Spectral properties and S parameter of N_f=8 QCD

Yasumichi Aoki KEK & RIKEN BNL Research Center

for the LatKMI collaboration

- @ Brookhaven Forum 2017 -

October 11, 2017

LatKMI collaboration

- KMI / Nagoya Univ.



T.Maskawa, K.Nagai, K.Yamawaki

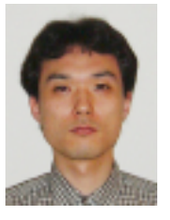
- KEK, Kyoto, Swansea, Keio, CPT Marseille, Nara, RBEC, Tsukuba











Y. A, T.Aoyama, E.Bennett, M.Kurachi, K.Miura, H.Ohki, E.Rinaldi, A.Shibata, T.Yamazaki

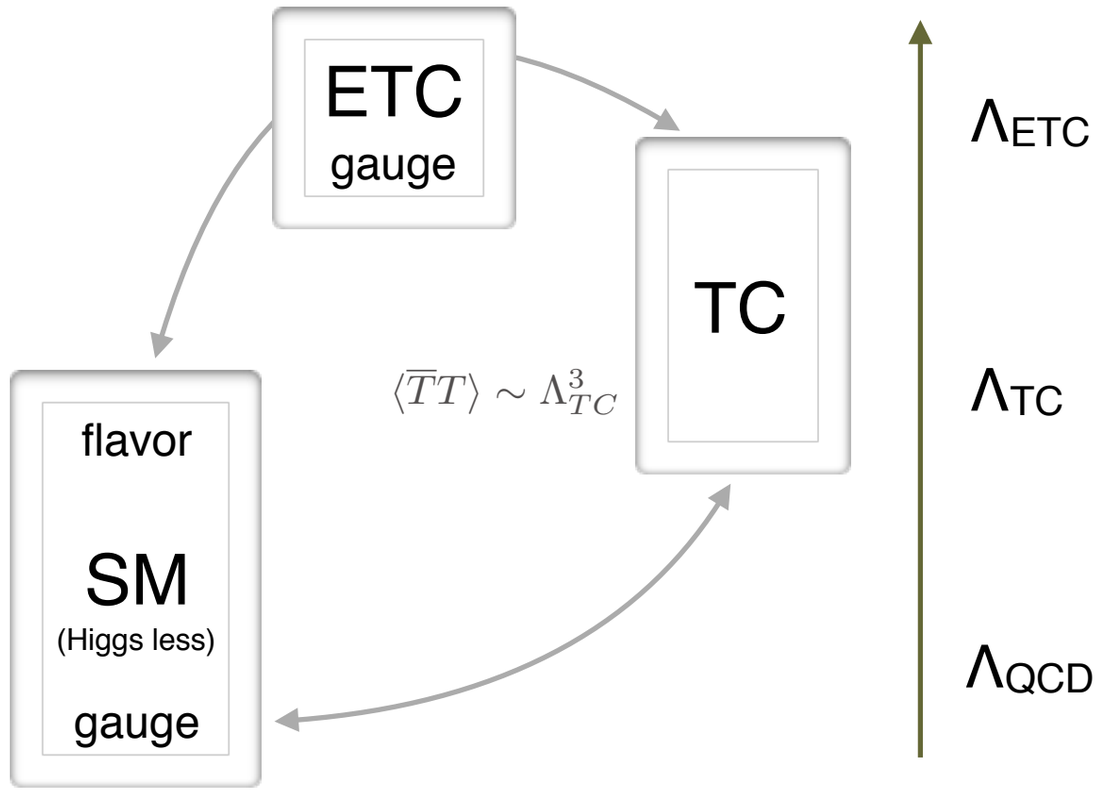
Thanks to…

- Kobayashi-Maskawa Institute, Nagoya University
- Computer Use
  - KMI φ
  - HPCI (High Performance Computing Infrastructure in Japan)
    - # hp160153, hp150157, hp140152
  - JLDG (Japan Lattice Data Grid)
  - Kyshu University CX400, Nagoya University CX400

- YA is / was supported by
  - JSPS Grants (C) No. 16K05320, (S) No. 22224003.

Technicolor

- QCD like dynamics can trigger the Electroweak symmetry breaking
- Techni pion act as NG mode of Higgs
  - give mass to W and Z bosons
- SM fermion masses are given through ETC
- Tension:
  - FCNC must be suppressed
  - sizable m_f needs to be generated



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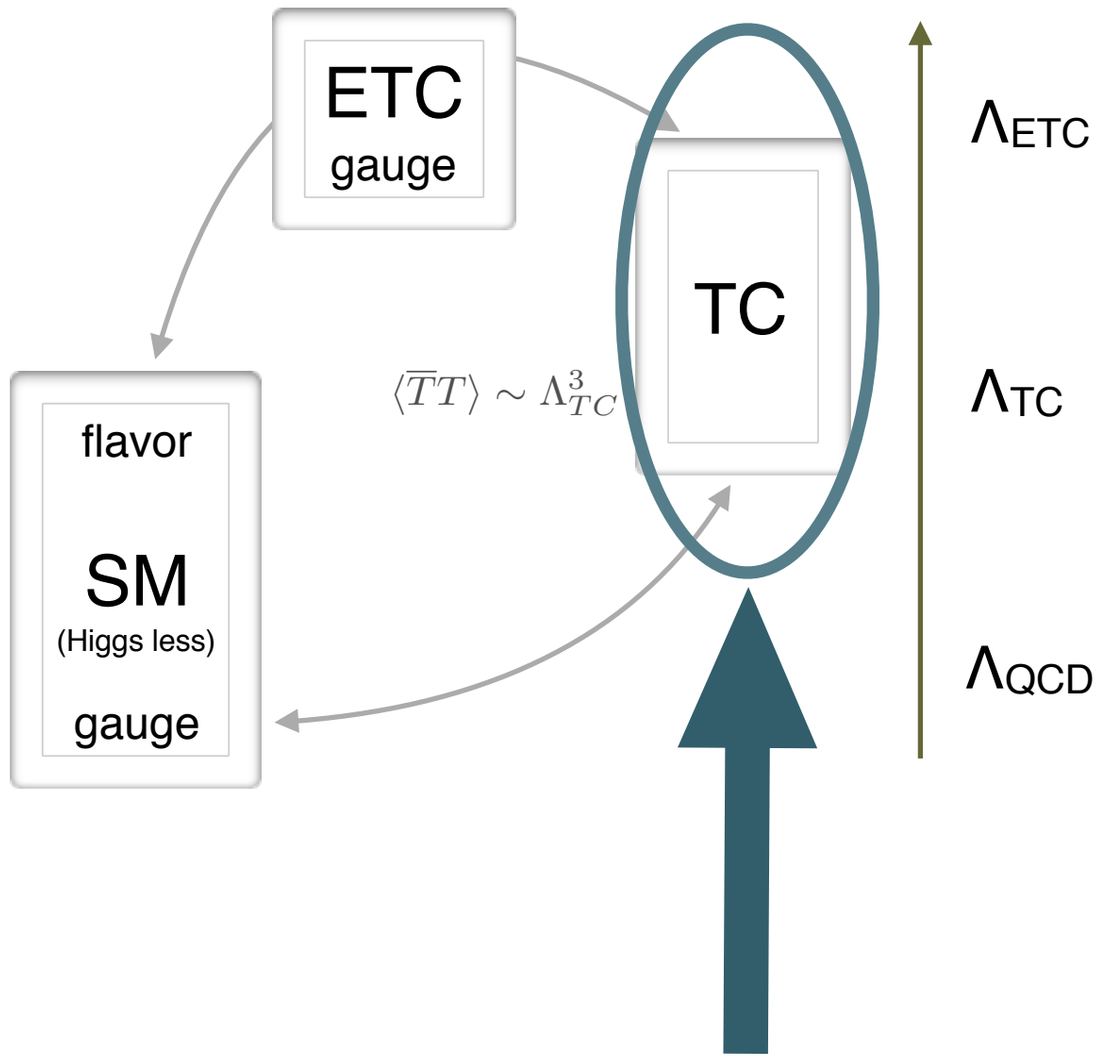
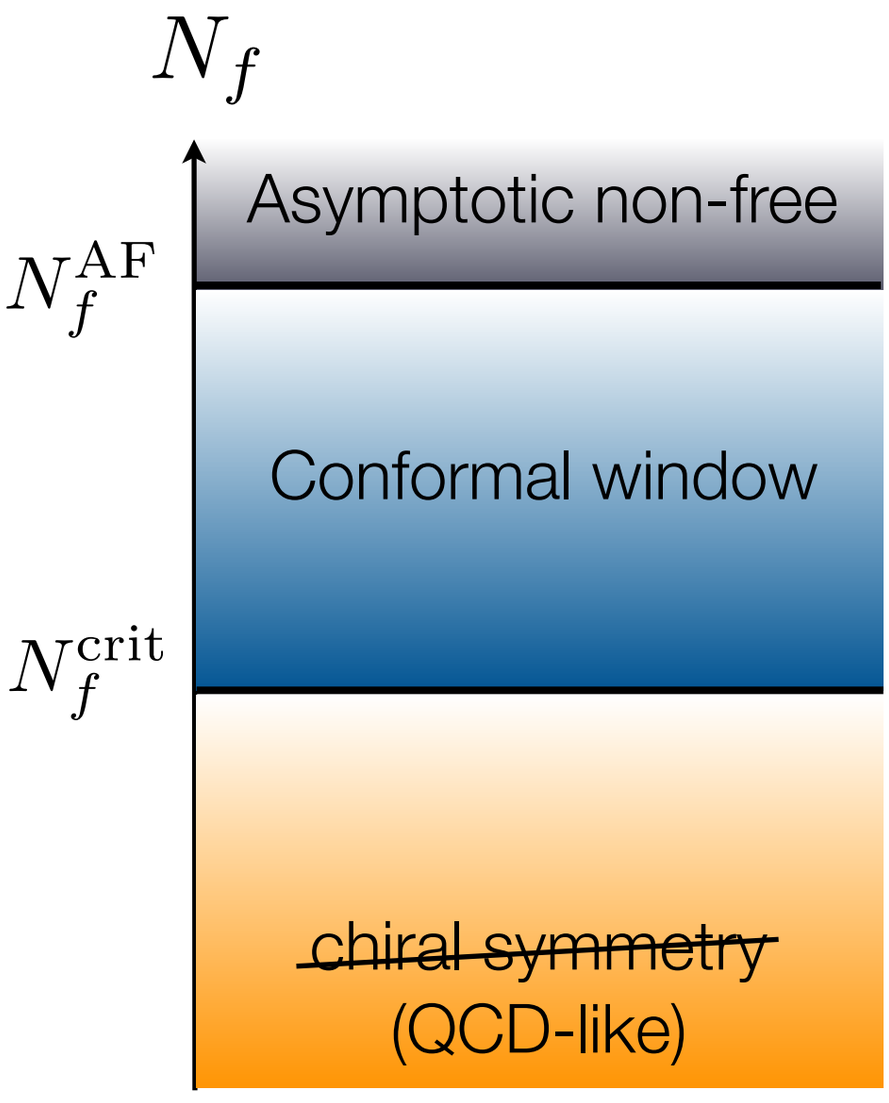
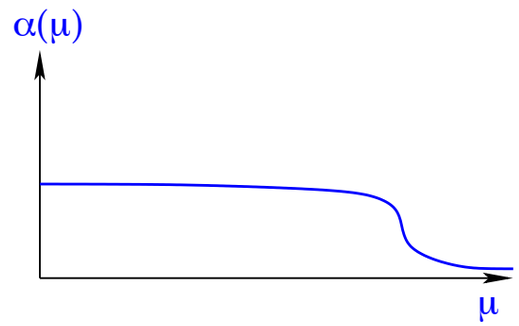


