Exploring for walking technicolor from QCD

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for the LatKMI collaboration

- Lattice meets experiment 2012 @ Boulder -

Oct. 27, 2012

名古屋大学

LatKMI collaboration

- YA, T.Aoyama, M.Kurachi, T.Maskawa, K.Nagai, H.Ohki,

     

E. Rinaldi, K.Yamawaki, T.Yamazaki

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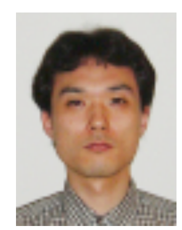
  

KMI

- A.Shibata

KEK

“Higgs boson”

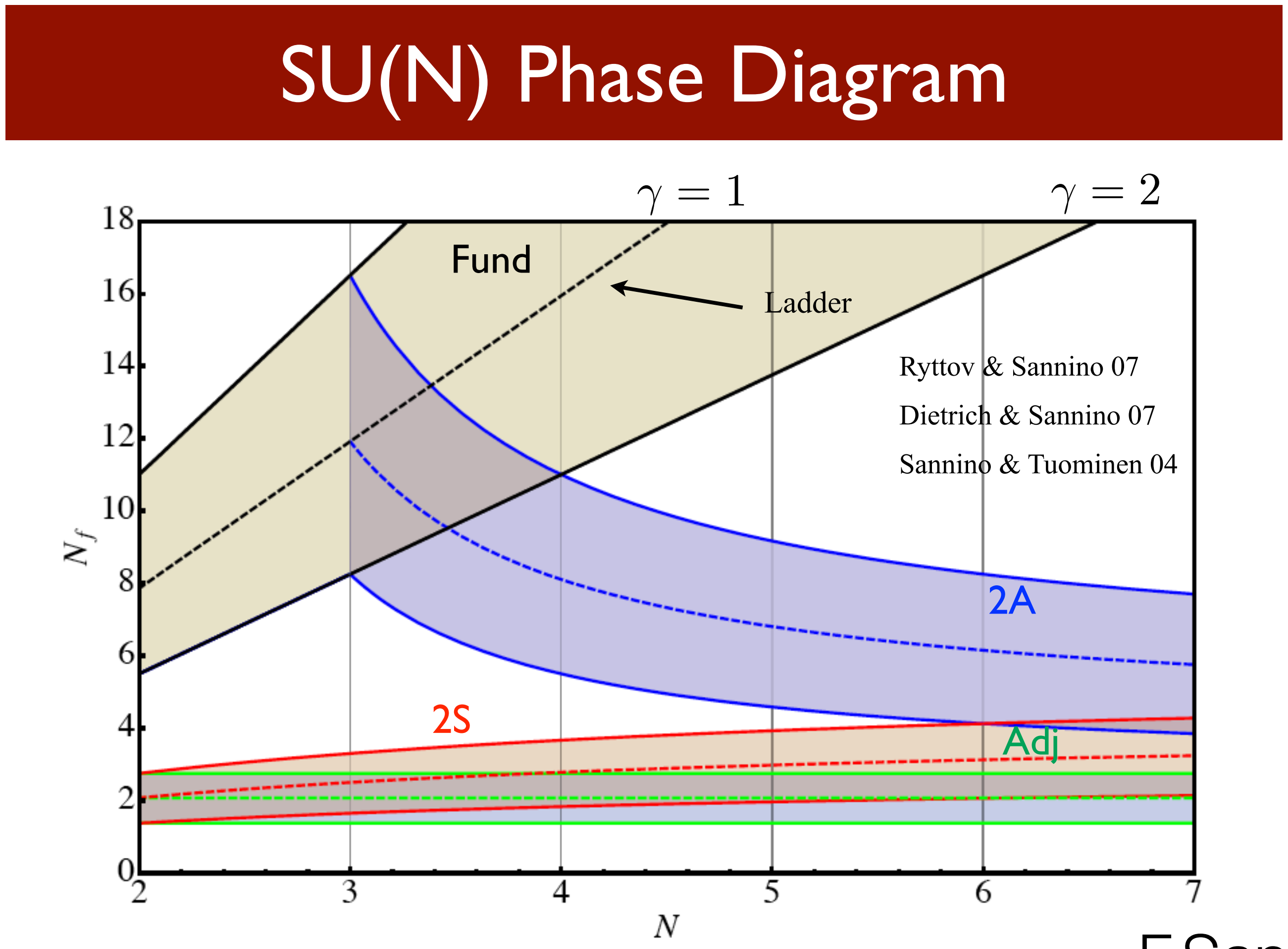
- Higgs like particle fund at LHC
- m_H = 126 GeV
- spin, parity, other properties are under investigation
- so far consistent with Standard Model Higgs ($J^{PC}=0^{++}$) fundamental scalar
- but it could be different
- one of the possibilities
  - walking technicolor
    - “Higgs” = pNGB due to breaking of the approximate scale invariance

requirements for model

- nearly conformal: walking
- $\gamma_m \sim 1$
- input: $F = 246 / \sqrt{N}$ GeV
  - N: # weak doublet from new techni-sector
- could m_H (0++) be made light: ~126 GeV

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



F.Sanino

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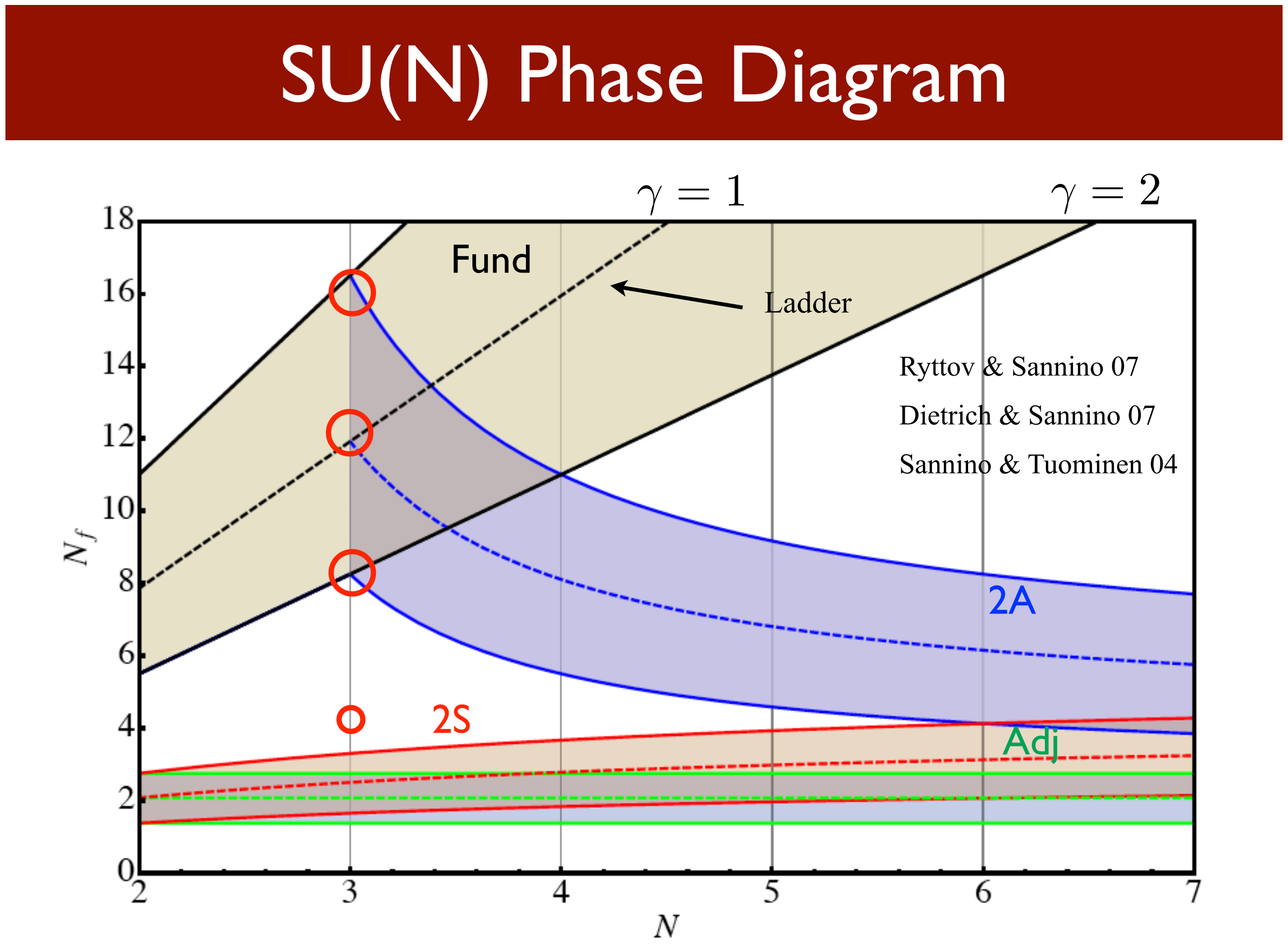

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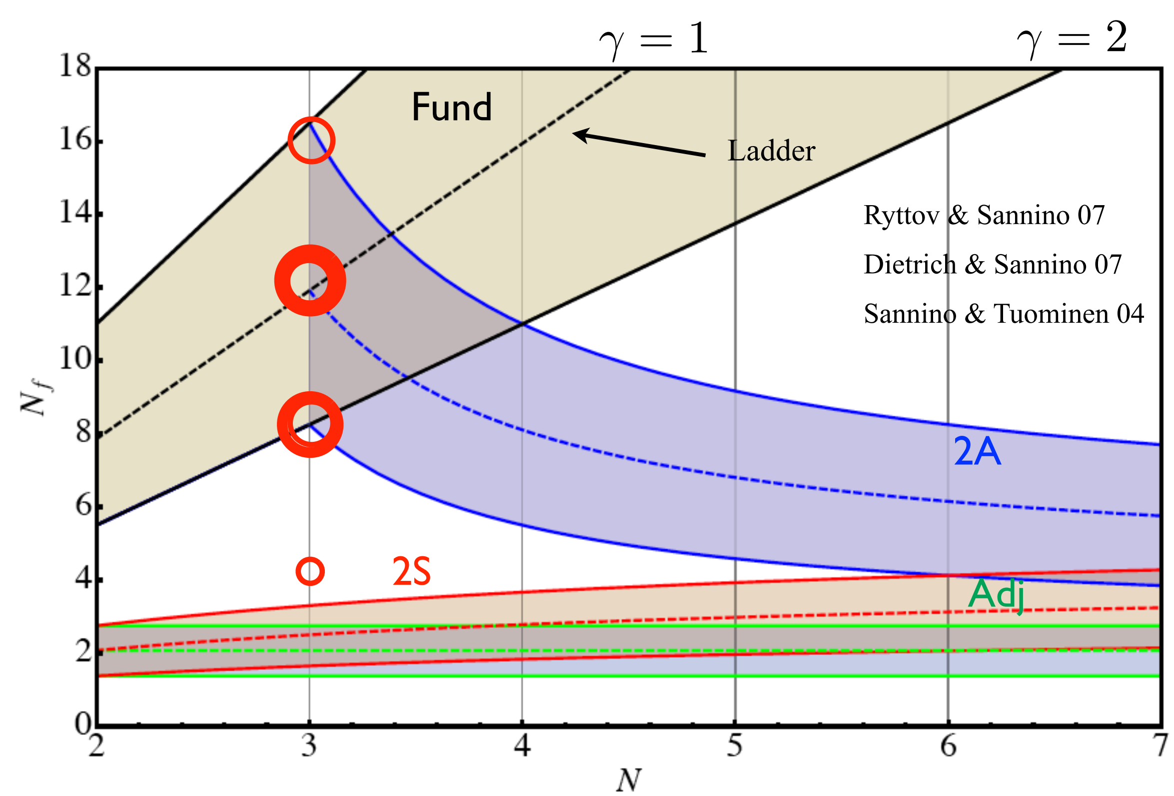
SU(N) Phase Diagram



SU(3) + N_f=12 [fundamental]

[LatKMI collab. PRD86 (2012) 054506]

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)
  - ratio of the masses, decay constant is constant as function of m_f
- S χ SB phase:
  - ChPT (but, large N_f, small F $\Leftrightarrow$ real QCD)
    - hard to get to the chiral regime
  - at leading: $M_\pi^2 \propto m_f$, ; $F_\pi = F + c\, m_f$

Simulation

- HISQ (Highly Improved Staggered Quarks)
  - being used for state-of-the-art QCD calculations / MILC,..
- tree level Symanzik gauge

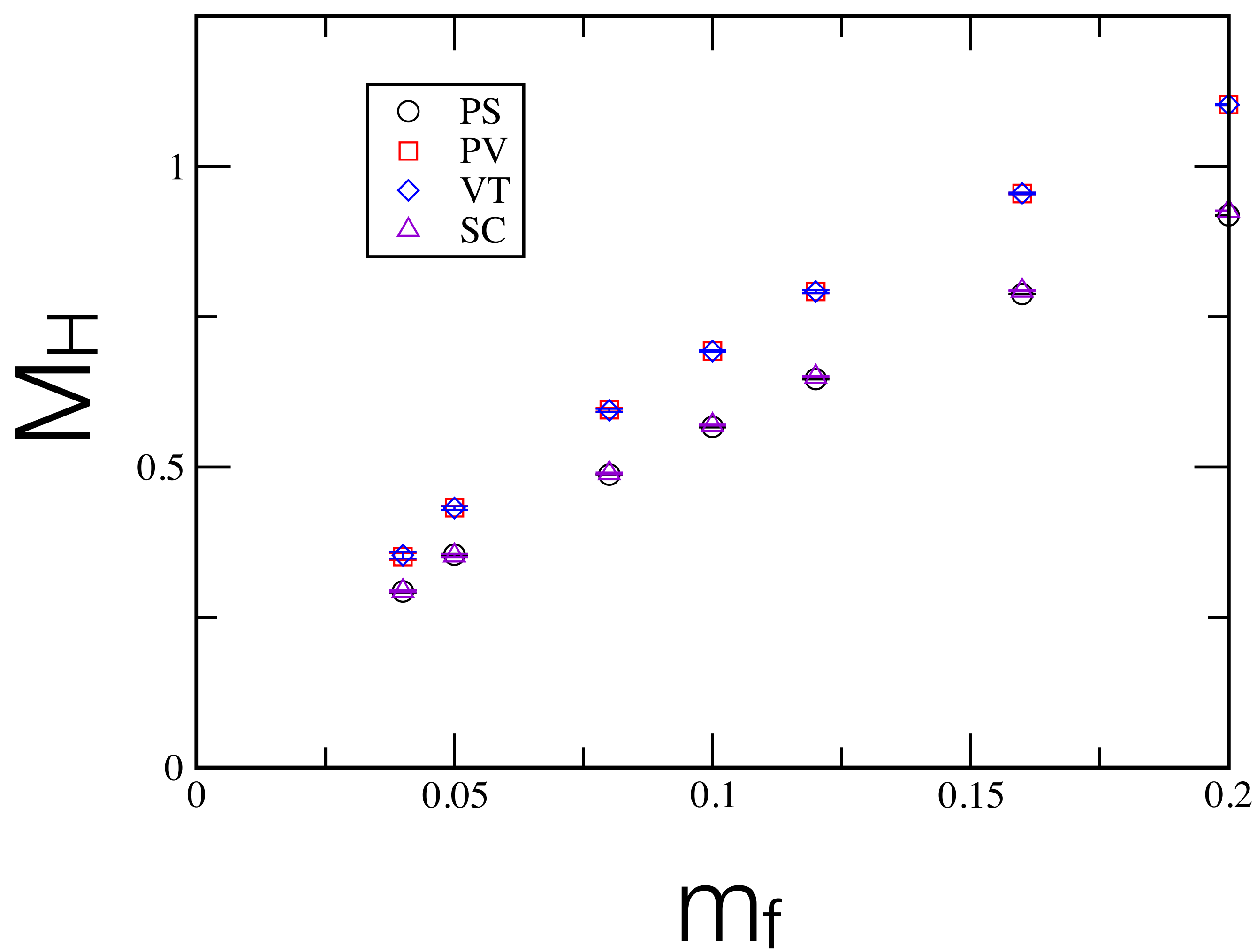
➡HISQ/tree

- $\beta=6/g^2=3.7$, $V=L^3xT$: $L/T=3/4$; $L=18, 24, 30$, $0.04 \leqq m_f \leqq 0.2$
- $\beta=6/g^2=4.0$, $V=L^3xT$: $L/T=3/4$; $L=18, 24, 30$, $0.05 \leqq m_f \leqq 0.24$
- $N_f=4$ HISQ for the reference of SχSB for comparison

- using MILC code v7 with some modifications (non-rational HMC)

staggered flavor symmetry for N_f=12 HISQ

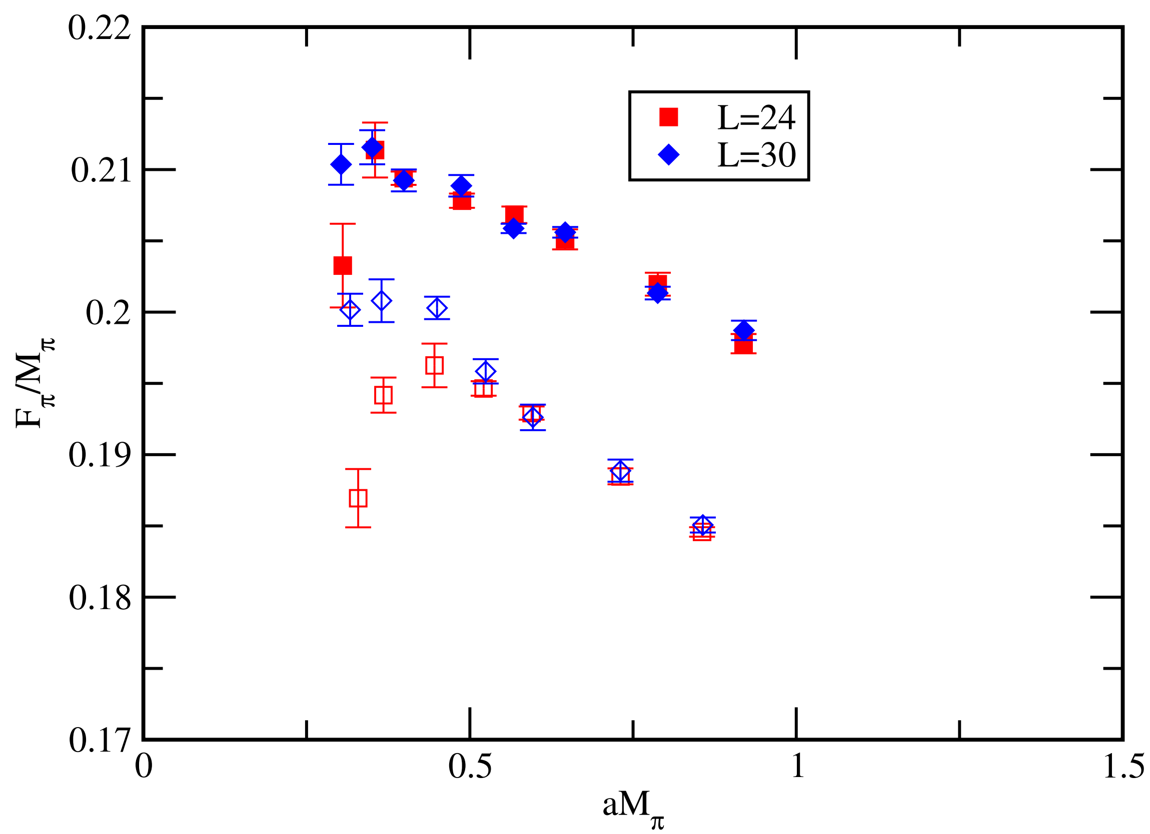
- comparing masses with different staggered operators for π & ρ for β=3.7



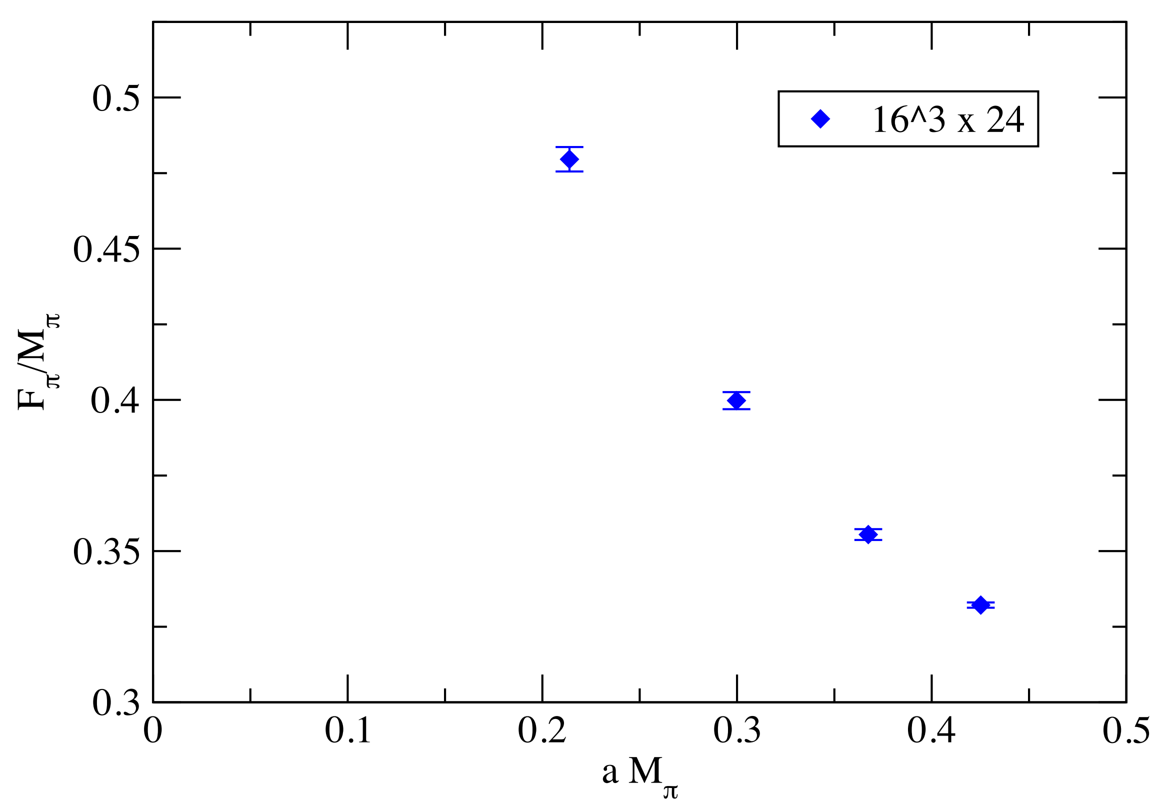
- excellent staggered flavor symmetry, thanks to HISQ

