The KMI lattice project
ー exploring for technicolor from QCD ー

Yasumichi Aoki
Kobayashi-Maskawa Institute (KMI), Nagoya University

for the KMI lattice collaboration

@ KMI Inauguration Conference

名古屋大学

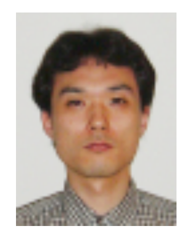
KMI lattice collaboration members

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

K.Yamawaki, T.Yamazaki

名古屋大学

KMI

- K.Hasebe

愛知大学 AICHI UNIVERSITY

A.Shibata

KEK

Origin of the mass of fundamental particles — Standard Model —

- Higgs mechanism:
  - VEV of scalar field breaks global gauge symmetry → NG boson (massless)
  - NG boson absorbed as longitudinal component of W, Z → massive W, Z
  - Yukawa interaction gives mass to fermions
  - fundamental scalar: UV power divergence
    - gauge hierarchy problem (fine tuning)

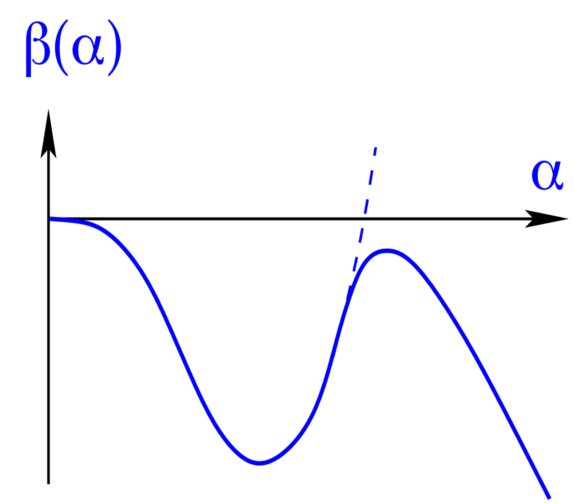
Origin of the mass of fundamental particles
ー Technicolor (alternative to Higgs mechanism) ー

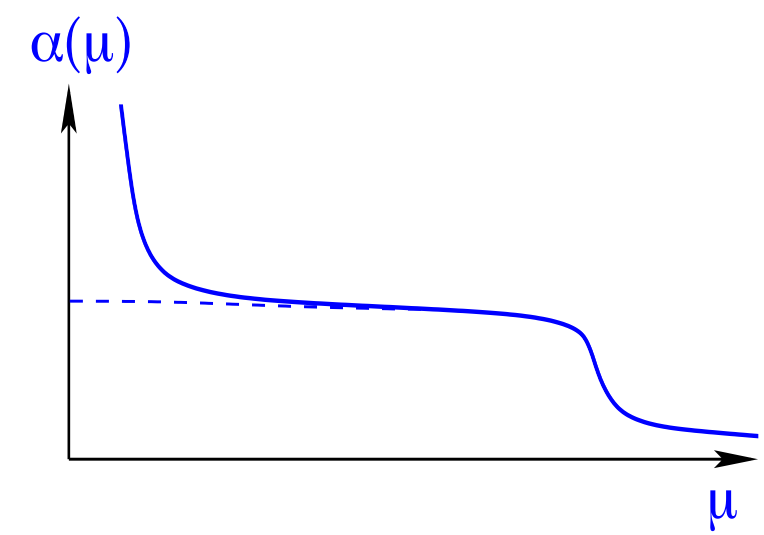
- Techni-fermion condensate <$T_R T_L$> at low energy (like <$q_R q_L$> in QCD)
  - breaks chiral symmetry
  - produces techni-pion π_{TC} (composite, like pion in QCD)
  - longitudinal component of W, Z
  - $M_W = M_Z \cos\theta_W = gF_\pi/2$ ($F_\pi = v_{weak} = 246$ GeV)
- no power divergence → no fine tuning necessary
- fermion masses → extended technicolor (ETC)
- for suppressed FCNC with appropriate size of fermion masses → walking TC

Walking Technicolor

- key: to realize suppressed FCNC and appropriate size of fermion masses

[Yamawaki-Bando-Matsumoto]

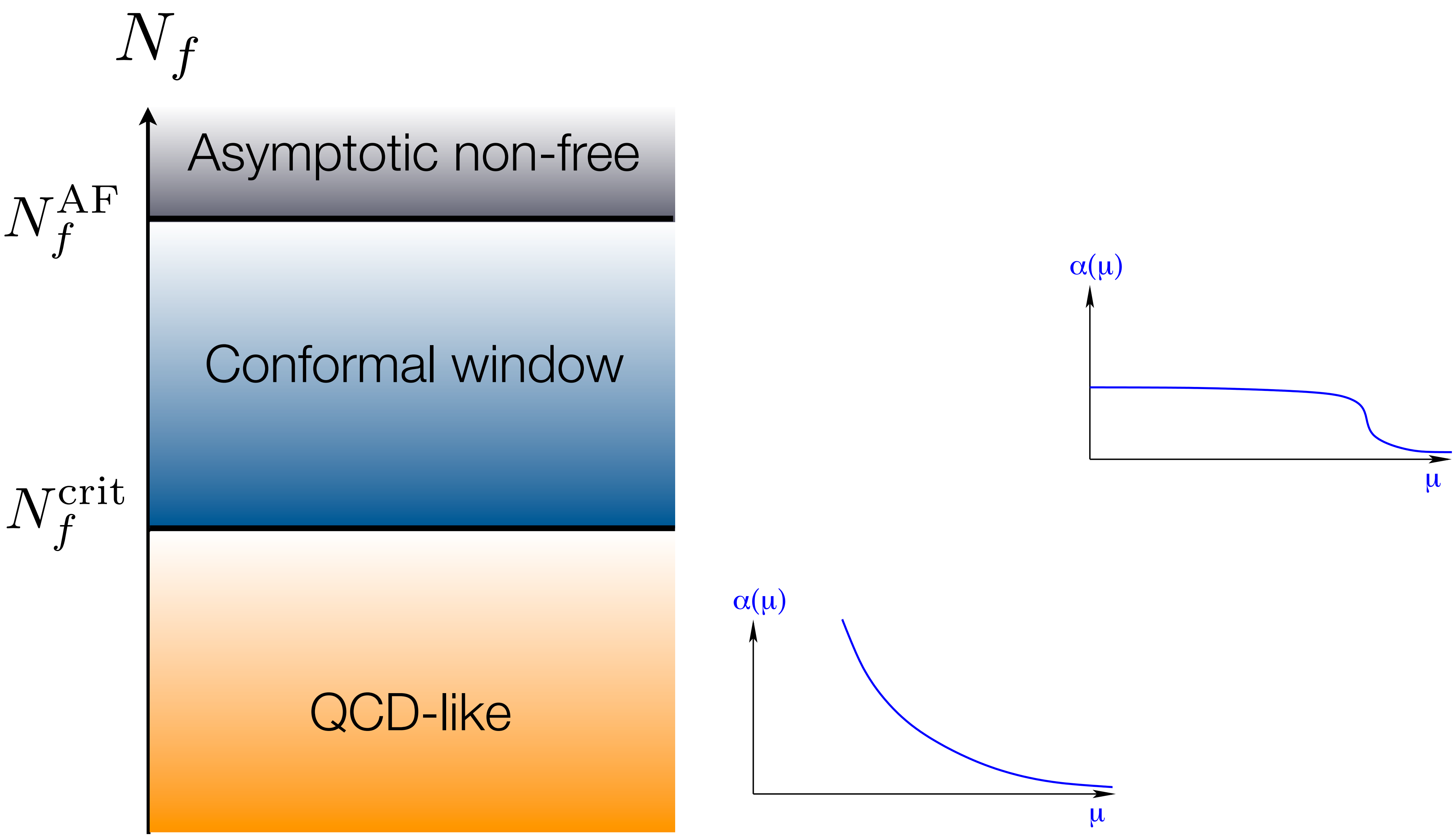




- renormalized gauge coupling
  - to run very slowly (walking)
  - logarithmically divergent at low energies → to produce techni pions
- mass anomalous dimension
  - large: $\gamma_m \sim 1$

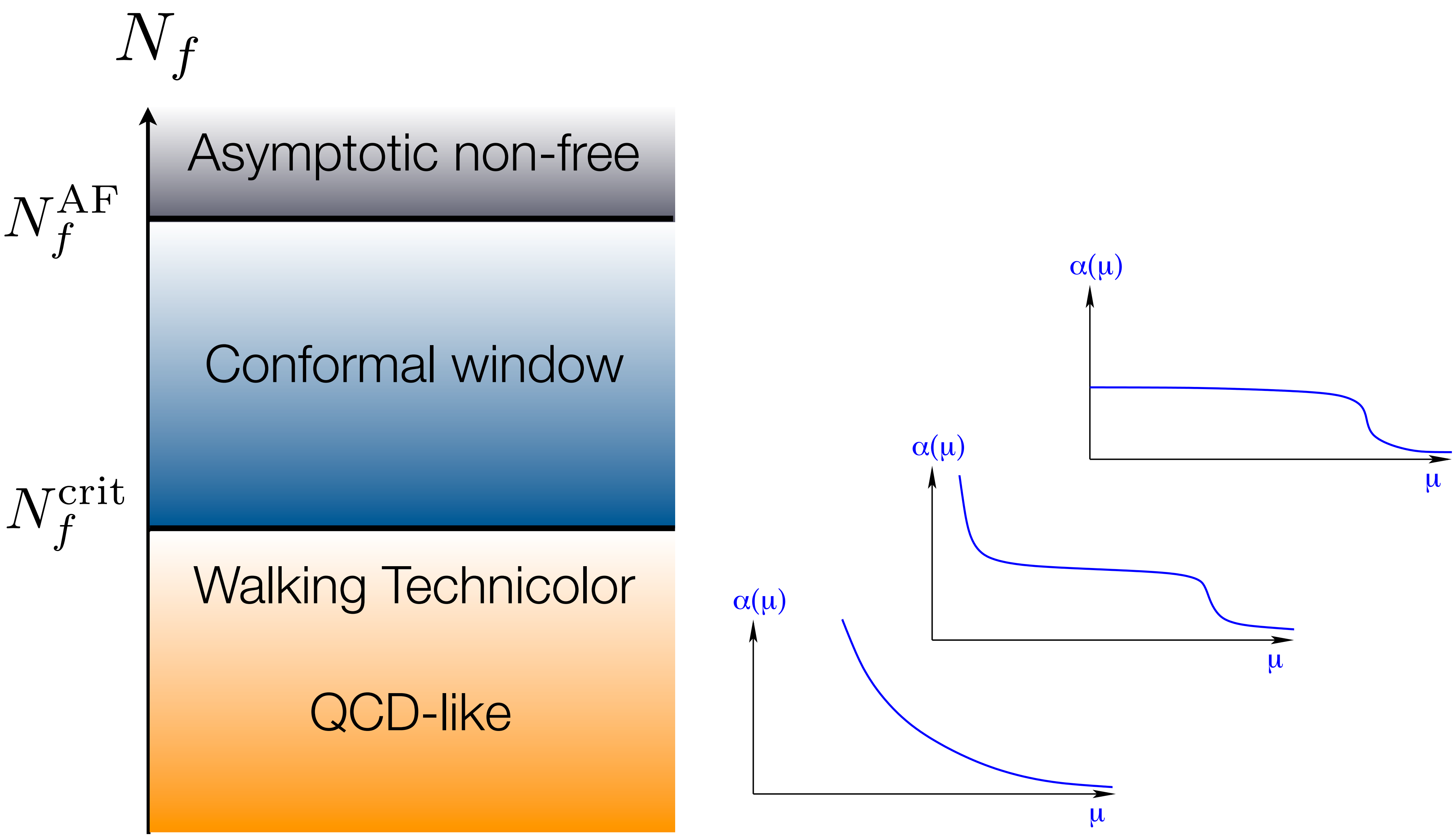
conformal window and walking coupling

- non-Abelian gauge theory with N_f massless fermions -



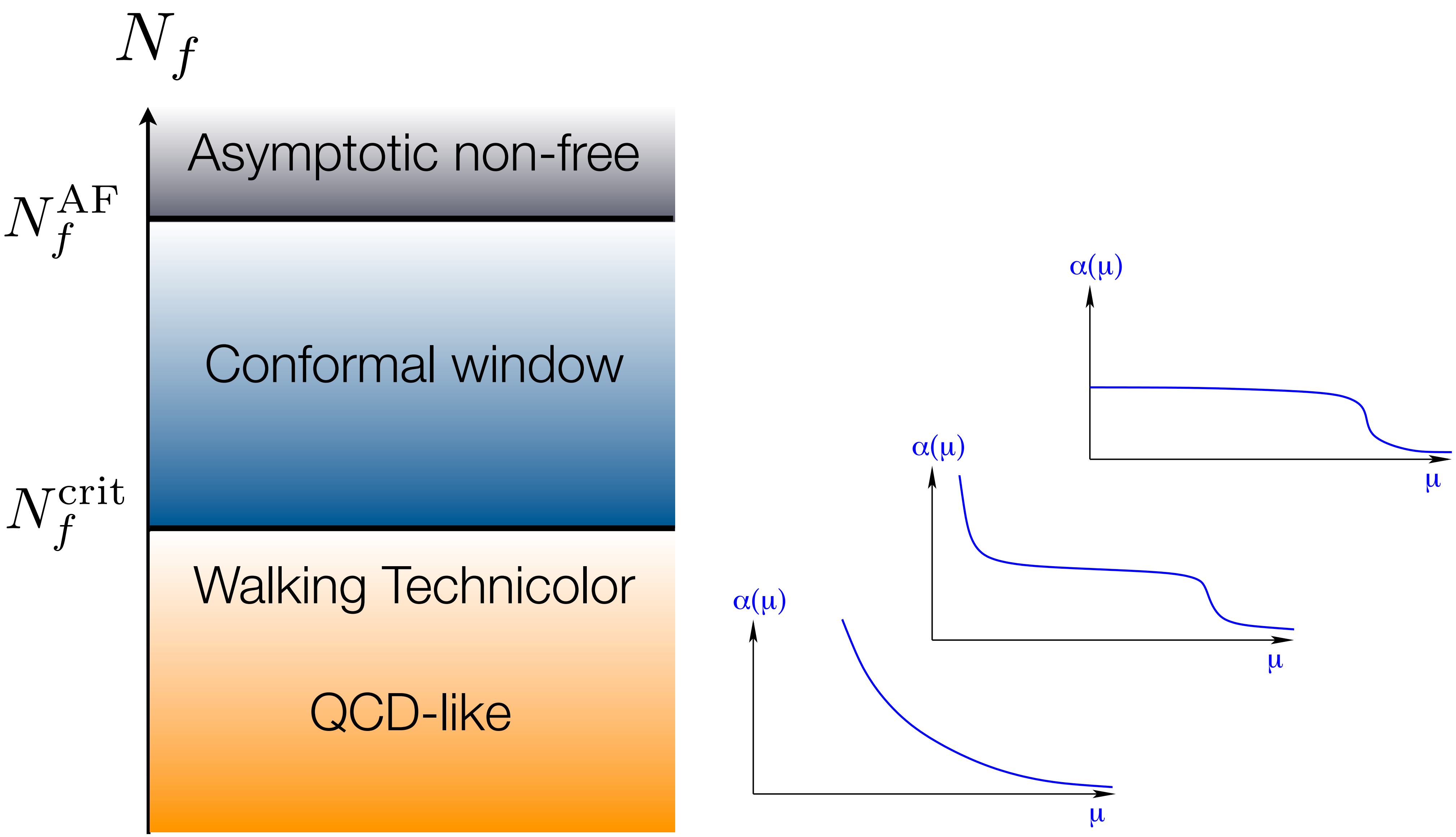
conformal window and walking coupling

- non-Abelian gauge theory with N_f massless fermions -



conformal window and walking coupling

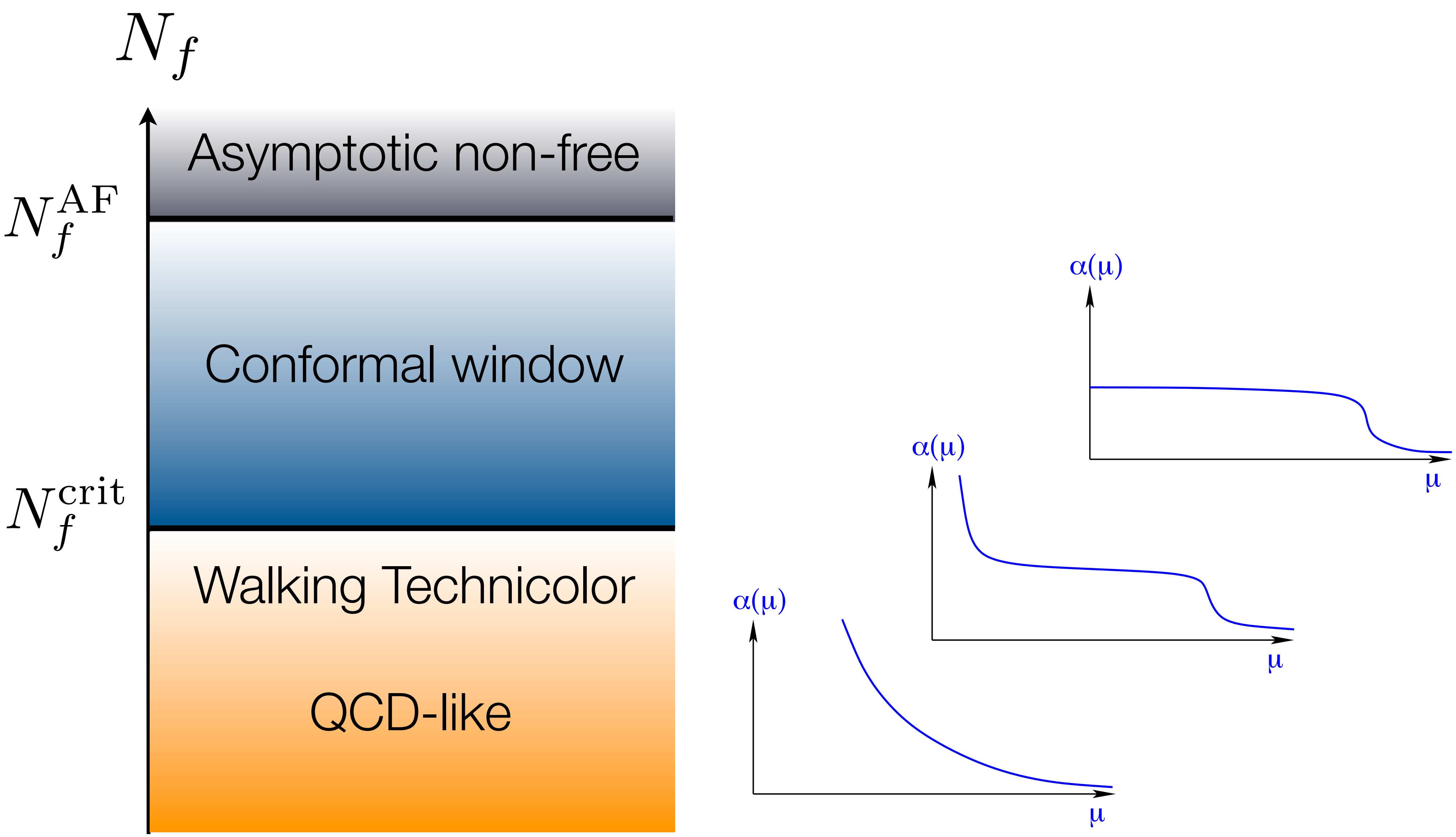
- non-Abelian gauge theory with N_f massless fermions -



