Light composite scalar and other spectra in Nf=8 QCD

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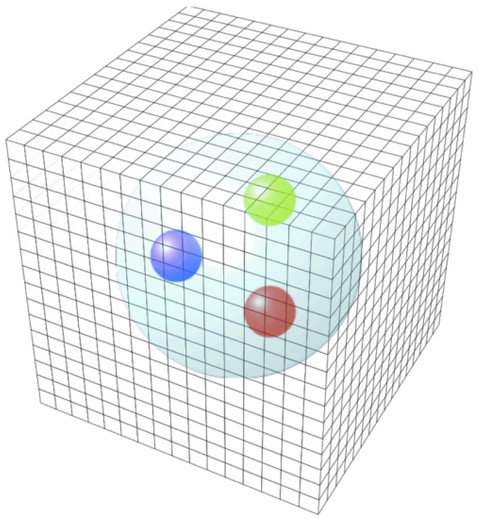
Plan of Talk:



1. Introduction

2. Walking signal of Nf=8 LQCD

   { Chiral Perturbation Theory (ChPT)
   { Finite Size Hyperscaling (FSHS)

♠ Nf=8 is a candidate for the walking.
Walking signals in Nf=8 QCD on the lattice
Published in **Phys.Rev. D87 (2013) 094511**, e-Print: **arXiv:1302.6859 [hep-lat]**.

+ update

3. Light composite scalar in Nf=8

♠Light scalar in Nf=8 .
Light composite scalar in eight-flavor QCD on the lattice
Published in **Phys.Rev. D89, 111502(R) (2014)**, e-Print: **arXiv:1403.5000 [hep-lat]**.

4. Summary

1. Introduction

Walking technicolor

N_f massless fermions + SU(N_{TC}) gauge at $O(1)$ TeV

Model requirement:

- Spontaneous chiral symmetry breaking
- Slow running (walking) coupling in wide scale range
- Large anomalous mass dimension $\gamma^* \sim 1$ in walking region

- Higgs ≈ Light composite scalar
  pNGB (technidilaton)
  of scale symmetry breaking

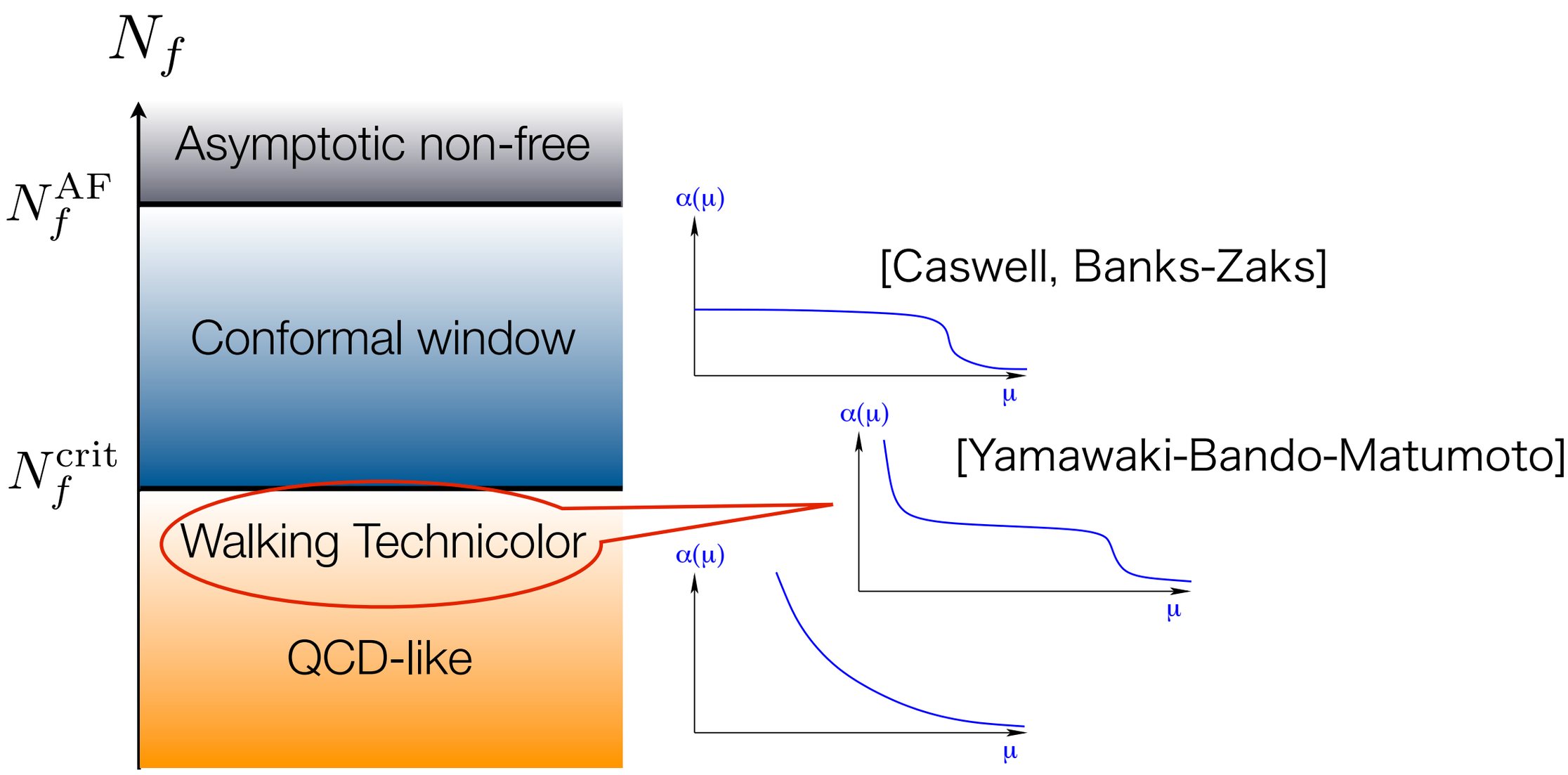
$$m_{\mathrm{Higgs}}/v_{\mathrm{EW}} \sim 0.5 = m_\sigma/(\sqrt{N_d}F)$$

F : decay constant, N_d : number of weak doublets

usual QCD $m_\sigma/F \sim 4$–5

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}

One-family Extended TechniColor model

$$\begin{pmatrix} u \\ d \\ u \\ d \\ u \\ d \\ e \\ \nu_e \end{pmatrix} \begin{pmatrix} c \\ s \\ c \\ s \\ c \\ s \\ \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} t \\ b \\ t \\ b \\ t \\ b \\ \tau \\ \nu_\tau \end{pmatrix} \begin{pmatrix} U_1 \\ D_1 \\ U_1 \\ D_1 \\ U_1 \\ D_1 \\ E_1 \\ N_1 \end{pmatrix} \cdots \begin{pmatrix} U_{N_{\rm TC}} \\ D_{N_{\rm TC}} \\ U_{N_{\rm TC}} \\ D_{N_{\rm TC}} \\ U_{N_{\rm TC}} \\ D_{N_{\rm TC}} \\ E_{N_{\rm TC}} \\ N_{N_{\rm TC}} \end{pmatrix}$$

$$SU(3+N_{\rm TC}) \xrightarrow{\Lambda_1} SU(2+N_{\rm TC}) \xrightarrow{\Lambda_2} SU(1+N_{\rm TC}) \xrightarrow{\Lambda_3} SU(N_{\rm TC})$$

8-flavor $\mathrm{SU}(N_{\rm TC})$ technicolor

Why Nf=8 QCD?

We consider

$$N_{\rm TC} = 3$$

Many flavor QCD

⇒ Candidate for walking/conformal

Our investigation in Nf=12

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

not favored as WTC (model building)

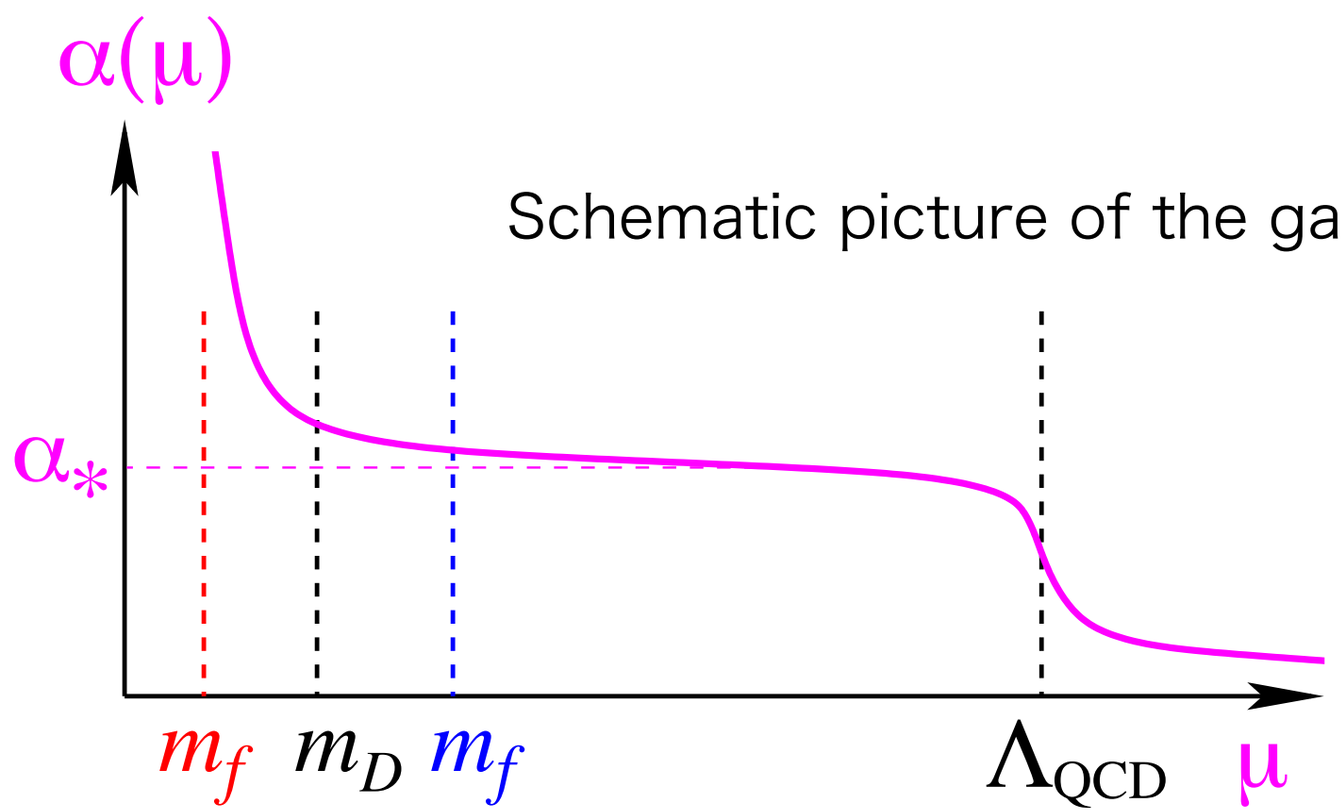
Thus, we investigate Nf=8 QCD.

strong coupling dynamics and non-perturbative

↓

Lattice simulation of Nf=8 QCD

What is the signal of walking?



Schematic picture of the gauge coupling

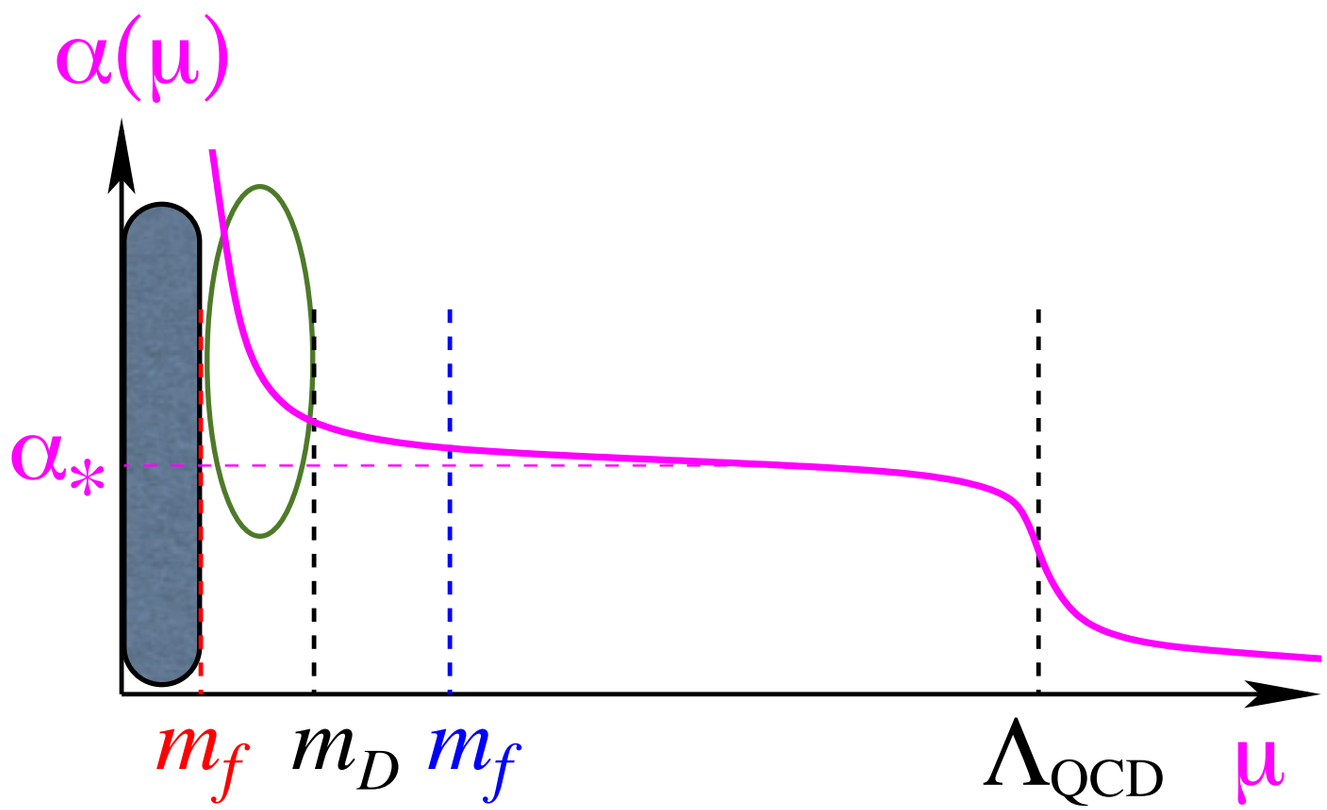
in Gauge Theories

$\Rightarrow$ Spectrum? Heuristically

SχSB and/or conformal ?

What is the signal of walking?