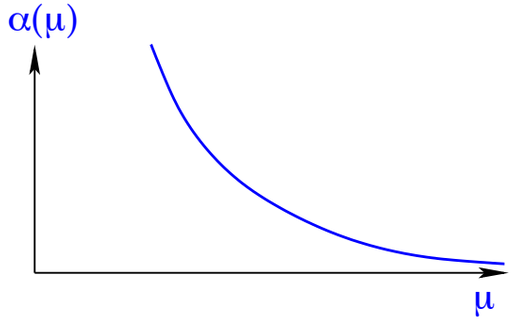
so far we are dealing with this only

conformal window and walking gauge coupling

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

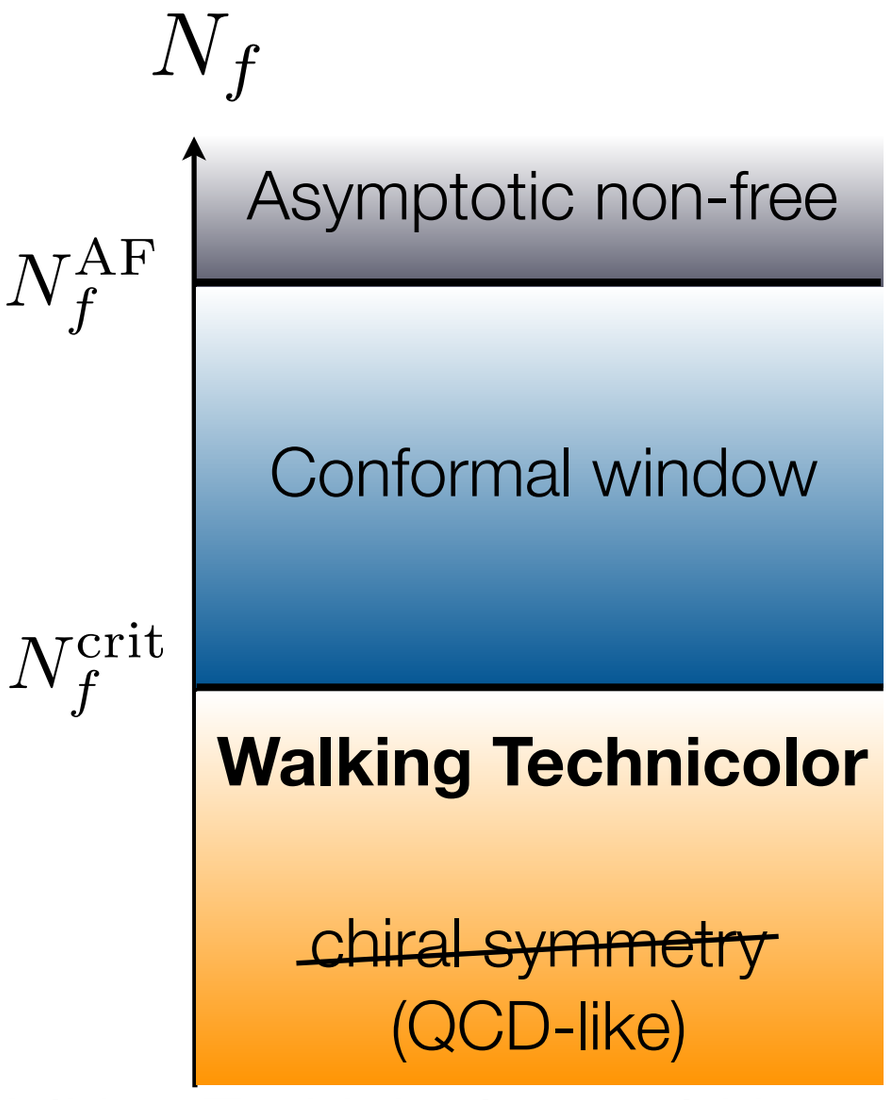


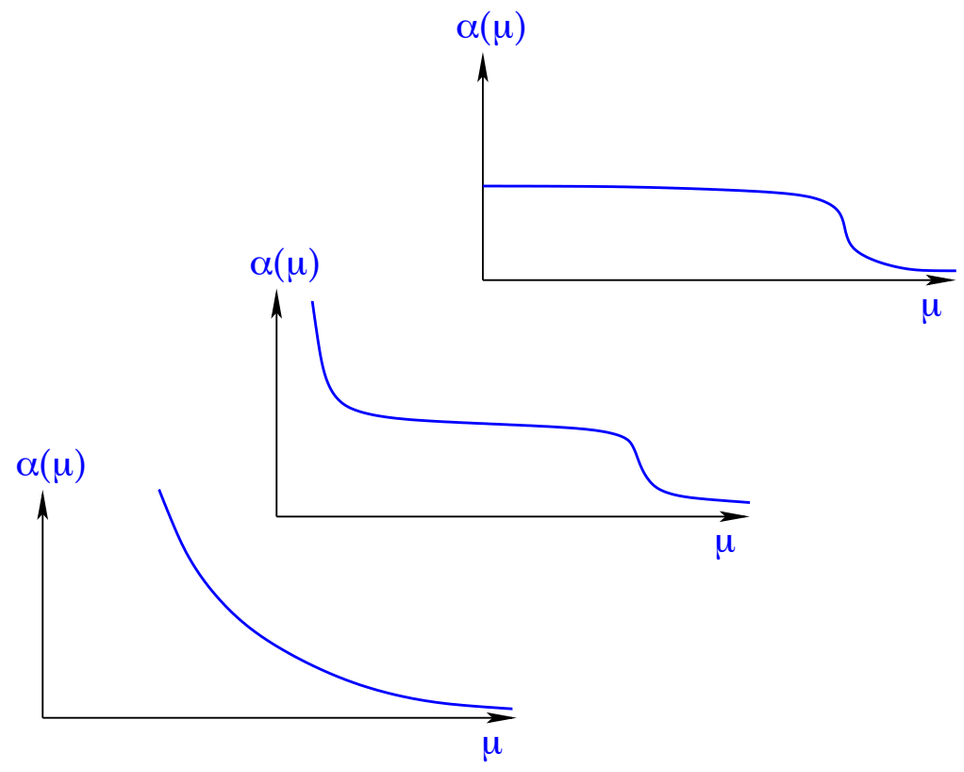




conformal window and walking gauge coupling

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

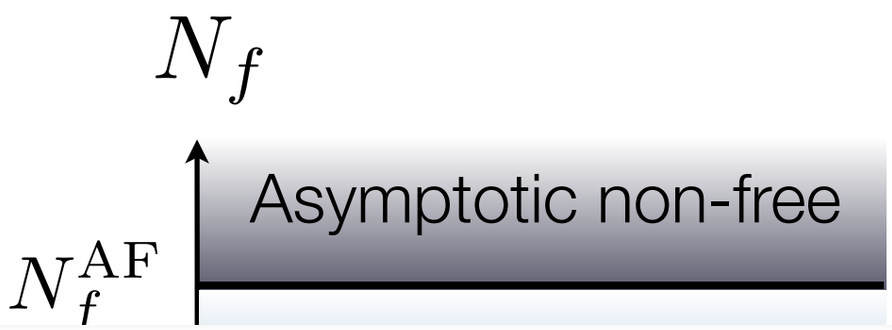




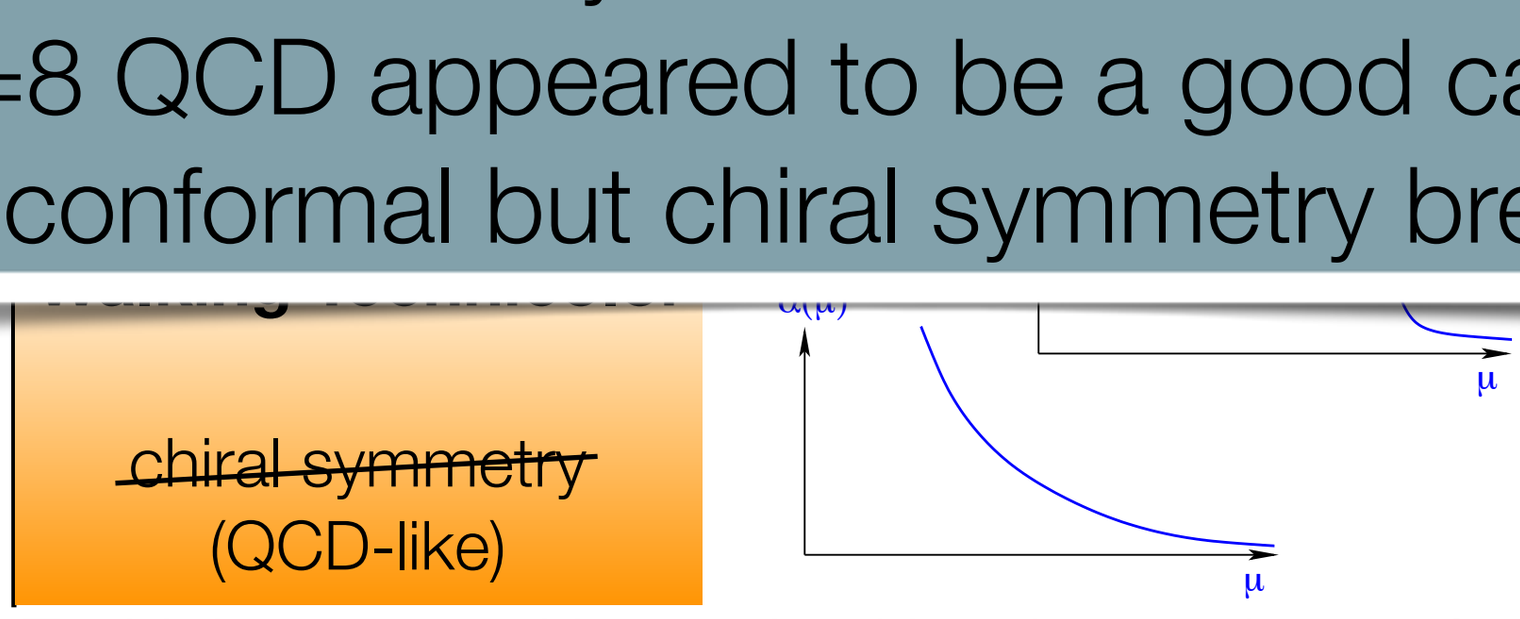
- Walking Techinicolor could be realized just below the conformal window
- crucial information: $N_f^{\rm crit}$ and...
- mass anomalous dimension γ & the composite mass spectrum around $N_f^{\rm crit}$

conformal window and walking gauge coupling

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



Through a series of systematic studies for N_f of LatKMI, N_f=8 QCD appeared to be a good candidate of near conformal but chiral symmetry breaking theory



- Walking Techinicolor could be realized just below the conformal window
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Contents of this talk on the N_f=8 QCD

- basic composite mass spectrum
  - scaling expected for (near) conformal theory
  - investigation of chiral symmetry breaking
    - techni rho meson
- flavor singlet scalar
  - does this have “light mass” to be able to replace Higgs ?
- flavor singlet pseudoscalar (preliminary)
- S parameter (preliminary)

scaling study results

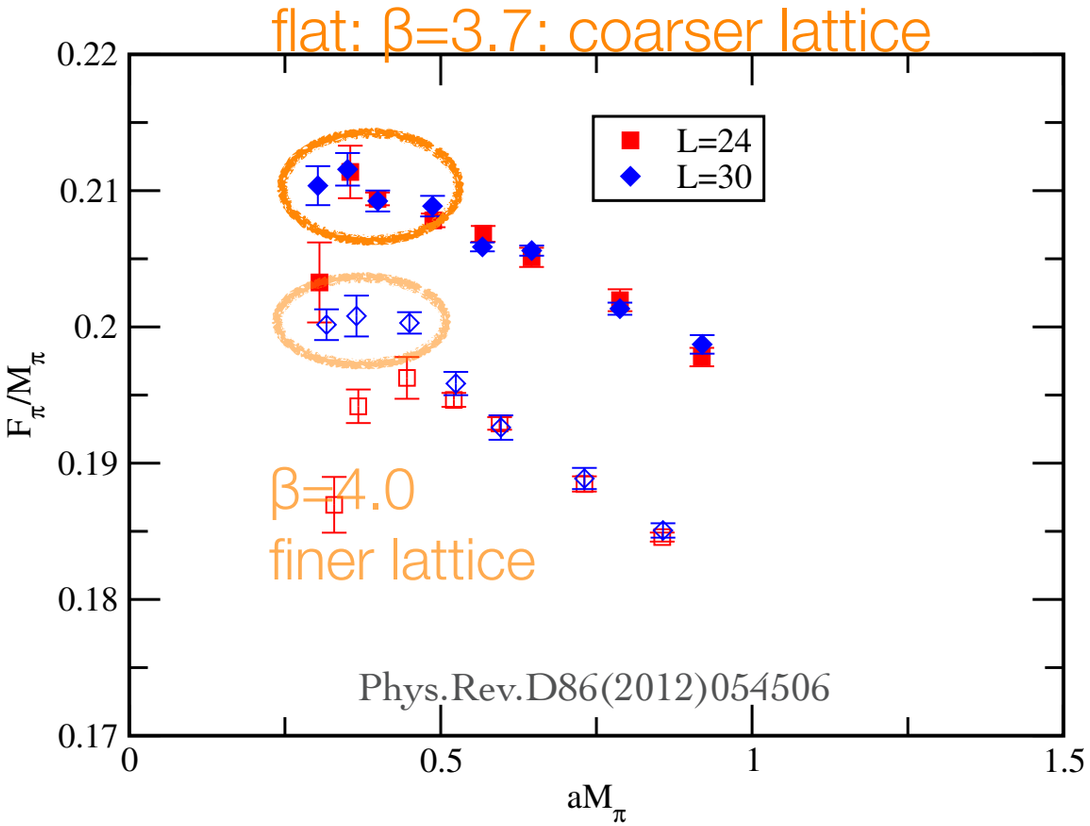
[LatKMI PRD96, 014508 (2017)]

