Exploring walking behavior in SU(3) gauge theory with 4 and 8 HISQ quarks

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Contents:

Introduction

To Understand,

EW symmetry breaking by composite particles

$\rightarrow$ Technicolor model

quark mass term; $\frac{1}{\Lambda_{ETC}^2}\langle\bar{Q}Q\rangle\bar{q}q$

$\langle\bar{Q}Q\rangle \neq 0$ $\rightarrow$ The quark mass is generated.

To explain the fact of FCNC $\rightarrow$ Walking behavior with $\gamma_m \simeq 1$

Thus,

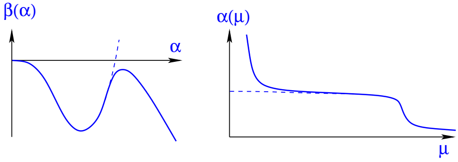
Strong dynamics $\rightarrow$ nonperturbative $\Rightarrow$ lattice gauge theories

$\Longrightarrow$ Application of lattice QCD technique

- Running coupling constant (lattice β-function)
- Spectroscopy (ChPT, Hyperscaling, ...)

A lot of lattice studies !

Why $N_f = 8$? (Walking/Conformal)



approximate IRFP

Walking Technicolor (K.Yamawaki *et.al.* ('86))
$\rightarrow$ large anomalous mass dimension ($\gamma_m \simeq 1$) and $\langle\bar{\psi}\psi\rangle \neq 0$

Phenomenologically; $N_f = 8$ is a natural setup in SM.
Farhi-Susskind model (one-family model):
3×2 in quark sector $+$ 2 in lepton $= 8$ flavors.

Our purpose is to find gauge theories for constructing the model of the walking technicolor.

Our project

♠ We want to know the phase structure of many flavor gauge theories for the EW sym. breaking by the composite particle.
♠ Exploration of the walking behavior $\leftarrow$ flavor dependence.
♠ We (LatKMI) investigate the spectrum for $N_f = (0)$, 4, 8, 12, 16 systematically.
$N_f = 12$ and 16 $\rightarrow$ H. Ohki's talk on Monday
♠ SD-eq. analysis with the finite-size and the mass correction $\rightarrow$ M. Kurachi's talk on Thursday

Then,
♠ In this talk, we investigate $N_f = 4$ as the typical χSB and $N_f = 8$ as the candidate for the walking technicolor model.

Lattice actions and the outline of simulations

♠ $S = S_G + \sum_{f=1}^{N_f} S_f^f$.
♠ S_G; Tree level Symanzik gauge action: $\beta = \frac{6}{g^2}$.
♠ $S_f = S_{HISQ}$; HISQ action for the fermion sector :
HISQ = Highly Improved Staggered Quarks
♠ First application of HISQ action to many flavor system.

♣ KMI computer system, "φ".
♣ We use the code based on MILC code version-7.
♣ Simulation → standard HMC for $N_f = 4n$.
♣ Observables: $M_\pi, M_\rho, f_\pi, \langle\bar{\psi}\psi\rangle$

Search parameters

- ♣ $N_f = 4$;
  $\beta = 3.5$, 3.6, 3.7, 3.8 on various lattice at various fermion masses.
- ♣ $N_f = 8$;
  $\beta = 3.6$, 3.7, 3.8, 3.9 and 4.0 on $12^3 \times 32$, $18^3 \times 24$, $24^3 \times 32$ and $30^3 \times 40$ at various fermion masses.
  (and on $36^3 \times 48$ at $m_f = 0.015$ for $\beta = 3.8$)

ChPT-like behavior

In χSB phase;

♠ ChPT analysis

- $M_\pi^2 = c_1 m_f + c_2 m_f^2$?
- In the limit of $m_f \to 0$, $f_\pi \neq 0$?
- In the limit of $m_f \to 0$, $M_\rho \neq 0$?
- In the limit of $m_f \to 0$, $\langle \bar{\psi}\psi \rangle \neq 0$?

