Exploring for walking technicolor from QCD

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for the LatKMI collaboration

- QUCS 2012 symposium @ Nara -

Dec. 16, 2012

名古屋大学

LatKMI collaboration

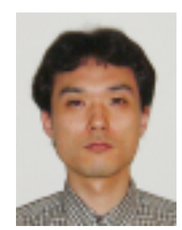
- YA, T.Aoyama, M.Kurachi, T.Maskawa, K.Nagai, H.Ohki,






E. Rinaldi, K.Yamawaki, T.Yamazaki





- A.Shibata

Walking Technicolor (WTC)

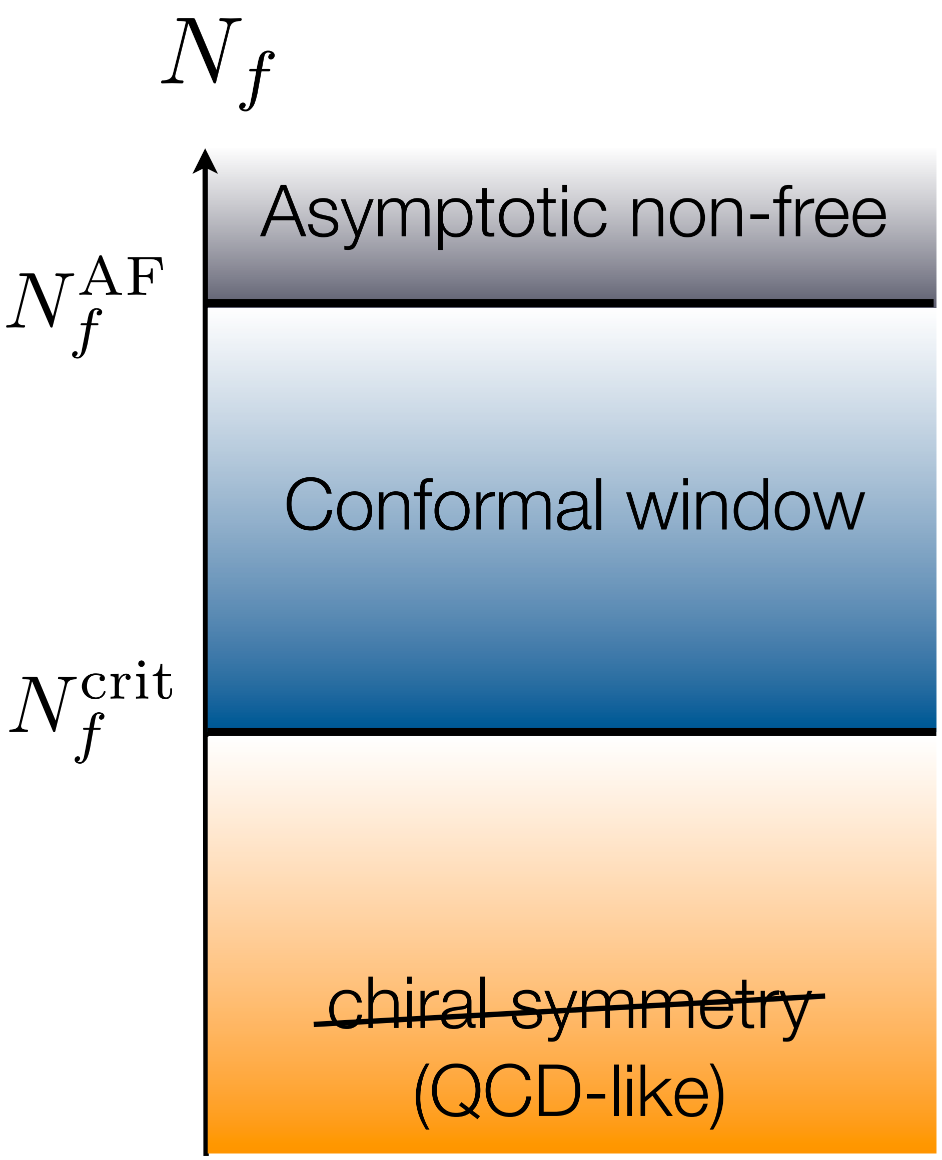
- a candidate of the new physics beyond the Standard Model of particles
- could replace Higgs sector of the Standard Model
  - Higgs sector is a low energy effective theory of WTC
- free from the gauge hierarchy problem (naturalness)
- gives explanation of the electro-weak gauge symmetry breaking,
  - thus origin of mass of the elementary particles
- “Higgs” = pseudo Nambu-Goldstone boson
  - due to breaking of the approximate scale invariance (Dilaton)

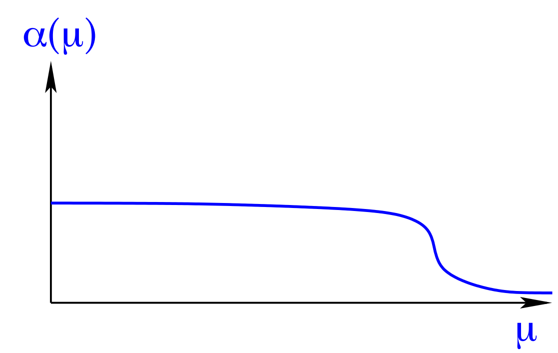
Requirements for the successful WTC theory

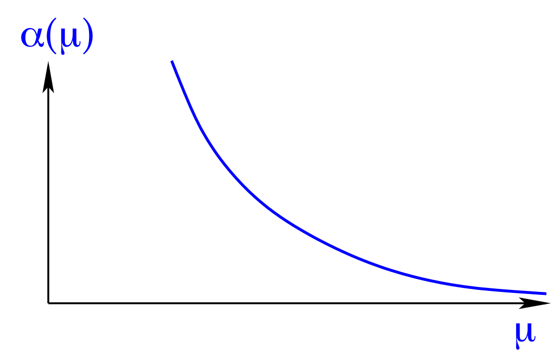
- spontaneous chiral symmetry breaking
- running coupling “walks” = slowly changing with μ → nearly conformal
- large mass anomalous dimension: $\gamma_m \sim 1$
- light scalar 0^{++} (m_H = 126 GeV @ LHC !)
  - with input $F_\pi = 246/\sqrt{N}$ GeV (N: # weak doublet in techni-sector)
    - to reproduce $W^\pm$ 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 gauge coupling

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







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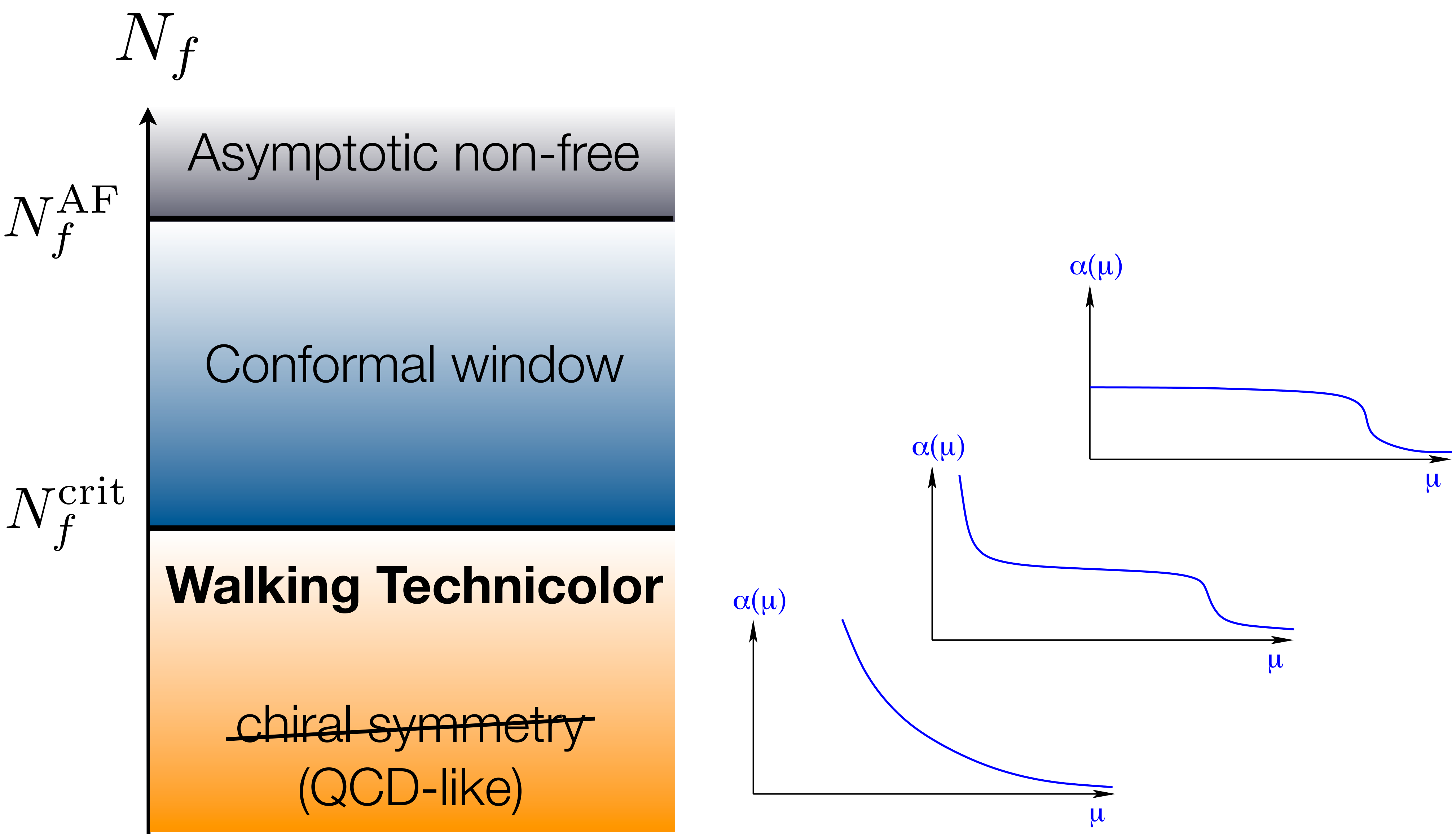

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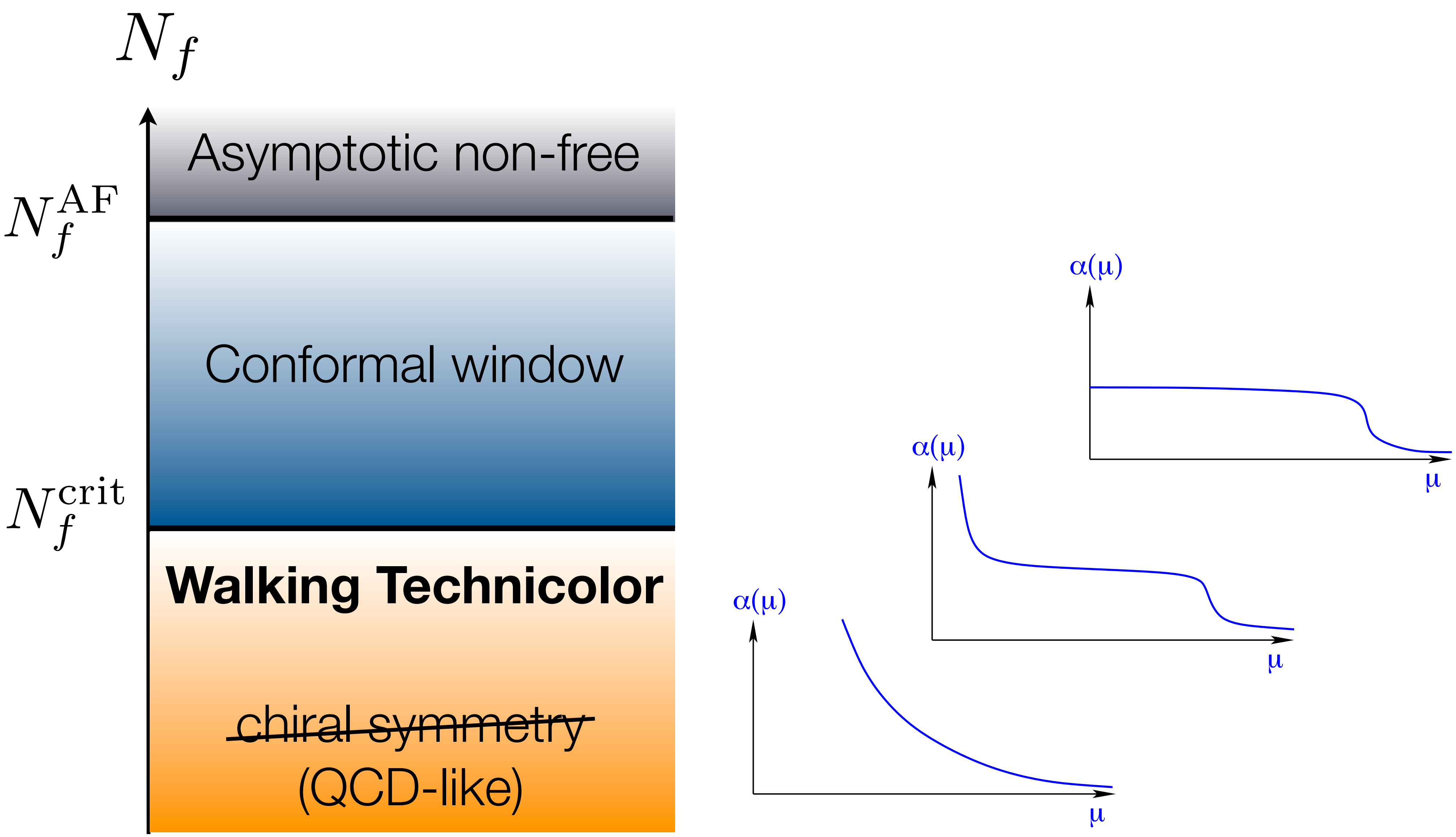

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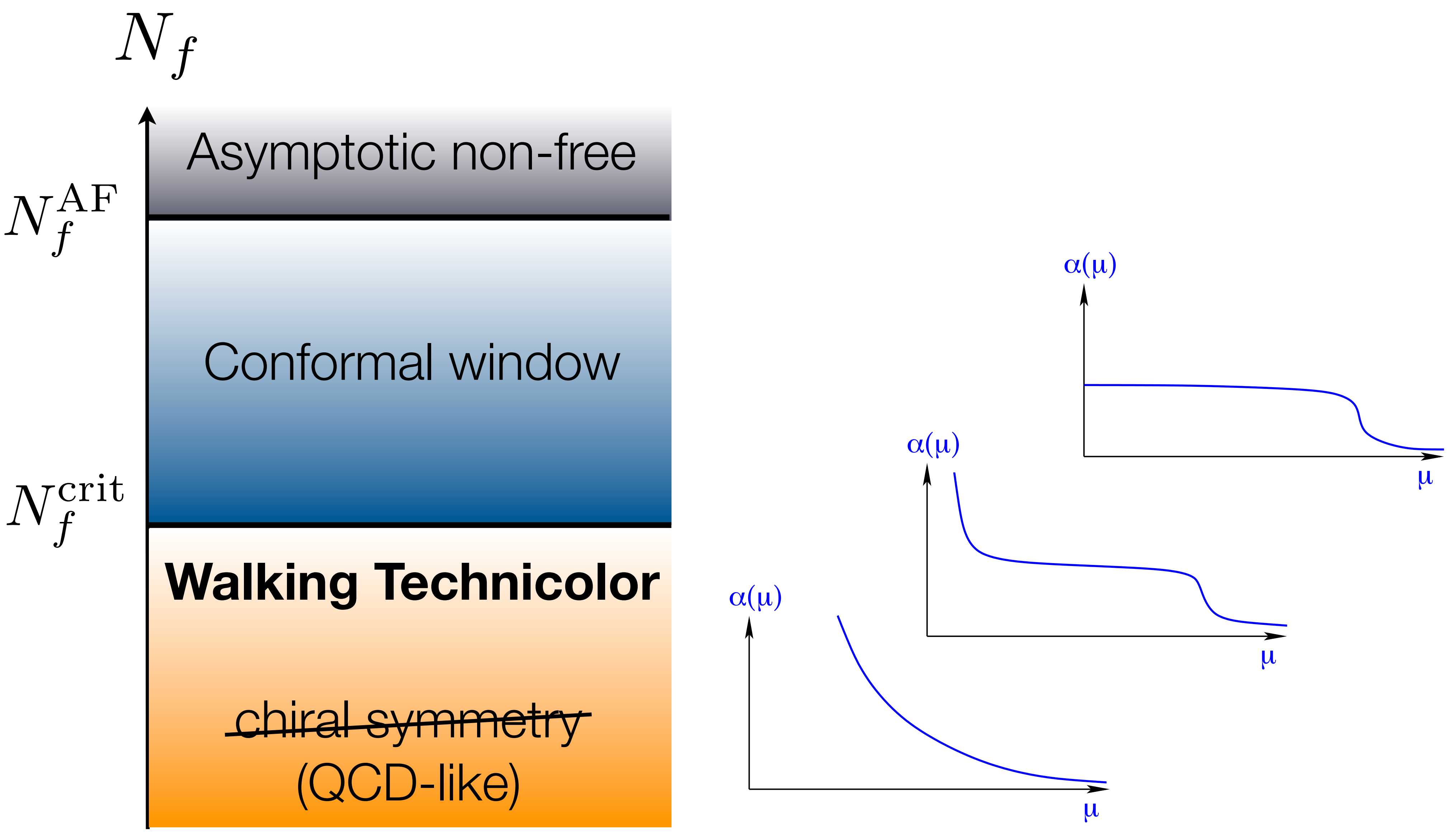
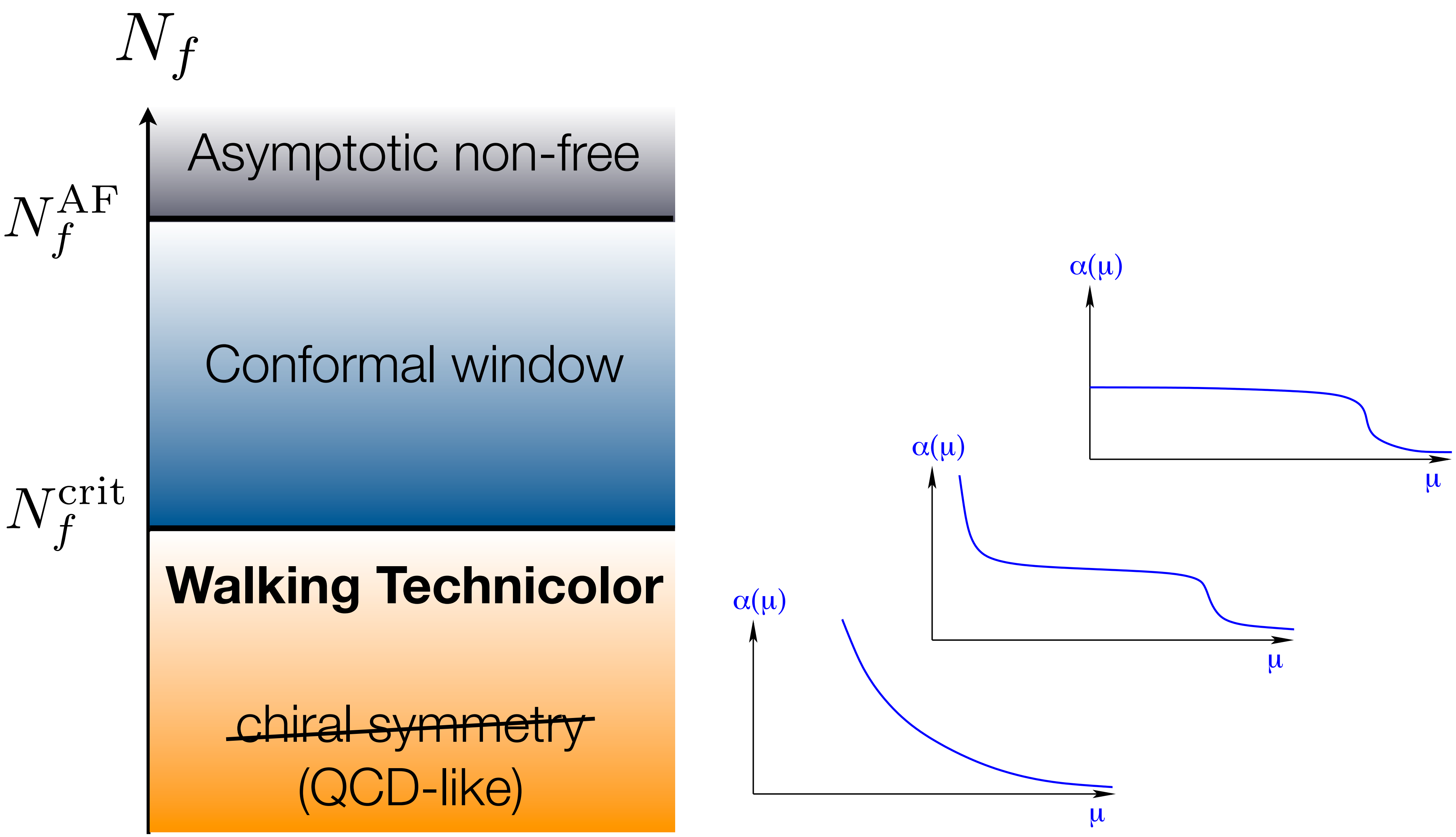


- Walking Techinicolor could be realized just below the conformal window
- crucial information: N_f^{crit} and...

conformal window and walking gauge coupling
- non-Abelian gauge theory with N_f *massless* fermions -

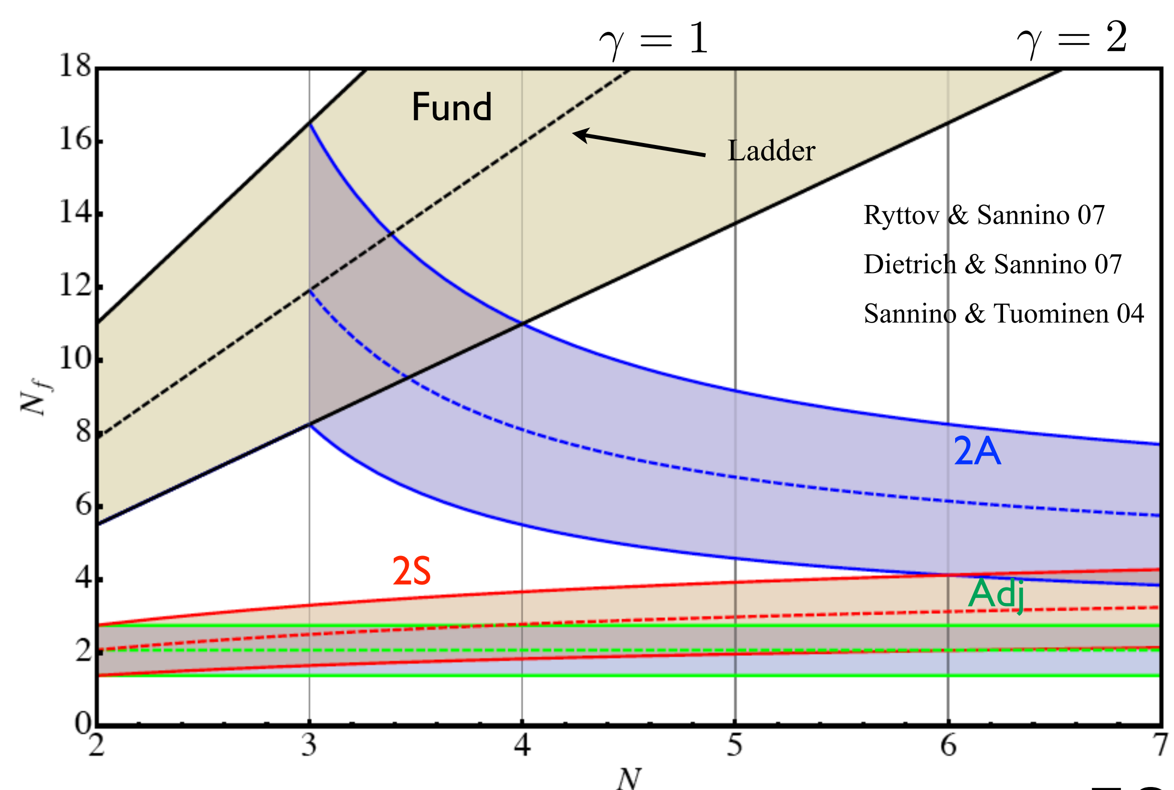


- Walking Techinicolor could be realized just below the conformal window
- crucial information: N_f^{crit} and...
- mass anomalous dimension γ & the composite mass spectrum around N_f^{crit}

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

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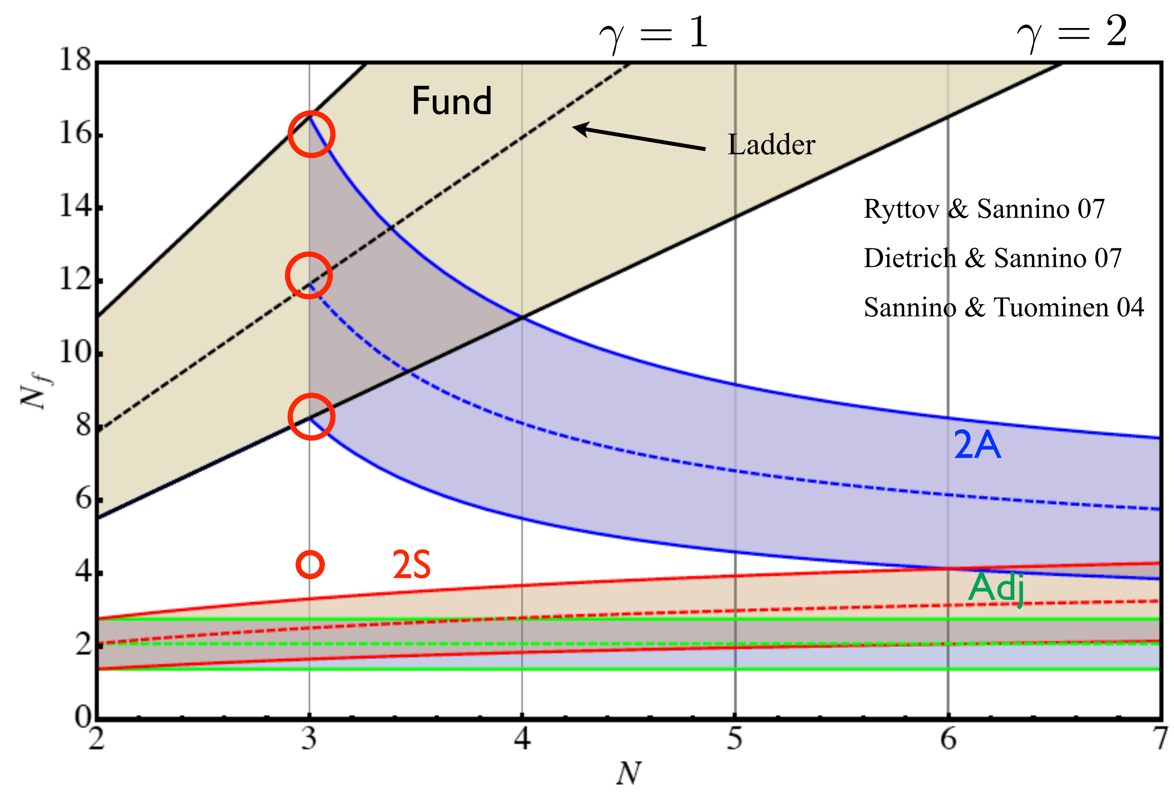