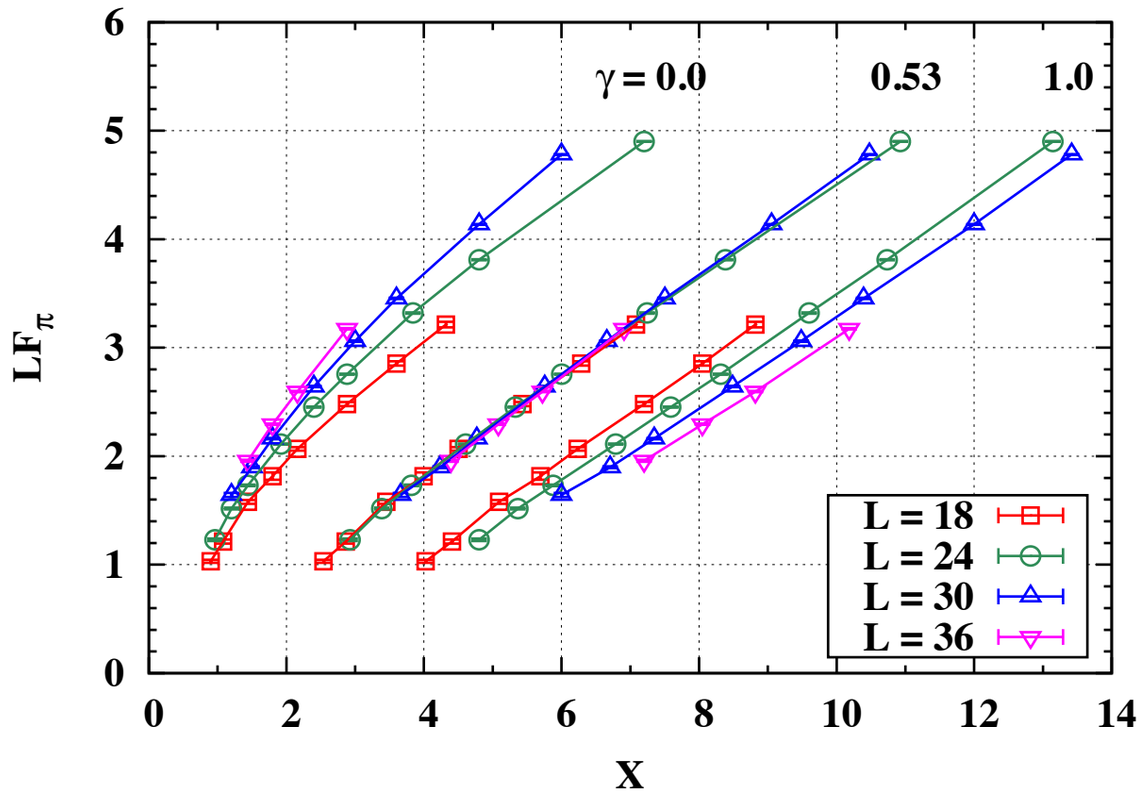
a crude study using ratios and universal hyperscaling [LatKMI PRD96, 014508 (2017)]

- conformal scenario:
  - $M_H \propto m_f^{1/(1+\gamma_m^*)}$; $F_\pi \propto m_f^{1/(1+\gamma_m^*)}$ for small m_f ; γ_m^*: mass anomalous dim
  - ★ $F_\pi/M_\pi \to$ 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 $m_f \to 0$
- finite size scaling in a L^4 box (DeGrand; Zwicky; 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

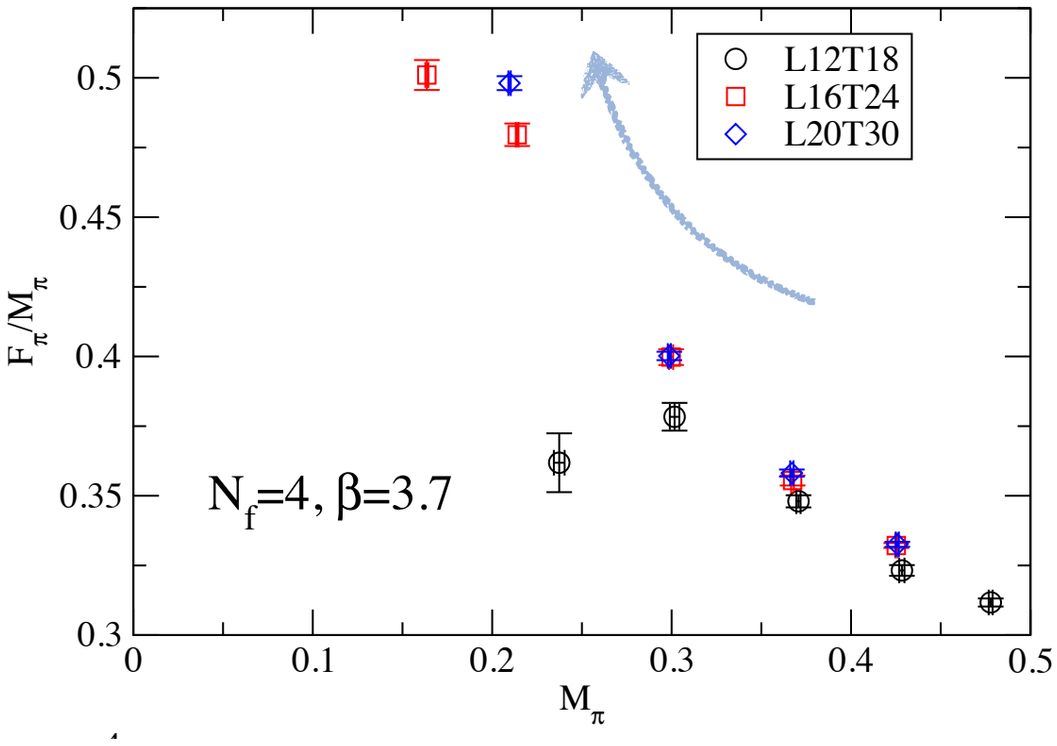


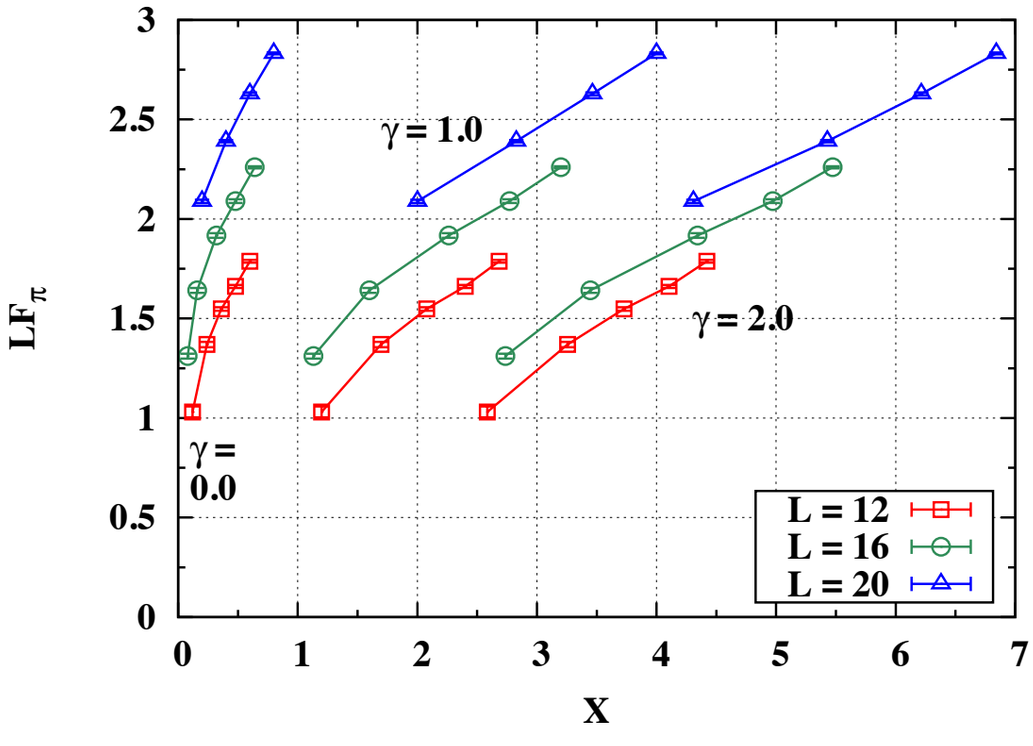


- F_π/M_π → constant ($m_f \to 0$)
  - expected for conformal theory

- finite size hyperscaling intact

N_f=4

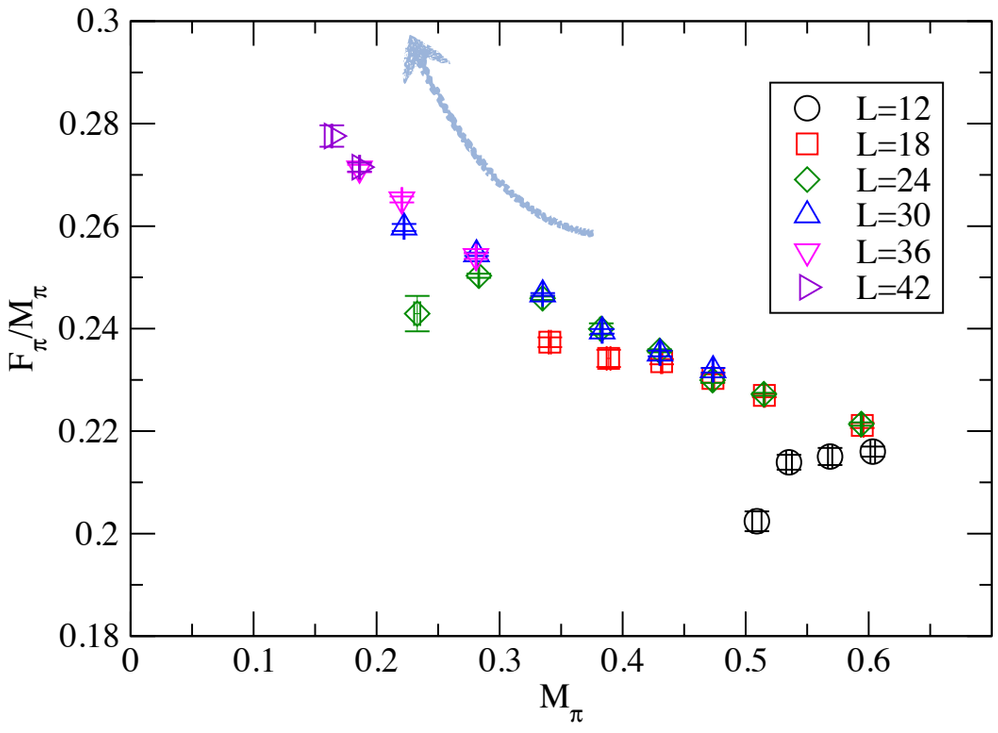


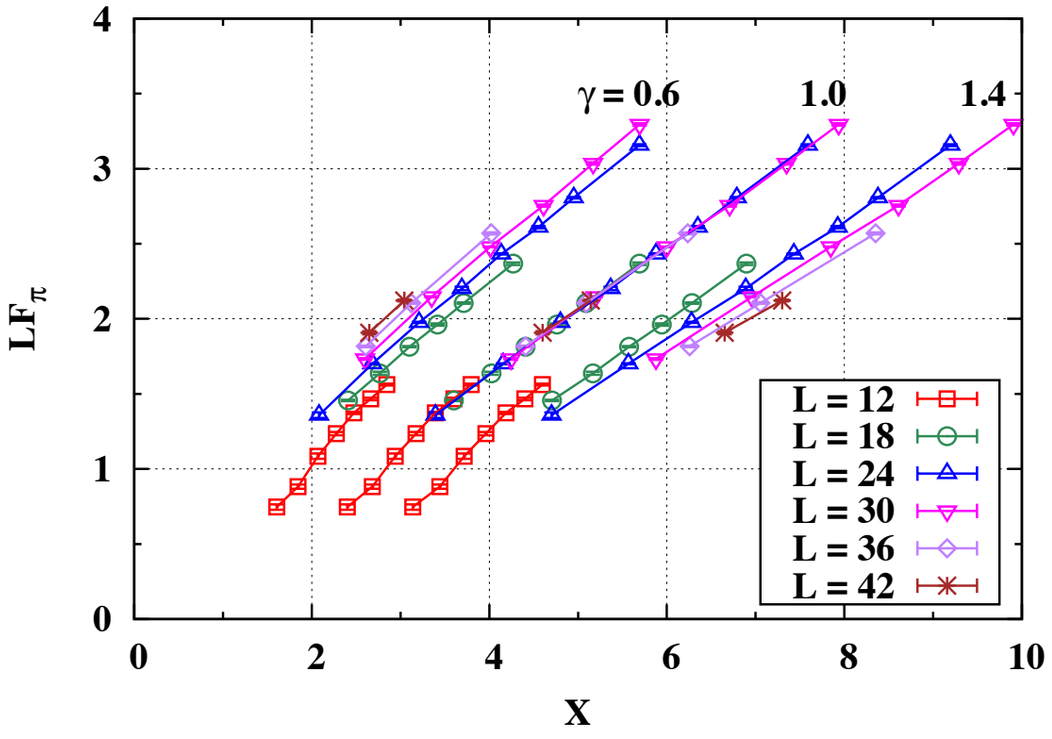


- F_π/M_π → tends to diverge ($m_f \to 0$)
  - expected for chiral symm.br. theory

