N_f=8 QCD

Yasumichi Aoki [Kobayashi-Maskawa Institute(KMI), Nagoya University]

for the LatKMI collaboration

- Lattice for Beyond the Standard Model Physics @ LLNL -

April 23, 2015

LatKMI collaboration (2015)

- YA, T.Aoyama, M.Kurachi, T.Maskawa, K.Miura,





K.Nagai, H.Ohki, K.Yamawaki

名古屋大学



- E. Bennett

Swansea University Prifysgol Abertawe

- E. Rinaldi

LAWRENCE LIVERMORE NATIONAL LABORATORY

- A.Shibata

KEK

- T. Yamazaki

University of Tsukuba 筑波大学

LatKMI collaboration (2015.4)

- KMI / Nagoya Univ.





- outside

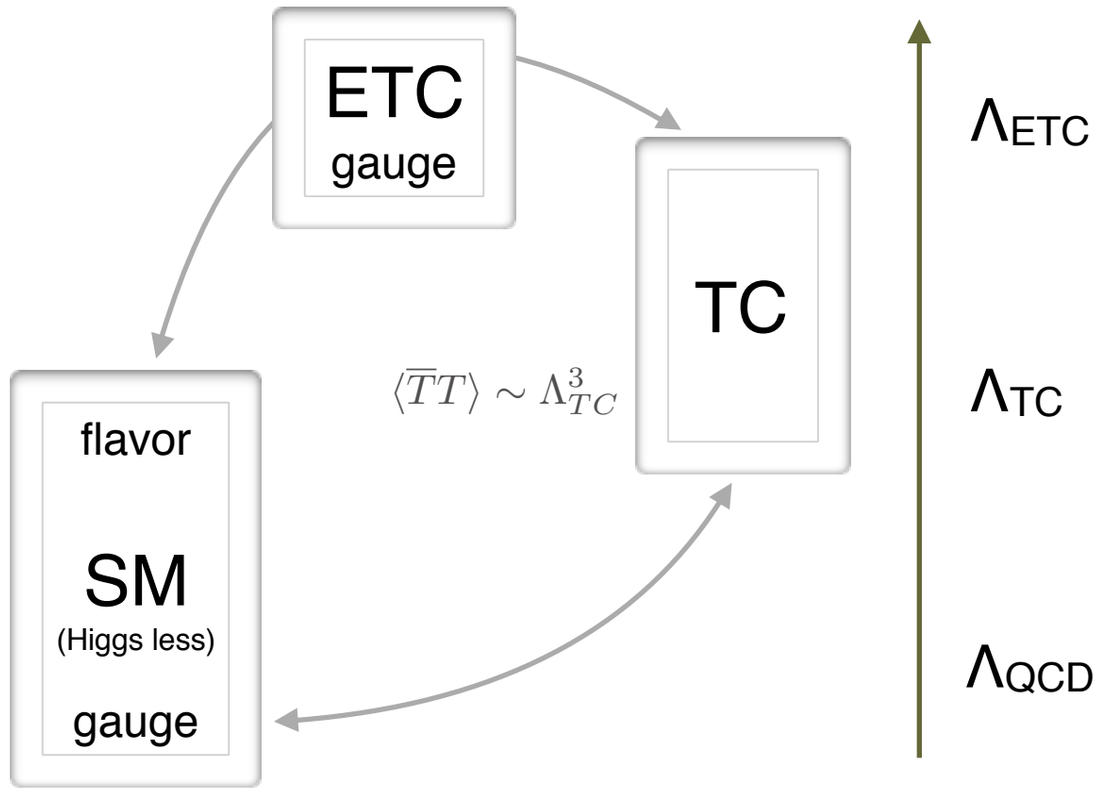






Technicolor and Extended Technicolor

- QCD like dynamics can trigger the Electroweak symmetry breaking
- Techni pion act as NG mode of Higgs
  - give mass to W and Z bosons
- SM fermion masses are given through ETC
- Tension:
  - FCNC must be suppressed
  - sizable m_f needs to be generated



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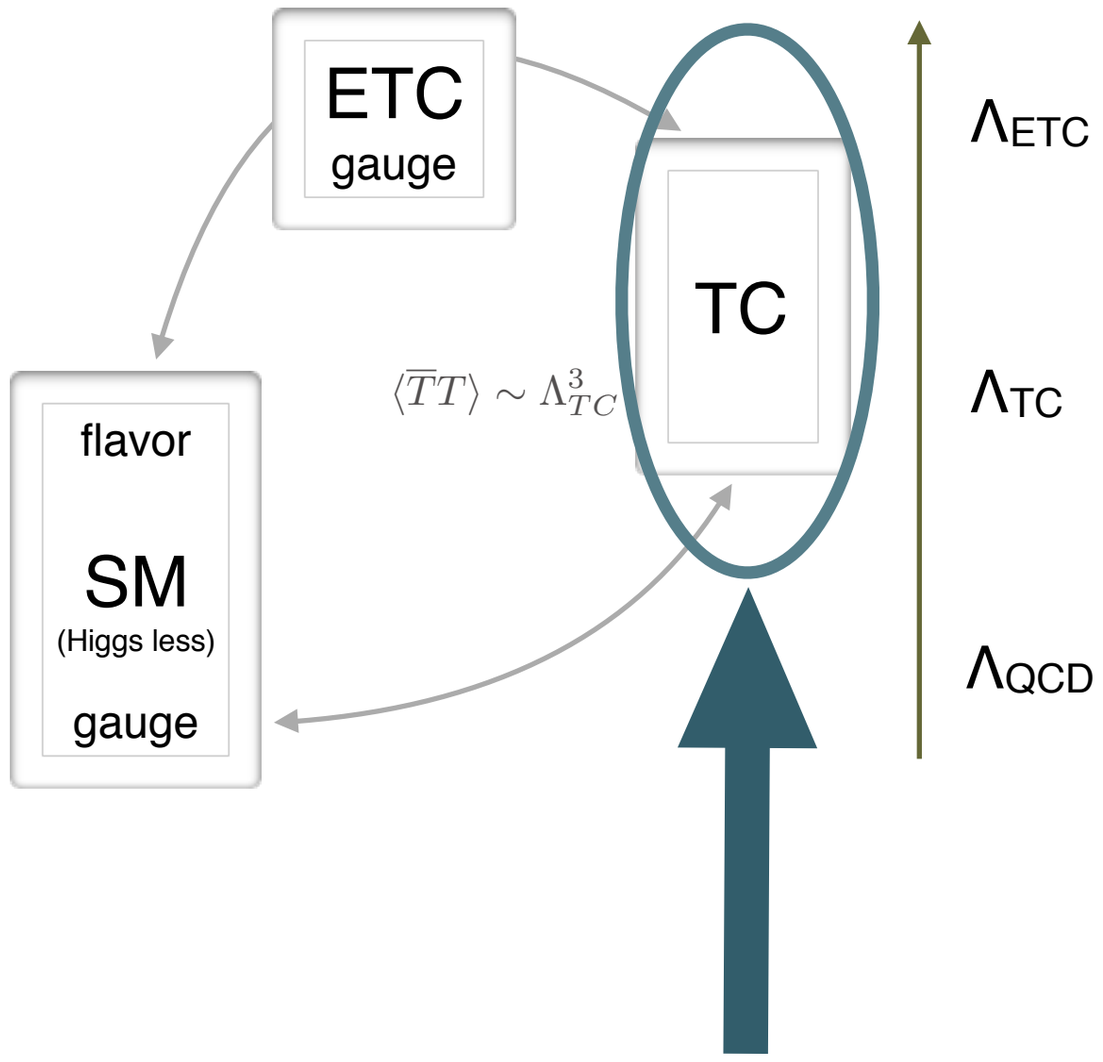

so far we are dealing with this only

LatKMI publications on related subjects

- LatKMI, PRD 85 (2012), “Study of the conformal hyperscaling relation through the Schwinger-Dyson equation” [non-lattice]

- LatKMI, PRD 86 (2012), “Lattice study of conformality in twelve-flavor QCD”

- LatKMI, PRD 87 (2013), “Walking signals in Nf=8 QCD on the lattice”

- LatKMI, PRL 111 (2013), “Light composite scalar in twelve-flavor QCD on the lattice”

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PHYSICAL REVIEW D **87,** 094511 (2013)

Walking signals in $N_f = 8$ QCD on the lattice

Yasumichi Aoki,[1] Tatsumi Aoyama,[1] Masafumi Kurachi,[1] Toshihide Maskawa,[1] Kei-ichi Nagai,[1] Hiroshi Ohki,[1] Akihiro Shibata,[2] Koichi Yamawaki,[1] and Takeshi Yamazaki[1]

(LatKMI Collaboration)

[1]*Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Nagoya 464-8602, Japan*
[2]*Computing Research Center, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*

(Received 27 February 2013; published 20 May 2013)

We investigate chiral and conformal properties of the lattice QCD with eight flavors ($N_f = 8$) through meson spectrum using the highly improved staggered quark (HISQ) action. We also compare our results with those of $N_f = 12$ and $N_f = 4$ which we study on the same systematics. We find that the decay constant F_π of the pseudoscalar meson "pion" π is nonzero, with its mass M_π consistent with zero, both in the chiral limit extrapolation of the chiral perturbation theory. We also measure other quantities which we find are in accord with the π data results: The ρ meson mass is consistent with nonzero in the chiral limit, and so is the chiral condensate, with its value neatly coinciding with that from the Gell-Mann-Oakes-Renner relation in the chiral limit. Thus, our data for the $N_f = 8$ QCD are consistent with the spontaneously broken chiral symmetry. Remarkably enough, while the $N_f = 8$ data near the chiral limit are well described by the chiral perturbation theory, those for the relatively large fermion bare mass m_f away from the chiral limit actually exhibit a finite-size hyperscaling relation, suggesting a large anomalous dimension $\gamma_m \sim 1$. This implies that there exists a remnant of the infrared conformality, and suggests that a typical technicolor ("one-family model") as modeled by the $N_f = 8$ QCD can be a walking technicolor theory having an approximate scale invariance with large anomalous dimension $\gamma_m \sim 1$.

Nf=8 QCD: candidate of Walking Technicolor

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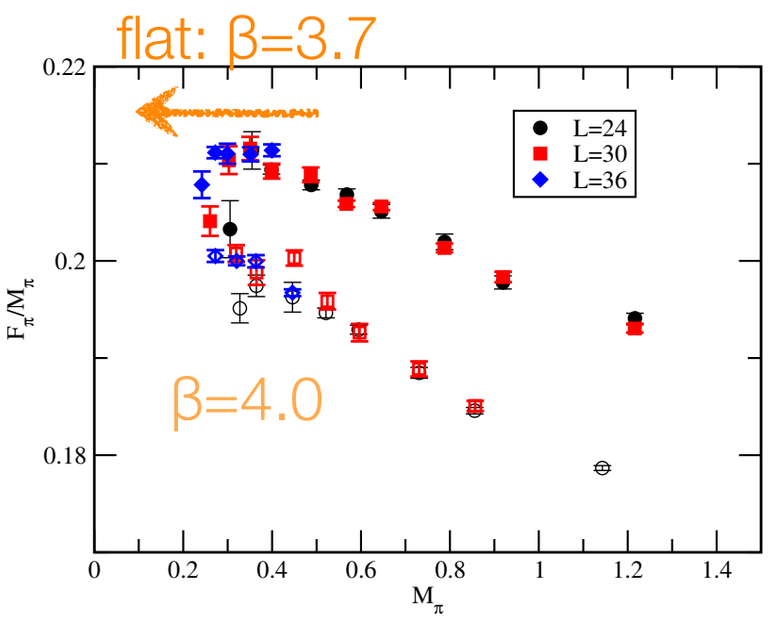
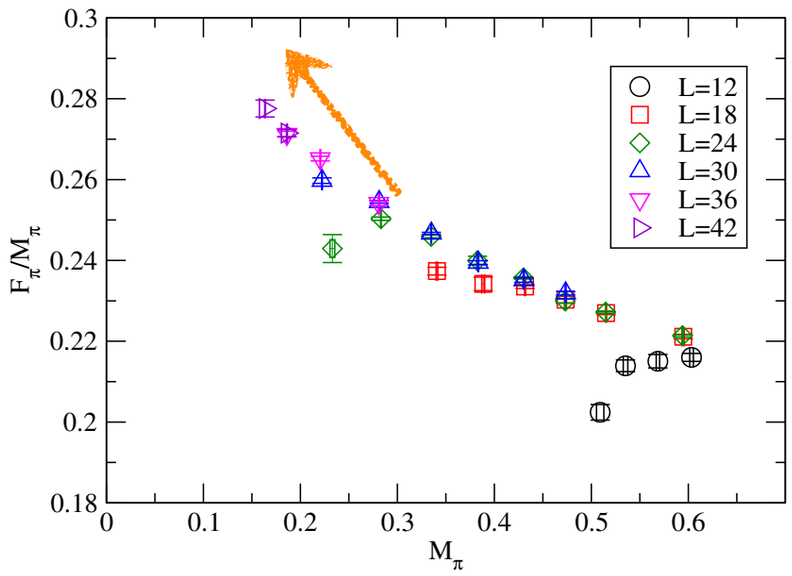
a crude analysis: F_π/M_π vs M_π leads to a likely scenario

N_f=12



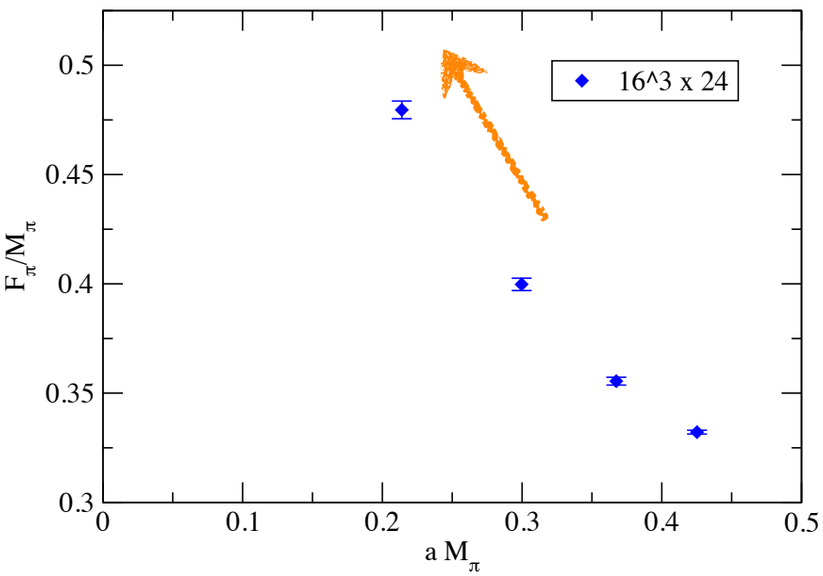
- conformality

N_f=8



- ~~chiral symmetry~~

N_f=4



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F_π vs m_f

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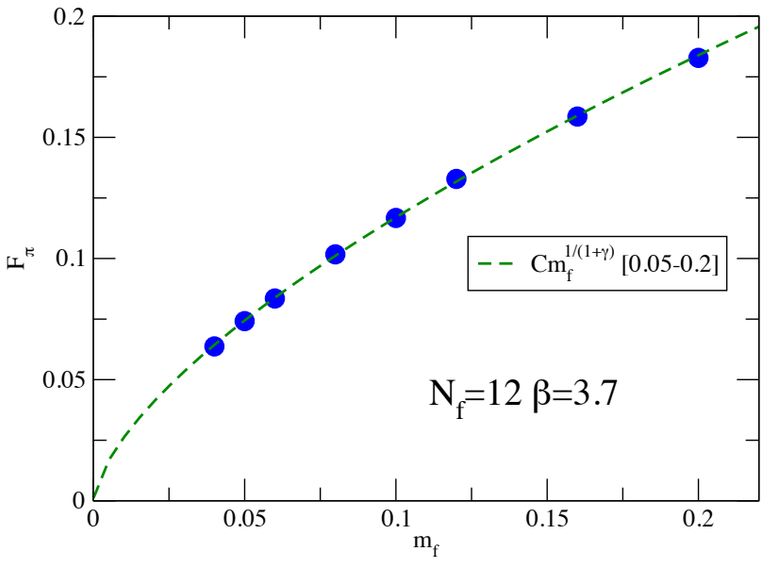

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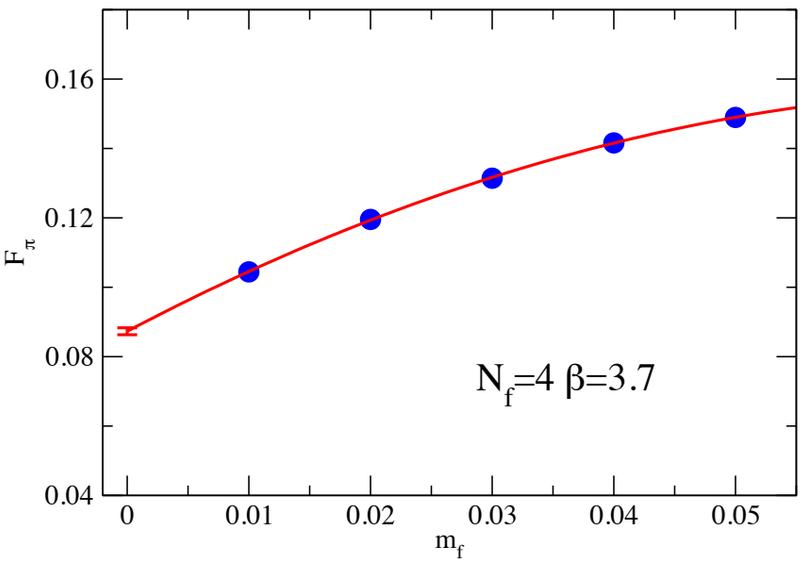
- $F_\pi \to C m_f^{1/(1+\gamma)}$
- γ~0.5

N_f=4



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F_π vs m_f

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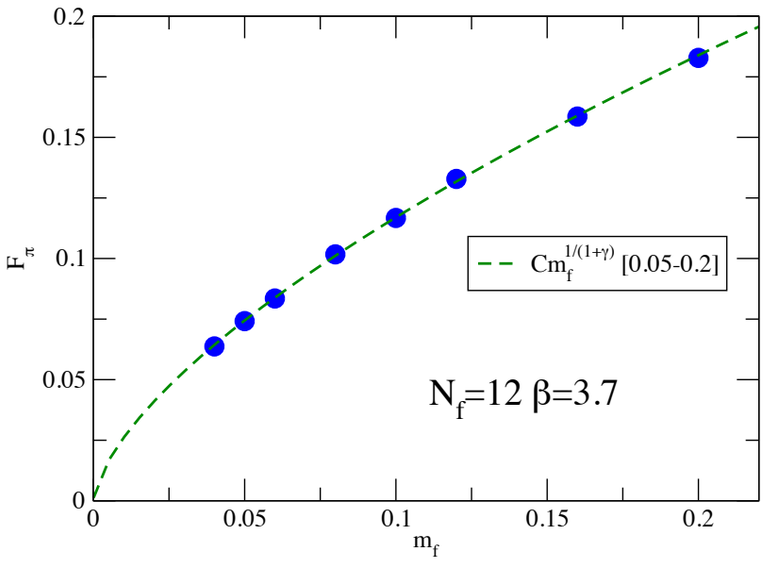