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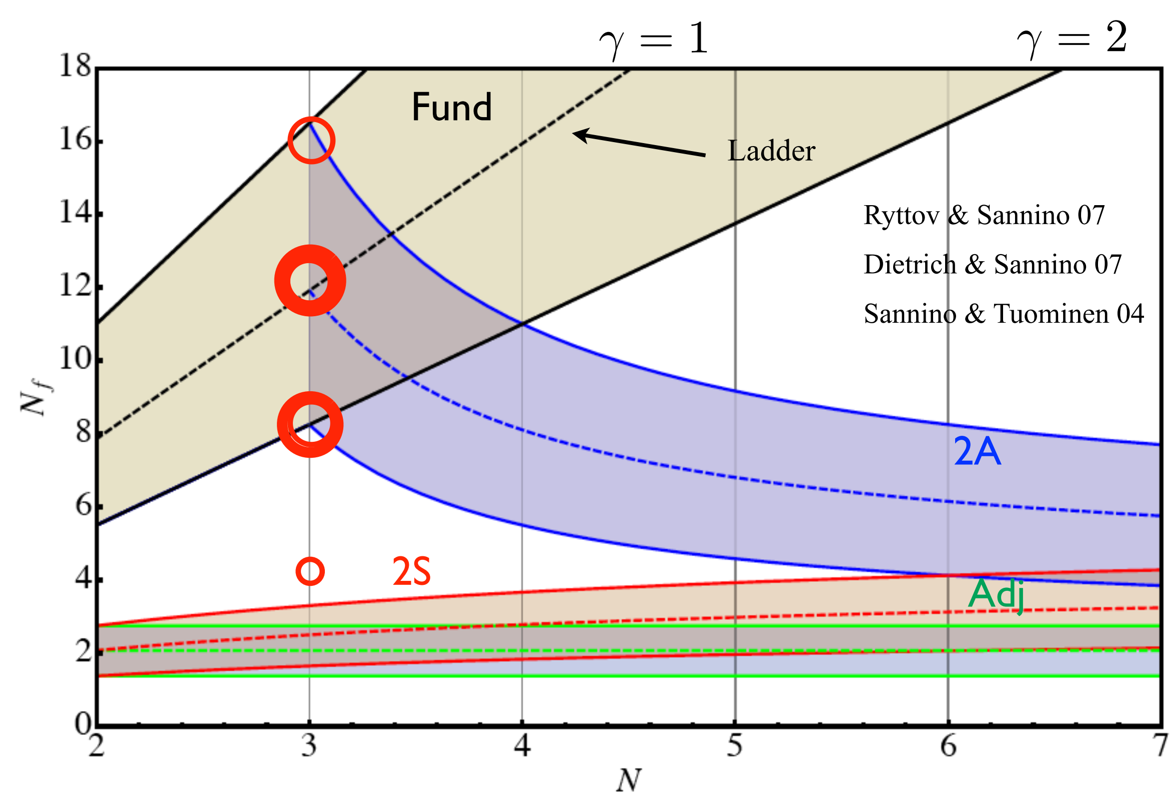
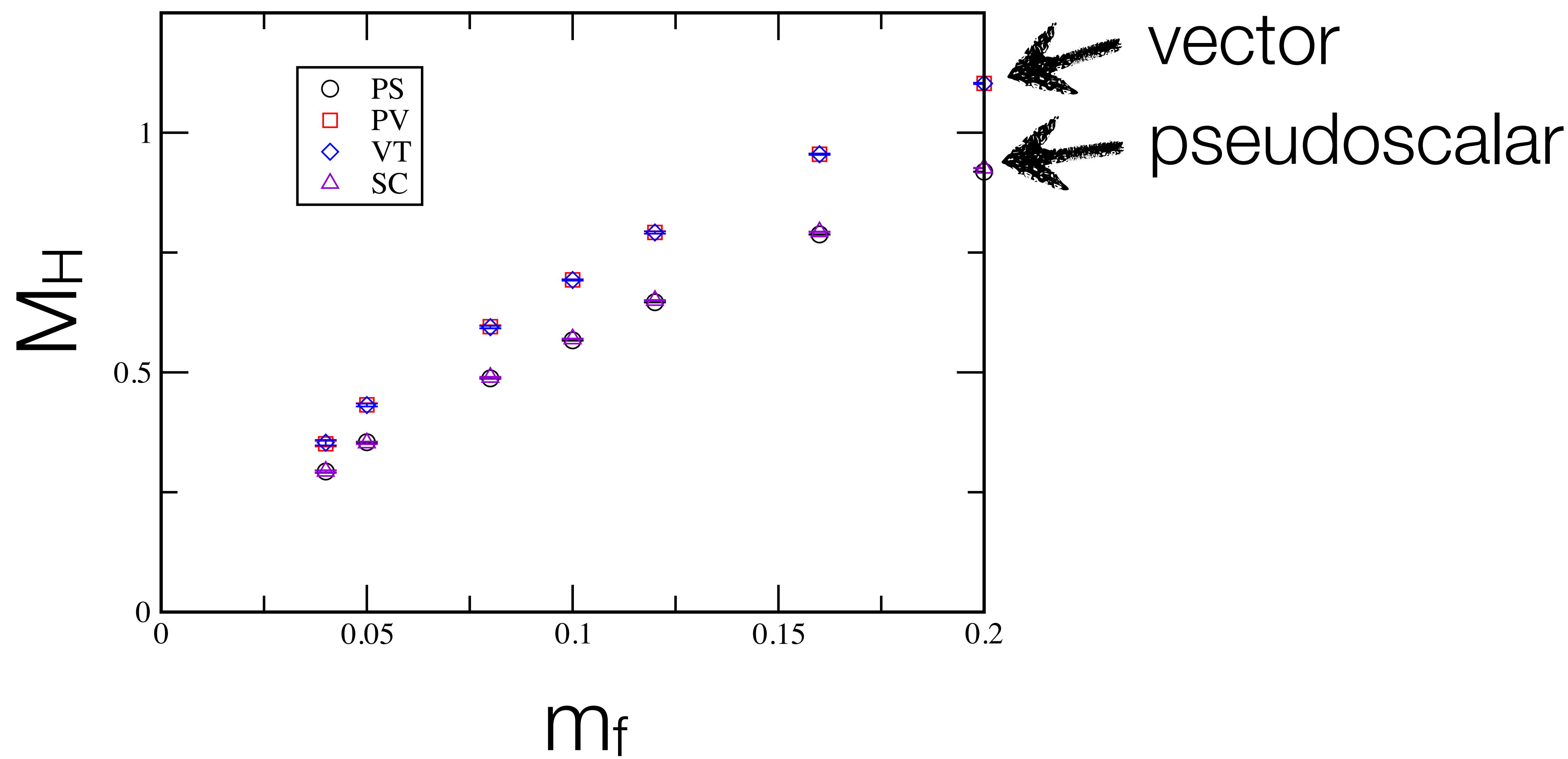


Simulation

- Fermion Formulation: HISQ (Highly Improved Staggered Quarks)
  - being used for state-of-the-art QCD calculations / MILC,..
- Gauge Field Formulation:tree level Symanzik gauge
- $N_f=4$: $\beta=6/g^2=3.7$, $V=L^3 \times T$: $L/T=2/3$; $L=12, 16$
- $N_f=8$: $\beta=6/g^2=3.8$, $V=L^3 \times T$: $L/T=3/4$; $L=18, 24, 30, 36$
- $N_f=12$ (two lattice spacings): [LatKMI collab. PRD86 (2012) 054506]
  - $\beta=6/g^2=3.7$, $V=L^3 \times T$: $L/T=3/4$; $L=18, 24, 30$, $0.04 \leqq m_f \leqq 0.2$
  - $\beta=6/g^2=4.0$, $V=L^3 \times T$: $L/T=3/4$; $L=18, 24, 30$, $0.05 \leqq m_f \leqq 0.24$
- using MILC code v7, with modification: HMC and speed up in MD

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

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

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

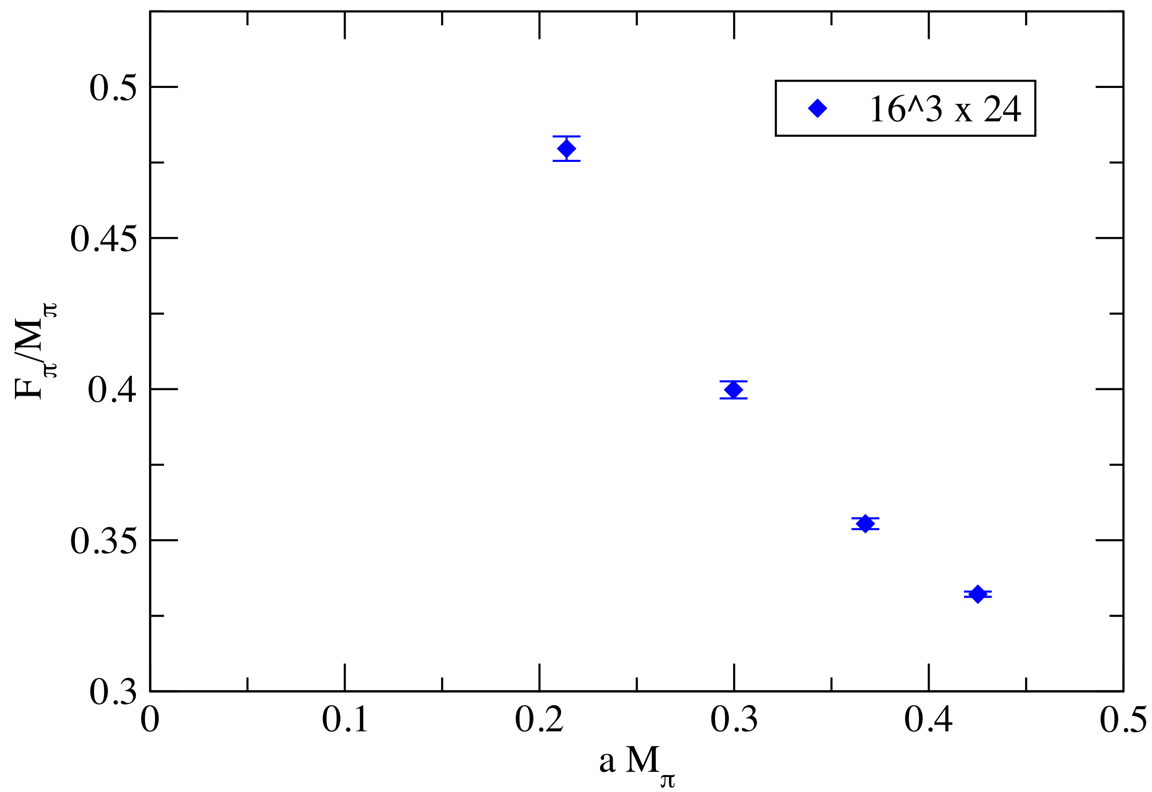
  ★ $M_\rho/M_\pi \rightarrow$ const. for small m_f

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

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

a crude analysis: F_π/M_π vs M_π

N_f=4



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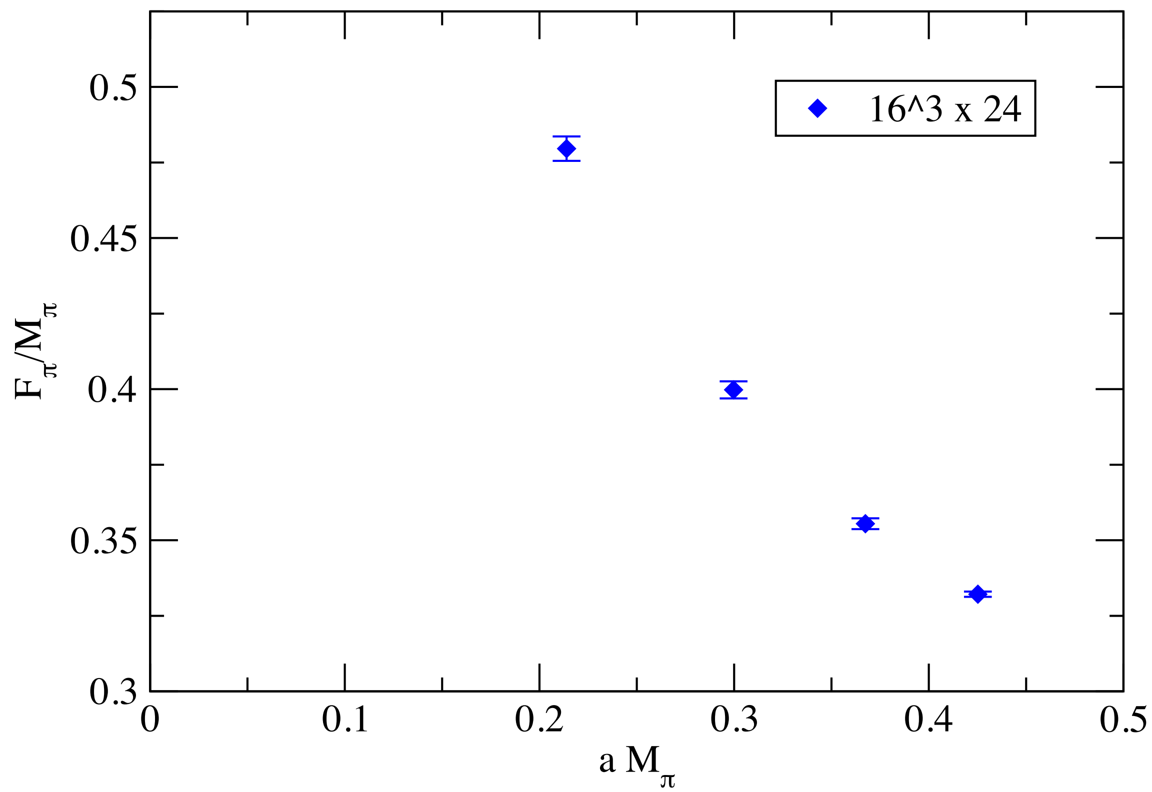

- tends to diverge towards the chiral limit ($M_\pi \to 0$)

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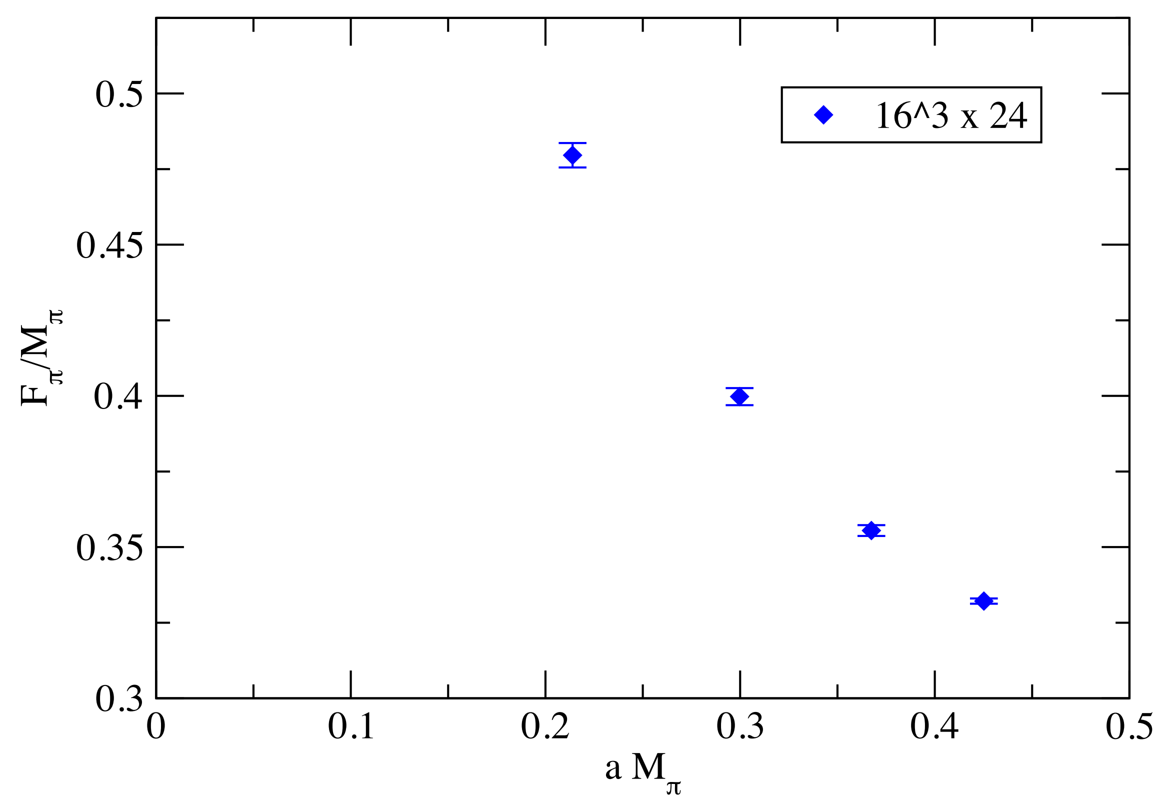
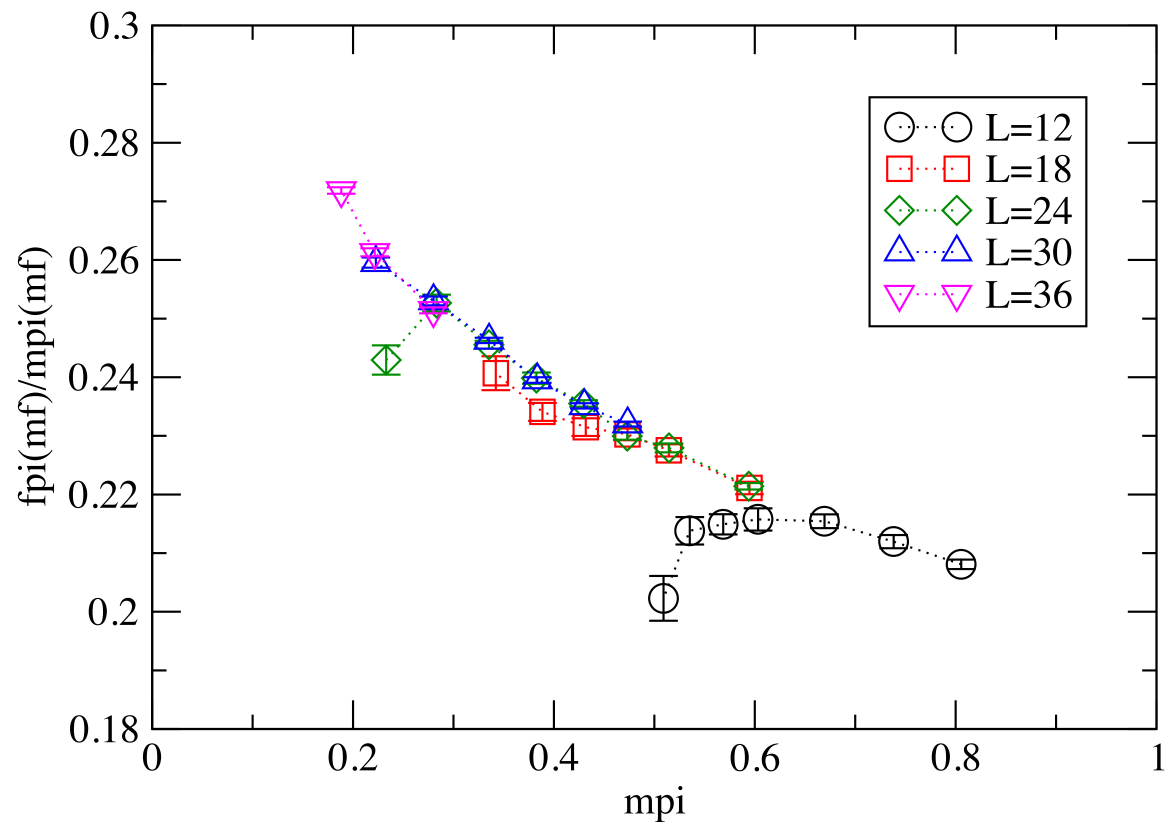


- tends to diverge towards the chiral limit ($M_\pi \to 0$)
- spontaneous chiral symmetry breaking

a crude analysis: F_π/M_π vs M_π

N_f=8



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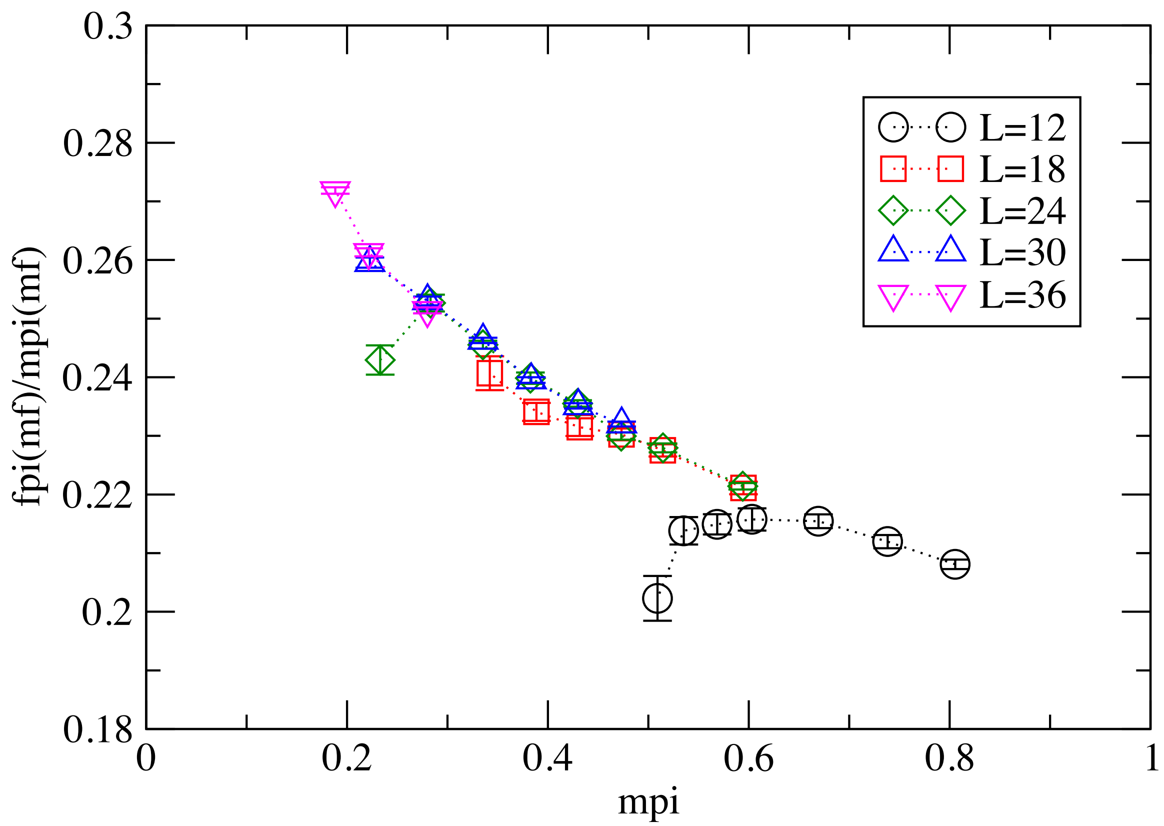

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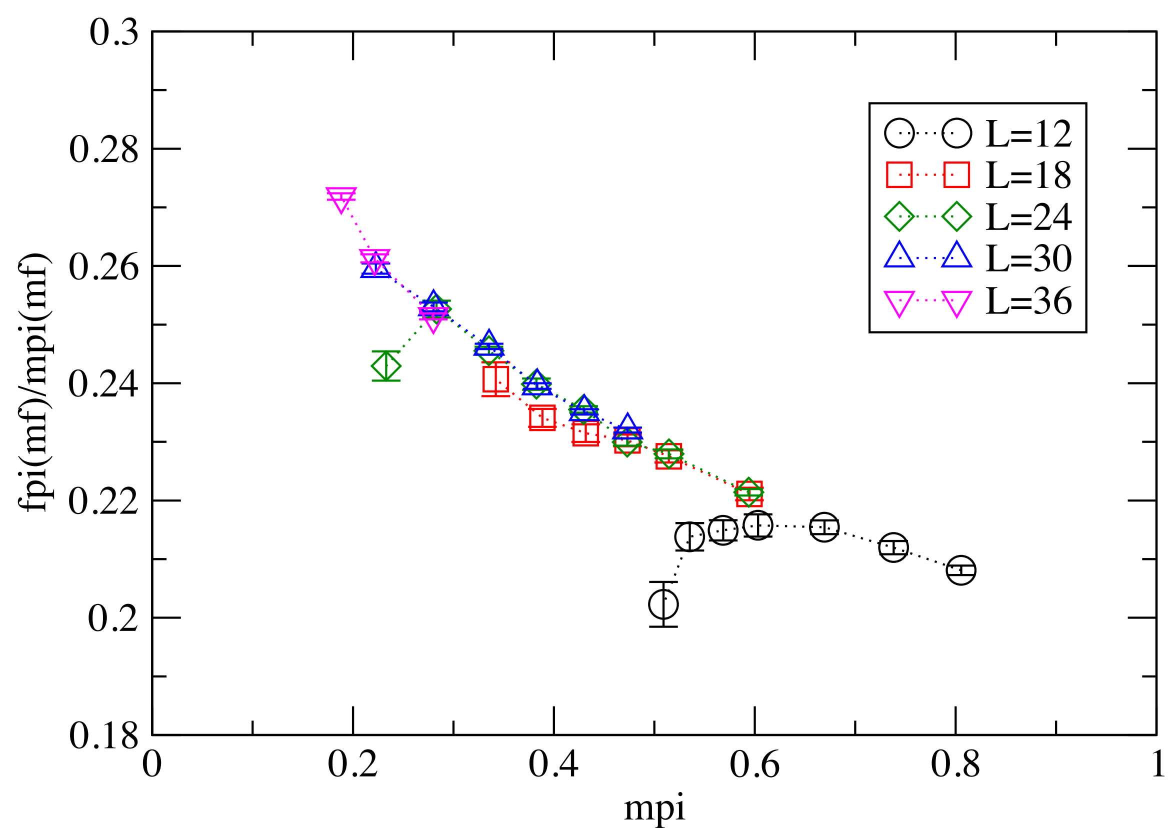

- tends to diverge towards the chiral limit ($M_\pi \to 0$)
- spontaneous chiral symmetry breaking, likely

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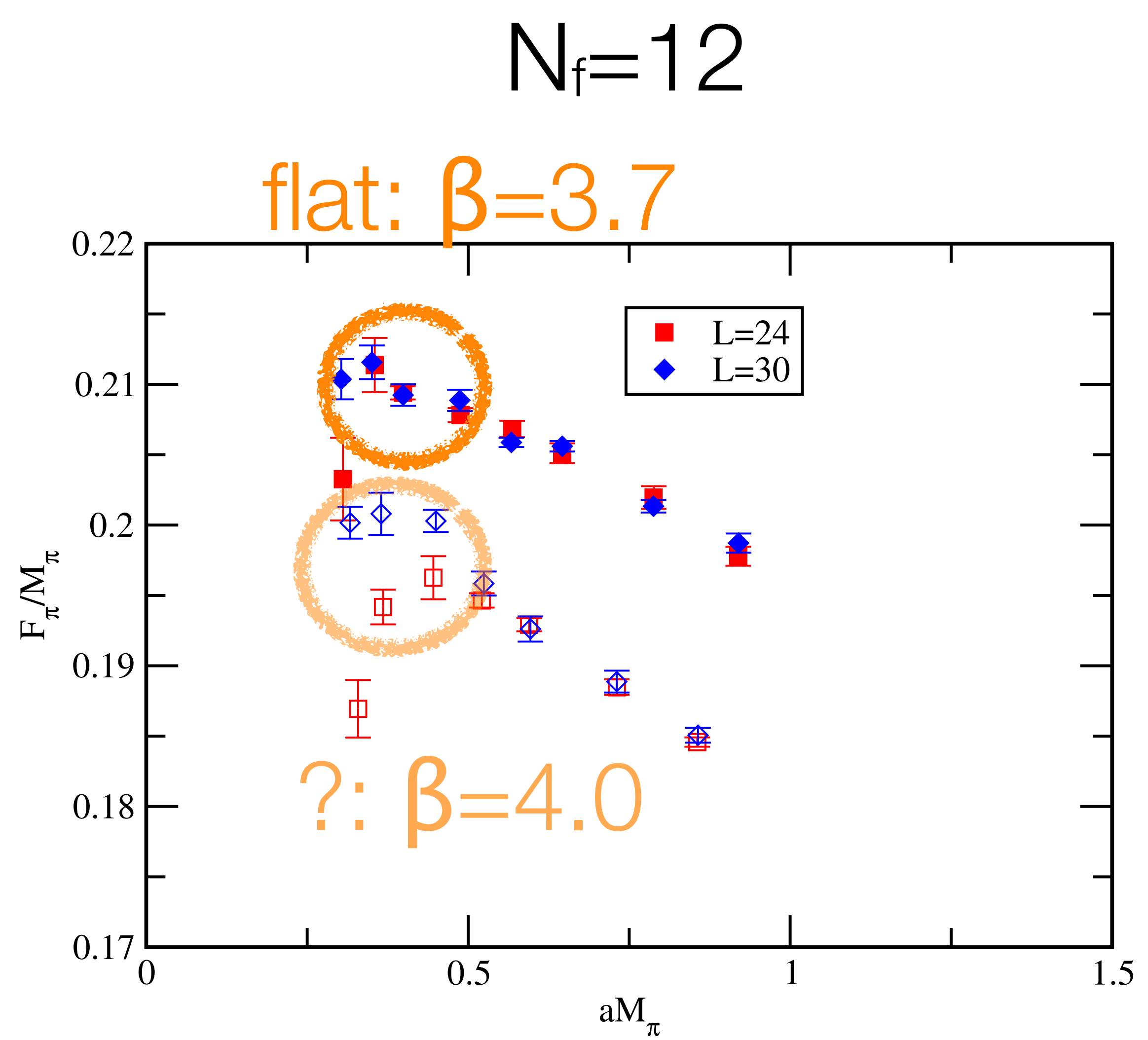

