Spectral properties of N_f=8 SU(3) gauge theory

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- SCGT15 @ Nagoya -

March 3, 2015

updates from LatKMI collaboration

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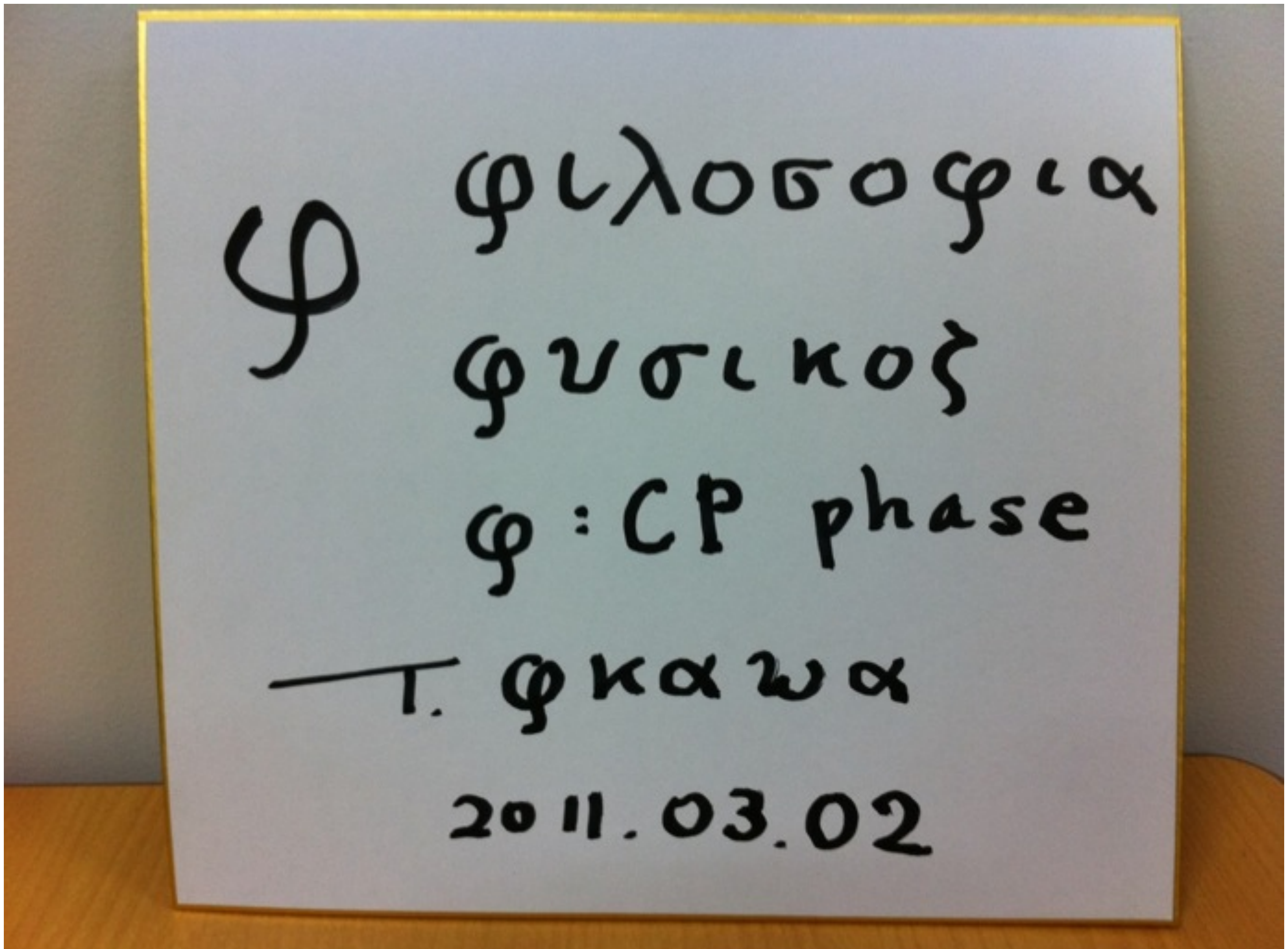
KMI computer

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

- 62 TFlops (peak; comparable to Japanese top 20 of top500 list @ 2012.10)

φ inauguration March 2, 2011

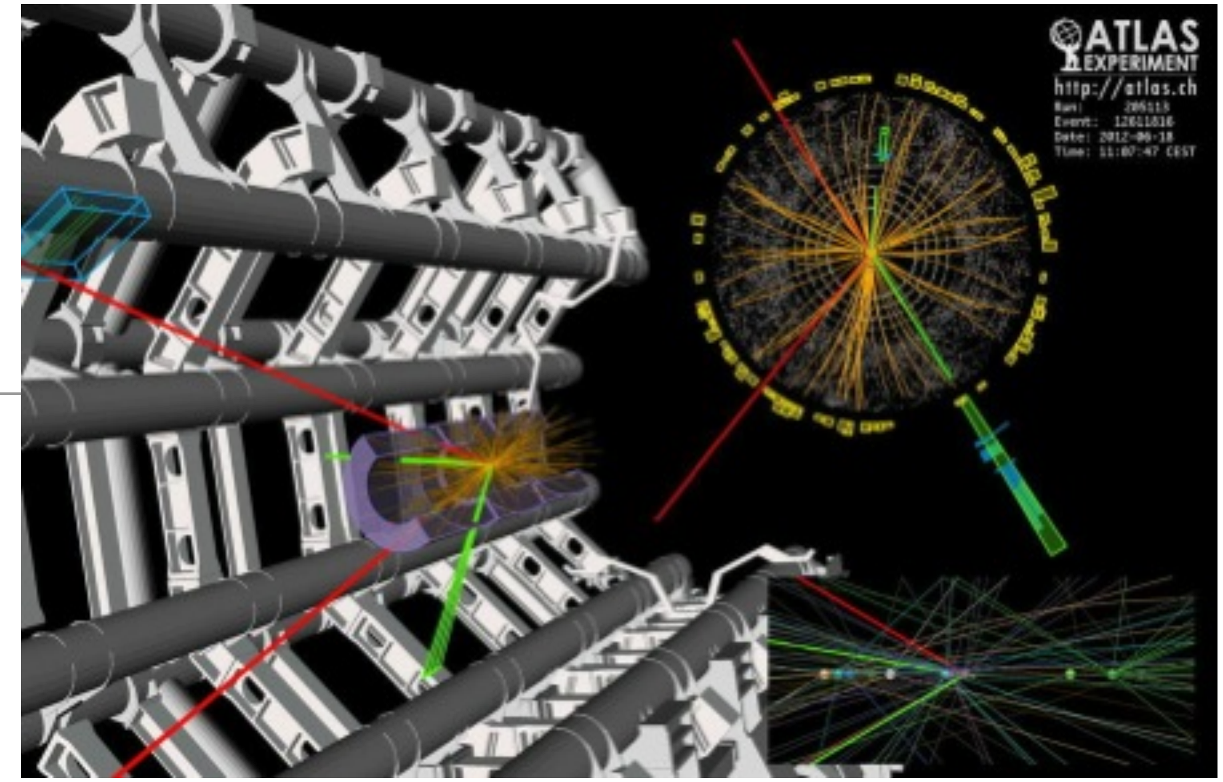
Inauguration Ceremony of φ
March 2nd, 2011



Computers

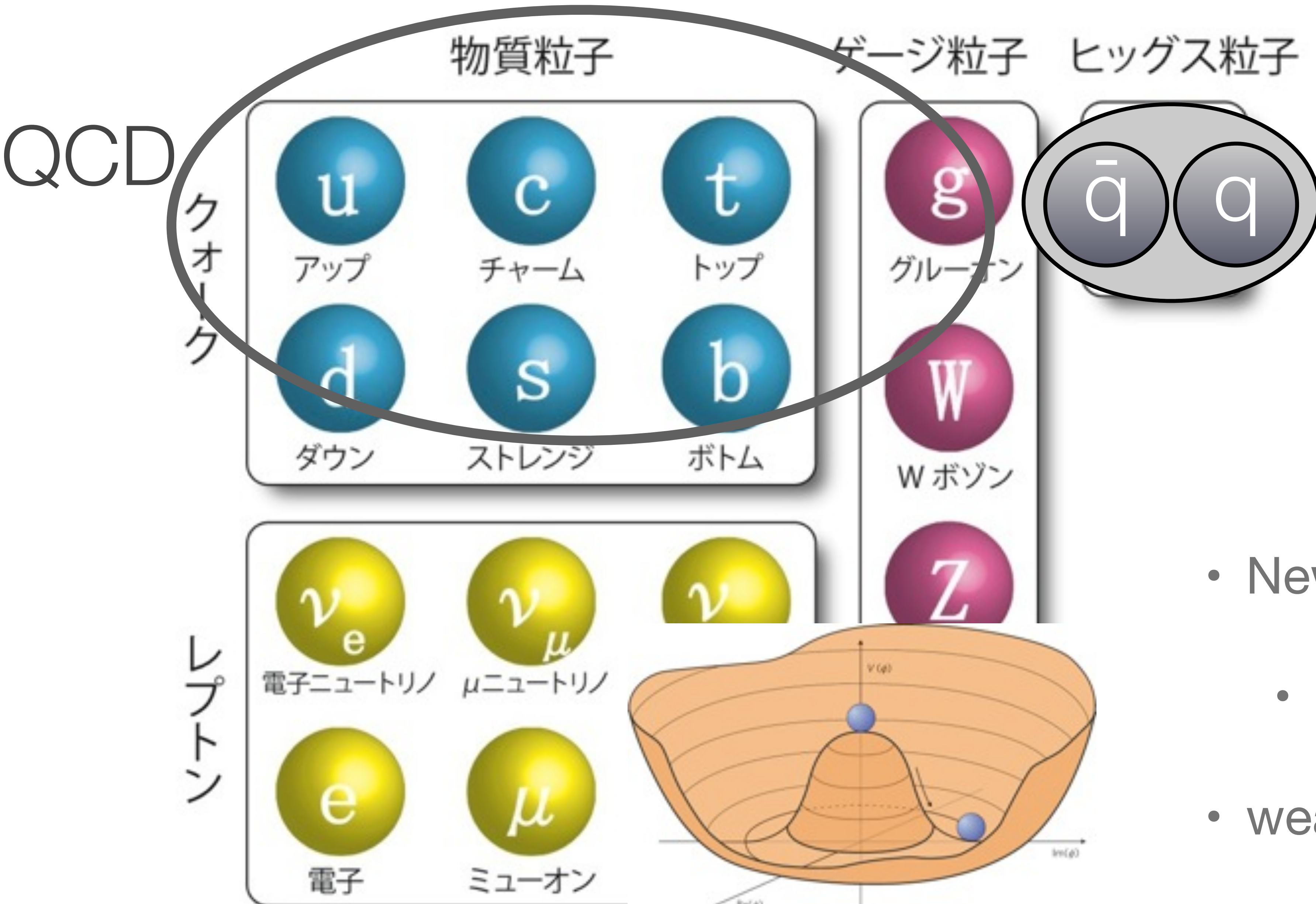
- we have been using comuters:
  - phi
  - CX400 at Kyushu University
  - CX400 at Nagoya Information Technology Center
  - CX400 use granted for HPCI

“Higgs boson”

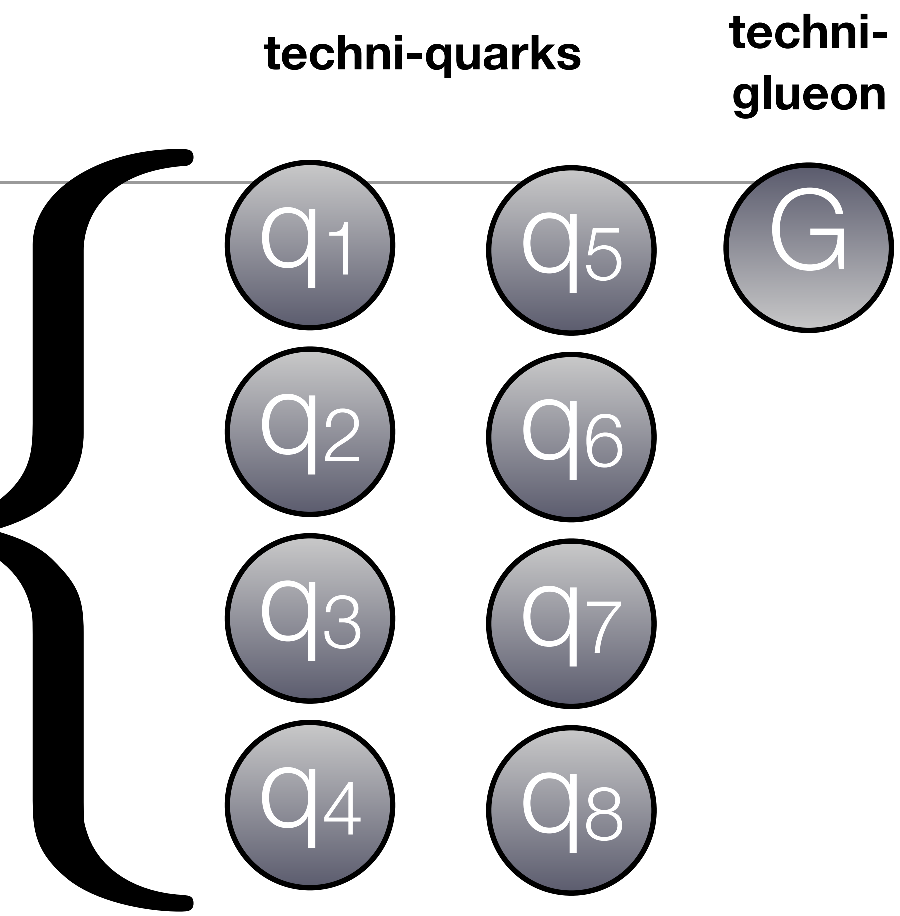


- Higgs boson fund at LHC
- m_H = 125 GeV
- so far consistent with Standard Model Higgs ($J^{PC}=0^{++}$) fundamental scalar
- but it could be different
- one of the possibilities:
  - composite Higgs through strong dynamics
  - SM Higgs is the low energy effective description of that, cf: ChPT ⇔ QCD

Physics motivation: new physics



Standard Model



- New techni sector
  - QCD like interaction
- weakly coupled with SM sector
- resemble Higgs mechanism
- produce Higgs like particle

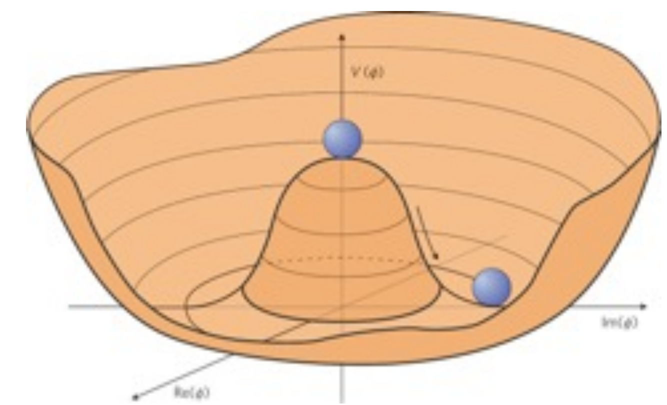
Thanks to Dr. Kimura (KMI PR office) for Standard Model diagram

Role of SM Higgs

- It’s about the origin of mass...
- (99% of the mass of visible universe is made by QCD dynamics)
- masses of fundamental particles: weak bosons, quarks, leptons
  - by EW gauge symmetry breaking through Higgs

Higgs mechanism (cf. Farhi & Susskind)

- Higgs potential : $V=\mu^2 |\phi|^2 + \lambda|\phi|^4$ with $\mu^2<0$: “wine bottle”
  - rotating: m=0 mode
  - radial: $m\neq0$: Higgs particle



- weak doublet: 4 fields: 1 massive Σ, 3 massless
- massless: $\Pi^\pm$, Π^0 : Nambu-Goldstone boson (rotational symm. br.)
- have coupling to weak current: $\langle 0|J_\mu^\pm|\Pi^\pm\rangle = F\, p_\mu$; $F = \langle 0|\phi|0\rangle = 246$ GeV
- make a massless pole in the vacuum polarization
- cancels massless pole of original $W^\pm$ propagator → massive gauge boson

$\langle 0|J_\mu^\pm|\Pi^\pm\rangle = F\, p_\mu$

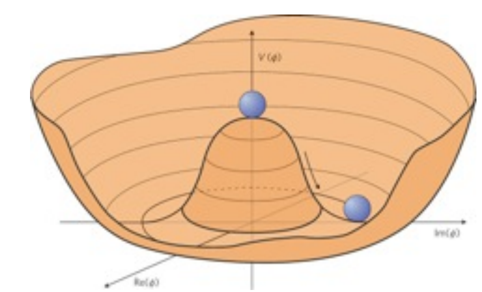
- Isn't it familiar ? : $\langle 0|J_\mu^\pm|\Pi^\pm\rangle = F\, p_\mu$ with massless boson $\Pi^\pm$
- pion decay: $\langle 0|A_\mu^\pm|\pi^\pm\rangle = f\, p_\mu$
  - $\pi^\pm$ π^0 Nambu-Goldstone boson made of u, q quarks due to
  - $SU(2)_L x SU(2)_R \to SU(2)_V$: spontaneous chiral symmetry breaking
  - f=93 MeV ⇔ F=246 GeV
- axial current $A_\mu^\pm$ is a part of weak current $J_\mu^\pm$: (V-A)
- Even if there is no Higgs, weak boson gets mass due to chiral br. in QCD

Technicolor (TC)

- $\langle 0|J_\mu^\pm|\Pi^\pm\rangle = F\, p_\mu$
- realize this with a new set of
  - **massless** quarks (techni-quarks)
  - which have coupling to weak bosons,
  - and interact with techni-gluons
  - which breaks the chiral symmetry in the techni-sector,
  - produces techni-pions which have decay constant

➡$F = 246/\sqrt{N}$ GeV: scale up version of QCD (N: # weak doublet from new techni-sector)

