Walking signals in Nf=8 QCD on the lattice

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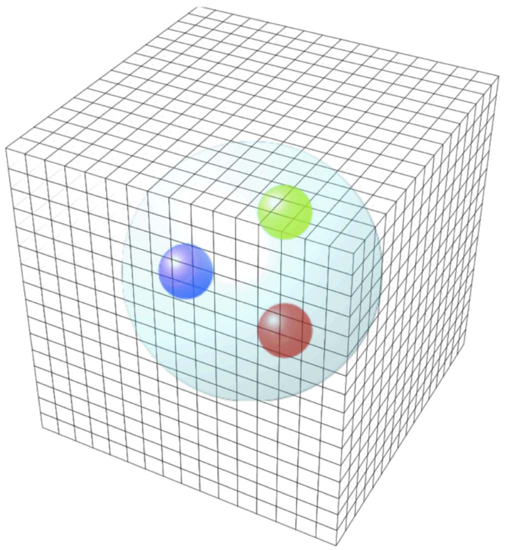
Plan of the Talk:



1. Introduction
2. Lattice study of Nf=8 QCD
   - Chiral Perturbation Theory (ChPT)
   - Finite Size Hyperscaling (FSHS)
3. Summary

♠ Nf=8 is the candidate of the walking behavior.

Walking signals in Nf=8 QCD on the lattice
Yasumichi Aoki, Tatsumi Aoyama, Masafumi Kurachi, Toshihide Maskawa, Kei-ichi Nagai, Hiroshi Ohki, Akihiro Shibata, Koichi Yamawaki, Takeshi Yamazaki, Feb 27, 2013,
Published in **Phys.Rev. D87 (2013) 094511**, e-Print: **arXiv:1302.6859 [hep-lat]**.

1. Introduction

- LQCD with many fermions
- BSM (quark mass, FCNC, ..., model building)
- ⇒ Candidate of the walking technicolor (WTC)

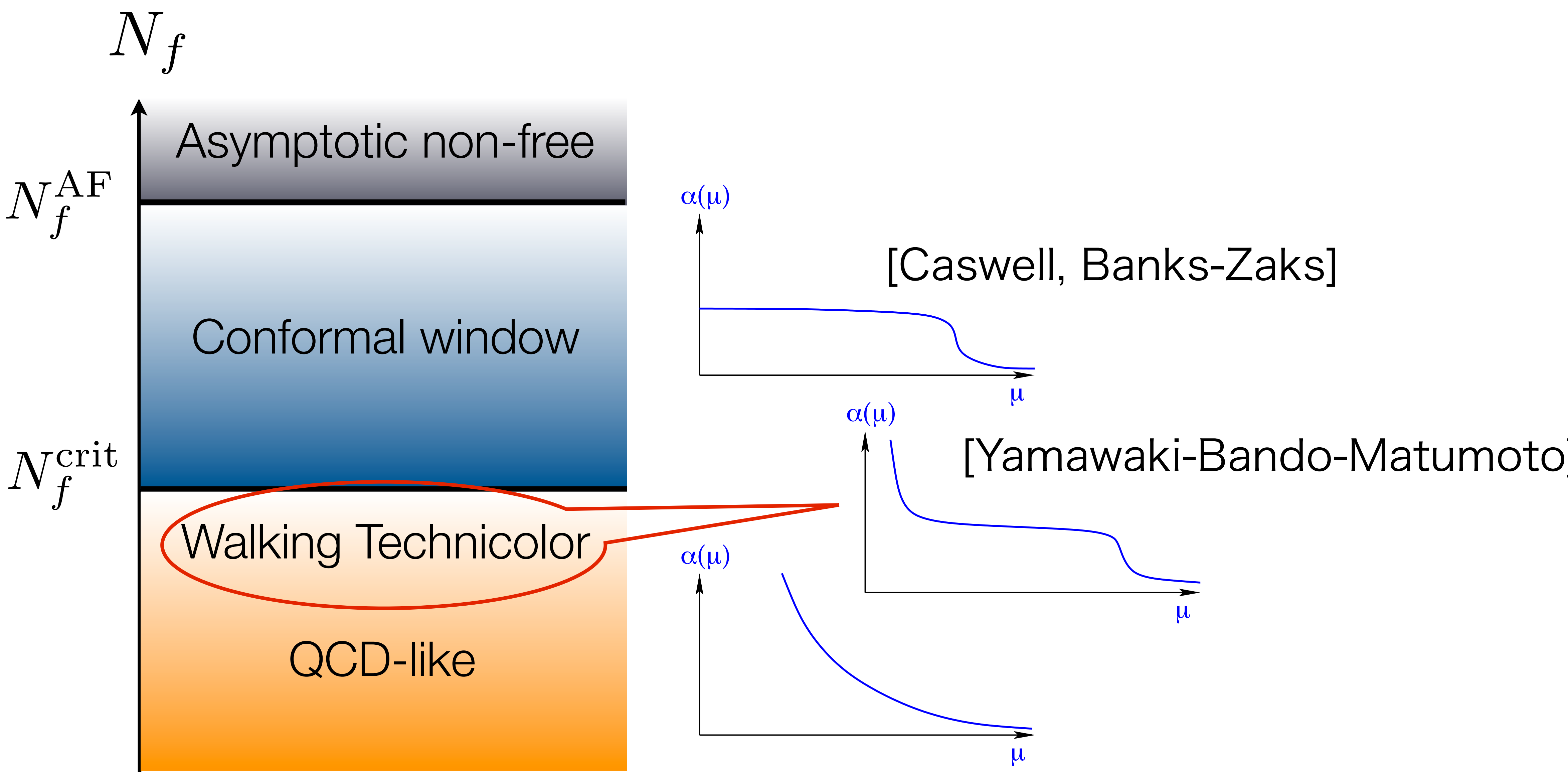
Requirements for the successful WTC theory

- spontaneous chiral symmetry breaking
- running coupling "walks" = slowly changing with μ: → nearly conformal
- large mass anomalous dimension: $\gamma_m \sim 1$
- light scalar 0^{++} (m_H = 126 GeV @ LHC !)
  - with input $F_\pi = 246/\sqrt{N}$ GeV (N: # weak doublet in techni-sector)
    - to reproduce $W^\pm$ mass
  - typical QCD like theory: $M_{Had} >> F_\pi$ (ex.: QCD: $m_\rho/f_\pi \sim 8$)
    - Naive TC: $M_{Had} > 1{,}000$ GeV
    - 0^{++} is a special case: pseudo Nambu-Goldstone boson of scale inv.

    ➡ is it really so ?

conformal window and walking coupling

- non-Abelian gauge theory with N_f massless fermions -



- Walking Technicolor could be realized just below the conformal window
- crucial information: N_f^{crit} & mass anomalous dimension around N_f^{crit}

Many flavor QCD

⇒ Candidate of walking/conformal

Our investigation in Nf=12 (Ohki's talk)

→ consistent with the conformal with γ=0.4--0.5 .

not favor as WTC (model building)

Thus, we investigate Nf=8 QCD.

strong coupling dynamics and non-perturbative

⇓

Lattice simulation of Nf=8 QCD

Lattice studies of Nf=8:

Y. Iwasaki et al. ('92, '04) [pioneering work] → conformal

K. Ishikawa et al. ('12, '13) → conformal
(Yukawa-type correlator in Nf=7 and 16)

A. Cheng et al. ('13) → large γ_m over a wide range
of energy scales (slow-running?)

A. Deuzeman et al.('08), K. Miura et al.('12)
→ SχSB, but near the conformal edge
(thermodynamics)

Z. Fodor et al. ('09) → SχSB

T. Appelquist et al. ('09) → no IRFP

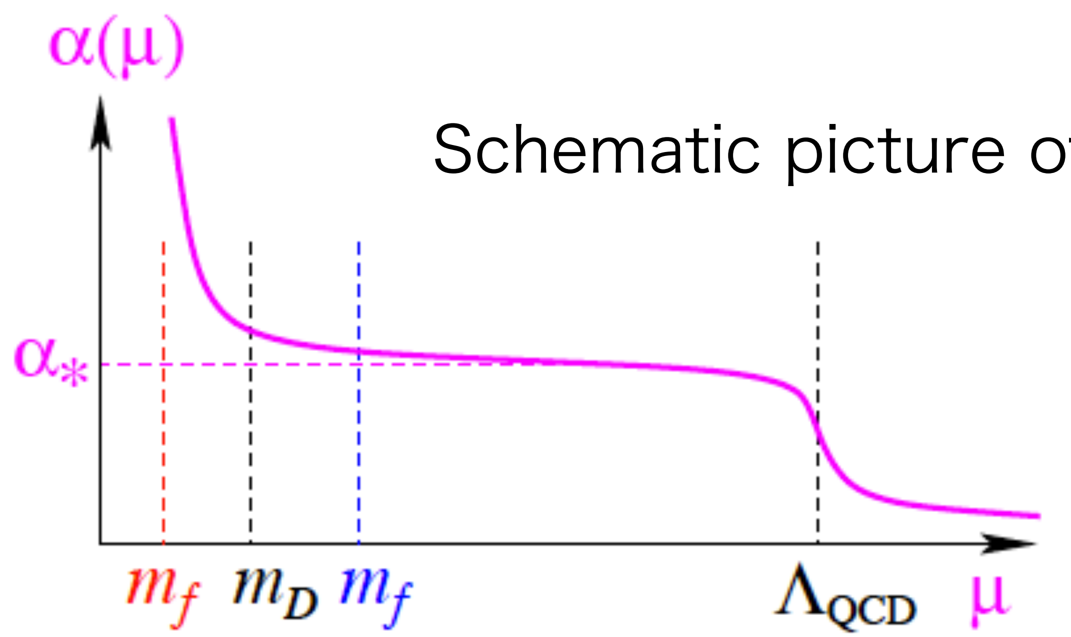
LatKMI('13) → In this talk (walking?)