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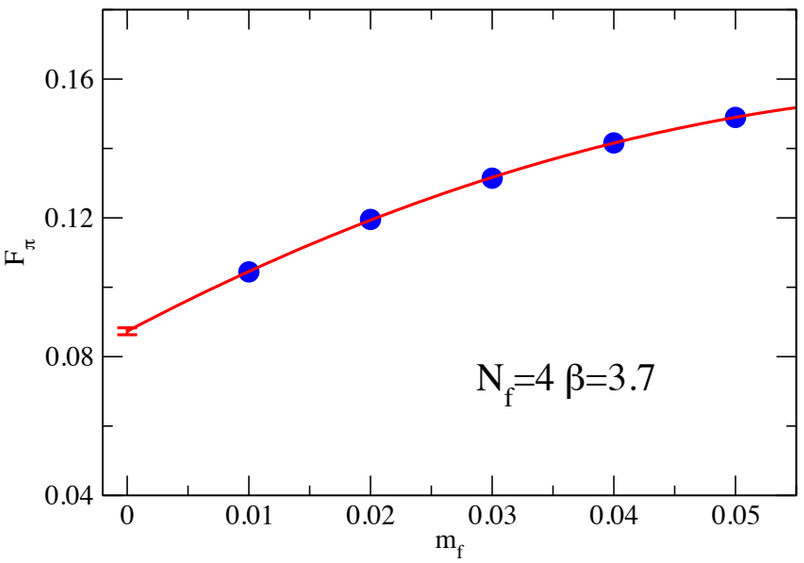

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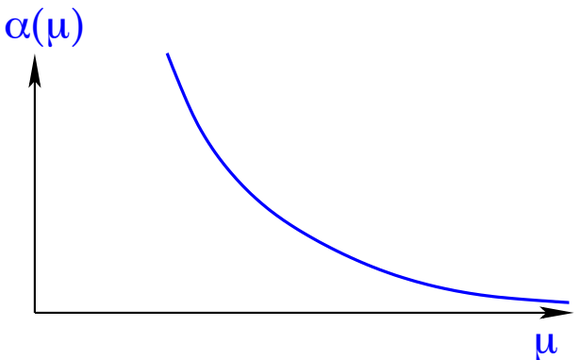

F_π vs m_f

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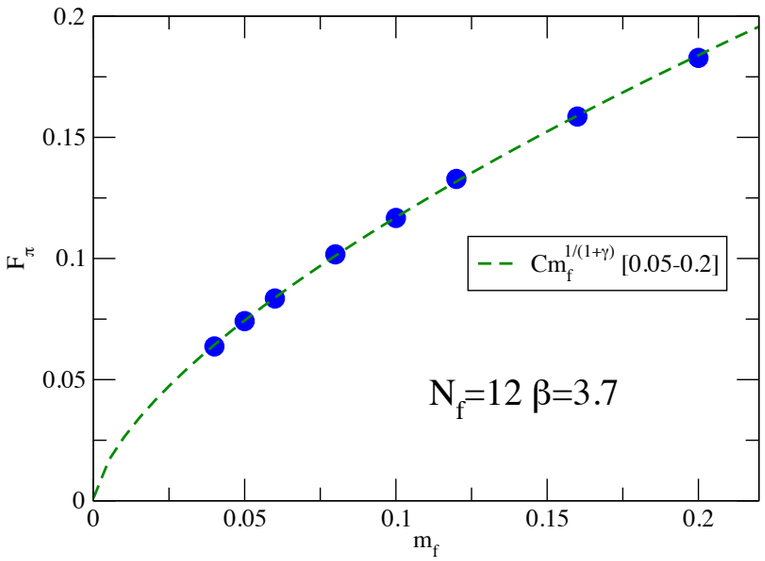

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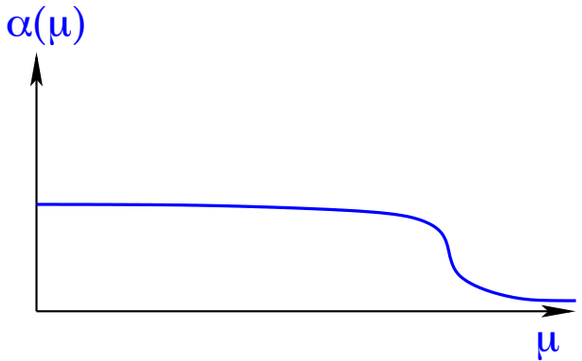

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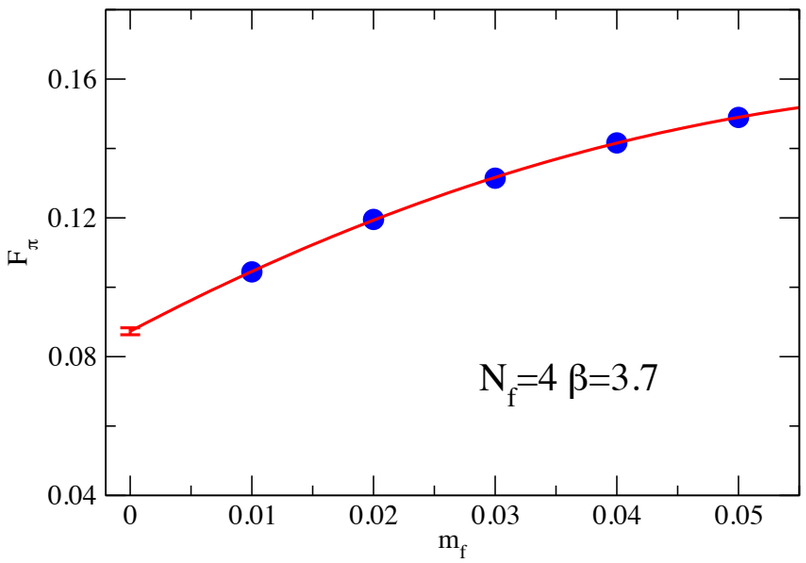

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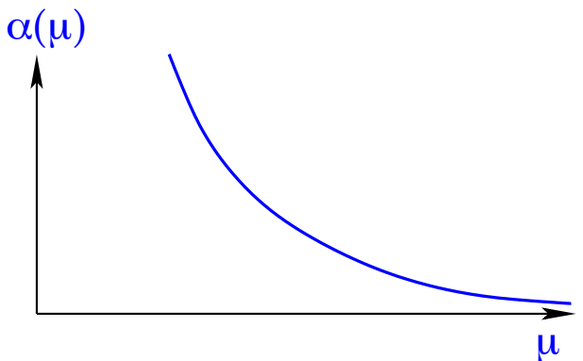

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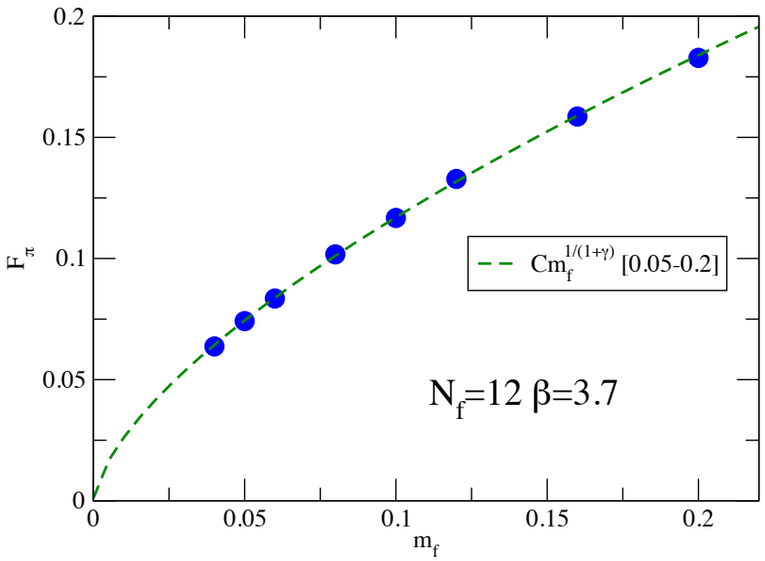

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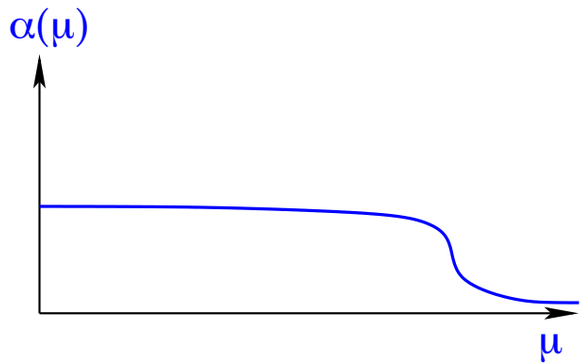

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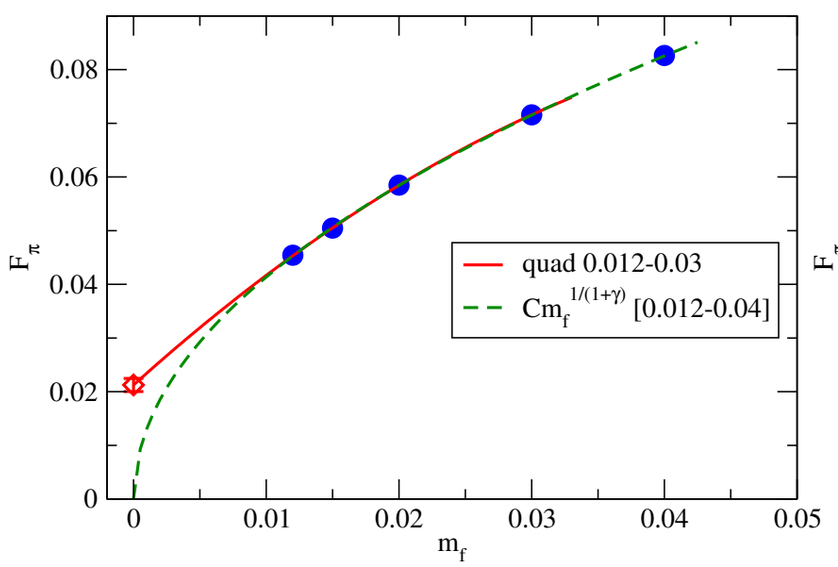

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- γ~1.0

$m_f \to 0$

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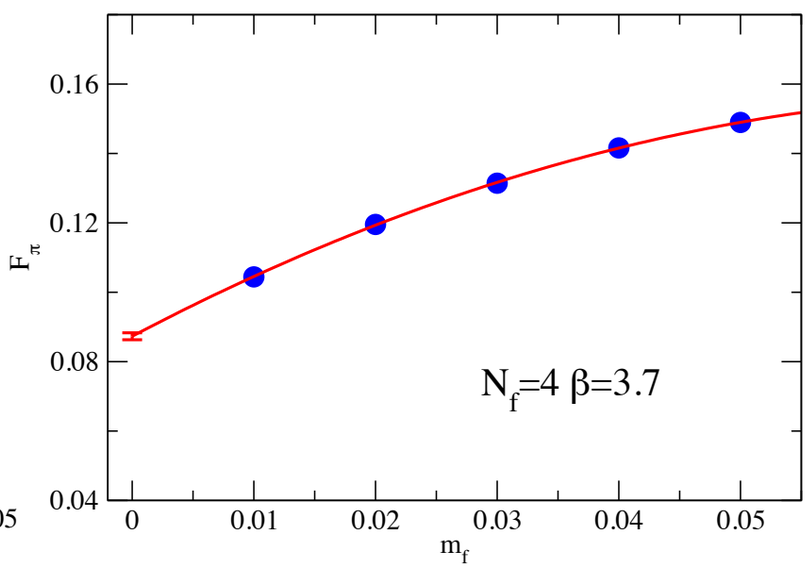

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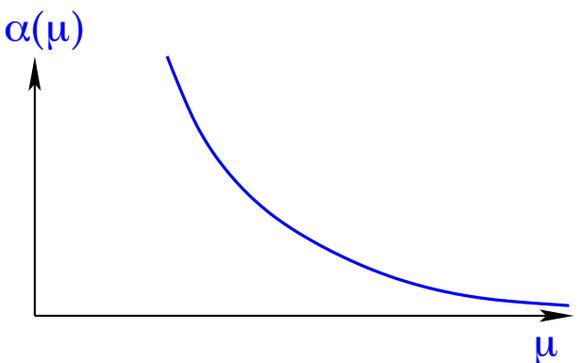

F_π vs m_f

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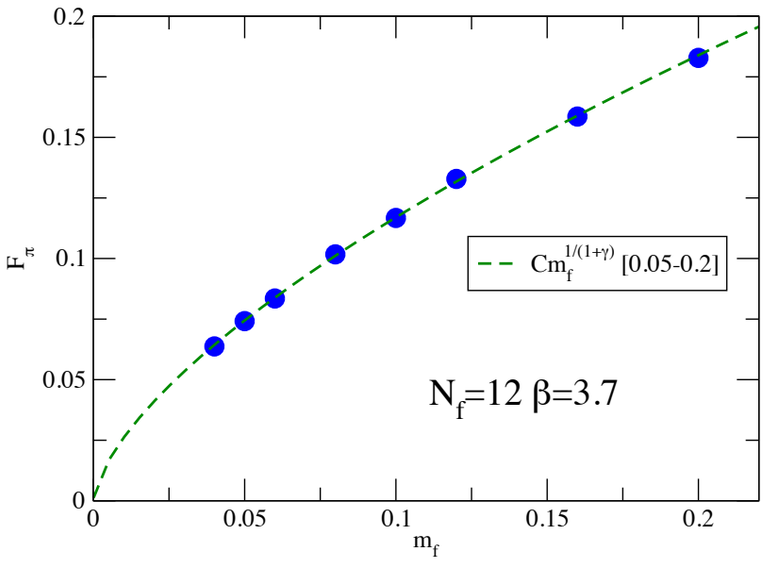

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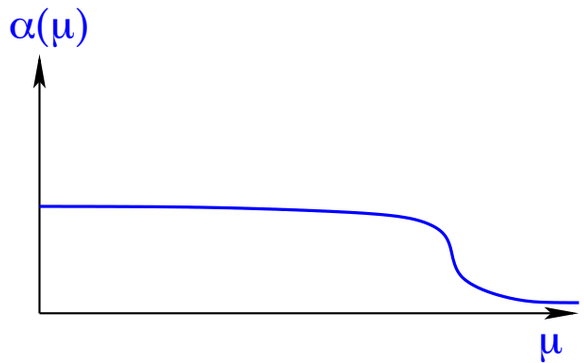

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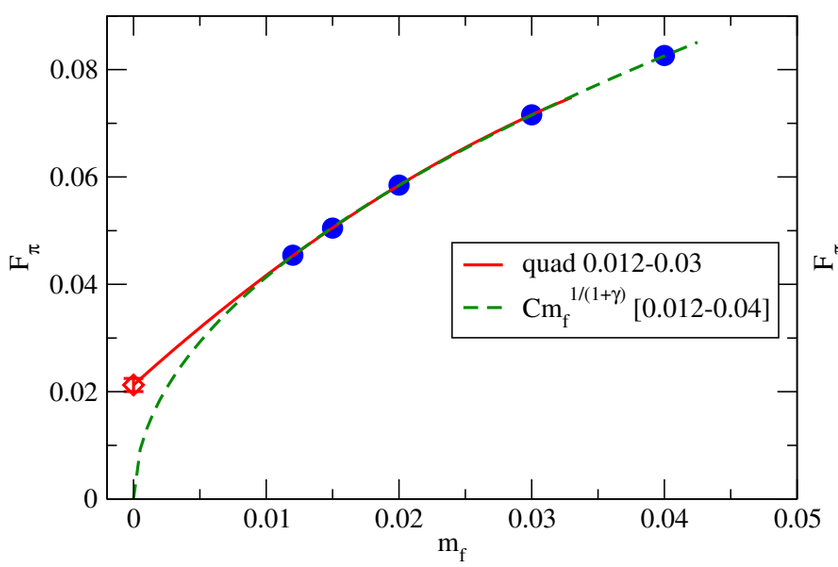

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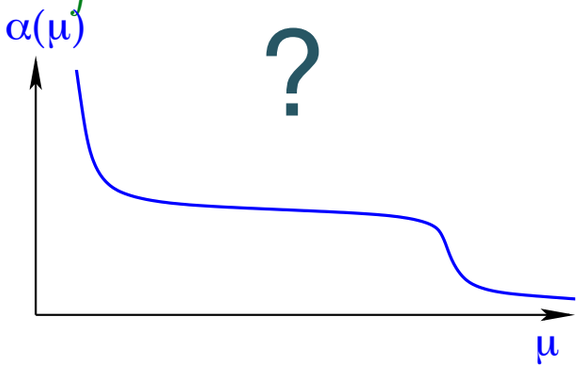

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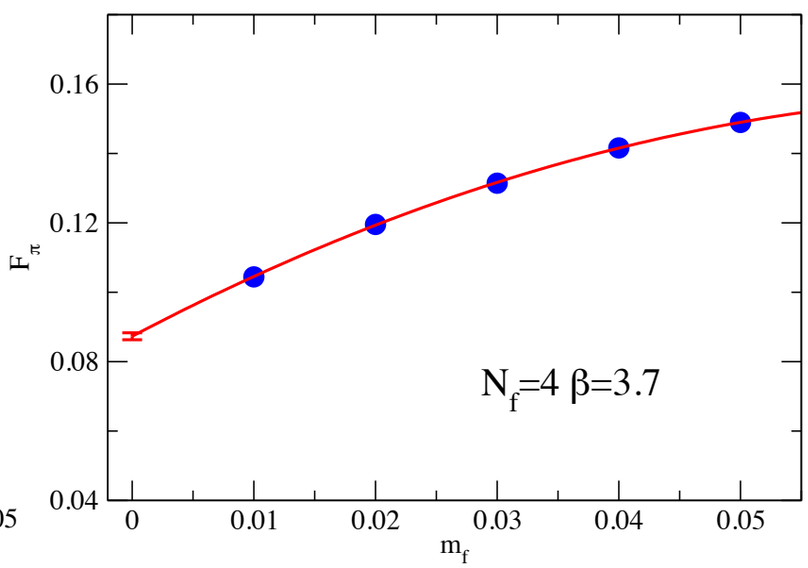

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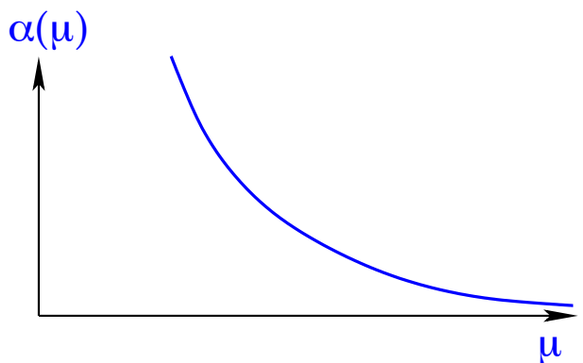

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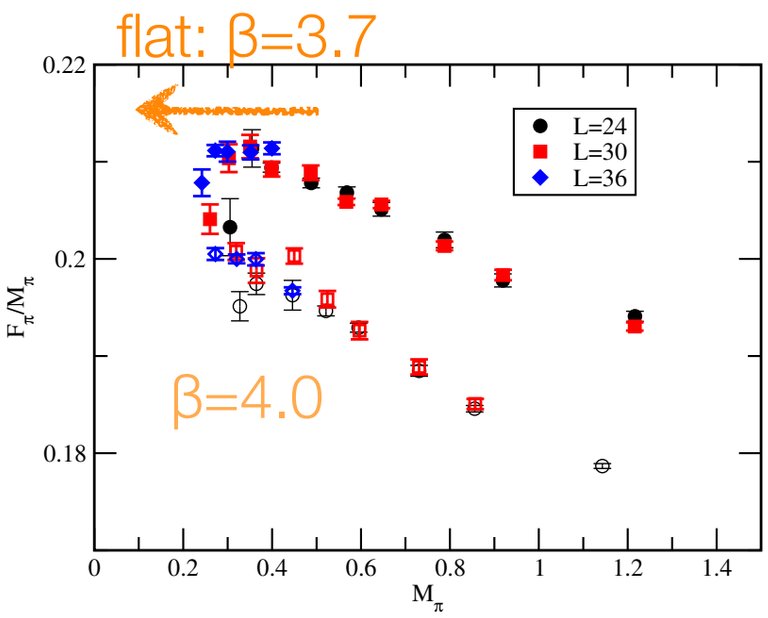