a crude analysis: F_π/M_π vs M_π

N_f=12: HISQ



N_f=4: HISQ β=3.7



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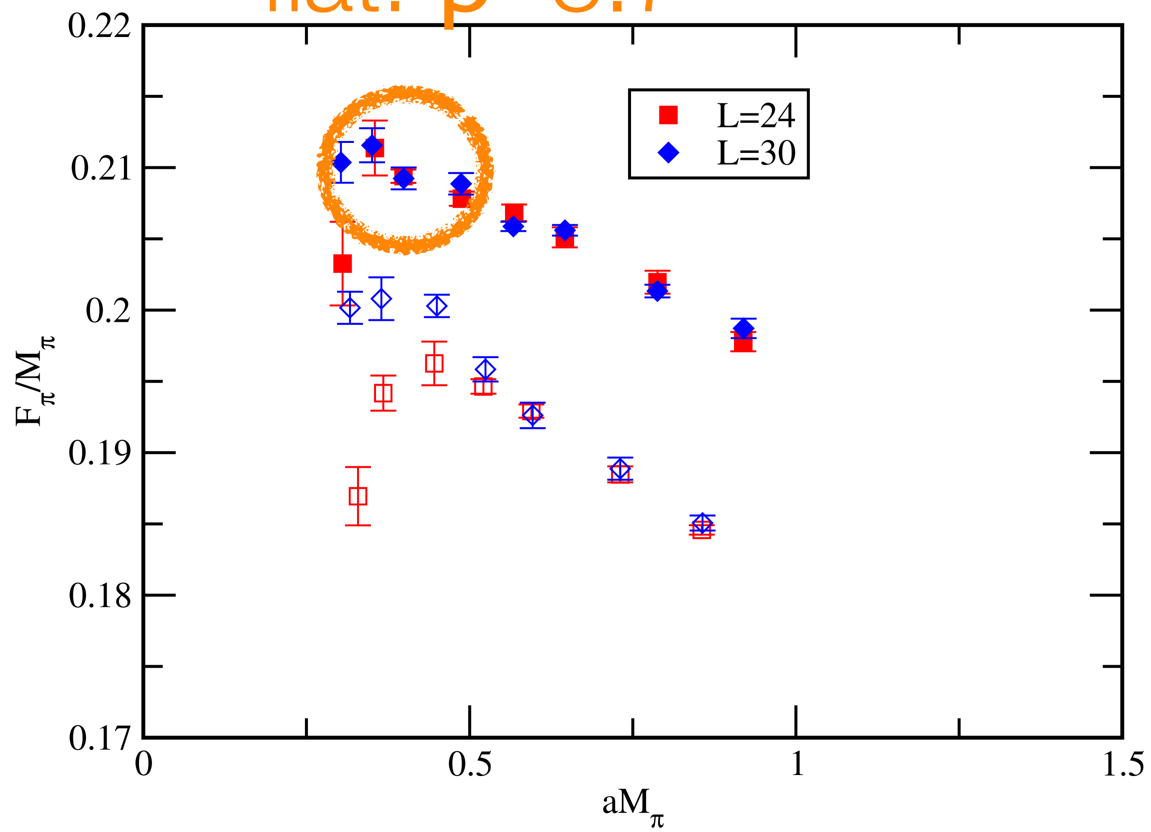
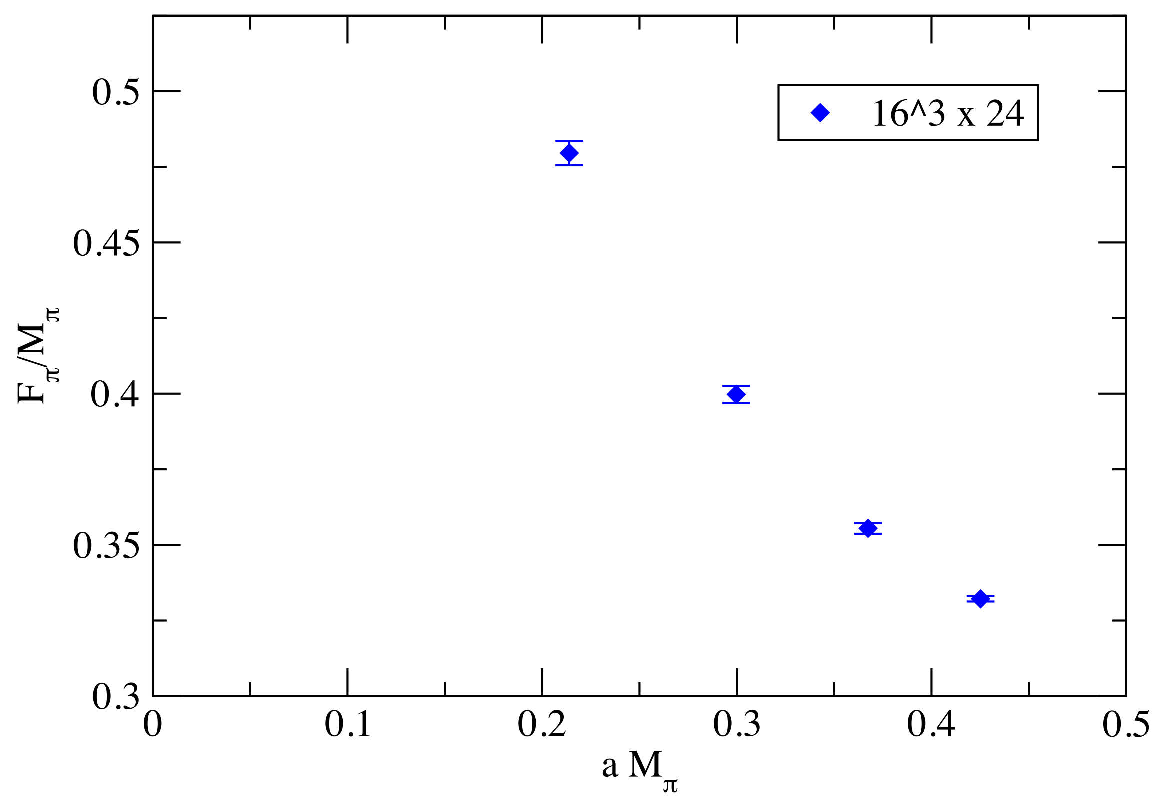
N_f=12: HISQ

N_f=4: HISQ β=3.7

flat: β=3.7





- β=3.7: small mass: consistent with hyper-scaling

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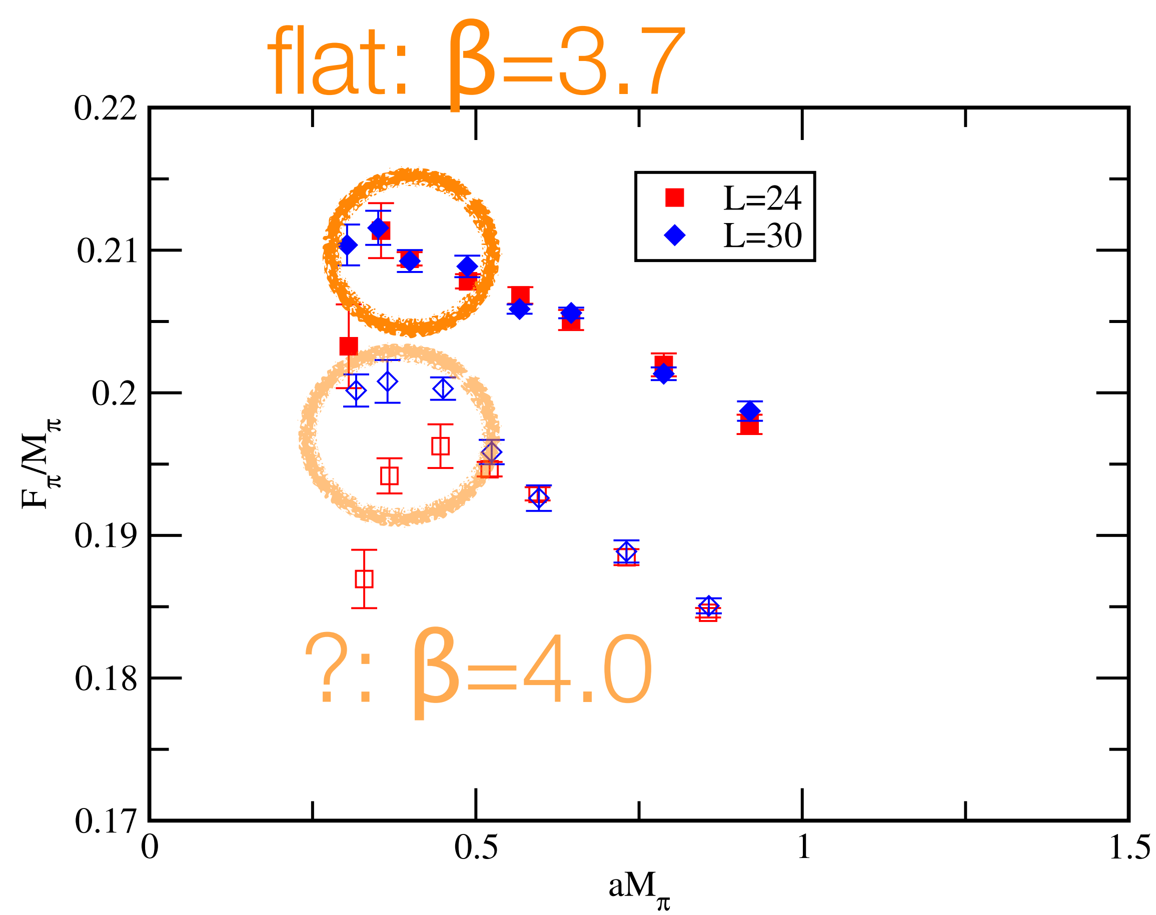
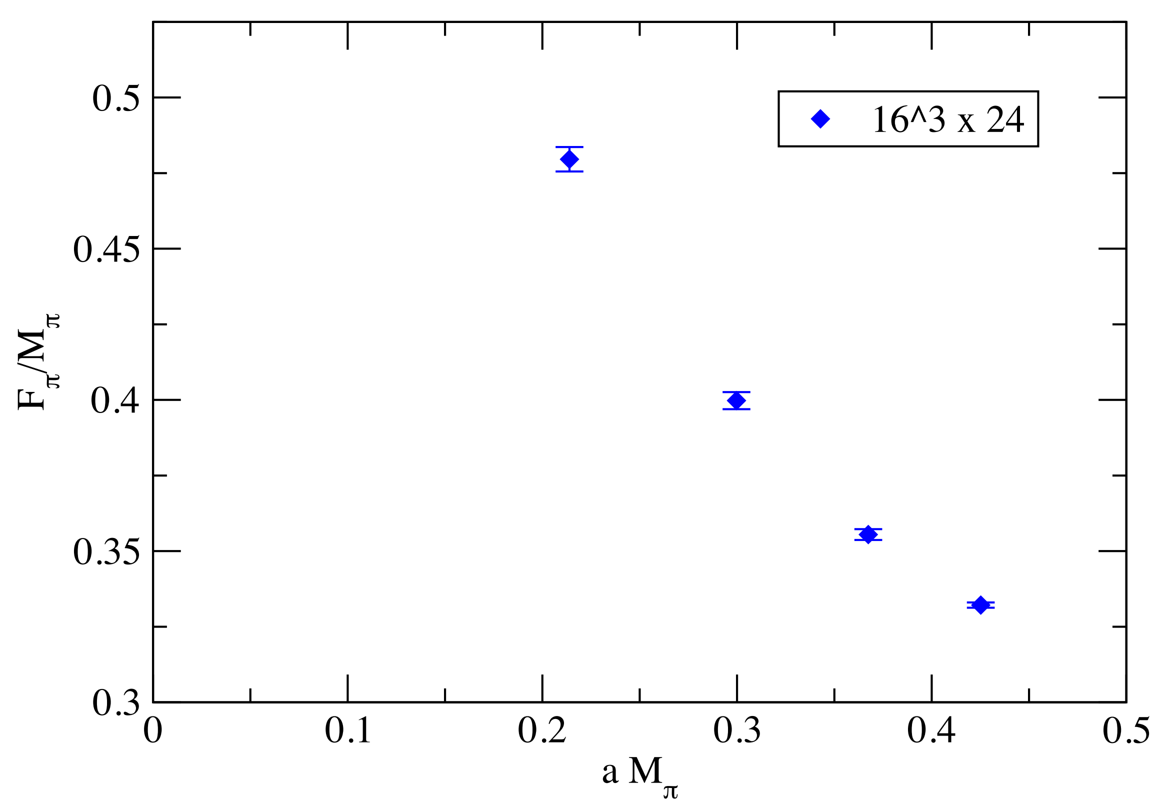


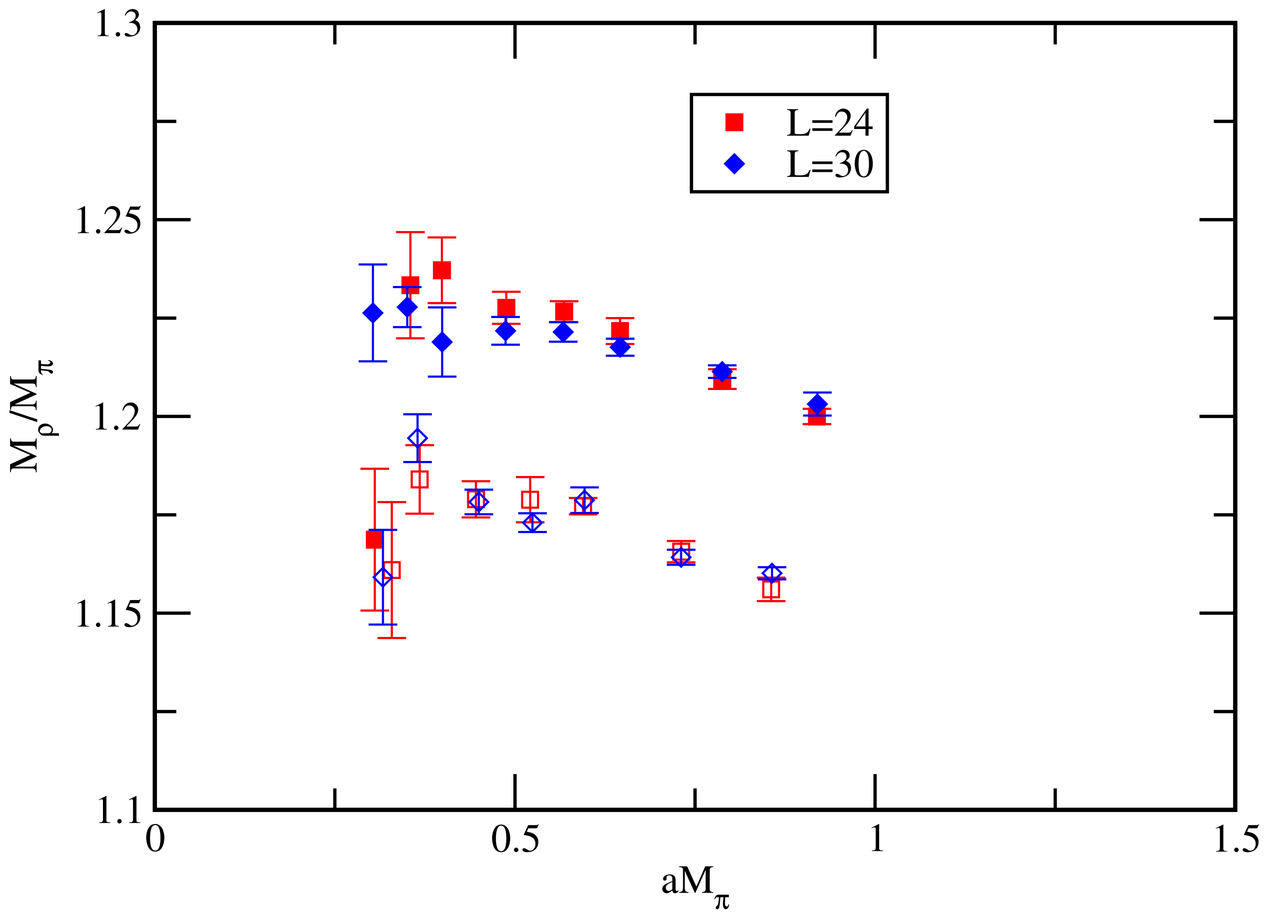
N_f=4: HISQ β=3.7



- β=3.7: small mass: consistent with hyper-scaling
- β=4.0: volume to small ? unlikely in the hyper-scaling region

a crude analysis: M_ρ/M_π vs M_π

N_f=12: HISQ



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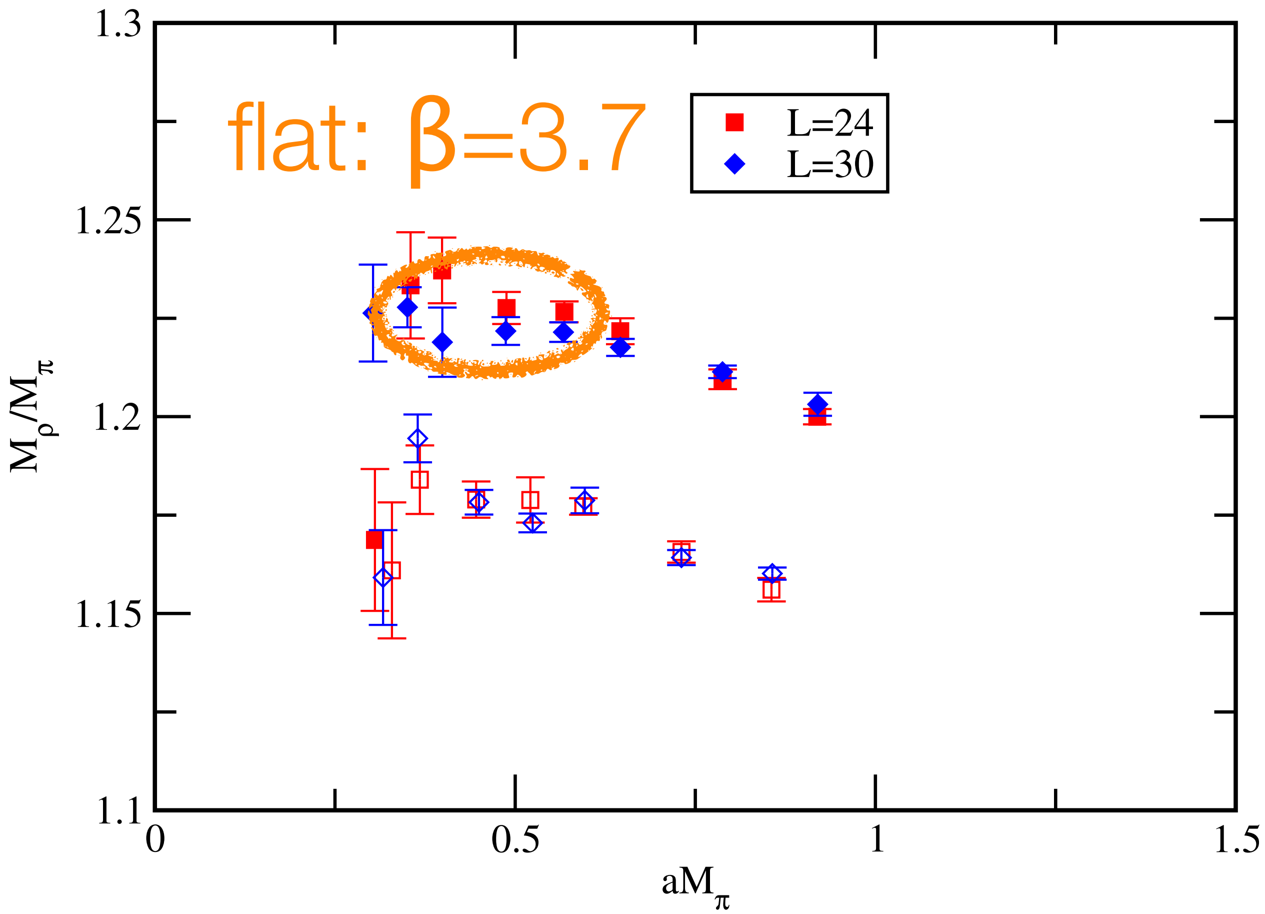

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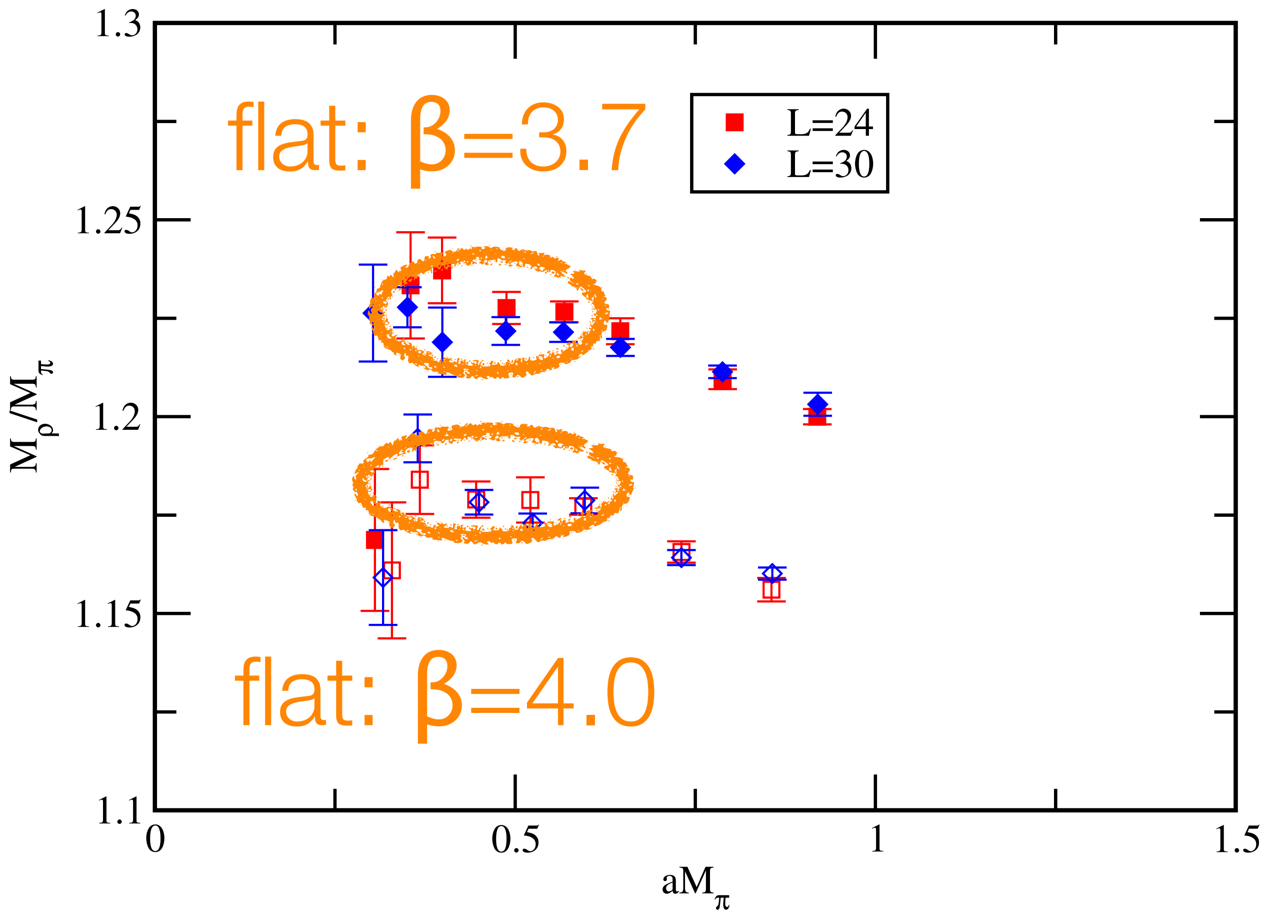

- β=3.7 & 4.0: small mass (wider than F_π): consistent with hyper scaling (HS)

