KITP Lattice 2015

The simplest composite Higgs with resonance spectrum in the 2 TeV range

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

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What is our composite Higgs paradigm?

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

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

strongly coupled gauge theory

fermions (Q) in gauge group reps:

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

light scalar separated from

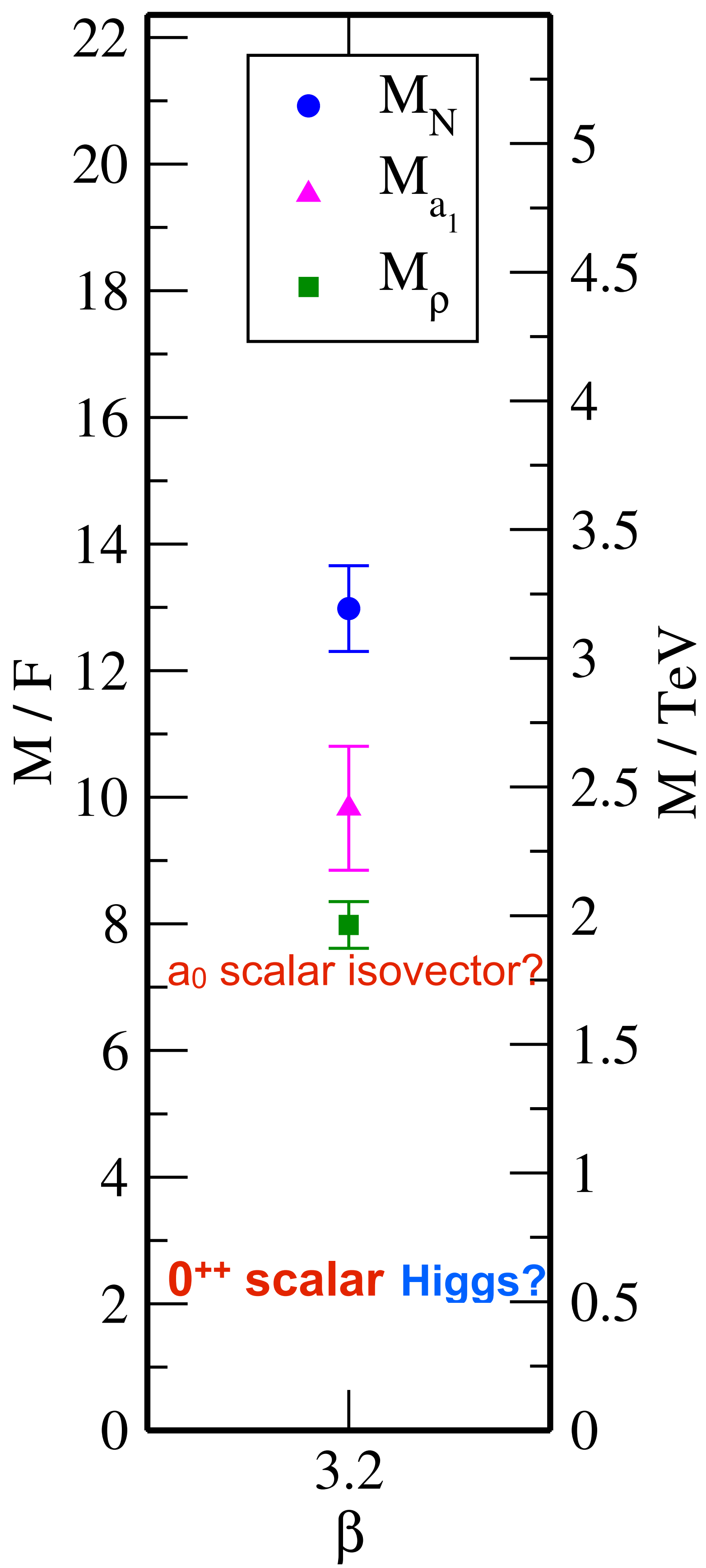
2-3 TeV resonance spectrum

has to be unlike QCD

needle in the BSM haystack?

QCD in 1971 was a needle in the haystack

Needle in the haystack?



theory has no tuning

minimal composite Higgs mechanism

incomplete (fermion mass origin?)

can be used in several extensions

fermion mass generation, …

explanation of the spectrum?

near-conformal linear sigma model? dilaton?

lattice: actually have to solve the theory

needs new tools

scaled up QCD cannot do this

The light 0++ scalar

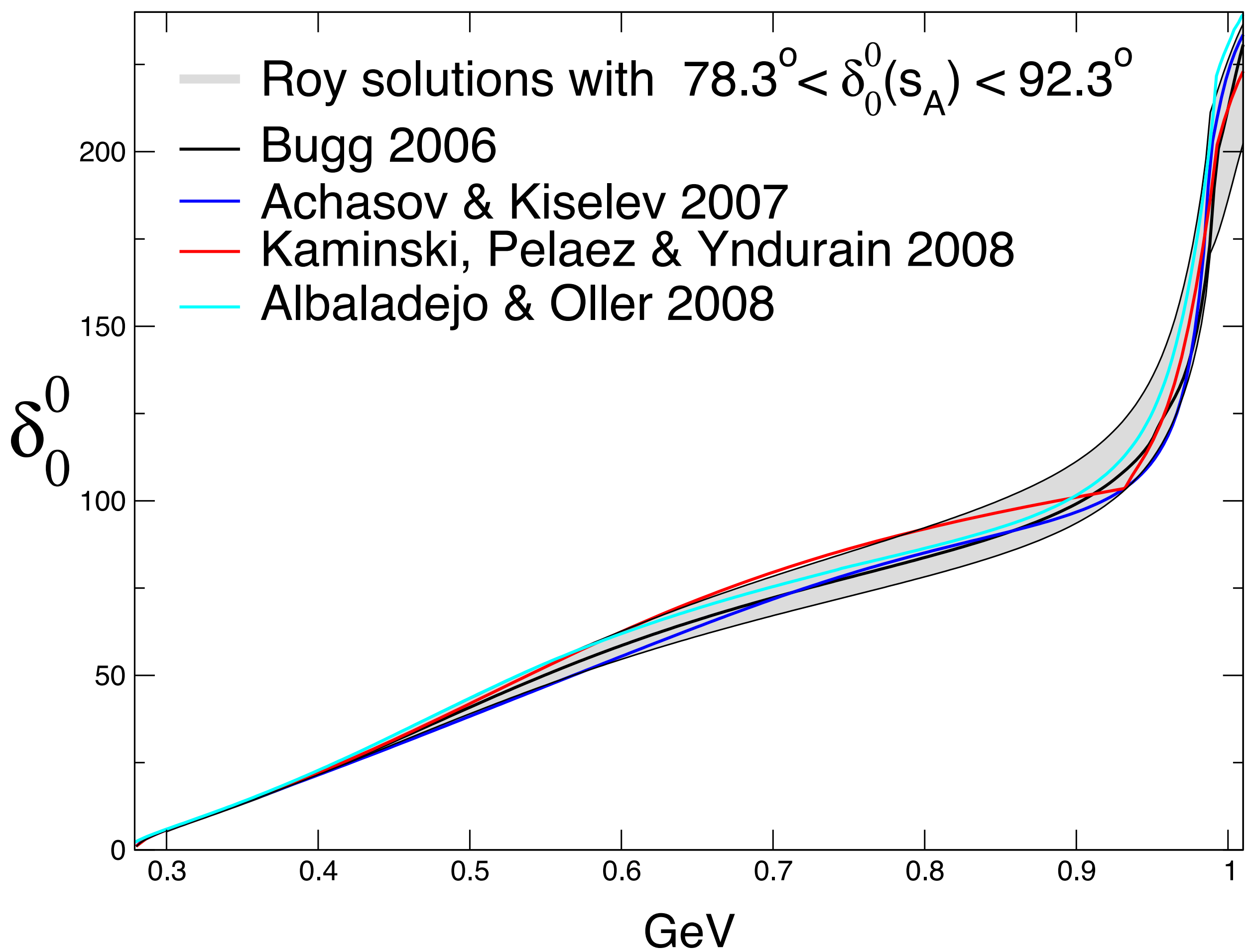
not scaled up QCD!

the failure of old Higgs-less technicolor:

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

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

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



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

Low scalar mass renormalizes F!
Will require new low energy effective action

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

Leutwyler:
dispersion theory combined with ChiPT

Outline

Near-conformal SCGT

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

Chiral Higgs condensate

new method
GMOR and mode number
epsilon regime and RMT
large mass anomalous dimension

Scale dependent renormalized coupling

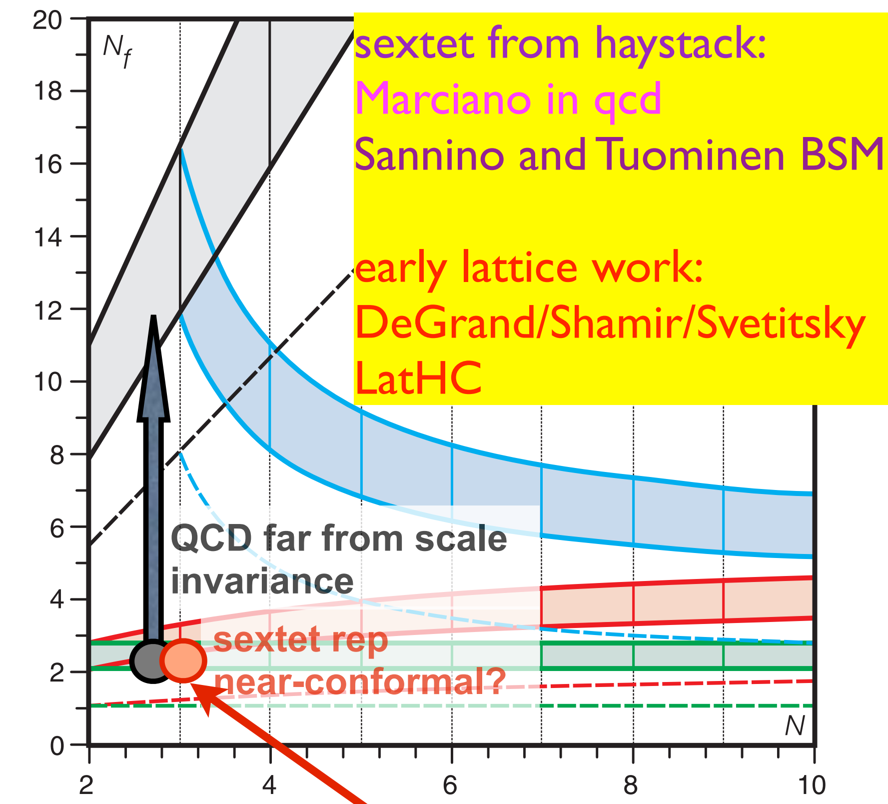
matching scale dependent coupling from
UV to IR with chiSB

Early universe

EW phase transition, sextet baryon, and dark matter

Summary

SCGT Theory Space



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

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

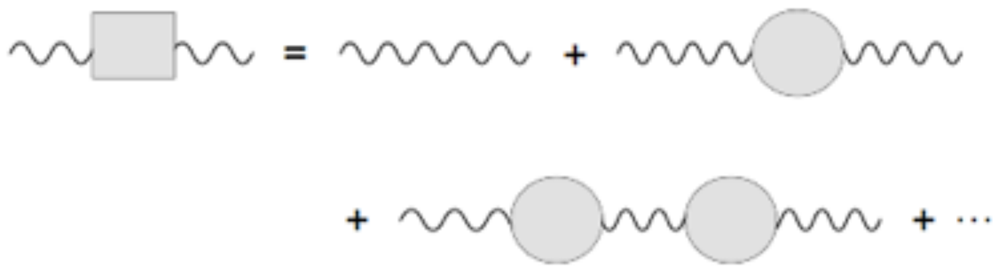
3 Goldstones > weak bosons
minimal realization of Higgs mechanism
adding lepton doublet is a choice
adding EW singlet massive flavor
is also a choice

QCD intuition for near-conformal
compositeness is plain wrong

Technicolor thought to be scaled up QCD
motivation of the project:
composite Higgs-like scalar close to the
conformal window with 2-3 TeV new physics

composite Higgs mechanism in text book QCD example:

the origin of Technicolor



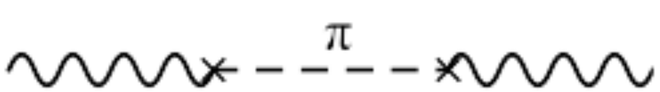
$$G_{\mu\nu}(q) = \frac{-i}{q^2 - g^2\Pi(q^2)/2}(P_T)_{\mu\nu}\,, \qquad (P_T)_{\mu\nu} \equiv \eta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}$$

$$i\Pi_{\mu\nu}(q) = -\int d^4x\, e^{-iq\cdot x}\langle 0|T\left(J^+_\mu(x)J^-_\nu(0)\right)|0\rangle$$

$$\Pi_{\mu\nu}(q) = \left(\eta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right)\Pi(q^2)\,.$$

$$\langle 0|J^+_\mu|\pi^-(p)\rangle = i\frac{f_\pi}{\sqrt{2}}p_\mu$$

Since we want something different from scaled up QCD, to understand the role of the composite Higgs condensate is critically important if model would become relevant for LHC predictions …



$$\Longrightarrow \qquad \Pi(q^2) = \frac{f_\pi^2}{2}$$

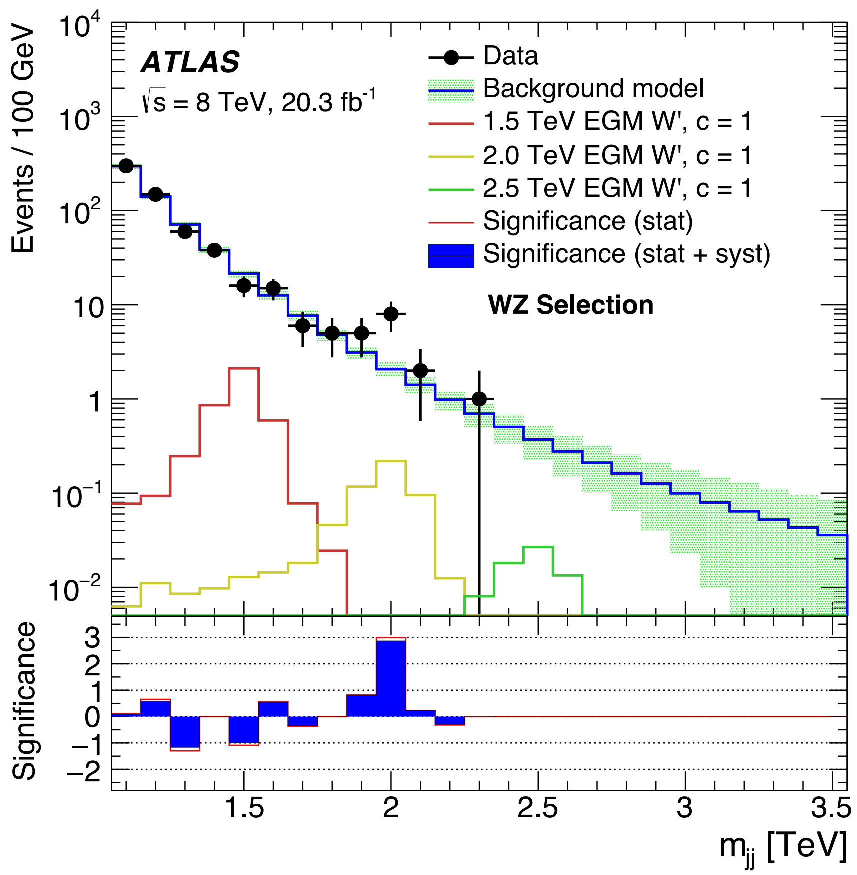
$$m_W = \frac{gf_\pi}{2} \simeq 29\,\mathrm{MeV}$$

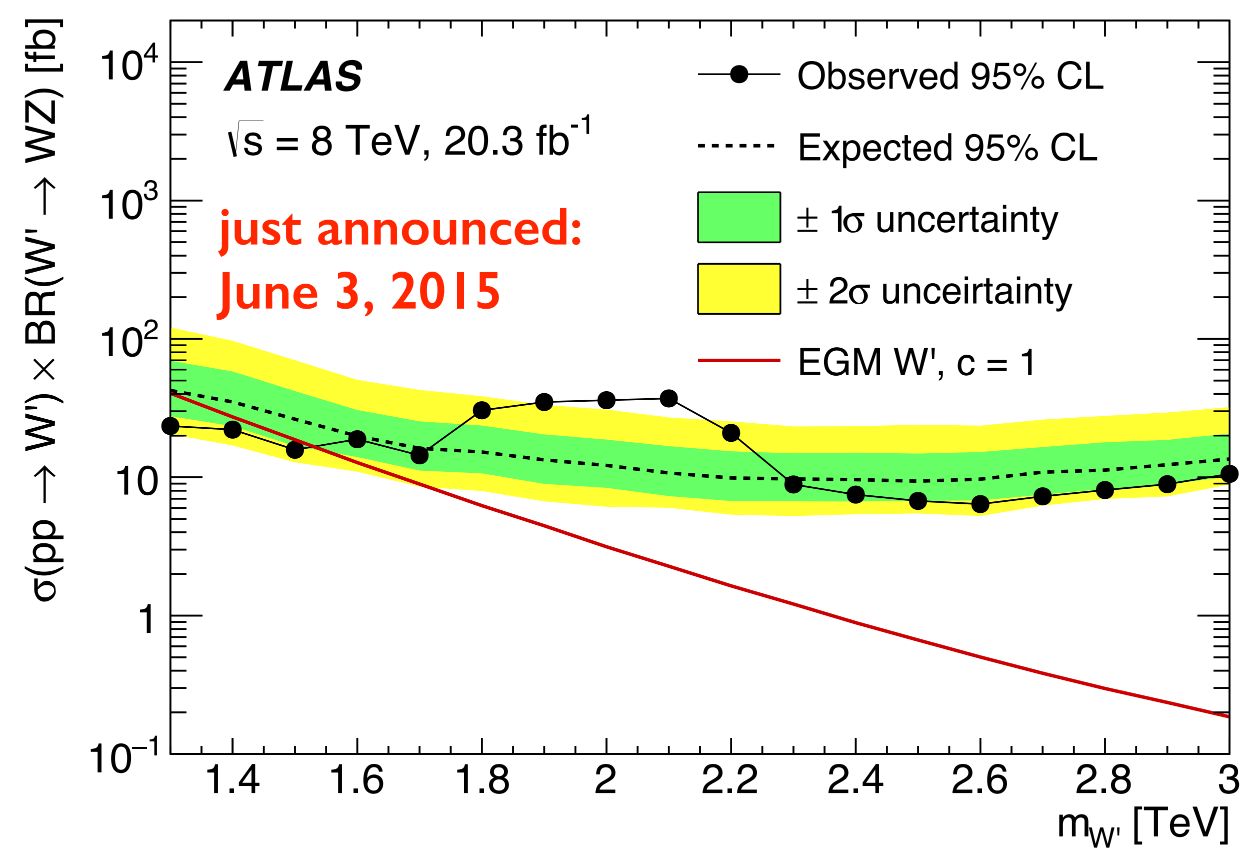
The light 0++ scalar

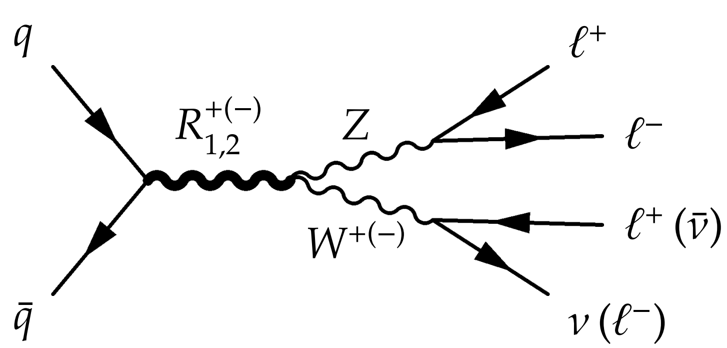
sextet model is not scaled up QCD!

composite Higgs with resonance spectrum in the 2 - 3 TeV range is a relevant model for LHC to consider

hints from ATLAS and CMS for rho-like resonance around 2 TeV:







exciting - paper flood is coming …

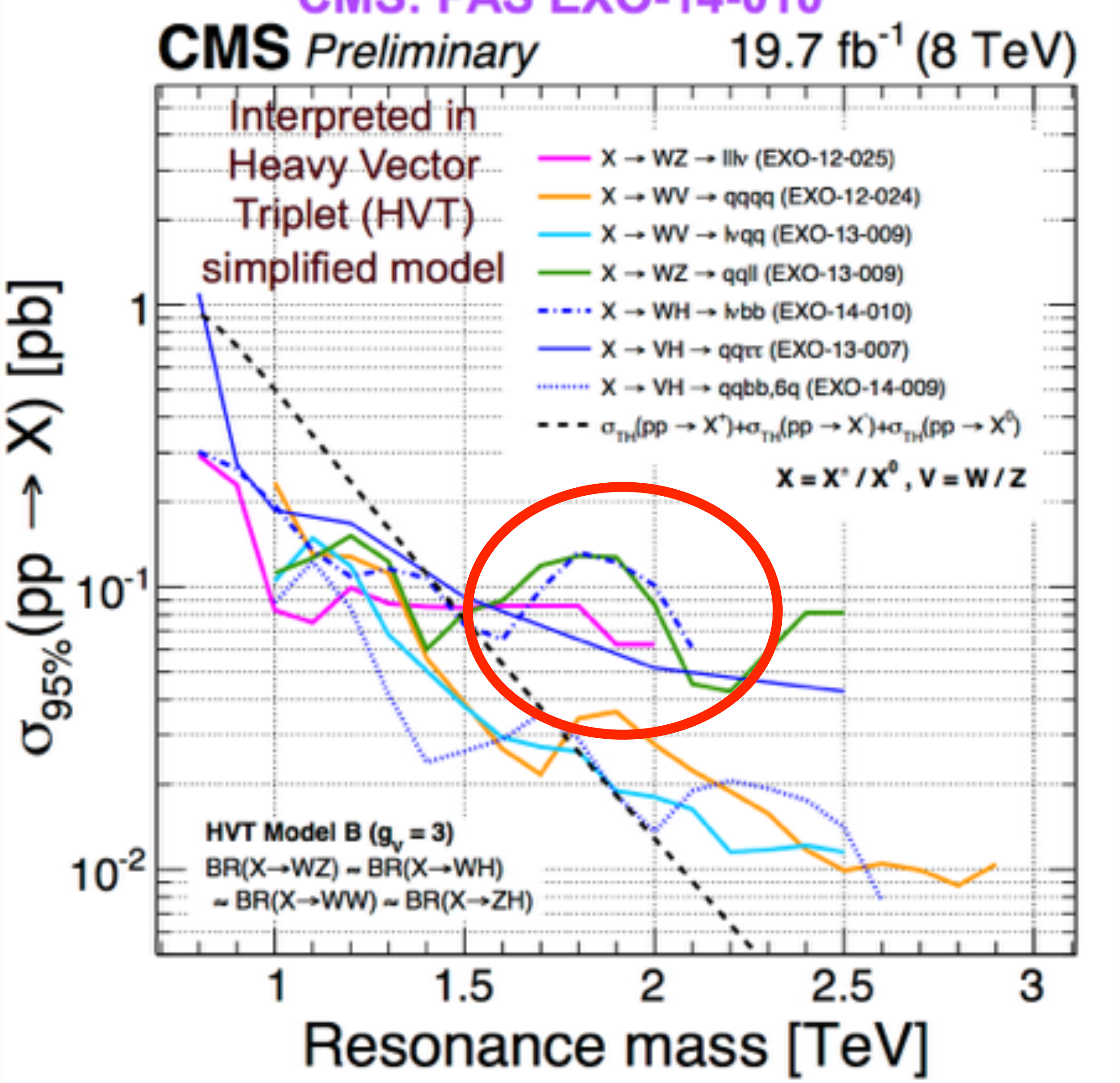
The fate of the sextet model is now connected with Run 2 of the LHC. It predicts a resonance spectrum in the 2-3 TeV range including a Rho-like bump just around 2 TeV!