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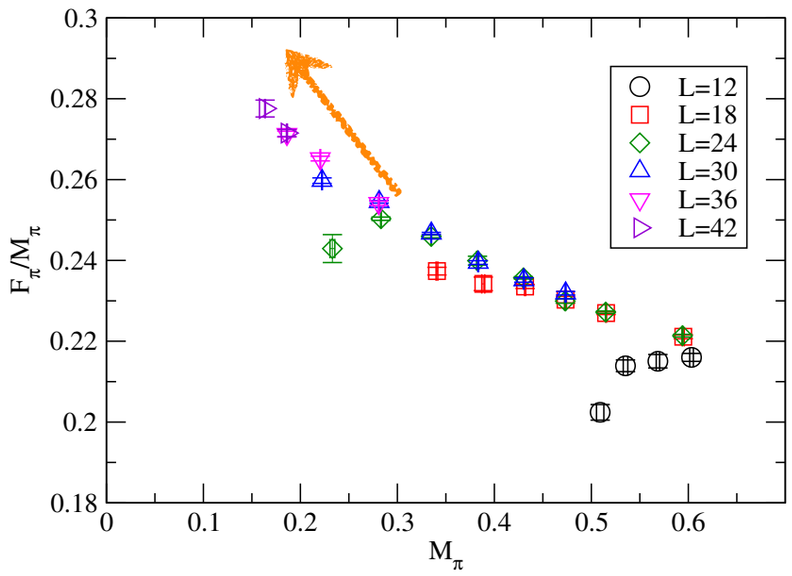

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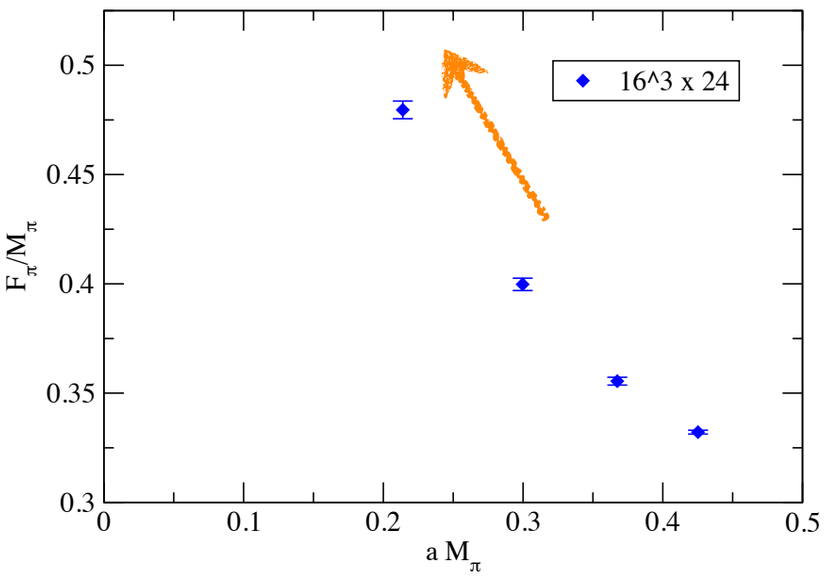


- ~~chiral symmetry~~

even with this case,

if the $F_\pi/M_\pi(M_\pi \to 0) < \infty$, constant with conformal

N_f=8: conformal vs chiral symm. br.

- various quantities are tested:
  - F_π, M_π, M_ρ, M_N, M_{N^*}, M_{a0}, M_{a1}, M_{b1}, chiral condensate
  - Finite size scaling (conformal) with some types of mass correction
- just confirm what found for F_π scaling

- results can be interpreted either way: conformal or chiral symm. br.
- but, scaling exponents between quantities are not completely consistent
- this property maybe a clue of walking technicolor theory
- further getting close to chiral limit will unfold the nature of this theory

In case of SχSB:

spectrum at chiral limit

↓

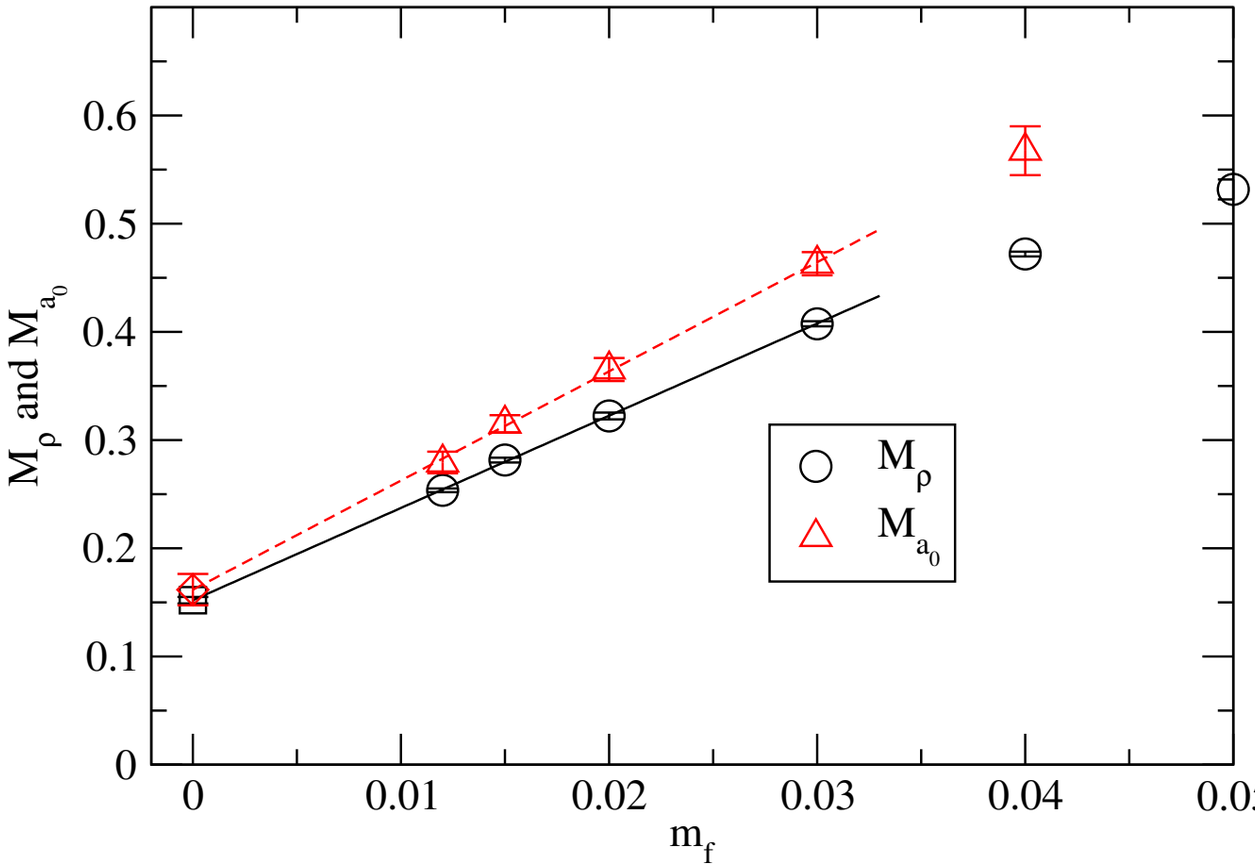
(with model structure)

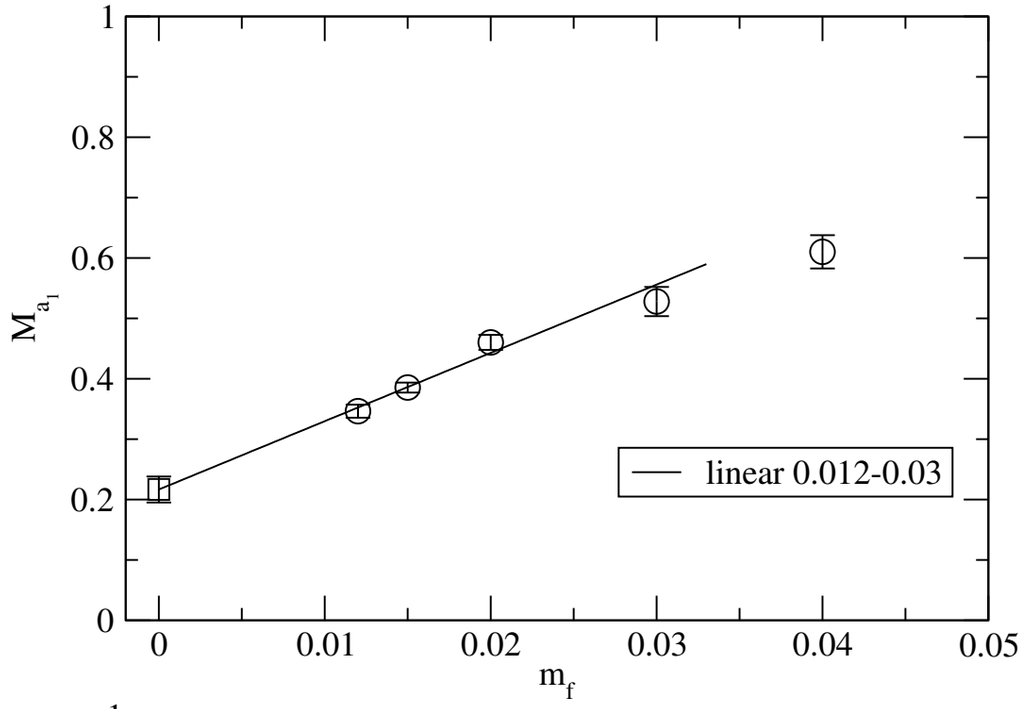
↓

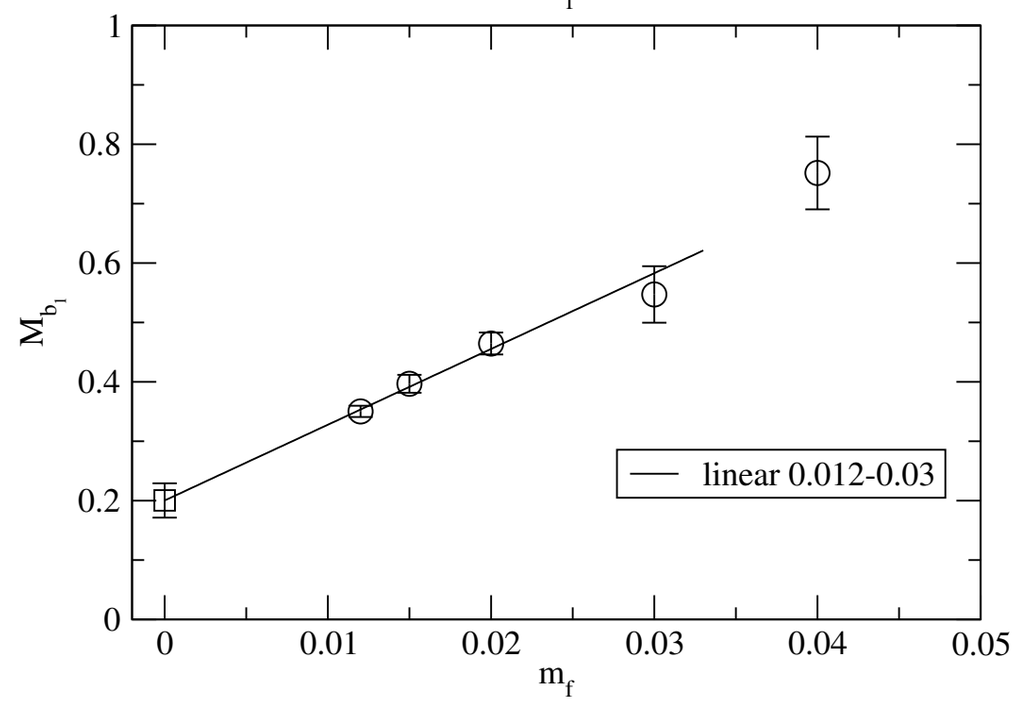
prediction to compare with experiment

following is “preliminary” results

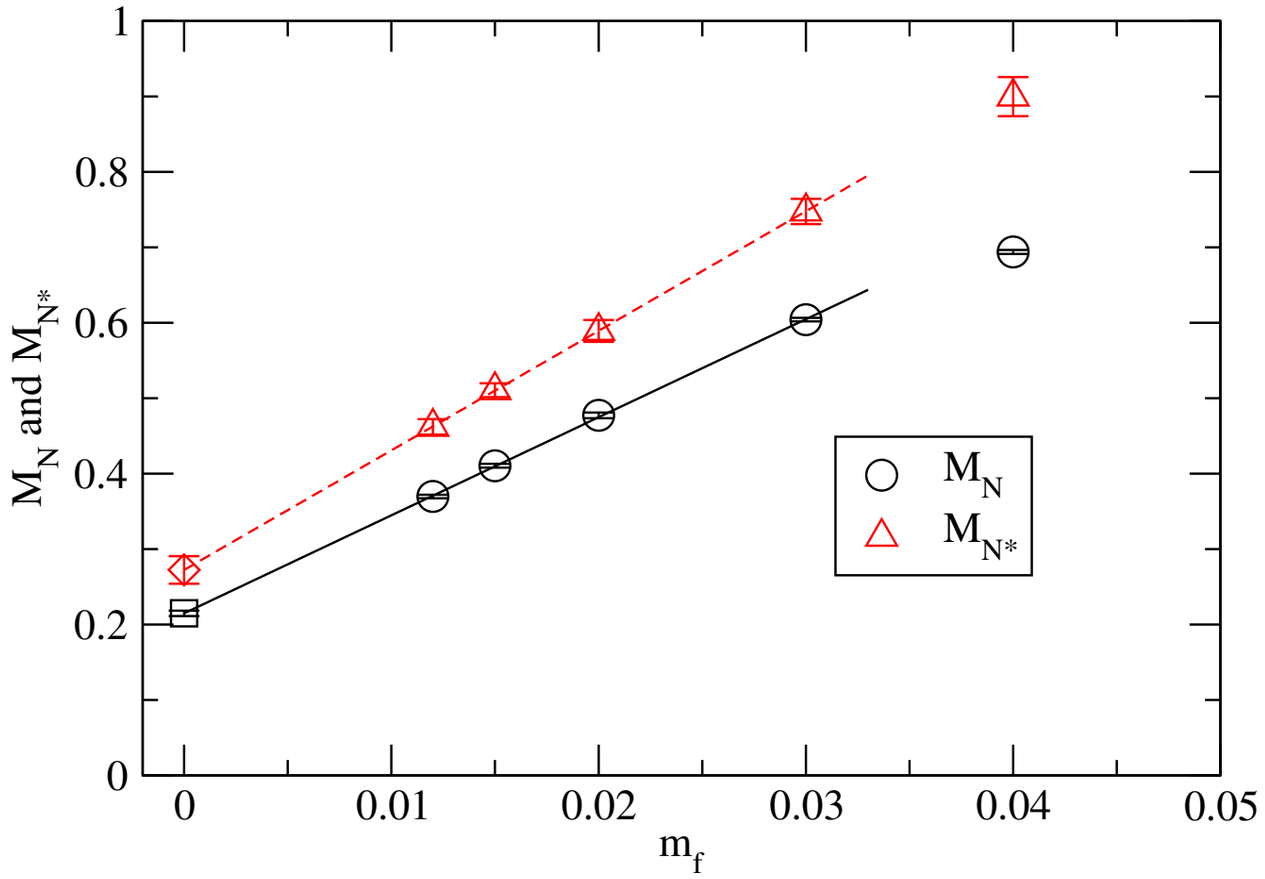
mesons: ρ, a_0, a_1, b_1



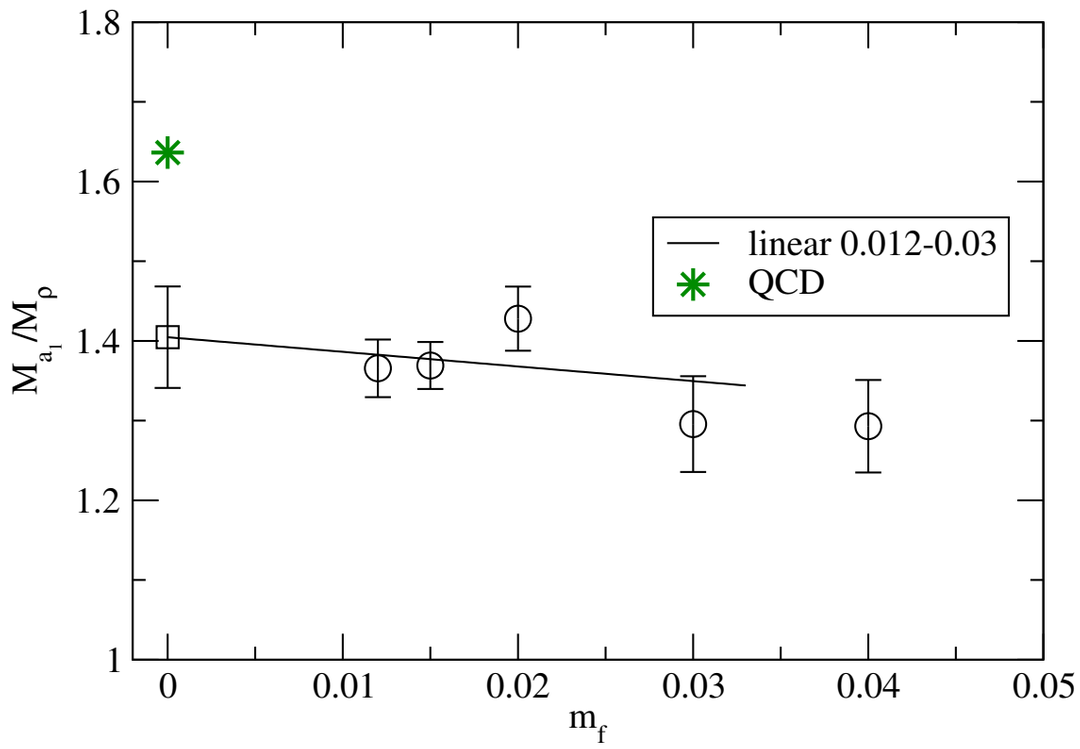


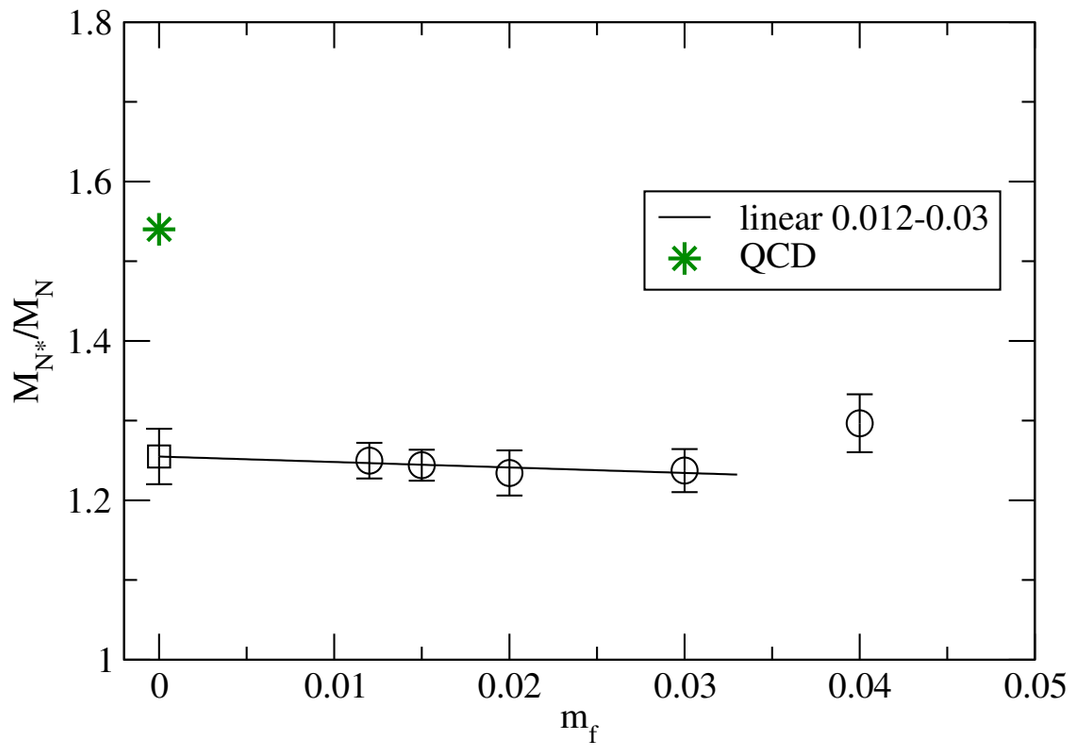


baryons: N, N*



mass ratio compared with real-life QCD





- moving toward “parity doubling” from smaller N_f to N_f=8
  - consistent with LSD collab. with domain-wall fermions

N_f=8 composite spectrum

$$\frac{M_\rho}{F/\sqrt{2}} = 10.1(0.6)(^{+5.0}_{-2.5})$$

$$\sqrt{N_d}F/\sqrt{2} = 246 \text{ GeV}$$

- NLO chiral log correction for F: dominant systematic error
- N_d depends on the model
- e.g. one family model: N_d=4 → M_ρ ~ 1.2 TeV

ρ	a_0	a_1	b_1	N	N^*
$10.1(0.6)(^{+5.0}_{-2.5})$	$10.8(1.1)(^{+5.3}_{-2.7})$	$14.4(1.7)(^{+7.1}_{-3.6})$	$13.3(2.1)(^{+6.6}_{-3.3})$	$14.3(0.9)(^{+7.0}_{-3.5})$	$18.1(1.6)(^{+8.9}_{-4.5})$

TABLE X. Ratios of $\sqrt{2}M_H/F$ with $H = \rho, a_0, a_1, b_1, N$, and N^*. The first and second errors are statistical and systematic errors.