- no scaling for γ's allowed range

N_f=8



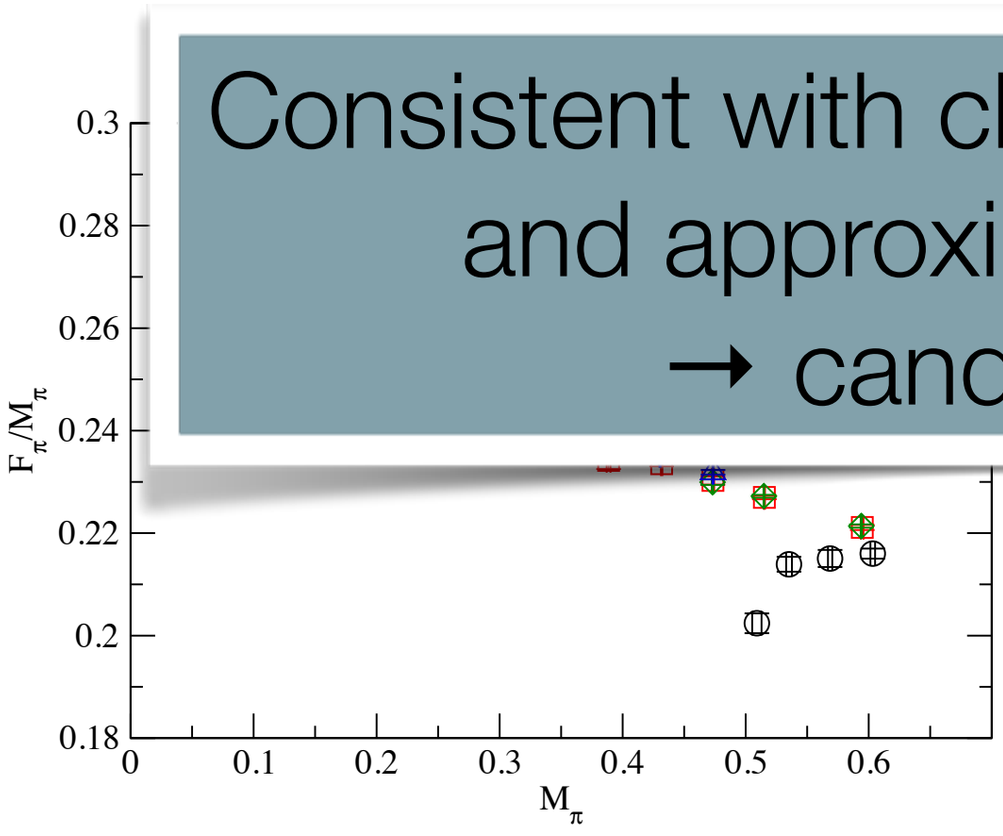


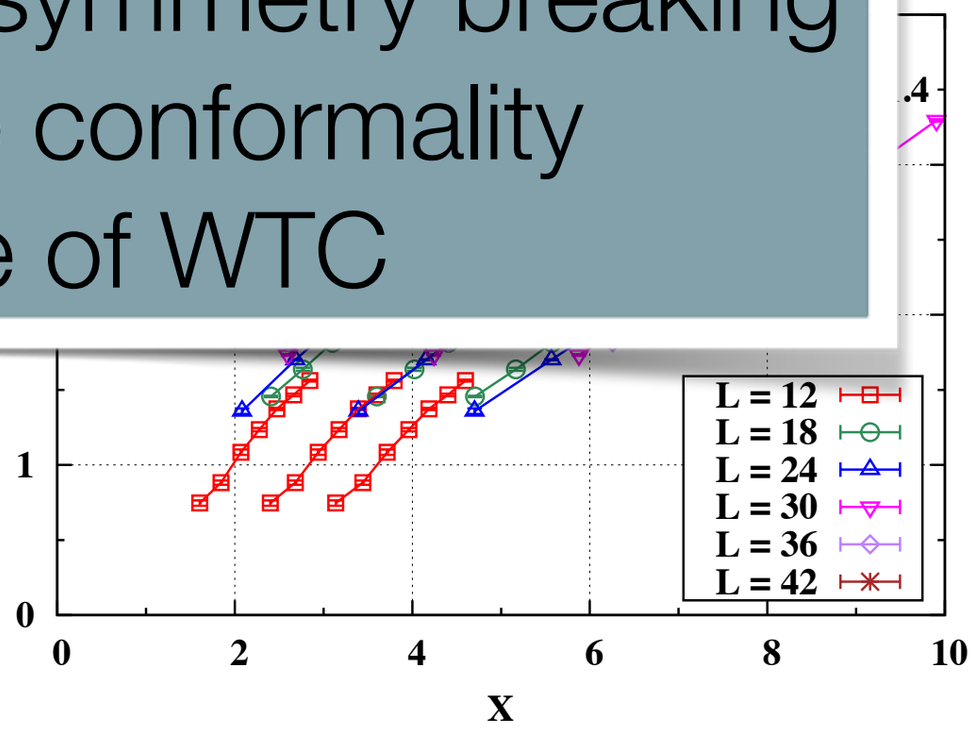
- F_π/M_π → tends to diverge ($m_f \to 0$)
  - expected for chiral symm.br. theory

- finite size hyperscaling intact
  - γ varies by quantity
  - approximate conformality

N_f=8

Consistent with chiral symmetry breaking
and approximate conformality
→ candidate of WTC





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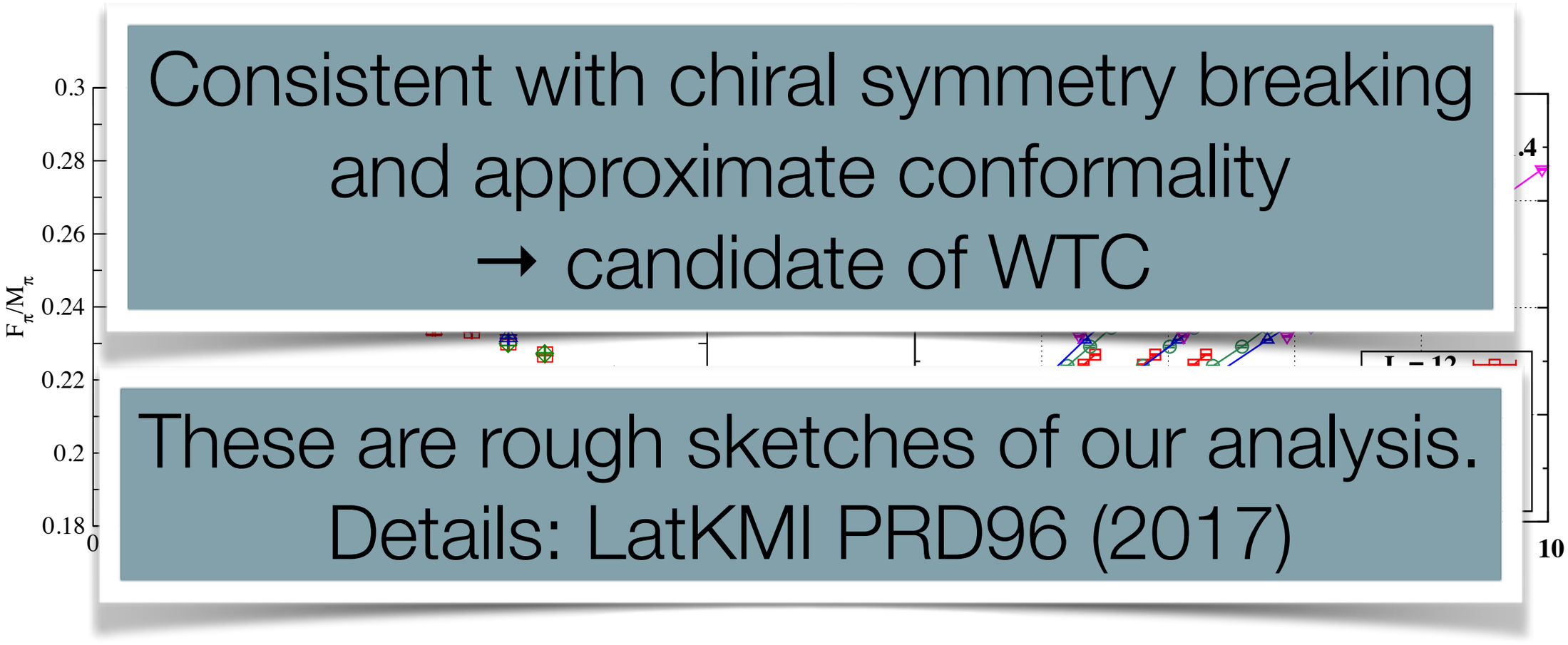

- F_π/M_π → tends to diverge ($m_f \to 0$)
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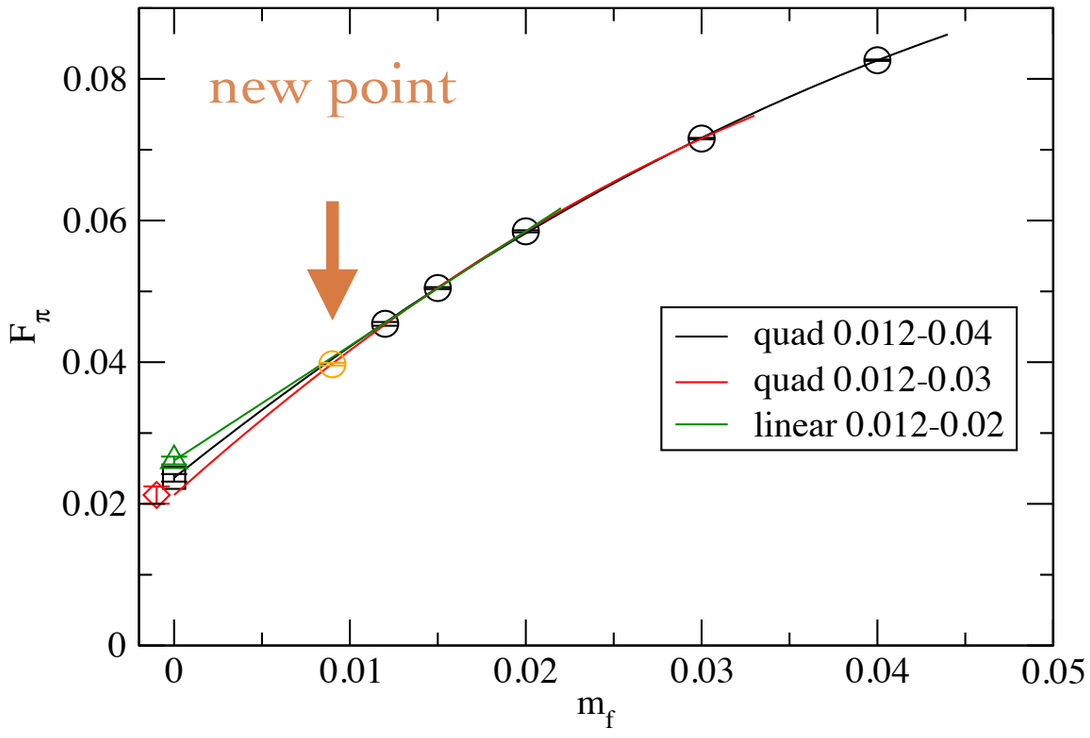
spectrum analysis of N_f=8 for chiral symmetry br.