- Walking Techinicolor could be realized just below the conformal window

conformal window and walking 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} & mass anomalous dimension around N_f^{crit}

SU(3) gauge theory with fundamental fermions

- perturbation theory
  - 2 loop universal running coupling at fixed point & 1 loop anomalous dim
    - N_f^{crit}~8.05
    - α^*~0.04, γ^*~0.03 for N_f=16 → likely in conformal phase
    - α^*~0.8, γ^*~0.5 for N_f=12

SU(3) gauge theory with fundamental fermions

- perturbation theory
  - 2 loop universal running coupling at fixed point & 1 loop anomalous dim
    - N_f^{crit}~8.05
    - α^*~0.04, γ^*~0.03 for N_f=16 → likely in conformal phase
    - α^*~0.8, γ^*~0.5 for N_f=12

      ➡requires non-perturbative method

most reliable method is lattice gauge theory

- success in QCD in SM: first principles calculation became possible
  - hadron spectrum
  - weak matrix elements: decay constants, bag parameters, form factors
  - running gauge coupling
- same quantity is indispensable and quite informative for technicolor
  - mass of the composite states
  - techni-pion decay constant
  - running technicolor coupling

KMI computer

KMI computer

φ

KMI computer φ

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

Inauguration Ceremony of φ
March 2nd, 2011

1st flagship project on φ

- SU(3) + large N_f fundamental fermions
- utilize knowledge and tools developed in past ~30 years of Lattice QCD
    - reinforced by the knowledge from the real world
- investigates spectrum: techni pion mass, decay constant

SU(3) gauge theory with large N_f [fundamental rep.]

- our goals:
  - understand the n_f dependence of the theory
  - find the conformal window
  - find the walking regime and investigate mass anomalous dimension
- status:
  - N_f=16 likely conformal
  - N_f=12: controversial
  - N_f=10: one study showing evidence of IR fixed point. Some more...
  - N_f=8: studies suggesting no IR fixed point ↔ one for conformal
  - N_f=6: confining: enhancement of condensation

our approach

- study N_f dependence systematically using single set up of the lattice simulation
  - target: N_f=(0), 4, 8, 12, 16
  - this talk mainly focuses on N_f=12 (most controversial in the community)
    - N_f=12 poster [Ohki]
    - N_f=16 poster [Yamazaki] (deep in conformal window ?)
      - results with 2 lattice spacings and a trial lattice spacing determination
    - N_f=8 poster [Nagai] (candidate for WTC?)
    - Swinger-Dyson approach and comparison with lattice N_f=4, 12 [Kurachi]

simulation strategy

- use of improved staggered action
  - to get nearly continuum results from non-zero lattice spacing
  - to reduce flavor violation for good SU(N) chiral symmetry
  - bound to N_f=4 n
- we use MILC version of HISQ (Highly Improved Staggered Quark) action
  - Asqtad + g^2a^2 taste exchange interaction & up to $(ma)^4$ removed, but
  - use tree level Symanzik gauge action
  - no $(ma)^2$ improvement (no interest to heavy quarks)
  - = HISQ/tree (HotQCD collaboration)

HISQ action

- proposed by HPQCD collaboration for
  - smaller taste violation than other approaches
  - better handling of heavy quarks
- being used in simulations (slightly changed versions)
  - MILC: Nf=2+1+1 QCD
  - HOTQCD: QCD thermodynamics: Bazavov-Petreczky (Lat'10 proceedings)
    - HISQ/tree is **best** of [HISQ/tree, Asqtad, stout]

      for flavor (taste) symmetry, dispersion relation

HISQ action

- proposed by HPQCD collaboration for
  - smaller taste violation than other approaches
  - better handling of heavy quarks
- being used in simulations (slightly changed versions)
  - MILC: Nf=2+1+1 QCD
  - HOTQCD: QCD thermodynamics: Bazavov-Petreczky (Lat'10 proceedings)
    - HISQ/tree is **best** of [HISQ/tree, Asqtad, stout]

      for flavor (taste) symmetry, dispersion relation

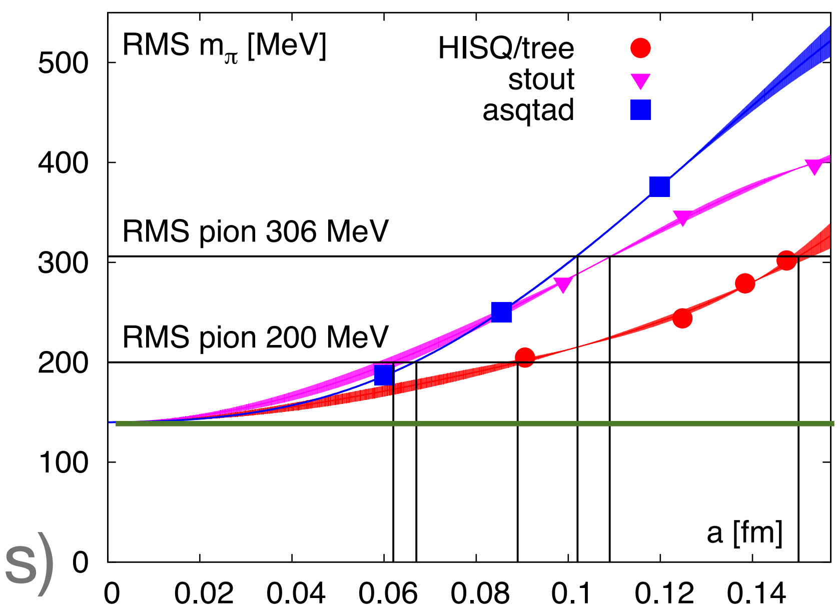


Figure 2: RMS pion mass when $m_{\gamma_5} = 140$ MeV. See details in the text.

simulation procedure

- using MILC code v7
  - changed to do simple HMC (remove R) with 3g1f Omelyan integrator
  - note: our $\beta=6/g^2$
- global search for β & m with small volume
- measure meson spectrum
  - in particular Goldstone pion mass and decay constants
- varying volume

N_f=12 SU(3): current situation

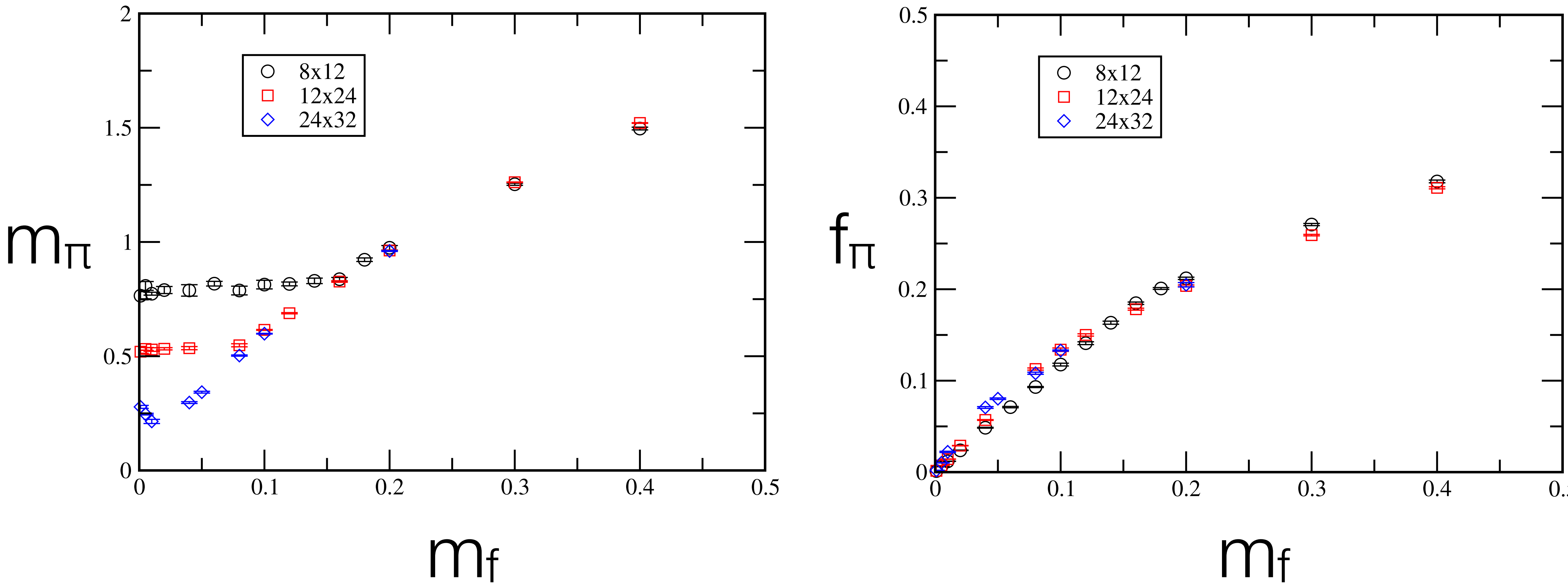
collaboration	conclusion	method	remarks
Fodor et al	χ Broken	spectrum	big V, single lat.spgs.
Columbia	χ Broken	spectrum, Tc	naive KS
Deutchman et al	Conformal	spectrum, Tc	KS+Naik
Itou et al	Conformal	coupling	naive KS + cont.lim.
Appelquist et al	Conformal	coupling	non-exact algorithm
Appelquist et al	Conformal	spectrum	using Fodor’s data
DeGrand	consistent with Conformal	spectrum	using Fodor’s data

now our results come.

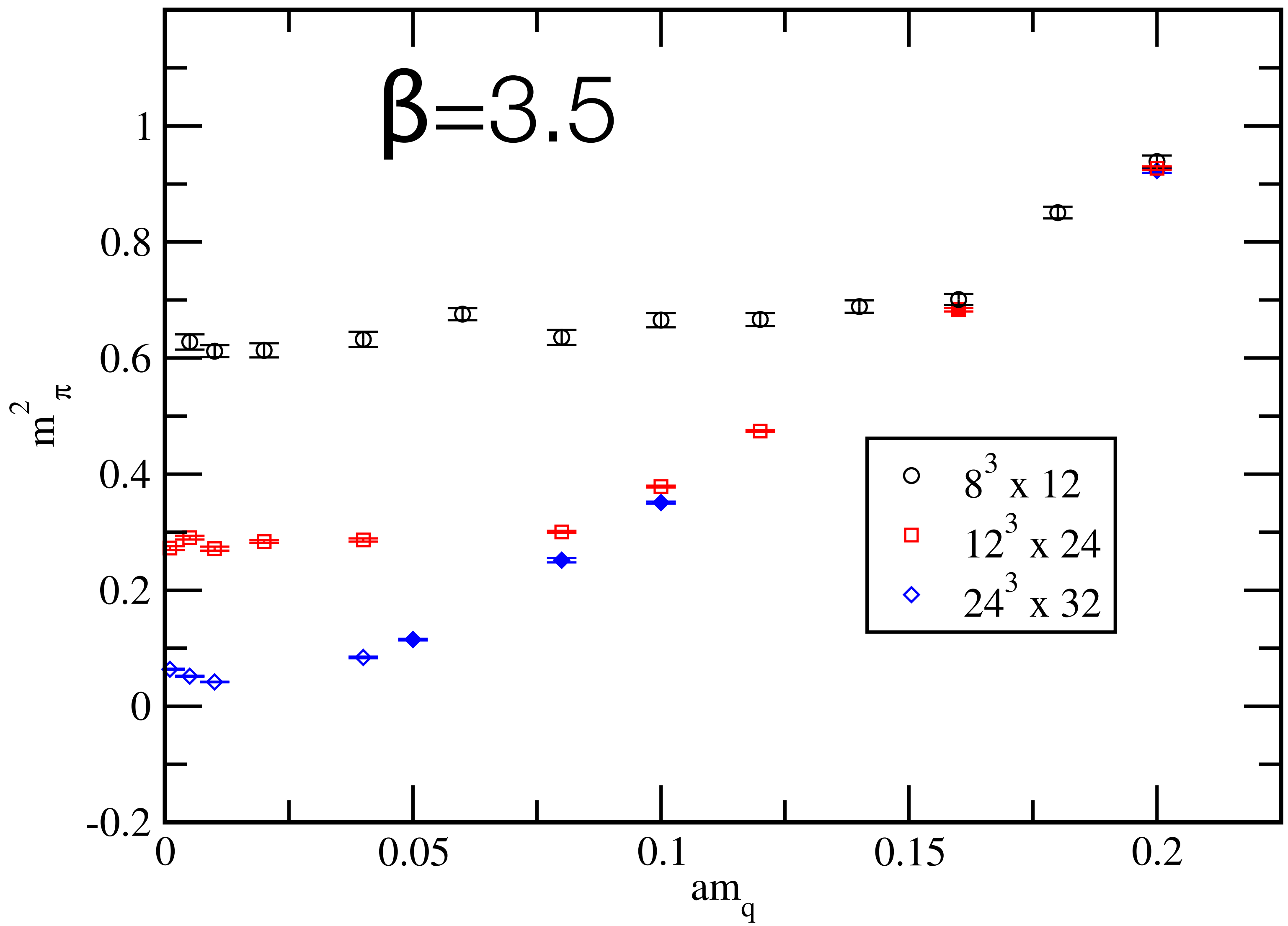
now our results come.

all the following results are preliminary...

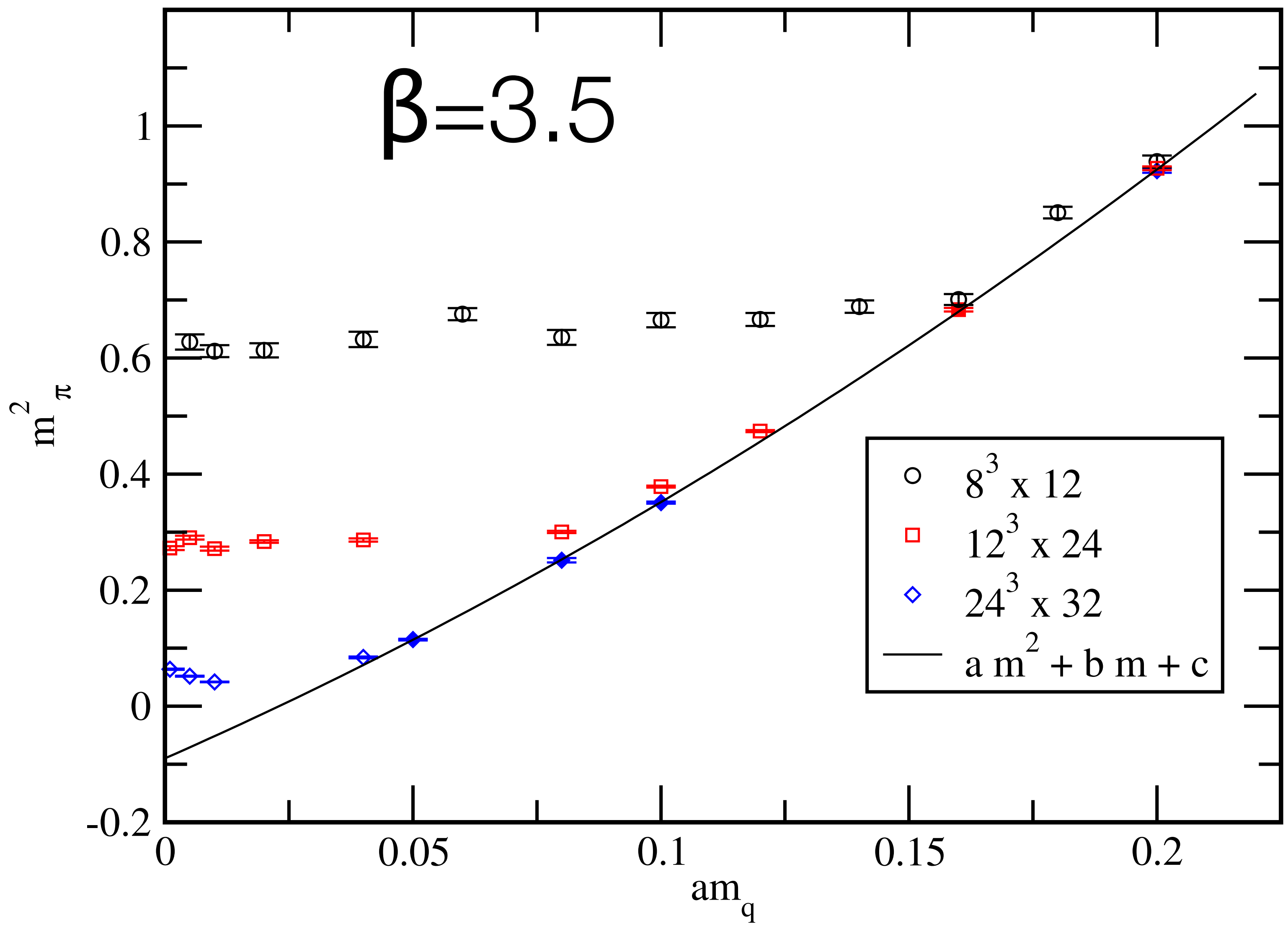
n_f=12 : pion mass and decay constant, β=3.5