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$$\sqrt{N_d}F/\sqrt{2} = 246\ \text{GeV} \qquad \text{(input)}$$

- NLO chiral log correction for F: dominant systematic error
- N_d depends on the model
- e.g. one family model: N_d=4 → M_ρ ~ 1.2 TeV

ρ	a_0	a_1	b_1	N	N^*
$10.1(0.6)(^{+5.0}_{-2.5})$	$10.8(1.1)(^{+5.3}_{-2.7})$	$14.4(1.7)(^{+7.1}_{-3.6})$	$13.3(2.1)(^{+6.6}_{-3.3})$	$14.3(0.9)(^{+7.0}_{-3.5})$	$18.1(1.6)(^{+8.9}_{-4.5})$

TABLE X. Ratios of $\sqrt{2}M_H/F$ with $H = \rho, a_0, a_1, b_1, N$, and N^*. The first and second errors are statistical and systematic errors.

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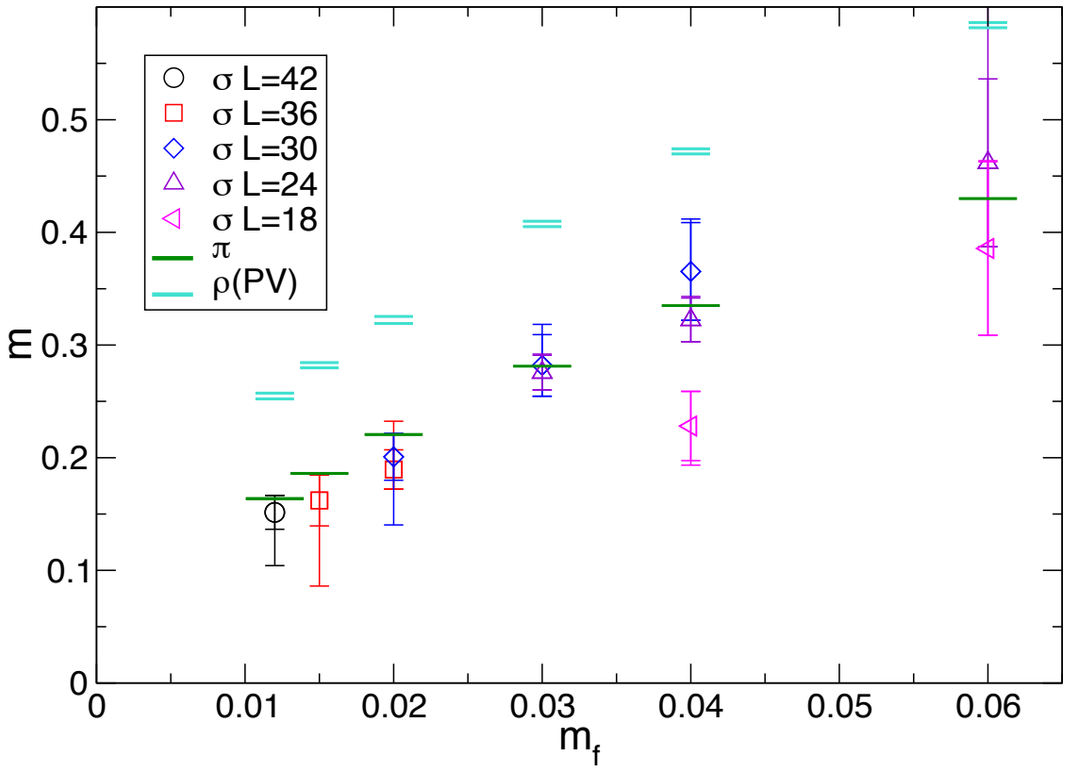
flavor singlet scalar : Higgs channel

- flavor singlet: known as a difficult problem in lattice QCD
- variance reduction method & high stat.
- σ as light as π

  ➡similar to N_f=12 [LatKMI 2013]

- clearly lighter than ρ

  ➡ far from heavy quark limit



- (update from PRD 2014 LatKMI)

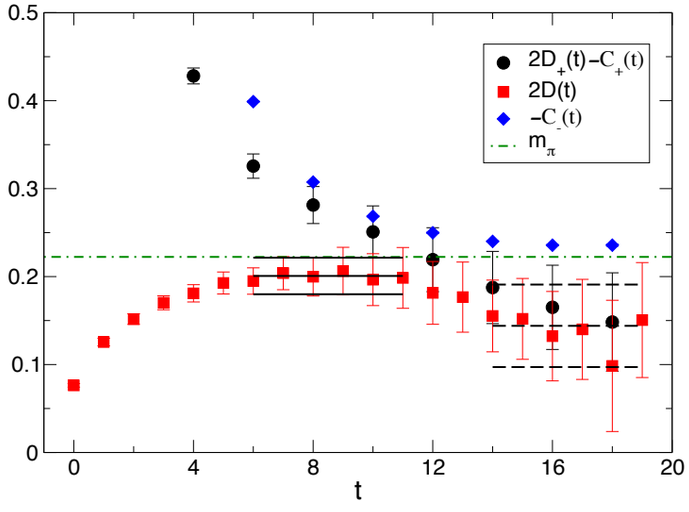
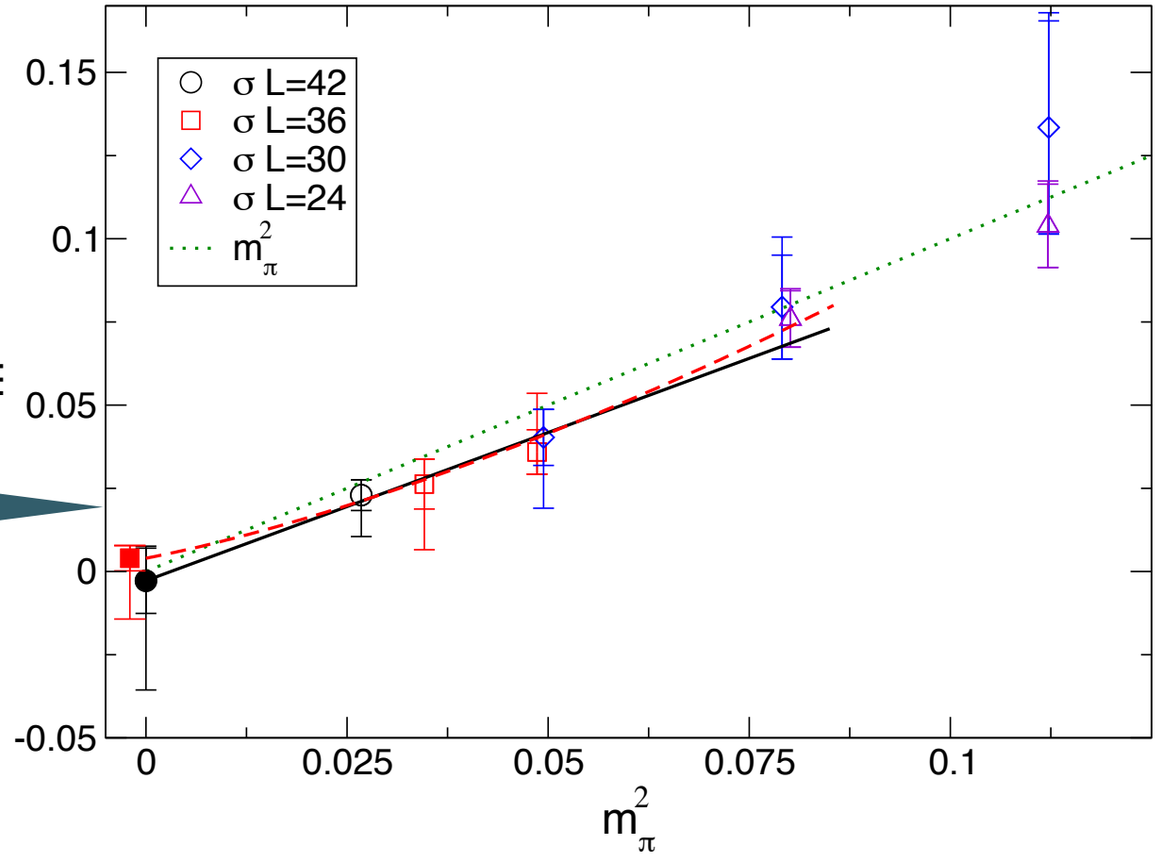


FIG. 16. Effective scalar mass m_σ from correlators with the projection for $L = 30$, $m_f = 0.02$.

trial chiral extrapolation for N_f=8 SU(3) m_σ [LatKMI NEW: update from PRD2014]

- though it is too far, so far
- 2 ways:
  - naive linear $m_\sigma = c_0 + c_1 m_f$
  - dilaton ChPT $m_\sigma^2 = d_0 + d_1 m_\pi^2$ (Matsuzaki-Yamawaki 2013)
    - differ only at higher order
- possibility to have ~125GeV Higgs
  - $F/\sqrt{2}$=123 GeV one-family model
- lighter mass data needed!

m_ρ



c_0 = 0.063(30)(+4-142)

d_0 = –0.0028(98)(+36-313)

c.f. $m_\sigma \simeq F/\sqrt{2} \rightarrow c_0 \simeq 0.014$ II $d_0 \simeq 0.0002$

d_1 = 0.89(26)(+75-12)

c.f. $d_1 \sim 1$ (holographic: $F_\sigma \sim \sqrt{N_f} F$)
[Matsuzaki & Yamawaki 2012]

Other low energy constant: on-going project

- Vector / Axial vector decay constant ↔ by-product of S parameter meas.
- dilaton decay constant
  - mainly by Ohki

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- Vector / Axial vector decay constant ↔ by-product of S parameter meas.
- dilaton decay constant
  - mainly by Ohki (from July)

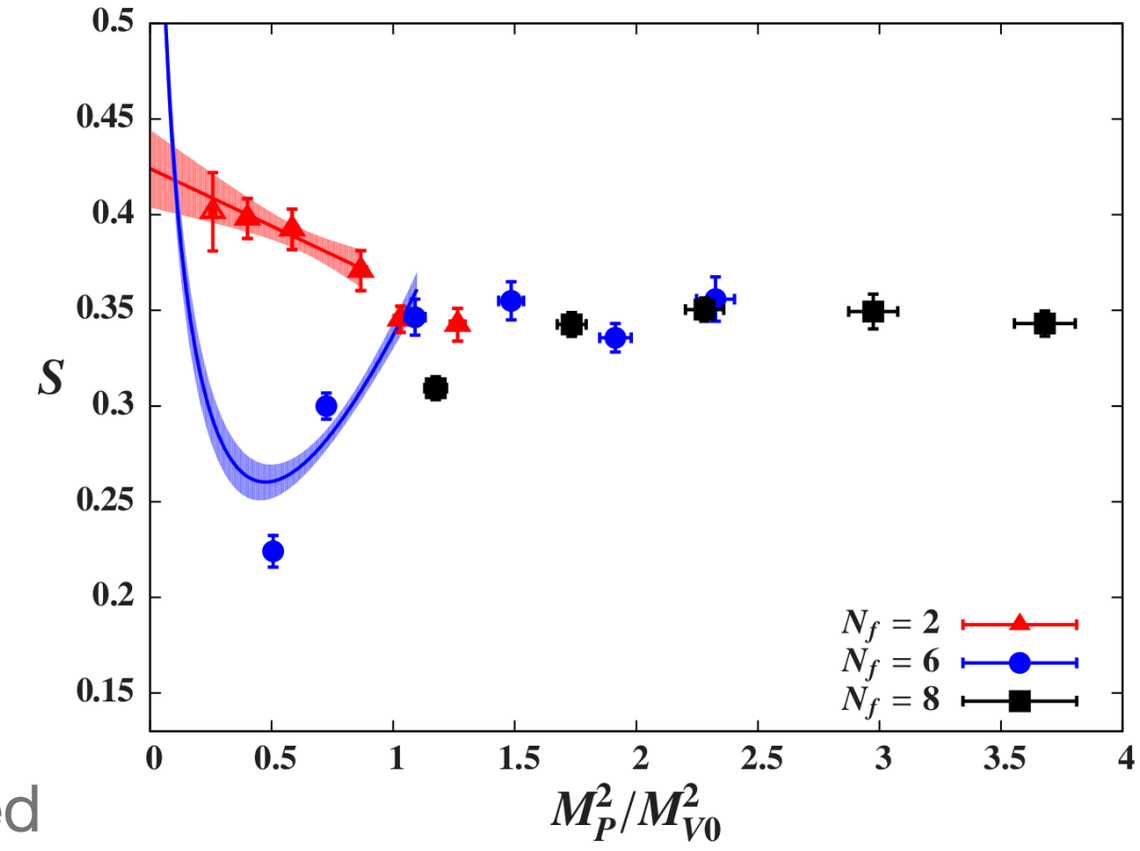
If you are interested,
please contact / discuss with him

S parameter: calculation method

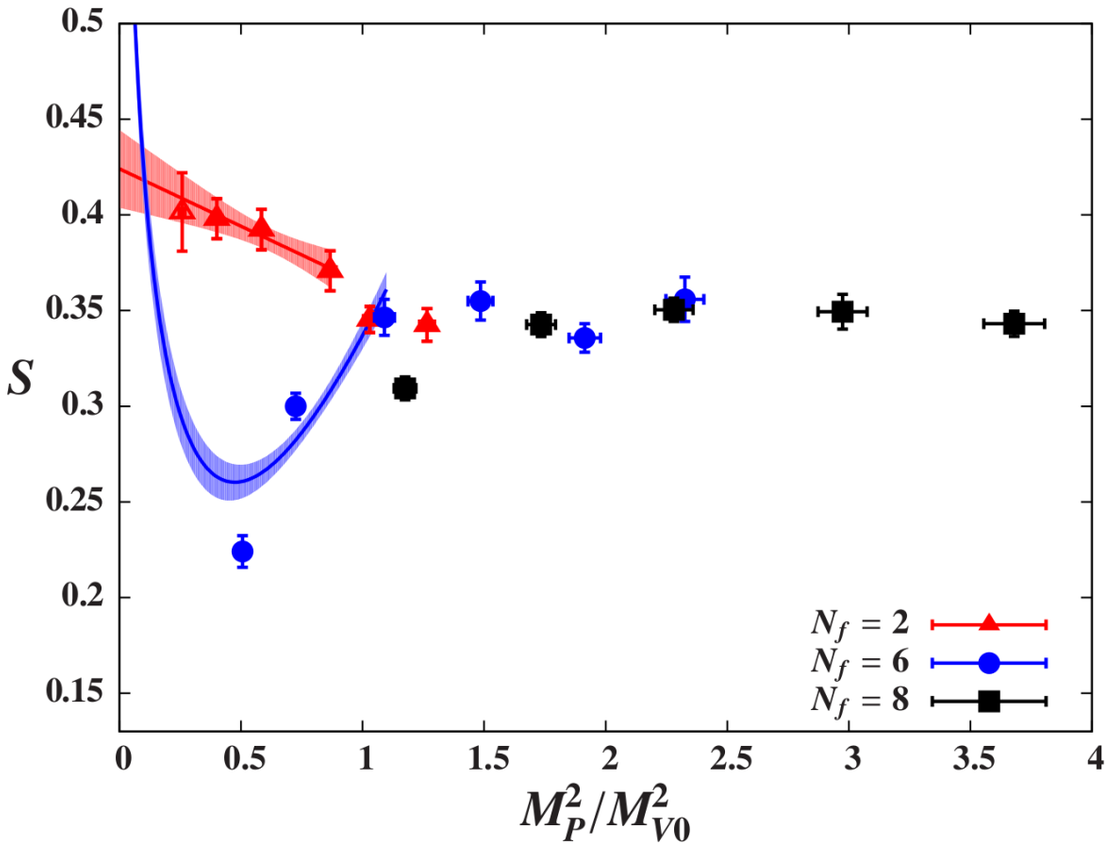
- calculated through vacuum polarization function of flavor non-singlet currents
- lattice calculation suffers from power divergence without exact chiral symm.
- so far, overlap and domain-wall fermion methods are reported
- Overlap
  - Nf=2 SU(3) [JLQCD Shintani et al PRL 2008]
- Domain-wall
  - Nf=2+1 SU(3) [RBC/UKQCD Boyle et al PRD 2010]
- Staggered (utilizing exact non-singlet symmetry due to multiple fields)
  - Nf=4n system setup on HISQ [Aoki (LatKMI) Lattice 2013]

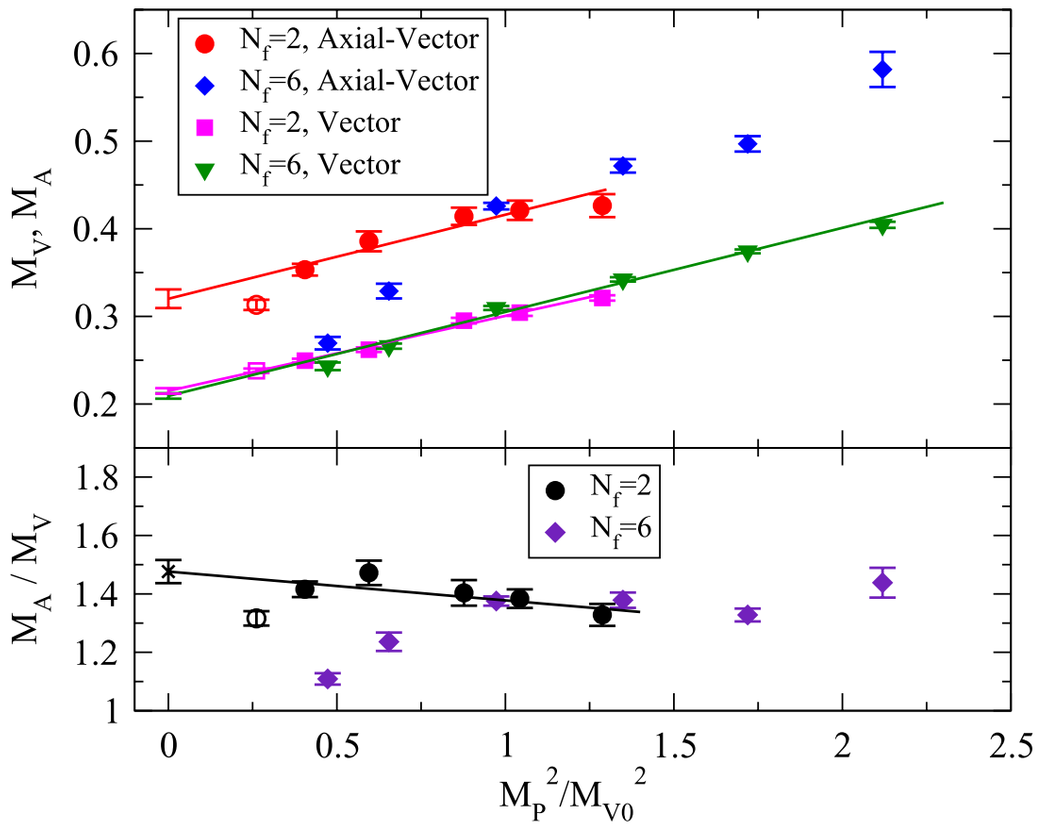
S parameter of QCD with Nf fundamental fermions [LSD, PRL 2011 & PRD 2014]