Di-bosons – excesses

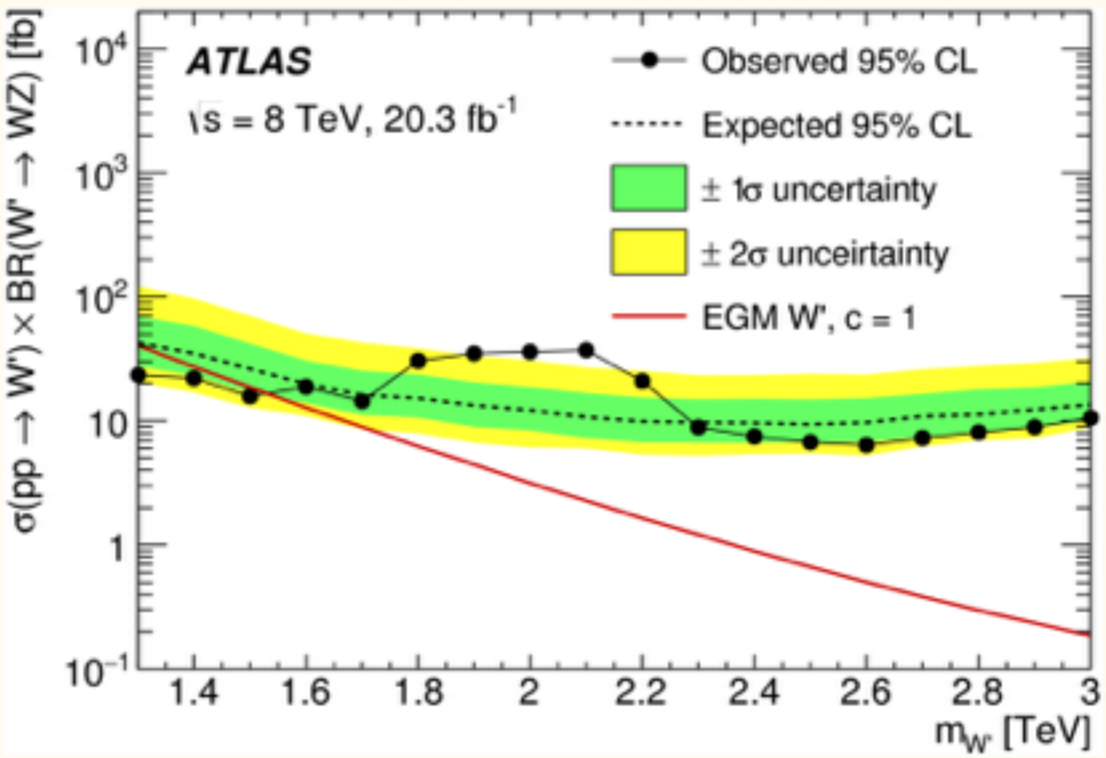
Ivan Mikulec

- **Moderate excesses observed in some channels around 1.8 – 2 TeV**
  - **Global significance 1.5 – 2.5 σ**
- **Excesses of 2σ not unusual, but ATLAS + CMS at similar place = excitement**

CMS: PAS EXO-14-010



ATLAS: arXiv 1506.00962



- **Not in all channels…**
- **Will know more after a few first fb^{-1} of Run 2 data**

before I get carried away:

(from *Julius Caesar*, spoken by Marc Antony)

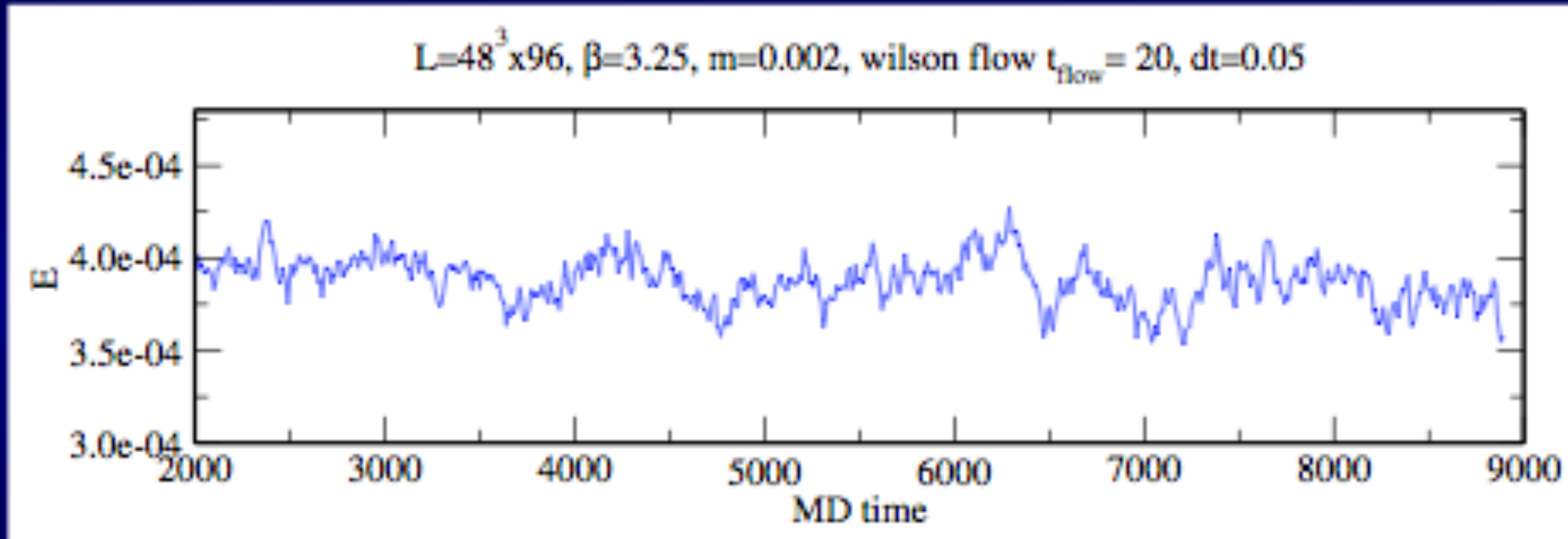
I come to bury Caesar, not to praise him.

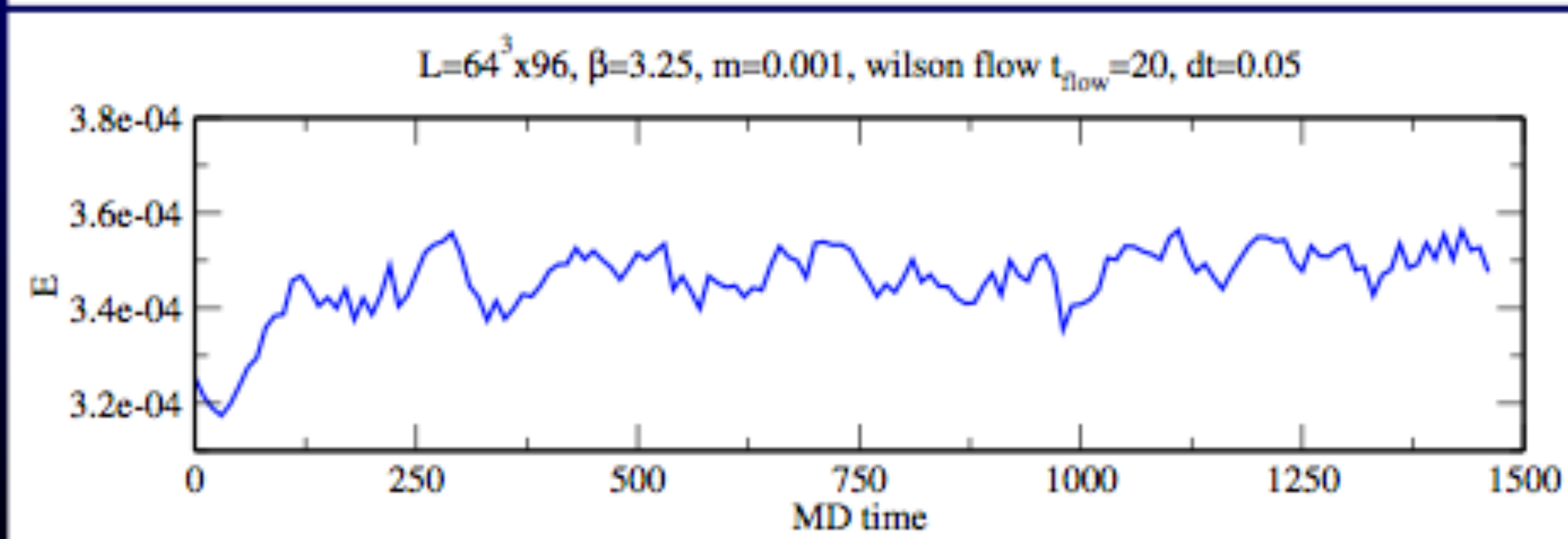
Hadron Spectroscopy on Extended Dataset - Simulation Details

- Action: Tree-level Symanzik-Improved gauge action with Staggered $N_f = 2$ Sextet SU(3) fermions
- RHMC algorithm with multiple time scales and Omelyan integrator
- $\beta \equiv 6/g^2 = 3.20, 3.25$ and 3.30, which is in the weak coupling regime
- Lattices available:($\sim 2000 - 9000$ Trajectories each)

β	L	T	m	β	L	T	m
3.20	56	96	$0.001 - 0.002$	3.25	64	96	0.001
	48	96	$0.001 - 0.004$		56	96	$0.001 - 0.002$
	40	80	$0.002 - 0.004$		48	96	$0.001 - 0.004$
	32	64	$0.003 - 0.008$		40	80	$0.002 - 0.004$
	28	56	$0.003 - 0.008$		32	64	$0.004 - 0.008$
	24	48	$0.003 - 0.014$		28	56	$0.003 - 0.008$
3.30	64	96	0.001		24	48	$0.003 - 0.008$
	56	96	$0.001 - 0.002$				
	32	64	$0.005 - 0.010$				

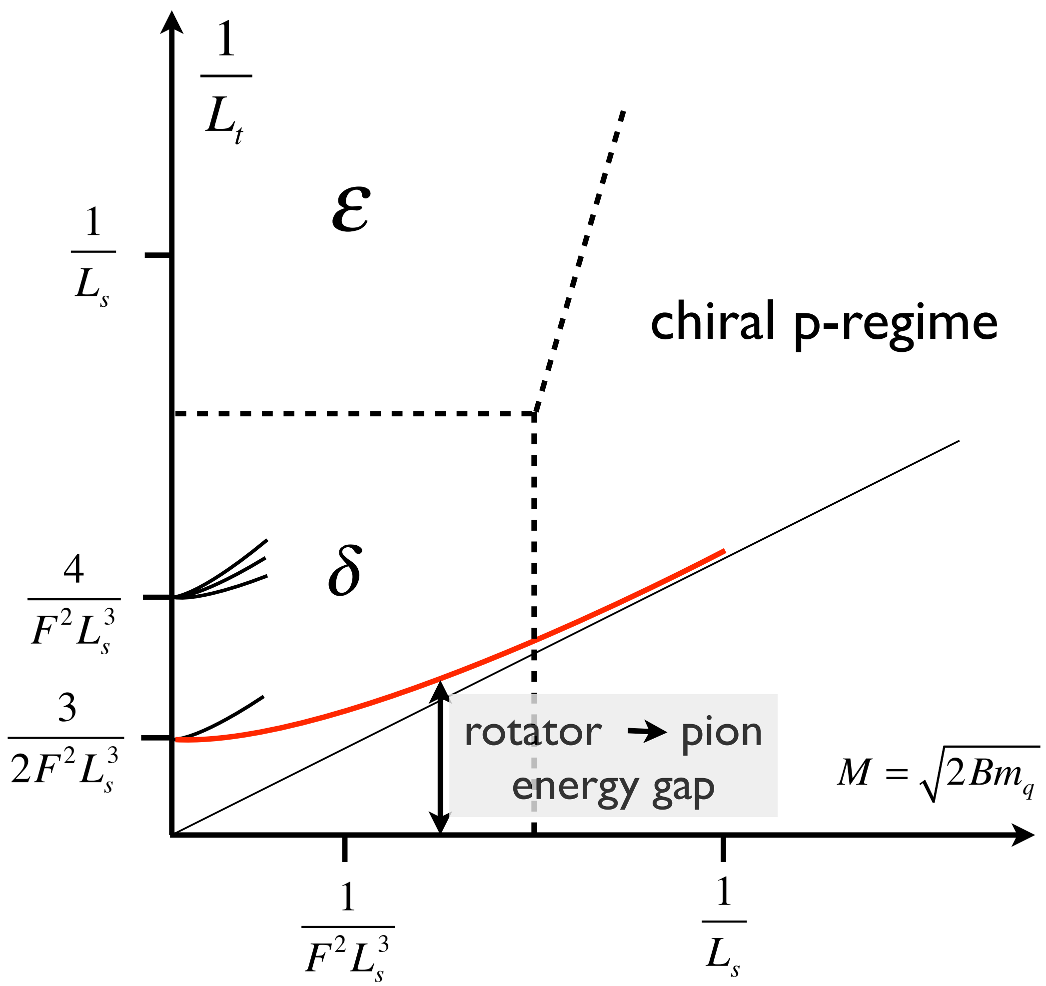
- Thermalization is monitored by E at Wilson or Symanzik flow time $t_{\text{flow}} = 20$ with $dt = 0.05$
- Examples:





Spoiler alert: $F^2L^2 < N_F \Rightarrow$ no theory

when in finite volume, 1/FL has to be small in all three regimes!



Condition of reaching the chiral expansion regime can be estimated from rotator spectrum $\Rightarrow$

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

direct application to sextet model

$\theta = F^2 L_s^3 \left(1 + \frac{C(N_f=2)}{F^2 L_s^2} + O(1/F^4 L_s^4)\right)$ (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

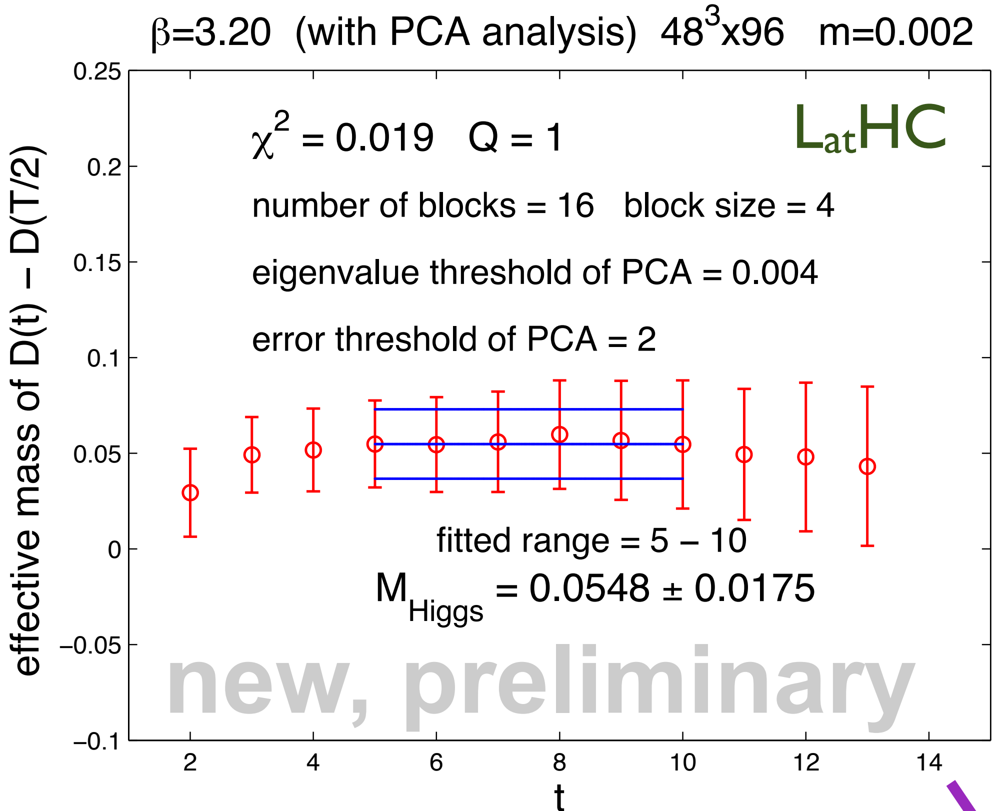
FL = 0.1 L=0.2 fm in QCD femto world OK to study volume dependent PT coupling running with V

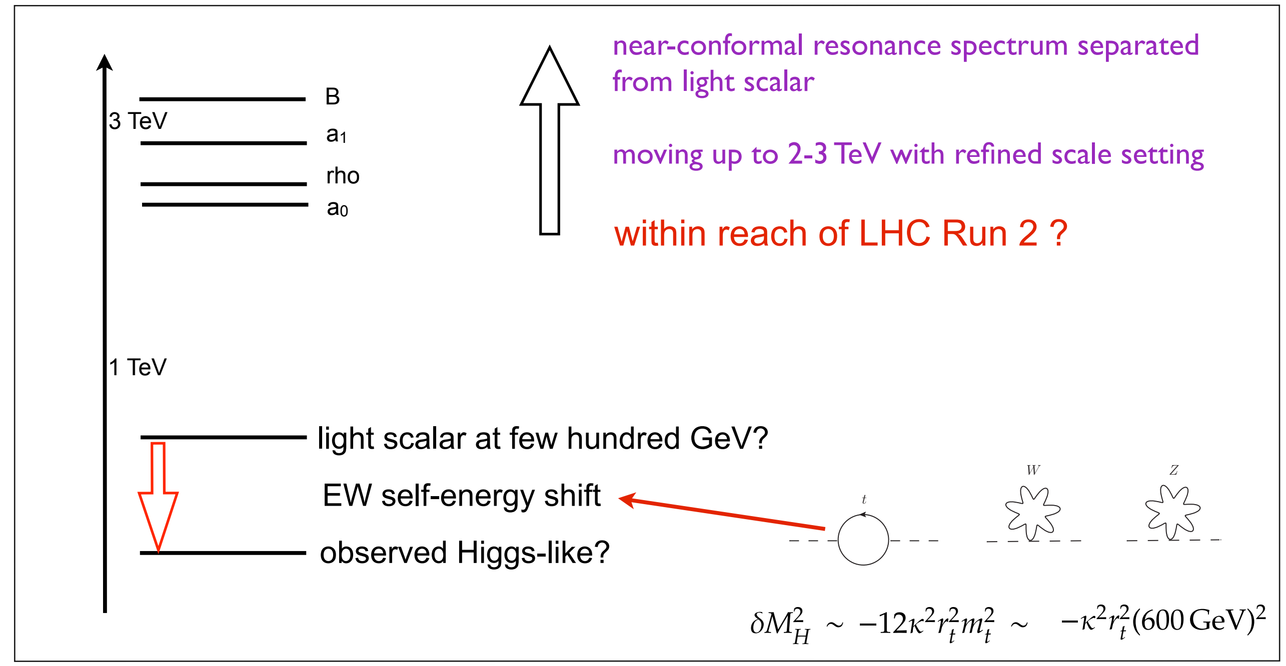
FL > 1 L= 2 fm in QCD and we crossed over to the χSB phase all 3 regimes (ε,δ,p) OK

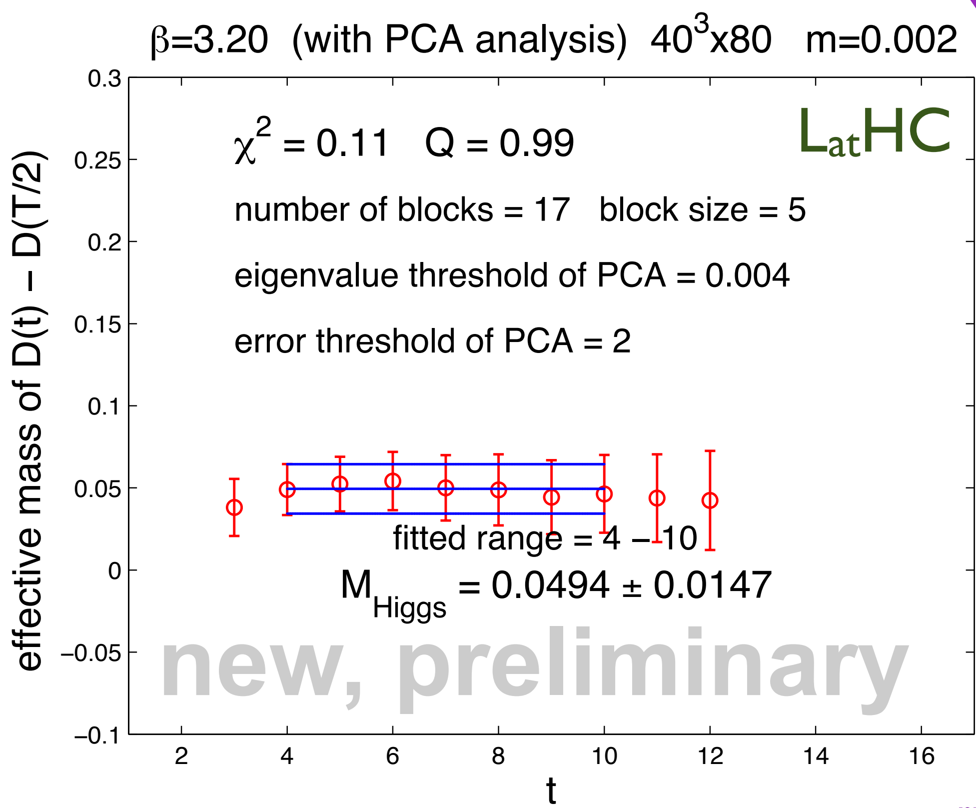
FL = 0.4 squeezed L= 0.8 fm, begins to look conformal not OK, misidentifies infinite volume phase

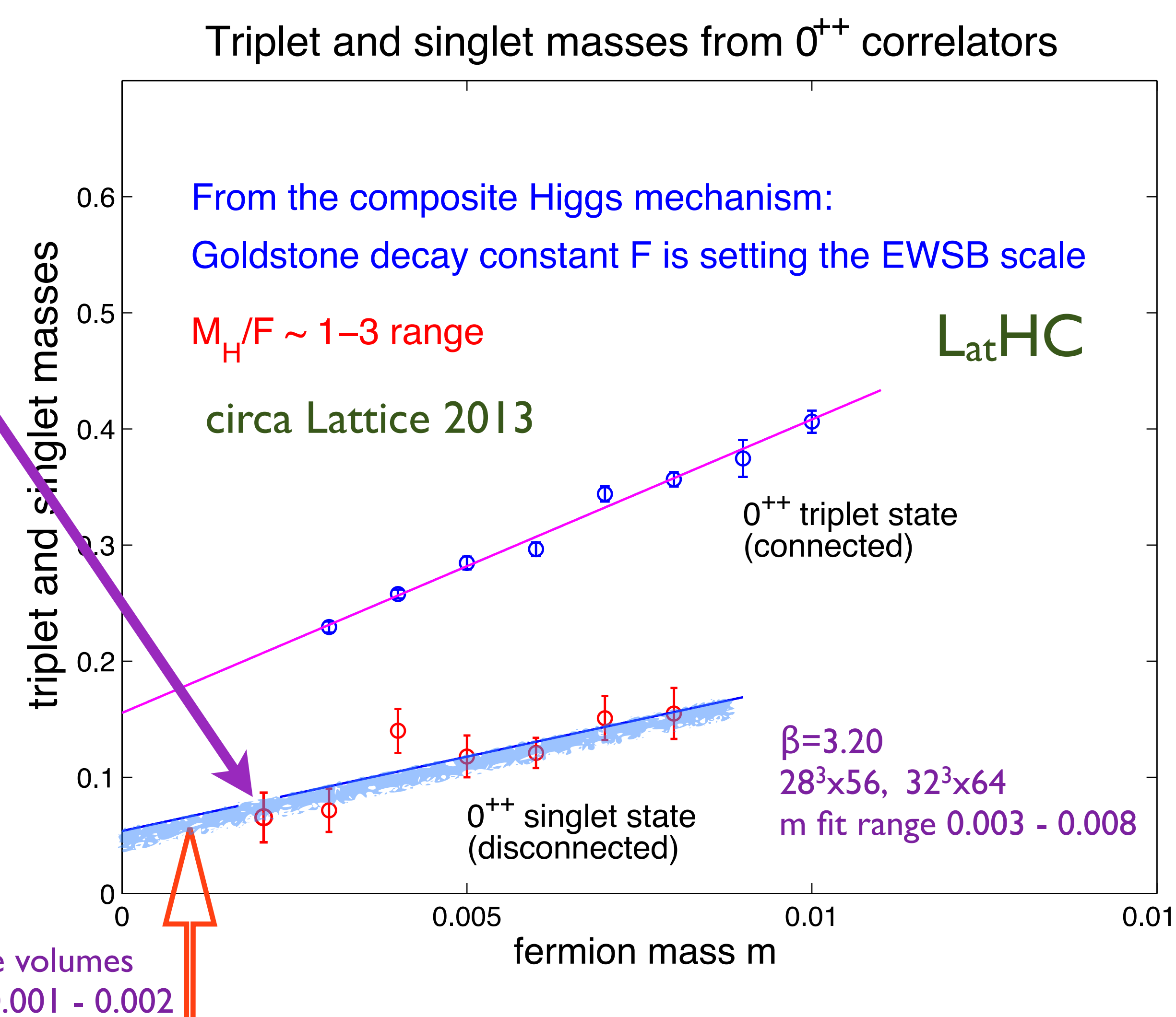
3-fold adiabatic hierarchy of delta-regime is a great tool to explore!