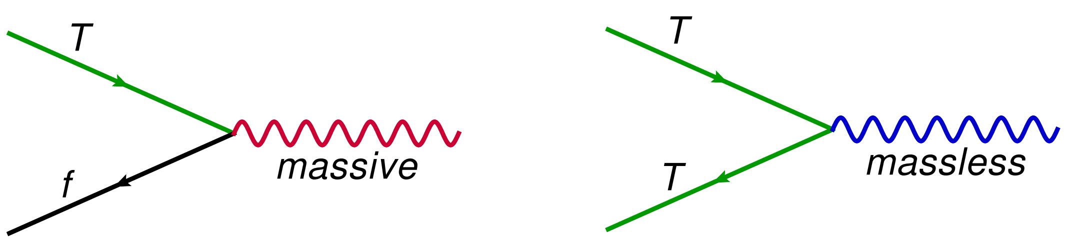
Technicolor ⇔ SM Higgs



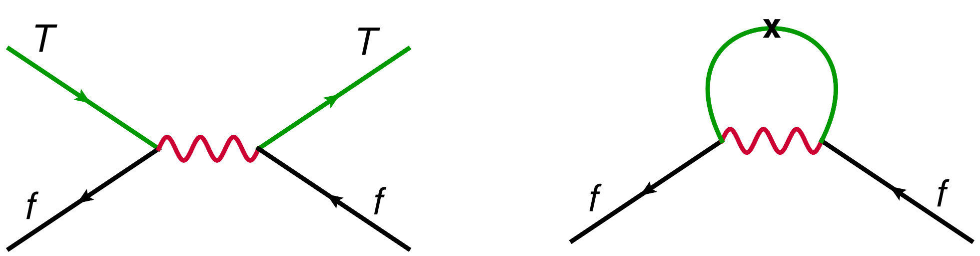
- success of technicolor
  - explaining the origin of EW symmetry breaking
    - dynamics of gauge theory ⇔ $\mu^2 < 0$
  - evading the gauge hierarchy problem: naturalness problem
    - due to logarithmic UV divergence ⇔ power divergence
- fermion masses ?
  - ETC effective 4 Fermi interaction ⇔ fermion-Higgs Yukawa coupling
  - produced by introducing interaction: techni-quarks and SM fermions

Extended Technicolor (ETC) for SM fermion mass

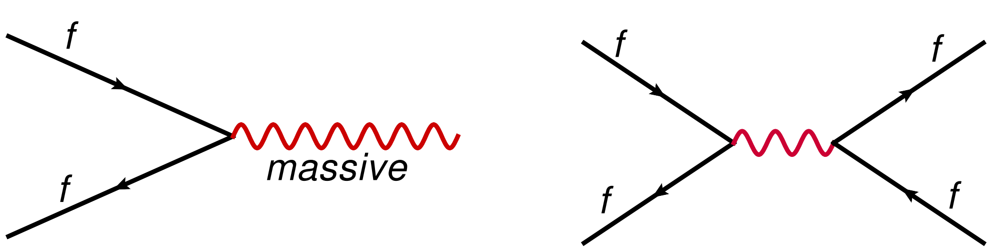
- New strong interaction of SU(N_{ETC}): $N_{ETC}>N_{TC}$, T_{ETC}=(T, f): T∈TC, f∈SM
- SSB: SU(N_{ETC})→SU(N_{TC}) x SM @ Λ_{ETC} ($\gg\Lambda_{TC}$)
- an ECT interaction ↔ TC interaction

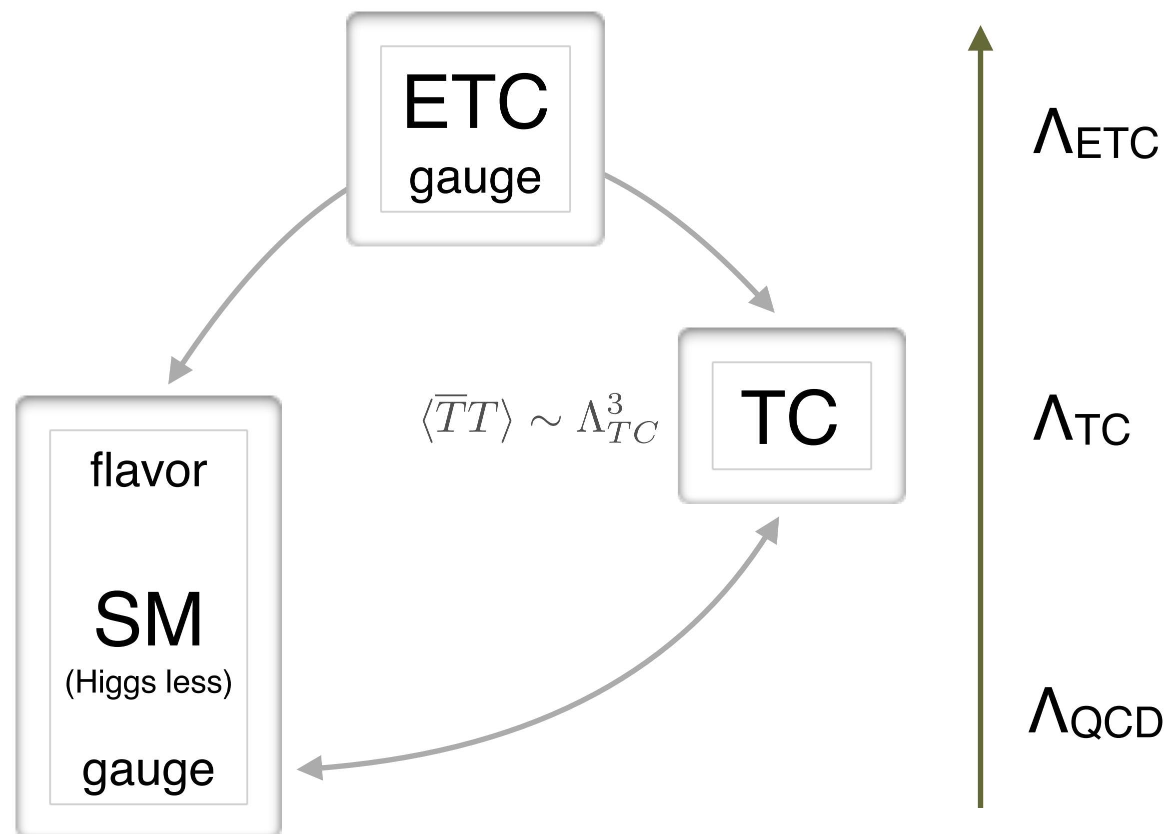


➡ 4 fermi → mass for f



- ya ETC interaction → 4 fermi → FCNC





SM fermion mass ↔ FCNC tension

- ETC interaction decouples at Λ_{ETC}
- neglecting QCD logarithmic running
- $$\frac{1}{\Lambda_{ETC}^2}\overline{T}T\overline{f}f \to m_f = \frac{\langle \overline{T}T\rangle_{ETC}}{\Lambda_{ETC}^2} = \frac{1}{\Lambda_{ETC}^2}\exp\left[\int_{\Lambda_{TC}}^{\Lambda_{ETC}}\frac{d\mu}{\mu}\gamma(\mu)\right]\langle \overline{T}T\rangle_{TC}$$
- $$\frac{1}{\Lambda_{ETC}^2}\overline{f}f\overline{f}f$$ FCNC
- FCNC should be small ⇔ top or bottom quark mass should be produced

➡ walking TC: for $\Lambda_{TC} < \mu < \Lambda_{ETC}$ ($\Lambda_{ETC} \gg \Lambda_{TC}$)

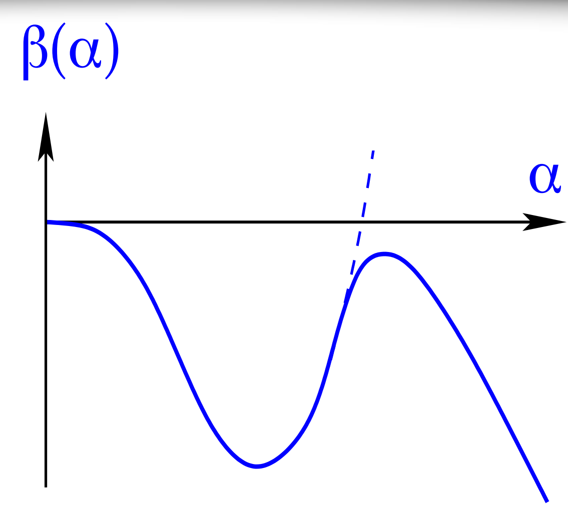
easing the tension

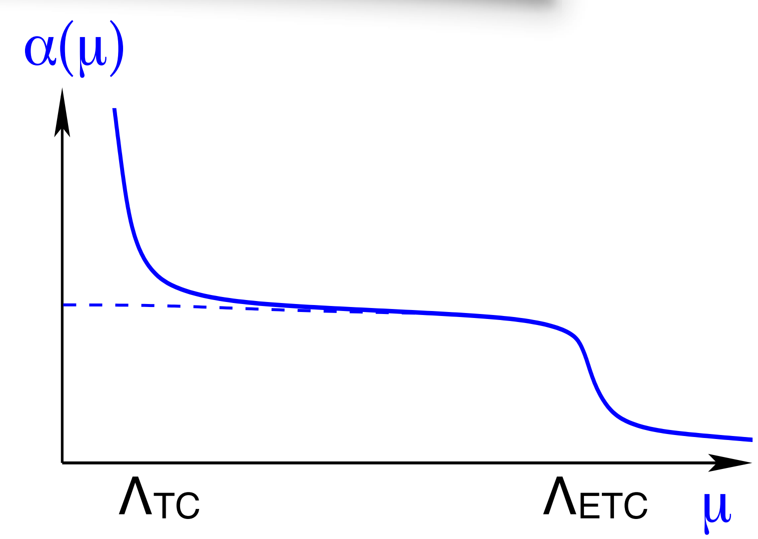
- coupling does not run → $$m_f = \frac{\langle \overline{T}T\rangle_{ETC}}{\Lambda_{ETC}^2} = \frac{1}{\Lambda_{ETC}^2}\left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma}\langle \overline{T}T\rangle_{TC}$$
- γ~1 → $$m_f \sim \frac{1}{\Lambda_{ETC}\Lambda_{TC}}\langle \overline{T}T\rangle_{TC}$$

Walking Technicolor

- key: t[...] moto]

Is it possible to construct such a theory ?





- renormalized gauge coupling
    - to run very slowly (walking)
    - eventually grows at low energies → to produce techni-pions
- mass anomalous dimension
    - large: $\gamma_m \sim 1$

after July 4, 2012

- Some people think technicolor is dead (how many times it should die ?)
  - m_H=125 GeV is too light for technicolor (typical composite mass ~ TeV)
- Some think walking technicolor is still OK
  - who ?
    - the authors of PRD 82 014510 (2010)
      - and people well aware the results
    - Yamawaki, Bando, Matumoto, PRL 56 1335 (1986)
      - and who believed that

Higgs as a techni dilaton
[Yamawaki, Bando, Matumoto, PRL 1986]

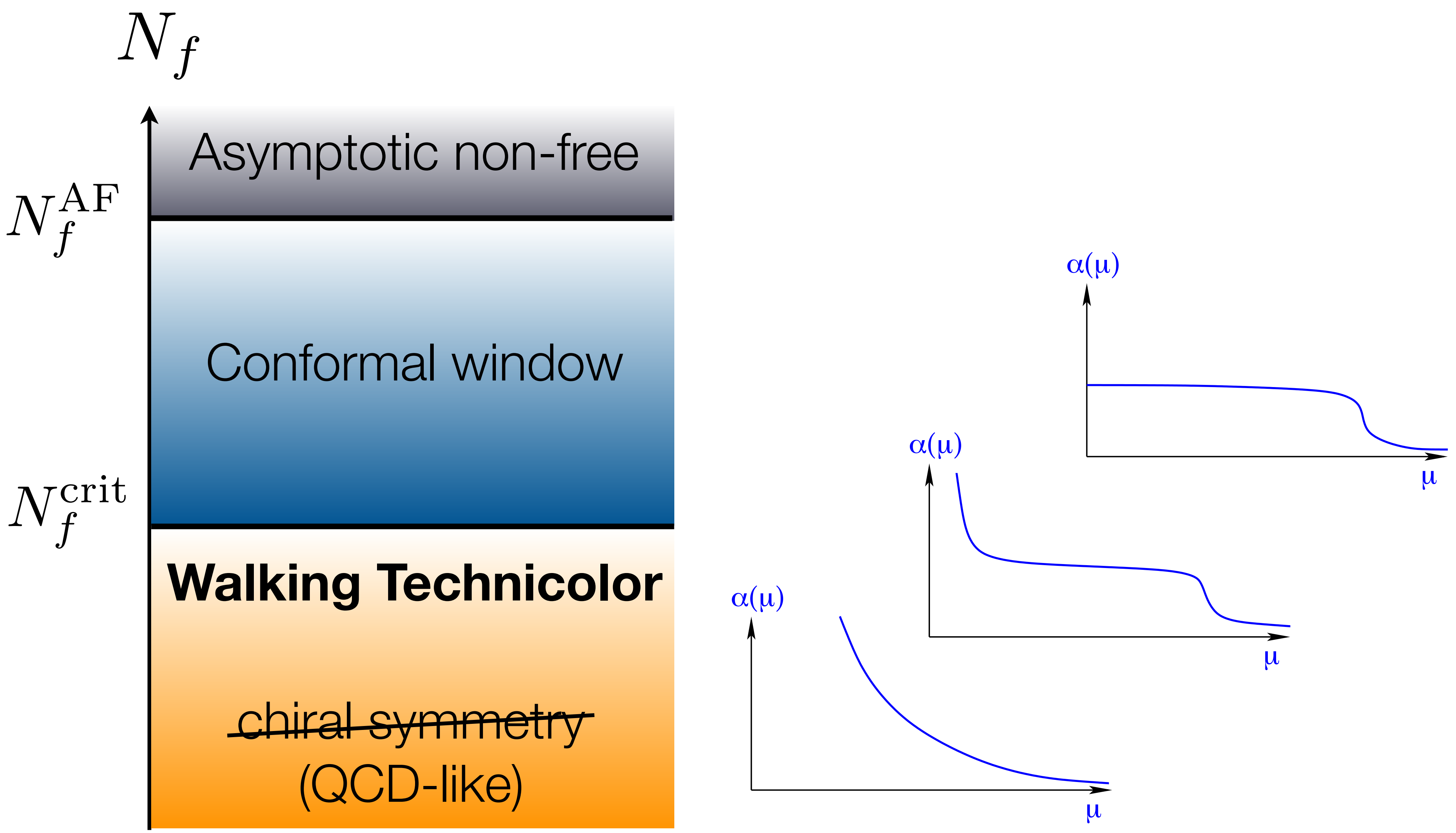
- approximate scale invariance in the walking technicolor theory
- spontaneously broken due to chiral symmetry breaking → dynamical mass
- composite Higgs particle behave like pseudo Nambu-Goldstone boson

  ➡light!

- We can test this using lattice QCD tools !
- I will review the progress in this direction and related works in (near) conformal theories on the lattice

conformal window and walking gauge coupling

- non-Abelian gauge theory with N_f *massless* fermions -

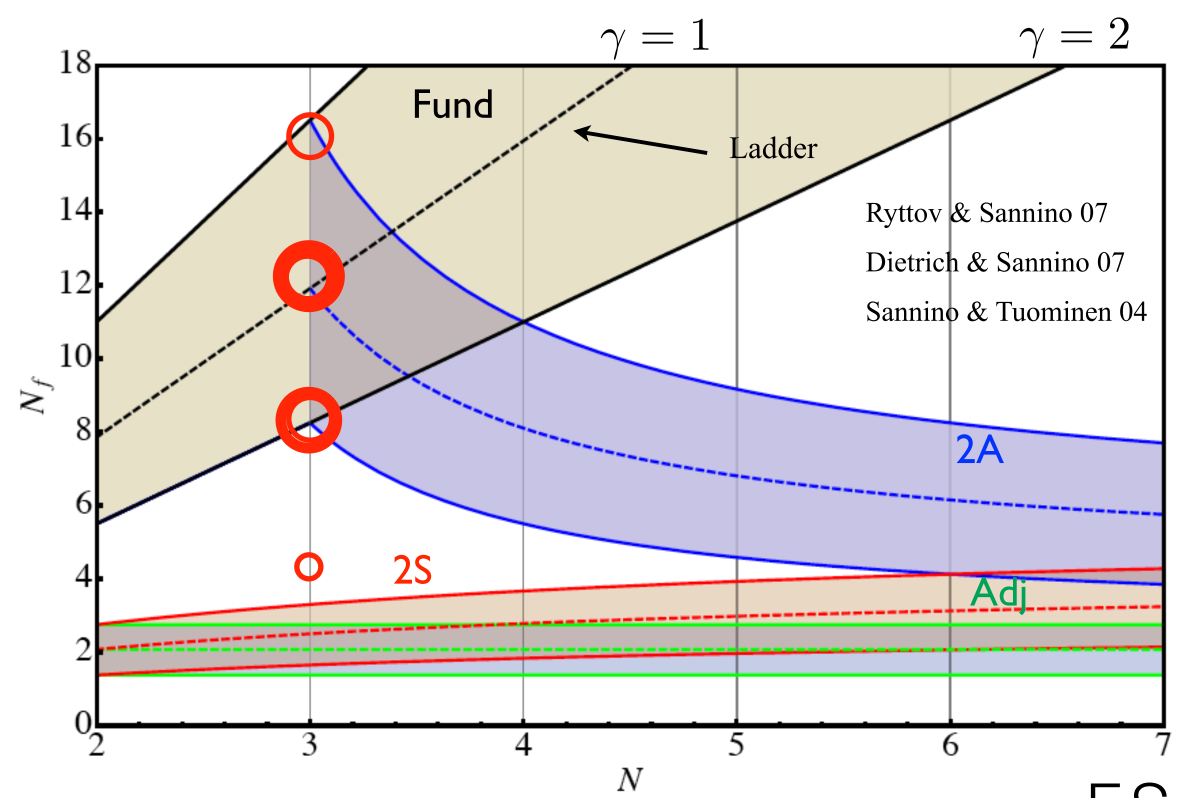


- Walking Techinicolor could be realized just below the conformal window
- crucial information: N_f^{crit} and...
- mass anomalous dimension γ & the composite mass spectrum around N_f^{crit}

models being studied:

- SU(3)
  - fundamental: Nf=6, 8, 10, 12, 16
  - sextet: Nf=2
- SU(2)
  - adjoint: Nf=2
  - fundamental: Nf=8
- SU(4)
  - decuplet: Nf=2

SU(N) Phase Diagram



F.Sannino

LatKMI publications

- 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”
- LatKMI, PRD89 (2014), “Light composite scalar in eight-flavor QCD on the lattice"

Simulation

- Fermion Formulation: HISQ (Highly Improved Staggered Quarks)
  - being used for state-of-the-art QCD calculations / MILC,..
- Gauge Field Formulation:tree level Symanzik gauge
- all of LatKMI simulations are done in this set-up

- using MILC code v7, with modification: HMC and speed up in MD

Parameters: fermion mass m_f and volume $L^3 \times T$ ($L/T=3/4$)

LatKMI, PRD 87 (2013), “Walking signals in Nf=8 QCD…”

✓: stat. ~ 1,000 HMC trajectories

LatKMI, UPDATED

○: increased stat. ≳ 10,000 HMC trajectories (typically)

◎: new points

m	48	42	36	30	24	18
0.009						
0.012						
0.015			✓			
0.020			✓	✓	✓	
0.030			✓	✓	✓	
0.040				✓	✓	✓
0.050				✓	✓	✓
0.060				✓	✓	✓
0.070				✓	✓	✓
0.080					✓	✓
0.100					✓	✓

OLD

m	48	42	36	30	24	18
0.009						
0.012		◎				
0.015		◎	○			
0.020			○	○	✓	
0.030			○	○	○	
0.040				○	○	✓
0.050				✓	✓	✓
0.060				✓	○	✓
0.070				✓	✓	✓
0.080					○	✓
0.100					✓	✓

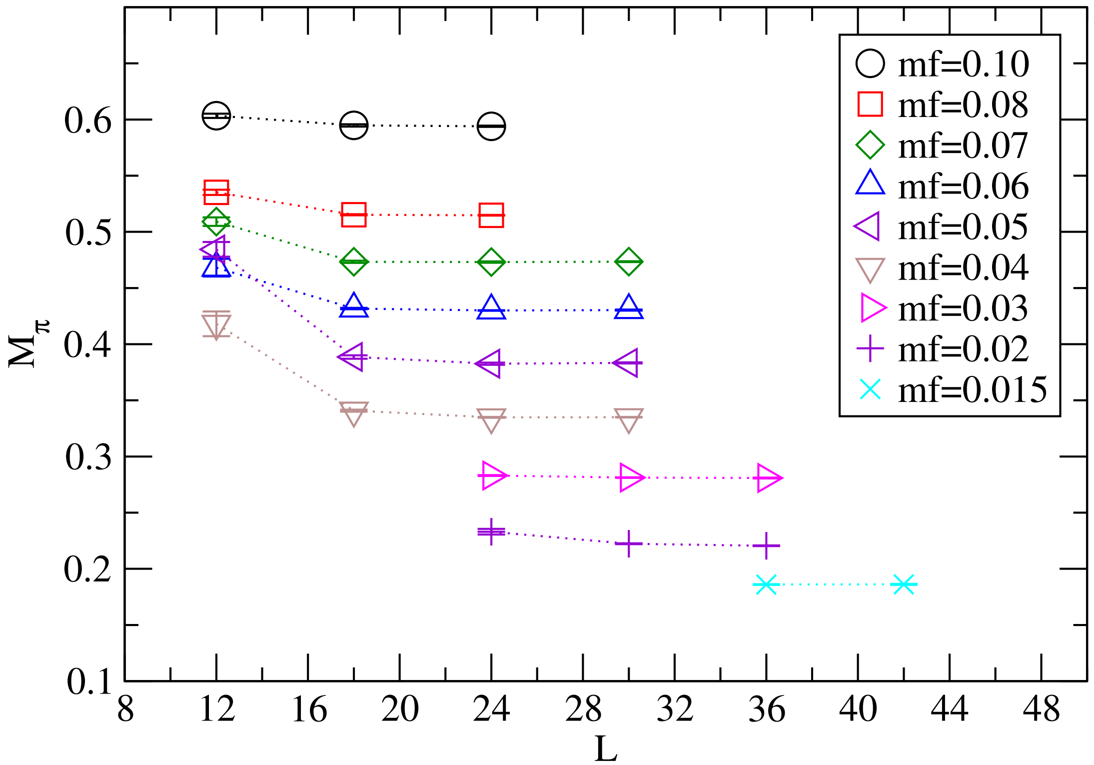
NEW

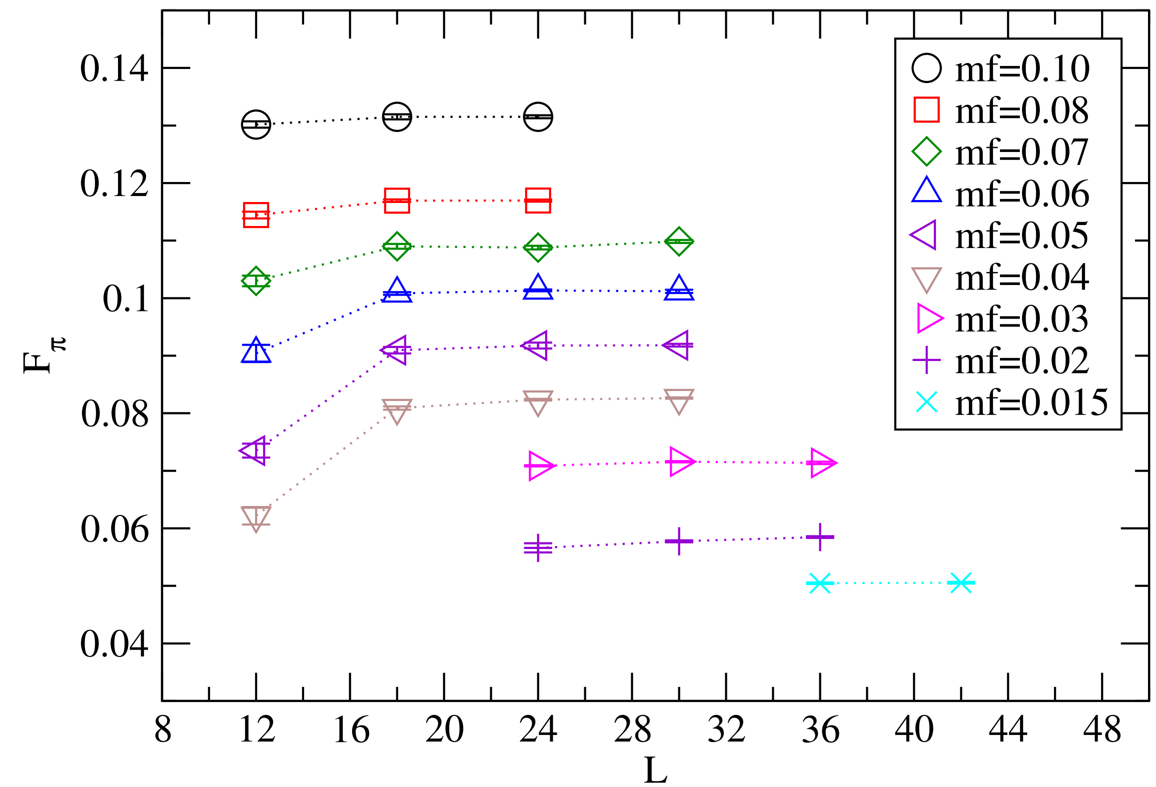
All NEW results are preliminary

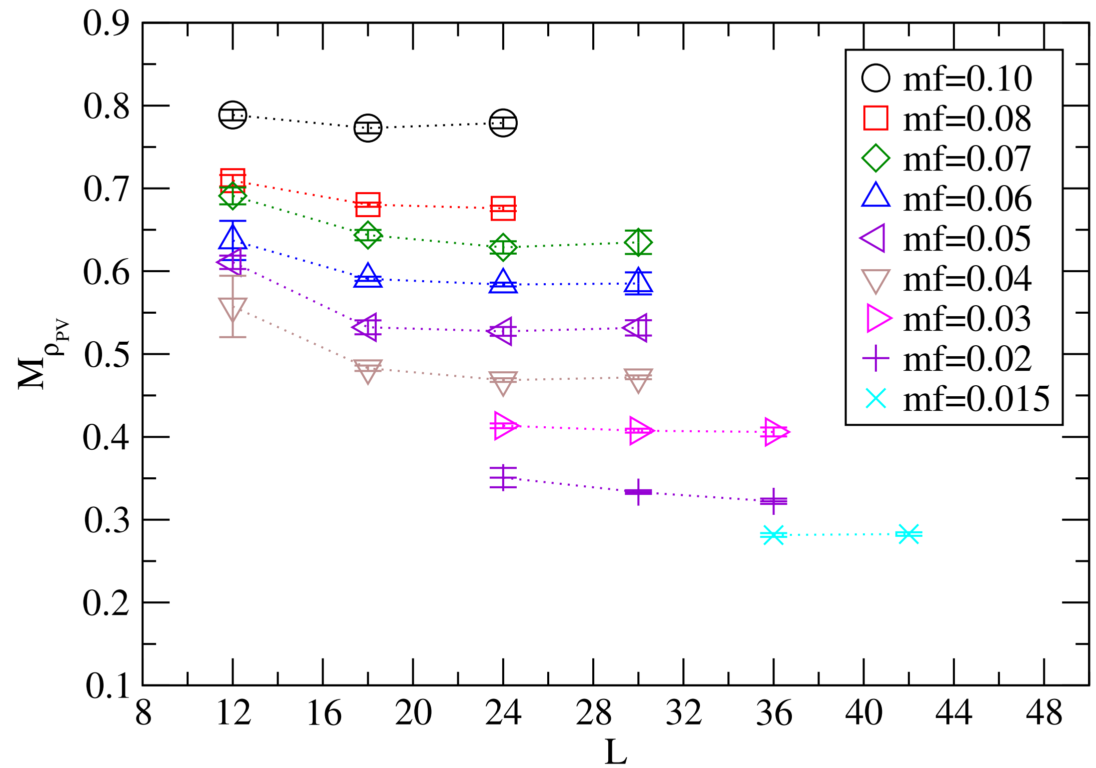
Finite Size Effect

- For analysis assuming infinite volume
  - use data which does not have SIGNIFICANT finite size effect
  - use statistically superior ensemble among them
- For the finite size scaling analysis, use all

Finite Size Data (NEW): M_π, F_π, M_ρ

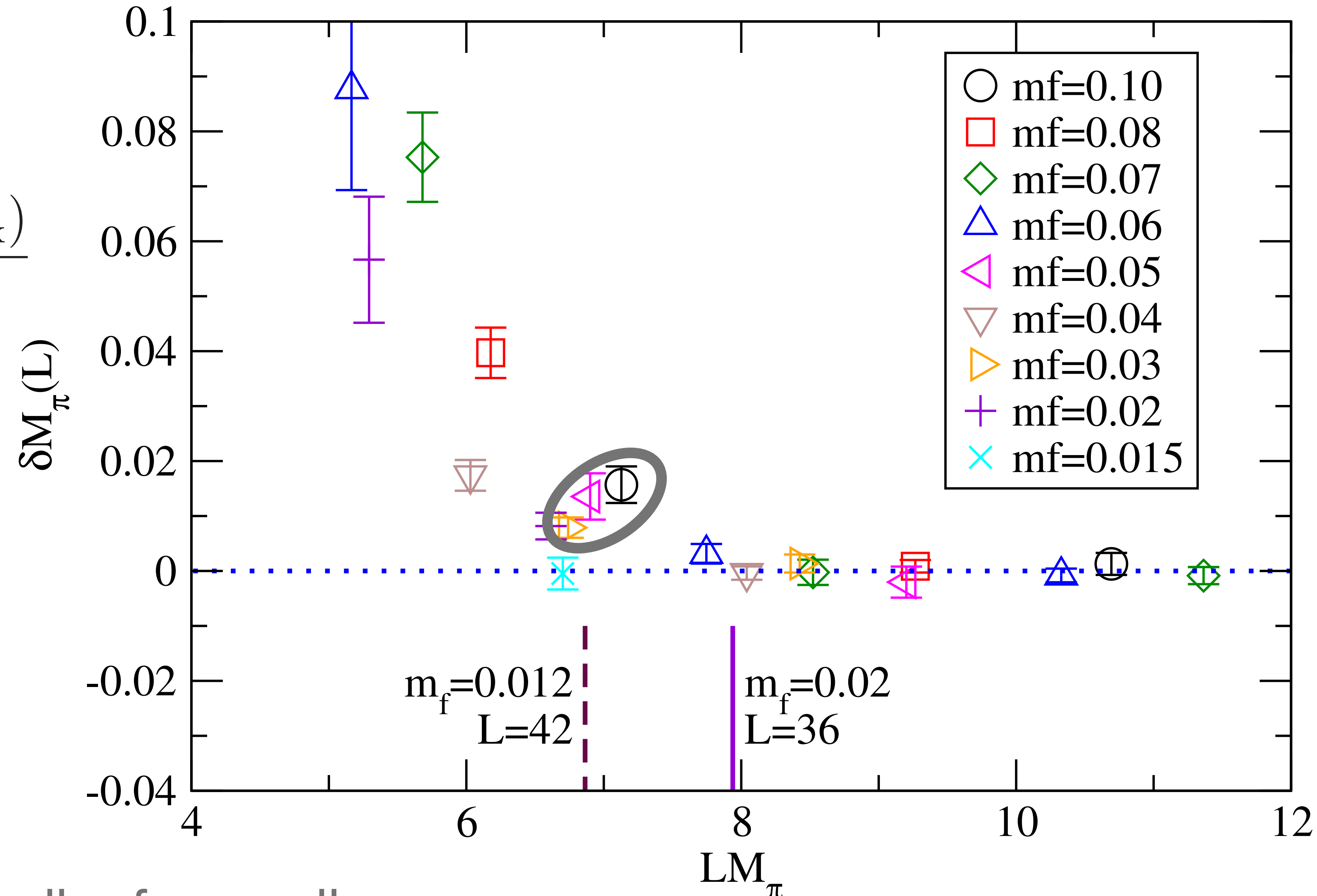






Finite Size Effect: M_π

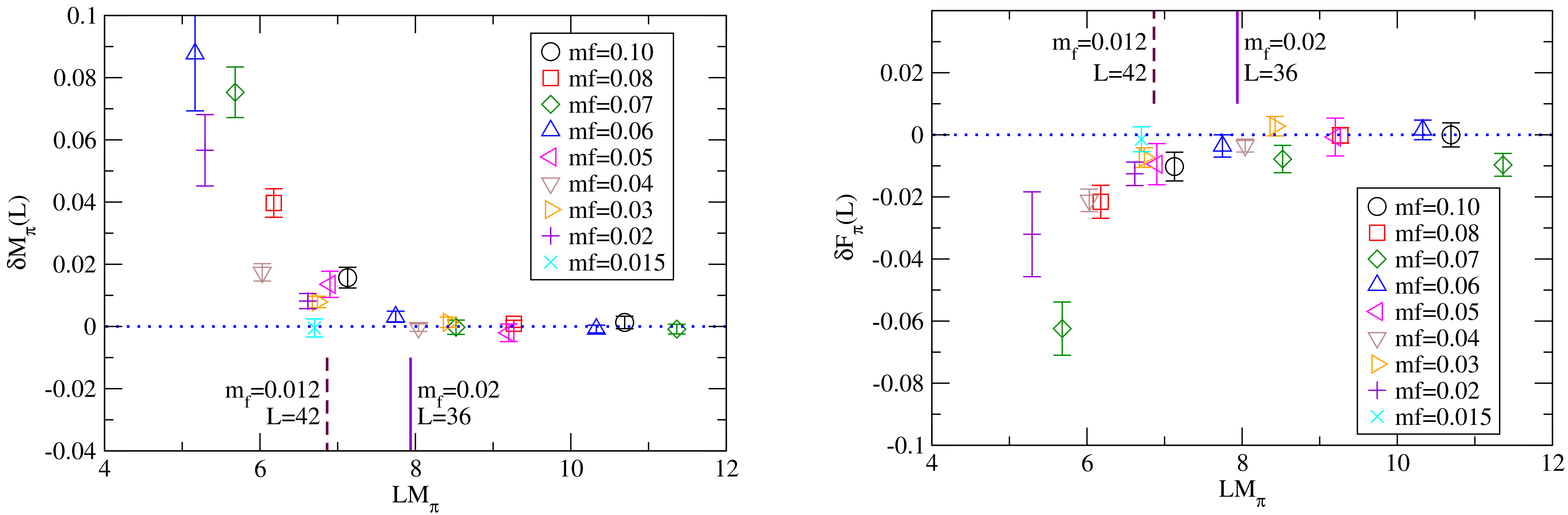
$$\delta M_\pi(L) = \frac{M_\pi(L) - M_\pi(L_{\max})}{M_\pi(L_{\max})}$$



- with same LM_π, FSF is smaller for smaller m_f
- L < L_{max}; second largest seems OK for all $m_f \geq 0.03$ and $m_f=0.015$, otherwise
- $m_f=0.02$: largest L=36 → region of insignificant finite V effect
- $m_f=0.012$: only one L=42 → region of insignificant finite V effect

Finite Size Effect: M_π, F_π

$$\delta M_\pi(L) = \frac{M_\pi(L) - M_\pi(L_{\rm max})}{M_\pi(L_{\rm max})} \quad \text{and} \quad \delta F_\pi(L) = \frac{F_\pi(L) - F_\pi(L_{\rm max})}{F_\pi(L_{\rm max})},$$