- domain wall fermions with Nf=2,6,8
- one doublet has EW charge →
- Nf=6
  - decreases as m_f enters chiral regime
  - turns up after chiral log sets in
  - low value of S possible for unabsorbed massive pions
- Nf=8
  - similar trend as Nf=6, but not conclusive



S parameter of Nf=6 and parity doubling [LSD, PRL 2011 & PRD 2014]

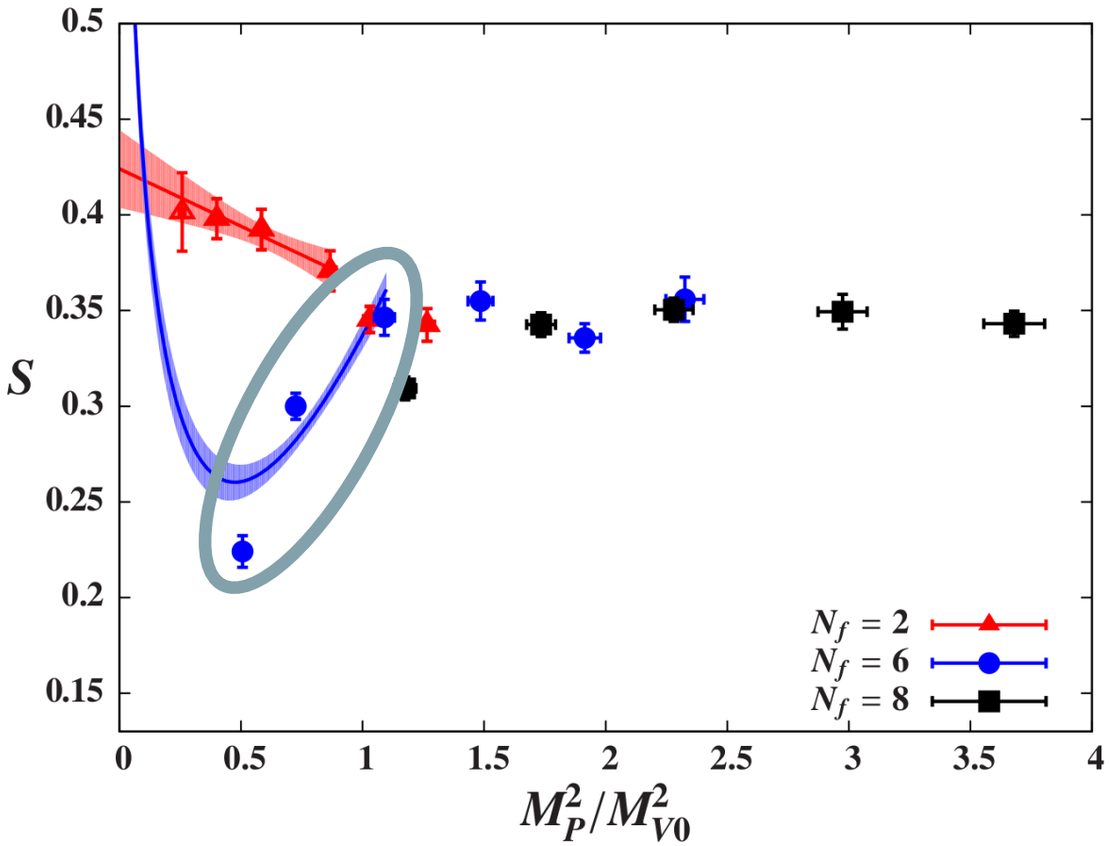


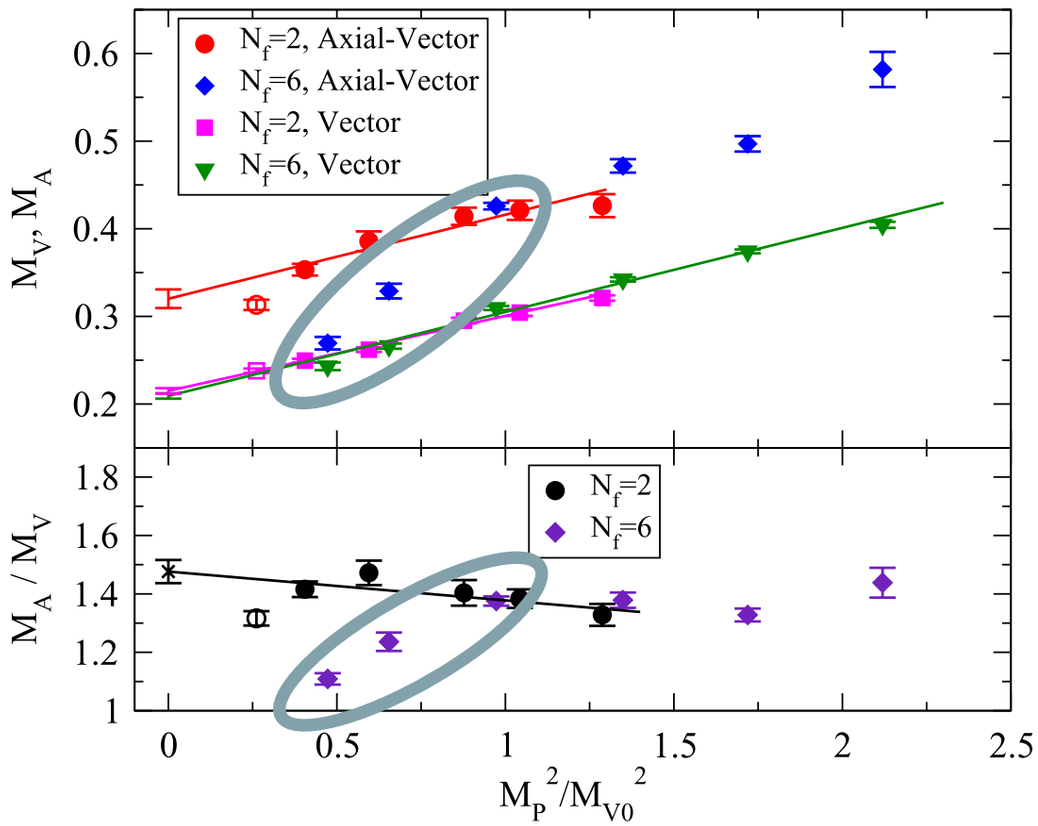


$$S = 4\pi(N_f/2)[\Pi'_{VV}(0) - \Pi'_{AA}(0)] - \Delta S_{\rm SM}$$
$$= \frac{1}{3\pi}\int_0^\infty \frac{ds}{s}\left\{(N_f/2)[R_V(s) - R_A(s)] - \frac{1}{4}\left[1 - \left(1 - \frac{m_H^2}{s}\right)^3 \theta(s - m_H^2)\right]\right\},$$

- parity doubling observed in the spectrum is consistent with the decrease

S parameter of Nf=6 and parity doubling [LSD, PRL 2011 & PRD 2014]





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- parity doubling observed in the spectrum is consistent with the decrease

currents and Ward-Takahashi identities: HISQ

- obtained through local variation on the action under the exact symmetries
- one link and Naik term (Asqtad, HISQ) → one link and three link terms
  - $\mathcal{V}_\mu^{(1,2)}(x) = V_\mu^{(1,2)}(x) + \text{three link terms}$
  - $\Delta_\mu \langle \mathcal{V}_\mu^{(1,2)}(x)\ O(0)\rangle = \langle \delta_V O(0)\rangle$
  - $\mathcal{A}_\mu^{(1,2)}(x) = A_\mu^{(1,2)}(x) + \text{three link terms}$
  - $\Delta_\mu \langle \mathcal{A}_\mu^{(1,2)}(x)\ O(0)\rangle = 2m_f \langle P^{(1,2)}\ O(0)\rangle + \langle \delta_A O(0)\rangle$

current-current correlation function for VPF: HISQ

- Conserved - OneLink correlators

$$\langle \mathcal{V}_\mu^{(1,2)}(x)\ V_\nu^{(2,1)}(0)\rangle$$

$$\Delta_\mu \langle \mathcal{V}_\mu^{(1,2)}(x)\ V_\nu^{(2,1)}(0)\rangle = (\delta_{x,0} - \delta_{x,0+\hat{\nu}})\ \langle \tilde{V}_\nu^{(1,2)}(0)\rangle$$

($\langle \mathcal{V}_\mu(x)\ V_\nu(0)\rangle^{\rm sub} = \langle \mathcal{V}_\mu(x)\ V_\nu(0)\rangle - \delta_{\mu,\nu}\delta_{x,0}\langle \tilde{V}_\nu(0)\rangle$ → HVPF)

$$\langle \mathcal{A}_\mu^{(1,2)}(x)\ A_\nu^{(2,1)}(0)\rangle$$

$$\Delta_\mu \langle \mathcal{A}_\mu^{(1,2)}(x)\ A_\nu^{(2,1)}(0)\rangle = 2m_f \langle P^{(1,2)}(x)\ A_\nu^{(2,1)}(0)\rangle + (\delta_{x,0} - \delta_{x,0+\hat{\nu}})\ \langle \tilde{V}_\nu^{(1,2)}(0)\rangle$$

- OneLink - OneLink used for sanity check of renormalization

$$\langle V_\mu^{(1,2)}(x)\ V_\nu^{(2,1)}(0)\rangle \qquad \langle A_\mu^{(1,2)}(x)\ A_\nu^{(2,1)}(0)\rangle$$

renormalization

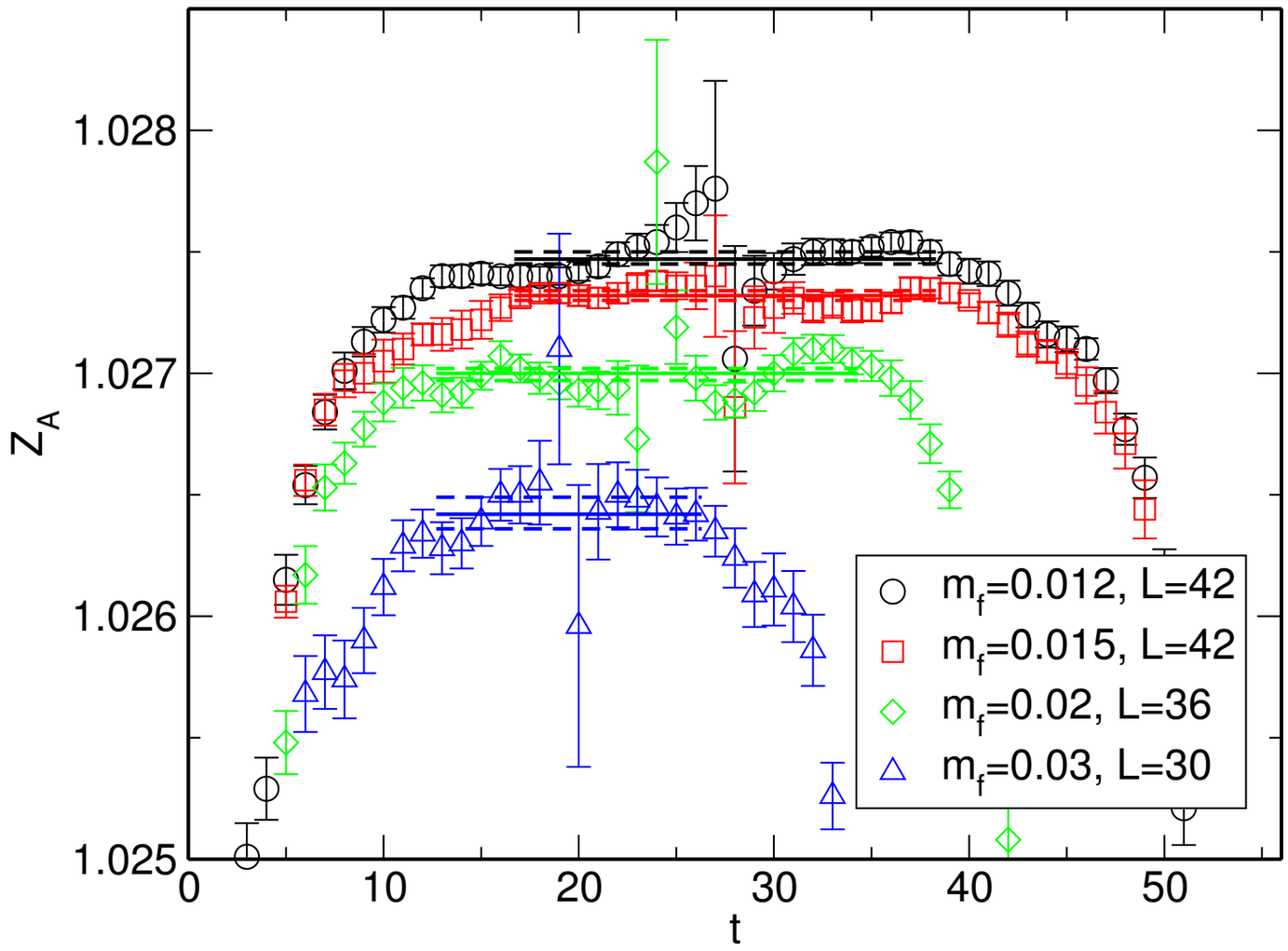
- sink: conserved, src: 1 link: src op needs renormalization

$$\langle \mathcal{A}_\mu^{(1,2)}(x)\ A_\nu^{(2,1)}(0)\rangle$$

- $\mathcal{A}_\mu = Z_A A_\mu \qquad\qquad Z_A = \dfrac{\langle \mathcal{A}_4(t) P(0)\rangle}{\langle A_4(t) P(0)\rangle}$
- $\mathcal{V}_\mu = Z_V V_\mu$
- $Z_V = Z_A$ for $m_f \to 0$ (chiral symmetry)

non-perturbative calculation of Z_A

- N_f=8, HISQ, β=3.8, L^3xT (L/T=4/3)
- choice of link in one link current: HISQ w/o Naik (so to mimic conserved)