light 0++ scalar and spectrum   sextet model   LatHC



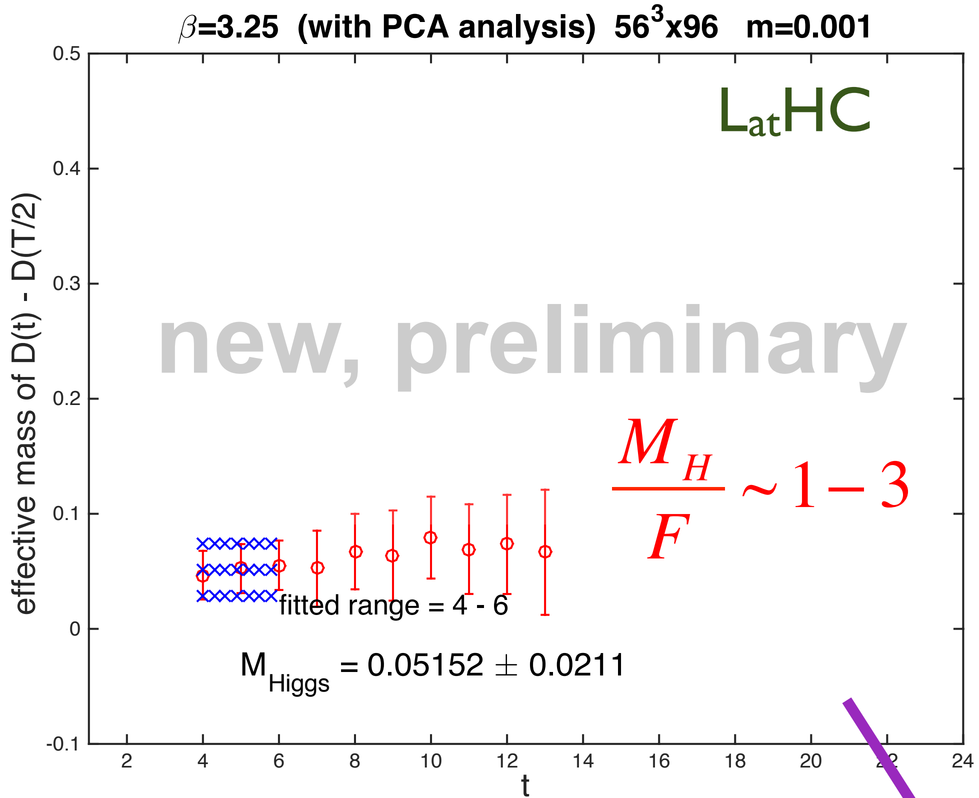


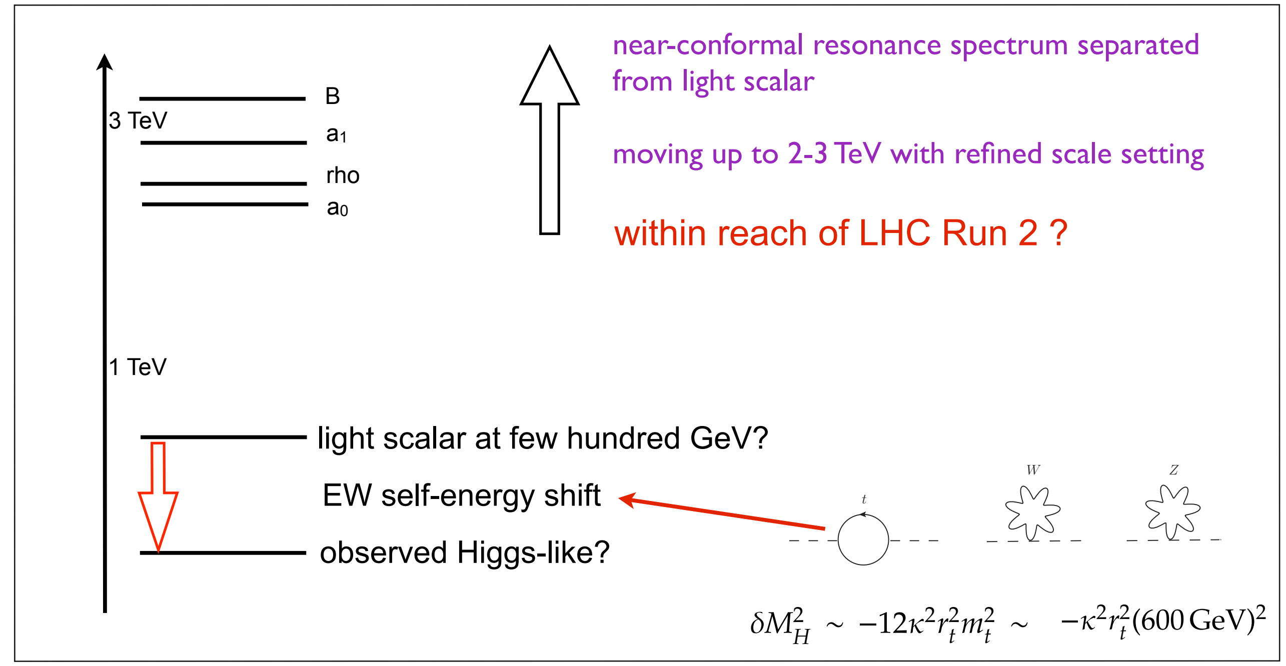


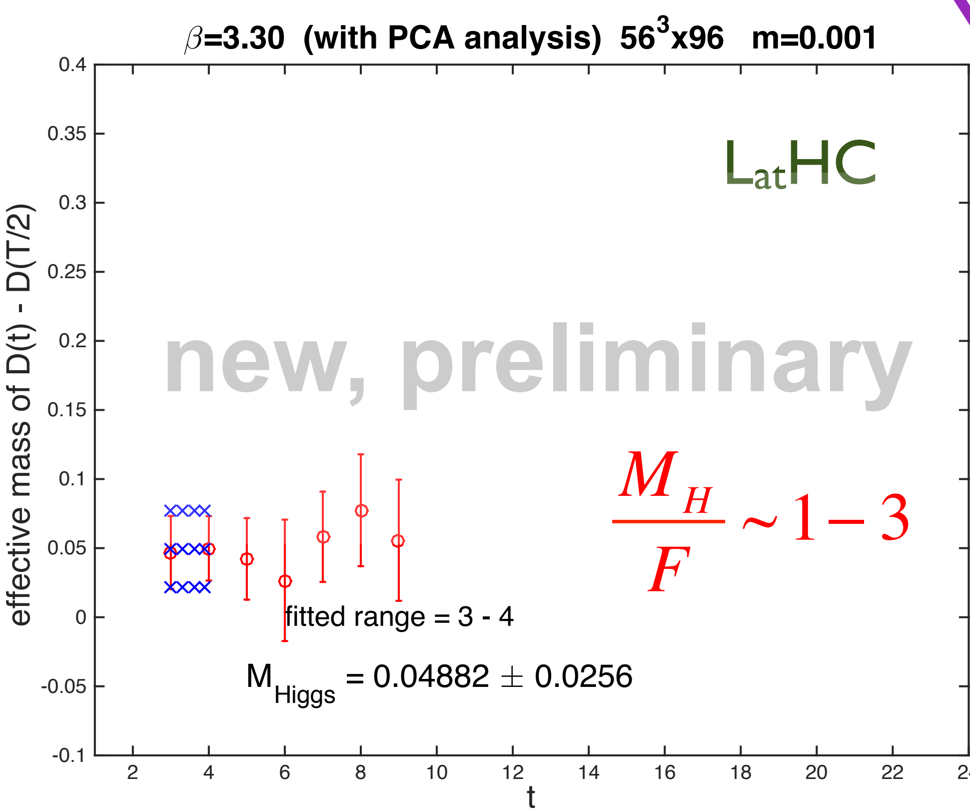


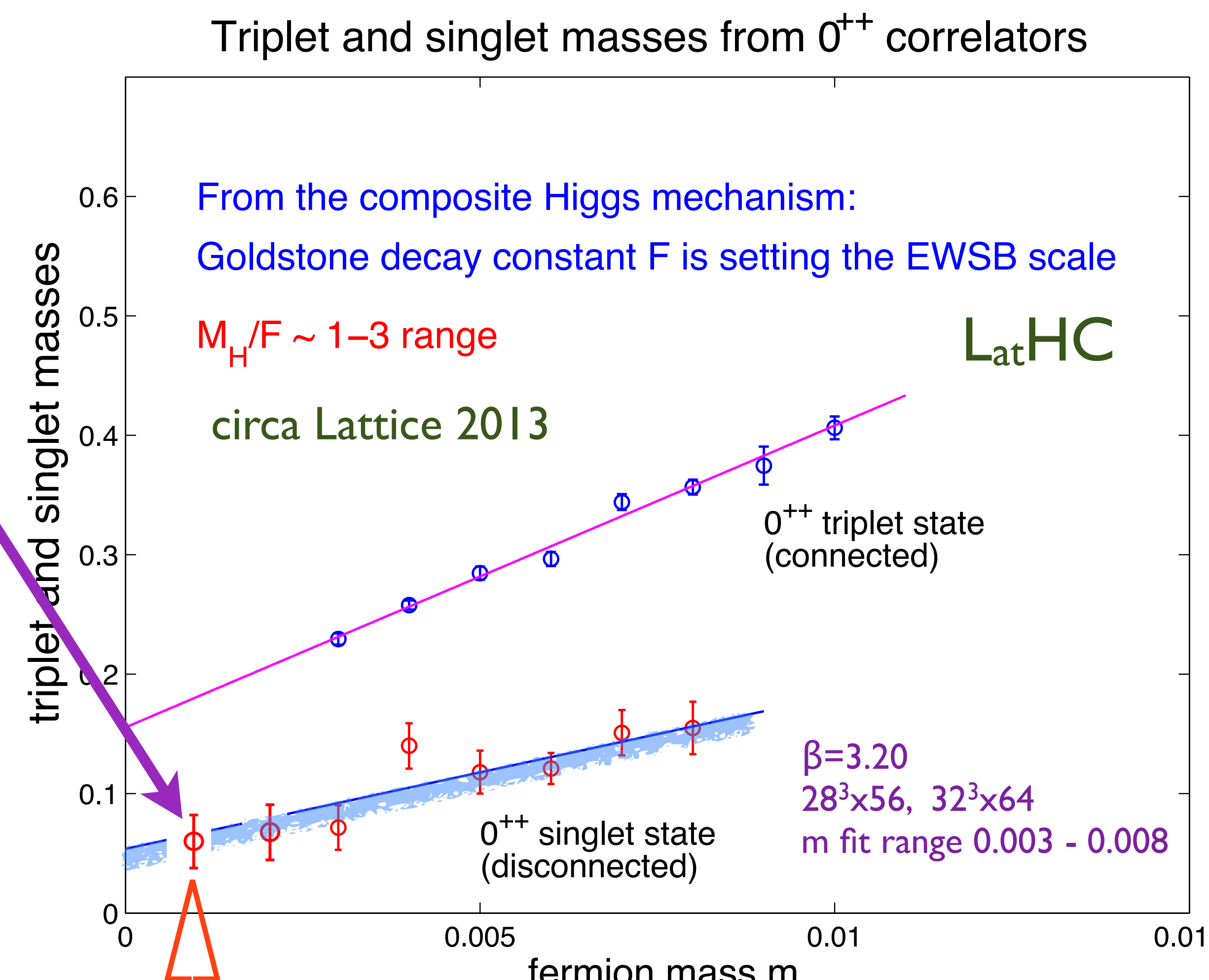
running large volumes
m fit range 0.001 - 0.002

light 0++ scalar and spectrum   sextet model   LatHC



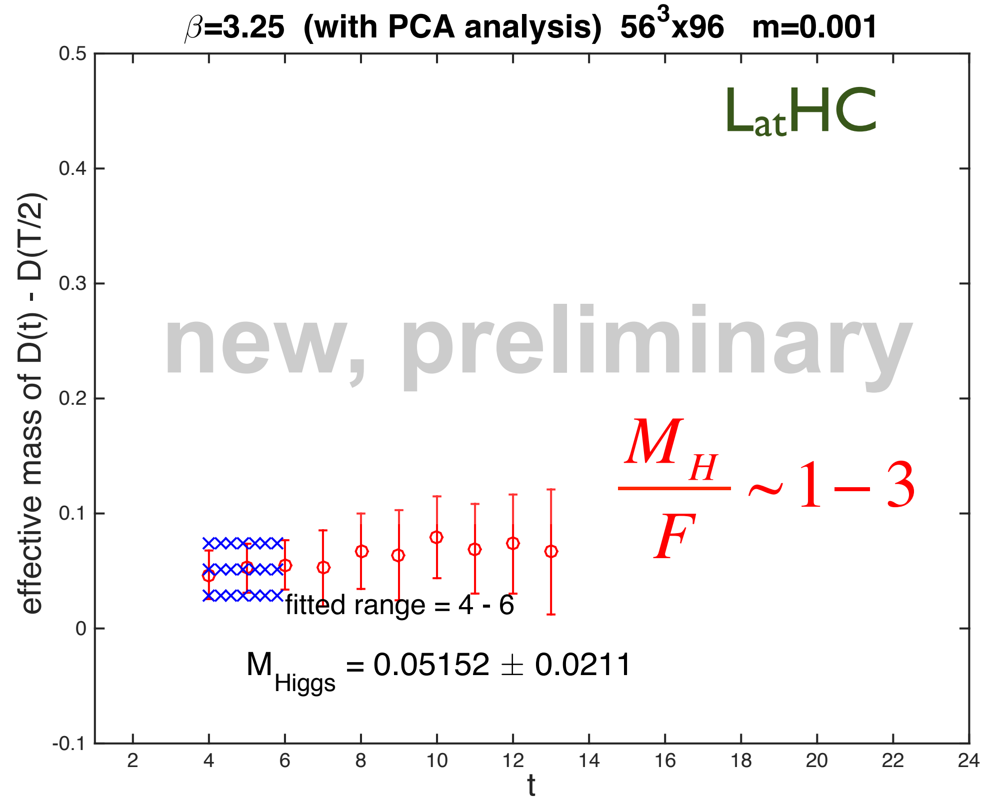


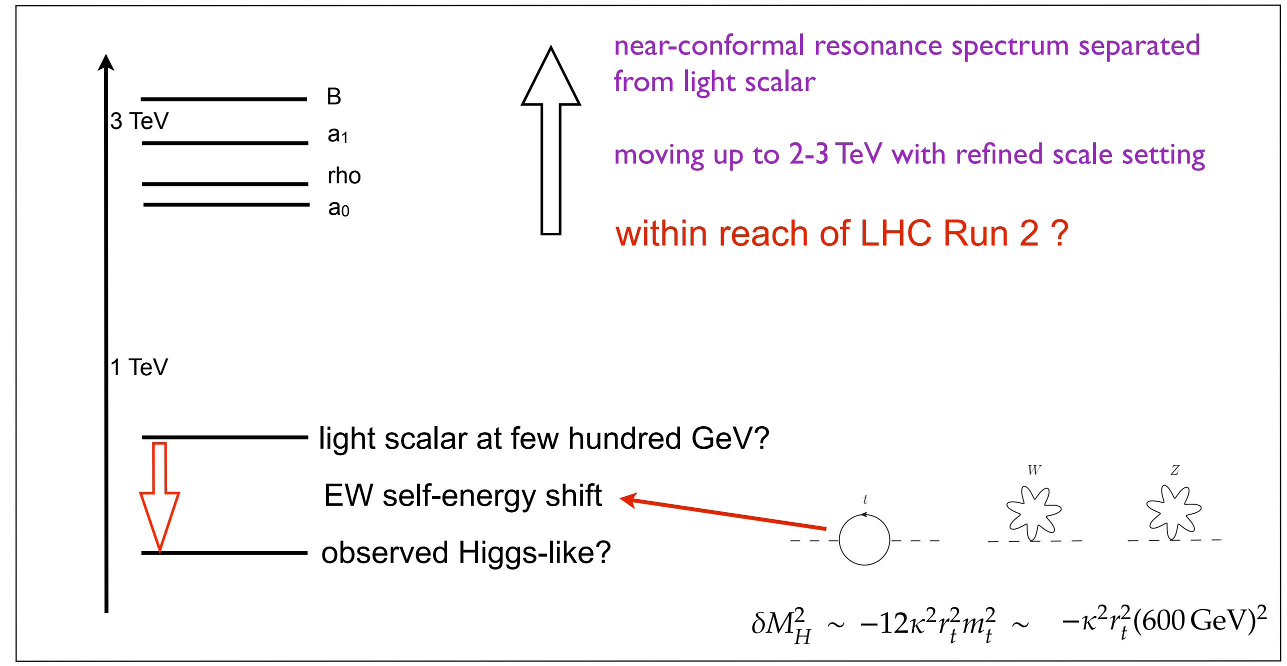


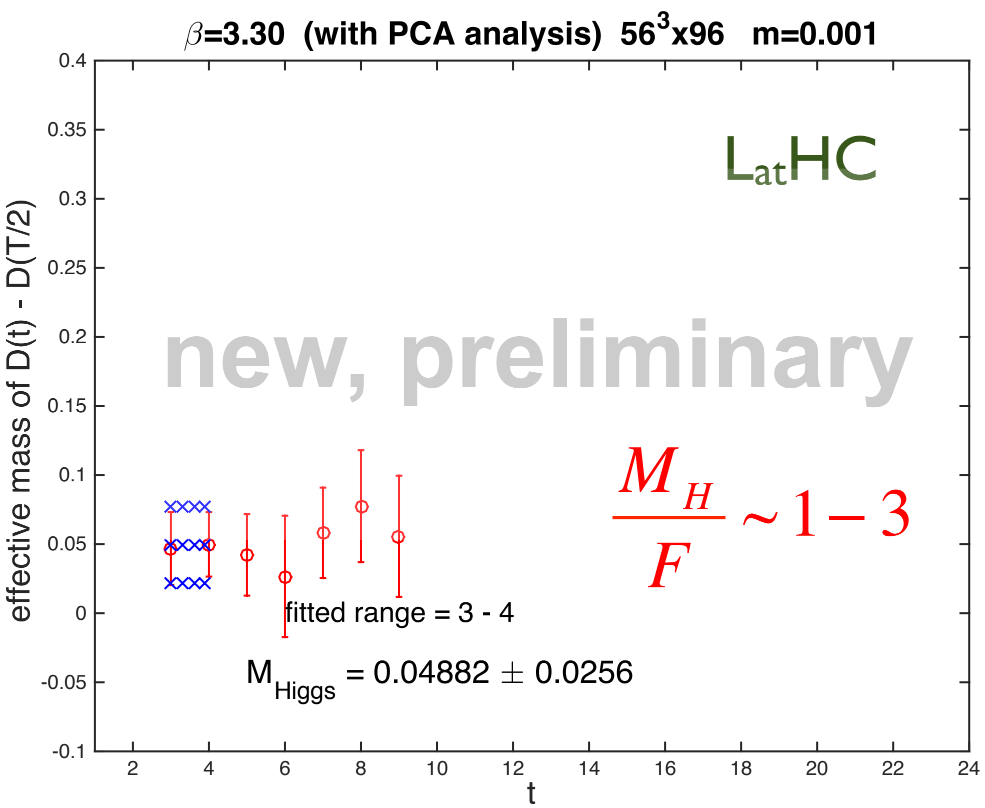


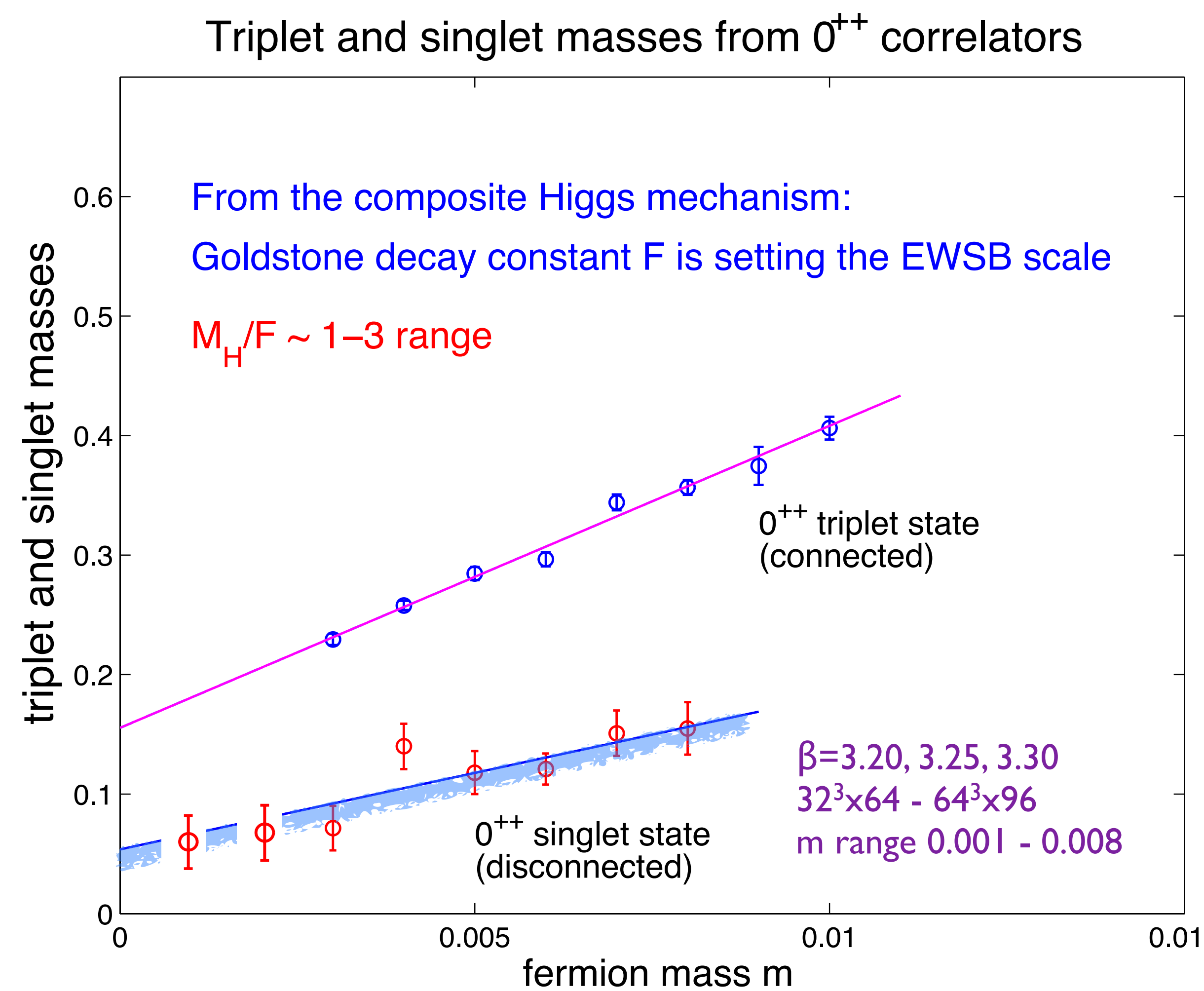
running large volumes
m fit range 0.001 - 0.002