[LatKMI PRD96, 014508 (2017)
and some updates (preliminary)]

techni pion decay constant



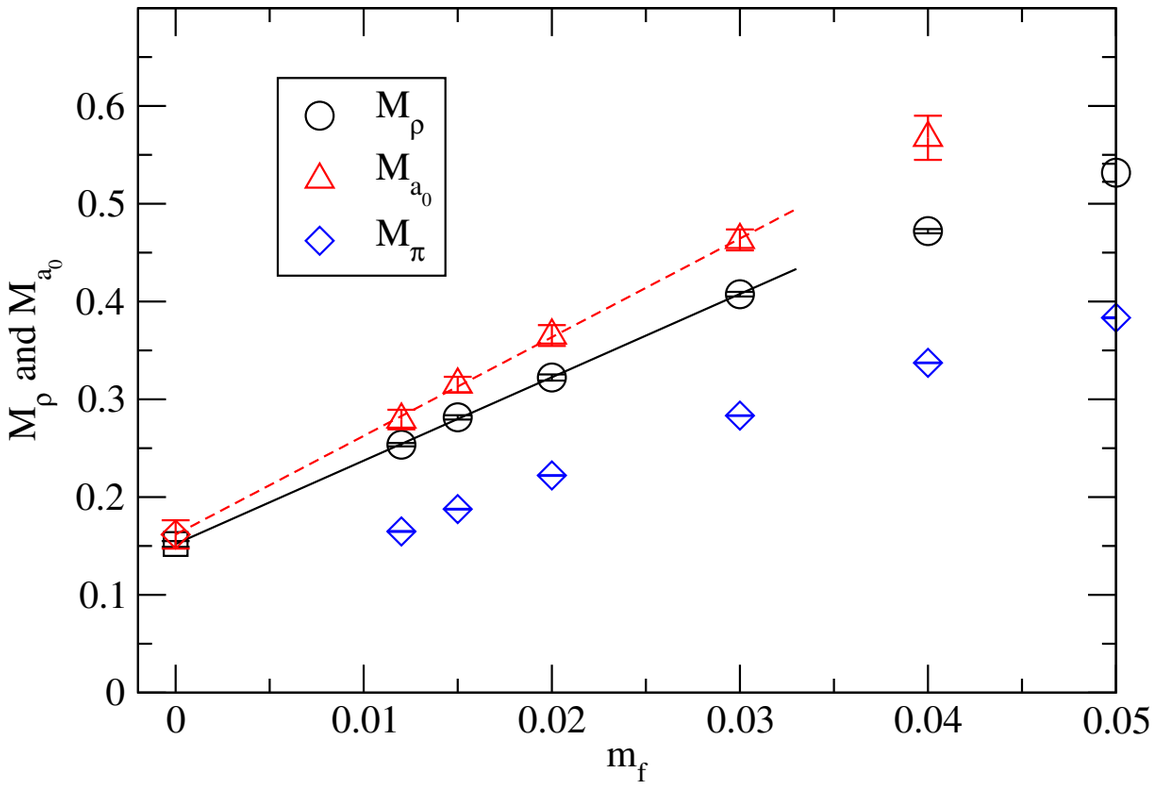
on top of Phys.Rev.D96(2017)

- lattice scale setting @ $m_f \to 0$

$$\frac{F_\pi}{\sqrt{2}} = \frac{246}{\sqrt{N_d}}\ \mathrm{GeV}$$

- determines a^{-1}
- typical models
  - $N_d = 1$ for one EW doublet
  - $N_d = 4$ for one-family model

techni rho meson mass



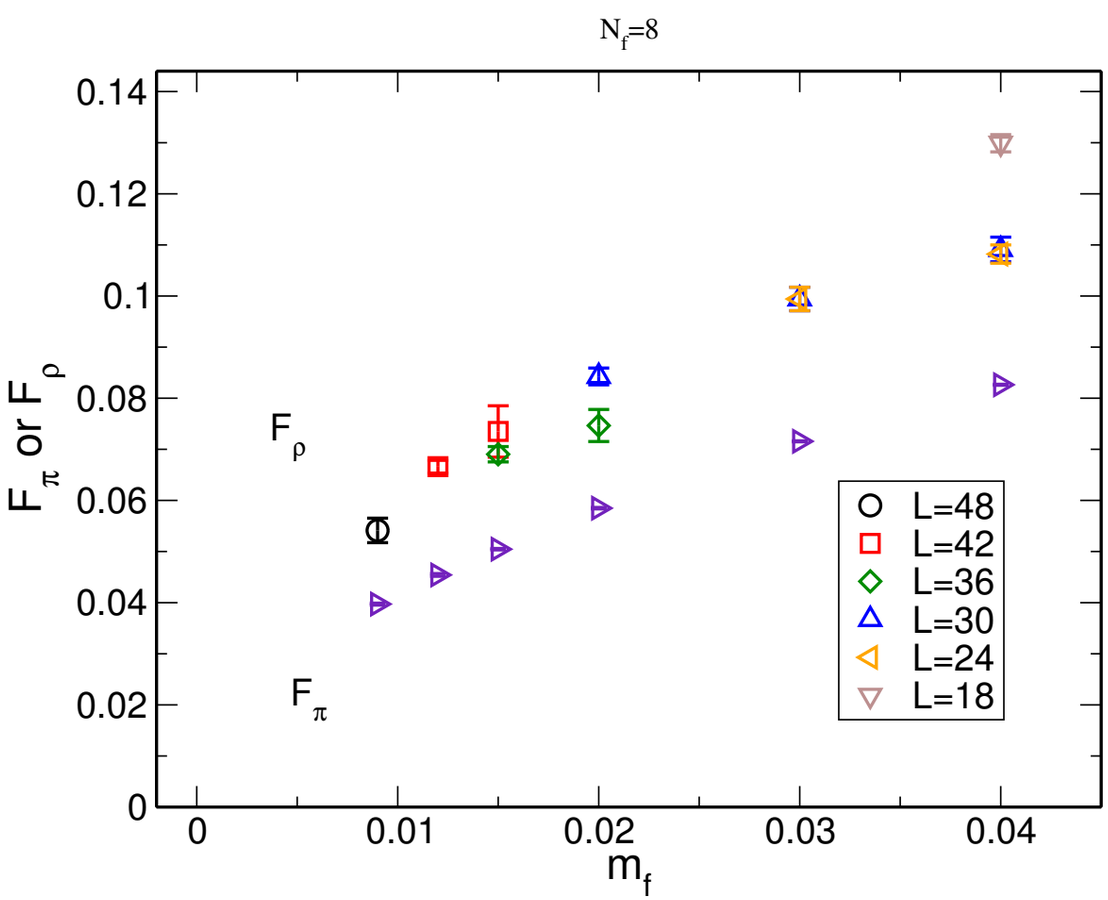
- at the chiral limit

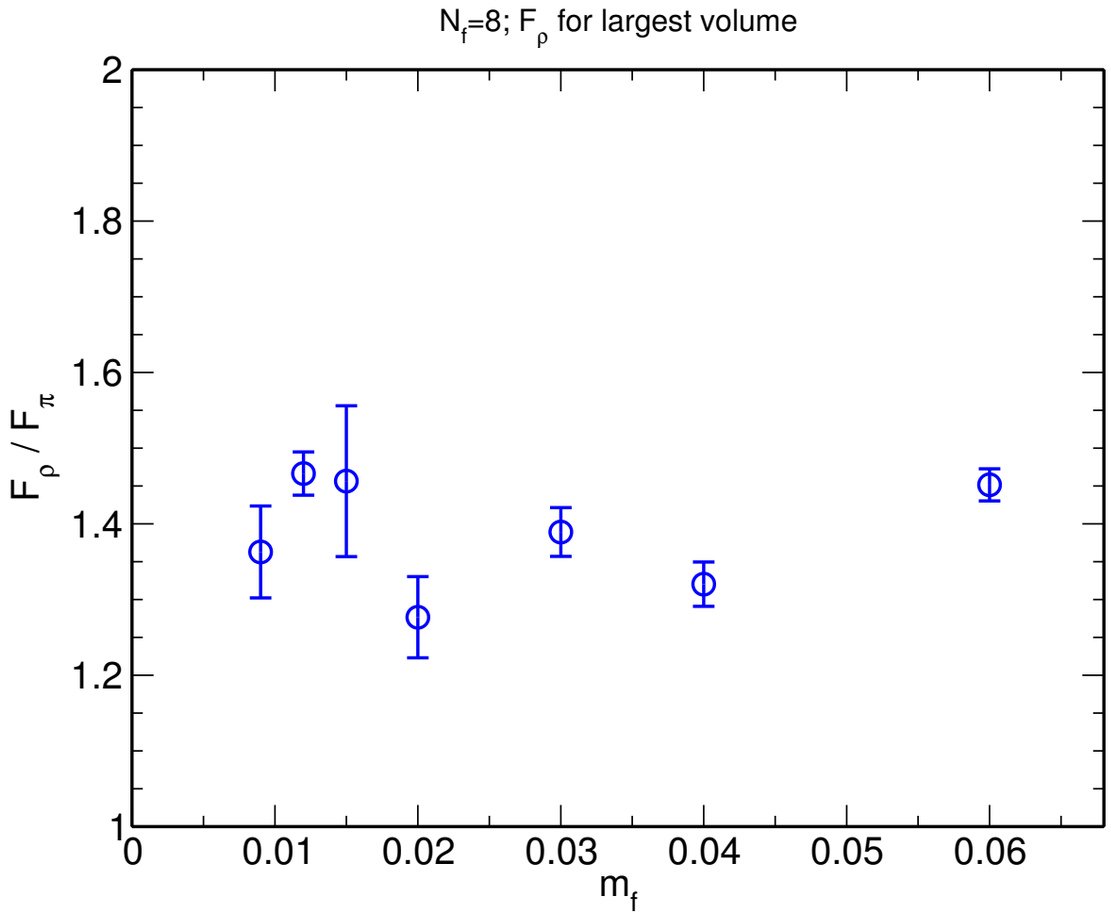
$$\frac{M_\rho}{F/\sqrt{2}} = 10.1(0.6)\begin{pmatrix}+5.0\\-1.9\end{pmatrix}.$$

  - including F_π chiral log sys. error

- M_ρ = 1 - 1.9 TeV for one family model
- M_ρ = 2 - 3.7 TeV for a N_d=1 model
- other hadrons, see→ LatKMI 2017

techni rho meson decay constants [preliminary]





- ratio $F_\rho/F_\pi \sim \sqrt{2}$
- consistent with LSD collab. [PDD93, 114514 (2016)]

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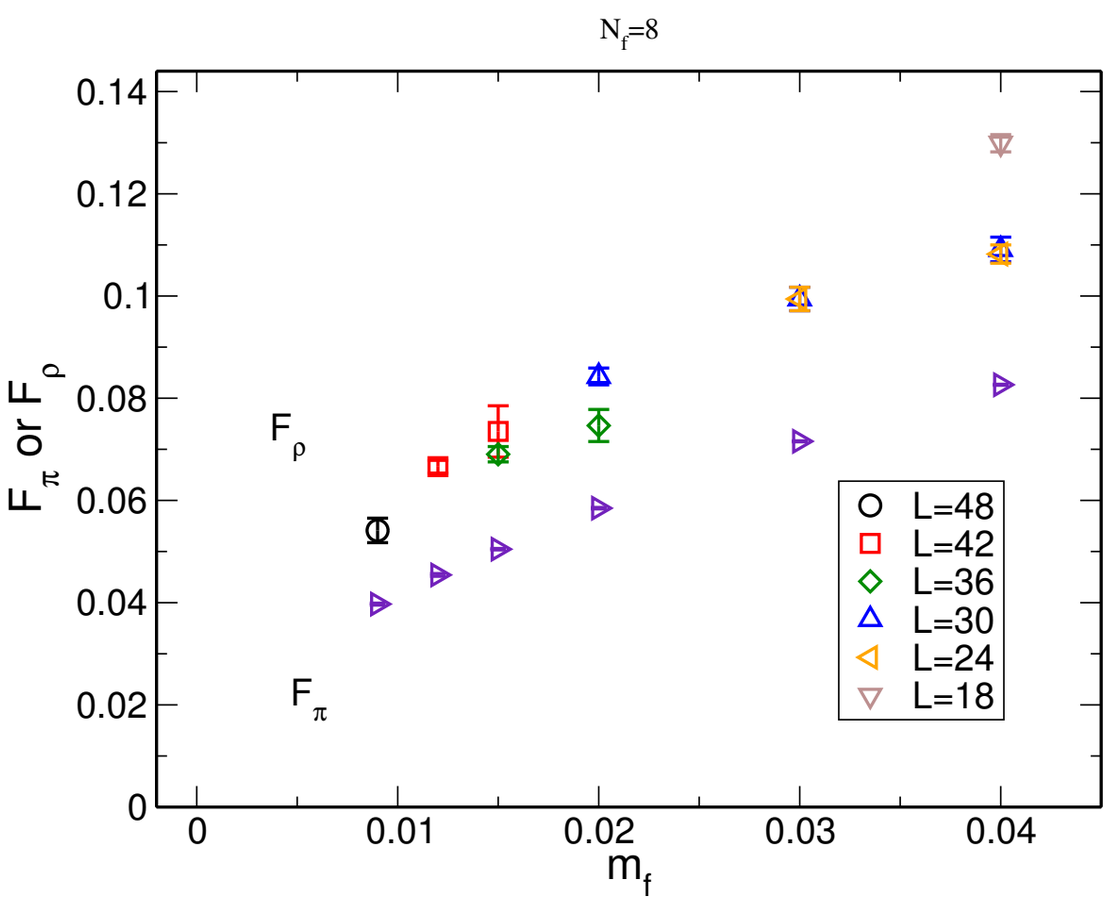