What is the signal of walking?

Scenario of Walking Dynamics ;

Case-1: probe mf << m_D → SχSB-like

Case-2: probe mf >> m_D → conformal-like



Schematic picture of the gauge coupling

FIG. 1. Schematic two-loop/ladder picture of the gauge coupling of the massless large N_f QCD as a walking gauge theory in the SχSB phase near the conformal window. m_D is the dynamical mass of the fermion generated by the SχSB. The effects of the bare mass of the fermion m_f would be qualitatively different depending on the cases: Case 1: $m_f \ll m_D$ (red dotted line) well described by ChPT, and Case 2: $m_f \gg m_D$ (blue dotted line) well described by the hyper scaling.

⇒ **Spectrum?**

SχSB and/or conformal in some mf region ?

2. Lattice Study of Nf=8 case

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Simulation for Nf=8 (same setup with Nf=12)

lattice action (Hybrid Monte-Carlo simulation)

- Tree-level Symanzik gauge action
- Highly Improved Staggered Quarks = **HISQ**

(without tadpole improvement and mass correction in Naik term)

★ parameter set

- $\beta\,(\equiv 6/g^2) =$ **3.8,** $V=L^3 xT$, T/L=4/3 fixed.

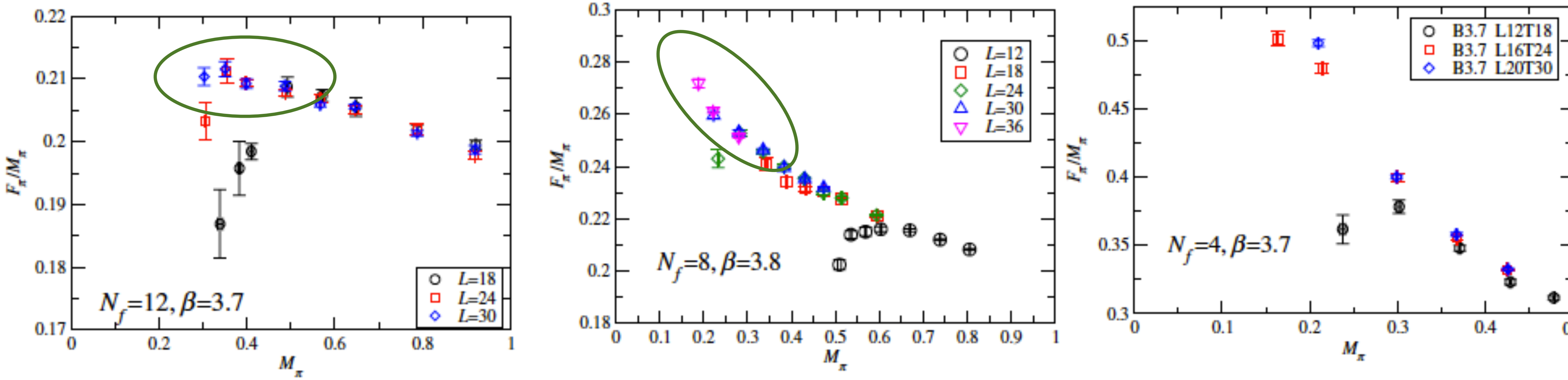
V	12^3 x 16	18^3 x 24	24^3 x 32	30^3 x 40	36^3 x 48
mf	0.01~0.16	0.04~0.1	0.02~0.1	0.02~0.07	0.015~0.03

★ Measurements (P+AP method ⇒ double size in T-dir.)

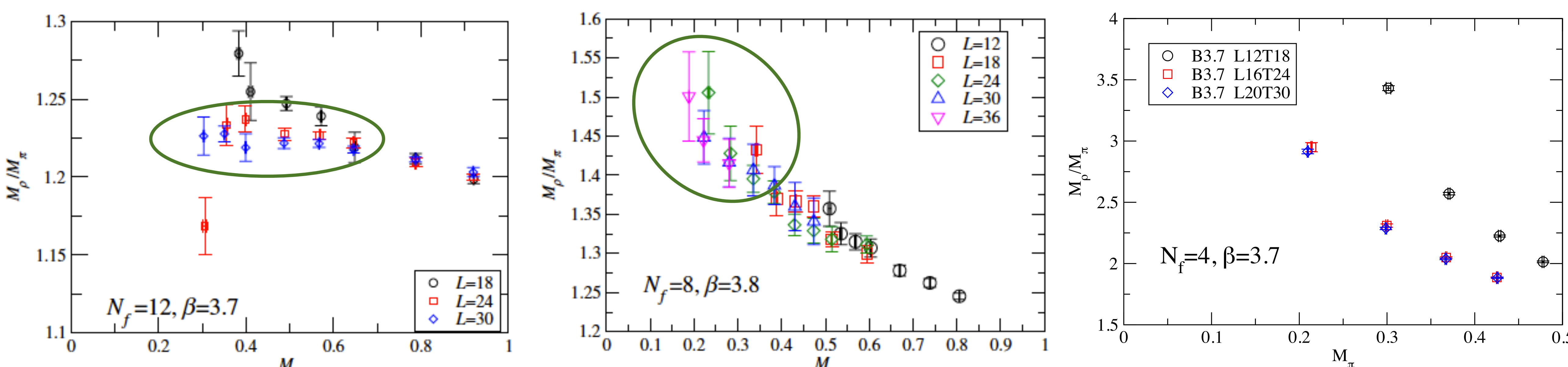
★ about 1000 trajectories after thermalization

- M_π, F_π, M_ρ, chiral condensate
- analysis for $M_\pi L > 6$ (to cut the finite size effect)

F_π/M_π for Nf=12, 8 and 4 (flat or divergent in χ-limit?)



M_ρ/M_π for Nf=12, 8 and 4 (flat or divergent in χ-limit?)



Nf=8 ⇒ spontaneous chiral symmetry breaking?

(SχSB)

Chiral Perturbation Theory (ChPT)

In SχSB; $M_\pi^2 = C_1^\pi m_f + C_2^\pi m_f^2 + \cdots, \quad F_\pi = F + C_1^F m_f + C_2^F m_f^2 + \cdots,$

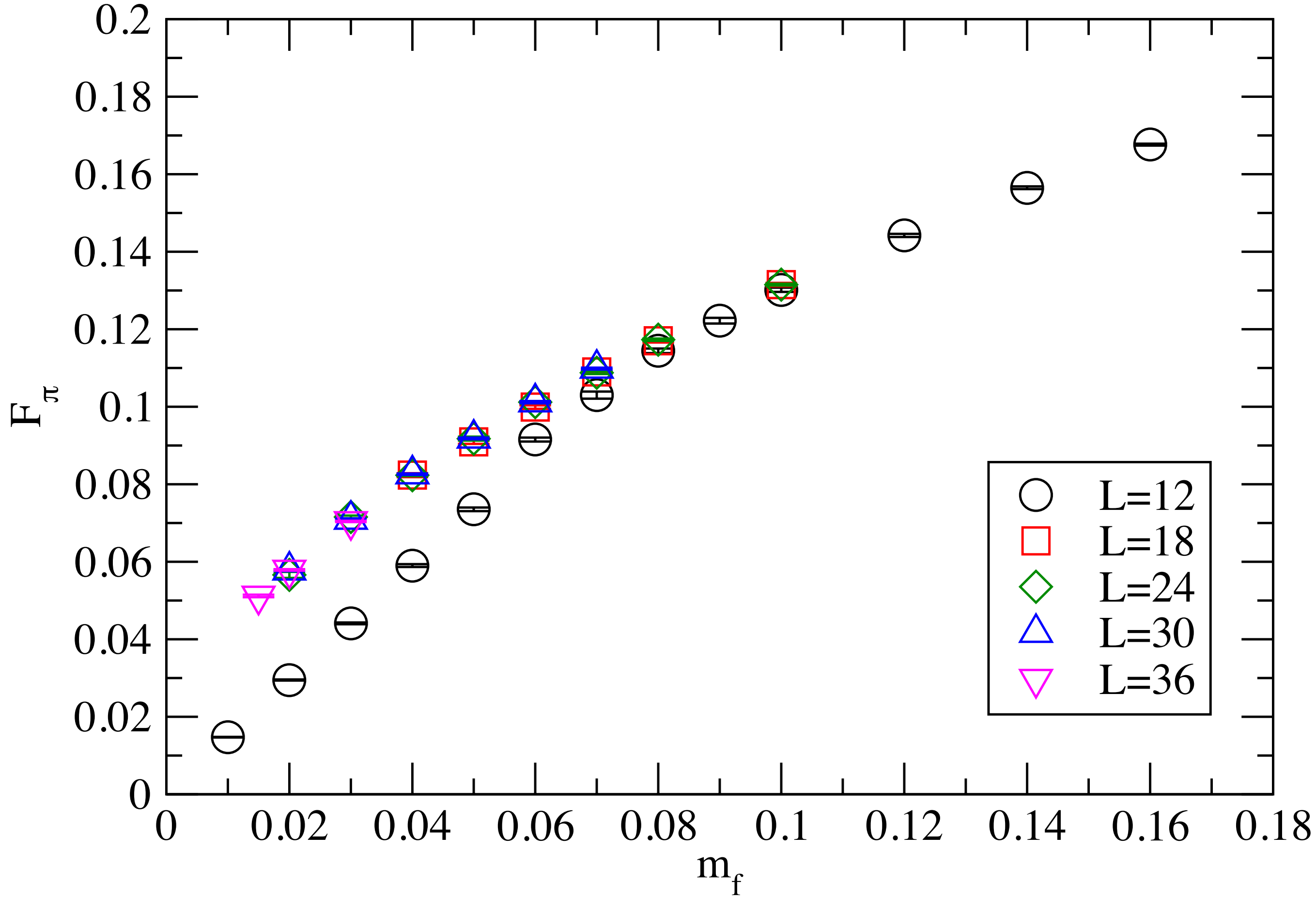
⇒ Polynomial fit in small mf region

We regard the data on the largest volume at each mf
as the ones on the infinite volume. (Backup figs.)