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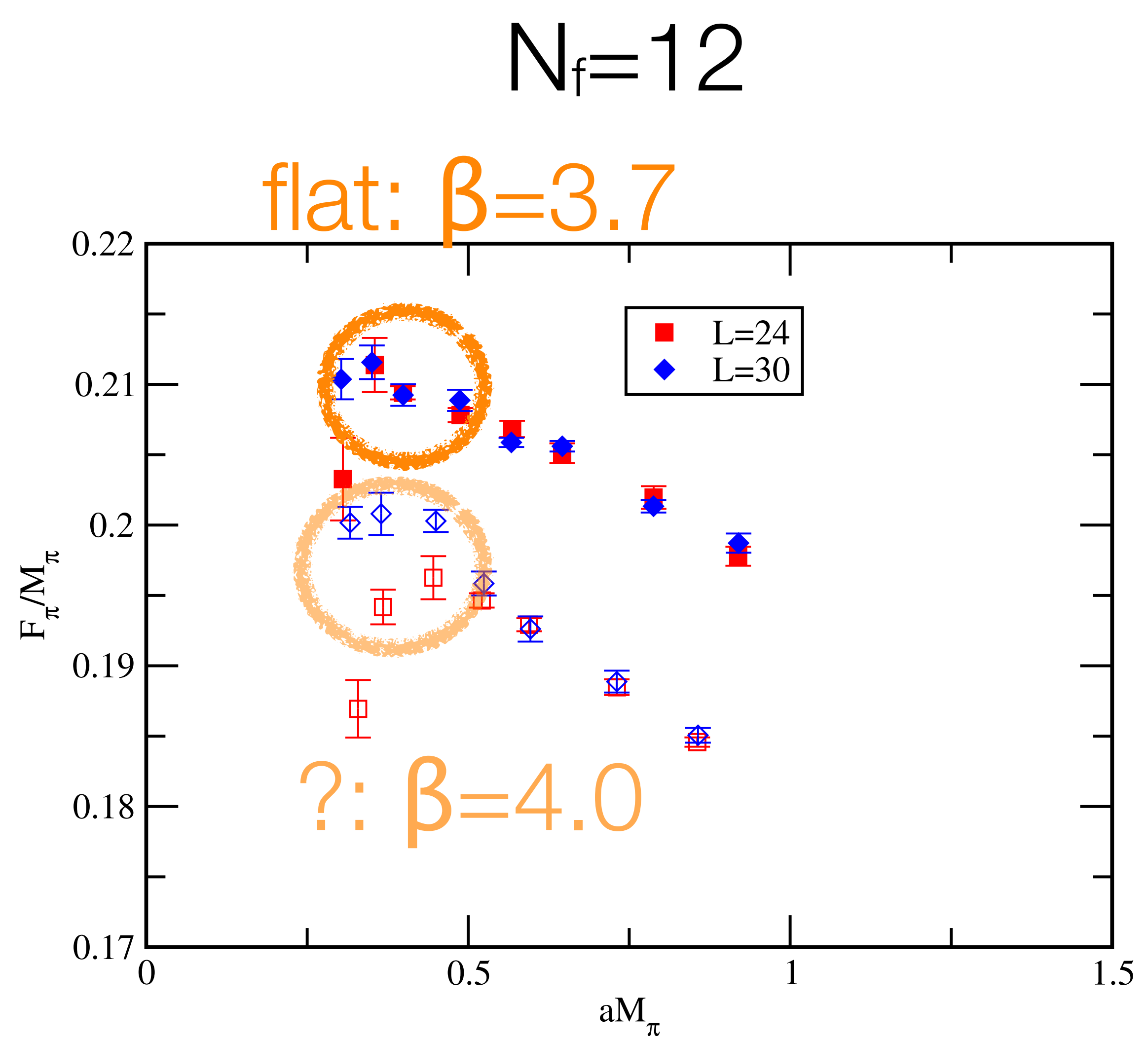
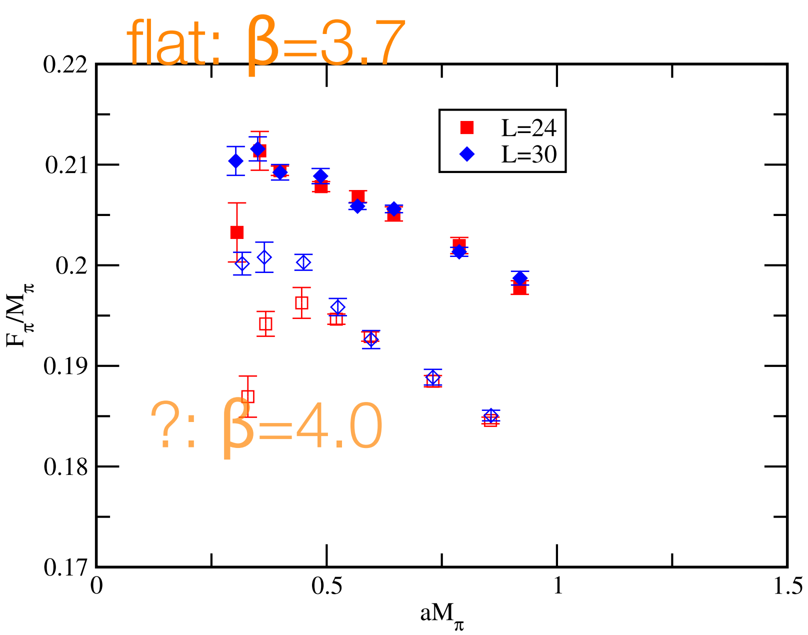


- β=3.7: small mass: consistent with conformal scenario
- β=4.0: volume likely to small to discuss the scaling

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

N_f=12



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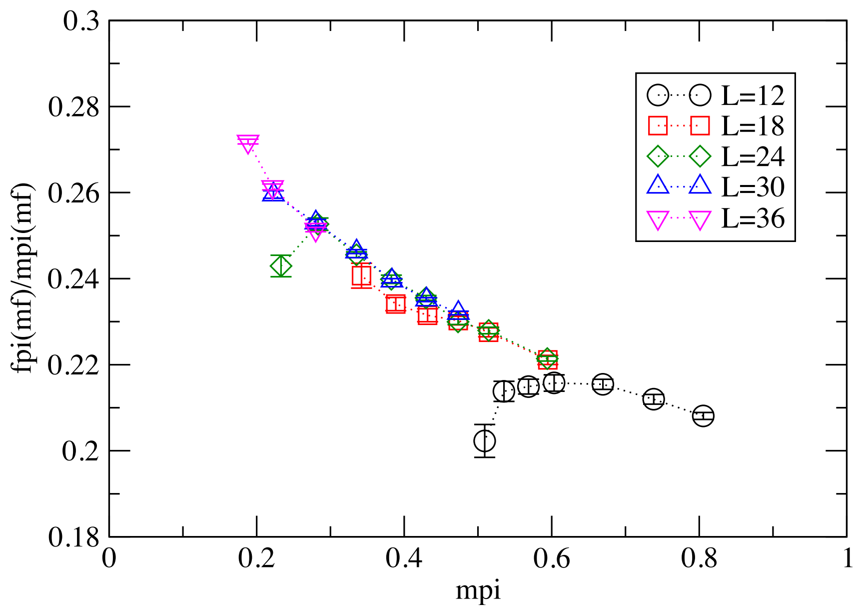

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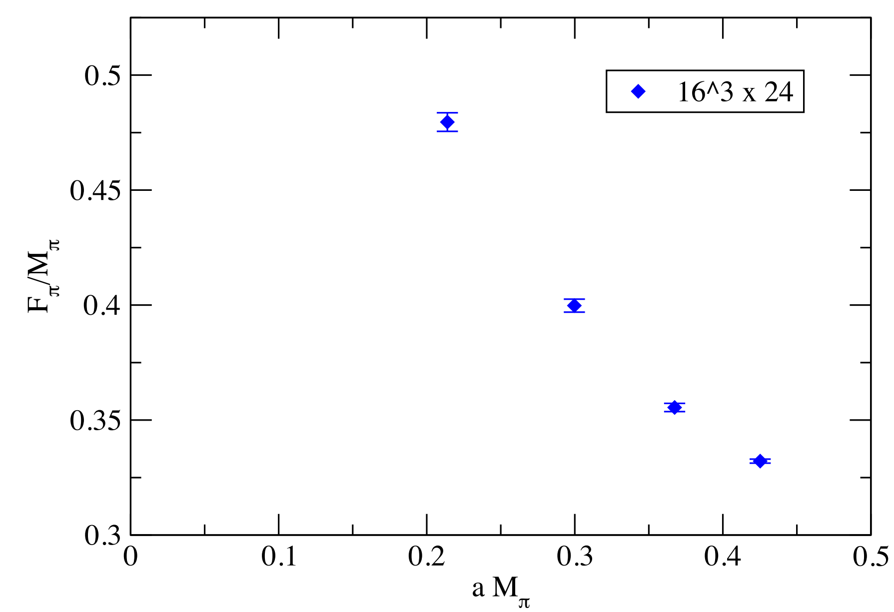

- conformality
- β=4.0: volume too small

- ~~chiral symmetry~~

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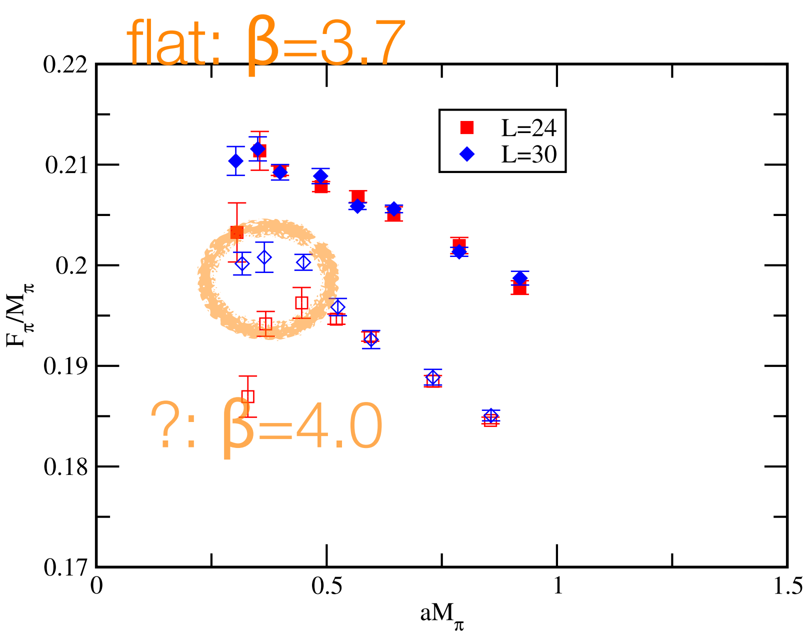

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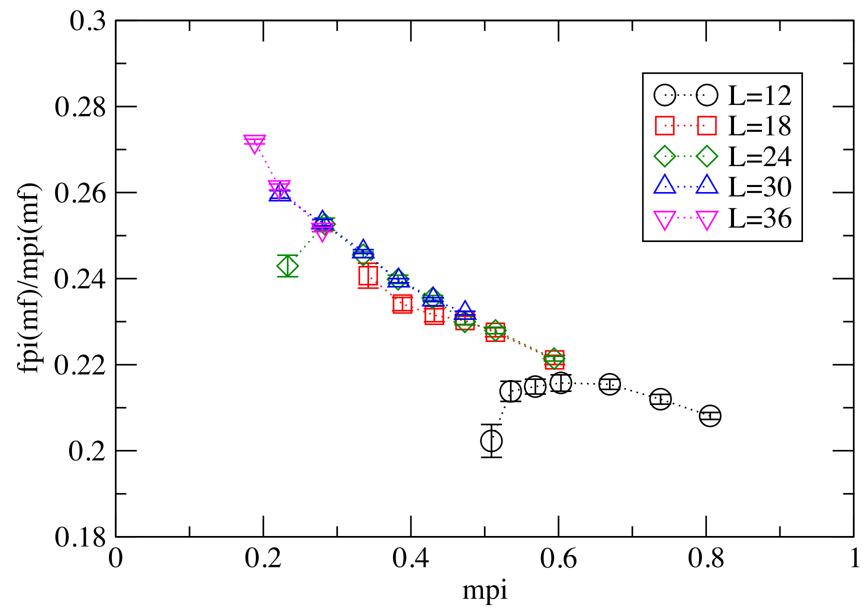

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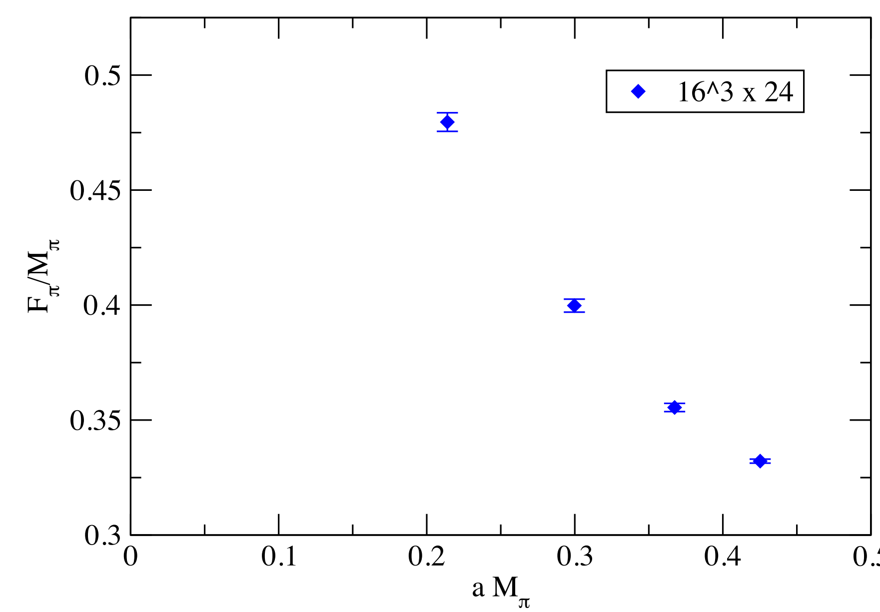

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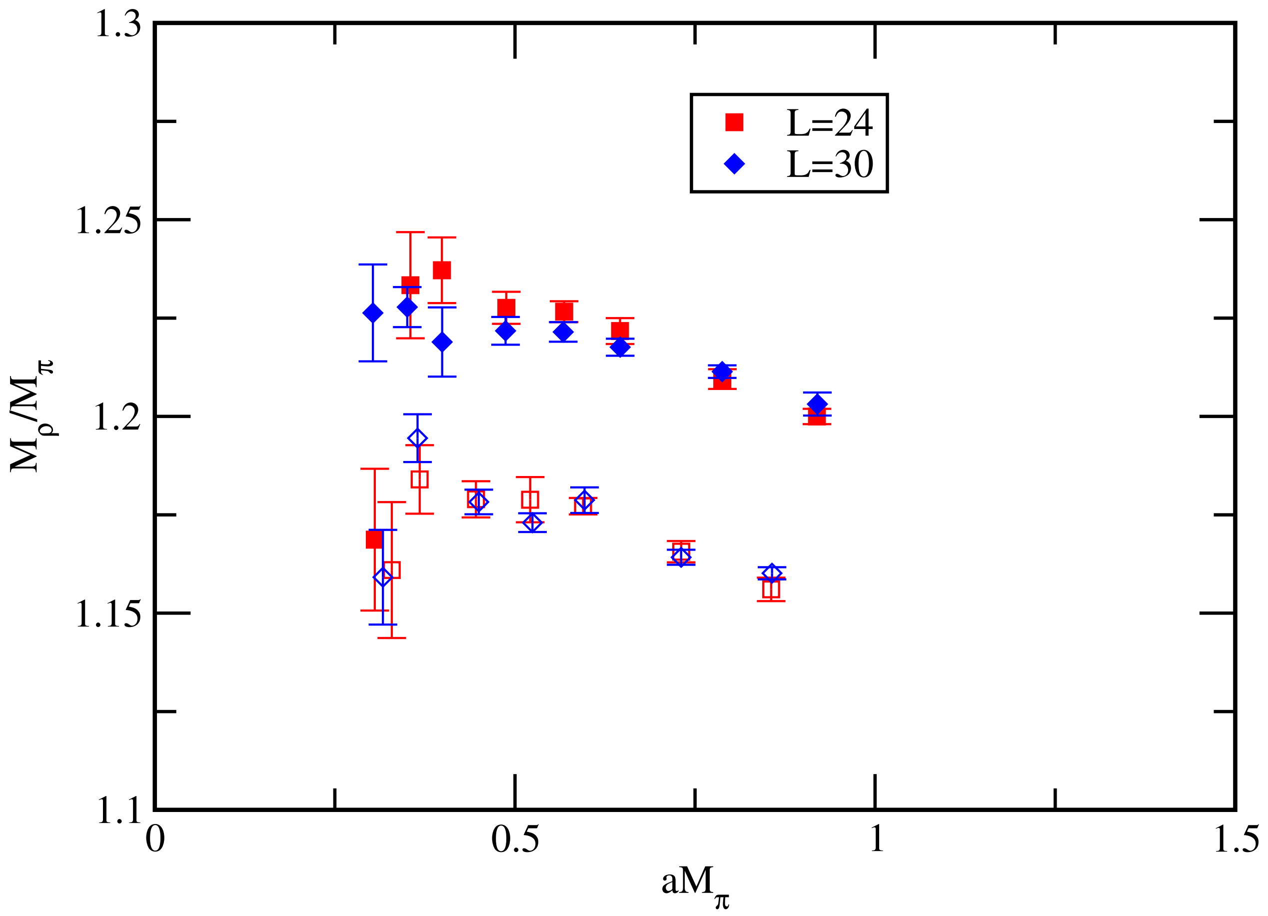

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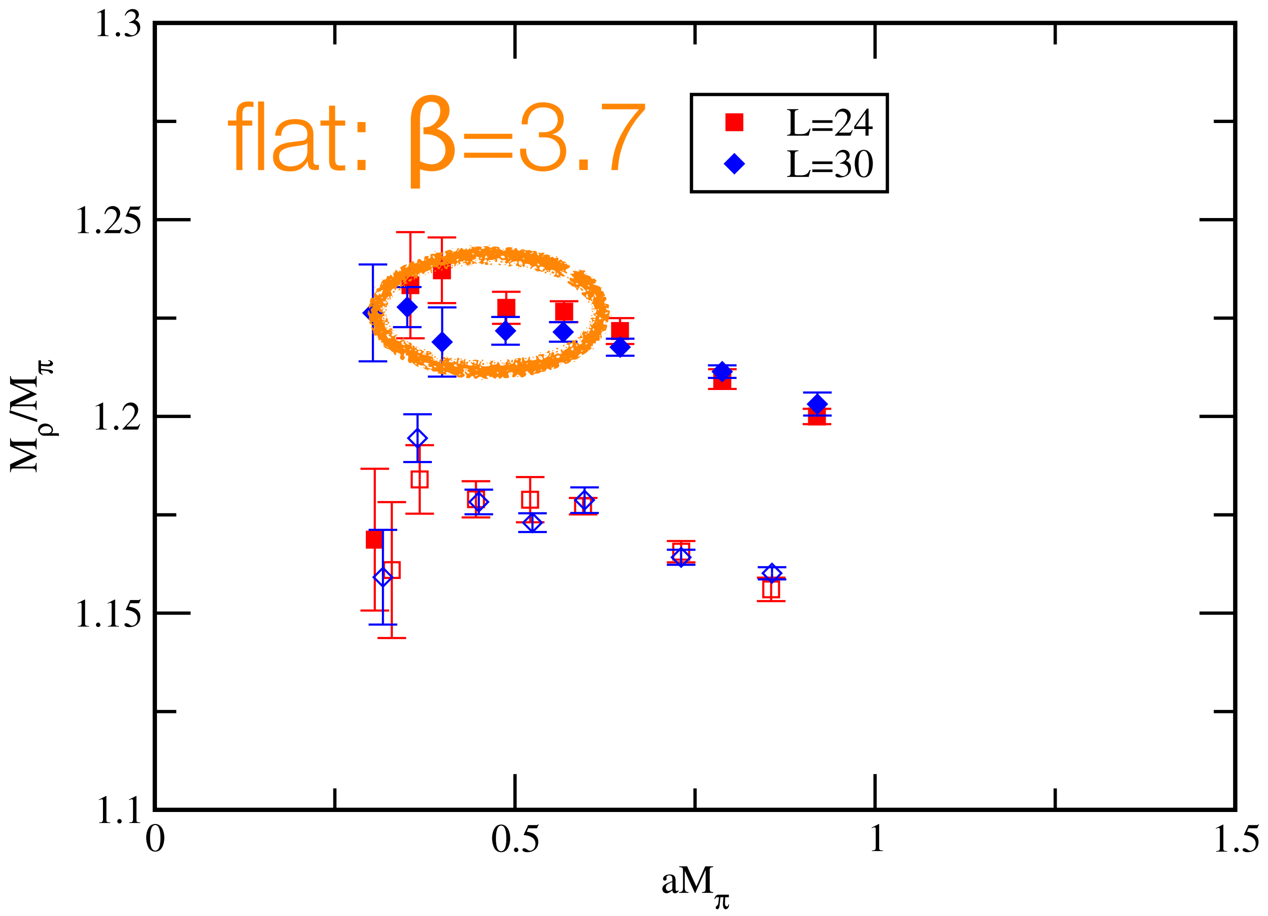

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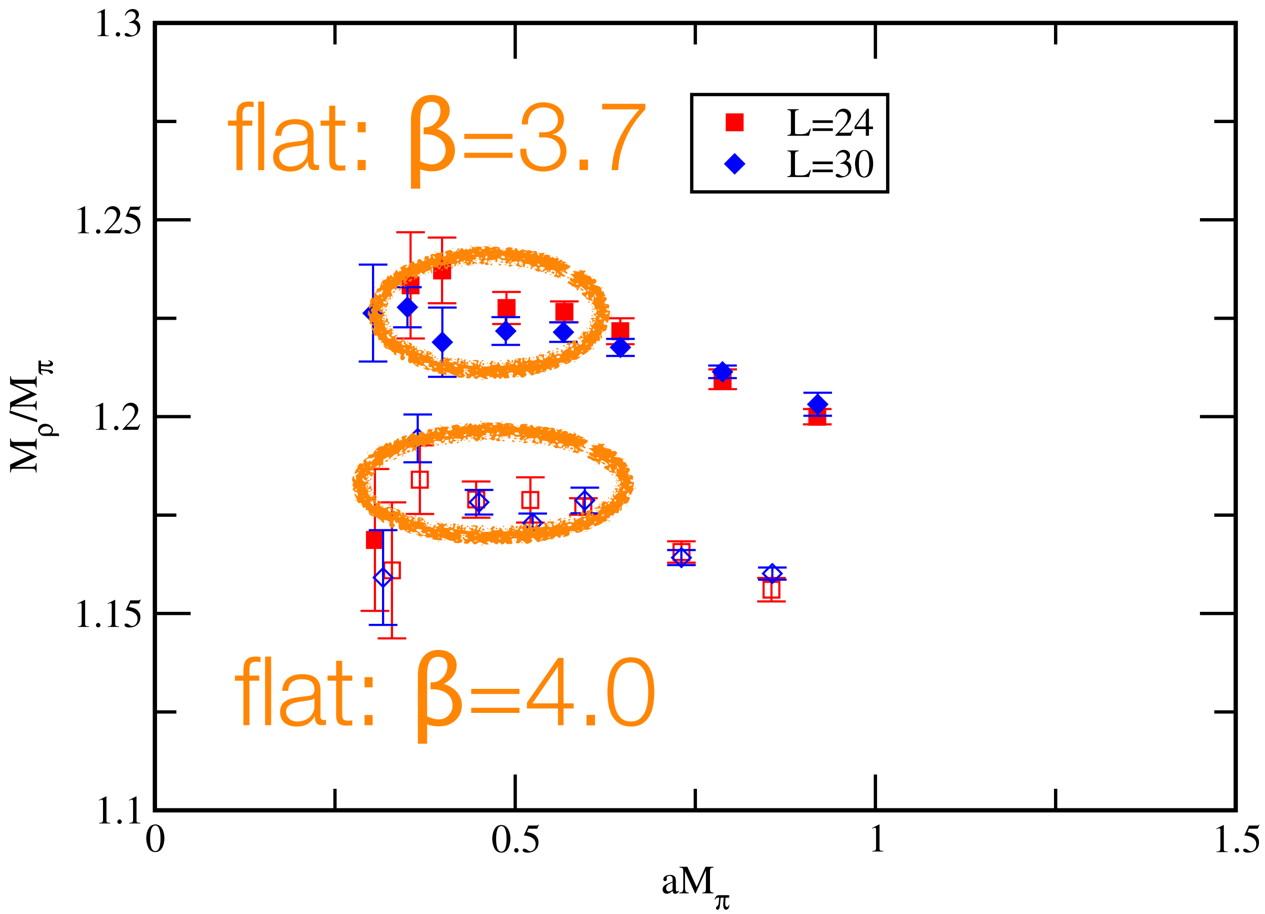

- β=3.7 & 4.0: small mass (wider than F_π): consistent with hyper scaling (HS)

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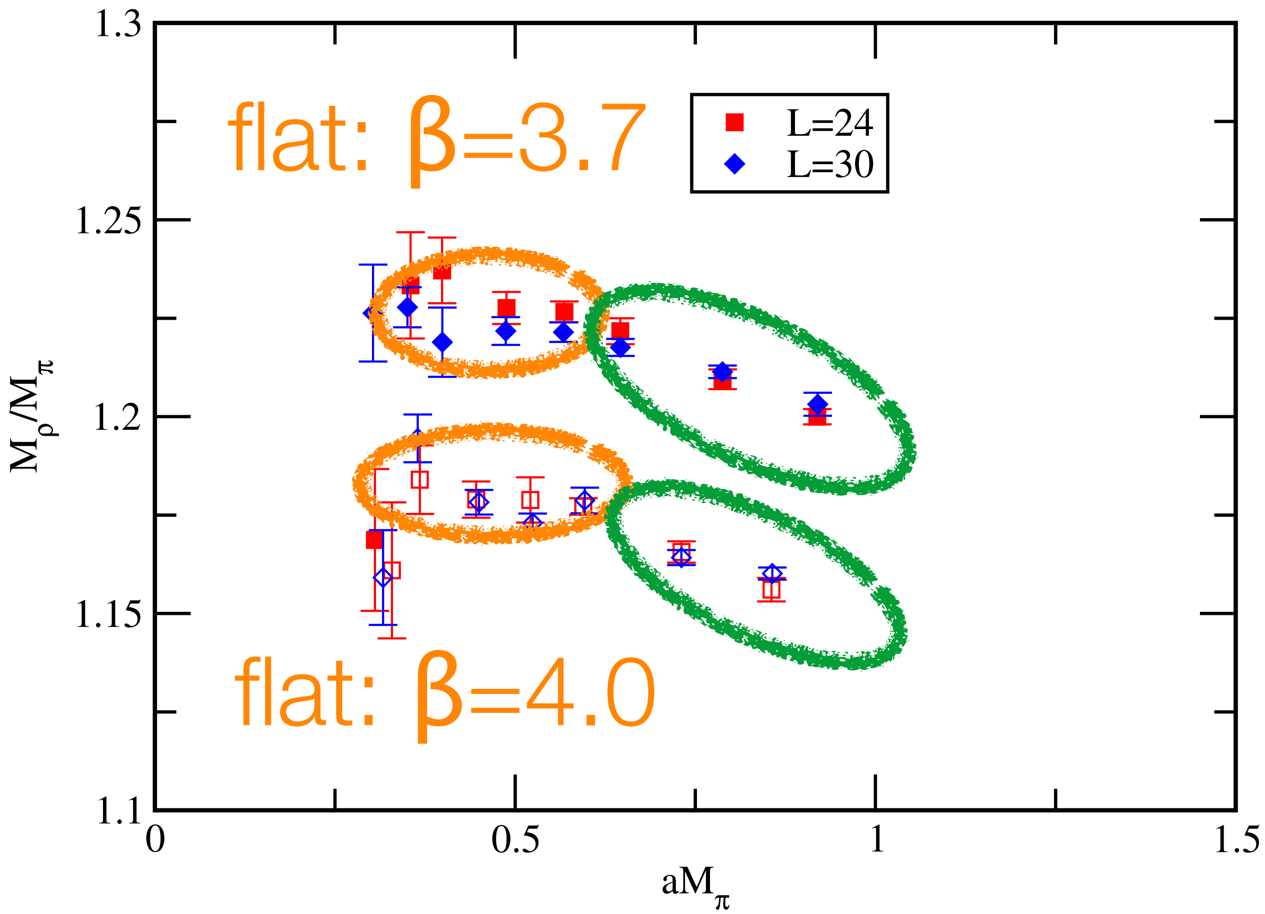

- β=3.7 & 4.0: small mass (wider than F_π): consistent with hyper scaling (HS)
- mass dependence at the tail is due to non-universal mass correction to HS

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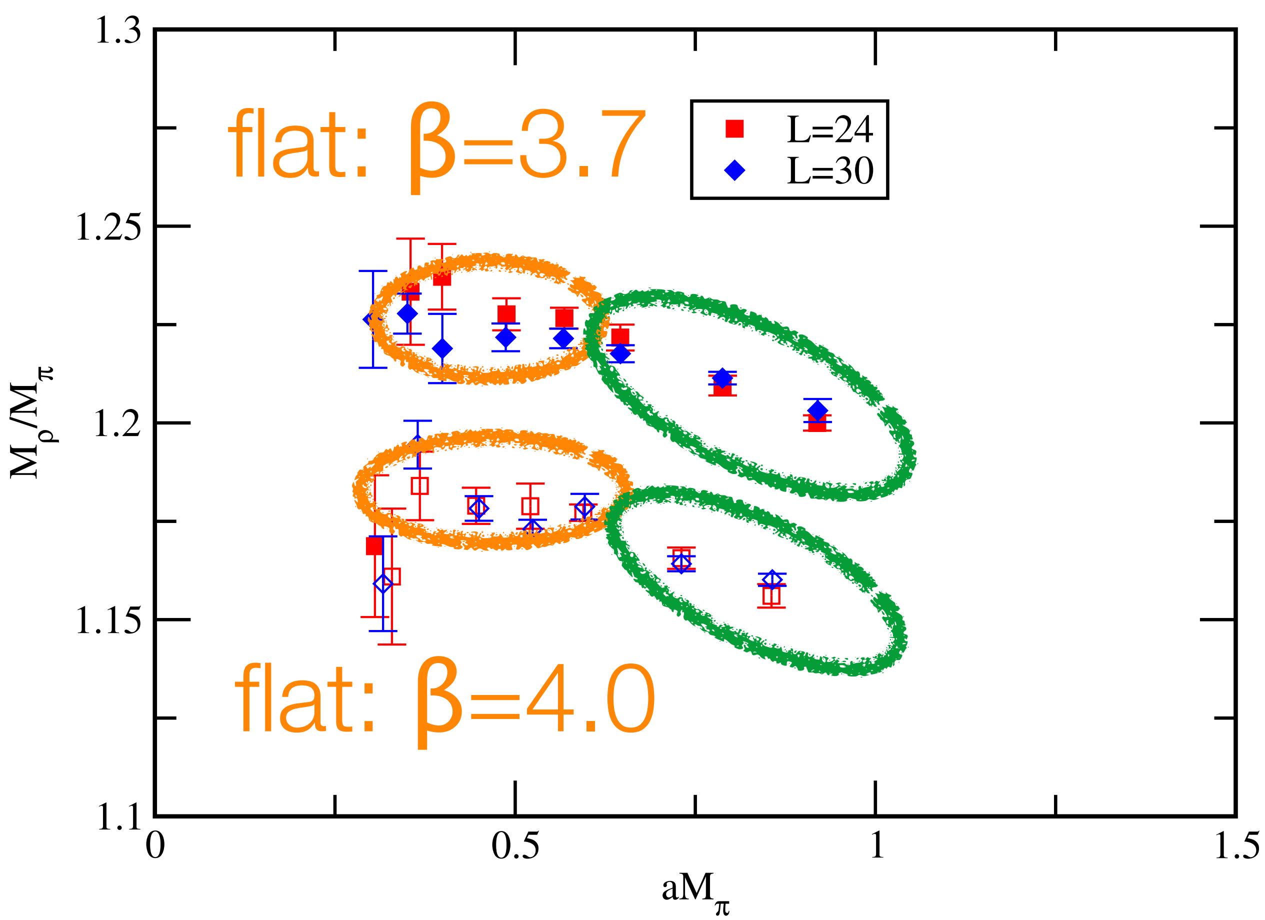