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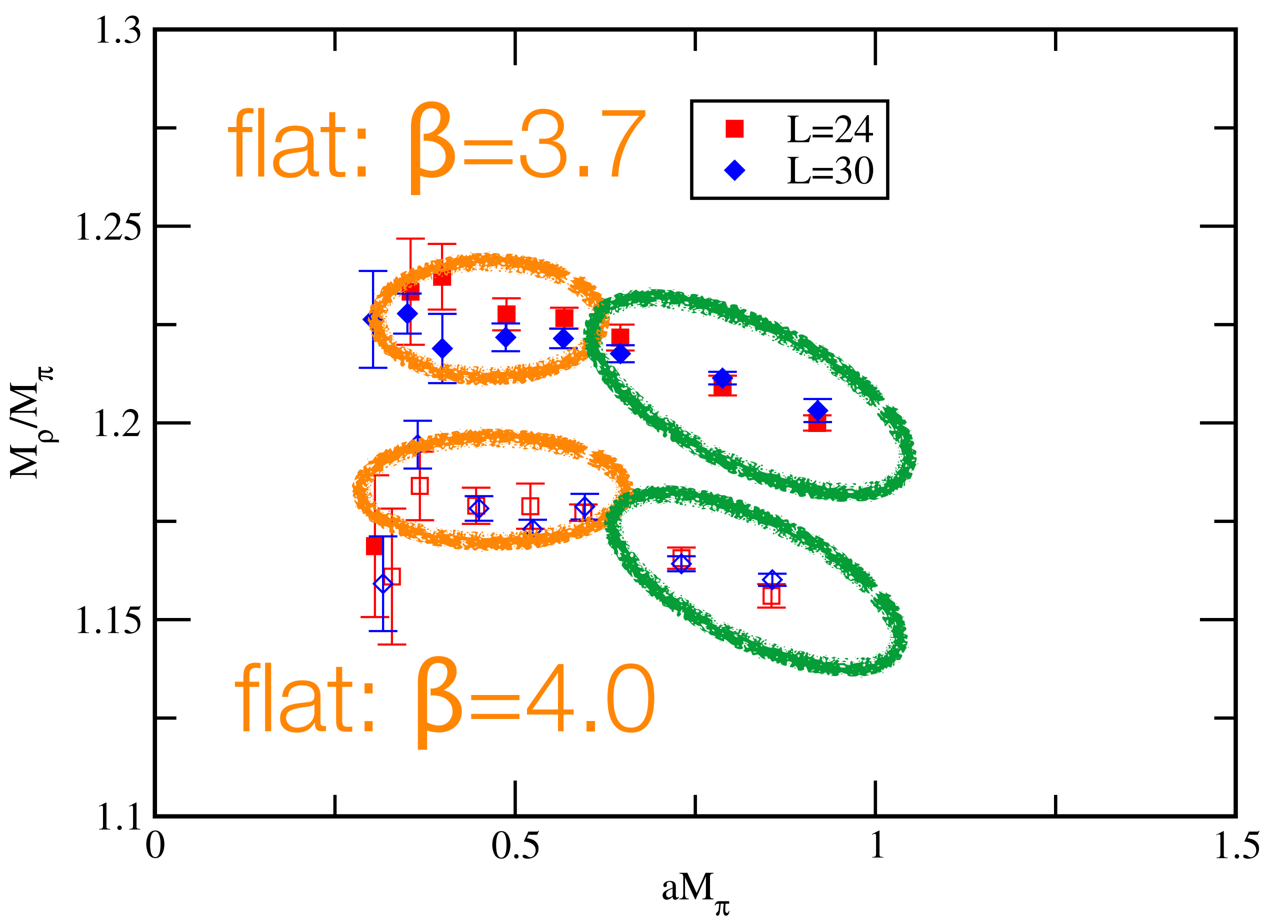
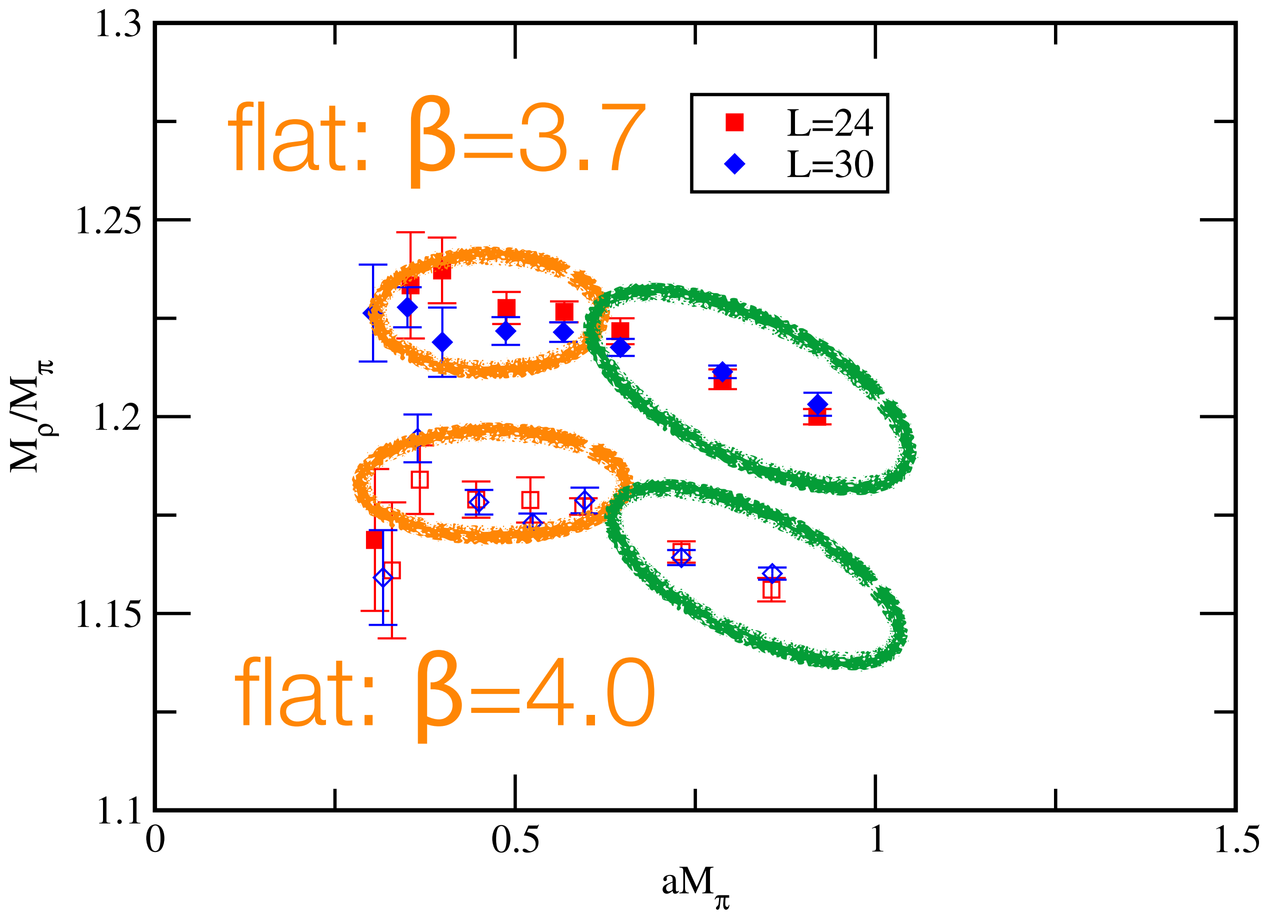
N_f=12: HISQ



- β=3.7 & 4.0: small mass (wider than F_π): consistent with hyper scaling (HS)
- mass dependence at the tail is due to non-universal mass correction to HS

a crude analysis: M_ρ/M_π vs M_π

N_f=12: HISQ



- one may attempt to perform a matching
- assuming $(am)^2$ error is small

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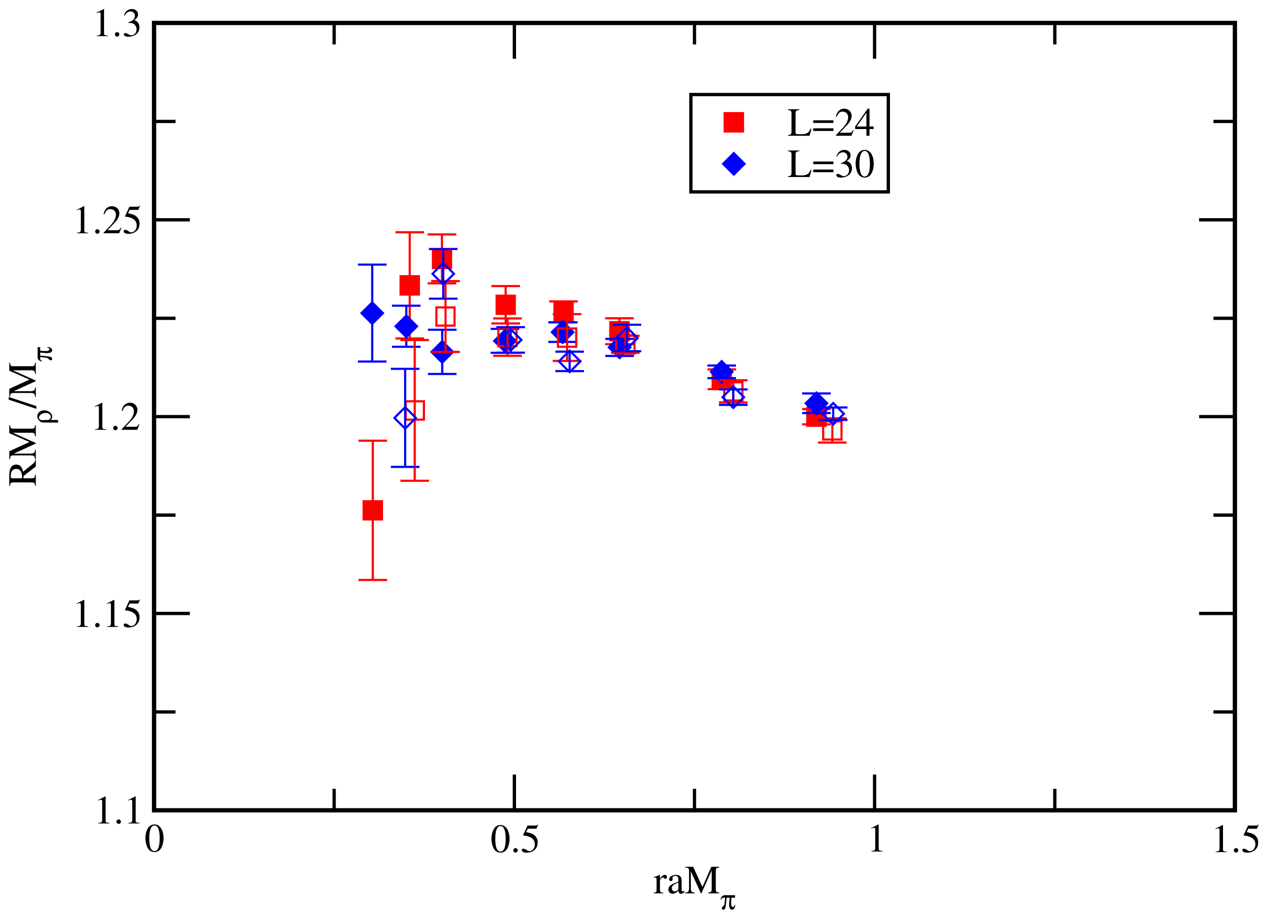

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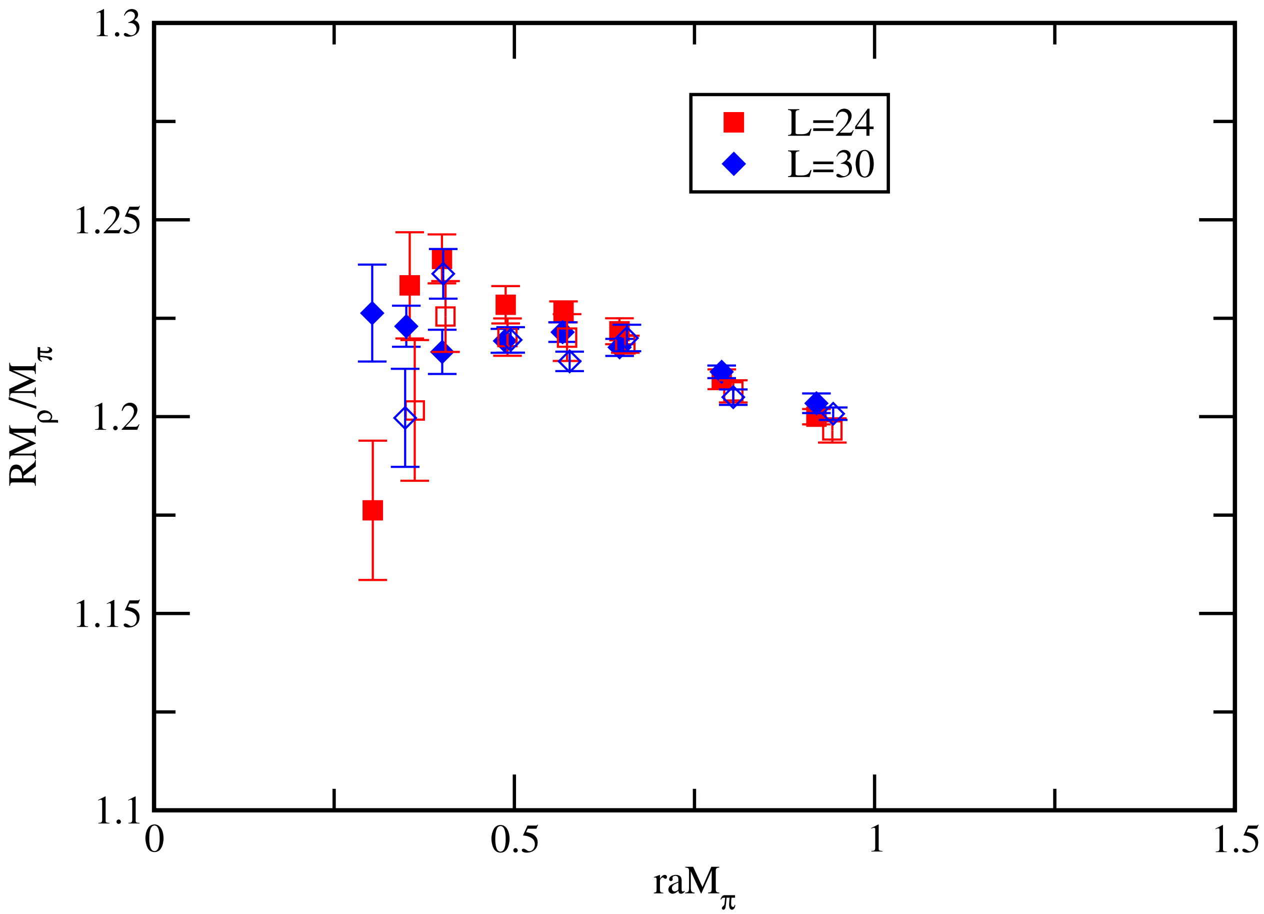

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  - movement: correct direction in asymptotically free domain !

- β=3.7 & 4.0: small mass (wider than F_π): consistent with hyper scaling (HS)
- mass dependence at the tail is due to non-universal mass correction to HS

conformal (finite size) scaling

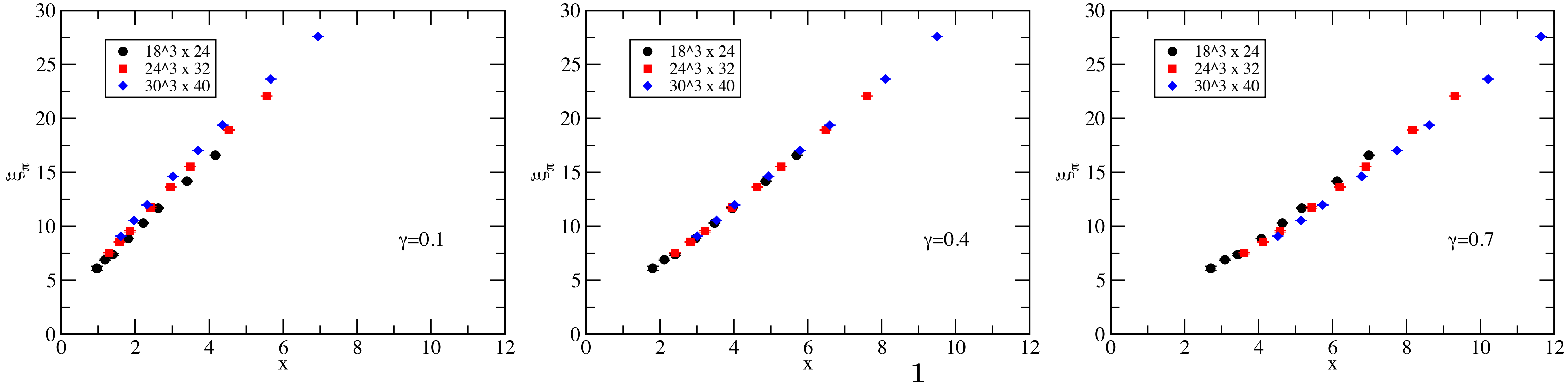
- Scaling dimension at IR fixed point [Wilson-Fisher]; Hyper Scaling [Miransky]
- mass dependence is described by anomalous dimensions at IRFP
  - quark mass anomalous dimension γ^*
  - operator anomalous dimension
- hadron mass and pion decay constant obey same scaling

$$M_H \propto m_f^{\frac{1}{1+\gamma^*}} \qquad F_\pi \propto m_f^{\frac{1}{1+\gamma^*}}$$

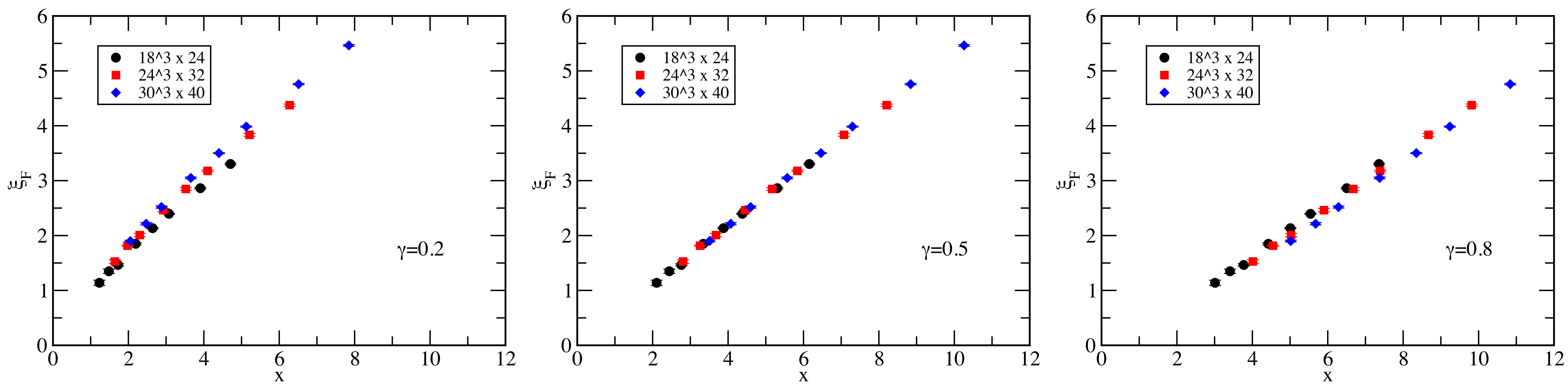
- finite size scaling in a L^4 box (DeGrand; Del Debbio et al)
  - scaling variable: $x = L m_f^{\frac{1}{1+\gamma^*}}$

$$L \cdot M_H = f_H(x) \qquad L \cdot F_\pi = f_F(x)$$

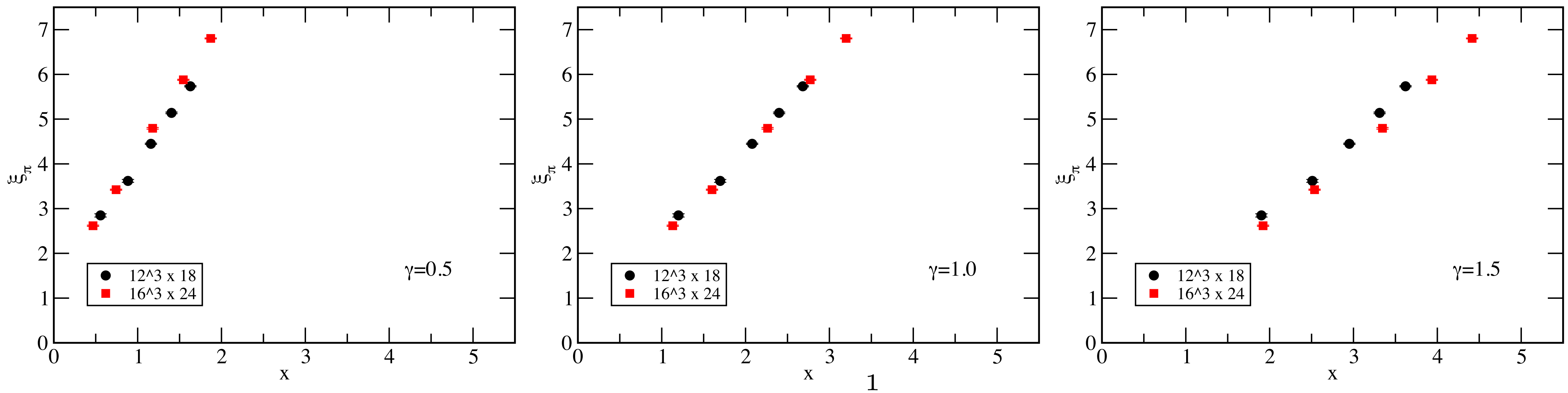
N_f=12 see if data align at some γ



$$x = Lm_f^{\frac{1}{1+\gamma}}$$



N_f=4 see if data align at some γ



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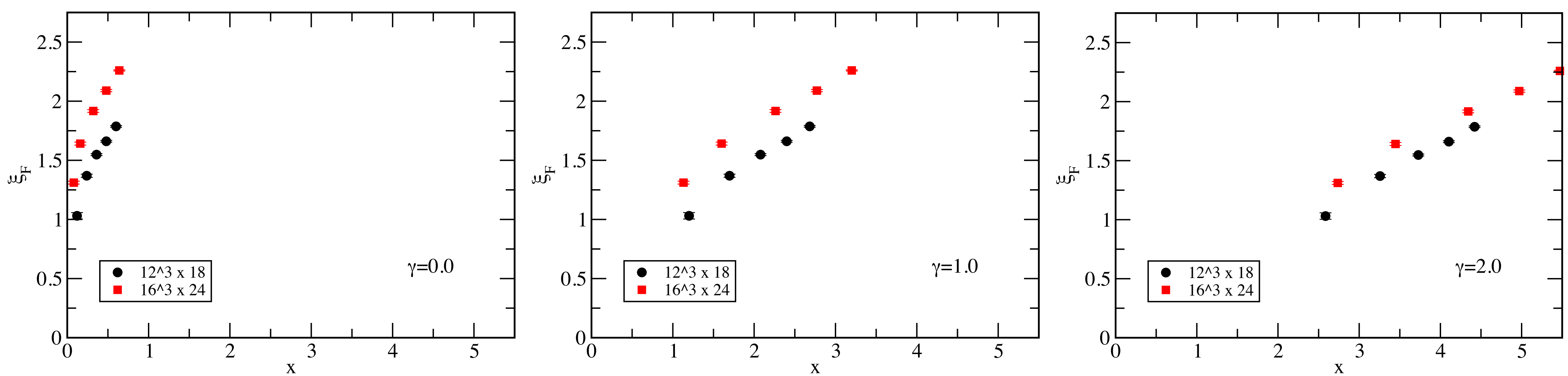

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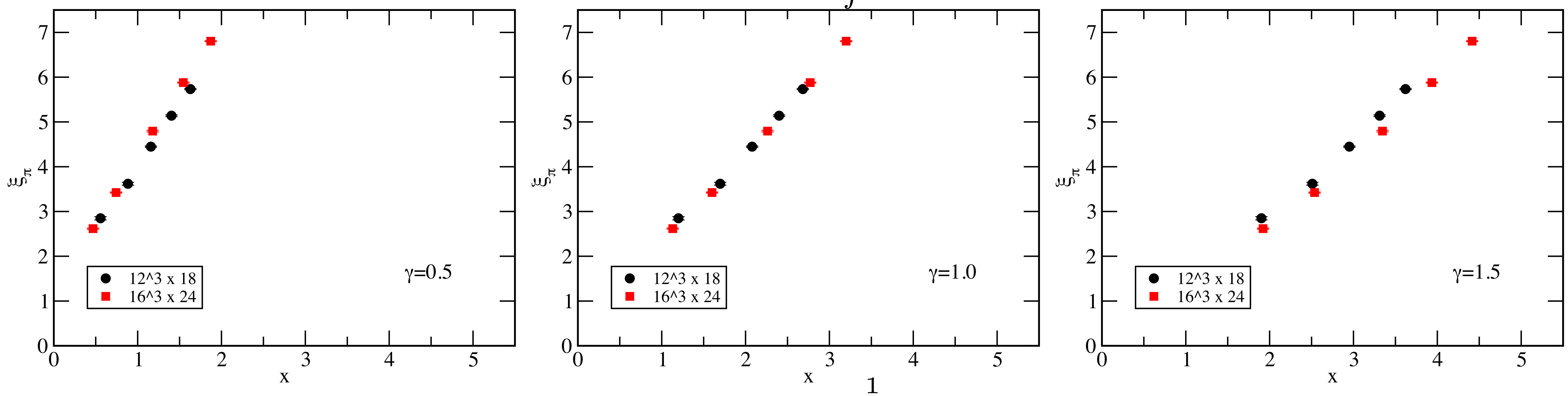
$$M_\pi L \propto m_f^{1/2} L$$



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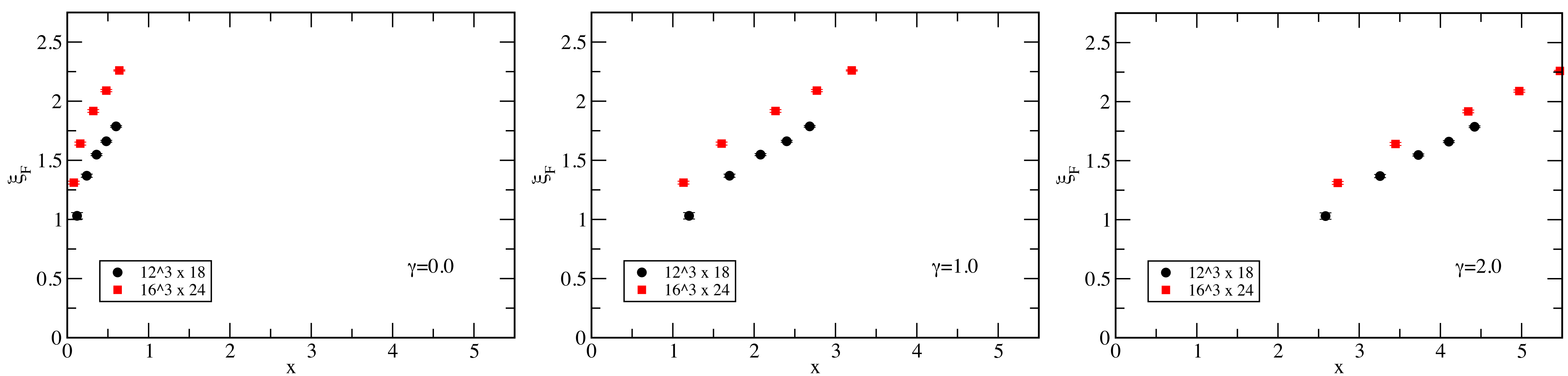

