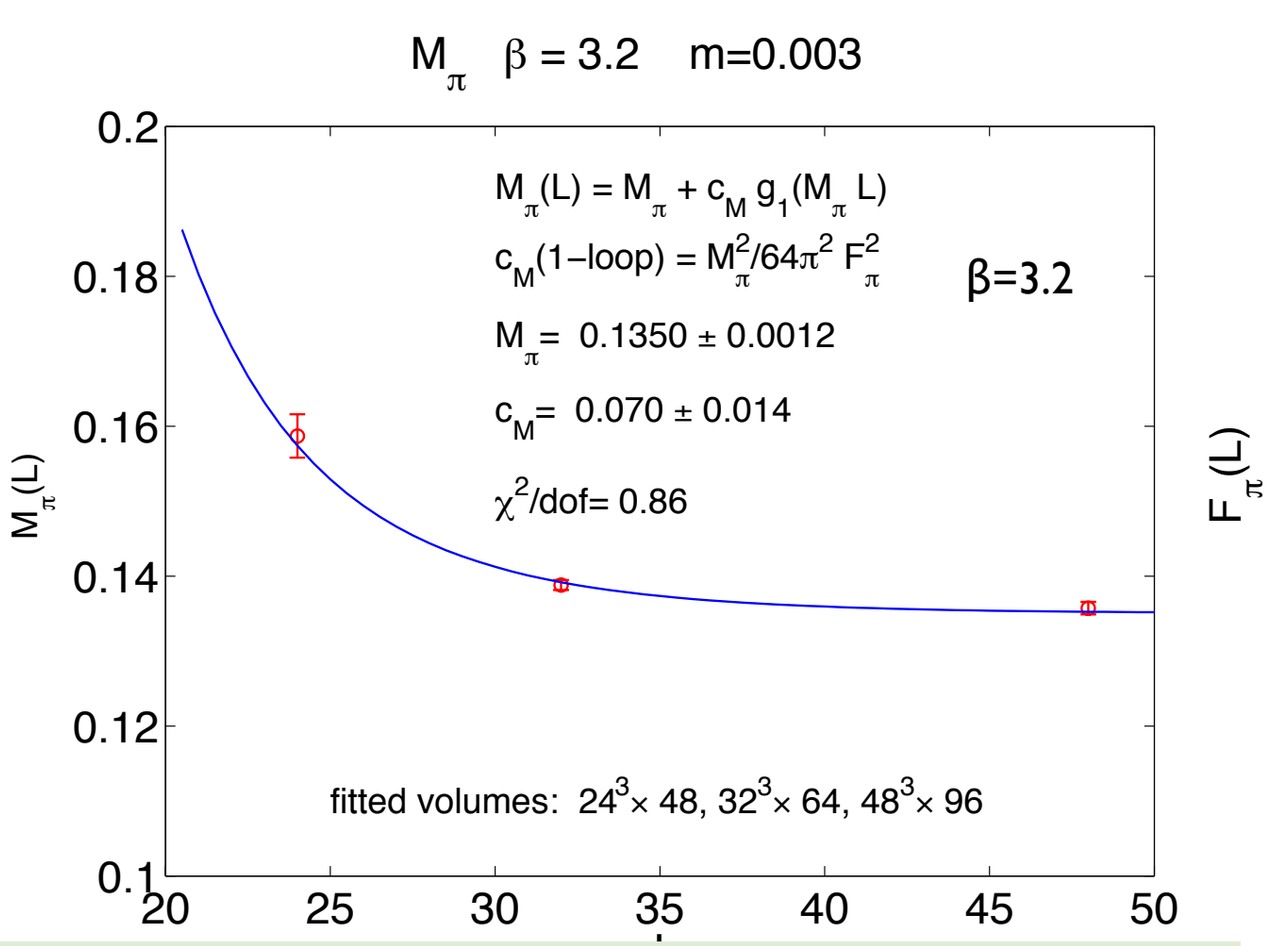
RHMC

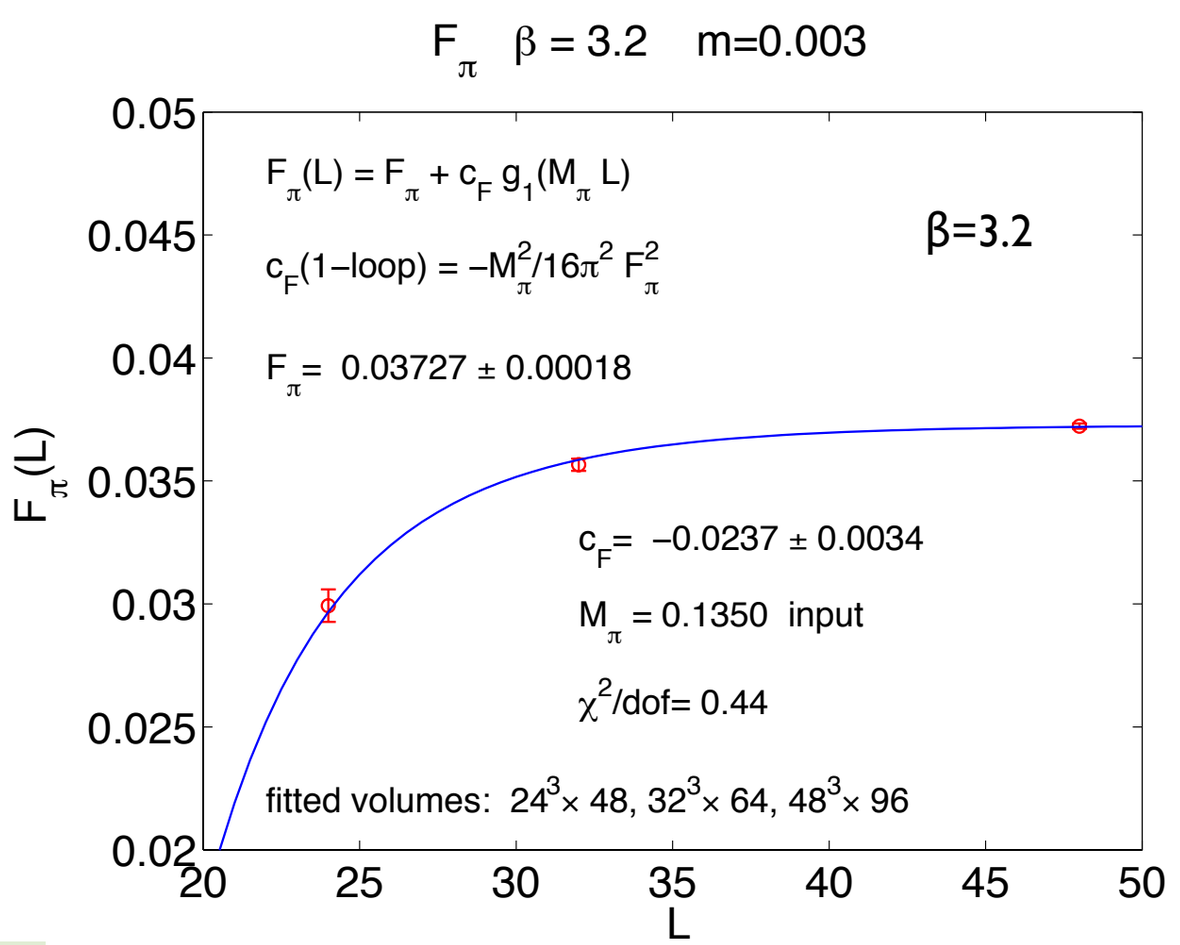
multiple time scales and Omelyan integrator

$\beta = 3.20$ m=0.003-0.010 mass range $24^3 \times 48$, $28^3 \times 56$, $32^3 \times 64$, $48^3 \times 96$ lattices

$\beta = 3.25$ m=0.004-0.008 mass range $24^3 \times 48$, $28^3 \times 56$, $32^3 \times 64$ lattices

error analysis: mass fits with double Jackknife procedure on covariance matrices





strategy: L→∞ extrapolation first

mass-deformed theory

close to m=0 critical surface

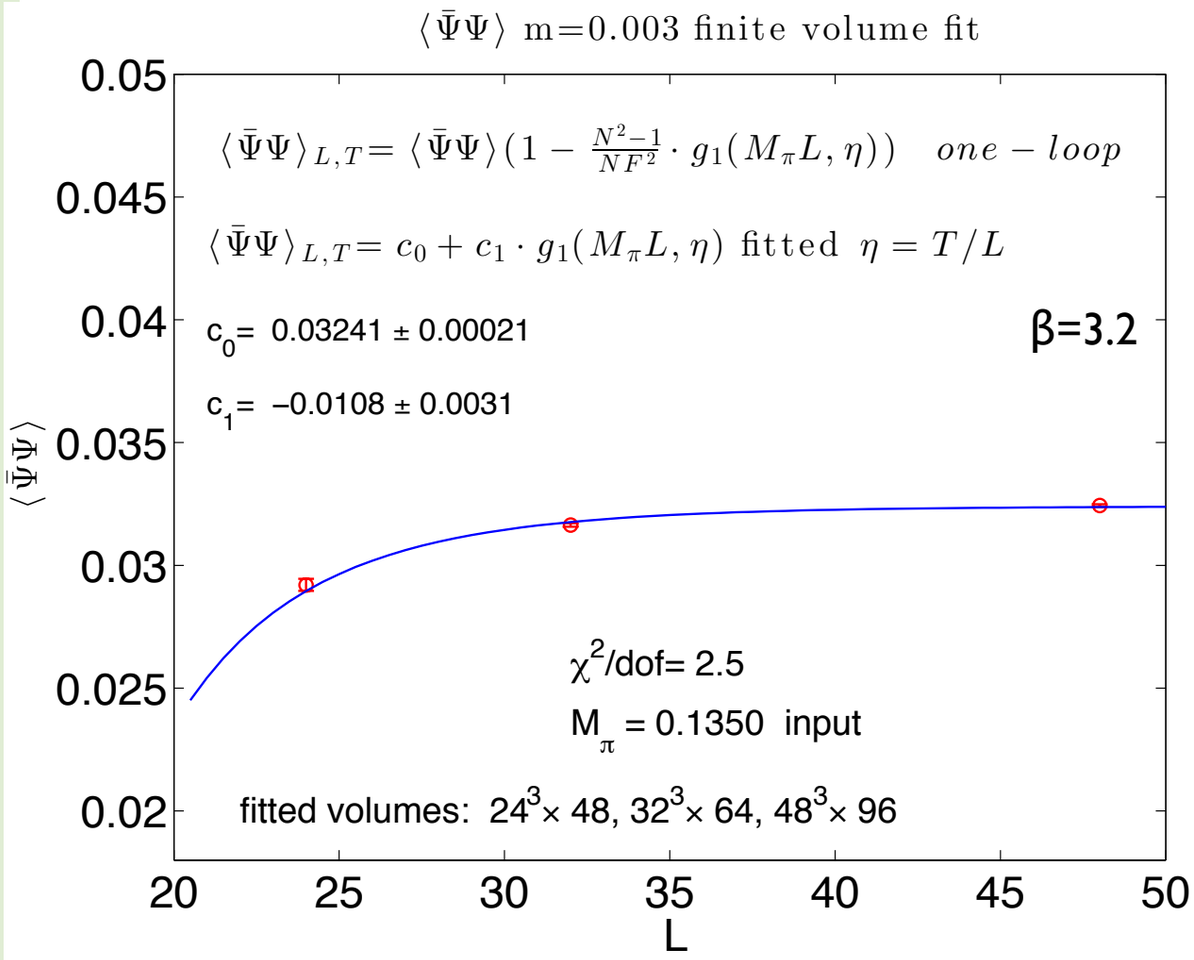
L→∞ extrapolated chiral and conformal

scaling tests in sextet model

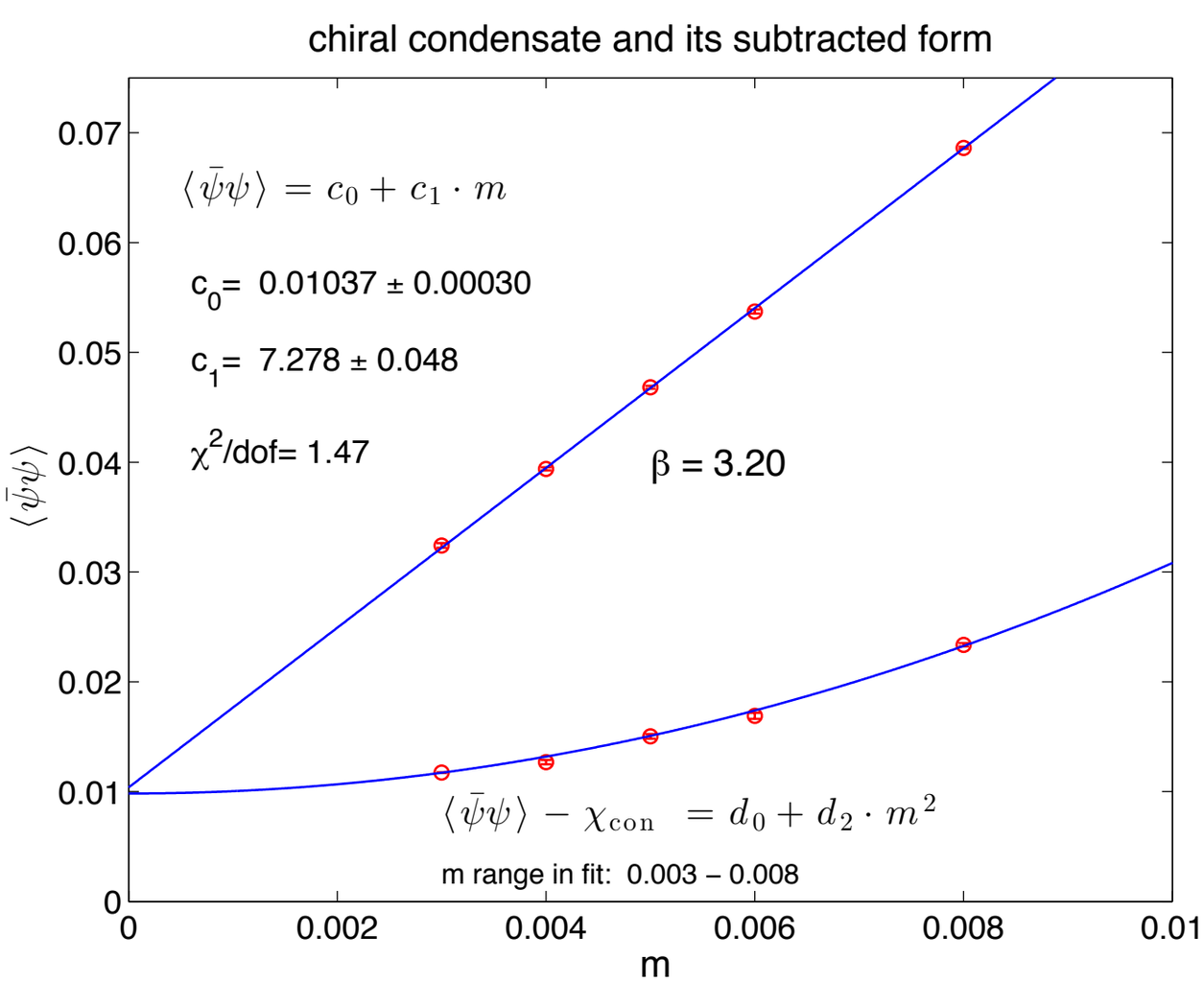
for L·Mπ > 5 less than one percent

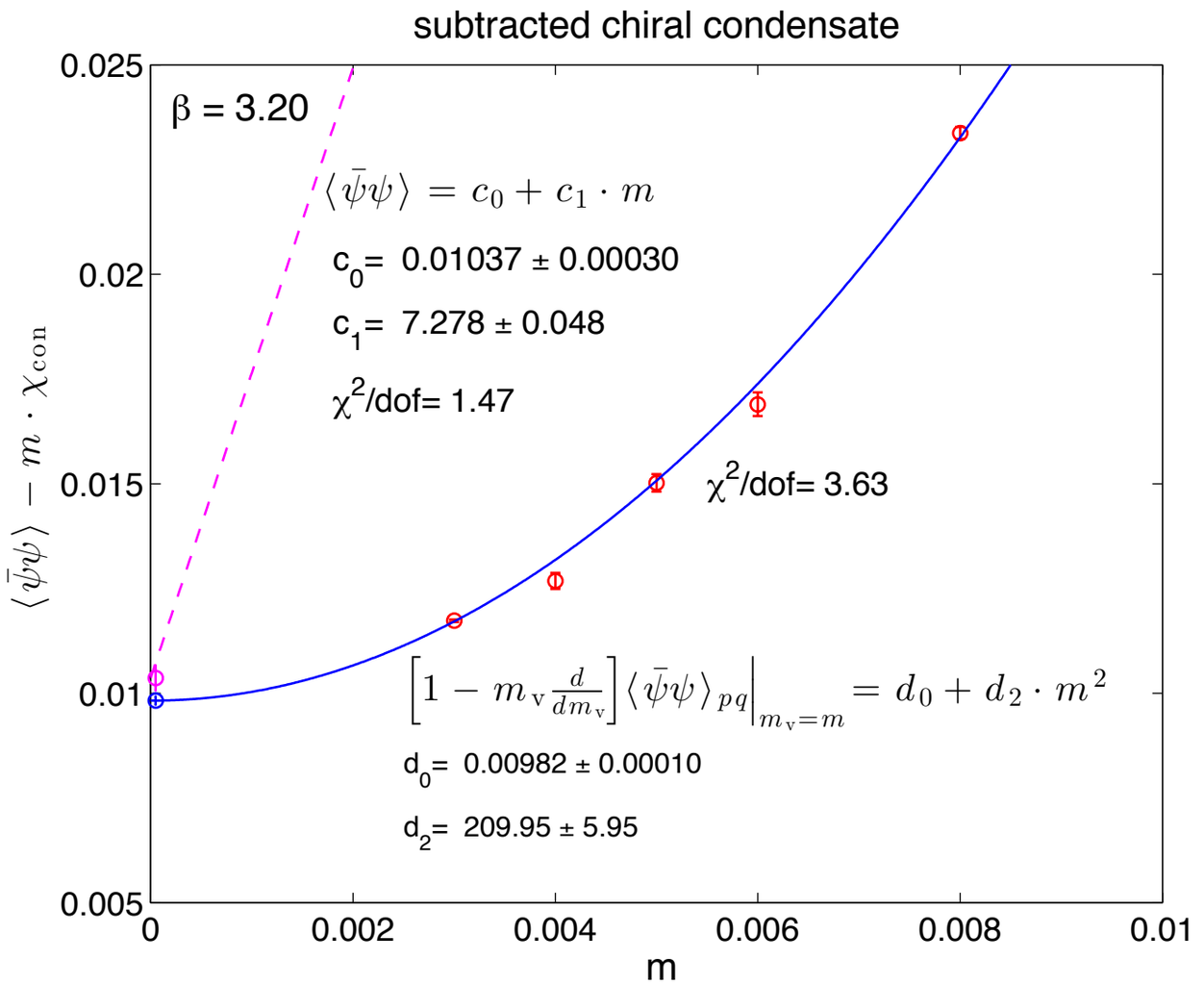
L correction left

C_M and C_F signs correct, numerically off



Nf=2 SU(3) sextet chiral condensate





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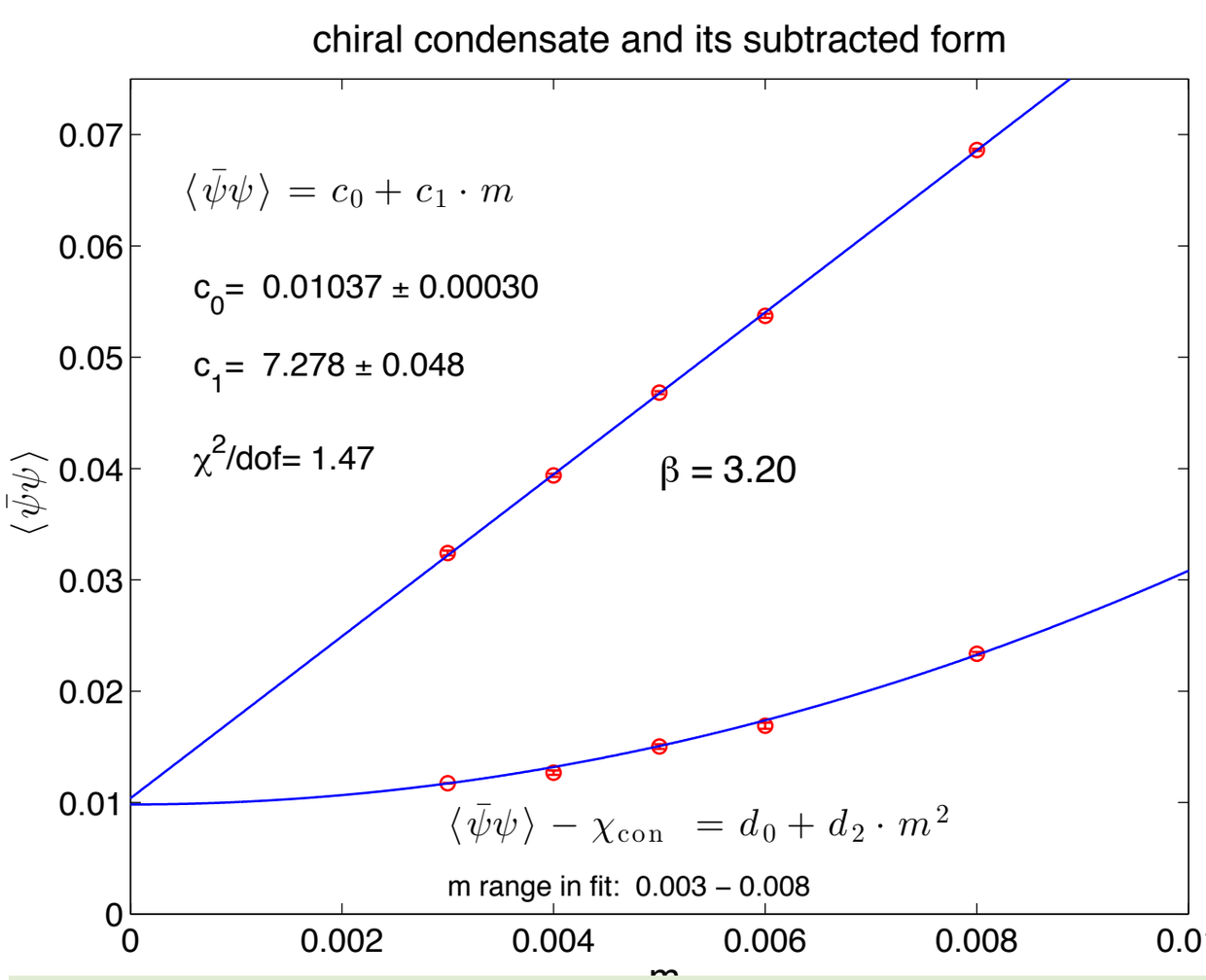

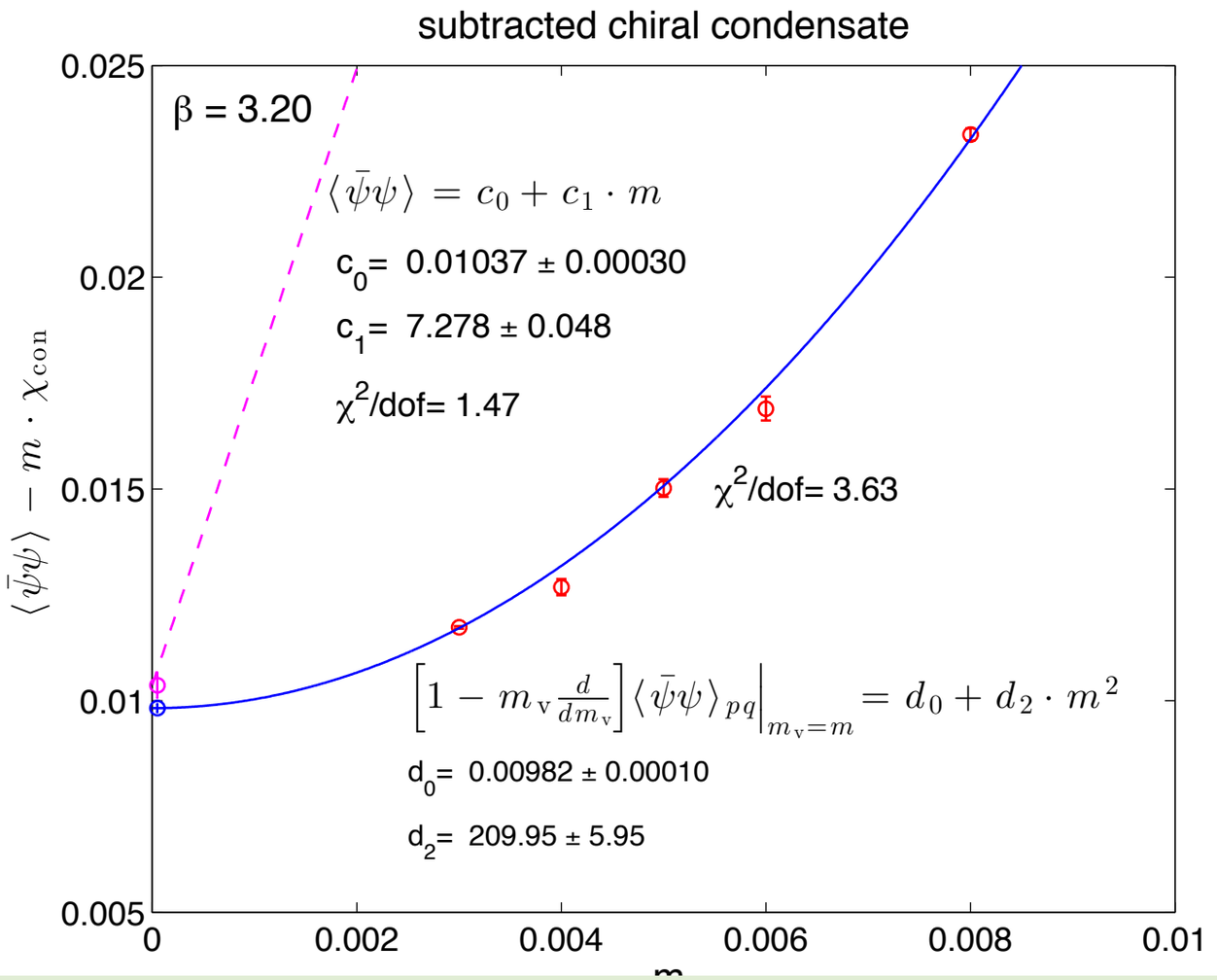

two independent determinations of the chiral condensate

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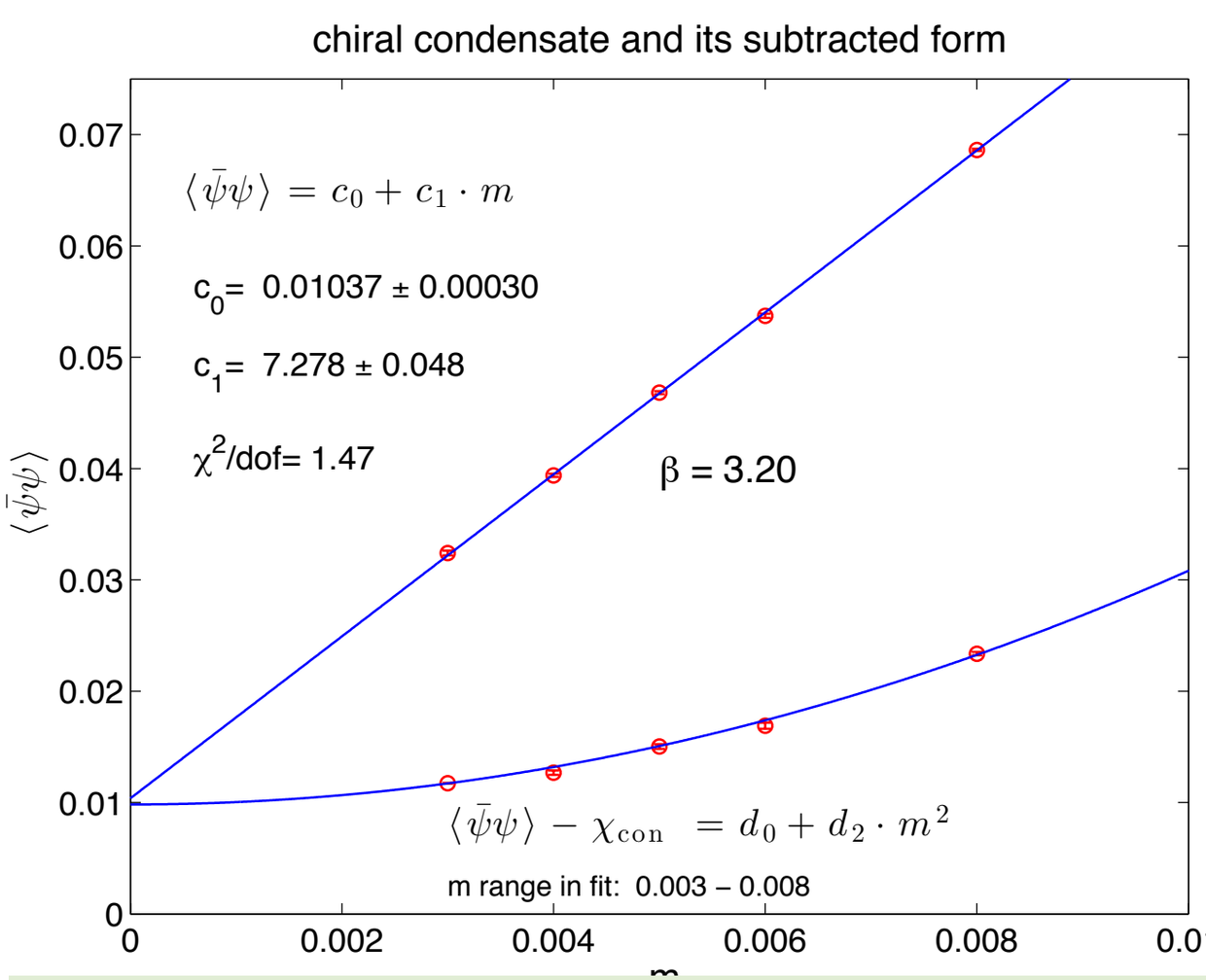

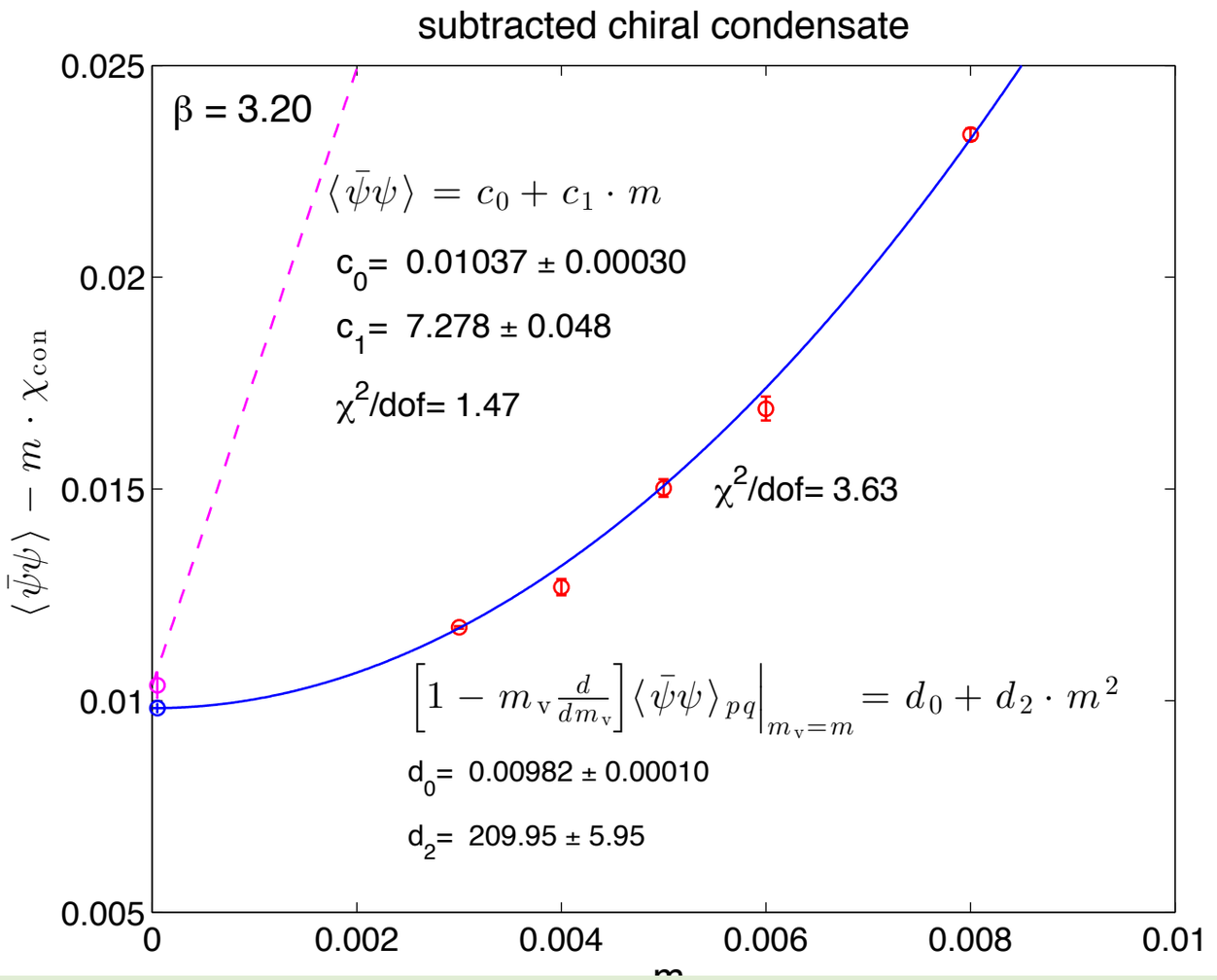

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(partially cancelled UV divergences in subtracted form)

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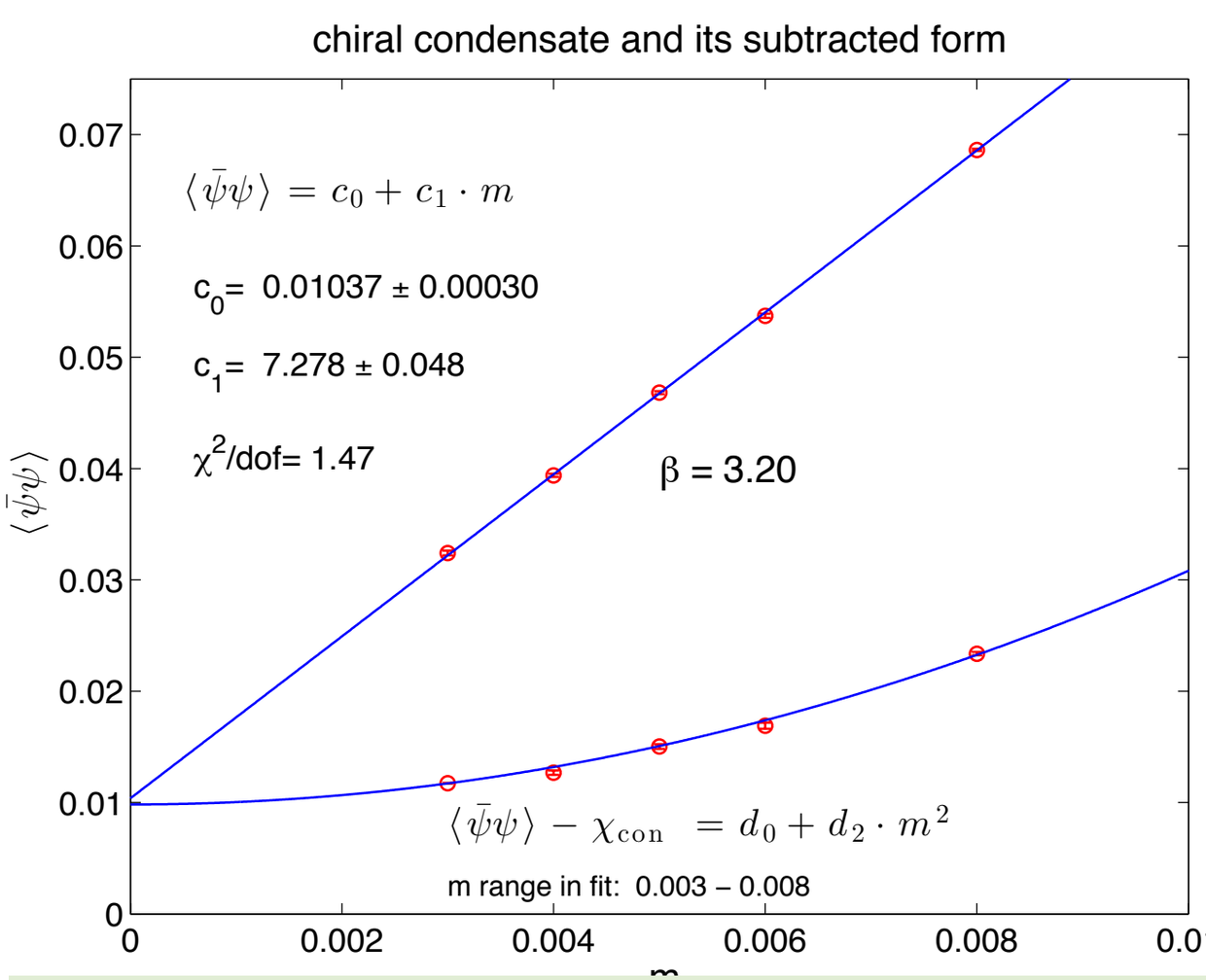

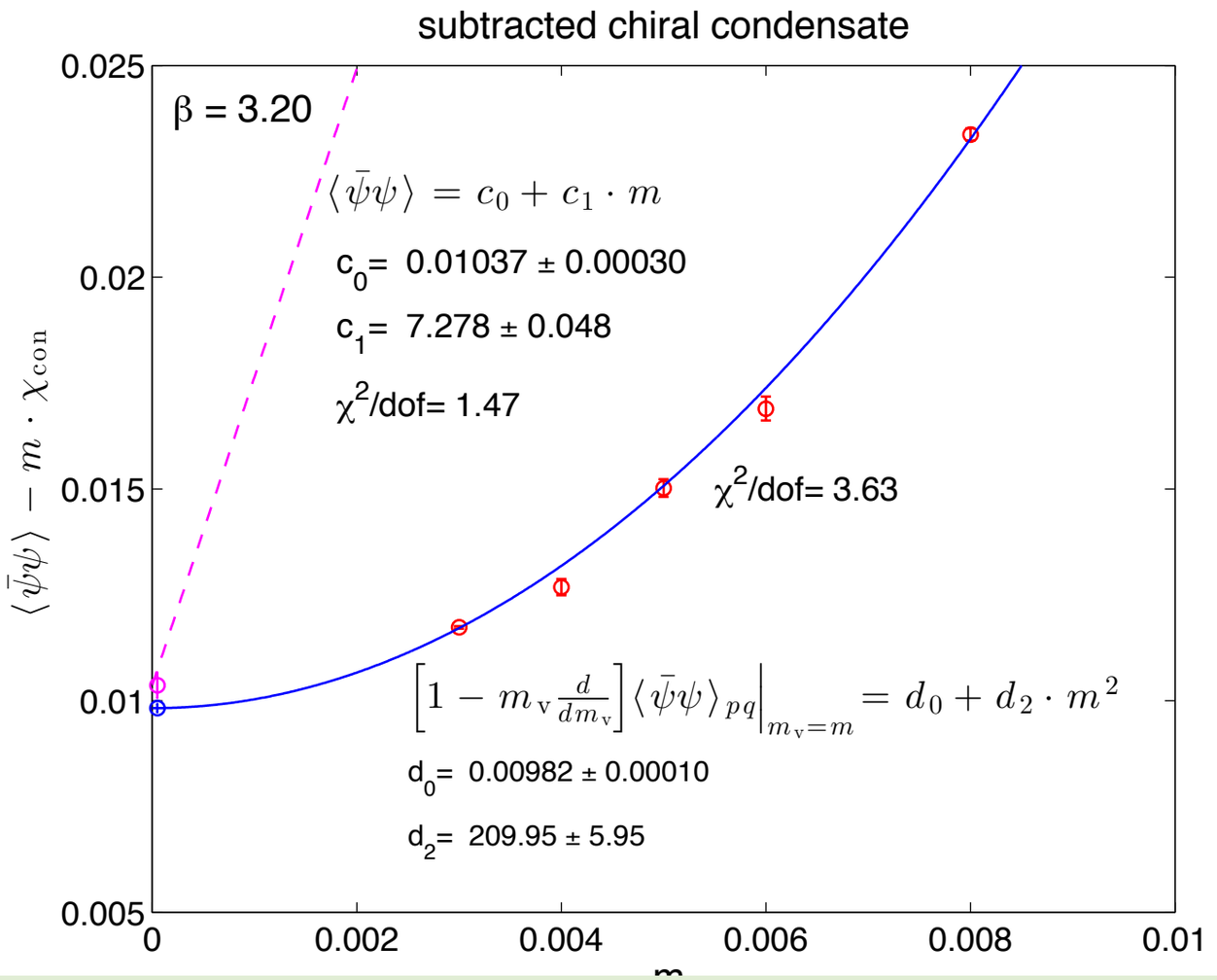

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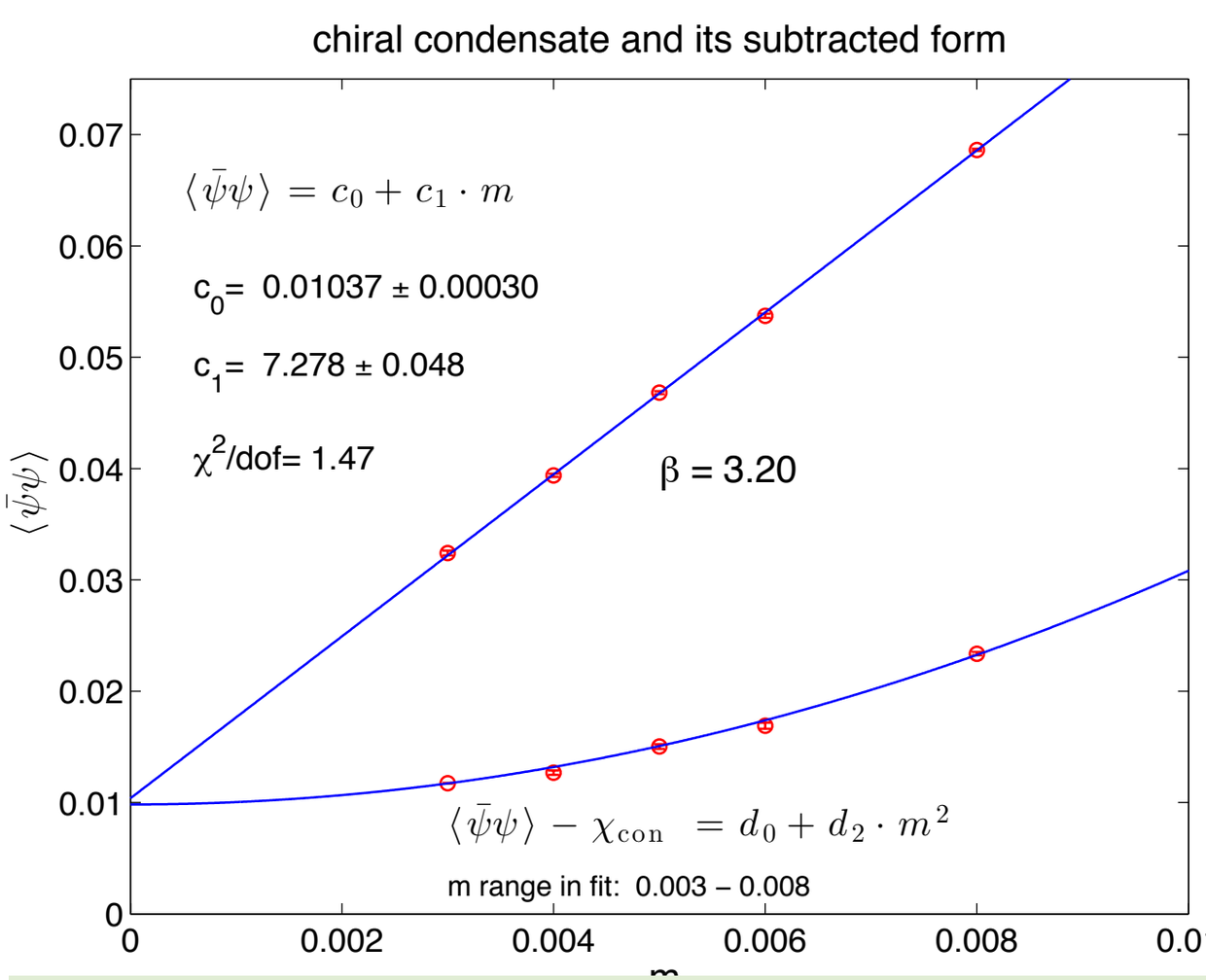