light 0++ scalar and spectrum   sextet model   LatHC

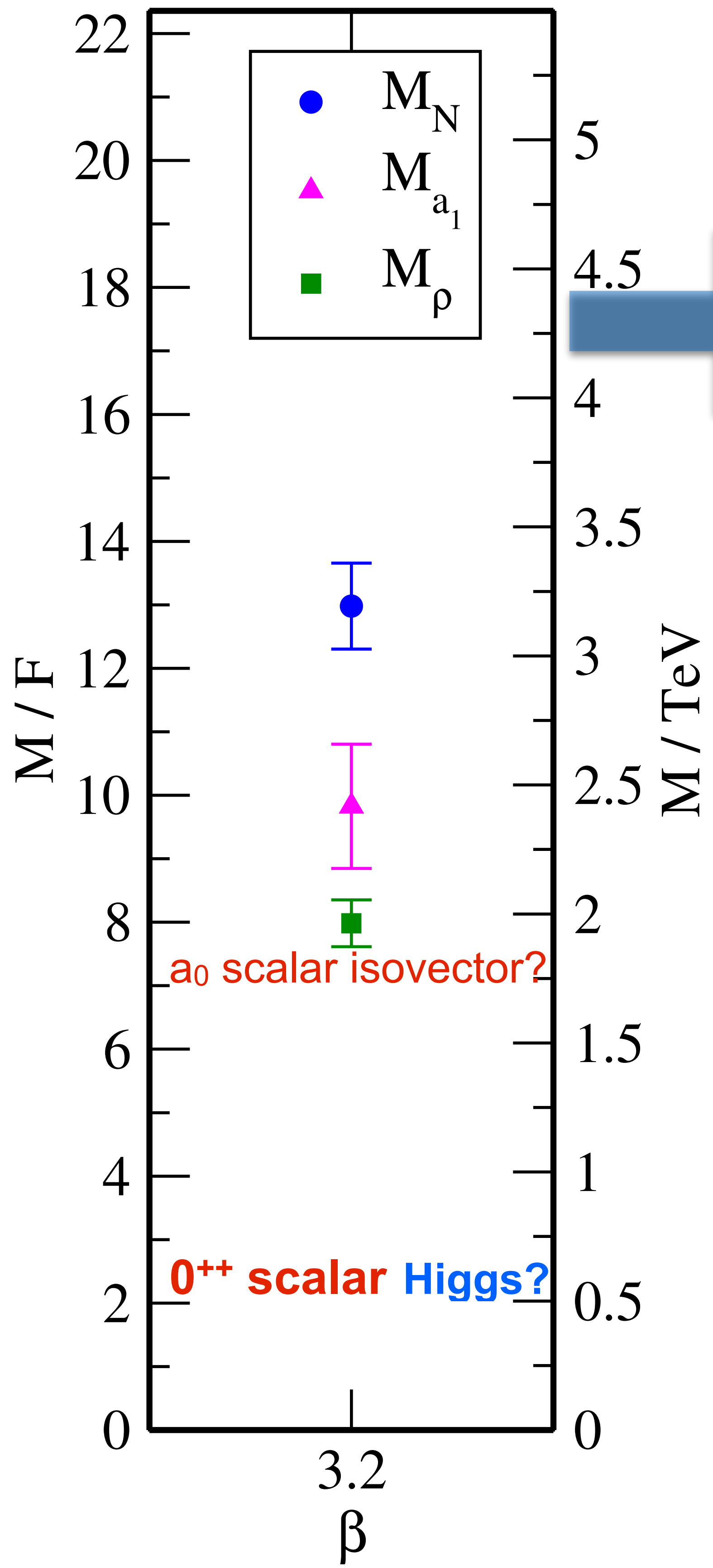


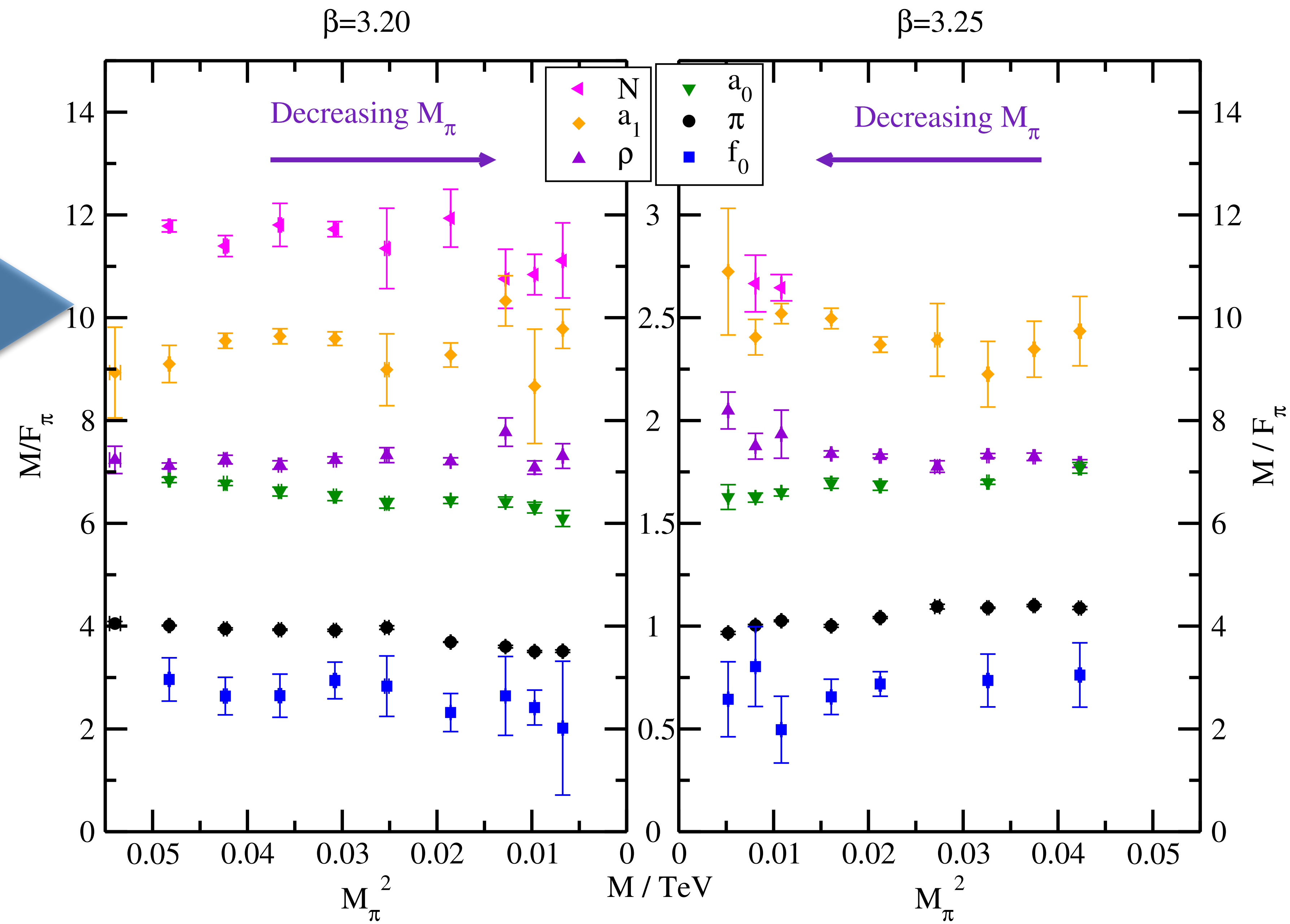






light 0++ scalar and spectrum sextet model LatHC

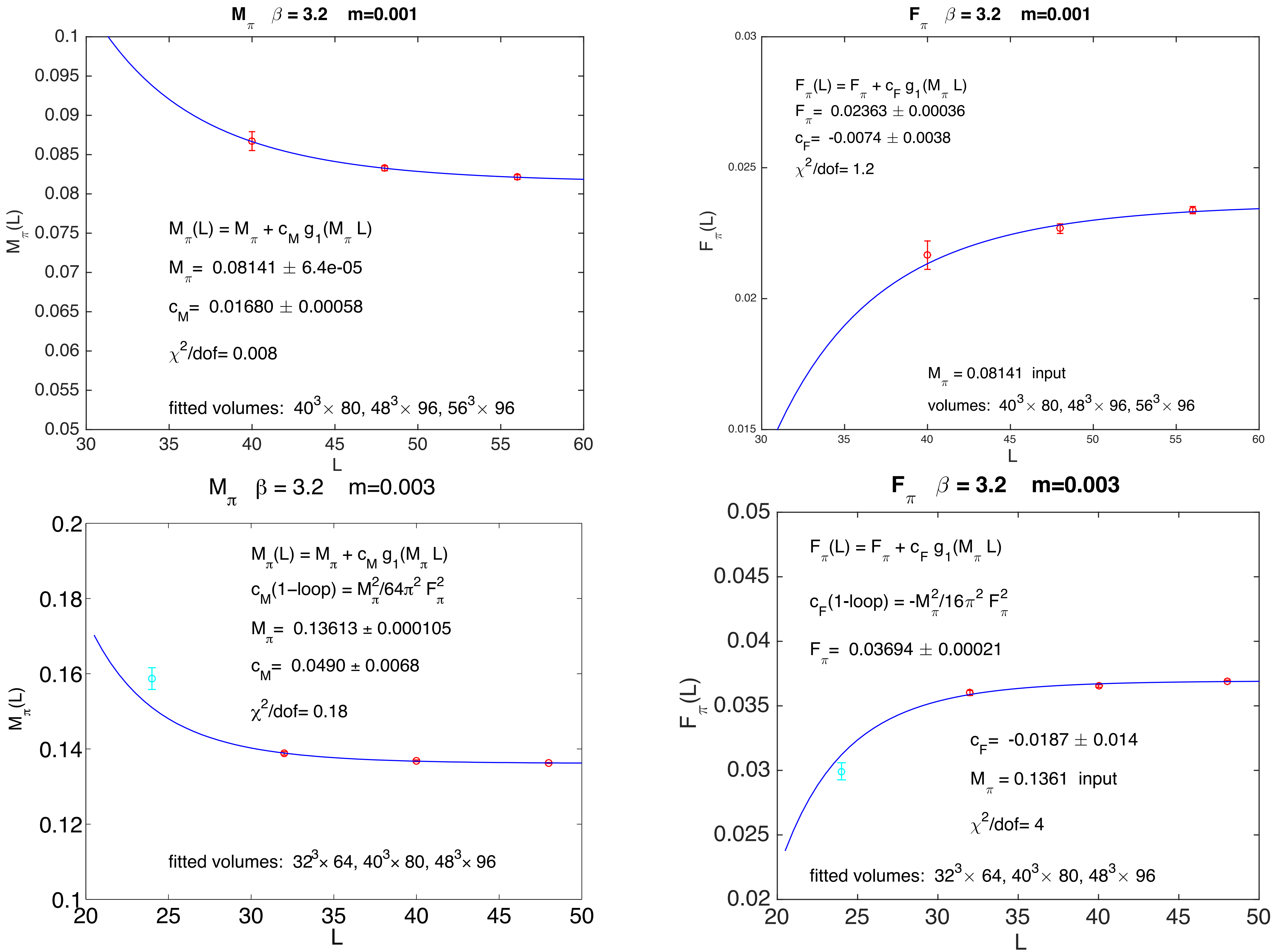




wait: does this looks like a conformal spectrum with hyperscaling?

let us look under the hood

rsChiPT analysis of Mpi and Fpi extrapolating to inf. vol.



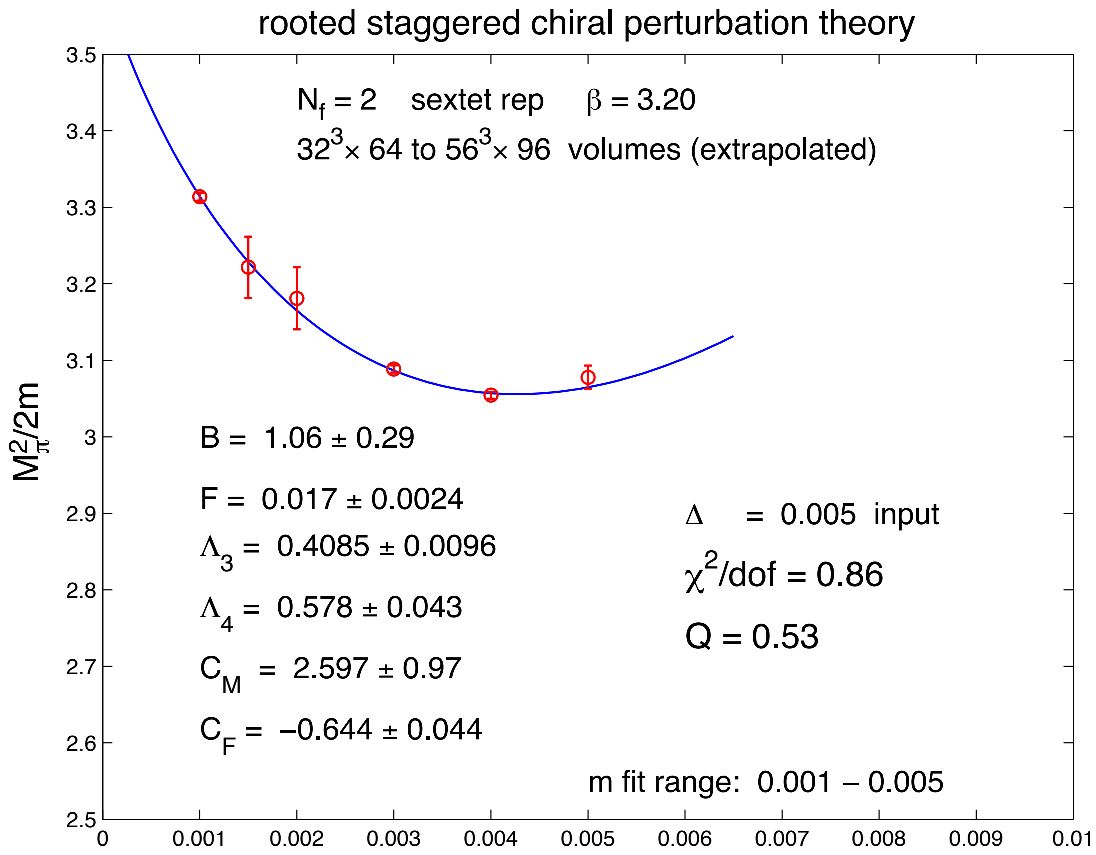
rsChiPT analysis of Mpi and Fpi

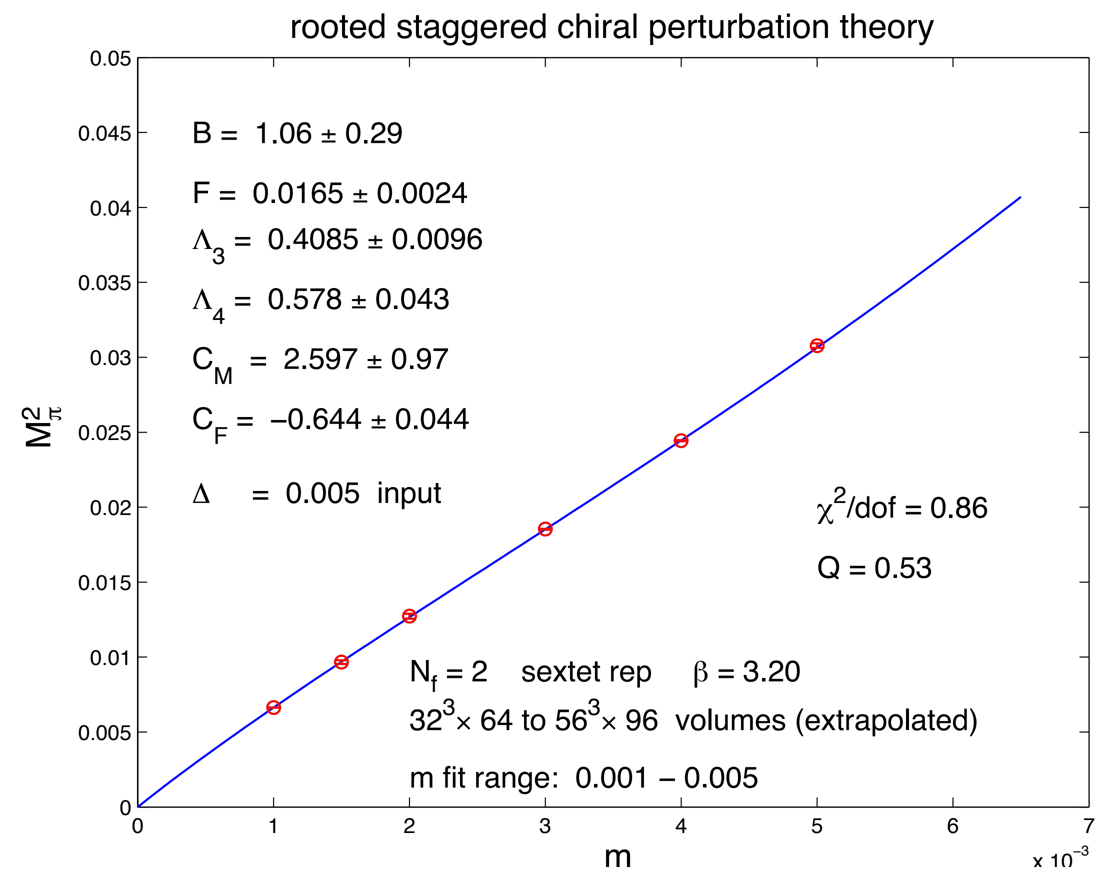
fitting functions

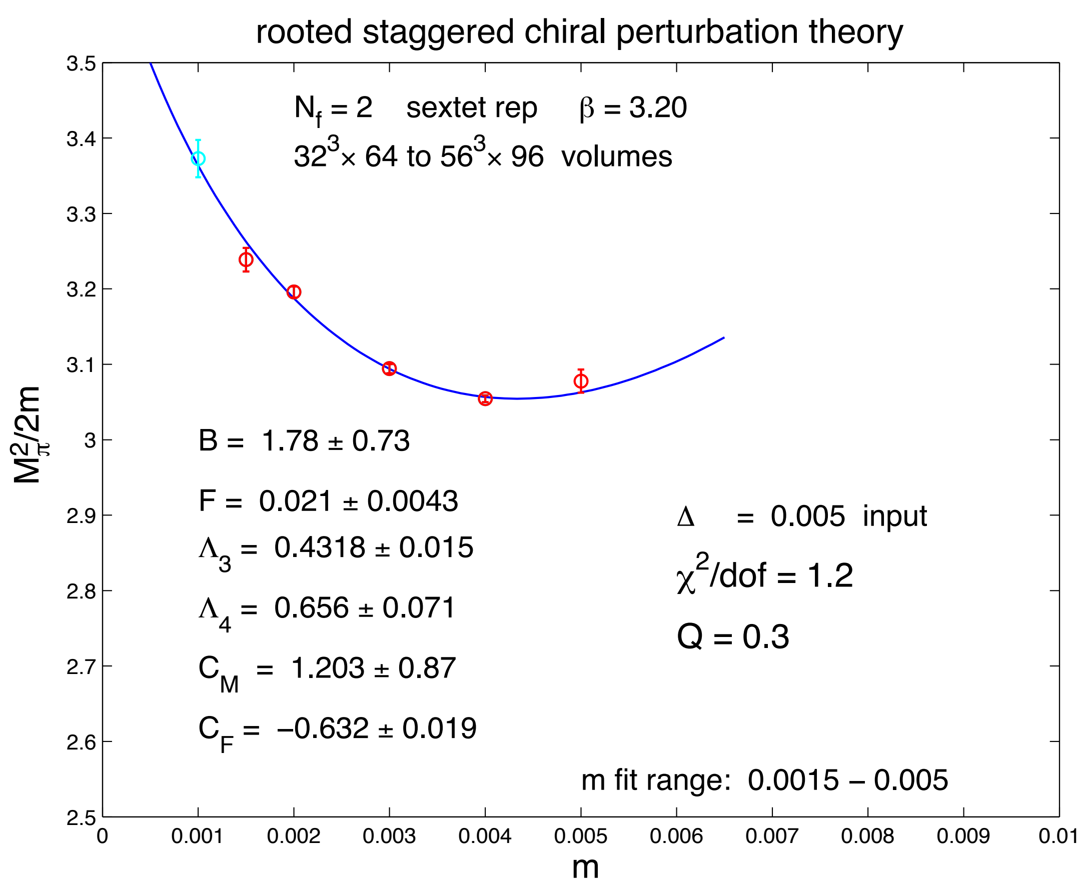
$$\frac{M_\pi^2}{2m} = B\left\{1+\frac{1}{32\pi^2F^2}\left[l(m_{U_I}^2)+4\left(l(m_{\eta'_V}^2)-l(m_{U_V}^2)\right)+4\left(l(m_{\eta'_A}^2)-l(m_{U_A}^2)\right)\right]+a^2C_M+\frac{4m\cdot B}{F^2}l_3\right\}$$

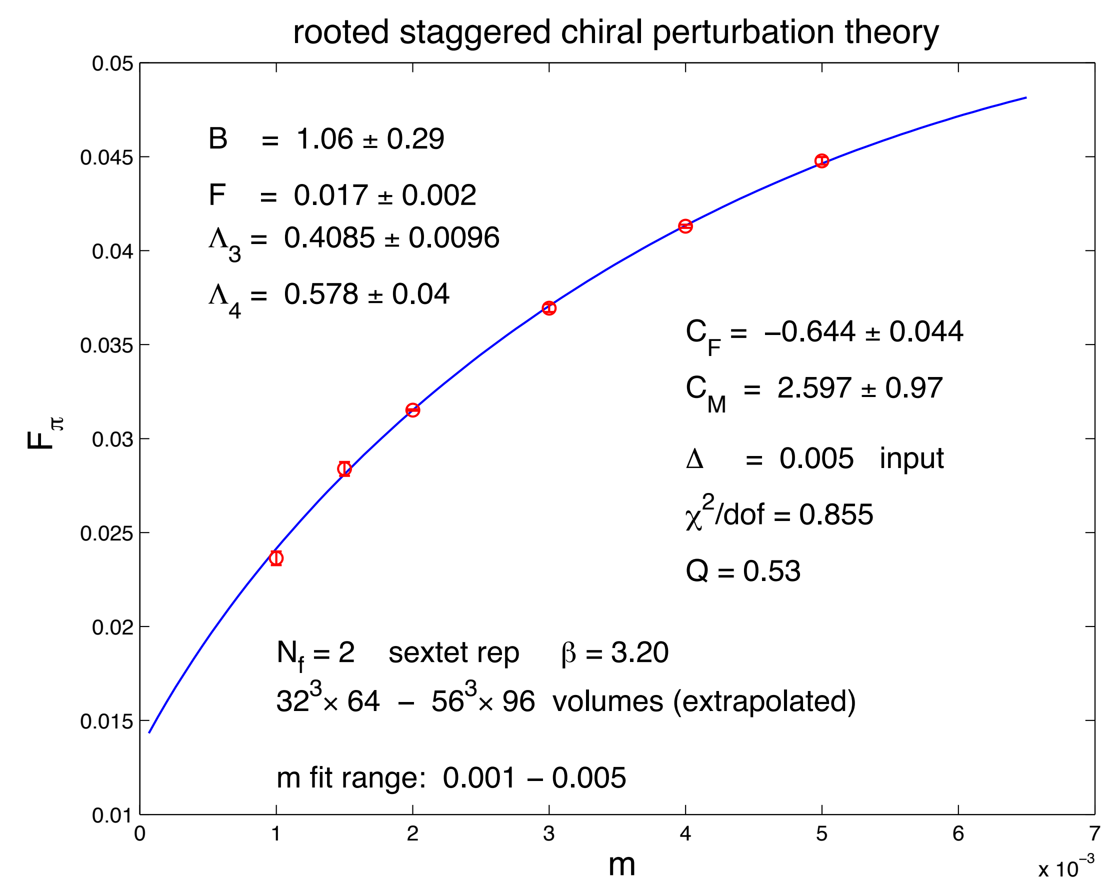
$$\begin{aligned} f_{\pi_5^+}^{1-\mathrm{loop}} &= f\left\{1+\frac{1}{16\pi^2f^2}\left[-4N_F\left(\frac{1}{16}\sum_B \ell(m_{\pi_B}^2)\right)\right.\right. \\ &\quad -\frac{2}{N_F}\left(\ell(m_{\eta'_V}^2)-\ell(m_{\pi_V}^2)\right)-\frac{2}{N_F}\left(\ell(m_{\eta'_A}^2)-\ell(m_{\pi_A}^2)\right) \\ &\quad \left.+\frac{16\mu}{f^2}\left(4N_Fm\right)L_4+\frac{8\mu}{f^2}(2m)L_5+a^2F\right\}, \end{aligned}$$

rsChiPT analysis of Mpi and Fpi   fitting results









rsChiPT analysis

taste breaking

B in our notation

from LO taste breaking ops in chiral Lagrangian

$$(m_\pi^2)_{\rm LO} = 2\mu \frac{m_i + m_j}{2} + a^2\Delta_F$$

$$(f^A)_{\rm LO} = f, \qquad (f^P)_{\rm LO} = \mu f$$

$$(m_\pi^2)_{\rm NLO} = (m_\pi^2)_{\rm LO} + (\delta m_\pi^2)_{\text{1-loop}} + (\delta m_\pi^2)_{m^2} + (\delta m_\pi^2)_{a^2 m} + (\delta m_\pi^2)_{a^4}.$$

$$(\delta m_\pi^2)_{\text{1-loop}} \sim [(m_\pi^2)_{\rm LO} + a^2]^2 \ln(m_\pi^2)_{\rm LO},$$

$$(\delta f^{A,P})_{\text{1-loop}} \sim [(m_\pi^2)_{\rm LO} + a^2] \ln(m_\pi^2)_{\rm LO}.$$

$$(\delta m_\pi^2)_{m^2} \sim m^2, \qquad (\delta m_\pi^2)_{a^2 m} \sim a^2 m, \qquad (\delta m_\pi^2)_{a^4} \sim a^4,$$

$$(\delta f^{A,P})_{m^2} \sim m, \qquad (\delta f^{A,P})_{a^2 m} \sim a^2$$

NLO analytic terms from NLO taste breaking operators

responsible for fan-out?

rsChiPT analysis

taste breaking

$$a^2(\mathcal{U} + \mathcal{U}')$$

$$-\mathcal{U} = C_1 \mathrm{Tr}(\xi_5^{(n)} \Sigma \xi_5^{(n)} \Sigma^\dagger) + C_6 \sum_{\mu<\nu} \mathrm{Tr}(\xi_{\mu\nu}^{(n)} \Sigma \xi_{\nu\mu}^{(n)} \Sigma^\dagger)$$
$$+ C_3 \tfrac{1}{2} \sum_\nu [\mathrm{Tr}(\xi_\nu^{(n)} \Sigma \xi_\nu^{(n)} \Sigma) + \mathrm{H.c.}]$$
$$+ C_4 \tfrac{1}{2} \sum_\nu [\mathrm{Tr}(\xi_{\nu 5}^{(n)} \Sigma \xi_{5\nu}^{(n)} \Sigma) + \mathrm{H.c.}],$$

LO SO(4) symmetric

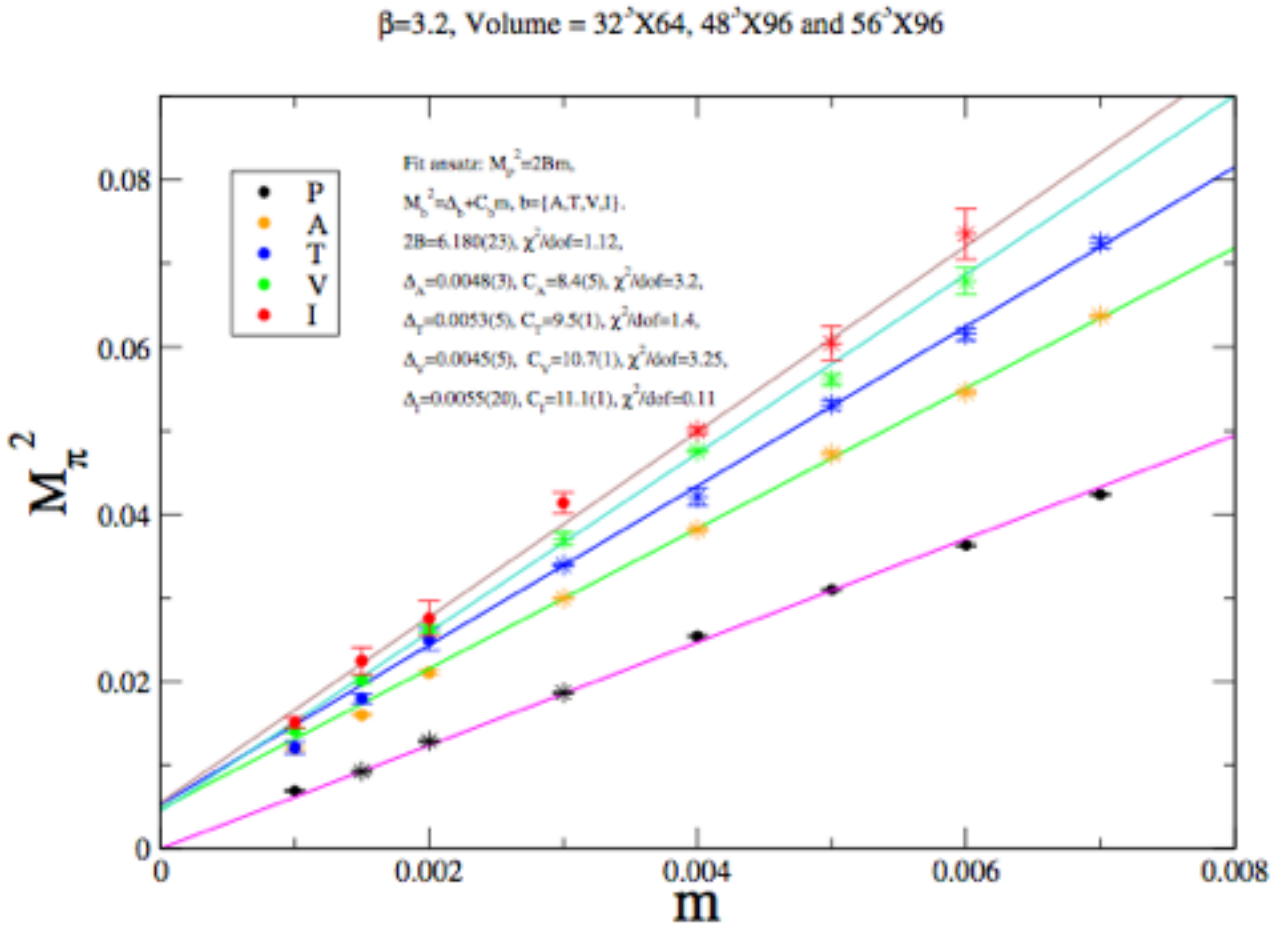
$$-\mathcal{U}' = C_{2V} \tfrac{1}{4} \sum_\nu [\mathrm{Tr}(\xi_\nu^{(n)} \Sigma) \mathrm{Tr}(\xi_\nu^{(n)} \Sigma) + \mathrm{H.c.}]$$
$$+ C_{2A} \tfrac{1}{4} \sum_\nu [\mathrm{Tr}(\xi_{\nu 5}^{(n)} \Sigma) \mathrm{Tr}(\xi_{5\nu}^{(n)} \Sigma) + \mathrm{H.c.}]$$
$$+ C_{5V} \tfrac{1}{2} \sum_\nu [\mathrm{Tr}(\xi_\nu^{(n)} \Sigma) \mathrm{Tr}(\xi_\nu^{(n)} \Sigma^\dagger)]$$
$$+ C_{5A} \tfrac{1}{2} \sum_\nu [\mathrm{Tr}(\xi_{\nu 5}^{(n)} \Sigma) \mathrm{Tr}(\xi_{5\nu}^{(n)} \Sigma^\dagger)],$$