- one may attempt to perform a matching
- assuming $(am)^2$ error is small

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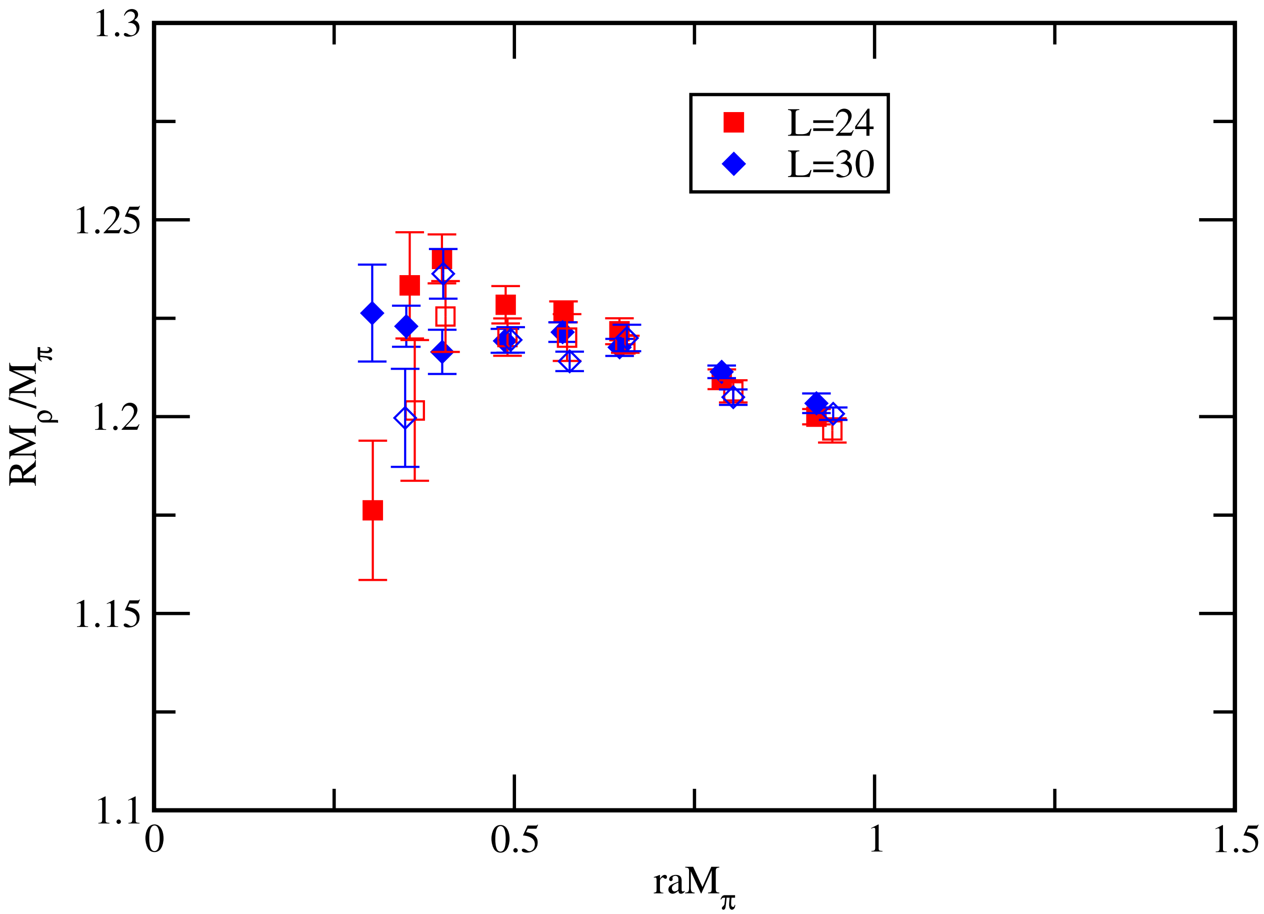

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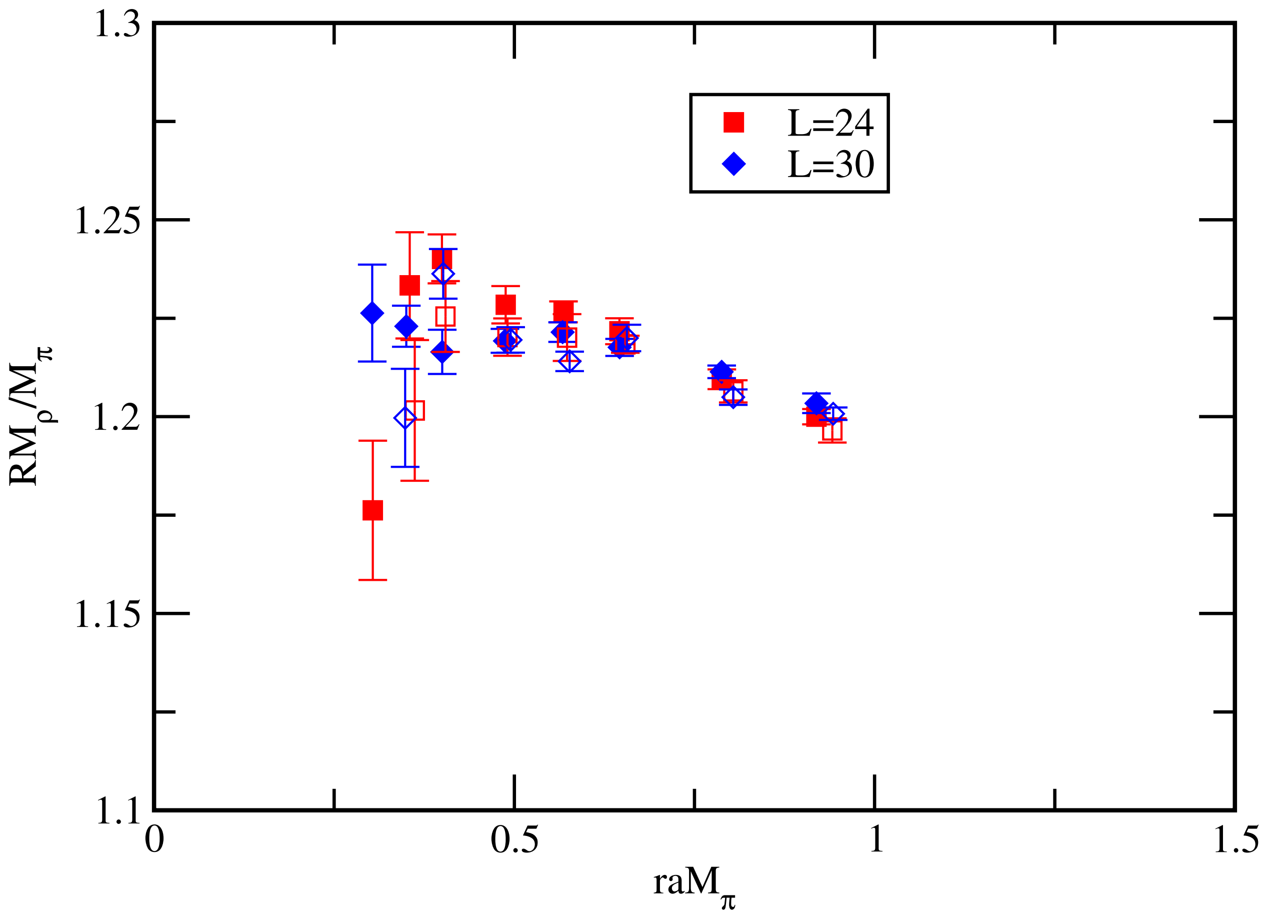

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- movement: correct direction in asymptotically free domain !

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conformal (finite size) scaling

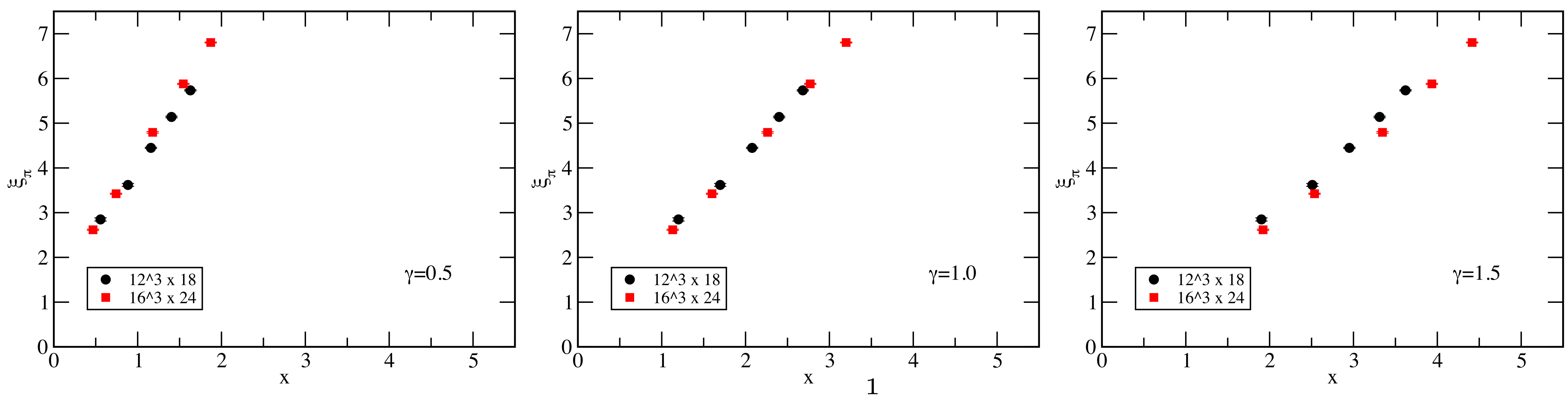
- Scaling dimension at IR fixed point [Wilson-Fisher]; Hyper Scaling [Miransky]
- mass dependence is described by anomalous dimensions at IRFP
  - quark mass anomalous dimension γ^*
  - operator anomalous dimension
- hadron mass and pion decay constant obey same scaling

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

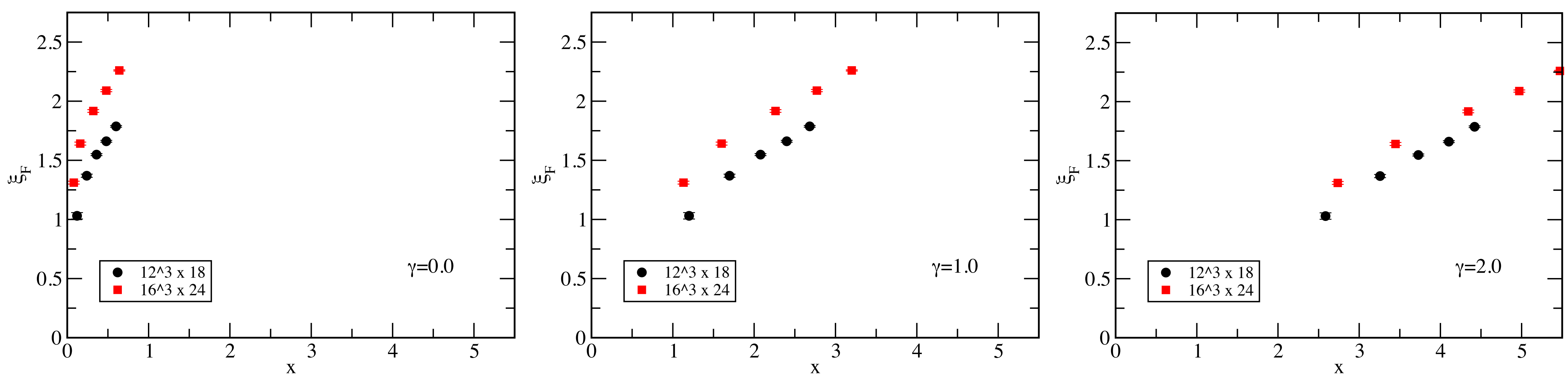
- finite size scaling in a L^4 box (DeGrand; Del Debbio et al)
  - scaling variable: $x = L m_f^{\frac{1}{1+\gamma^*}}$

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

N_f=4 see if data align at some γ



$$x = L m_f^{\frac{1}{1+\gamma}}$$



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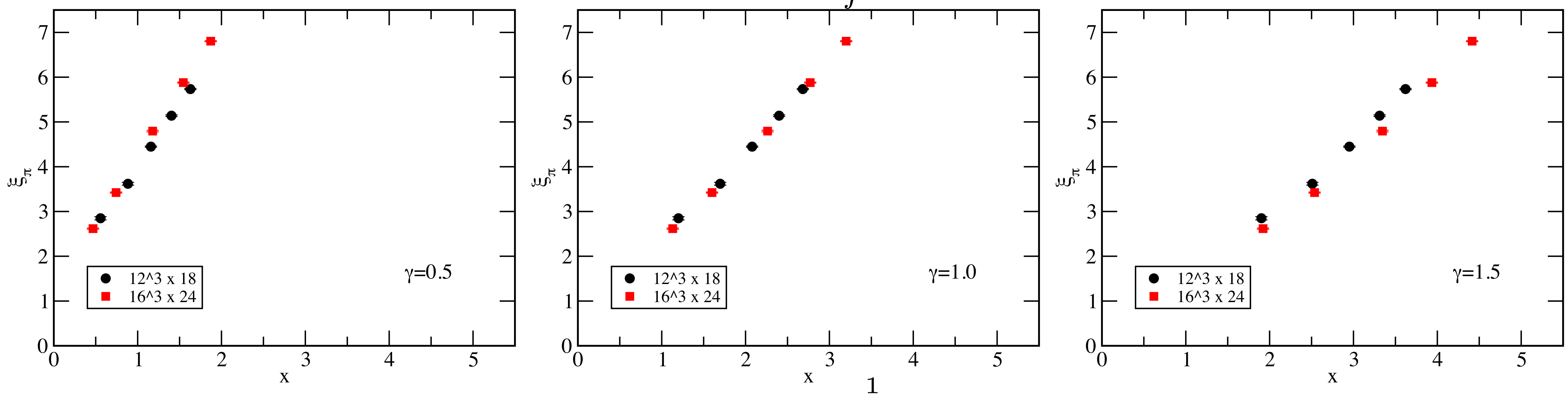
$$M_\pi L \propto m_f^{1/2} L$$



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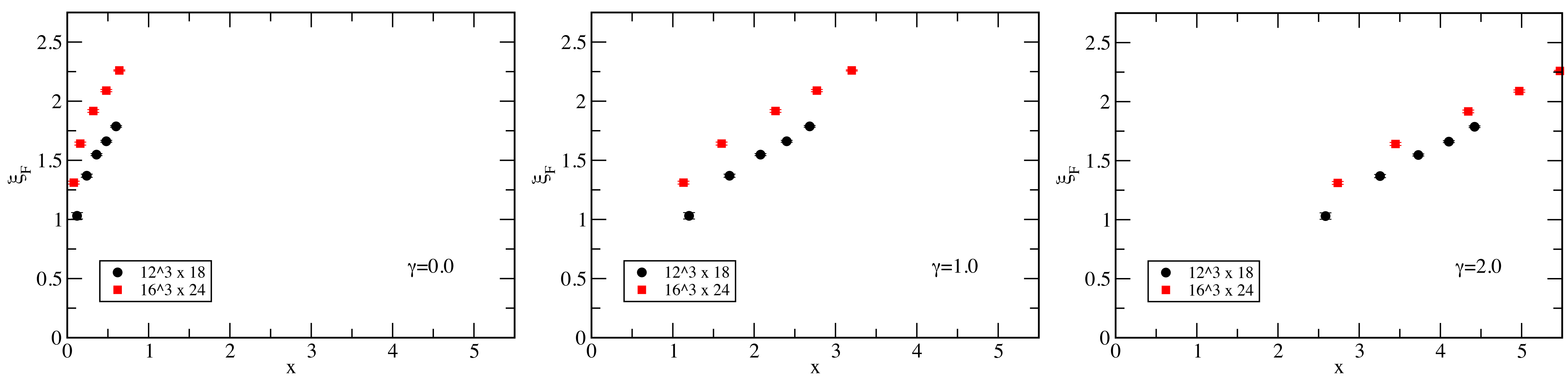

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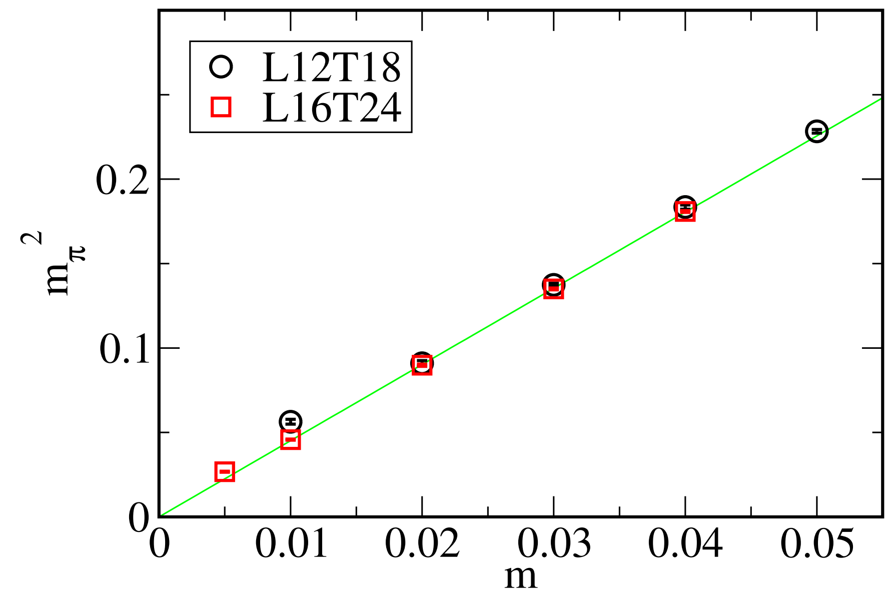

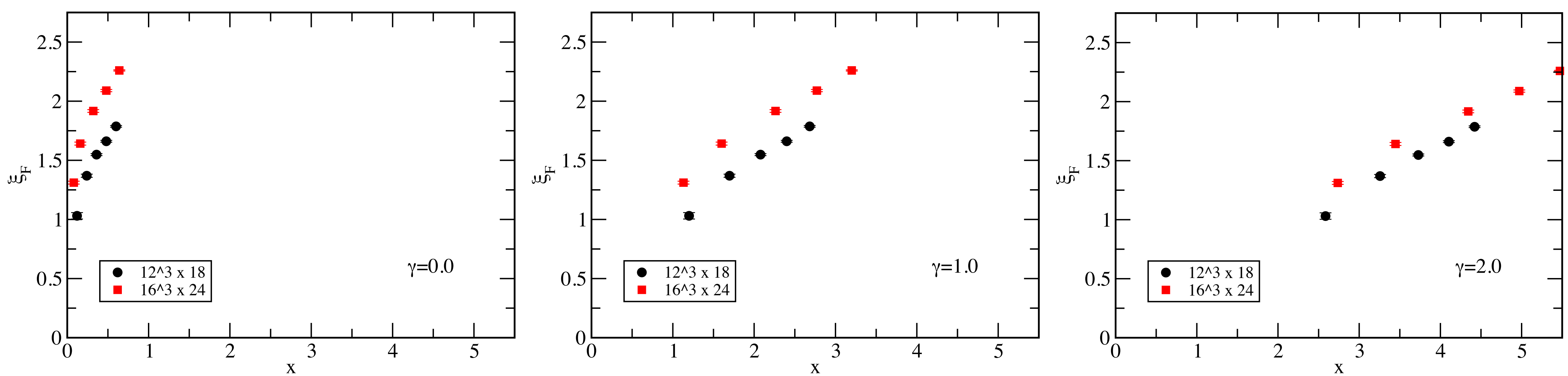

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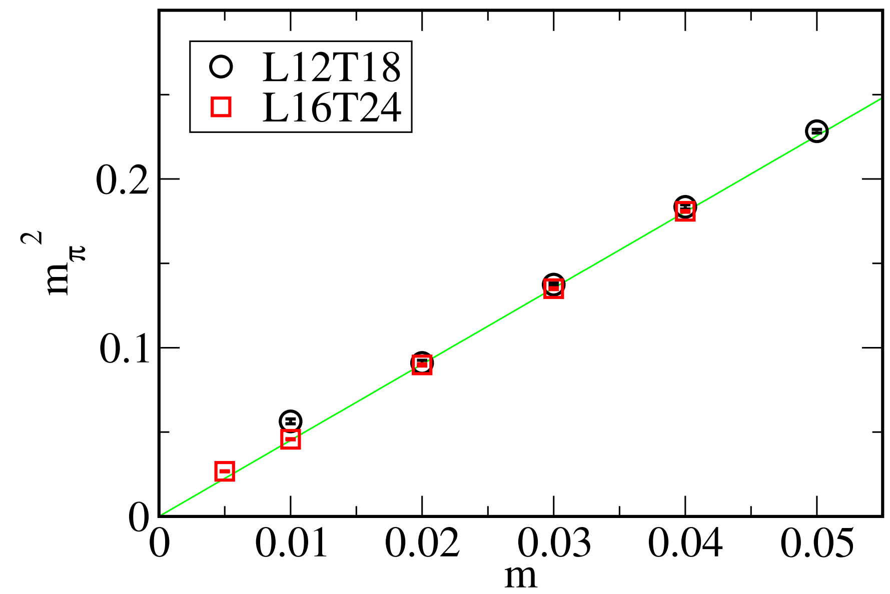
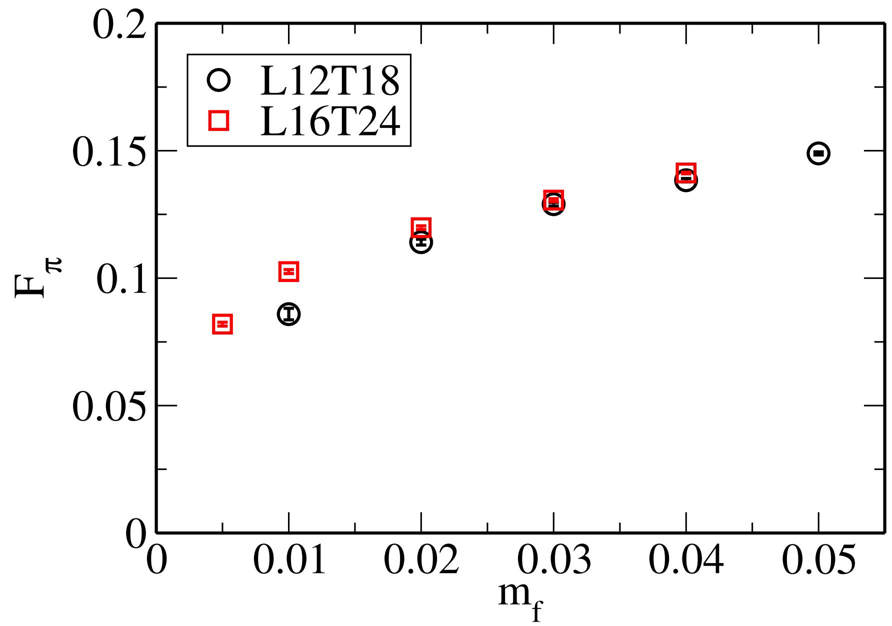
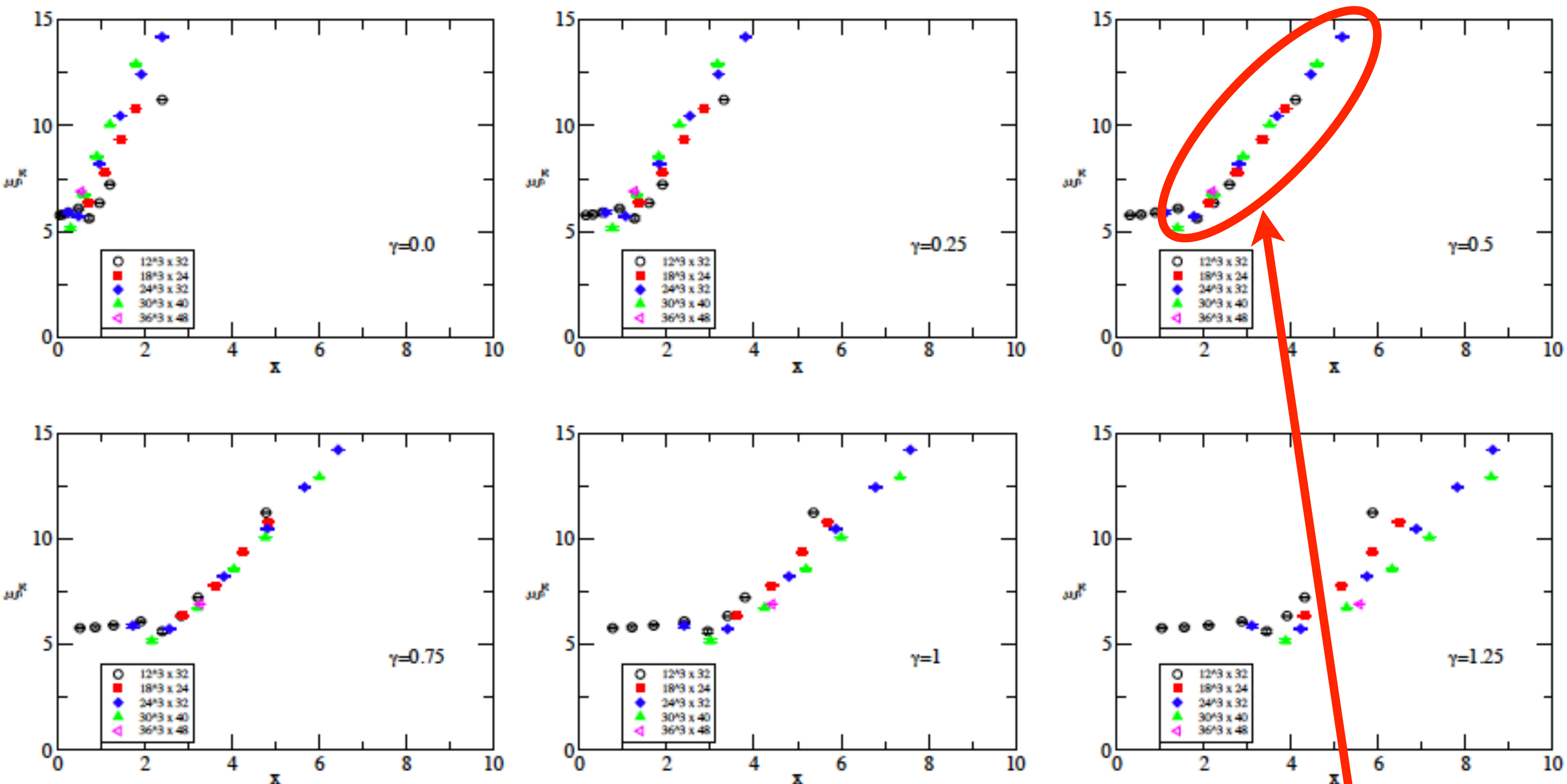




N_f=8 see if data align at some γ: M_π

γ =0.5



good alignment

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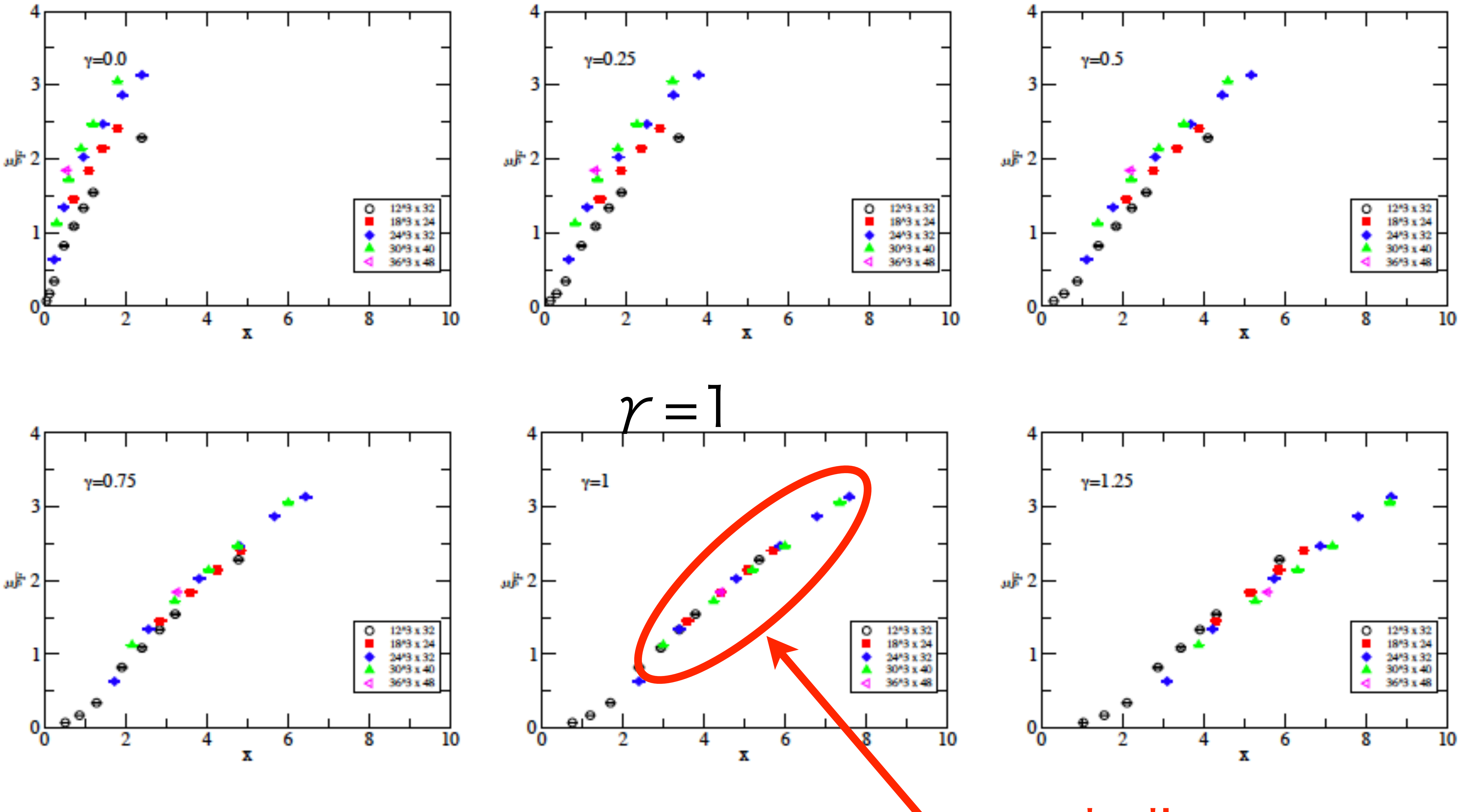