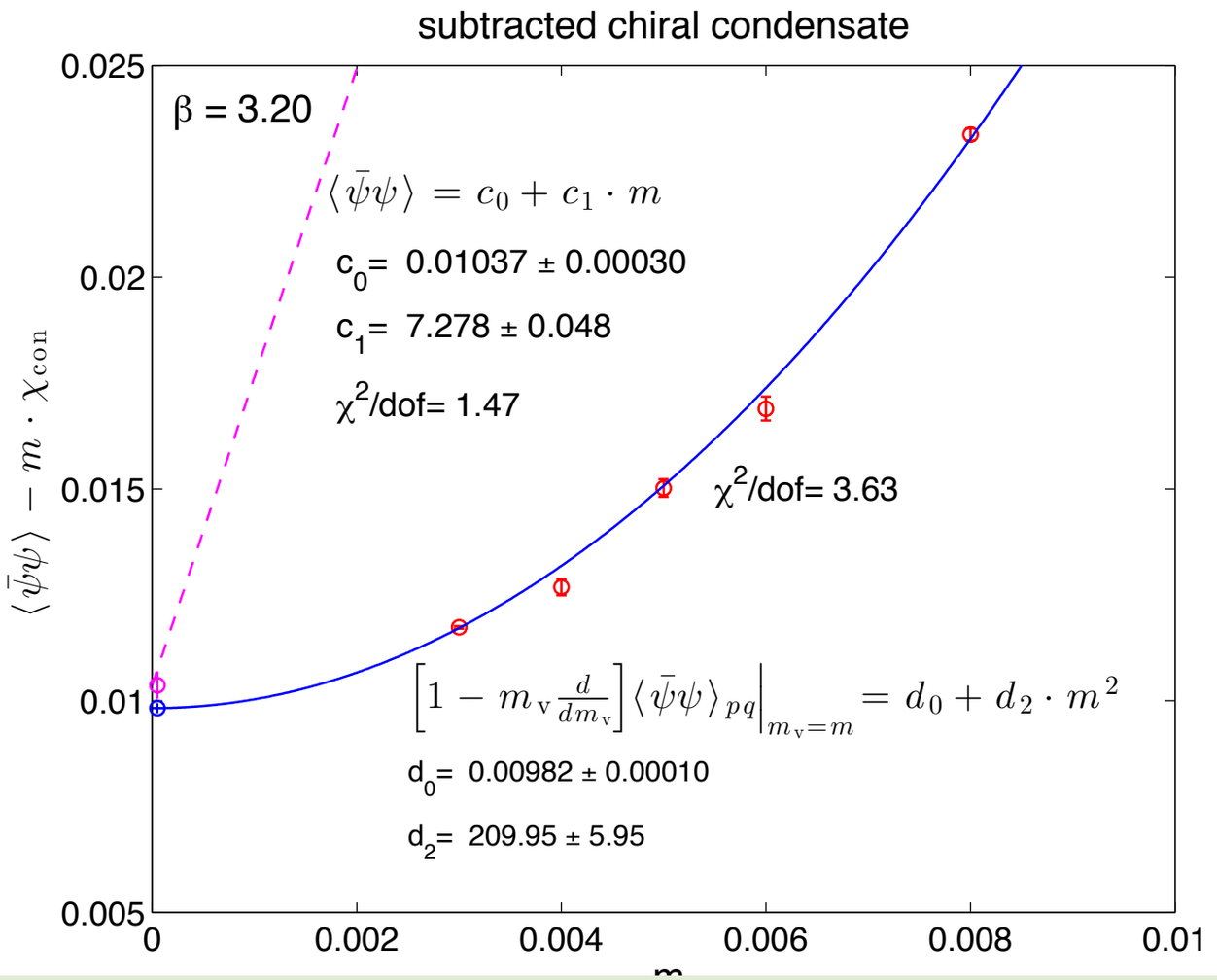

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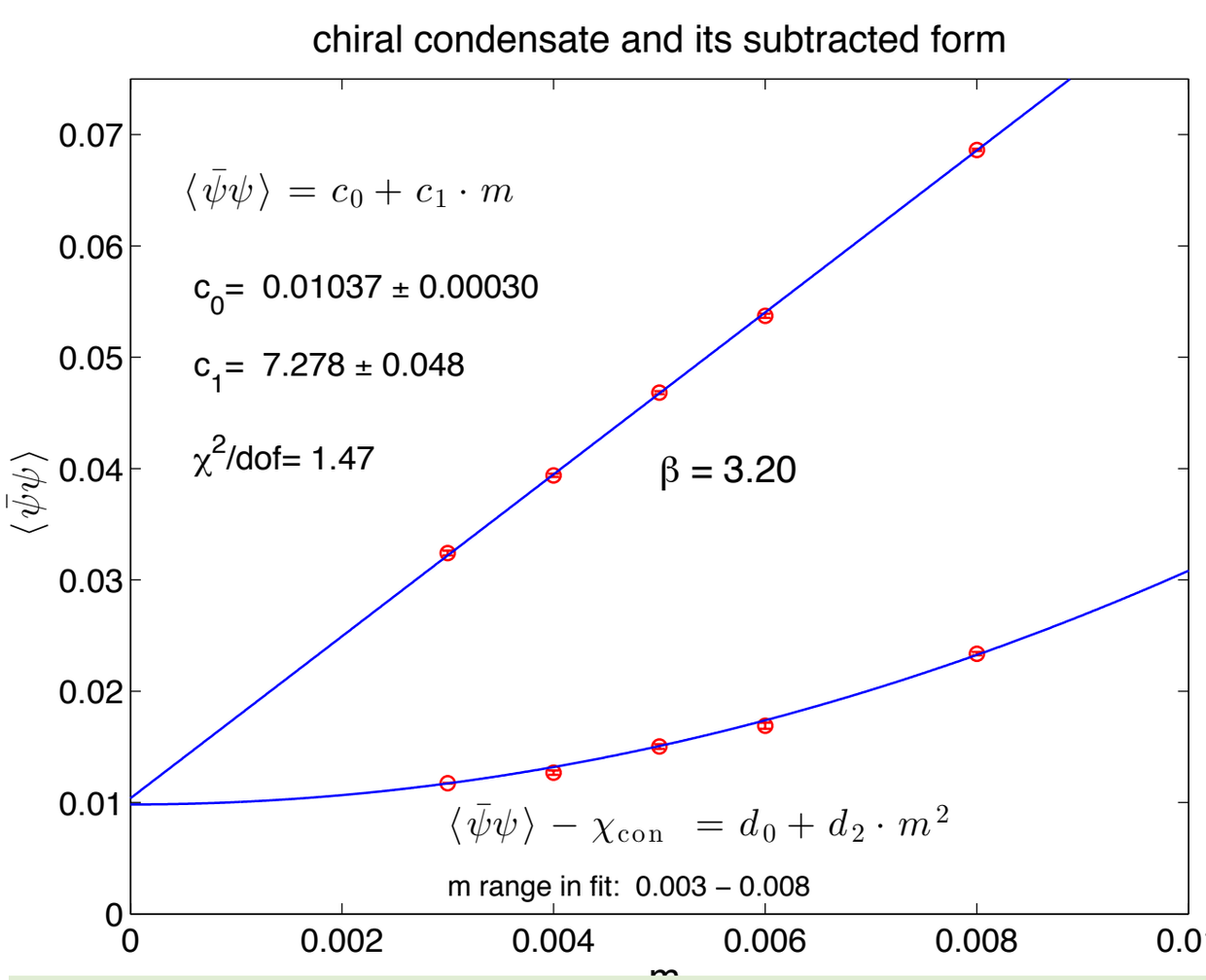

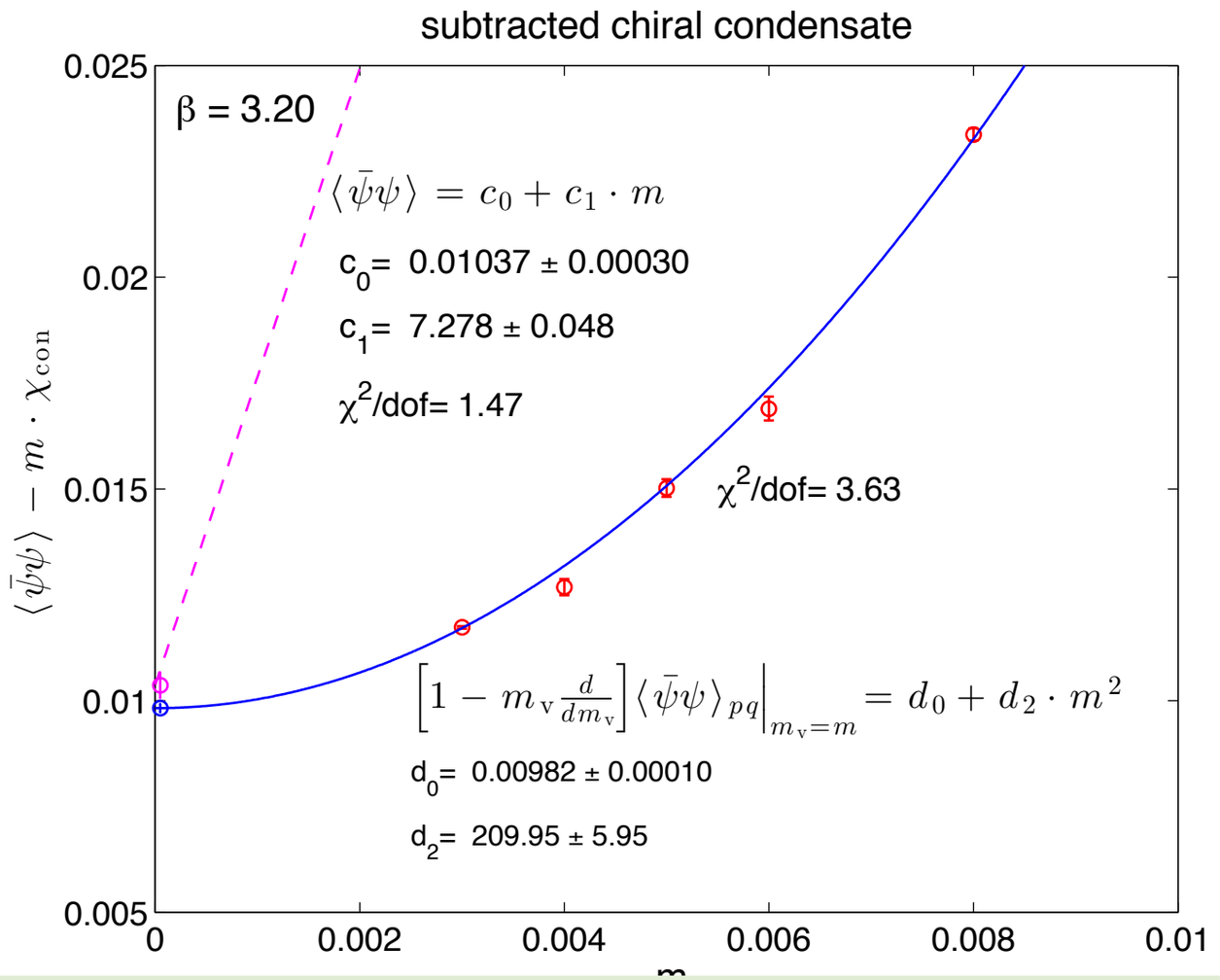

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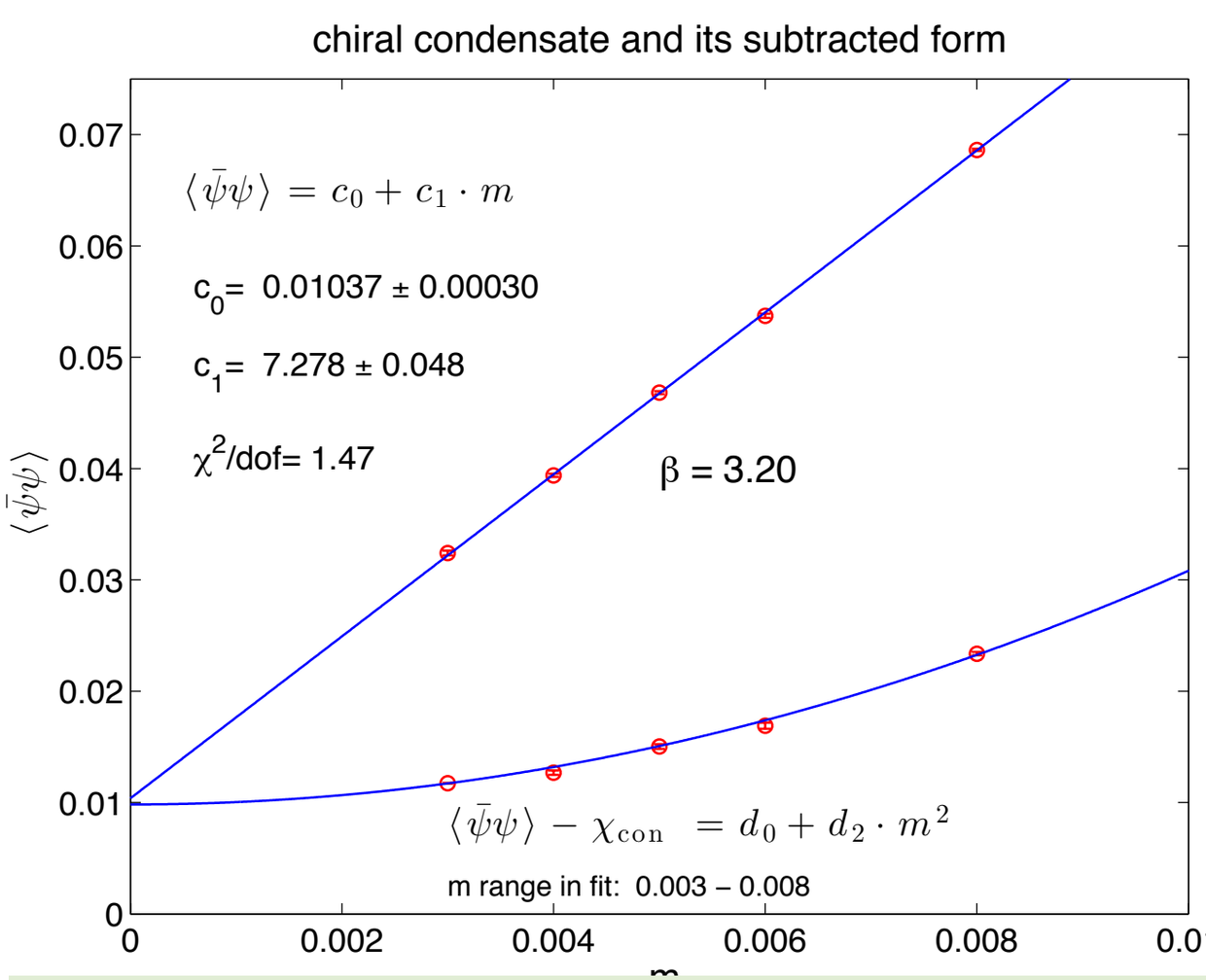

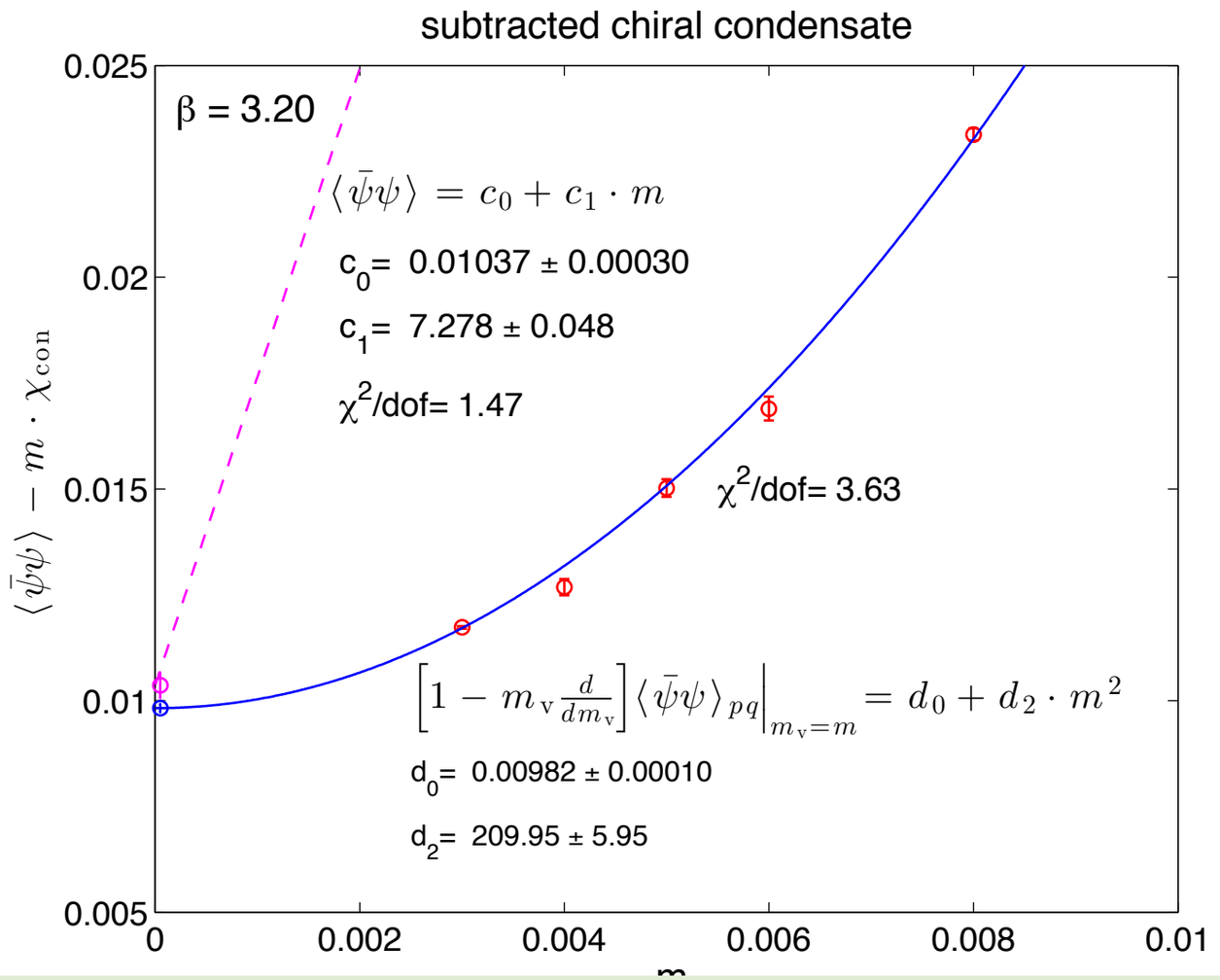

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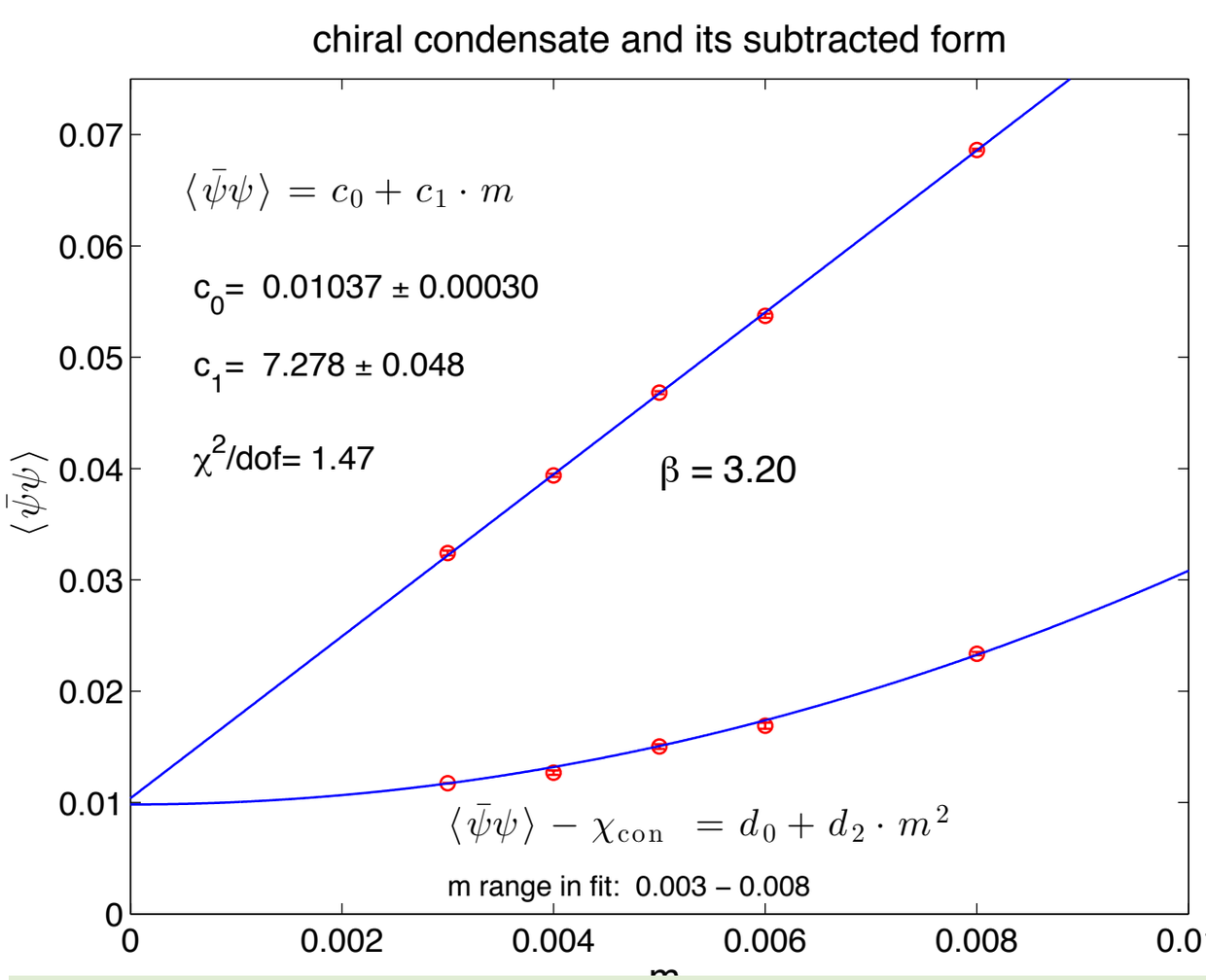

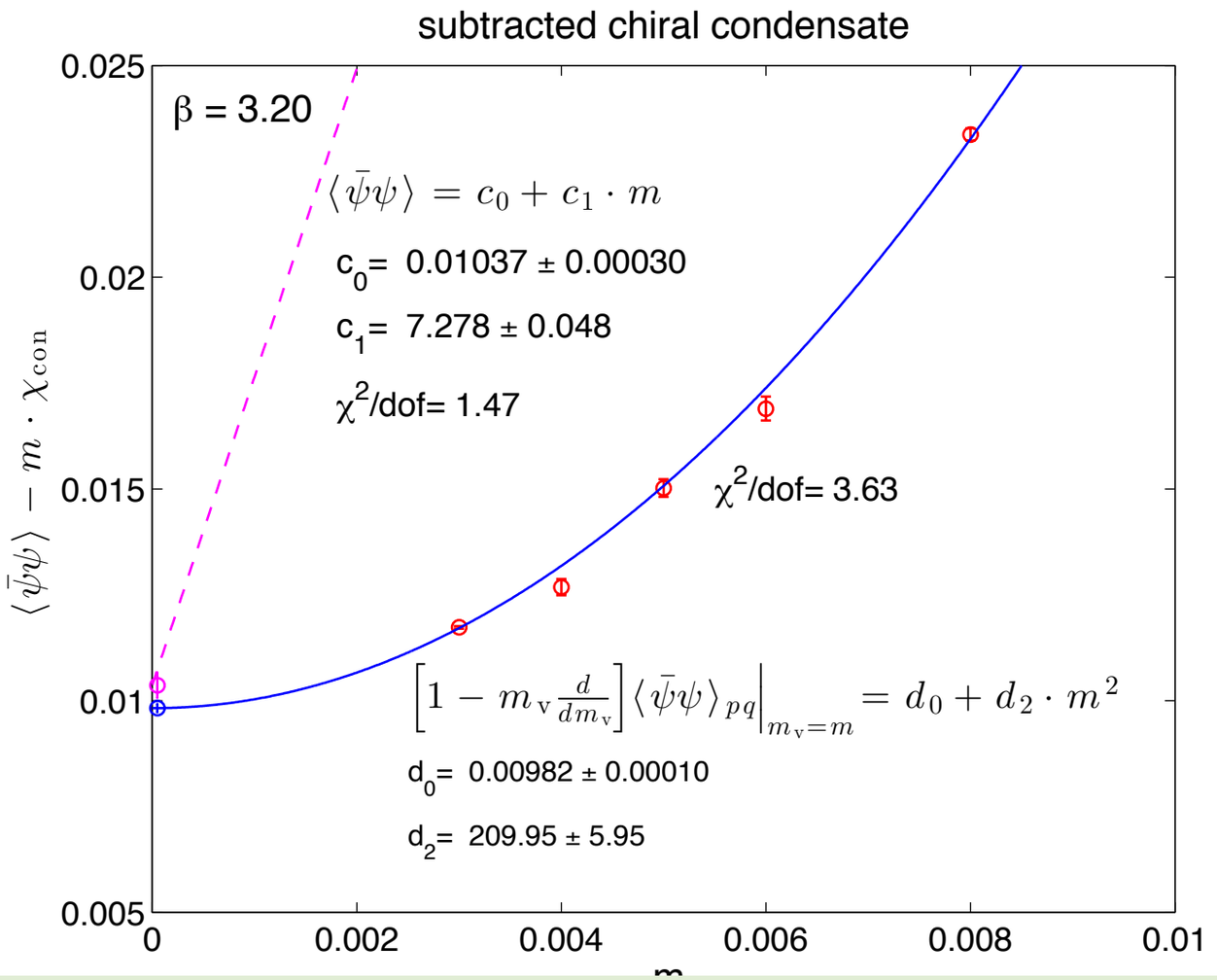

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spectral density analysis more powerful

(Del Debbio et al., Giusti and Luscher, Boulder group, Patella ...)

complete control on UV divergences: **node number density of chiral condensate**

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

spectral density

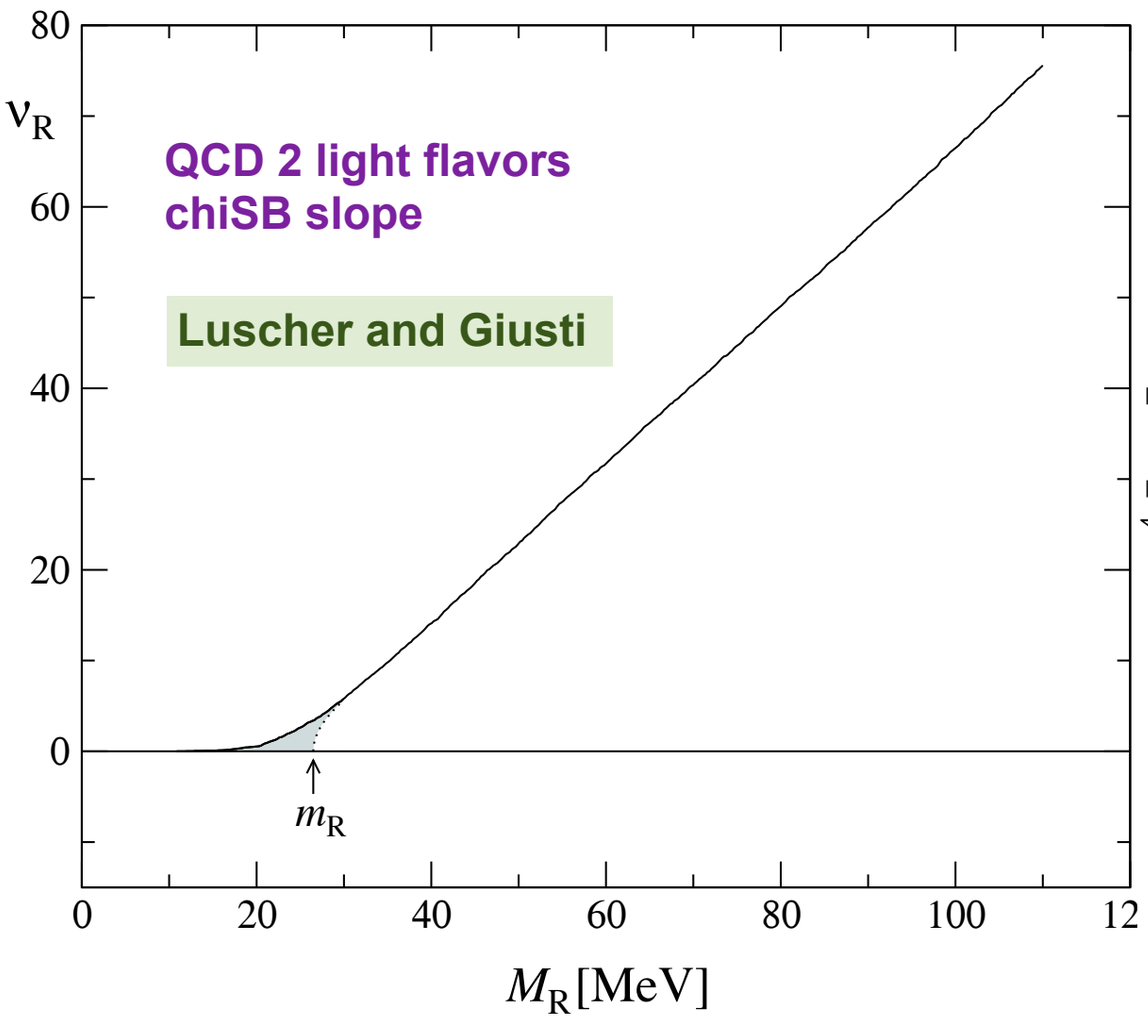
$$\nu(M, m) = V \int_{-\Lambda}^{\Lambda} \mathrm{d}\lambda \, \rho(\lambda, m), \qquad \Lambda = \sqrt{M^2 - m^2}$$

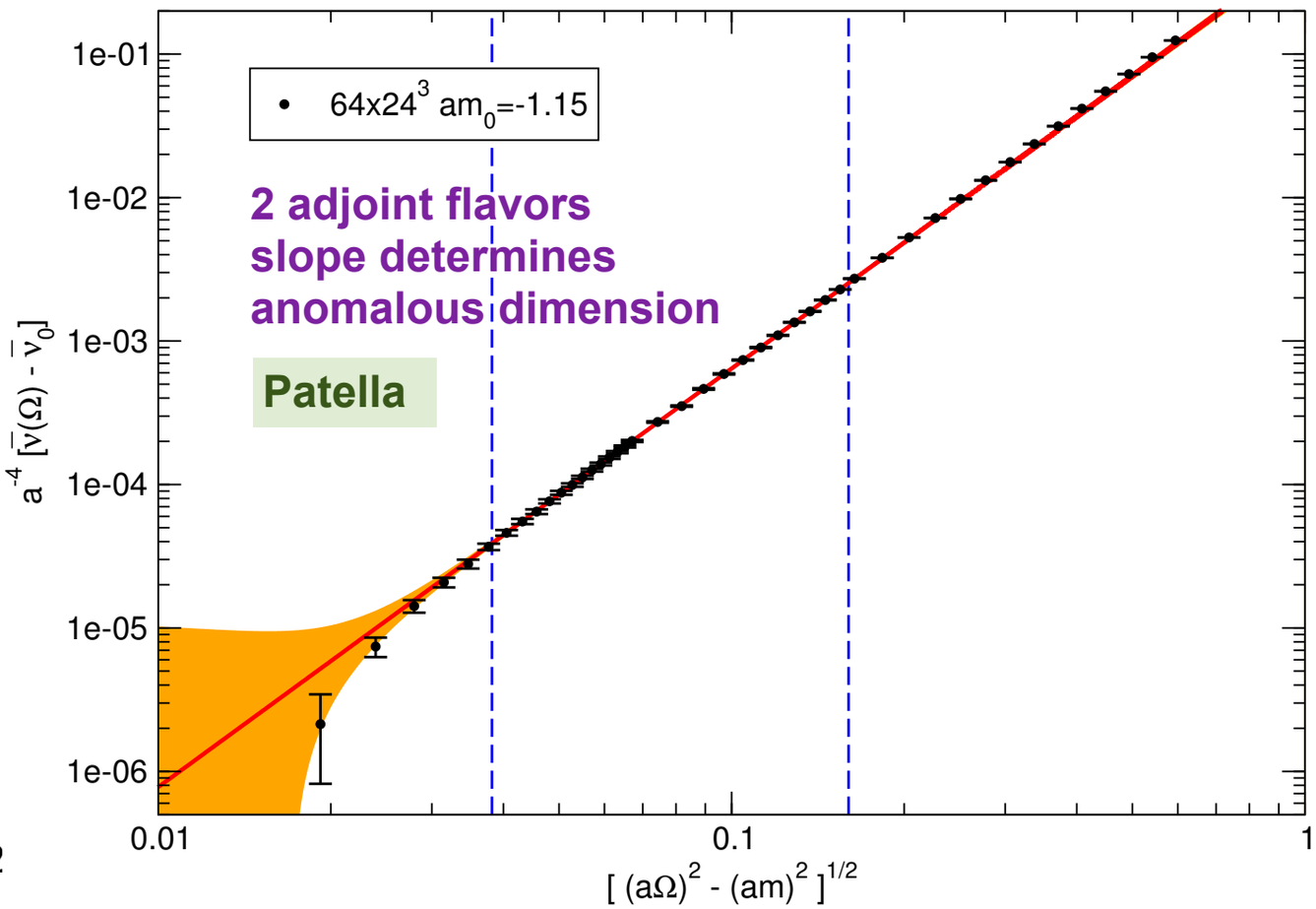
node number density

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

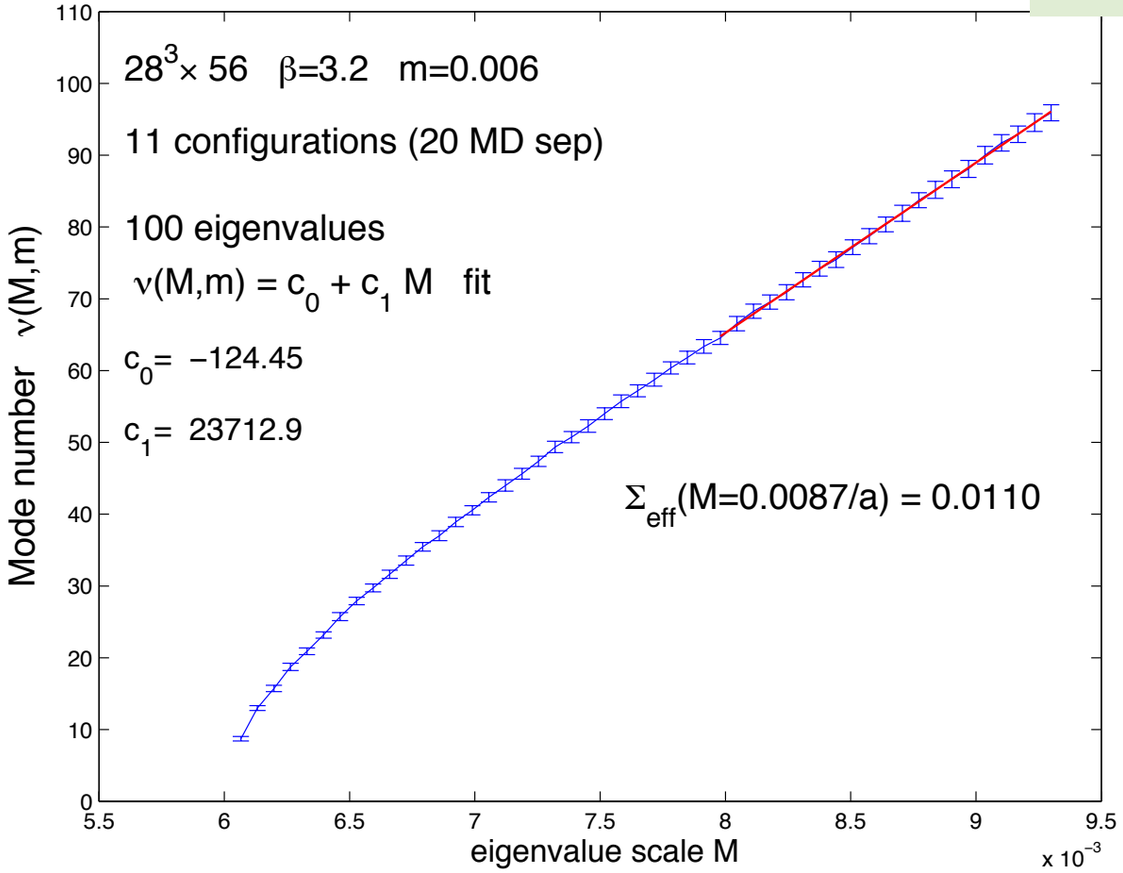
renormalized and RG invariant

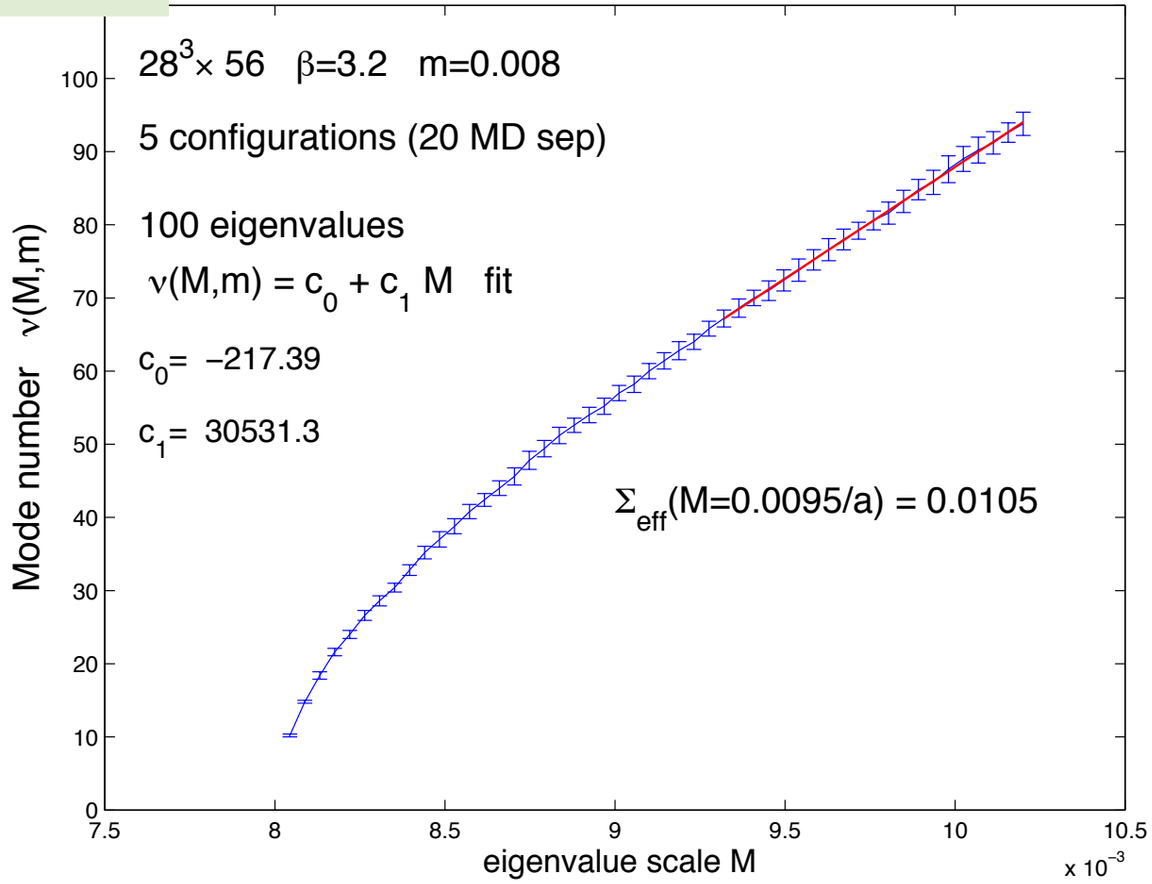
Del Debbio et al.
Luscher and Giusti
Patella
Boulder group





sextet model





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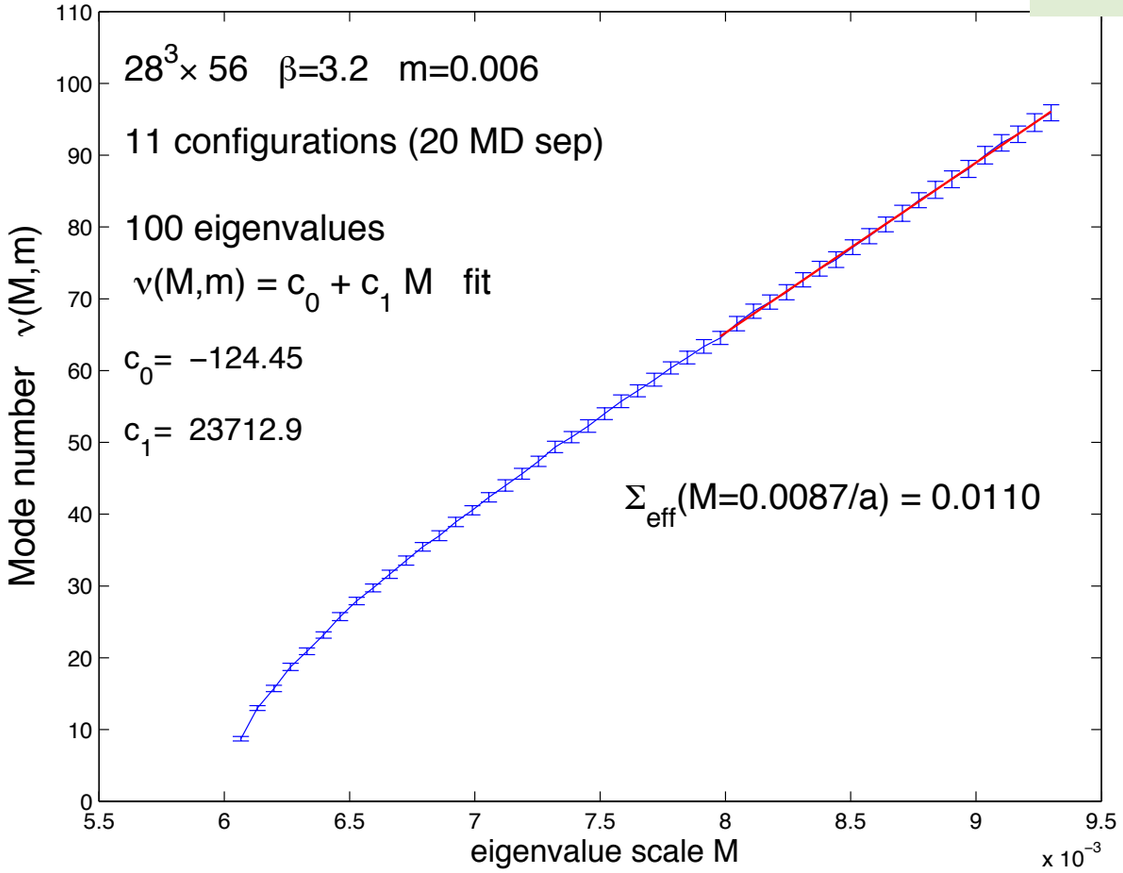