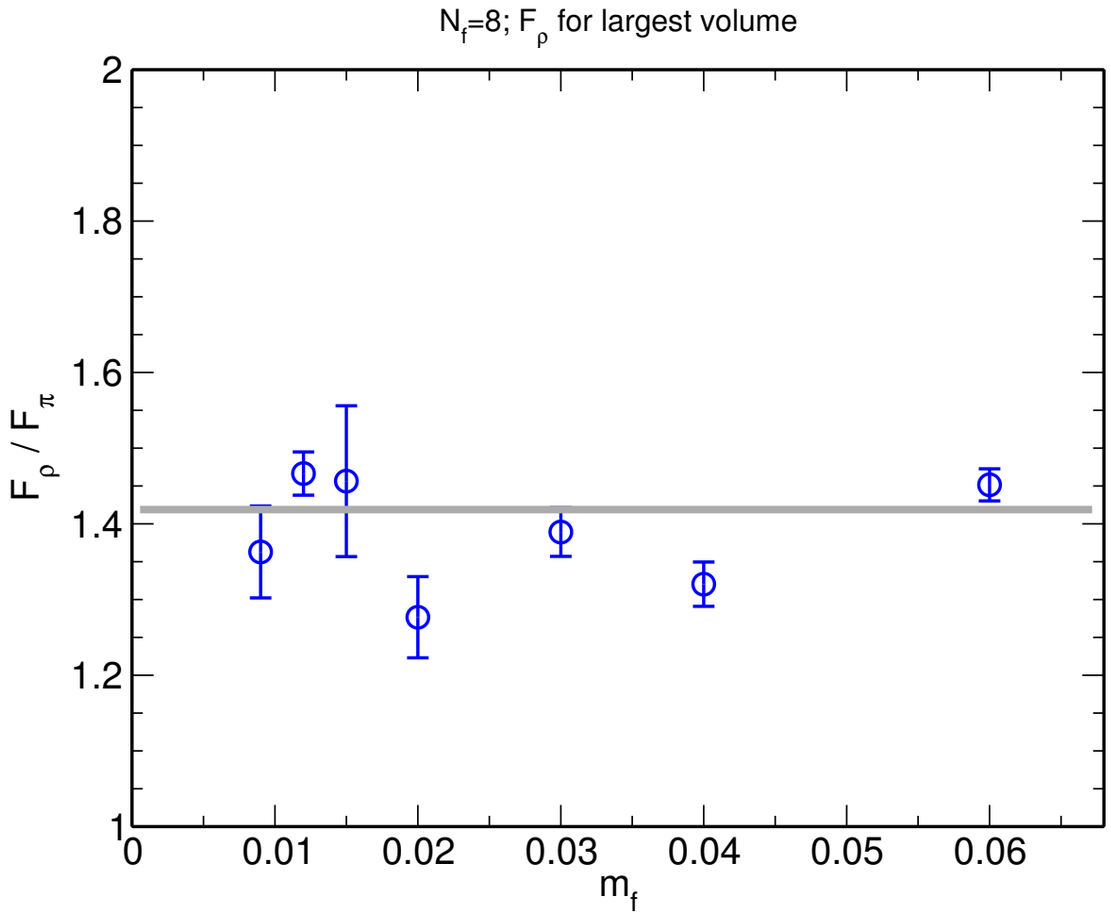

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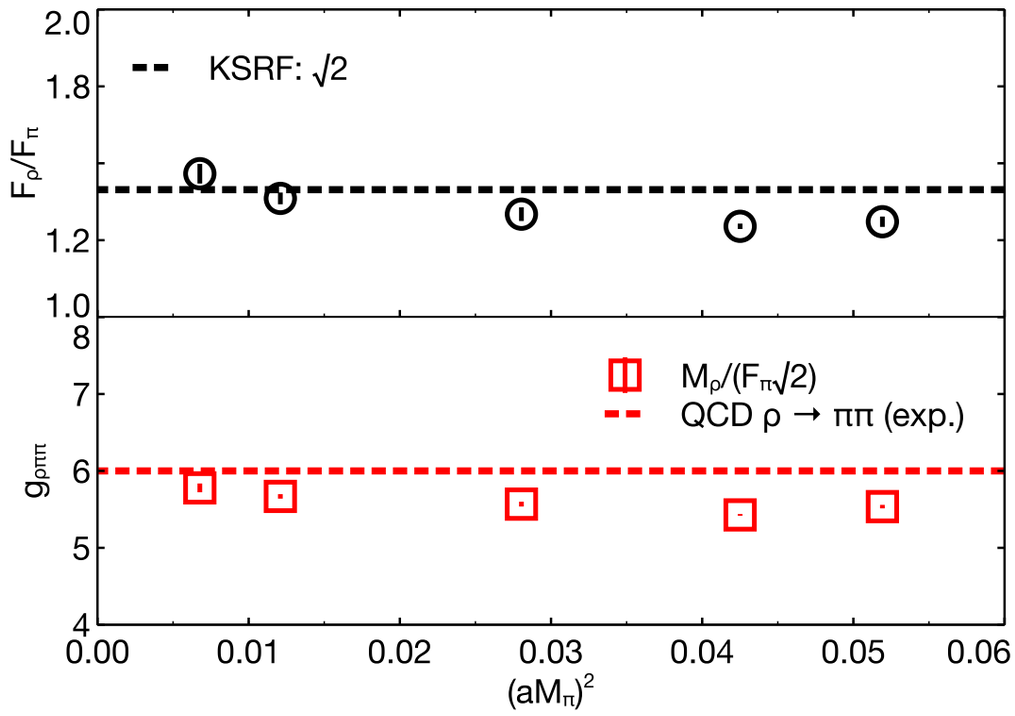
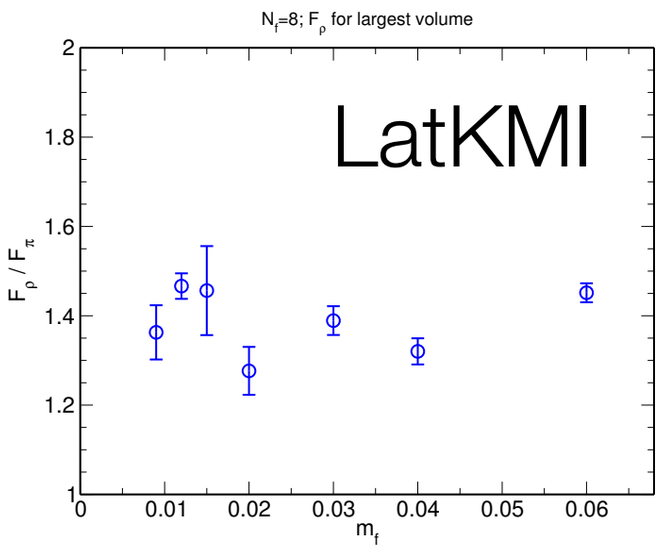
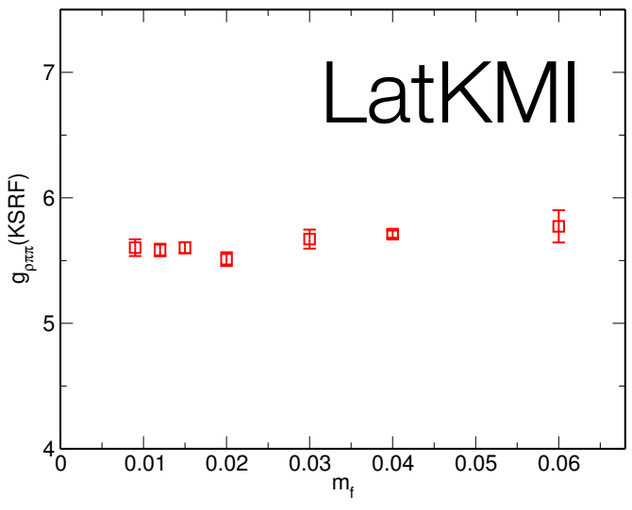
techni rho meson property (through KSRF relation)

LSD collaboration



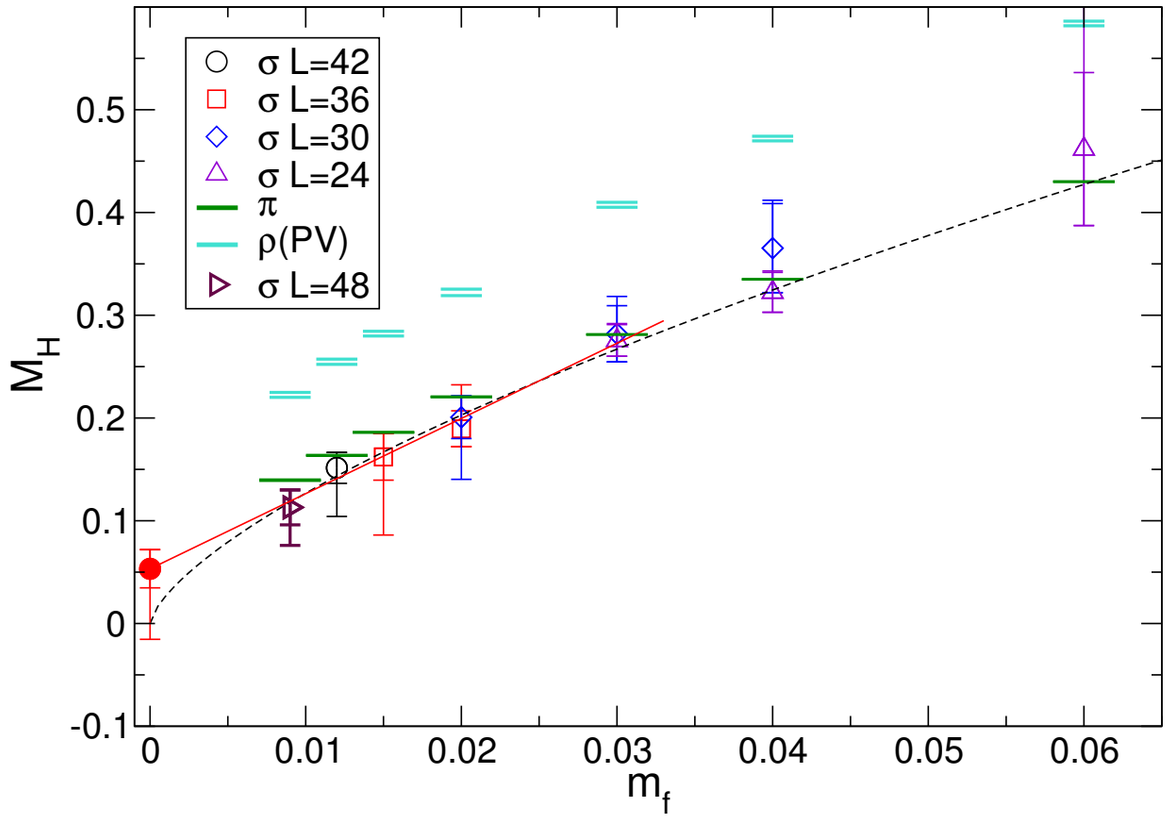




- KSRF (Kawarabayashi-Suzuki-Riazuddin–Fayyazuddin) relations
  - $F_\rho = \sqrt{2}F_\pi \qquad g_{\rho\pi\pi} = \dfrac{M_\rho}{\sqrt{2}F_\pi}$
    - $g_{\rho\pi\pi}$ (LatLMI) is also ~ 6
- decay width of techni rho
  - $\Gamma_{\rho\to\pi_L\pi_L} \equiv \Gamma_\rho \approx \dfrac{g^2_{\rho\pi\pi}M_\rho}{48\pi} \approx \dfrac{M^3_\rho}{96\pi F^2_\pi}.$
  - Γ (LatKMI) is also ≳ 450 GeV for N_d=1: rather broad

N_f=8 spectrum — σ: flavor singlet scalar

- σ is a candidate of Higgs in a successful walking technicolor theory
- observed hierarchy of spectrum (parametrically)
  - **$m_\pi \simeq m_\sigma < m_\rho$ (N_f=8)**
  - unlikely due to “heavy quark”
  - also in other (near) conformal th.
    - N_f=12, N_f=2 sextet, SU(2) 2 adj..
- contrast to QCD (physical point)
  - **$m_\pi \ll m_\sigma < m_\rho$ (~N_f=2+1)**
- eventually $m_\pi < m_\sigma$ should be seen
  - but, far from our simulation points
  - this continues to even lighter points: see LSD 2016