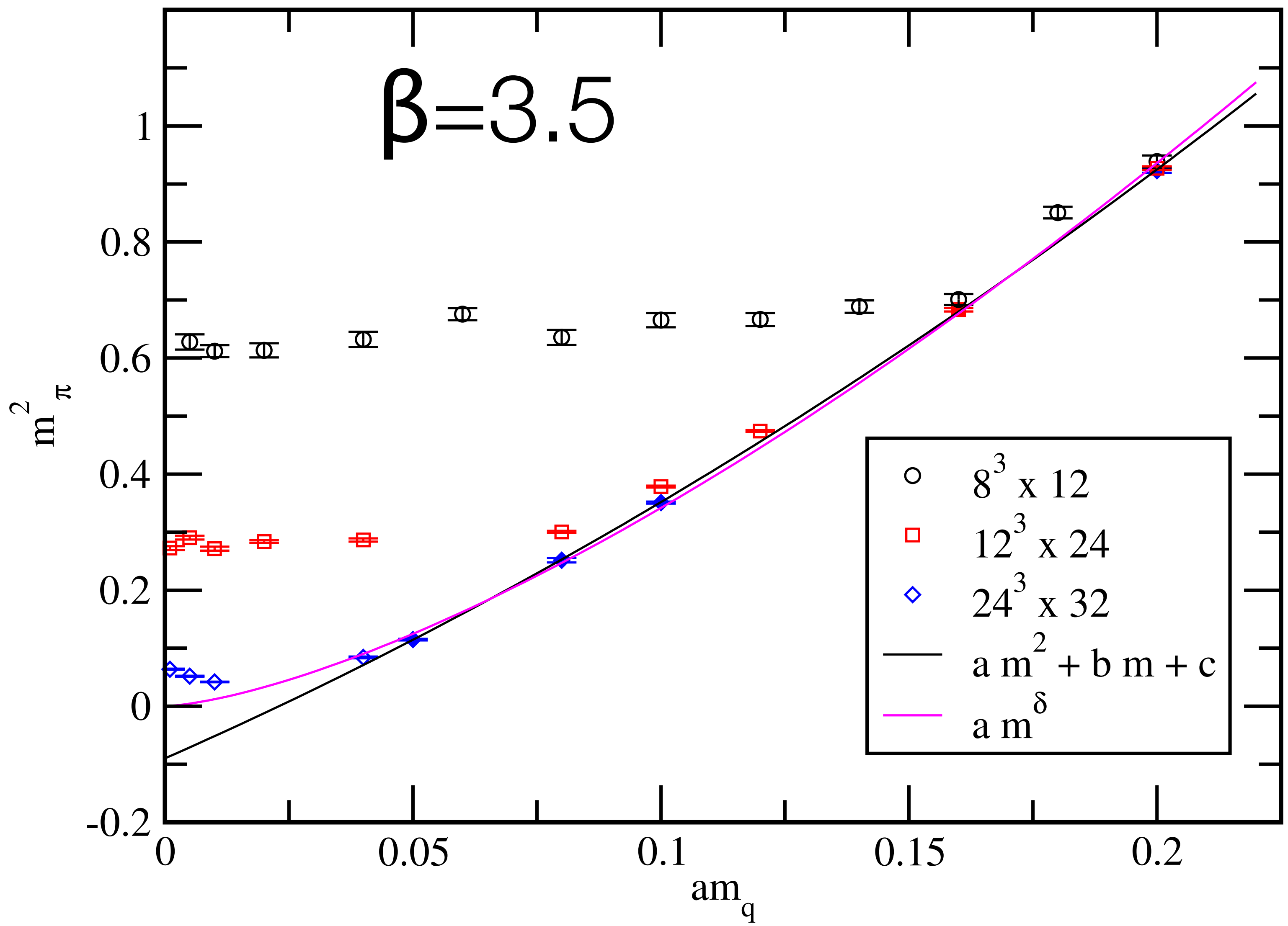
n_f=12 : pion mass : fit for χ broken scenario ?



n_f=12 : pion mass : fit for χ broken scenario ?

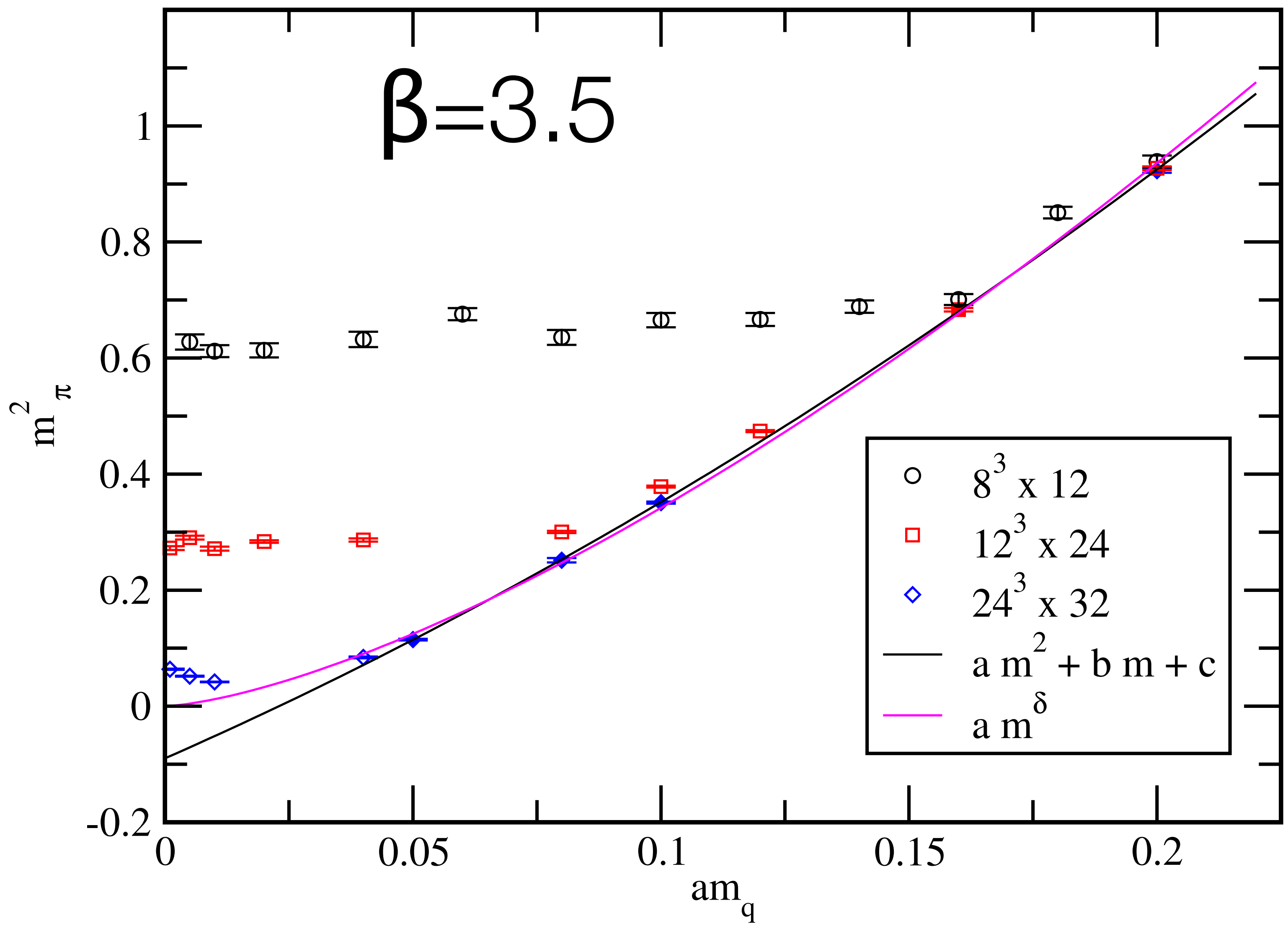


n_f=12 : pion mass : fit for χ broken scenario ?



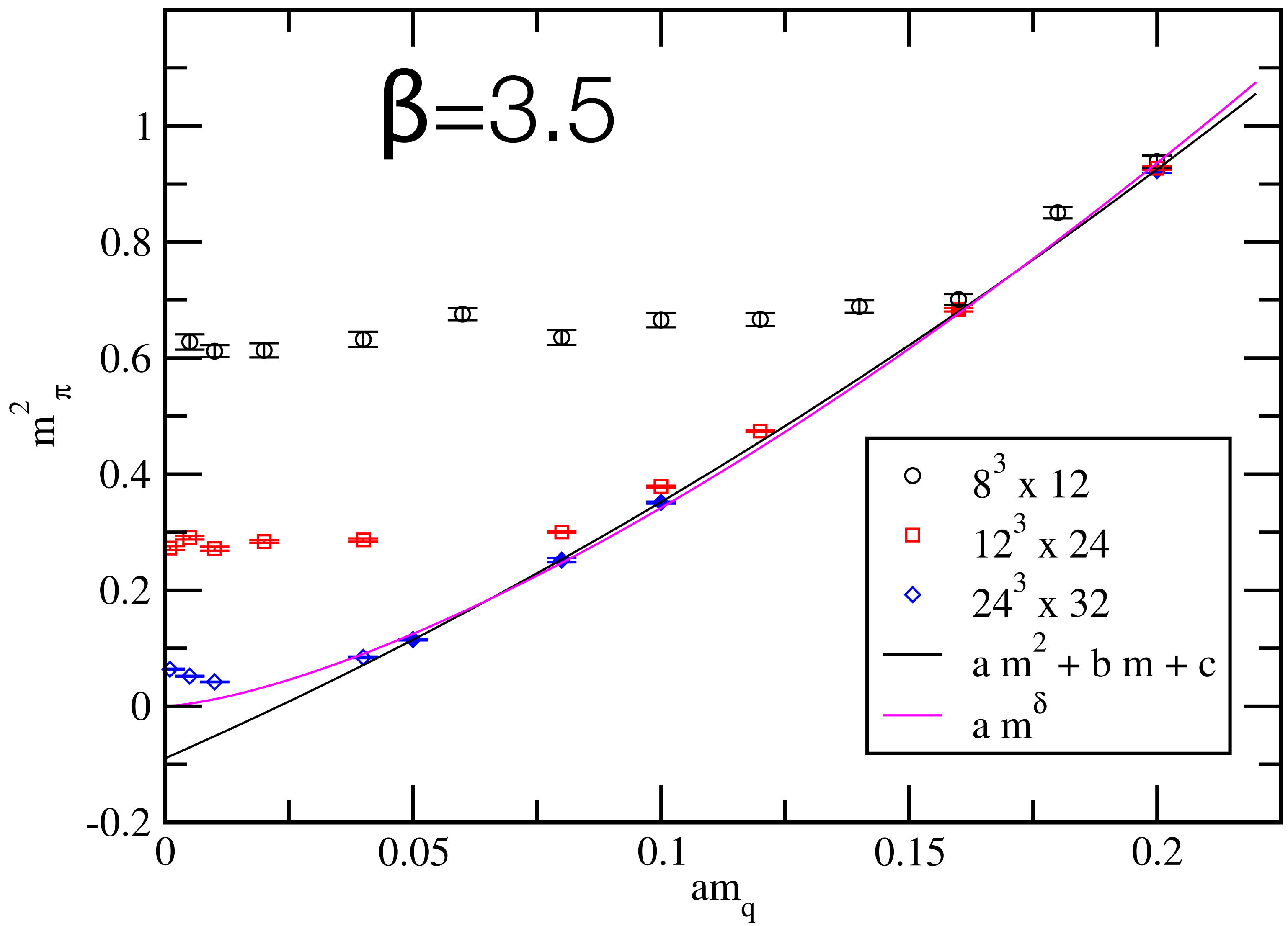
- $a m_q^2 + b m_q + c$

n_f=12 : pion mass : fit for χ broken scenario ?



- $a\,m_q^2 + b\,m_q + c$
  - c=-0.090(5), χ^2/dof=1.1

n_f=12 : pion mass : fit for χ broken scenario ?



- a m_q^2 + b m_q + c
  - c=-0.090(5), χ^2/dof=1.1
  - c=0 → χ^2/dof=104

n_f=12 : pion mass : fit for χ broken scenario ?

β=3.5

- $a\, m_q^2 + b\, m_q + c$
  - $c=-0.090(5)$, $\chi^2/\mathrm{dof}=1.1$
  - $c=0$ → $\chi^2/\mathrm{dof}=104$
- $a\, m_q^\delta$

n_f=12 : pion mass : fit for χ broken scenario ?

β=3.5

- $a\, m_q^2 + b\, m_q + c$
  - $c=-0.090(5)$, $\chi^2/\text{dof}=1.1$
  - $c=0$ → $\chi^2/\text{dof}=104$

- $a\, m_q^{\delta}$
  - $\delta=1.45(7)$, $\chi^2/\text{dof}=32$

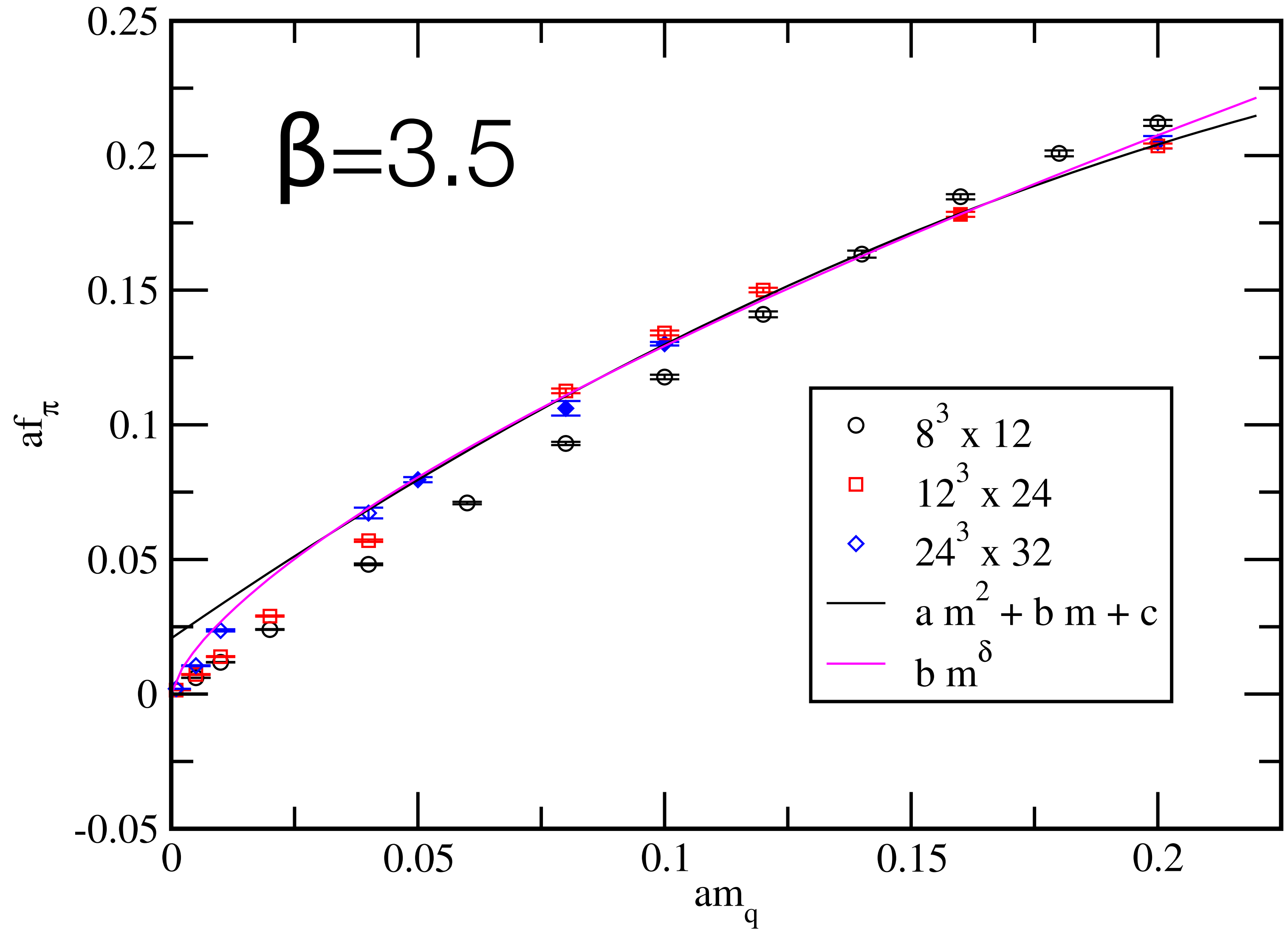
n_f=12 : pion mass : fit for χ broken scenario ?