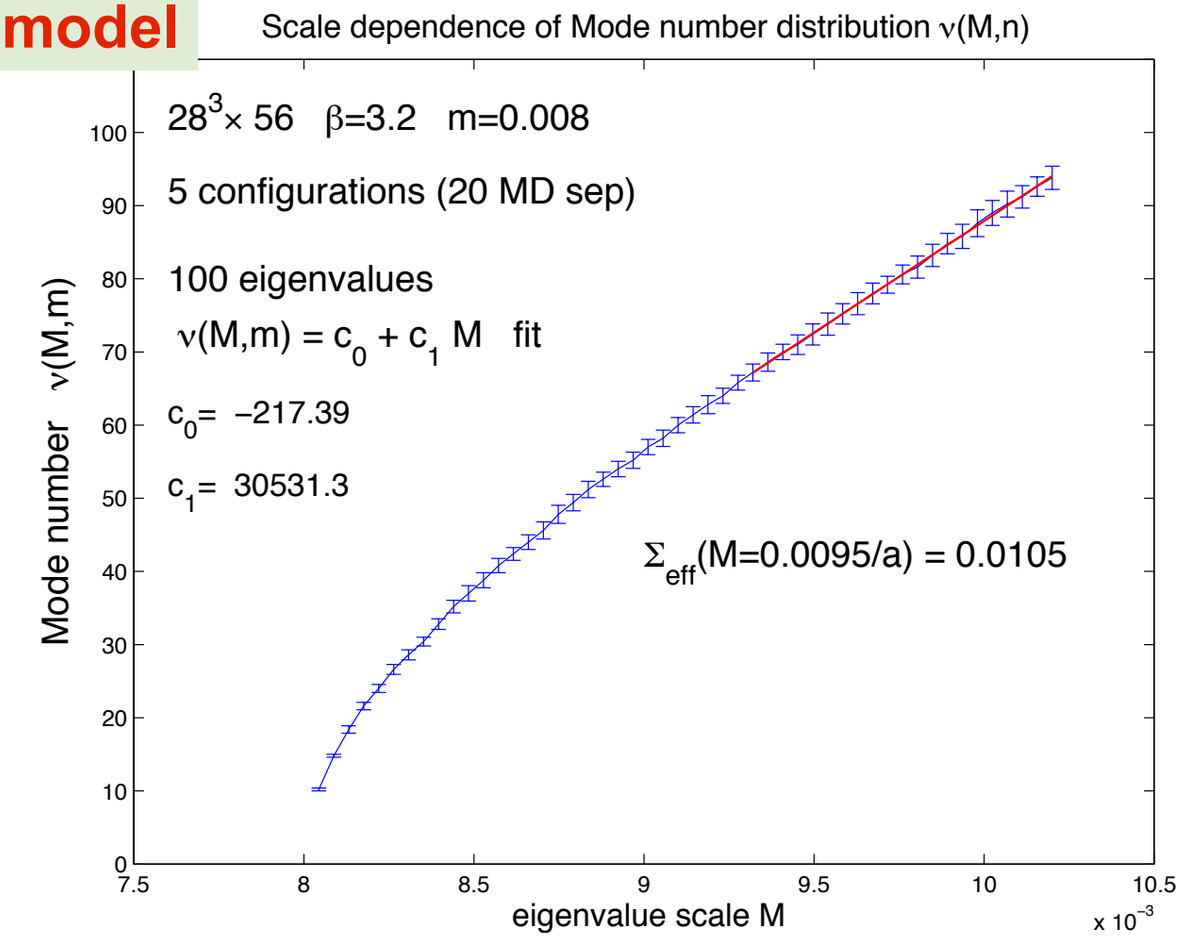

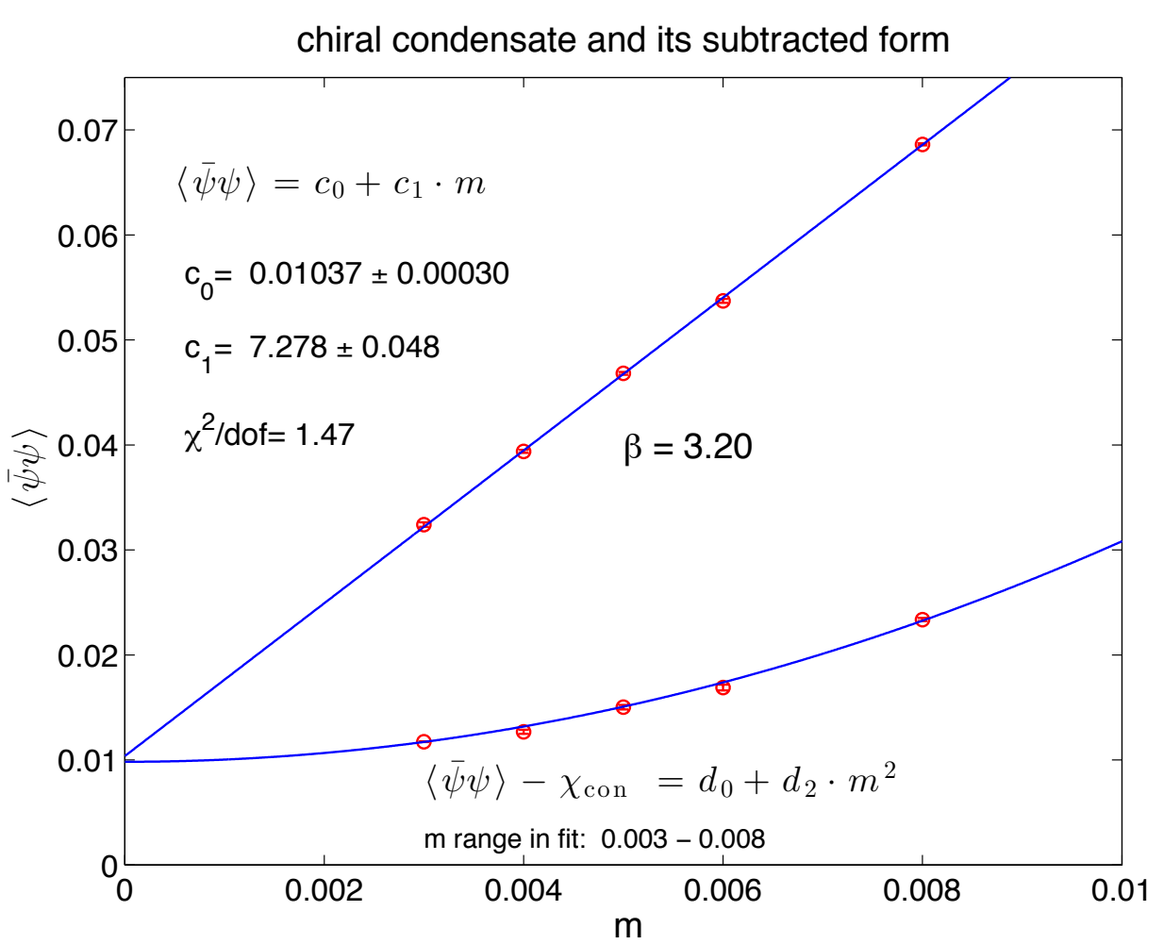

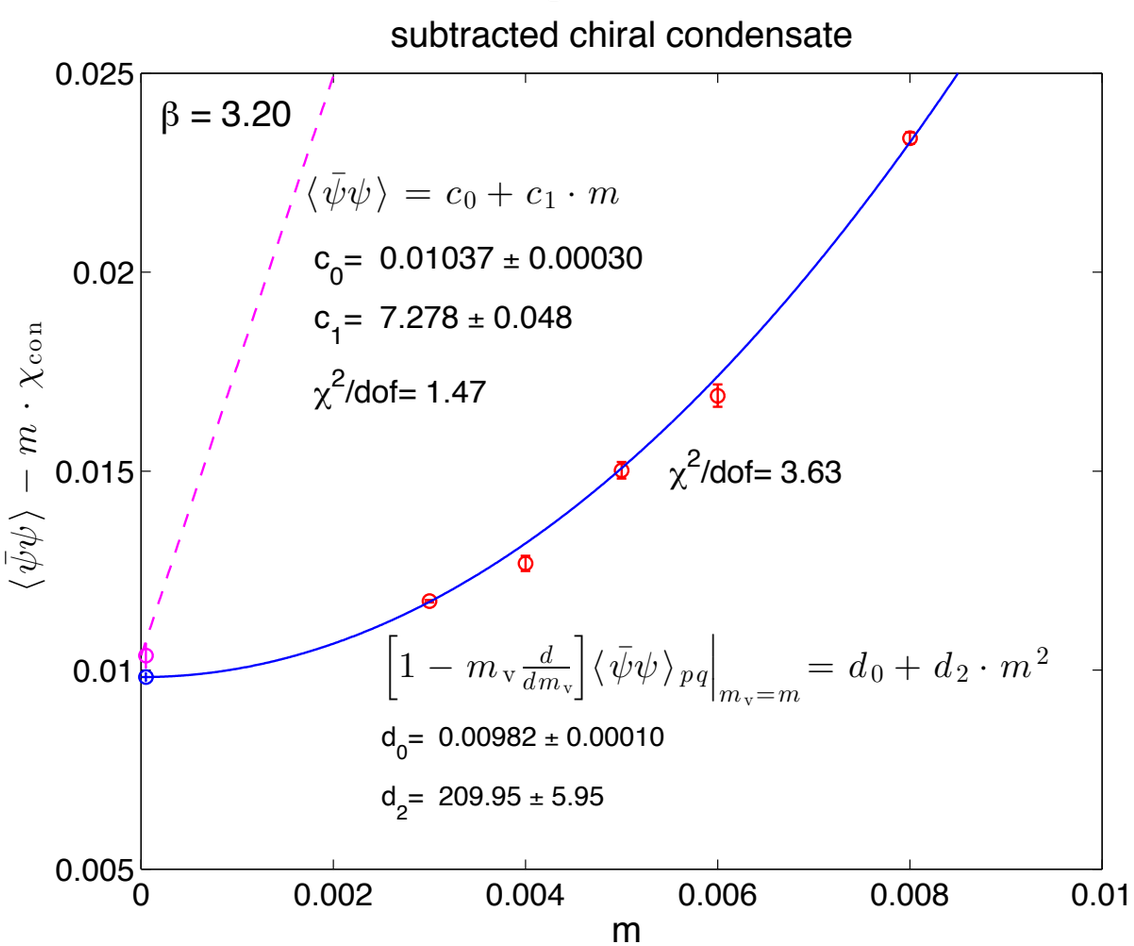

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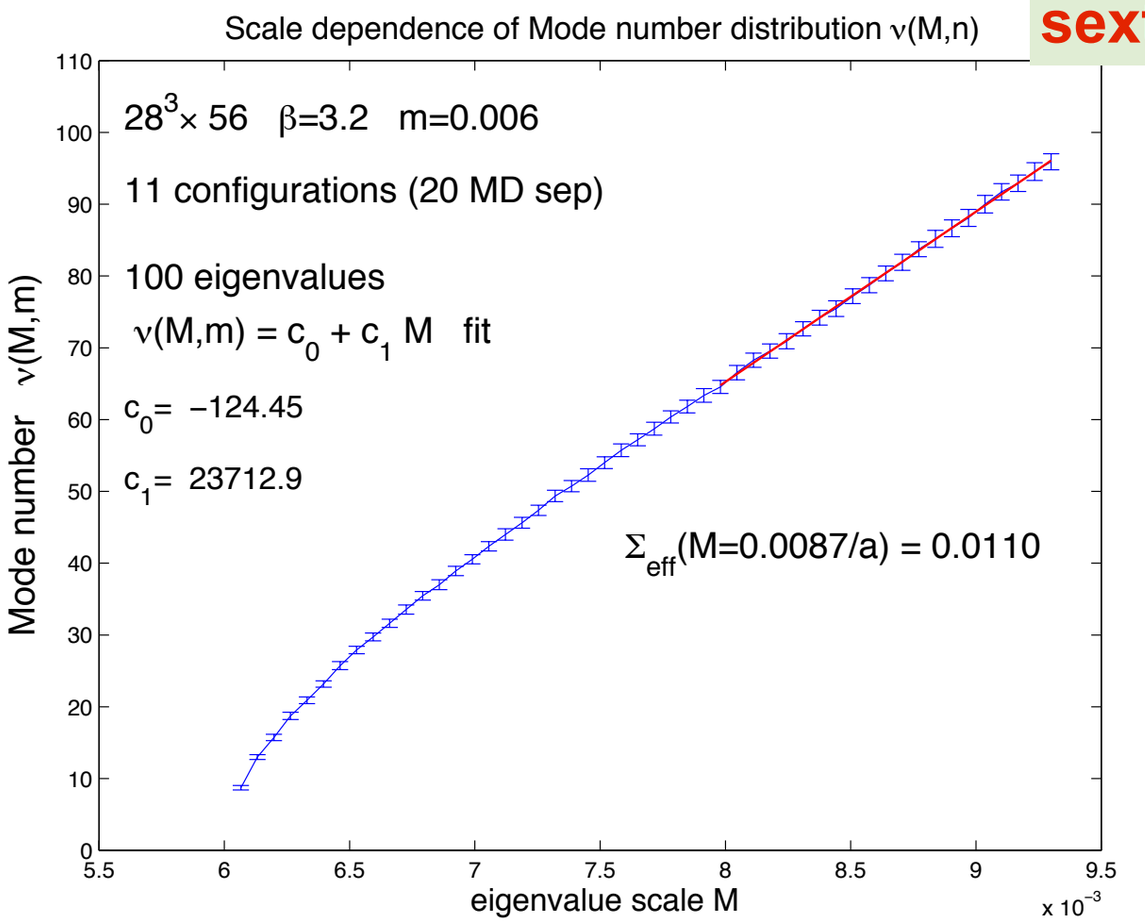

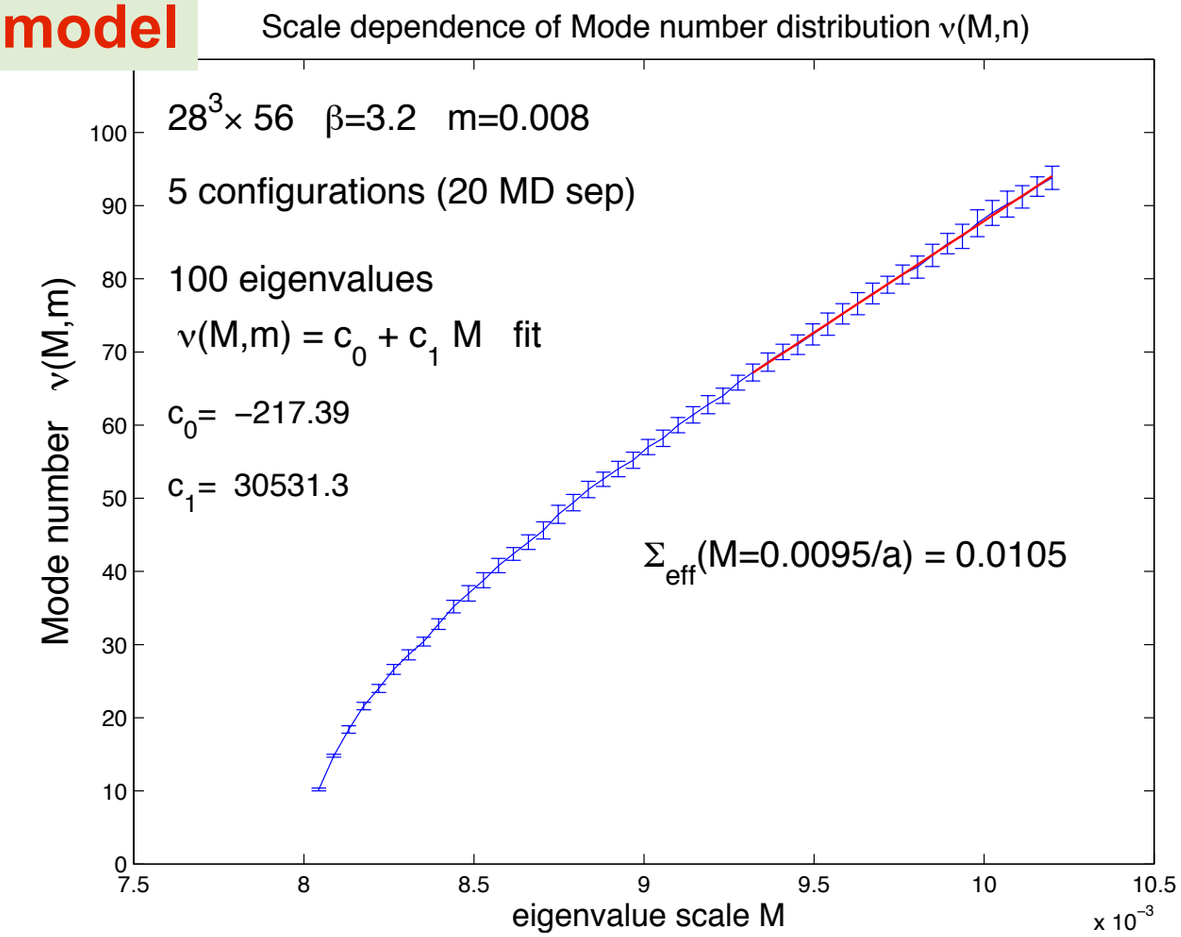

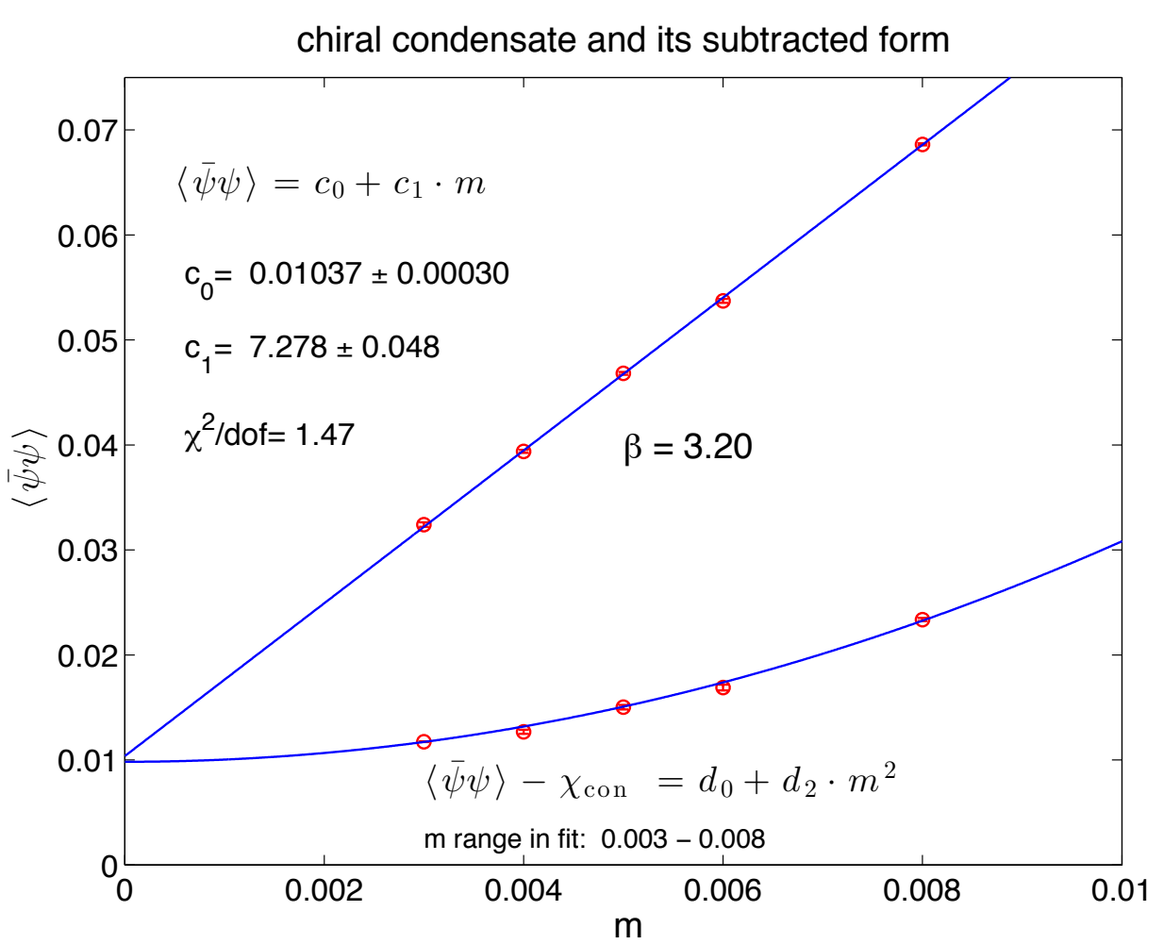

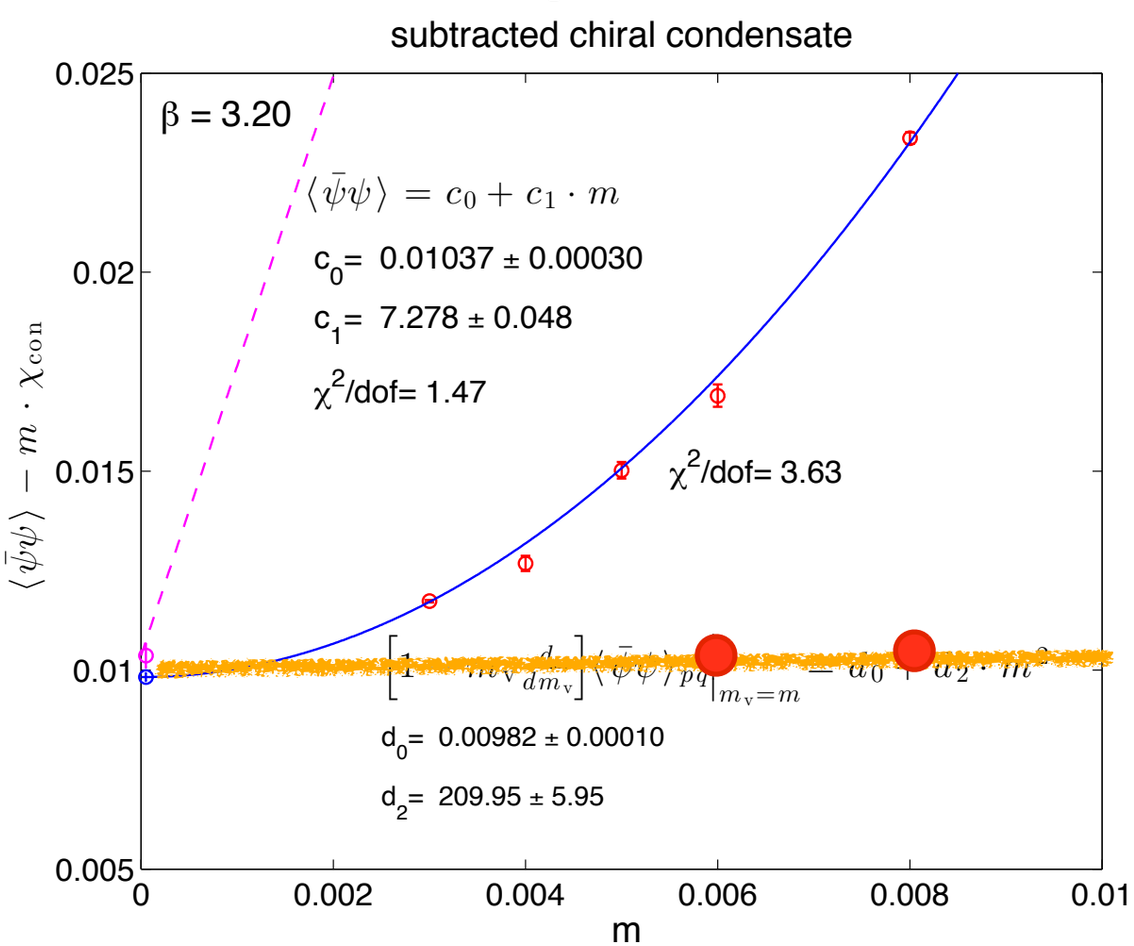

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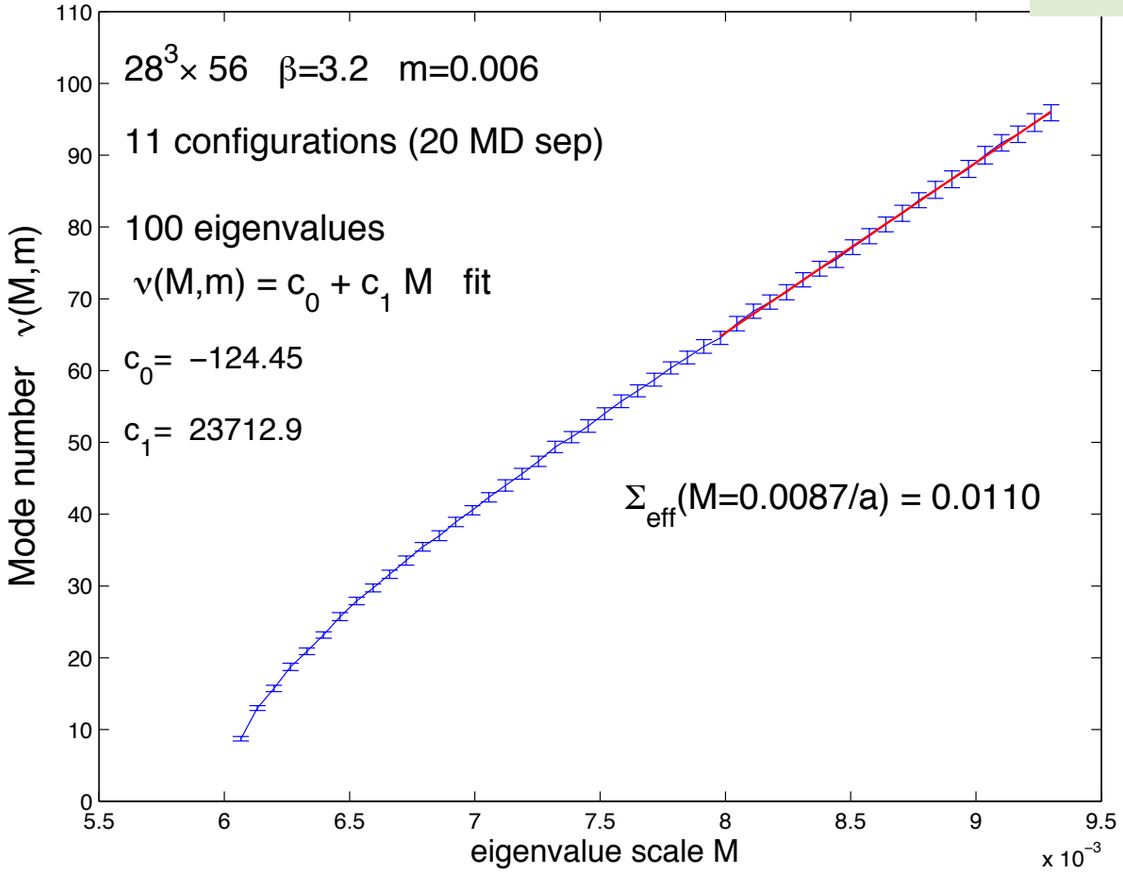