In ChPT, the expansion parameter is $\chi = N_f \left(\frac{M_\pi(m_f)}{4\pi F_\pi(m_f=0)} \right)^2$.

$\chi \lesssim 1$?

Finite-size Hyperscaling analysis for the conformal

The mass deformed hyperscaling in the conformal behavior;

$$M_H \propto m_f^{\frac{1}{1+\gamma}} \,. \tag{1}$$

Finite-size Hyperscaling analysis;

$$M_H = \frac{1}{L}\mathcal{F}(X) \quad \text{where} \quad X = Lm_f^{\frac{1}{1+\gamma}} \,. \tag{2}$$

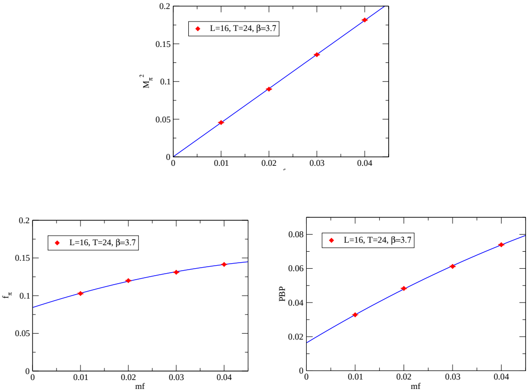
on $L^3 \times T$ at a fixed ratio, $\frac{L}{T}$.
Eq. (2) in the infinite volume limit $\longrightarrow$ Eq. (1)

$$\mathcal{F}(X) = C_0 + C_1 Lm_f^{\frac{1}{1+\gamma}} \,. \tag{3}$$

Thus, the finite-size hyperscaling

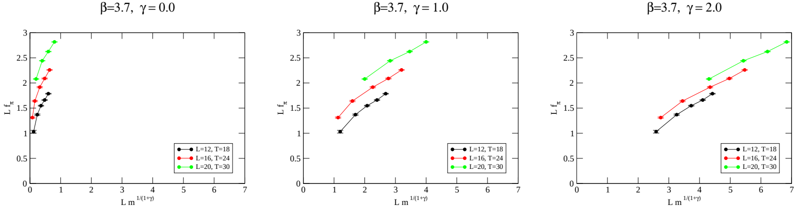
$$LM_H = C_0 + C_1 X, \quad \text{where} \quad X = Lm_f^{\frac{1}{1+\gamma}} \,. \tag{4}$$

ChPT analysis in $N_f = 4$



$M_\pi^2 \propto m_f, f_\pi \neq 0$ and $\langle\bar{\psi}\psi\rangle \neq 0$ at $m_f = 0$ (as $m_f \to 0$) in the quadratic fit. $\Longrightarrow$ $N_f = 4$ is in χSB phase.

Hyperscaling test in $N_f = 4$ case, f_π

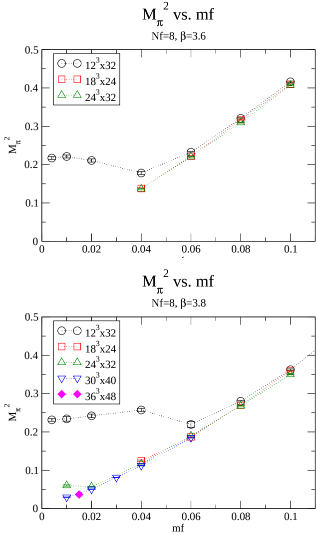


the finite-size hyperscaling:

$$LM_H = \mathcal{F}(X) \text{ where } X = Lm_f^{\frac{1}{1+\gamma}};$$

No alignment in the range of $0 < \gamma < 2 \Rightarrow$ No hyperscaling!
(The example to know what happens in the explicit χSB phase)

Spectroscopy in $N_f = 8$. (M_π^2)