β=3.5

- $a\, m_q^2 + b\, m_q + c$
  - $c=-0.090(5)$, $\chi^2/\text{dof}=1.1$
  - $c=0$ → $\chi^2/\text{dof}=104$
- $a\, m_q^{\delta}$
  - $\delta=1.45(7)$, $\chi^2/\text{dof}=32$

  ➡$\gamma^*=0.38(7)$

n_f=12 : pion decay constant



- $a\, m_q^2 + b\, m_q + c$
  - $c=0.021(3)$, $\chi^2/dof=1.7$
  - $c=0$ → $\chi^2/dof=17$
- $b\, m_q^\delta$
  - $\delta=0.681(9)$, $\chi^2/dof=2.3$

  ➡$\gamma^*=0.47(2)$

hyper scaling

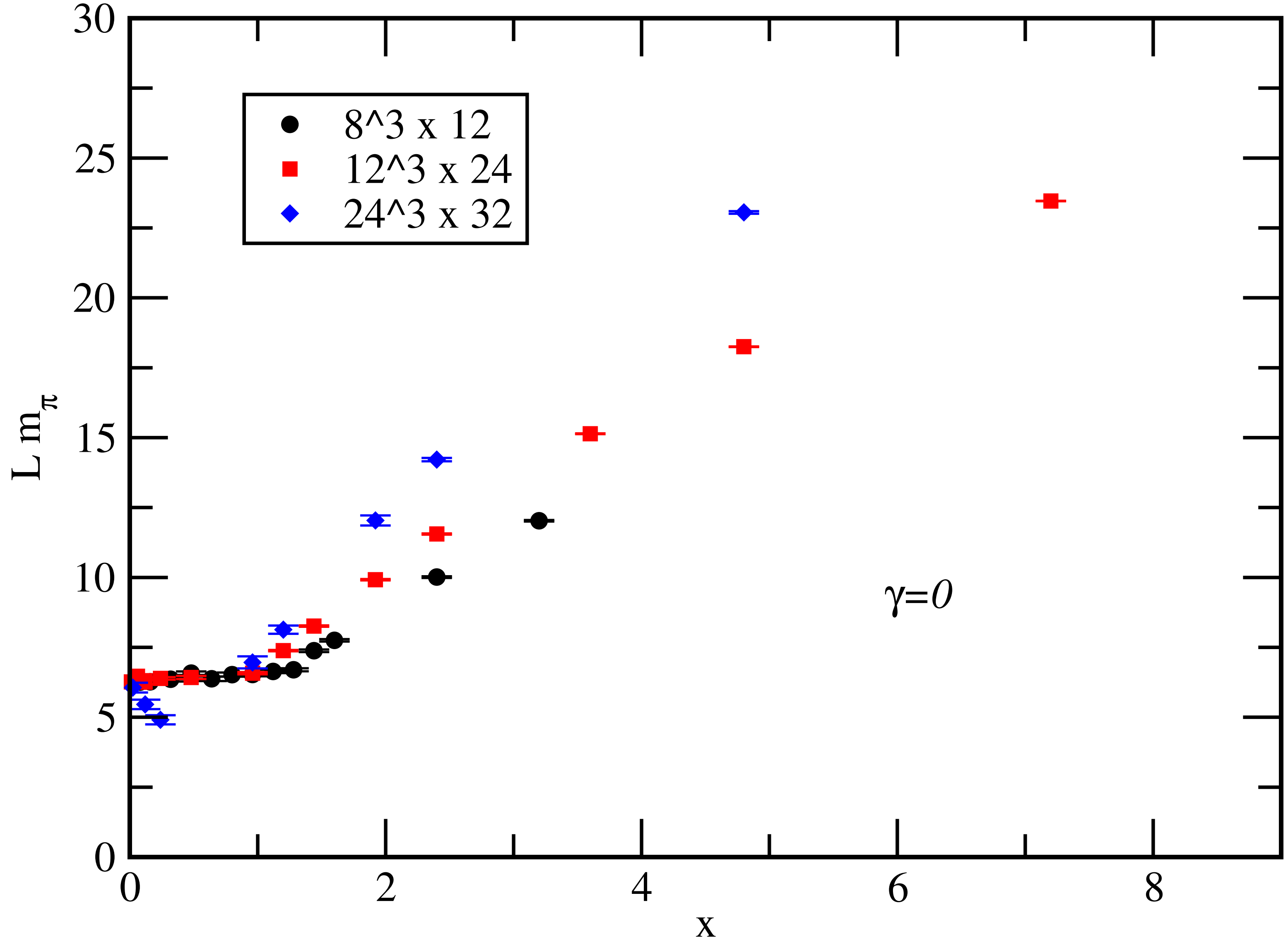
- mass deformation in a massless conformal theory: Miransky 1999.
- mass dependence is described by anomalous dimensions at IRFP
  - quark mass anomalous dimension γ^*
  - operator anomalous dimension
- meson mass and pion decay constant obey same scaling

$$m_\pi = c_m m_f^{\frac{1}{1+\gamma^*}} \qquad f_\pi = c_f m_f^{\frac{1}{1+\gamma^*}}$$

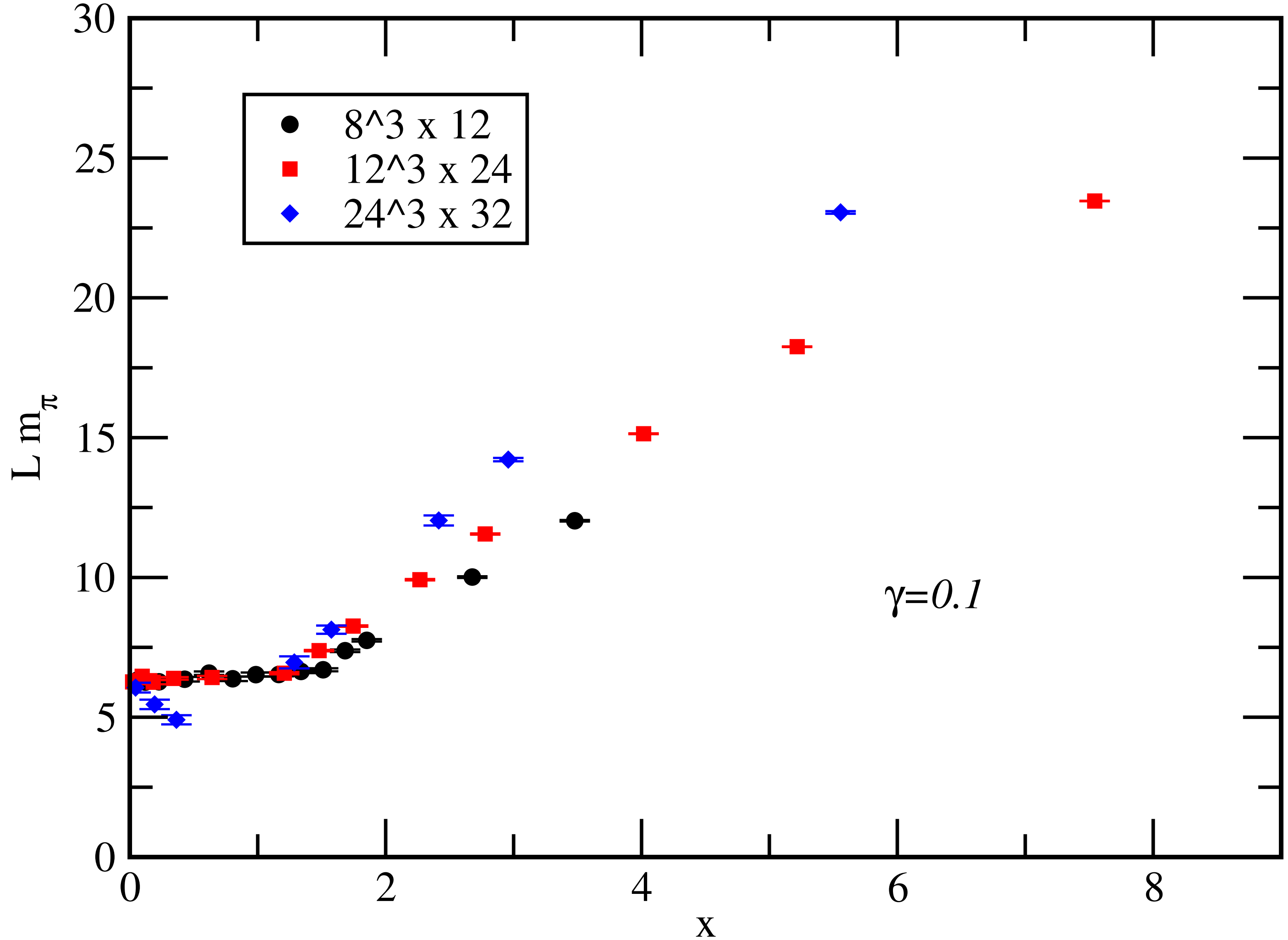
- finite size scaling formula (Del Debbio et al)
  - scaling variable: $x = L m_f^{\frac{1}{1+\gamma^*}}$

$$L f_\pi = F(x) \qquad L m_\pi = G(x)$$

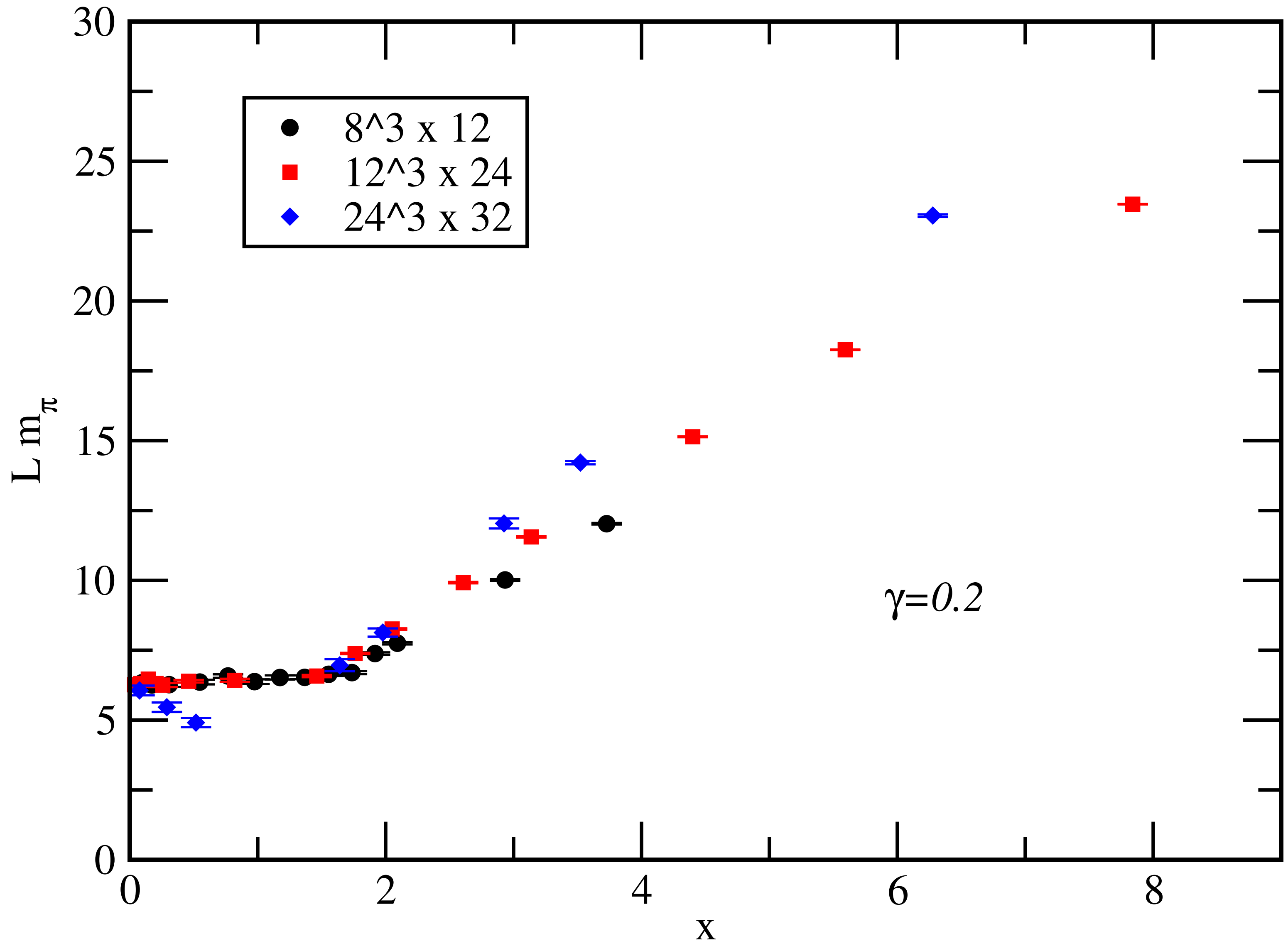
m_π: finite size hyper scaling N_f=12, β=3.5



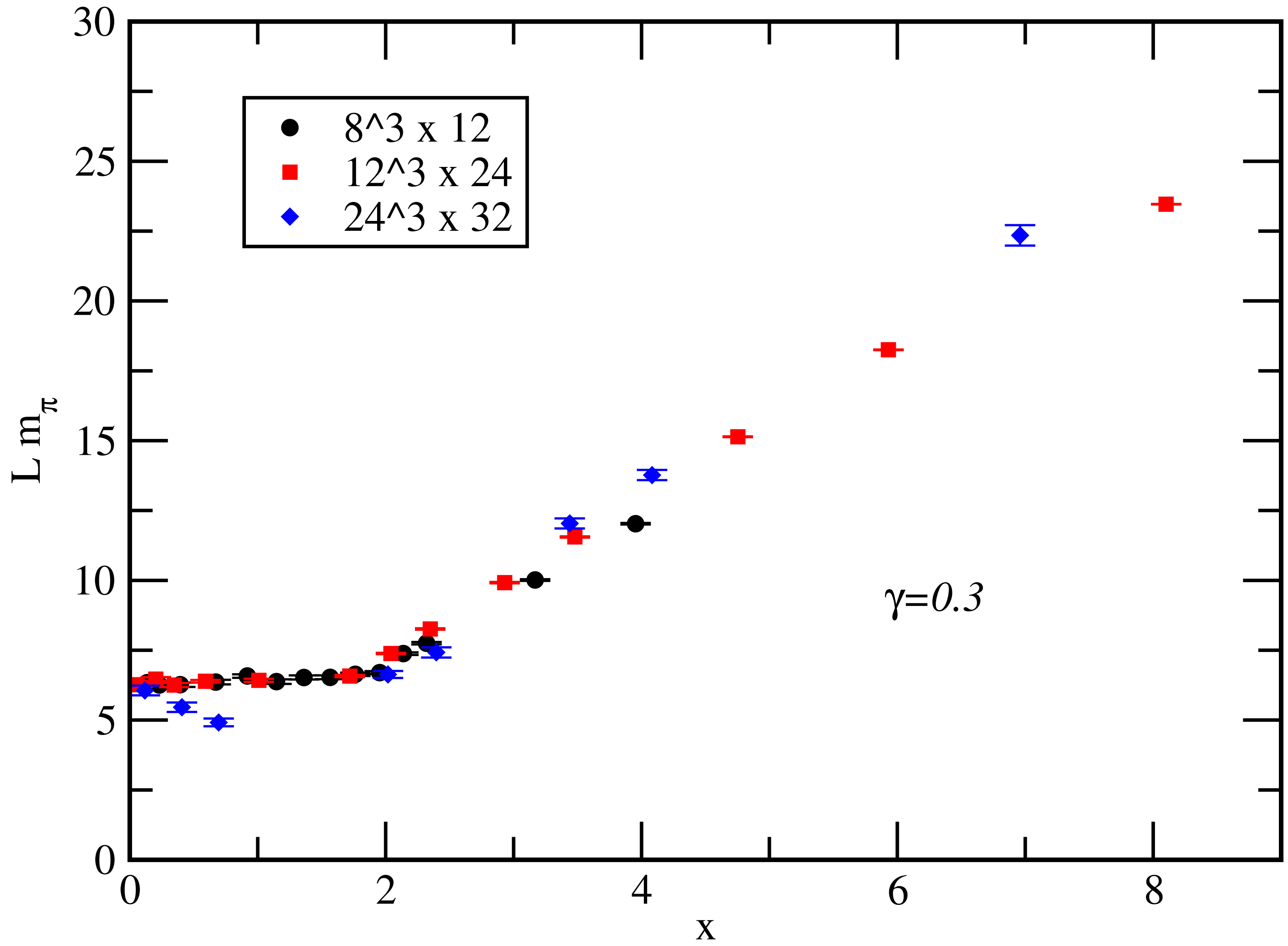
m_π: finite size hyper scaling N_f=12, β=3.5



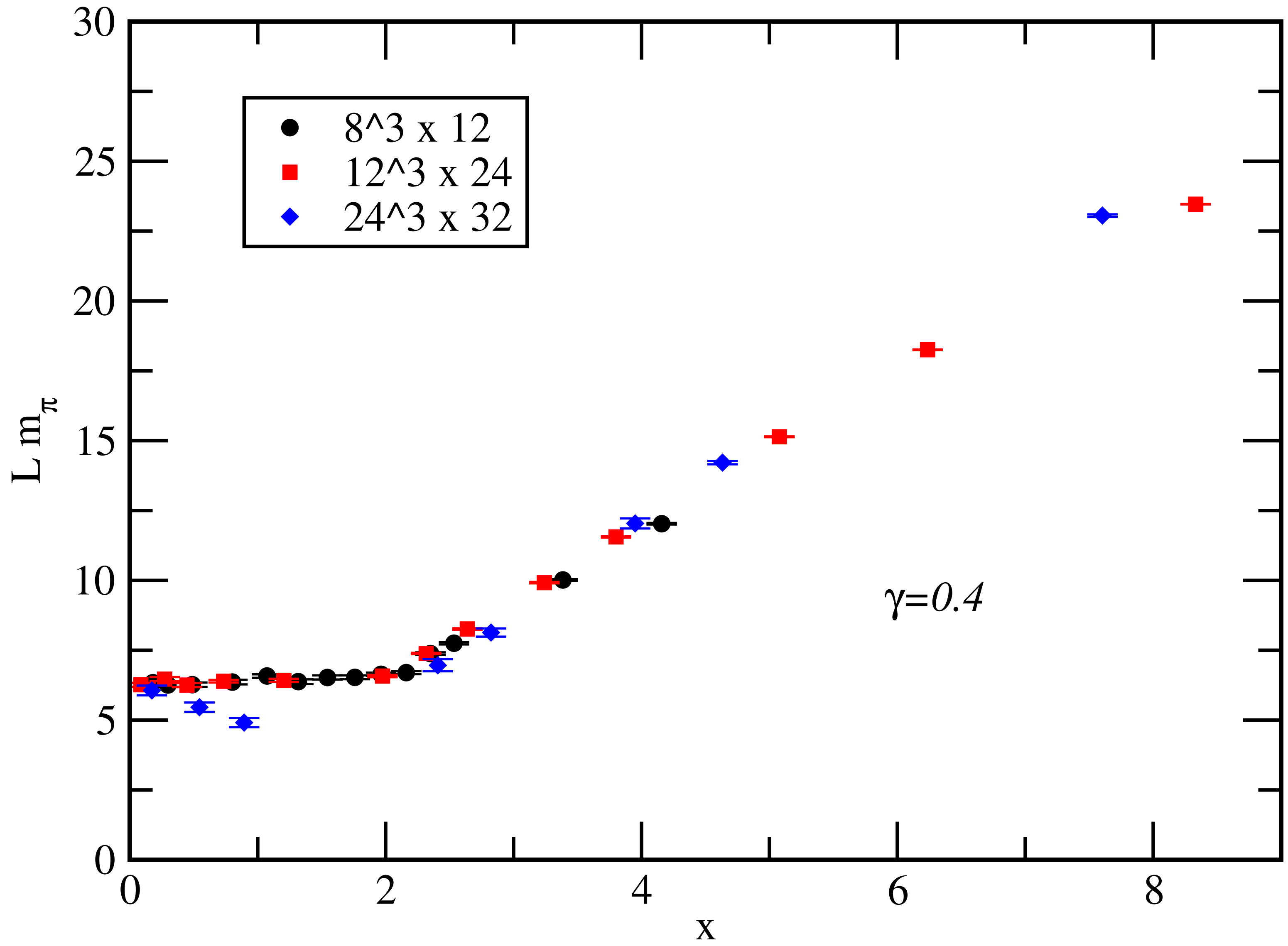
m_π: finite size hyper scaling N_f=12, β=3.5