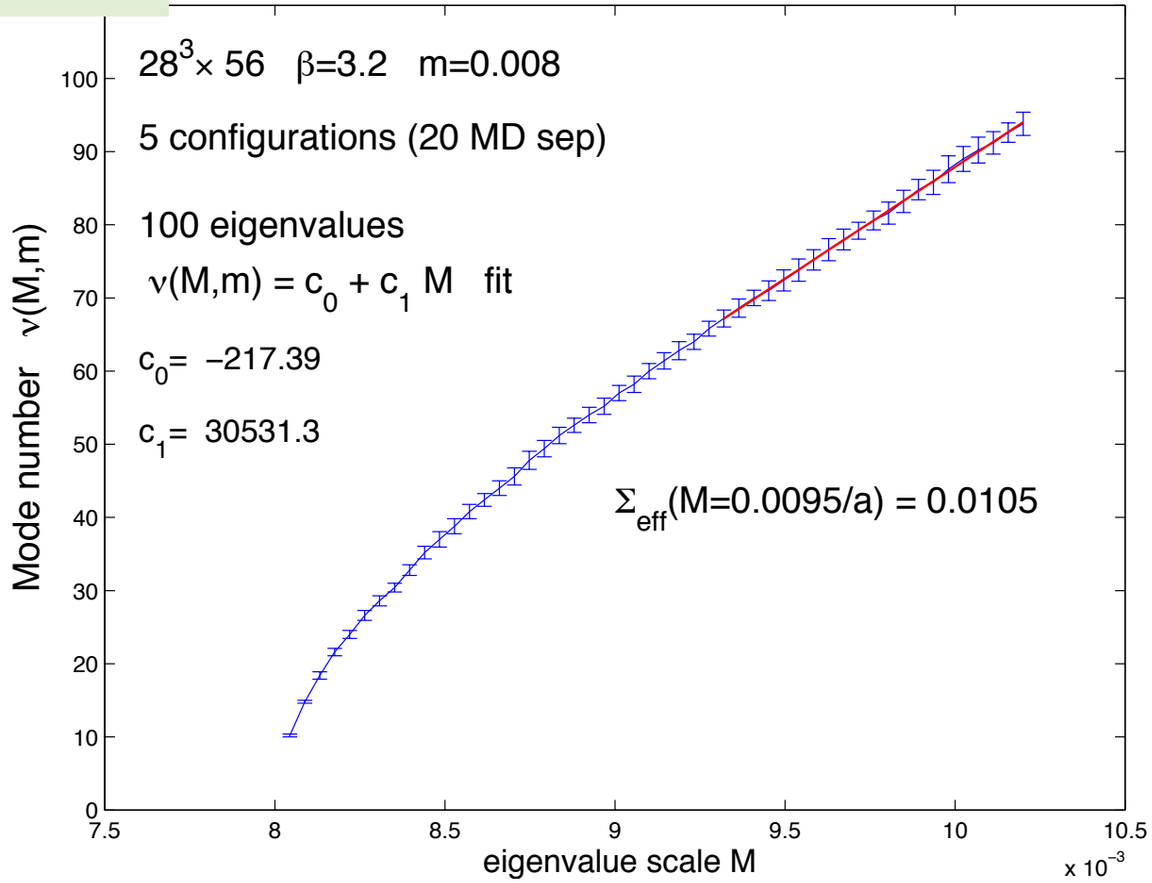

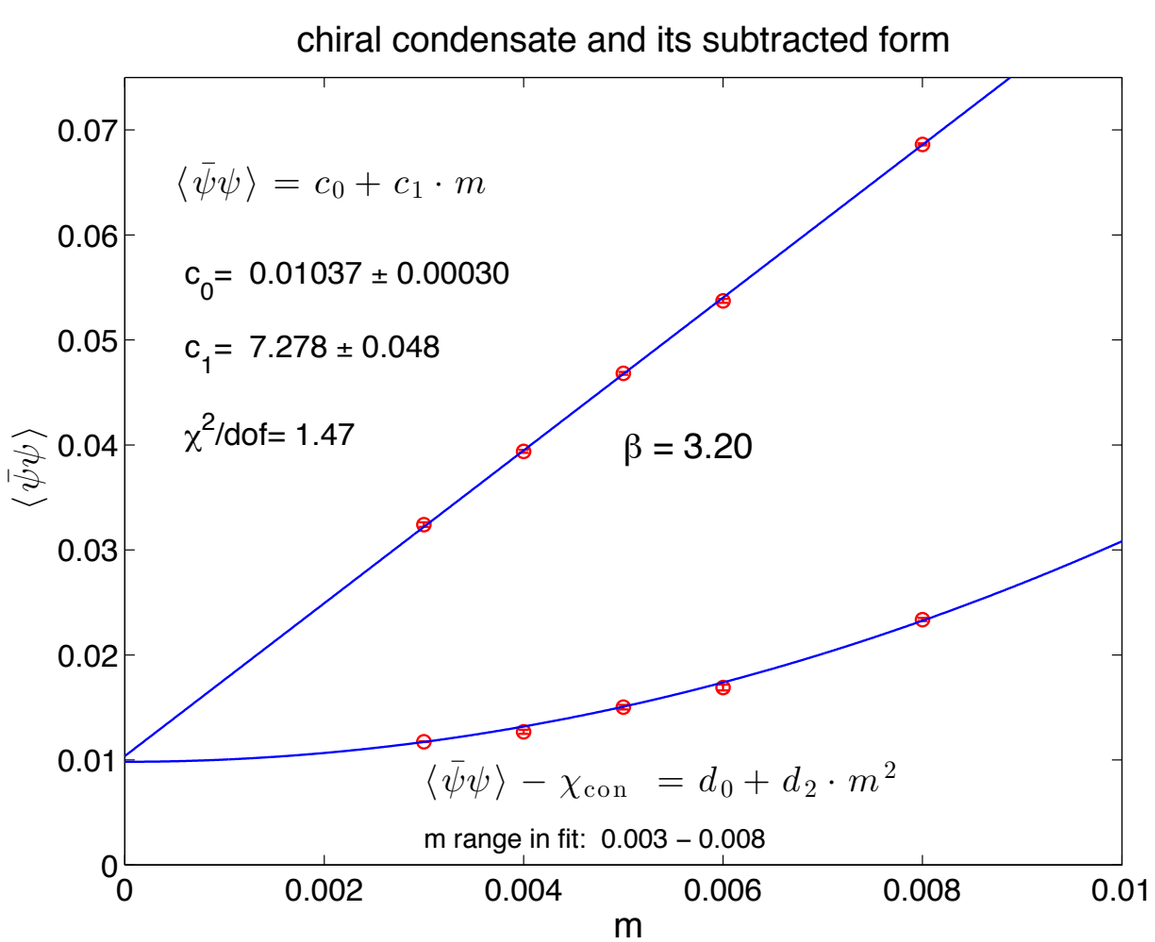

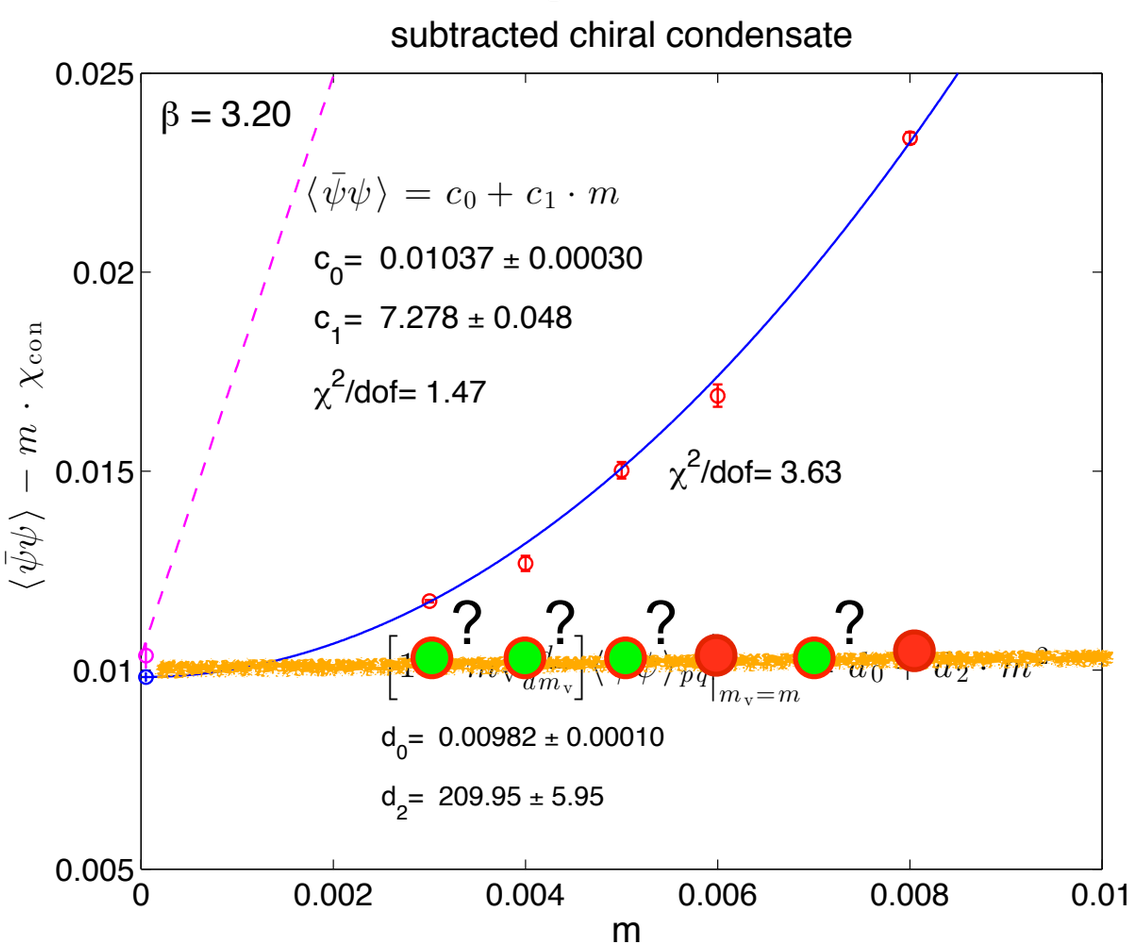

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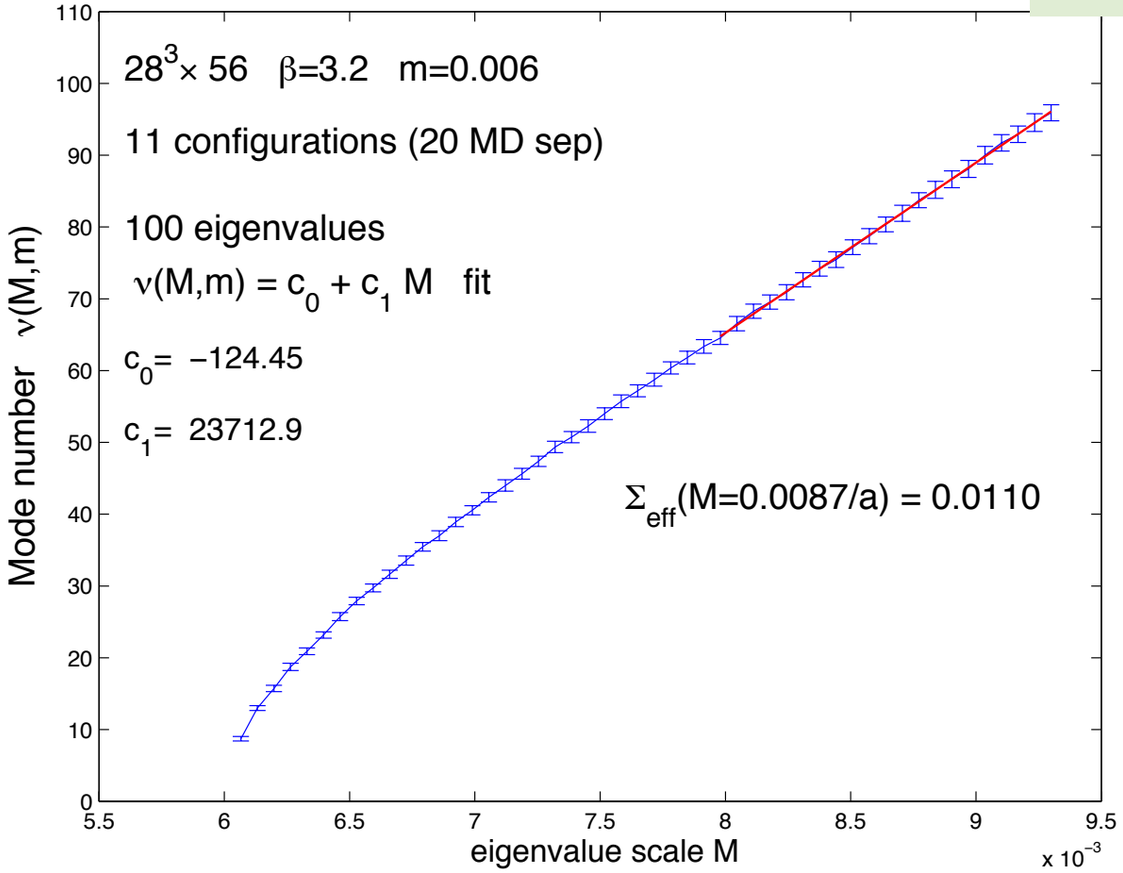
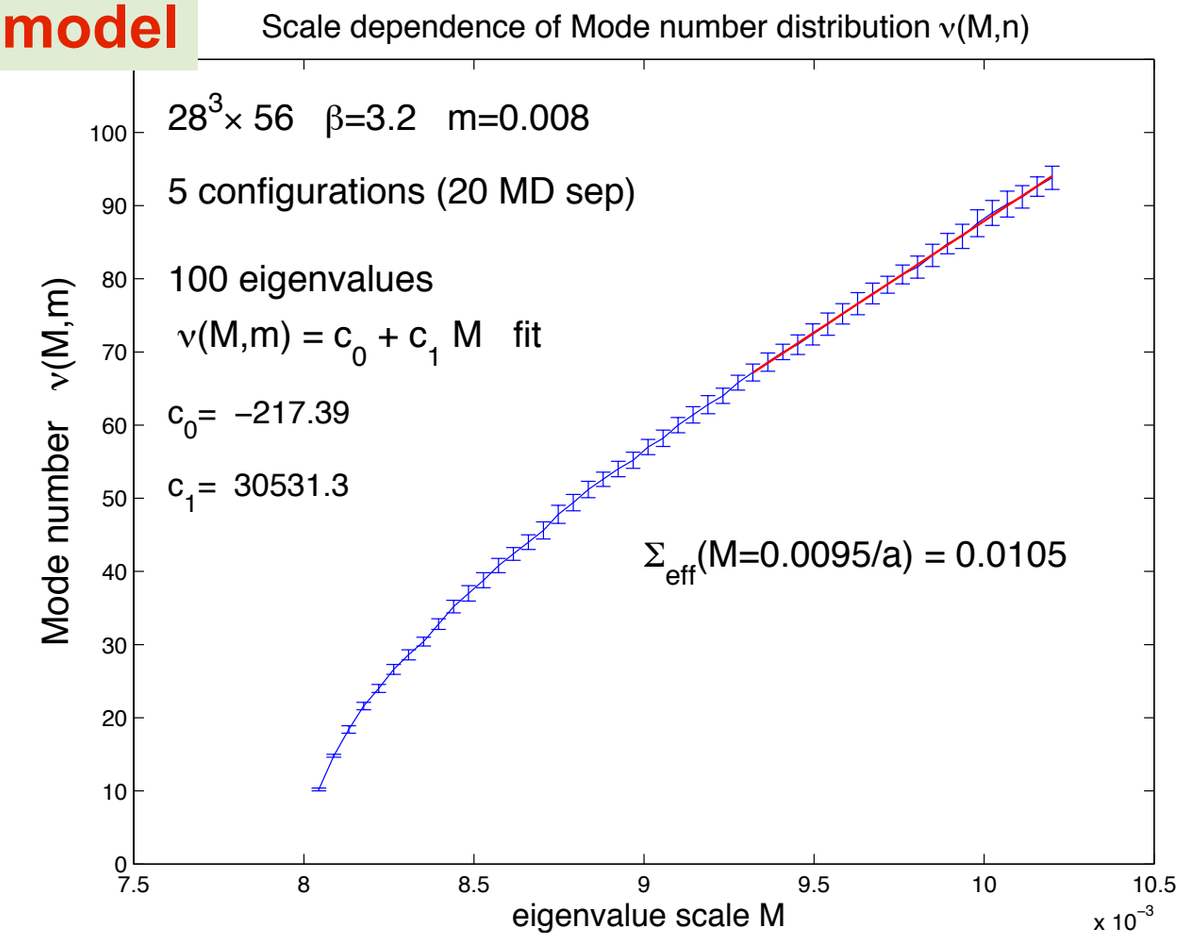
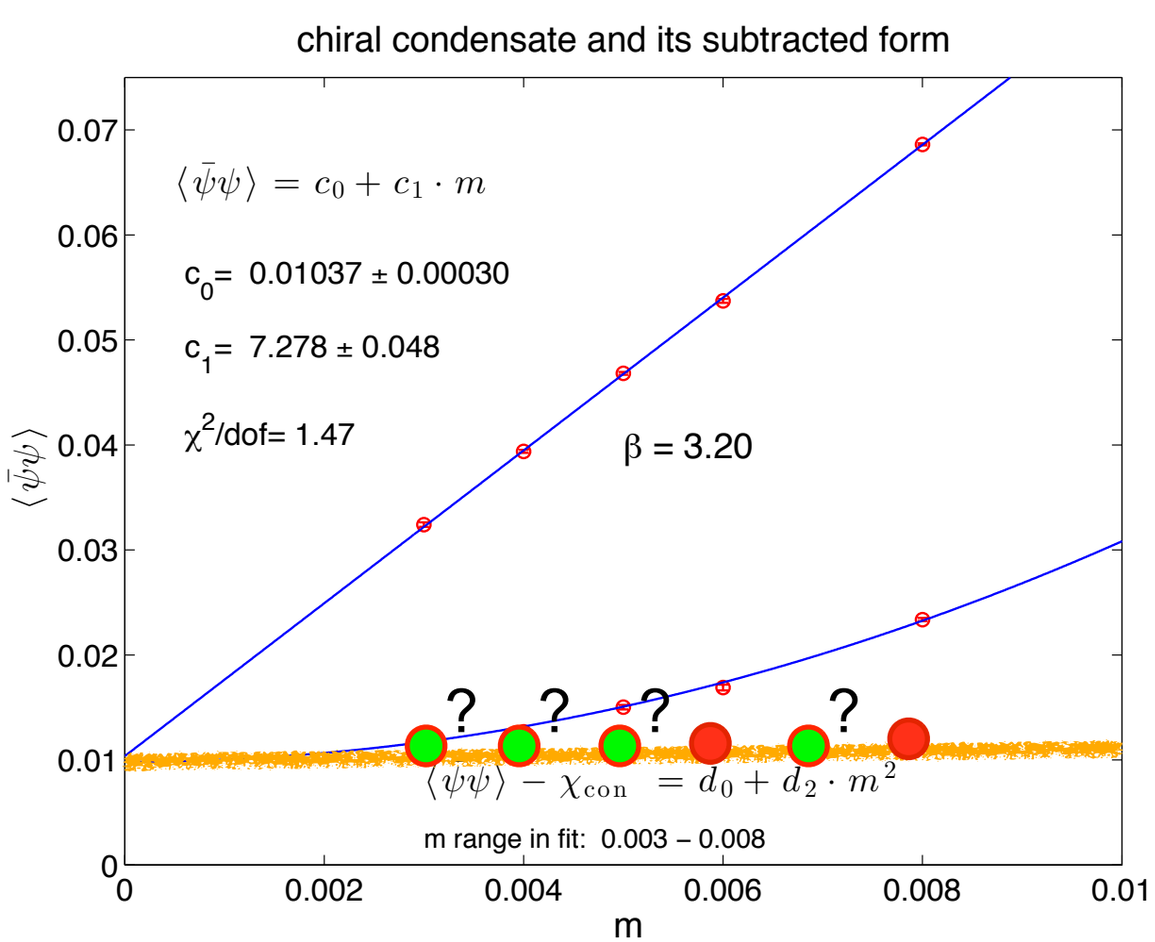
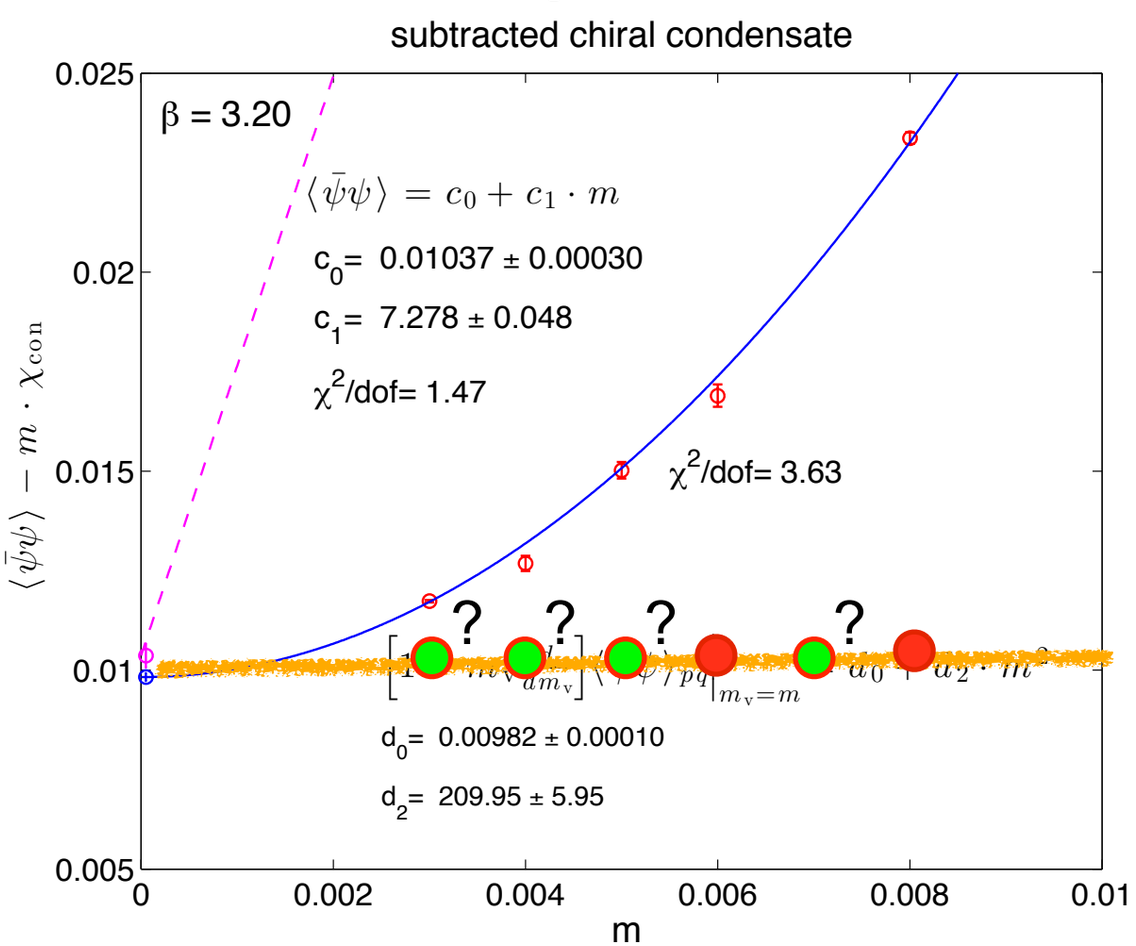


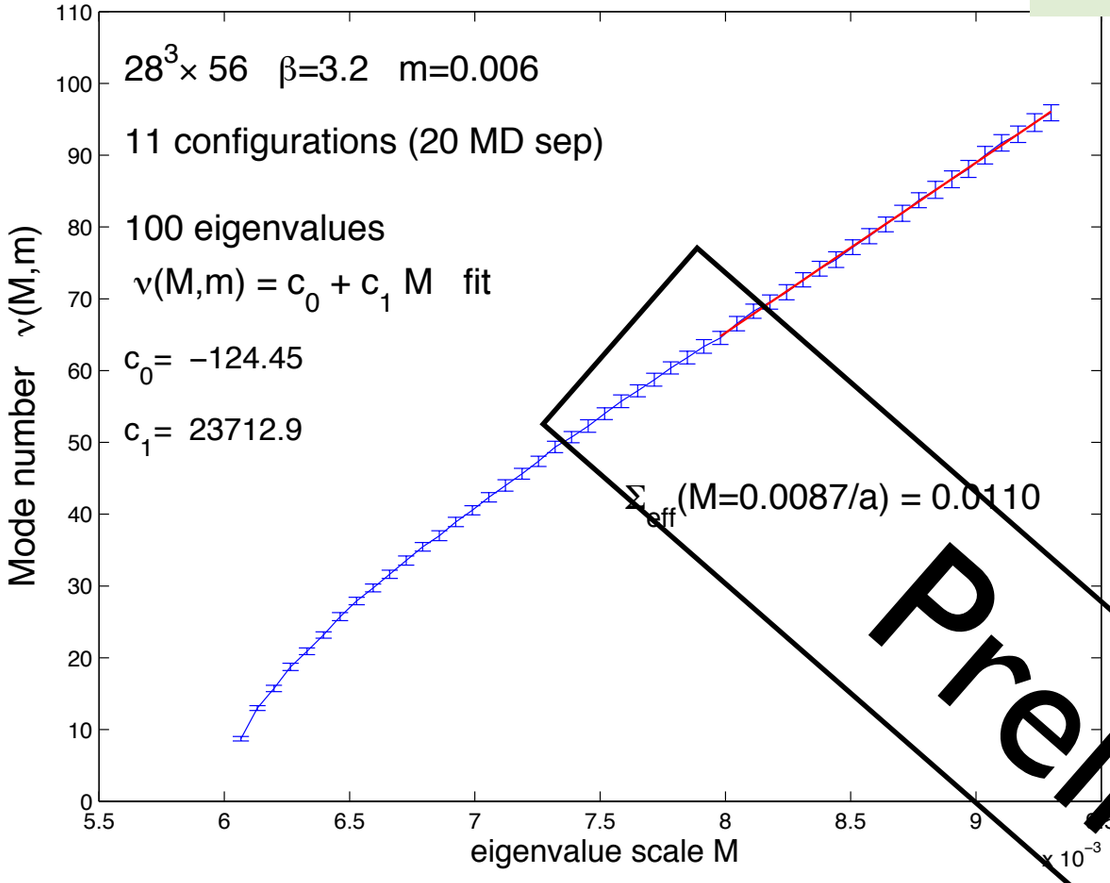






sextet model

Scale dependence of Mode number distribution ν(M,n)



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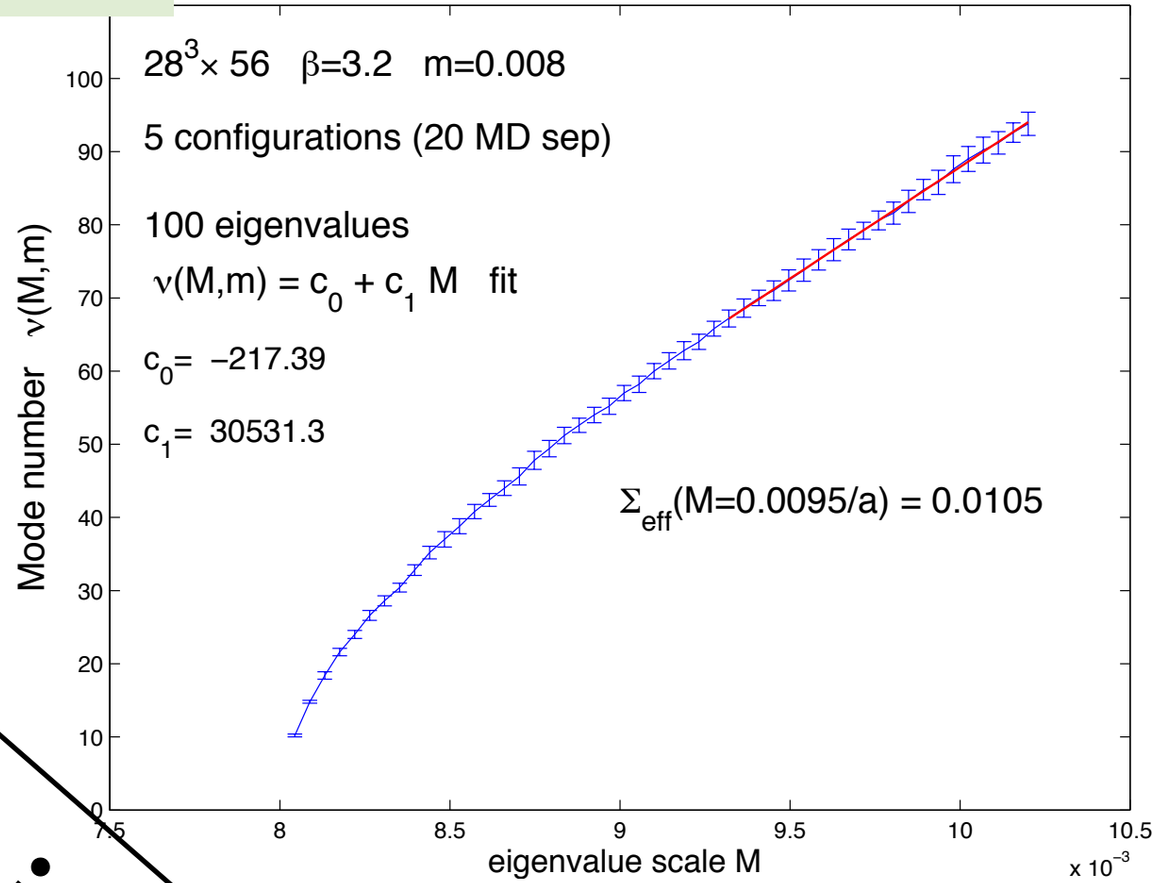
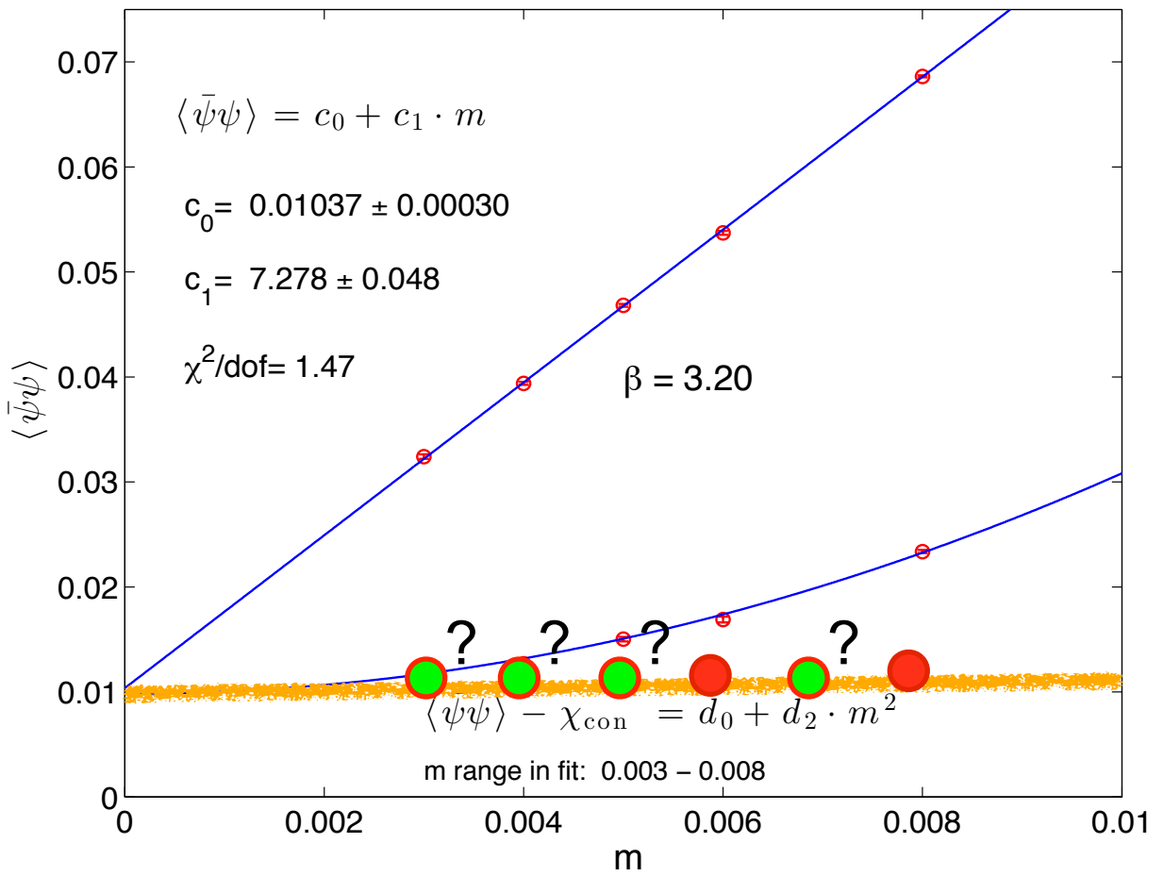
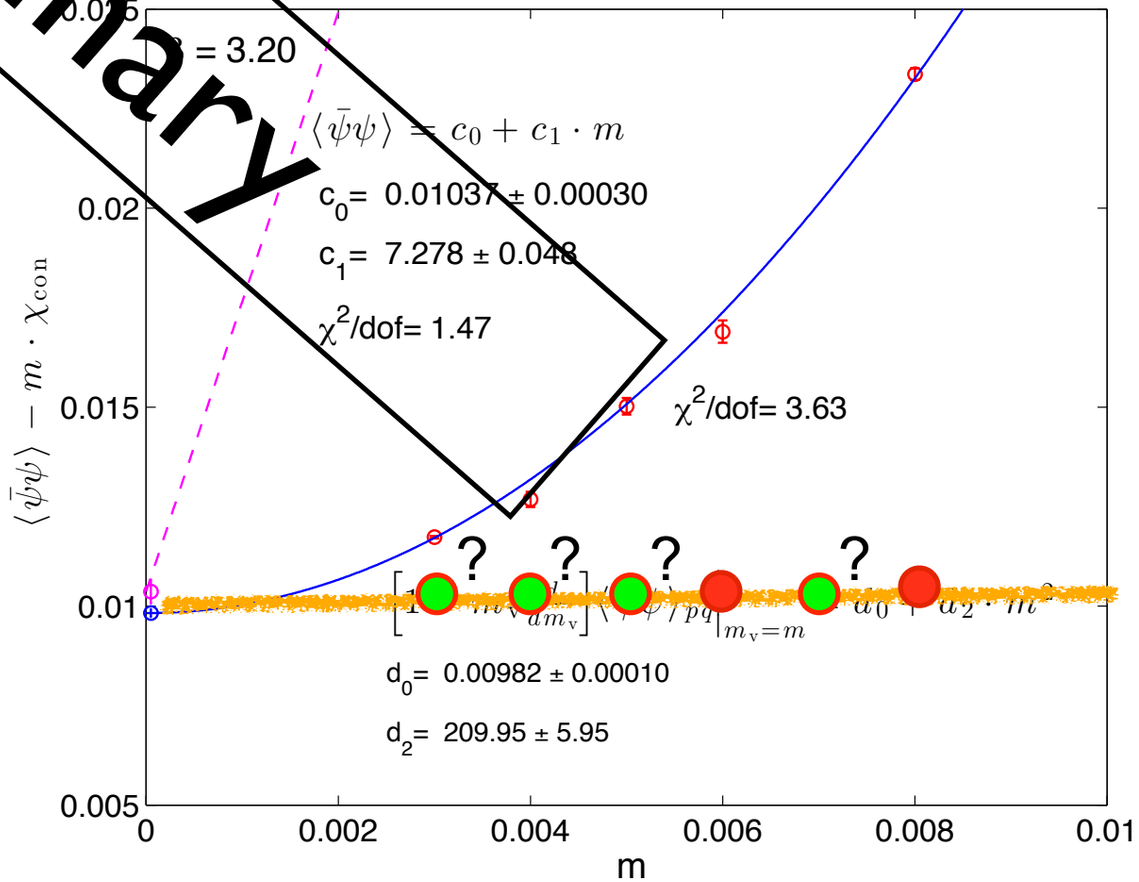


Preliminary

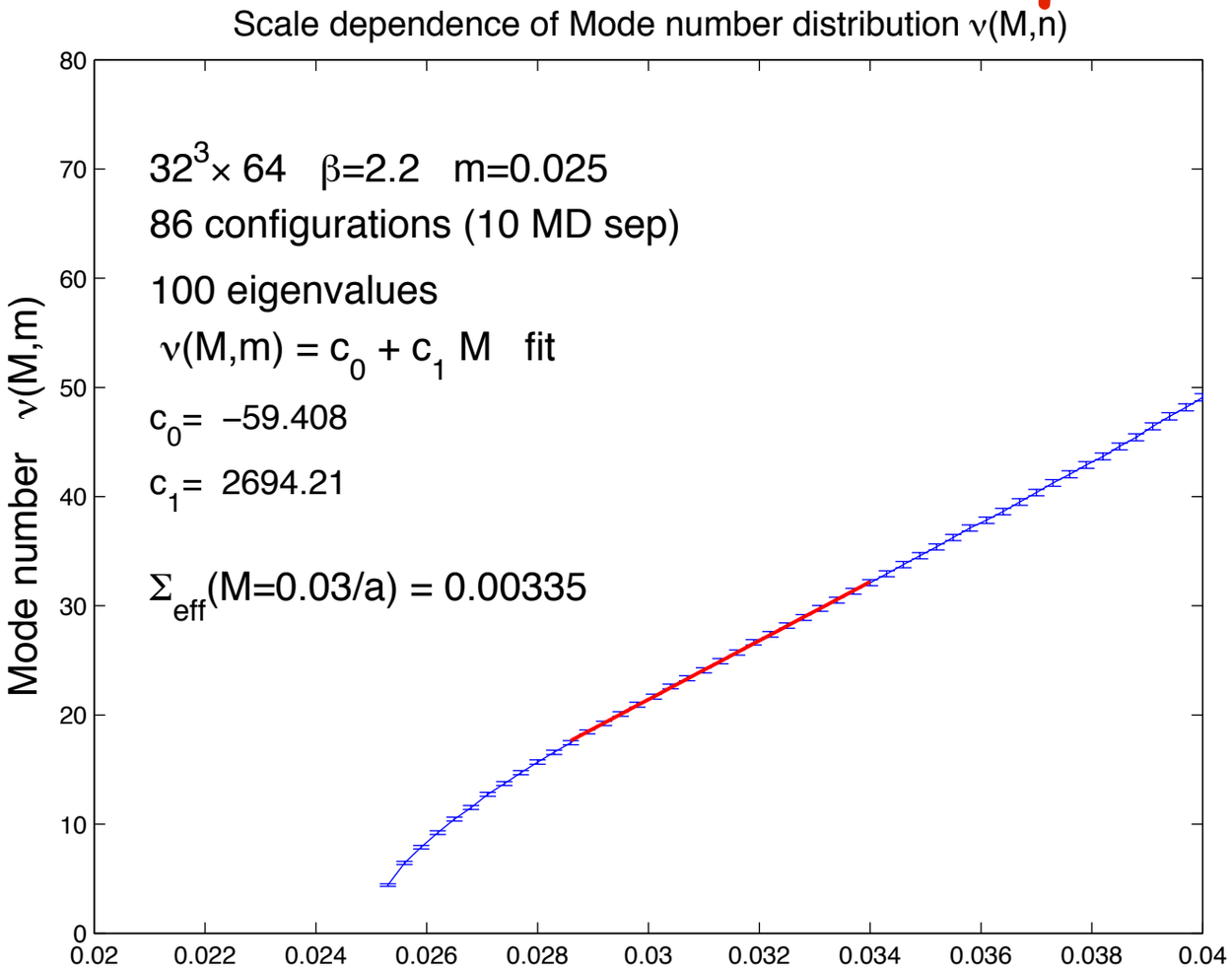
chiral condensate and its subtracted form

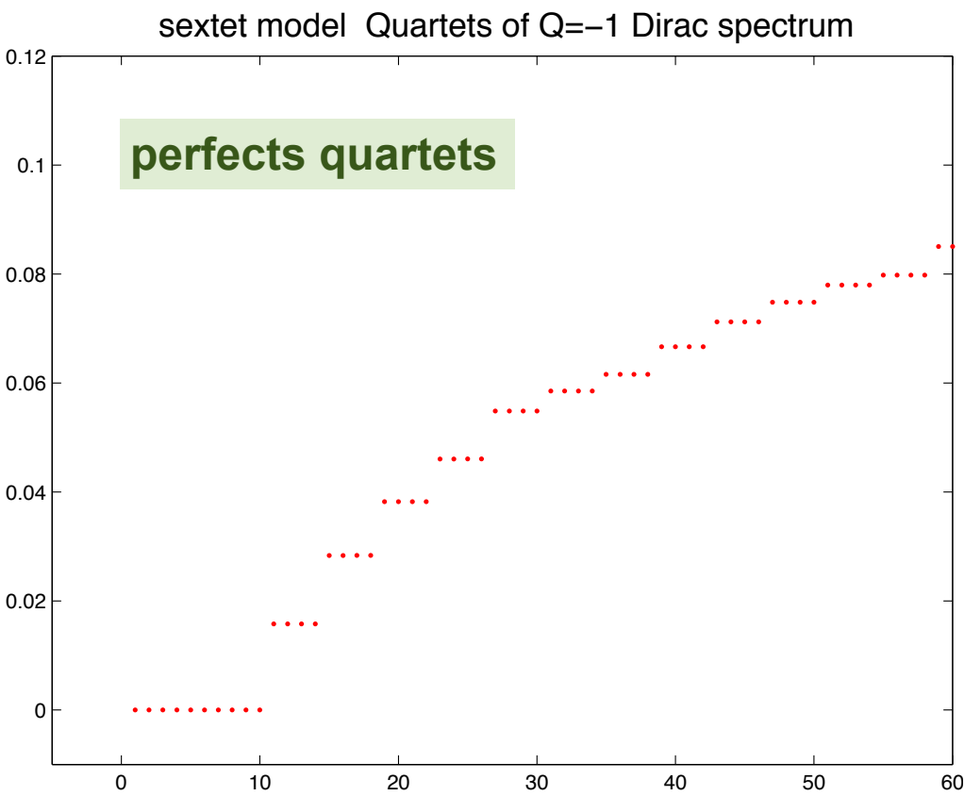


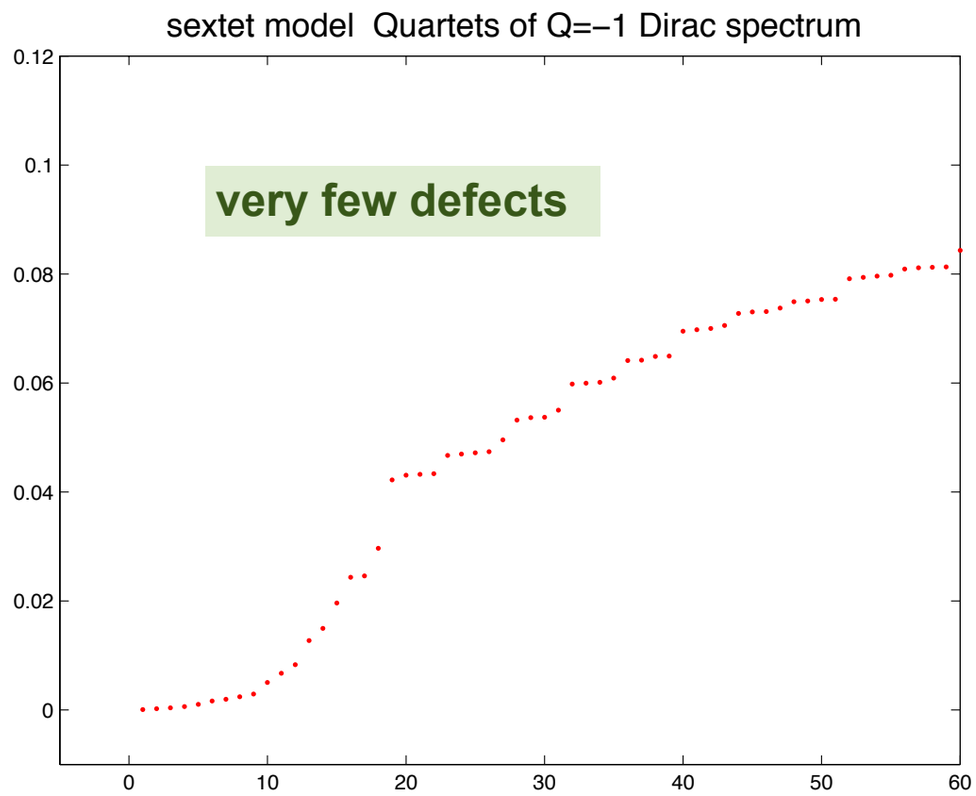
subtracted chiral condensate



Nf=12 fundamental rep:







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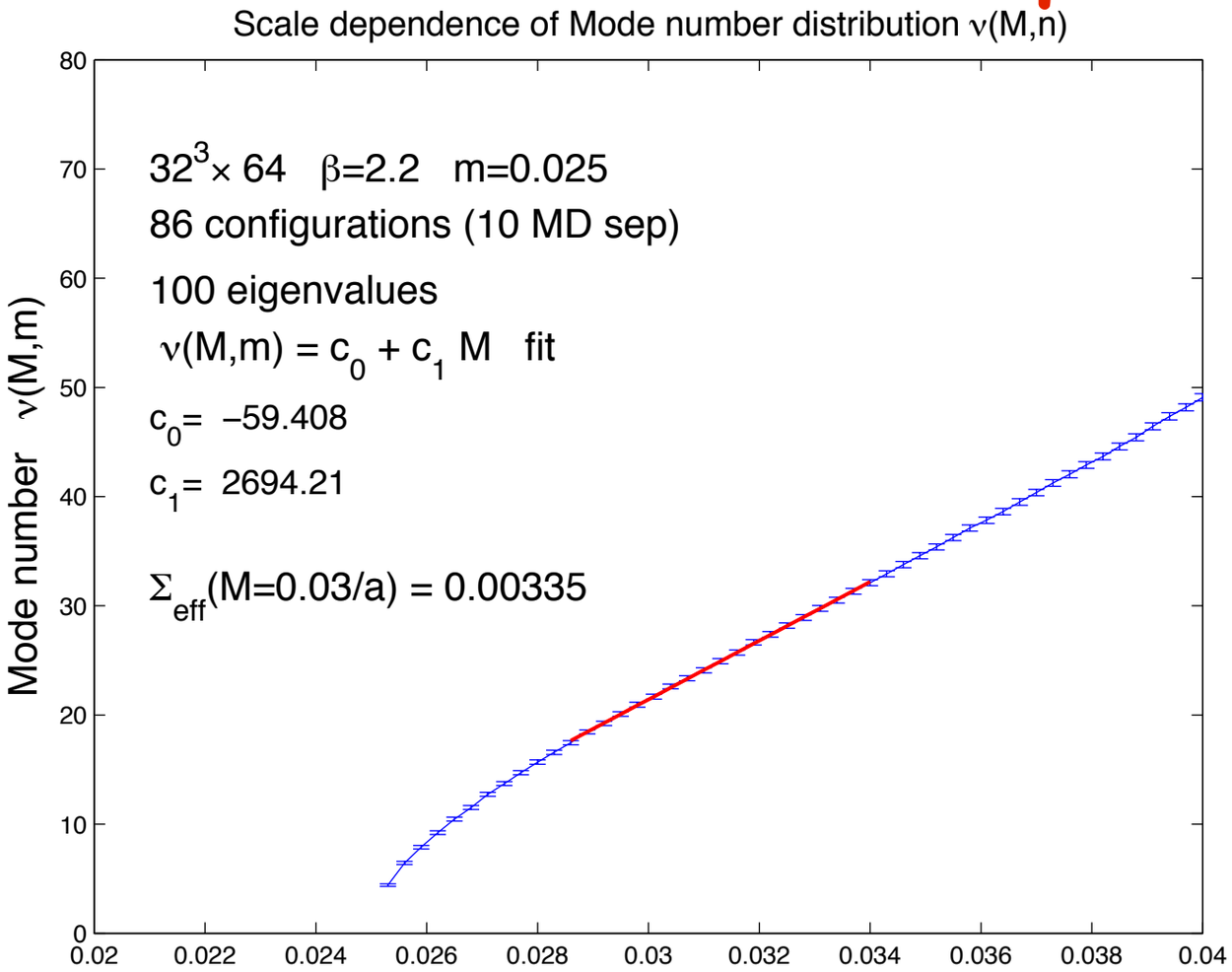