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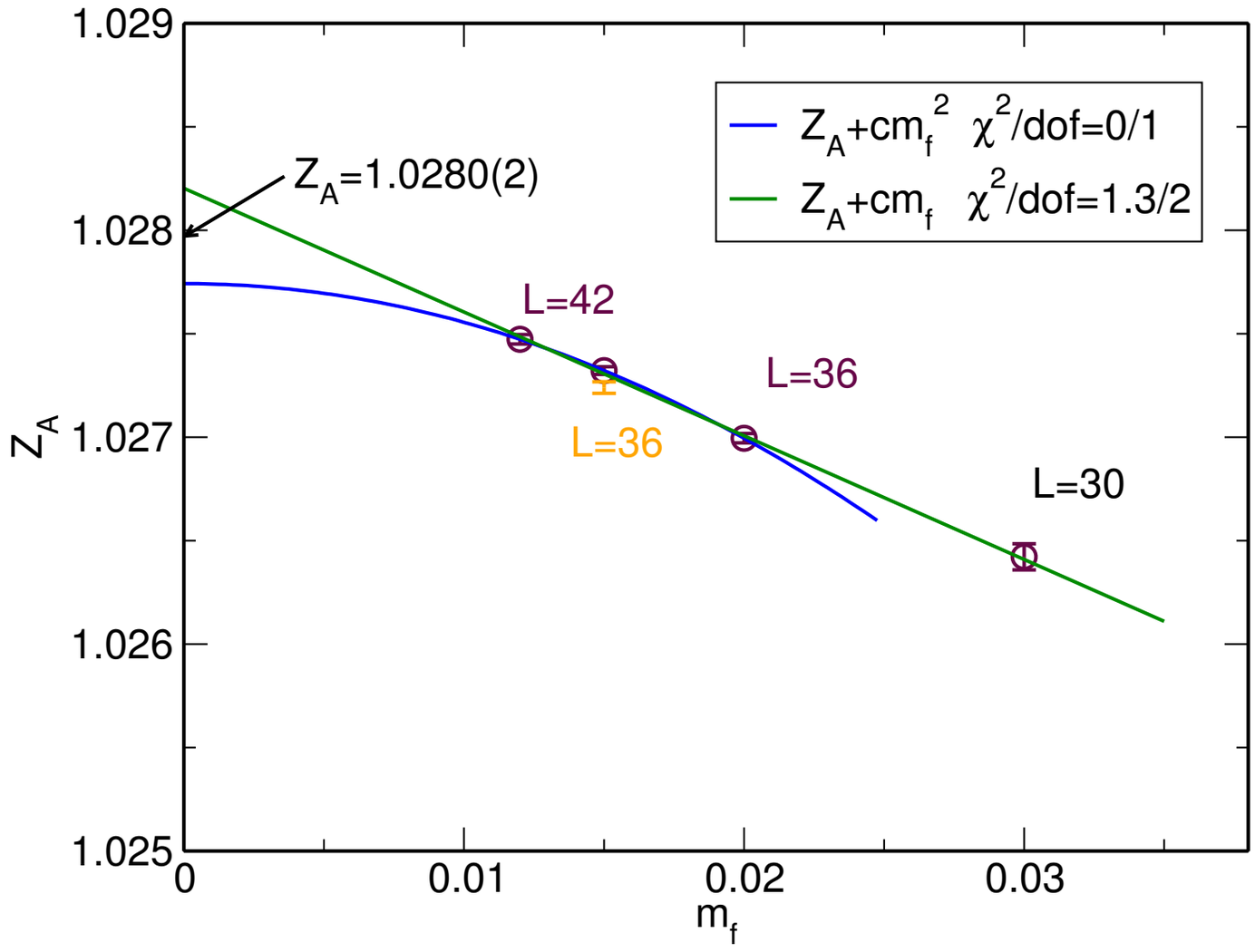
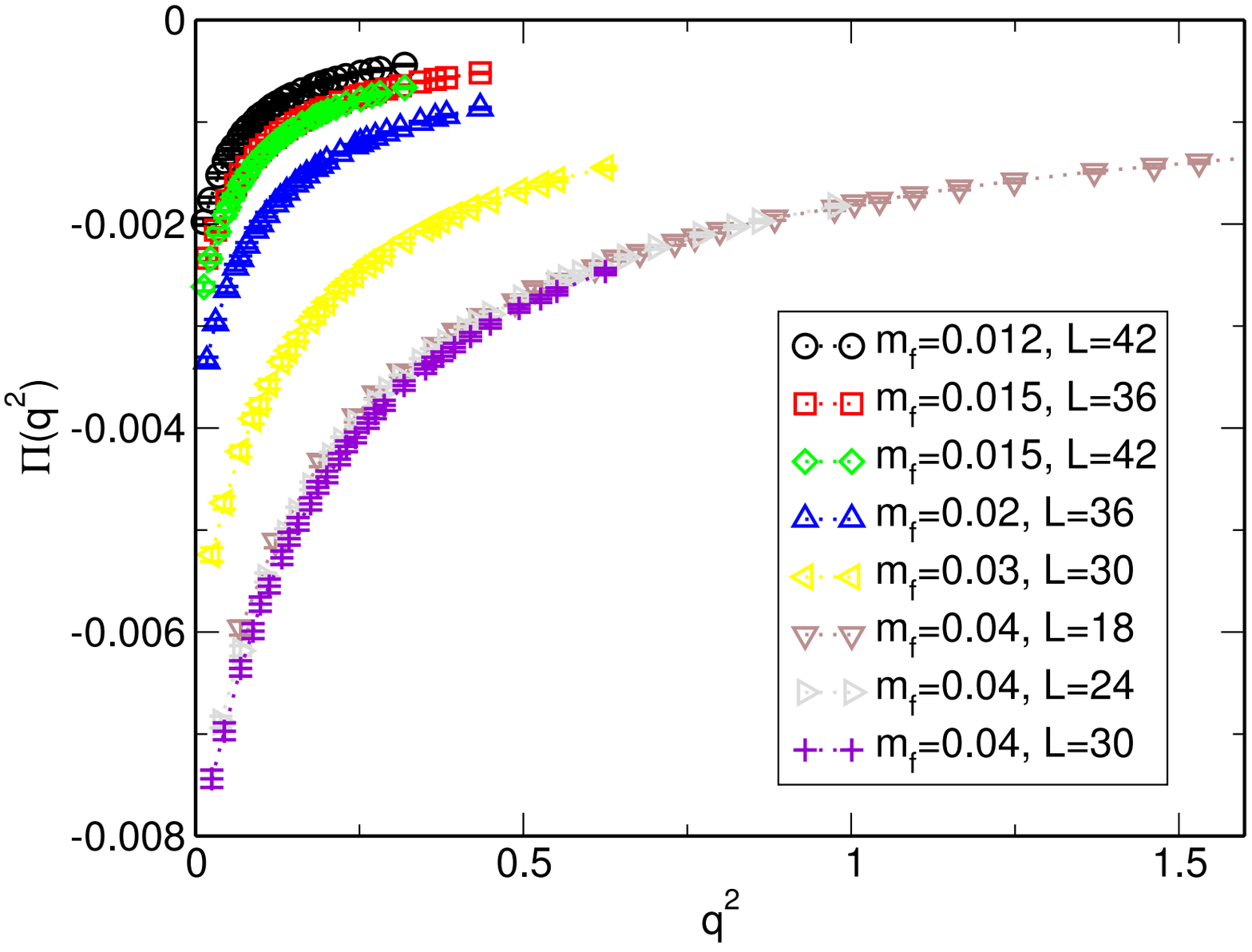
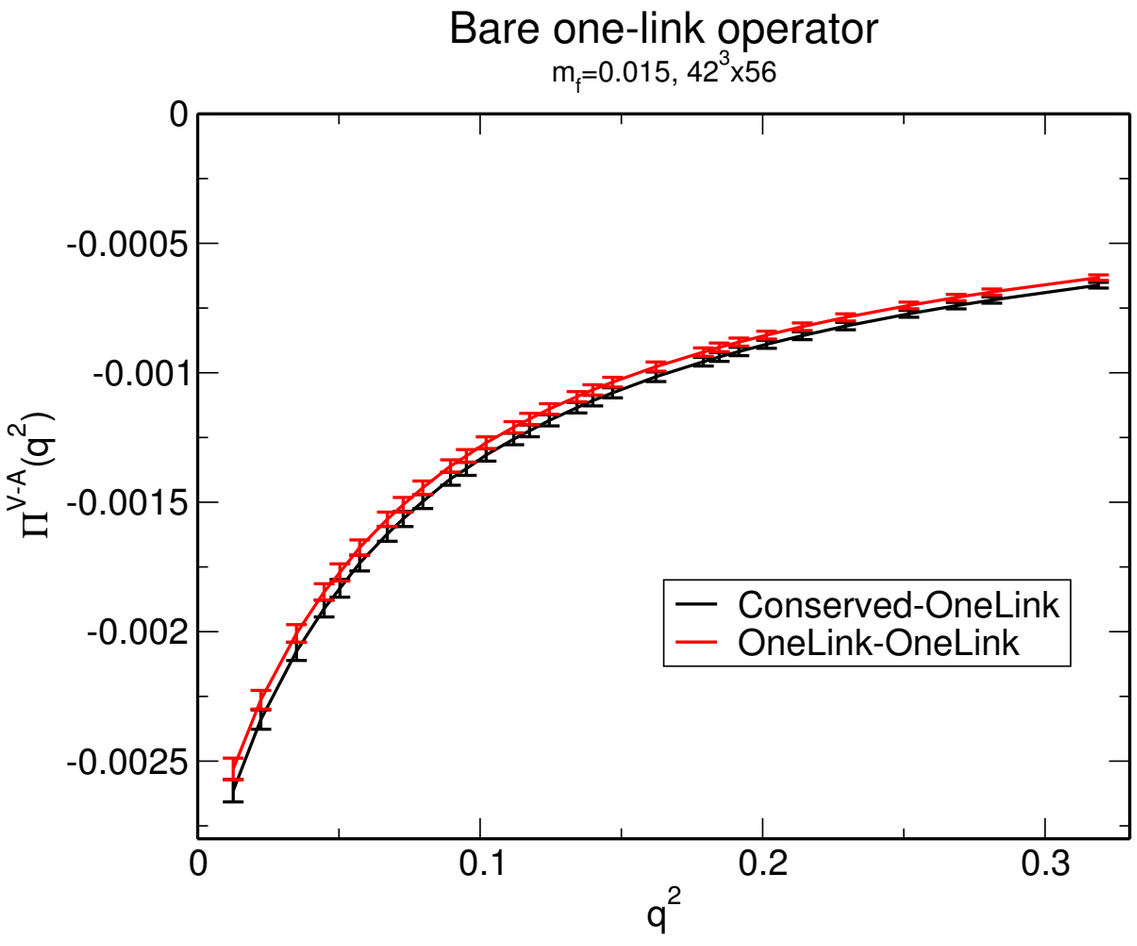
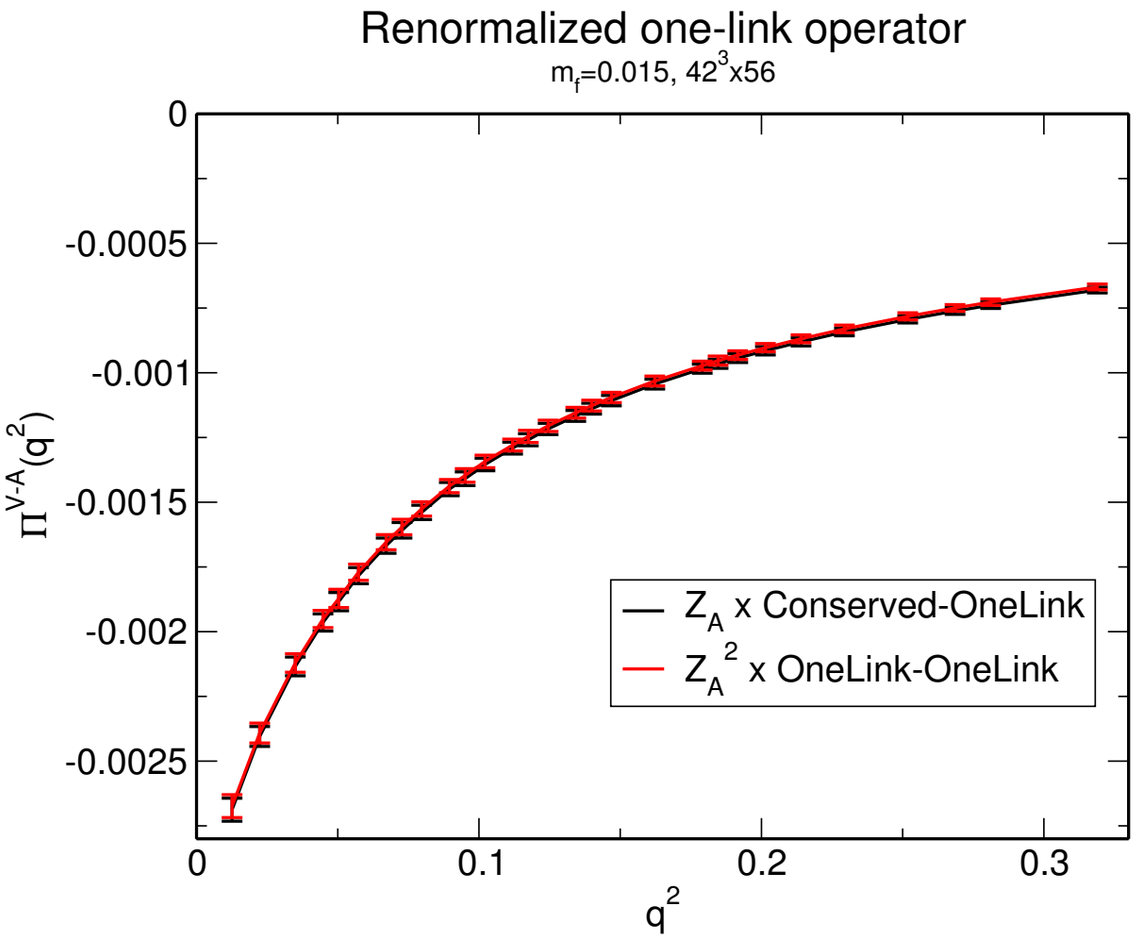


V-A vacuum polarization function (transverse)



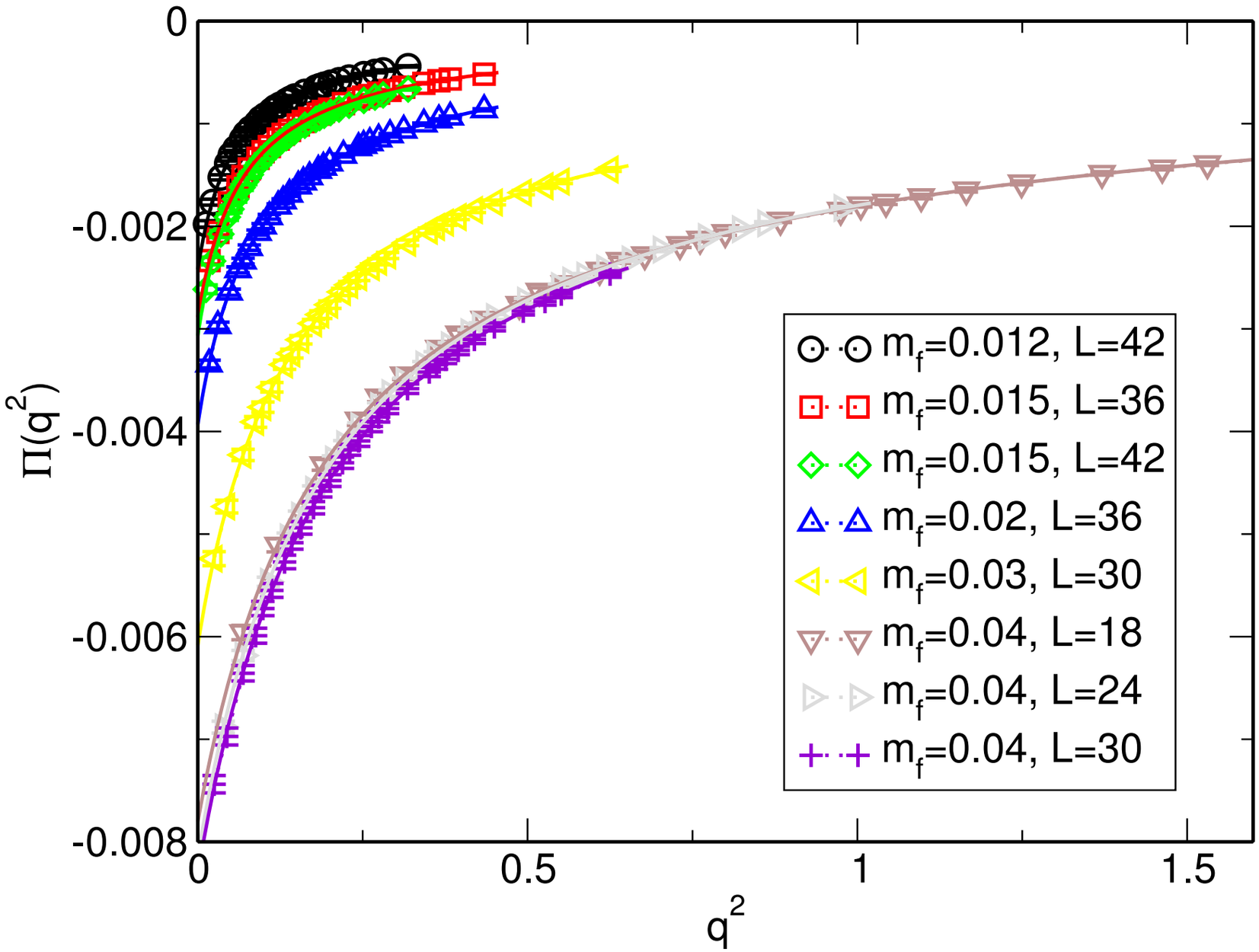
sanity check of non-perturbative renormalization





- non-perturbative renormalization is working, especially well at low q^2

V-A vacuum polarization function: Pade(1,2) fit



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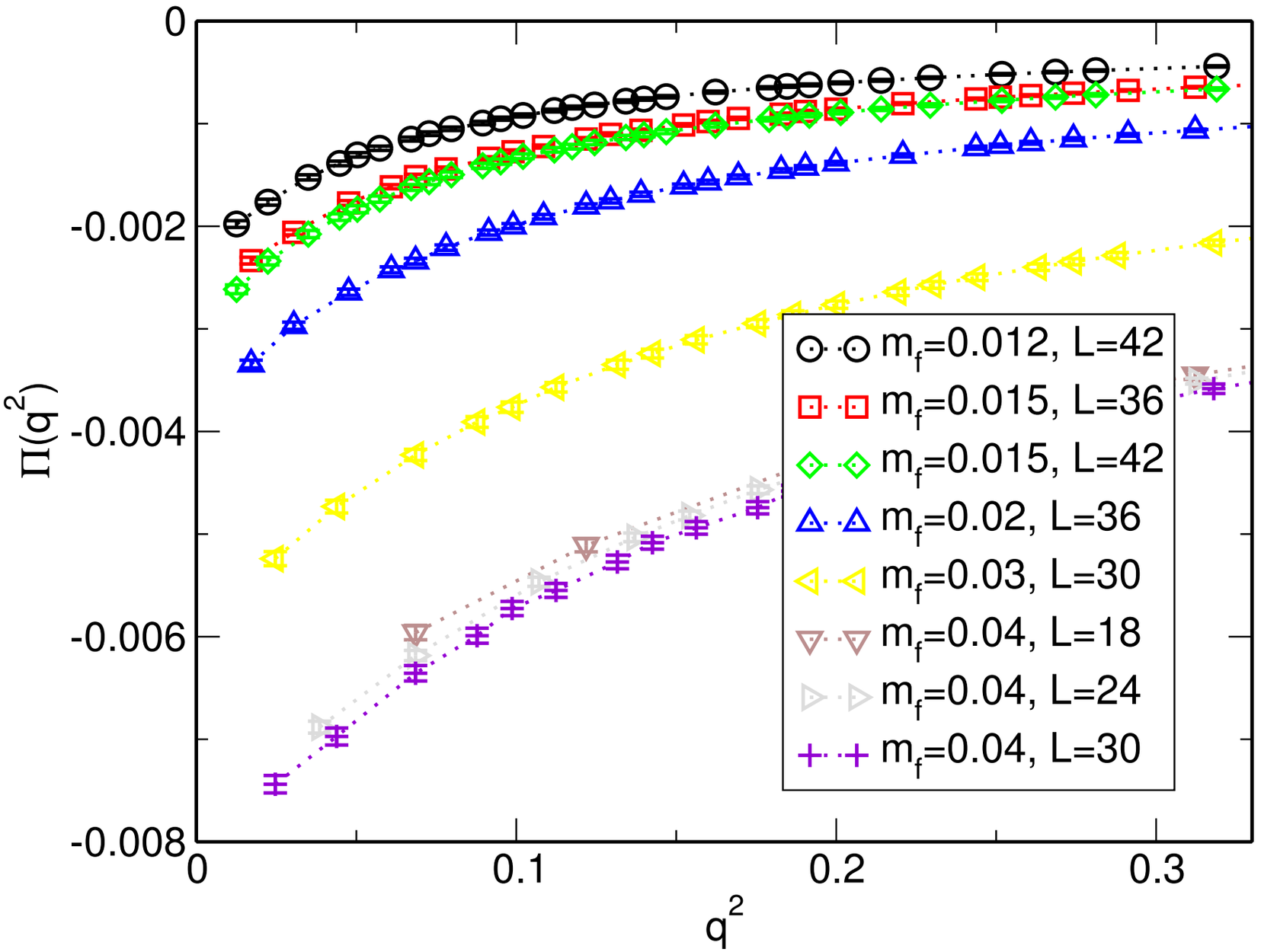
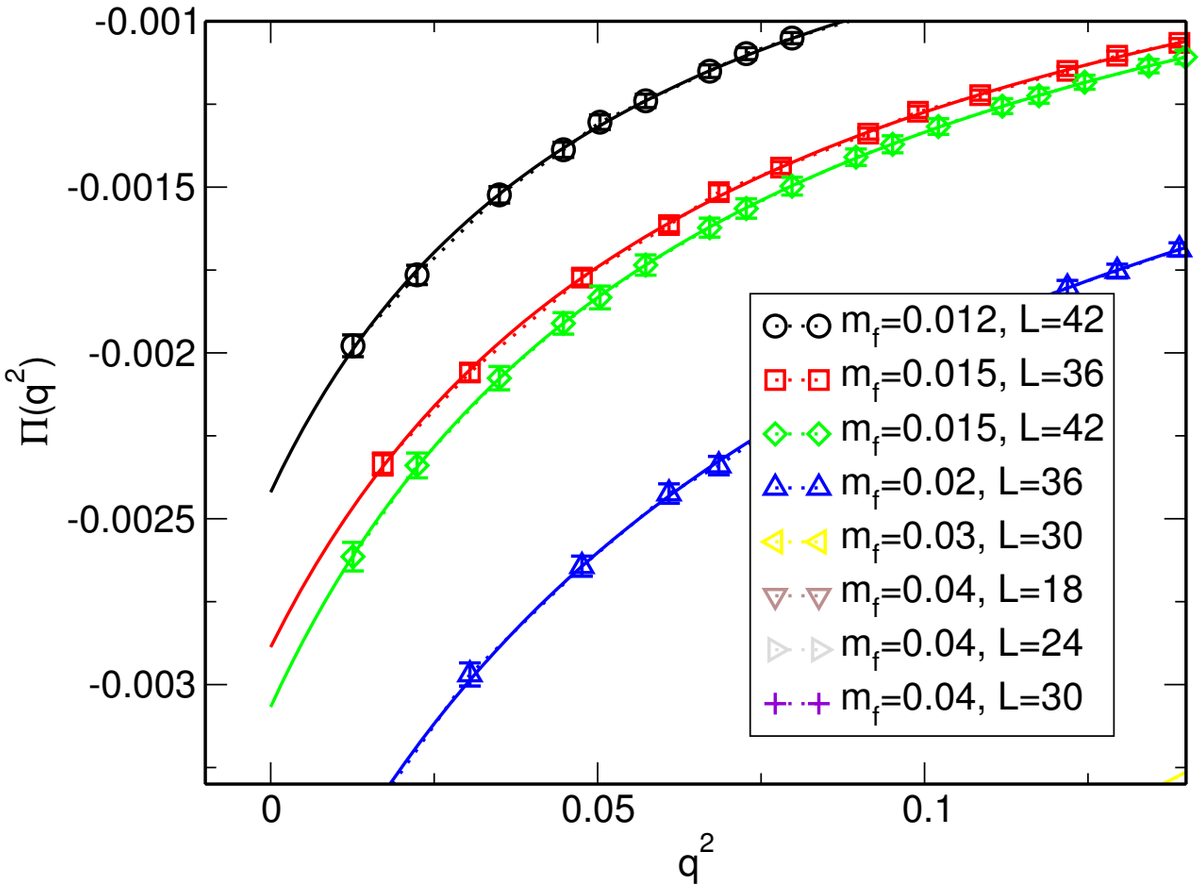
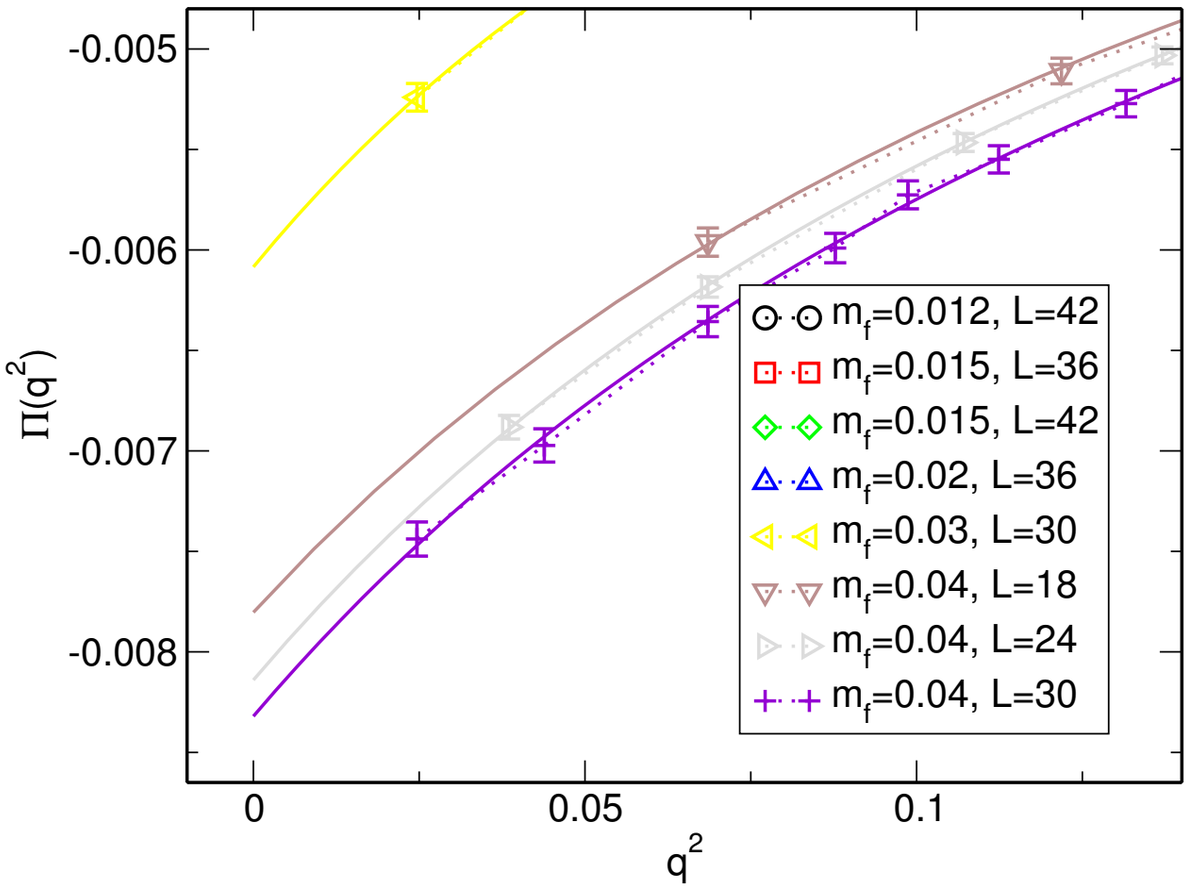