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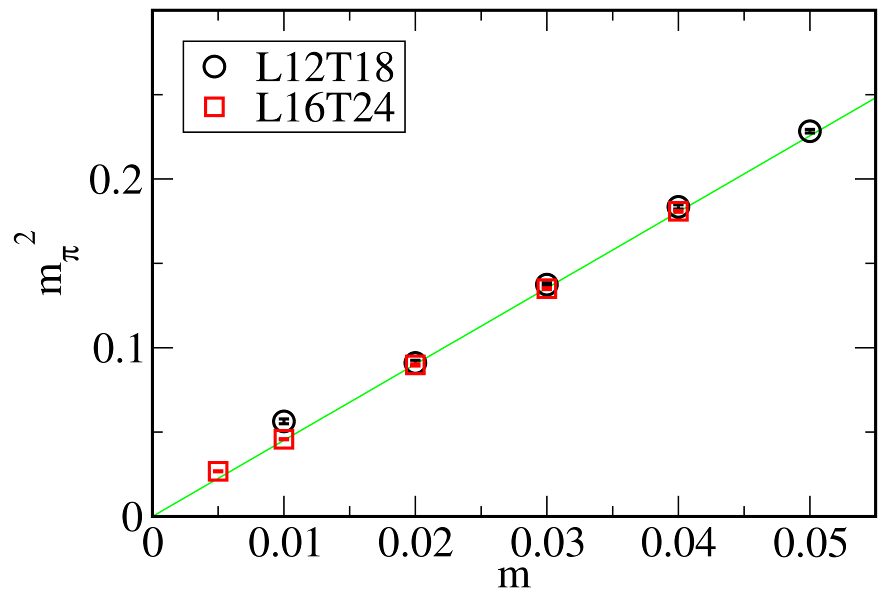

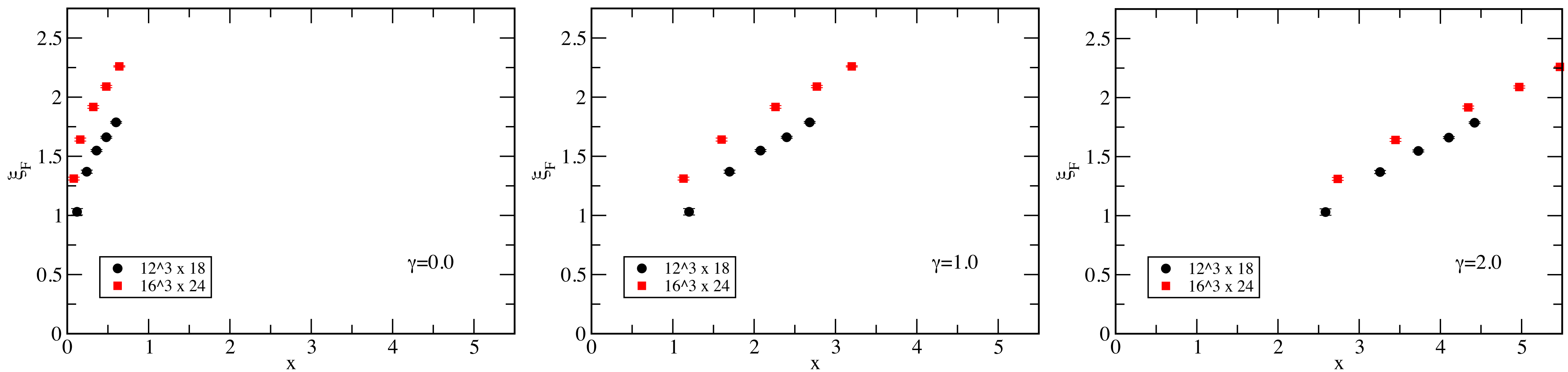

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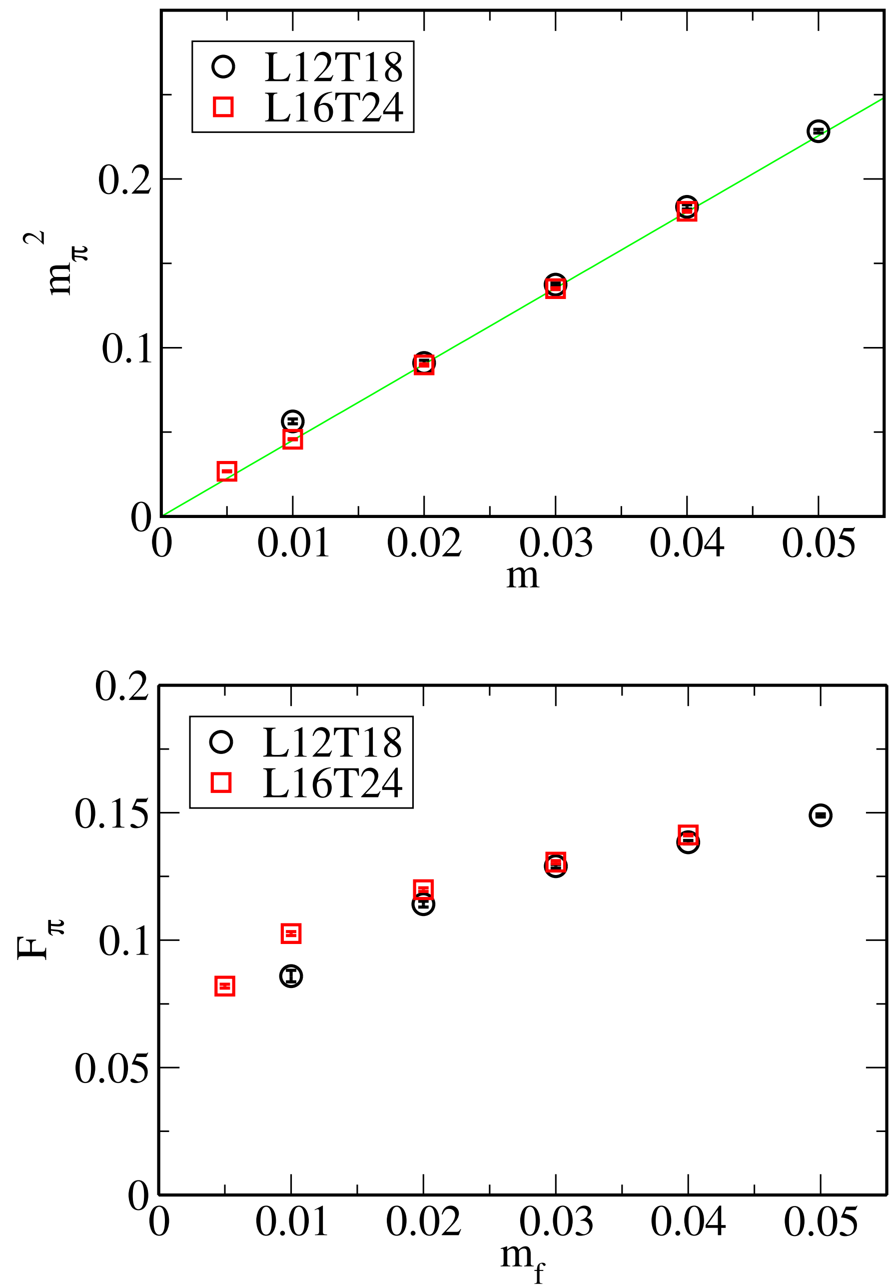

measure of the “alignment” without resorting to a model

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- γ of optimal alignment will minimize:

$$P_p(\gamma) = \frac{1}{\mathcal{N}} \sum_K \sum_{j \notin K} \frac{|\xi_p^j - f_p^{(K)}(x_j)|^2}{\delta^2 \xi_p^j}$$

  - $\xi_p = LM_p$ for $p = \pi, \rho$; $\xi_F = LF_\pi$
  - $f_p(x)$: interpolation .... linear
    - (quadratic for a systematic error)
- if ξ^j is away from $f(x_i)$ by $\delta\,\xi^j$ as average → $P=1$
- optimal γ from the minimum of P
- similar definition of the measure: DeGrand, Giedt & Weinberg

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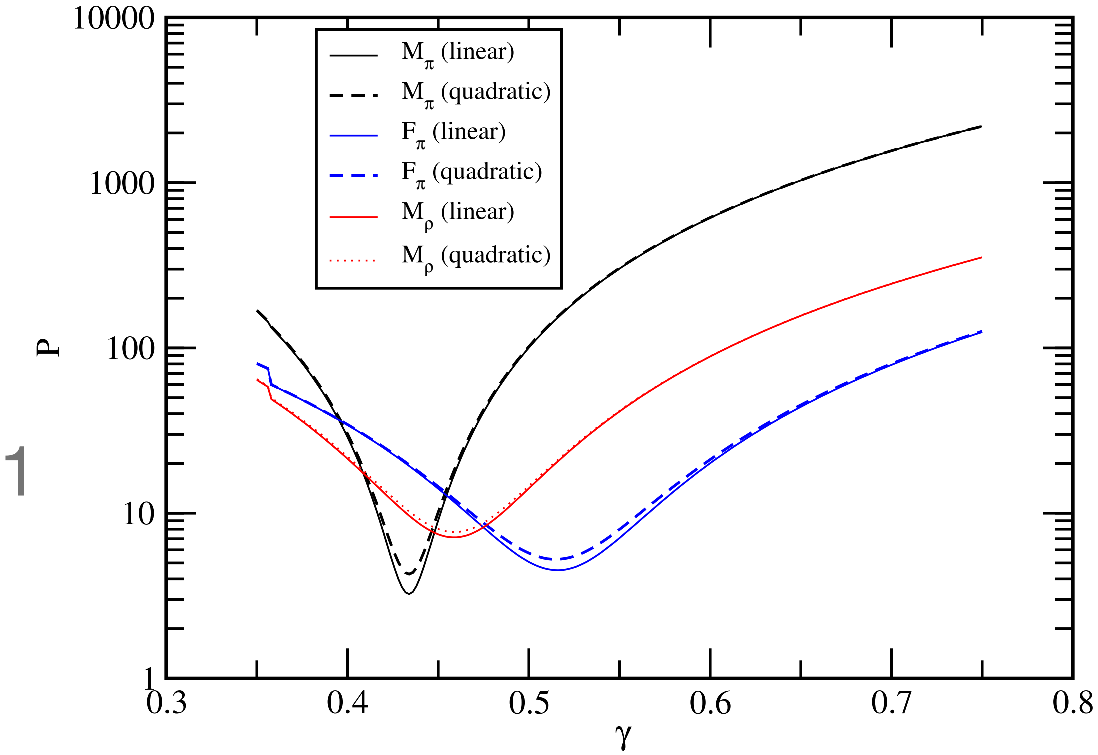
P(γ) for Mπ,Fπ,Mρ at β=3.7



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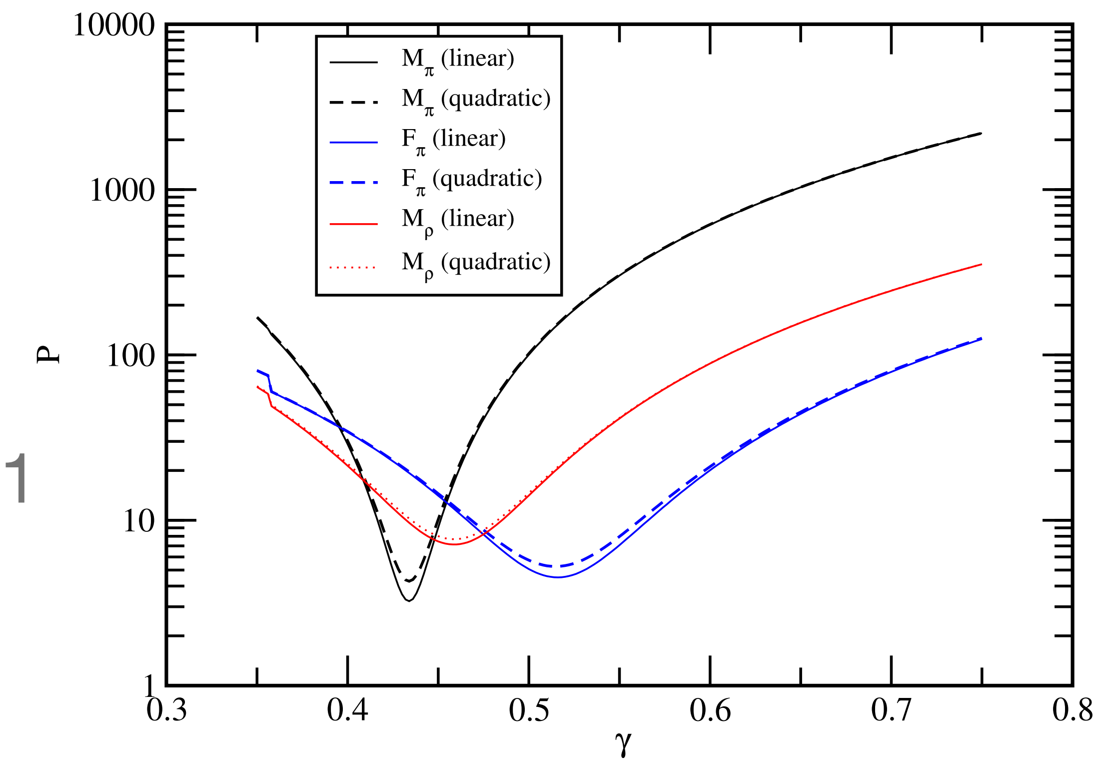
P(γ) for M_π, F_π, M_ρ at β=3.7



- similar definition of the measure: DeGrand, Giedt & Weinberg
- systematic error due to small L, large m estimated by examining the x and L range dependence

TABLE VII. Summary of the optimal values of γ. See the text for details.

quantity	β	all
M_π	3.7	0.434(4)
F_π	3.7	0.516(12)
M_ρ	3.7	0.459(8)

TABLE VII. Summary of the optimal values of γ. See the text for details.

quantity	β	all	x range 1	x range 2	x range 3
M_π	3.7	0.434(4)	0.425(9)	0.436(6)	0.437(4)
F_π	3.7	0.516(12)	0.481(19)	0.512(19)	0.544(14)
M_ρ	3.7	0.459(8)	0.411(17)	0.461(10)	0.473(8)

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- β=3.7: smaller m : closer to M_π

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M_π	3.7	0.434(4)	0.425(9)	0.436(6)	0.437(4)	0.438(6)	0.433(4)	0.429(8)
F_π	3.7	0.516(12)	0.481(19)	0.512(19)	0.544(14)	0.526(18)	0.514(11)	0.505(24)
M_ρ	3.7	0.459(8)	0.411(17)	0.461(10)	0.473(8)	0.491(15)	0.457(8)	0.414(18)

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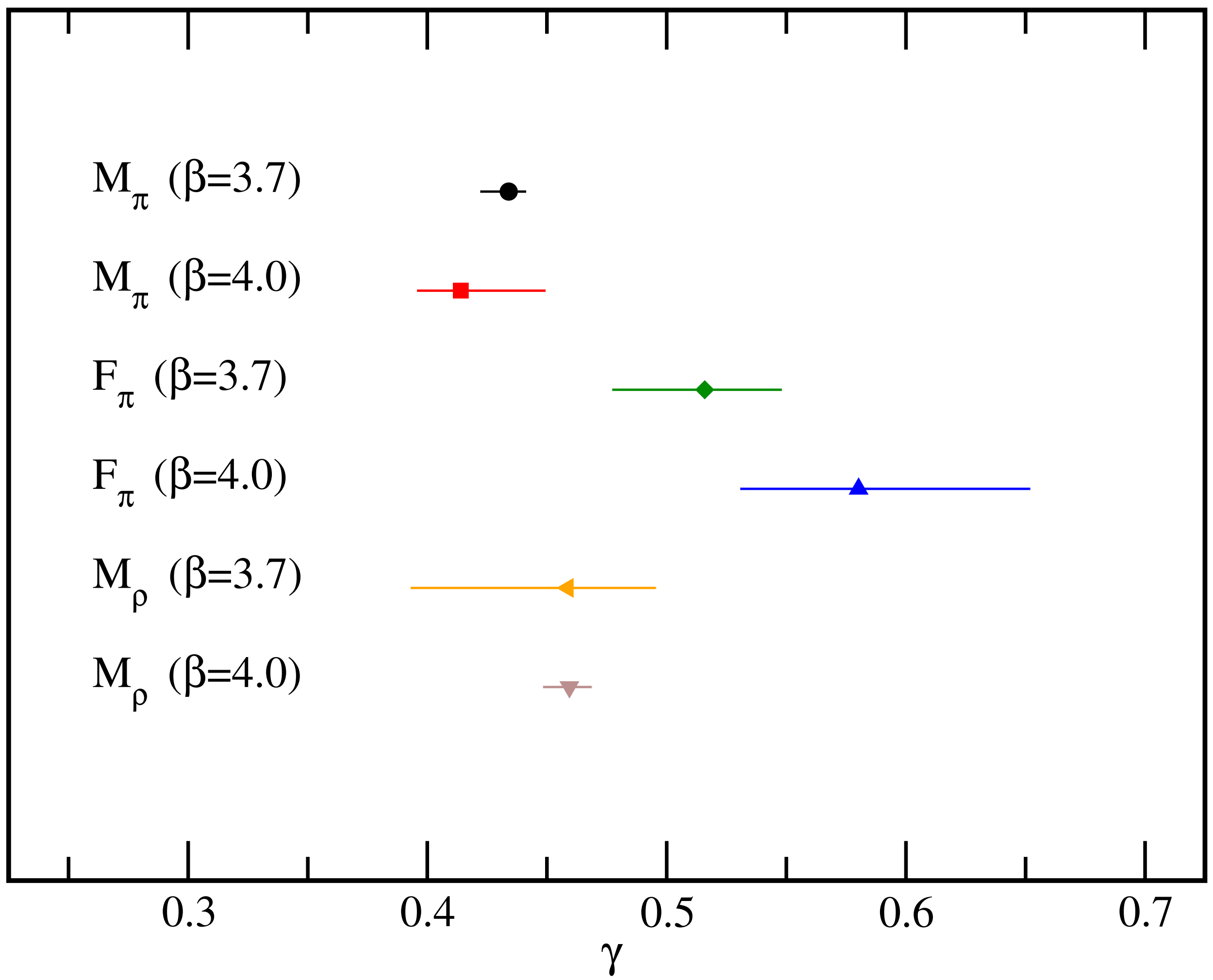
M_π	3.7	0.434(4)	0.425(9)	0.436(6)	0.437(4)	0.438(6)	0.433(4)	0.429(8)
M_π	4	0.414(5)	0.420(7)	0.418(6)	0.411(5)	0.397(7)	0.414(4)	0.447(9)
F_π	3.7	0.516(12)	0.481(19)	0.512(19)	0.544(14)	0.526(18)	0.514(11)	0.505(24)
F_π	4	0.580(15)	0.552(21)	0.602(20)	0.605(19)	0.544(27)	0.577(14)	0.645(32)
M_ρ	3.7	0.459(8)	0.411(17)	0.461(10)	0.473(8)	0.491(15)	0.457(8)	0.414(18)
M_ρ	4	0.460(9)	0.458(13)	0.455(14)	0.460(8)	0.457(16)	0.459(8)	0.463(15)

- β=3.7: smaller m : closer to M_π
- β=3.7: larger V: closer to M_π
- β=4.0: not conclusive: possibly due to large m → take variation as sys. err.

summary of γ obtained by minimizing P(γ)



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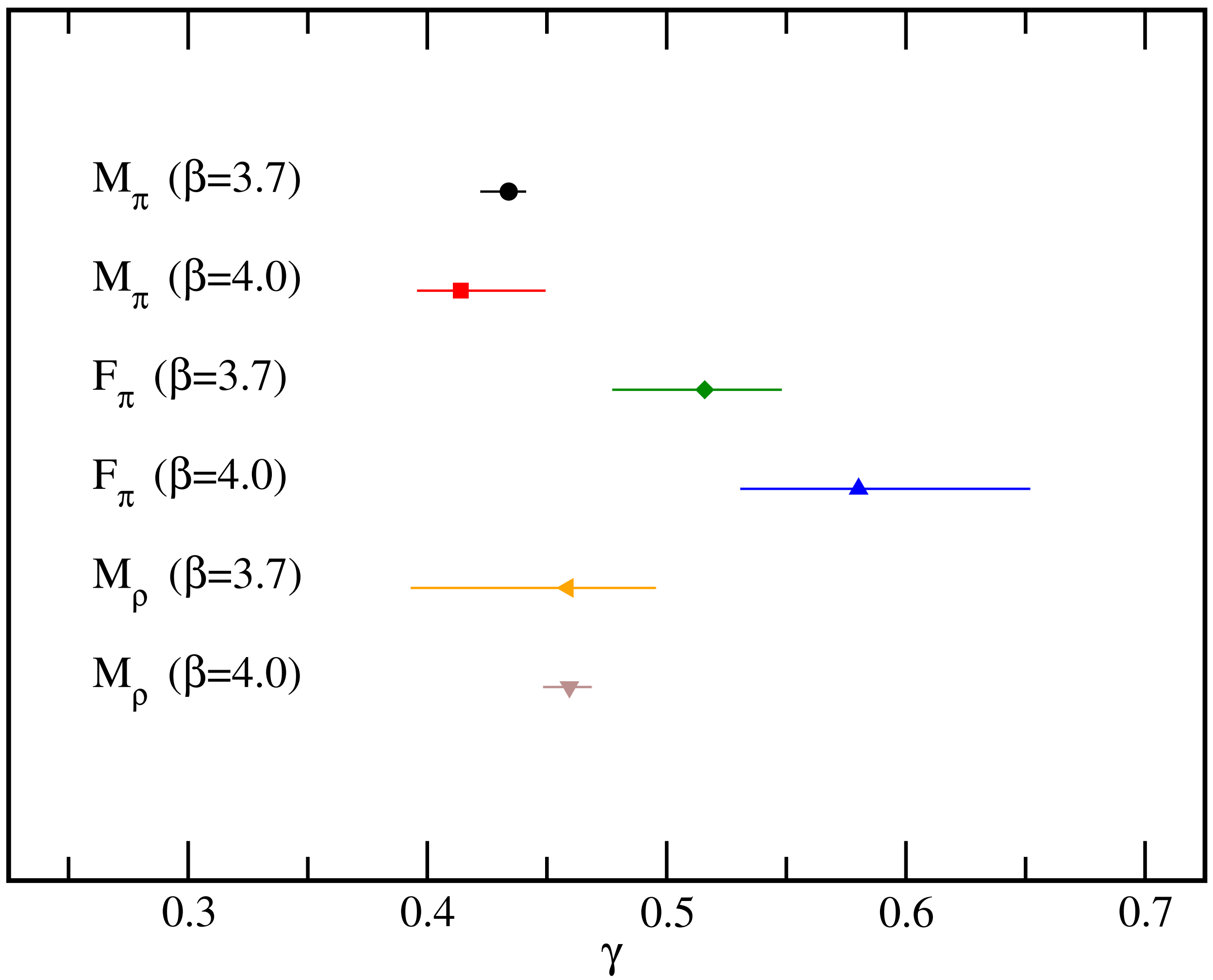

- γ: consistent with 2 σ level except for F_π at β=4.0

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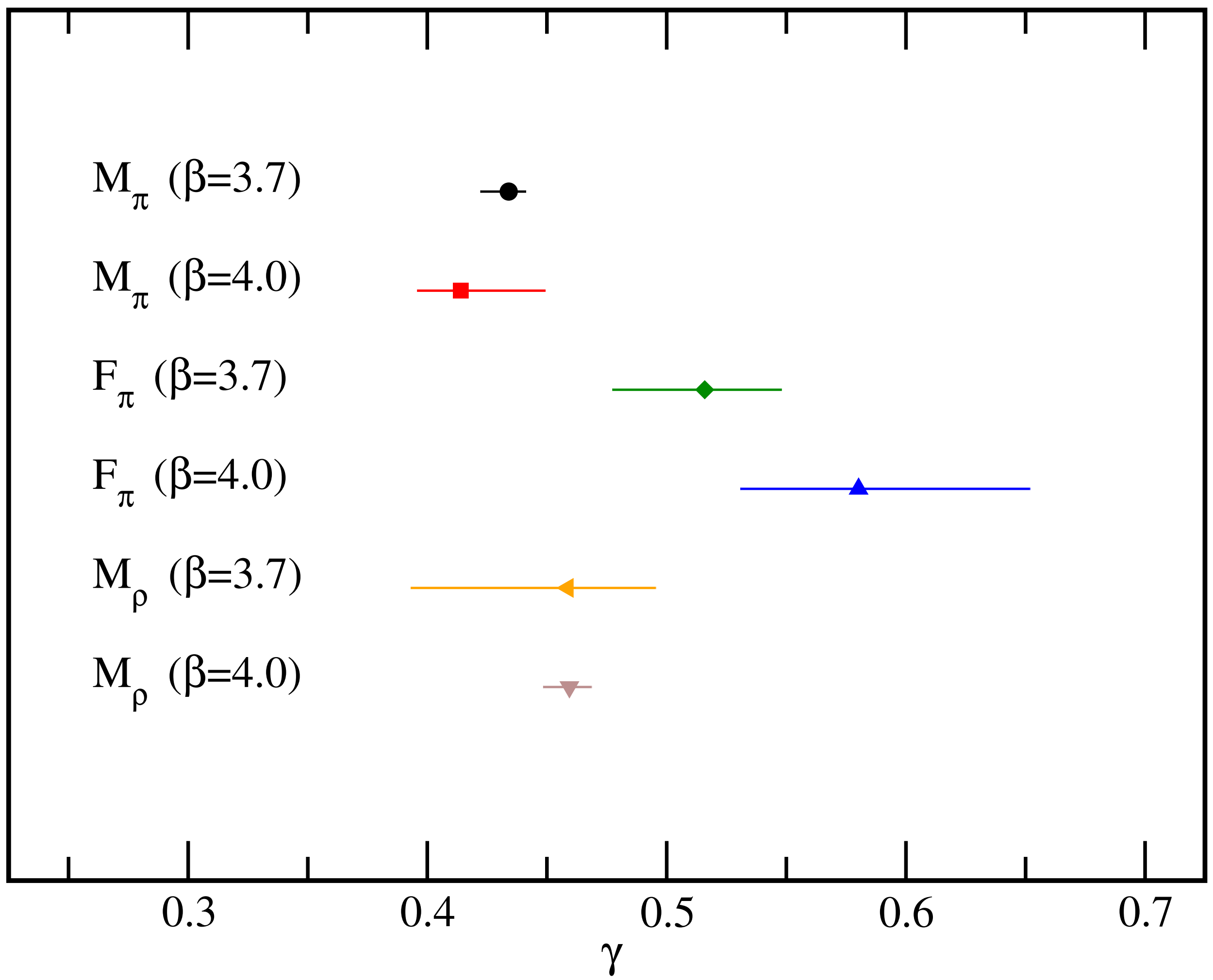