We don't discuss the chiral log behavior in this talk.

However, we discussed the chiral log in the published paper.

Fπ vs mf on various Lattice sizes

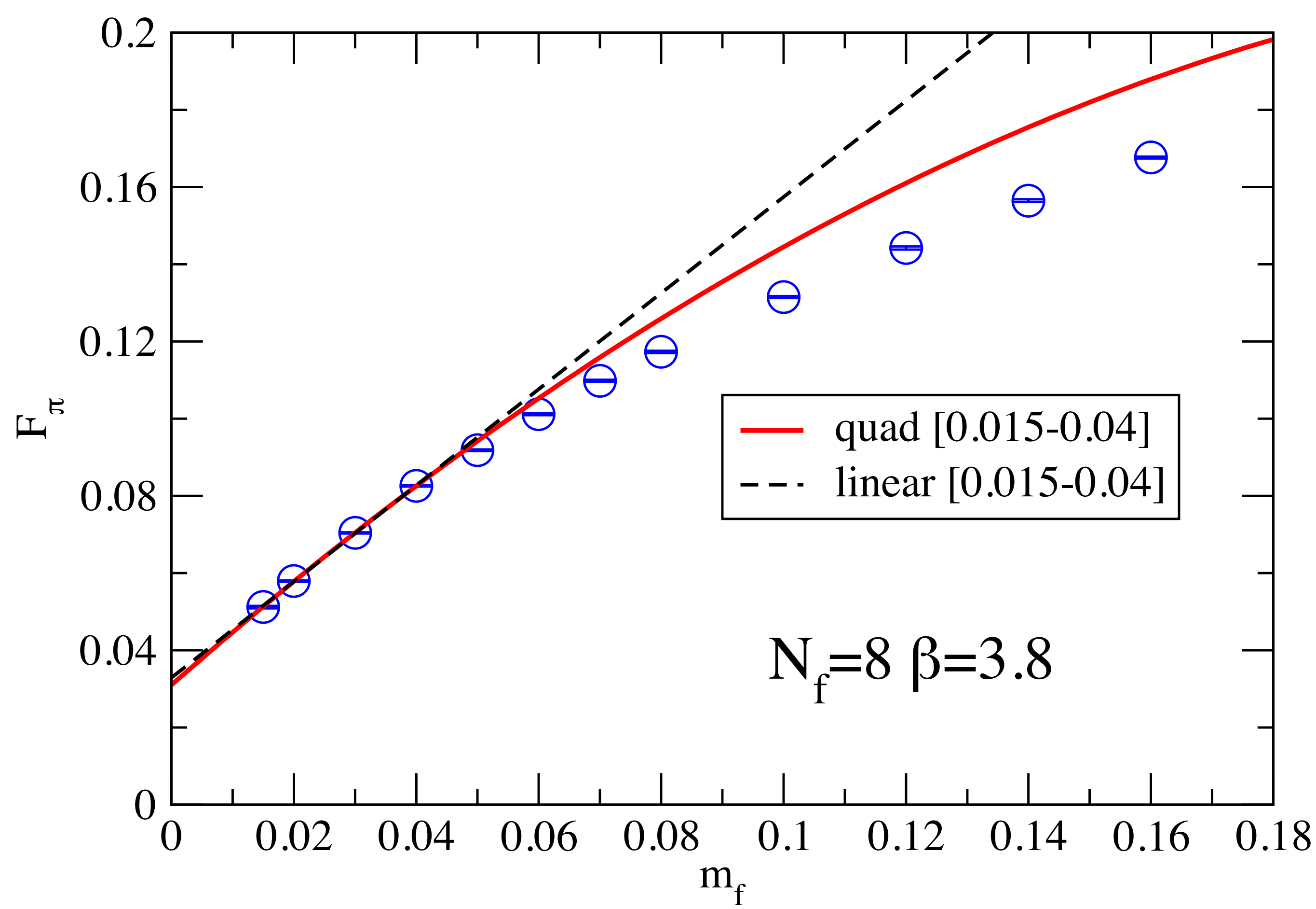


for the ChPT fit (to cut the size effect) ;

Fπ data on the largest volume at each mf

F_π
Quadratic fit in mf=[0.015, 0.04]
Linear fit in mf=[0.015, 0.04]

In wider fit range, χ^2/dof becomes worse.

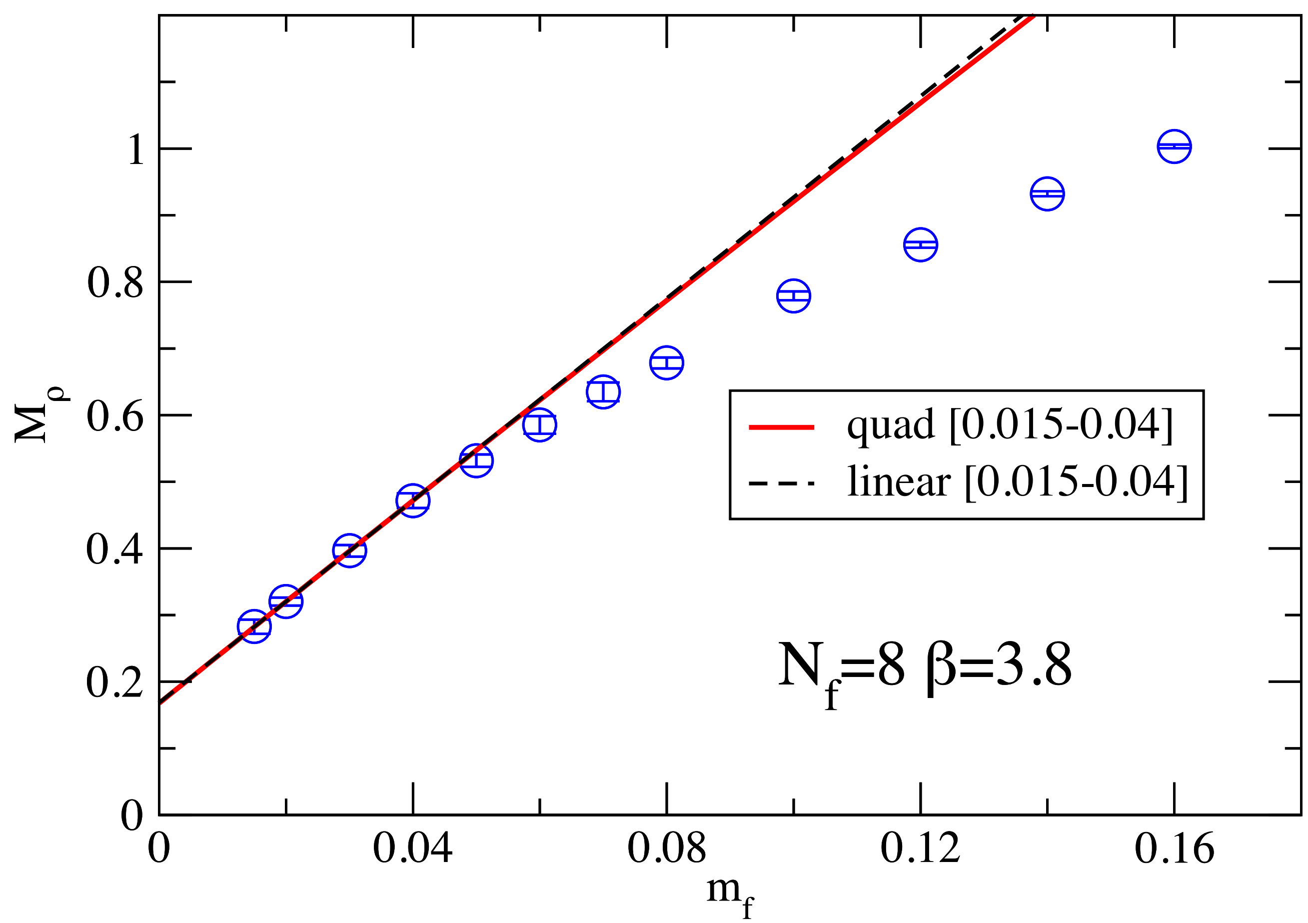


F_π=0.0310(13) + 1.4(1) mf - 2.6(1.7) mf^2 (χ2/dof=0.46)

F_π=0.0329(3) + 1.24(1) mf (χ2/dof=1.4)

M_ρ
Quadratic fit in mf=[0.015, 0.04]
Linear fit in mf=[0.015, 0.04]

Nf=8 (F_π and M_ρ) in small mf is consistent with ChPT.