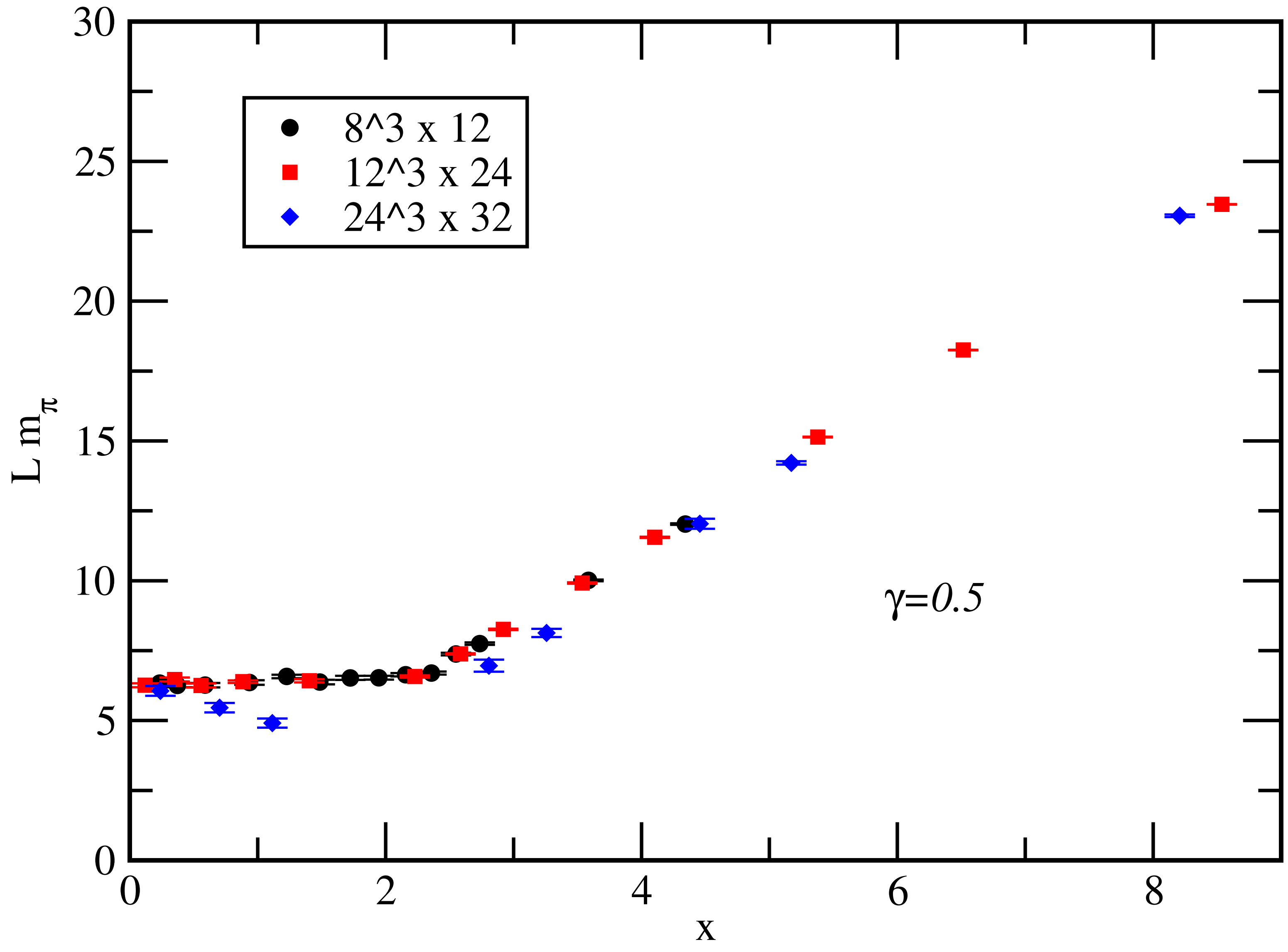
m_π: finite size hyper scaling N_f=12, β=3.5



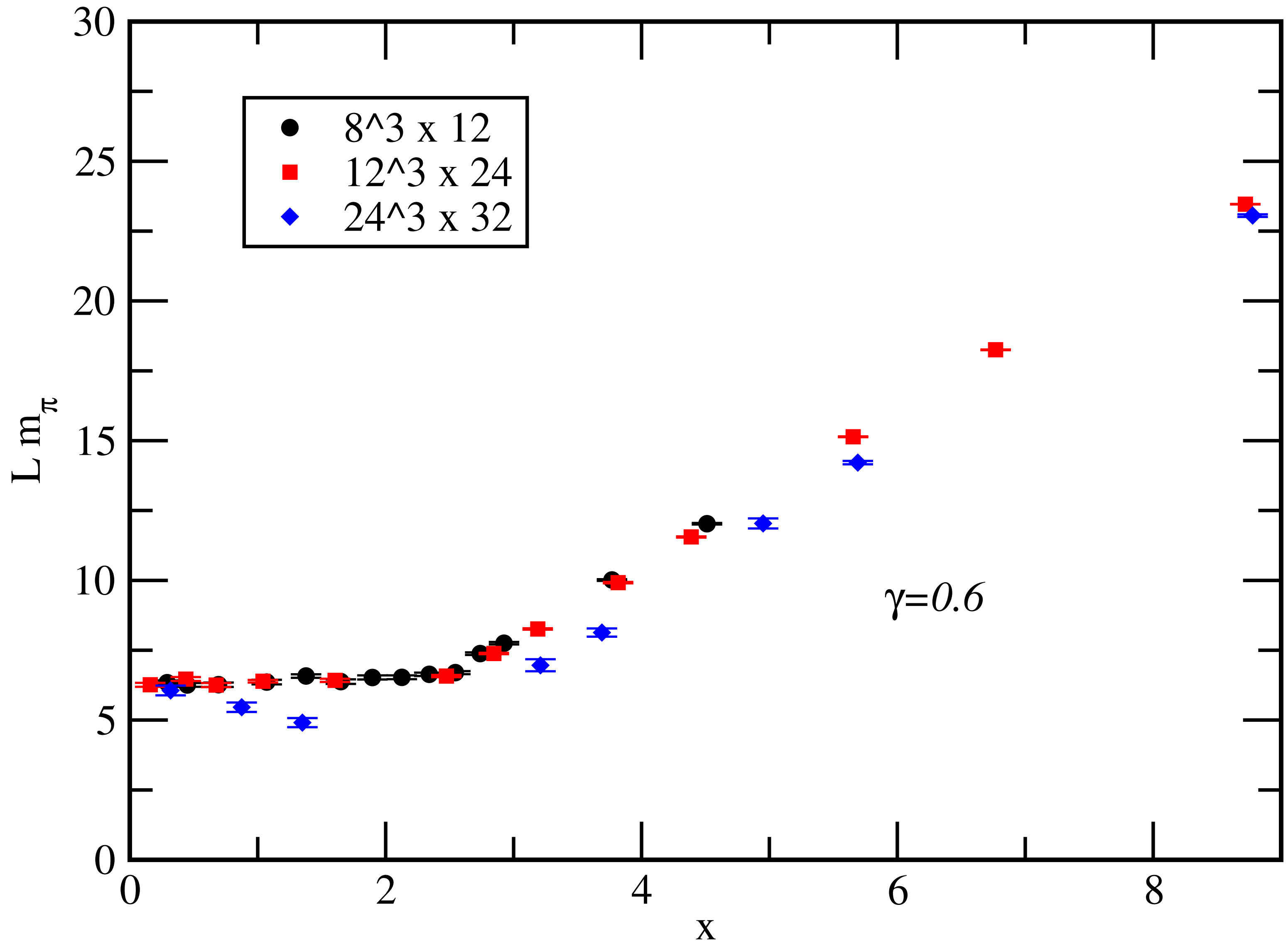
m_π: finite size hyper scaling N_f=12, β=3.5



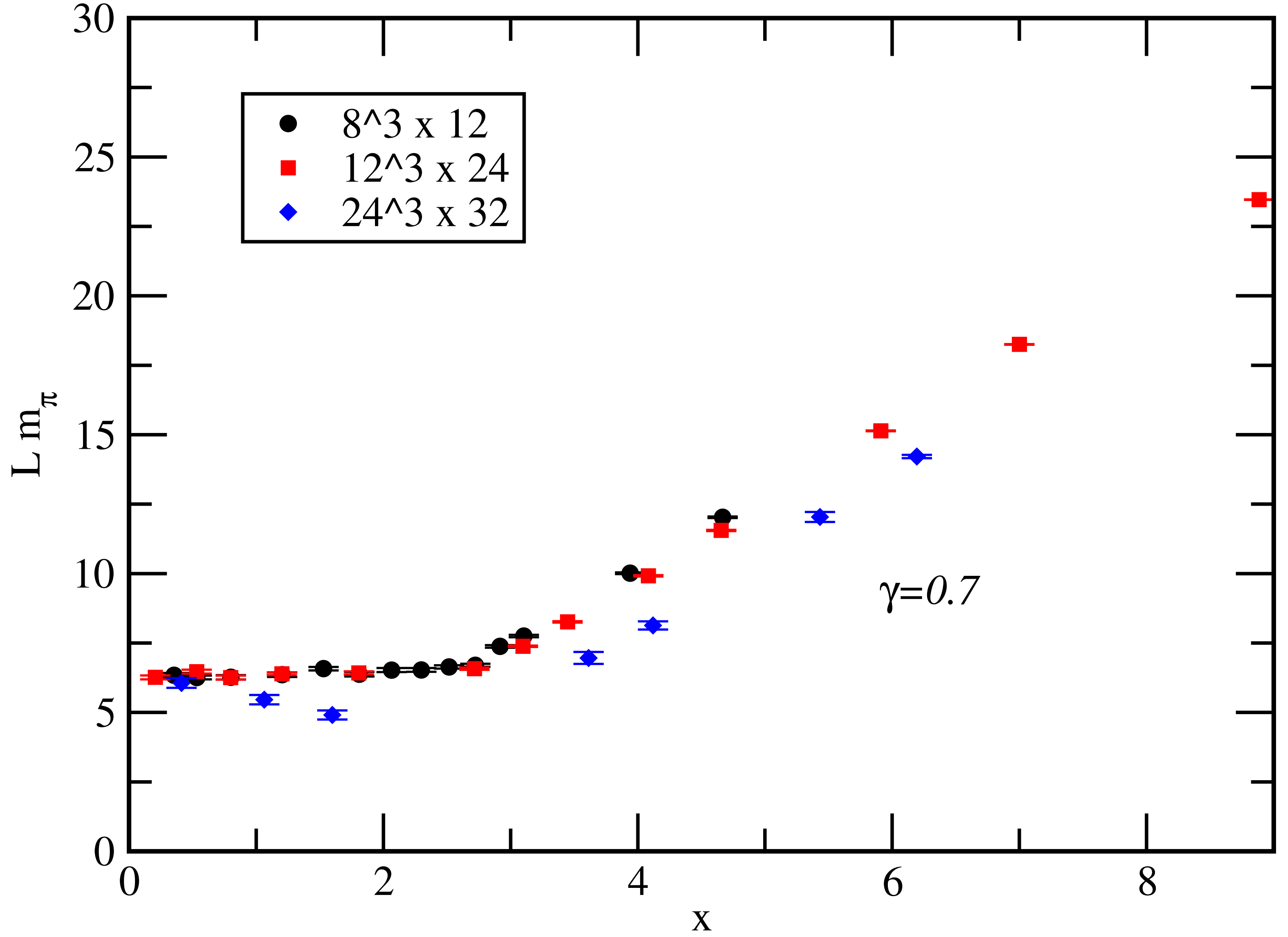
m_π: finite size hyper scaling N_f=12, β=3.5



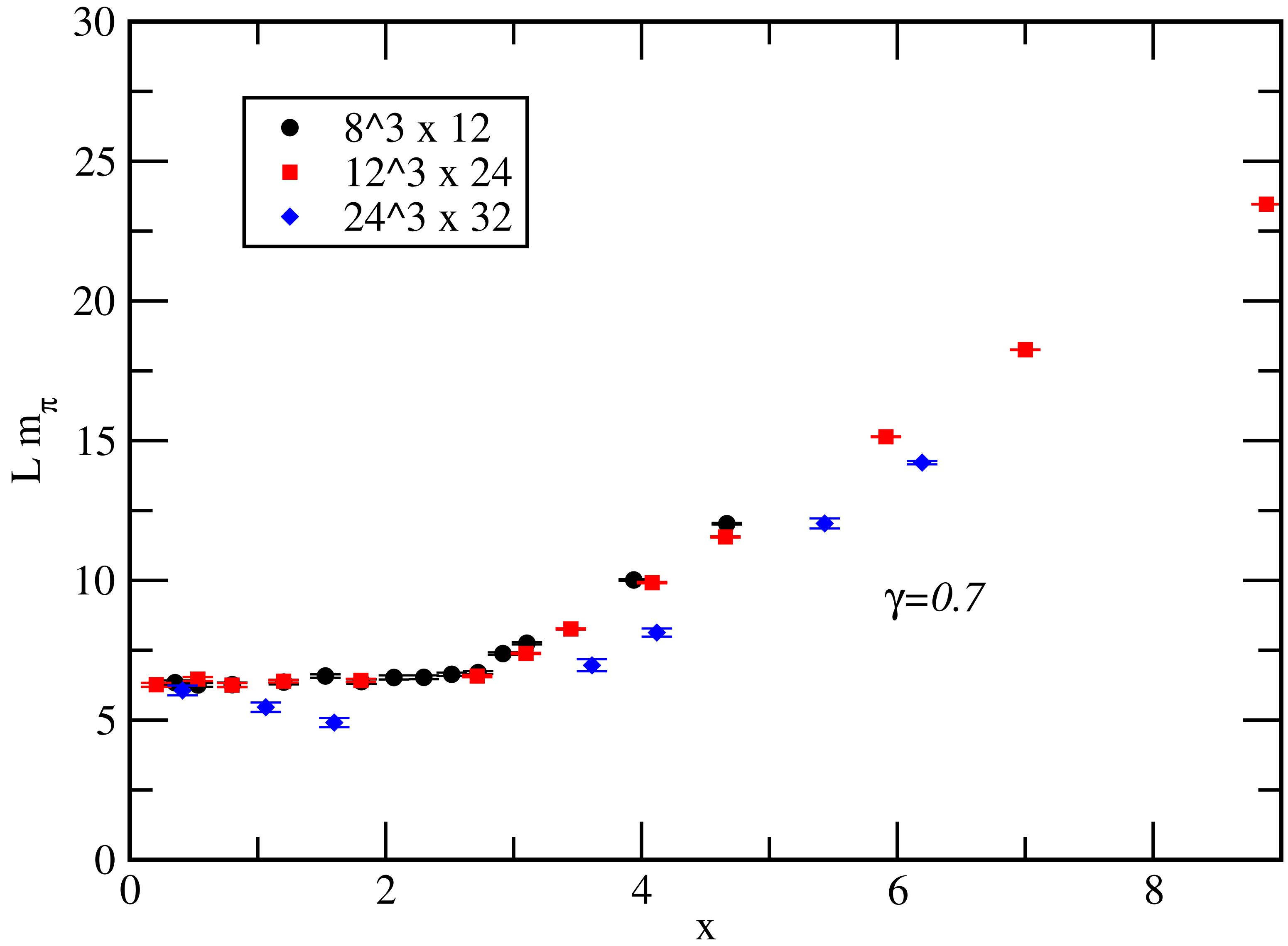
m_π: finite size hyper scaling N_f=12, β=3.5