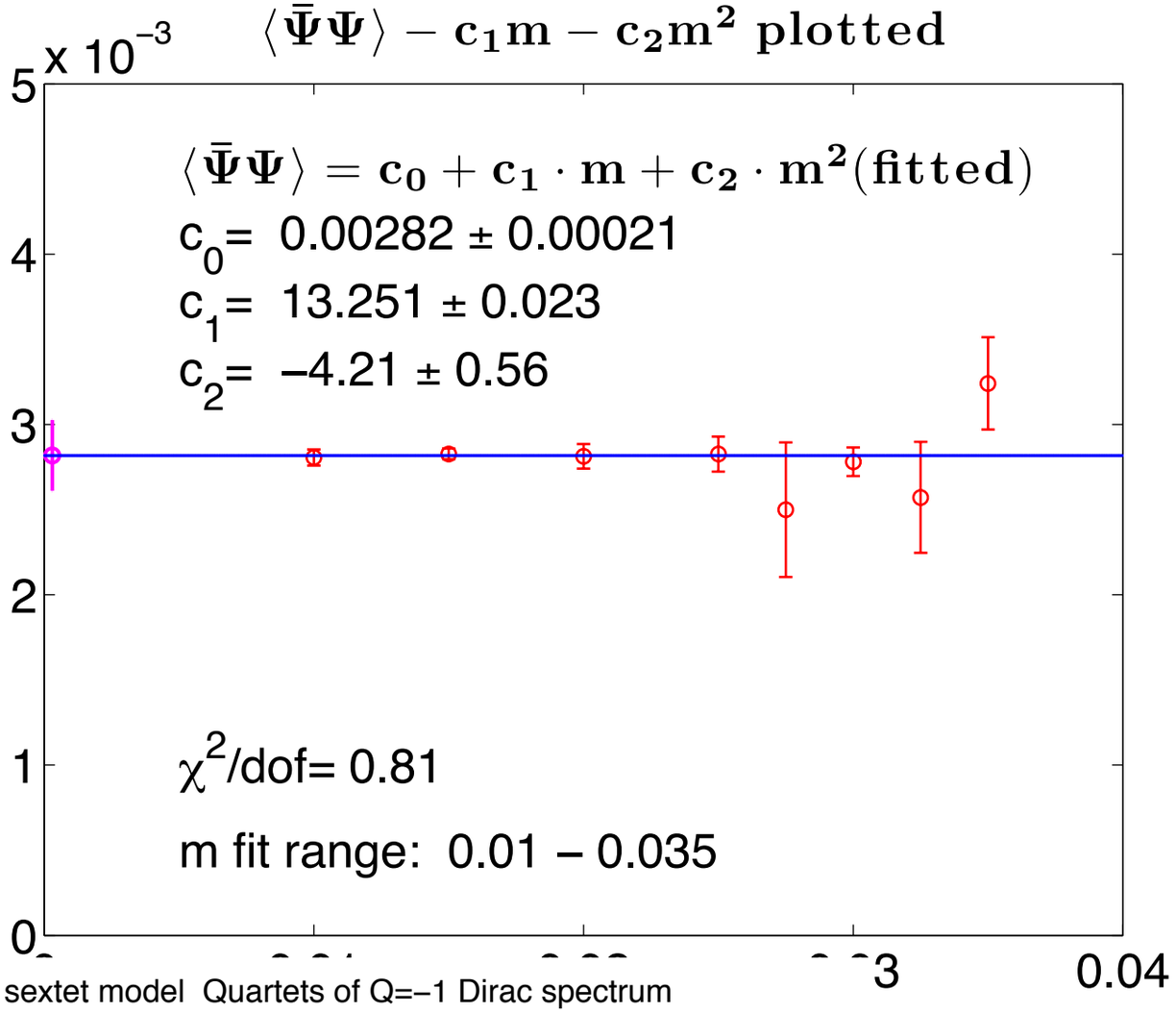

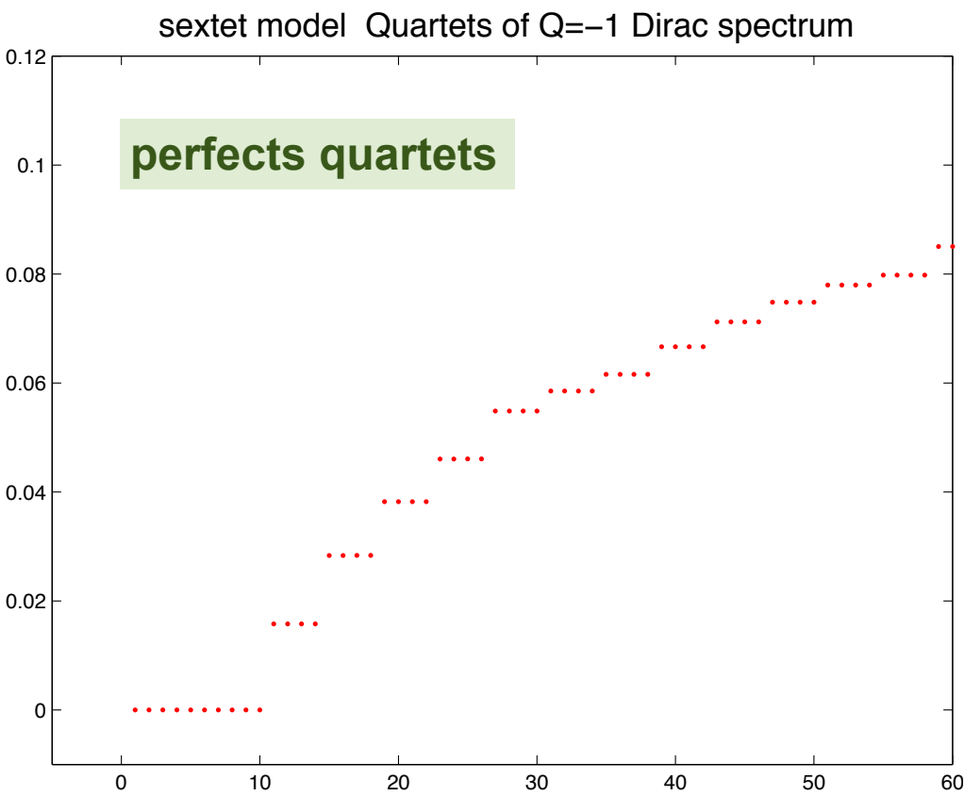

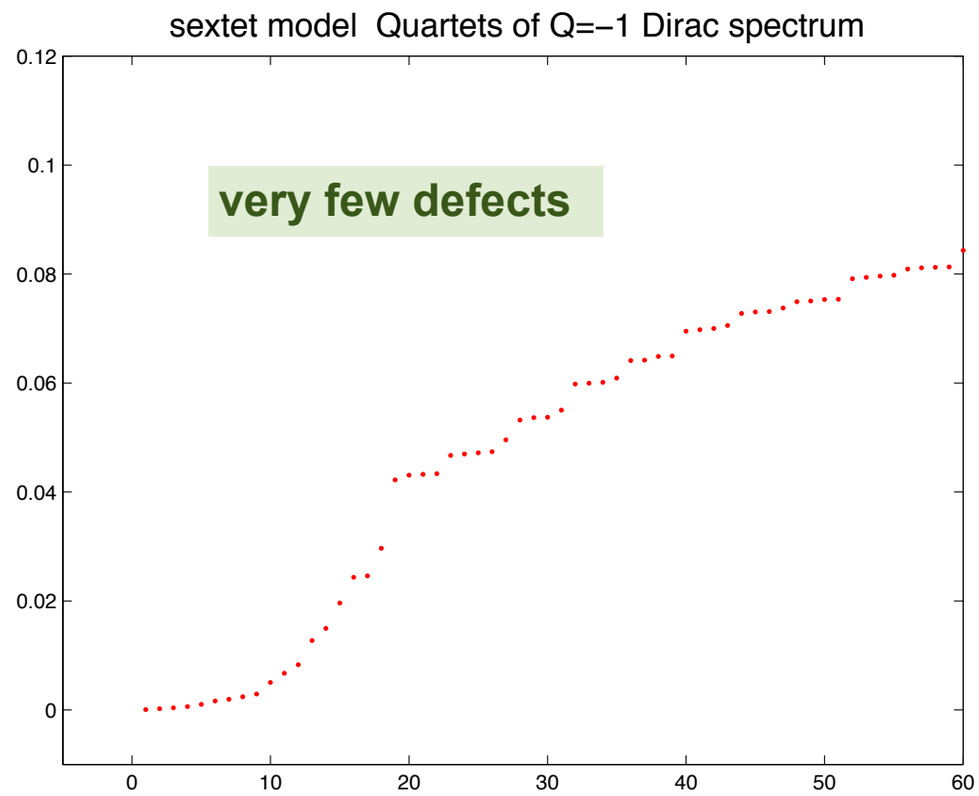

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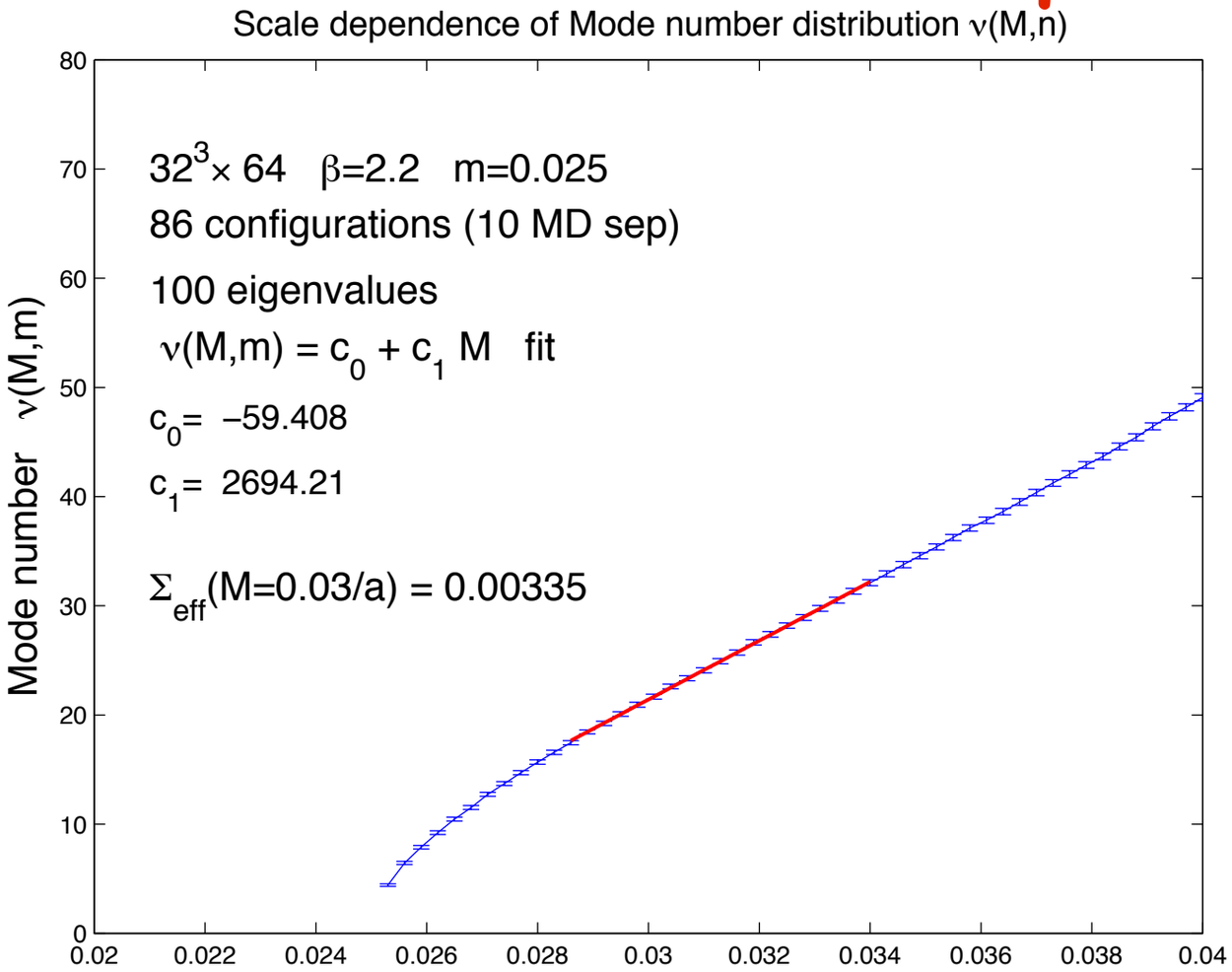

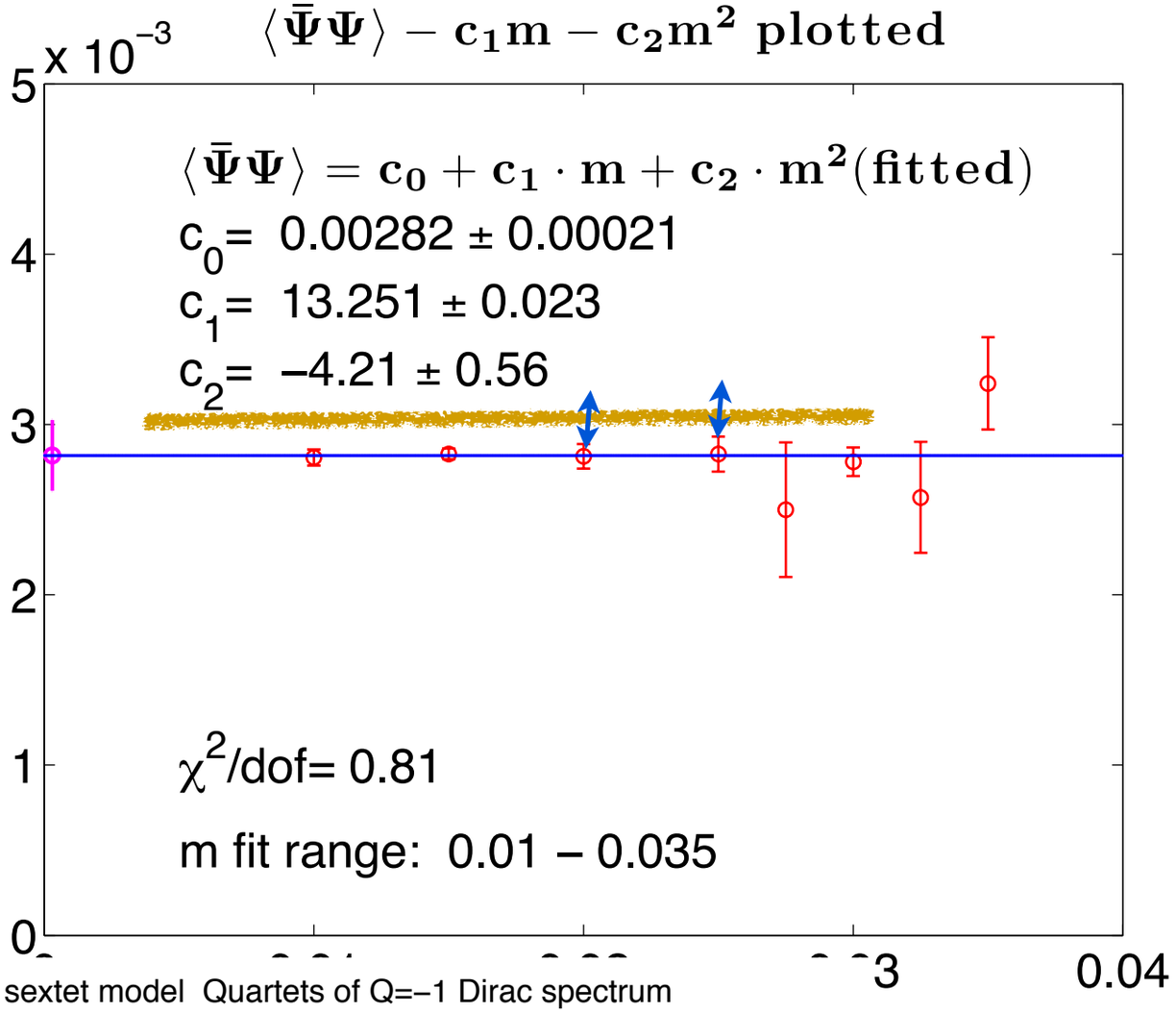

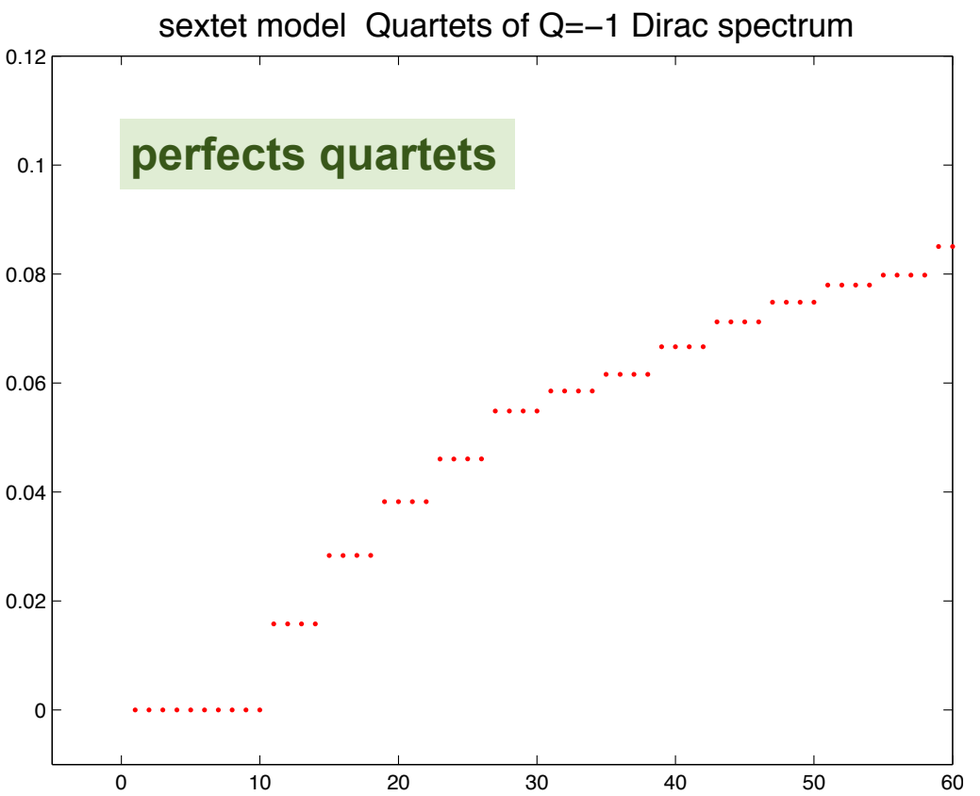

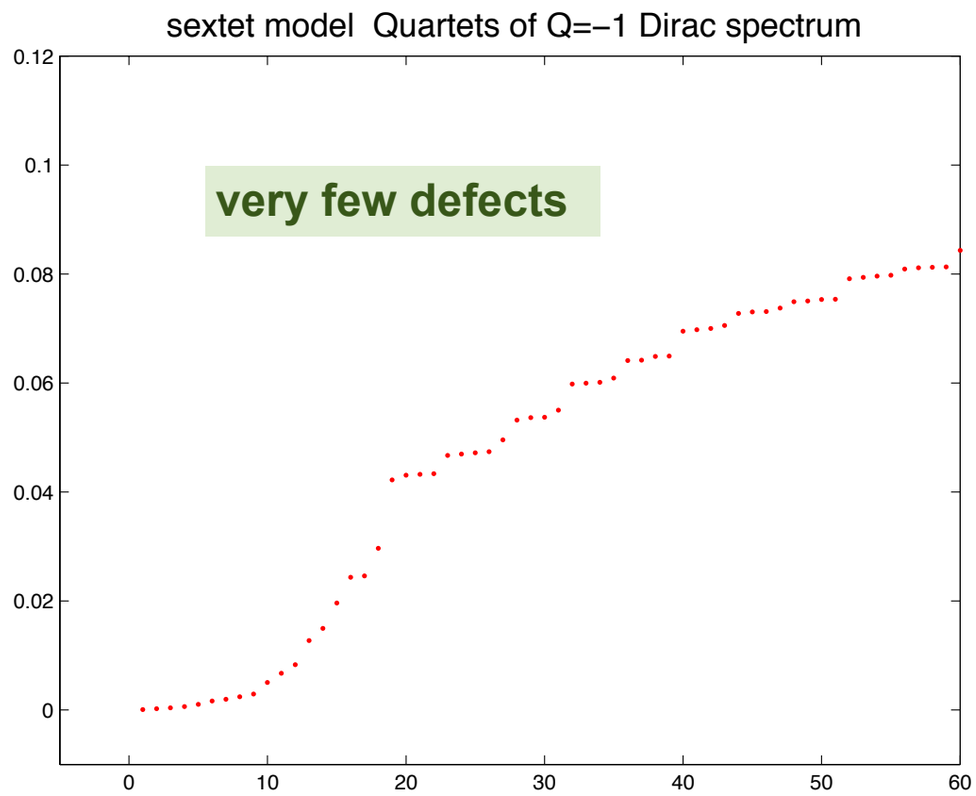

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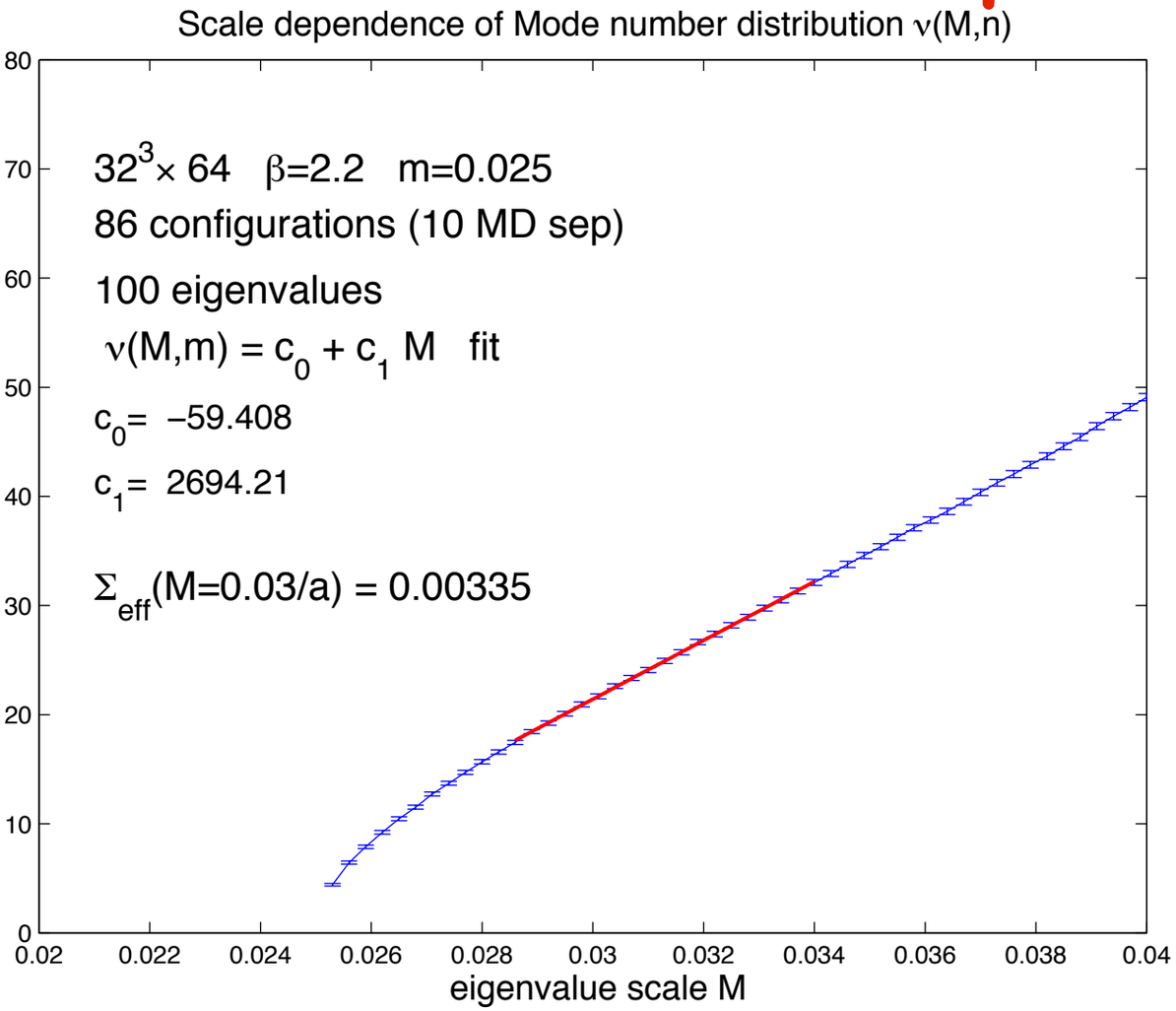
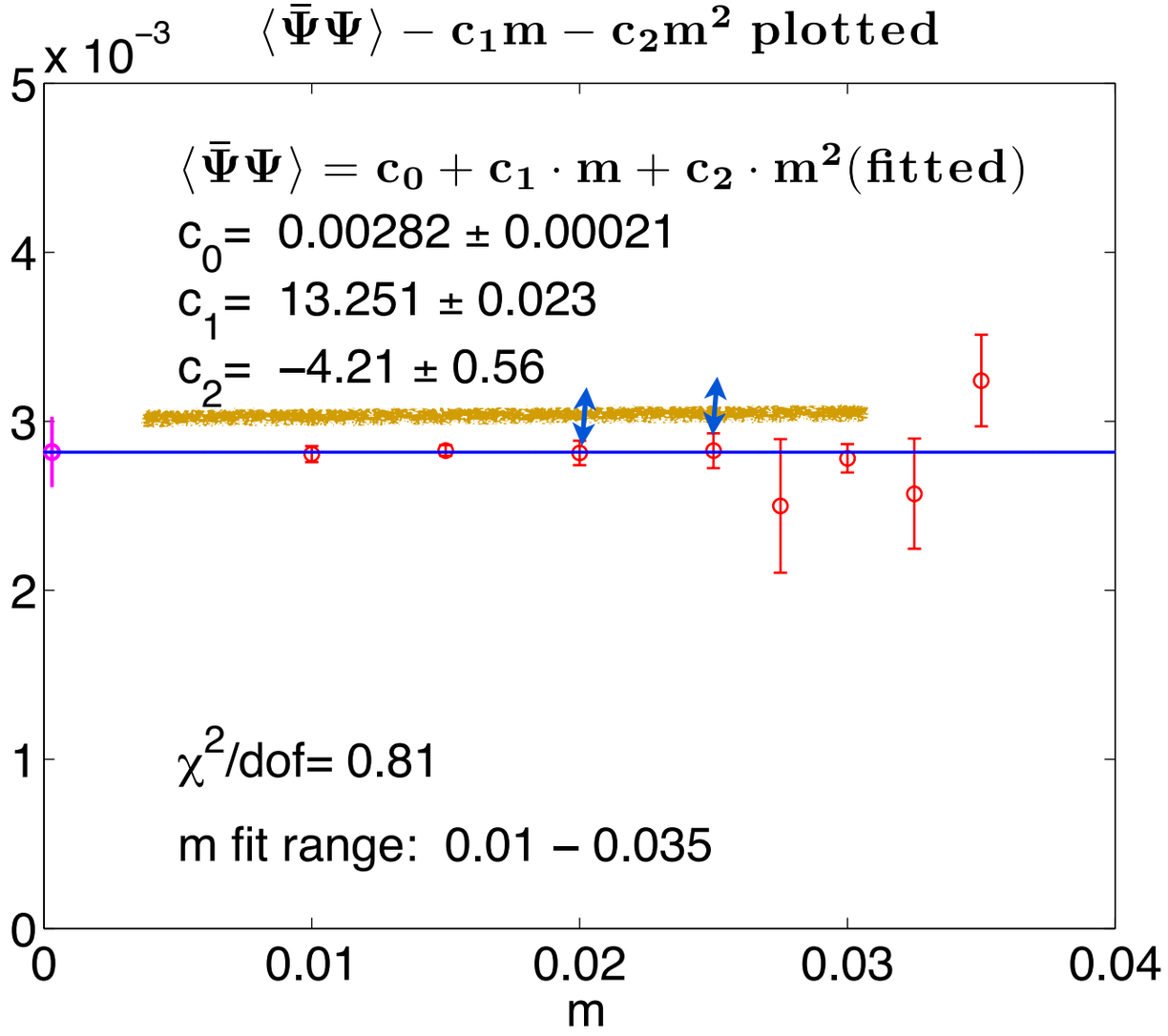
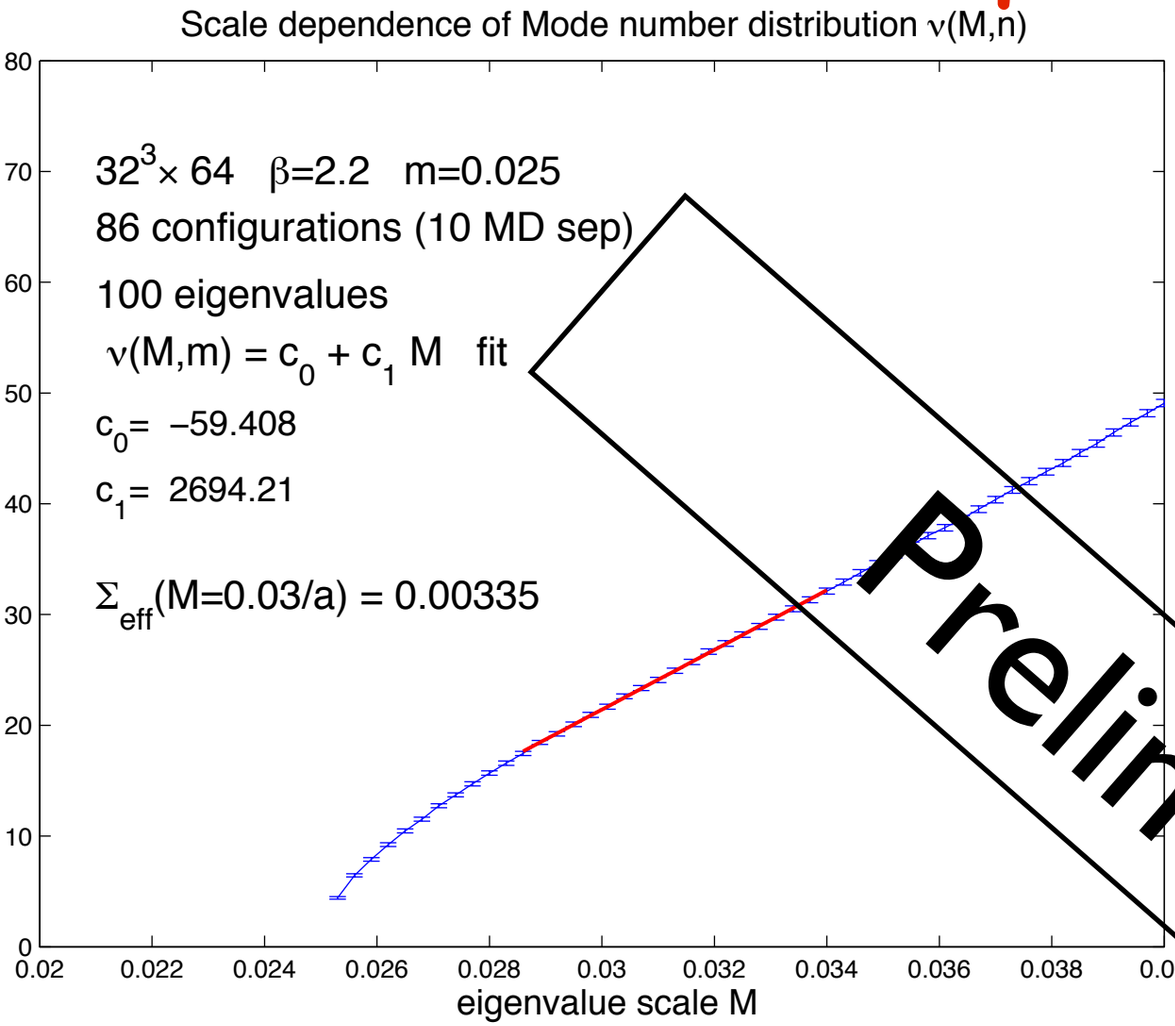
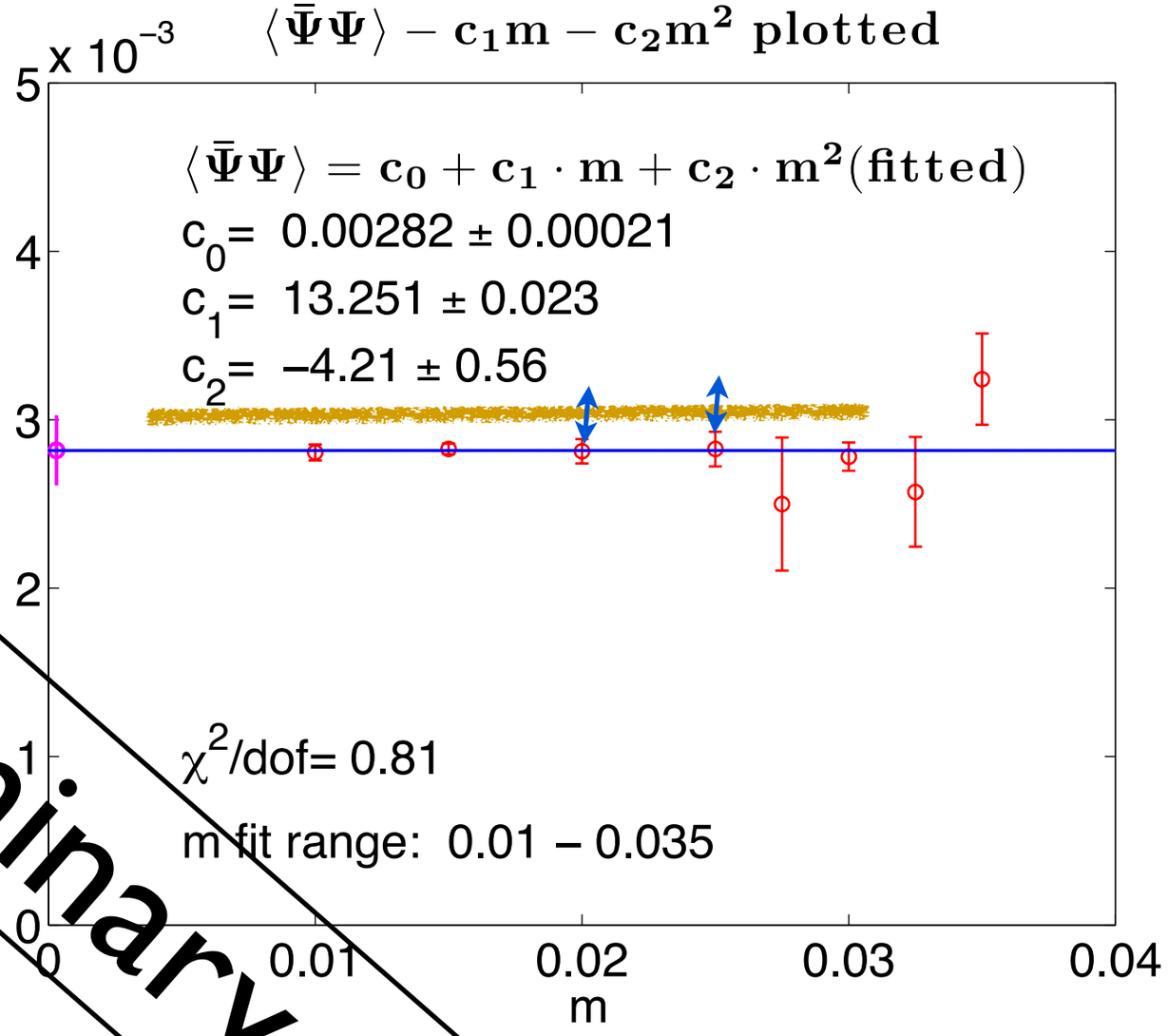




Nf=12 fundamental rep:





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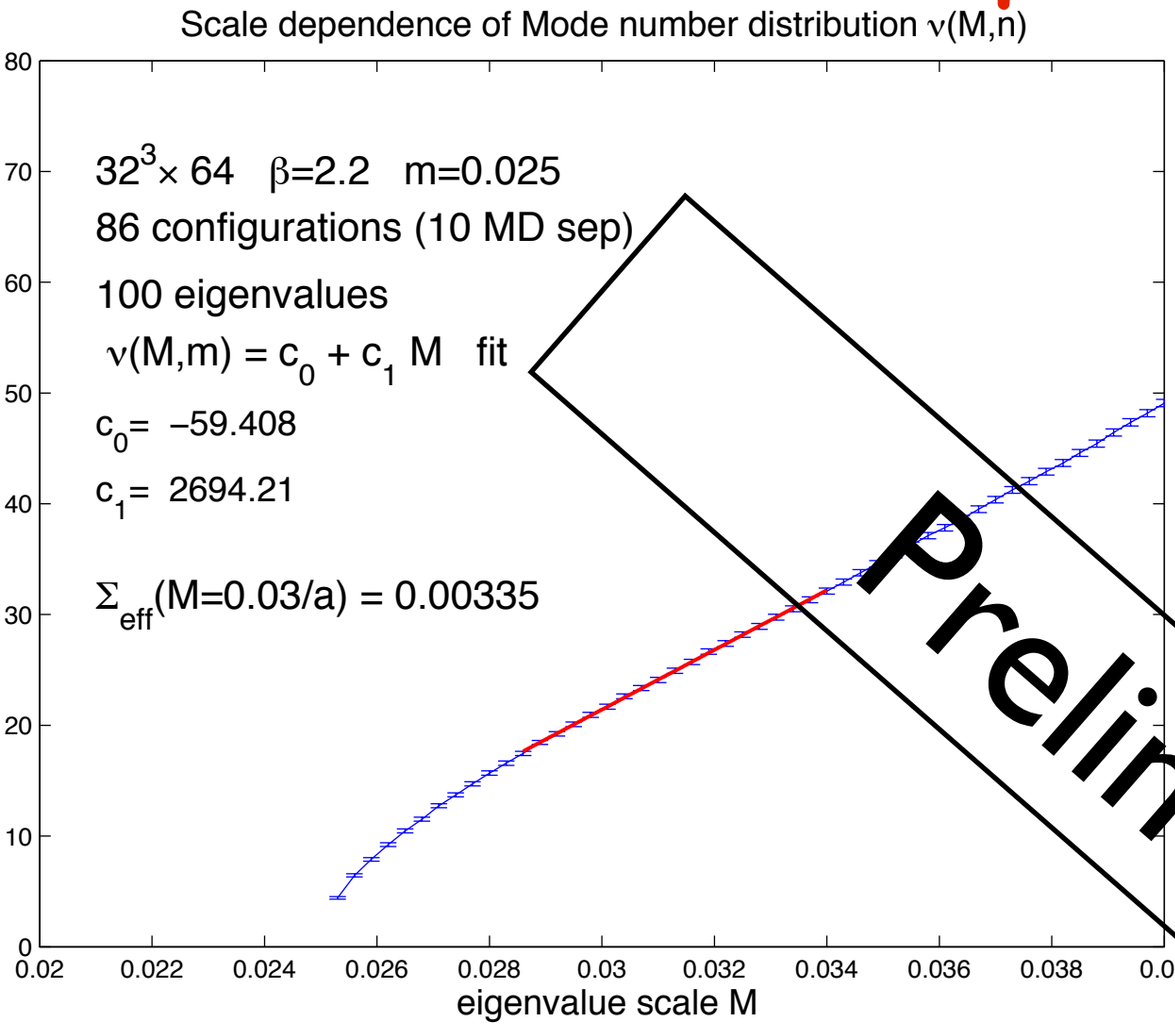
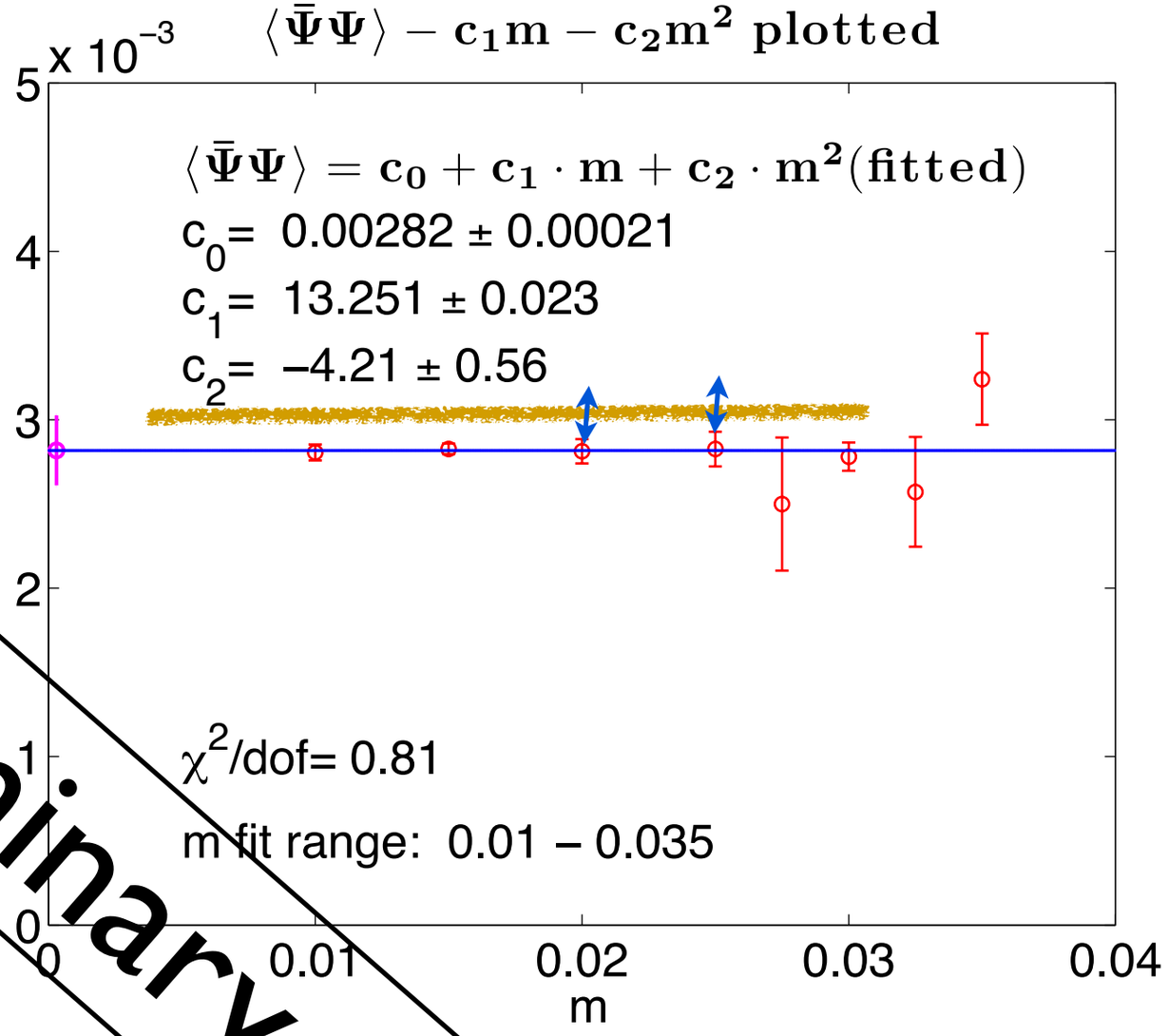
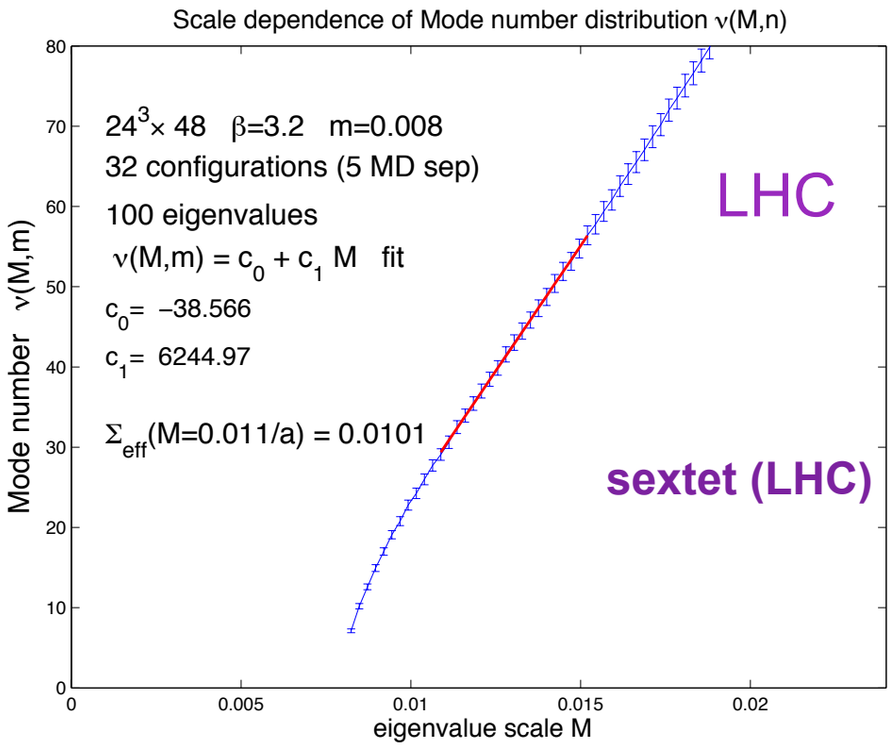