Case-1: probe mf << m_D → SχSB-like

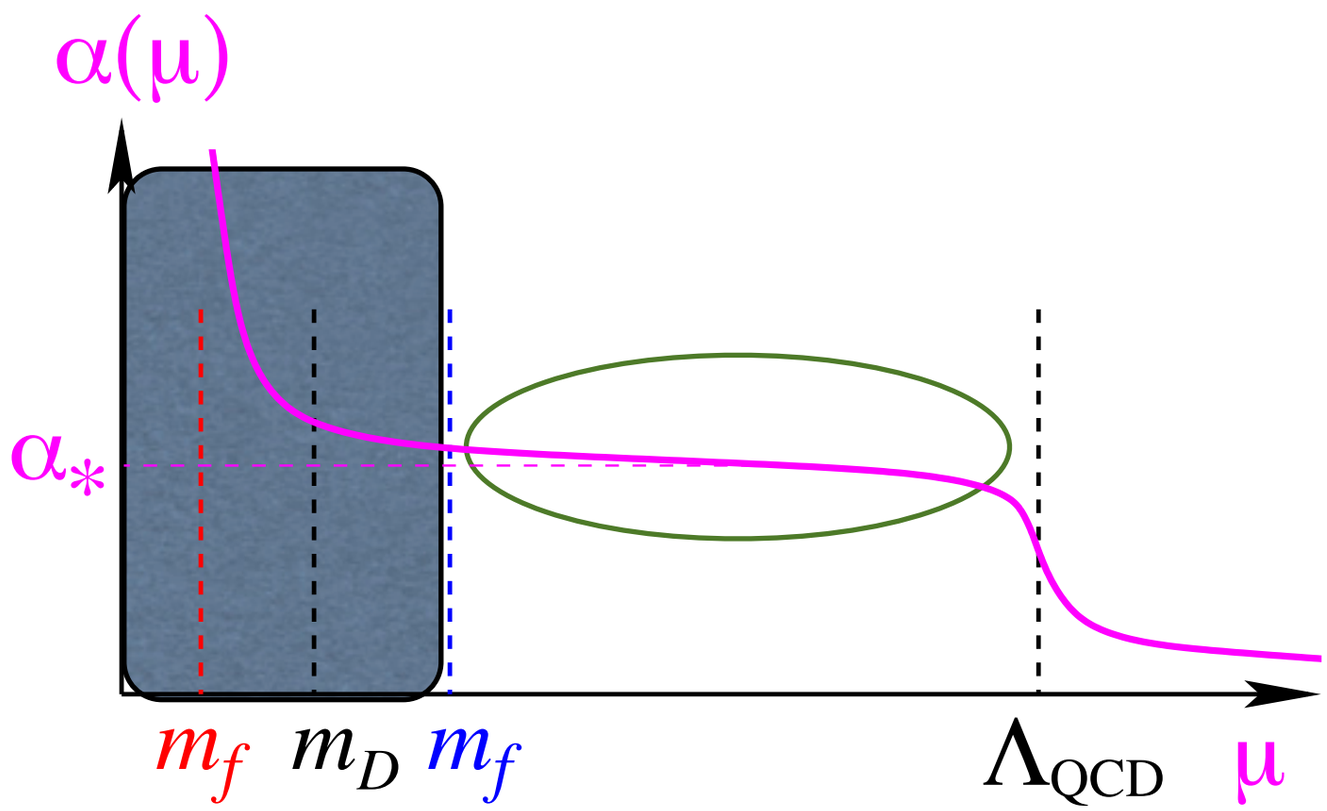


⇒ Spectrum?

SχSB and/or conformal ?

What is the signal of walking?

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



⇒ Spectrum?

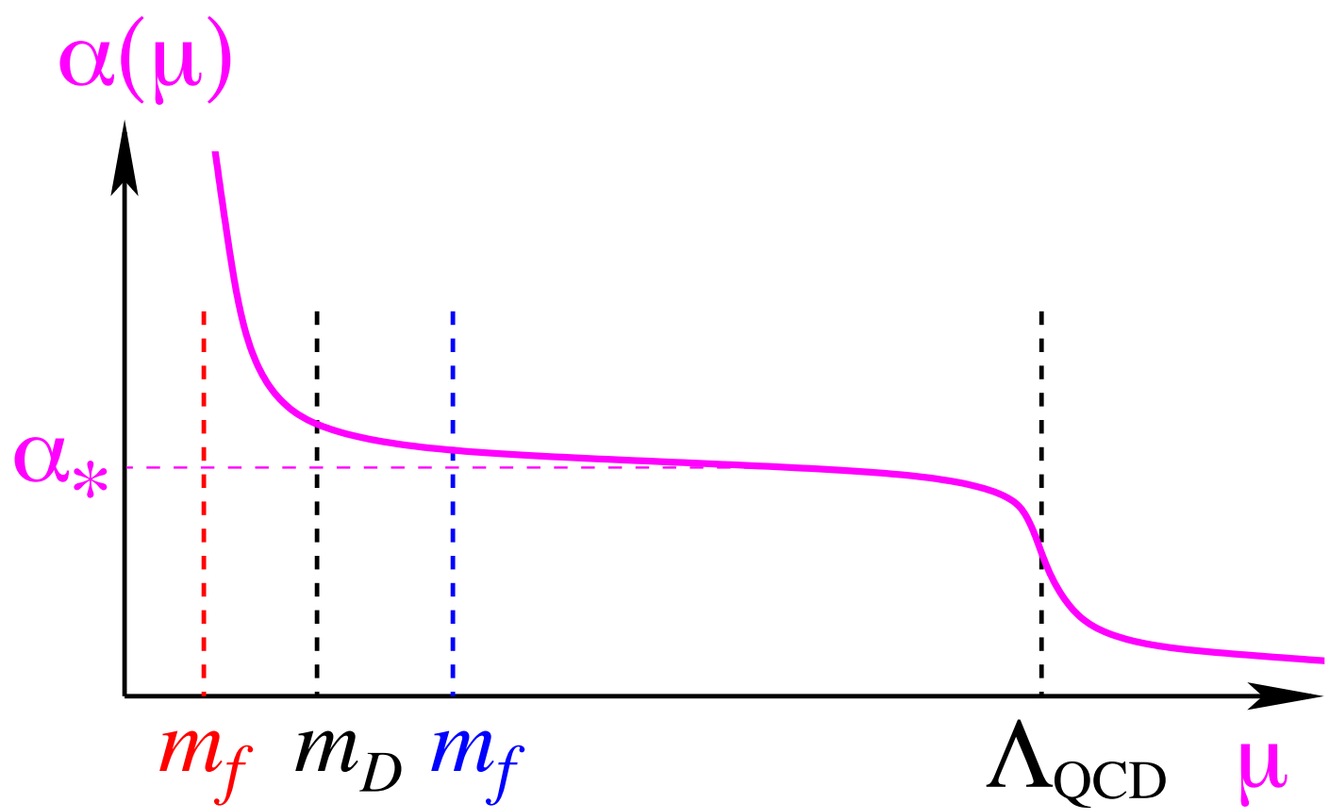
SχSB and/or conformal ?

Case-1: probe mf << m_D → SχSB-like

(ChPT near χ-limit)

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

(Hyperscaling w/ or w/o mass corrections)



(Also, LSD collab. paper, arXiv:1405.4752)

⇒ Spectrum?

SχSB and/or conformal ?

2. Walking signals in Nf=8 QCD

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,** $V=L^3 \times T$, $T/L=4/3$ fixed.

V	12^3x16	18^3x24	24^3x32	30^3x40	36^3x48	42^3x56
mf	0.01~0.16	0.04~0.1	0.02~0.1	0.03,0.04~0.07	0.015,0.02,0.03	0.012

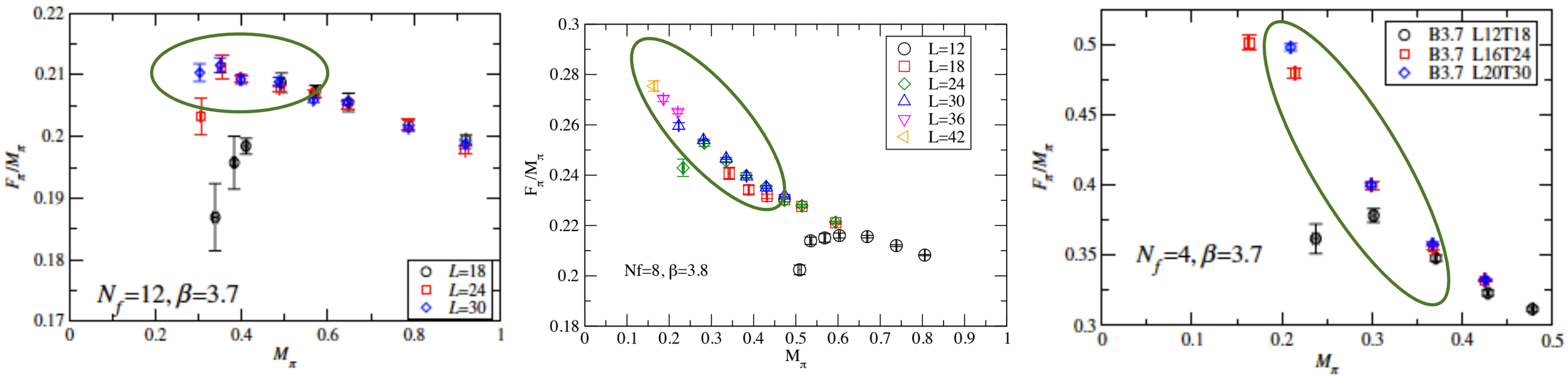
(updated) (new)

★ Gauge configurations for scalar measurement

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

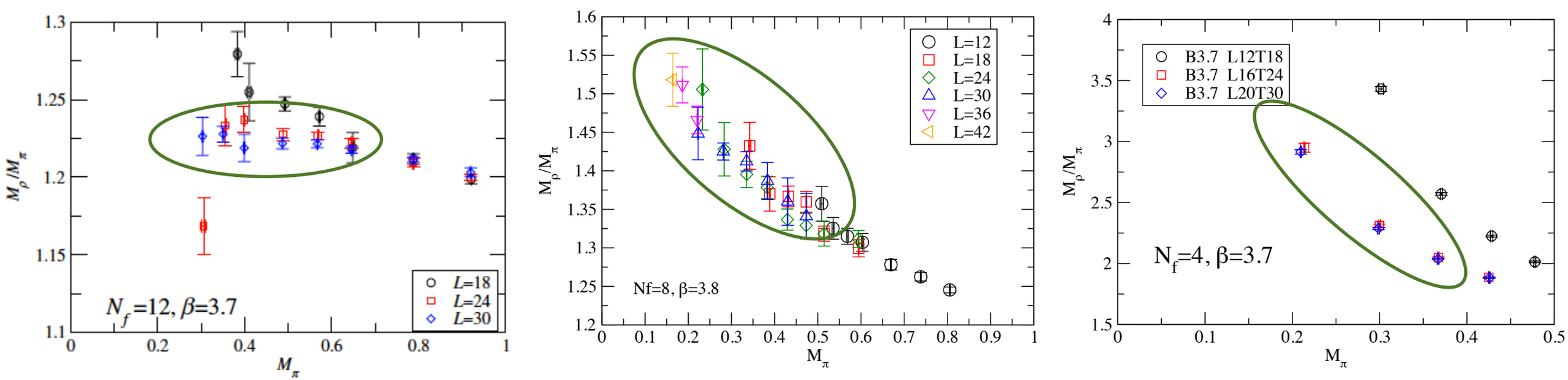
- M_π, F_π, M_ρ, chiral condensate
- analysis for $M_\pi L > 6$

F_π/M_π for Nf=12, 8 and 4



(updated: 2013→2014)

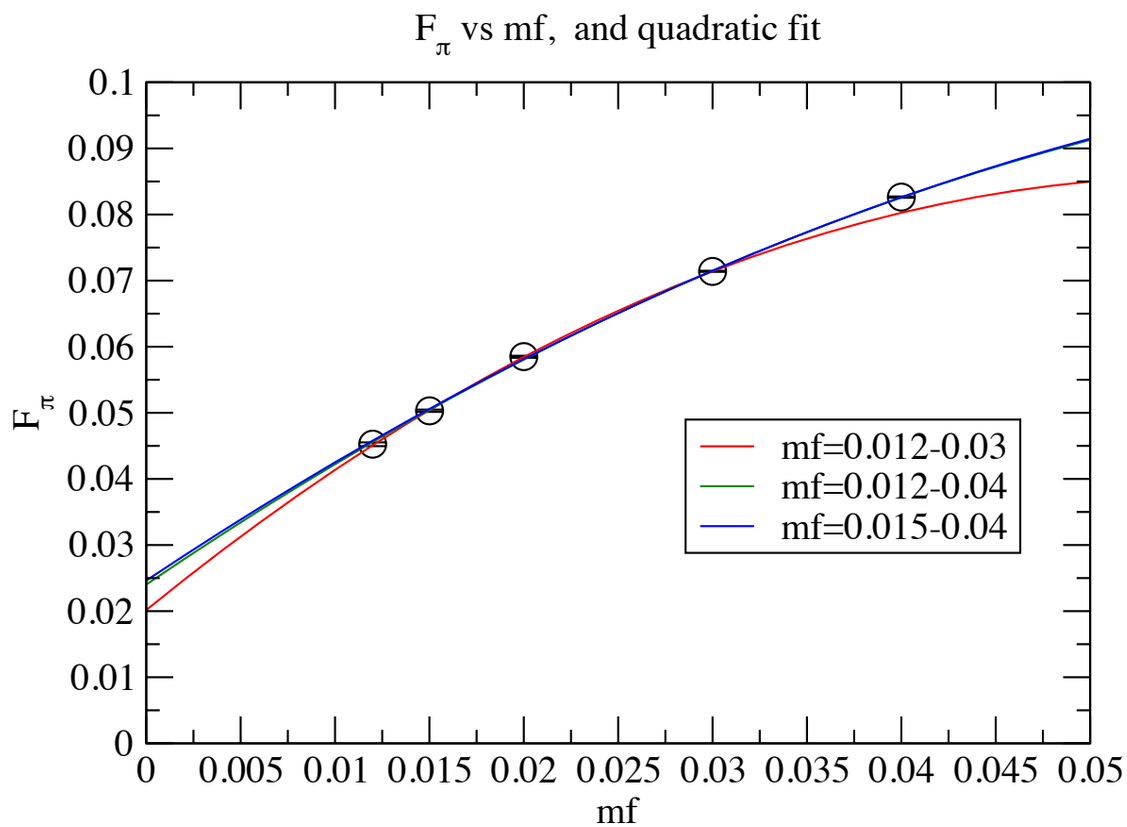
M_ρ/M_π for Nf=12, 8 and 4



(updated: 2013→2014)

ChPT analysis in small mf region

$F\pi$ vs mf with quadratic-func. fit : $y=C_0+C_1*mf+C_2*mf^2$



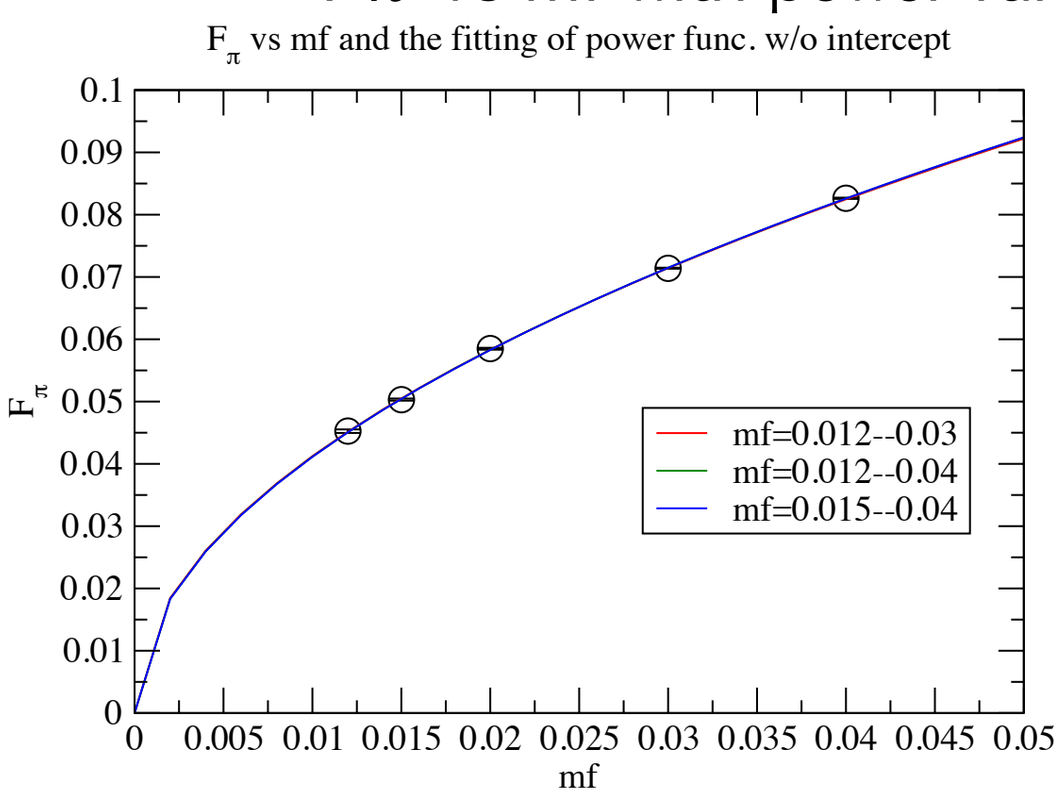
red : C_0=0.0202(13), χ2/dof=0.60 (dof=1)

green: C_0=0.0240(5), χ2/dof=5.9 (dof=2)

blue : C_0=0.0246(7), χ2/dof=9.4 (dof=1)

ChPT seems to be good in 0.012≦mf≦0.03.