V-A vacuum polarization function: close-up

for m_f=0.015

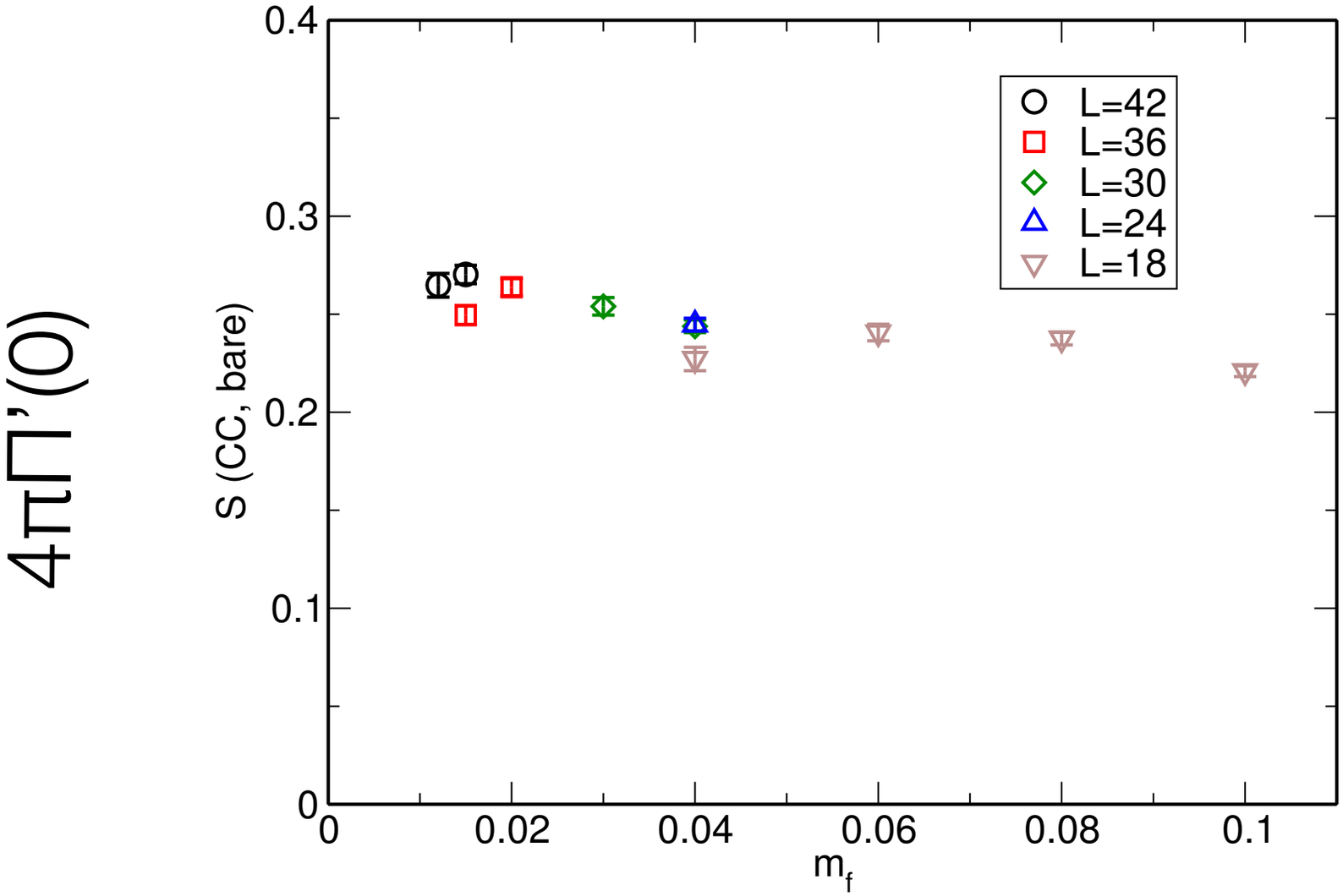


for m_f=0.04



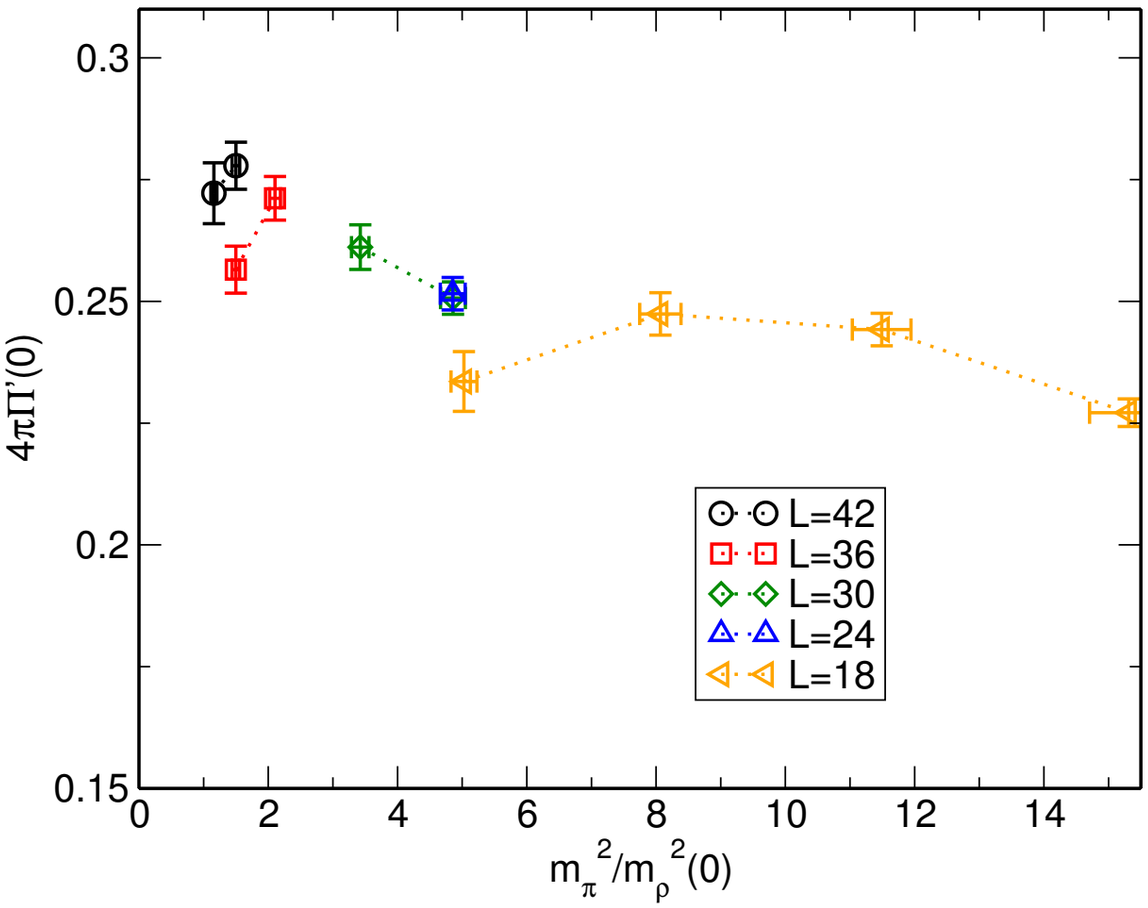
- finite volume effect on $\Pi(q^2)$ and $\Pi'(0)$?

S(m_f): TC contribution per EW doublet (preliminary)



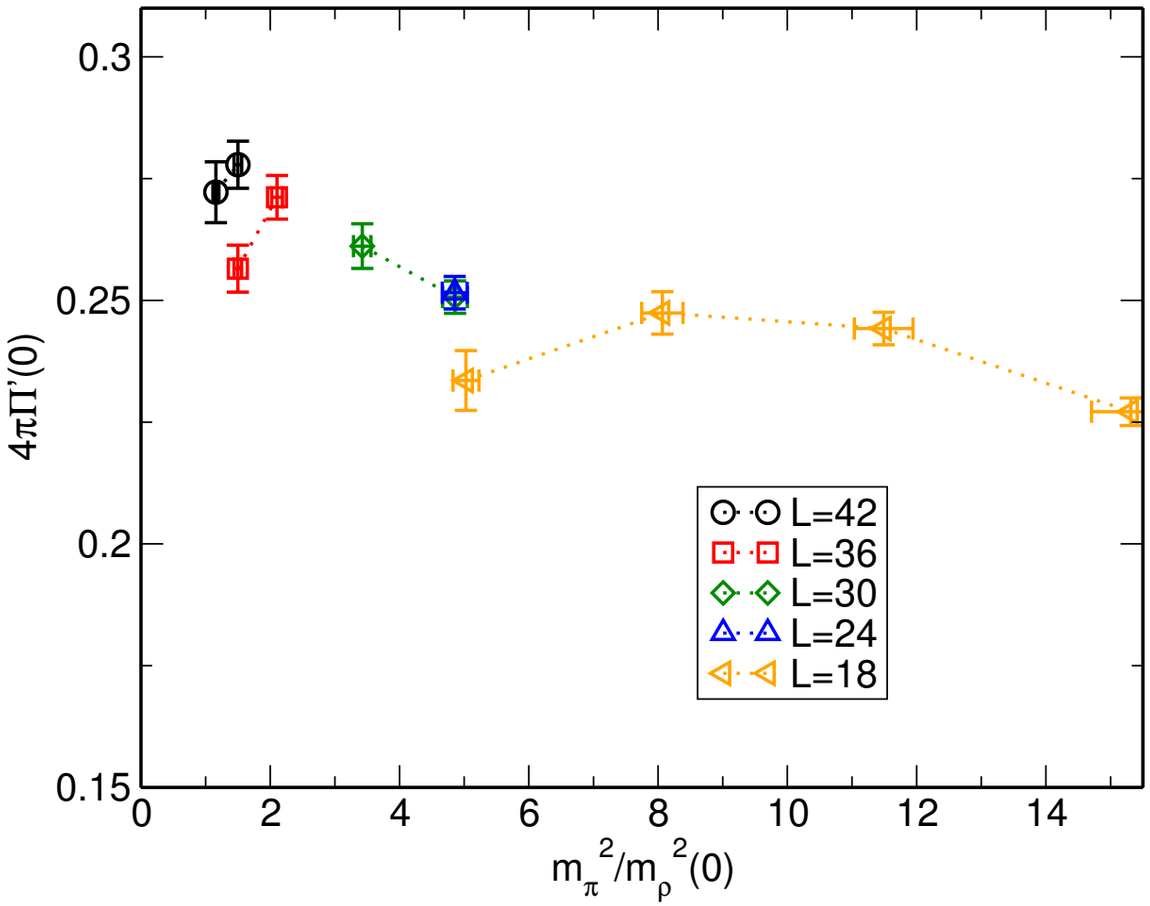
- finite size effect, somehow large, observed
- 8%↓ @ m_f=0.02; L=42→36 c.f. pion mass: 0.04%↓ (zero consistent)

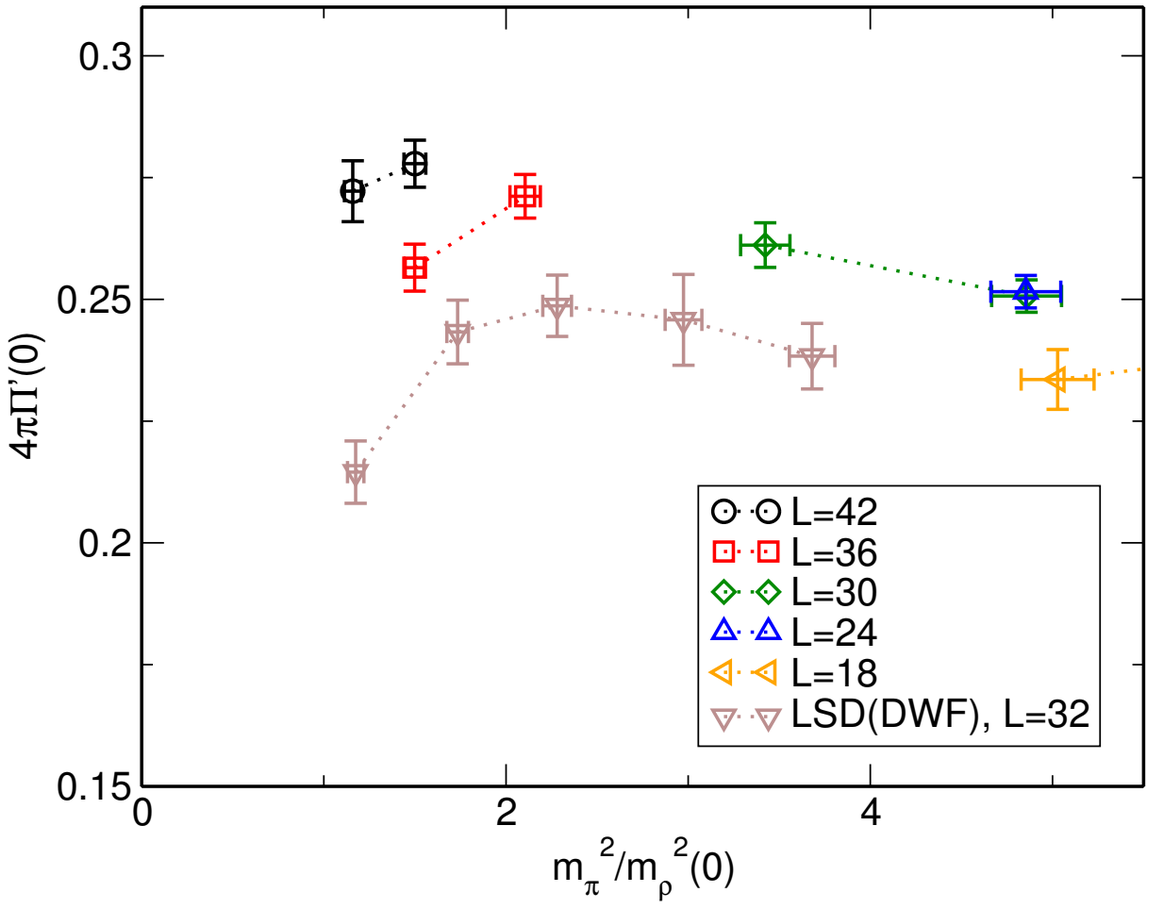
$S(m_\pi^2)$: TC contribution per EW doublet (preliminary)



- x axes: normalized with ρ mass in $m_f \to 0$ (linearly extrapolated)
- finite volume effect tends to reduce S

$S(m_\pi^2)$: TC contribution per EW doublet (preliminary)





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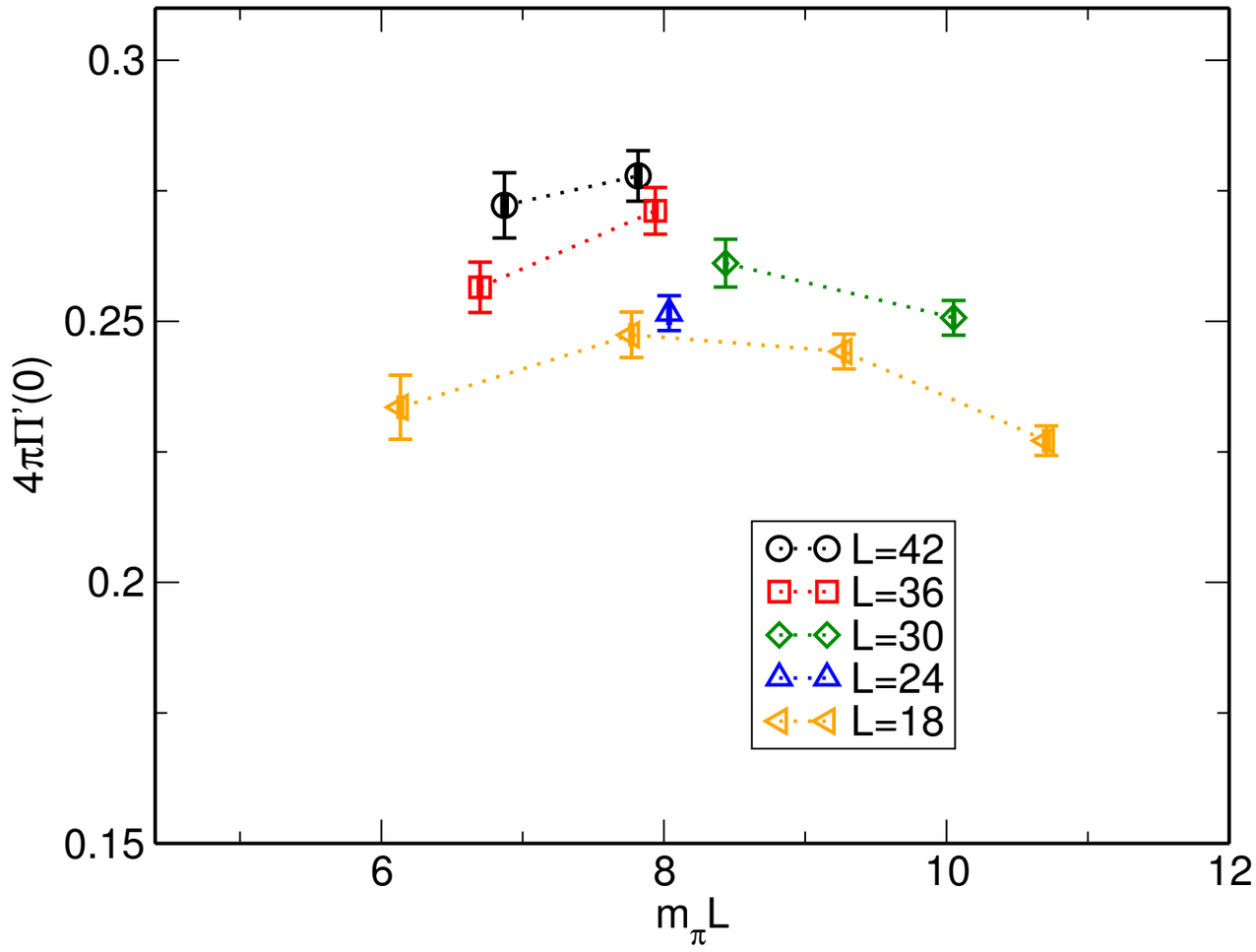
$S(m_\pi L)$: TC contribution per EW doublet (preliminary)