m_π: finite size hyper scaling N_f=12, β=3.5

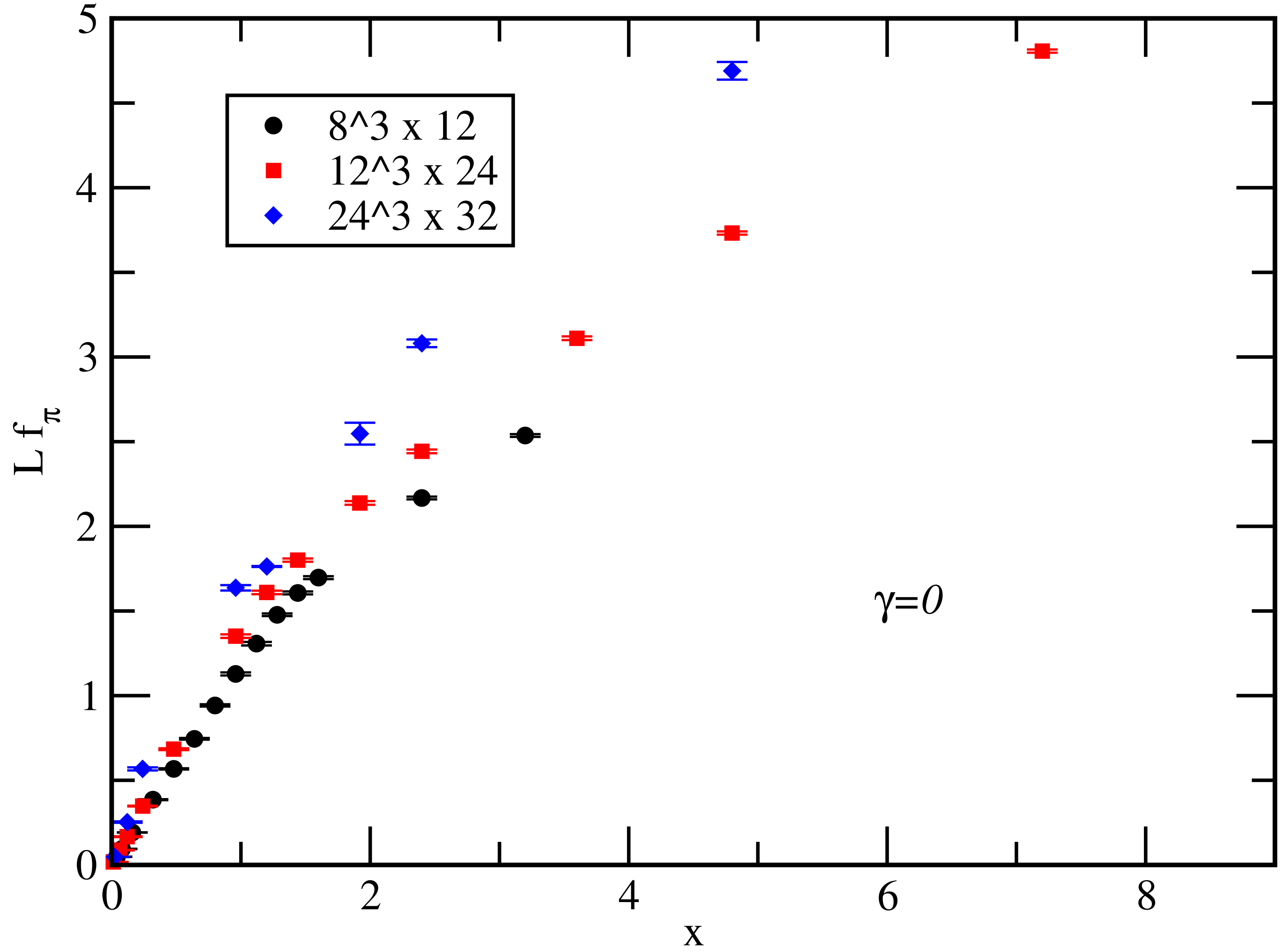


m_π: finite size hyper scaling N_f=12, β=3.5

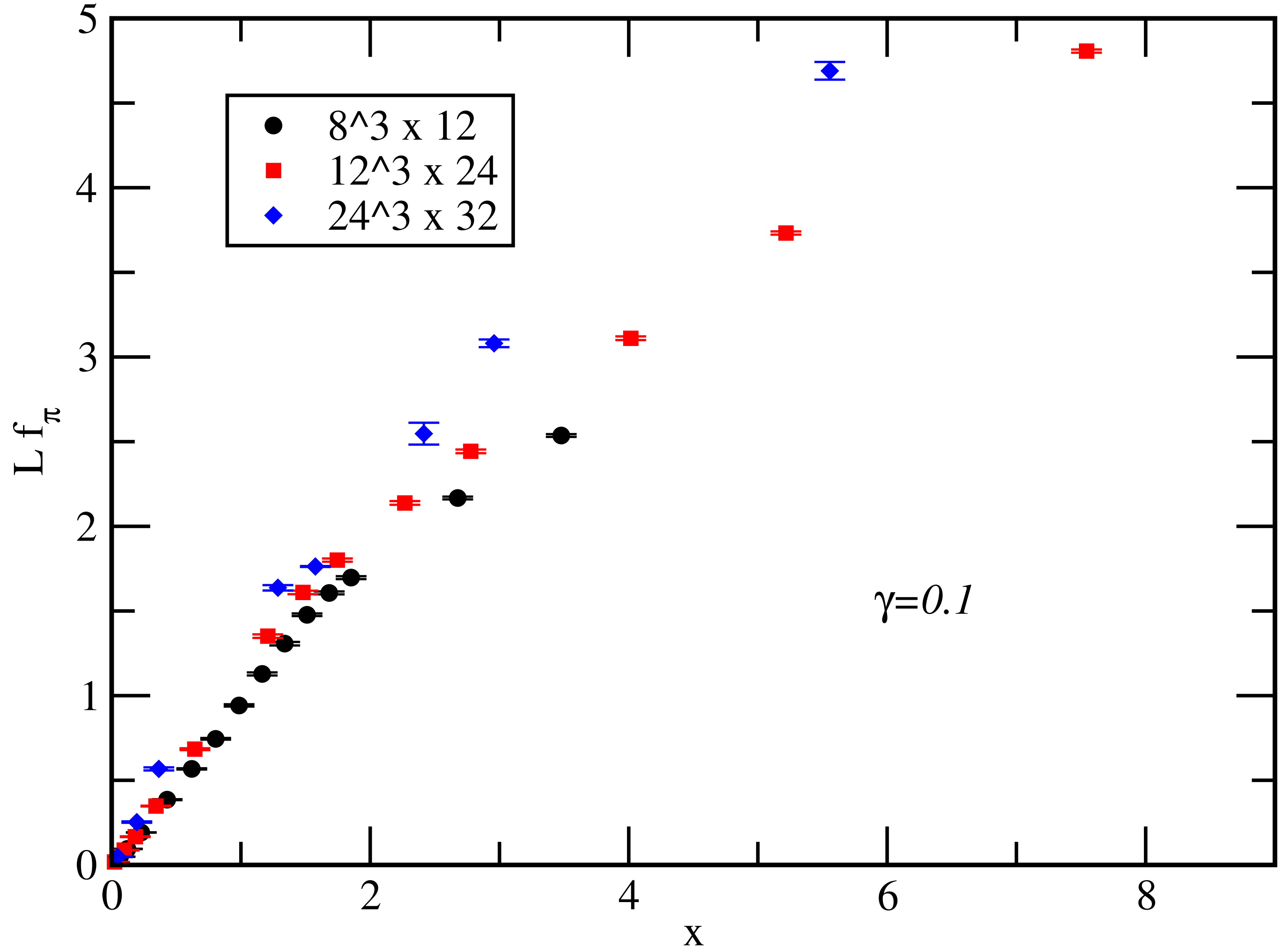


- optimal: γ*=0.4--0.6

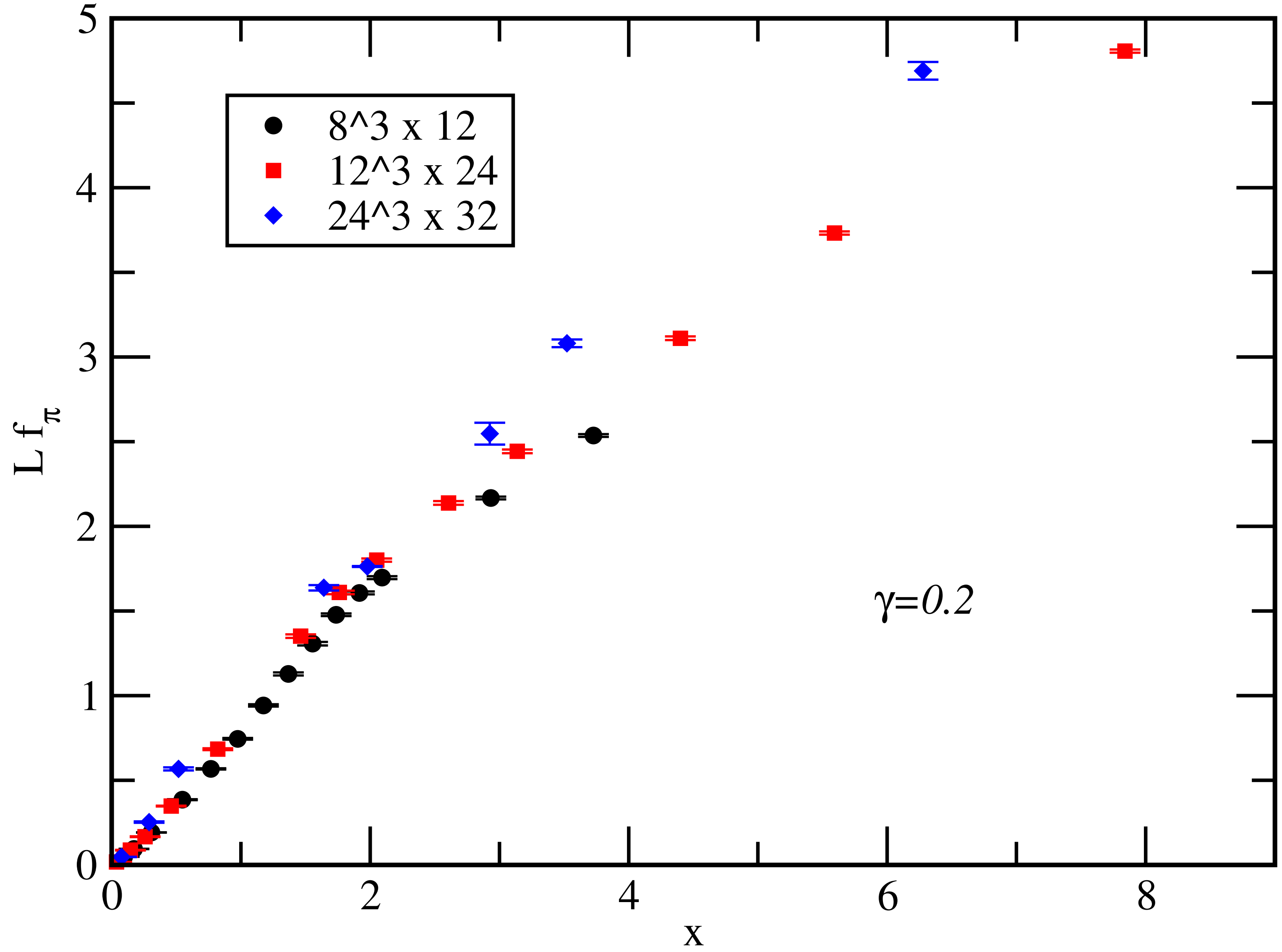
f_π: finite size hyper scaling N_f=12, β=3.5



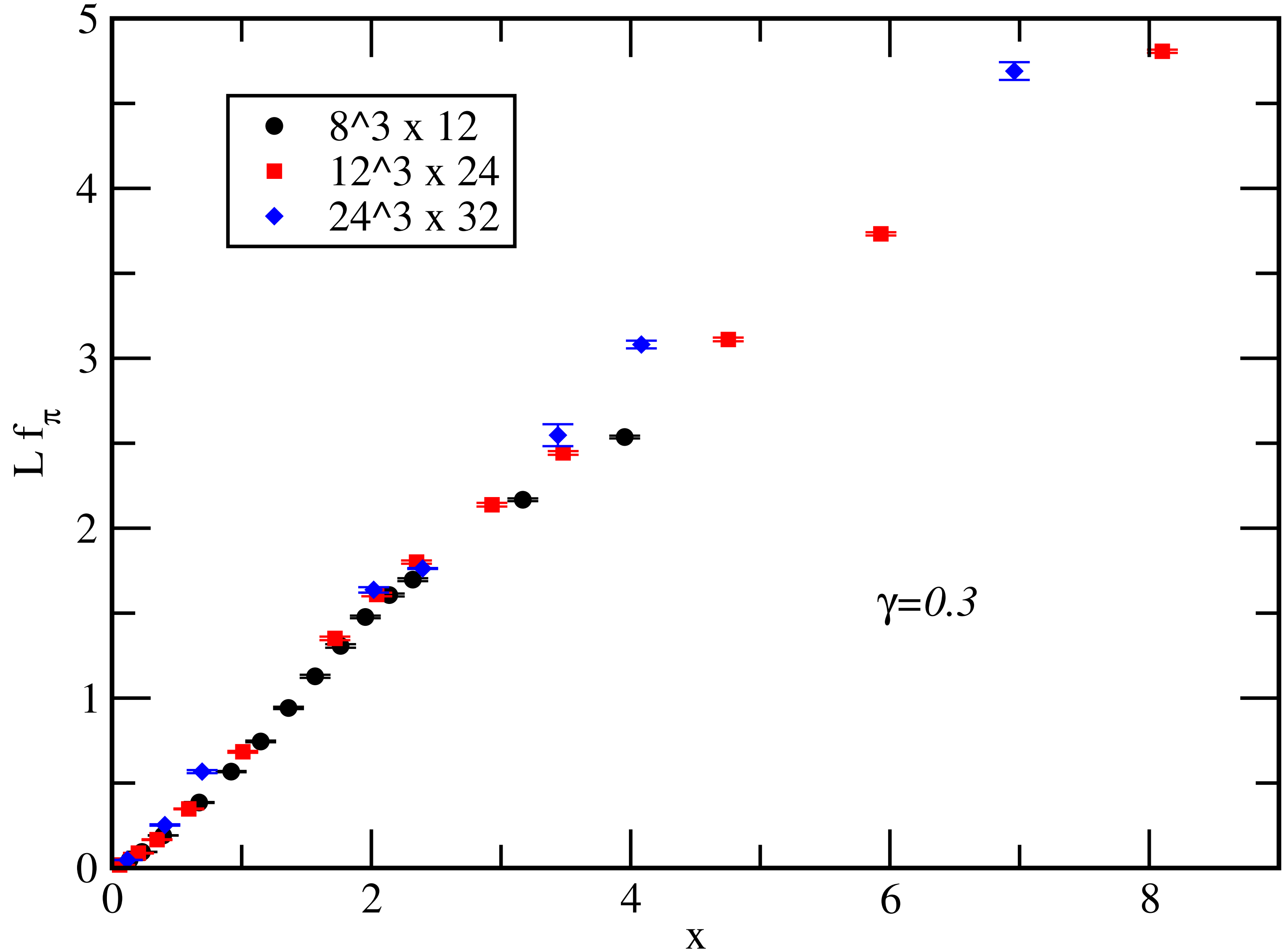
f_π: finite size hyper scaling N_f=12, β=3.5



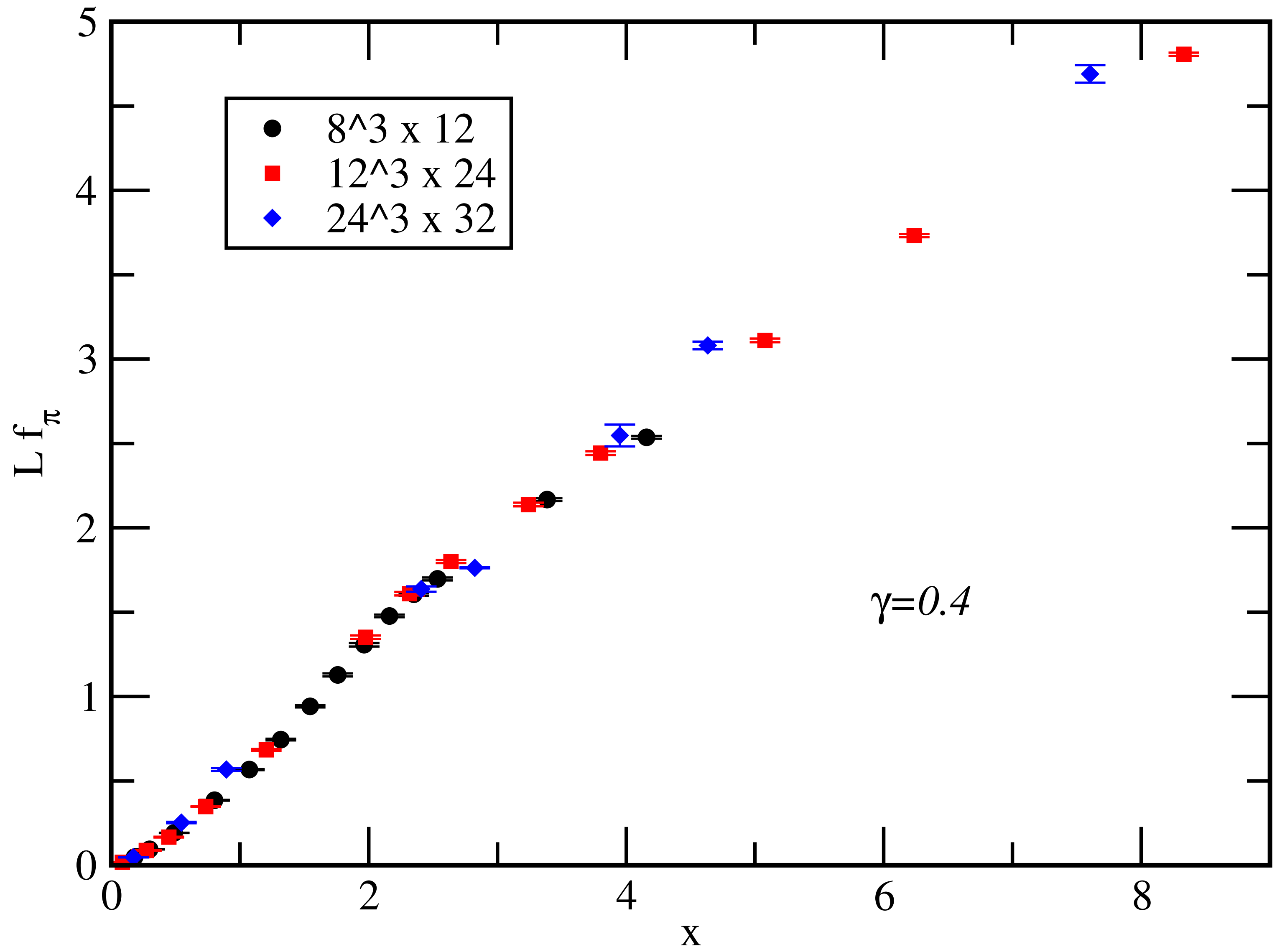
f_π: finite size hyper scaling N_f=12, β=3.5