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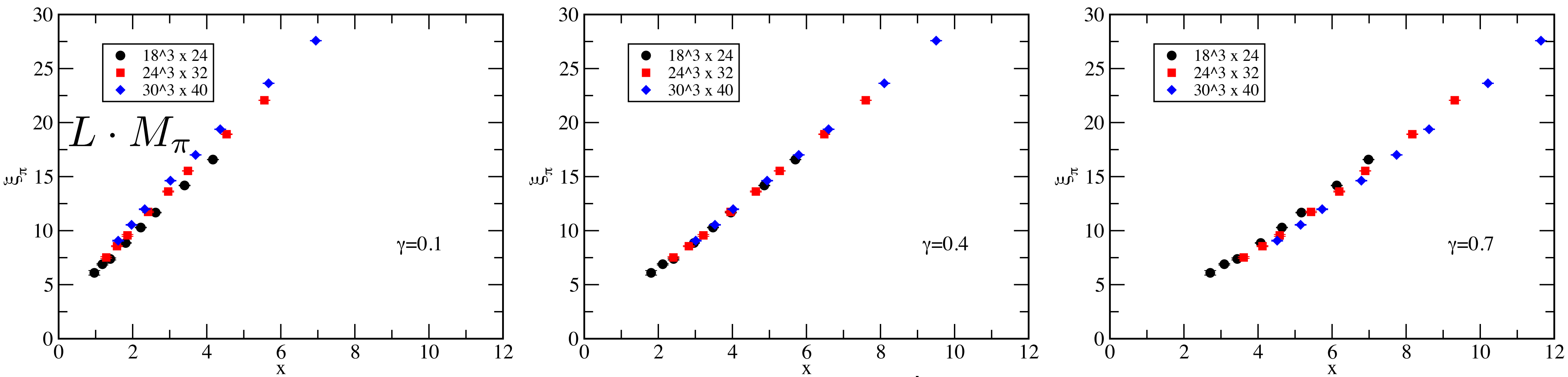
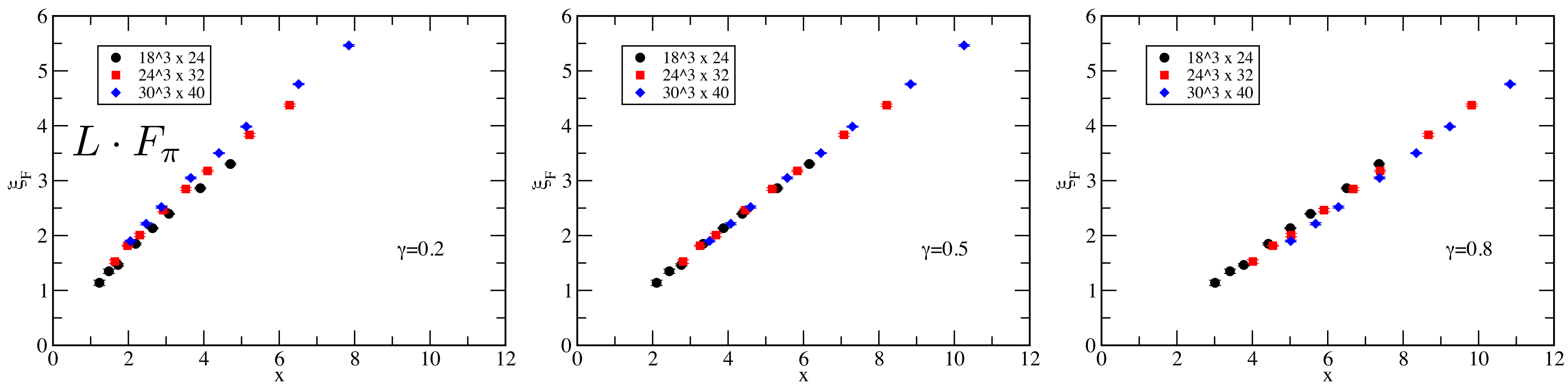


$$x = Lm_f^{\frac{1}{1+\gamma}}$$



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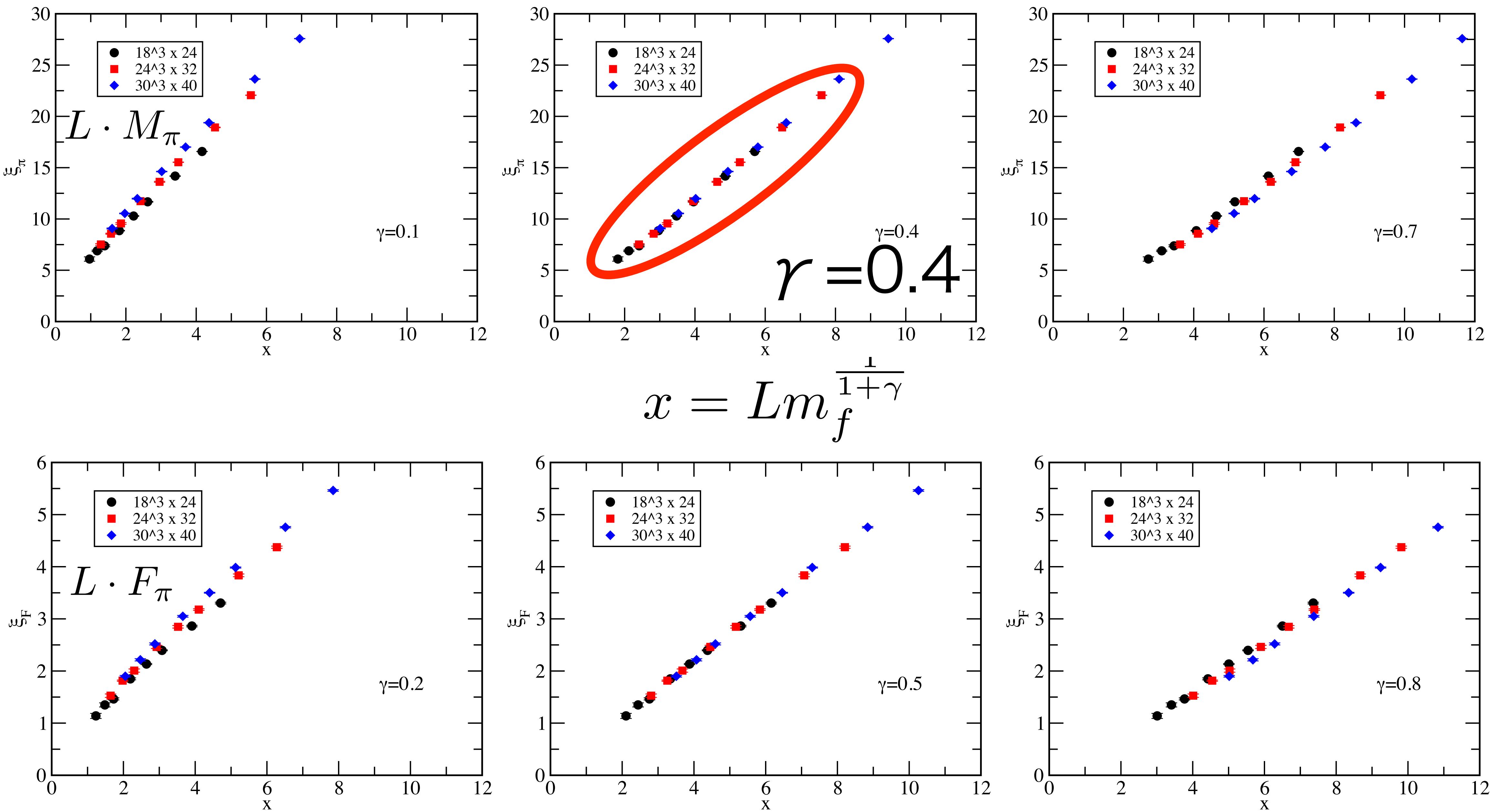

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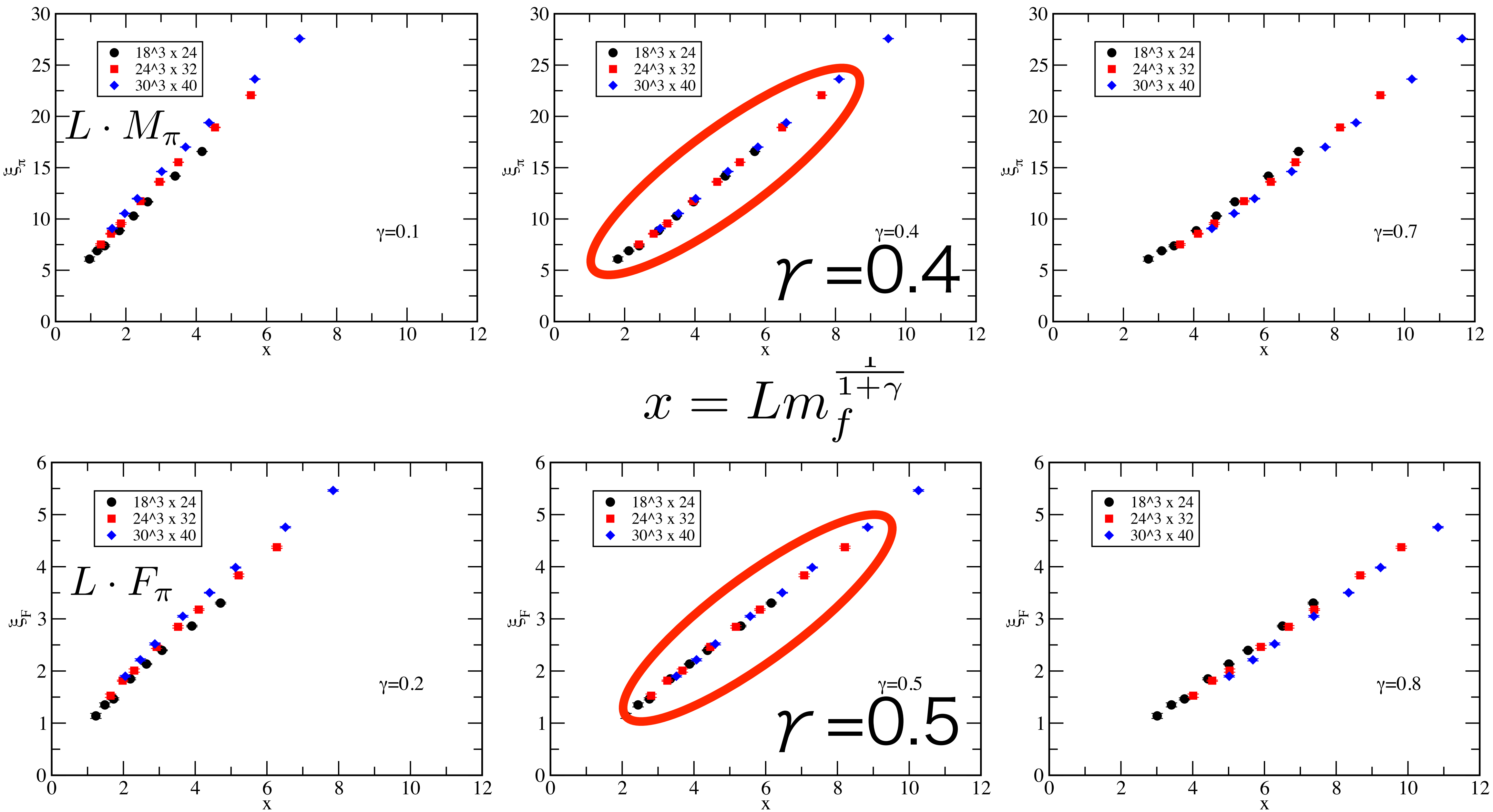

measure of the “alignment”
without resorting to a model

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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=π, ρ; $\xi_F = LF_\pi$
  - $f_p(x)$: 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

measure of the "alignment" without resorting to a model

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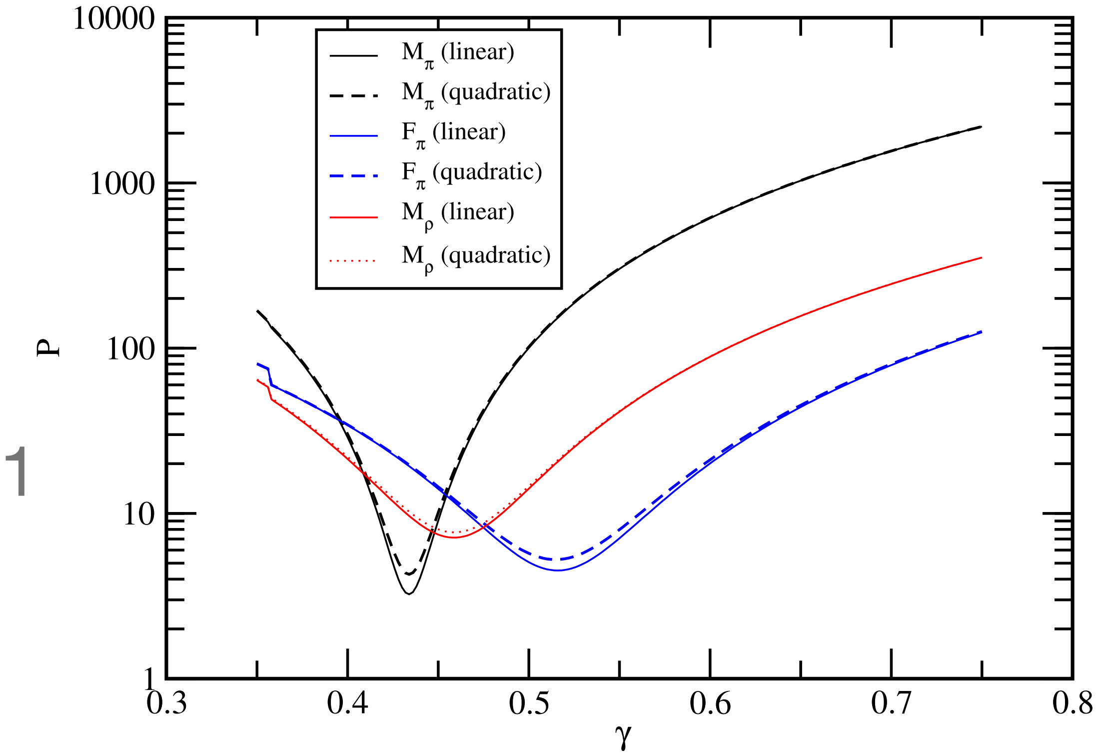
P(γ) for M_π,F_π,M_ρ at β=3.7



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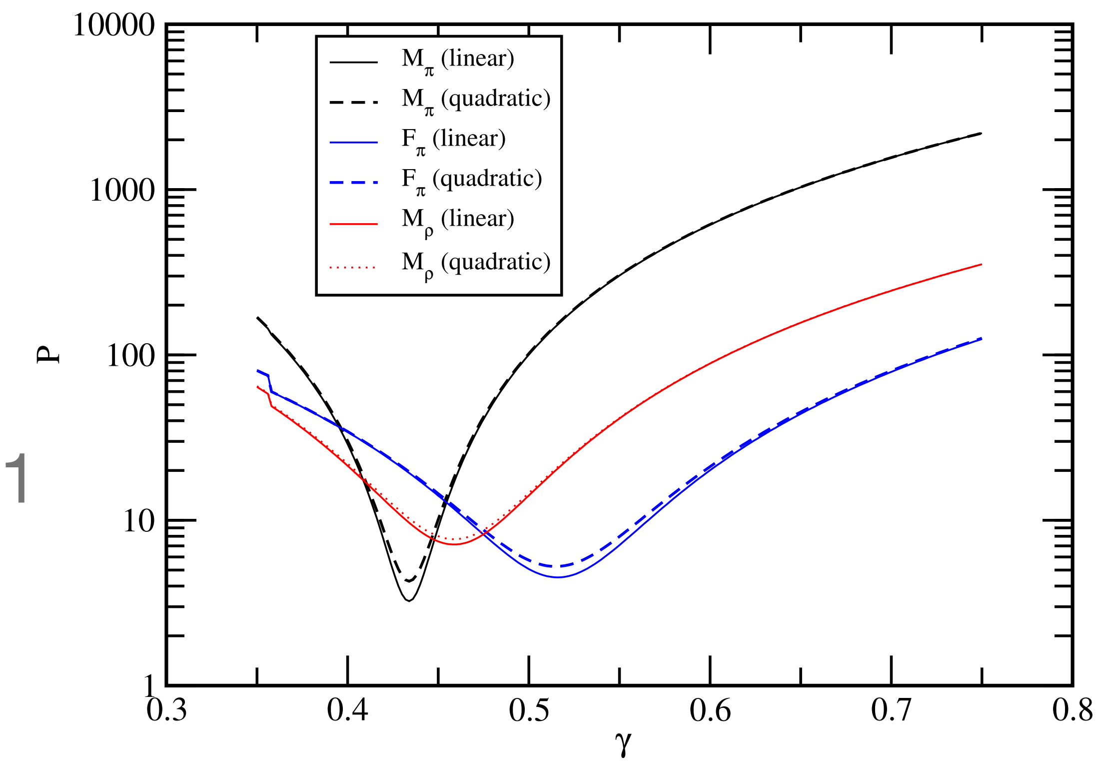
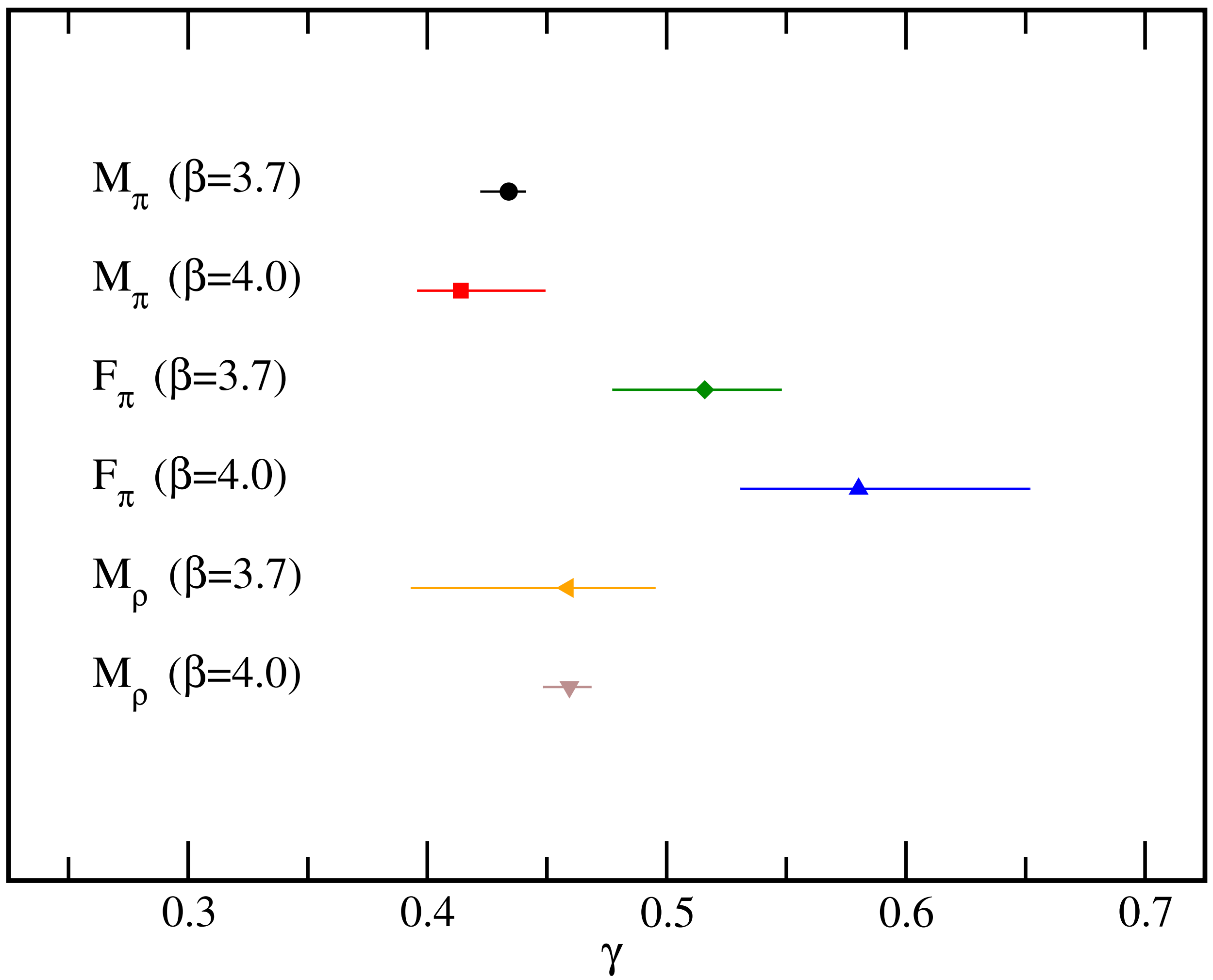


summary of γ from P(γ) for N_f=12



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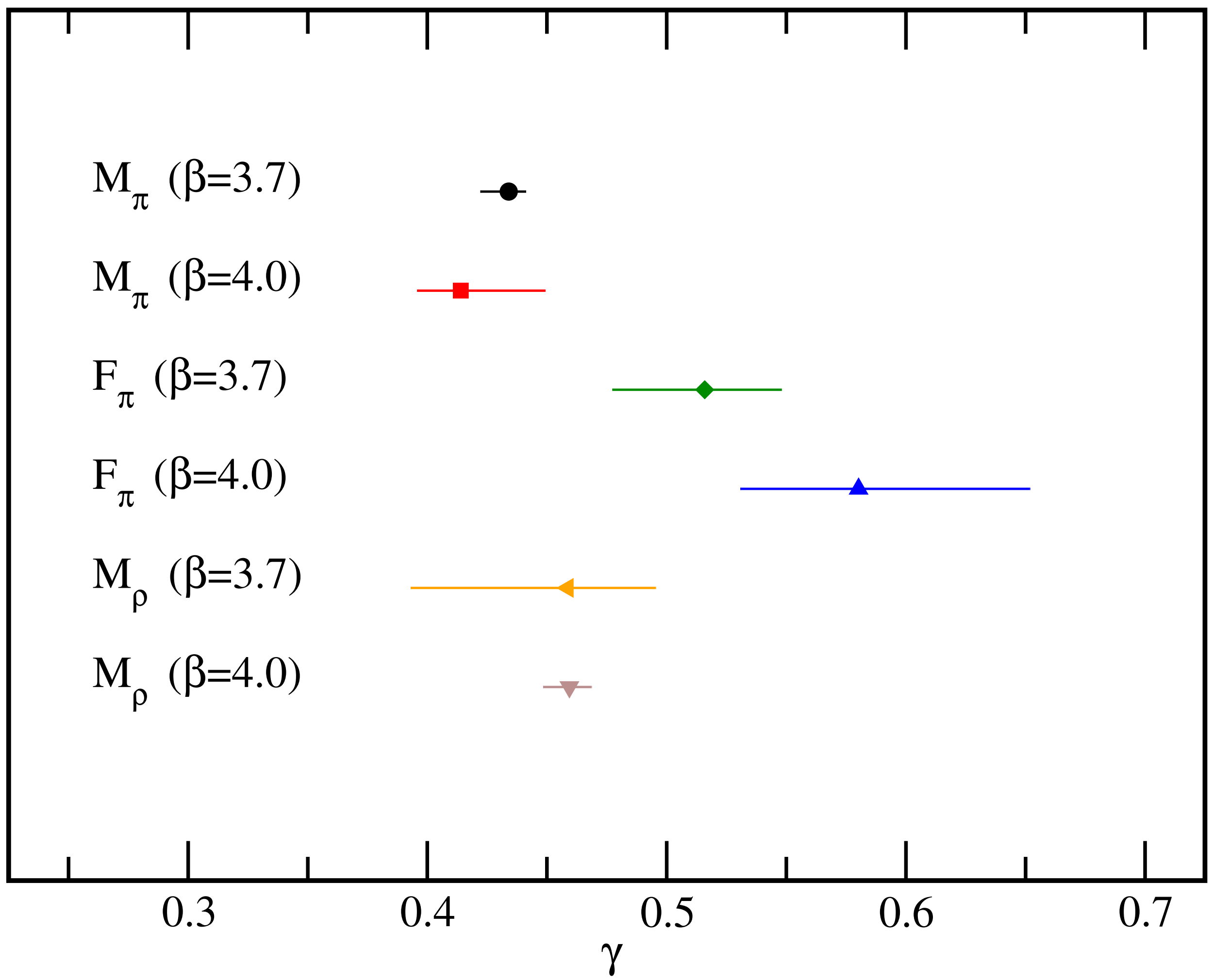

- γ: consistent with 2 σ level except for F_π at β=4.0

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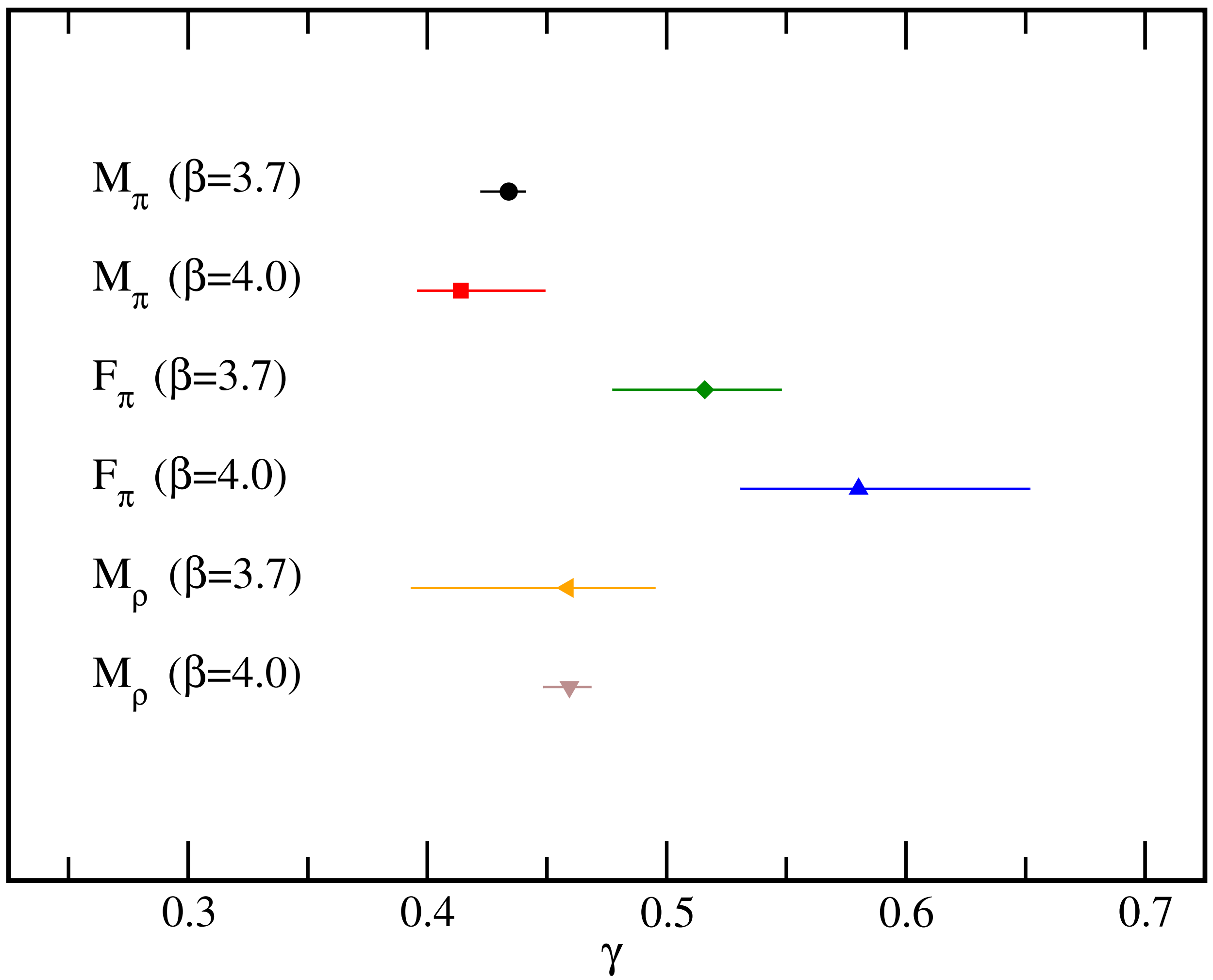