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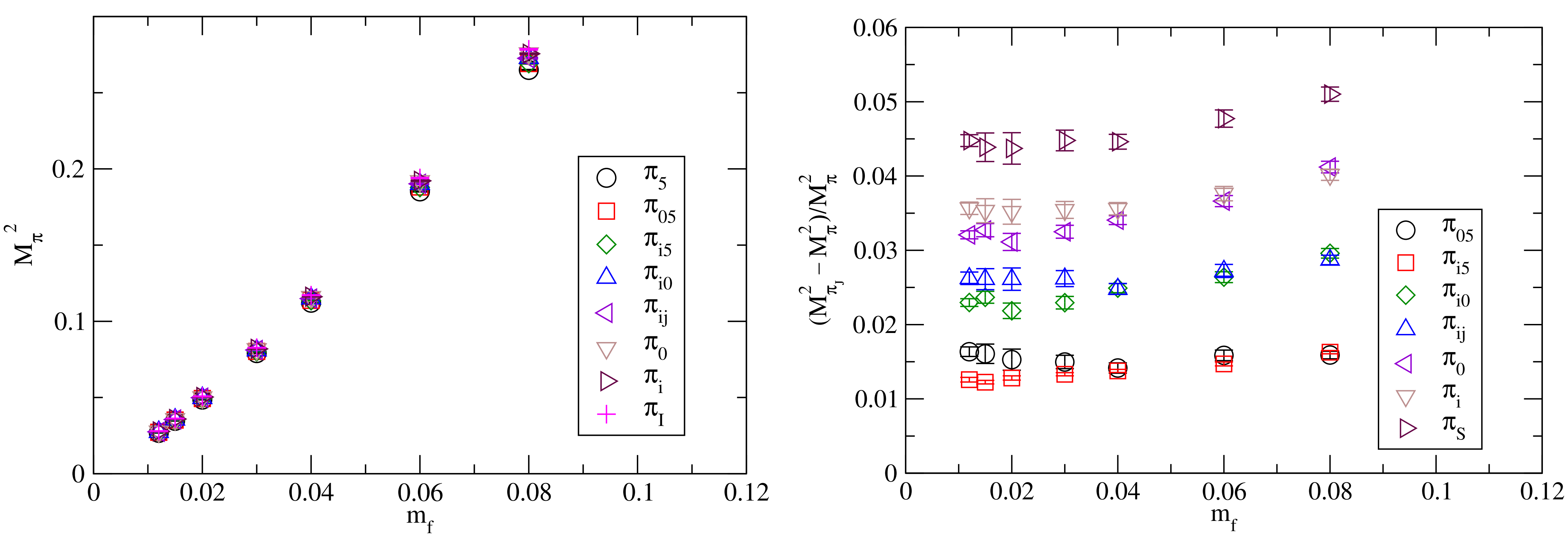
- $m_f = 0.02$: largest L=36 → region of insignificant finite V effect
- $m_f = 0.012$: only one L=42 → region of insignificant finite V effect

staggered flavor (taste) symmetry for N_f=8 HISQ

- comparing masses with different staggered operators for π & ρ for β=3.8



- excellent staggered flavor symmetry, thanks to HISQ

Hadron spectrum: m_f-response in mass deformed theory

- IR conformal phase:
  - coupling runs for $\mu<m_f$: like $n_f=0$ QCD with $\Lambda_{QCD}\sim m_f$
  - multi particle state : $M_H \propto m_f^{1/(1+\gamma_m^*)}$; $F_\pi \propto m_f^{1/(1+\gamma_m^*)}$ (criticality @ IRFP)
- SχSB phase:
  - ChPT
  - at leading: $M_\pi^2 \propto m_f$, ; $F_\pi = F + c\, m_f$

a crude study using ratios

- conformal scenario:
  - $M_H \propto m_f^{1/(1+\gamma_m^*)}$; $F_\pi \propto m_f^{1/(1+\gamma_m^*)}$ for small m_f

★ $F_\pi/M_\pi \to$ const. for small m_f

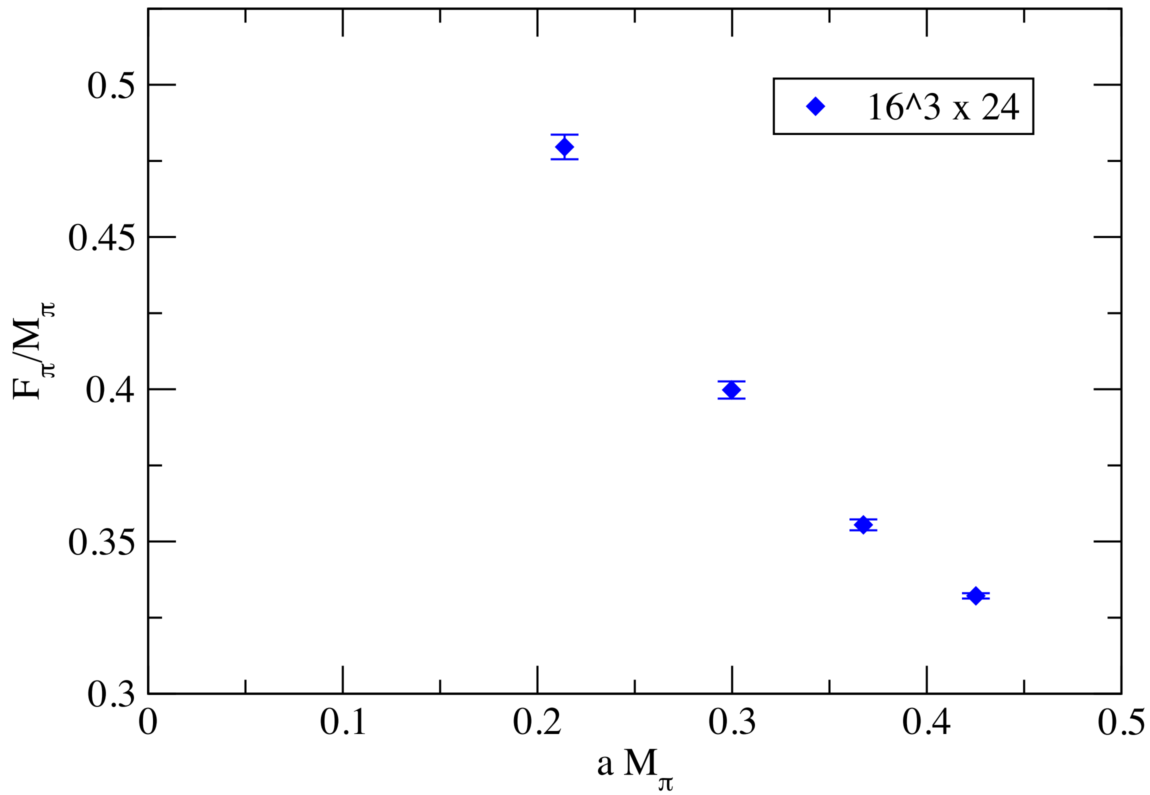
★ $M_\rho/M_\pi \to$ const. for small m_f

- chiral symmetry breaking scenario:
  - $M_\pi^2 \propto m_f$, ; $F_\pi = F + c' M_\pi^2$ for small m_f

★ $F_\pi/M_\pi \to \infty$ for $m_f \to 0$

a crude analysis: F_π/M_π vs M_π

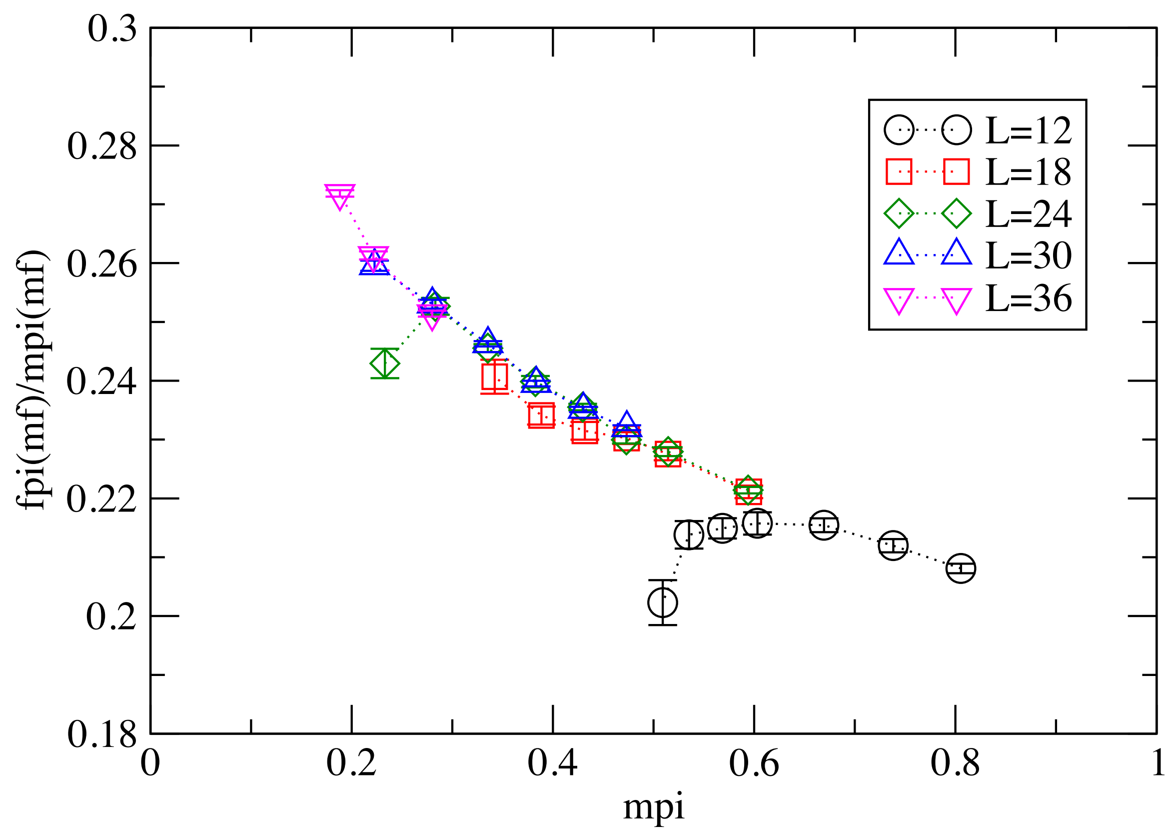
N_f=4



- tends to diverge towards the chiral limit ($M_\pi \to 0$)
- spontaneous chiral symmetry breaking

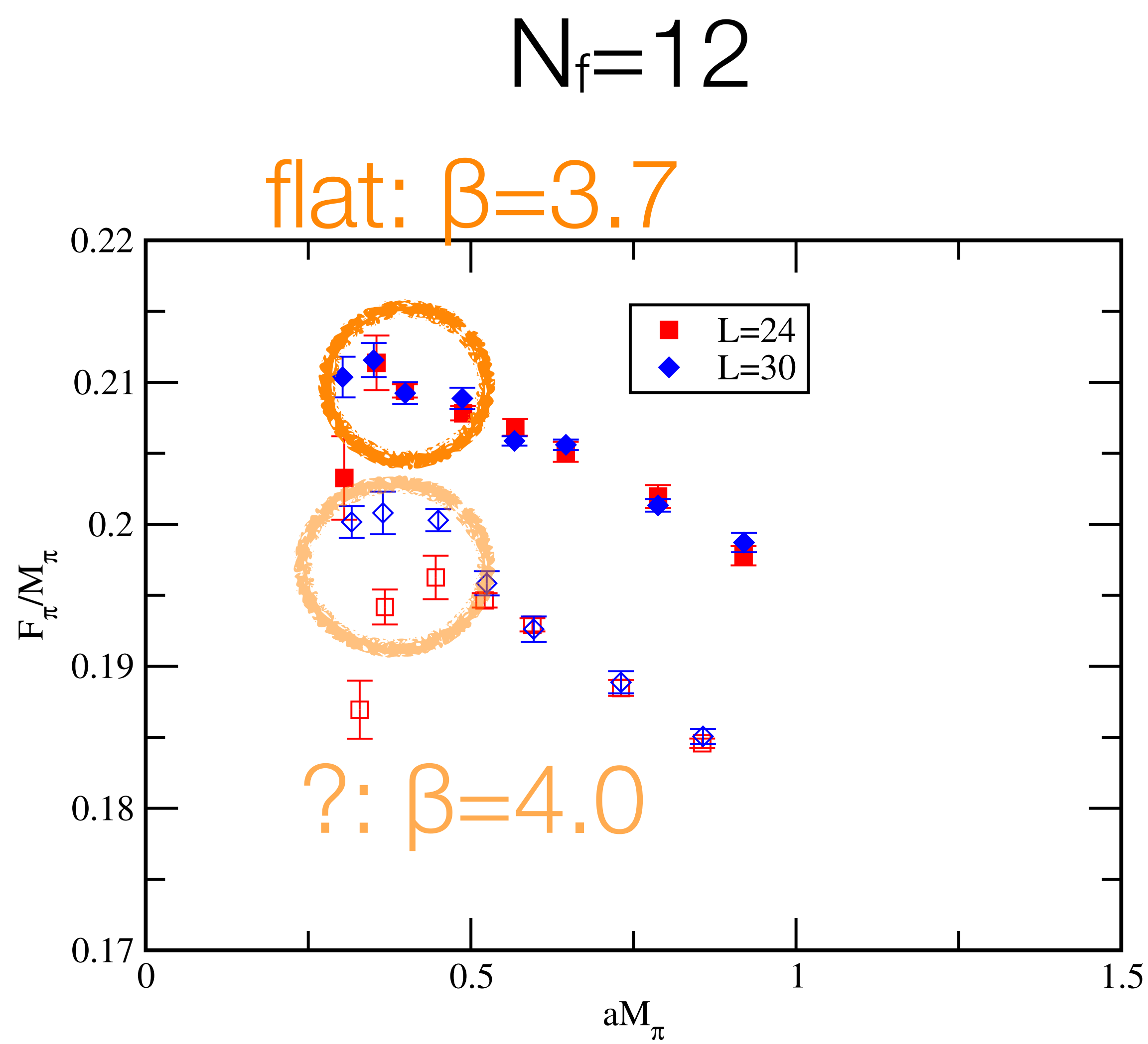
a crude analysis: F_π/M_π vs M_π

N_f=8



- tends to diverge towards the chiral limit ($M_\pi \to 0$)
- spontaneous chiral symmetry breaking, likely

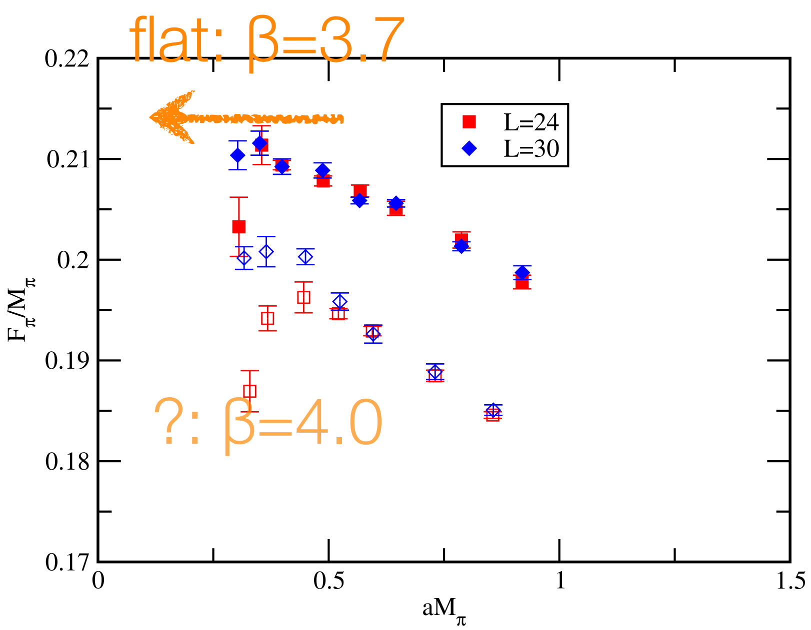
a crude analysis: F_π/M_π vs M_π



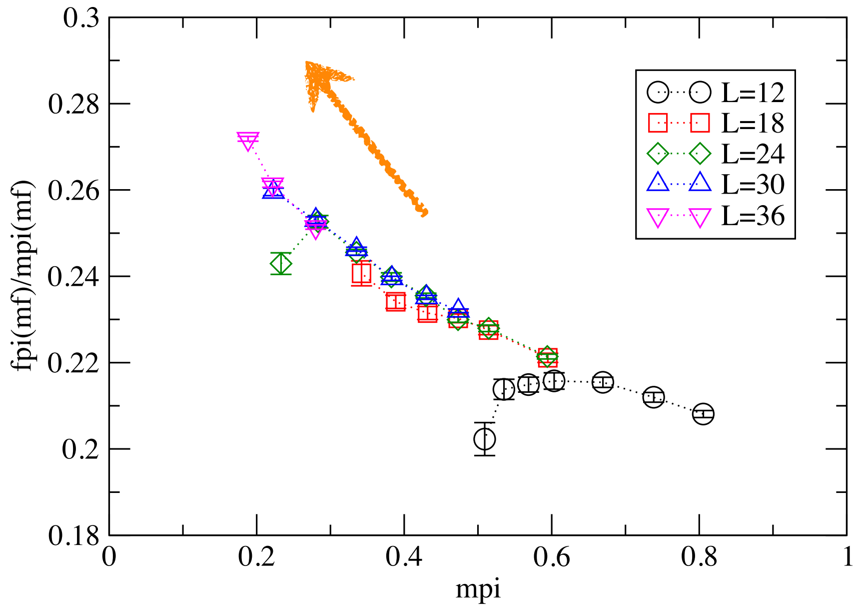
- β=3.7: small mass: consistent with conformal scenario
- β=4.0: volume likely to small to discuss the scaling