χSB test in $N_f = 8$

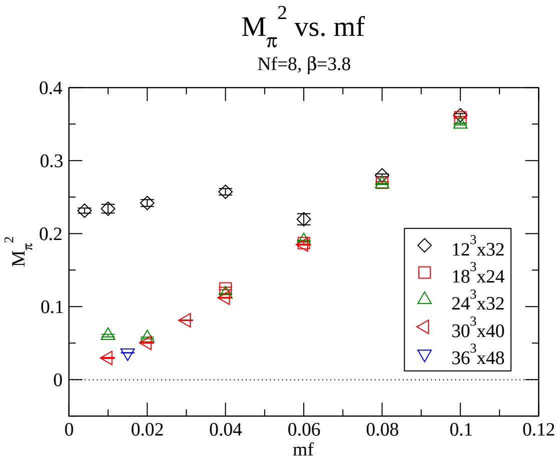
♠ χSB behavior; polynomial fit

- $M_\pi^2 = c_1 m_f + c_2 m_f^2$?
- In the limit of $m_f \to 0$, $f_\pi \neq 0$?
- In the limit of $m_f \to 0$, $M_\rho \neq 0$?
- In the limit of $m_f \to 0$, $\langle \bar{\psi}\psi \rangle \neq 0$?

♠ conformal behavior; power fit

- In the limit of $m_f \to 0$, $M_\pi^2, f_\pi, M_\rho, \langle \bar{\psi}\psi \rangle \to 0$?

fit trial in $N_f = 8$ at $\beta = 3.8$



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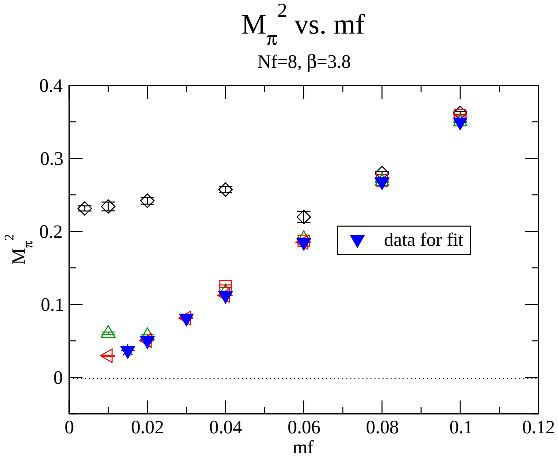

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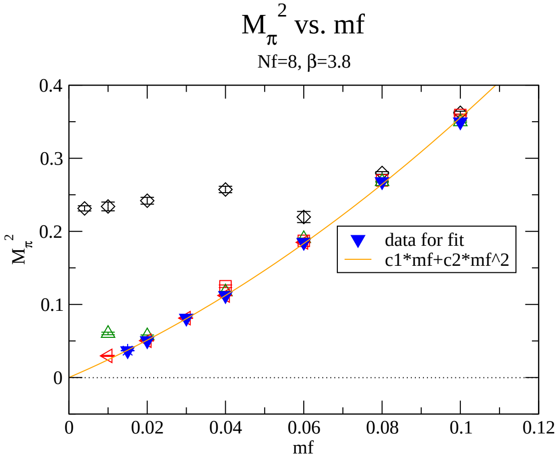