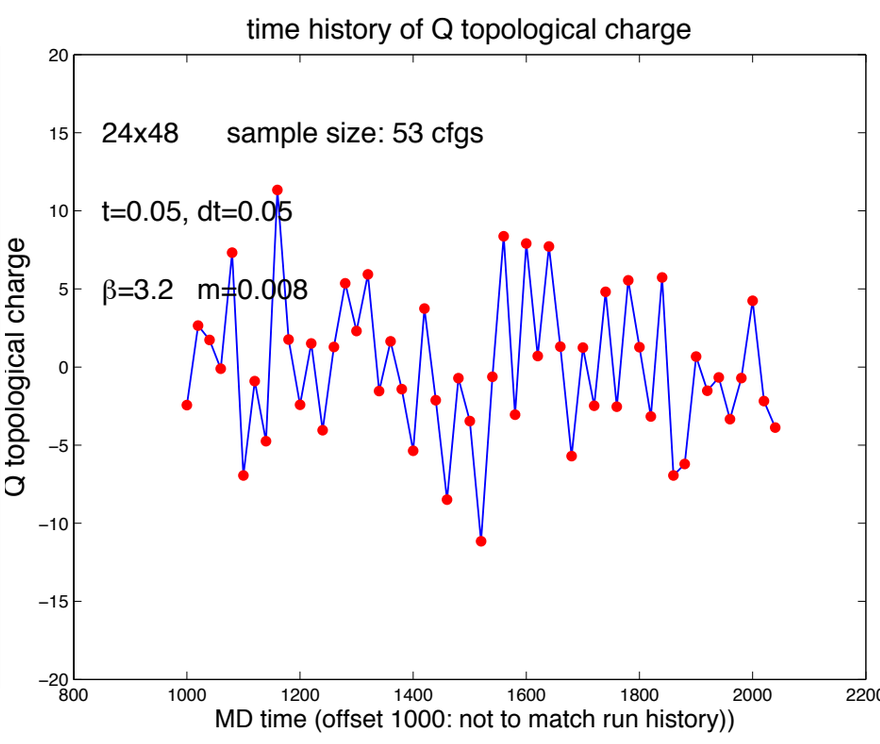


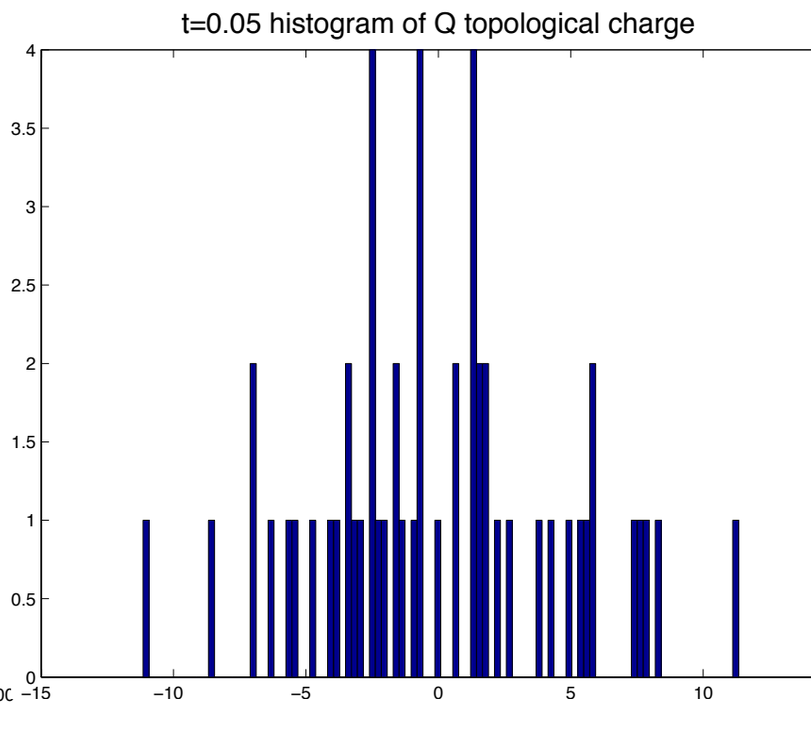
Preliminary

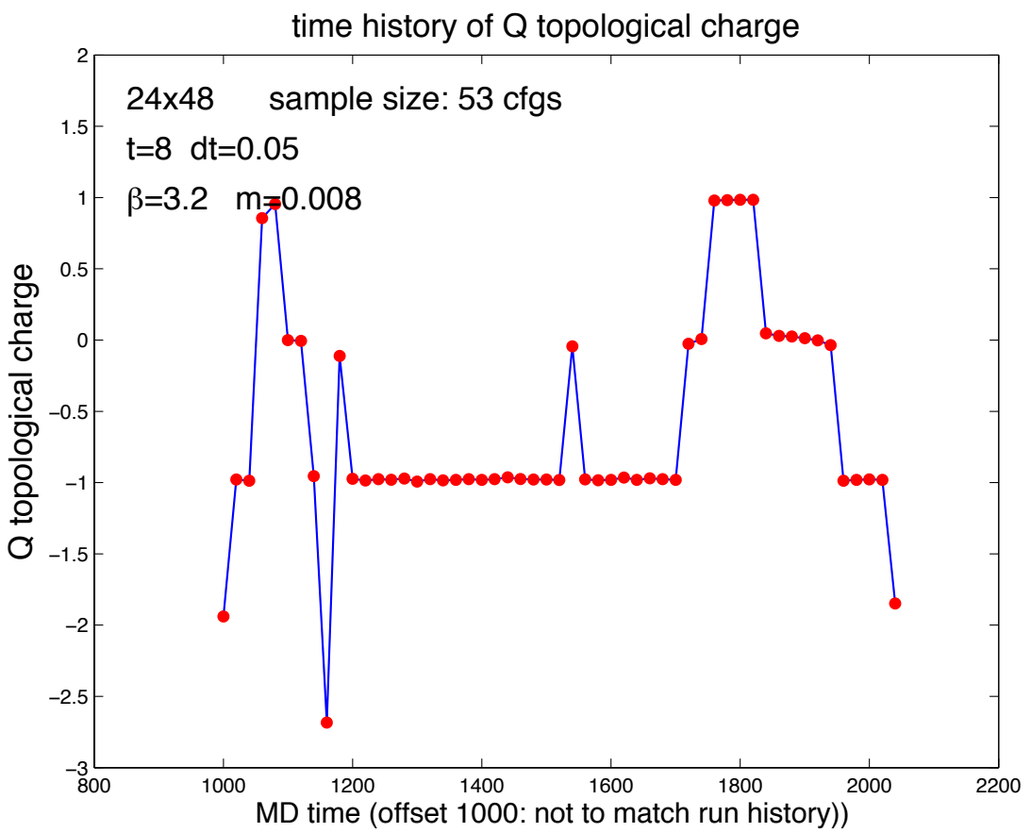
is Nf=12 chirally broken after all? :)

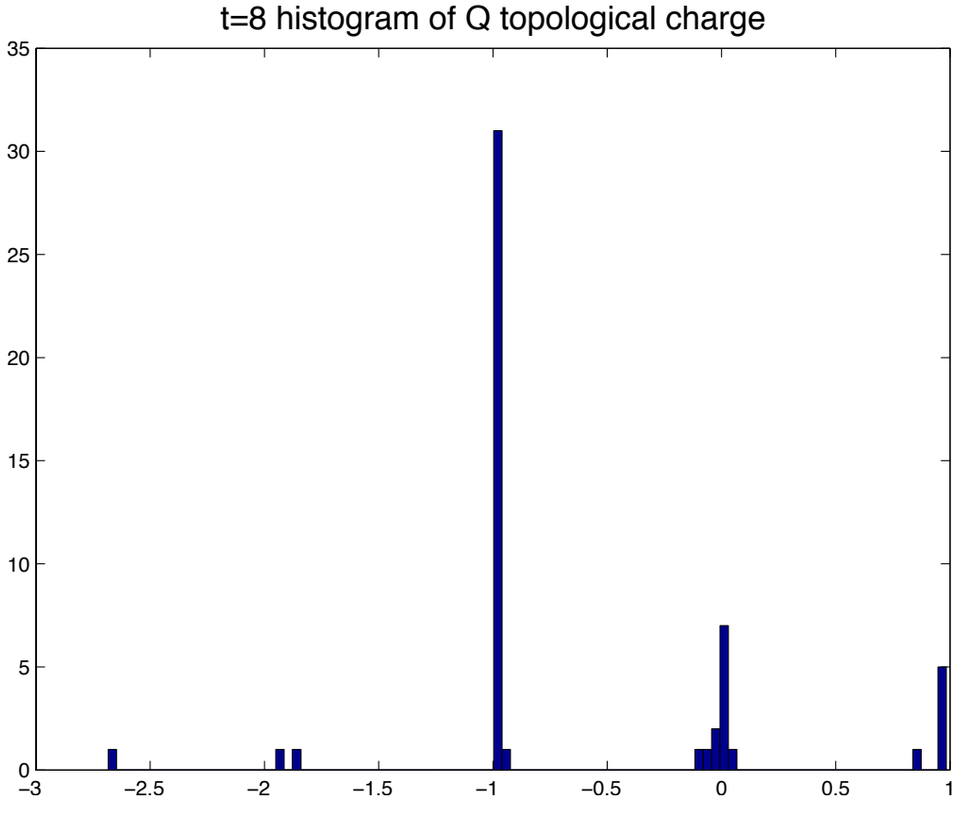
gradient flow reveals problems with slowly developing topological distribution:











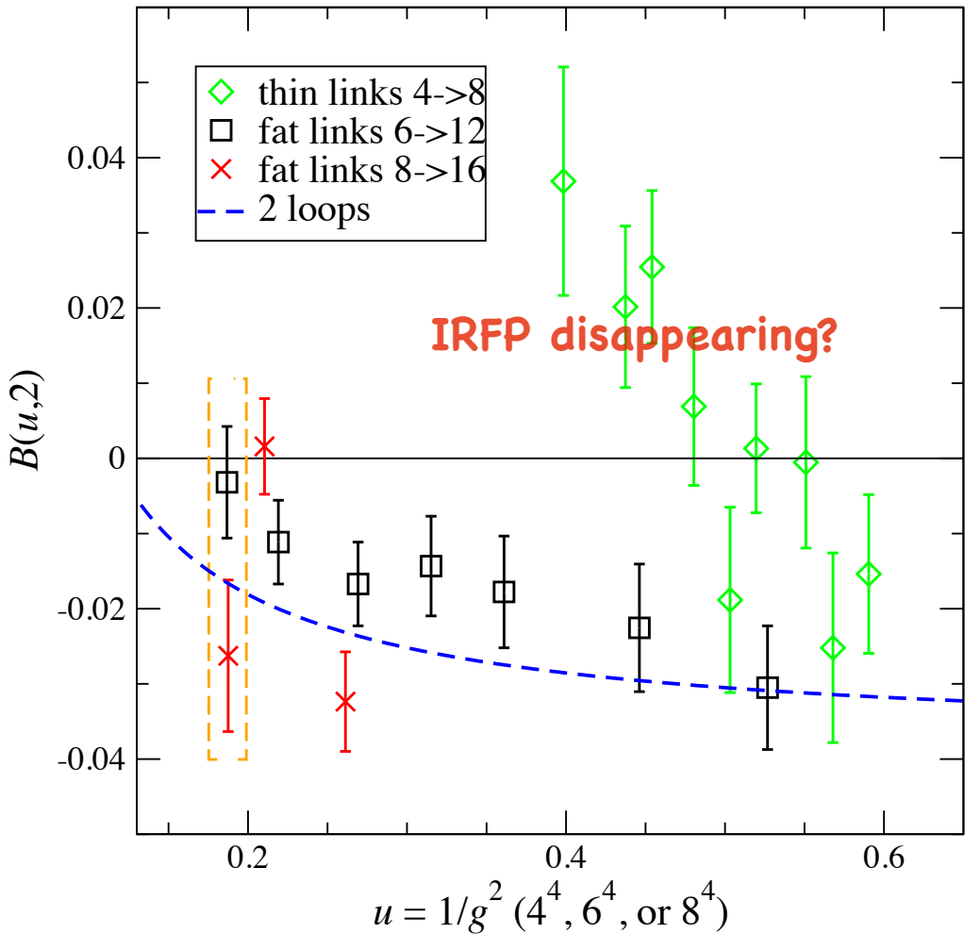
running (walking?) gauge coupling

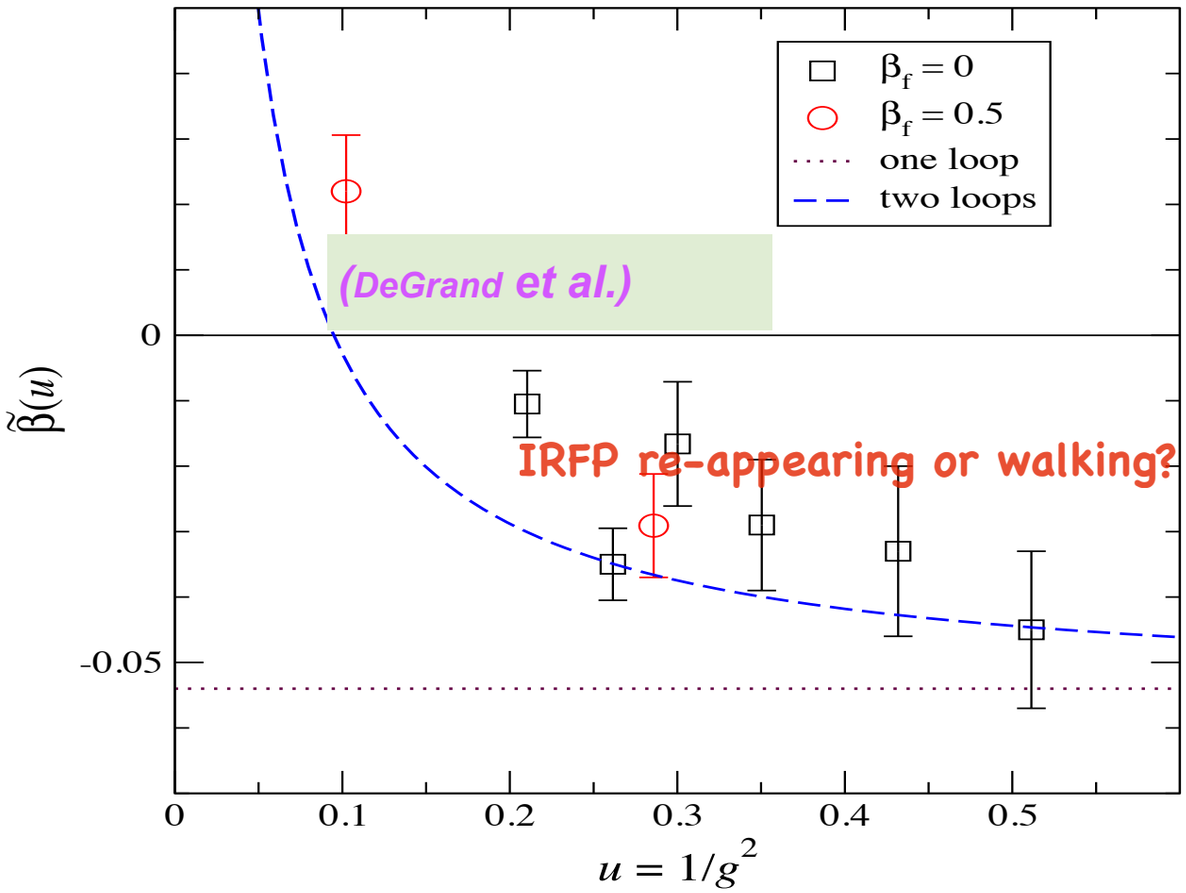
DeGrand et al. find: very small Nf=2 sextet beta function

IRFP zero or walking

χSB is inconsistent with IRFP slow running (walking?) what is $\gamma(\mu)$?

$\gamma(\mu)$ < 0.45 cannot happen with χSB





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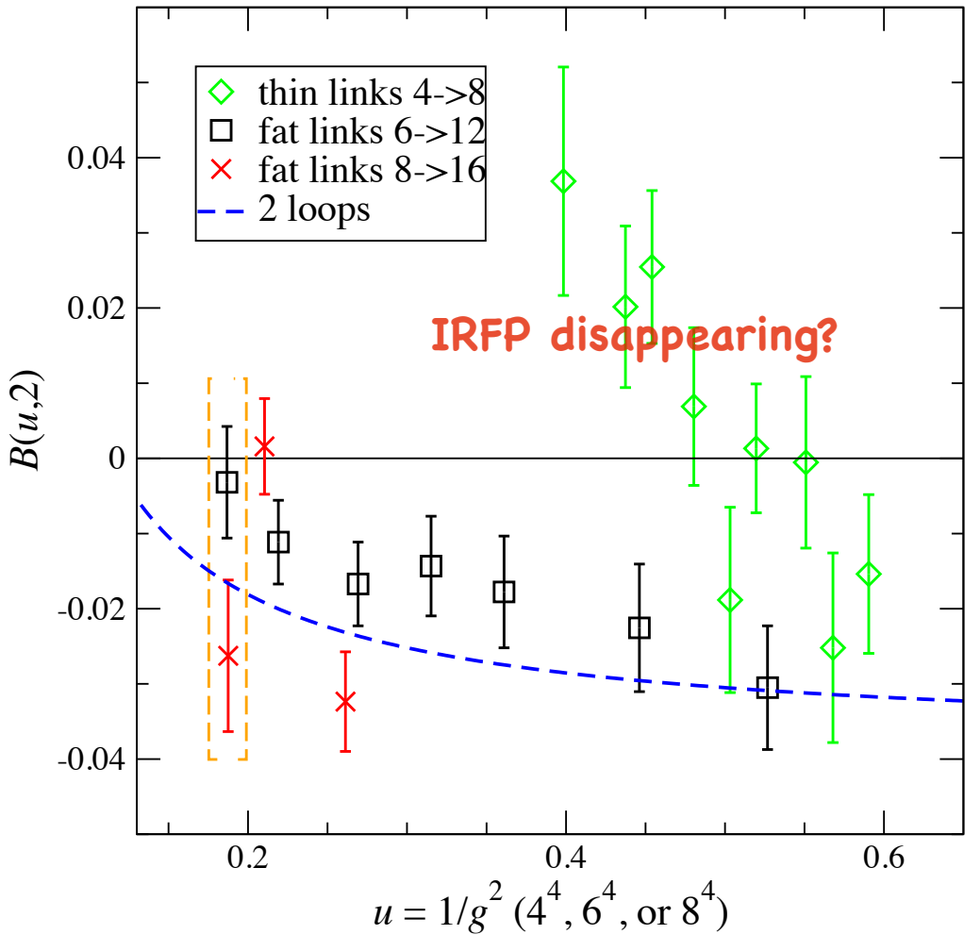

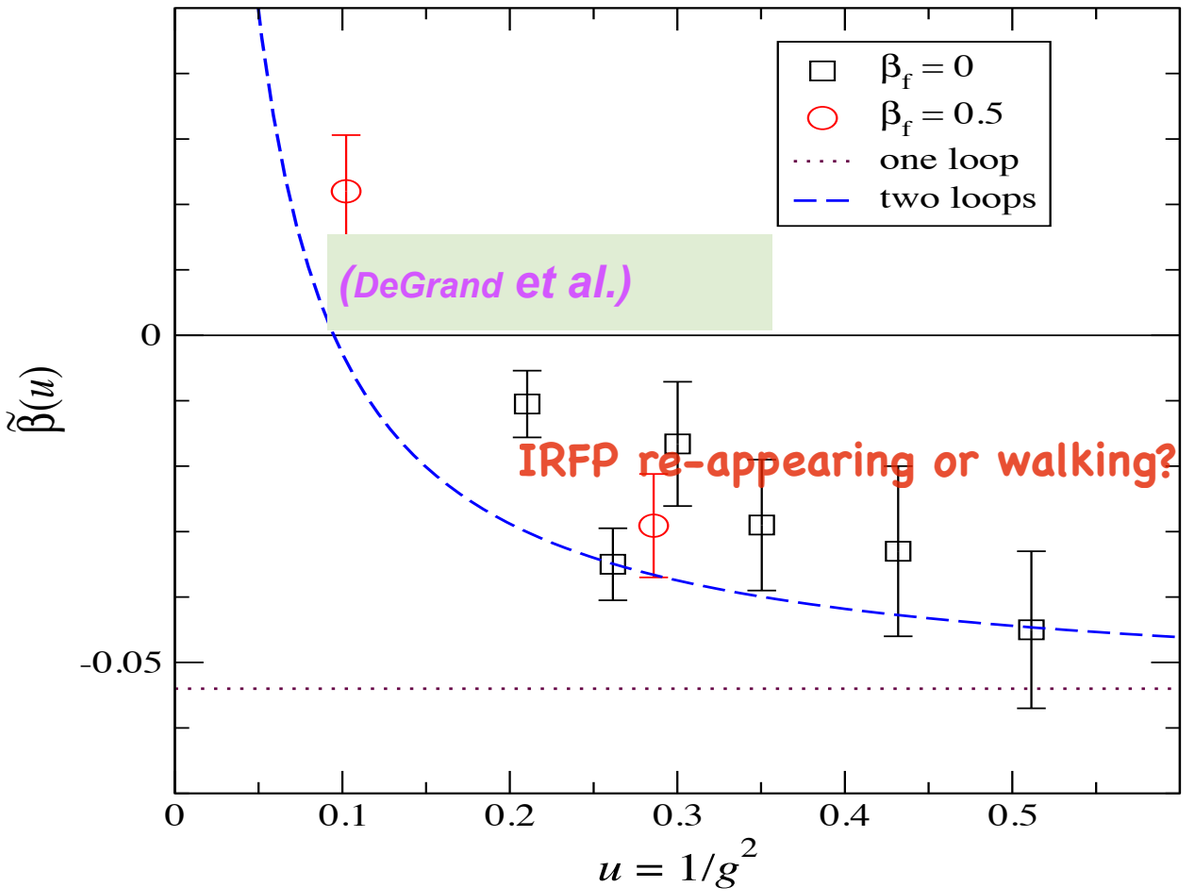

sextet model becomes legitimate target

for dilaton-like scenario with Higgs impostor

dilaton as Higgs impostor?

The light Higgs and the dilaton near conformality

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

Partially Conserved Dilatation Current (PCDC)

n.p. stress-energy from gradient flow?

there are two different expectations when conformal window is approached: $g(\mu=\Lambda)=g_c$

1. dilaton mass parametrically vanishes $m_\sigma^2 \simeq (N_f^c - N_f)\cdot\Lambda^2$ $\frac{m_\sigma}{f_\sigma}\to 0$

2. dilaton mass finite in the limit $f_\sigma \simeq \Lambda$ $\frac{m_\sigma}{f_\sigma}\to const$

important role of $\frac{f_\pi}{f_\sigma}$ in electroweak phenomenology

both scenarios expect light Higgs-like dilaton

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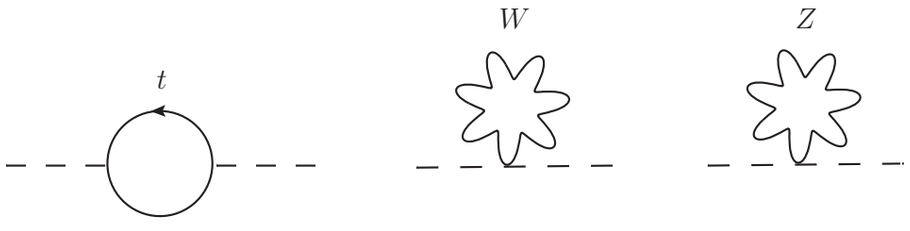
Sannino 500 GeV might do it:



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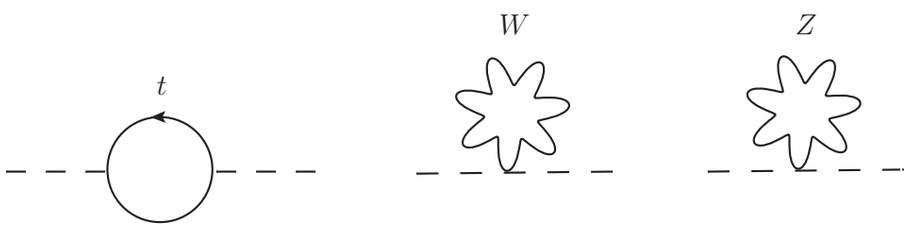

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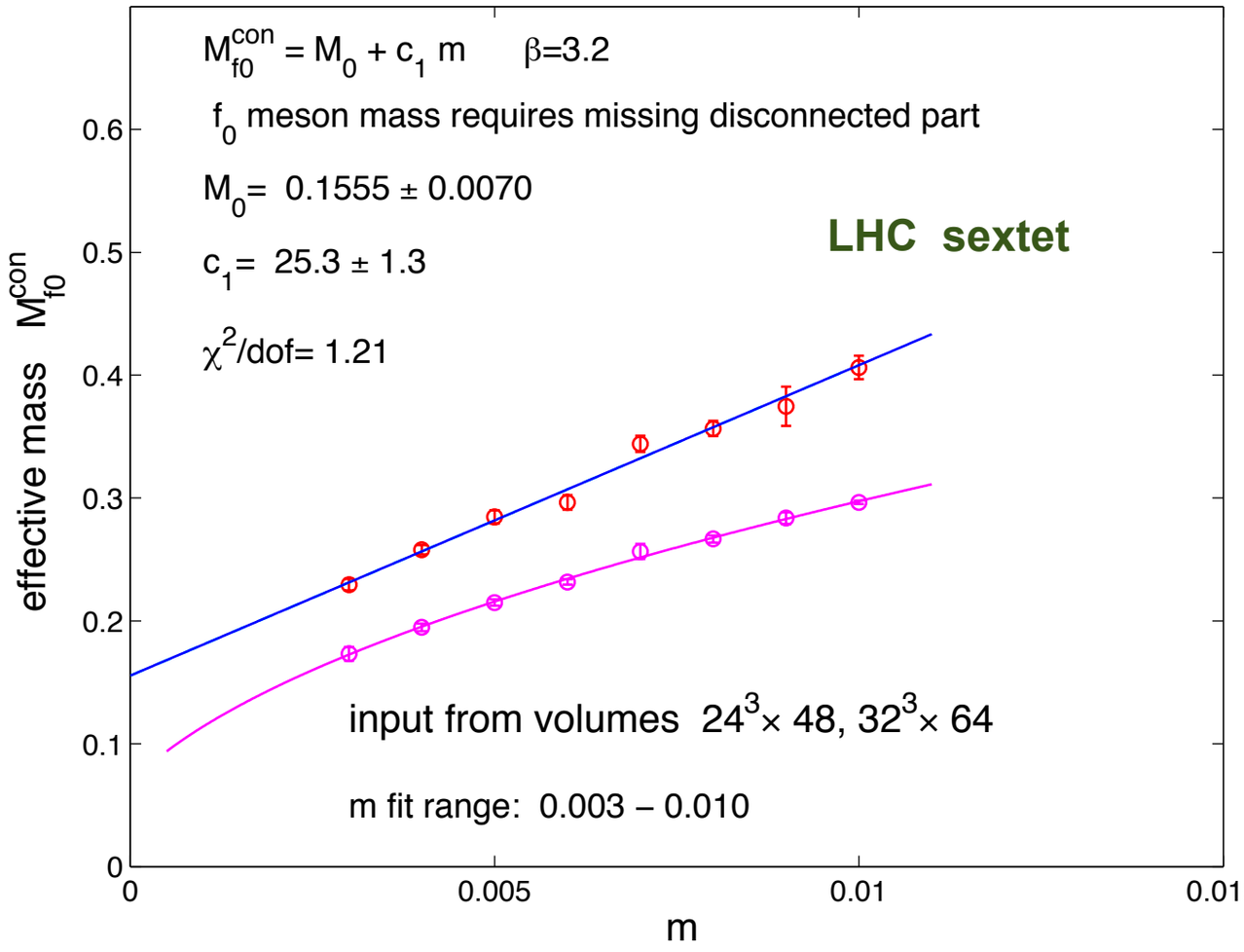
effective mass M_{f0}^{con} from 0^{++} connected correlator



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Partially Conserved Dilatation Current (PCDC)

n.p. stress-energy from gradient flow?

there are two different expectations when conformal window is approached: $g(\mu=\Lambda)=g_c$

1. dilaton mass parametrically vanishes $m_\sigma^2 \simeq (N_f^c - N_f)\cdot\Lambda^2$ $\frac{m_\sigma}{f_\sigma}\to 0$

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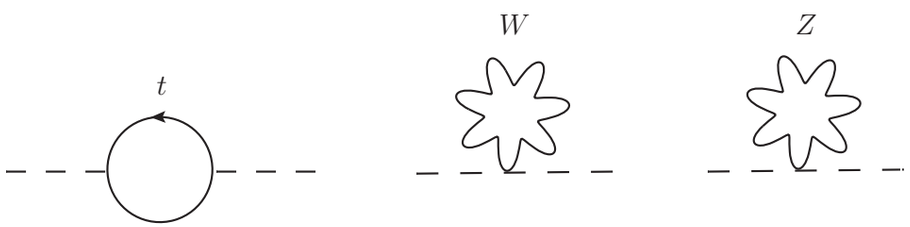
important role of $\frac{f_\pi}{f_\sigma}$ in electroweak phenomenology

both scenarios expect light Higgs-like dilaton

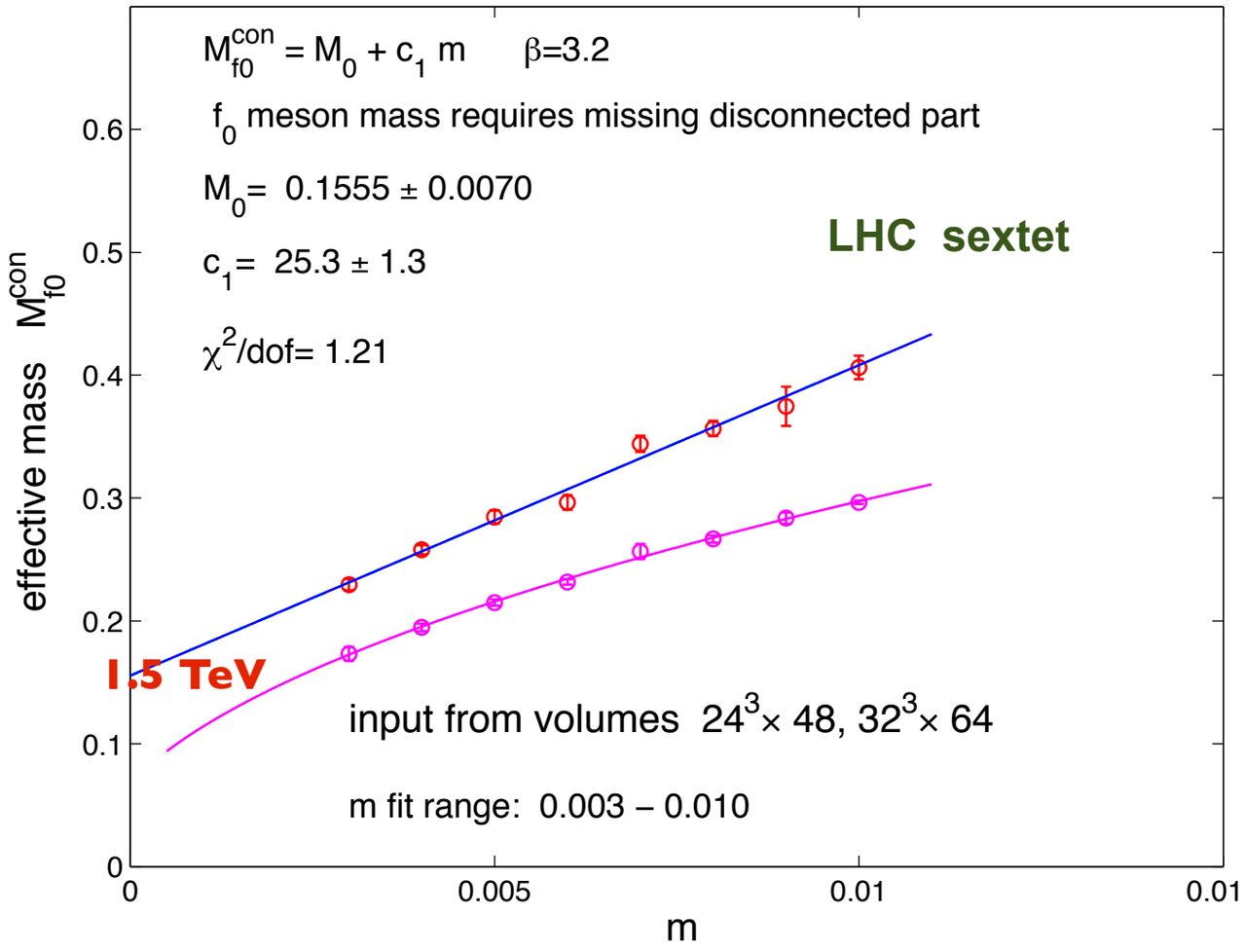
but how light is light ? would 500 GeV do it?

Sannino 500 GeV might do it:



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

effective mass M_{f0}^{con} from 0^{++} connected correlator



The light Higgs and the dilaton near conformality

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

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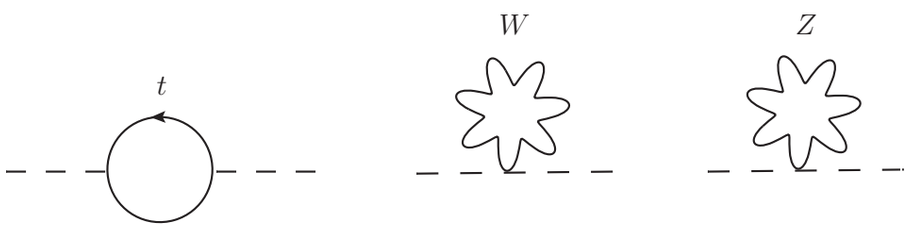

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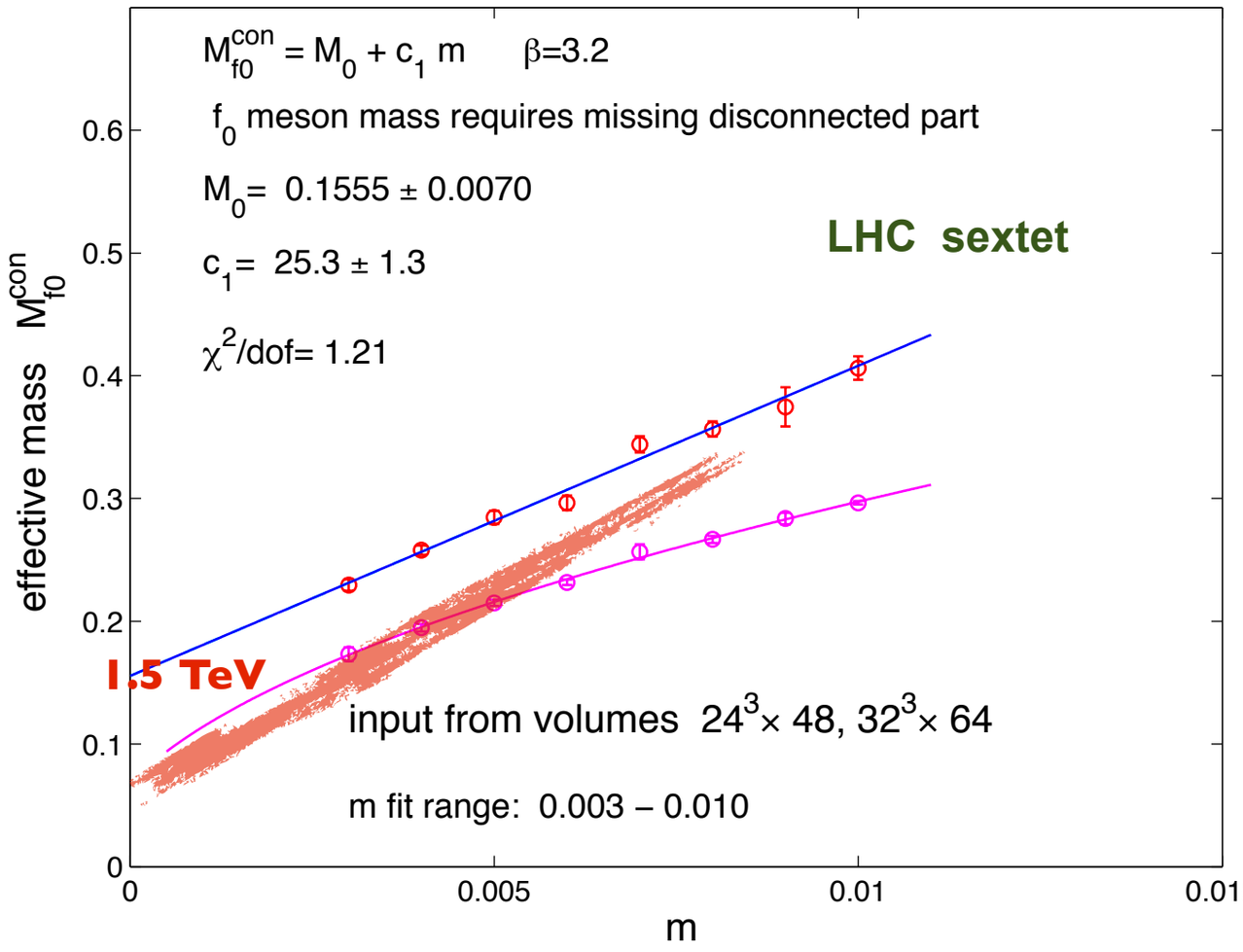

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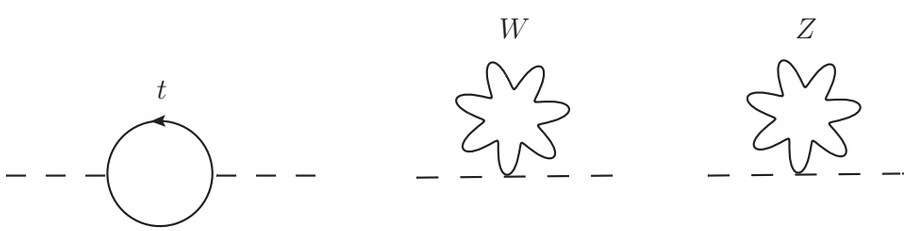

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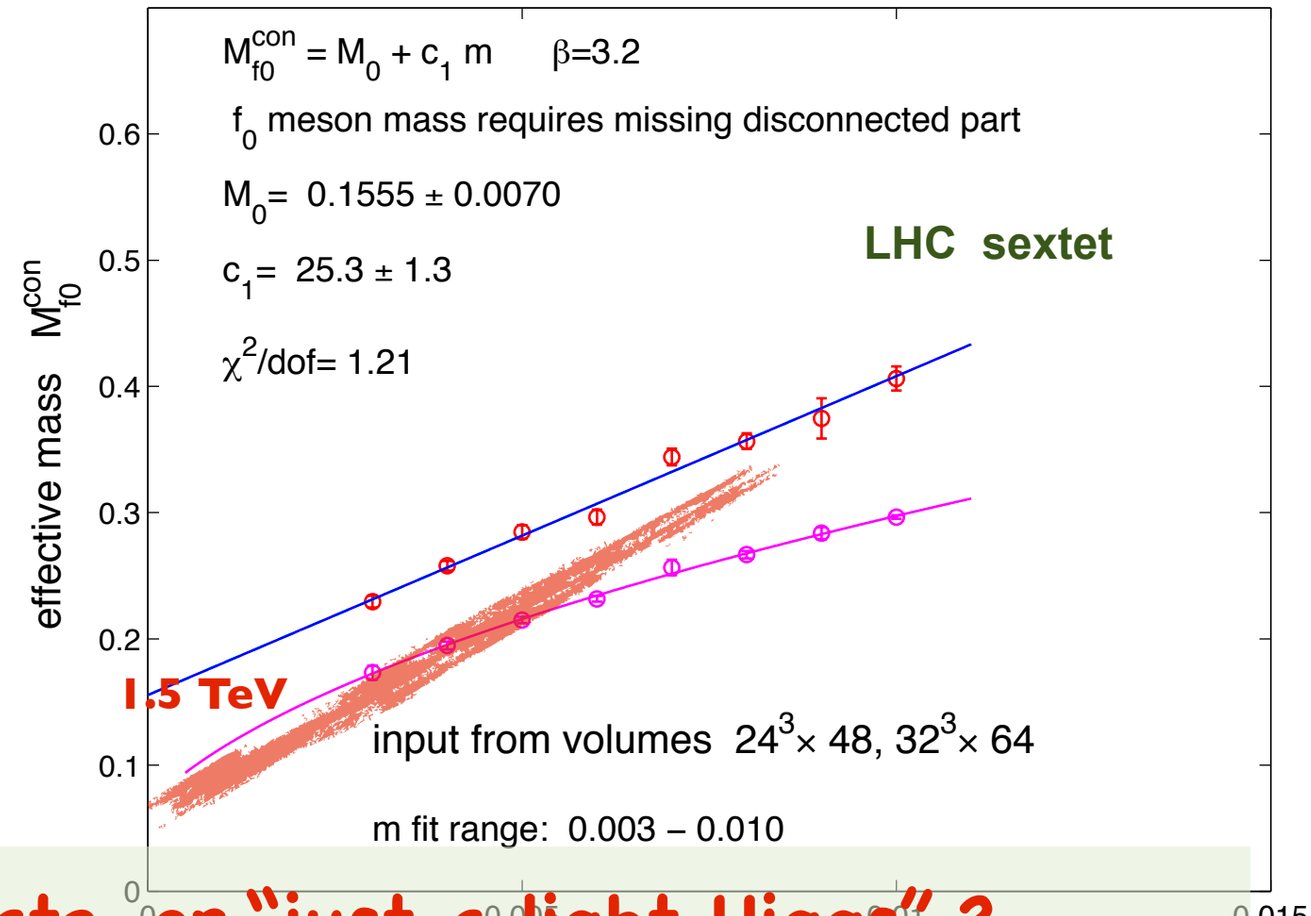
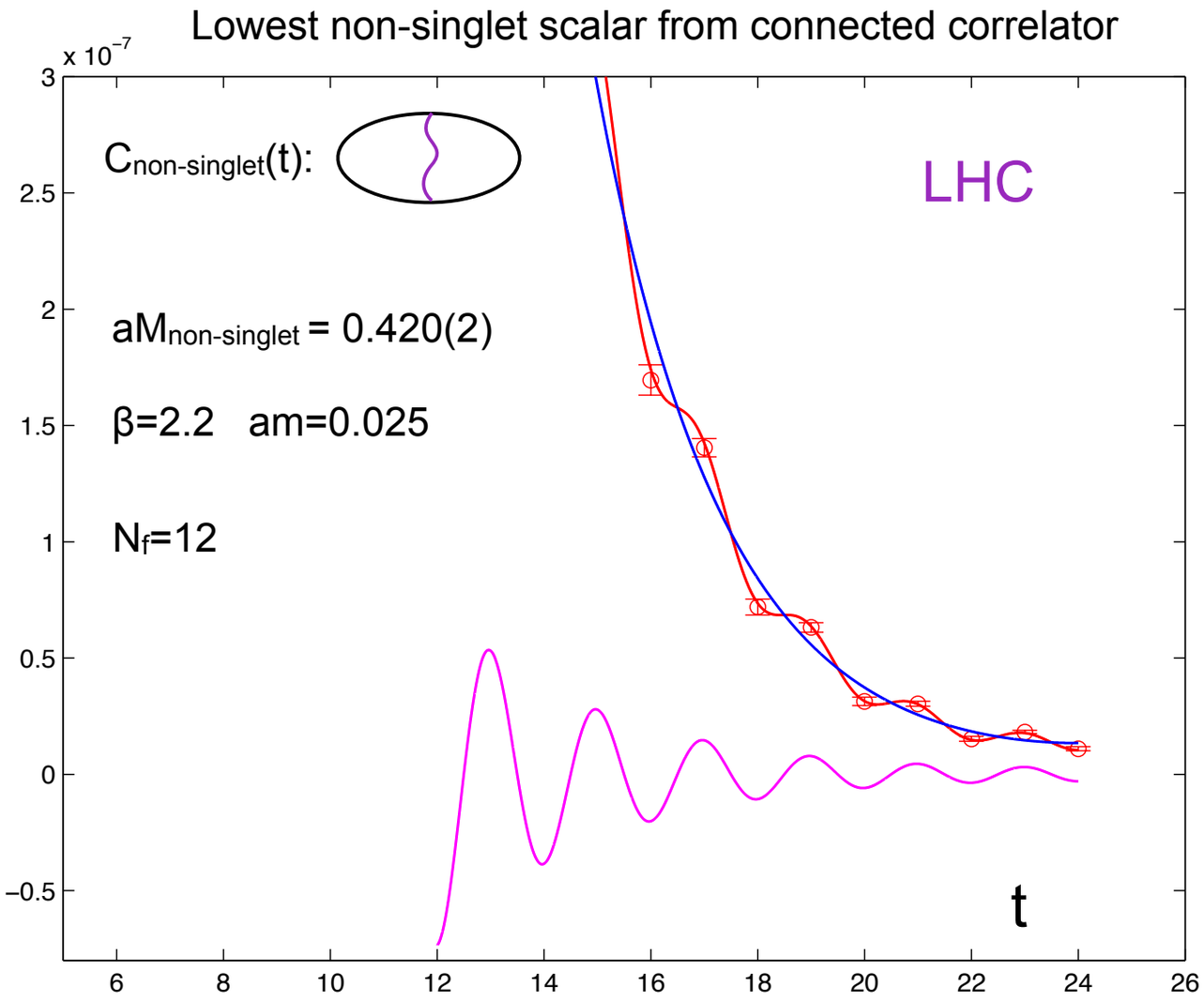
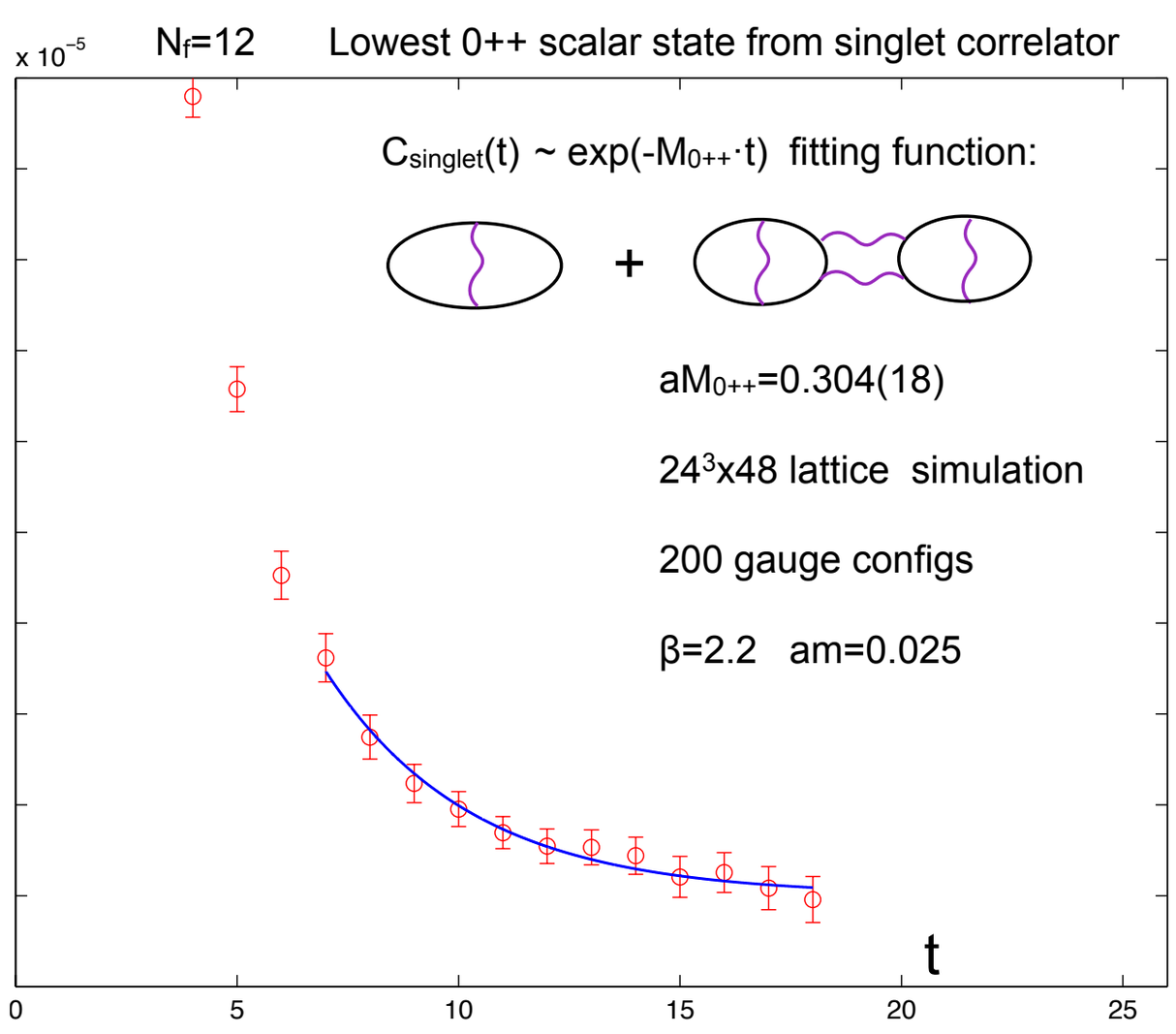


is this SCGT dilaton-like scalar state, or "just a light Higgs" ?