$F\pi$ vs mf with power-func. fit (hyperscaling) : $y=D_1*mf^{\alpha}$



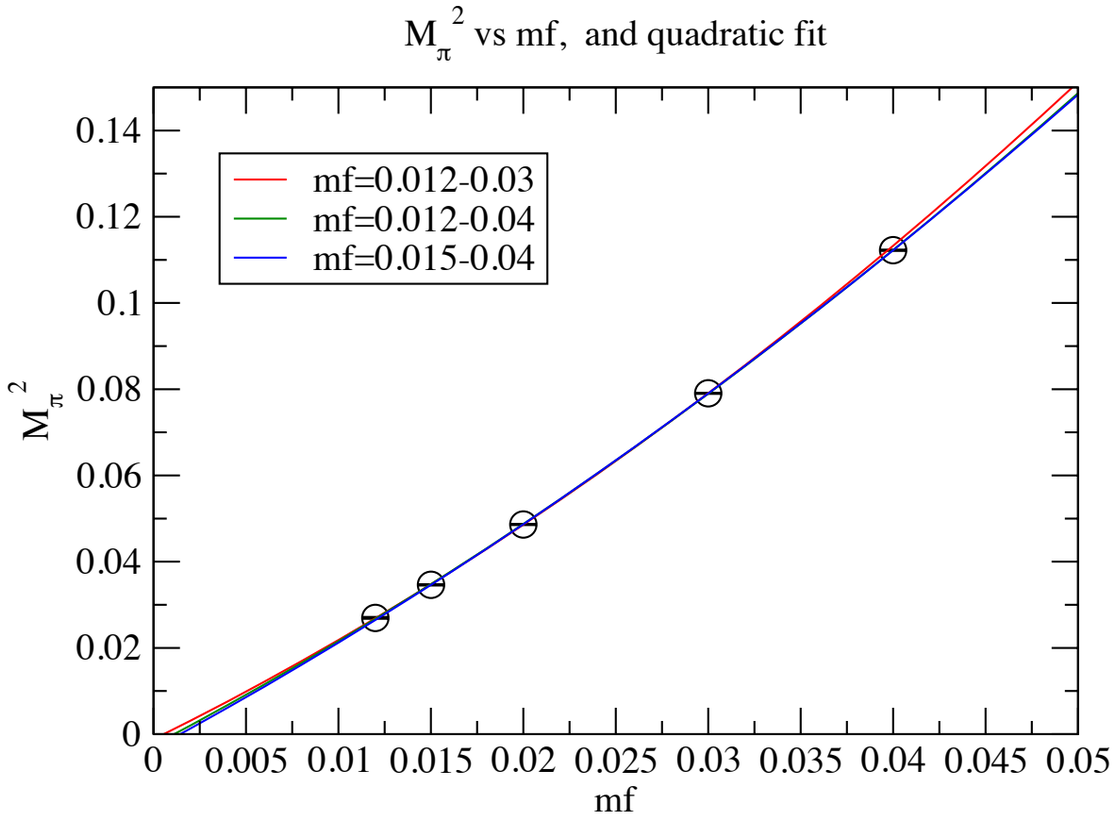
red : α=0.500(4), χ2/dof=1.22 (dof=2)

green: α=0.0502(3), χ2/dof=1.07 (dof=3)

blue : α=0.0503(3), χ2/dof=1.46 (dof=2)

HS fit seems to be good in 0.04≦mf.

$M_\pi{}^2$ vs mf with quadratic-func. fit



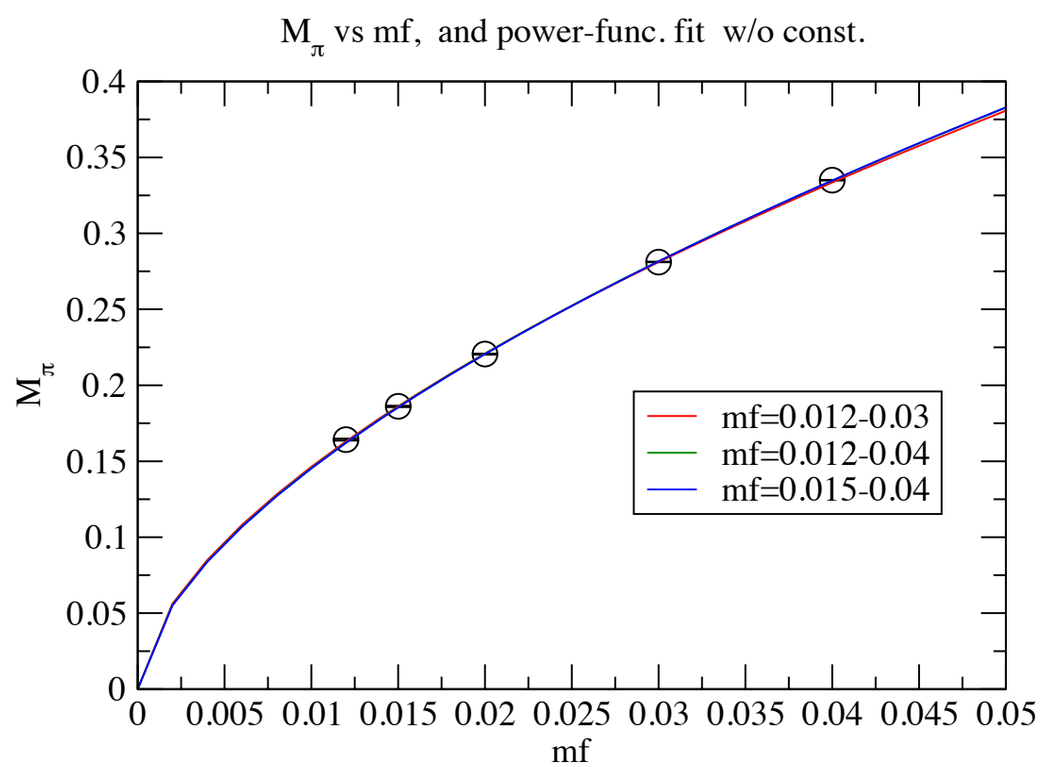
red : C_0=-0.0012(11), χ2/dof=0.79 (dof=1)

green: C_0=-0.0025(6), χ2/dof=1.4 (dof=2)

blue : C_0=-0.0034(8), χ2/dof=0.24 (dof=1)

ChPT in 0.012≦mf≦0.03.

$M\pi$ vs mf with power-func. fit (hyperscaling) : y=D_1*mf^α



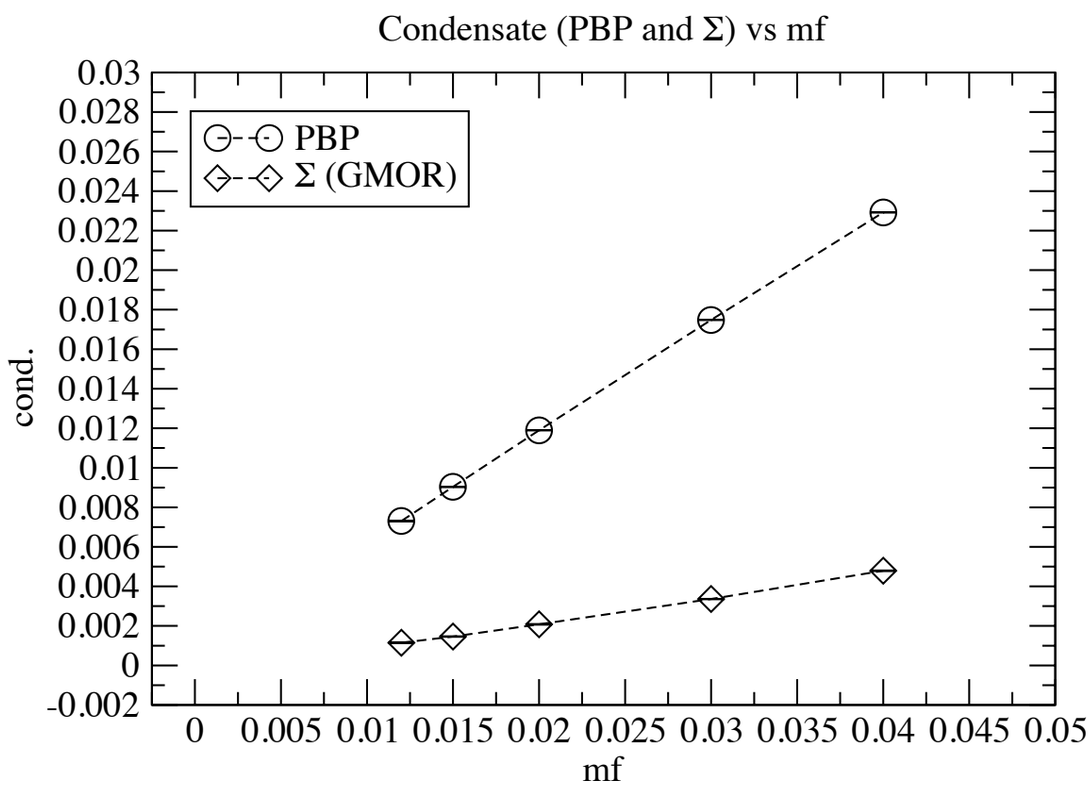
red : α=0.594(3), χ2/dof=2.5 (dof=2)

green: α=0.600(2), χ2/dof=5.0 (dof=3)

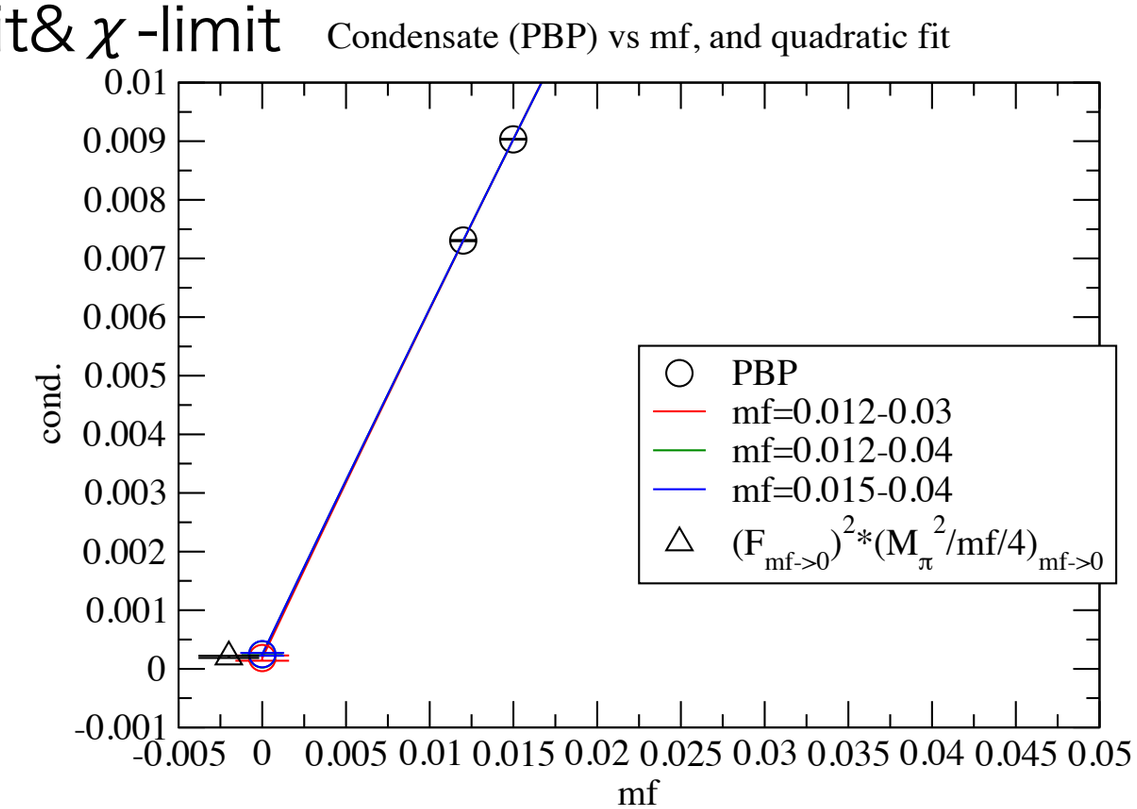
blue : α=0.602(2), χ2/dof=2.9 (dof=2)

Condensate (PBP and Σ) and quadratic-func. fit

PBP=Tr[Prop(x,x)/4], $\Sigma = f_\pi^2 M_\pi^2/mf/4$



Fit& χ -limit



PBP

red : C_0=0.00018(5), χ^2/dof=0.89

green: C_0=0.00024(2), χ^2/dof=1.61

blue : C_0=0.00025(2), χ^2/dof=3.18

$\Sigma = F_\pi M_\pi^2/mf/4$

$(F_\pi)^2_{mf\to 0} * (M_\pi^2/mf/4)_{mf\to 0}$ = 0.00021(2)

In 0.012≦mf≦0.03, consistent value

Hyperscaling analysis in the heavy mf region

Finite size Hyperscaling analysisin a intermediate mf

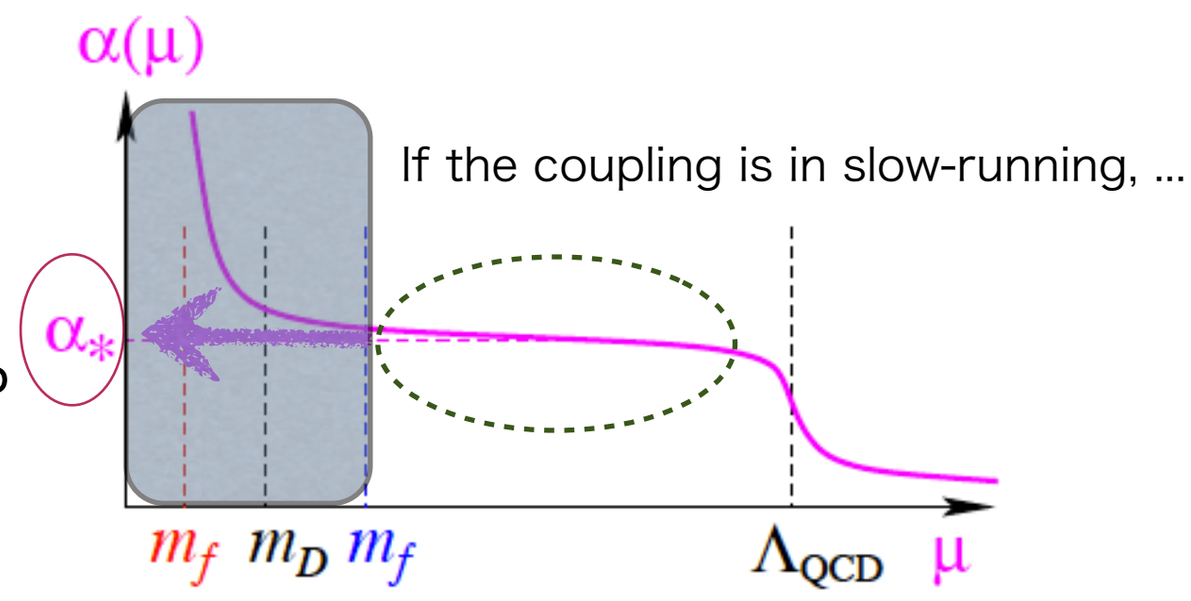
Comformal → Finite size Hyperscaling behavior with universal γ

$$LM_H = \mathcal{F}_H(x), LF_H = \mathcal{G}_F(x)$$ (DeGrand, Del Debbio et al.)