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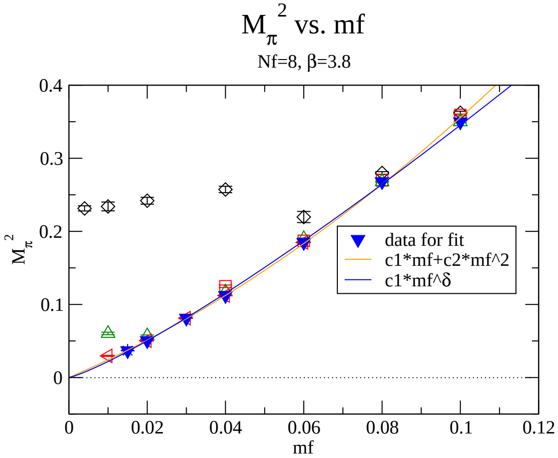
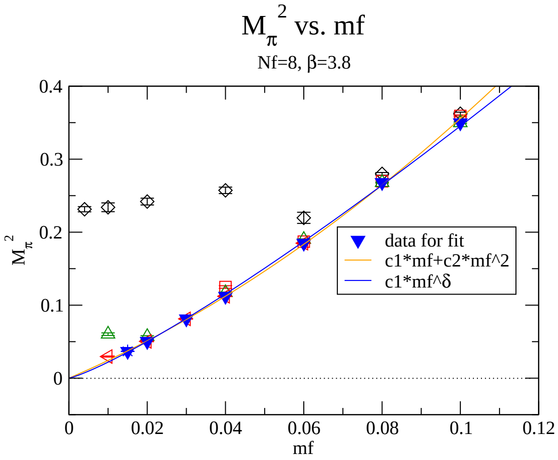


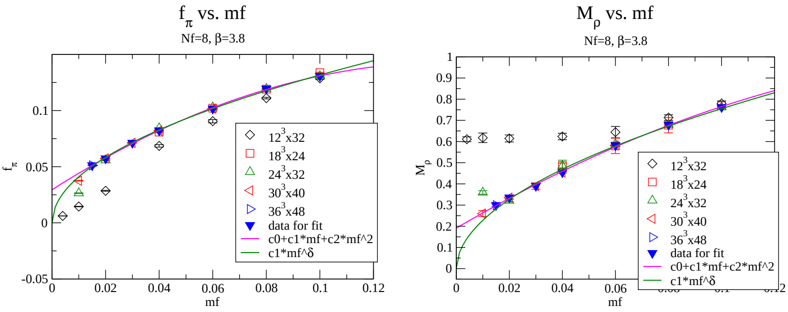
fit result of M_π^2 in $N_f = 8$ at $\beta = 3.8$



$$M_\pi^2 = 2.31(2) m_f + 12.5(1) m_f^2, \quad \chi^2/dof = 17.9\,.$$

$$M_\pi^2 = 5.43(4) m_f^{1.197(3)}, \quad \chi^2/dof = 34.0\,,$$

f_π and M_ρ in $N_f = 8$ at $\beta = 3.8$



Power fit:$\chi^2(f_\pi)/\mathrm{dof} = 14.7$, $\chi^2(M_\rho)/\mathrm{dof} = 6.5$
Polynomial fit: $\chi^2(f_\pi)/\mathrm{dof} = 6.1$, $\chi^2(M_\rho)/\mathrm{dof} = 1.3 \to$ better and
$f_\pi = 0.0295(3)$ and $M_\rho = 0.191(8)$ in the limit $m_f \to 0$.

χSB test in $N_f = 8$

In χ^2/dof monitoring,
the polynomial fit is better than the power fit.$\rightarrow$ χSB phase

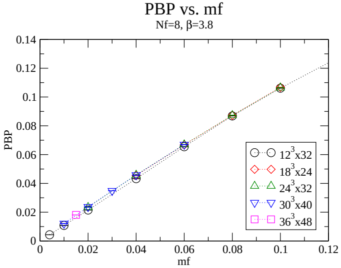
However, M_π^2 in $N_f = 8$ seems to be different from that in $N_f = 4$.
(The quadratic term is visible.)

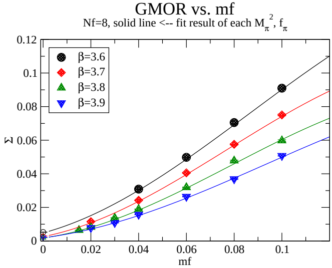
In this analysis (in this talk);

- The infinite volume limit is not taken into account.
- In ChPT, $F = F_\pi(m_f = 0) \simeq 0.03 \sim 0.04$.
  At $M_\pi = 0.2$, $\chi = N_f(\frac{M_\pi^2}{4\pi F})^2 \simeq 1.22 \sim 2.25$