M_ρ=0.168(32)+7.6(4.1) mf -1.2(73.4) mf^2 (χ2/dof=0.0017)

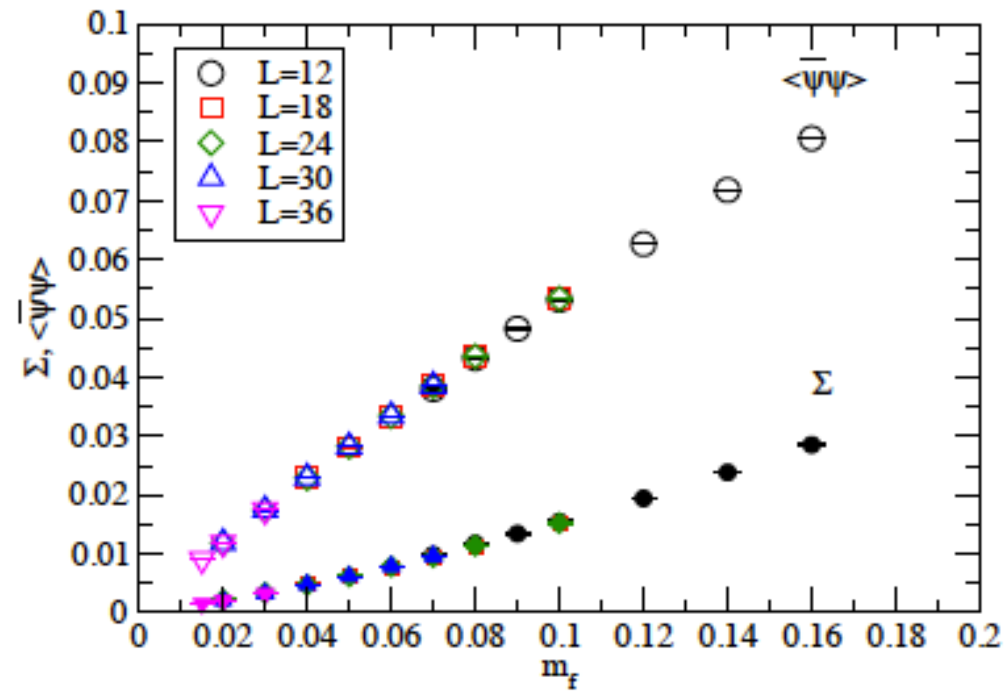
M_ρ=0.169(13) +7.6(5) mf (χ2/dof=0.0010)

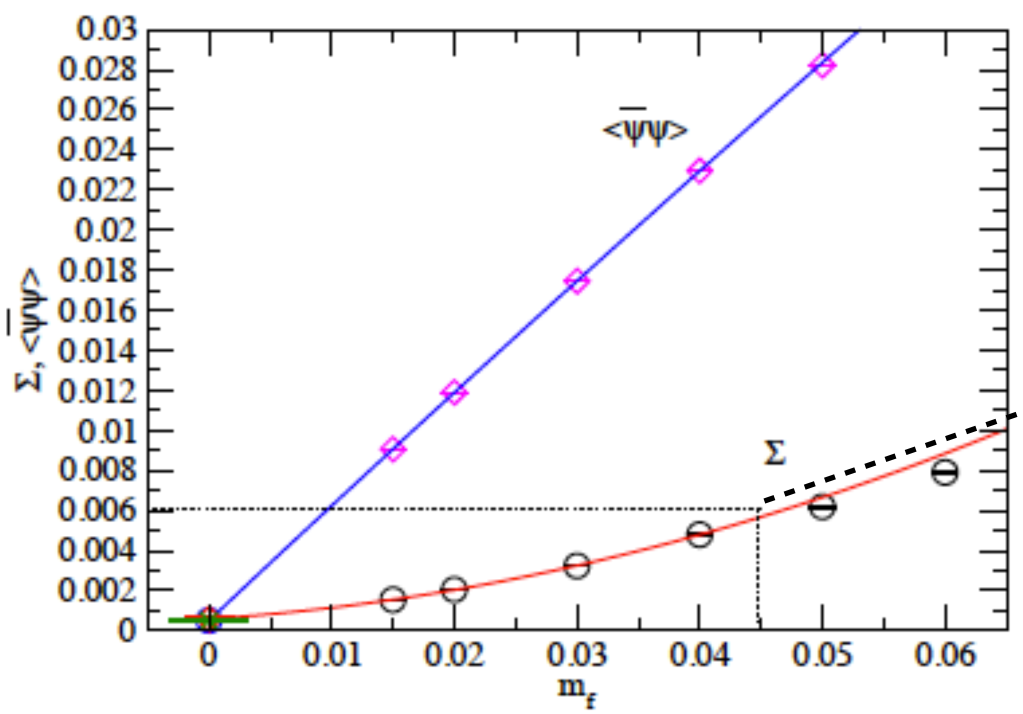
Chiral condensate (direct and indirect calc.)

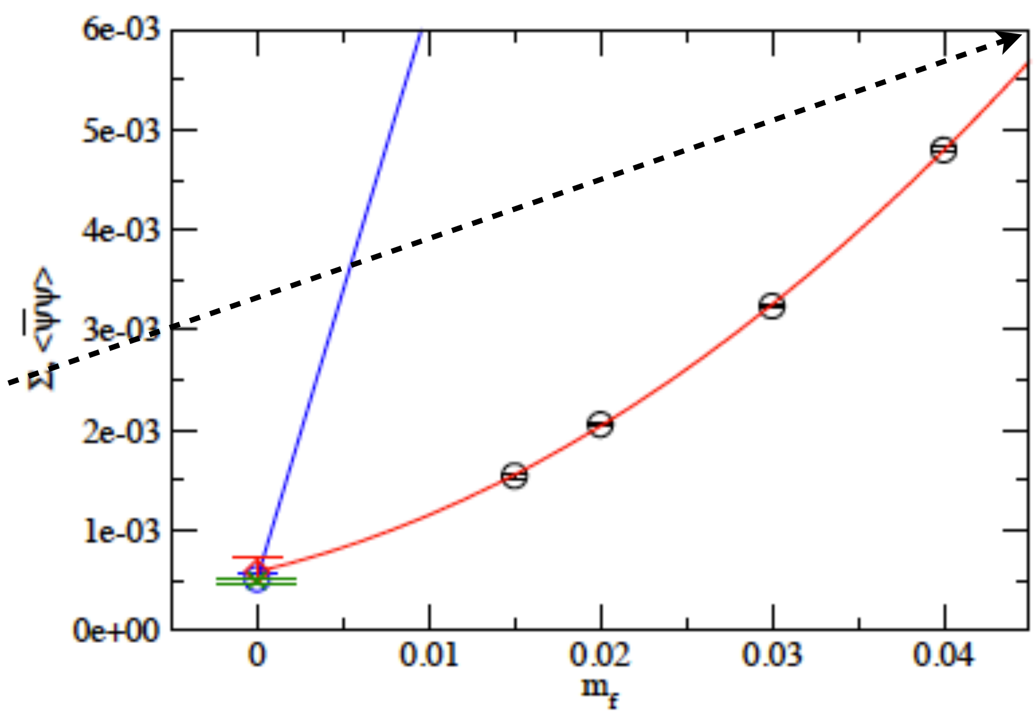
direct: = $\mathrm{Tr}[D_{HISQ}^{-1}(x,x)]/4$

indirect: $\Sigma = F_\pi^2 M_\pi^2/(4mf)$

based on the GMOR relation







In chiral limit (quadratic fit in 0.015≦mf≦0.04)

$$\langle\bar{\psi}\psi\rangle\big|_{m_f\to 0} = 0.00052(5), \quad \Sigma|_{m_f\to 0} = 0.00059(13). \qquad F^2 \cdot \left(\frac{M_\pi^2}{4m_f}\right)\Bigg|_{m_f\to 0} = 0.00050(3)$$