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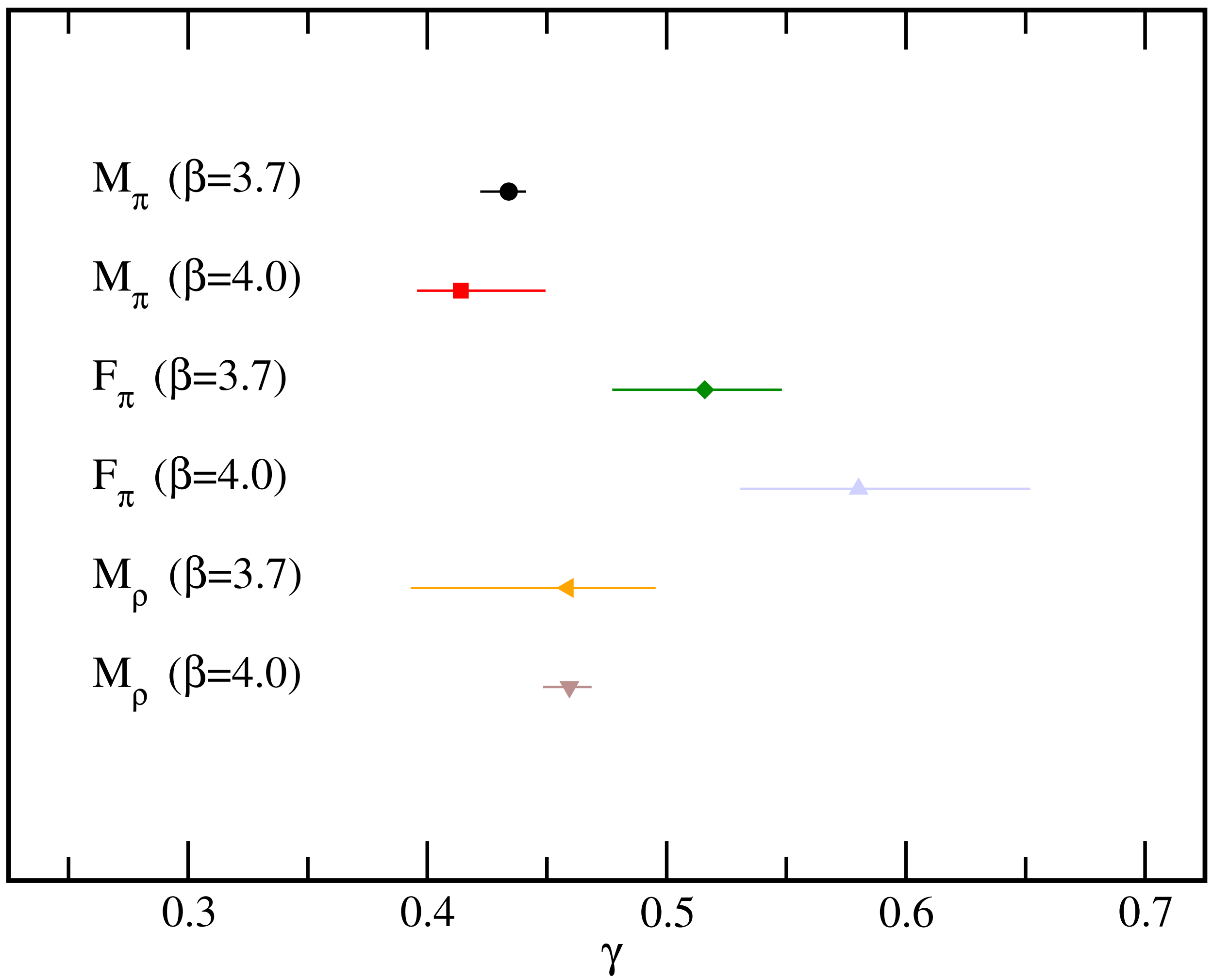


- γ: consistent with 2 σ level except for F_π at β=4.0
- remember: F_π at β=4.0 speculated to be out of the scaling region
- universal low energy behavior: good with $0.4<\gamma_*<0.5$

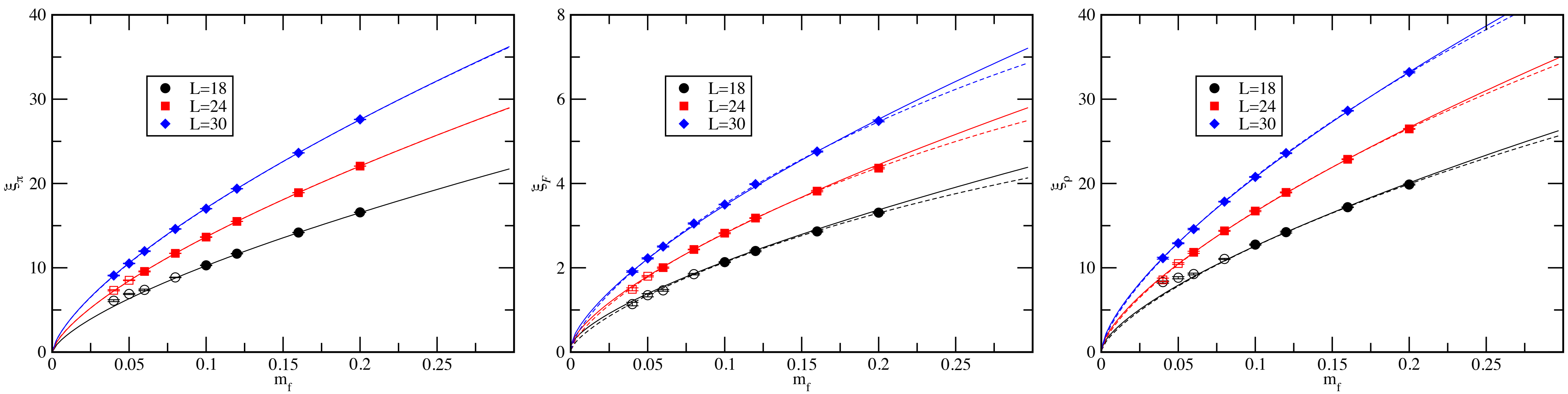
Conformal type global fit
with finite volume correction

$$\xi = LM_\pi,\ LF_\pi,\ LM_\rho$$

$$\xi = c_0 + c_1 L m_f^{1/(1+\gamma)} \quad \cdots \text{fit a},$$

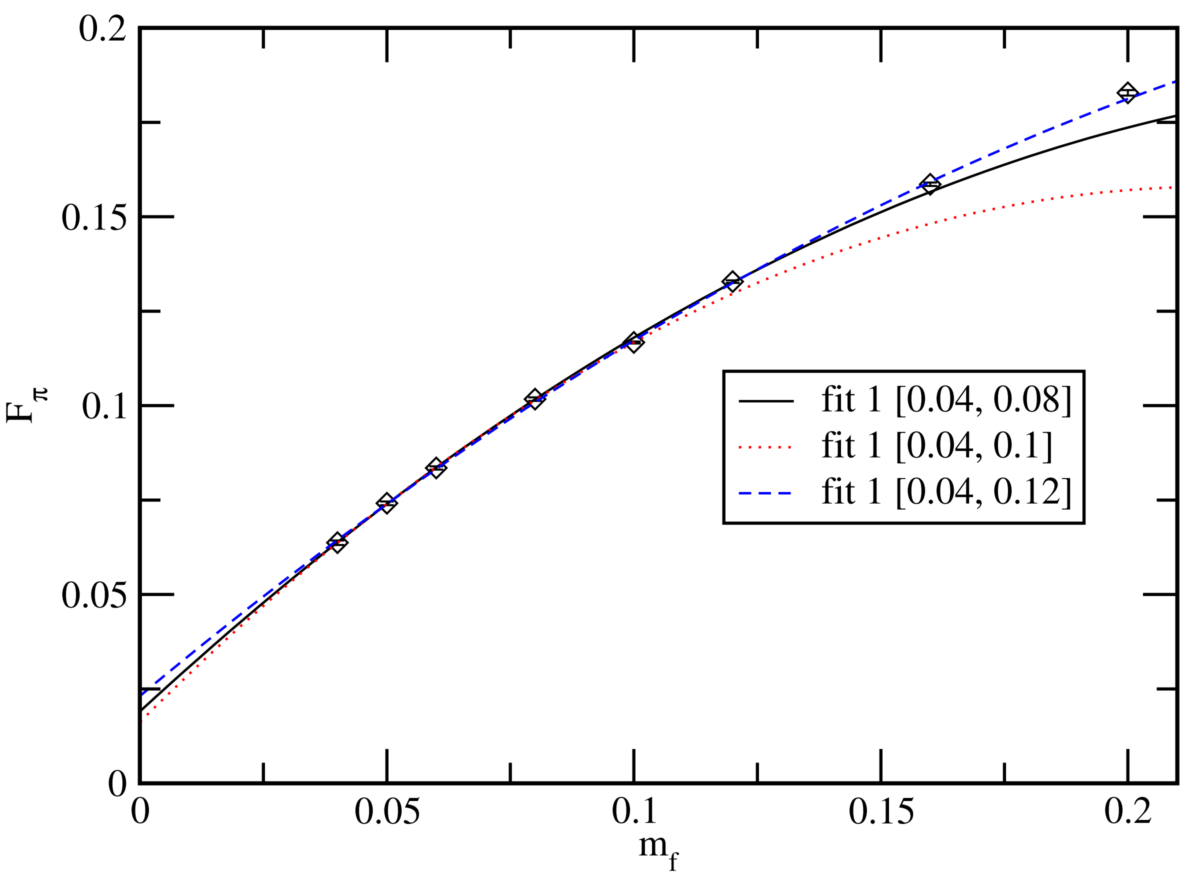
$$\xi = c_0 + c_1 L m_f^{1/(1+\gamma)} + c_2 L m_f^{\alpha} \quad \cdots \text{fit b}.$$

	γ	α	χ^2/dof
fit a	0.449(3)	-	4.52
fit b-1	0.411(9)	$\frac{(3-2\gamma)}{(1+\gamma)}$	1.23
fit b-2	0.423(7)	[2]	1.15



- simultaneous fit it with a leading mass dependent correction is not bad
  - b-1: Ladder Schwinger-Dyson, b-2: $(am)^2$ lattice artifact
    [see, LatKMI PRD85(2012)074502]
- resulting γ is consistent with the model independent analysis

ChPT fit (after infinite volume extrapolation)



$$h(m_f) = c_0 + c_1 m_f + c_2 m_f^2$$

fit range	c_0	c_1	c_2	χ^2/dof
fit 1 : $[0.04, 0.08]$	0.0190(52)	1.21(18)	-2.2(1.5)	0.29
fit 1 : $[0.04, 0.1]$	0.0162(30)	1.31(85)	-3.01(58)	0.37
fit 1 : $[0.04, 0.12]$	0.0231(18)	1.093(48)	-1.51(29)	3.30

- 2nd order polynomial fit is reasonably good for small mass range & c_0>0

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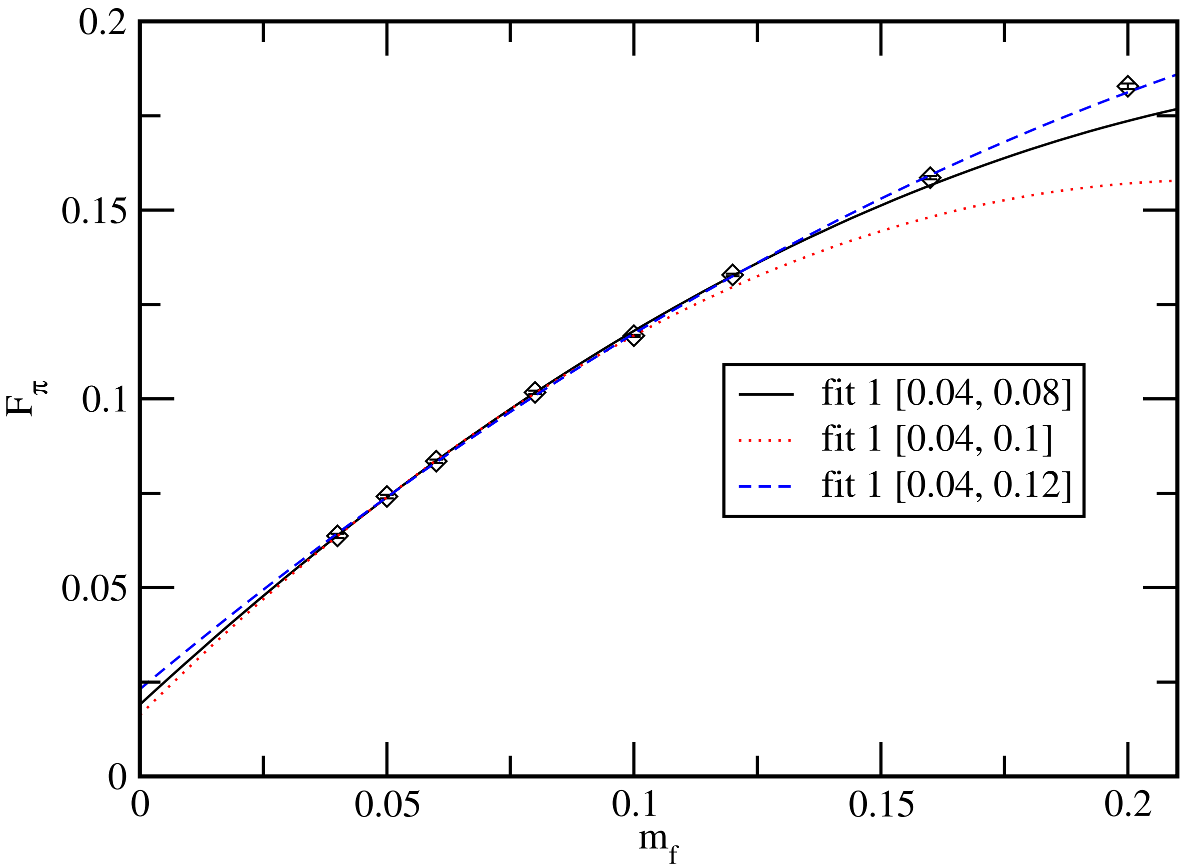

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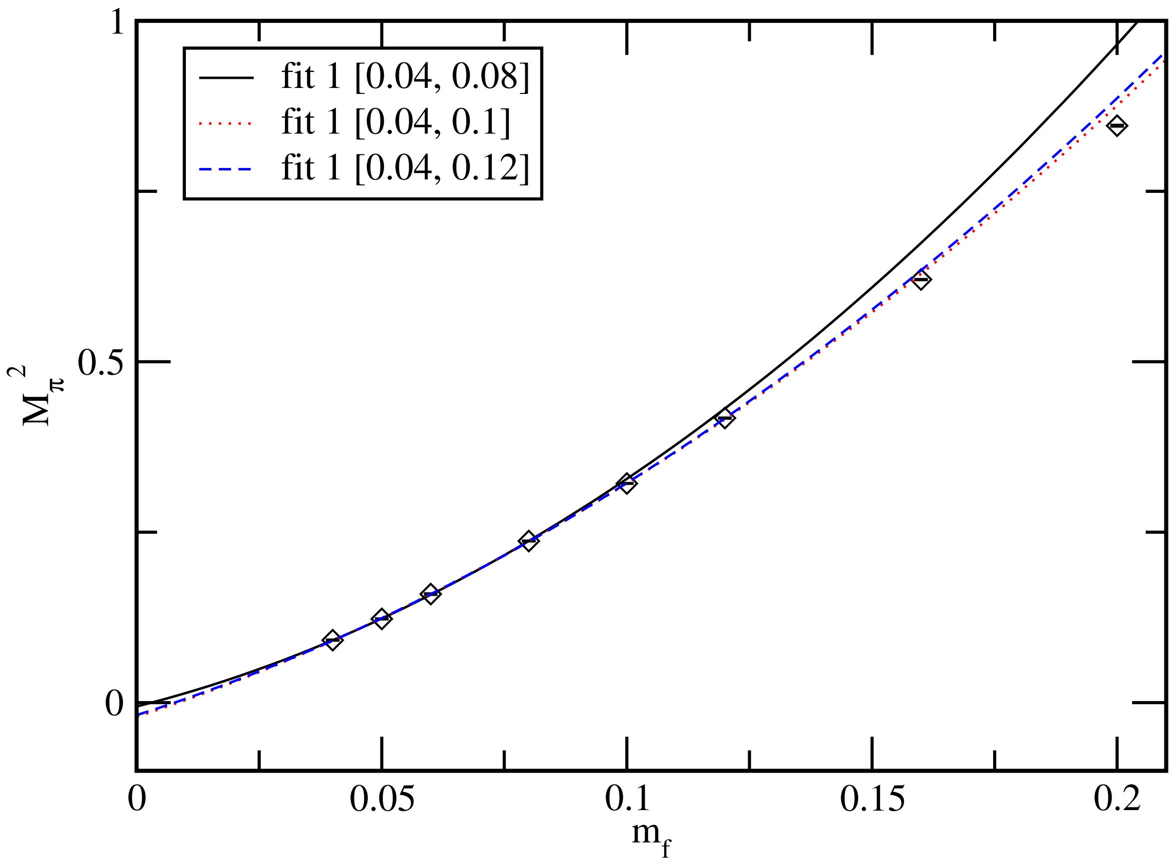

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fit range	c_0	c_1	c_2	χ^2/dof
fit 1 : [0.04, 0.08]	-0.0057(91)	1.82(32)	15.2(2.6)	1.35
	[0]	1.62(3)	16.76(45)	0.88
fit 1 : [0.04, 0.1]	-0.0209(48)	2.37(15)	10.6(1.1)	2.59
	[0]	1.729(21)	14.99(25)	8.33
fit 1 : [0.04, 0.12]	-0.0183(31)	2.28(87)	11.21(55)	1.90
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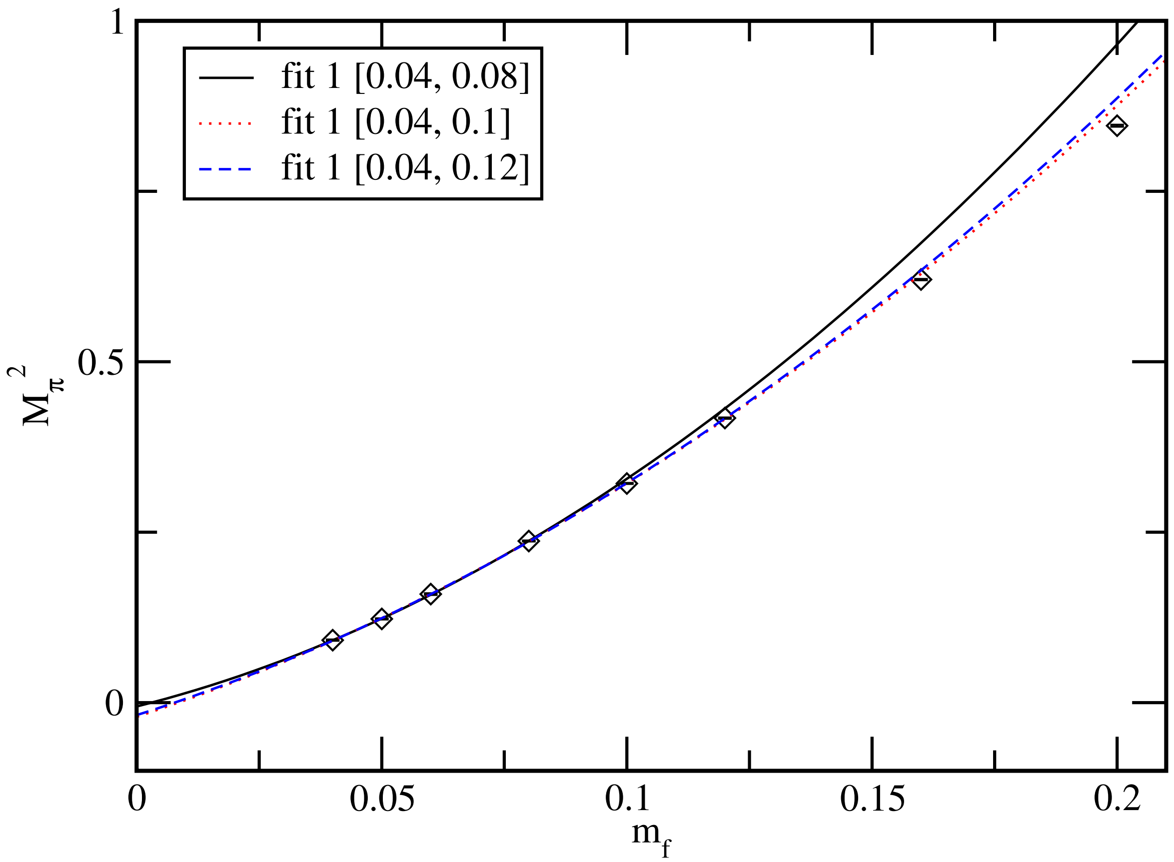

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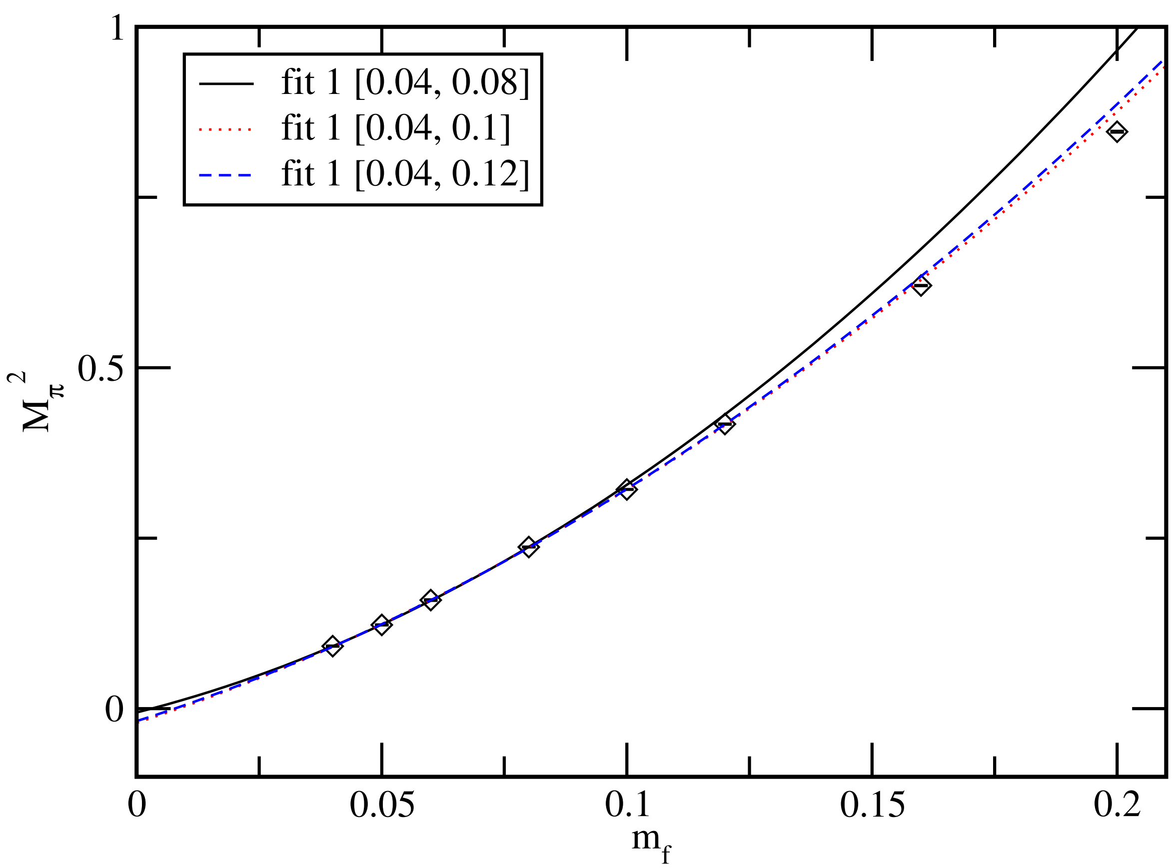

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- consistent with c_0=0 for the smallest mass range
- But: $N_f[M_\pi/(4\pi F)]^2 \sim 40$ at lightest point → difficult to tell real chiral behavior

N_f=12 Summary

for details, see LatKMI collaboration, PRD86 (2012) 054506 [arXiv:1207.3060].