To obtain the definite conclusion $\Longrightarrow$ future work

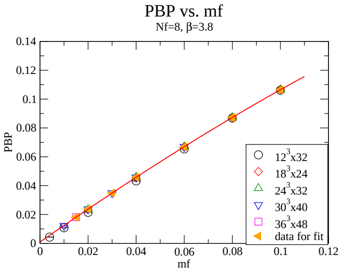
Condensate: PBP=$Tr[S(x,x)]$ and GMOR relation; $\Sigma = \frac{f_\pi^2 m_\pi^2}{m_f}$

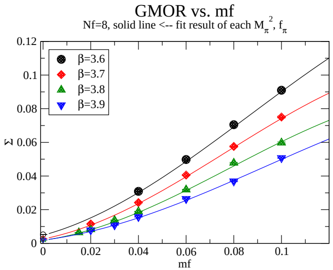




Left: $PBP \sim m_f$, in contrast to $N_f = 4$ case.
Right: Solid line $\leftarrow$ quadratic fit of each M_π^2 and f_π

Condensate: PBP=$Tr[S(x,x)]$ and GMOR relation; $\Sigma = \frac{f_\pi^2 m_\pi^2}{m_f}$

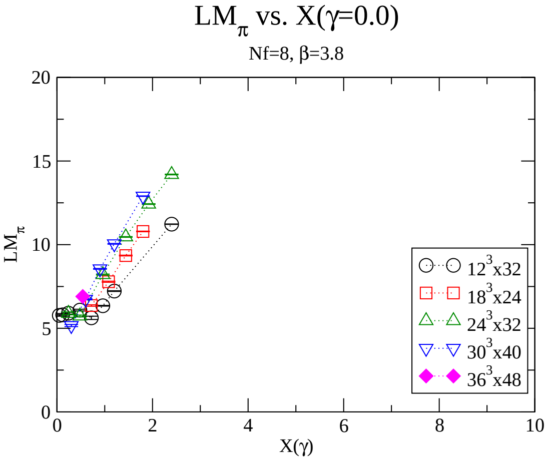




In the limit $m_f \to 0$,
Left: $PBP \simeq 0.001$
Right: GMOR $\simeq$ 0.002.
If in χSB phase $\Rightarrow \langle \bar{Q}Q \rangle$ is very small.

Remnant of the conformal behavior ? $\to$ Hyperscaling test

$N_f = 8$, $\beta = 3.8$: $LM_\pi = C_0 + C_1 L m_f^{\frac{1}{1+\gamma}}$



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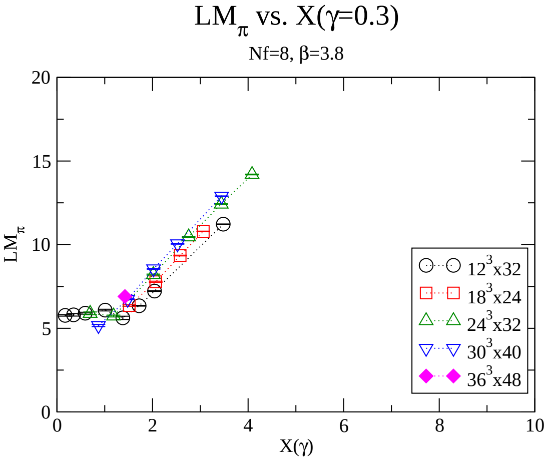

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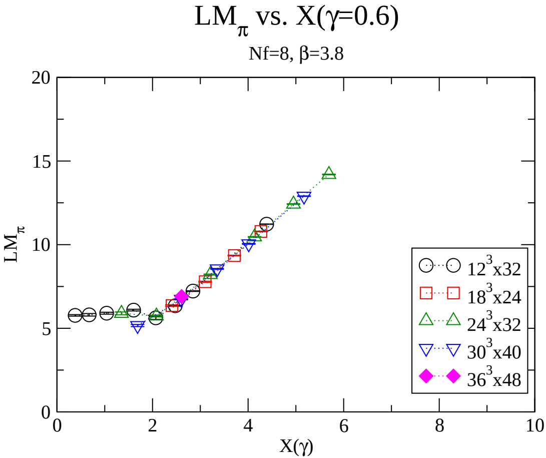