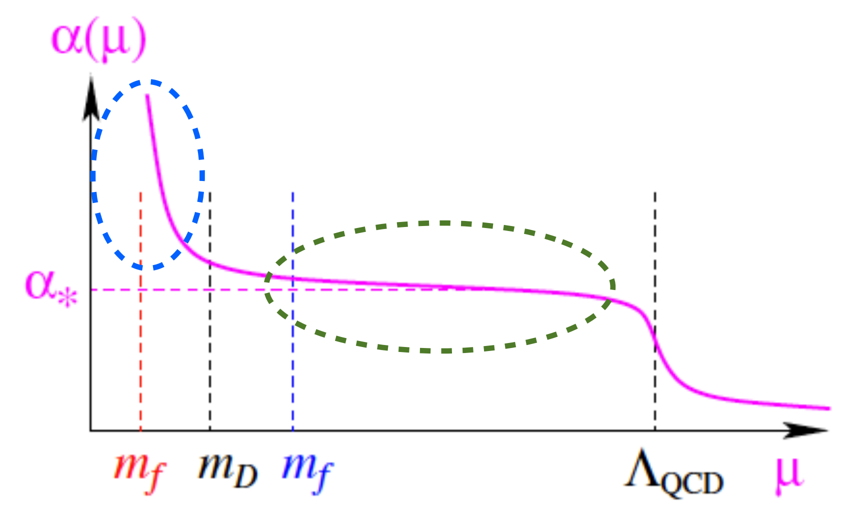
Summary-1, ChPT analysis

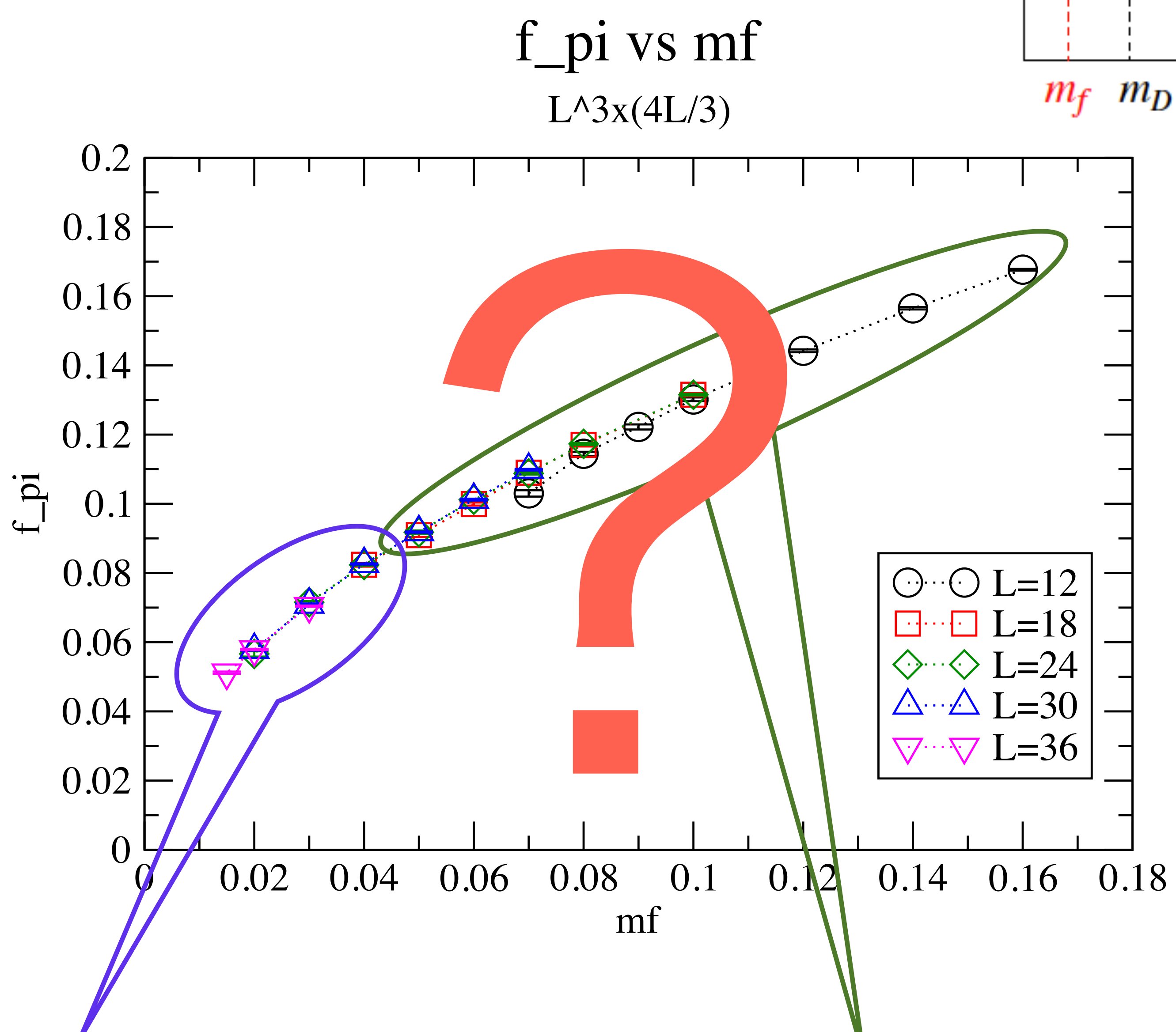
- The quadratic fit was done in $0.015 \leqq mf \leqq 0.04$.
- Nf=8 is consistent with SχSB in the small mf region.
- $F_\pi>0$, $M_\rho>0$, Condensate>0, $M_\pi=0$ in the χ-limit.
- In the χ-limit. $F_\pi=0.0310(13)$, $M_\rho/(F_\pi/\sqrt{2})=7.7(1.5)$.
- The expansion parameter $\chi=O(1)$ of ChPT in the smallest mf (self-consistent), in contrast to Nf=12.
- ⇒ simple SχSB phase?

$$\chi = N_f \left(\frac{M_\pi}{4\pi F}\right)^2$$

F_π vs mf :

How is in the region mf≧0.05?





Polynomial-like behavior

(ChPT-like)

Power-like behavior ?

(Remnant of conformality ?)

Finite size Hyperscaling analysis

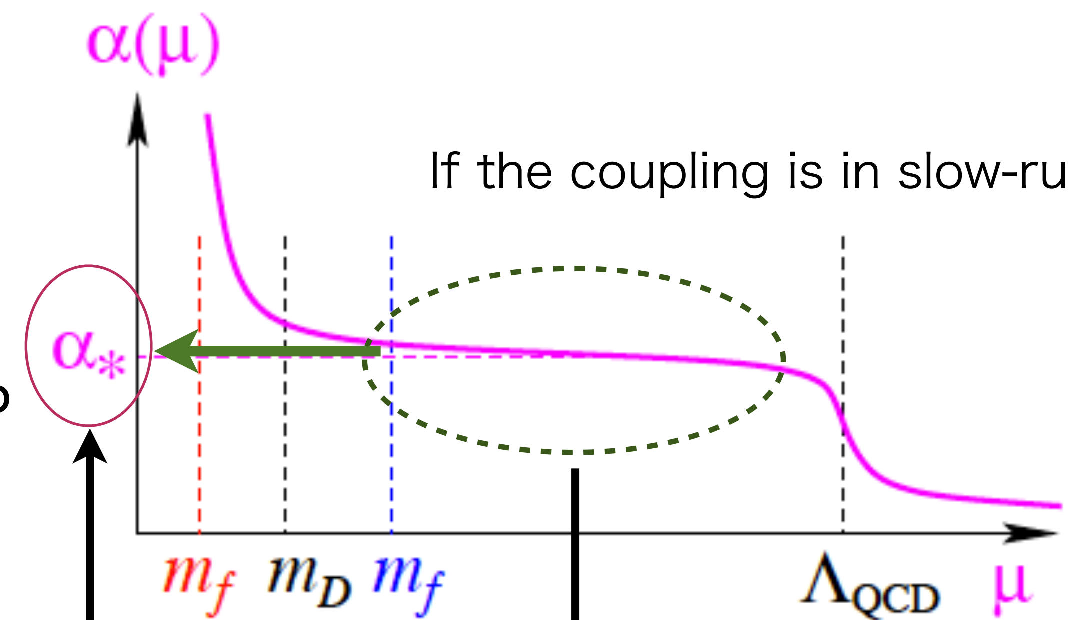
(critical phenomena in conformal transition)

$$LM_H = \mathcal{F}_H(x), LF_H = \mathcal{G}_F(x)$$

(DeGrand, Del Debbio et al.)

$x \equiv L\, m^{1/1+\gamma}$ (: universal γ)

information
at (approximate) IRFP



Dig it out!

from the data in this region

The hyperscaling with mass corrections is needed,
from the lesson of Schwinger-Dyson analysis (our paper, '12).

Finite size Hyperscaling analysis

Comformal → Finite size Hyperscaling behavior with universal γ

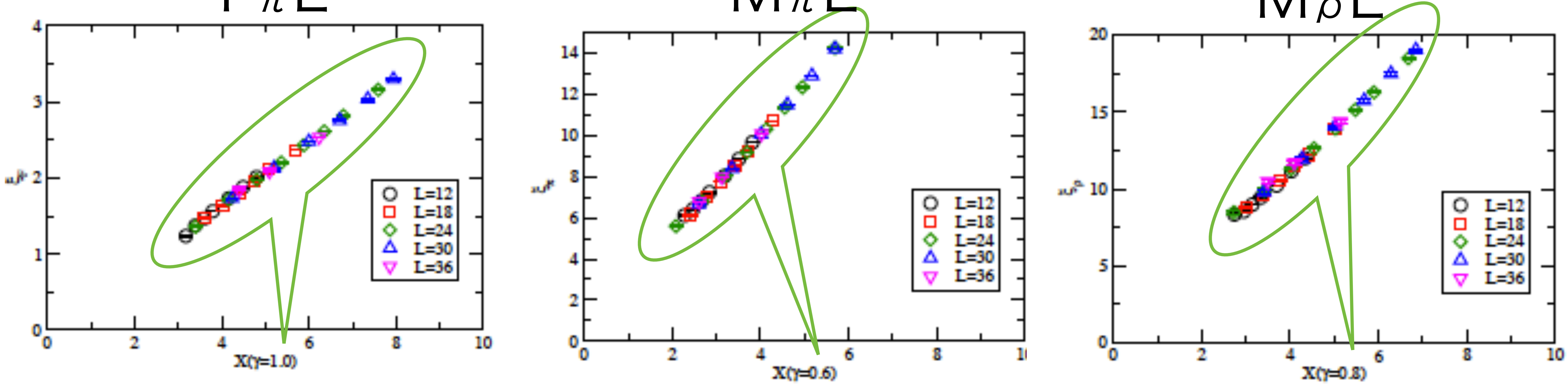
(Critical exponent obtained from the finite volume setup)

$$LM_H = \mathcal{F}_H(x), LF_H = \mathcal{G}_F(x)$$

$$x \equiv L\, m^{1/1+\gamma}$$

data aligned → different from Nf=4

$F_\pi L$ $M_\pi L$ $M_\rho L$



$\gamma(F\pi)\sim1.0, \gamma(M\pi)\sim0.6, \gamma(M\rho)\sim0.8$

different from Nf=12

Simultaneous fit of Hyperscaling with mass corrections

$$\xi_H = C_0^H + C_1^H X + C_2^H L m_f^{\alpha}.$$

in the middle region of mf≧0.05 and ξ_π (=MπL) ≧8

(Schwinger-Dyson eq. with large mass)

ξ_H(=M_HL) vs mf (not X): α=1 fixed (example)