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

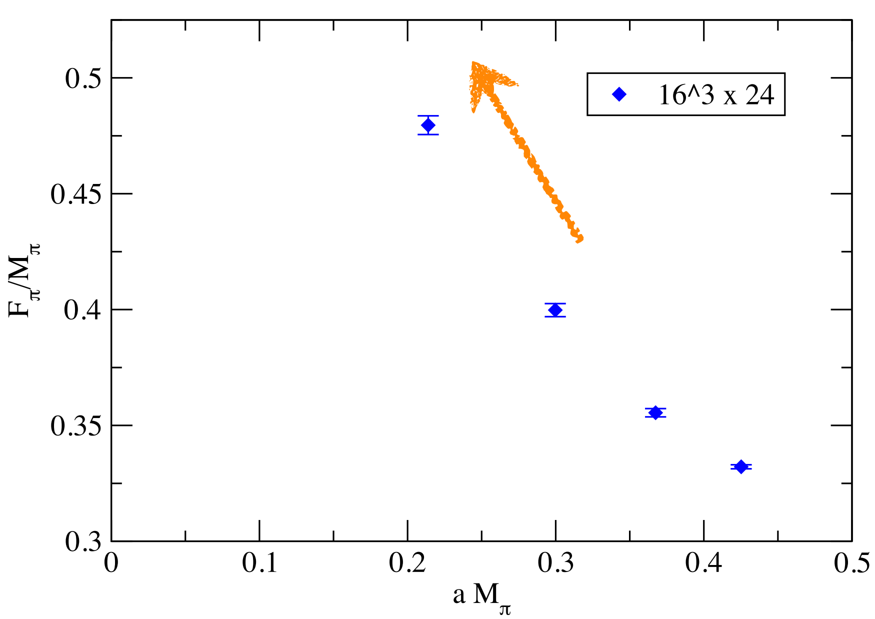
N_f=12



N_f=8



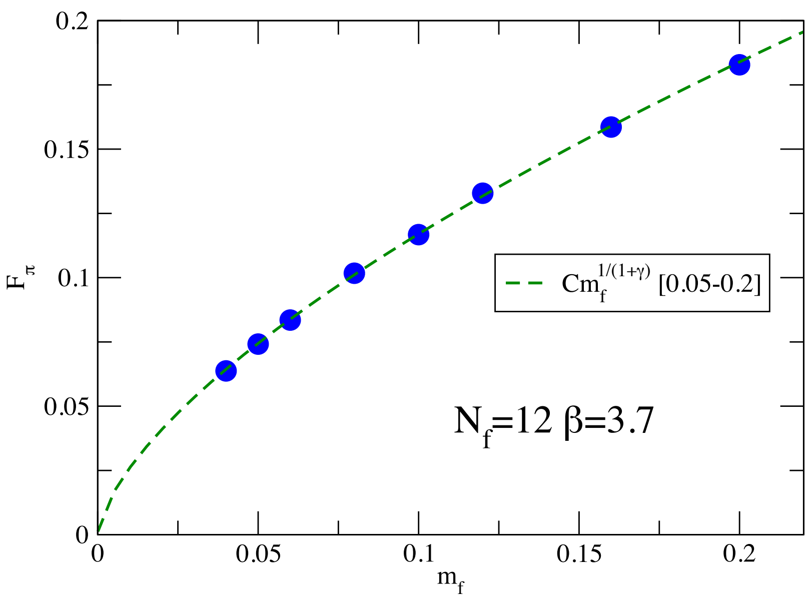
N_f=4



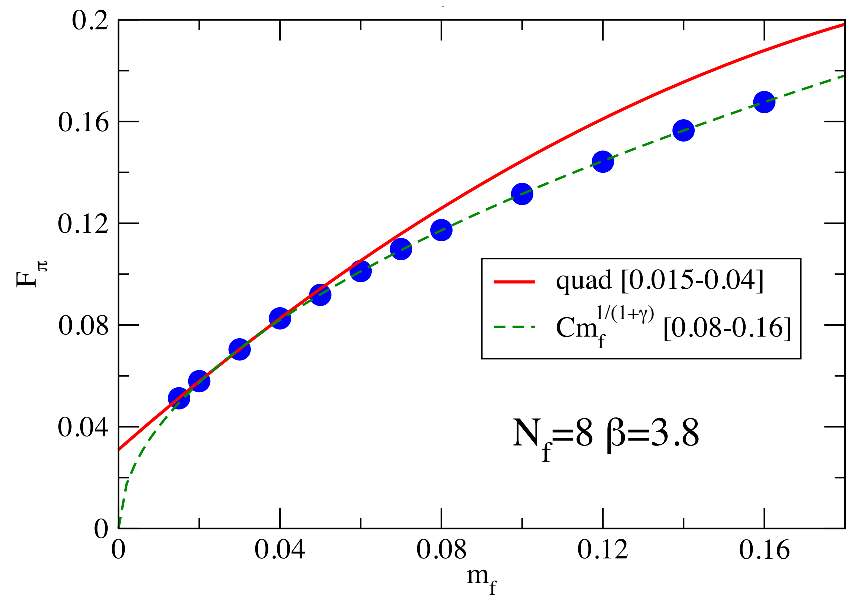
- conformality
- ~~chiral symmetry~~
- ~~chiral symmetry~~

F_π vs m_f

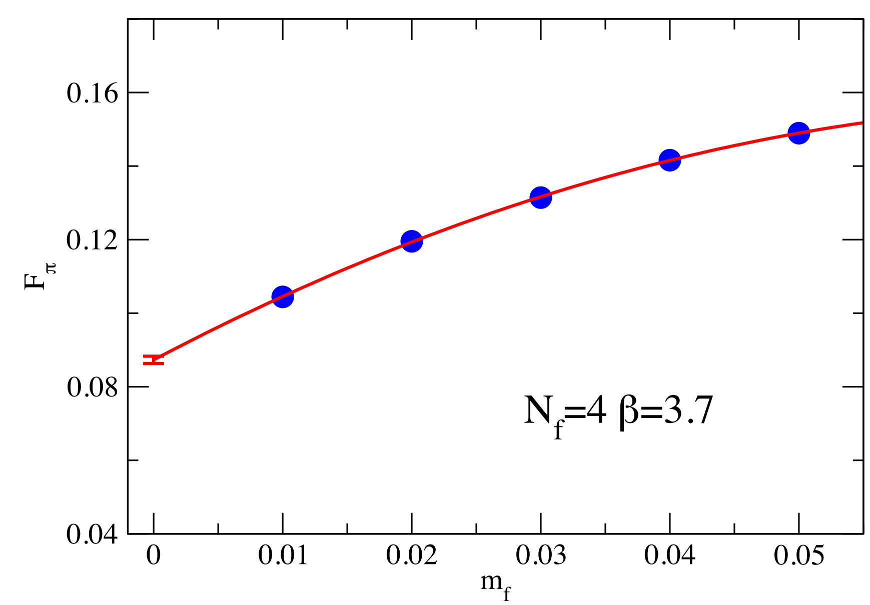
N_f=12



N_f=8



N_f=4

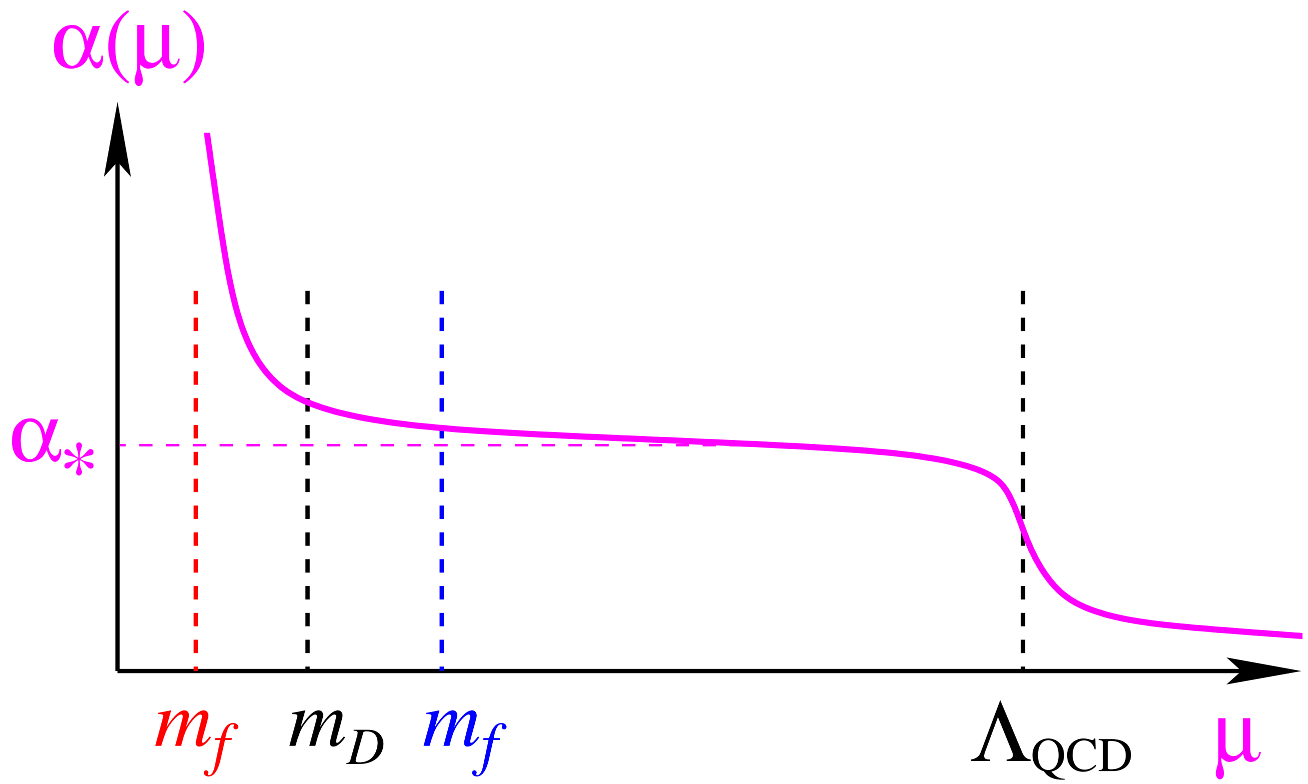


- conformality
- $F_\pi \to C m_f^{1/(1+\gamma)}$
- γ~0.5

- ~~chiral symmetry~~
- $F_\pi \to F \neq 0$ $m_f \to 0$
- $F_\pi \to C m_f^{1/(1+\gamma)}$ intermediate m_f
- γ~0.9

- ~~chiral symmetry~~
- $F_\pi \to F \neq 0$

walking coupling and hyperscaling



- conformal type scaling expected for $m_D < m_f < \Lambda_{QCD}$
- but not for further smaller mass: $m_f < m_D$
- finding such transition would be a smoking gun of the walking dynamics

hyperscaling test with various m_f range (OLD)

- conformal type scaling
  - good for $0.04<m_f$
  - NG for $m_f<0.04$
  - getting worse as $m_f \to 0$
- successful ChPT fit for $m_f<0.04$
- seems like a smoking gun!

TABLE V. Power fit results of F_π for various fit ranges, using $F_\pi = C_1 m_f^{1/(1+\gamma)}$. The top part of the table shows the results for the ranges with minimum mass set to the lightest, $m_f = 0.015$, while the bottom does those with maximum mass being the heaviest $m_f = 0.16$.

Fit range (m_f)	C_1	γ	χ^2/dof
0.015–0.04	0.415(7)	0.988(19)	14.8
0.015–0.05	0.414(5)	0.991(15)	9.84
0.015–0.06	0.418(4)	0.979(12)	7.88
0.015–0.07	0.424(3)	0.963(9)	7.35
0.015–0.08	0.425(3)	0.961(8)	6.15
0.015–0.10	0.426(2)	0.958(7)	5.31
0.015–0.16	0.428(1)	0.952(4)	3.98
0.02–0.16	0.429(1)	0.947(4)	2.22
0.03–0.16	0.431(1)	0.942(5)	1.94
0.04–0.16	0.429(2)	0.950(10)	1.23
0.05–0.16	0.431(2)	0.941(7)	0.66
0.06–0.16	0.429(2)	0.948(9)	0.44
0.07–0.16	0.429(3)	0.950(10)	0.52
0.08–0.16	0.431(3)	0.939(14)	0.20
0.10–0.16	0.432(4)	0.934(19)	0.23

summary for N_f=8 (OLD), 12 spectrum study

- careful finite size analysis for various observables:
  - test with finite size hyper scaling (conformal scenario)
  - test with ChPT
- Nf=12:
  - likely conformal [γ~0.4-0.5]
- Nf=8
  - consistent with Ch symm. br. @ $m_f \to 0$
  - as well as conformal property [γ~0.6-1] @ intermediate m_f (not so small)
  - candidate of walking technicolor theory

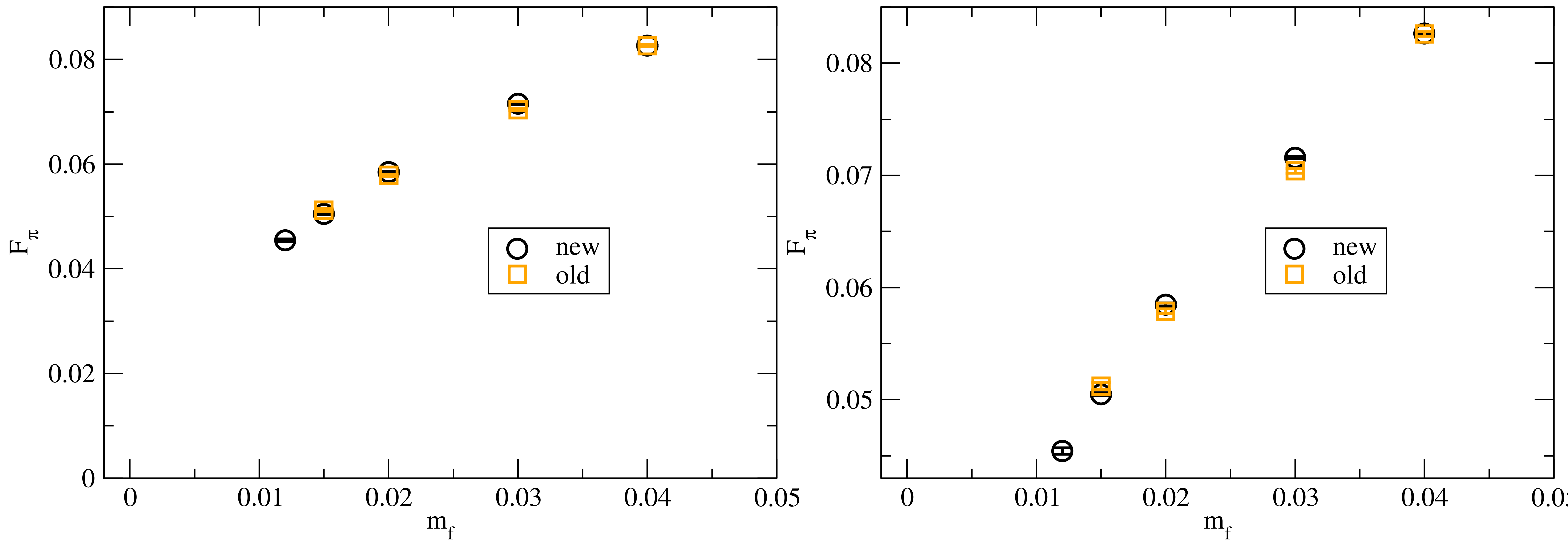
[LatKMI, PRD 86 (2012) for 12 flavor, PRD 87 (2013) for 8 flavor]

summary for N_f=8 (**NEW**), 12 spectrum study

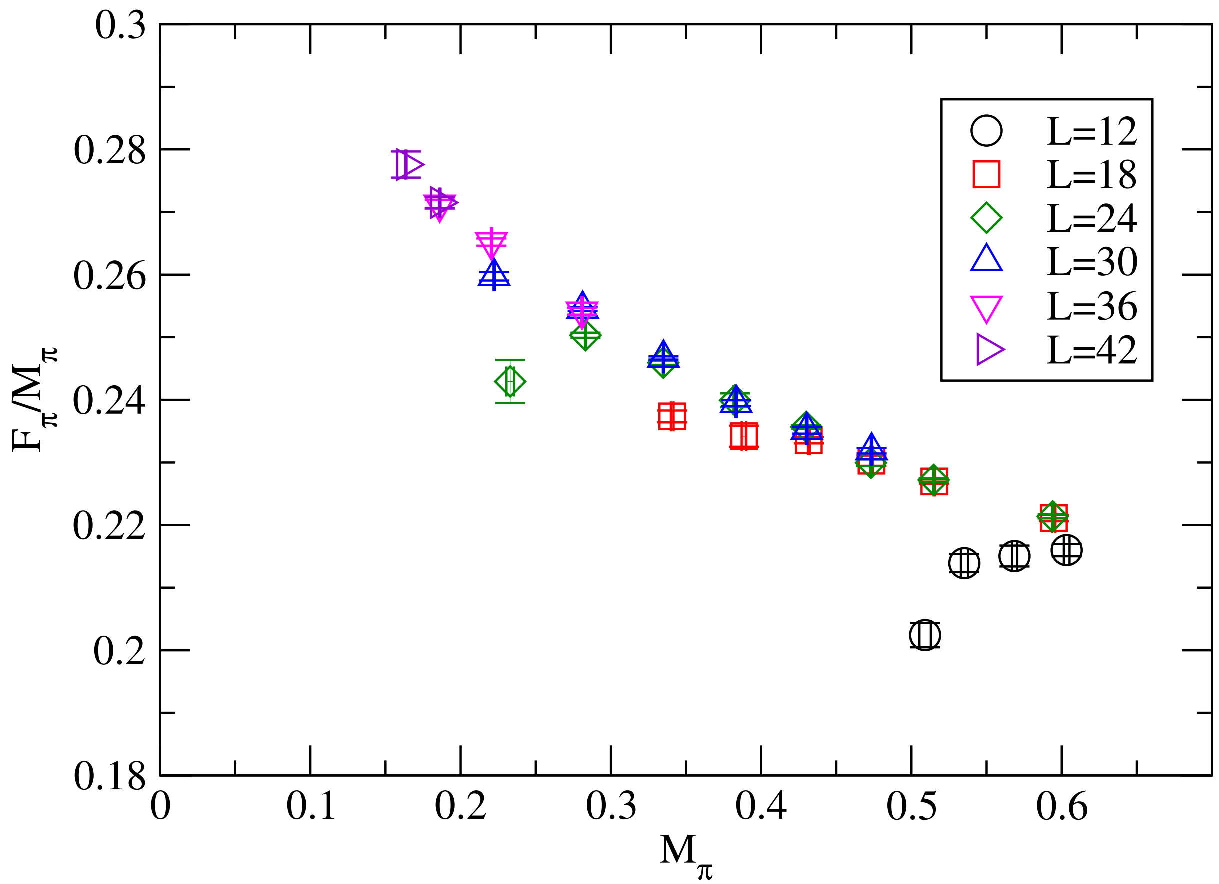
- careful finite size analysis
  - finite size hyper scaling (conformal scenario)
  - ChPT
- Nf=12:
  - likely conformal [γ~0.4-0.5]
- Nf=8
  - consistent with Ch symm. br. @ $m_f \to 0$
  - as well as conformal property [γ~**0.7**-1] @ intermediate **to small** m_f
  - candidate of walking technicolor theory