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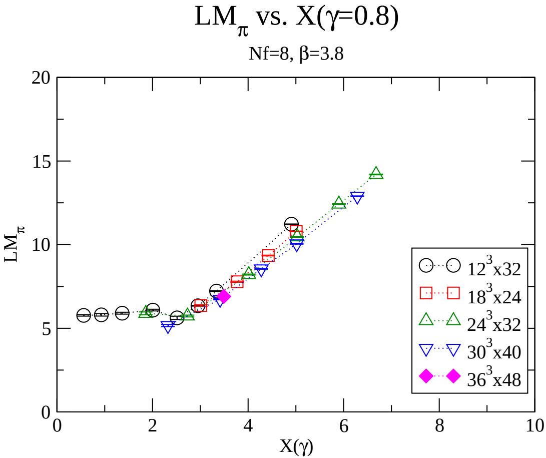

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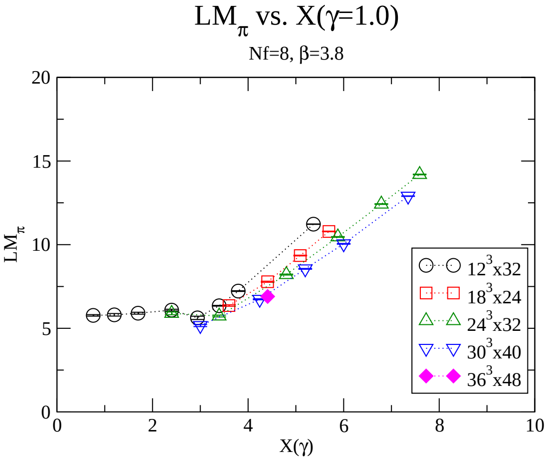
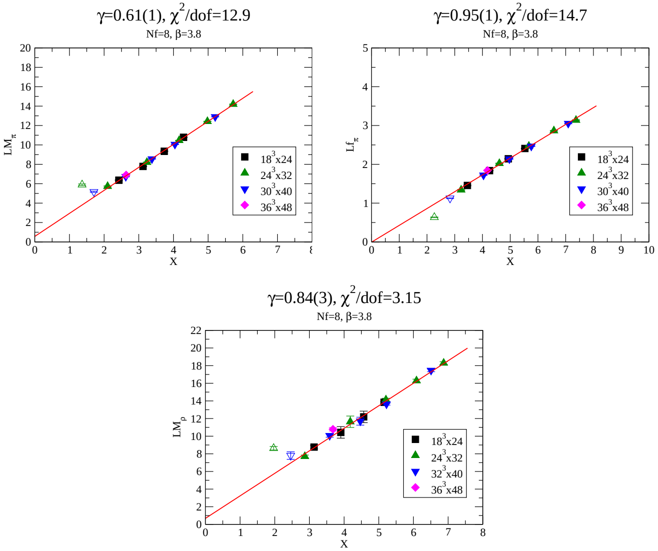


Finite-size hyperscaling test in $N_f = 8$, $\beta = 3.8$



The value of γ in the finite-size hyperscaling test

	$\beta = 3.6$	$\beta = 3.7$	$\beta = 3.8$	$\beta = 3.9$	$\beta = 4.0$
γ in M_π	0.64(1)	0.63(1)	0.61(1)	0.56(1)	0.56(1)
γ in f_π	0.98(2)	0.99(1)	0.95(1)	0.92(1)	0.91(1)
γ in M_ρ	1.02(2)	0.91(4)	0.84(3)	0.79(4)	0.77(6)