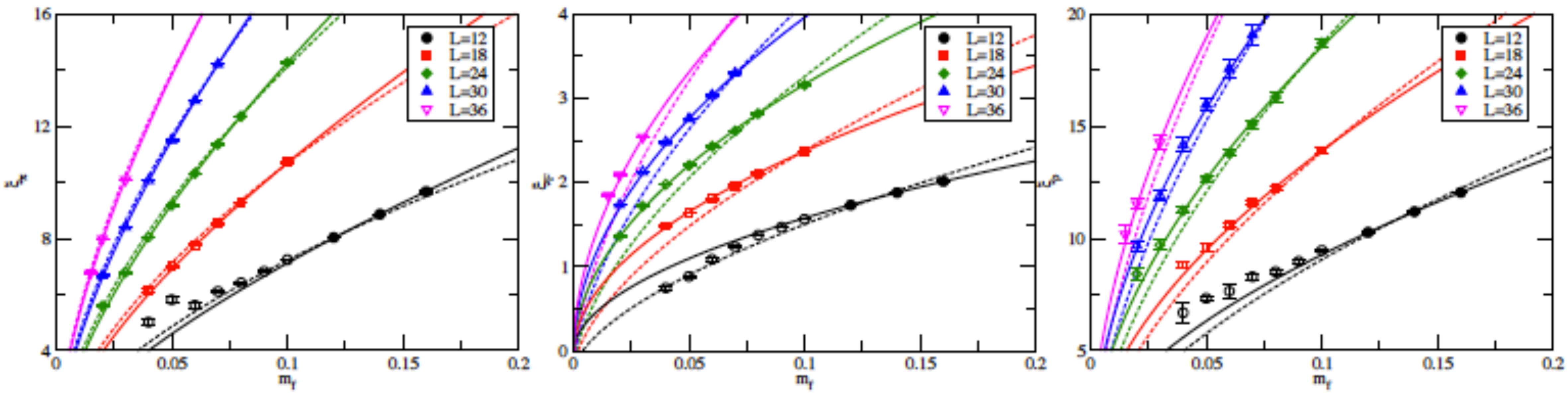


Fig. 5. Simultaneous FSHS fit in ξ_π(left), ξ_F(center) and ξ_ρ(right) with $\alpha = 1$. The filled symbols are included in the fit, but the open symbols are omitted. The fitted region is $m_f \geq 0.05$ and $\xi_\pi \geq 8$. The solid curve is the fit result. For a comparison, the simultaneous fit result without correction terms is also plotted by the dashed curve, whose $\chi^2/dof = 83$.

In this case, the mass correction works well
with γ=0.874(25), χ^2/dof=0.75, dof=32.

- From various trials of this analysis: γ=0.78—0.93 ～1

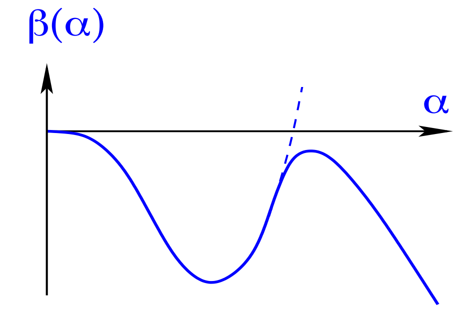
Summary-2, Finite-size Hyperscaling analysis

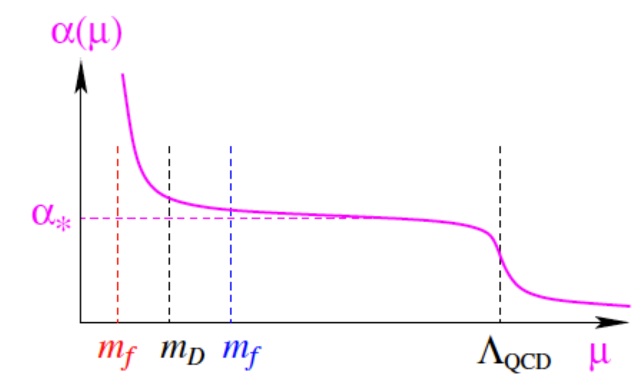
- In the region of mf≧0.05, hyperscaling is seen. (different from Nf=4)
- non-universal γ for each observable in the finite-size hyperscaling (different from Nf=12)
- Lesson from the Schwinger-Dyson analysis with the (large) mass.
- Simultaneous fit of hyperscaling with mass correction gives the universal γ=0.78--0.93 ～1. [requirement for the successful walking technicolor.]
- Nf=8 has the “remnant” of the conformality in the middle range of mf.

Summary

- SU(3) gauge theories with 4, 12 and 8 HISQ quarks.
- Nf=8; consistent with SχSB in the small mass region of our simulation and the remnant of the conformality in the middle region of mf with γ~1. (In contrast to Nf=4 and 12 cases.)

Nf=8 → Candidate of Walking dynamics





In Progress:

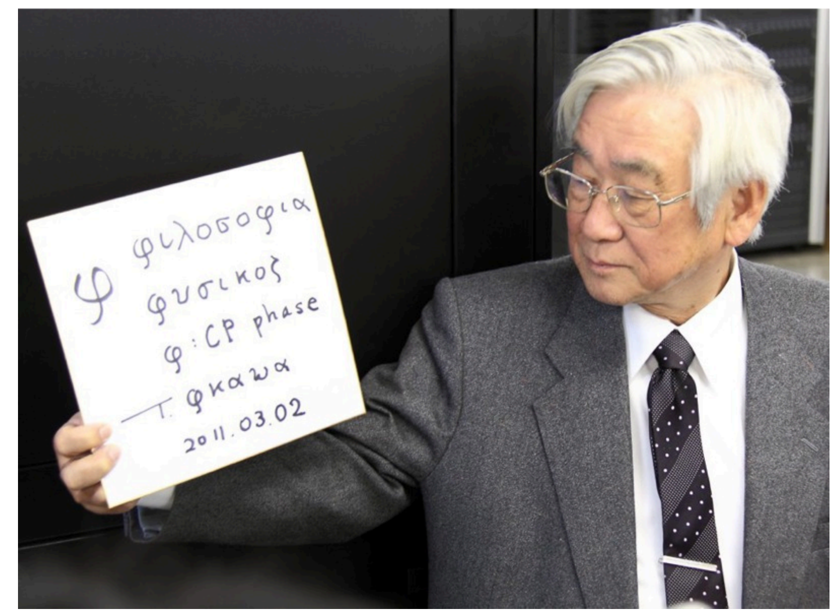
- Simulation on larger volumes at lighter masses
- Finite Size Effect (due to the difficulty to take V=∞)
- Lattice spacing dependence (Enhancement) ←many β
- Spectroscopy ($M_{glueball}$, $M_{\text{"scalar"}}$, M_{baryon}, M_{meson}, $F_{\rho/\sigma}$, S-param. etc.)
- String tension
- $M_{\text{"flavor-singlet light scalar"}}$ ⇒ 125GeV? (→ Yamazaki's talk; next)

Thank you

Backup

KMI computer, φ

- non GPU nodes
  - 148 nodes
  - 2x Xenon 3.3 GHz
  - 24 TFlops (peak)
- GPU nodes
  - 23 nodes
  - 3x Tesla M2050
  - 39 TFlops (peak)



Size dependence of Mπ and Fπ at β=3.8

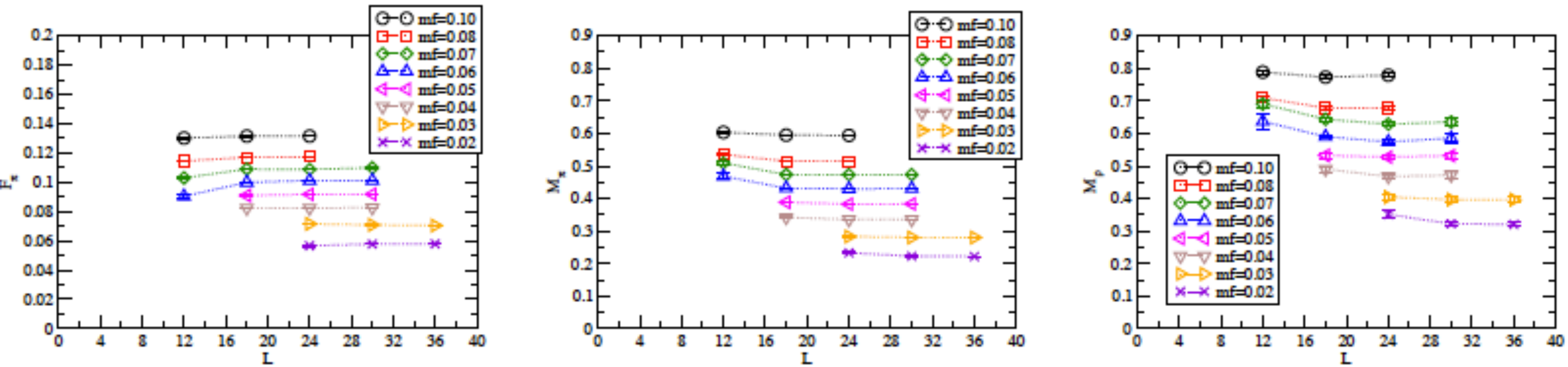


FIG. 7. F_π (left), M_π (center) and M_ρ (right) as functions of L.

On the larger volume, there is not (or very tiny) size dependence.

We use the data on the largest volume at each mf.