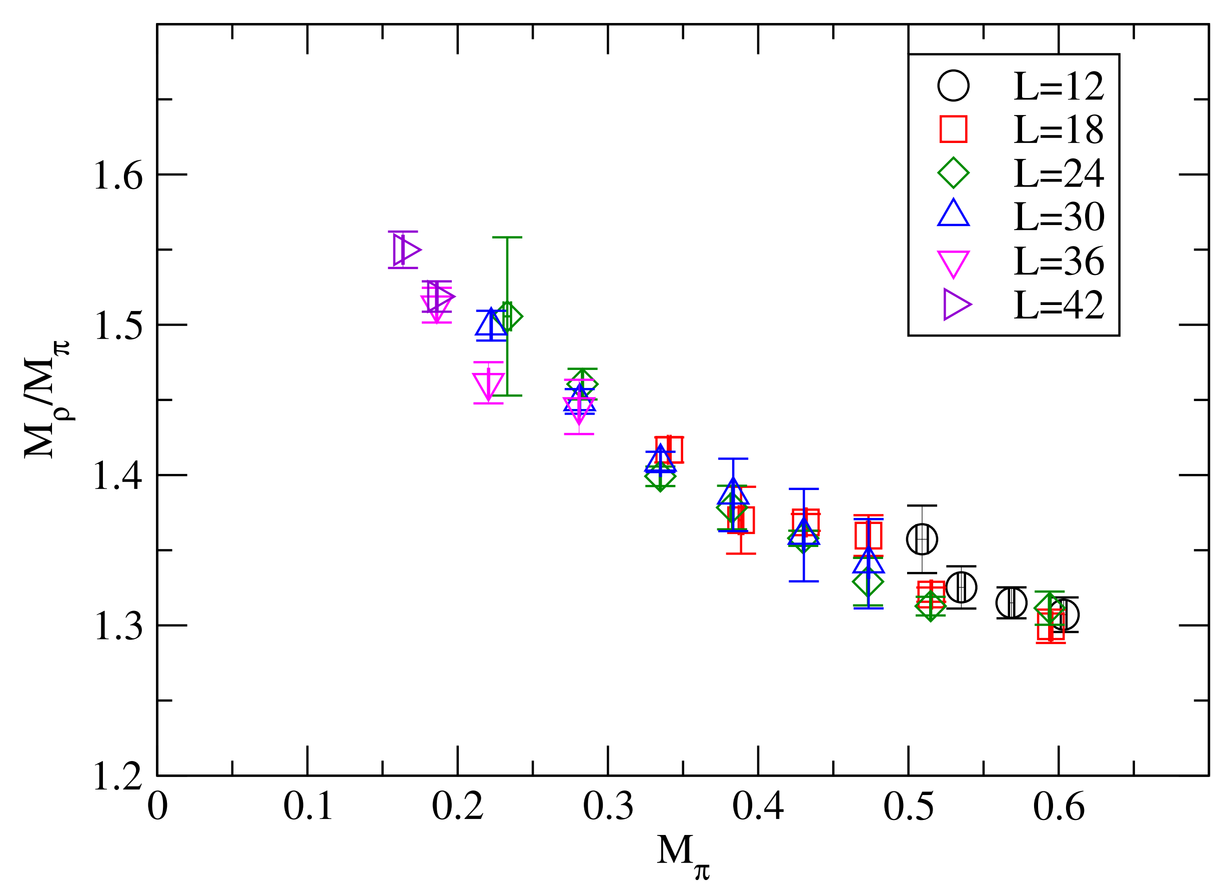
[LatKMI, PRD 86 (2012) for 12 flavor, PRD 87 (2013) for 8 flavor, **& update**]

New data compared against old: F_π



ratio towards the chiral limit (NEW)





- tends to diverge in the chiral limit → indicating Ch symm. br.
- NEW results unchanged from OLD

Hyperscaling (infinite volume) (NEW)

- no transition point observed, hyperscaling fit is good for whole range
- but difference of γ with different observables
- different kinds of fits with different types of corrections

Hyperscaling: finite size

- $O^*L = c_0 + c_1 L m_f^{1/(1+\gamma_m^*)} + c_2 L m_f^{\alpha}$
  - $c_2 = 0$
  - $\alpha = 1$
  - $\alpha = 2$
  - $\alpha = (3-2\gamma)/(1+\gamma)$ Schwinger-Dyson
- $\alpha = 1$ & 2 works equally well
- γ~**0.7**-1
- $O^*L = (1 + c_3 m_f^{\omega}) (c_0 + c_1 L m_f^{1/(1+\gamma_m^*)})$ → end up almost same as $\alpha=1$

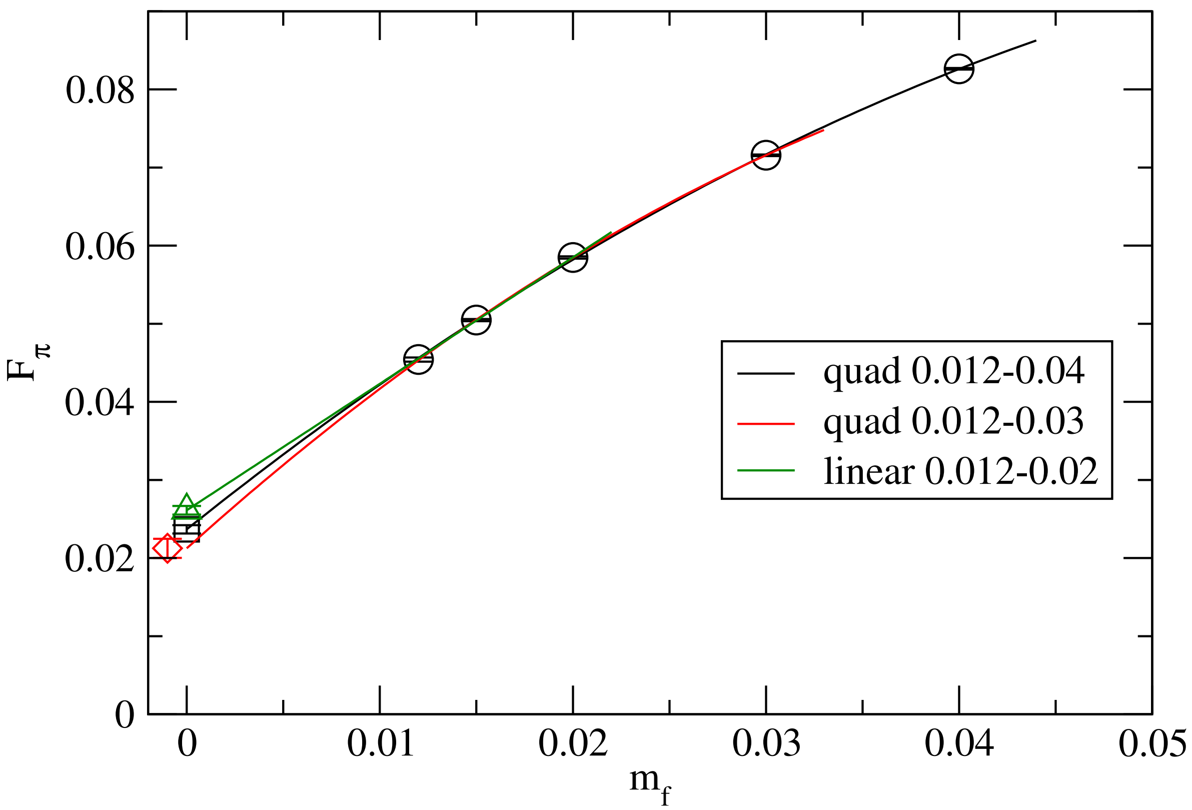
L*Mh=C0+C1*L*mf^{1/(1+γ)}+C2*L*mf^α, where naive and α=1, 2, (3-2γ)/(1+γ)

Obs.	correction type	γ	χ2/dof	1/(1+γ) {no error}
Fπ	0	1.000(4)	2.66	0.500
	1	1.078(26)	2.31	0.481
	2	1.028(10)	2.29	0.493
	SD	1.000(30)	2.79	0.500
Mπ	0	0.622(2)	15.97	0.617
	1	0.843(15)	3.21	0.543
	2	0.685(4)	3.24	0.593
	SD	0.755(13)	8.29	0.570
Mρ	0	0.890(10)	1.47	0.529
	1	1.002(73)	1.40	0.500
	2	0.930(24)	1.36	0.518
	SD	0.932(62)	1.53	0.518
N	0	0.810(11)	2.58	0.552
	1	0.917(81)	2.64	0.522
	2	0.845(28)	2.64	0.542
	SD	0.882(80)	2.76	0.531
N*	0	0.945(50)	1.49	0.514
	1	0.794(383)	1.60	0.557
	2	0.897(124)	1.61	0.527
	SD	0.743(186)	1.60	0.574

Hyperscaling: finite size and global

- with common γ
- on-going project…

ChPT: F_π

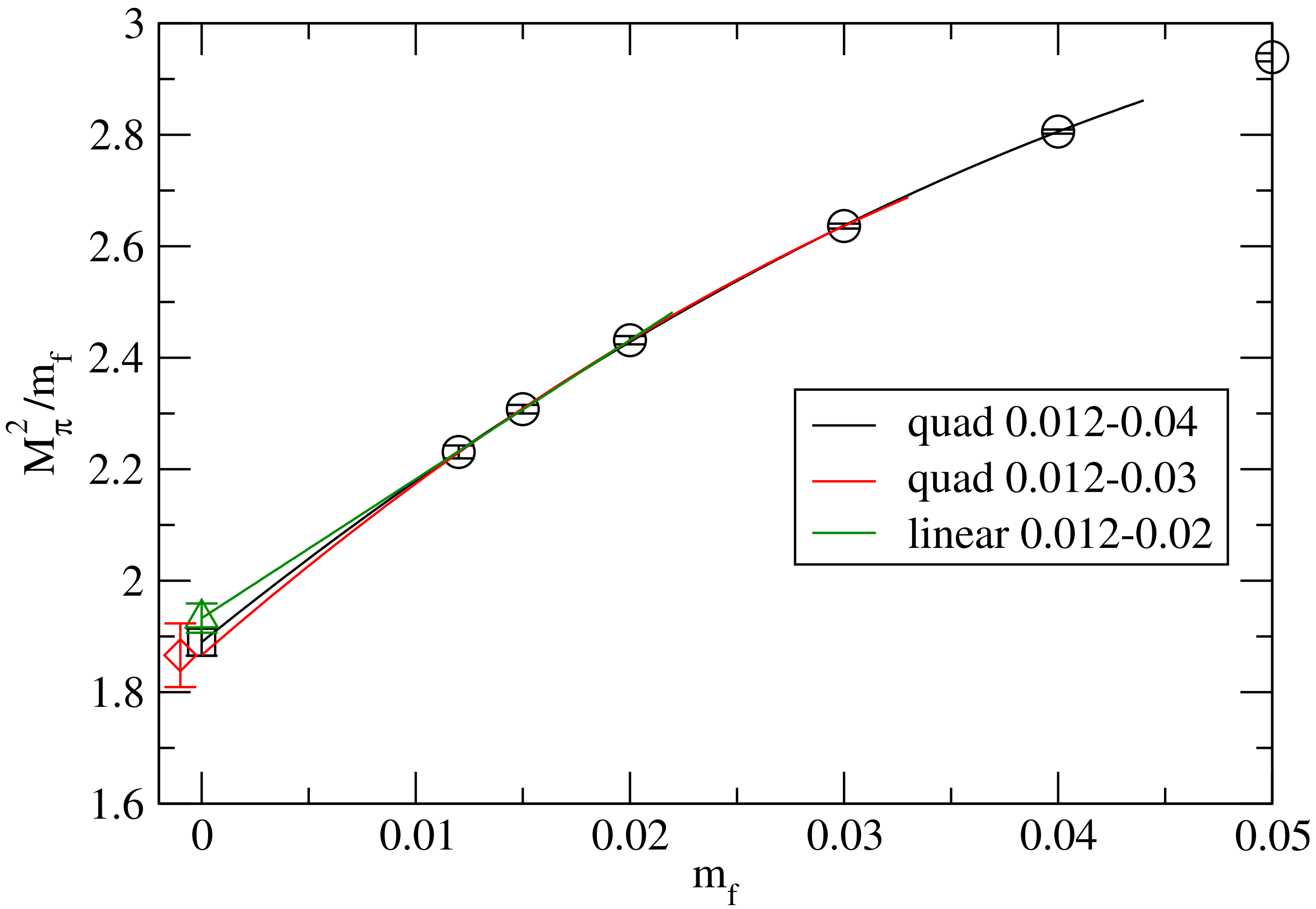


fit range (m_f)	F	$\mathcal{X}(m_f^{\min} = 0.012)$	$\mathcal{X}(m_f = m_{\max})$	χ^2/dof	dof
0.012-0.02*	0.02612(55)	3.978(17)	7.22(31)	0.43	1
0.012-0.03*	0.02953(24)	3.111(53)	9.19(15)	23.8	2
0.012-0.03	0.0212(12)	6.01(70)	17.8(2.1)	0.31	1
0.012-0.04	0.02368(54)	4.84(22)	20.29(92)	2.58	2
0.012-0.05	0.02435(41)	4.57(16)	25.10(85)	3.00	3
0.012-0.06	0.02633(30)	3.911(90)	27.02(61)	14.4	4

TABLE III. Results of chial fit of F_π with $F_\pi = F + C_1 m_f + C_2 m_f^2$ for various fit ranges. Asterisk (*) denotes linear fit.

- consistent with Ch symm. br.

ChPT: M_π^2/m_f → Low Energy Constant: 2B

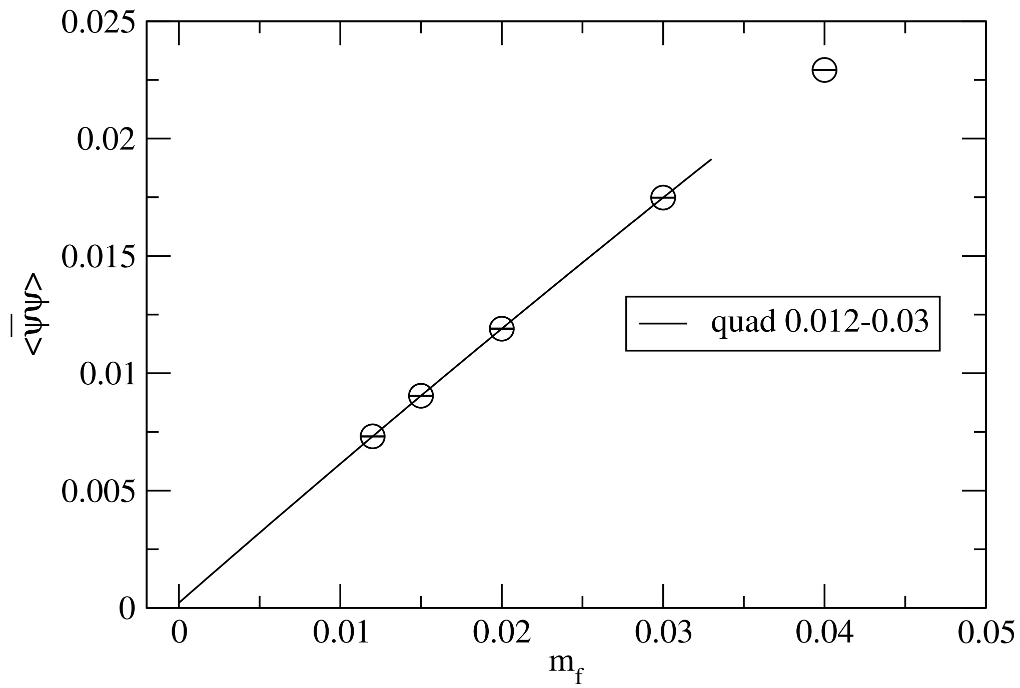


fit range (m_f)	C_0	χ^2/dof	dof
0.012-0.02*	1.933(26)	0.23	1
0.012-0.03*	1.981(12)	2.13	2
0.012-0.04*	2.0282(83)	12.2	3
0.012-0.03	1.866(57)	0.04	1
0.012-0.04	1.890(24)	0.12	2
0.012-0.05	1.896(18)	0.12	3
0.012-0.06	1.934(13)	2.57	4

- consistent with Ch symm. br.
- $B=C_0/2$

TABLE IV. Results of chial fit of M_π^2/m_f with $M_\pi^2/m_f = C_0 + C_1 m_f + C_2 m_f^2$ for various fit ranges. Asterisk (*) denotes linear fit.