The light Higgs and the dilaton near conformality

proof of life:





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

staggered correlator

The light Higgs and the dilaton near conformality

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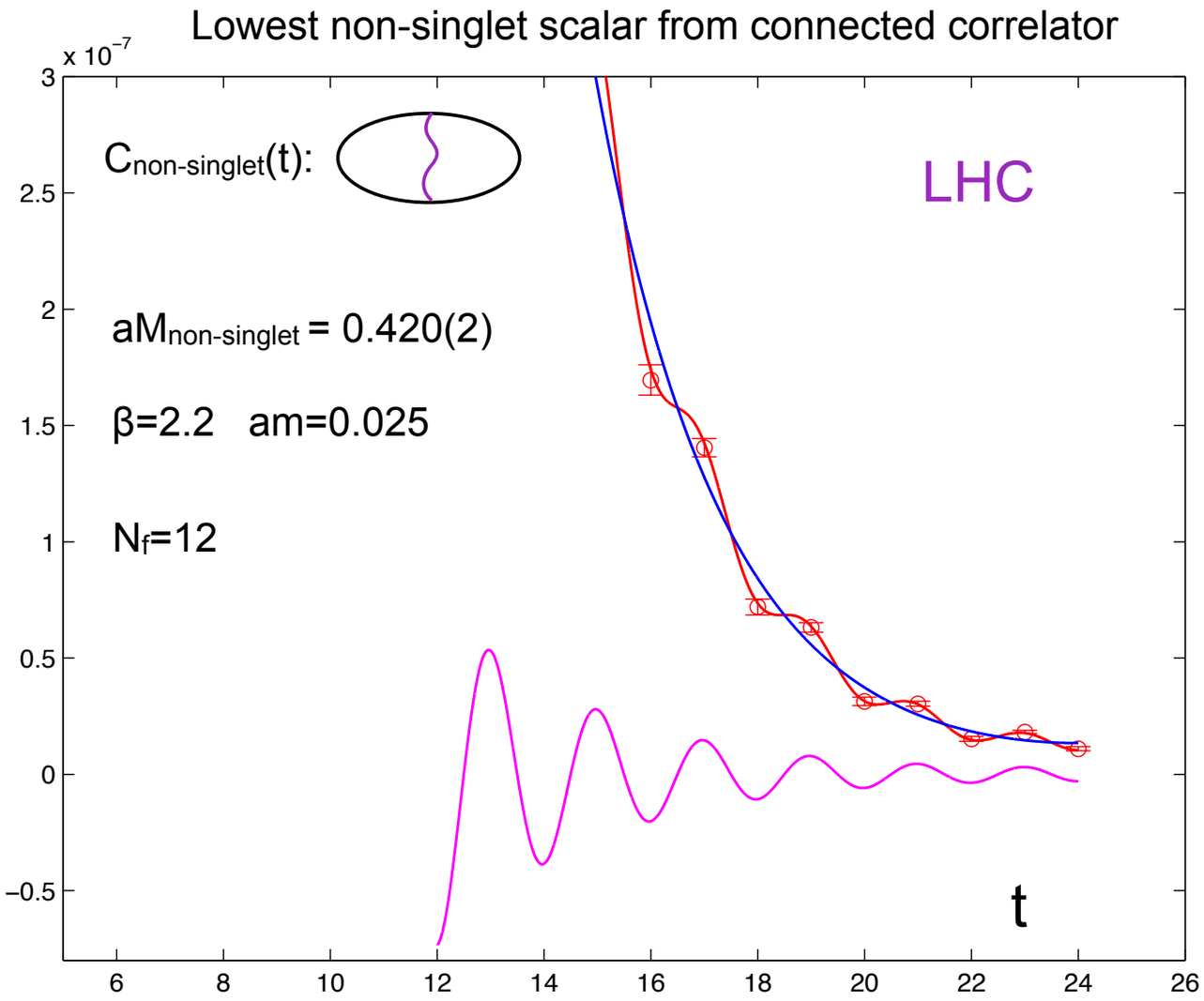

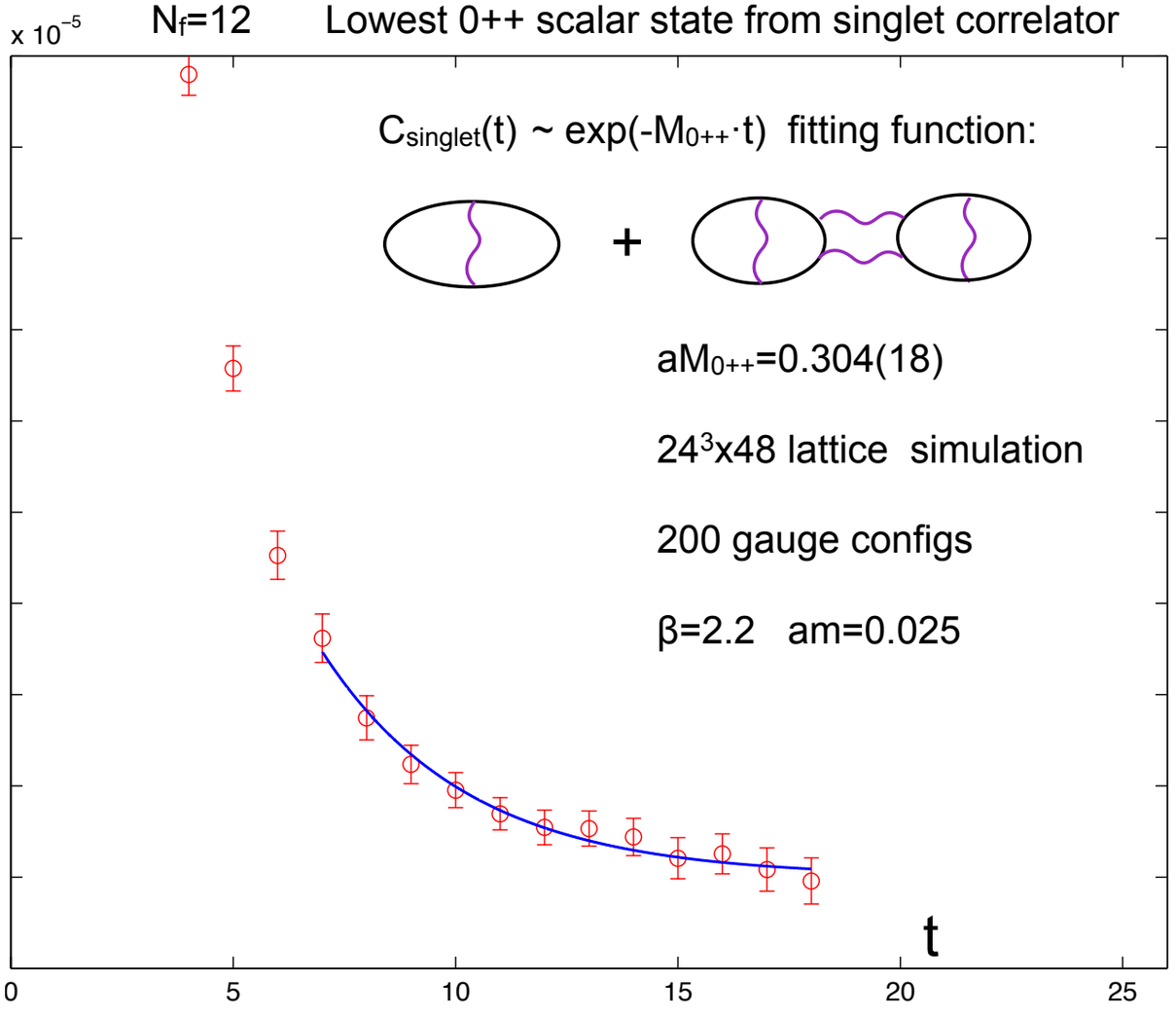

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similar analysis is being done in sextet model with Nf=2

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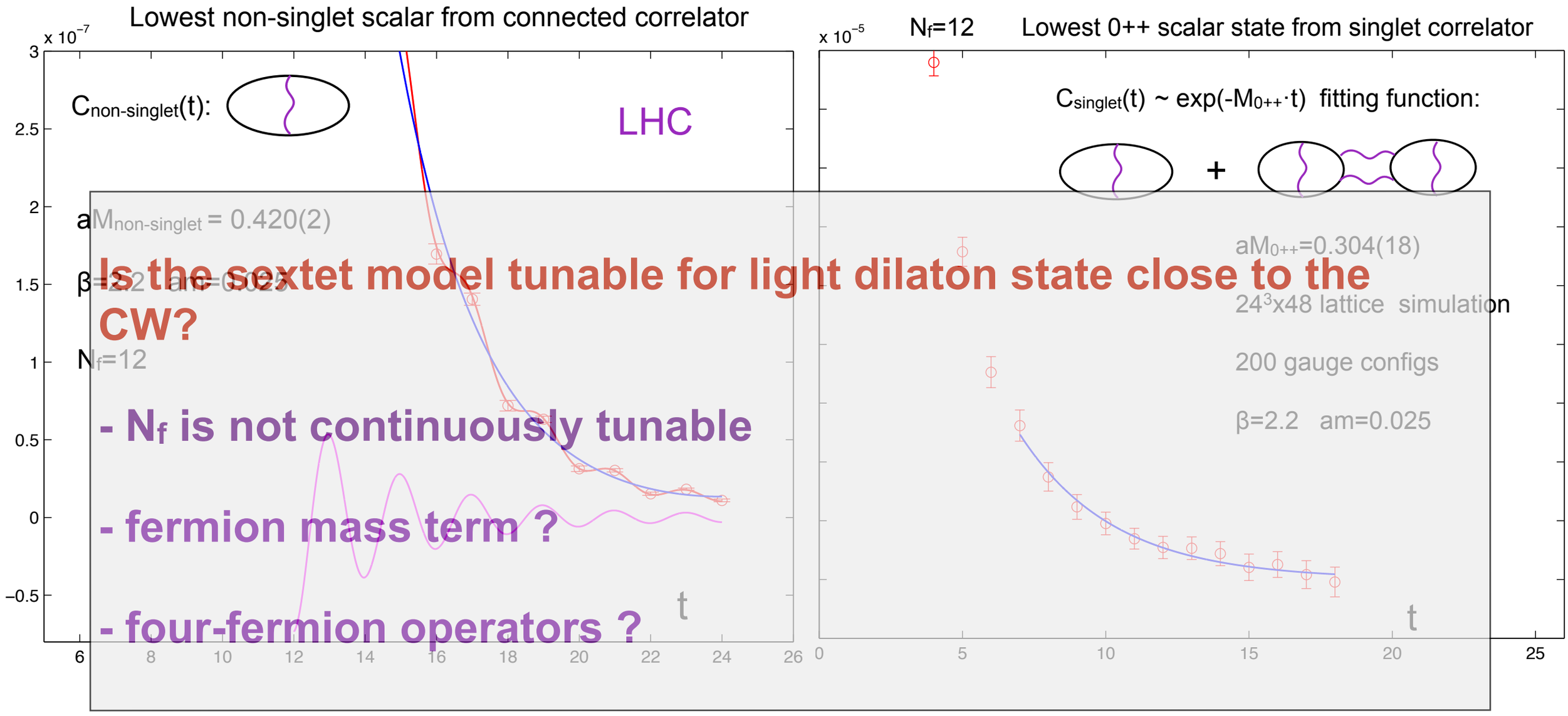

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staggered correlator

similar analysis is being done in sextet model with Nf=2

mass tuning, like partially gauged (conformal) Technicolor?

Sannino, Dietrich, Luty, ...

freeze-out from N_f=3 to N_f=2 inside conformal window

mass-dependent beta-function of sextet model

MOM scheme (Yoshino and Hagiwara)

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

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

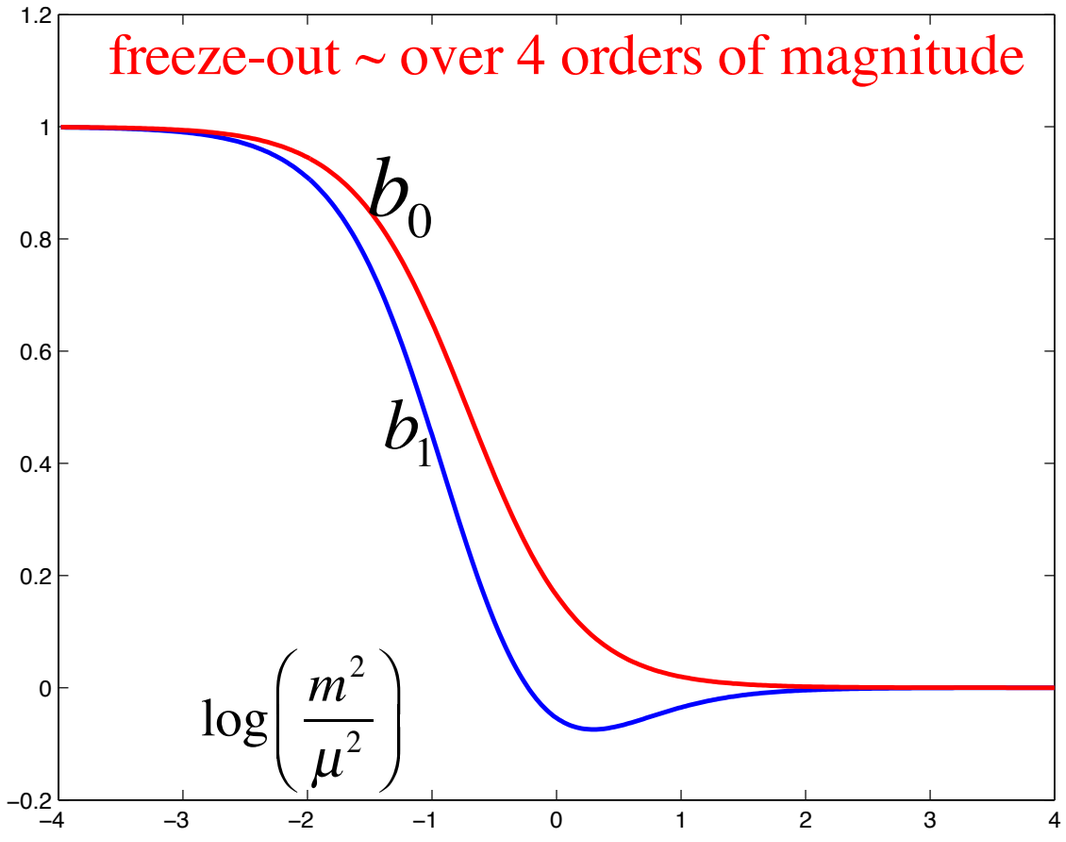
$$\beta_0 = \frac{11}{6}C_A - \frac{2}{3}T_F\sum_f b_0(x), \qquad x = \frac{m_f^2}{\mu^2}$$

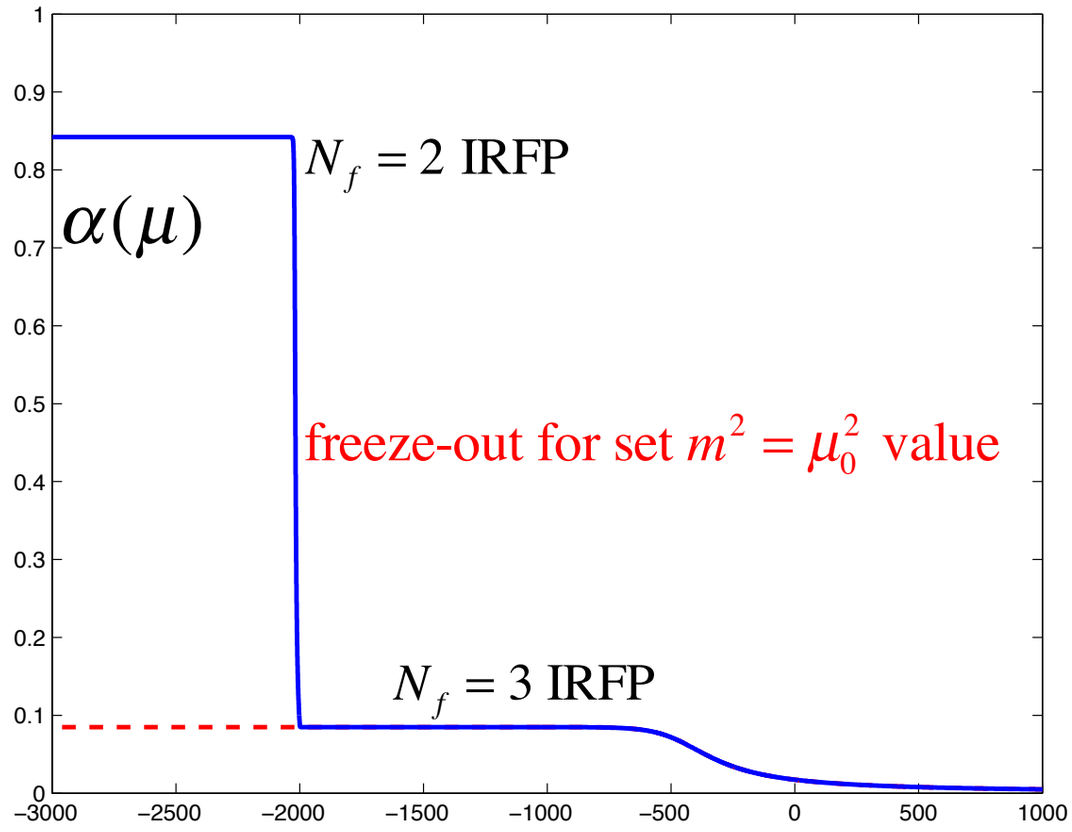
$$b_0(x) = 1 - 6x + \frac{12x^2}{\sqrt{1+4x}}\ln\frac{\sqrt{1+4x}+1}{\sqrt{1+4x}-1}$$

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

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

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





four-fermion operator

tunable deformation of IRFP?

large-N double trace limit

Witten, Rastelli, Vecchi ...

which scenario is realized will depend on the scaling dimension Δ of $\langle\bar{\psi}\psi\rangle$ and on other intrinsic properties of IRFP

for any model choice things are set

$$\mathcal{L}_{\rm CFT} + \frac{f}{2}\mathcal{O}^\dagger_{ij}\mathcal{O}^{ij}$$

$$\mathcal{L}_{\rm def} = f(q^\dagger_R q_L)(q^\dagger_L q_R) \qquad \langle e^{i\int \mathcal{L}_{\rm def}}\rangle_{\rm CFT}$$

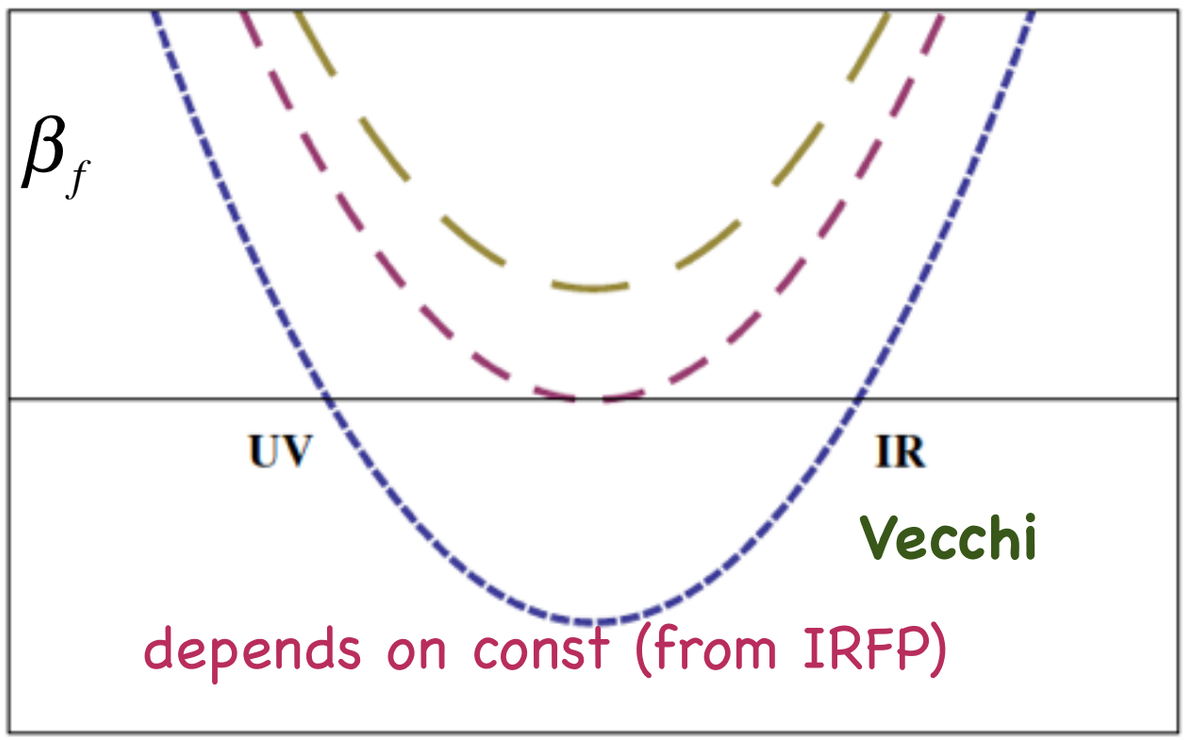
$$f(\Lambda) - \frac{v}{2\Delta - d} f^2(\Lambda)(\Lambda^{2\Delta-d} - \Lambda'^{2\Delta-d}) = f(\Lambda')$$

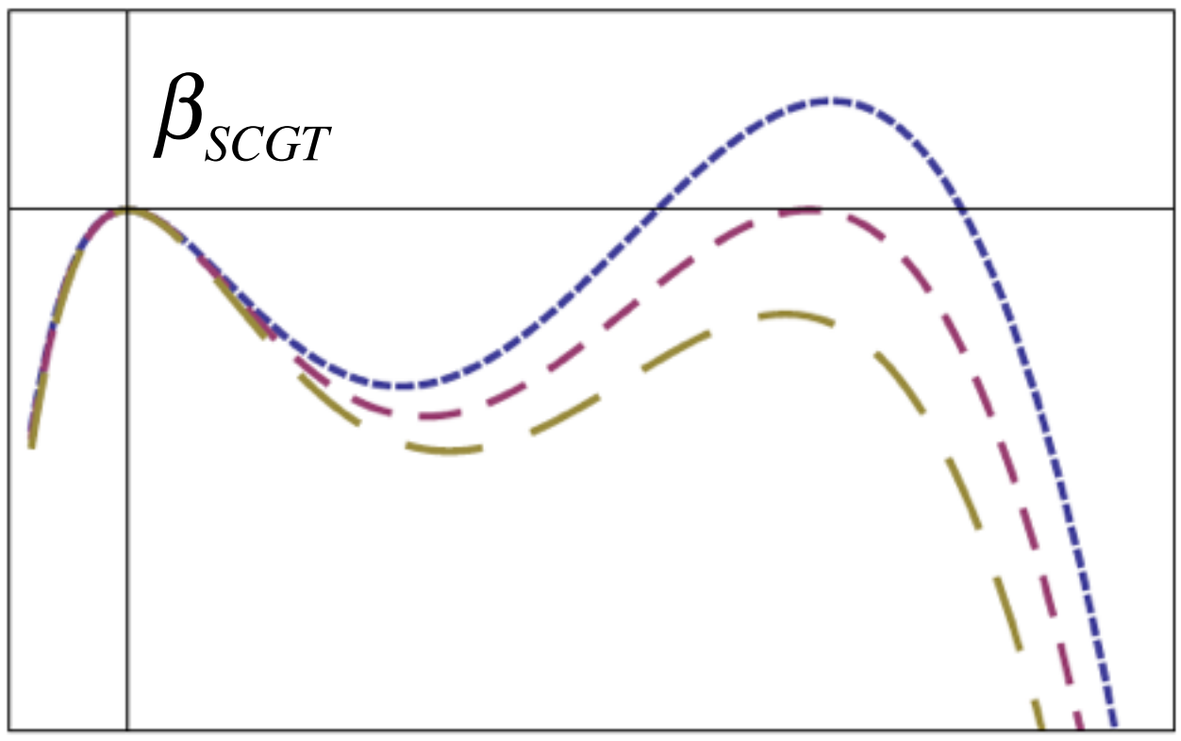
$$\langle \mathcal{O}(x)\mathcal{O}(y)\rangle \equiv \frac{v}{|x-y|^{2\Delta}} \frac{\Gamma(d/2)}{2\pi^{d/2}}$$

$$\Lambda \frac{d\bar{f}}{d\Lambda} = v\bar{f}^2 + (2\Delta - d)\bar{f}$$

+ const (from conform IRFP)

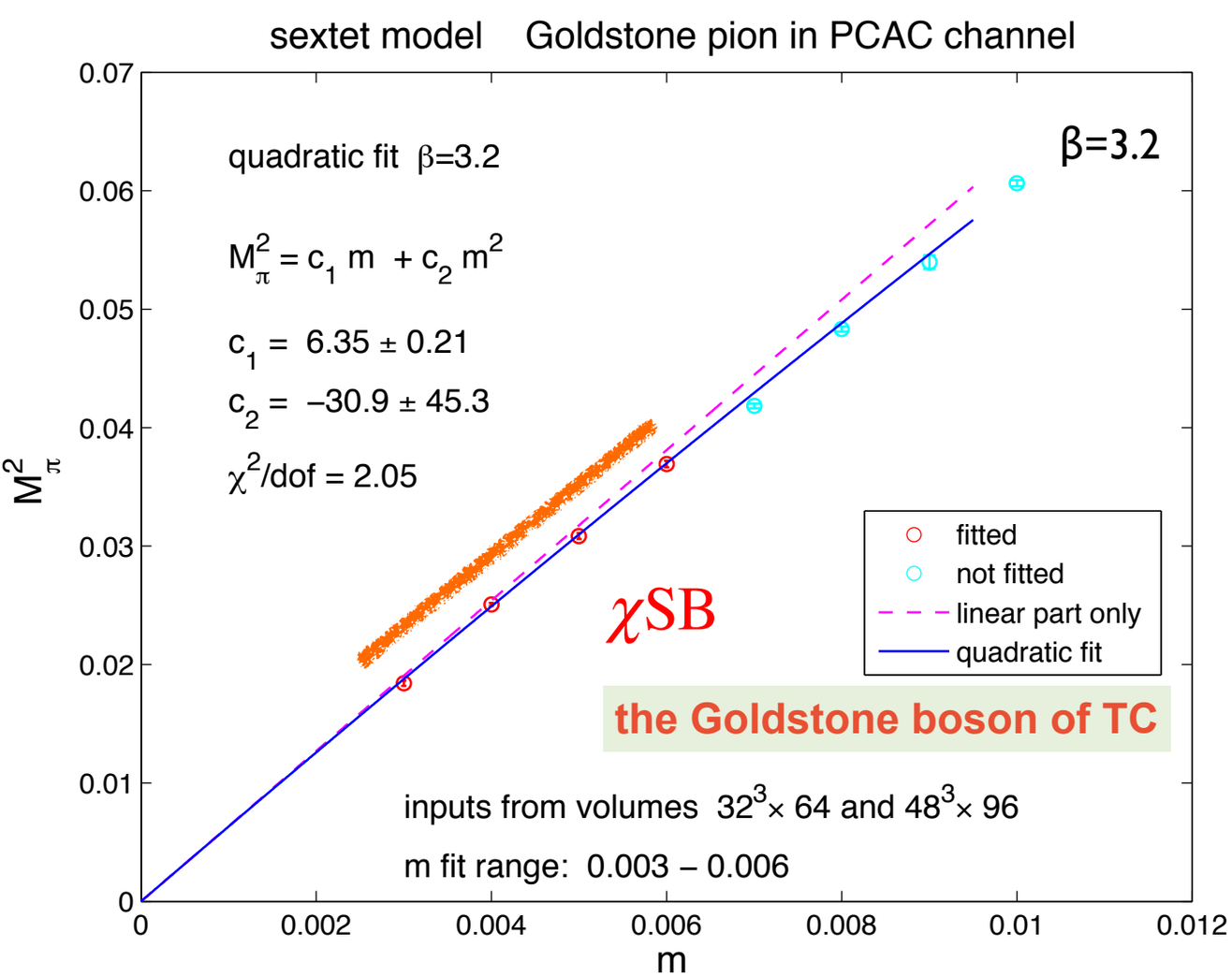
f flows to fixed points not continuously tunable, no guarantee

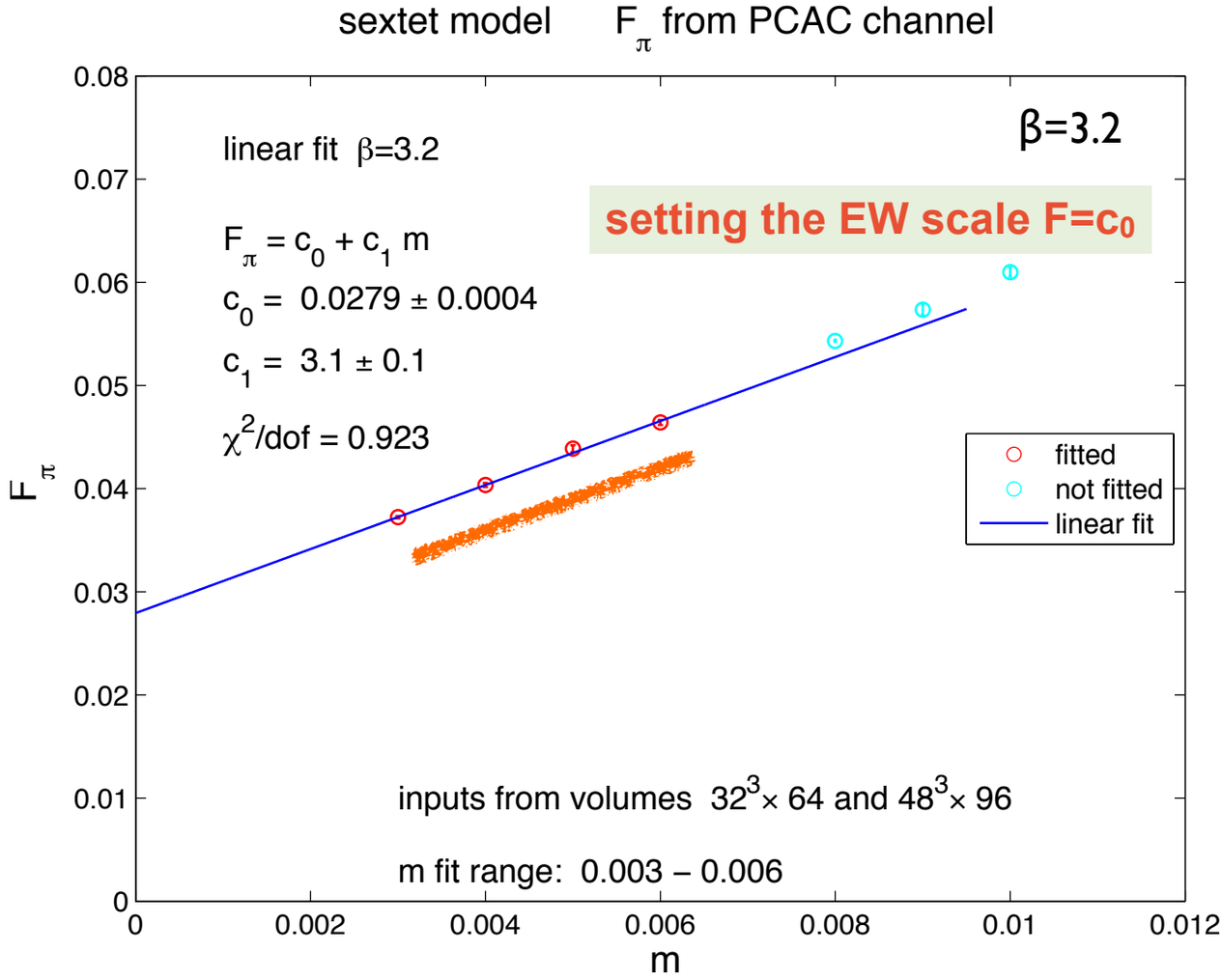




spectroscopy and confining force

Nf=2 SU(3) sextet chiral fits of M_π and F_π





m=0.003-0.006 range close to chiral log regime? Nf=2 helps, more QCD-like

log detection will require even more precise data

consistency with partially quenched staggered chiral perturbation theory?