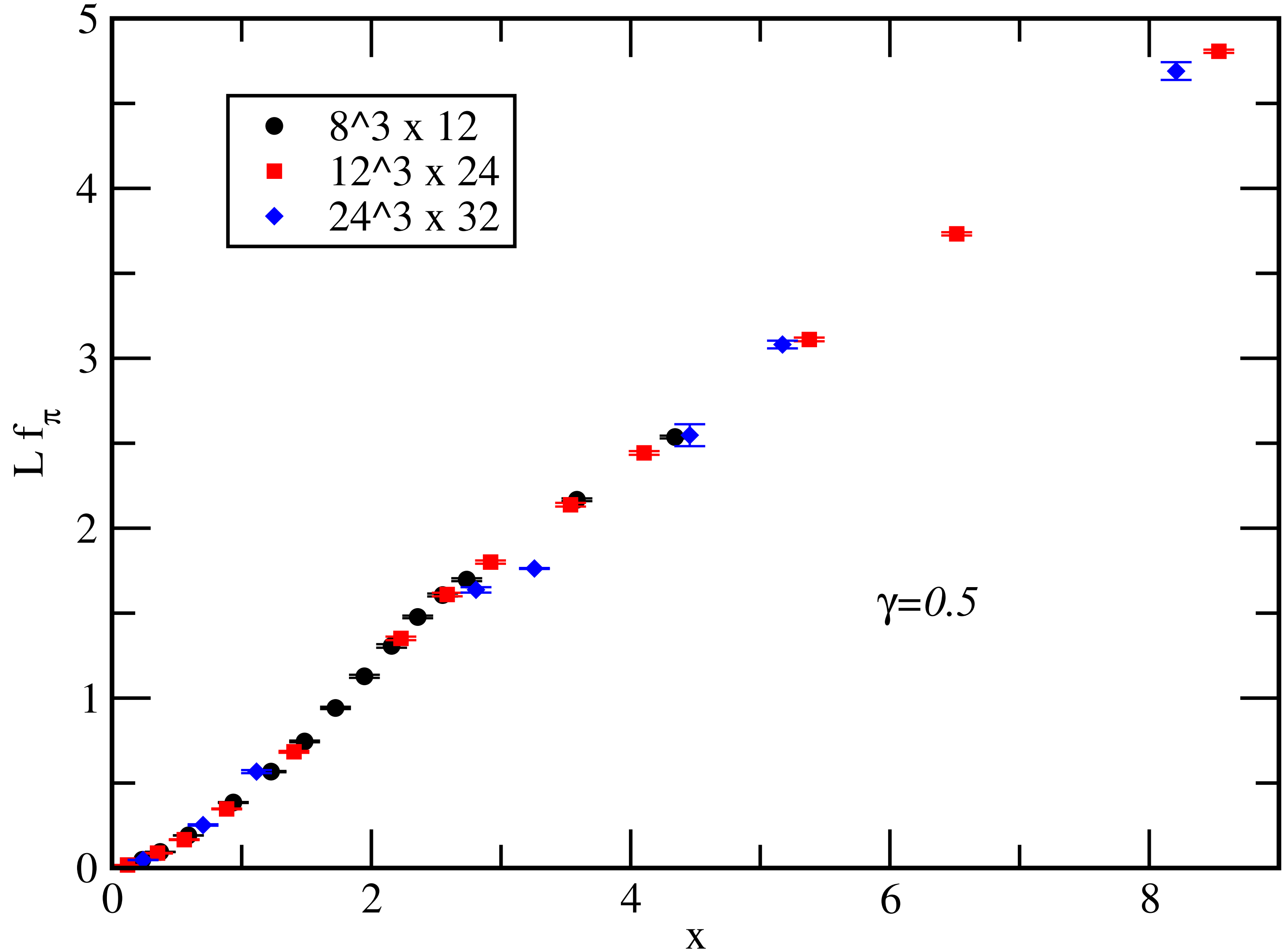
f_π: finite size hyper scaling N_f=12, β=3.5



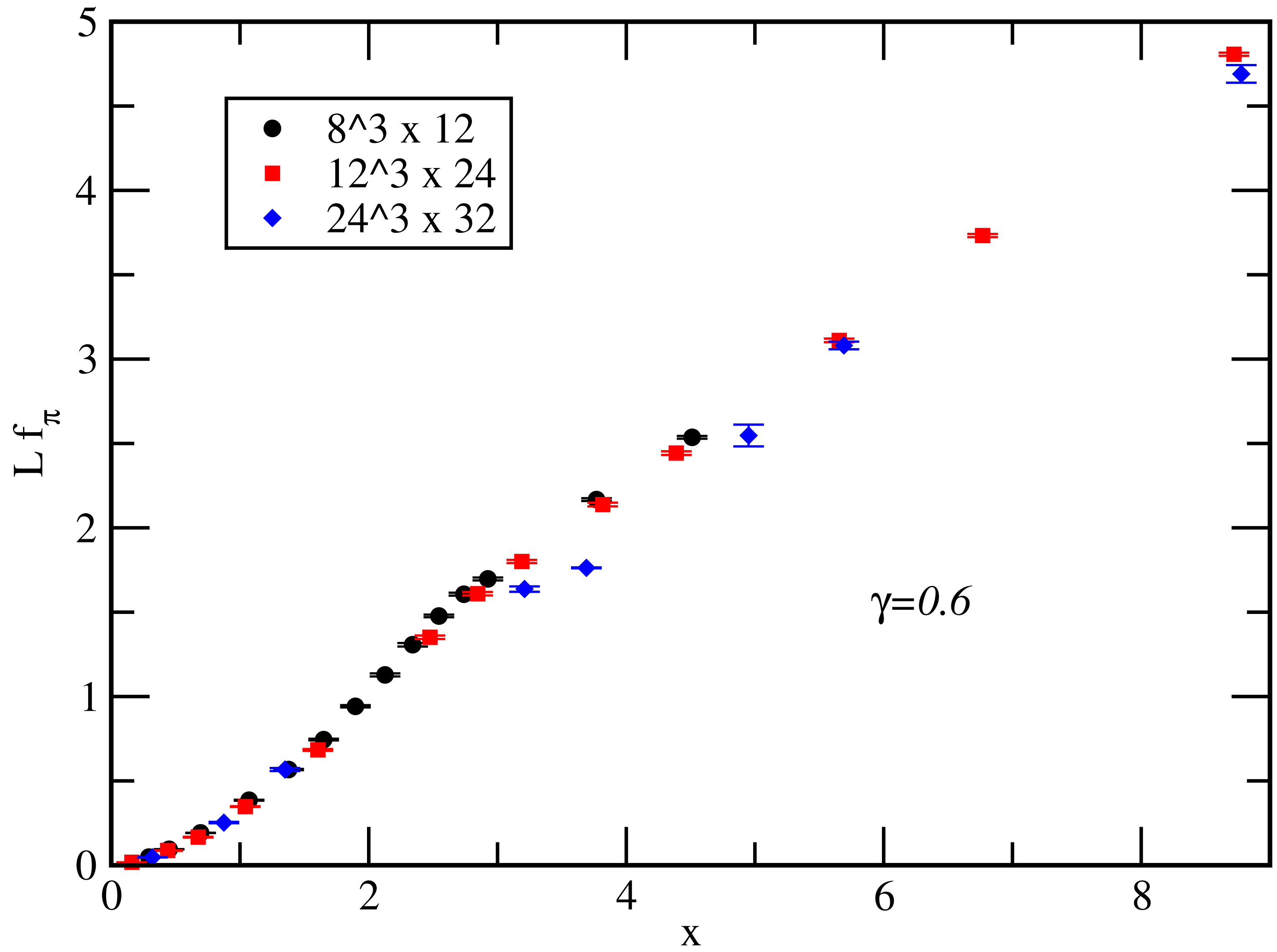
f_π: finite size hyper scaling N_f=12, β=3.5



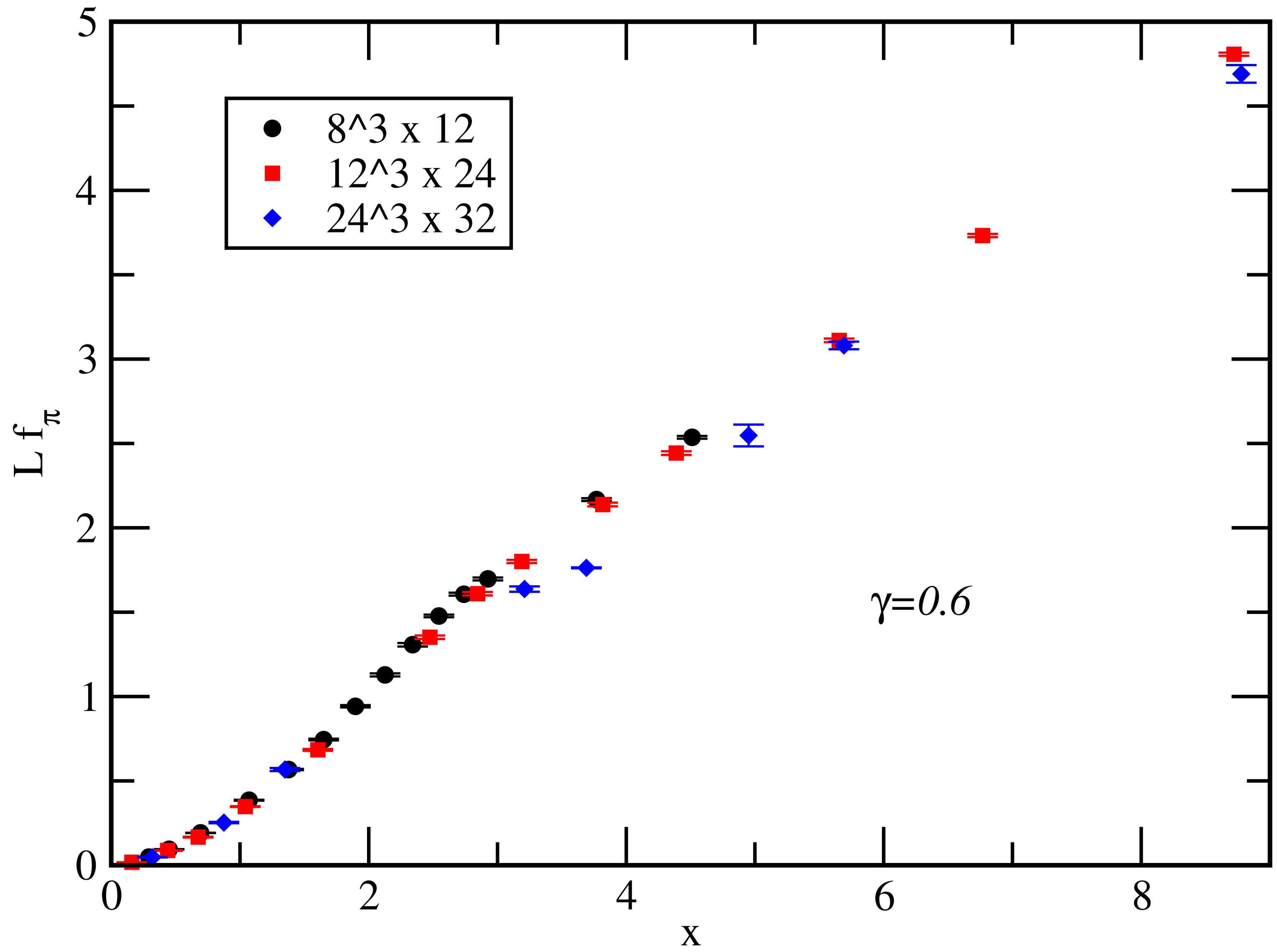
f_π: finite size hyper scaling N_f=12, β=3.5



f_π: finite size hyper scaling N_f=12, β=3.5



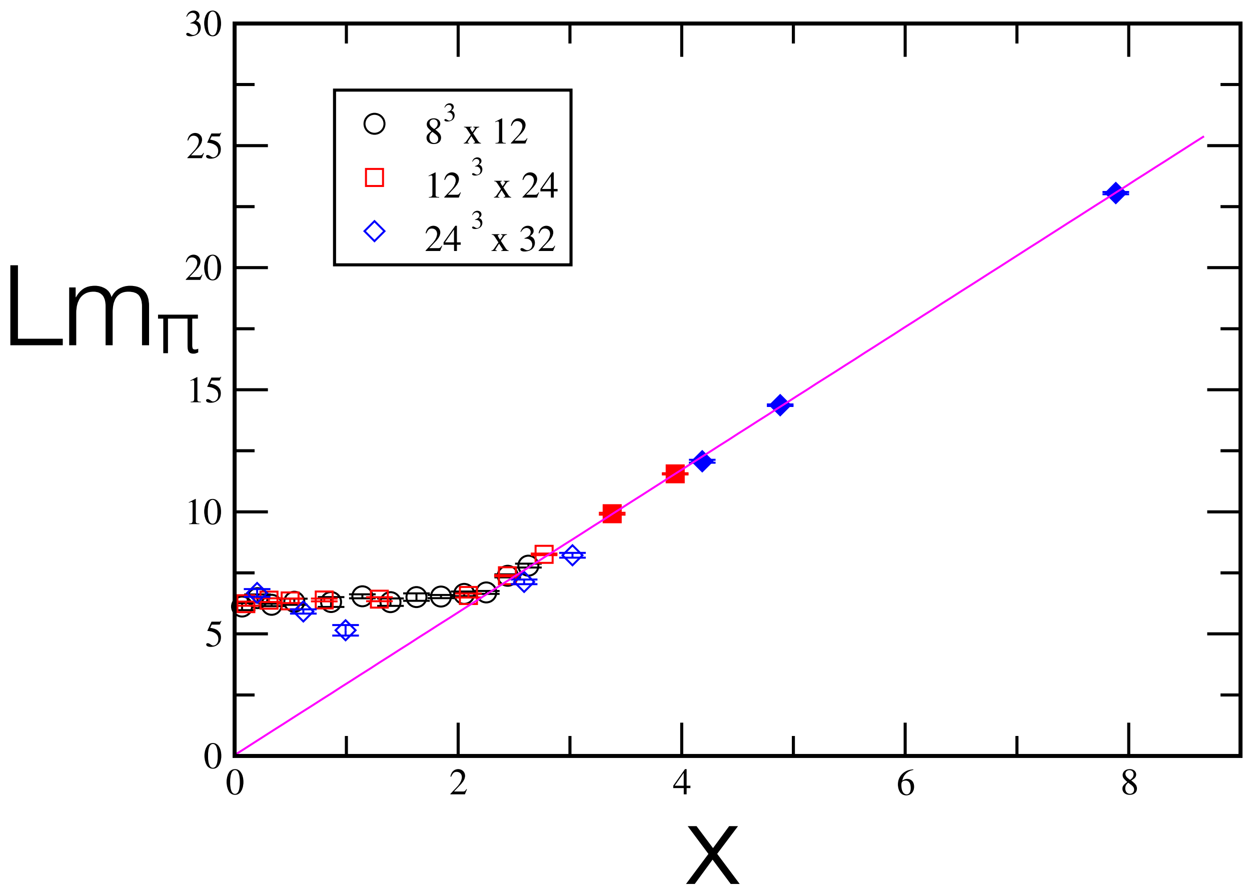
f_π: finite size hyper scaling N_f=12, β=3.5

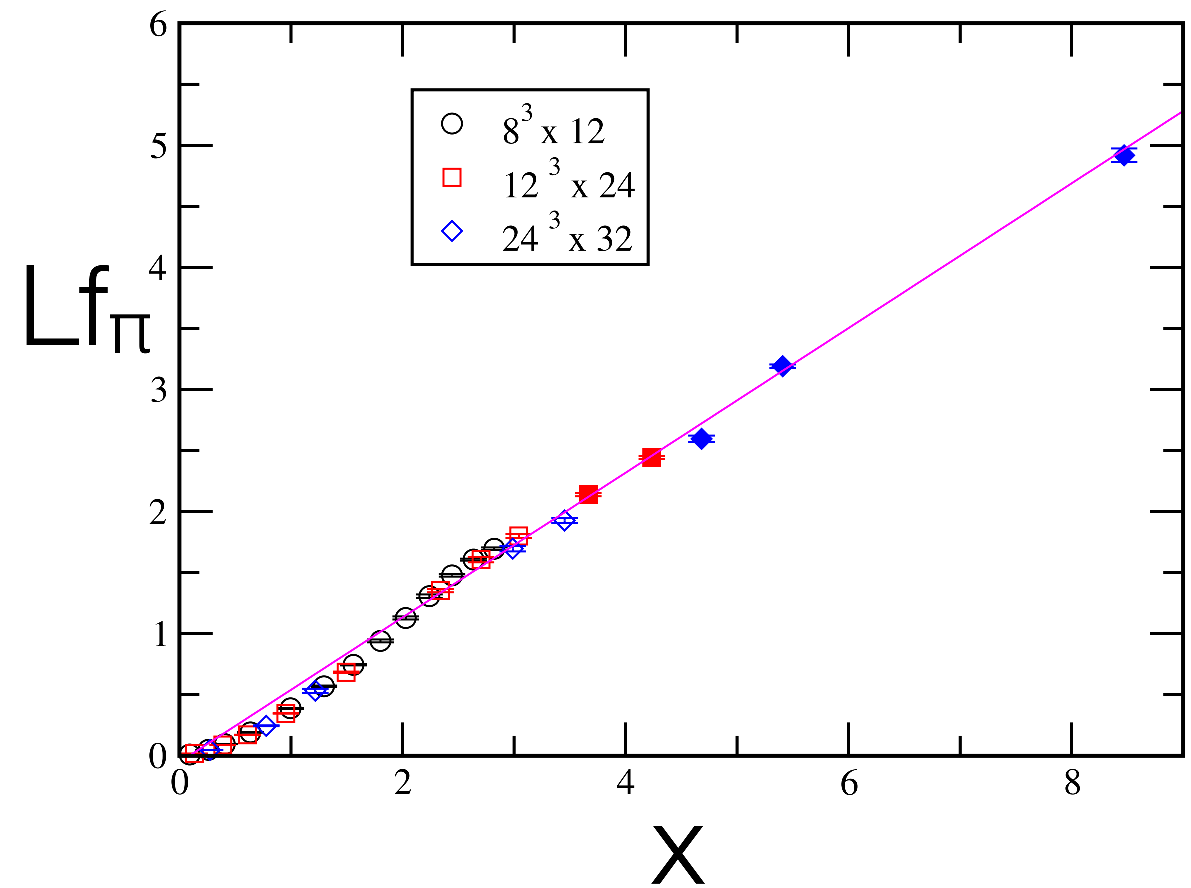


- optimal: γ*=0.4--0.6

γ^* from a fit: β=3.5

- $y = b\, L\, m_q^{1/(1+\gamma^*)} + c$ for large x where linearity is observed





m_π: γ^*=0.446(7)

χ^2/dof=7.2

f_π: γ^*=0.545(2)