ChPT: chiral condensate



fit range (m_f)	C_0	χ^2/dof	dof	$BF^2/2$
0.012-0.02*	0.000436(19)	0.92	1	0.000330(15)
0.012-0.03*	0.0005867(84)	37.4	2	0.0004319(74)
0.012-0.03	0.000221(43)	0.54	1	0.000211(25)
0.012-0.04	0.000255(18)	0.65	2	0.000265(12)
0.012-0.05	0.000263(15)	0.63	3	0.000281(10)
0.012-0.06	0.000313(10)	5.97	4	0.0003352(79)

TABLE V. Chiral fit result of $\langle\bar\psi\psi\rangle$ with $\langle\bar\psi\psi\rangle = C_0 + C_1 m_f + C_2 m_f^2$ in various fit ranges. $BF^2/2$ is evaluated using the results in Tables VIII and III. Asterisk (*) denotes linear fit.

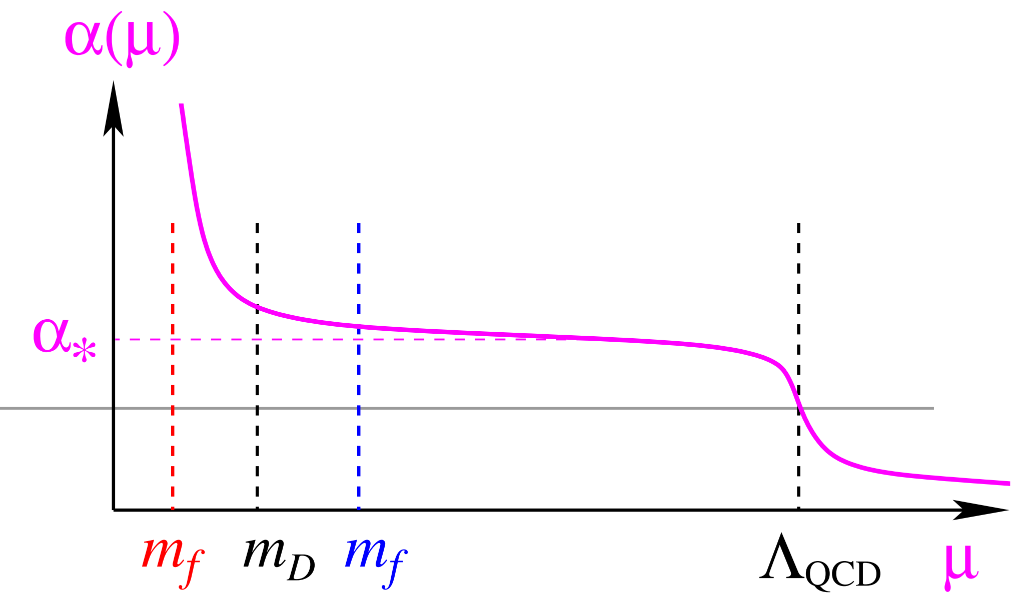
- direct measurement & GMOR @ chiral limit give consistent results

summary for N_f=8 (**NEW**), 12 spectrum study

- careful finite size analysis
  - finite size hyper scaling (conformal scenario)
  - ChPT
- Nf=12:
  - likely conformal [$\gamma \sim 0.4$-0.5]
- Nf=8
  - consistent with Ch symm. br. @ $m_f \to 0$
  - as well as conformal property [$\gamma \sim$ **0.7**-1] @ intermediate **to small** m_f
  - candidate of walking technicolor theory

  [LatKMI, PRD 86 (2012) for 12 flavor, PRD 87 (2013) for 8 flavor, **& update**]

N_f=8 (**NEW**) discussion



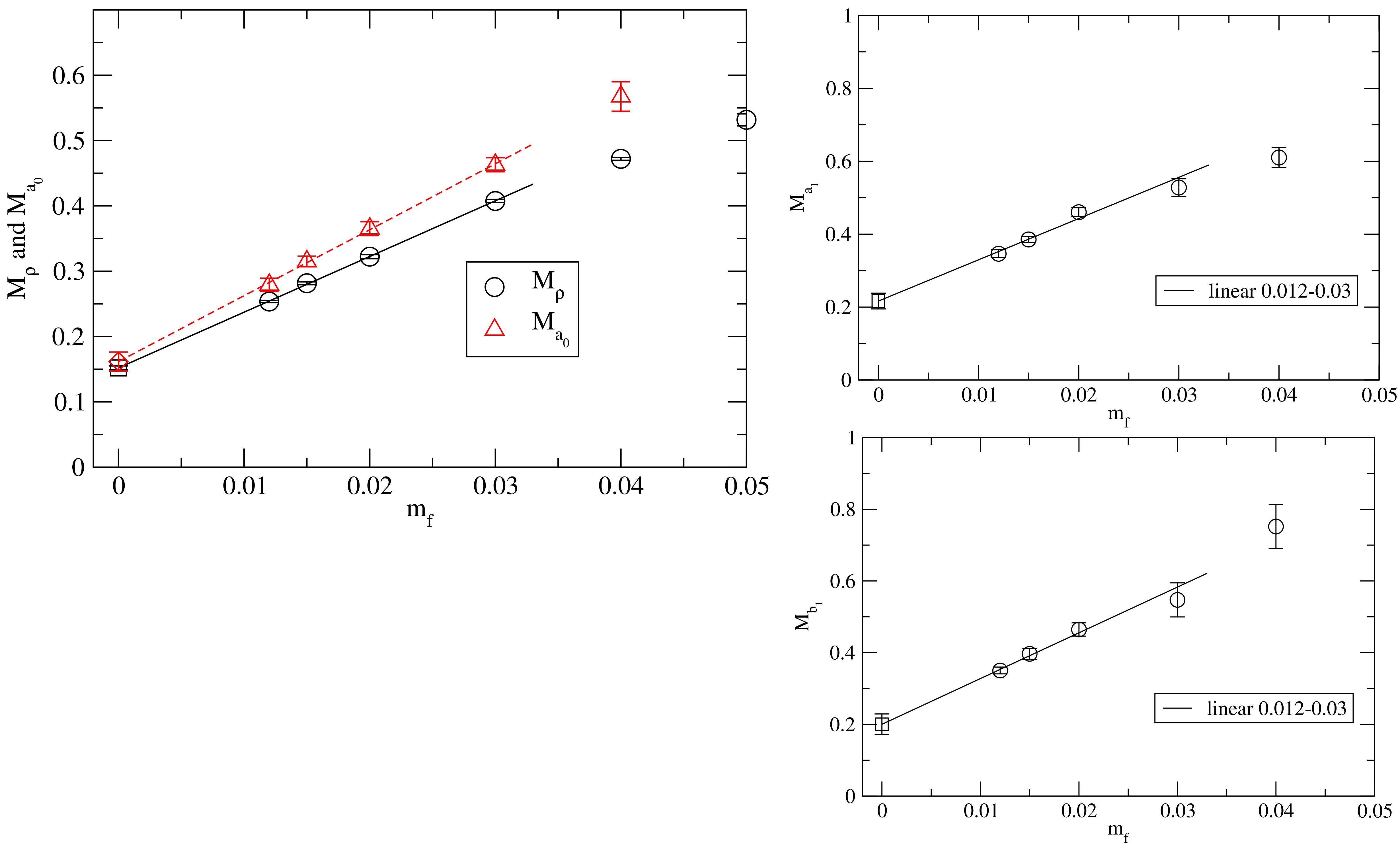
- Nf=8
  - consistent with Ch symm. br. @ $m_f \to 0$
  - as well as conformal property [γ~**0.7**-1] @ intermediate **to small** m_f
  - candidate of walking technicolor theory

    [LatKMI, PRD 86 (2012) for 12 flavor, PRD 87 (2013) for 8 flavor, **& update**]
- no clear-cut evidence of conformal fit fails @ $m_f \to 0$

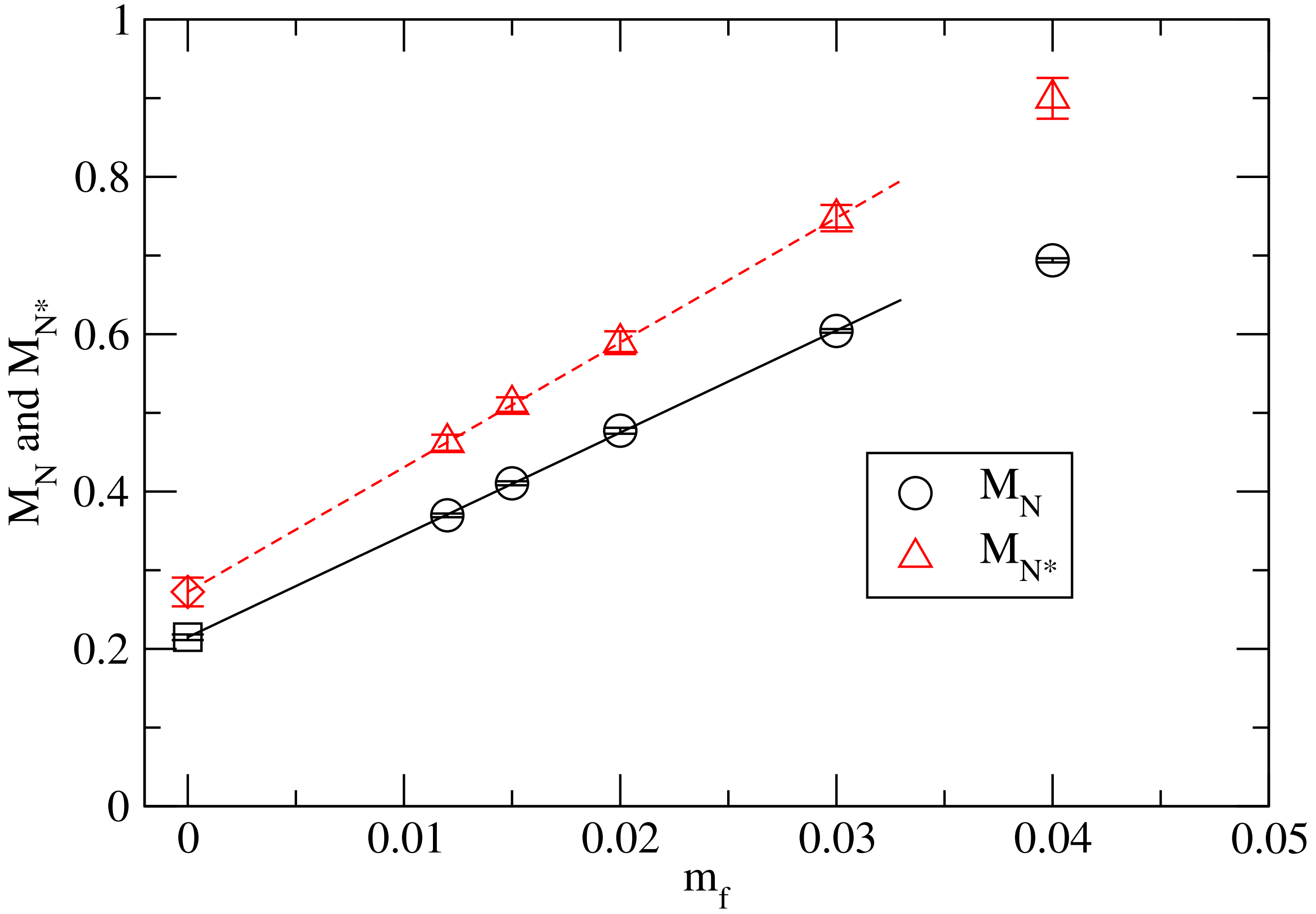
  ➡no clear-cut evidence of chiral symm. br. (bad news for hunting WTC ?)
- needs more in depth study towards chiral, as well as with other approaches
  - happy to hear what other groups do: today and in next few days….
- Nf=8 might be a very good WTC with a wide walking range (good news !)

nice to look at spectrum at chiral limit $\leftrightarrow$ experiment

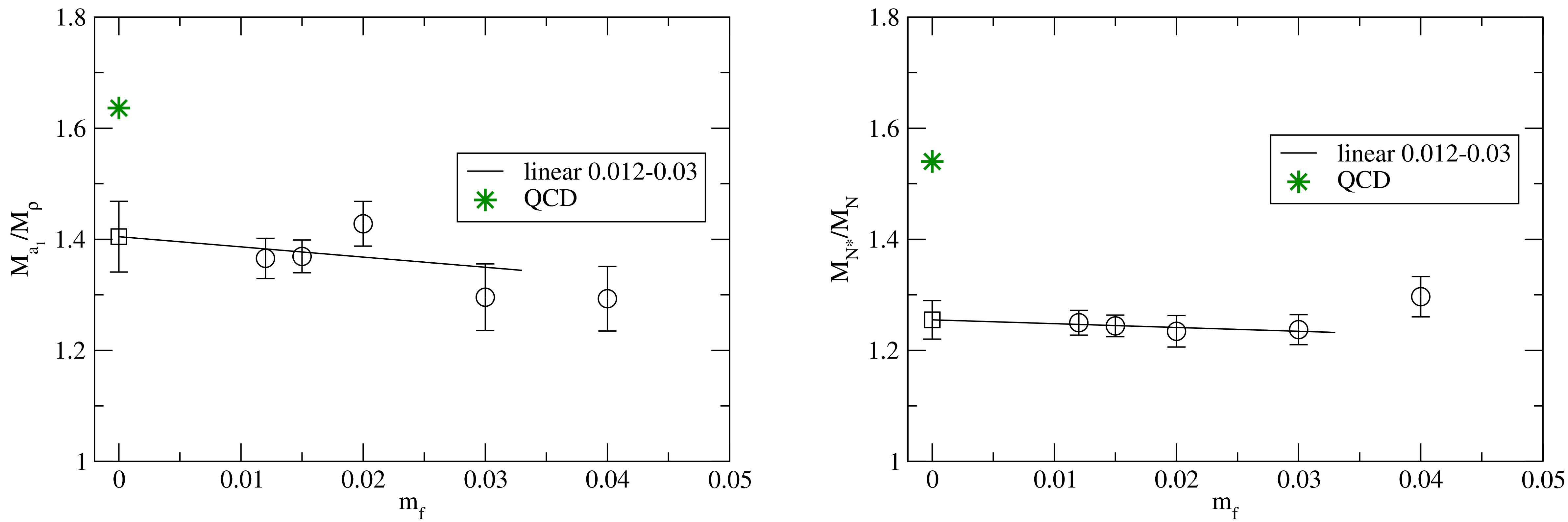
mesons: ρ, a_0, a_1, b_1



baryons: N, N*



mass ratio compared with real-life QCD



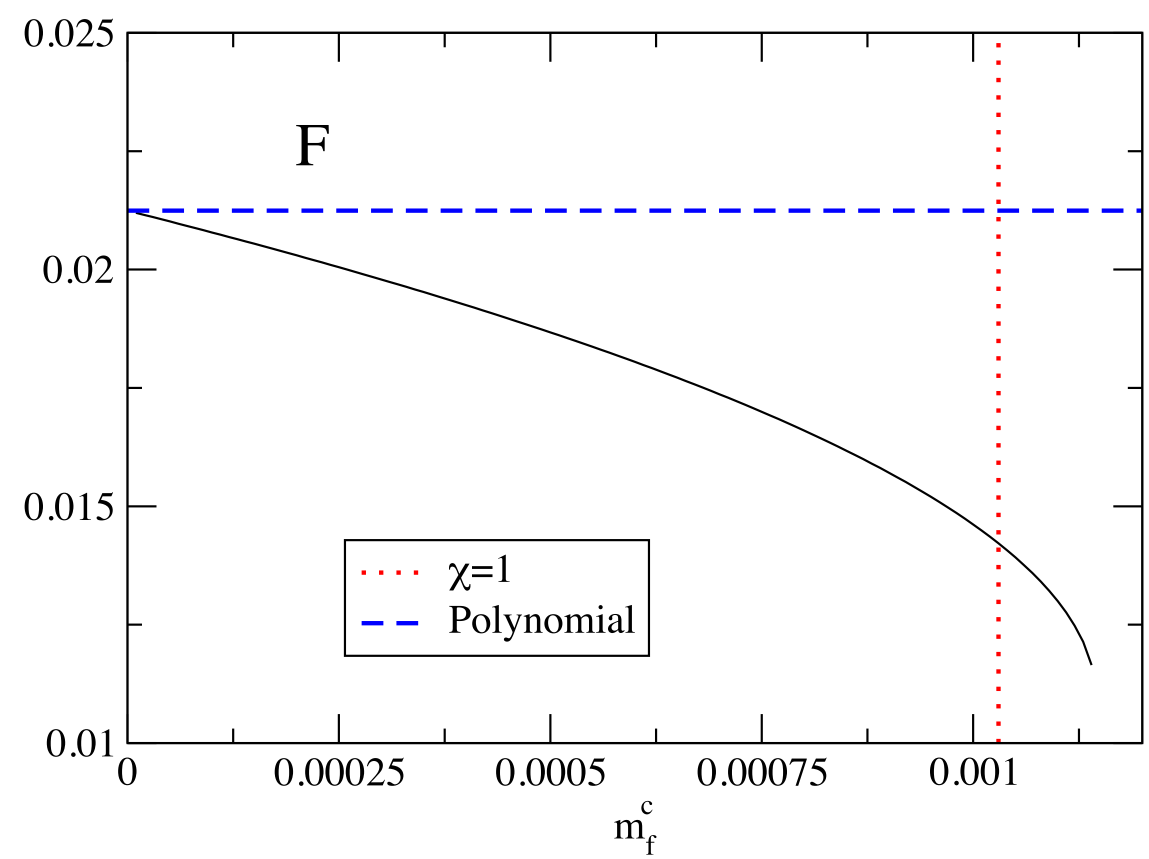
- moving toward “parity doubling” from smaller N_f to N_f=8
  - consistent with LSD collab. with domain-wall fermions

for predictions of composite spectrum

- chiral log effect on F_π is estimated
- polynomial extrapolation is matched with NLO ChPT at $\mathcal{X} = 1$
- natural expansion param. $\mathcal{X} = N_f \left(\frac{M_\pi}{4\pi F/\sqrt{2}} \right)^2$

$$F_\pi = F \left(1 - \frac{N_f\, x}{2} \log(x) + c_4 x \right)$$

$$F = 0.0212(12)(^{+49}_{-70})$$



Nf=8 composite spectrum

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

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

- 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.