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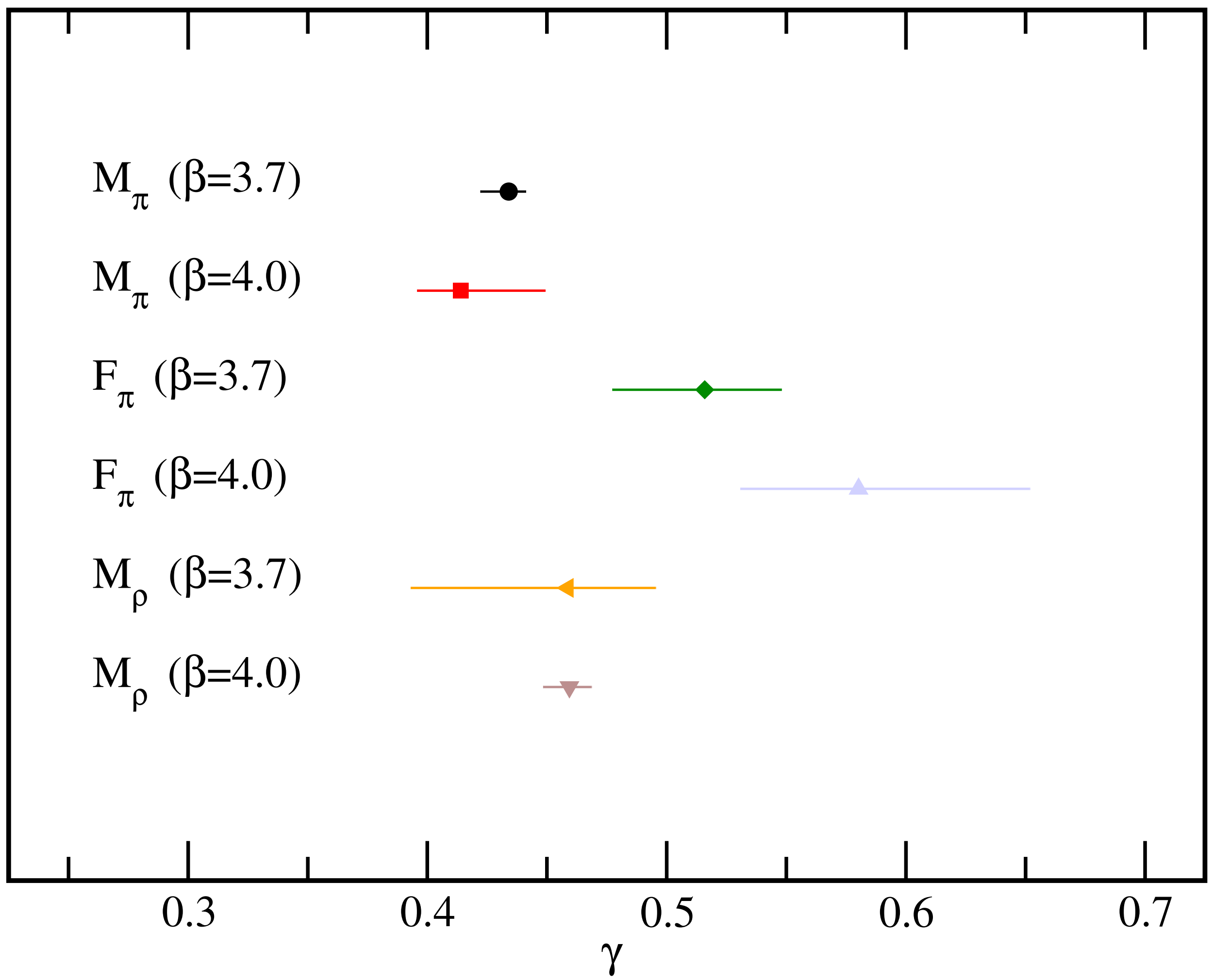
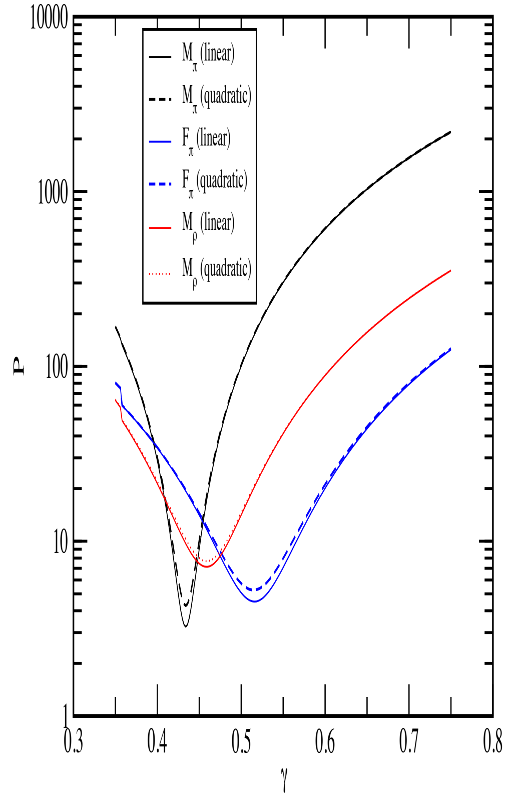
summary of γ from $P(\gamma)$ for N_f=12



- 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 $0.4<\gamma_*<0.5$

$P(\gamma)$ analysis for N_f=8



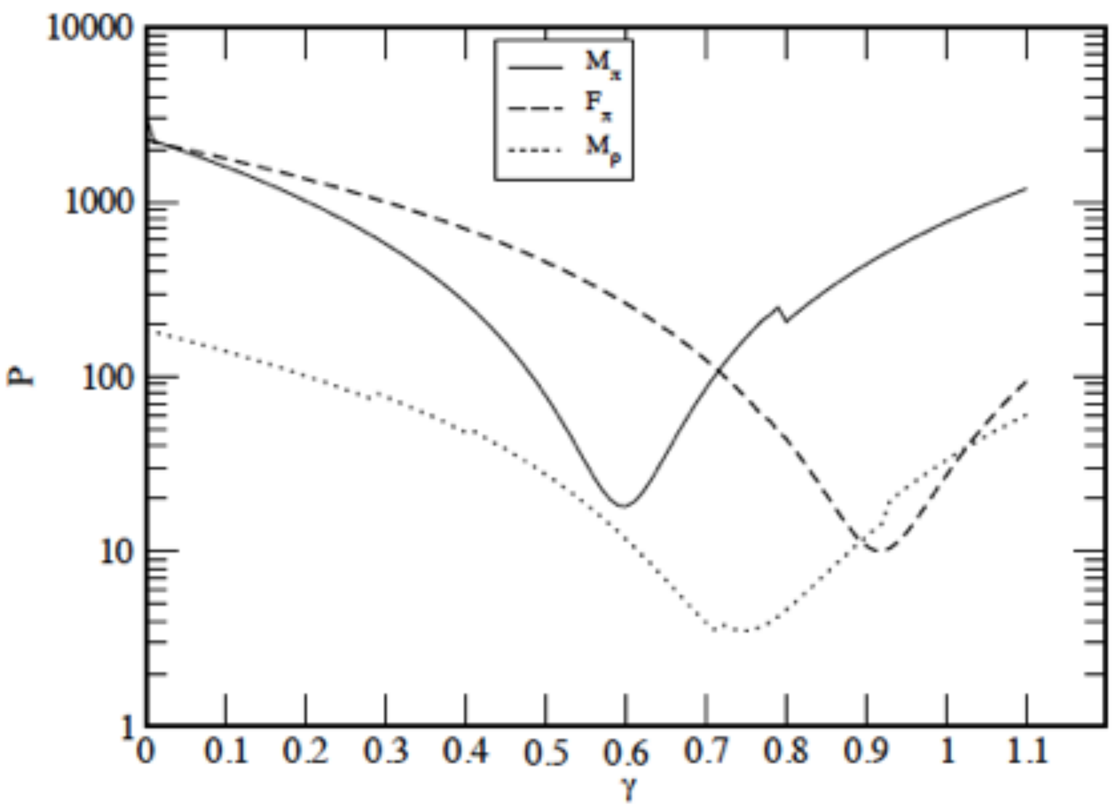
N_f=12

quantity	γ
M_π	0.434(4)
F_π	0.516(12)
M_ρ	0.459(8)

statistical error only

N_f=8

quantity	γ
M_π	0.593(2)
F_π	0.955(4)
M_ρ	0.844(10)



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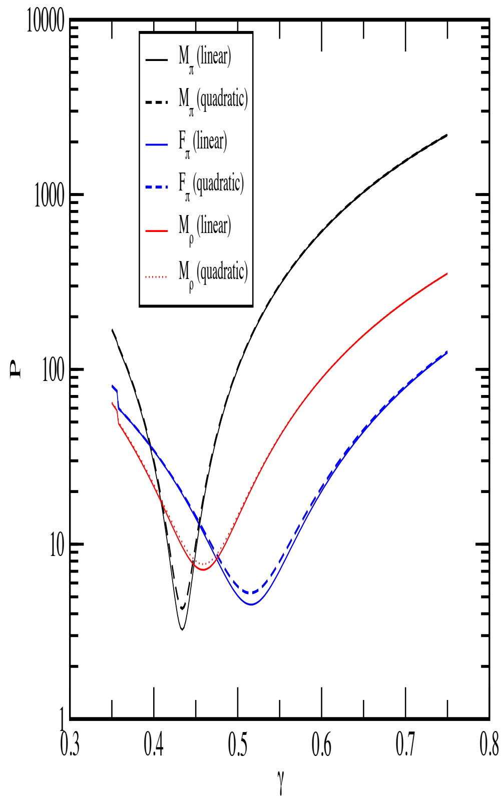

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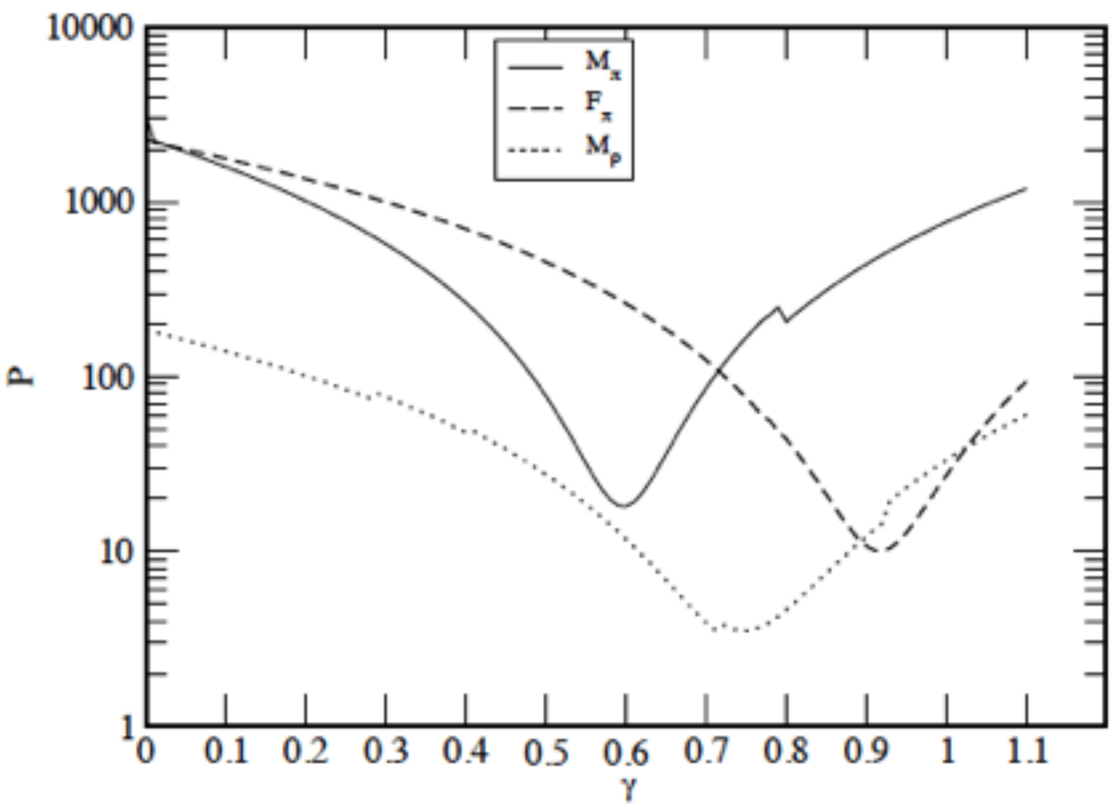

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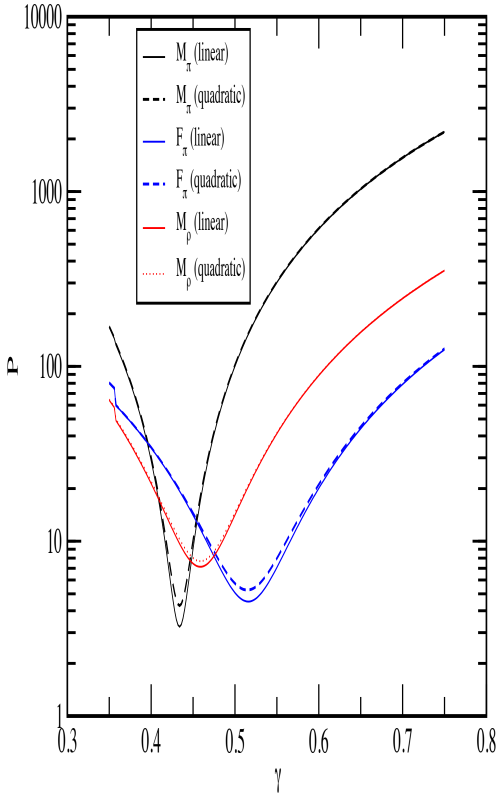

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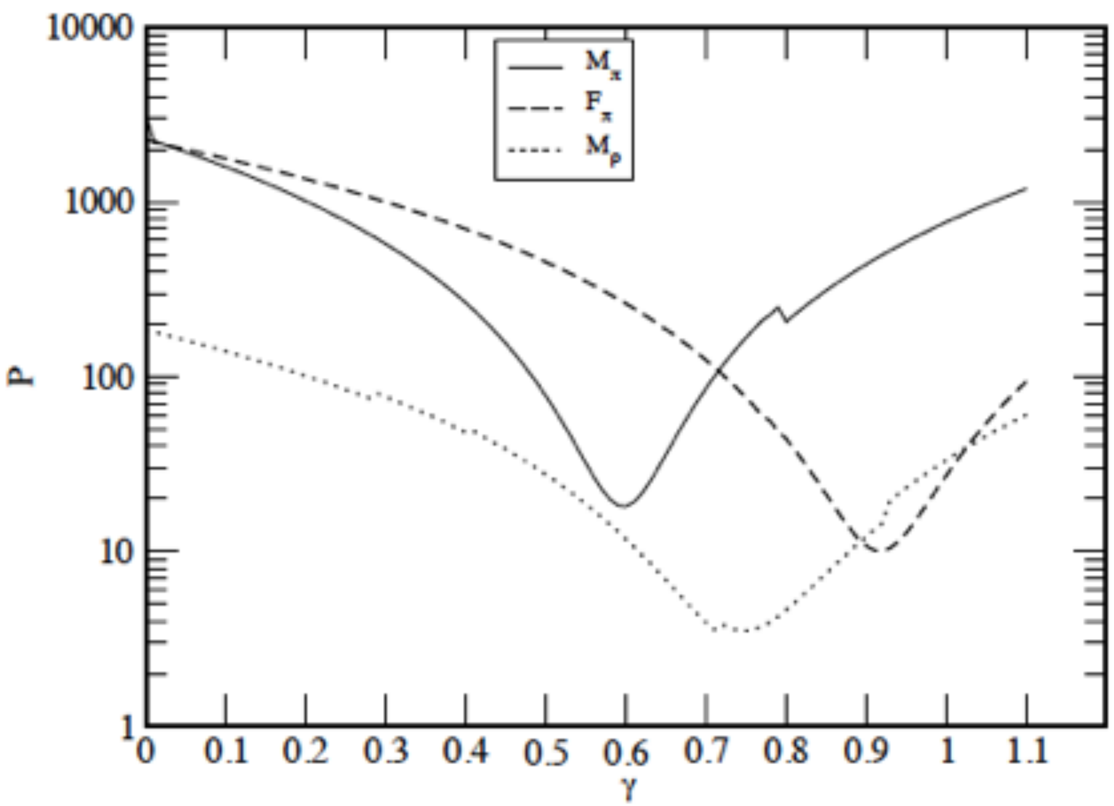

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- γ scattered→no exact conformality

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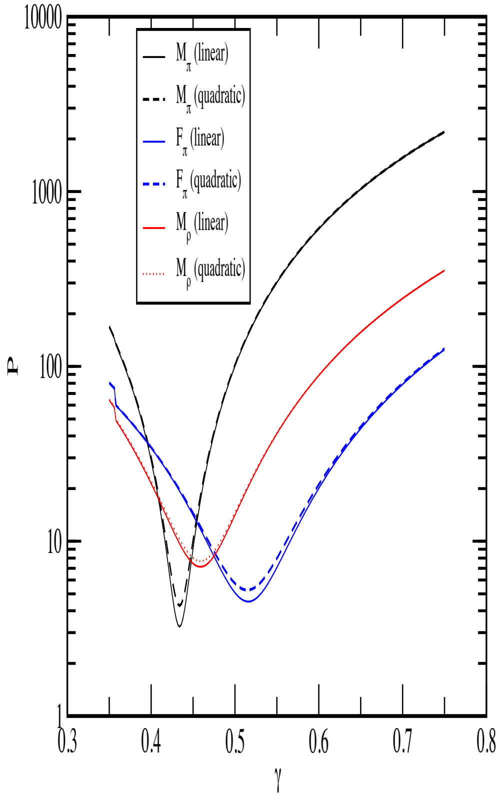

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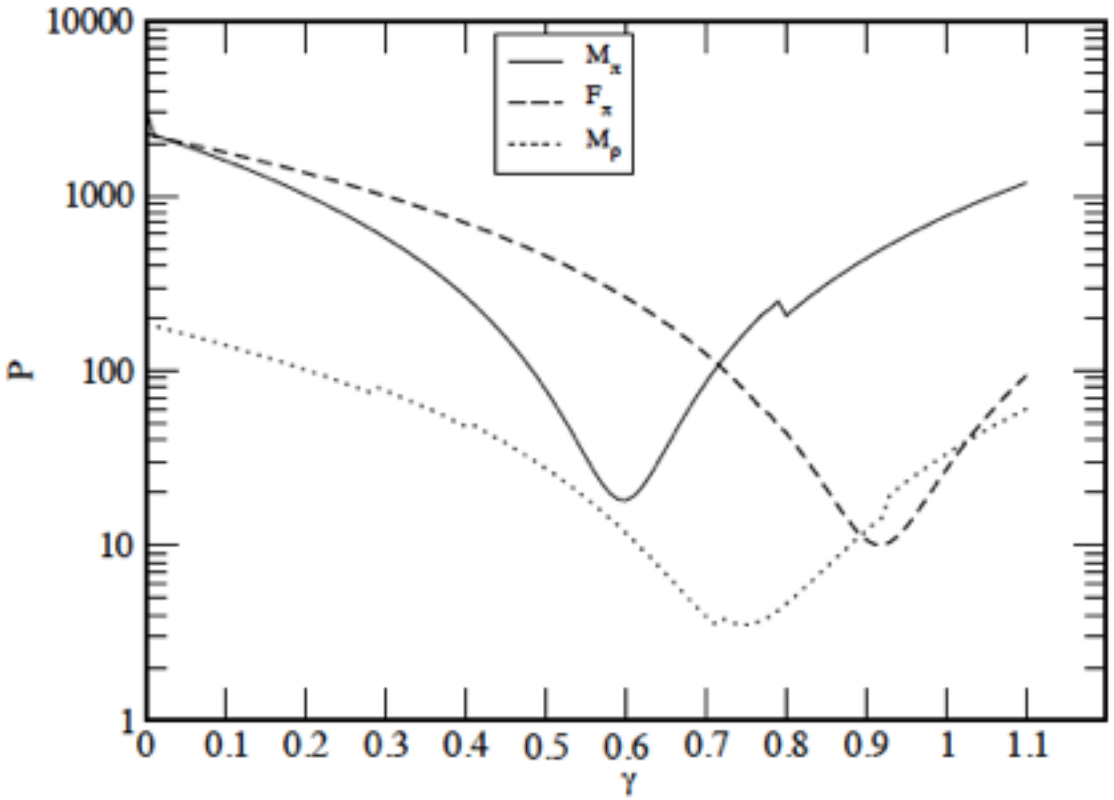

- Optimal γ obtained for each quantity
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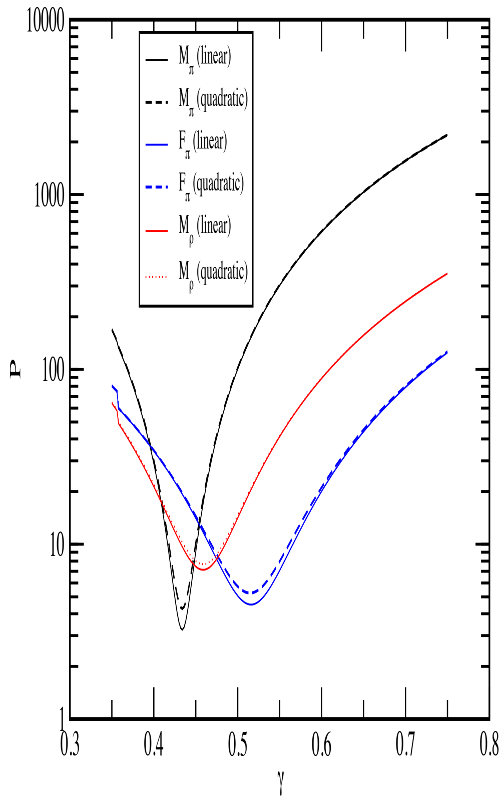
$P(\gamma)$ analysis for N_f=8



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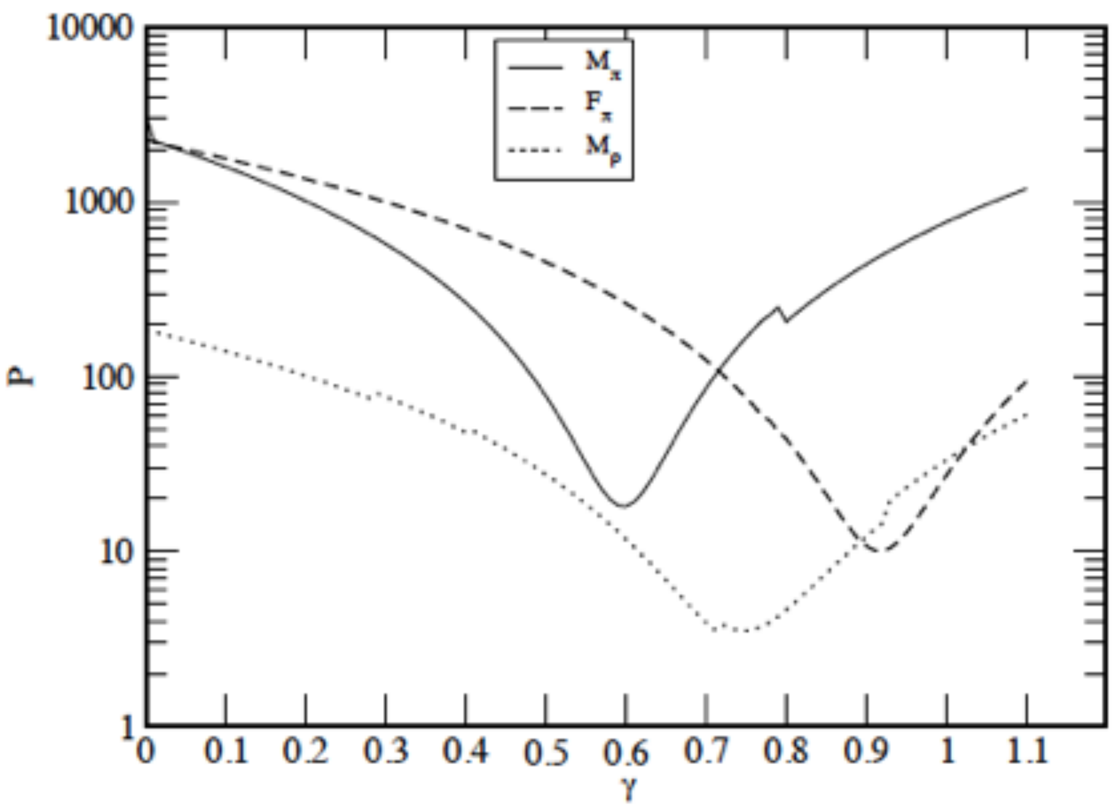

- Optimal γ obtained for each quantity
- γ scattered→no exact conformality
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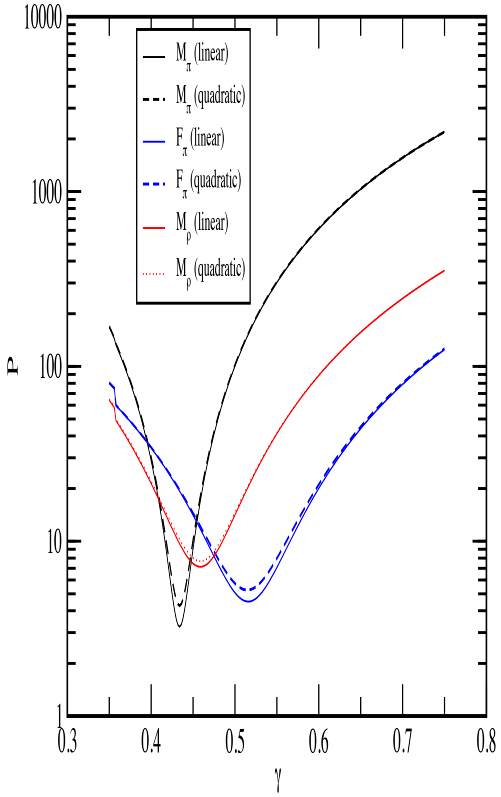
- remember: ~~chiral symmetry~~

$P(\gamma)$ analysis for N_f=8



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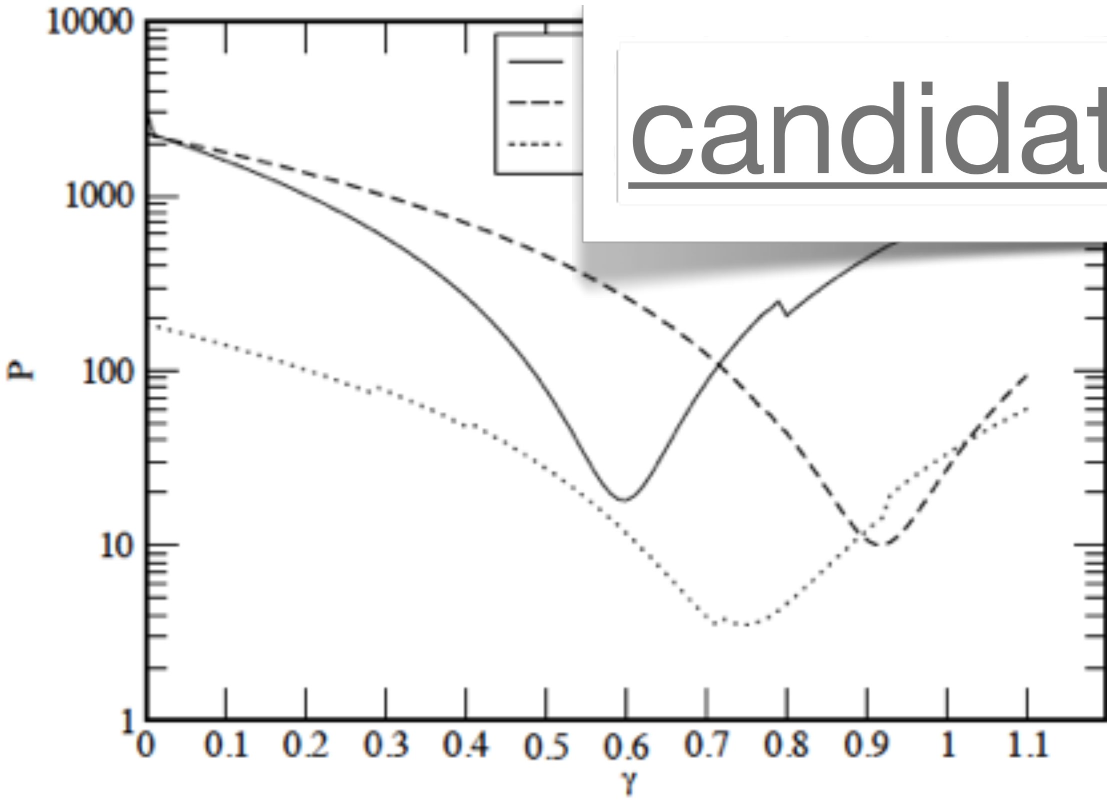
statistical error only

N_f=8

quantity	γ
M_π	0.593(2)
[illegible]	5(4)
[illegible]	4(10)



candidate of walking TC

- Optimal γ obtained for each quantity
- γ scattered→no exact conformality
- scaling→remnant conformality
- remember: ~~chiral symmetry~~

0++ spectrum

[preliminary]