$$x \equiv L\, m^{1/1+\gamma}$$ (near the χ-limit)

However, in our walking scenario,

information
of (approximate) IRFP



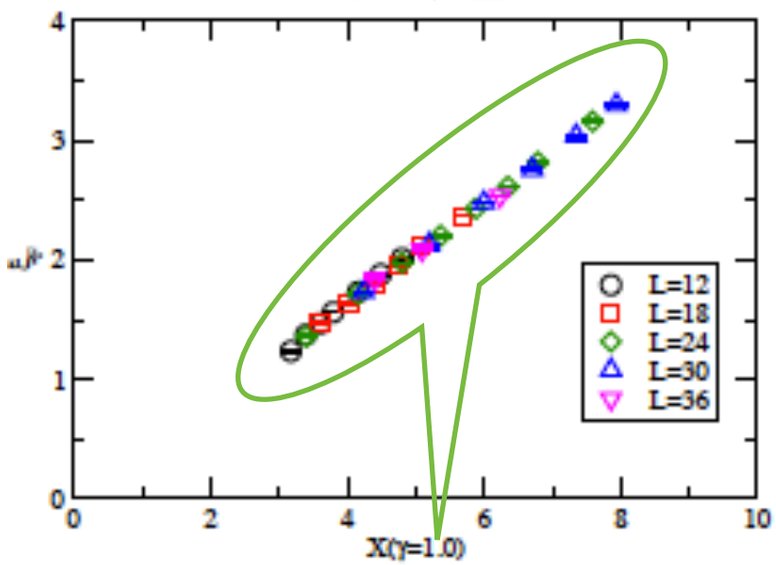
Finite size Hyperscaling analysis

Comformal → Finite size Hyperscaling behavior with universal γ

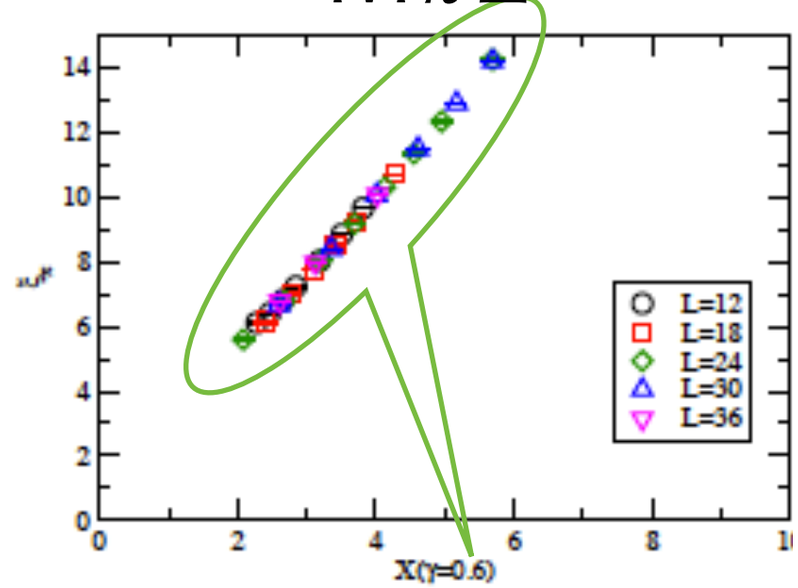
$$LM_H = \mathcal{F}_H(x), LF_H = \mathcal{G}_F(x)$$

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

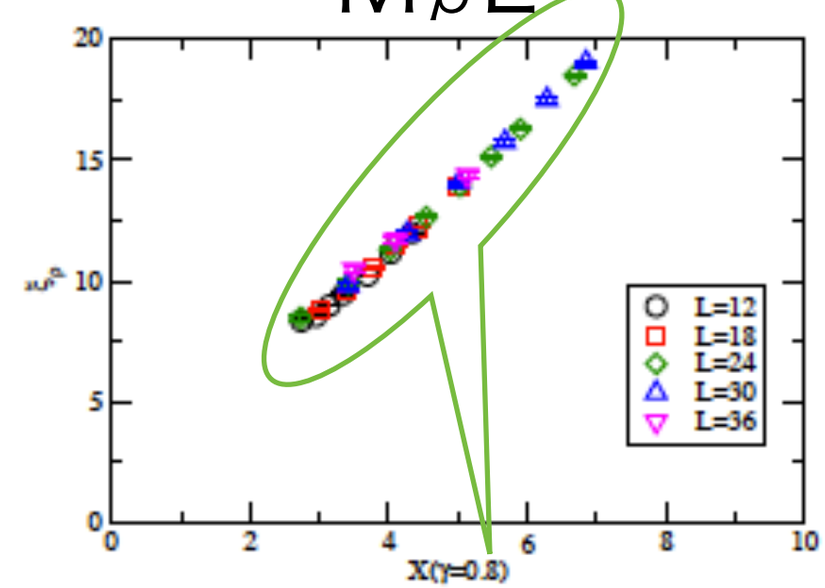
$F_\pi L$



$M_\pi L$



$M_\rho L$

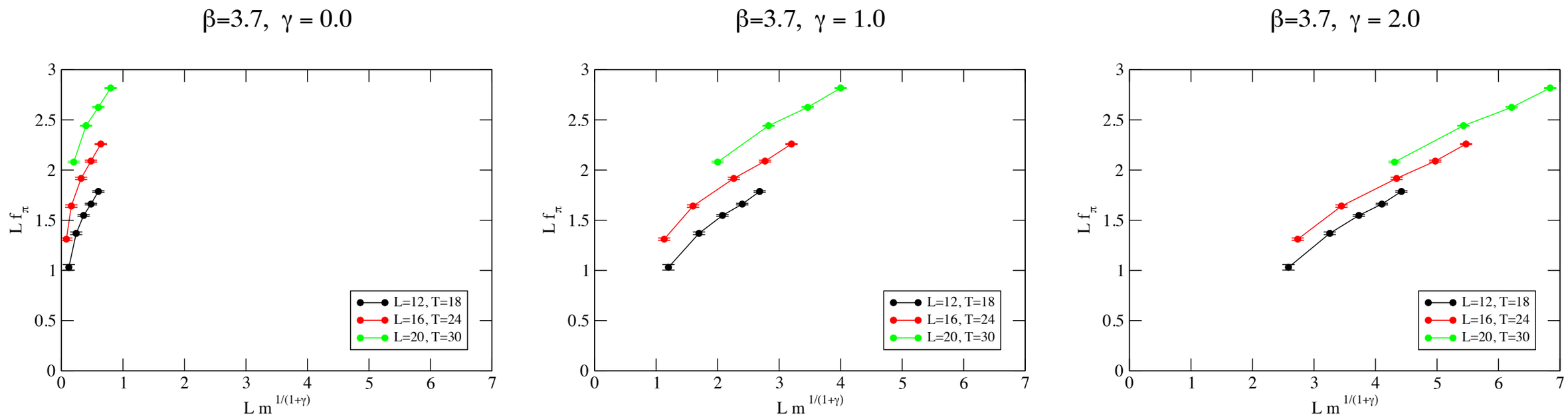


$\gamma\,(F_\pi) \sim 1.0,\ \gamma\,(M_\pi) \sim 0.6,\ \gamma\,(M_\rho) \sim 0.8$

different from Nf=4 and12

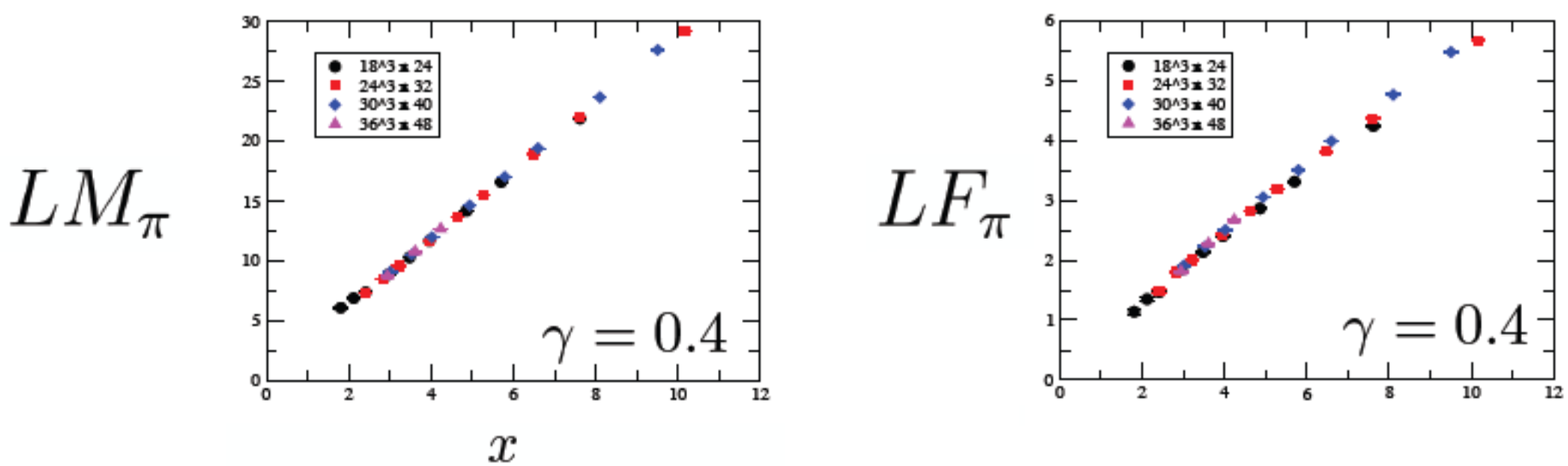
non-universal γ in the naive FSHS analysis

Comparison with Nf=4
: hyperscaling of Fπ (in SχSB)



F$_\pi$: no data collapsing for 0<γ<2

Comparison with Nf=12: universal γ



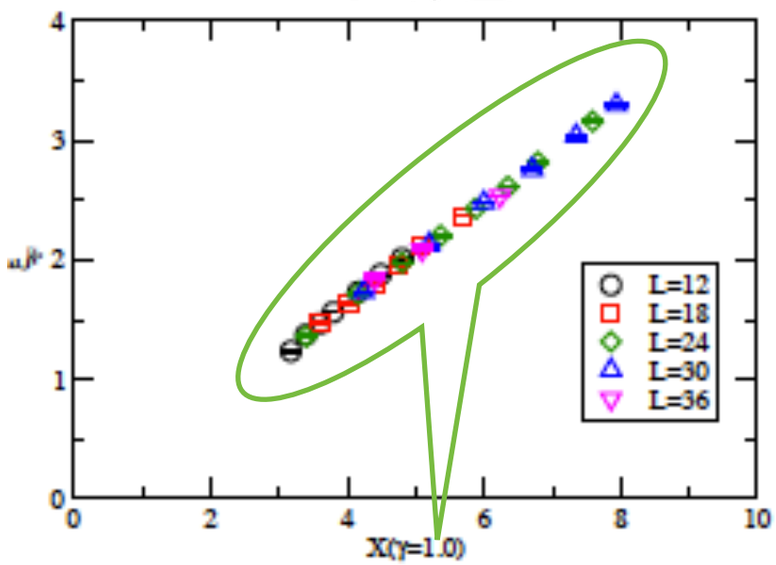
Finite size Hyperscaling analysis

Comformal → Finite size Hyperscaling behavior with universal γ

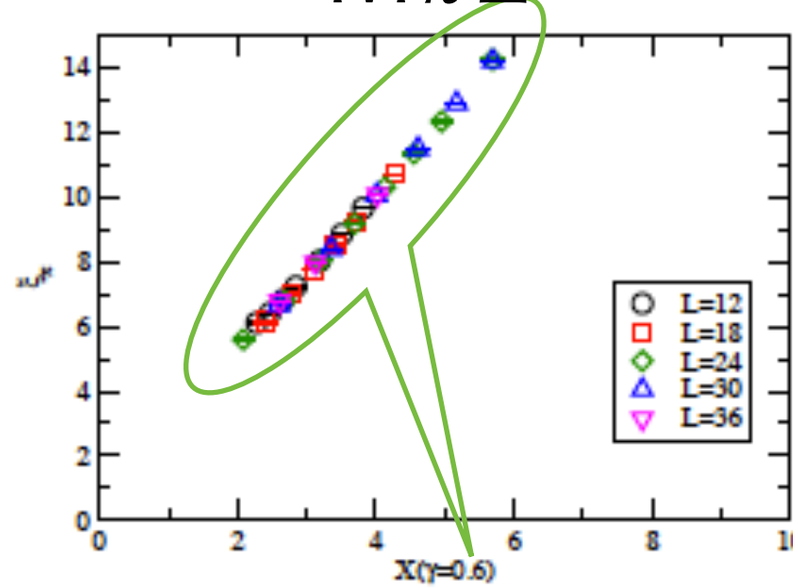
$$LM_H = \mathcal{F}_H(x), LF_H = \mathcal{G}_F(x)$$