χ^2/dof=16.3

- errors are statistical only

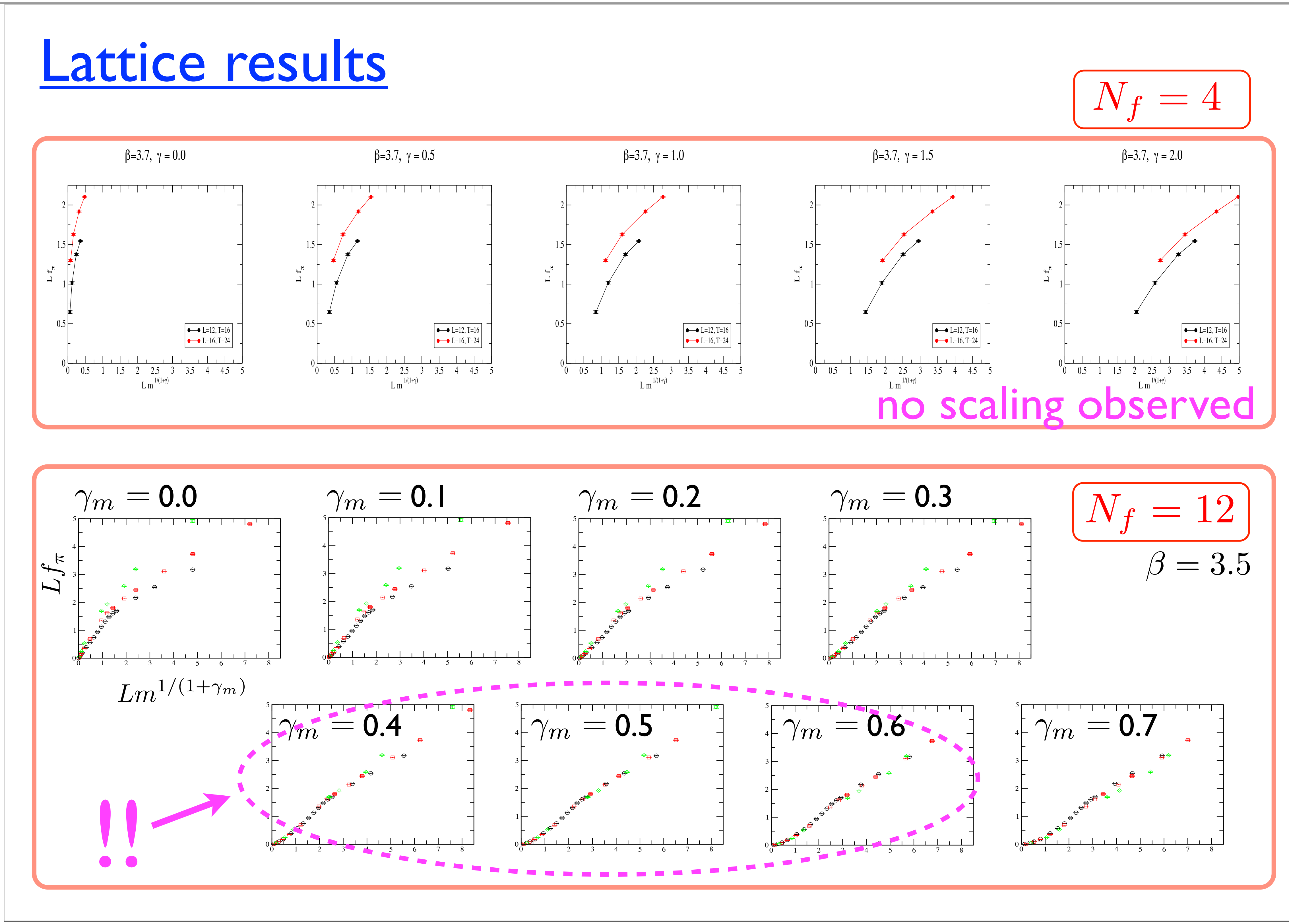
γ^*: extending calculation towards continuum limit

- from poster by Ohki: N_f=12
  - beta=3.5 not included due to non-uniform aspect ratio etc...
- consistent with conformal hypothesis

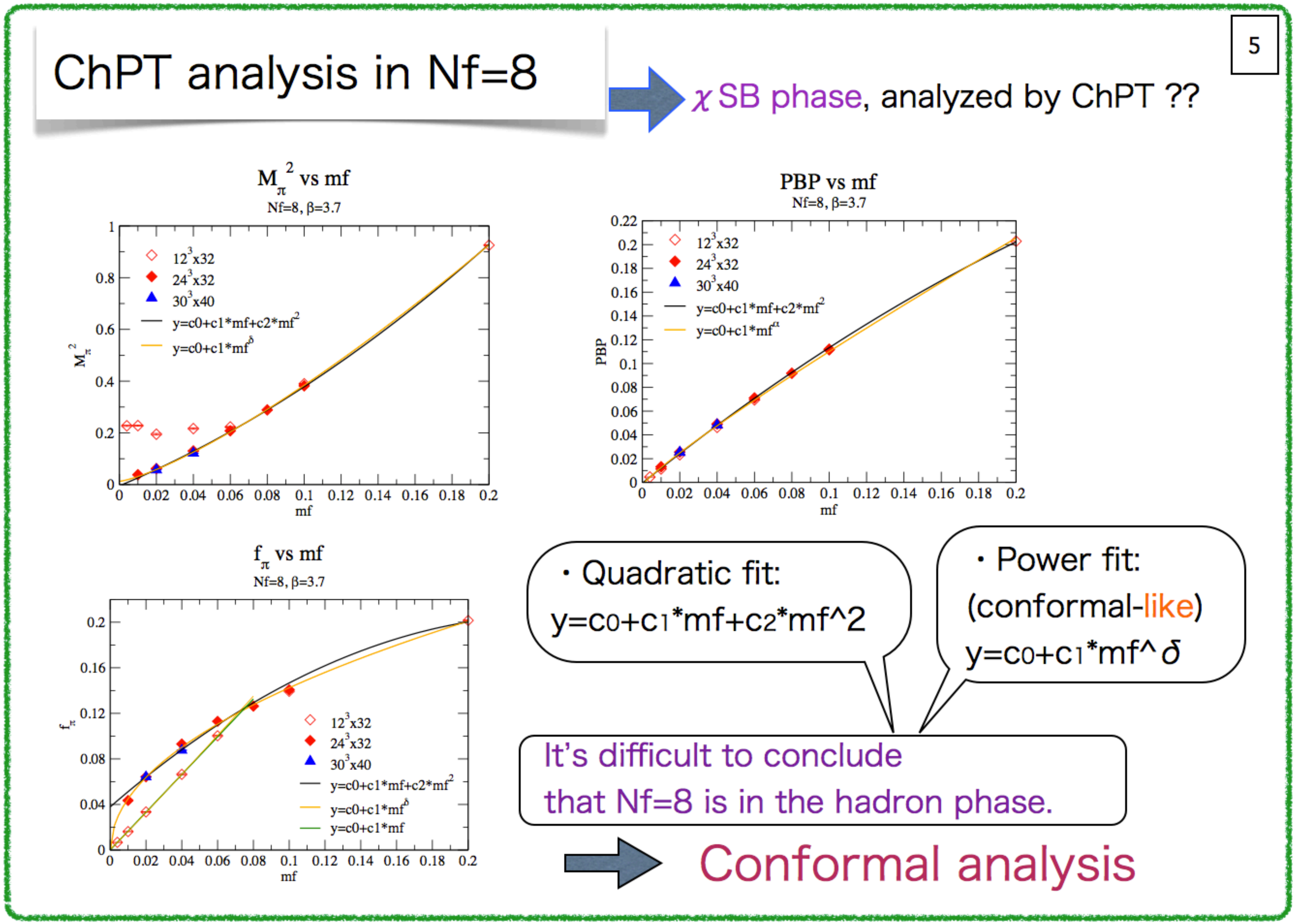
beta	gamma* (m_π)	gamma* (f_π)
3.7	0.44(1)	0.44(3)
4.0	0.39(1)	0.40(2)

- errors are statistical only
- consistency between: m_π and f_π
- tends to decreases towards the continuum limit, BUT, it could be
  - due to lattice artifact (UV), reduced physical volume (IR) or other sys err.?

N_f=4 from poster by Kurachi



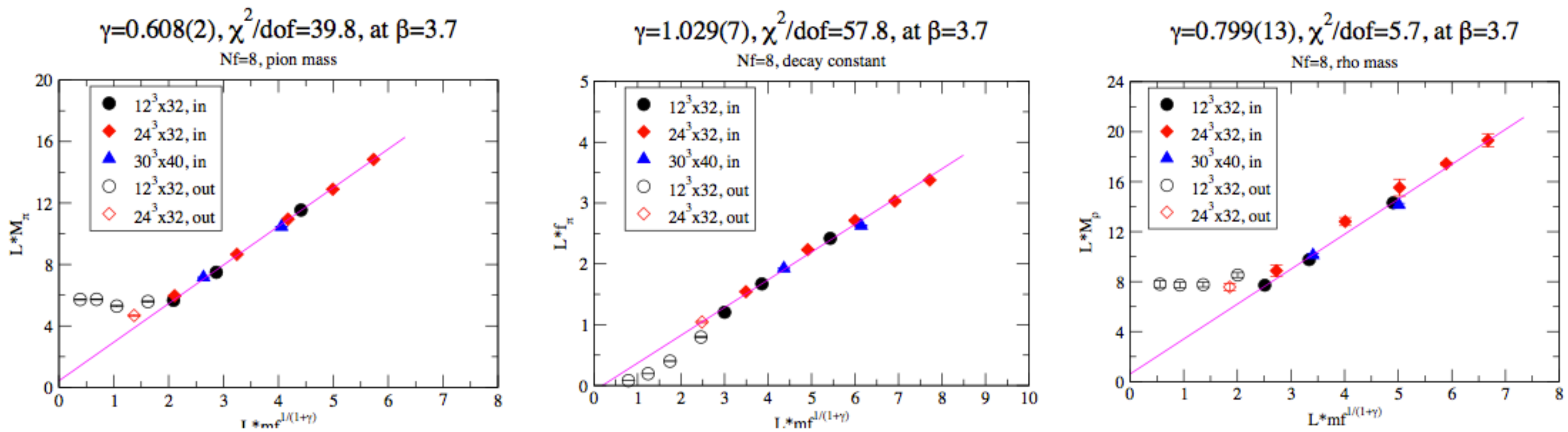
N_f=8 from poster by Nagai



N_f=8 from poster by Nagai

Fit result of the hyperscaling in the conformal hypothesis for Nf=8

7



	$\beta = 3.6$	$\beta = 3.7$	$\beta = 3.8$	$\beta = 3.9$
γ in M_π	0.608(2)	0.607(3)	0.563(3)	0.757(14)
γ in M_ρ	0.766(40)	0.799(13)	0.862(59)	1.18(32)
γ in f_π	1.02(1)	1.03(1)	0.98(1)	1.13(3)

Table:

It seems not to be simple hadronic phase: $\gamma \neq 1$. *c.f.* Nf=4 case.

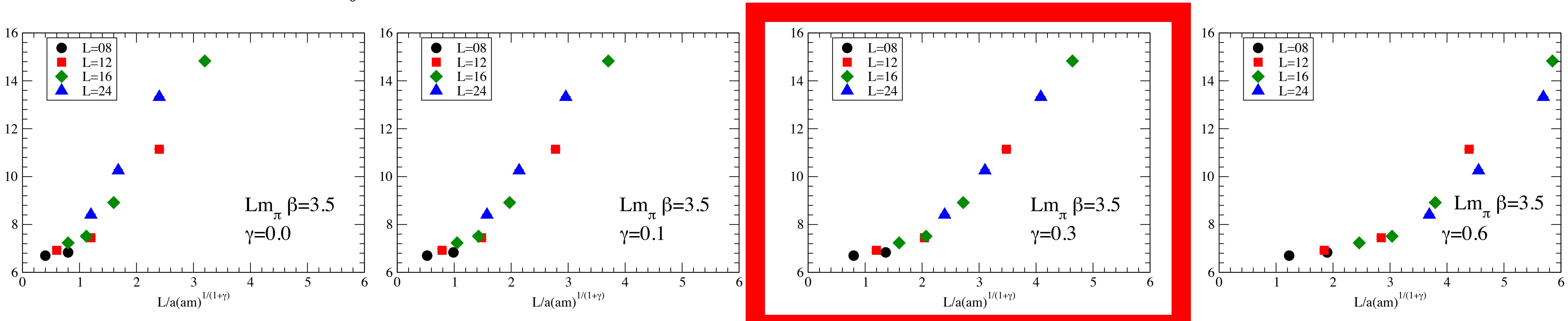
$\gamma \fallingdotseq 1$, walking ??

- ♠ Nf=8 shows the good behavior of the hyperscaling.
- ♠ Still, $\gamma(M_\pi) < \gamma(M_\rho) < \gamma(f_\pi)$ ⟶ not exact Conformal ??

N_f=16 from poster by Yamazaki

5. Results of mass and finite size deformed case

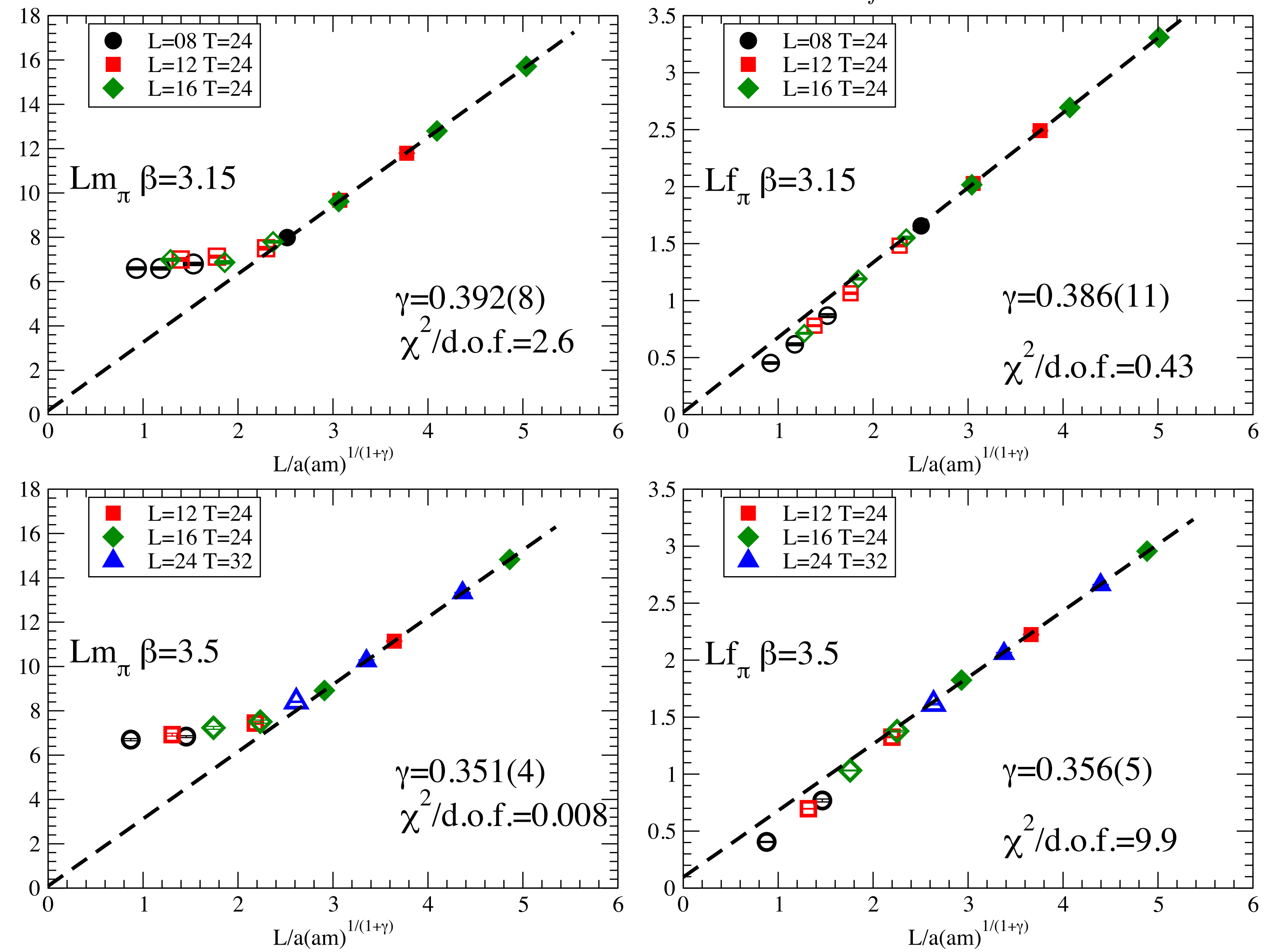
Changin γ_* of Lm_π vs $Lm_f^{\frac{1}{1+\gamma_*}}$ $(\beta = 3.50)$



$\gamma_* \sim 0.3$ gives a nice scaling at larger value of x-axis.

N_f=16 from poster by Yamazaki

Lm_π and Lf_π fit with asymptotic form : $Lm_\pi = c_0 + c_1 x, \quad x = Lm_f^{\frac{1}{1+\gamma_*}}$



γ_* at $\beta = 3.50$ is consistent with the one of mass deformed case.

Two γ_* from different observables reasonably agree with each other at both β.

However, γ_* at both β is much larger than the perturbative result, $\gamma_*^{\mathrm{pert}} \sim 0.015$.

summary

- large N_f SU(3) gauge theory with fundamental rep. is being investigated
  - quest for the walking technicolor
- using a HISQ type fermion and the tree-level Symanzik gauge action
- aiming to explore a wide range of the N_f systematically
- This talk mainly described N_f=12 study
  - three lattice spacings ($\beta=6/g^2$) studied, with spatial size up to L_s=30
  - pion mass and decay constant are studied
  - approximate finite size scaling for conformal scenario is observed
  - with the current lattice volume, results favor conformal theory
  - assuming an IR fixed point, mass anomalous dimension calculated
    - γ^*~0.4

comparison to other works on Nf=12 SU(3)

collaboration	conclusion	method	remarks
Fodor et al	χ Broken	spectrum	big V, single lat.spgs.
Columbia	χ Broken	spectrum, Tc	naive KS
Deutchman et al	Conformal	spectrum, Tc	KS+Naik
Itou et al	Conformal	coupling	naive KS + cont.lim.
Appelquist et al	Conformal	coupling	non-exact algorithm
Appelquist et al	Conformal	spectrum	using Fodor's data
DeGrand	consistent with Conformal	spectrum	using Fodor's data
KMI	consistent with Conformal	spectrum	HSIQ, 3 lat.spgs.

summary (continued)

- N_f=4
  - clearly in χ broken phase
  - finite size hyper scaling not observed
- N_f=8
  - more study needed for definite conclusion
- N_f=12
  - results are consistent with conformal hypothesis
- N_f=16
  - consistent with conformal, but with large anomalous dimension
  - study with weaker coupling necessary

outlook

- to meet our goals
- for N_f=8, 12
    - larger size than L_s=30 is needed to investigate further IR regime
        - make it possible to study lighter mass
    - glueball mass to check hyper scaling
    - masses for other mesons, baryons, flavor singlets: to check hyper scaling
- for N_f=16
    - much weaker coupling

Thank you for your attention