HISQ with Nf=8:

effective mass for the lowest mf(=0.015)
on the largest size(L=36)

$M_\pi^{PS}=M_\pi^{SC}$, $M_\rho^{PV}=M_\rho^{VT}$
→ good flavor symmetry

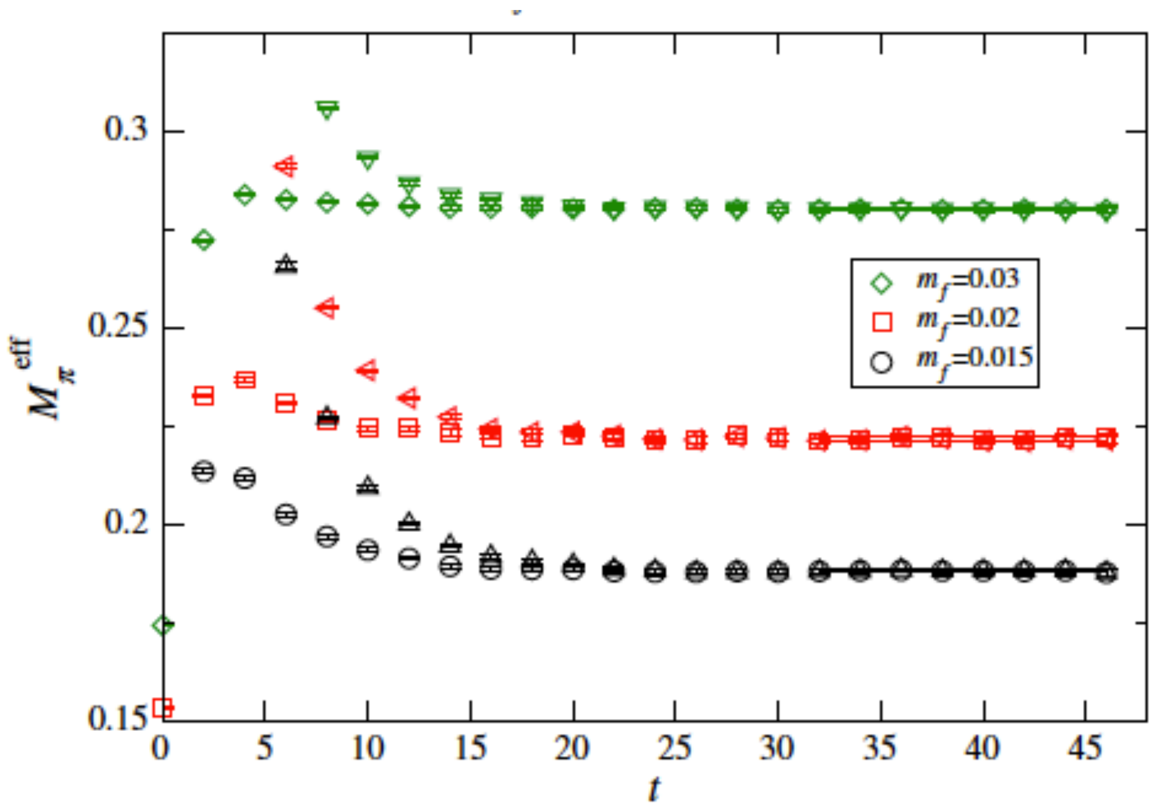


FIG. 2 (color online). Effective masses of PS meson, $M_\pi^{\rm eff}$, at $L = 36$. Triangles and other symbols denote results from point sink correlators with random wall source and corner wall source, respectively. Fit results with error band obtained from random wall source correlator are also plotted by solid lines.

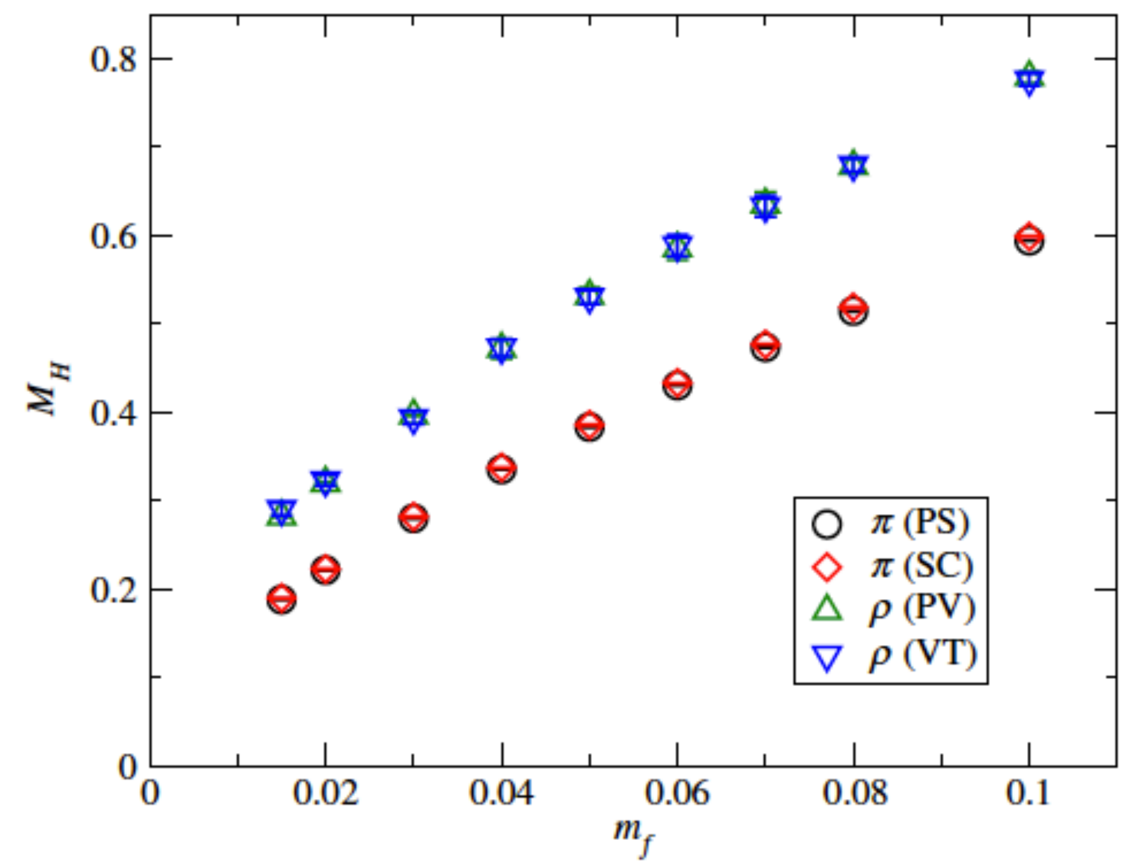
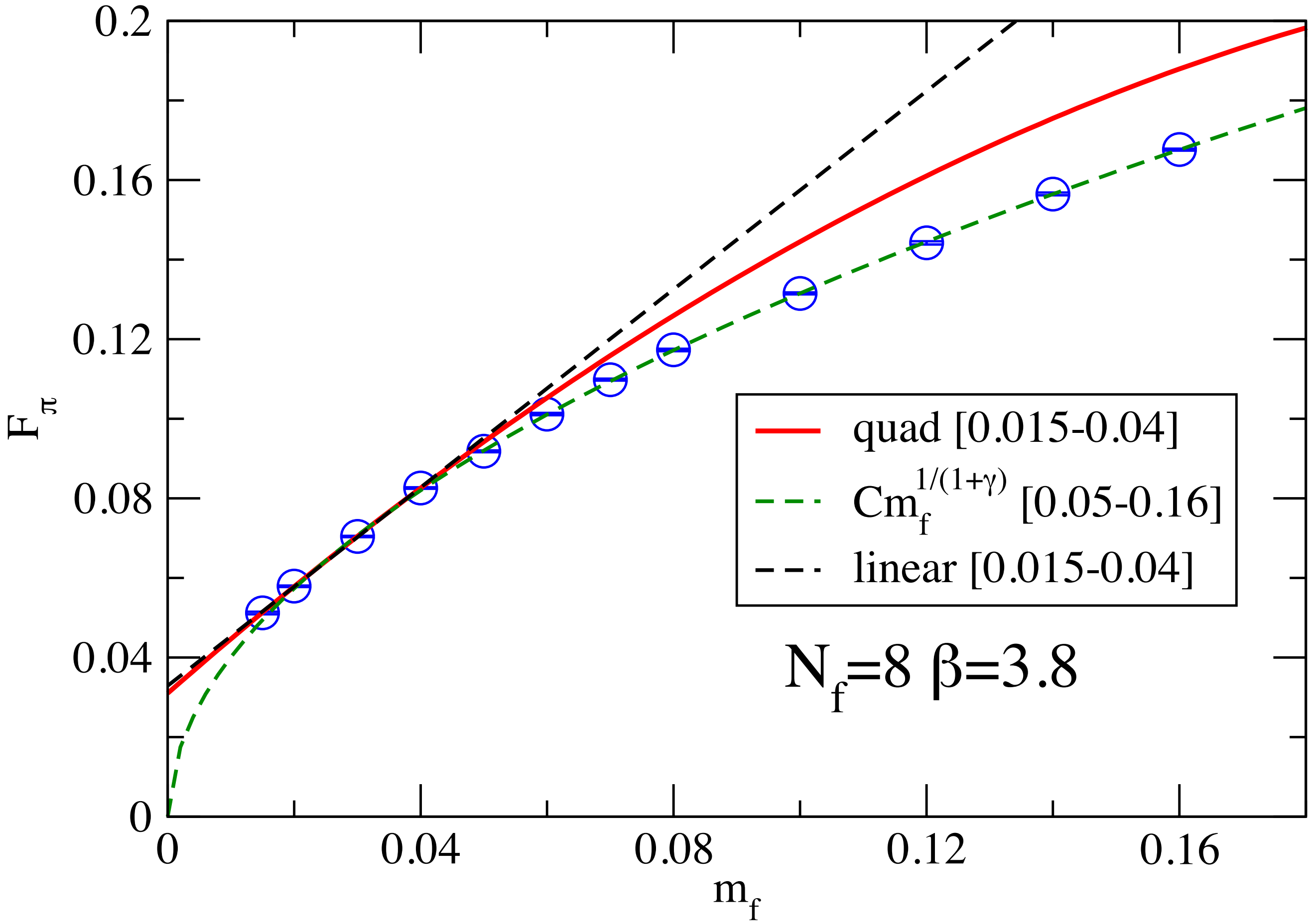