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

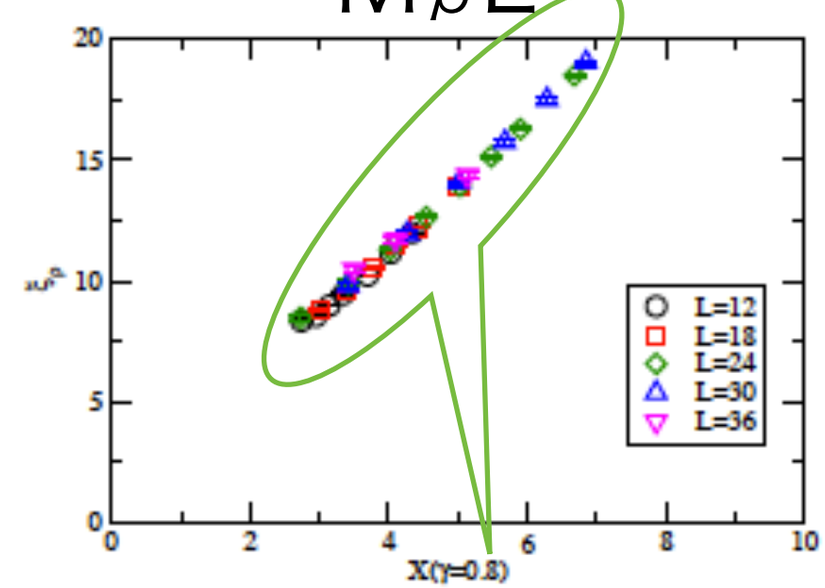
$F_\pi L$



$M_\pi L$



$M_\rho L$



$\gamma\,(F_\pi) \sim 1.0,\ \gamma\,(M_\pi) \sim 0.6,\ \gamma\,(M_\rho) \sim 0.8$

different from Nf=4 and12

non-universal γ in the naive FSHS analysis

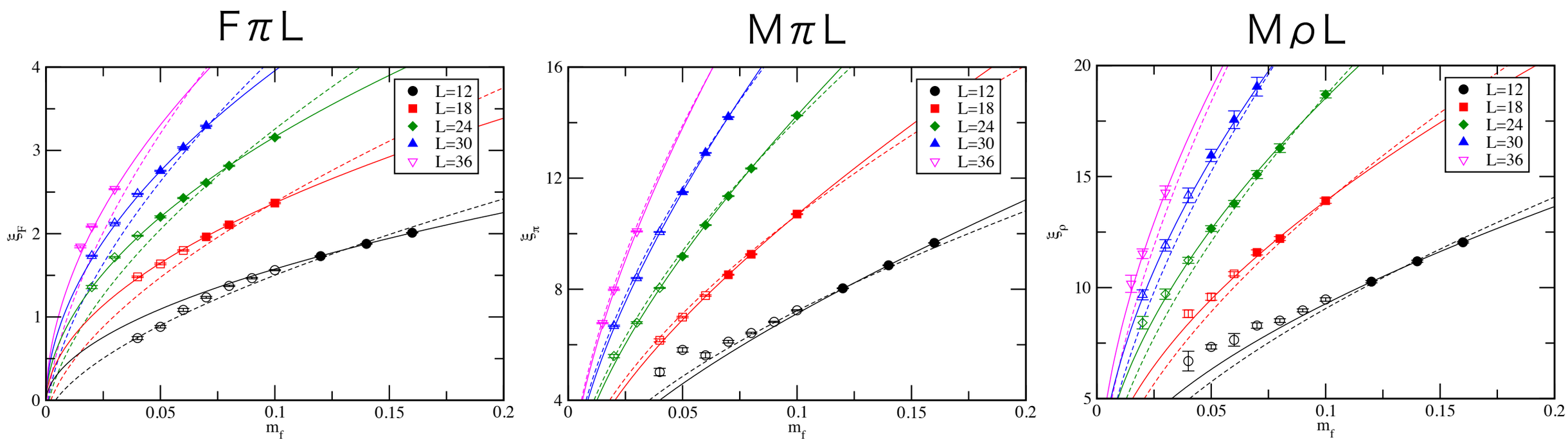
Simultaneous fit of Hyperscaling with mass corrections

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

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

(Schwinger-Dyson eq. analysis with large mass: e.g. $\alpha=(3-2\gamma)/(1+\gamma)$)

ξ_H(=$M_H L$) vs mf (not X): $\alpha=1$ fixed (⇓example)



In this case, the mass correction works well

with γ=0.874(25), χ^2/dof=0.75, dof=32. (solid line)

- In various trials of this analysis: γ=0.78−0.93 ∼1

Walking signals,

+updated (this talk)

- Nf=8 is (still) consistent with ChPT(SχSB) in the small mf region. (0.015≦mf≦0.04 ⇒ 0.012≦mf≦0.03)
- In the χ-limit., F=0.031(1)(+2-10) ⇒ 0.0202(13)(+54-67),

  $M_\rho/(F/\sqrt{2})$=7.7(1,5) ⇒ 8.5(2.1) , Cond=0.00052(5) ⇒ 0.00021(2).
- The expansion parameter χ=O(1) of ChPT in the smallest mf (self-consistent), in contrast to Nf=12.

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

- In the region of mf≧0.05, hyperscaling is seen. (different from Nf=4)
- non-universal γ for each observable in the naive finite-size hyperscaling (different from Nf=12)
- Simultaneous fit of hyperscaling with mass correction (from SD analysis) universal $\gamma\sim$1. [remnant of conformality]

3. Light composite scalar in Nf=8

$\mathrm{SU}(N_{\mathrm{TC}})$ gauge theory with 8 fundamental fermions

Techni-fermion condensate is the origin of the EWSB

$$f_\pi^2 = v_{\mathrm{EW}}^2/N_D$$
$$= (123\ \mathrm{GeV})^2$$

N_D : # of weak doublet

=

4

$$\underbrace{\begin{pmatrix} U_1 \\ D_1 \\ U_1 \\ D_1 \\ U_1 \\ D_1 \\ E_1 \\ N_1 \end{pmatrix} \cdots \begin{pmatrix} U_{N_{\mathrm{TC}}} \\ D_{N_{\mathrm{TC}}} \\ U_{N_{\mathrm{TC}}} \\ D_{N_{\mathrm{TC}}} \\ U_{N_{\mathrm{TC}}} \\ D_{N_{\mathrm{TC}}} \\ E_{N_{\mathrm{TC}}} \\ N_{N_{\mathrm{TC}}} \end{pmatrix}}_{\text{Techni-fermions}}$$

126 GeV Higgs
= Composite Higgs
= Techni-Dilaton

$$m_H \simeq f_\pi$$

Dilaton ChPT (DChPT)

S. Matsuzaki and K.Yamawaki, arXiv:1311.3784

$m_\sigma^2 = d_0 + d_1 m_\pi^2$, where $d_1 = \frac{(3-\gamma)(1+\gamma)}{4}\frac{N_F F_\pi^2}{F_\sigma^2} \sim 1$

For Scalar measurement;

m_f	$L^3 \times T$	$N_{\rm cf}[N_{\rm st}]$	m_σ	m_π	F_π
0.015	$36^3 \times 48$	3200[2]	$0.155(21)(^{0}_{41})$	$0.1861(4)^*$	$0.0503(2)^*$
0.02	$36^3 \times 48$	5000[1]	$0.190(17)(^{39}_{0})$	$0.2205(3)^*$	$0.0585(1)^*$
0.02	$30^3 \times 40$	8000[1]	$0.201(21)(^{0}_{60})$	0.2227(9)	0.0578(2)
0.03	$30^3 \times 40$	16500[1]	$0.282(27)(^{24}_{0})$	$0.2812(2)^*$	$0.07140(9)^*$
0.03	$24^3 \times 32$	36000[2]	$0.276(15)(^{6}_{0})$	0.2832(14)	0.0715(4)
0.04	$30^3 \times 40$	12900[3]	$0.365(43)(^{17}_{0})$	$0.3349(3)^*$	$0.0826(1)^*$
0.04	$24^3 \times 32$	50000[2]	$0.322(19)(^{8}_{0})$	0.3353(7)	0.0823(2)
0.04	$18^3 \times 24$	9000[1]	$0.228(30)(^{0}_{16})$	0.3421(29)	0.0823(5)
0.06	$24^3 \times 32$	18000[1]	$0.46(7)(^{12}_{0})$	0.4295(6)	0.1012(3)
0.06	$18^3 \times 24$	9000[1]	$0.386(77)(^{12}_{0})$	0.4317(15)	0.0999(5)

TABLE I: Simulation parameters for $N_f = 8$ QCD at $\beta = 3.8$. $N_{\rm cf}(N_{\rm st})$ is the total number of gauge configurations (Markov chain streams). The second error of m_σ is a systematic error coming from the fit range. The values for m_π and F_π are from Ref. [10], but the ones with (*) have been updated.

Difficulty of flavor-singlet scalar meson

- Flavor non-singlet scalar meson $S_{NS}(t) = \sum_{\vec{x}} \overline{\psi}_a(\vec{x},t)\psi_b(\vec{x},t)$ $(a \neq b)$

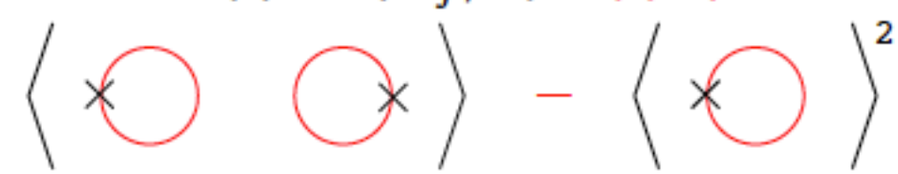
$\langle 0|S_{NS}(t)S^\dagger_{NS}(0)|0\rangle \quad =$  $= -C(t)$

c.f. m_π, F_π from non-singlet pseudoscalar

$O(100)$ configurations $\times$ $O(1)$ $D^{-1}[U](x,y)$

- Flavor-singlet scalar meson $S(t) = \sum_{\vec{x}} \overline{\psi}_a(\vec{x},t)\psi_a(\vec{x},t)$

$\langle 0|S(t)S^\dagger(0)|0\rangle \quad = -C(t) + (N_f/4)D(t)$ (disconnected)

$D(t) =$ 

Much harder but essential for flavor-singlet

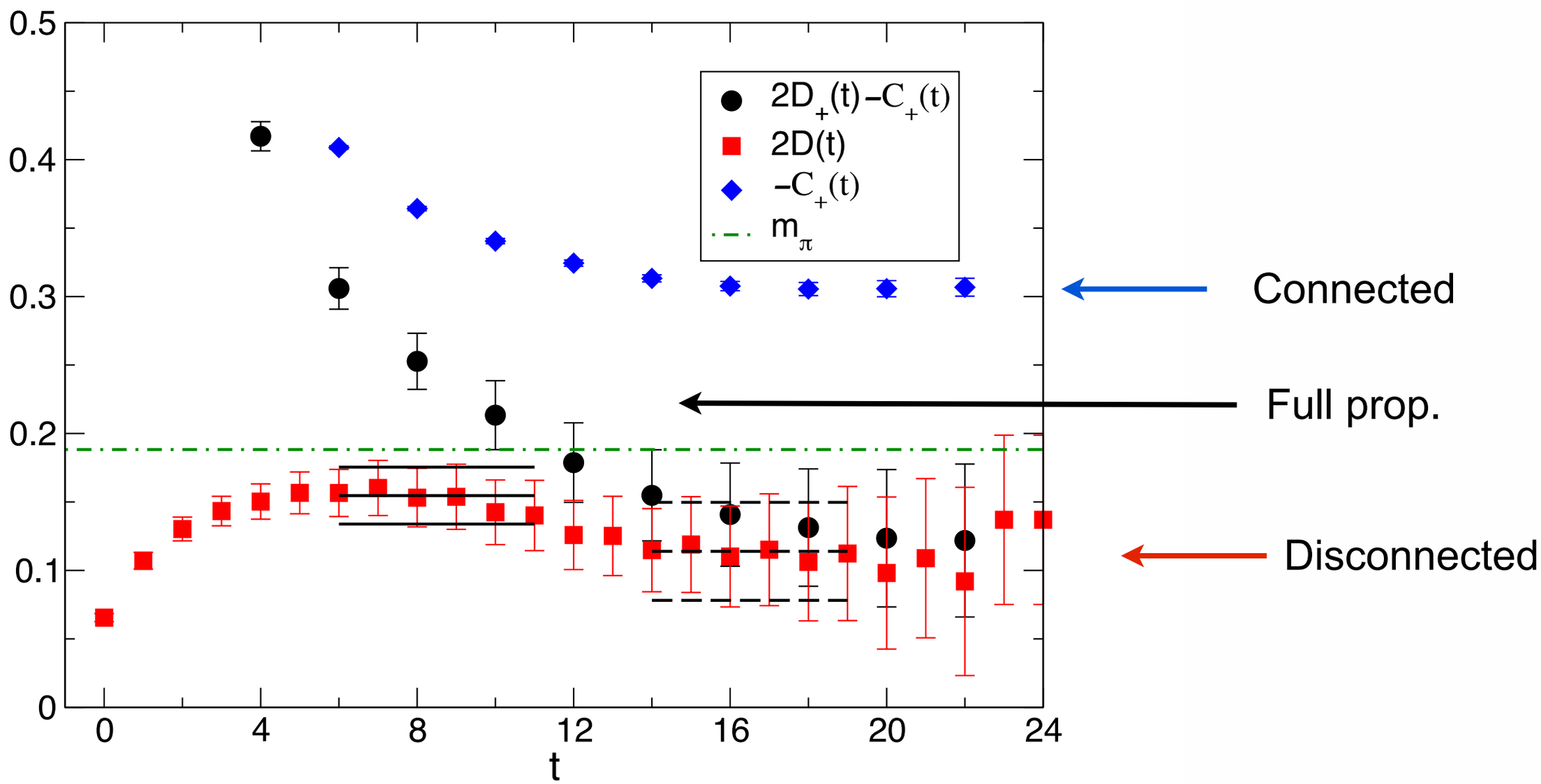
$O(10000)$ configurations $\times$ $O(10)$ $D^{-1}[U](x,x)$

using noise reduction method

'97 Venkataraman and Kilcup

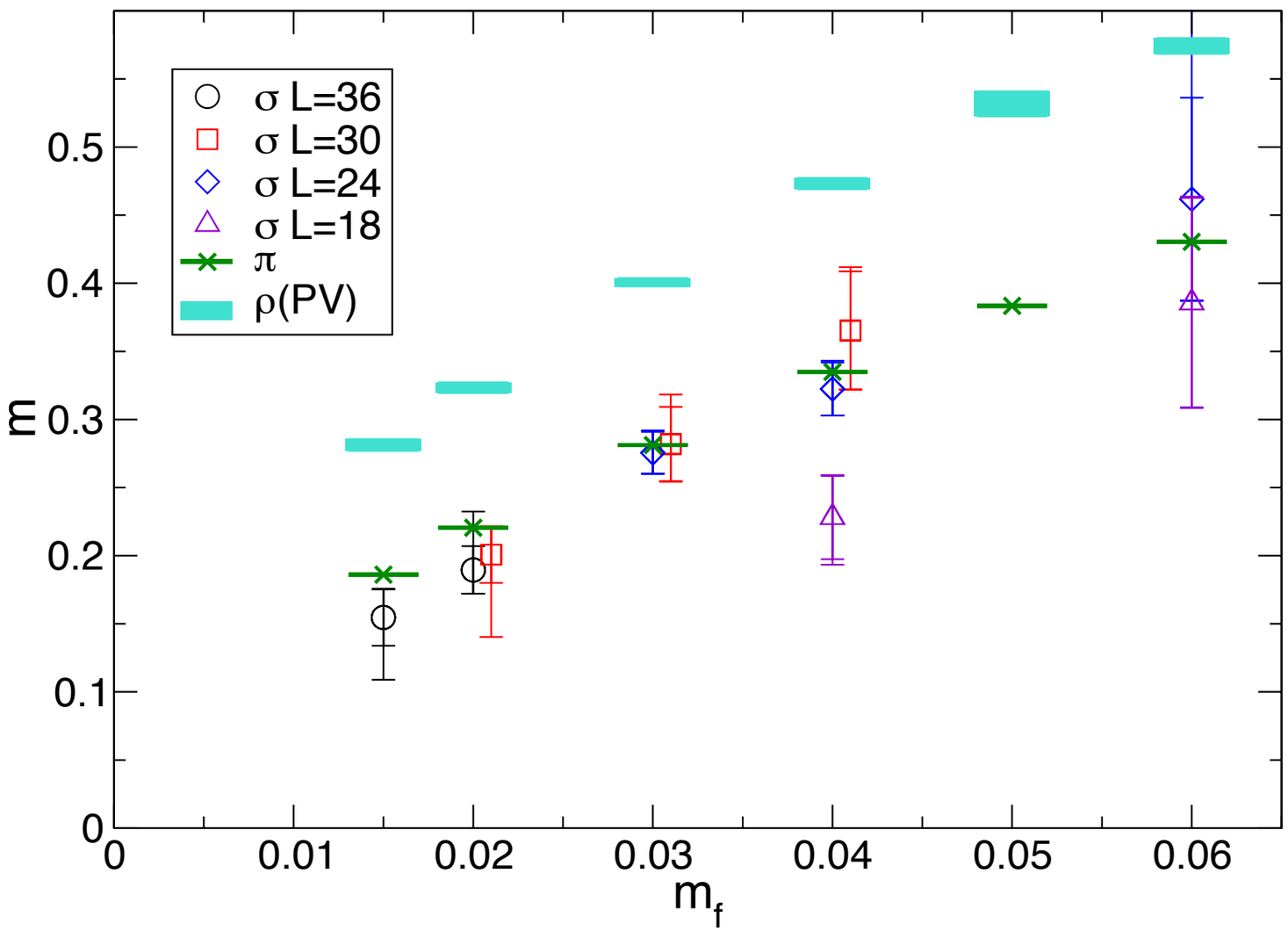
Effective mass (mf=0.06, L=24, 14000config., Nf=8)

$$m_{\text{eff}}(t) = \log(C_H(t)/C_H(t+1)) \xrightarrow{t \gg 1} m_H$$



good signal !!