Table: the statistical error only

For $N_f = 8$, $\gamma(M_\pi) \neq \gamma(f_\pi)$
$\rightarrow$ not conformal
$\rightarrow$ the remnant of the conformal property
$\rightarrow$ finite-mass and -size correction? $\Rightarrow$ M. Kurachi's talk
However, $0.5 < \gamma(f_\pi) \lesssim 1.0$.
$\rightarrow$ What's the meaning? Walking?
$\rightarrow$ Phenomenologically interesting (one-family model)

Summary

♠ In LatKMI collaboration, the investigation of the many flavor QCD ($N_f = 0$, 4, 8, 12 and 16) on KMI computer system "φ", for IRFP search and the exploration of the walking behavior.
♠ Tree level Symanzik gauge action $+$ HISQ staggered fermion for many flavor system.

♠ $N_f = 4$ case shows the property of χSB.
♠ $N_f = 12$ is in good agreement with the hyperscaling.
$\Longrightarrow$ consistent with the conformal (H. Ohki's talk)

♠ $N_f = 8$ is consistent with χSB. (but, a little diff. from $N_f = 4$)
$+$ the remnant of the conformal property.
$\Longrightarrow$ Walking?

Summary

♣ Flavor dependence of γ, (roughly,) in the hyperscaling test: $LM = \mathcal{F}(Lm_f^{1/(1+\gamma)})$,

N_f	4	8	12
$\gamma(M_\pi)$	$= 1.0$	~ 0.6	~ 0.45
$\gamma(f_\pi)$	> 2.0	~ 1.0	~ 0.5

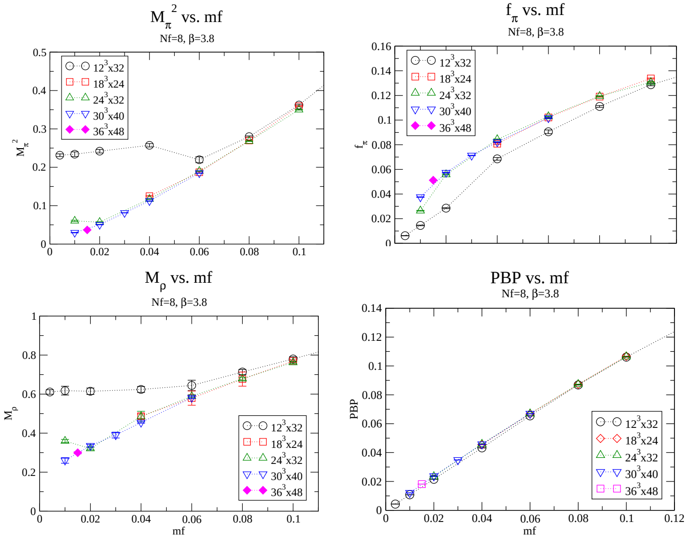
♠ To obtain the definite conclusion $\Rightarrow$ on larger lattices at lighter fermion masses. (In progress)

♠ $N_f = 8$ $SU(3)$ gauge theory is phenomenologically interesting and important. $\rightarrow$ Walking technicolor model with $\gamma_m \simeq 1$.

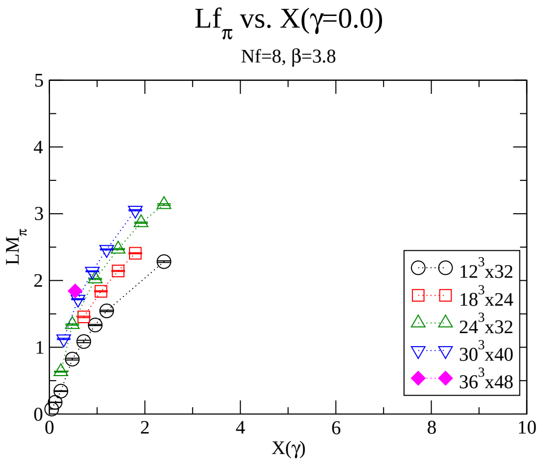
♠ To make "the particle data booklet" = Techni-Spectroscopy (singlet-scalar, glueball, condensate, string tension, S-parameter, *etc.*) in LHC era.