- β=3.7, 4.0: consistent with being in the asymptotically free regime
- M_π, F_π, M_ρ: consistent with the finite size hyper scaling for conformal theory
- resulting γ^* from different quantities, lattice spacings are consistent except
  - F_π at β=4.0 (m_f likely too heavy for universal mass dep. to dominate)
- careful continuum scaling required to get more accurate than $0.4<\gamma^*<0.5$
- real / remnant (approximate) conformal property definitely exists
- could not exclude SχSB with very small breaking scale
- even if SχSB, γ_m too small for walking theory of phenomenological interest
- N_f<12 should be examined for the quest of the walking technicolor theory

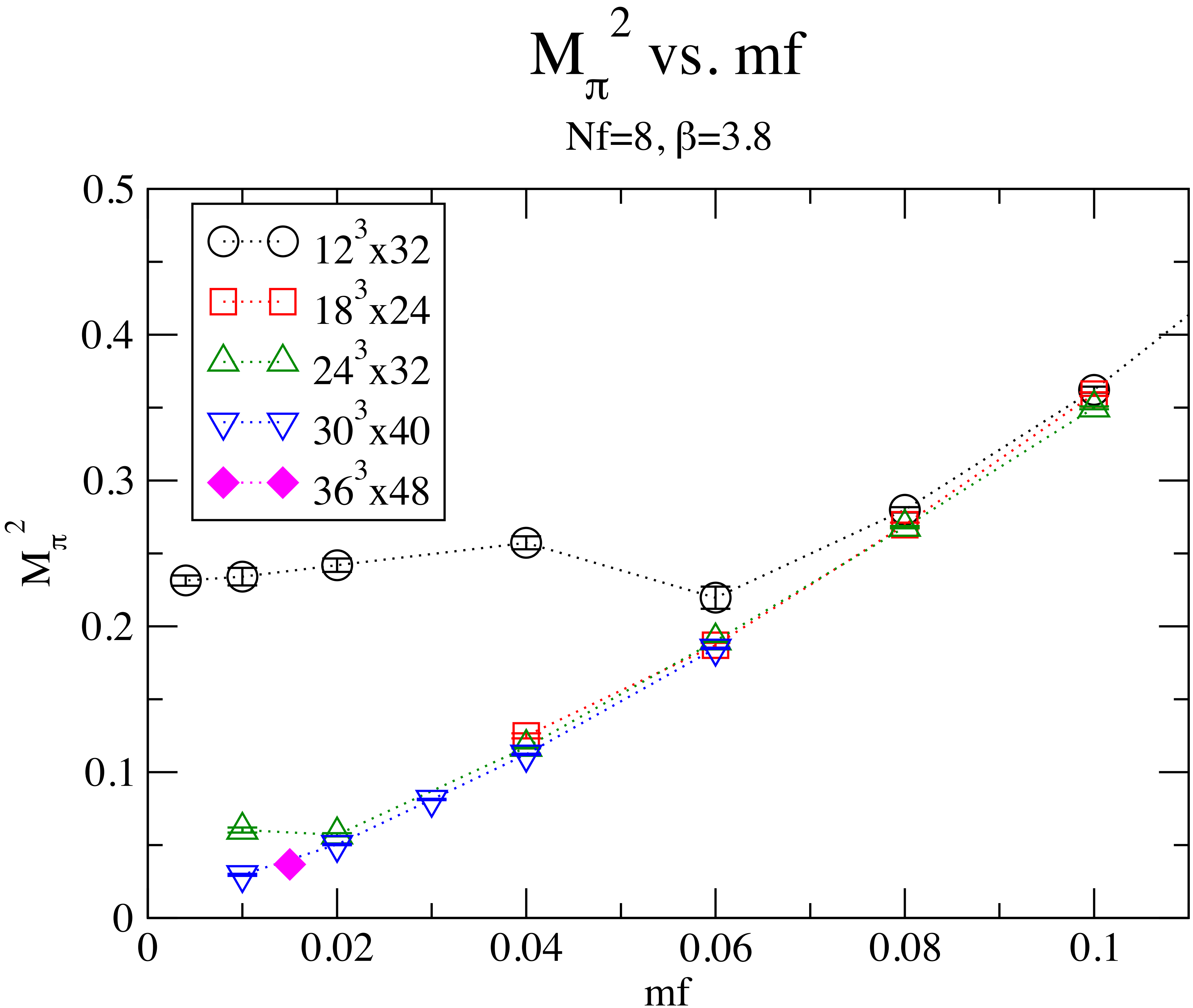
SU(3) + N_f=8   [fundamental]

examined with same setup / method

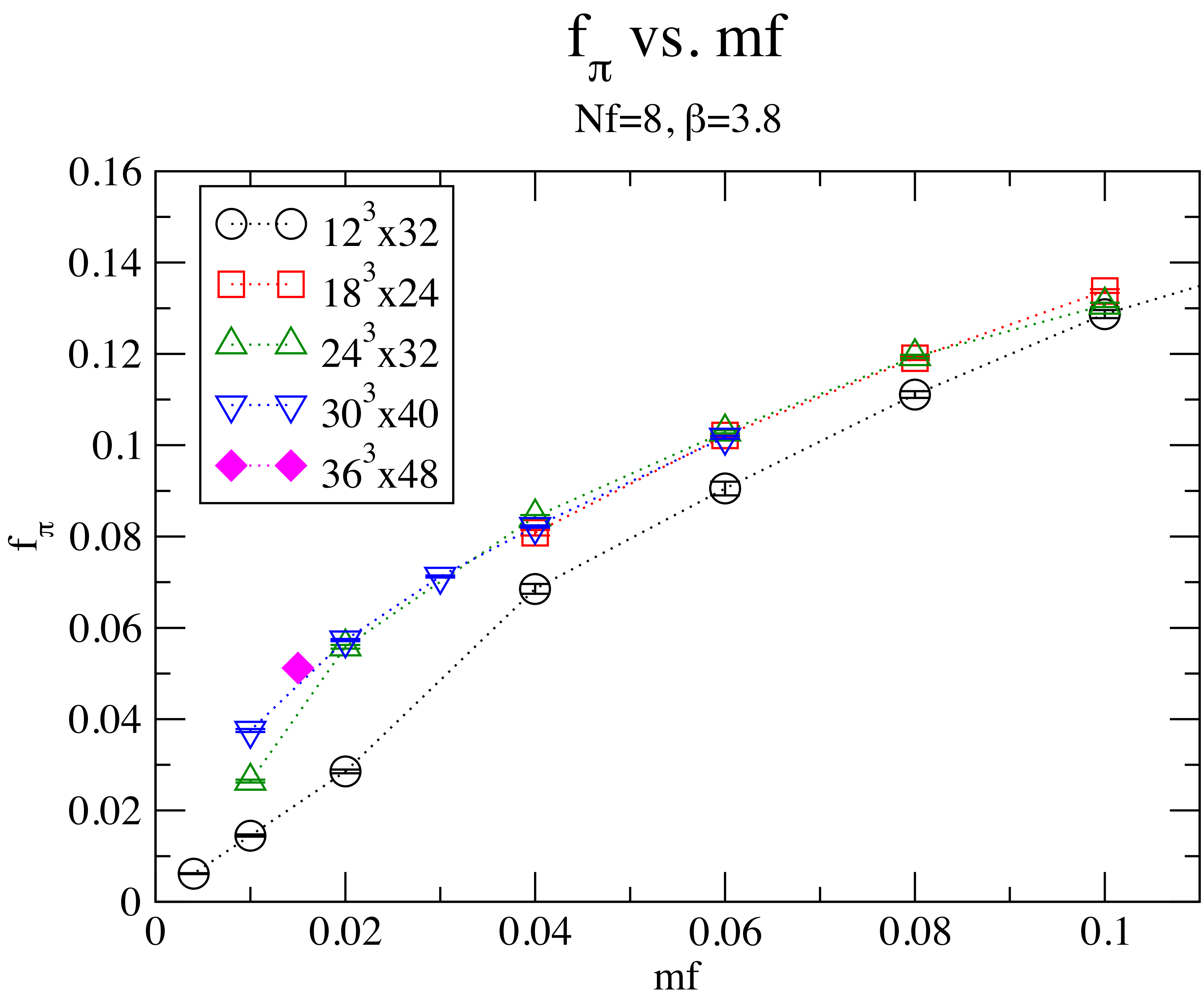
candidate of the walking technicolor ?

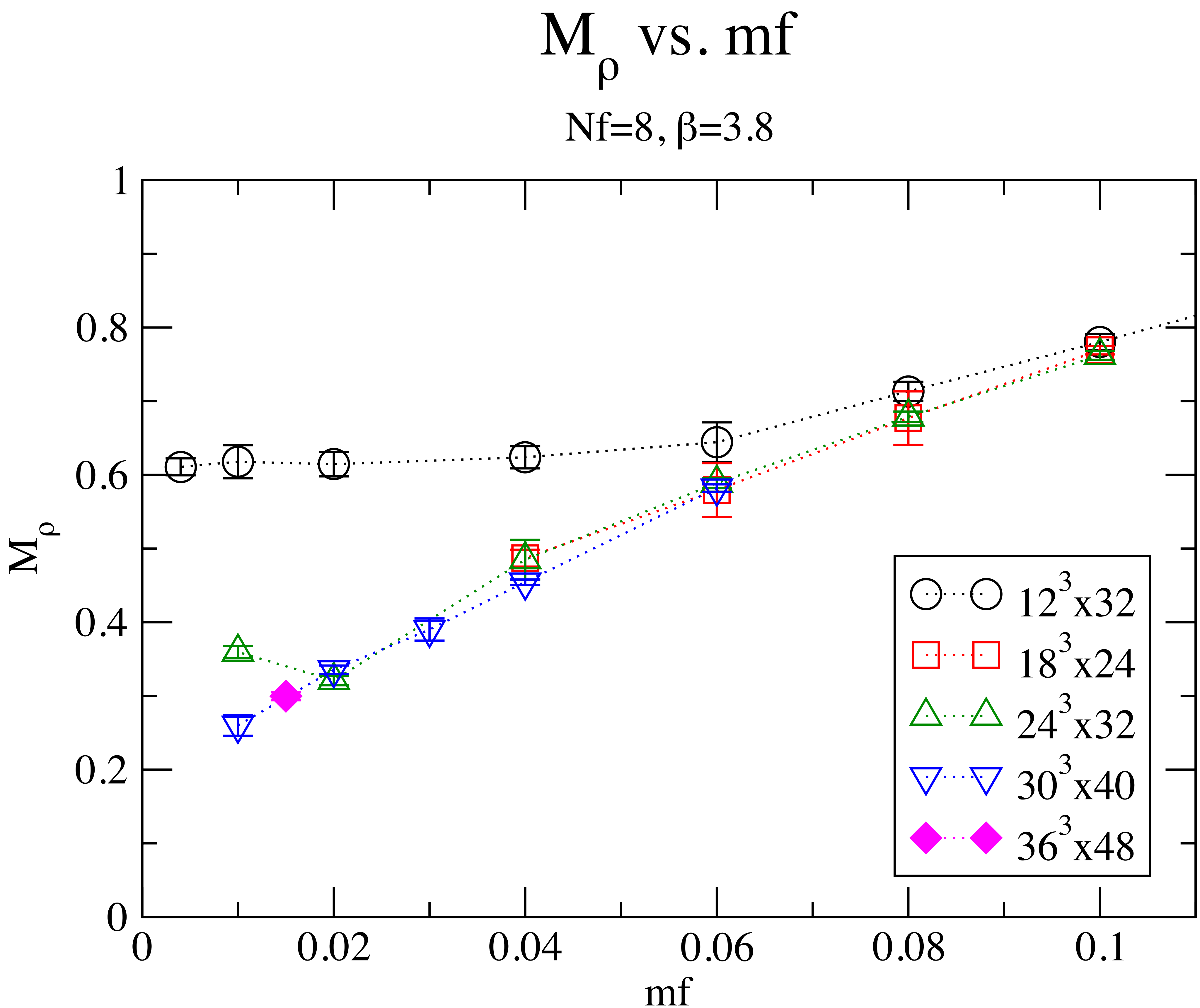
[preliminary]

[LatKMI collab., Lattice2011/2012]



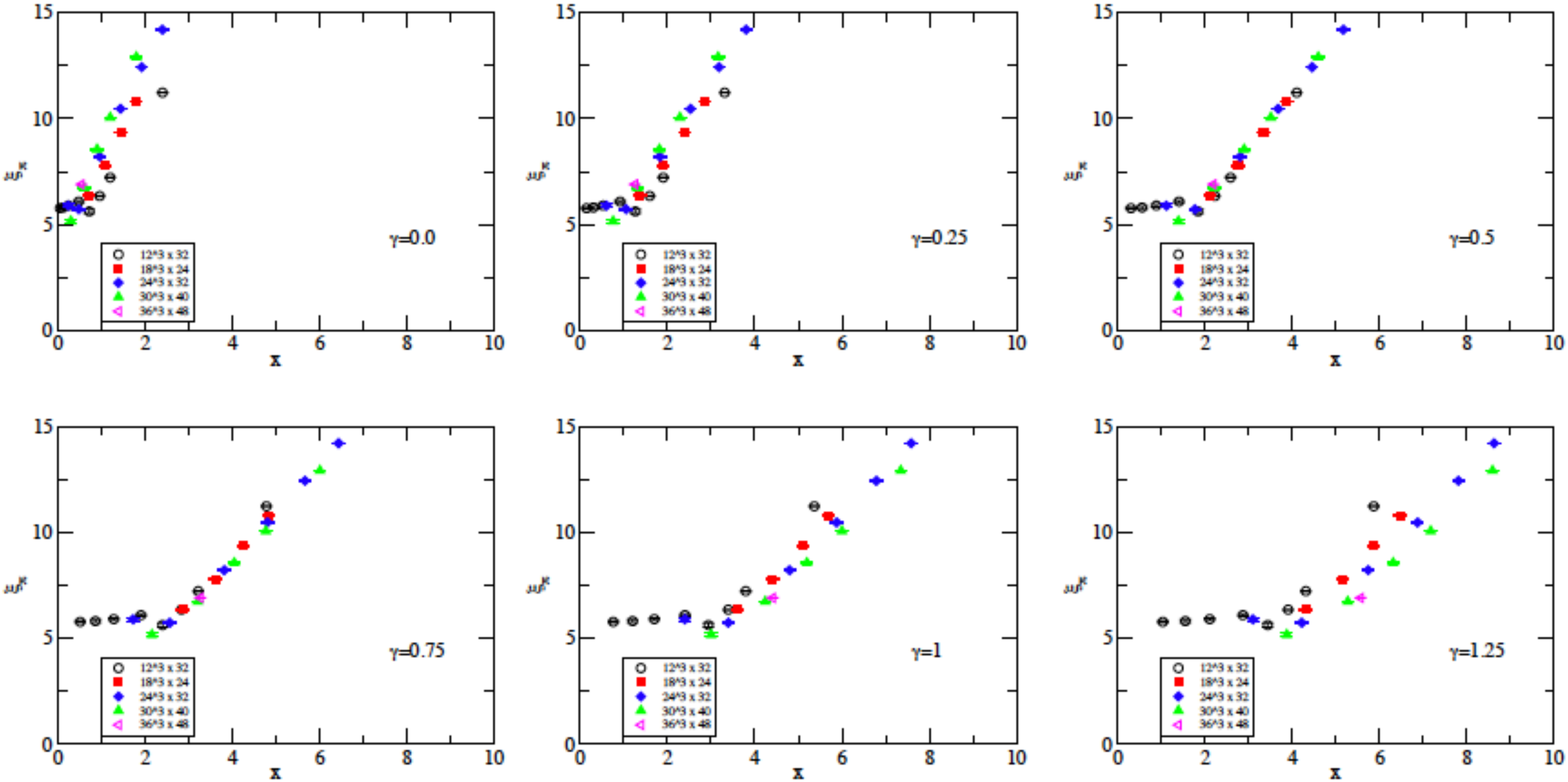
2012年10月27日土曜日


fπ vs. mf
Nf=8, β=3.8
12³x32
18³x24
24³x32
30³x40
36³x48
fπ
mf
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16



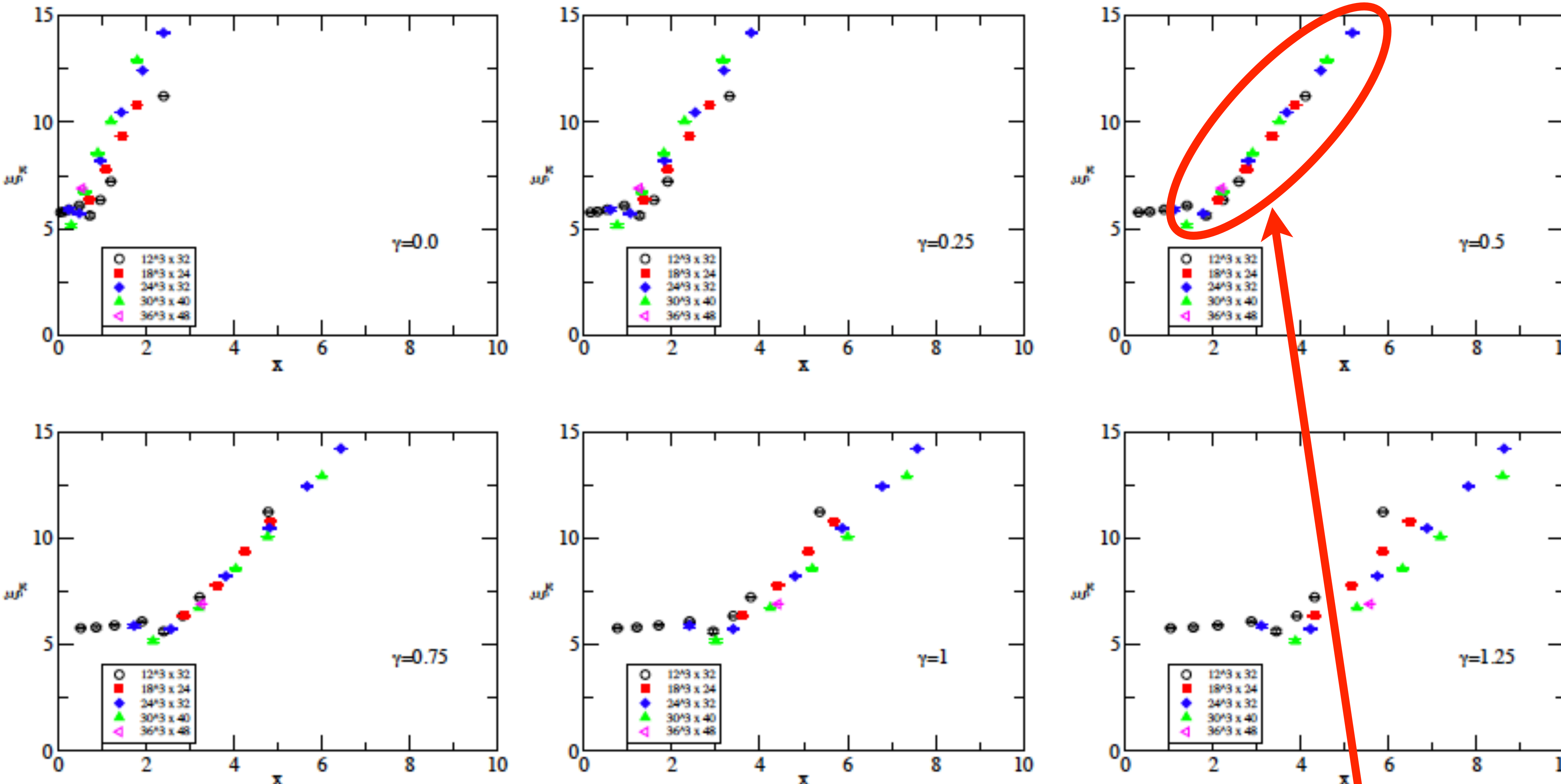
M_ρ vs. mf
Nf=8, β=3.8
M_ρ
mf
0
0.2
0.4
0.6
0.8
1
0
0.02
0.04
0.06
0.08
0.1
12^3x32
18^3x24
24^3x32
30^3x40
36^3x48