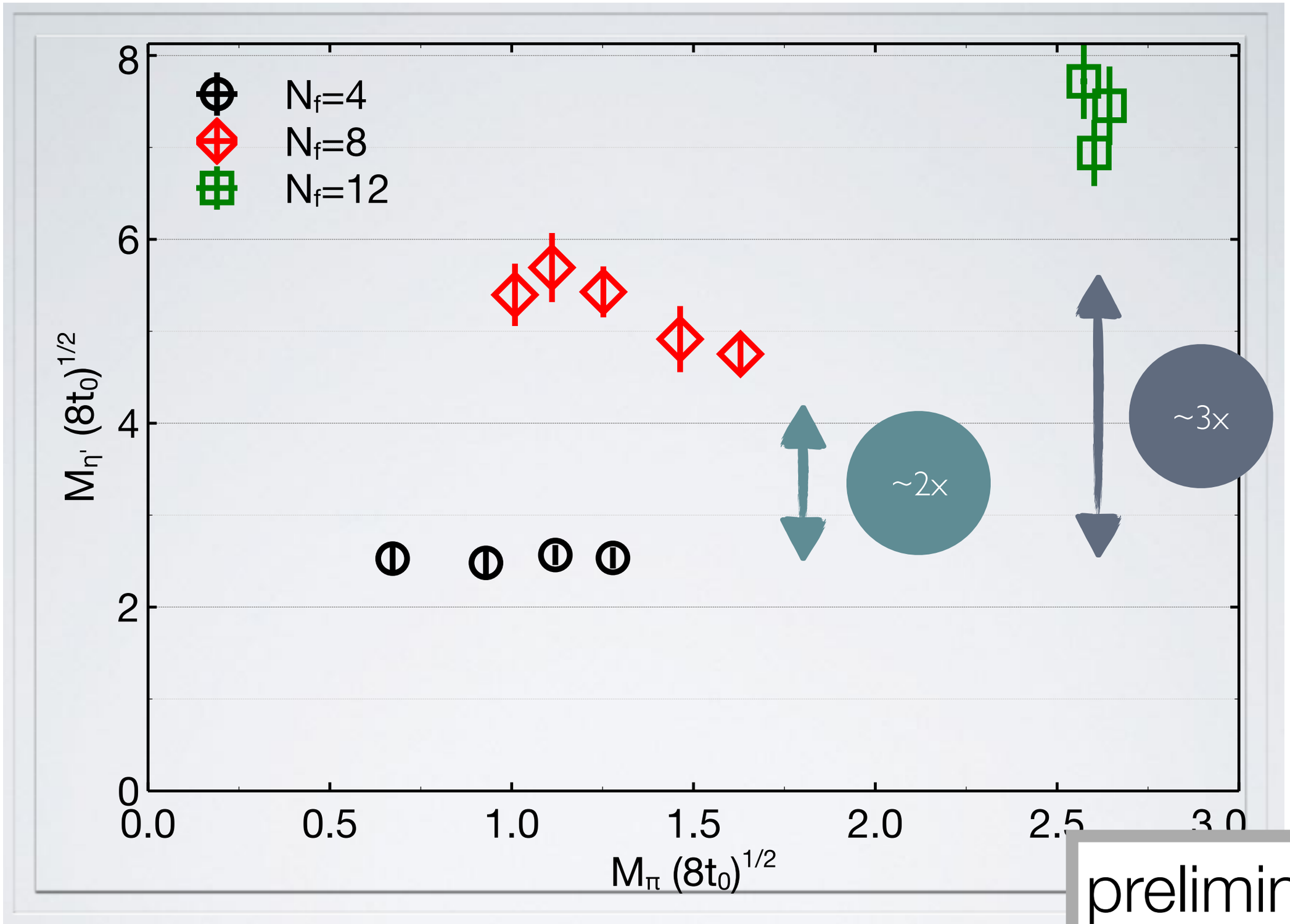
updated from Phys.Rev.D96(2017)
m_f=0.009 (lightest) is new

flavor singlet pseudoscalar

[LatKMI E. Rinaldi talk at Lattice 2017]

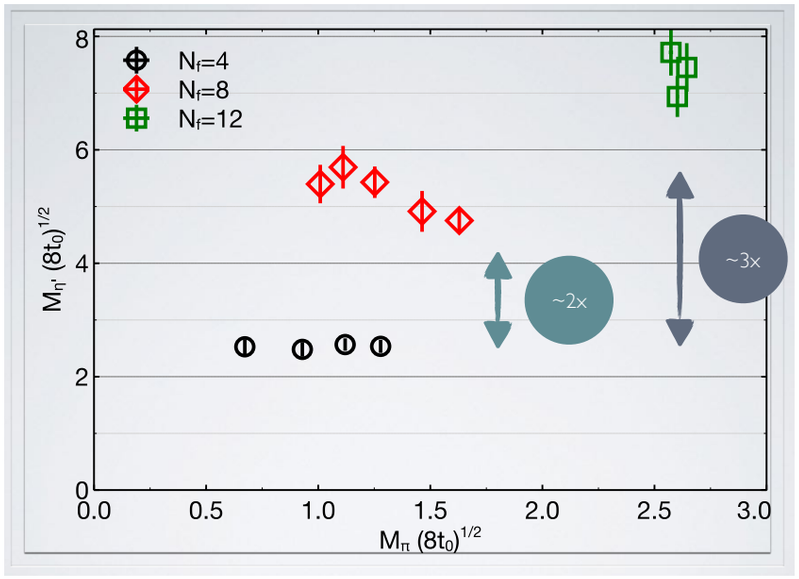
η’ mass for Nf=4, 8, 12

[LatKMI Rinaldi Lattice 2017]



η’ mass [preliminary]

- provide access to chiral anomaly and N_f dependence
- challenging for lattice computation due to noise
- reasonable signal obtained by
  - high statistics and Wilson flow
  - use of 4d convolution with gluonic operator



- results:
  - consistent with an enhancement of chiral anomaly effect
  - “anti-Venetiano limit” ~ (N_f/N_c) [Matsuzaki-Yamawaki JHEP(2015)053]

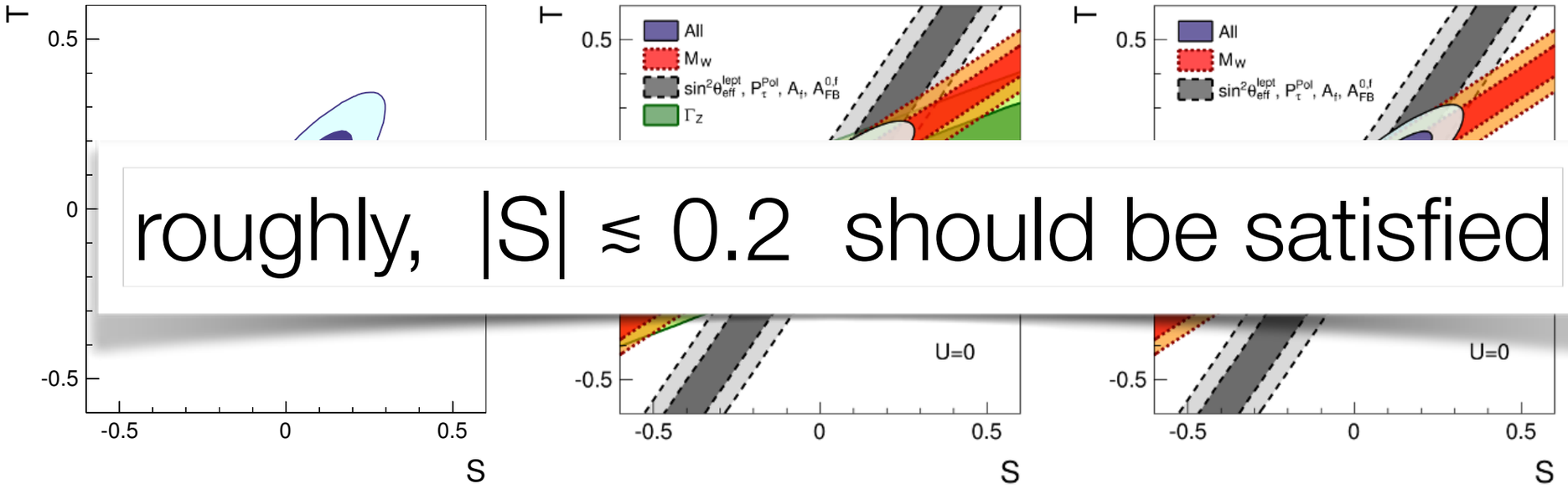
- other ratio needs to be investigated

S parameter for N_f=8 QCD

[LatKMI Lattice 2015 and updates(preliminary)]

Peskin - Takeuchi S parameter

- S parameter provides important constraint on composite models
- Ciucini et al JHEP1308 106 (M_H=126GeV)

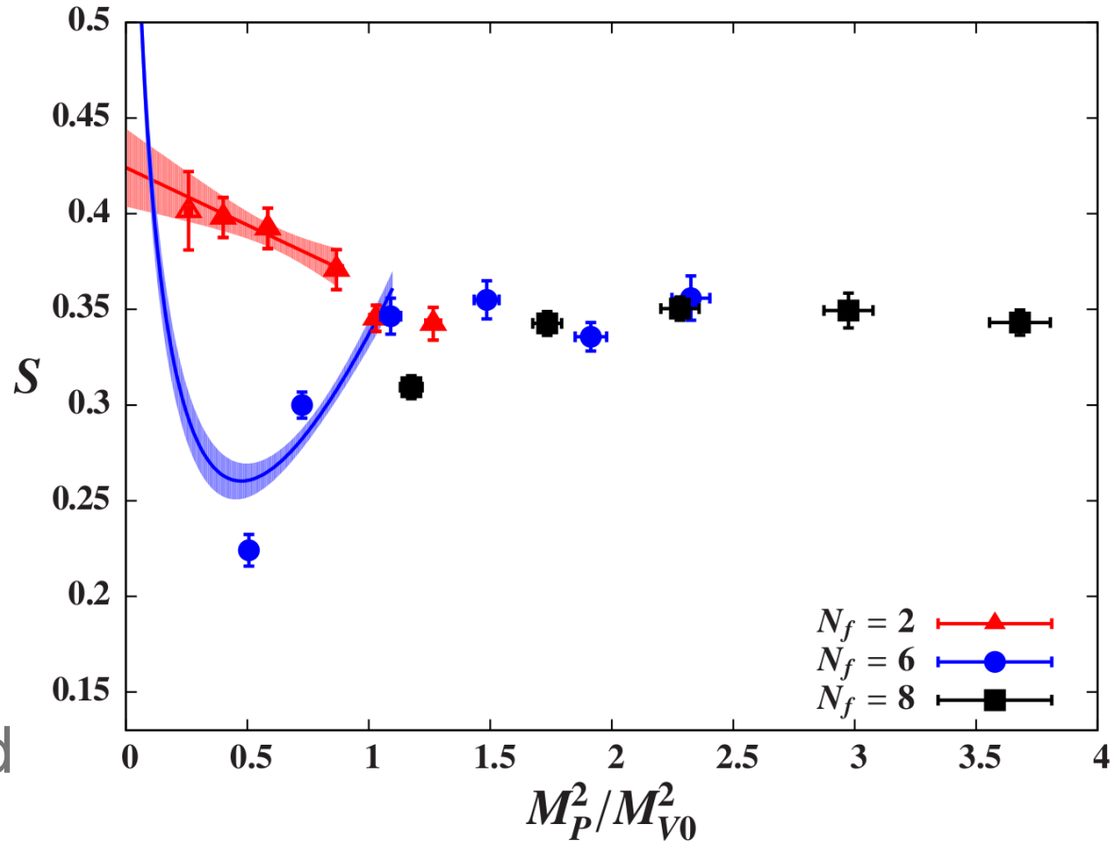


roughly, $|S| \lesssim 0.2$ should be satisfied

Figure 4. Left: two-dimensional probability distribution for the oblique parameters S and T obtained from the fit with S, T, U and the SM parameters, with the large-m_t expansion for the two-loop fermionic EW corrections to ρ_Z^f. Center: two-dimensional probability distribution for the oblique parameters S and T obtained from the fit with S, T and the SM parameters with $U = 0$, with the large-m_t expansion for the two-loop fermionic EW corrections to ρ_Z^f. The individual constraints from M_W, the asymmetry parameters $\sin^2\theta_{\rm eff}^{\rm lept}$, $P_\tau^{\rm pol}$, A_f and $A_{\rm FB}^{0,f}$ with $f = \ell, c, b$, and Γ_Z are also presented, corresponding to the combinations of parameters A, B and C in eq. (3.5). Right: same as center, but using the results of ref. [16, 83]. In this case, the constraint from Γ_Z cannot be used.

S parameter of QCD with N_f fundamental fermions [LSD, PRL 2011 & PRD 2014]

- Only one “published” result
- one doublet has EW charge →
- N_f=6
  - decreases as m_f enters chiral regime
  - turns up after chiral log sets in
  - low value of S possible for unabsorbed massive pions → **promising**
  - **note: ETC effect may decrease the size**
- N_f=8
  - similar trend as Nf=6, but not conclusive