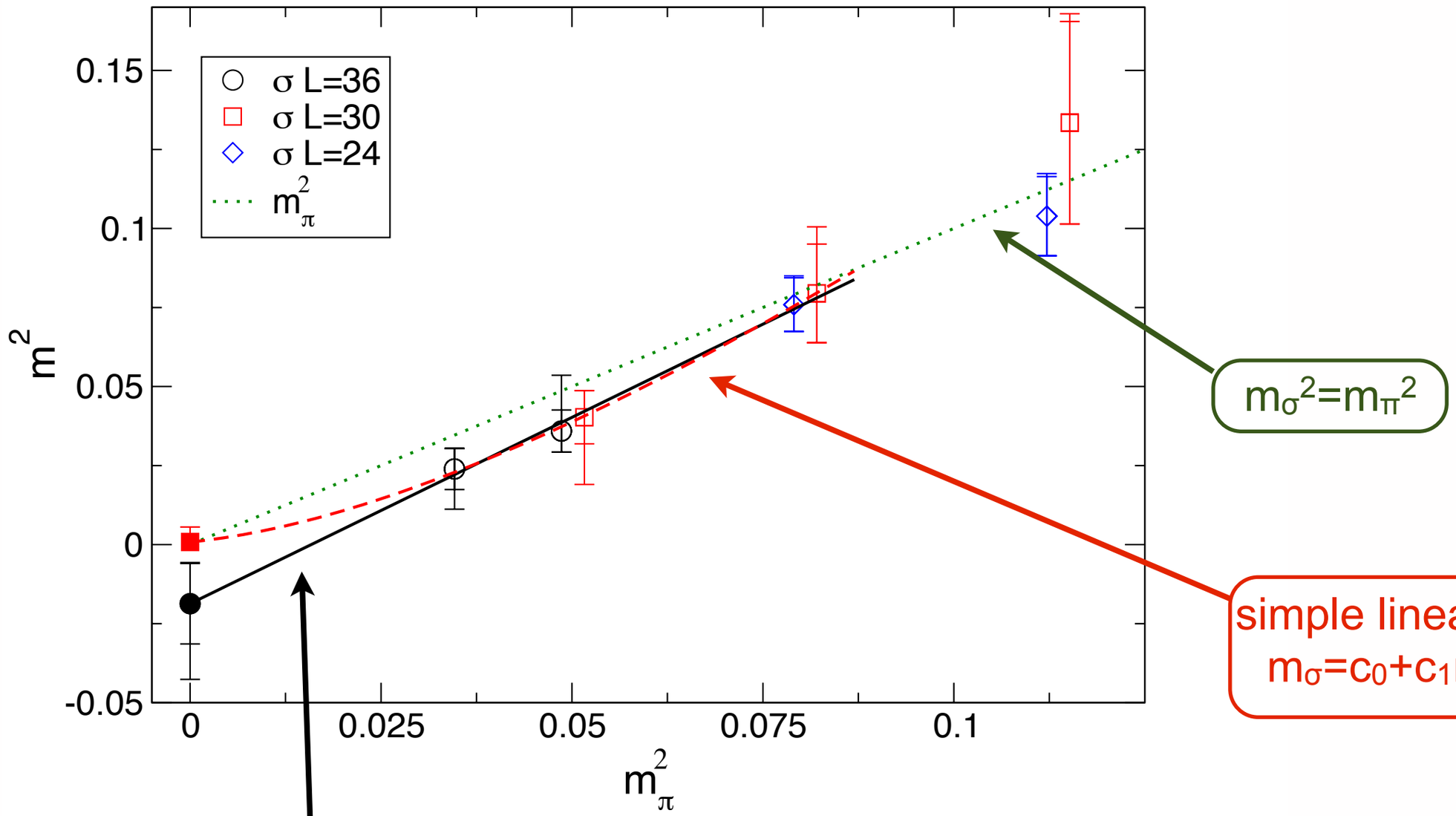
Results: Nf=8



Mρ > Mσ ∼ Mπ

Nf=8 QCD is in sharp contrast to the real-life QCD

Fit to the data in the small mf region where ChPT works



Dilaton ChPT (DChPT) fit

S. Matsuzaki and K.Yamawaki, arXiv:1311.3784

$m_\sigma^2=d_0+d_1 m_\pi^2$, where $d_1 = \frac{(3-\gamma)(1+\gamma)}{4}\frac{N_F F_\pi^2}{F_\sigma^2} \sim 1$

Comparison of m_σ in $N_f = 8$ with m_{Higgs}

In chiral limit:

$F/\sqrt{2} = 123$ GeV; One-family model (four-doublet fermions)

- Simple linear fit

$$m_\sigma/(F/\sqrt{2}) \;=\; 2.0(2.7)(^{8}_{5})$$

- ChPT with spontaneous scale symmetry breaking

Dilaton ChPT (DChPT) fit

S. Matsuzaki, K. Yamawaki arXiv:1311.3784

$$m_\sigma^2 = d_0 + d_1 m_\pi^2$$

lattice result: $d_0 = -0.019(13)(^{3}_{9})$

($f_\pi = F/\sqrt{2}$, $F \fallingdotseq 0.02$ input)

Nearly consistent with

$m_\sigma^2 \simeq f_\pi^2 \, (\simeq 0.0002)$

though uncertainty is still large

→ very large error for very small value → not inconsistent

⇒ Possibility of reproduce m_{Higgs}

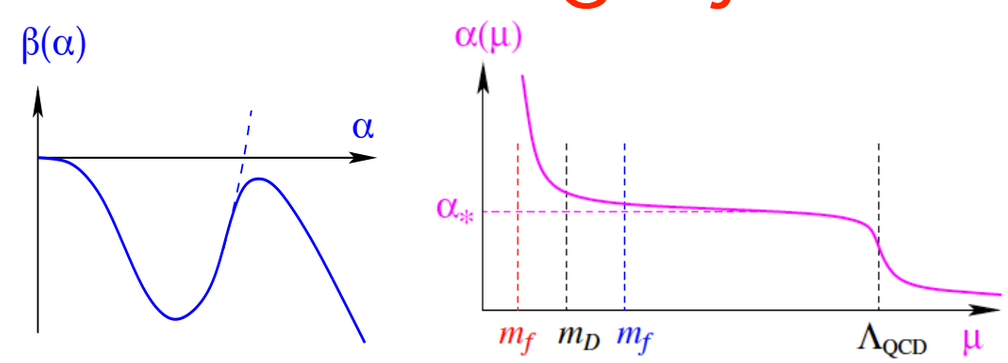
Summary

- SU(3) gauge theories with 4, 12, 16 and 8 HISQ quarks.

Preliminary (data updated: 2013→2014)

- Nf=8; possibility of 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.)
- Light Scalar (flavor singlet scalar meson, techni-dilaton)

Nf=8 → Candidate for Walking dynamics



Phenomenologically preferable?

In Progress:

- Simulation on larger volumes at lighter masses
- Finite Size Effect (one-volume: mf=0.015 on L=36, mf=0.012 on L=42)
- Finite Size Scaling
- Lattice spacing dependence (cont' limit) ←many β
- Spectroscopy ($M_{glueball}$, $M_{"scalar"}$, M_{baryon}, M_{meson}, F_σ, S-param., string tension, etc.)

$M_{"scalar"}$, $M_{glueball}$, string tension

- $M_{"flavor\text{-}singlet\ light\ scalar"}$

Nf=12

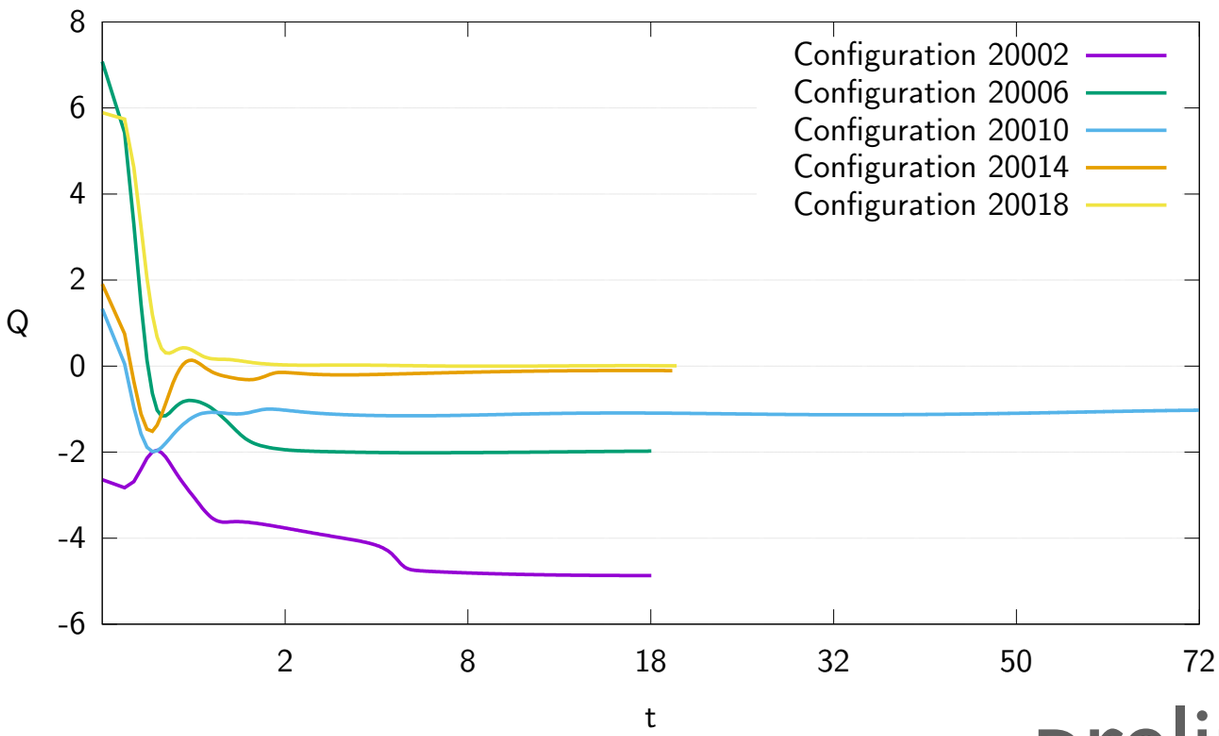
Ohki's talk (Next!)

Aoki-Rinaldi's poster

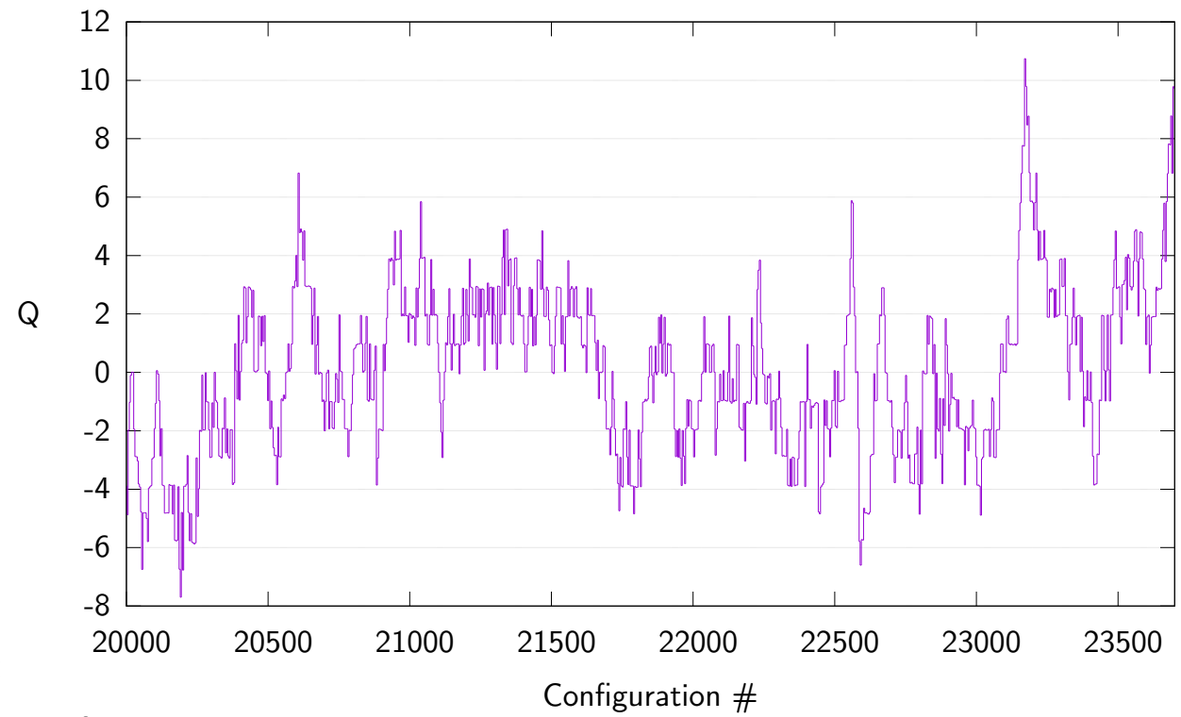
- Topological charge and susceptibility
- Gradient flow
- Eigenvalues