- finite volume effect tends to reduce S
- $m_\pi L \lesssim 7$ likely affected by finite volume effect

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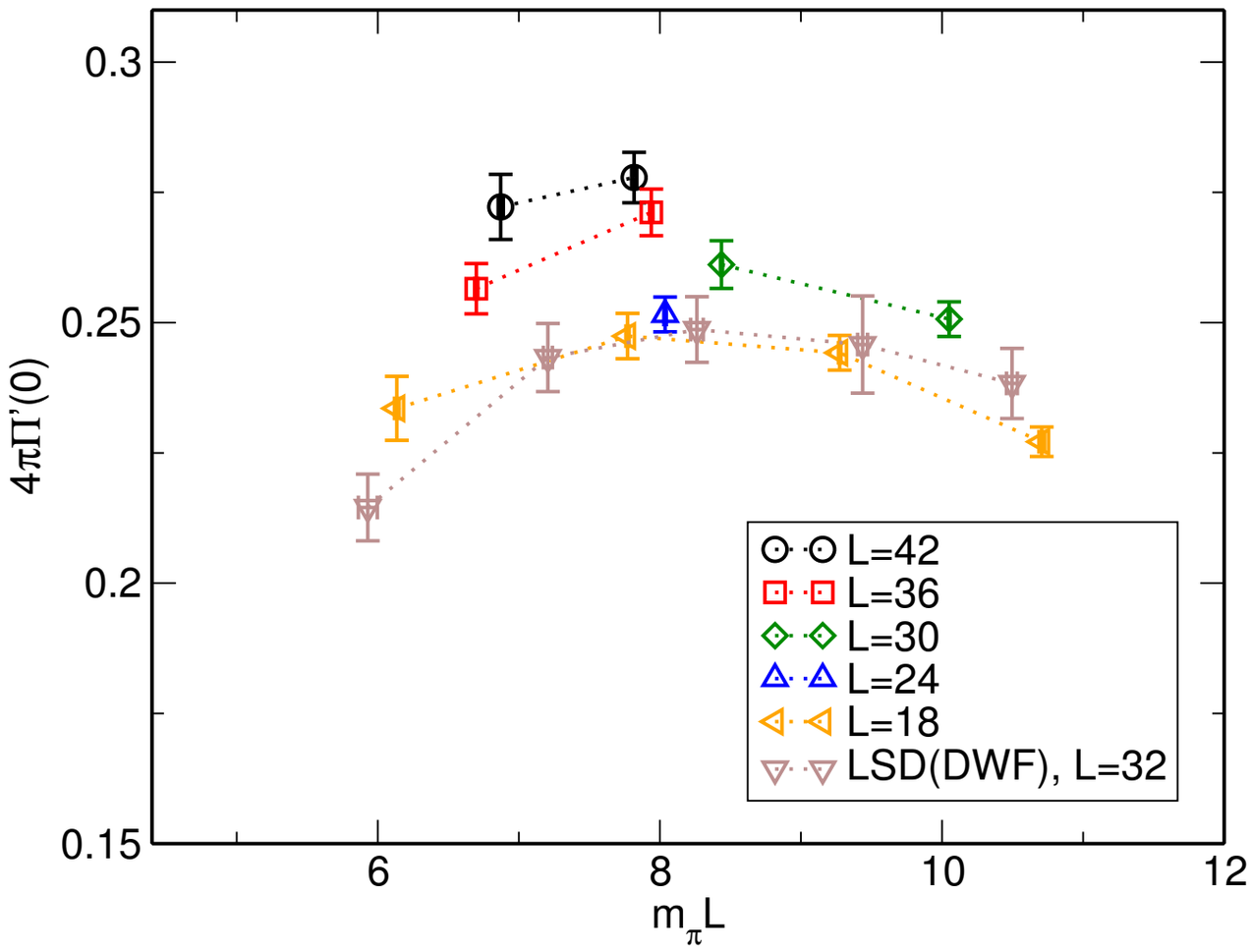

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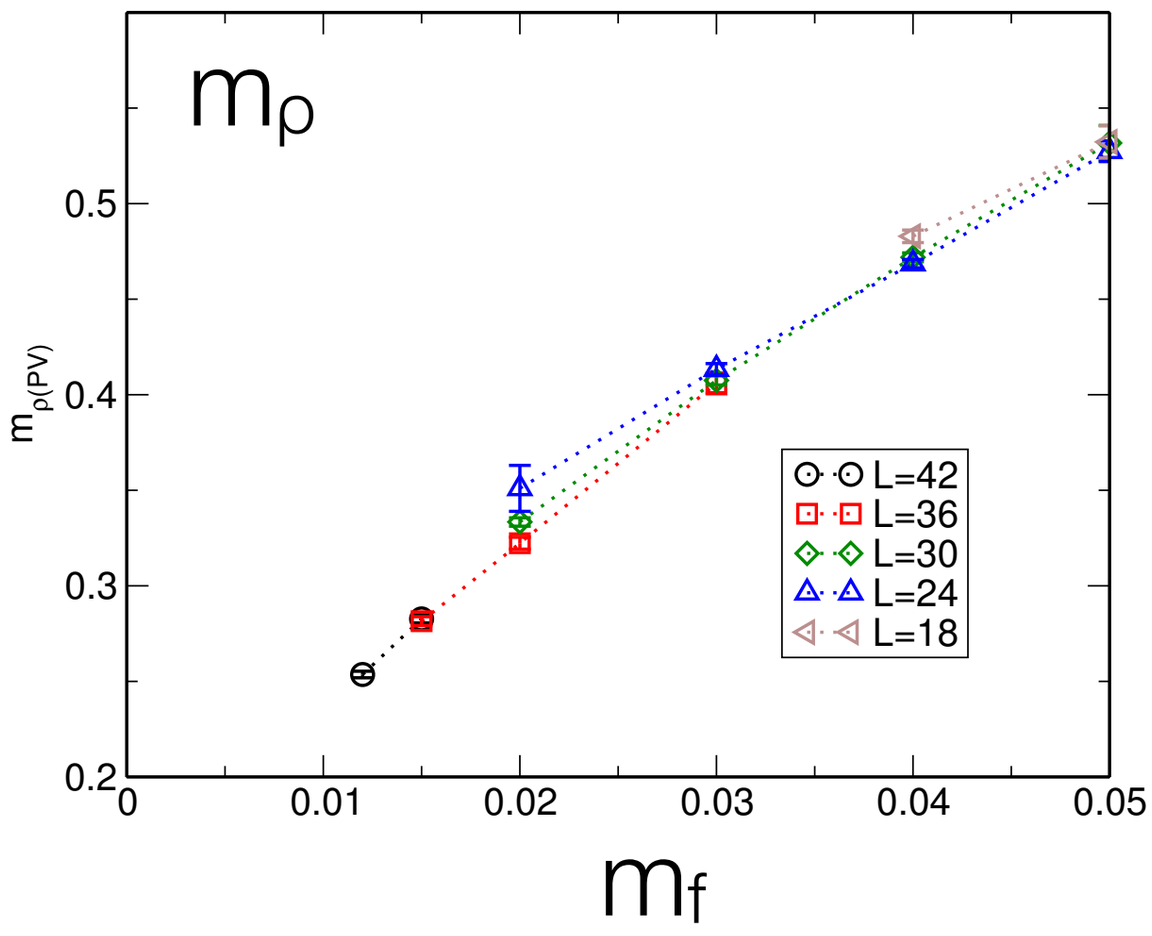
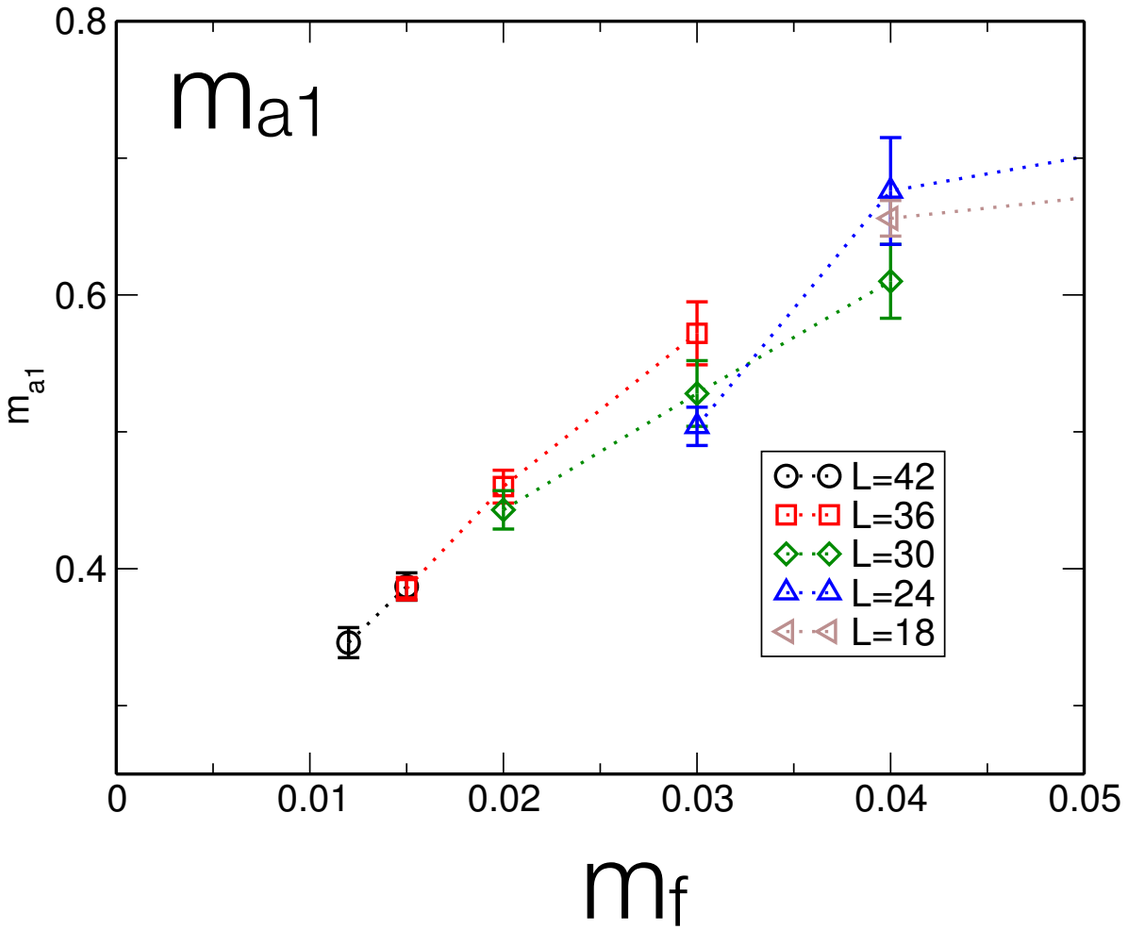
spectrum in vector and axialvector channel

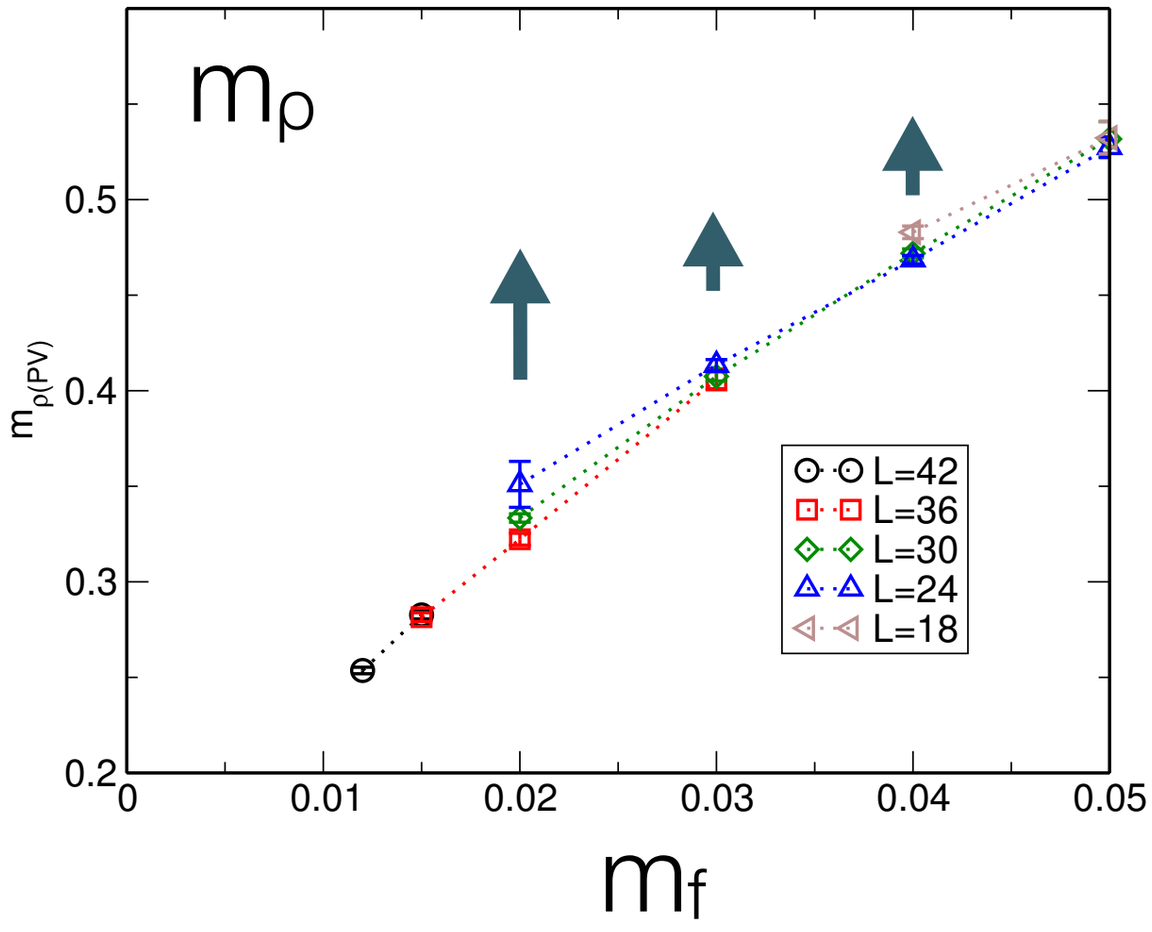


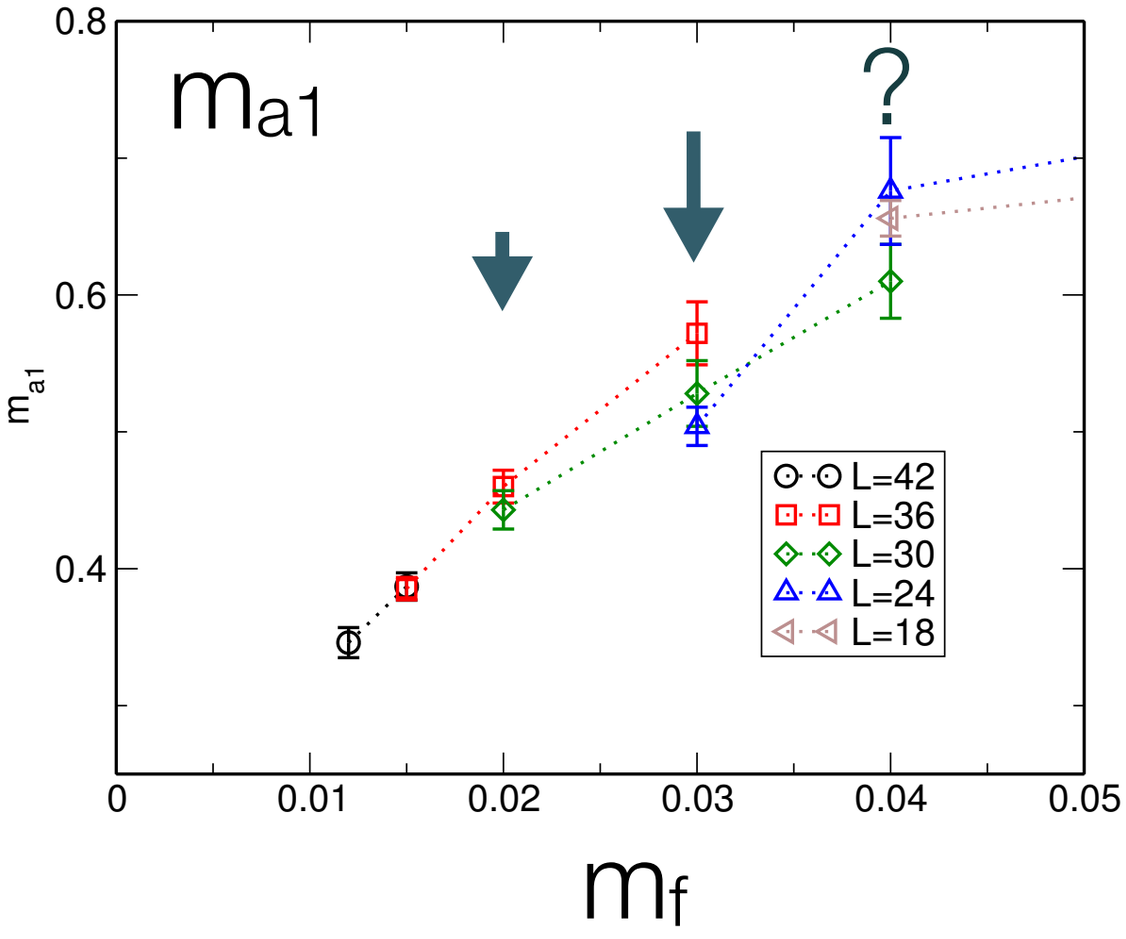


- measured with local operators (spin-taste: PV)
- indicating finite volume effect tends to push toward parity doubling

spectrum in vector and axialvector channel

finite volume effect





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summary and outlook

- Nf=8 QCD is still a candidate of Walking Technicolor
- Spectrum (rough for the moment) is predicted
- Important to go light towards chiral limit: we are still doing such effort
- S parameter is investigated for Nf=8 QCD
  - staggered SU(N_f/4) vector & axial exact symmetry allows a clean calculation
  - large “finite volume effect” on S, to make it reduced, is observed
  - axial vector meson mass has interesting volume effect
  - further checks required for establish the observation (on-going)
  - for sure, one needs careful volume analysis for the S parameter