hyperscaling test m_π



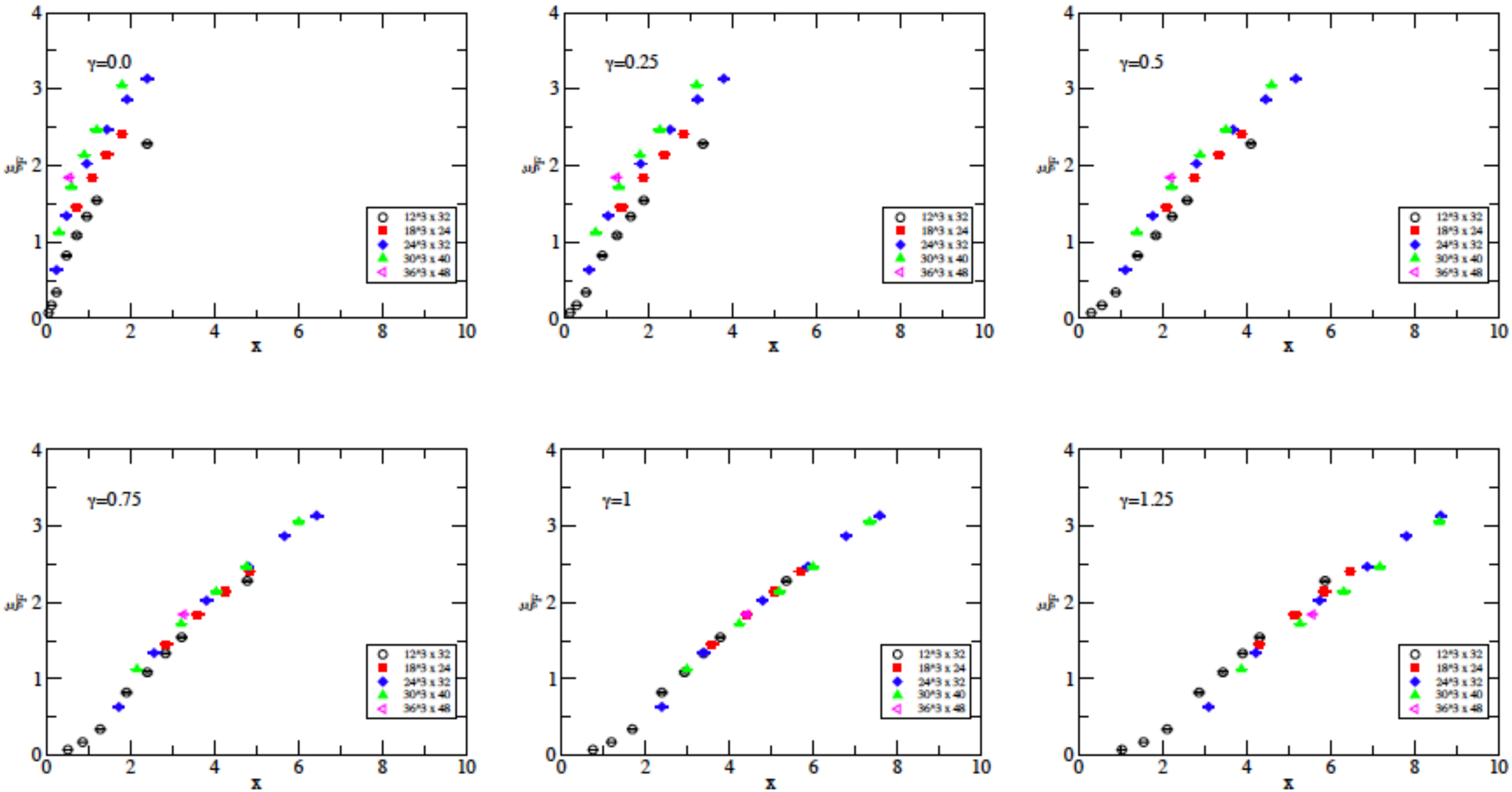
hyperscaling test m_π

γ =0.5

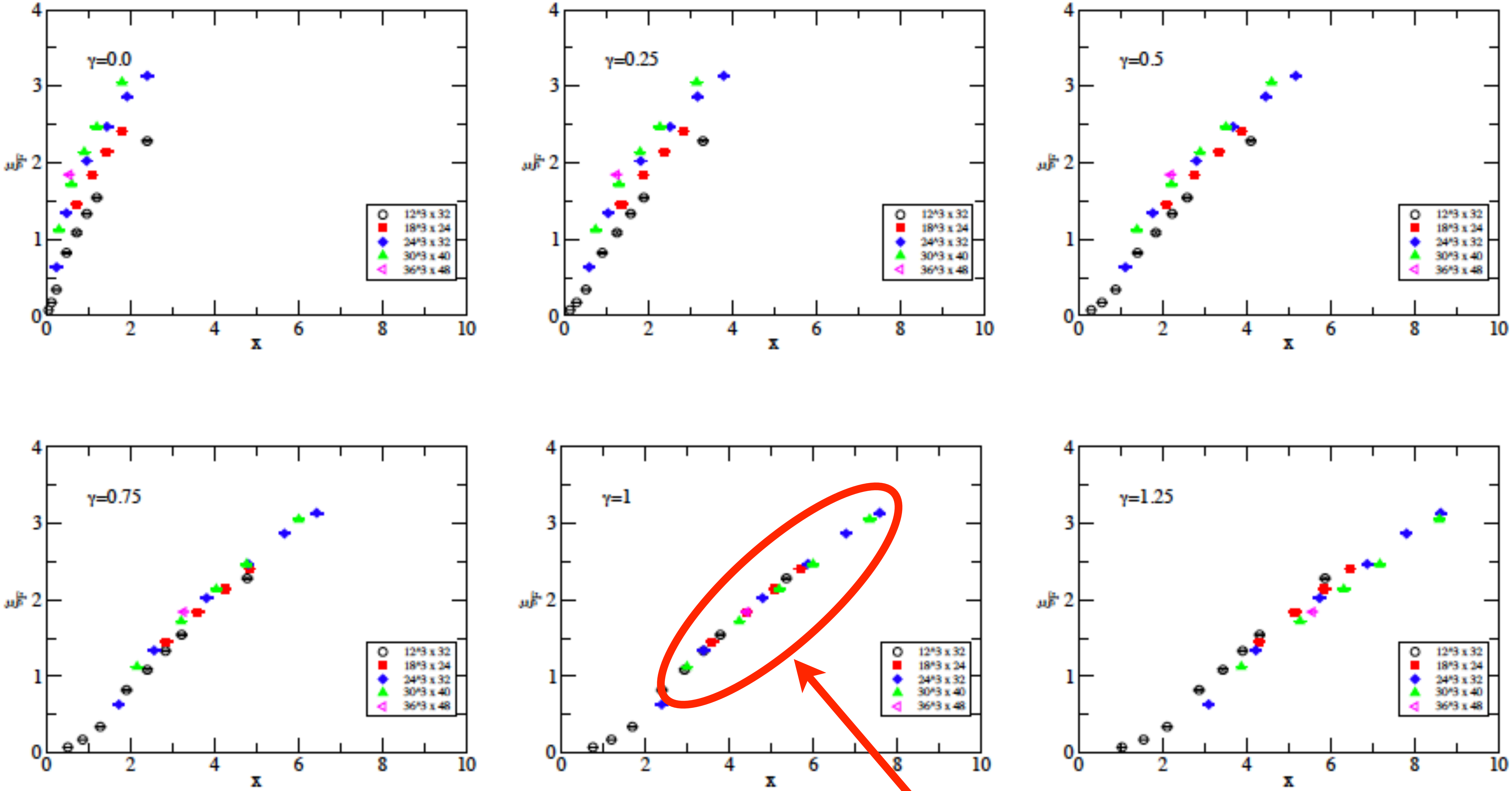


good alignment

hyperscaling test f_π

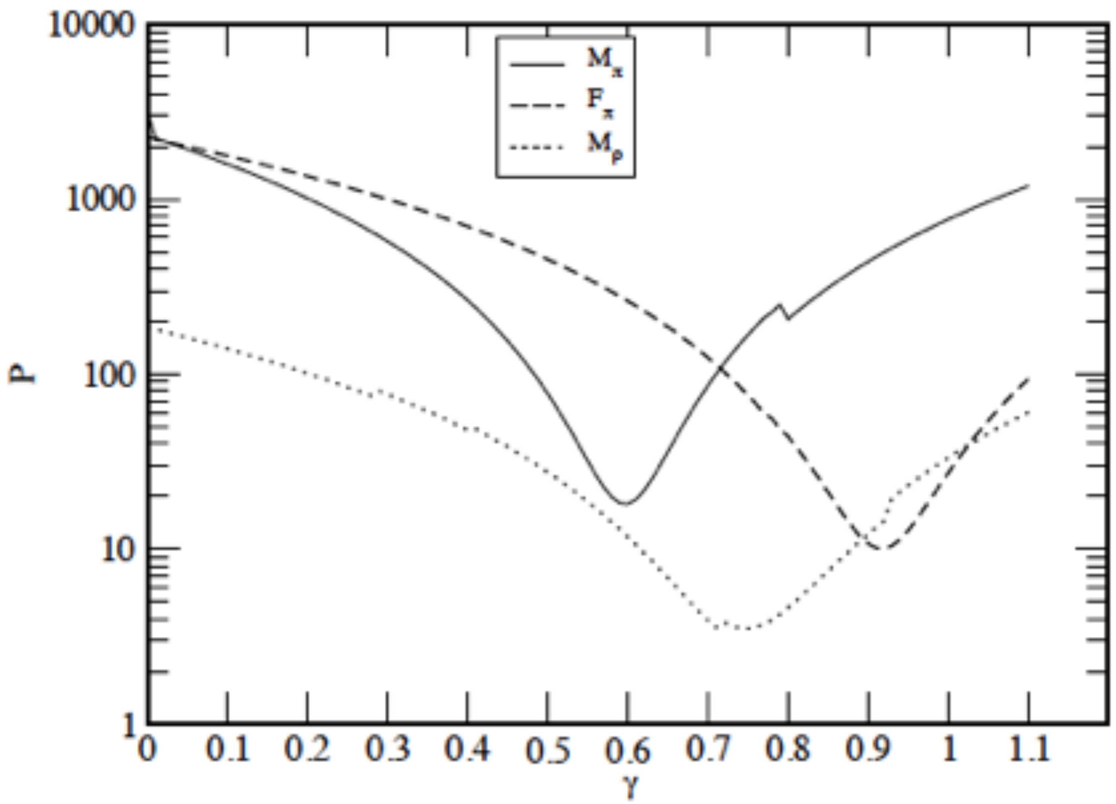


hyperscaling test f_π



$\gamma = 1$ good alignment

$P(\gamma)$ analysis



$N_f=8$

quantity	γ
M_π	0.596(7)
f_π	0.917(11)
M_ρ	0.741(34)

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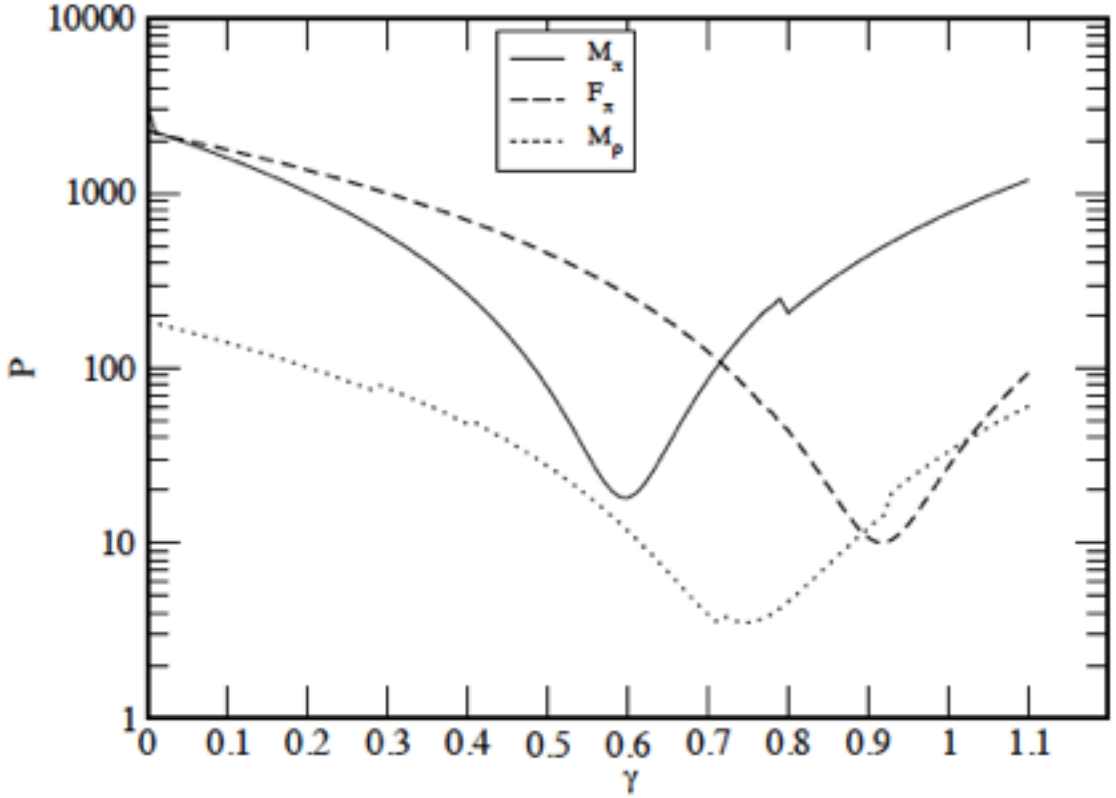

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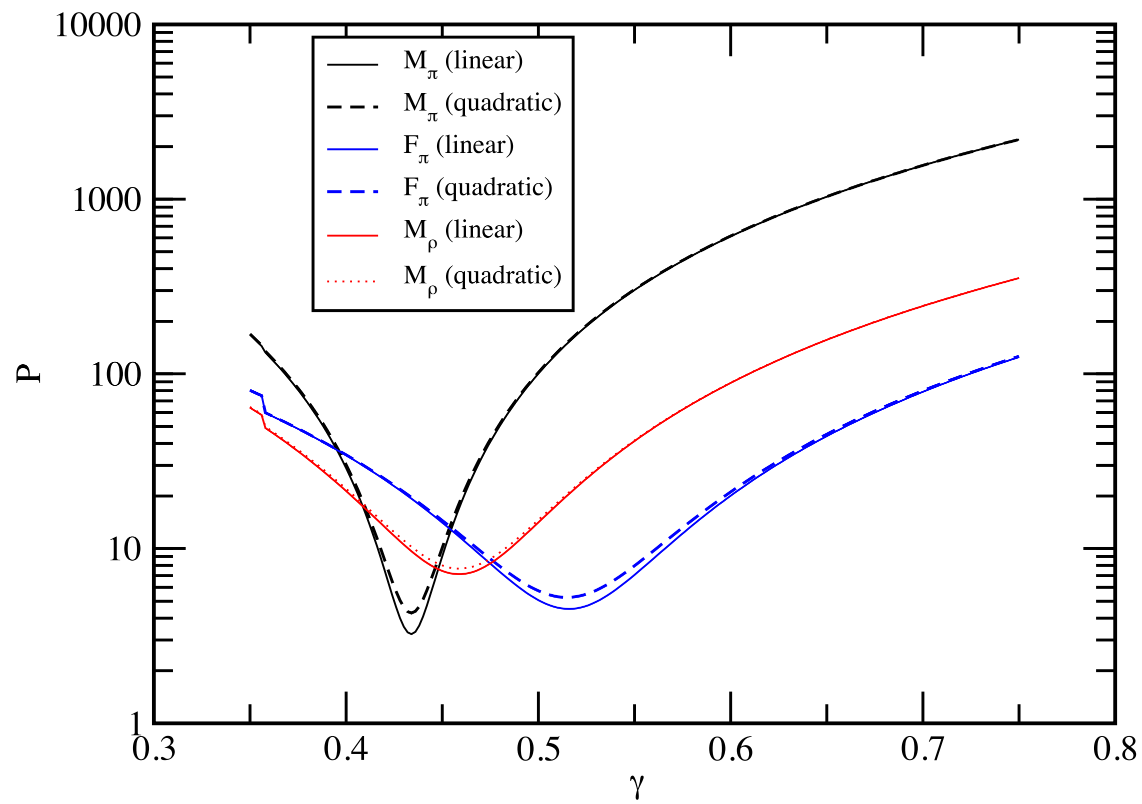
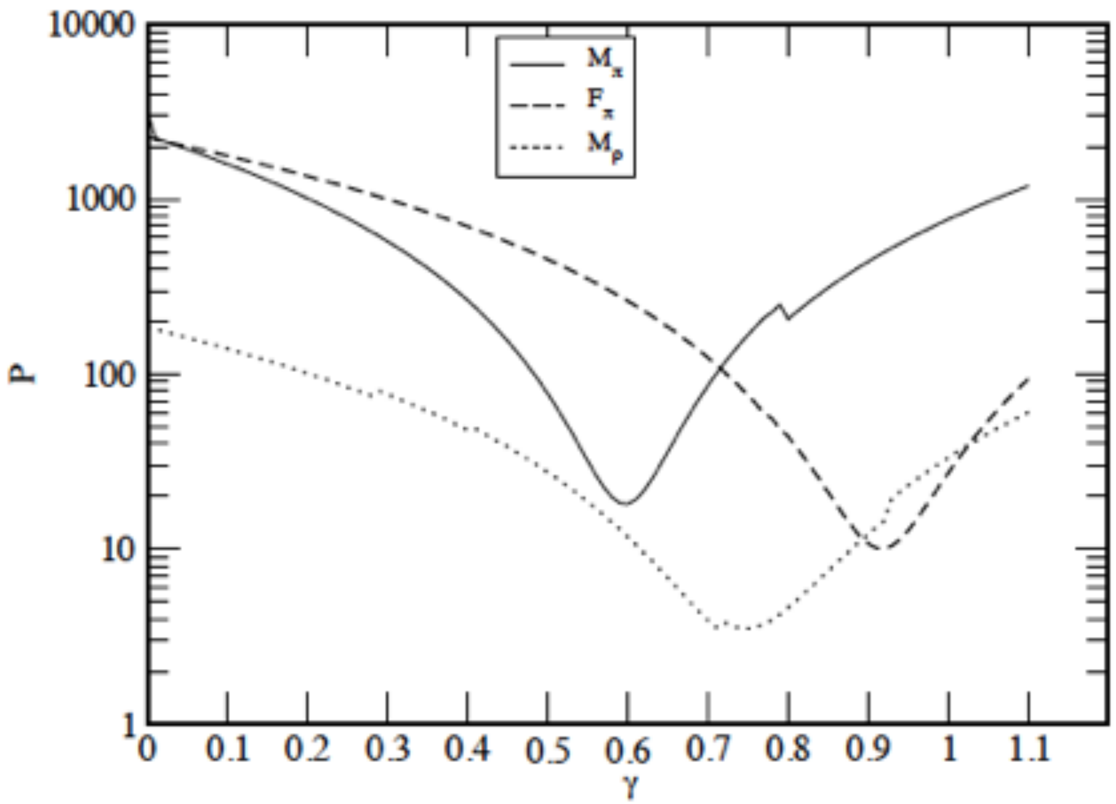


Nf=12

$P(\gamma)$ analysis



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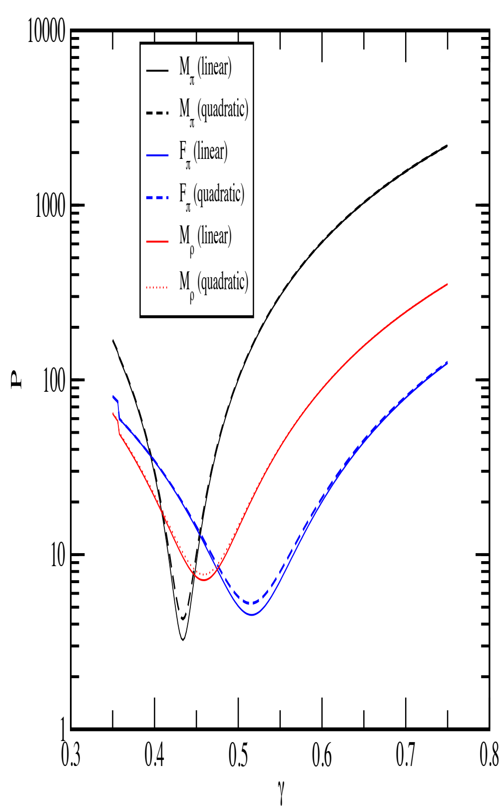

$N_f=12$

N_f=8 [preliminary] Summary

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- likely: $f_\pi \neq 0$, $m_\rho \neq 0$ for $m_f \to 0$
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- candidate of walking ?
- needs further study!

0^{++} glueball spectrum

[VERY preliminary]

0++ glueball

0++ glueball

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0++ glueball

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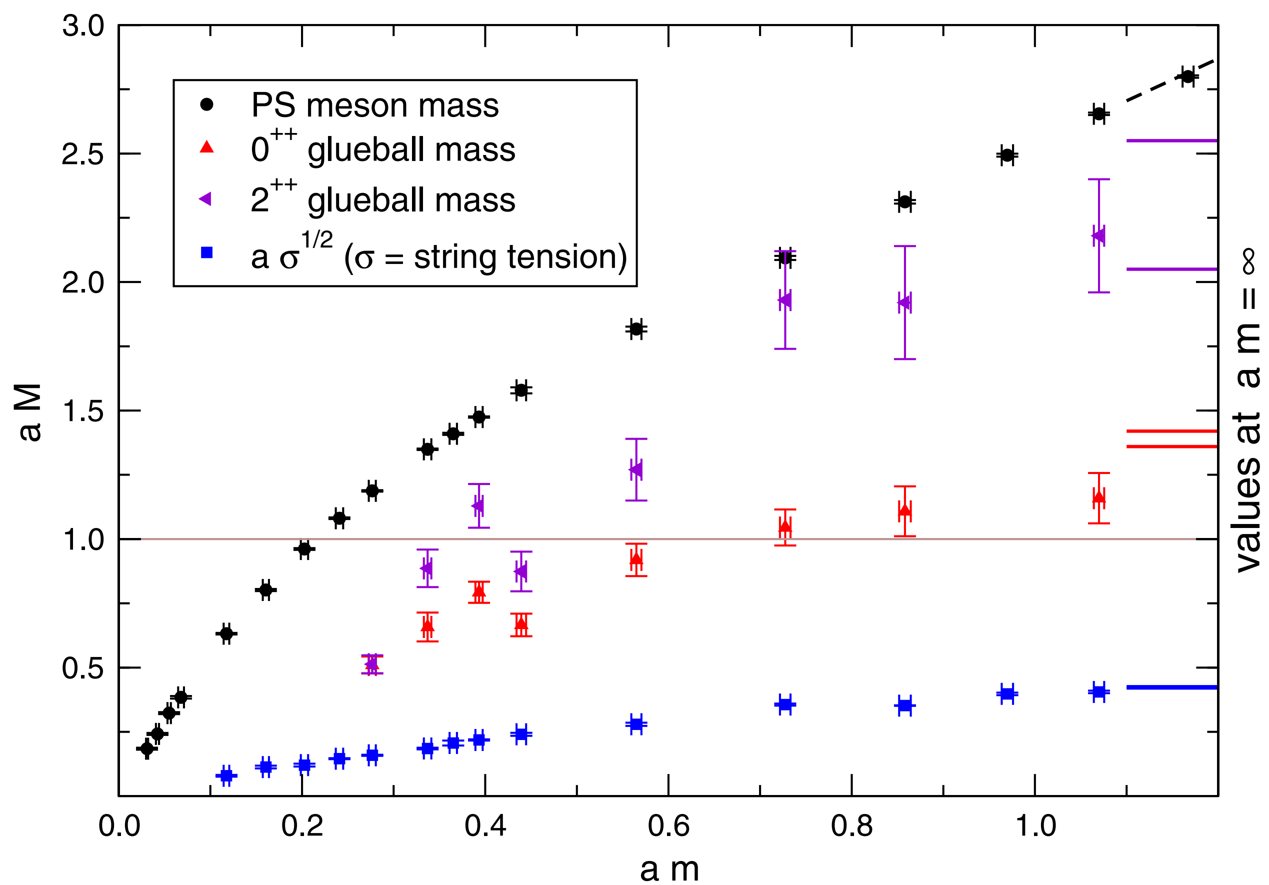

0++ glueball

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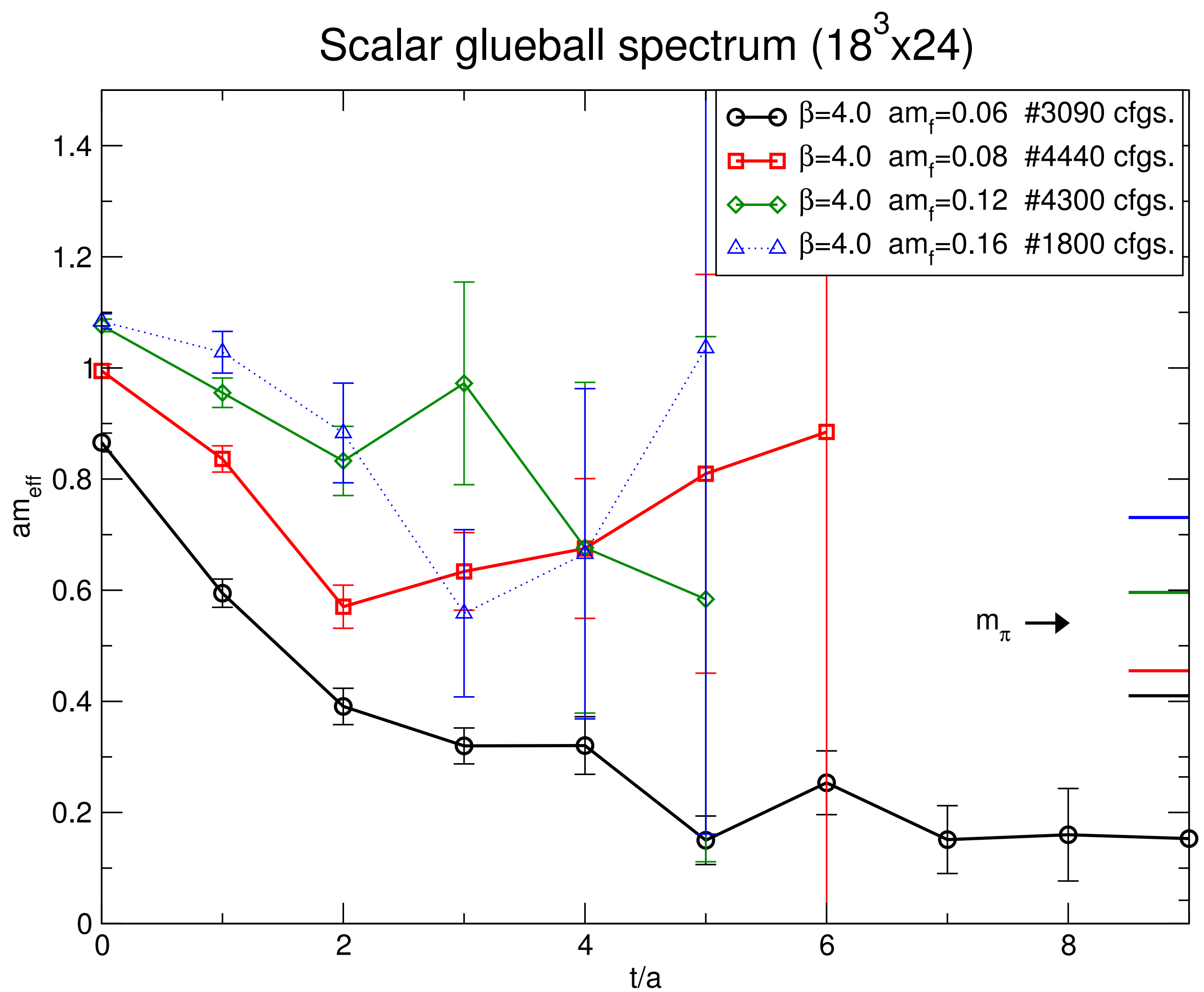
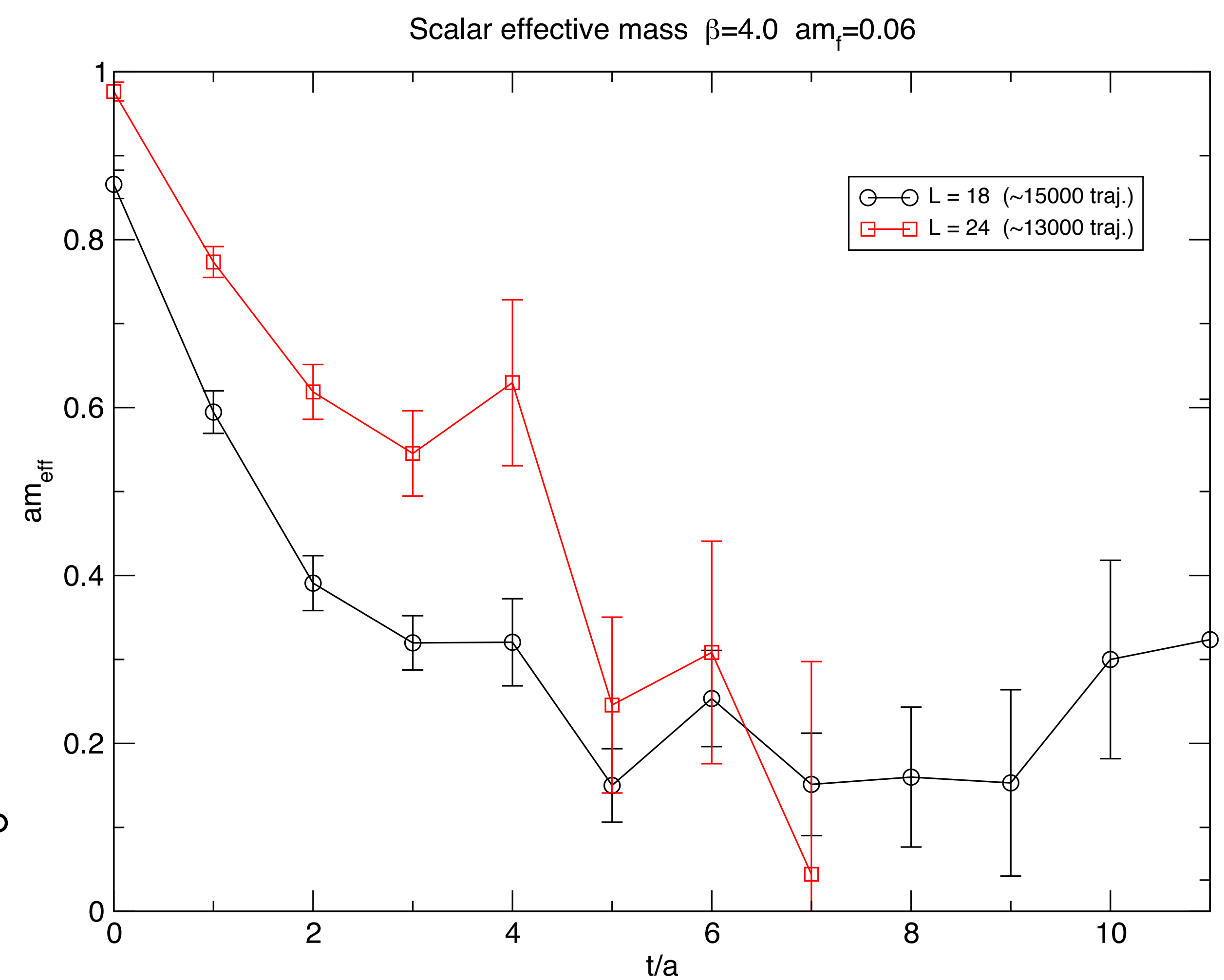
- promising results from a model in the conformal window: SU(2) + 2 adjs
    - Del Debbio et al [PRD82 (2010) 014510]: $m_f \neq 0$, 0++ glueball lighter than pion
- test for SU(3) n_f=12 (consistent with conformal) underway...