In Nf=8 at mf=0.06 on L=24

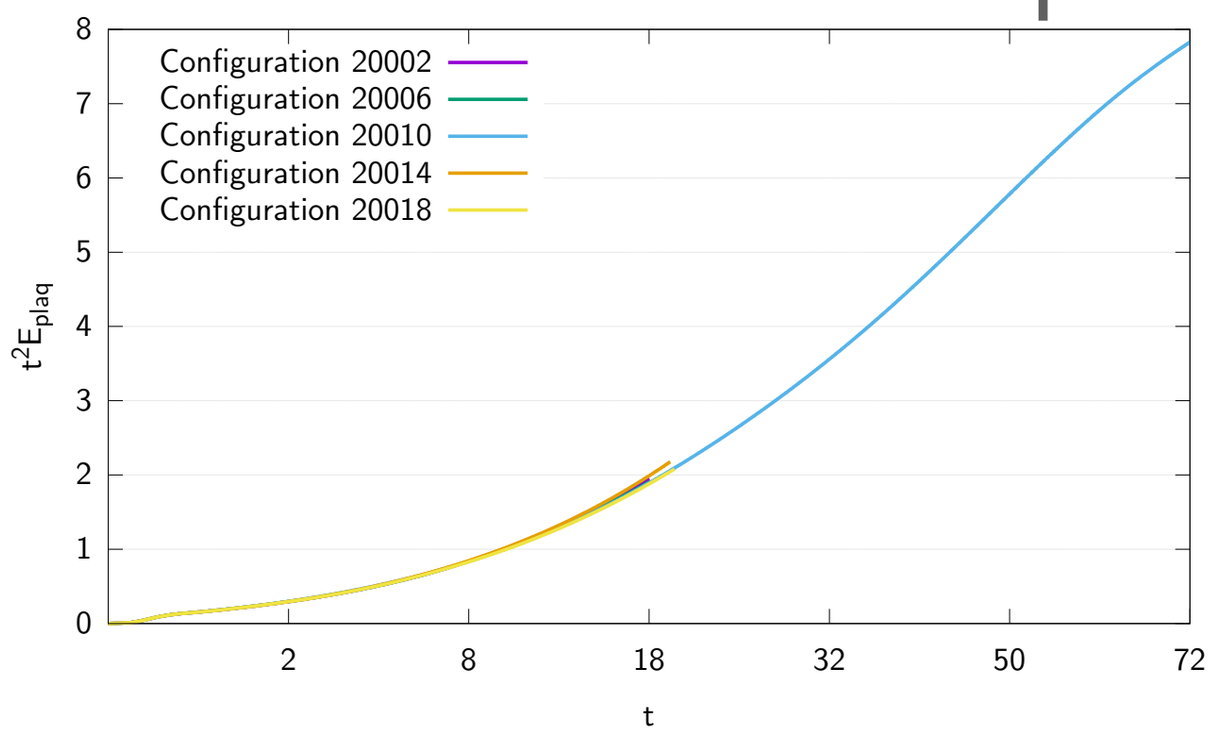
Qtop vs Symanzik flow time



Qtop vs #trajectory



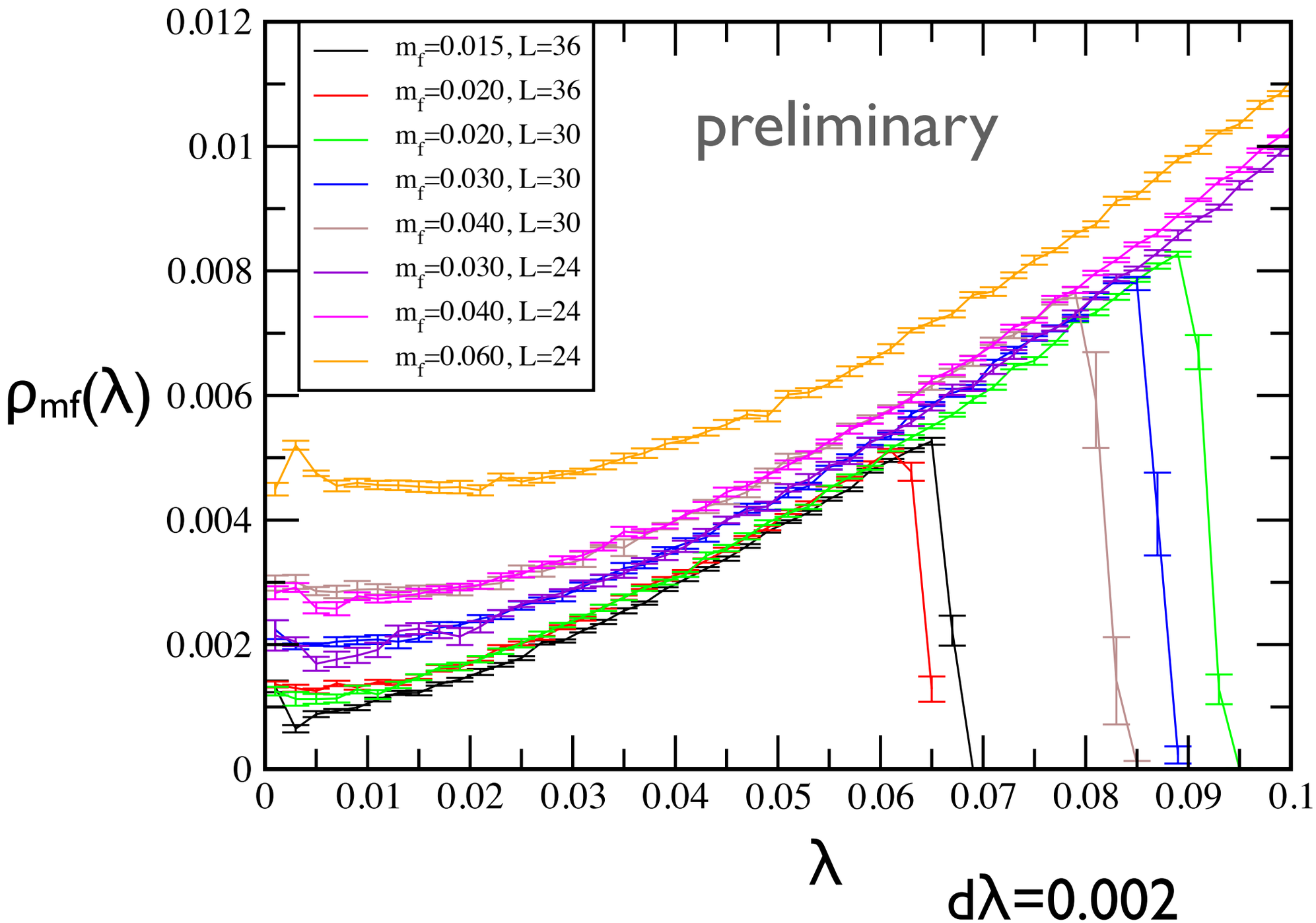
preliminary



t^2E_{plaq} vs flow time

$\rho_{mf}(\lambda)$ in Nf=8

$\lambda=\sqrt{EV(D^{\dagger}_{HISQ}D_{HISQ})}$, for $D^{\dagger}_{HISQ}D_{HISQ}+m^2$



$d\lambda=0.002$

$\Rightarrow$ Σ, γ, ..., RMT, ..., in the near future

In Progress:

- Simulation on larger volumes at lighter masses
- Finite Size Effect (one-volume: mf=0.015 on L=36, mf=0.012 on L=42)
- Finite Size Scaling
- Lattice spacing dependence (cont' limit) ←many β
- Spectroscopy ($M_{glueball}$, $M_{"scalar"}$, M_{baryon}, M_{meson}, F_σ, S-param., string tension, etc.)

$M_{"scalar"}$, $M_{glueball}$, string tension

Nf=12

- $M_{"flavor\text{-}singlet\ light\ scalar"}$

Ohki's talk (Next!)

Aoki-Rinaldi's poster

- Topological charge and susceptibility
- Gradient flow
- Eigenvalues

Thank you

Backup

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

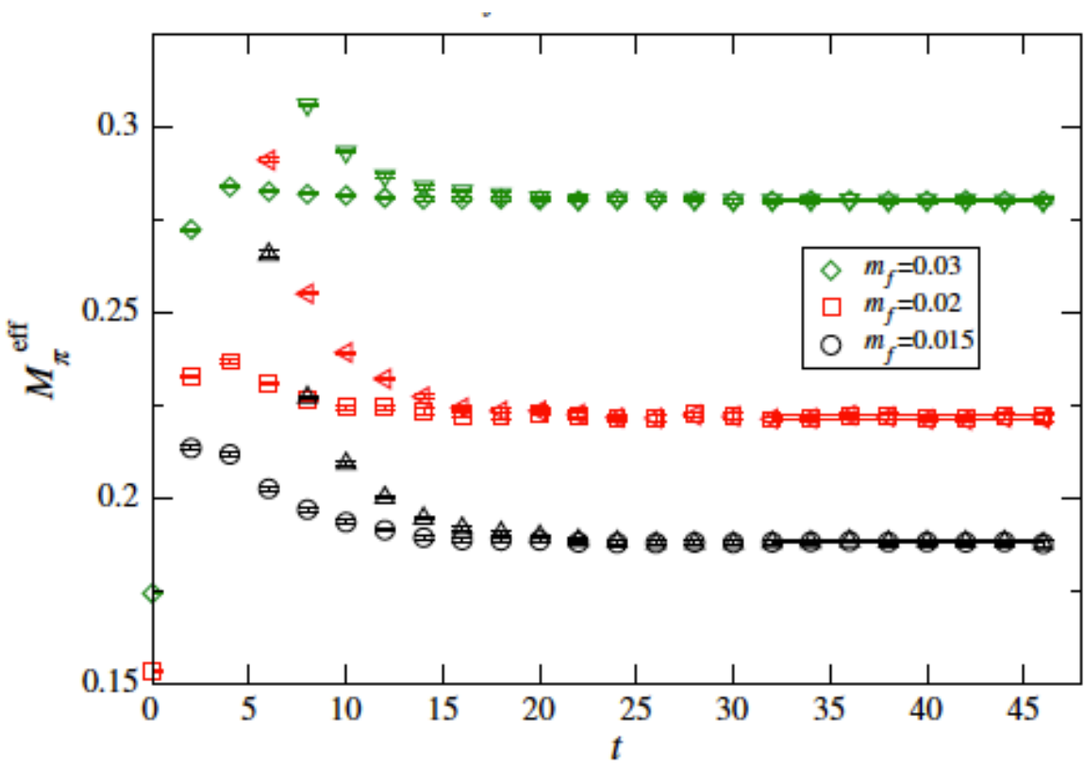


FIG. 2 (color online). Effective masses of PS meson, $M_\pi^{\rm eff}$, at $L = 36$. Triangles and other symbols denote results from point sink correlators with random wall source and corner wall source, respectively. Fit results with error band obtained from random wall source correlator are also plotted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

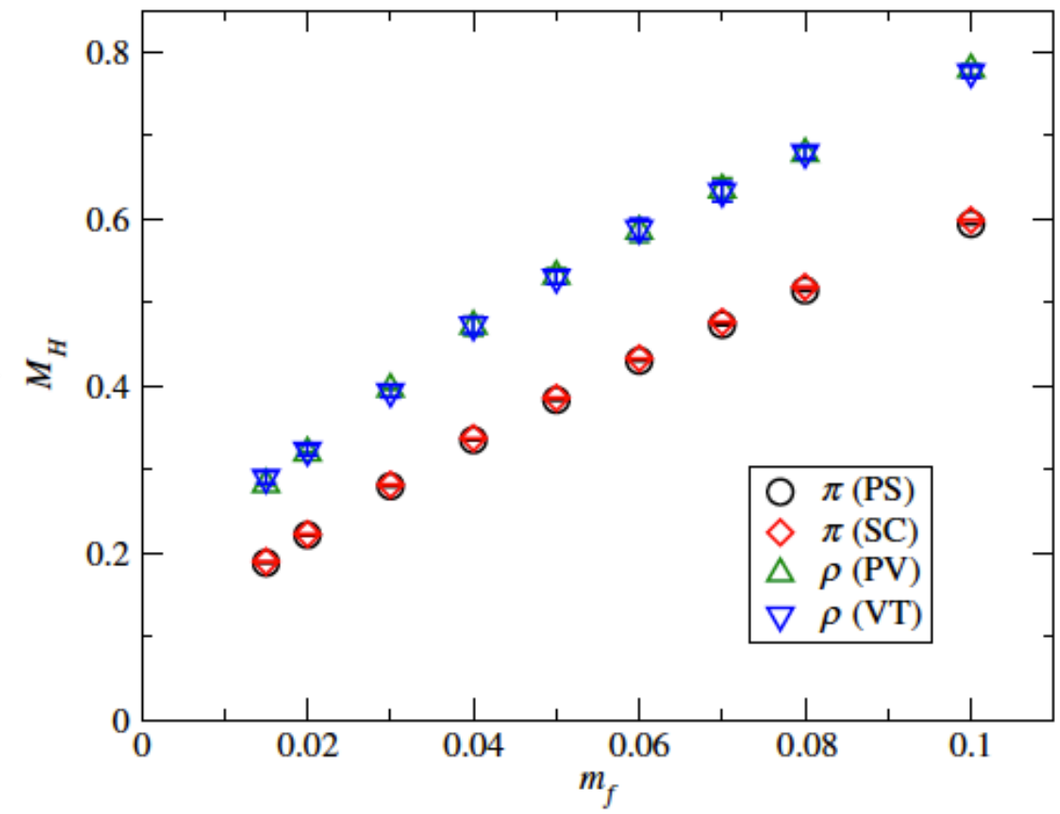
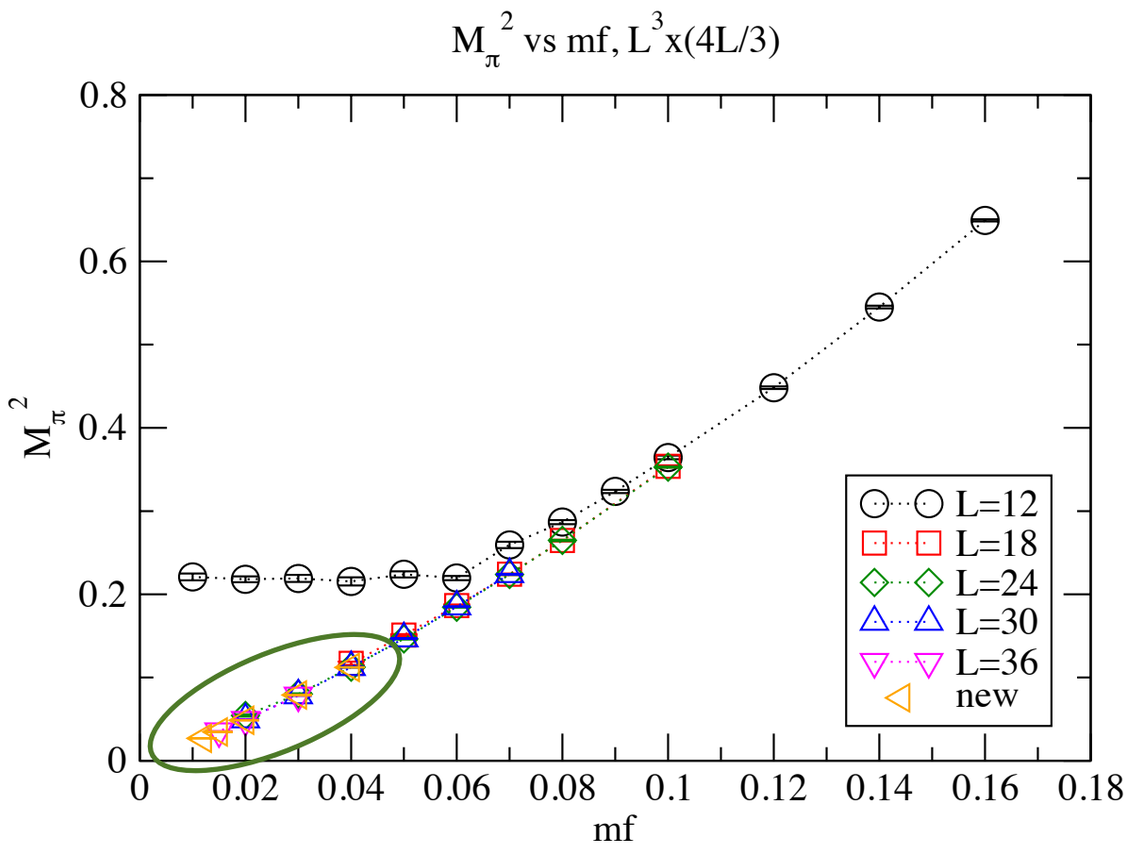
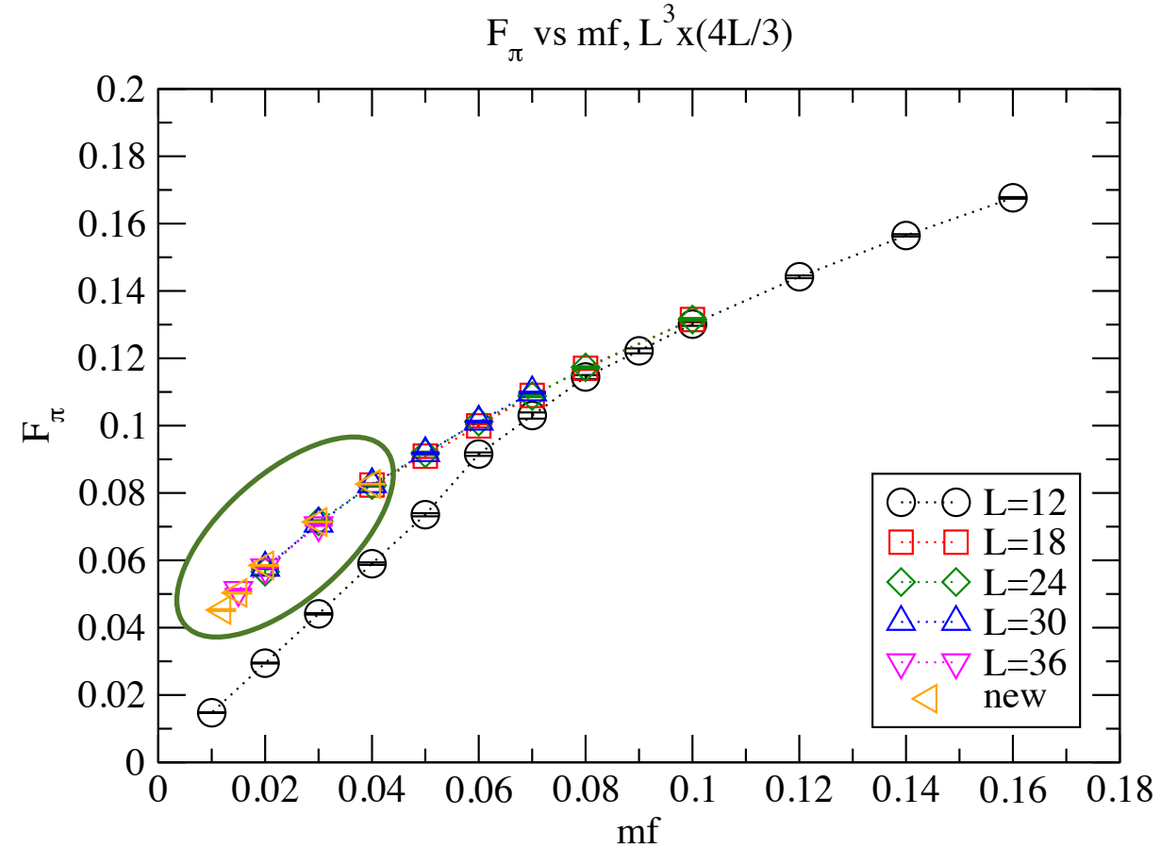