To better understand GMOR relation

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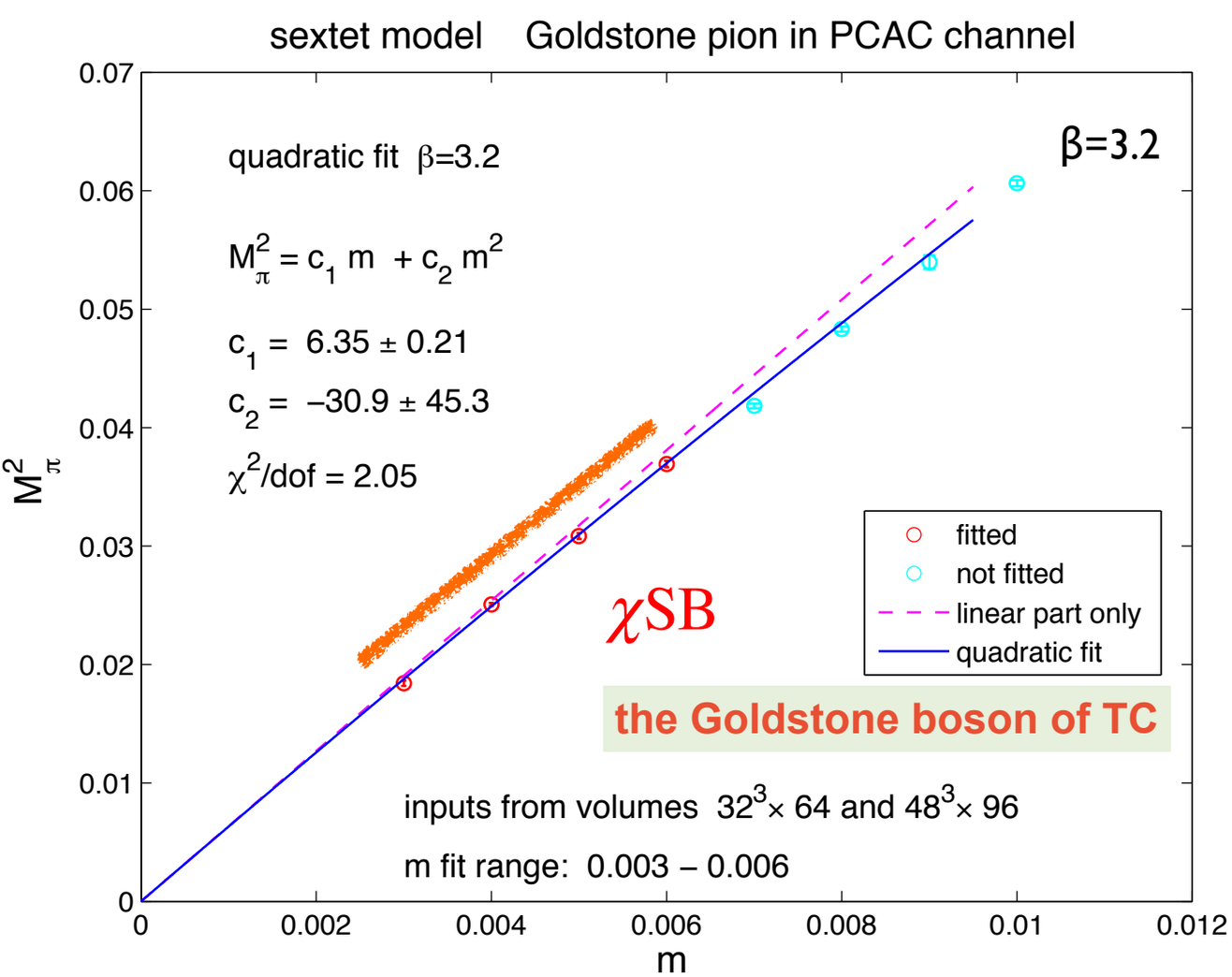

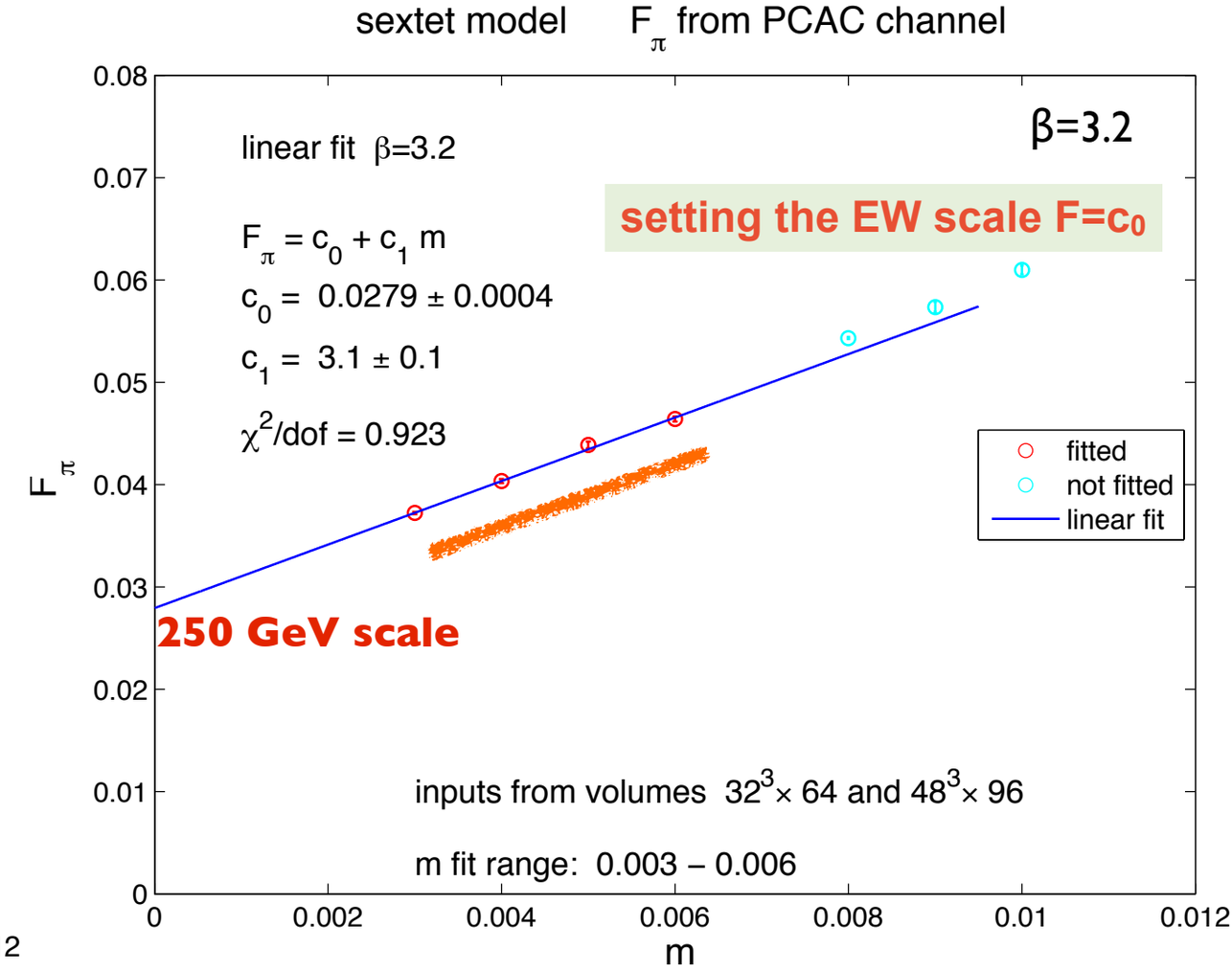

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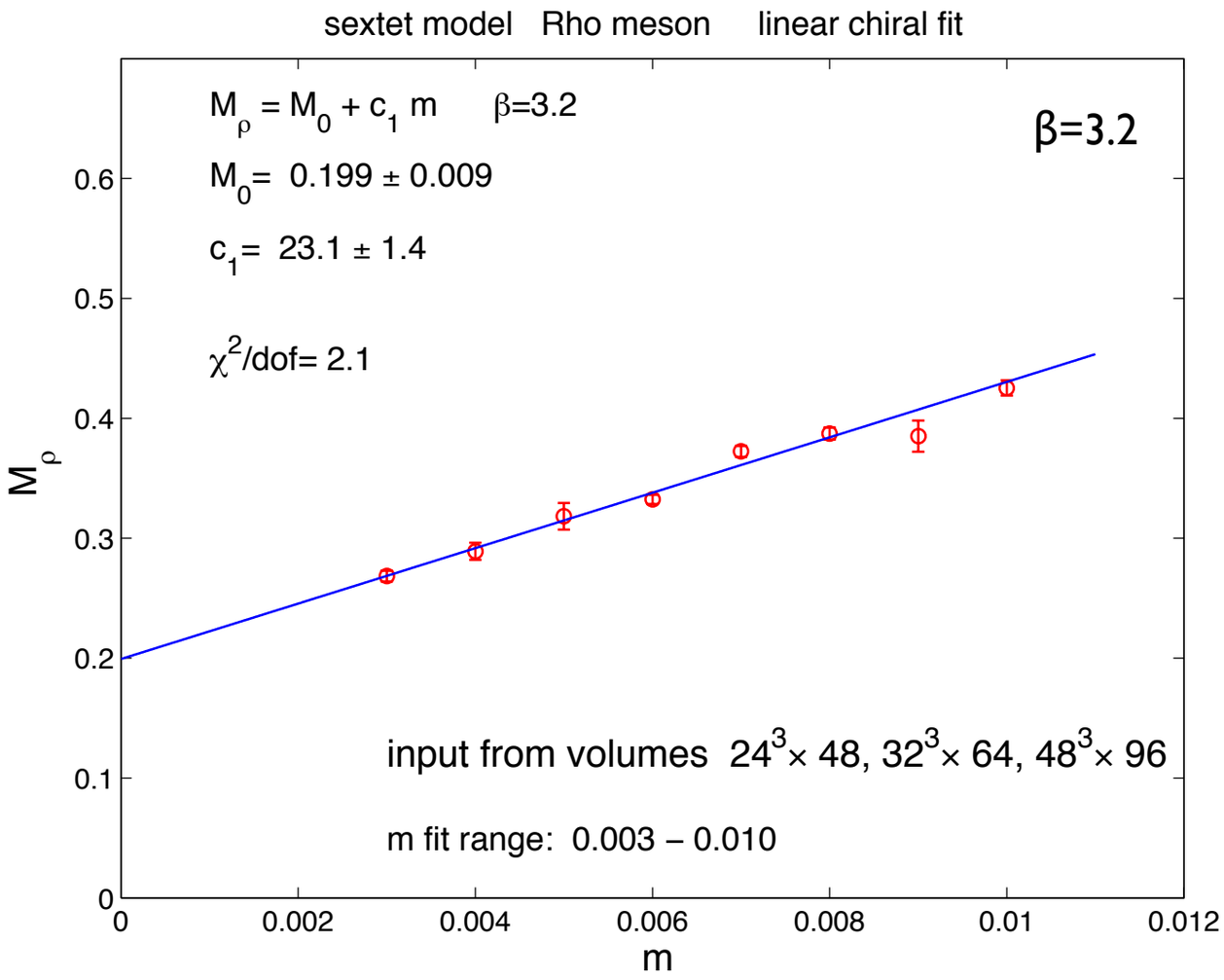

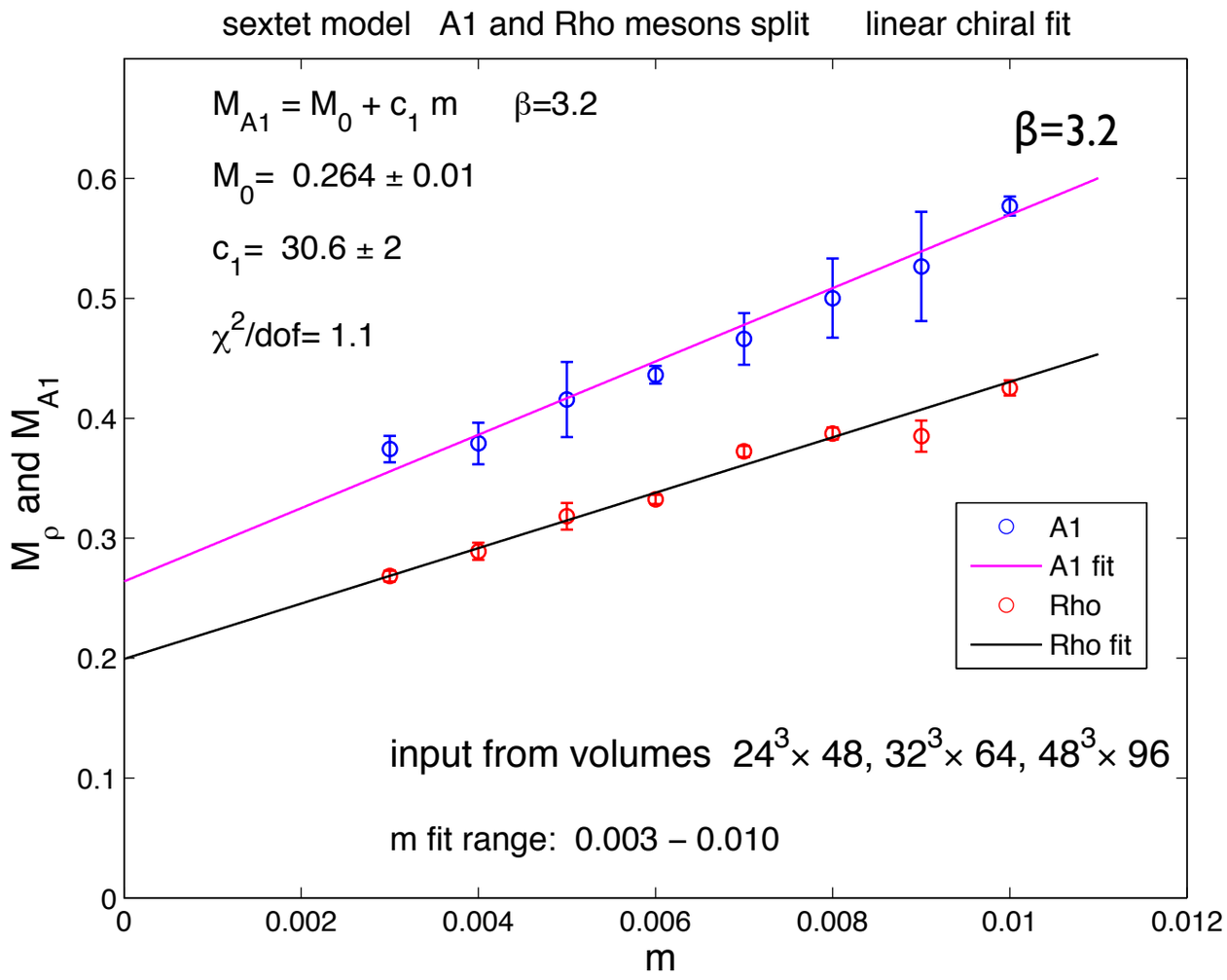

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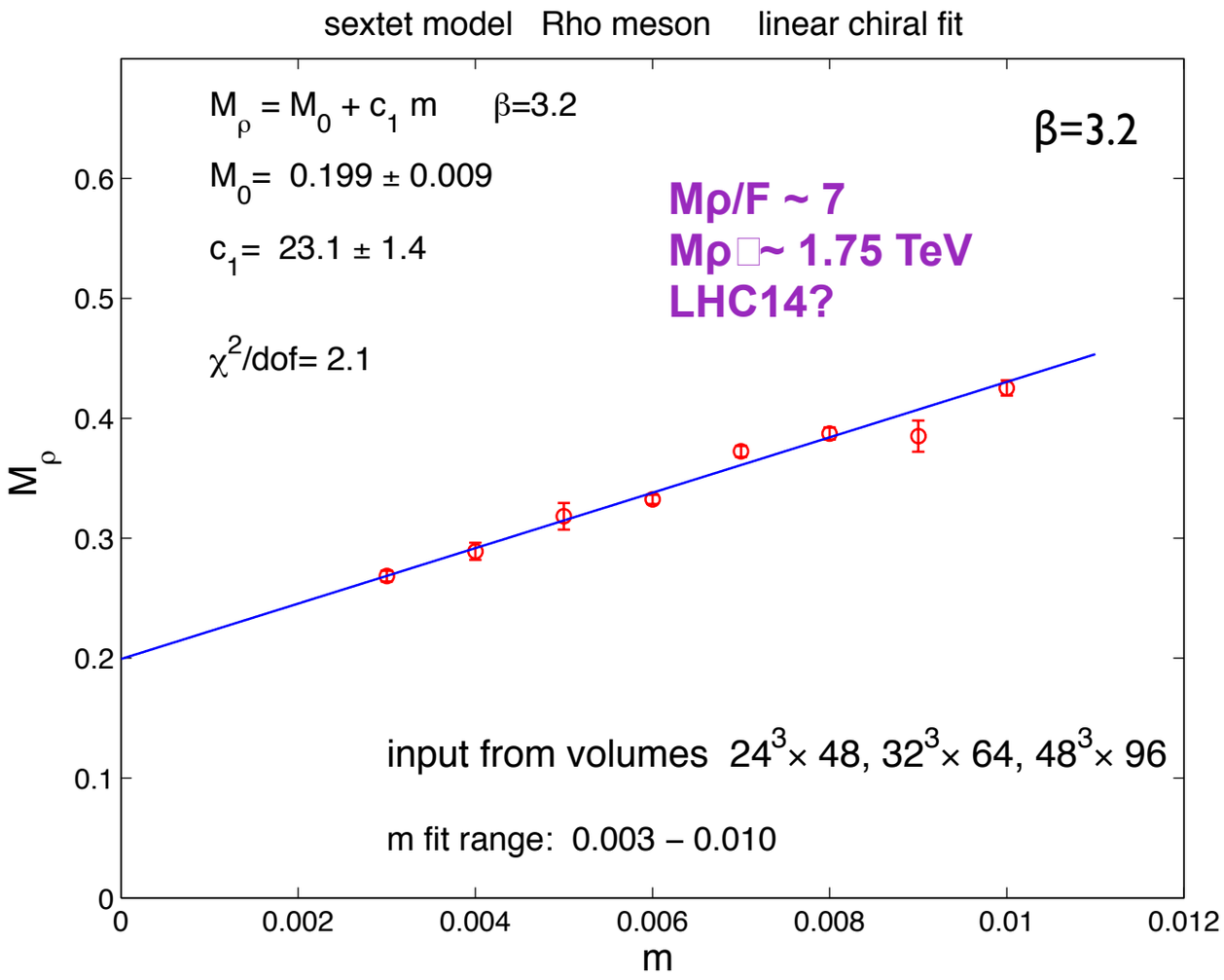

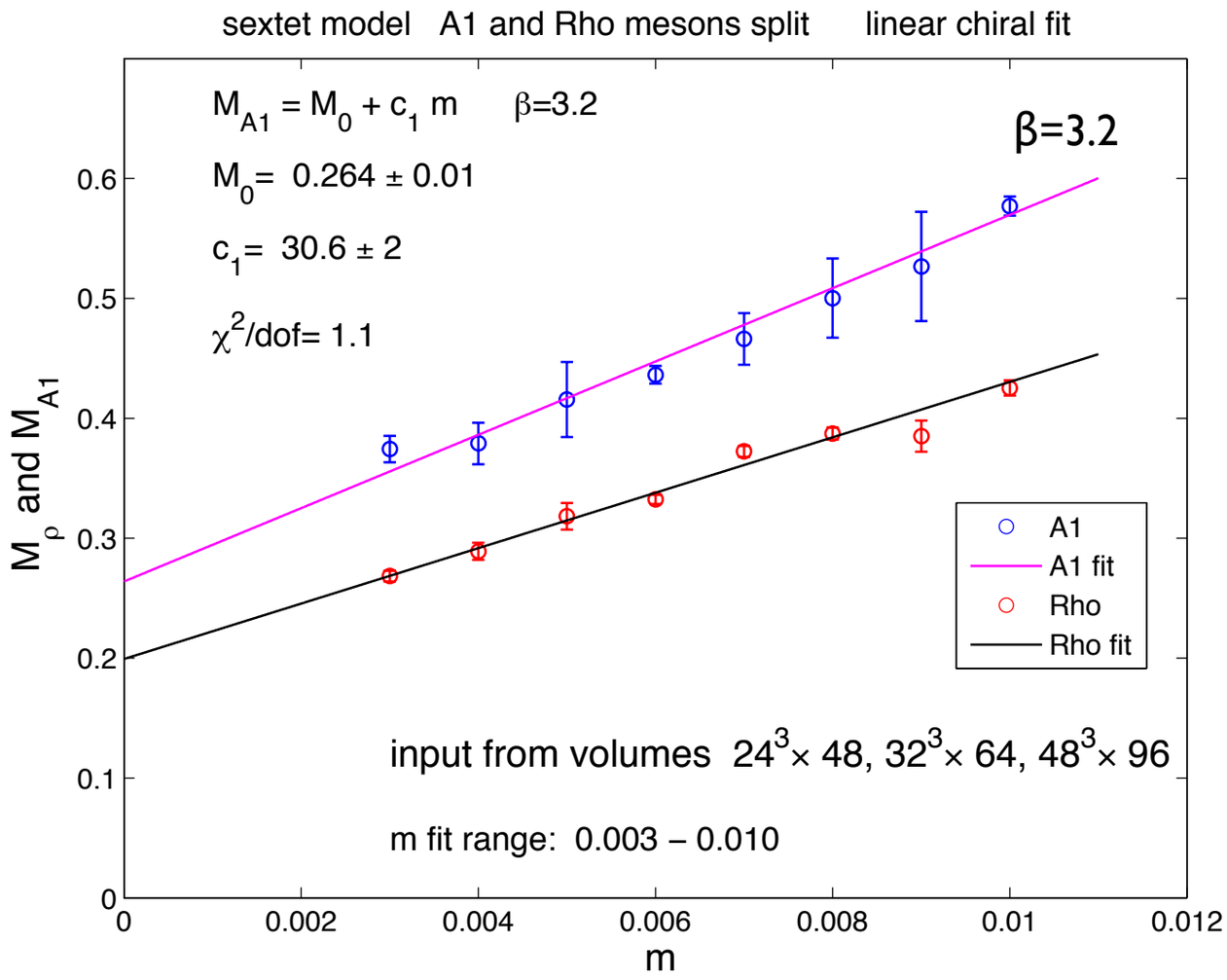

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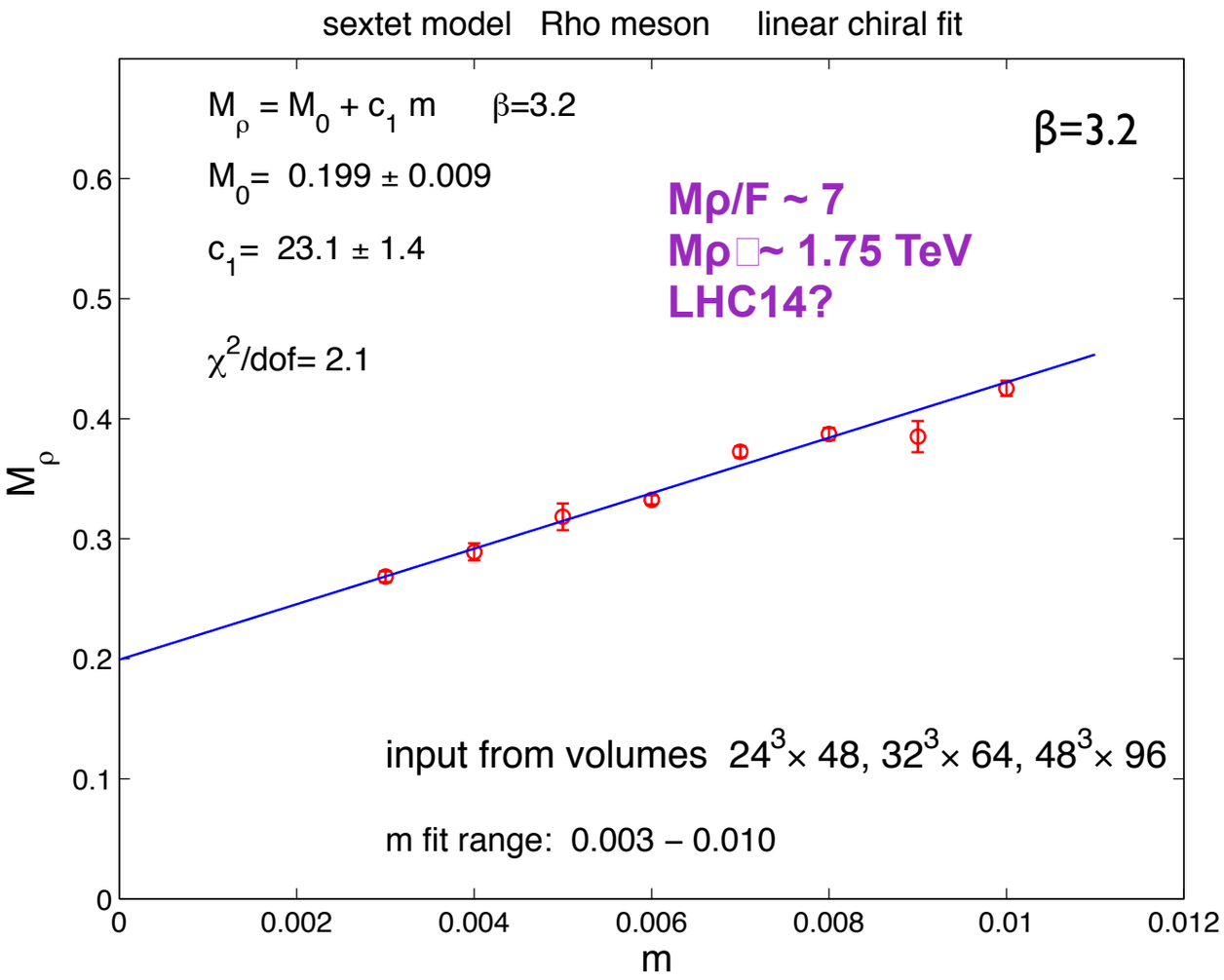
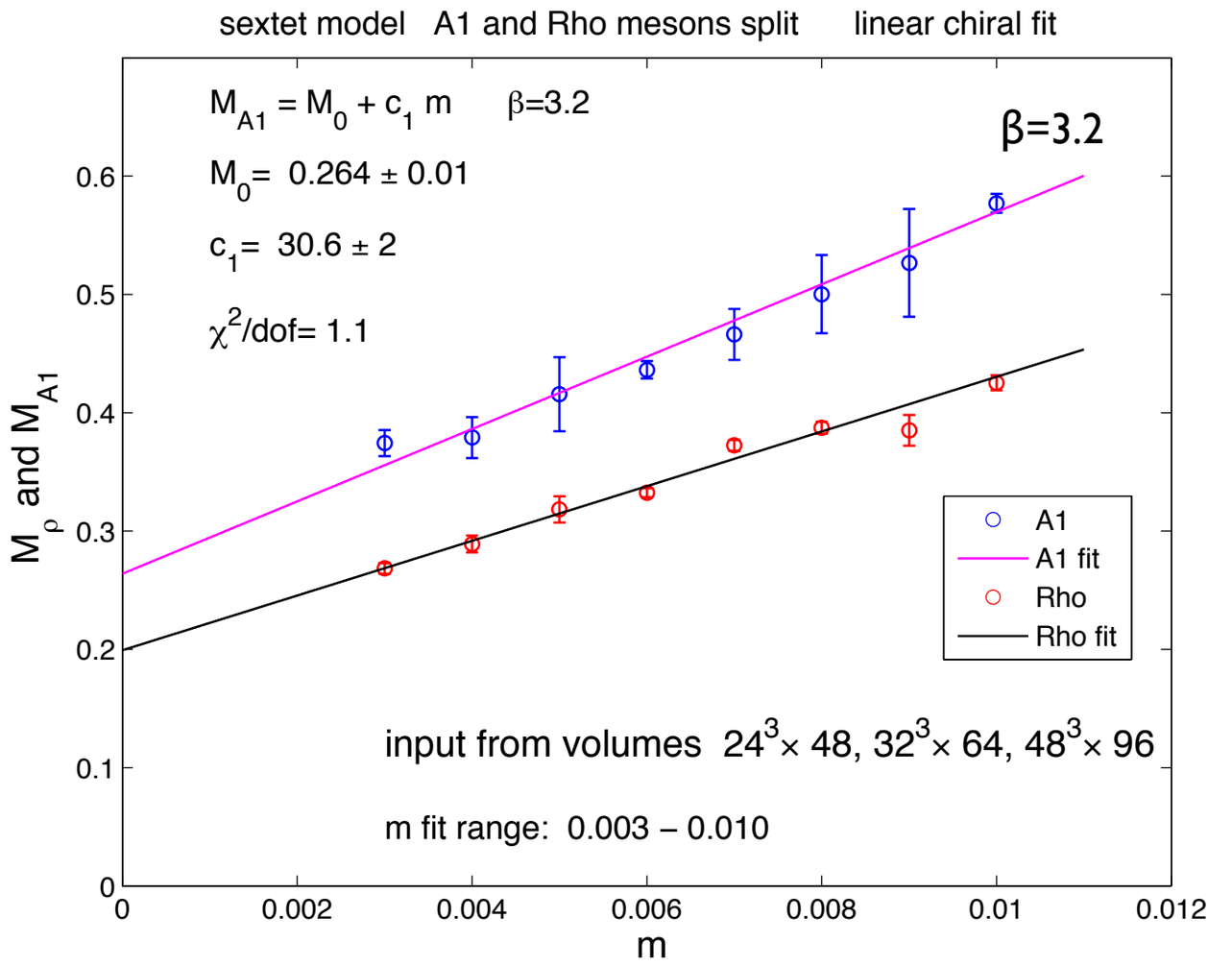


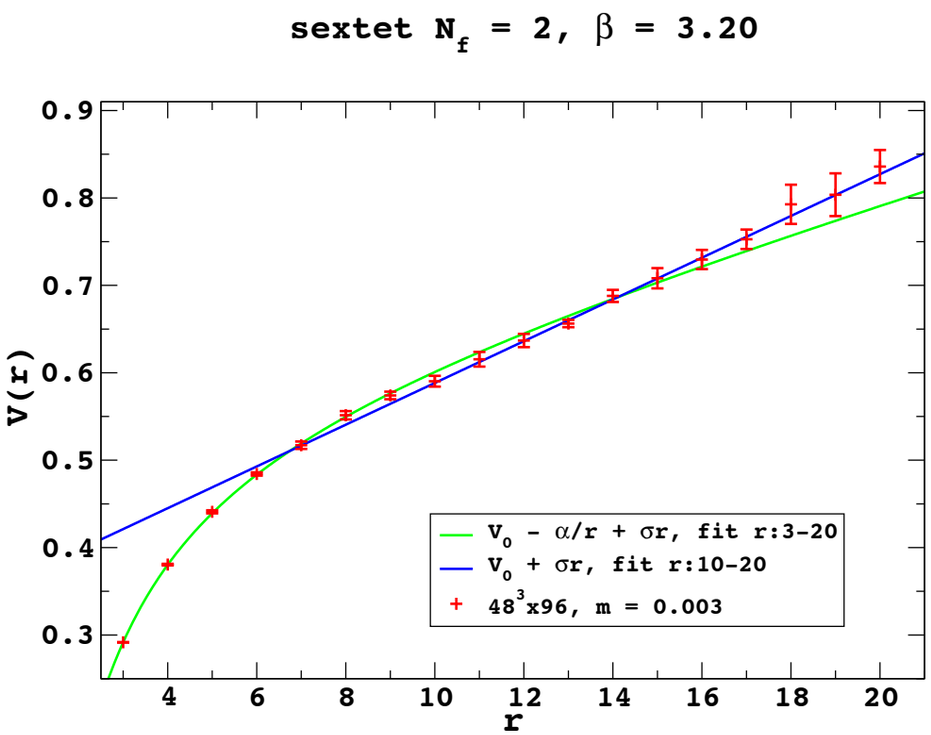


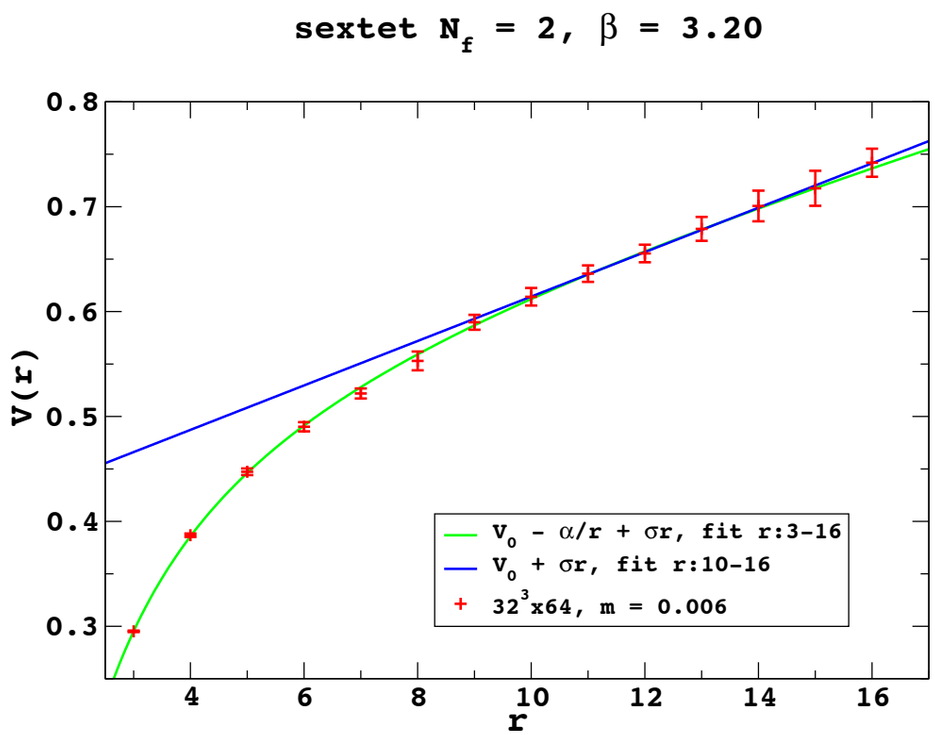
M_ρ remains heavy in massless fermion limit

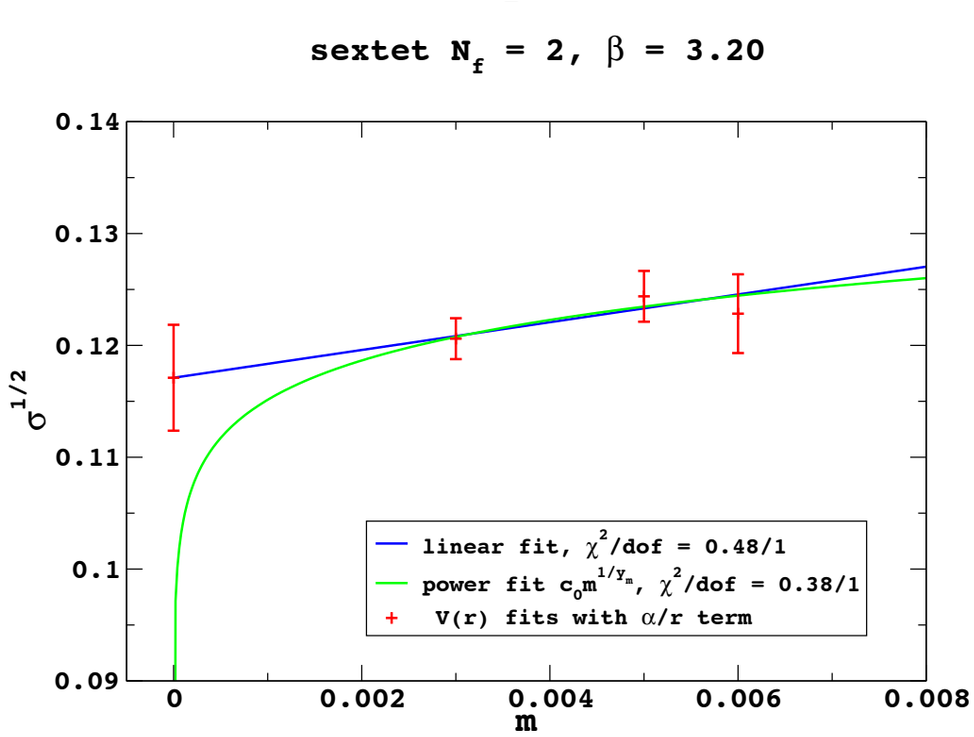
perhaps within LHC reach?

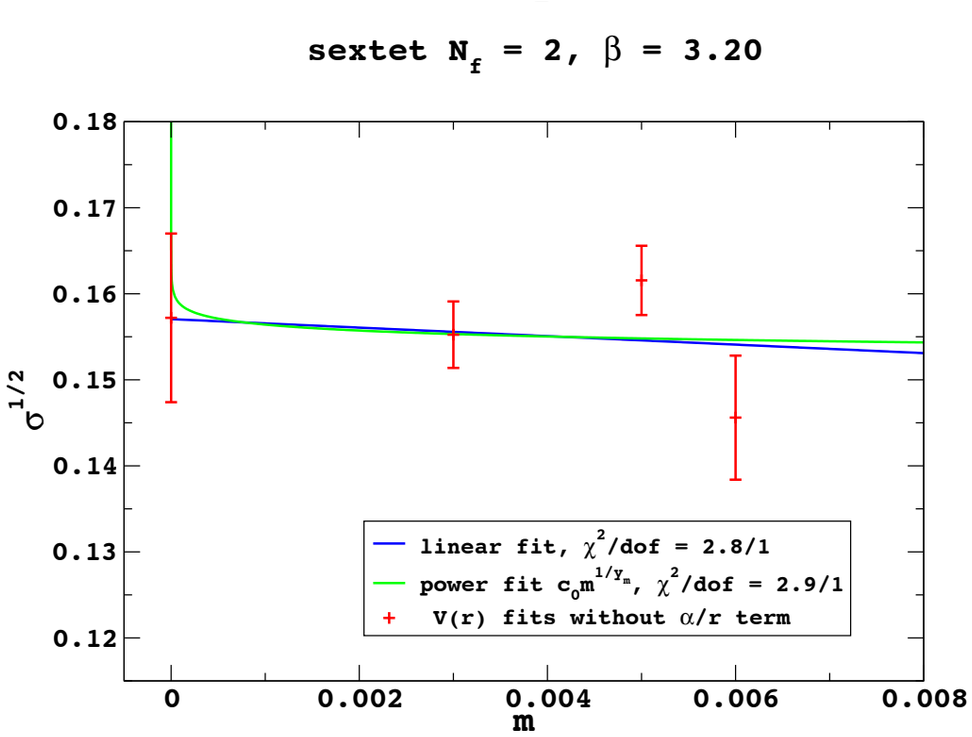
parity partners remain split in massless fermion limit

sextet simulations confining force at finite m (LHC group)









1/1+γ ~0.04(4) ? conformal γ~infinite would be needed

finite temperature

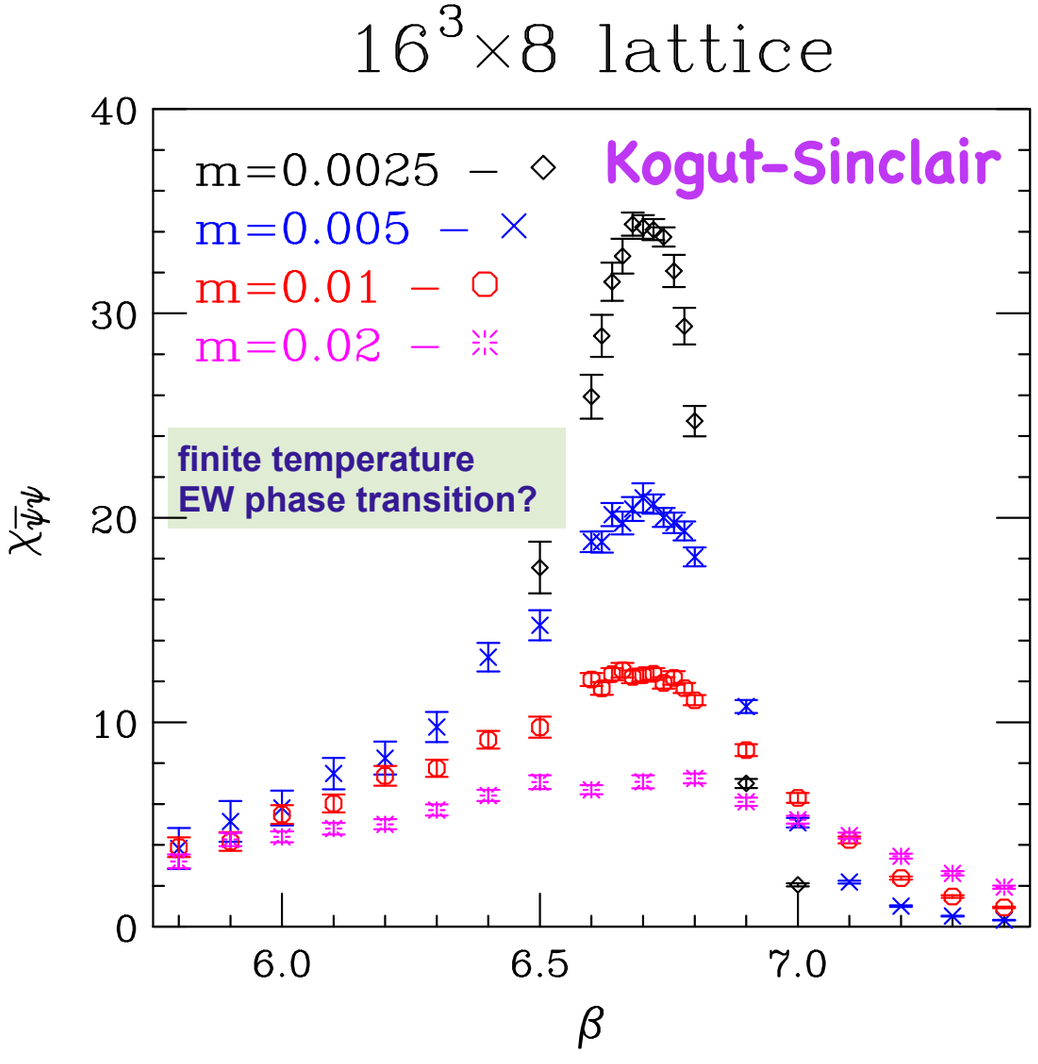
EW phase transition in sextet model - early universe

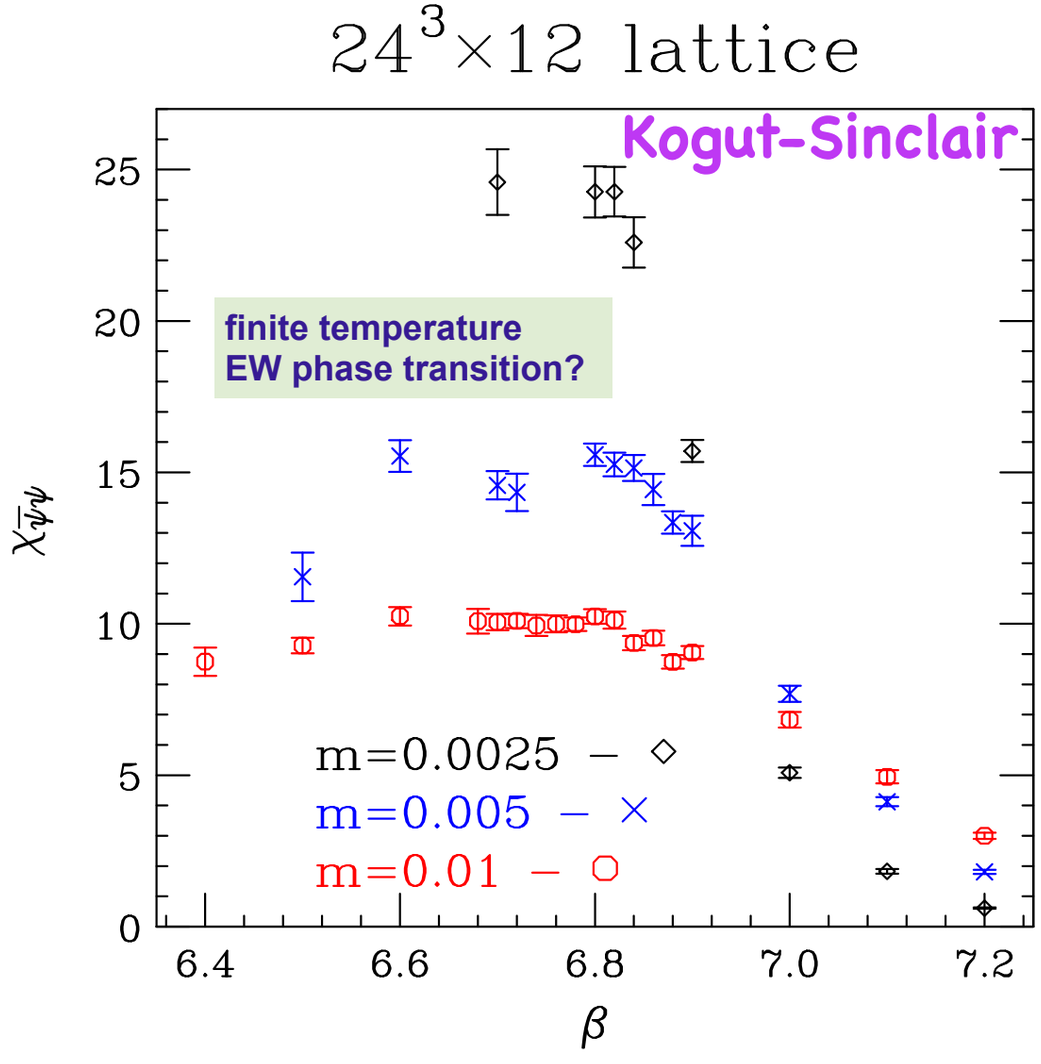
Kogut-Sinclair consistent with χSB phase at T=0

relevance in early cosmology

We are planning to run sextet thermo after model passed other tests

Third massive fermion flavor (electroweak singlet) dark matter?





Summary and Outlook

Consistency with χSB in Nf=2 SU(3) sextet model

Results of DeGrand et al. reconciled if walking or nearly walking coupling

Scalar spectrum from disconnected correlator remains highest priority
dilaton-like?

Scale-dependent anomalous dimension of condensate from Dirac spectrum?

S-parameter and WW scattering if model remains standing? LHC14 phenomenology

Dark matter and electroweak phase transition ?

Do we have an impostor?