SU(3) N_f=12, 0^{++} techni-glueball [preliminary]

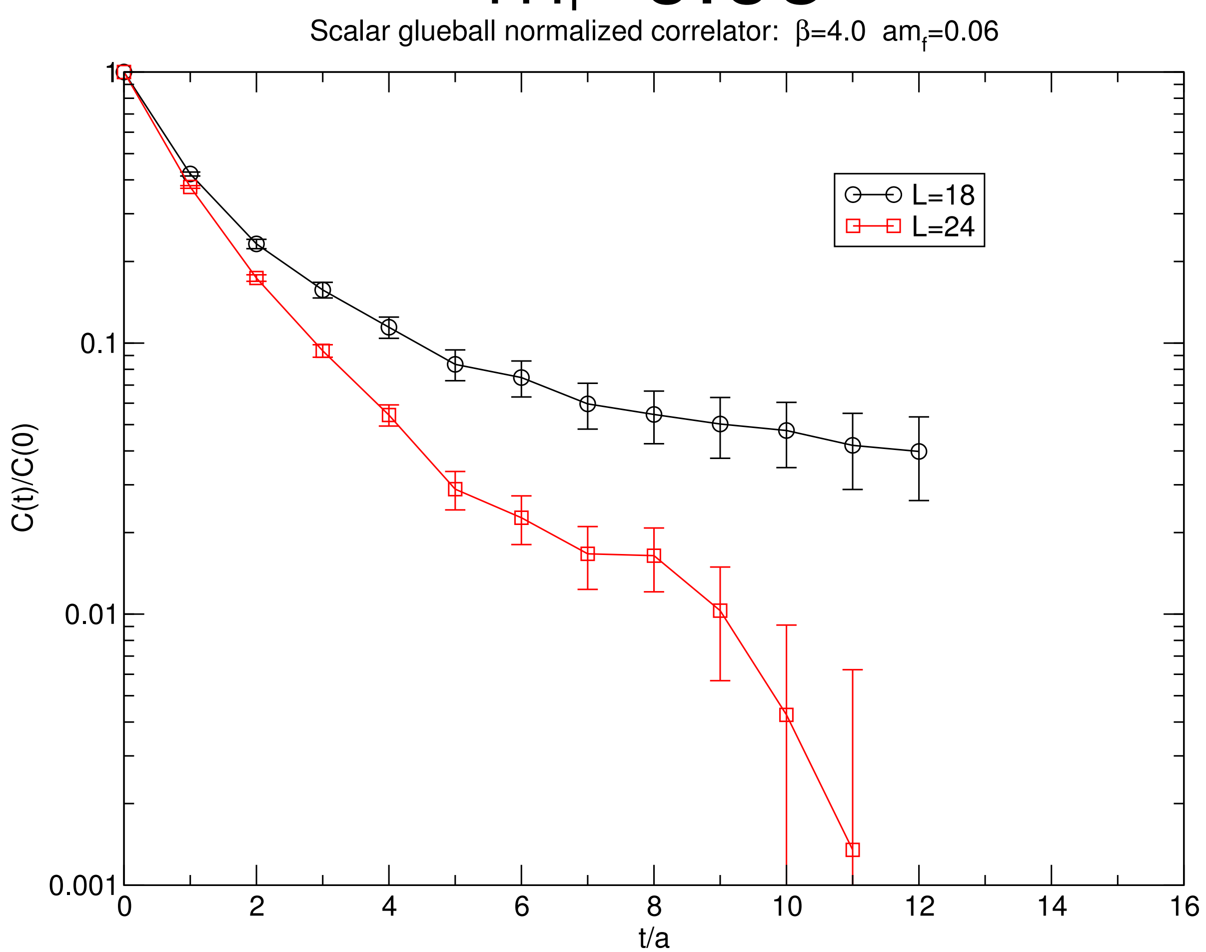




- effective mass from variational method (e.g. E. Gregory et al arXiv:1208.1858)
- 0^{++} techni-glueball is righter than techni-pion @ m_f=0.06
- but...

SU(3) N_f=12, 0^{++} techni-glueball [preliminary]

m_f=0.06



SU(3) N_f=12, 0^{++} techni-glueball [preliminary]

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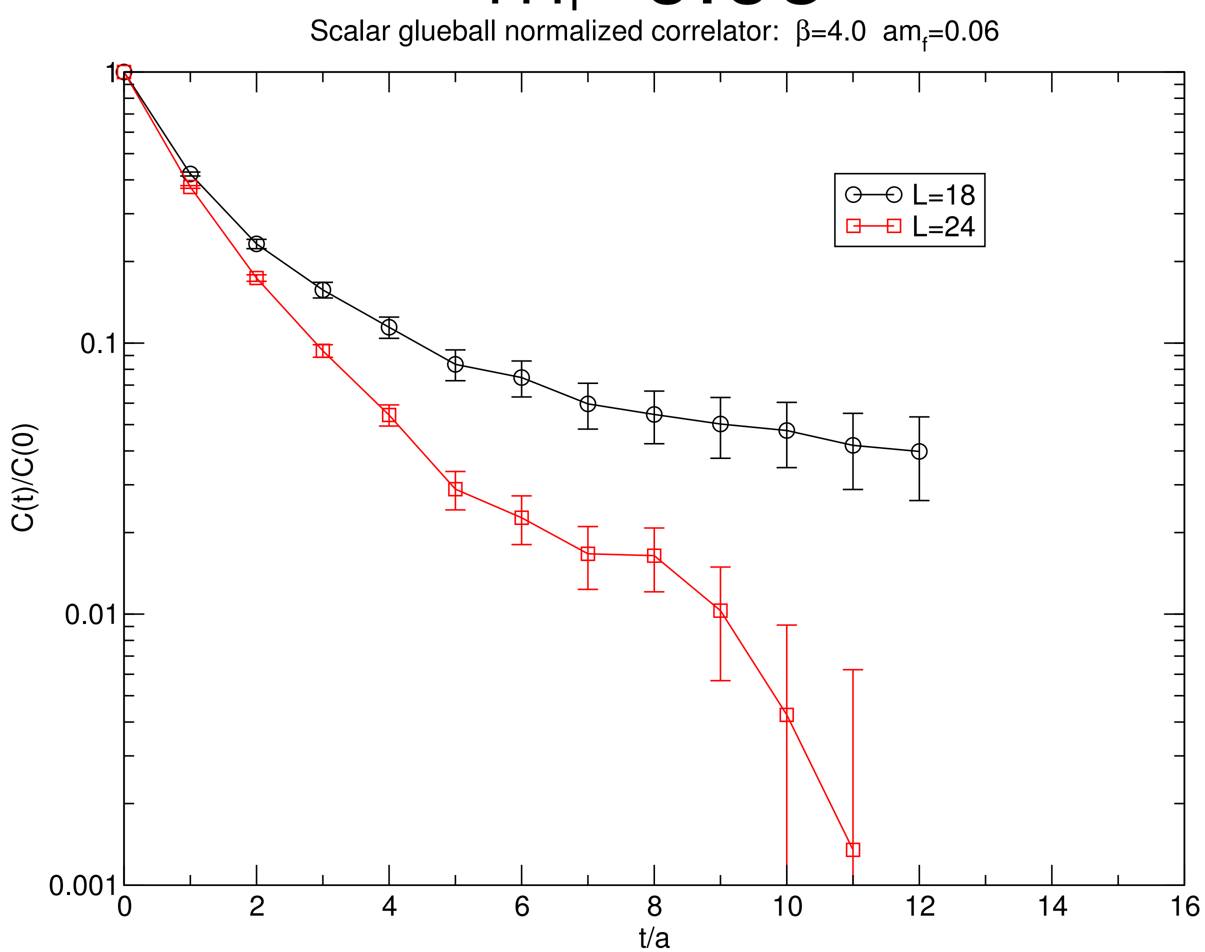
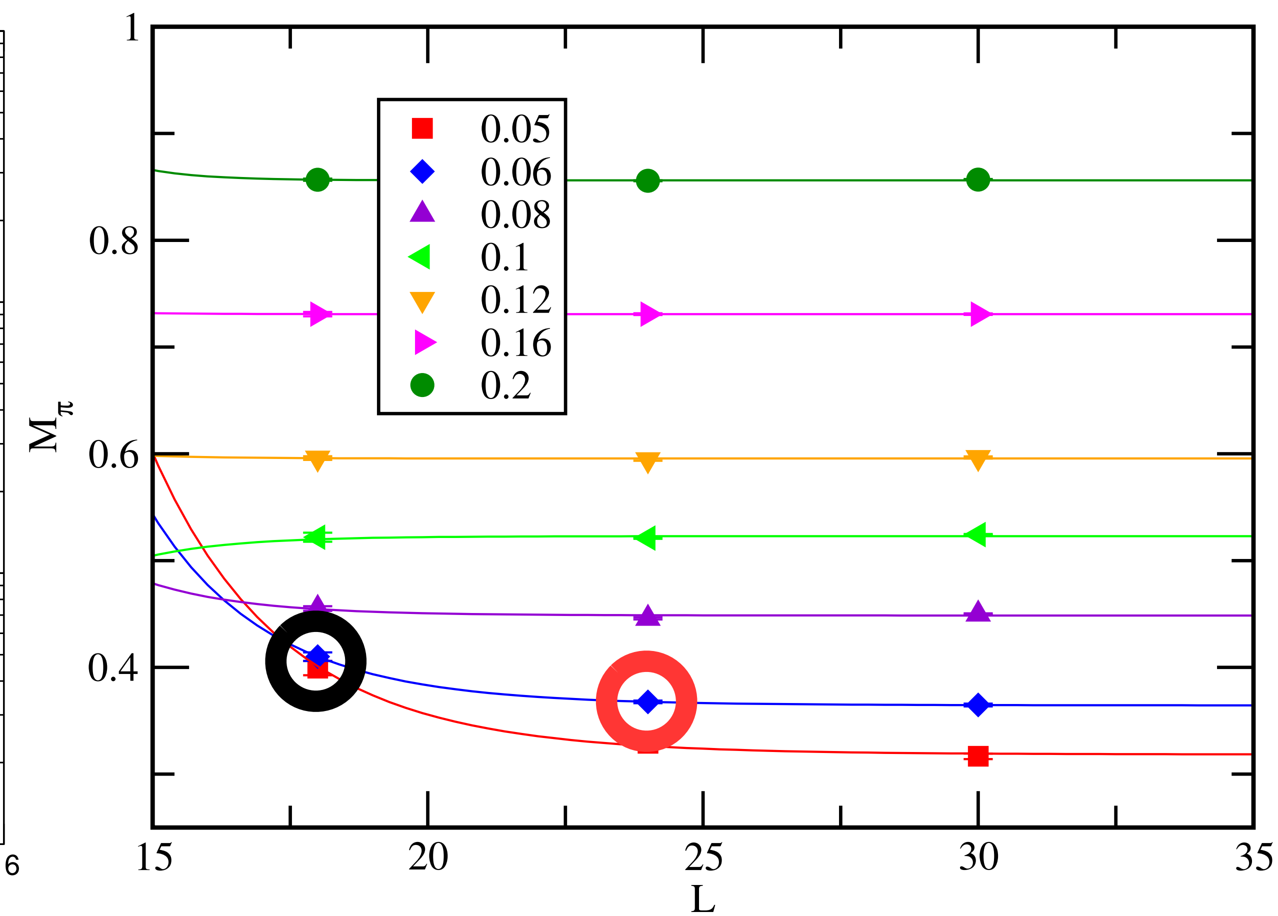
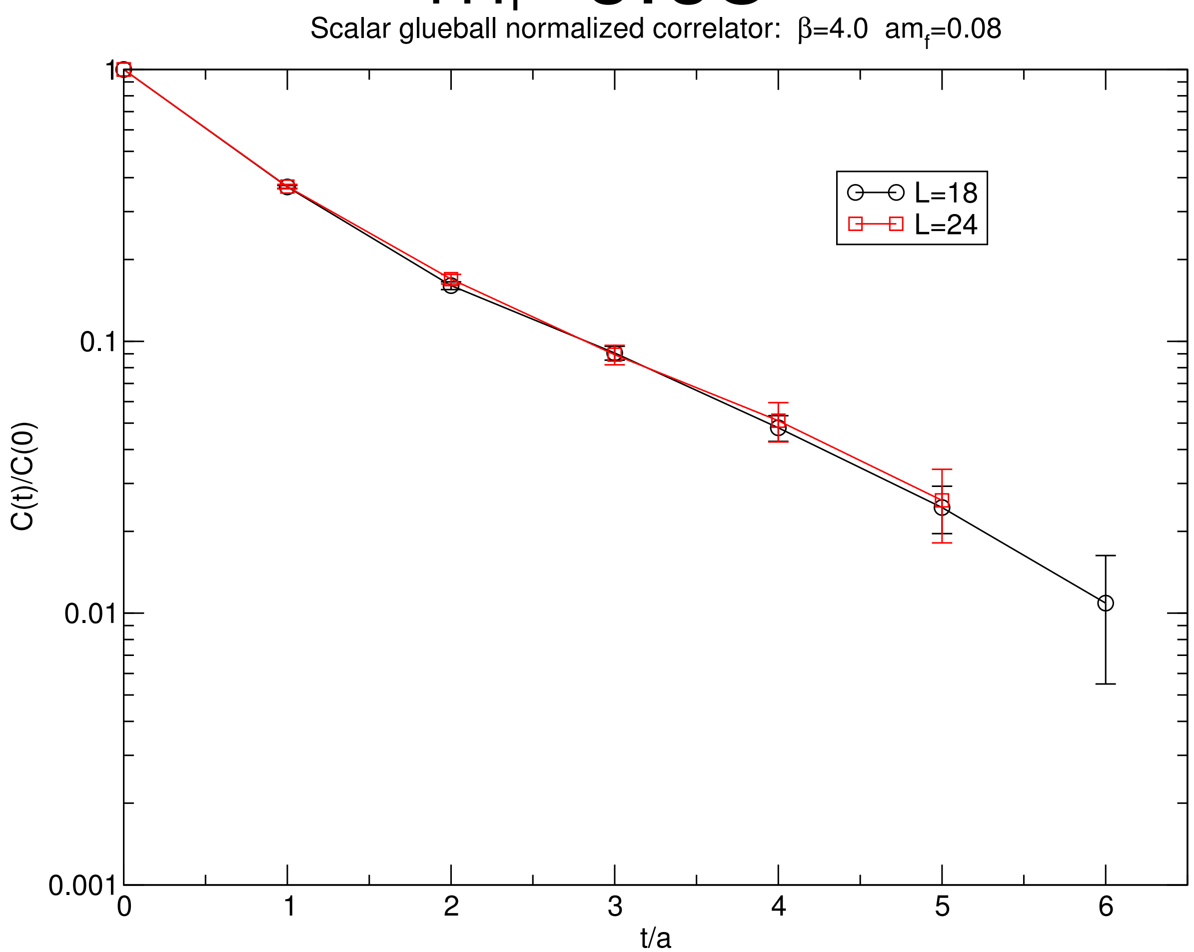
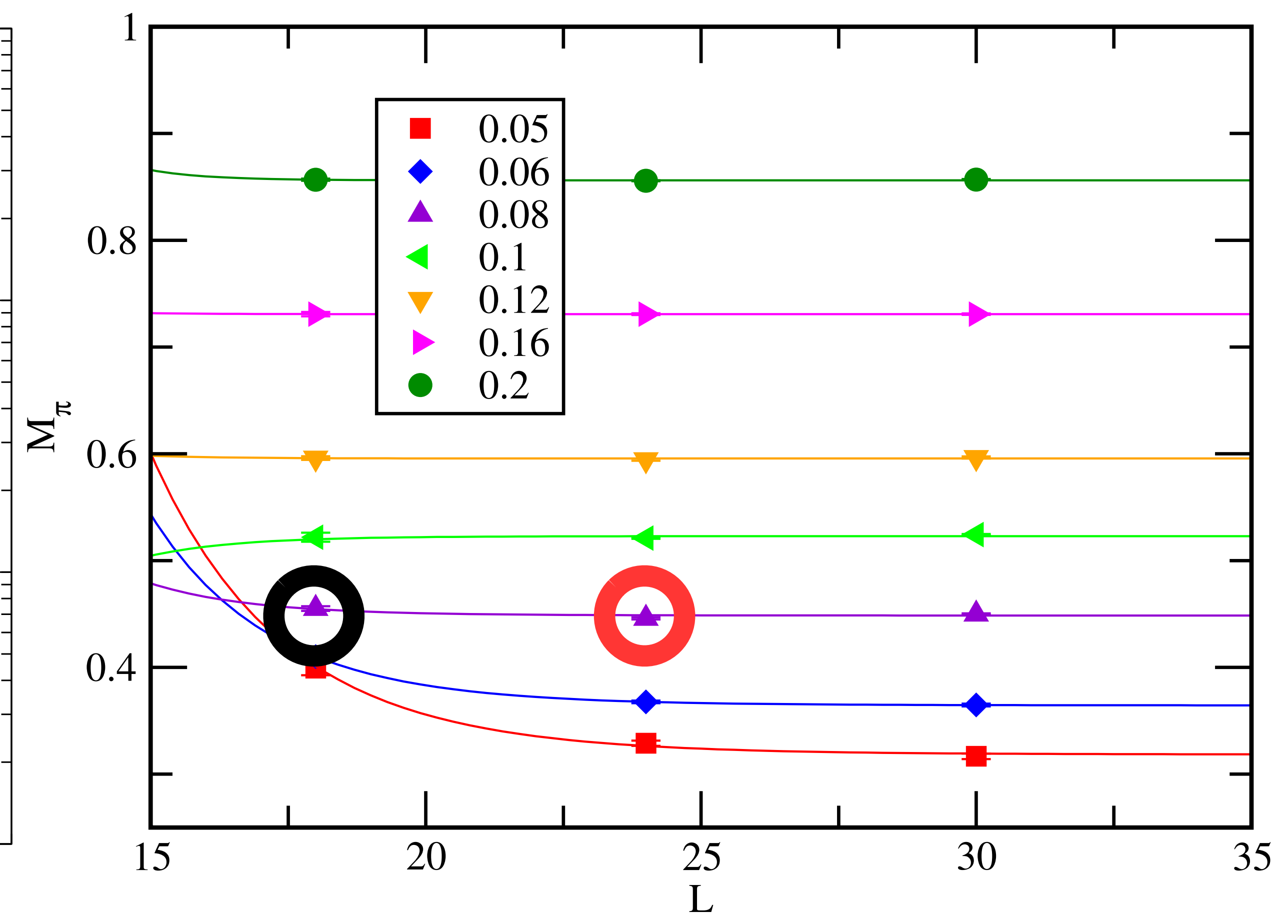




SU(3) N_f=12, 0^{++} techni-glueball [preliminary]

m_f=0.08





- finite volume effect needs to be carefully studied...

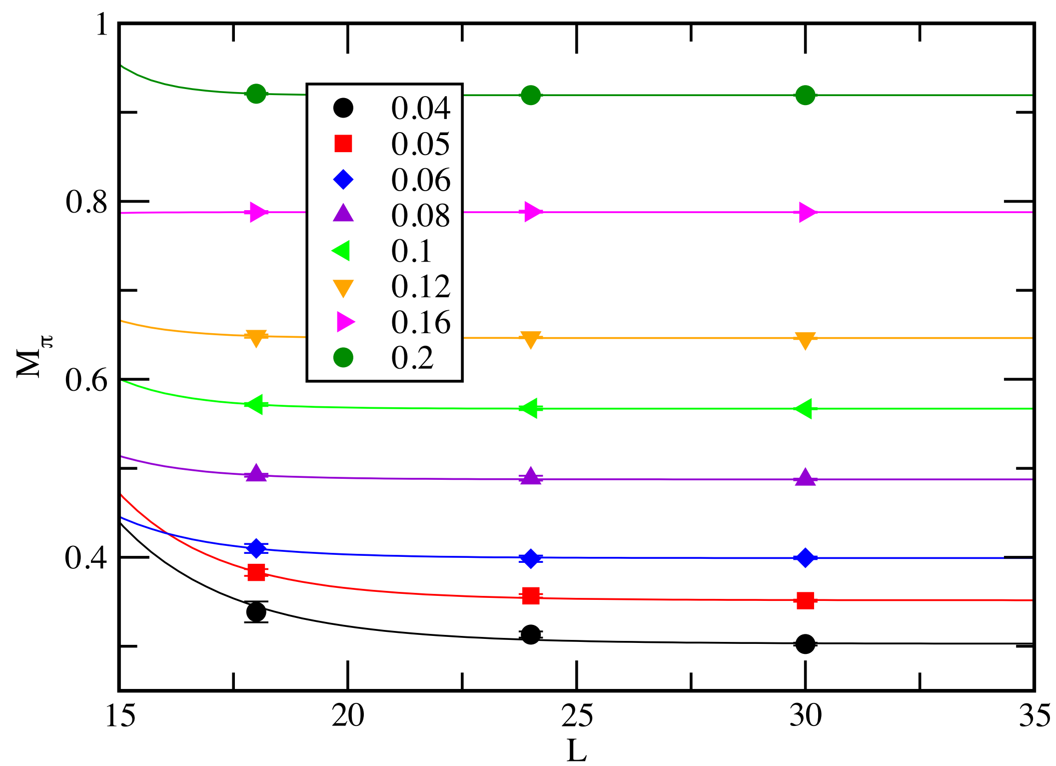
Outlook

- continue for SU(3) N_f=8, 12
- underway / planned / wish list for both N_f=12 / 8
  - lighter mass
  - more hadrons
  - glueball: study of finite volume effects
  - isosinglet scaler
  - and more...

Thank you for your attention

ChPT inspired infinite volume limit (β=3.7)

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



- ChPT type finite volume effect → chiral fit results not inconsistent with S χ SB