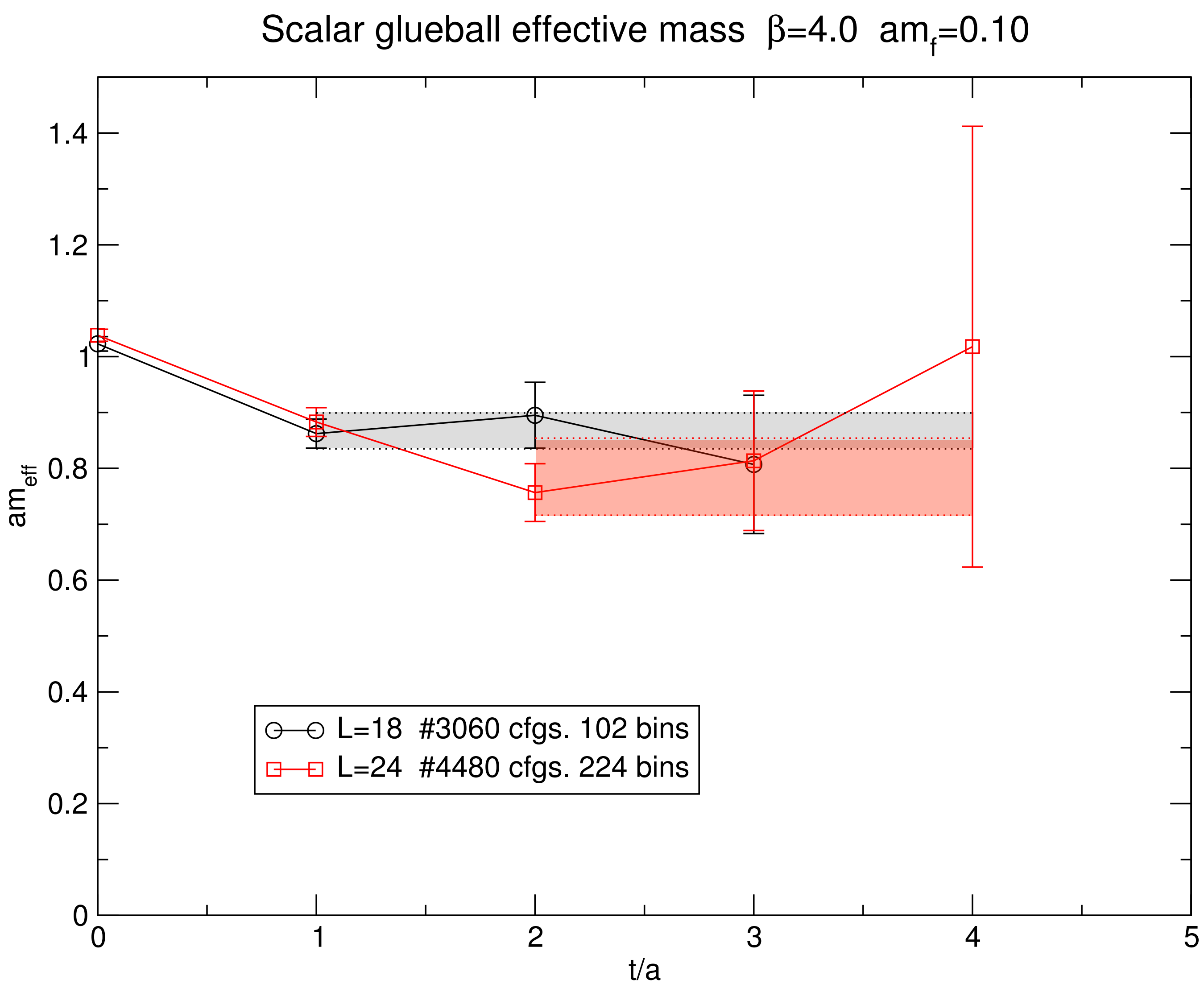
motivation

- adding another quantity to the scaling analysis
- see if light 0++ state (→ Higgs in WTC) emerges
- noisy, thus, difficult quantity in QCD

method

- 0++ glueball
  - variational method with many ops. (e.g. E. Gregory et al arXiv:1208.1858)
- flavor singlet scalar from fermion bilinear
  - stochastic estimator with 64 random vectors
- high statistics: a few 1000 ~14000 configurations

Results: scalar glueball



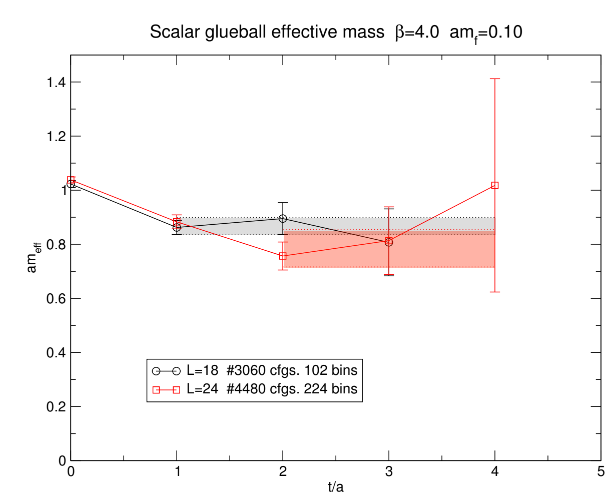
$m_{0^{++}} > m_{\pi}$

L=18 → am=0.867(32)

L=24 → am=0.785(69)

2012年12月16日日曜日

Results: scalar glueball



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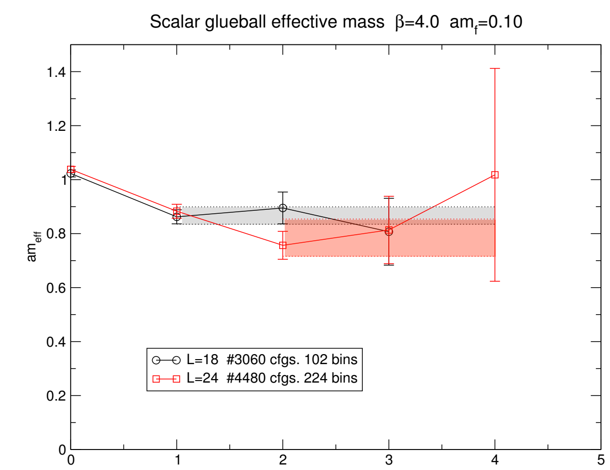

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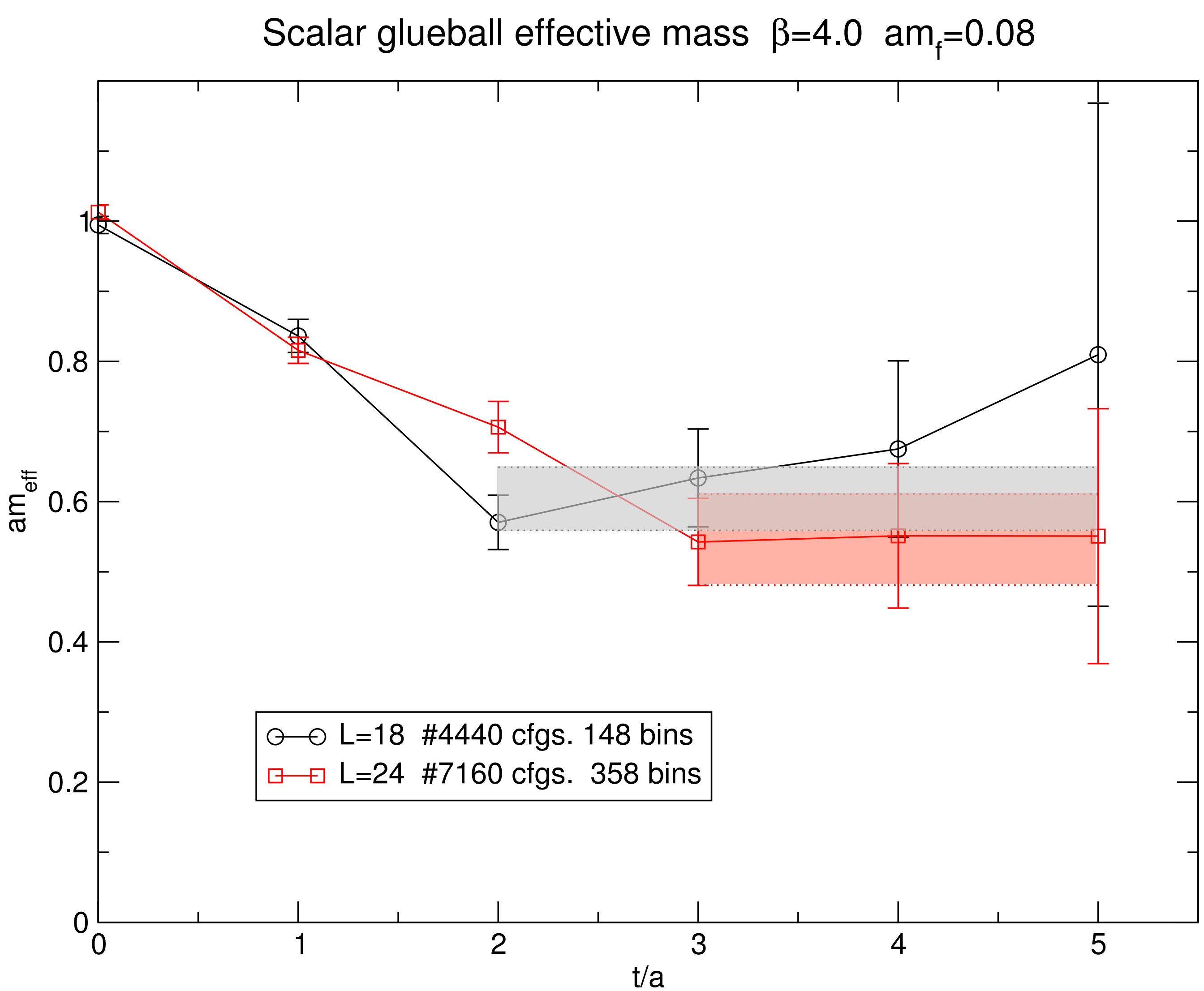
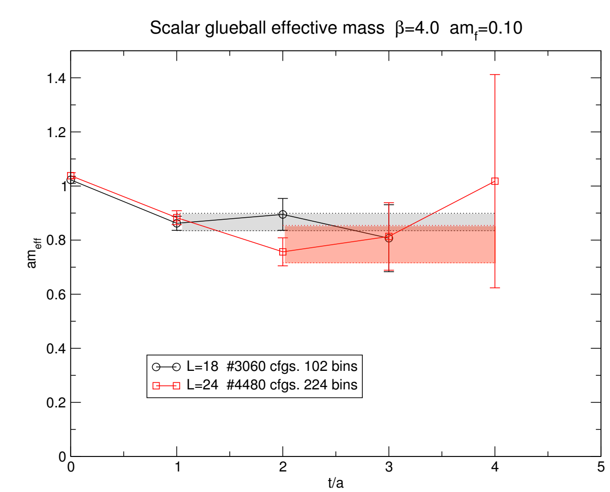


$$m_{0^{++}} \gtrsim m_\pi$$

L=18 → am=0.604(45)

L=24 → am=0.546(65)



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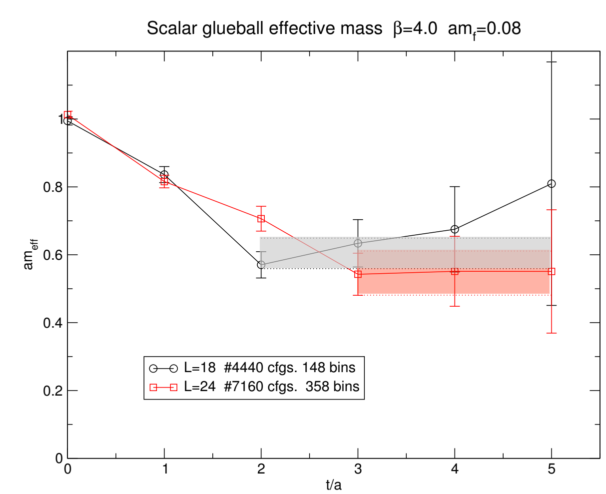

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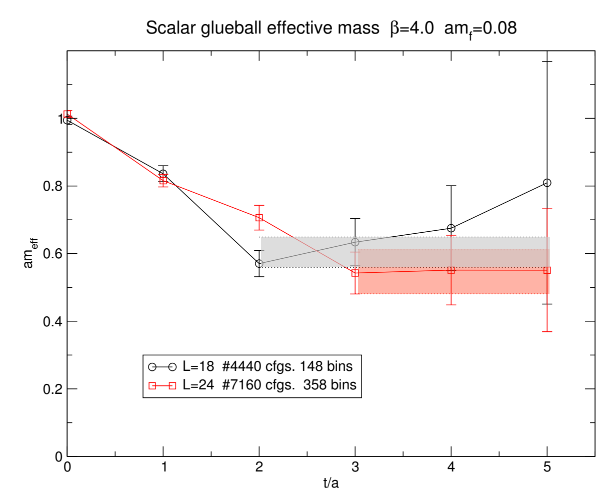

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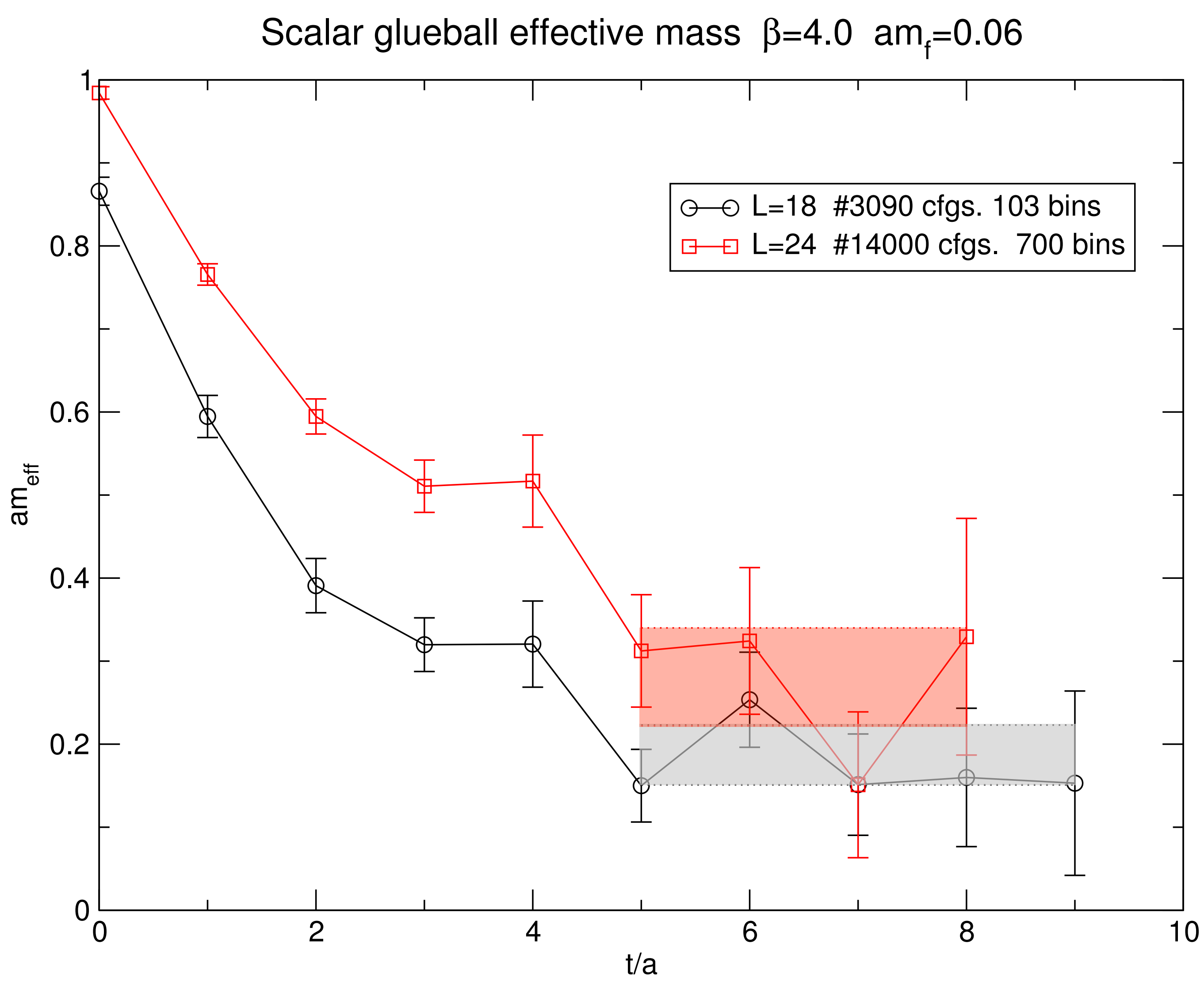
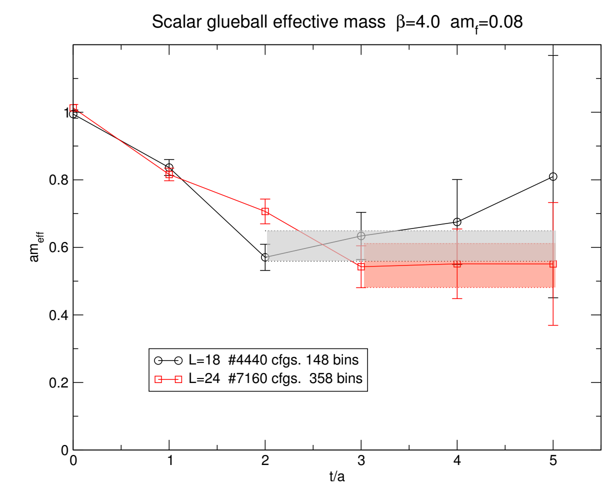


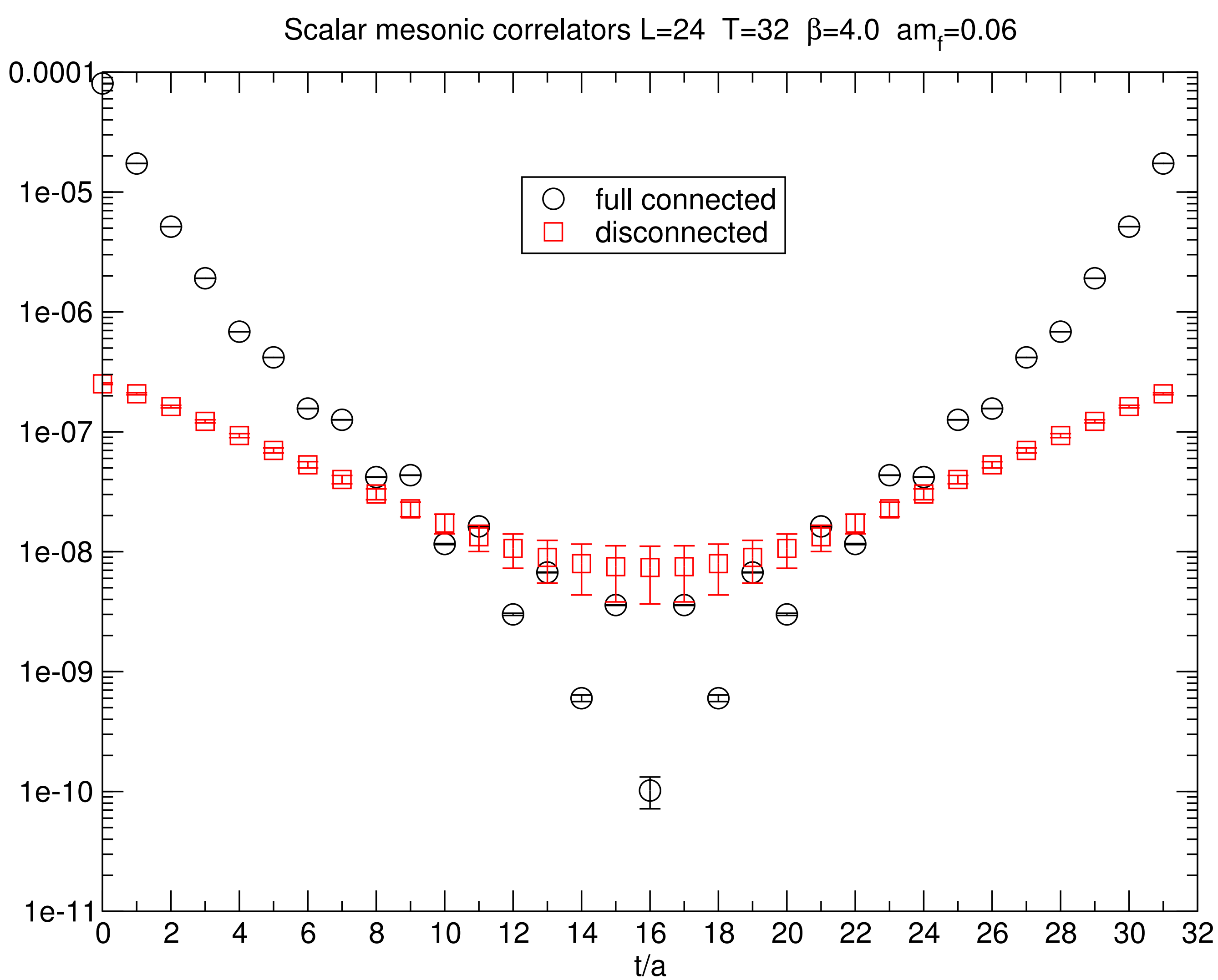
$m_{0^{++}} \lesssim m_\pi$

L=18 → am=0.187(36)

L=24 → am=0.281(59)



Results: scalar flavour-singlet meson



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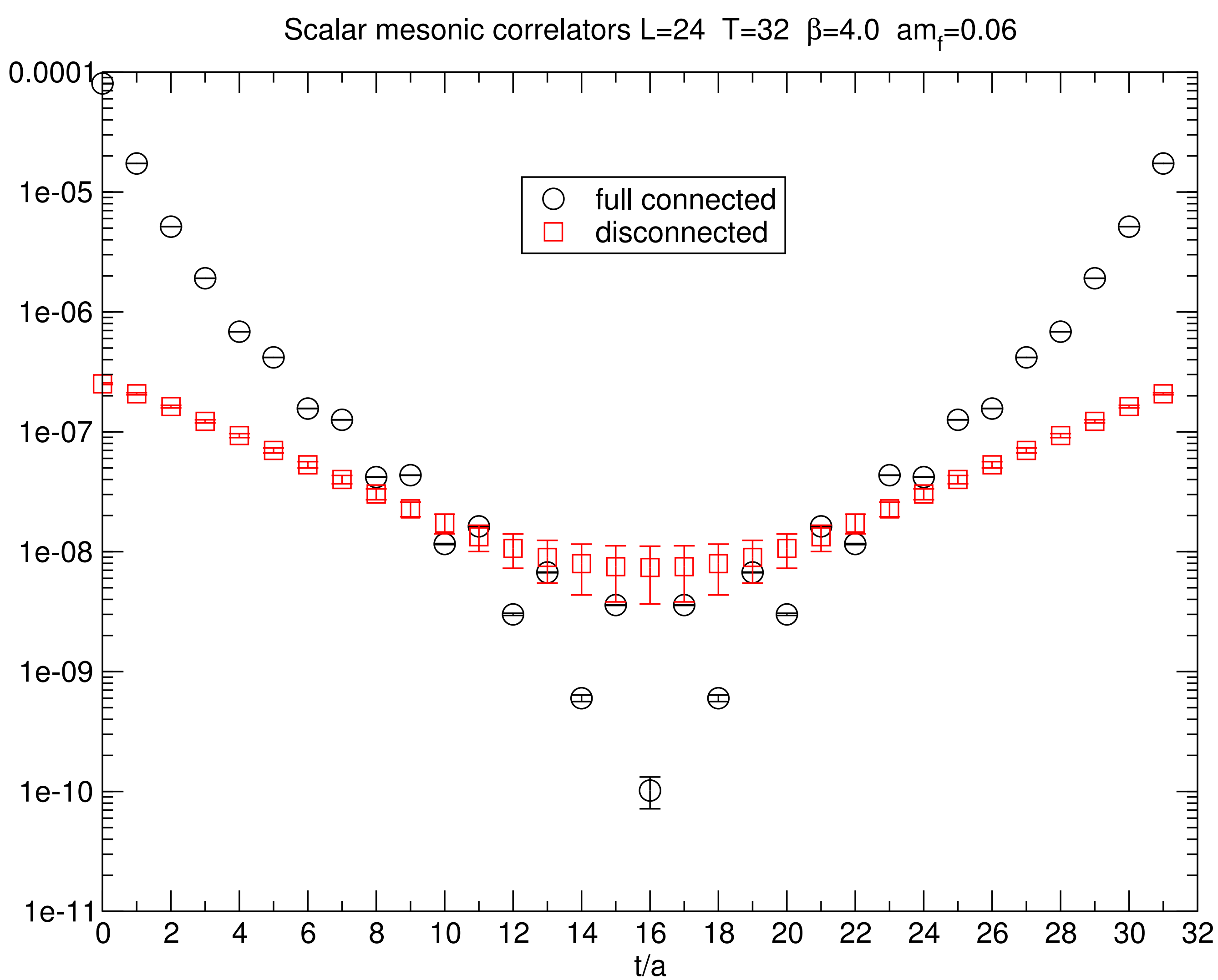

- using 14000 configurations

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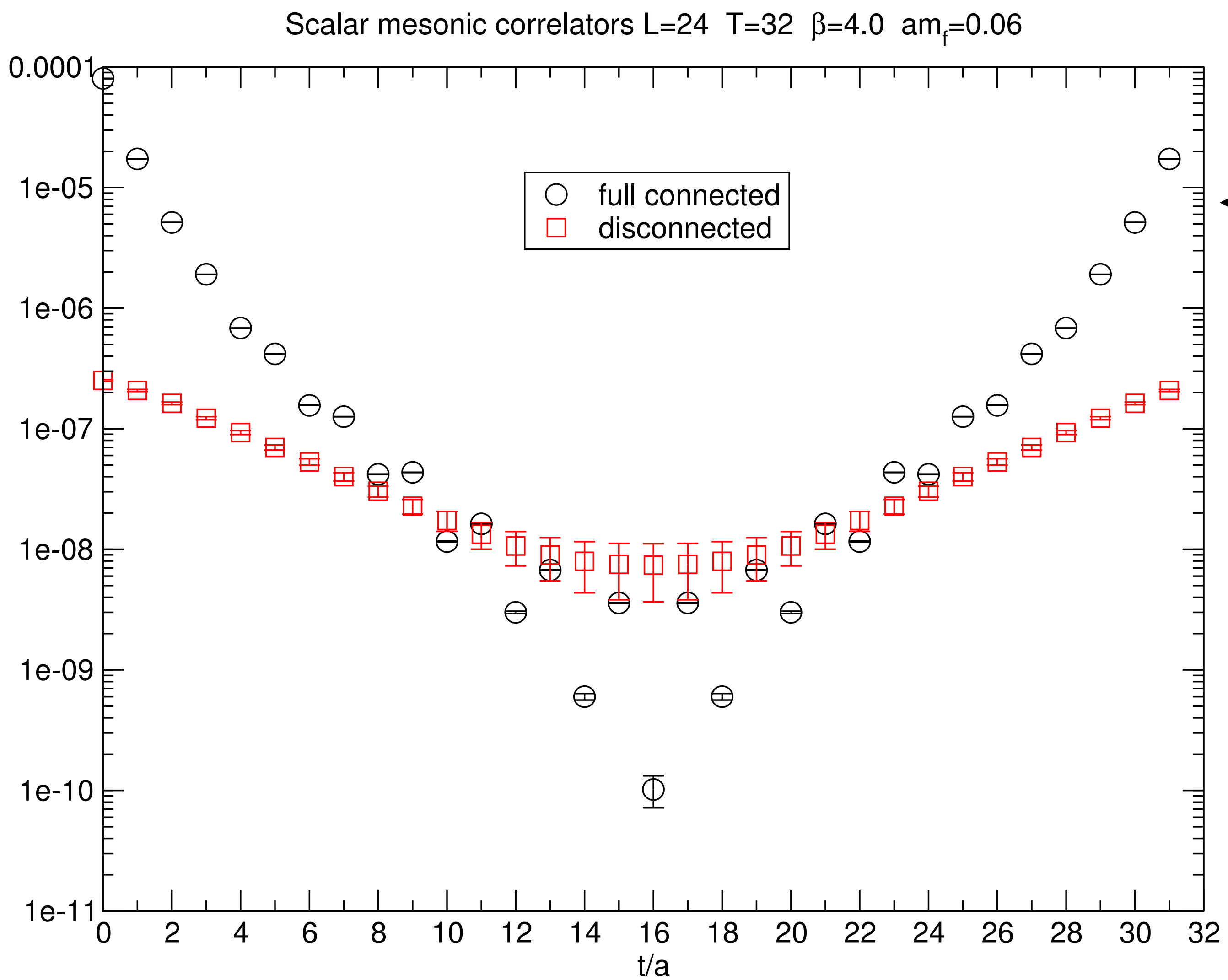
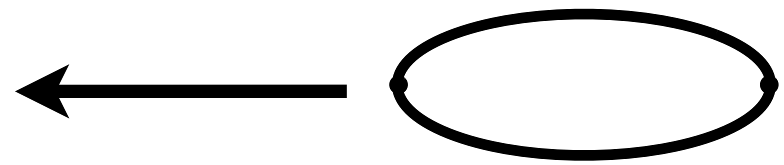
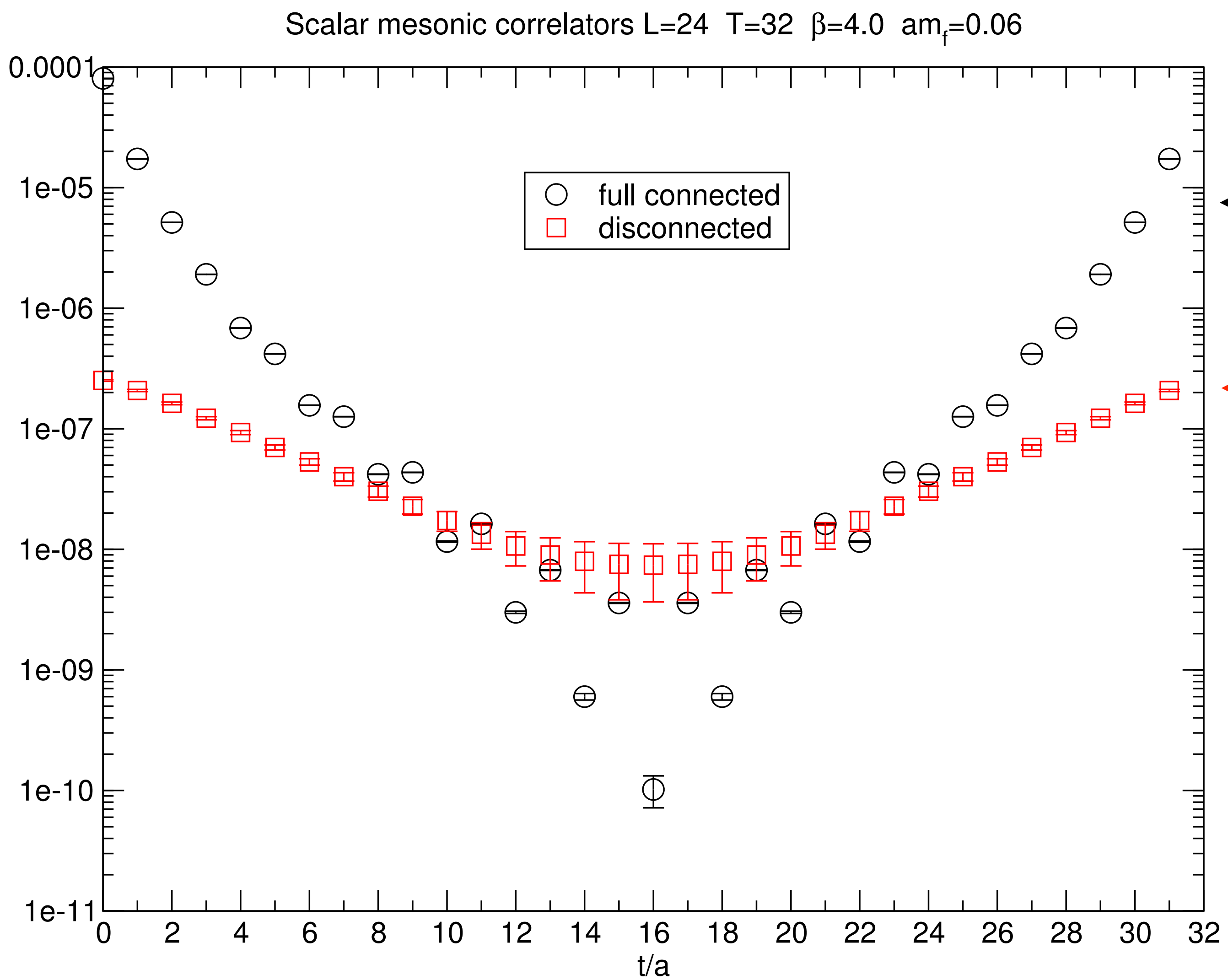
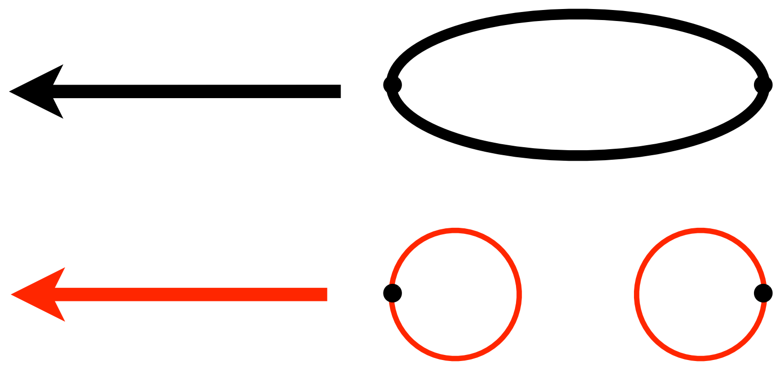