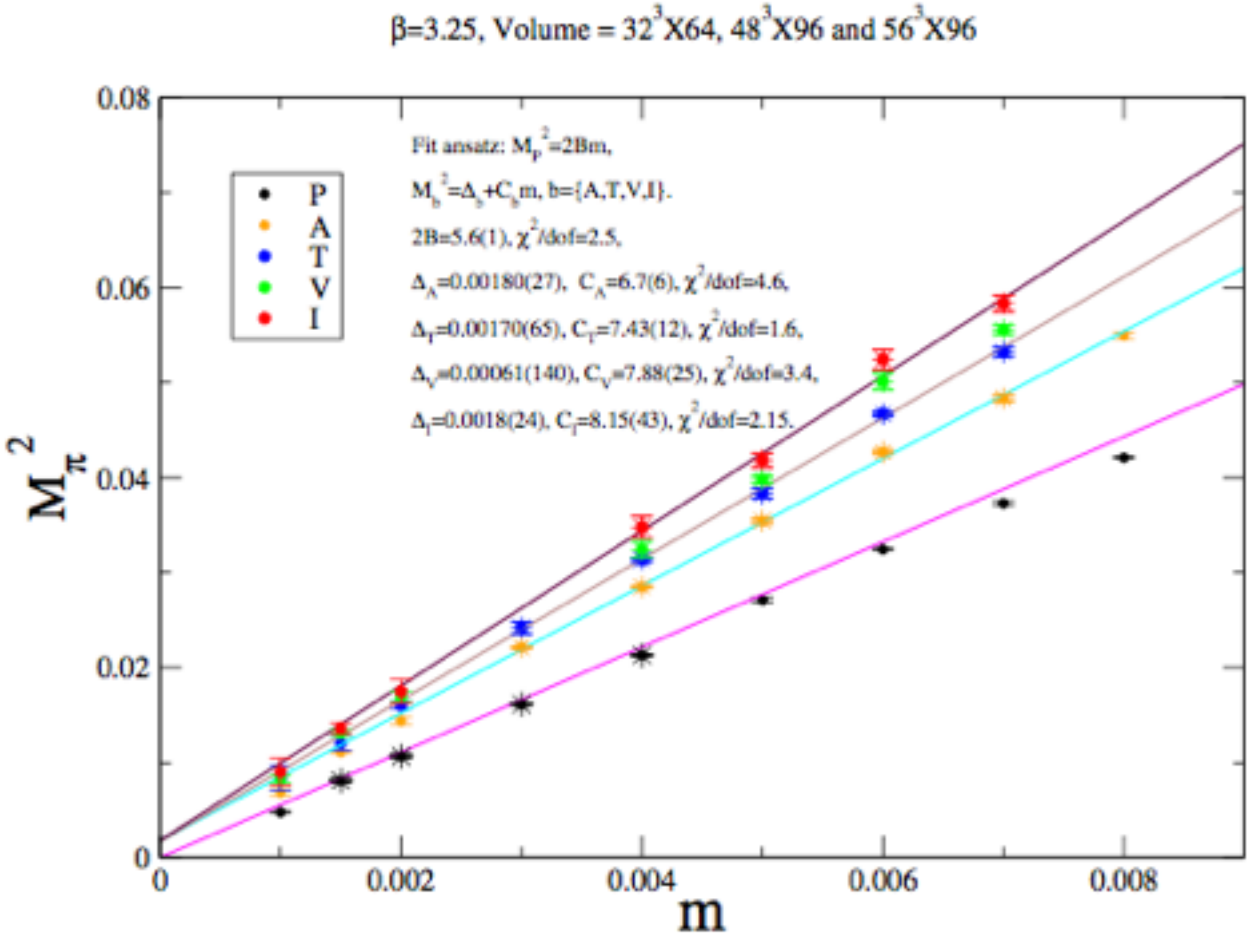
$$a^2 \sum_\mu \sum_{\nu\neq\mu} \{C_2 \mathrm{Str}(\partial_\mu \Sigma^\dagger \xi_{\mu\nu} \partial_\mu \Sigma \xi_{\nu\mu}) + C_7 \mathrm{Str}(\Sigma \partial_\mu \Sigma^\dagger \xi_{\mu\nu}) \mathrm{Str}(\Sigma^\dagger \partial_\mu \Sigma \xi_{\nu\mu}) + C_{10}[\mathrm{Str}(\Sigma \partial_\mu \Sigma^\dagger \xi_{\mu\nu} \Sigma \partial_\mu \Sigma^\dagger \xi_{\nu\mu}) + \mathrm{p.c.}]$$
$$+ C_{13}[\mathrm{Str}(\Sigma \partial_\mu \Sigma^\dagger \xi_{\mu\nu}) \mathrm{Str}(\Sigma \partial_\mu \Sigma^\dagger \xi_{\nu\mu}) + \mathrm{p.c.}]\} + a^2 \sum_\mu \{C_{36V} \mathrm{Str}(\Sigma \partial_\mu \Sigma^\dagger \xi_\mu \Sigma^\dagger \partial_\mu \Sigma \xi_\mu)$$
$$+ C_{36A} \mathrm{Str}(\Sigma \partial_\mu \Sigma^\dagger \xi_{\mu 5} \Sigma^\dagger \partial_\mu \Sigma \xi_{5\mu}) + C_{41V} \mathrm{Str}(\partial_\mu \Sigma^\dagger \xi_\mu) \mathrm{Str}(\partial_\mu \Sigma \xi_\mu)$$
$$+ C_{41A} \mathrm{Str}(\partial_\mu \Sigma^\dagger \xi_{\mu 5}) \mathrm{Str}(\partial_\mu \Sigma \xi_{5\mu})\}.$$

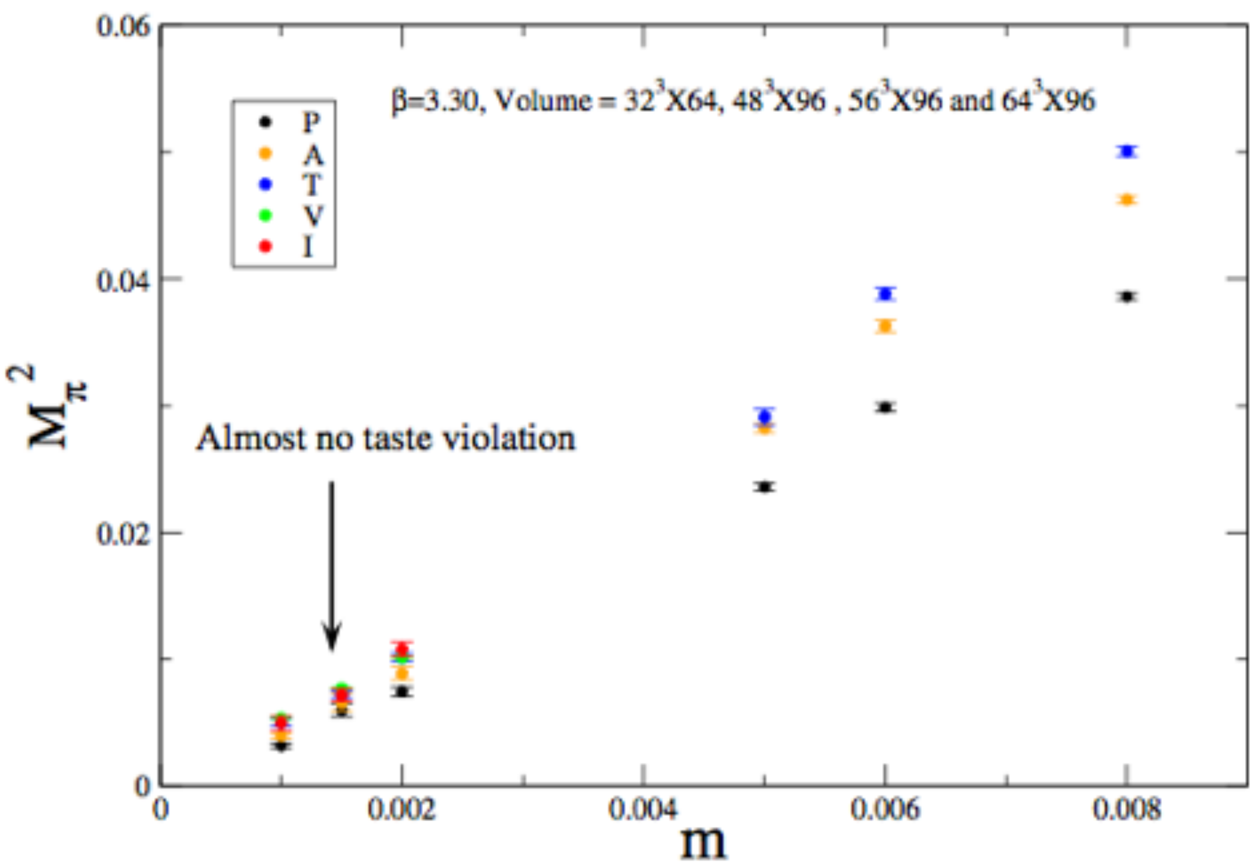
NLO SO(4) non-symmetric

rsChiPT analysis

taste breaking







$$M^2_{\pi_b^{+/-}} = 2B(m_u+m_d) + a^2\Delta(\xi_b) \text{ taste label b } \in \{5, \mu 5, \mu\nu, \mu, I\}$$

$$C_1 = C_3 = C_4 = C_6 = \frac{\Delta f^2}{128}$$

The SχPT prediction for taste breaking of Goldstone and non-Goldstone pion masses at NLO can be expressed as,

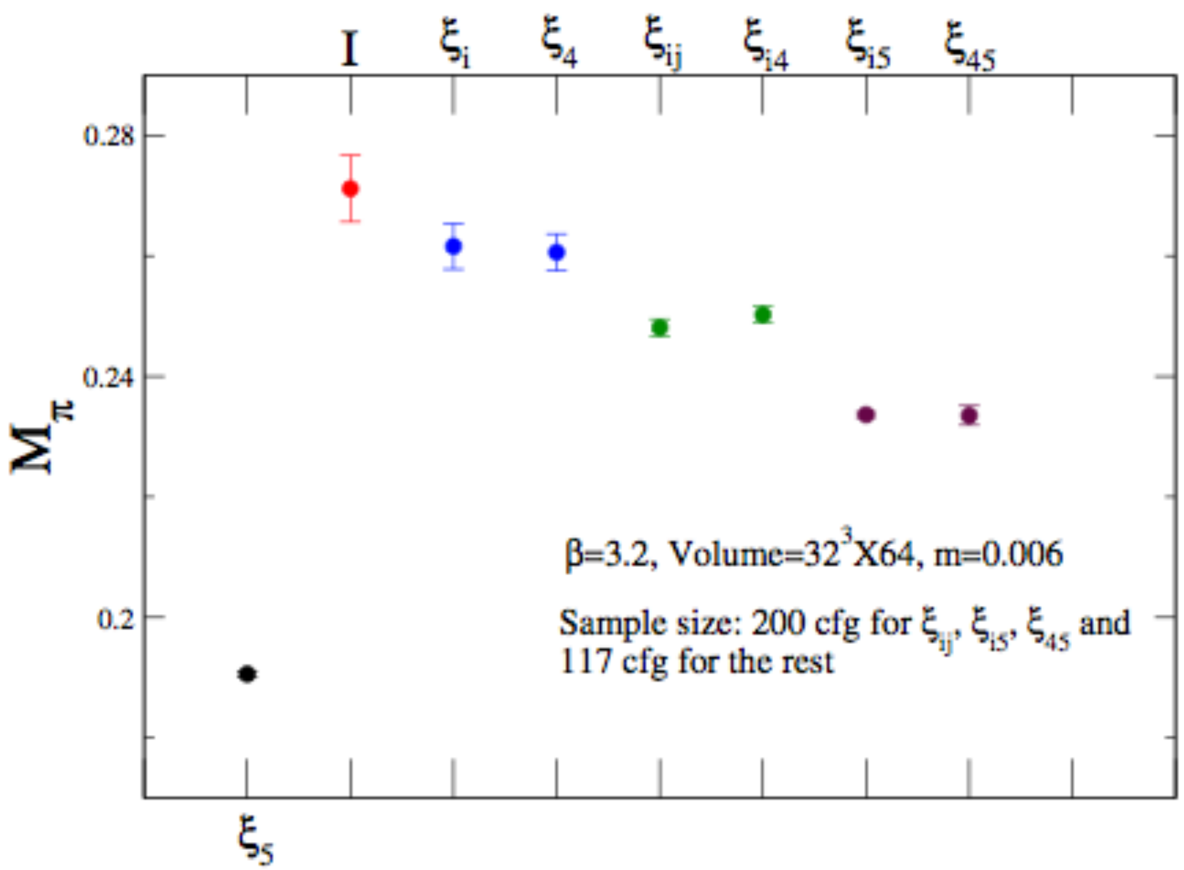
$$M^2_{NLO} = M^2_{LO}(1+\delta_{b'}) \text{ taste label b}' \in \{5, i5, 45, ij, i4, i, 4, I\},$$

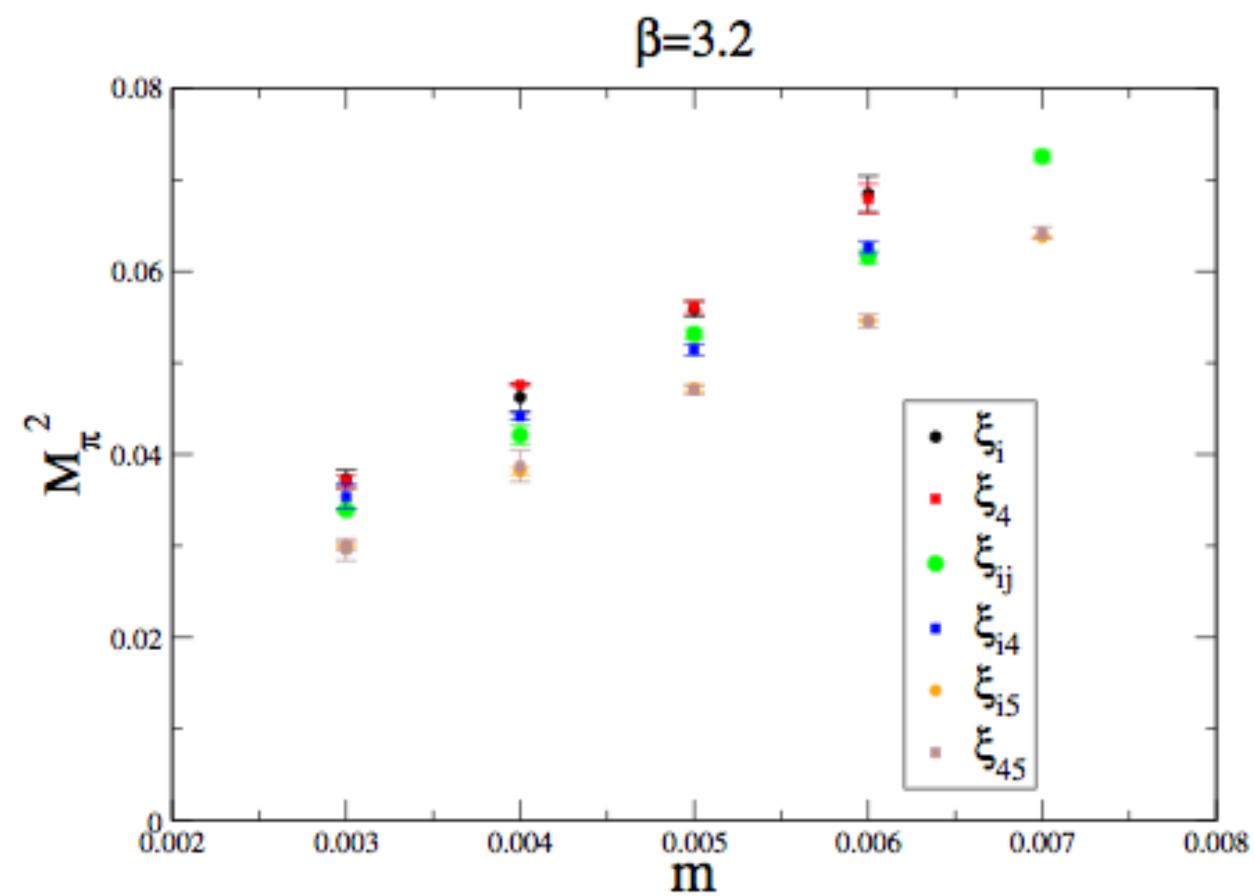
and $\delta_{b'} \sim \mathcal{O}(a^2)$.

rsChiPT analysis

SO(4) taste symmetry is approximate

Data show three almost degenerate pairs, {i5,45}, {ij, i4}, {i,4}





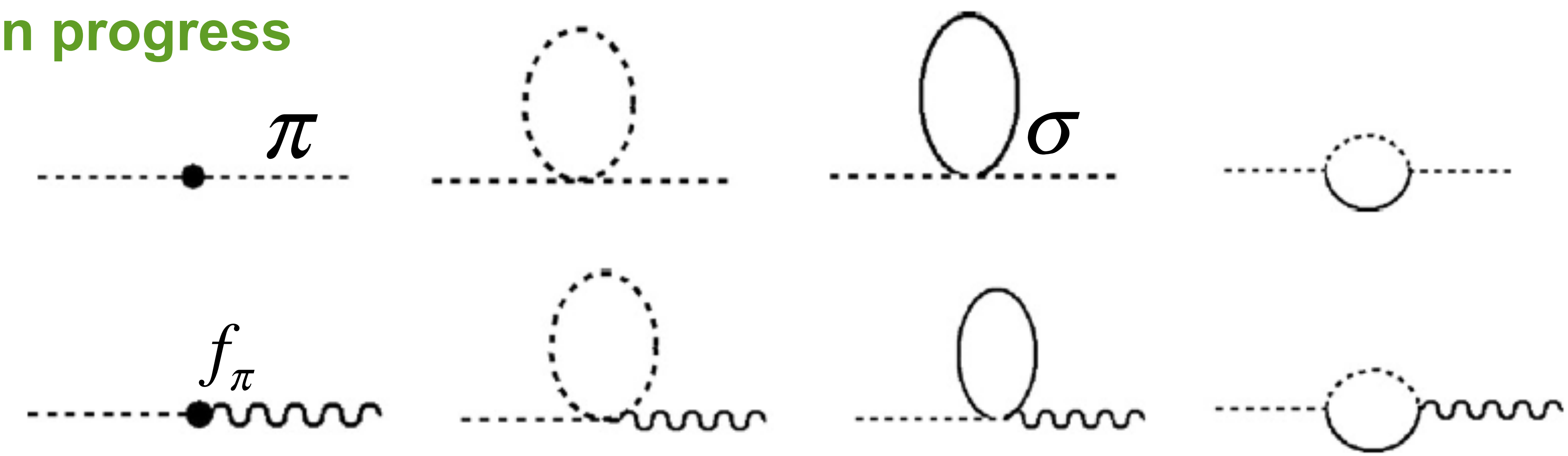
two outstanding spectroscopy problems:

1. effective low energy theory for Goldstone dynamics coupled to the low mass scalar nonlinear sigma model or dilaton?

2. effect of slow topology on the analysis

Goldstone dynamics coupled to low mass scalar

work in progress



$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right] \qquad \Sigma = e^{i\sigma_a \pi^a / v}$$

$$V(h) = \frac{1}{2}m_h^2 h^2 + d_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4 \frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots$$

M_π, F_π, M_σ are calculated now to 1-loop: extended chiral SU(2) flavor dynamics

We are analyzing the small pion mass region in the $M_\pi = 0.07 - 0.013$ range of the p-regime, and lower in the RMT regime

To reach the nonlinear sigma model range requires very small pion masses

cutoff effects from taste breaking?

pion mass and decay constant slow topology

$$m_\pi^2(\theta)|_{rmNLO} = m_\pi^2(\theta)\left[1+\left(\frac{m_\pi(\theta)}{4\pi f}\right)^2\left(\ln\left(\frac{m_\pi(\theta)}{m_\pi^{\rm phys}}\right)^2-\bar{l}_3^{\rm phys}\right)\right],$$

$$f_\pi(\theta)|_{rmNLO} = f\left[1-2\left(\frac{m_\pi(\theta)}{4\pi f}\right)^2\left(\ln\left(\frac{m_\pi(\theta)}{m_\pi^{\rm phys}}\right)^2-\bar{l}_4^{\rm phys}\right)\right],$$

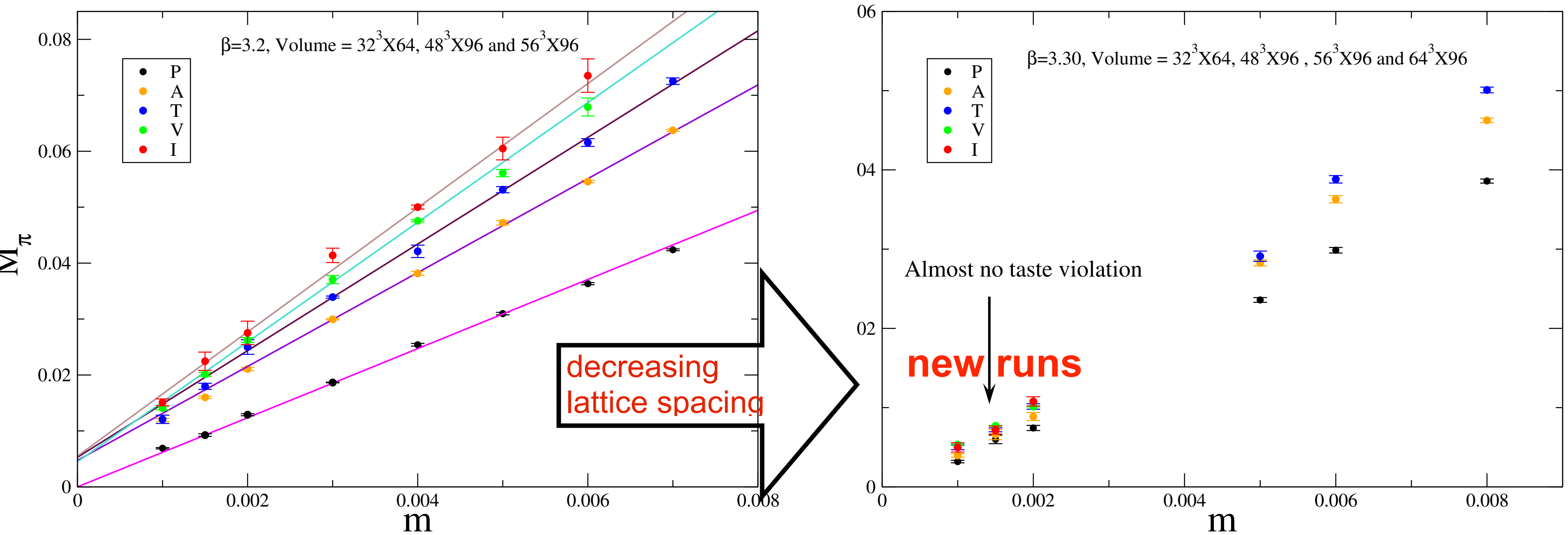
$$m_\pi^2(\theta)\equiv 2B_0m_q\cos\left(\frac{\theta}{N_f}\right)$$

$$\frac{m_\pi^{Q_{\rm top}=0}}{m_\pi(\theta=0)} = 1-\frac{1}{16V\chi_t}\left[1+\left(\frac{m_\pi^{\rm tree}(\theta=0)}{4\pi f}\right)^2\left(\ln\left(\frac{m_\pi^{\rm tree}(\theta=0)}{m_\pi^{\rm phys}}\right)^2-\bar{l}_3^{\rm phys}+1\right)\right],$$

$$\frac{f_\pi^{Q_{\rm top}=0}}{f_\pi(\theta=0)} = 1+\frac{1}{4V\chi_t}\left(\frac{m_\pi^{\rm tree}(\theta=0)}{4\pi f}\right)^2\left(\ln\left(\frac{m_\pi^{\rm tree}(\theta=0)}{m_\pi^{\rm phys}}\right)^2-\bar{l}_4^{\rm phys}+1\right),$$