FIG. 4 (color online). Comparisons of M_π and $M_{\rm SC}$, and of $M_{\rho({\rm PV})}$ and $M_{\rho({\rm VT})}$ as a function of m_f with largest volume data at each m_f.

data in the Nf=8 paper + updated data

M_π^2, F_π vs. m_f on various L

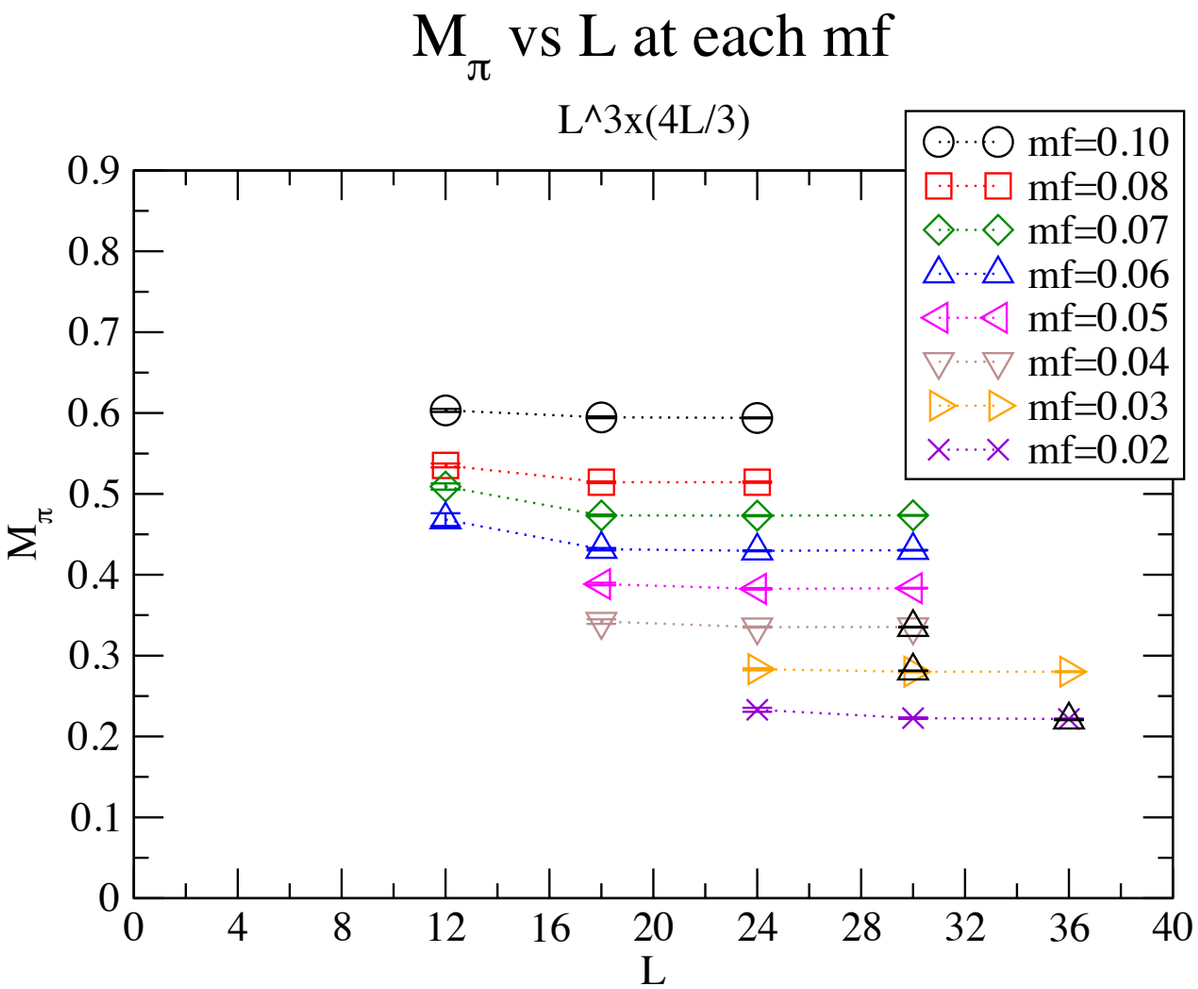


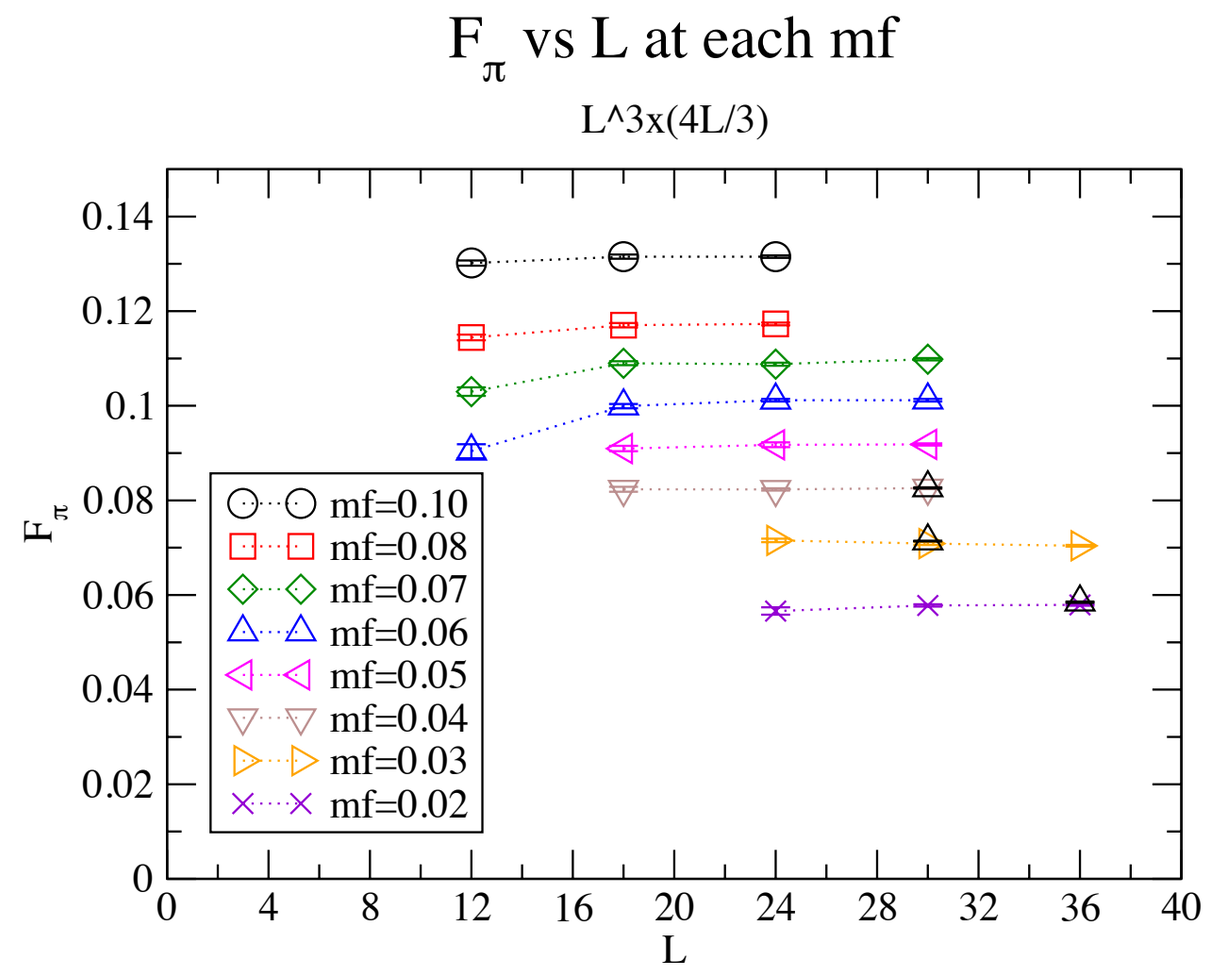


Preliminary

Size dependence of Mπ and Fπ at β=3.8

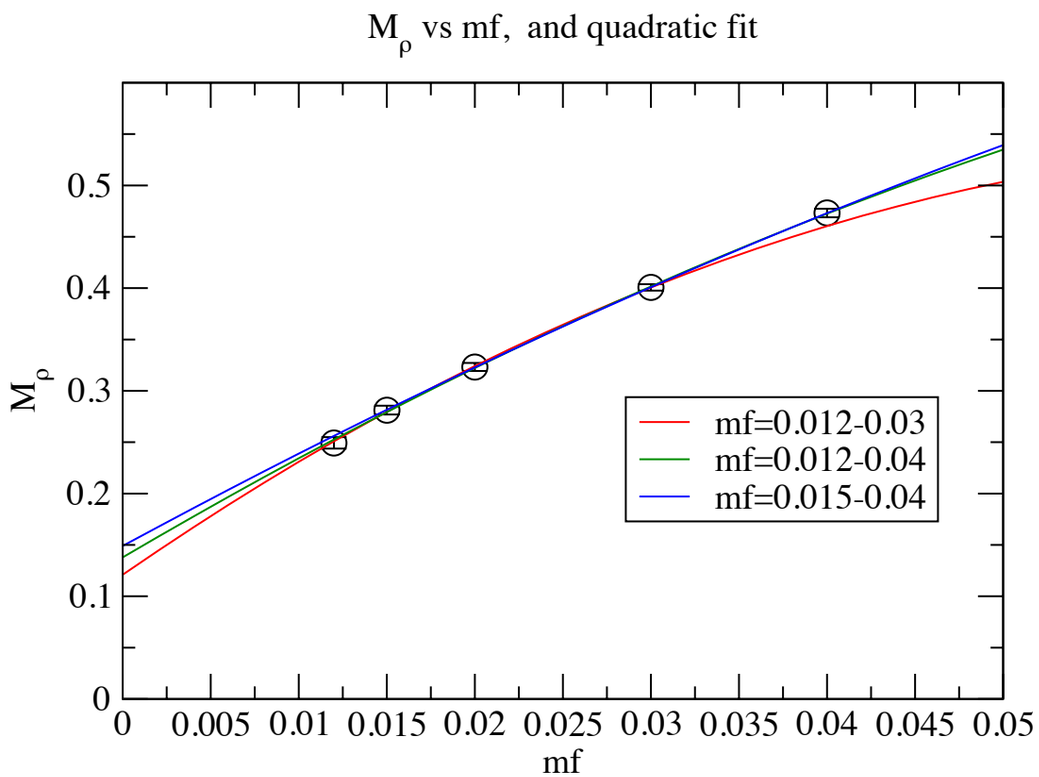
△=updated





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

$M\rho$ vs mf with quadratic-func. fit : $y=C_0+C_1*mf+C_2*mf^2$

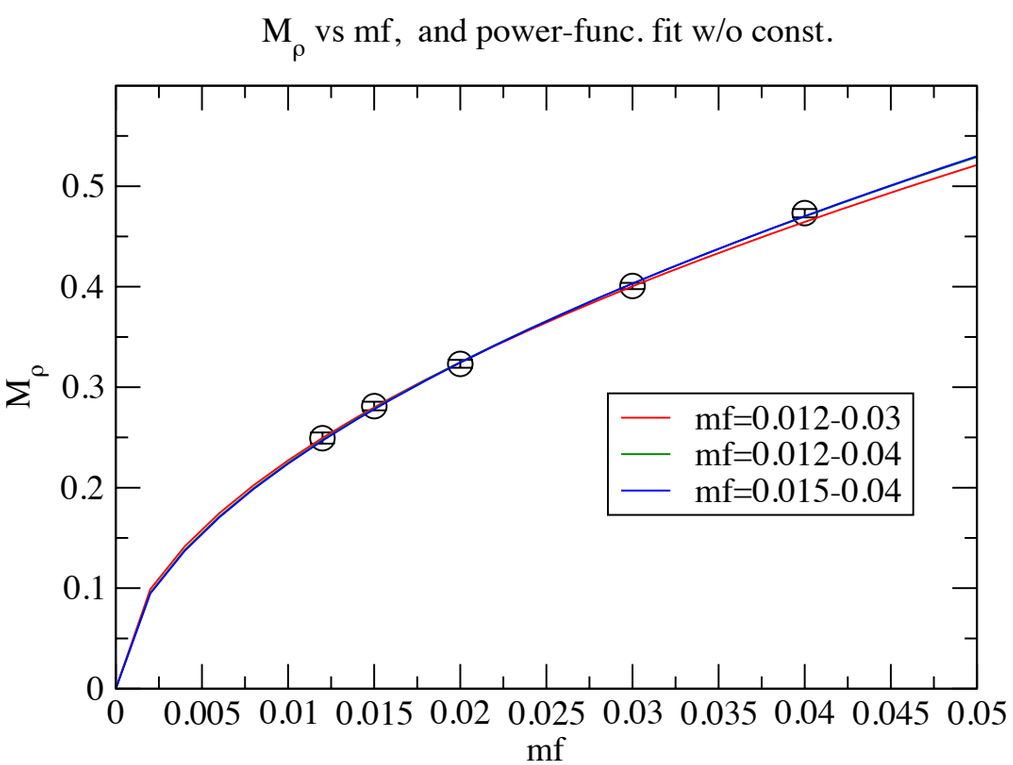


red : C_0=0.121(29), χ2/dof=0.27 (dof=1)

green: C_0=0.138(15), χ2/dof=0.36 (dof=2)

blue : C_0=0.149(20), χ2/dof=0.025 (dof=1)

$M\rho$ vs mf with power-func. fit (hyperscaling) : $y=D_1*mf^{\alpha}$



red : α=0.516(18), χ2/dof=0.12 (dof=2)

green: α=0.532(14), χ2/dof=0.62 (dof=3)

blue : α=0.535(16), χ2/dof=0.86 (dof=2)

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 (=MπL) ≧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.