- using 14000 configurations
- 2 stochastic gaussian sources for connected piece

Results: scalar flavour-singlet meson





- using 14000 configurations
- 2 stochastic gaussian sources for connected piece
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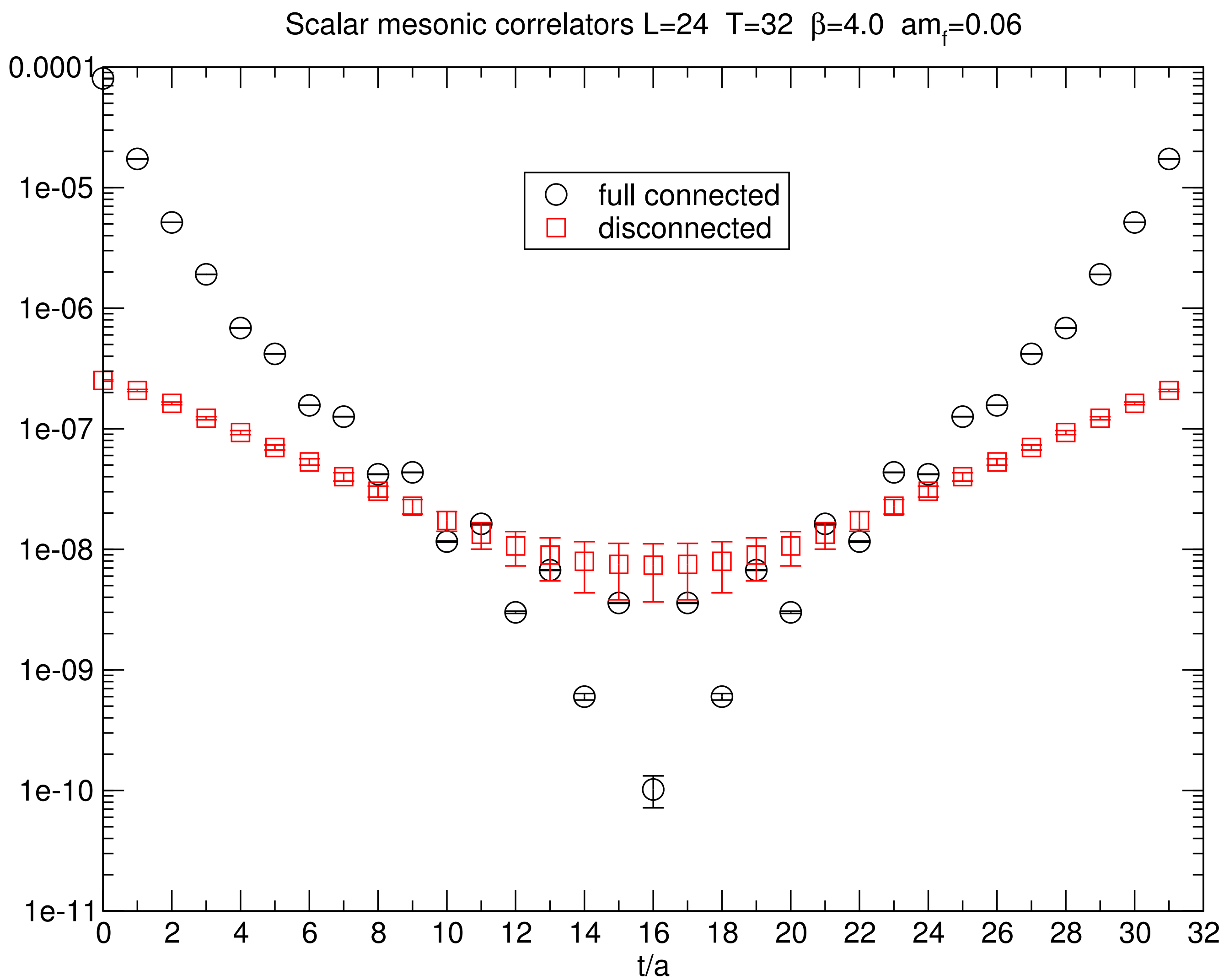
Results: scalar flavour-singlet meson



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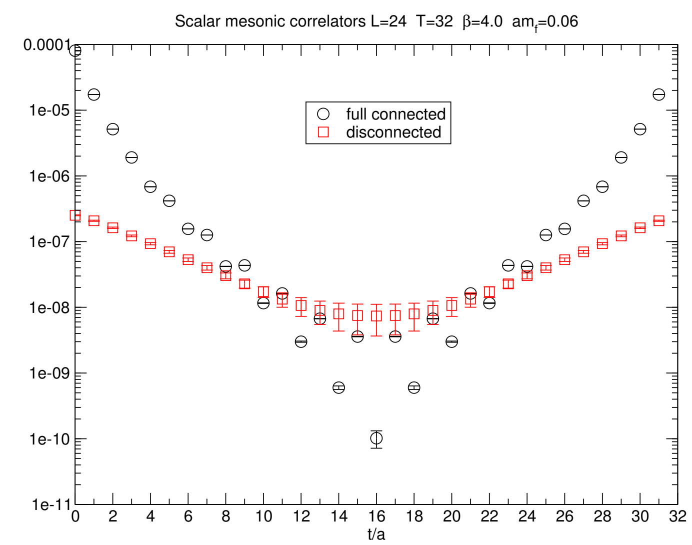

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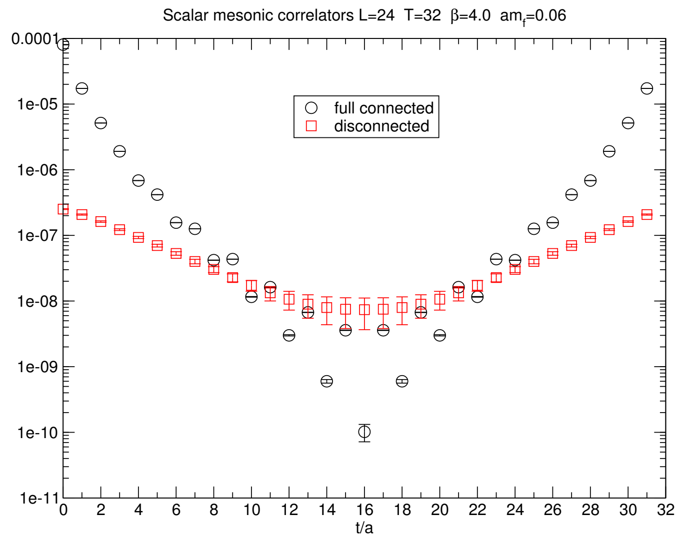

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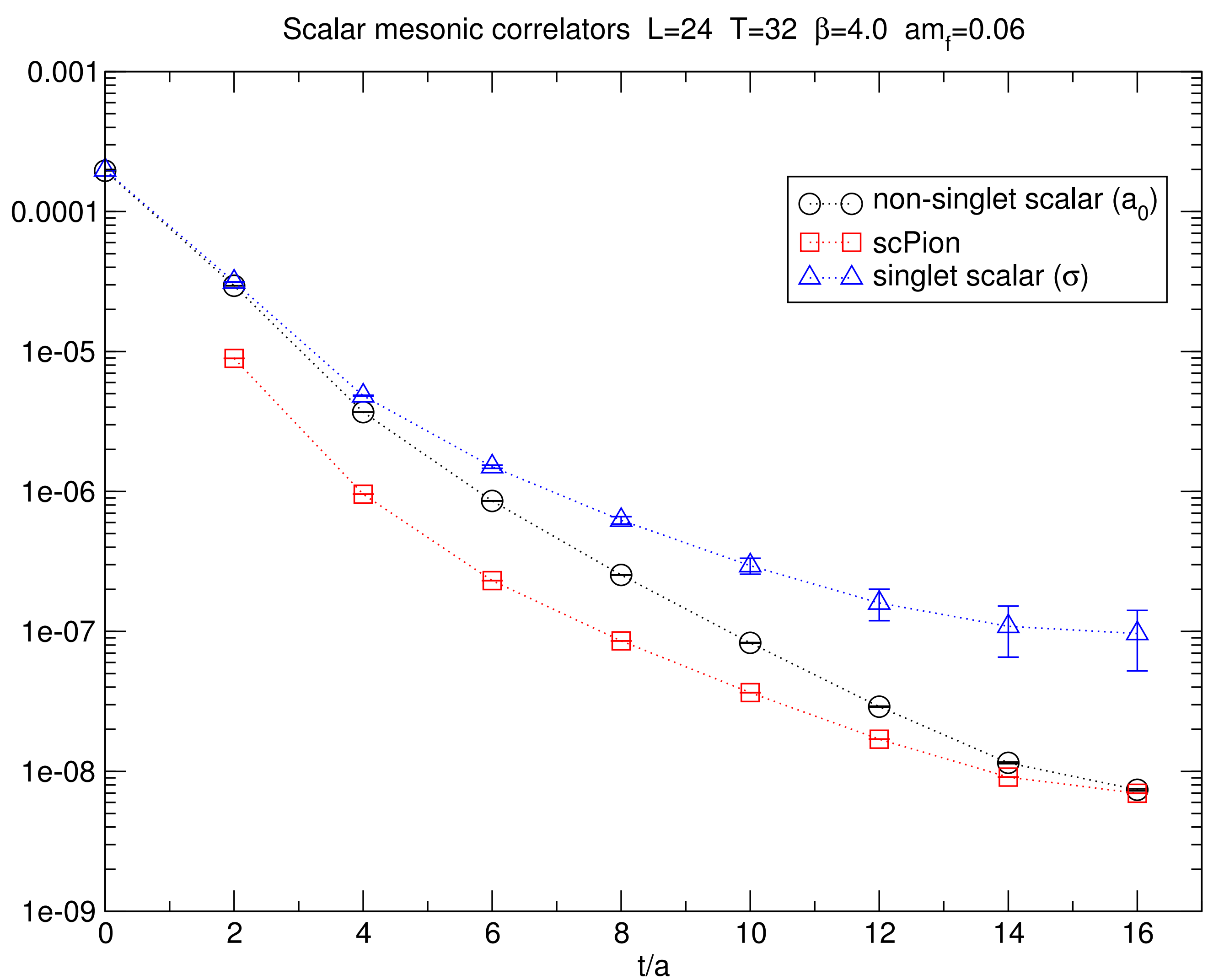
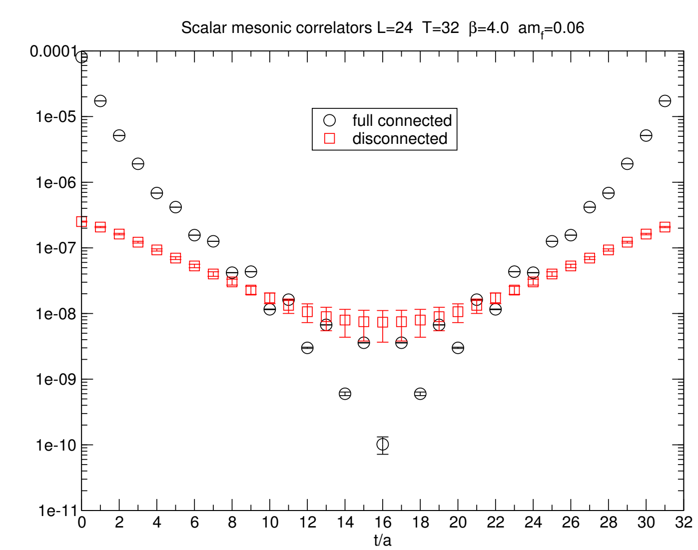


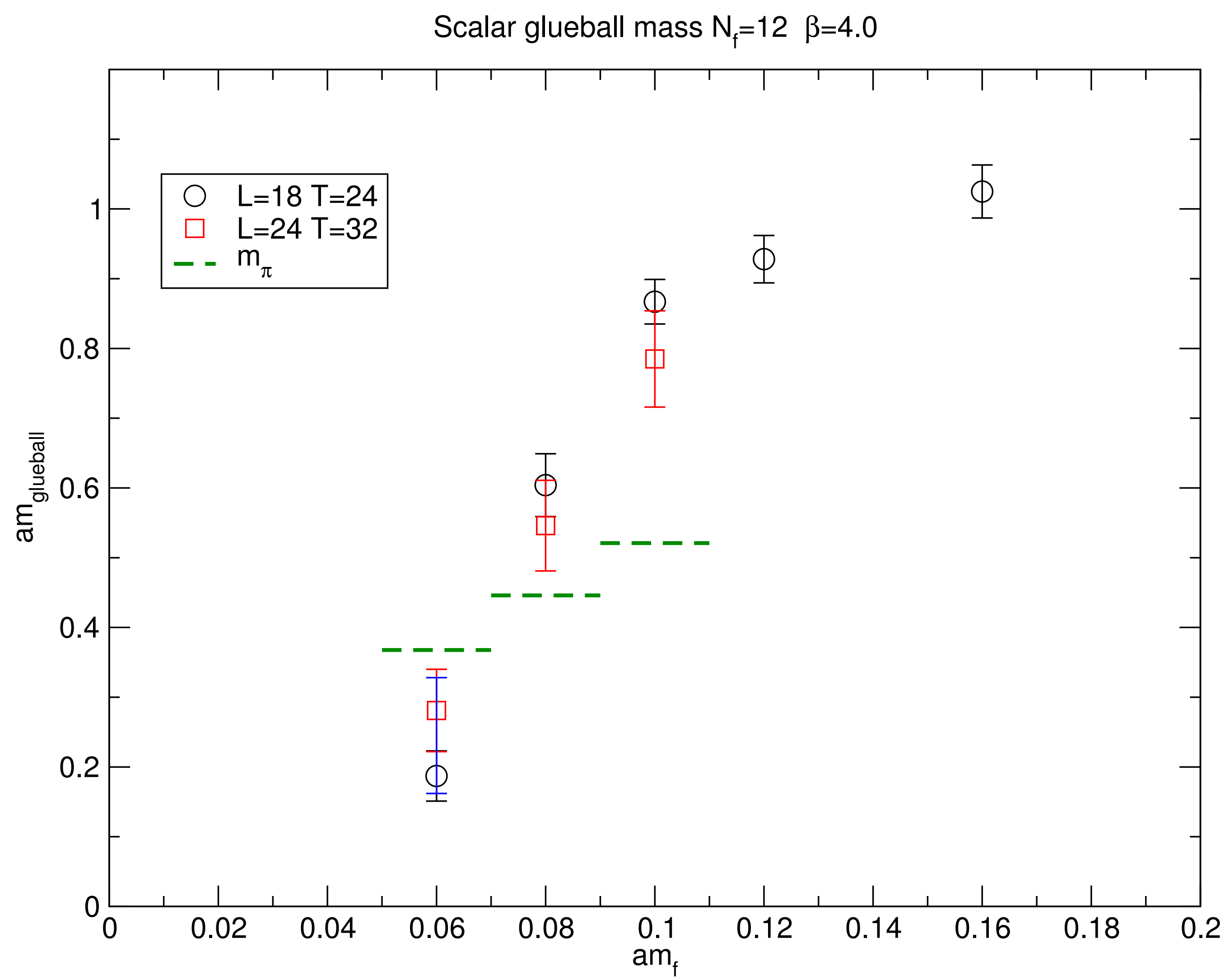
$$C_{0+}(t) = 2C(t) + C(t+1) + C(t-1)$$

$$C_{0-}(t) = 2C(t) - C(t+1) - C(t-1)$$

$$C_{\sigma}(t) = -C_{0+}(t) + 3D_{0+}^{2}(t)$$



Results: summary



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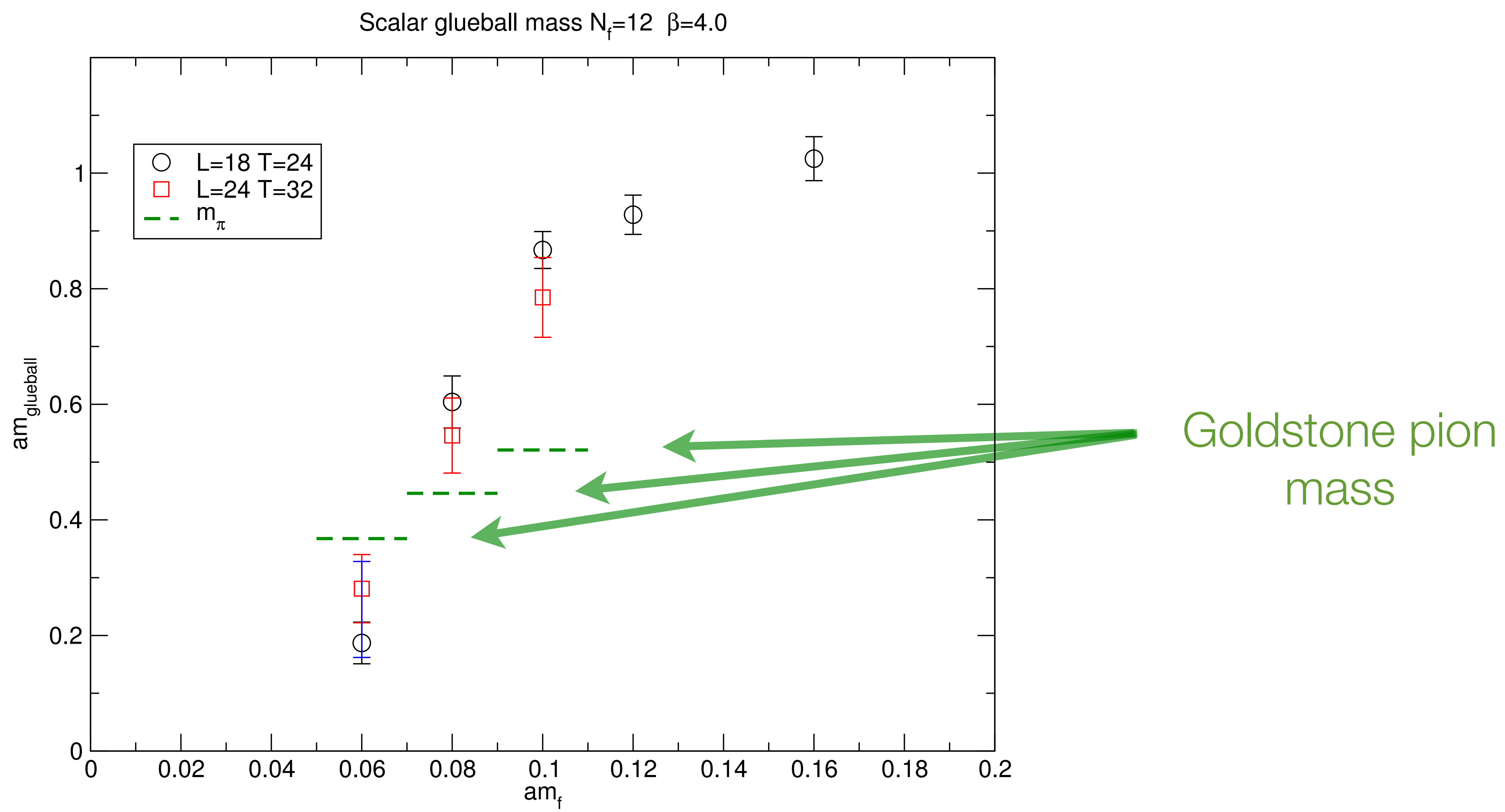

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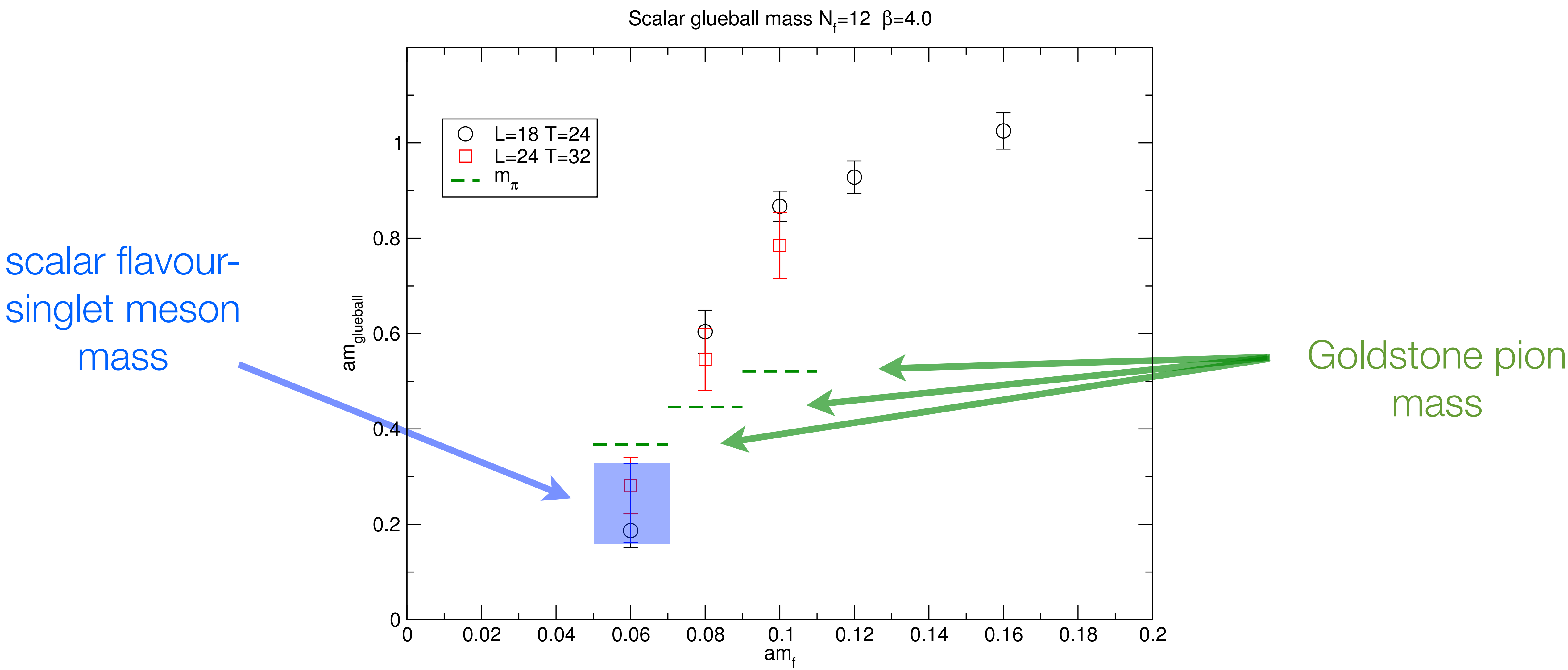

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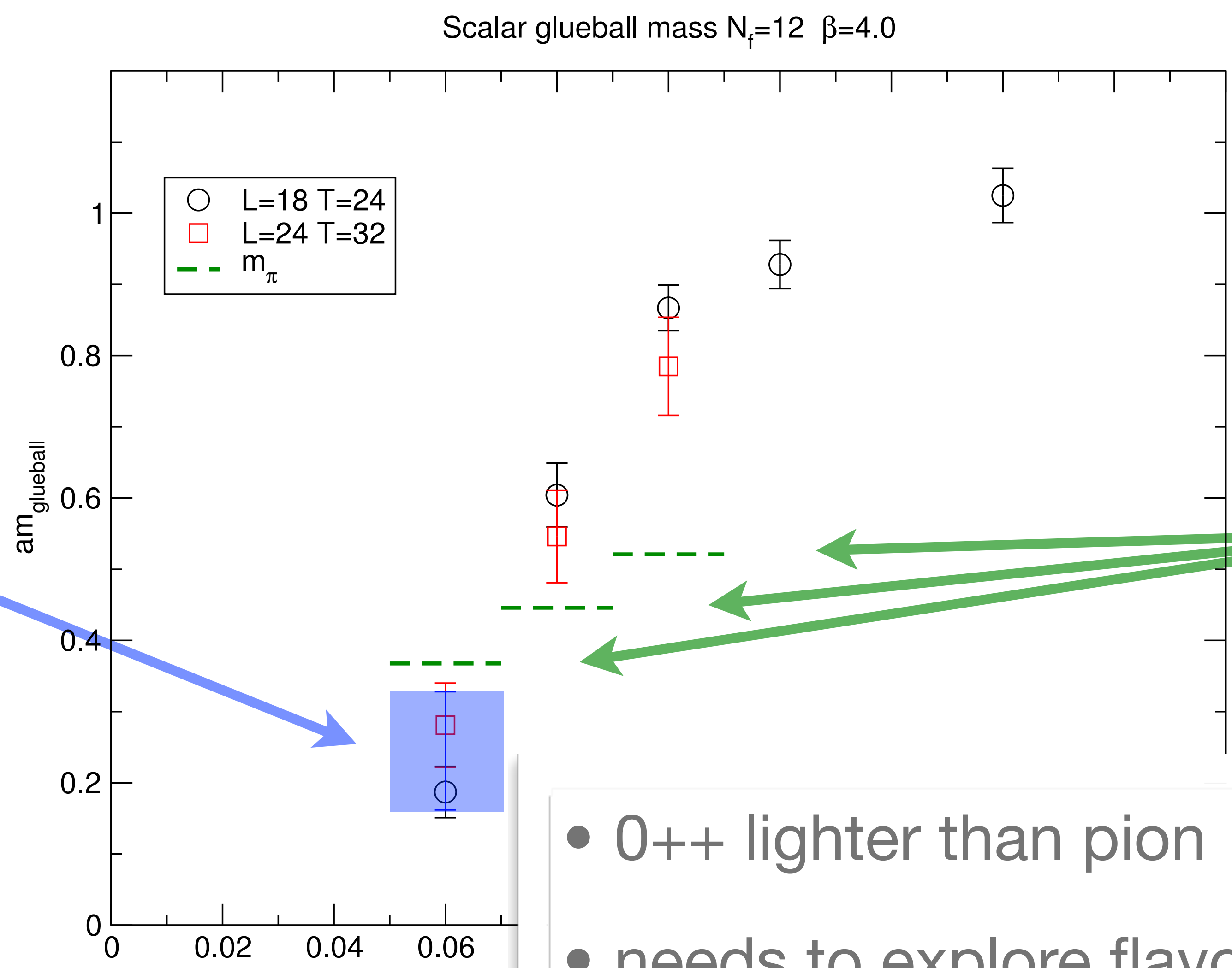

scalar flavour-singlet meson mass

Goldstone pion mass

- 0++ lighter than pion
- needs to explore flavor singlet for other m_f

➡hope to have light 0++: Higgs for N_f=8

Summary and Outlook

- SU(3) gauge theory + N_f fundamental fermions
- N_f=12 likely conformal
- N_f=8 candidate of WTC
- existence of light 0++ is promising!

- N_f=12, 0_{++} be continued
- N_f=8 large scale simulation
  - detailed chiral analysis for F, m_{Had}, $m_{0^{++}}$
  - anomalous dimension γ (method that does not assume conformality)
  - S parameter...

Thank you for your attention