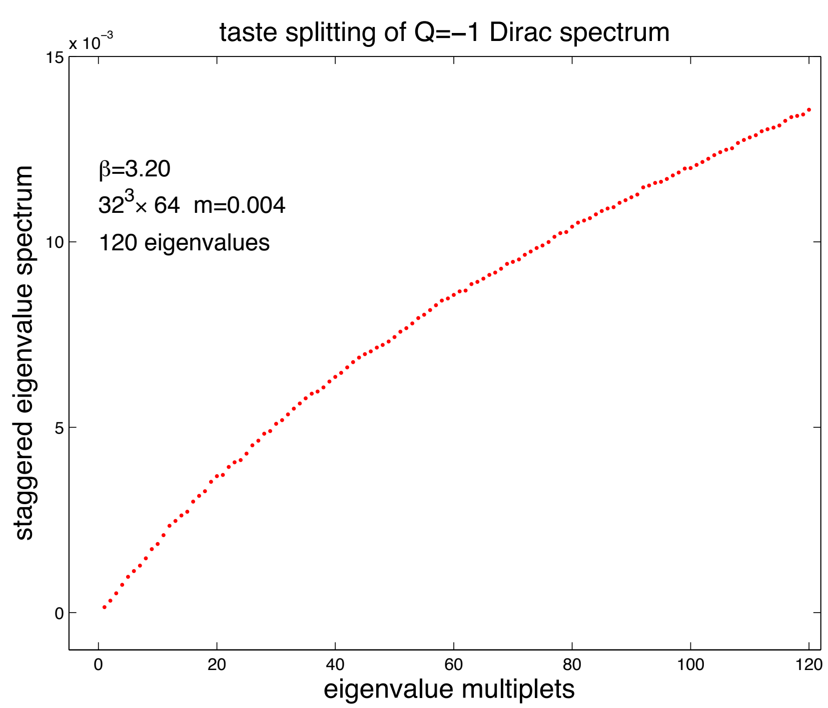
$$m_\pi^{\rm tree}(\theta)^2 = 2B_0m_q\cos(\theta/N_f)$$

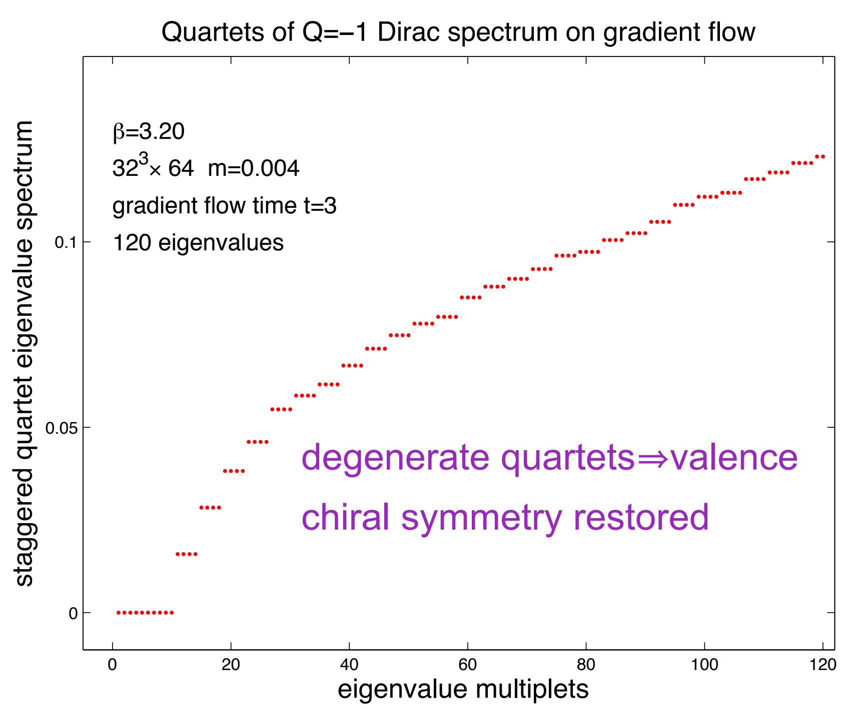
taste breaking and mixed action

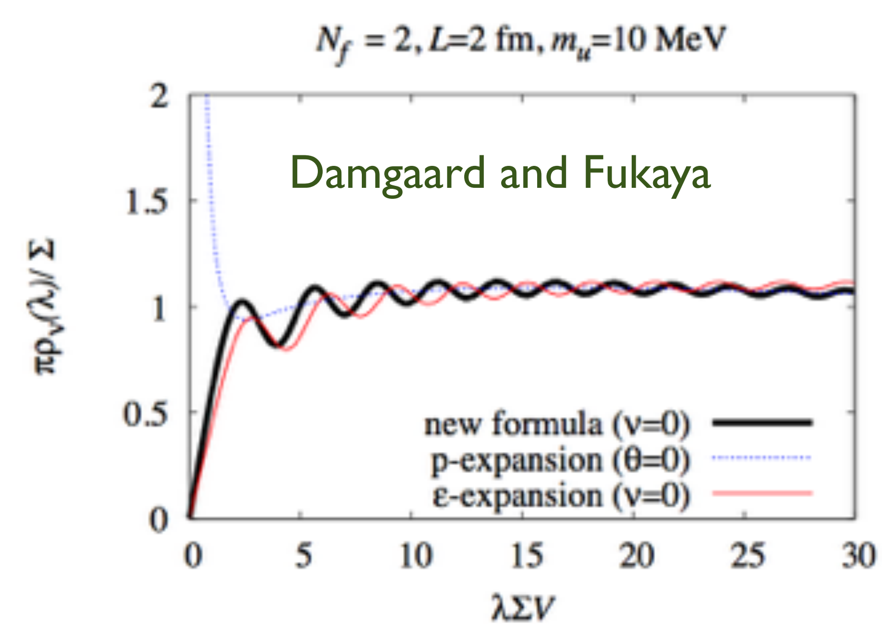


idea for improvement:

- 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!

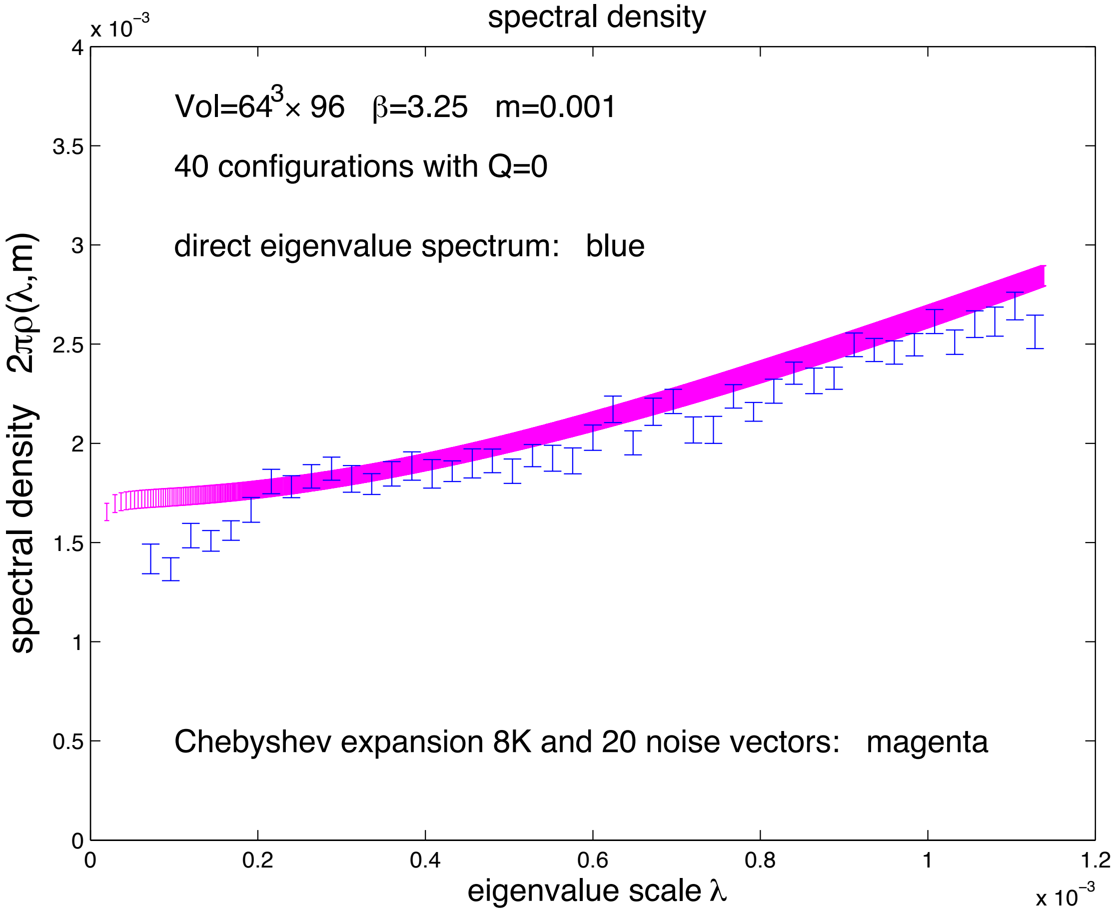


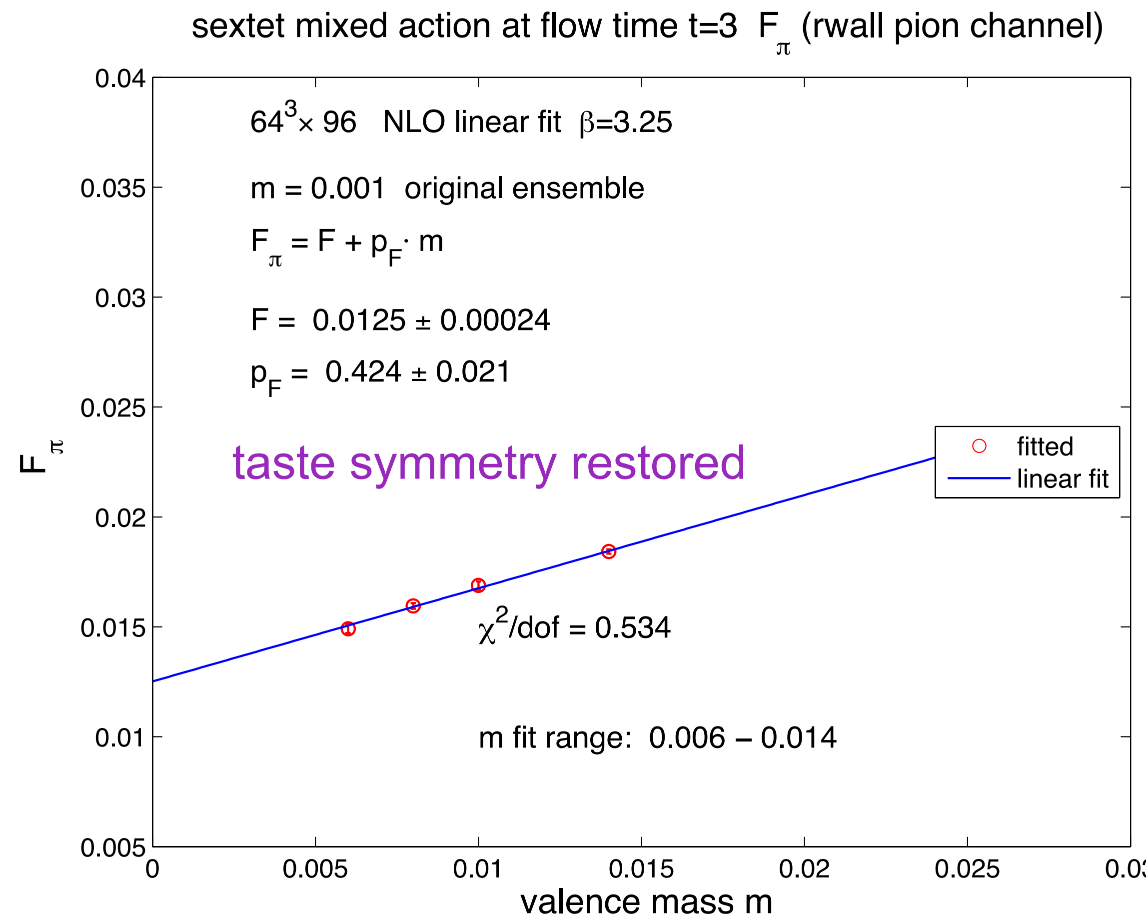


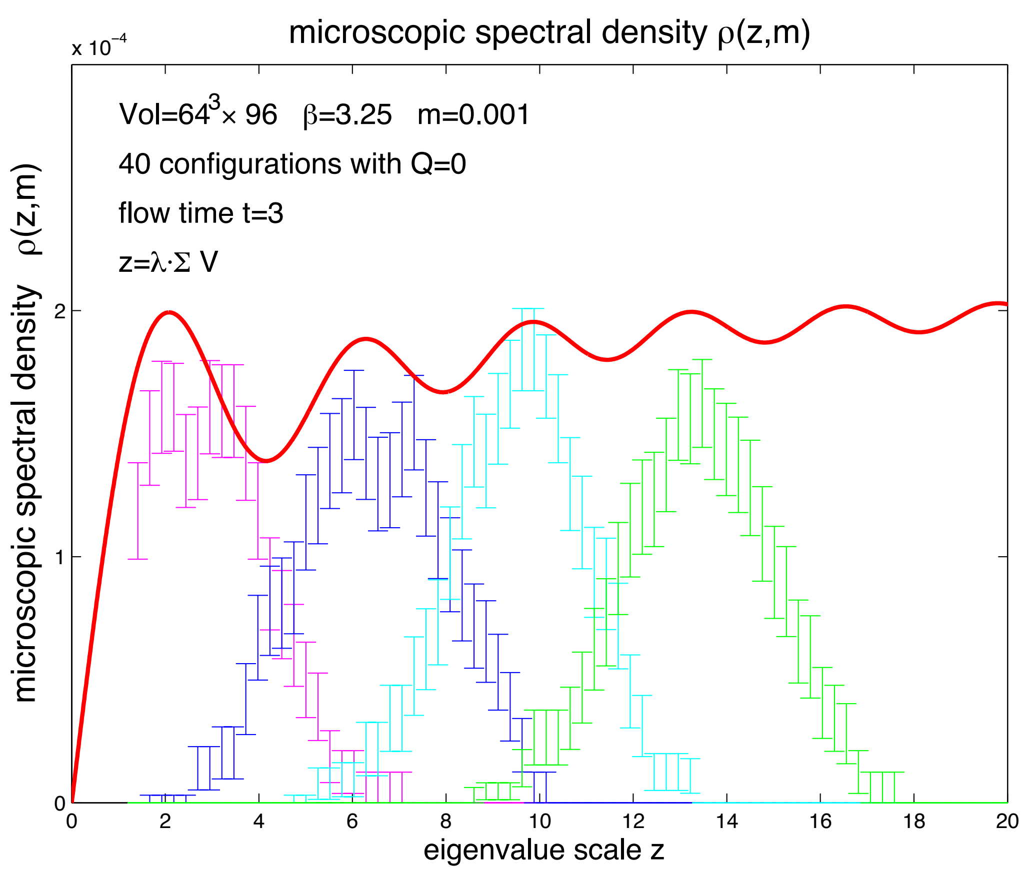


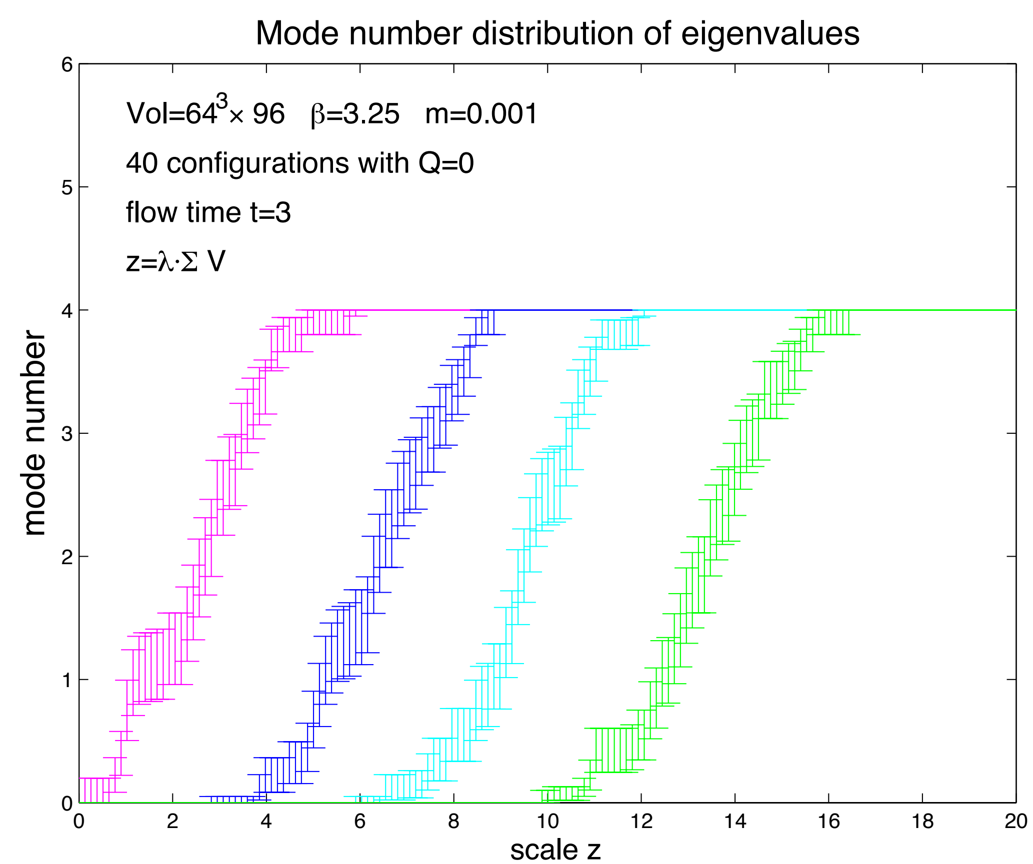
new analysis in crossover and RMT regime opens up with mixed action on gradient flow

taste breaking and mixed action RMT regime









The chiral condensate new method

chiral condensate and RG: mode number distribution of Dirac spectrum

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

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

$$\nu_R(M_R,m_R) = \nu(M,m\ \ )$$

renormalized and RG invariant

(Giusti and Luscher)

L_{at}HC publication SCGT15

for method and results: Lattice 2015 Poster Session

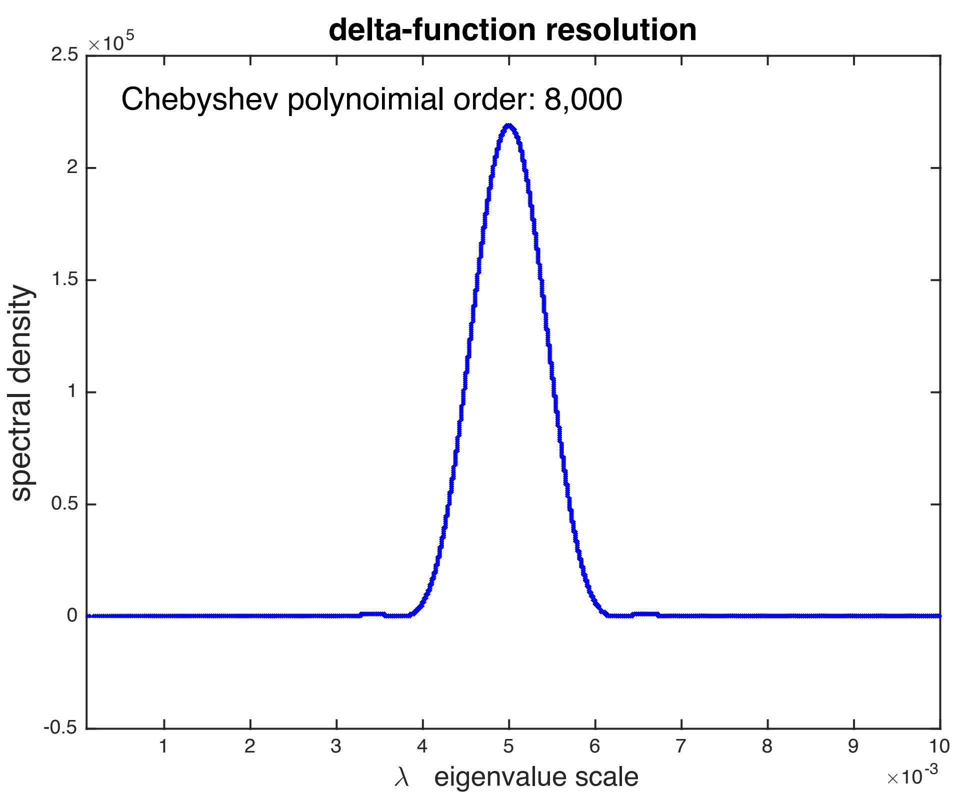
spectral density ρ(t) from ensemble averages over the $D^\dagger D$ matrix with dimension N

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

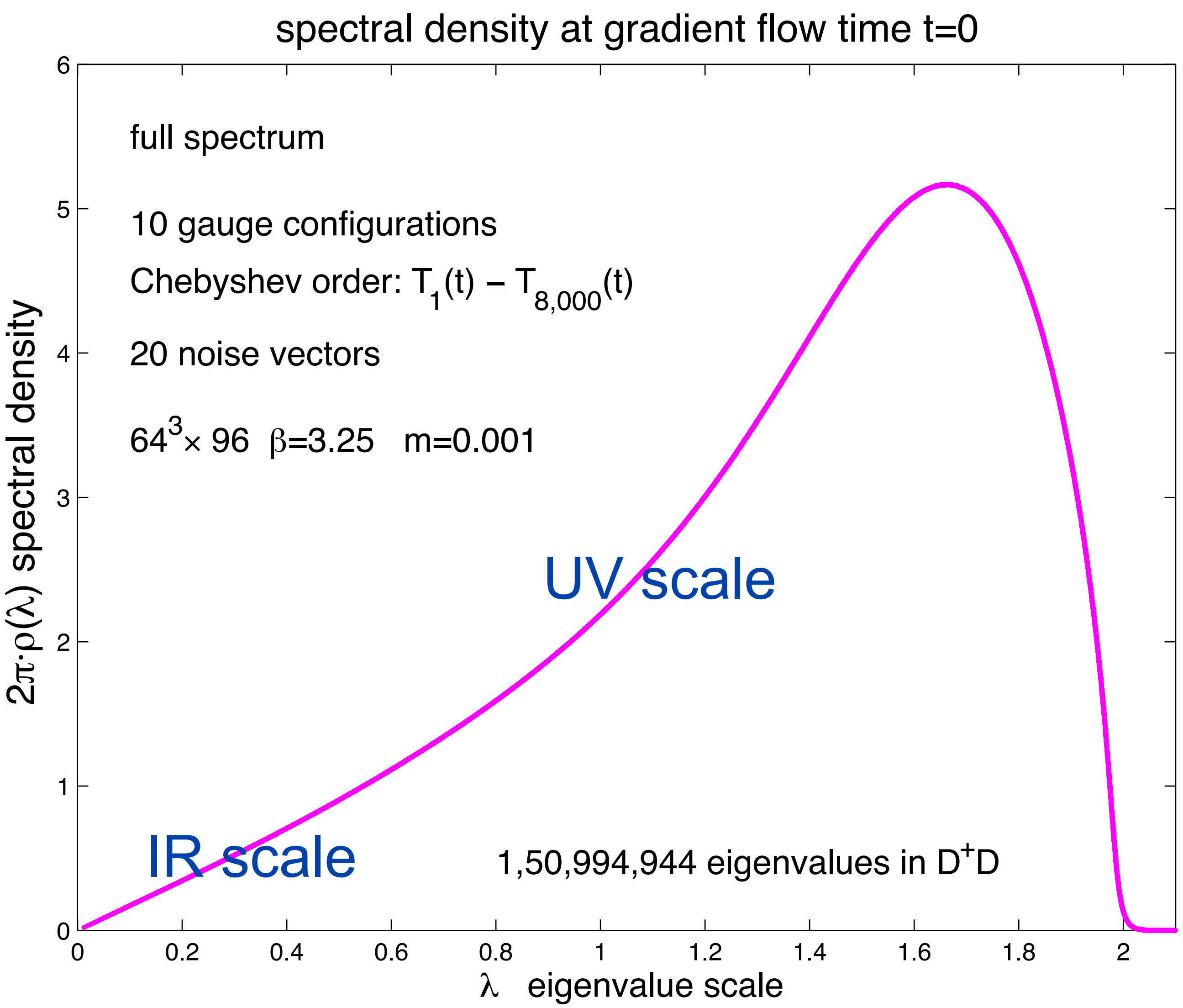
$$\rho(t) = \frac{1}{\sqrt{1-t^2}}\sum_{k=0}^{\infty}c_k T_k(t)$$ expansion in Cebyshev polynomials