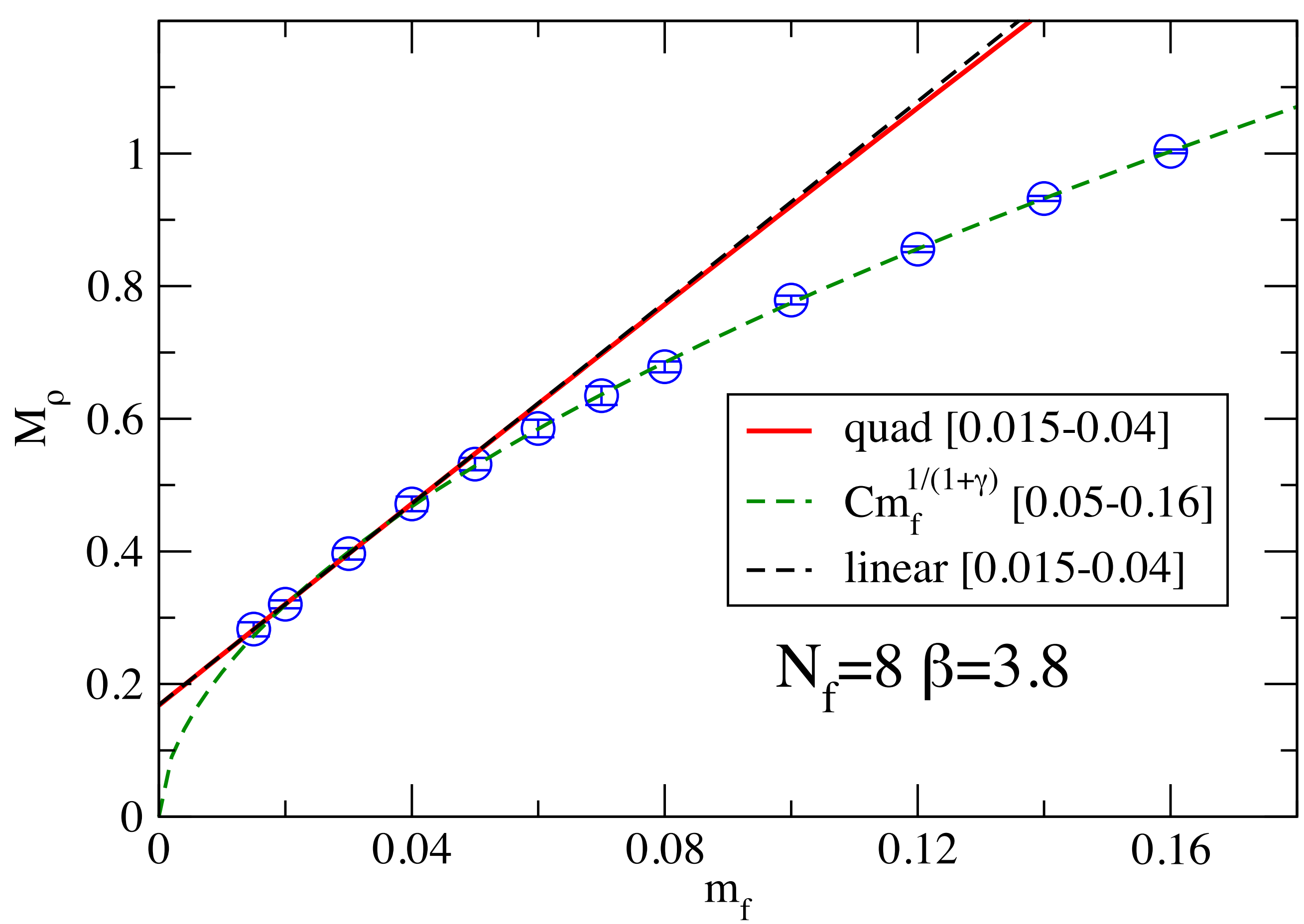
FIG. 4 (color online). Comparisons of M_π and $M_{\rm SC}$, and of $M_{\rho(\rm PV)}$ and $M_{\rho(\rm VT)}$ as a function of m_f with largest volume data at each m_f.

Fπ (left panel) and Mρ (right panel):

quadratic and linear fit in 0.015 ≦ mf ≦ 0.04

power function fit (critical phenomena) in 0.05 ≦ mf.





non-universal:

$\gamma(F_\pi)$～1.0, $\gamma(M_\rho)$~0.8

different from Nf=4 and12

Simultaneous fit of hyperscaling with mass corrections

$\xi_H = C_0^H + C_1^H X + C_2^H L m_f^\alpha$. (same method with Nf=12)

Hyperscaling? in the middle region of mf (mf≧0.05 and ξ_π (=$M_\pi L$) ≧8)

The mass corrections might be needed, as done in Nf=12, from the lesson in SD analysis.

TABLE XI. Simultaneous FSHS fit with a correction term, $\xi = C_0^H + C_1^H X + C_2^H L m_f^\alpha$ using several choices of α. The fitted region is $m_f \geq 0.05$ and $\xi_\pi \geq 8$.

$\alpha = 0.889(55)$	C_0^H	C_1^H	C_2^H
ξ_π	−0.005(25)	1.338(96)	1.494(37)
ξ_F	−0.0275(98)	0.4435(36)	—
ξ_ρ	0.53(16)	2.476(39)	—
	$\gamma = 0.9130(76)$, $\chi^2/\text{dof} = 1.73$, dof = 33		

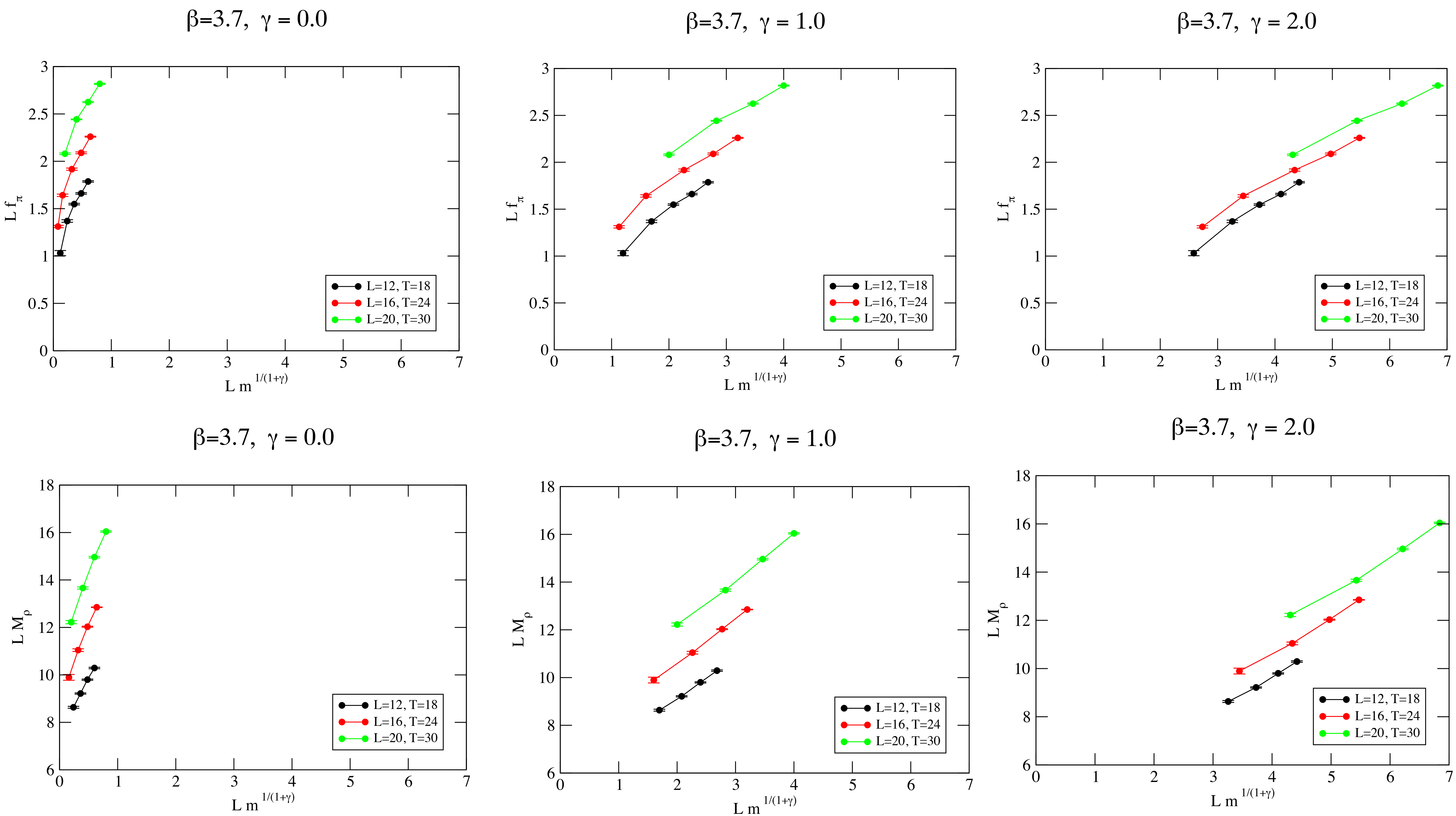
$\alpha = 1$ fixed	C_0^H	C_1^H	C_2^H
ξ_π	−0.014(24)	1.61(10)	1.31(15)
ξ_F	−0.012(10)	0.484(30)	−0.068(44)
ξ_ρ	0.01(19)	2.60(17)	0.25(24)
	$\gamma = 0.874(25)$, $\chi^2/\text{dof} = 0.75$, dof = 32		

$\alpha = \frac{3-2\gamma}{1+\gamma}$ fixed	C_0^H	C_1^H	C_2^H
ξ_π	0.020(24)	1.52(39)	1.17(35)
ξ_F	−0.011(10)	0.572(34)	−0.158(52)
ξ_ρ	0.03(19)	2.91(30)	−0.15(36)
	$\gamma = 0.775(56)$, $\chi^2/\text{dof} = 0.93$, dof = 32		

⇒ good χ^2/dof, but unclear which α is better.

Comparison with $N_f = 4$

: trial of hyperscaling in $F_\pi L$ and $M_\rho L$ (in SχSB)



no scaling in $0<\gamma<2$