N_f=8 spectrum

- Higgs mass ?
  - 125 GeV (LHC) seems very light for technicolor ↔ light dilation idea
  - 0++: one of the difficult quantities on the lattice
  - multi-faceted nature of N_f=8 adds another difficulty: delicate chiral extrapl.

➡ first analyze simpler N_f=12, which shares "conformality" → techni dilaton

[Yamawaki-Bando-Matumoto '86]

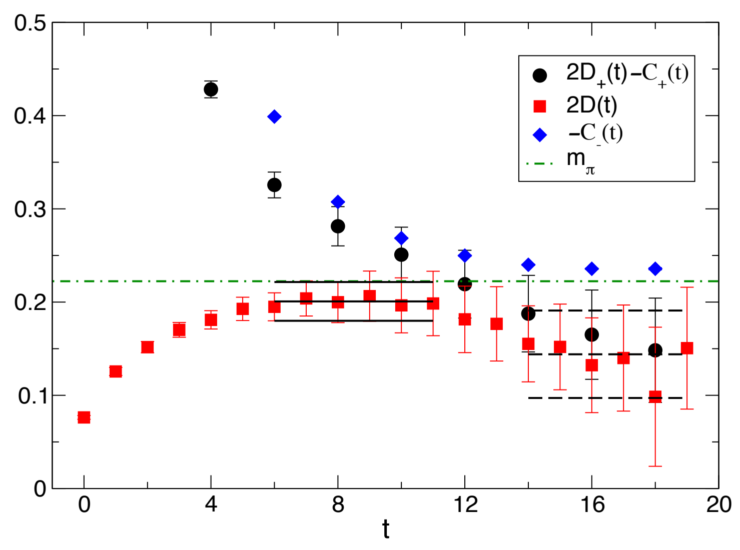
➡Is 0++ state light in (mass deformed) N_f=12 theory ?

➡ yes! [LatKMI PRL 2013]

➡Nf=8 shares similar property [LatKMI PRD 2014]

flavor singlet scalar : Higgs channel

- update from PRD 2014 LatKMI
- σ as light as π
- clearly lighter than ρ
    - ➡ far from heavy quark limit



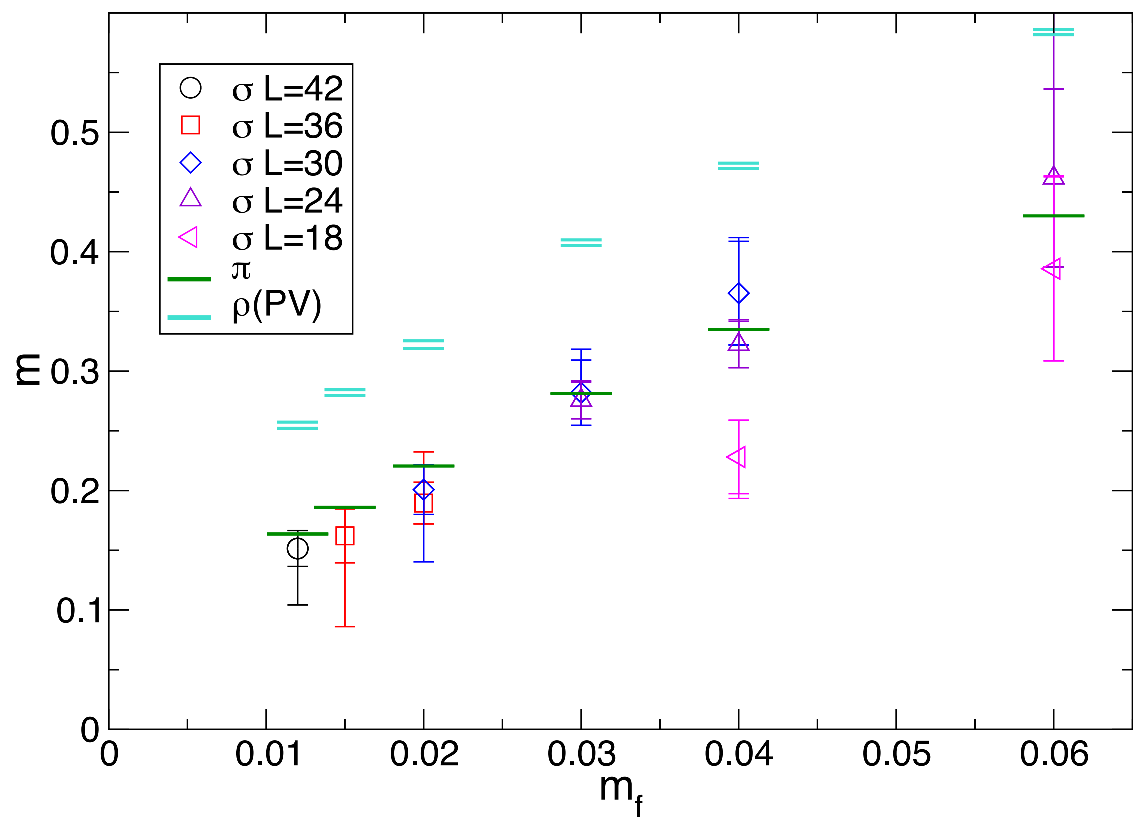
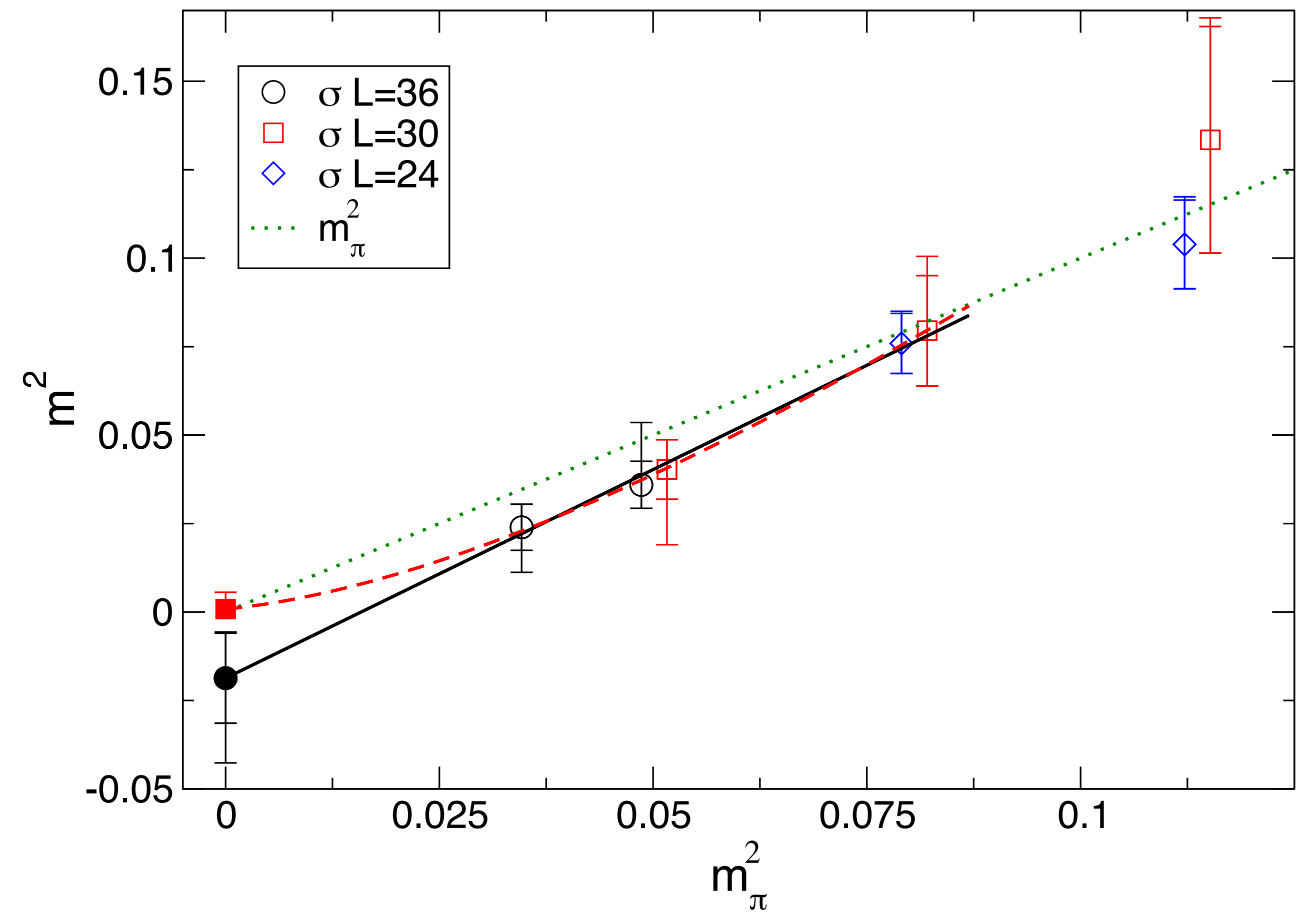


FIG. 16. Effective scalar mass m_σ from correlators with the projection for $L = 30$, $m_f = 0.02$.

trial chiral extrapolation for N_f=8 SU(3) m_σ [LatKMI: 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!



$c_0 = 0.029(39)(+8-72)$

$d_0 = -0.019(13)(+3-20)$

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

$d_1 = 1.18(24)(+35-7)$

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

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

- 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
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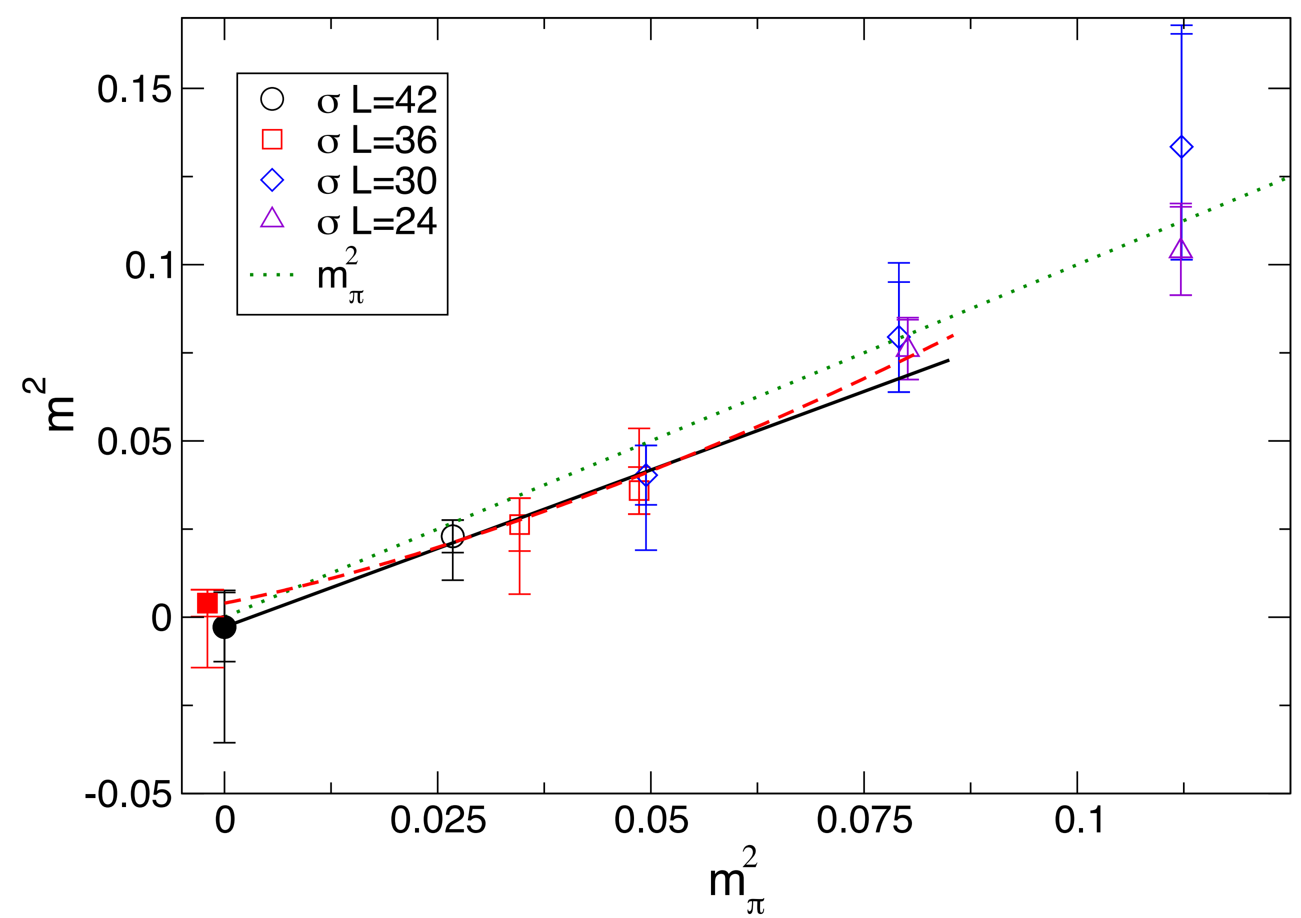


$c_0 =$ 0.063(30)(+4-142)

$d_0 =$ −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]

Summary and Outlook

- LatKMI collaboration is investigating the physics near the conformal phase boundary in SU(3) gauge theory; we focus here for Nf=8 QCD

- data taken so far is consistent with both Ch. br. and conformal scenario

- Nf=8 QCD is very close to the conformal ↔ Ch. symm. br. boundary

- now it is not a toy model of WTC, but, really serious candidate

➡difficult to study.   But, study towards the chiral limit is necessary!

- prediction of spectrum in F_π unit is made: $$\frac{M_\rho}{F/\sqrt{2}} = 10.1(0.6)(^{+5.0}_{-2.5})$$

    - ex. M_ρ~1.2 (1) +0.6-0.3 TeV for one-family mode

Summary and Outlook

- Flavor Singlet scaler appears to be as light as pion !
    - chance to have composite Higgs as light as 125GeV with this dynamics
- For more qualitative discussion
    - lighter mass data needed and careful chiral limit needs to be taken

Other Studies in LatKMI

- all calculations are done with same set-up: HISQ, Nf=4*n
- Nf=8 spectrum of Dirac operator and topology → Nagai (talk)
- Nf=8 scalar and baryons for Dark Matter → Ohki (talk)
- Nf=8 at finite temperature → Miura (poster)
- Nf=4 for chiral symm. br. → Kurachi (poster)

- Nf=8 S-parameter under investigation

Thank you so much for coming this workshop

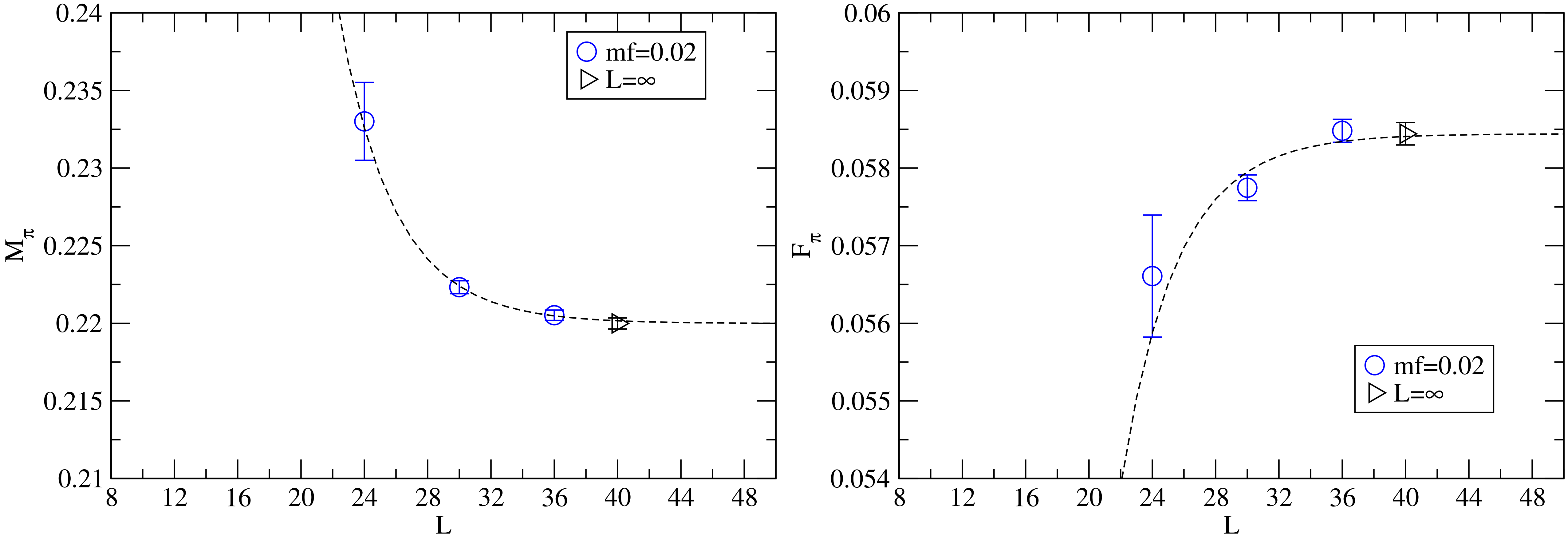
and thank you very much for listening.

back up slides

Finite Size Effect on Mπ & Fπ for m_f=0.02

$$M_\pi(L) = M_\pi + c_{M_\pi}\frac{e^{-LM_\pi}}{(LM_\pi)^{3/2}}$$

$$F_\pi(L) = F_\pi + c_{F_\pi}\frac{e^{-LM_\pi}}{(LM_\pi)^{3/2}}$$



- ChPT inspired fits: results at L=36 is consistent with infinite volume.