BACK UP

Spectroscopy in $N_f = 8$ at $\beta = 3.8$



$N_f = 8$, $\beta = 3.8$: $Lf_\pi = C_0 + C_1 Lm_f^{\frac{1}{1+\gamma}}$



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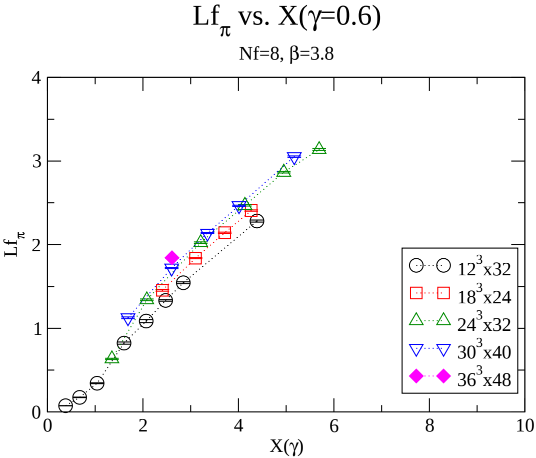

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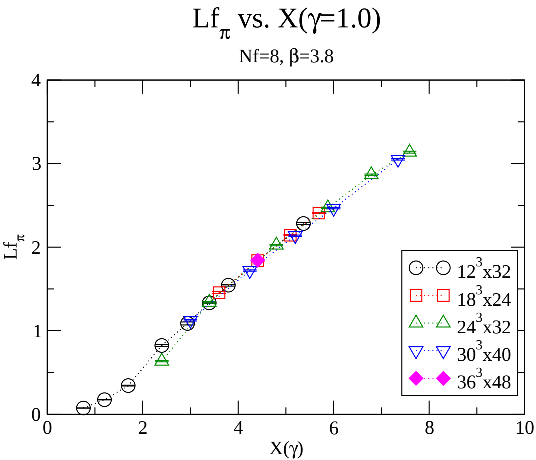

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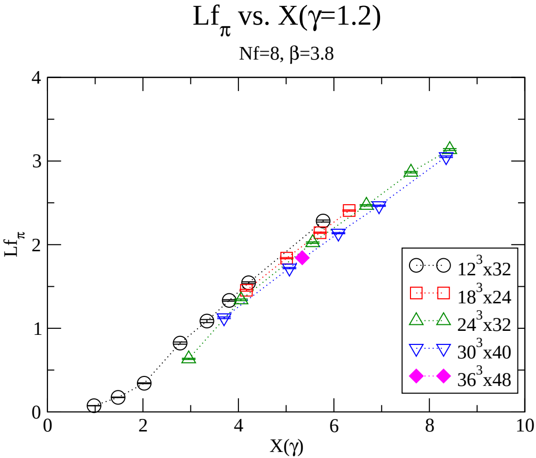

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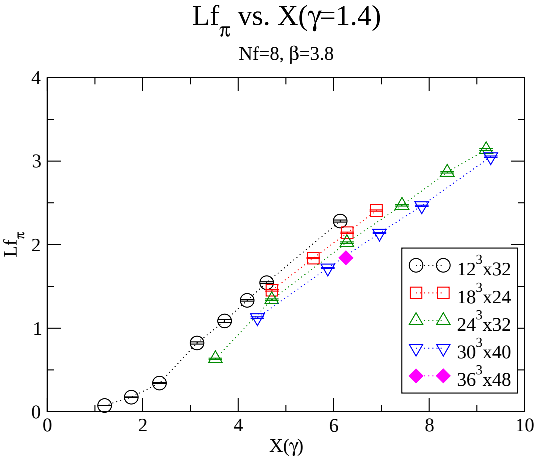

Hyperscaling test in $N_f = 8$ at $\beta = 3.8$ with on $12^3 \times 32$;