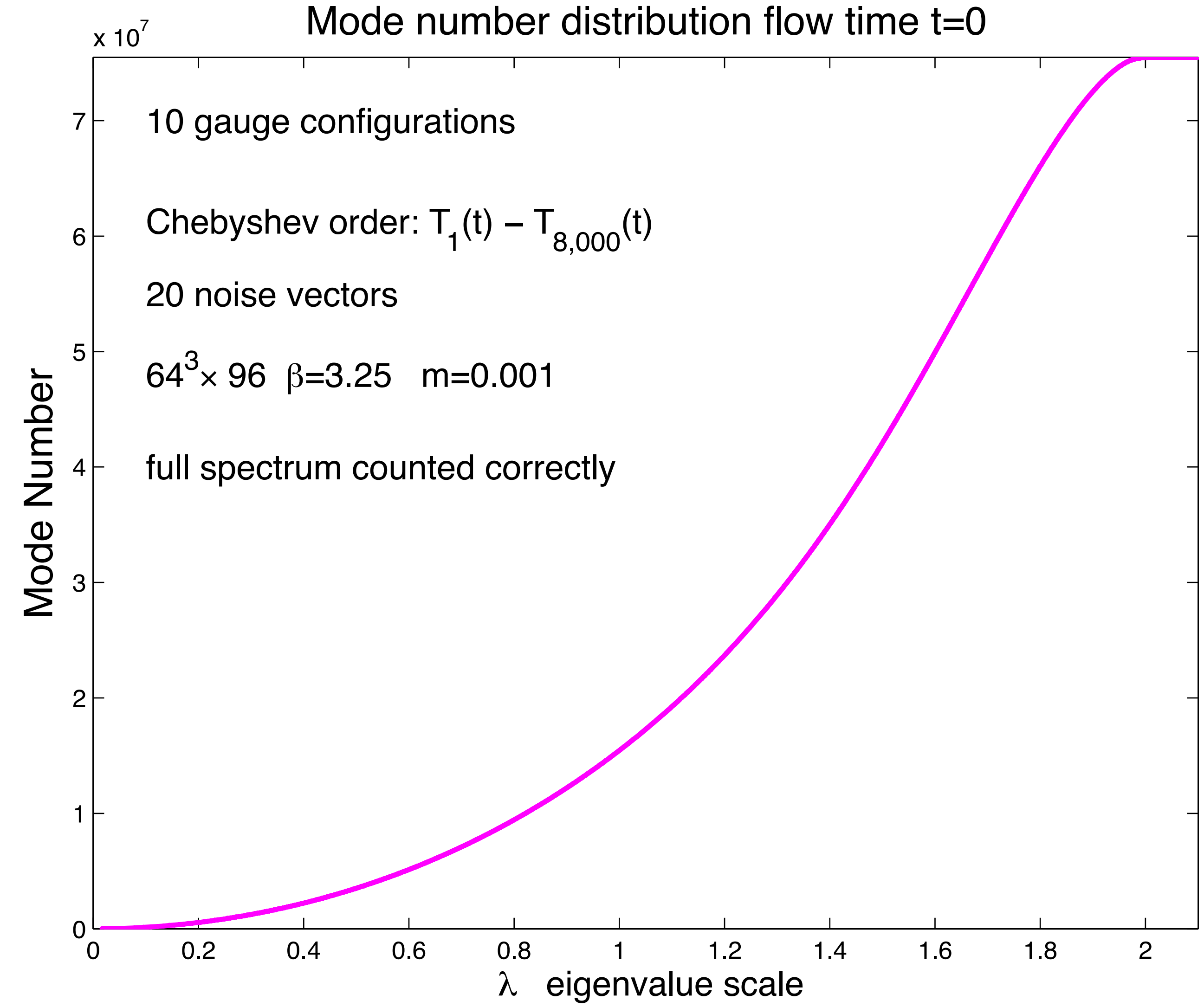
$$c_k = \begin{cases} \frac{2}{\pi}\int_{-1}^{1}T_k(t)\rho(t) & \mathrm{k}=0 \\ \frac{1}{\pi}\int_{-1}^{1}T_k(t)\rho(t) & \mathrm{k}\neq 0 \end{cases} \Rightarrow c_k = \begin{cases} \frac{2}{N\pi}\sum_{i=1}^{N}T_k(\lambda^2{}_i) & \mathrm{k}=0 \\ \frac{1}{N\pi}\sum_{i=1}^{N}T_k(\lambda^2{}_i) & \mathrm{k}\neq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

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



The chiral condensate full spectrum t=0

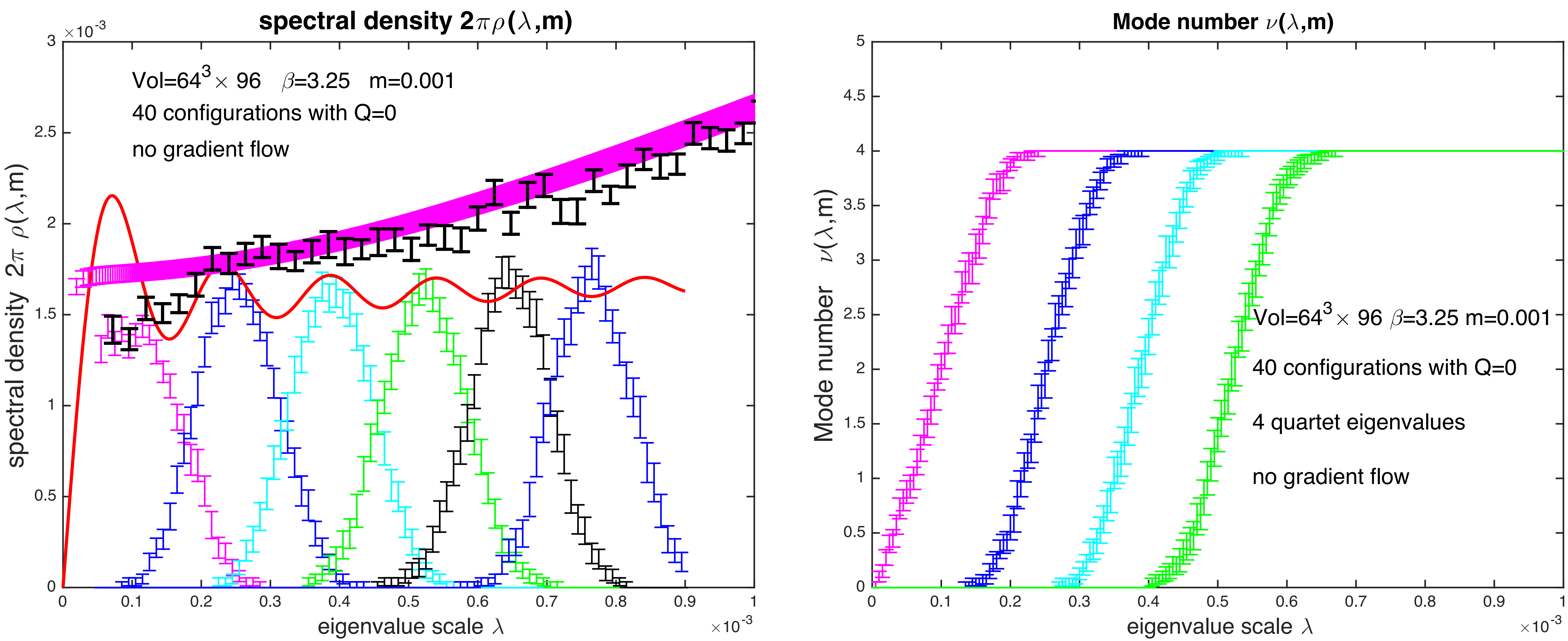




- nf=2 sextet example illustrates results from the Chebyshev expansion
- full spectrum with 8,000 Chebyshev polynomials in the expansion
- the integrated spectral density counts the sum of all eigenmodes correctly
- Jackknife errors are so small that they are not visible in the plots.

The chiral condensate RMT spectrum t=0

reached on original configurations without flow, or MA:

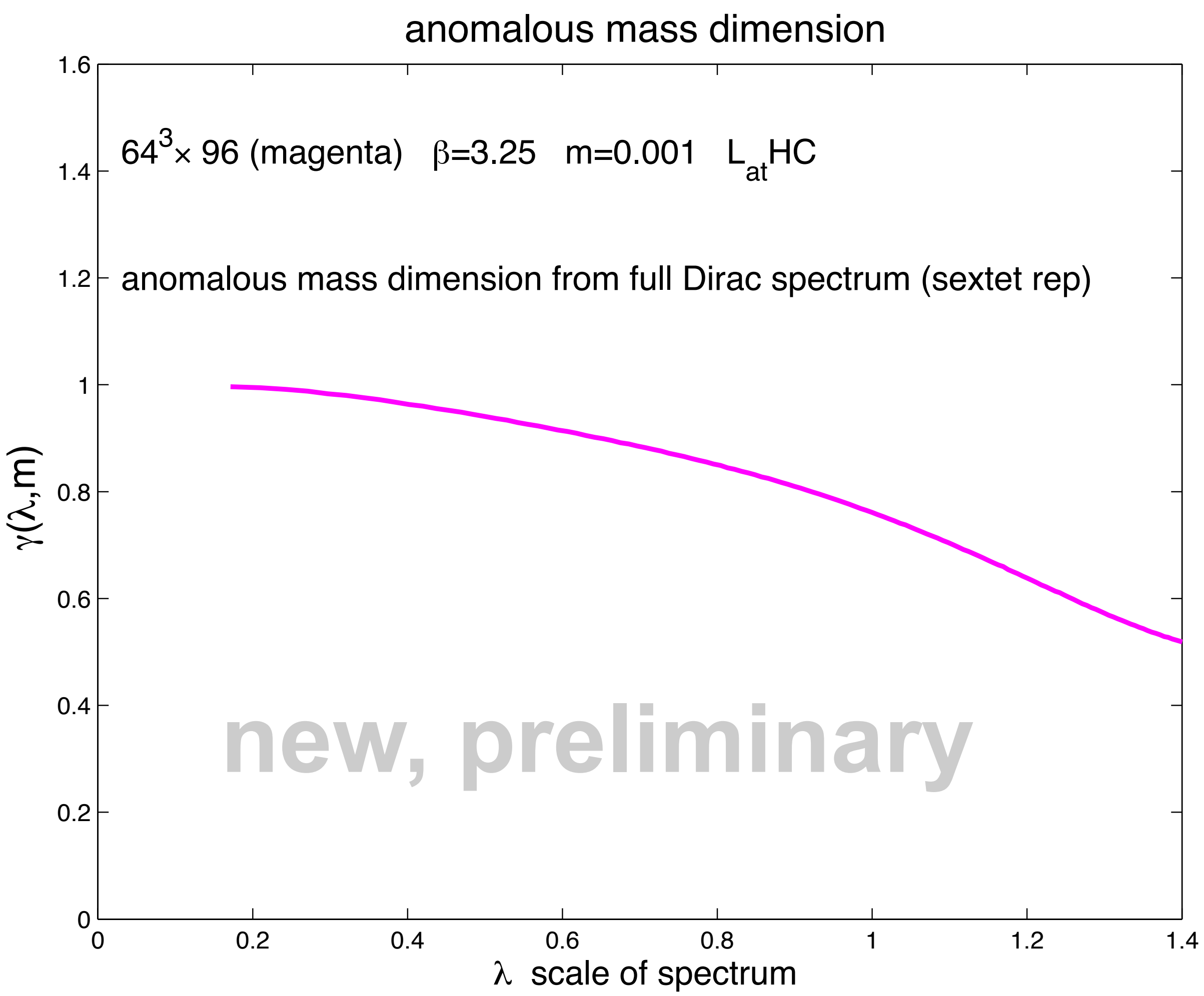


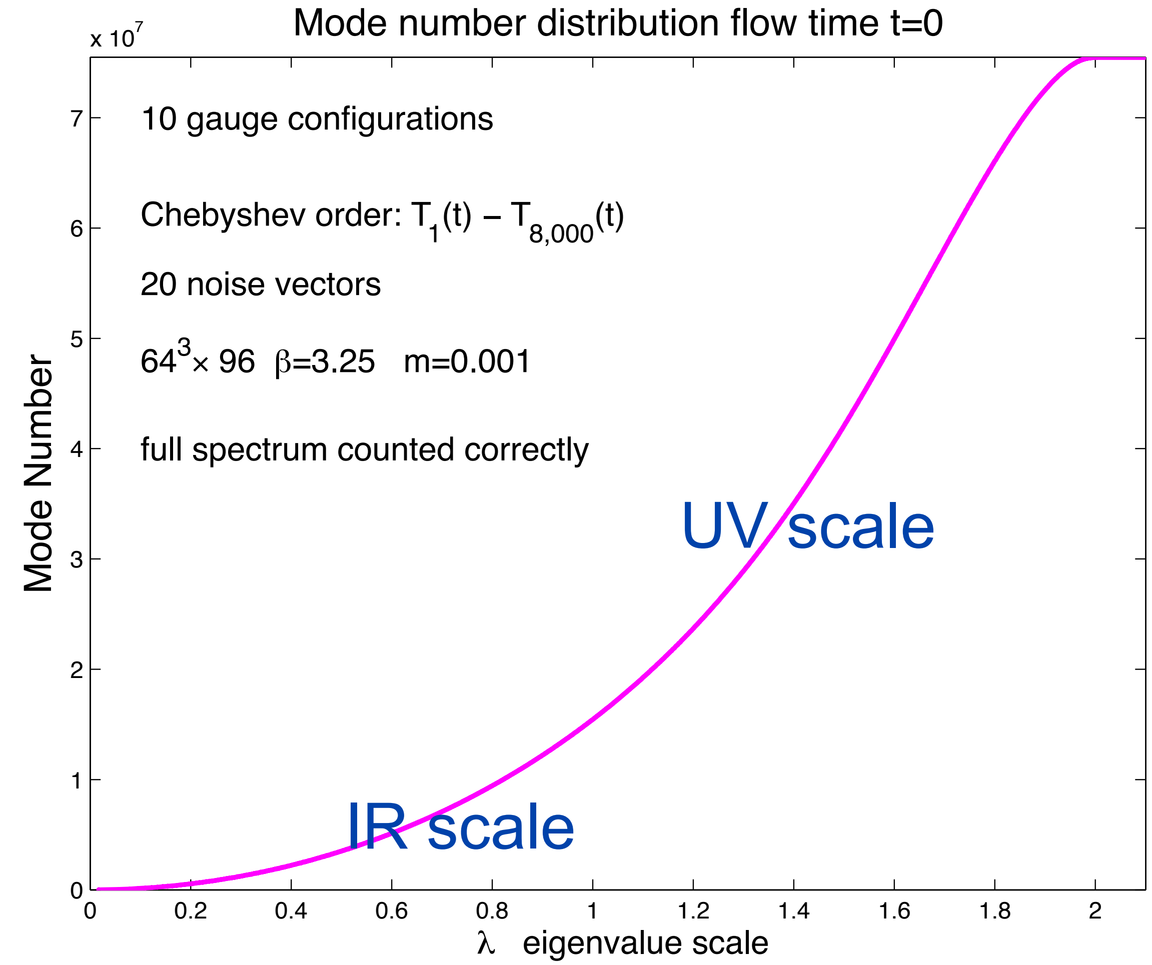
The chiral condensate mass anomalous dimension

Del Debbio and collaborators and Boulder group pioneered fitting procedures

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

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

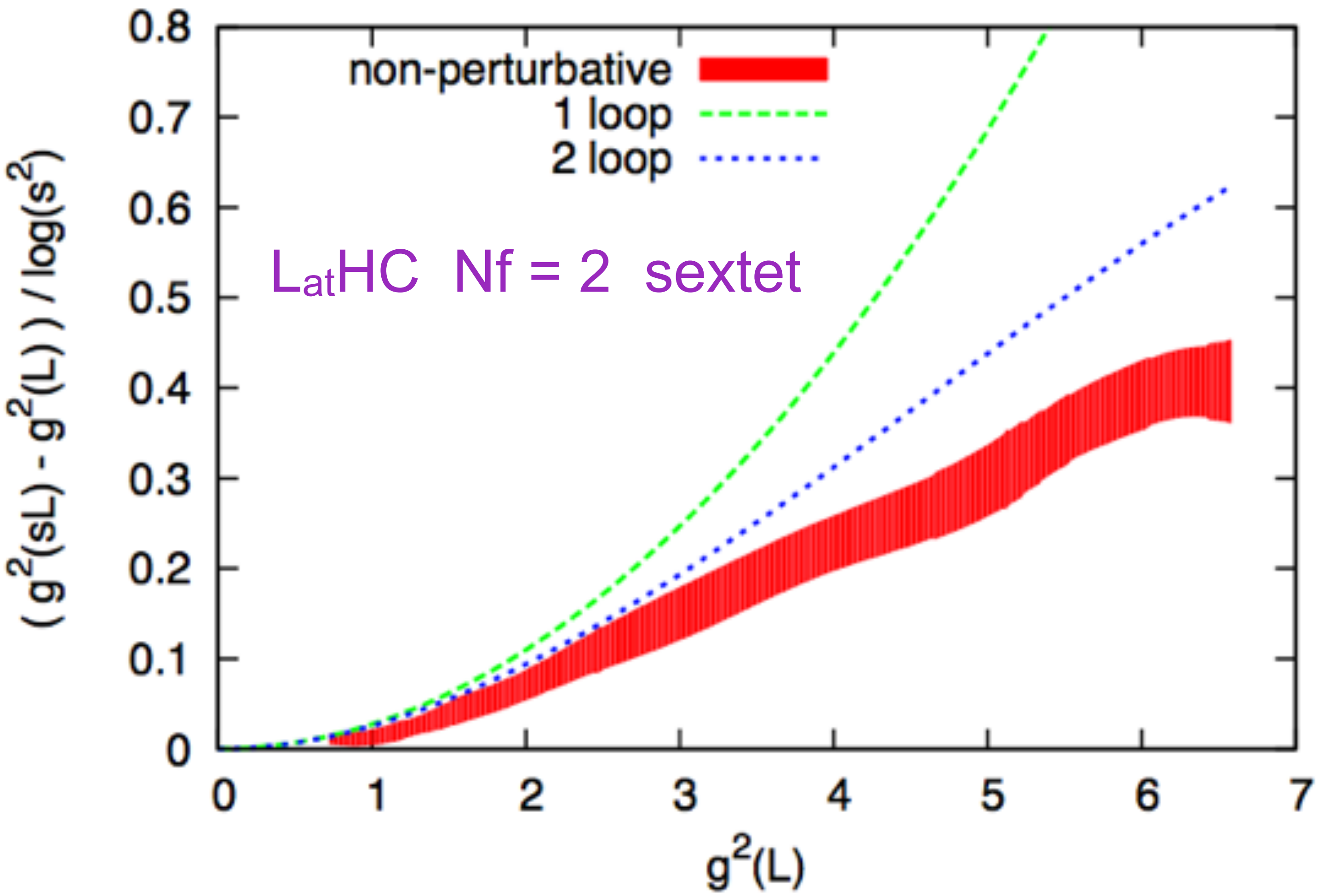




How to match λ scale and g^2 ?

the running coupling and the β function   finite volume

arXiv:1506.06599
The running coupling of the minimal sextet composite Higgs model
Zoltan Fodor, Kieran Holland, Julius Kuti, Santanu Mondal, Daniel Nogradi, Chik Him Wong



no sign of IRFP zero in step beta function in explored range

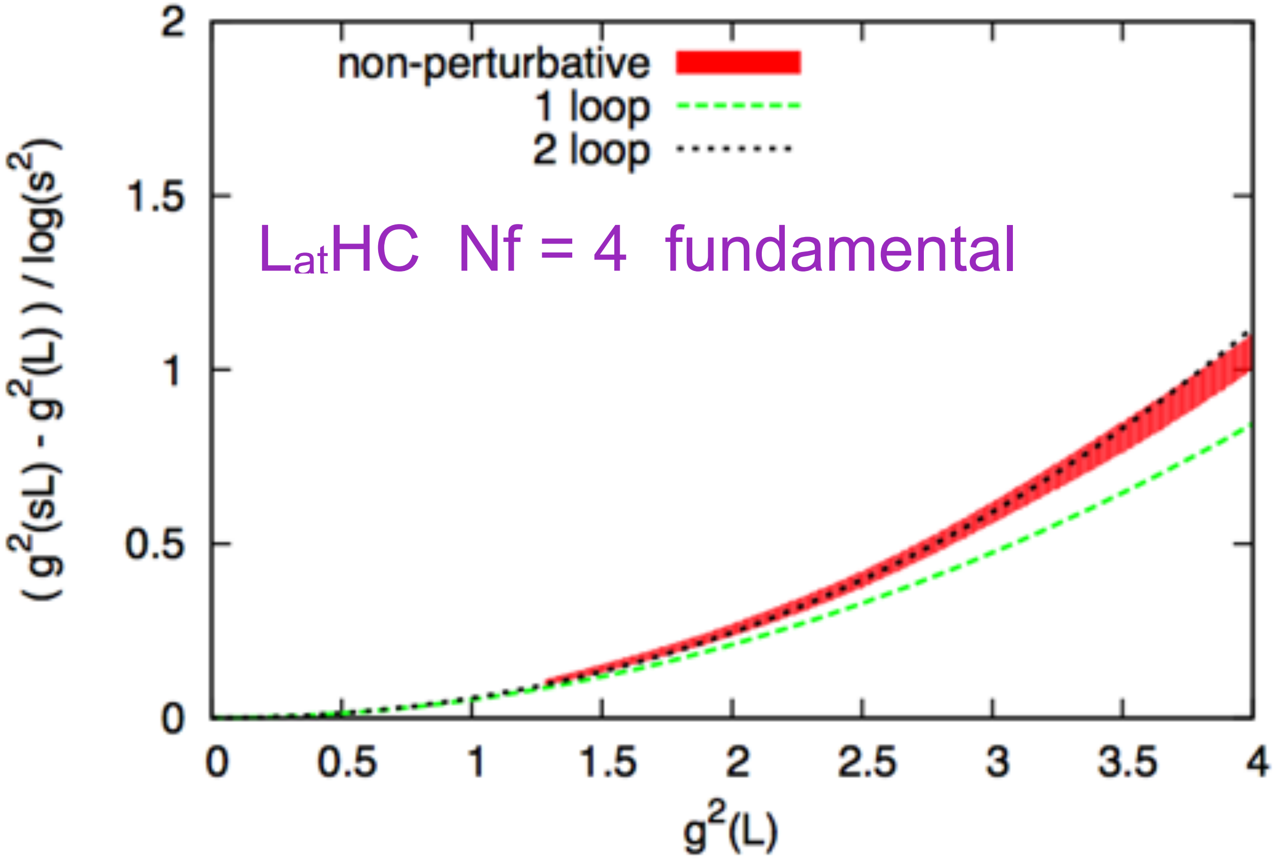
Control on systematics is important

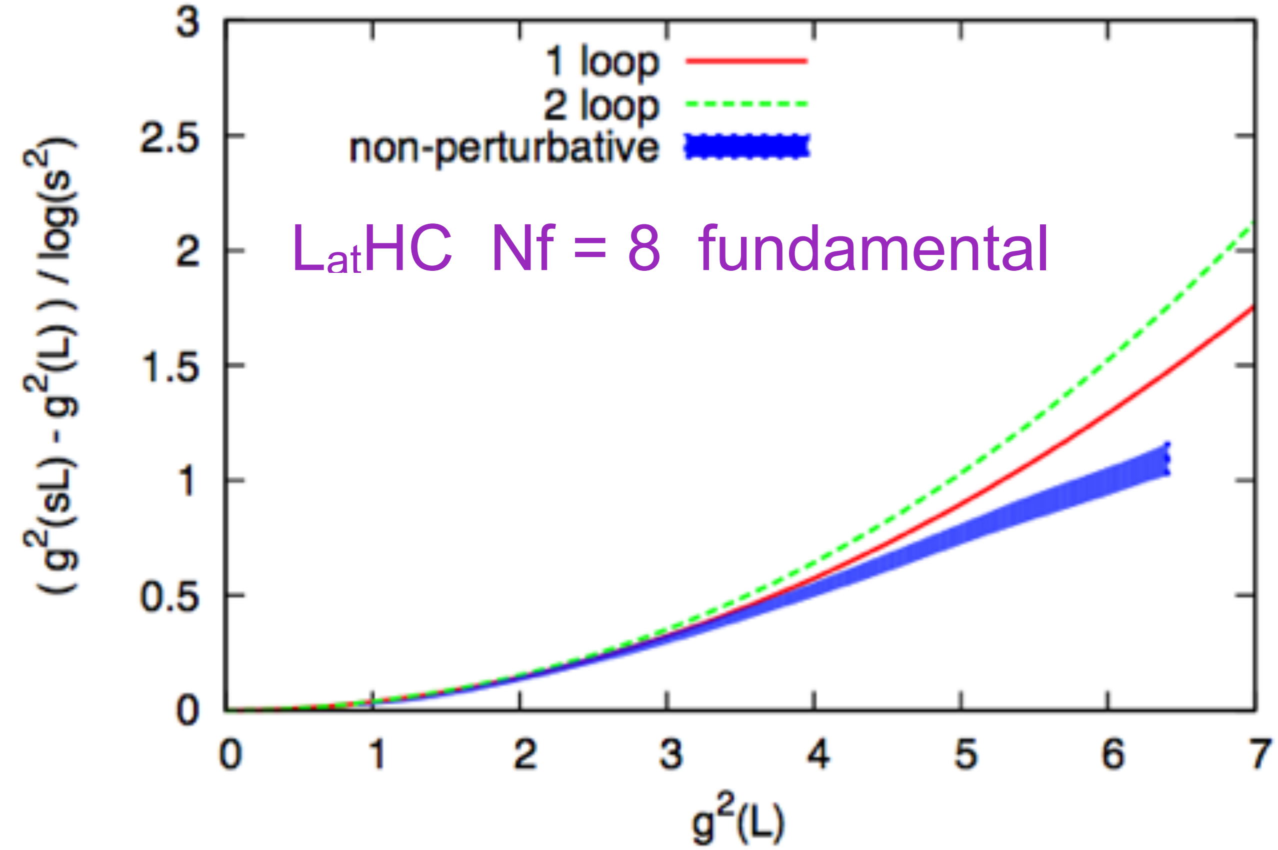
Two strategies to connect UV with IR:

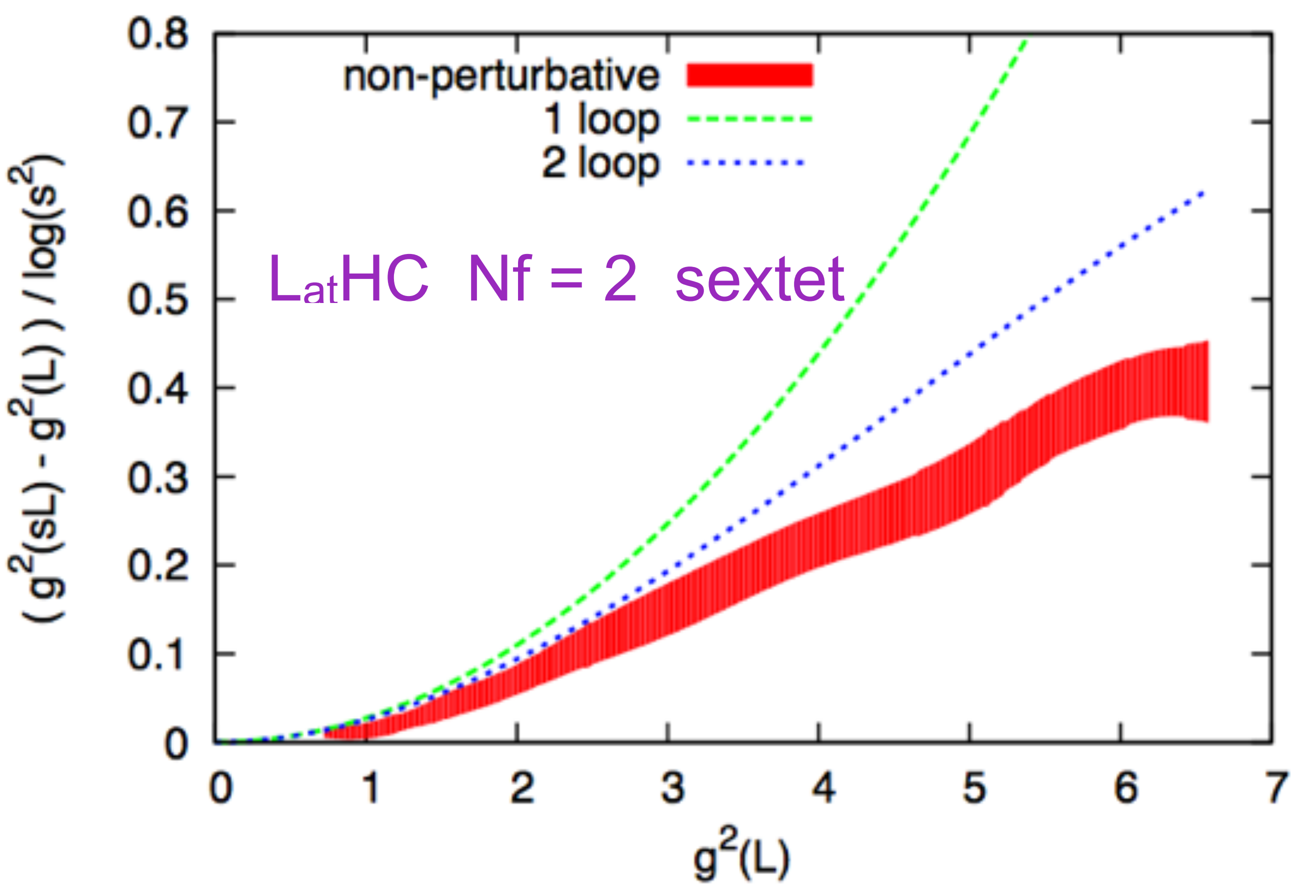
1. push into RMT regime with the method

2. use mass deformation in chiSB phase to bridge UV and IR

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**

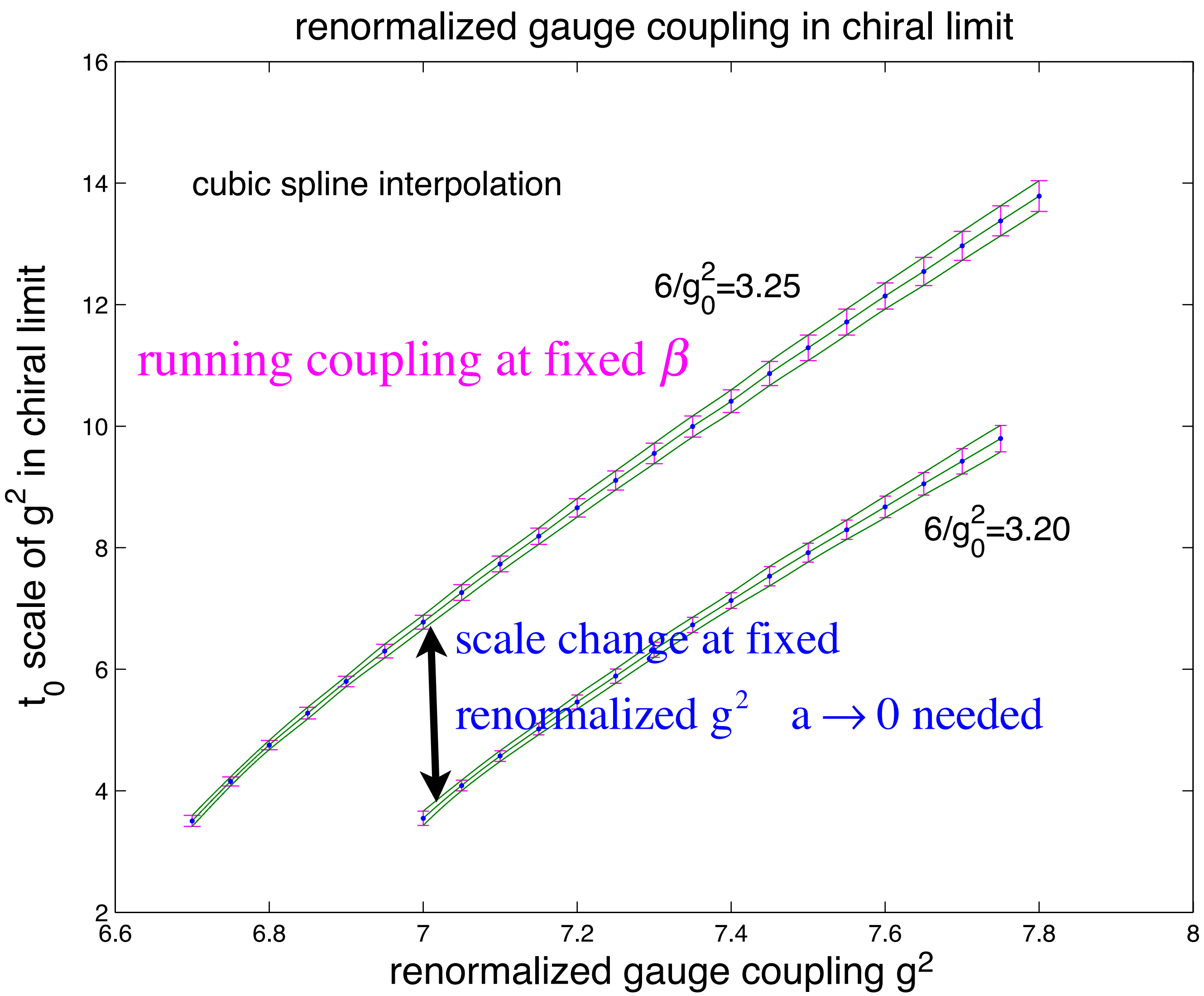


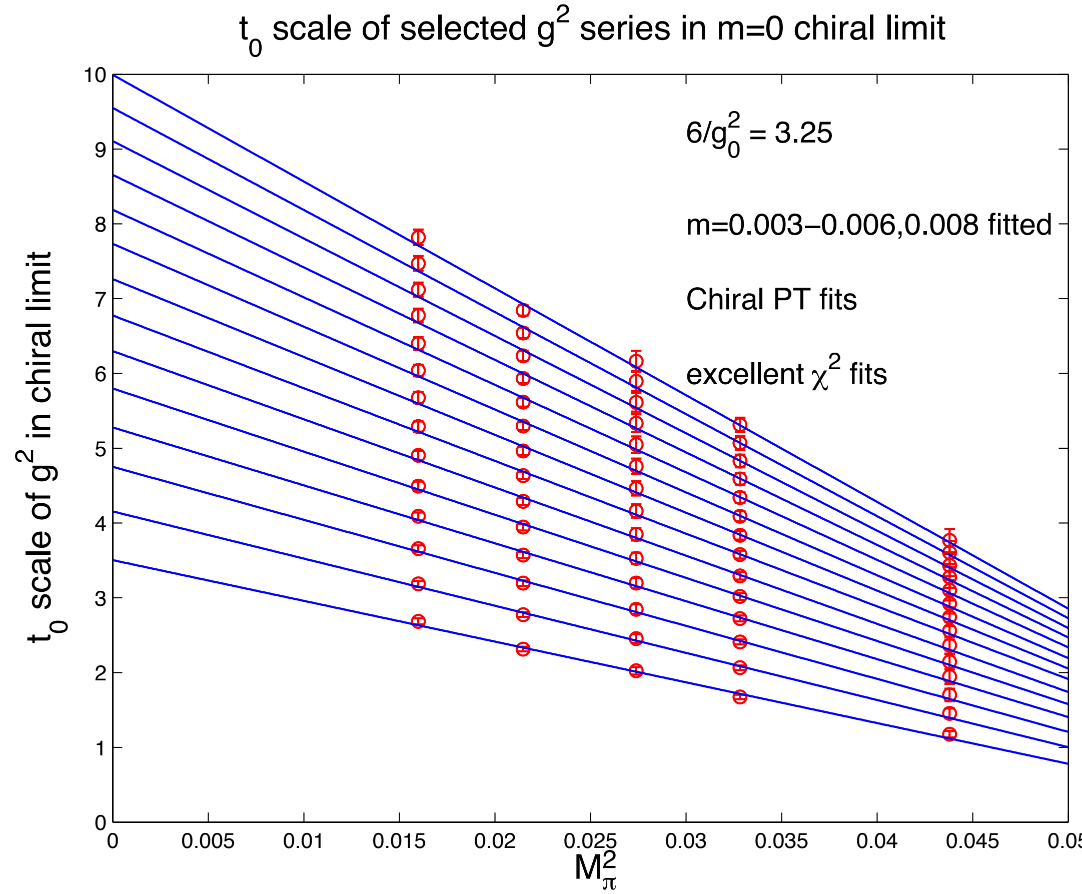


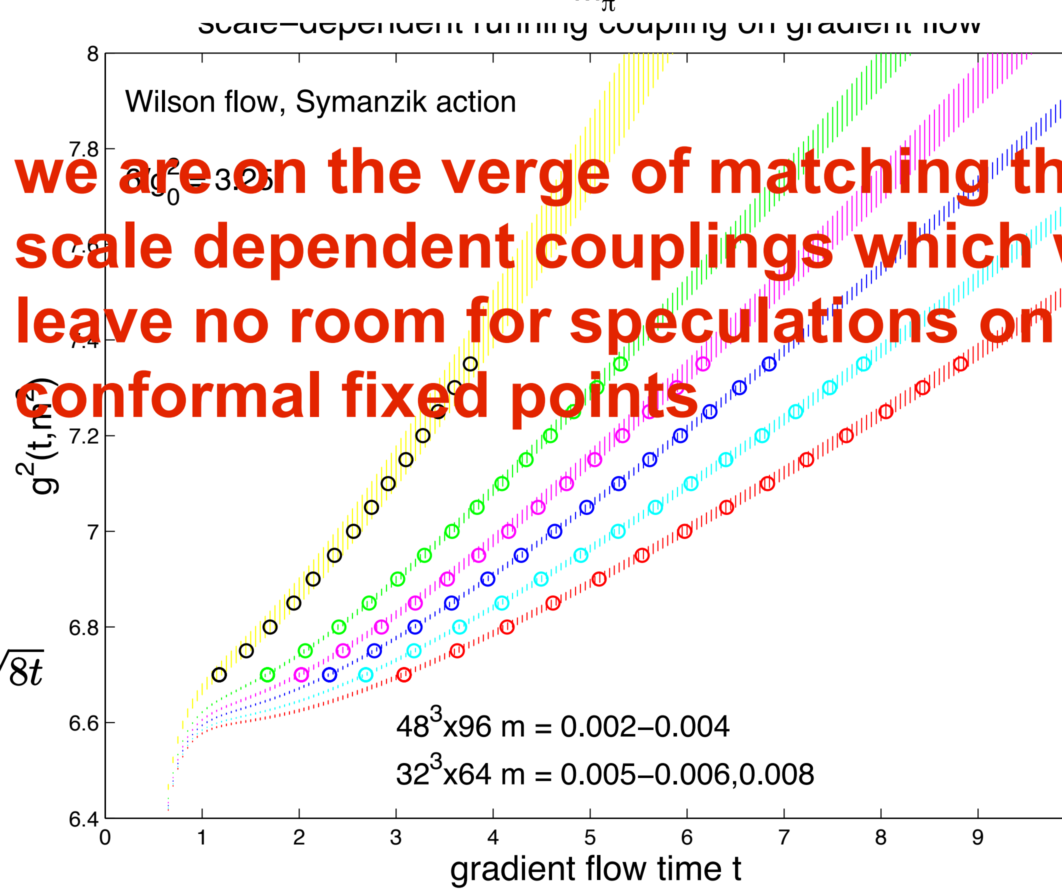


very small sextet beta function!

scale-dependent coupling matching IR to UV







we are on the verge of matching the two scale dependent couplings which will leave no room for speculations on conformal fixed points

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

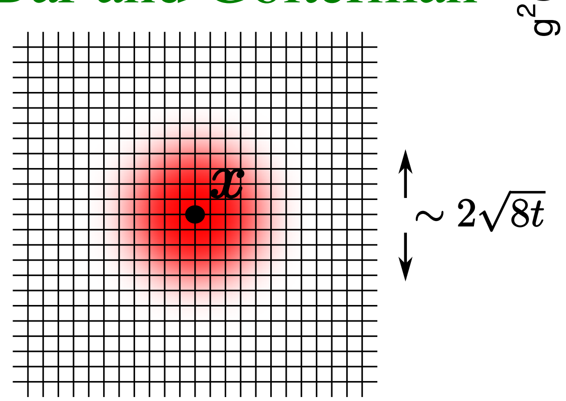
based on gradient flow chiPT Bär and Golterman

works better than expected

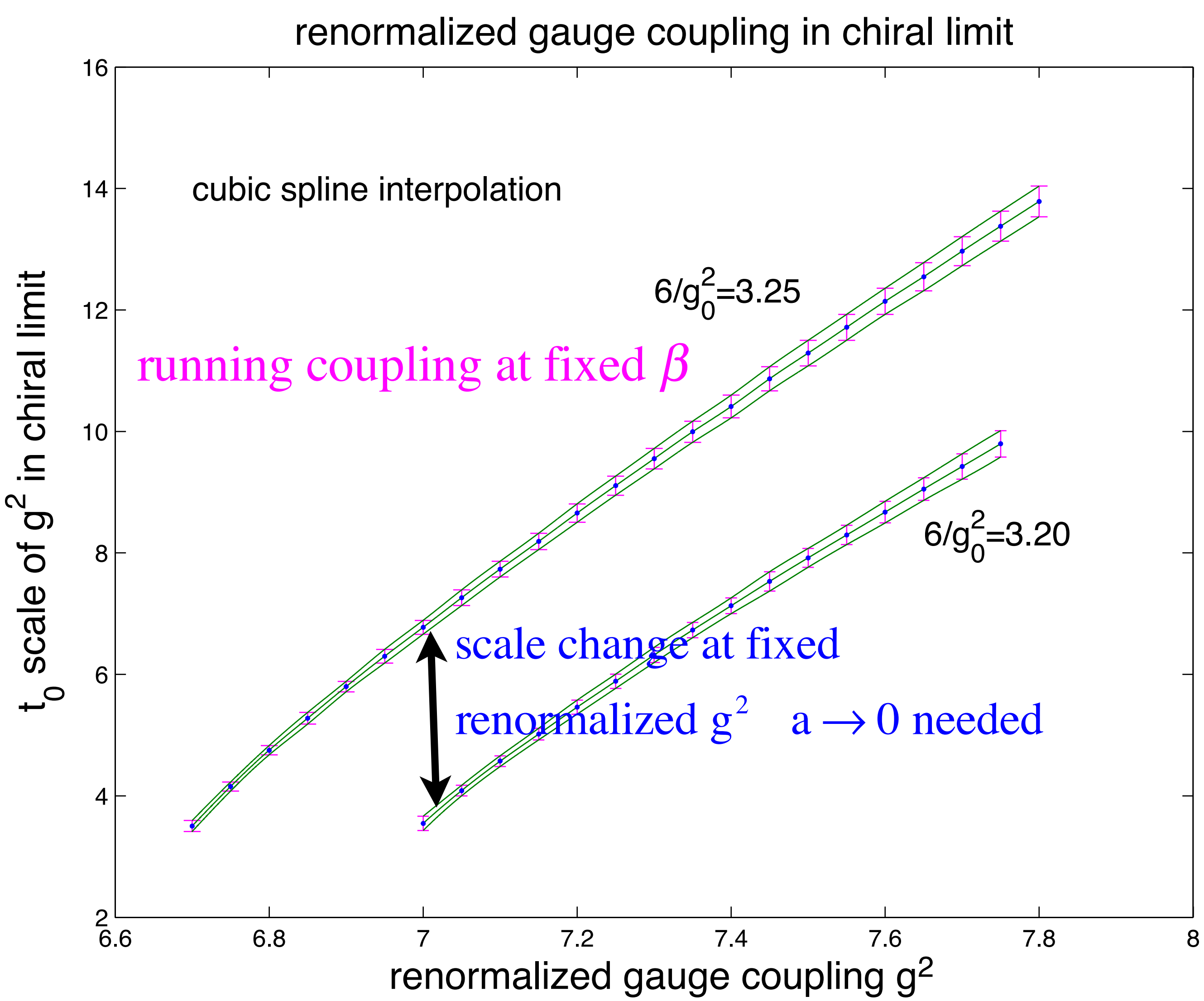
chiral logs are not detectable

decoupling of the scalar has

to be better understood



scale-dependent coupling matching IR to UV



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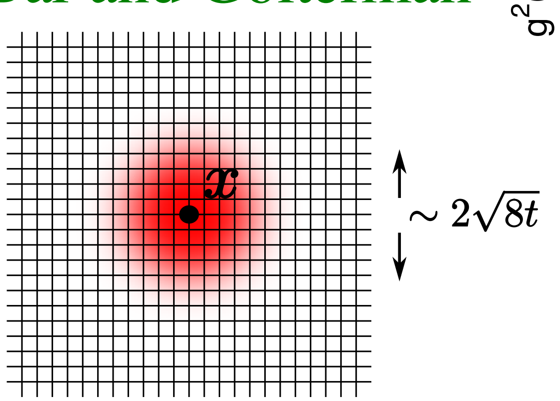
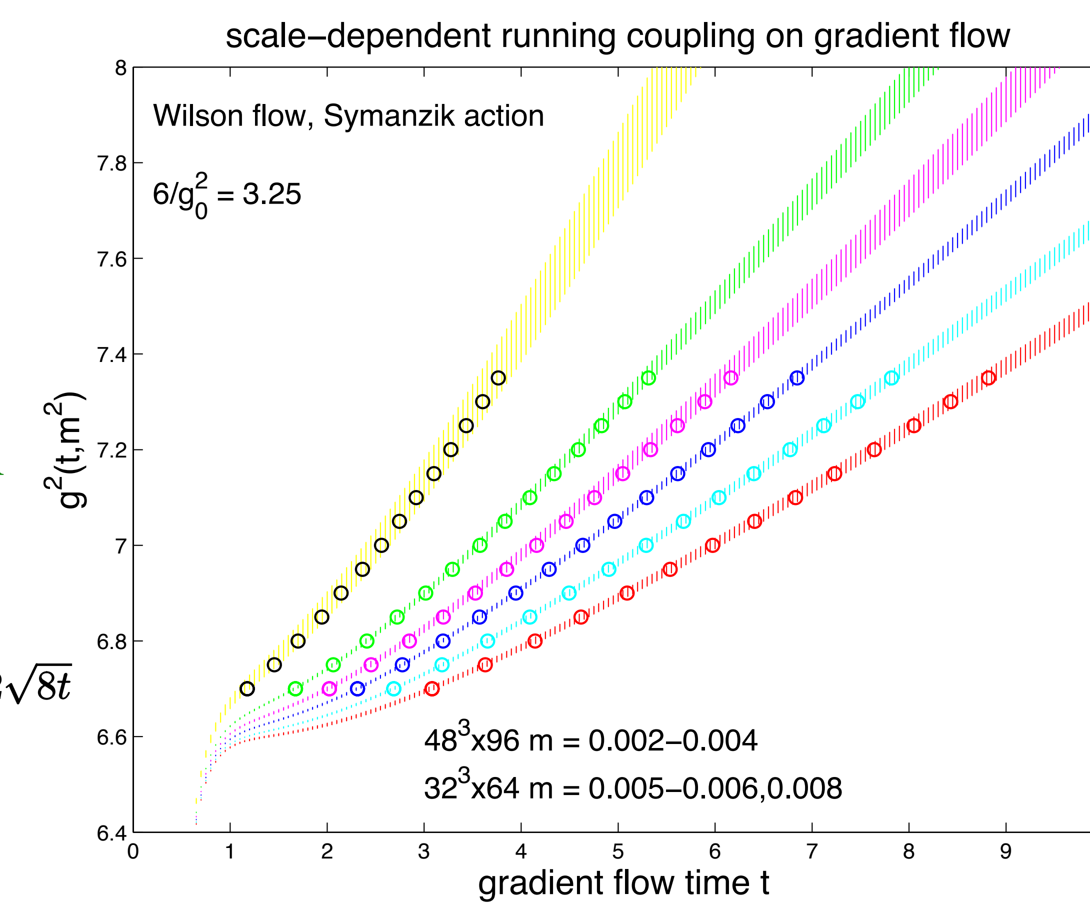
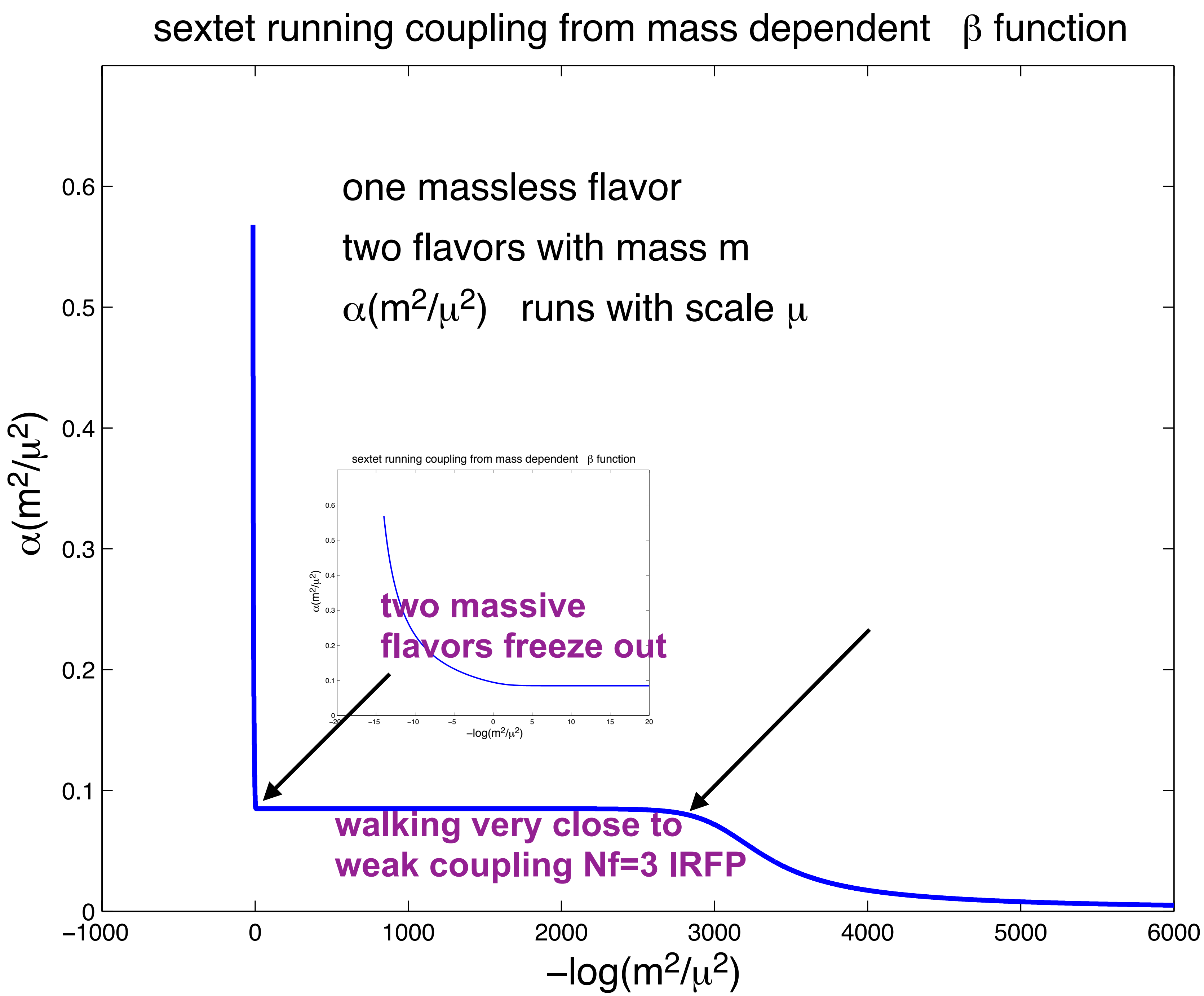




scale-dependent coupling   mass dependent tuning?



in 1+2 freeze-out scenario anything to learn about strong coupling dynamics of single massless flavor?

Similarly, in 2+1 freeze-out scenario anything to learn about strong coupling dynamics of doublet massless flavor?

Not likely that light scalar mass can be tuned this way

Early universe

Kogut-Sinclair 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: model exhibits chiSB with a light composite scalar (near-conformal?)

• no sign of IRFP	close to conformal window?
• spectroscopy	resonance spectrum ~ 2-3 TeV LHC!
• chiral condensate, large $\gamma(\lambda)$	Chebyshev expansion very promising
• RMT regime is being explored	mixed action strategy is applied
• Fixed topology requires special analysis	
• running (walking) coupling no IRFP	Gradient Flow
• Electroweak phase transition and baryon	intriguing
• Staggered fermion action is not the issue	rooting works
• Analysis of low mass scalar coupled to Goldstones remains a challenge	