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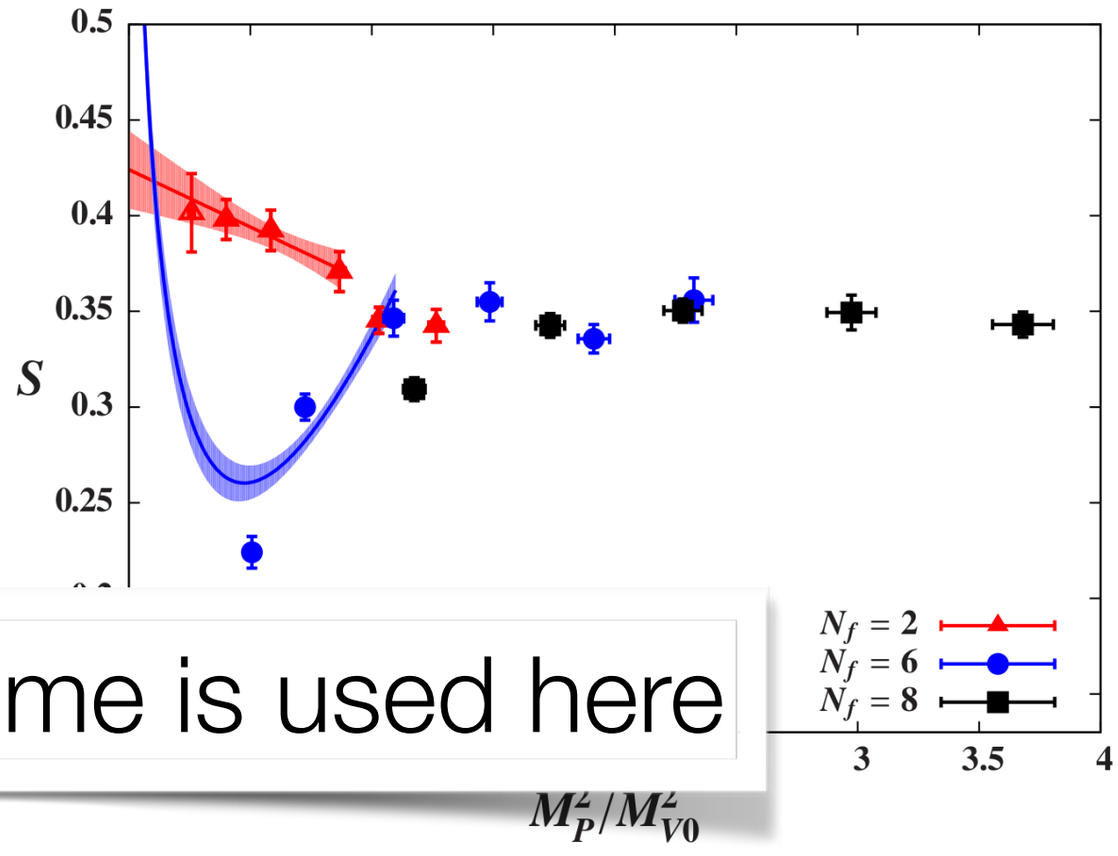
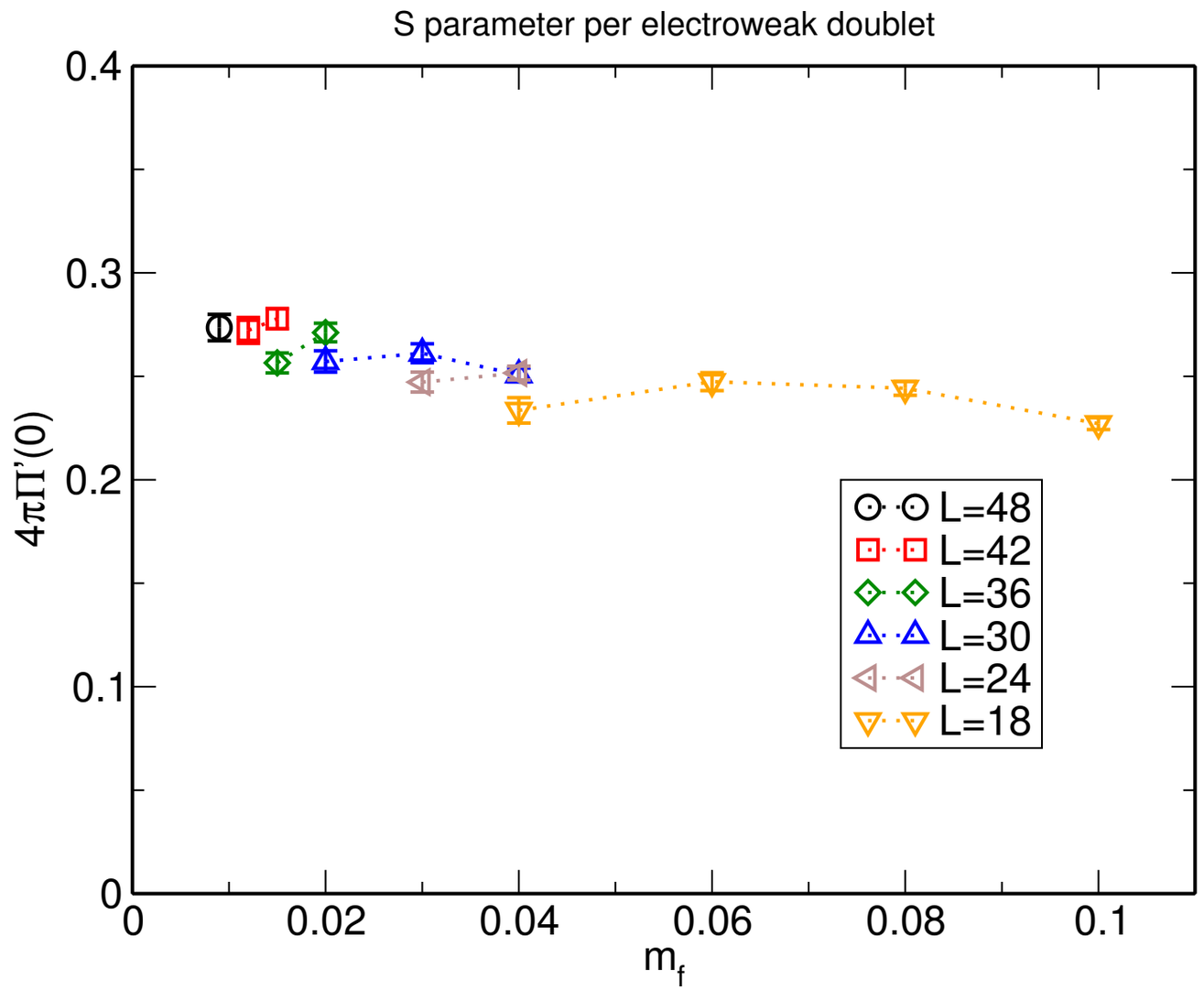
caveat: only one volume is used here

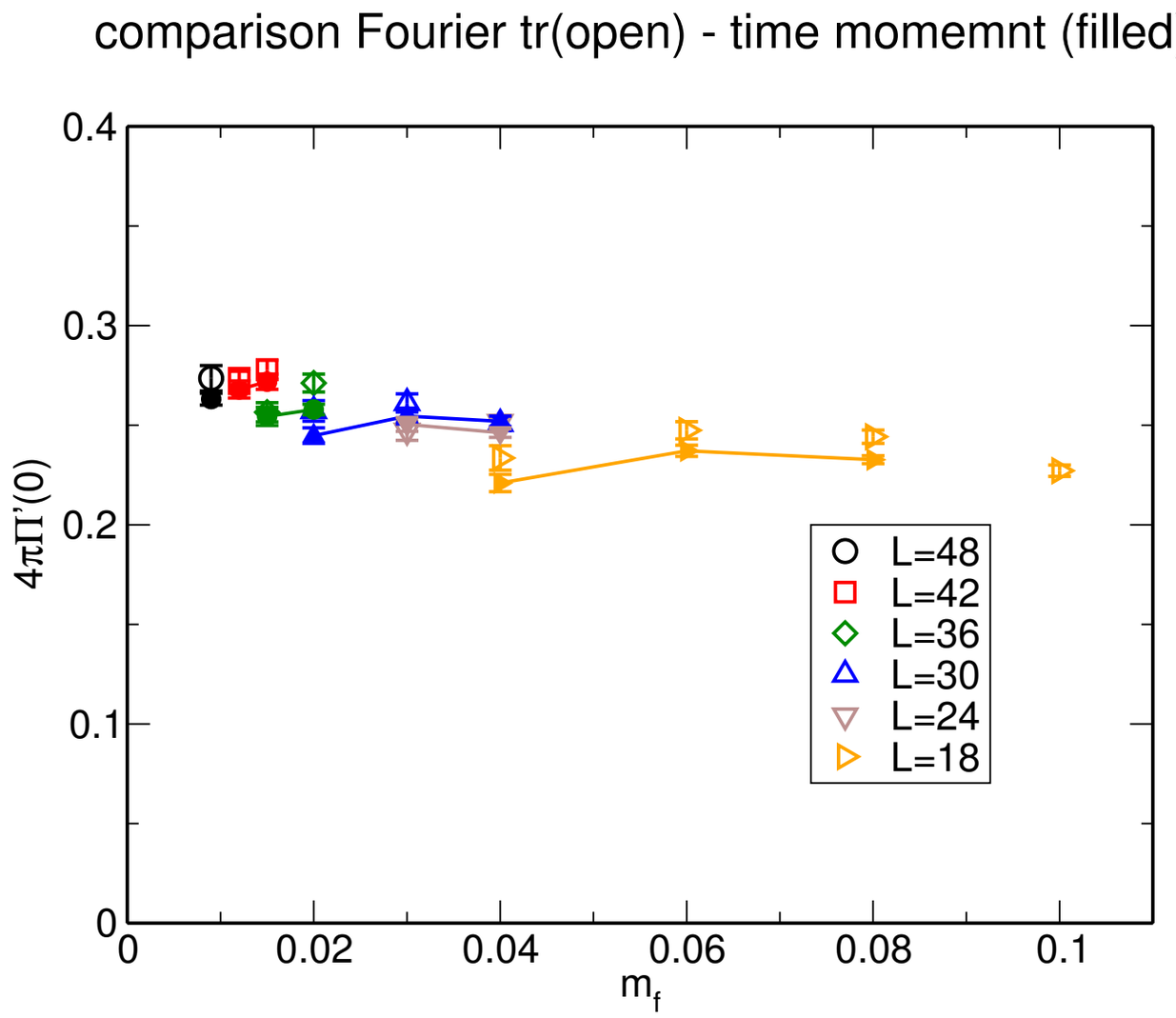


LatKMI
S(m_f): TC contribution per EW doublet (preliminary)



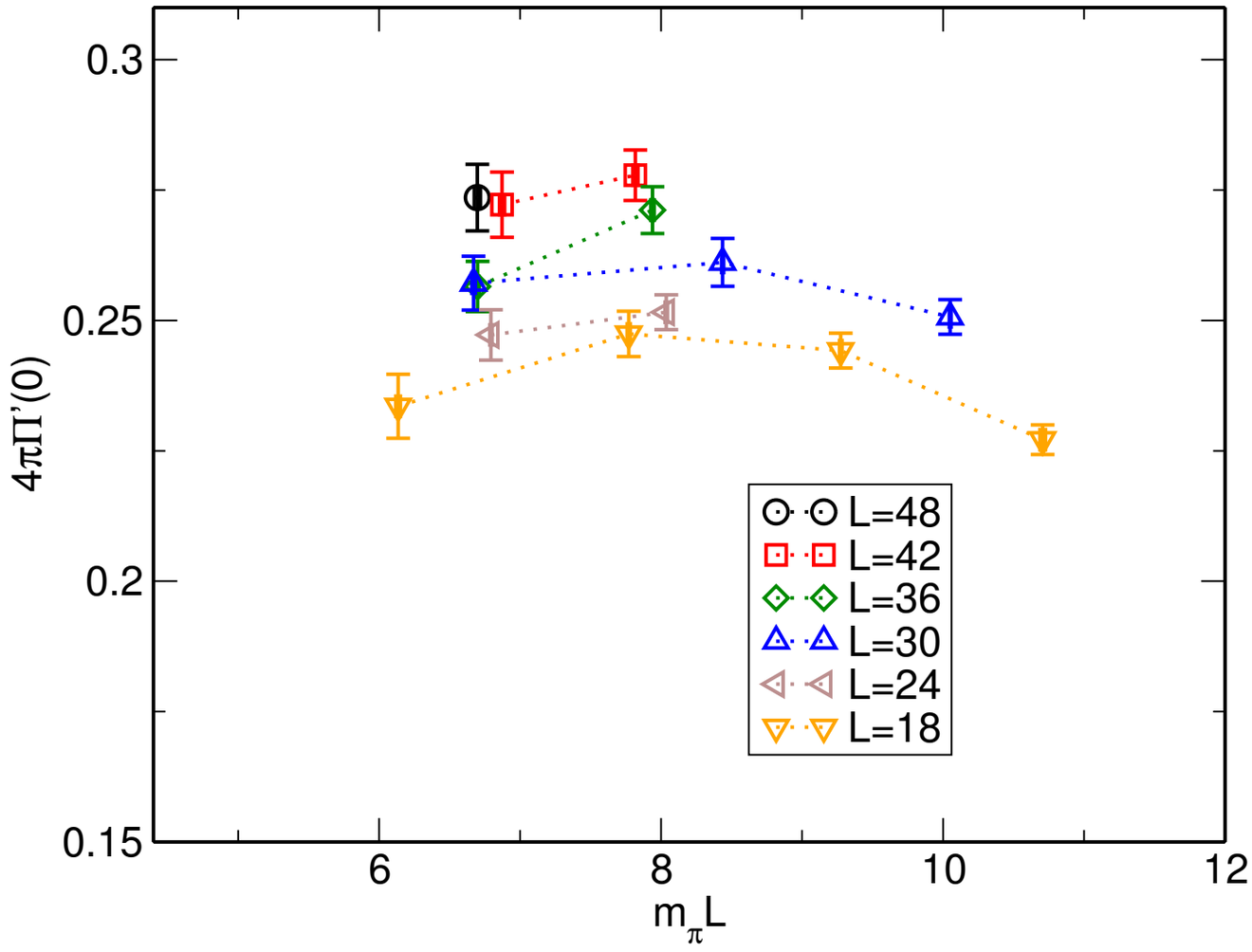
- finite size effect, somehow large, observed
- 8%↓ @ m_f=0.015; L=42→36 c.f. pion mass: 0.04%↓ (zero consistent)

LatKMI
$S(m_f)$: TC contribution per EW doublet (preliminary)



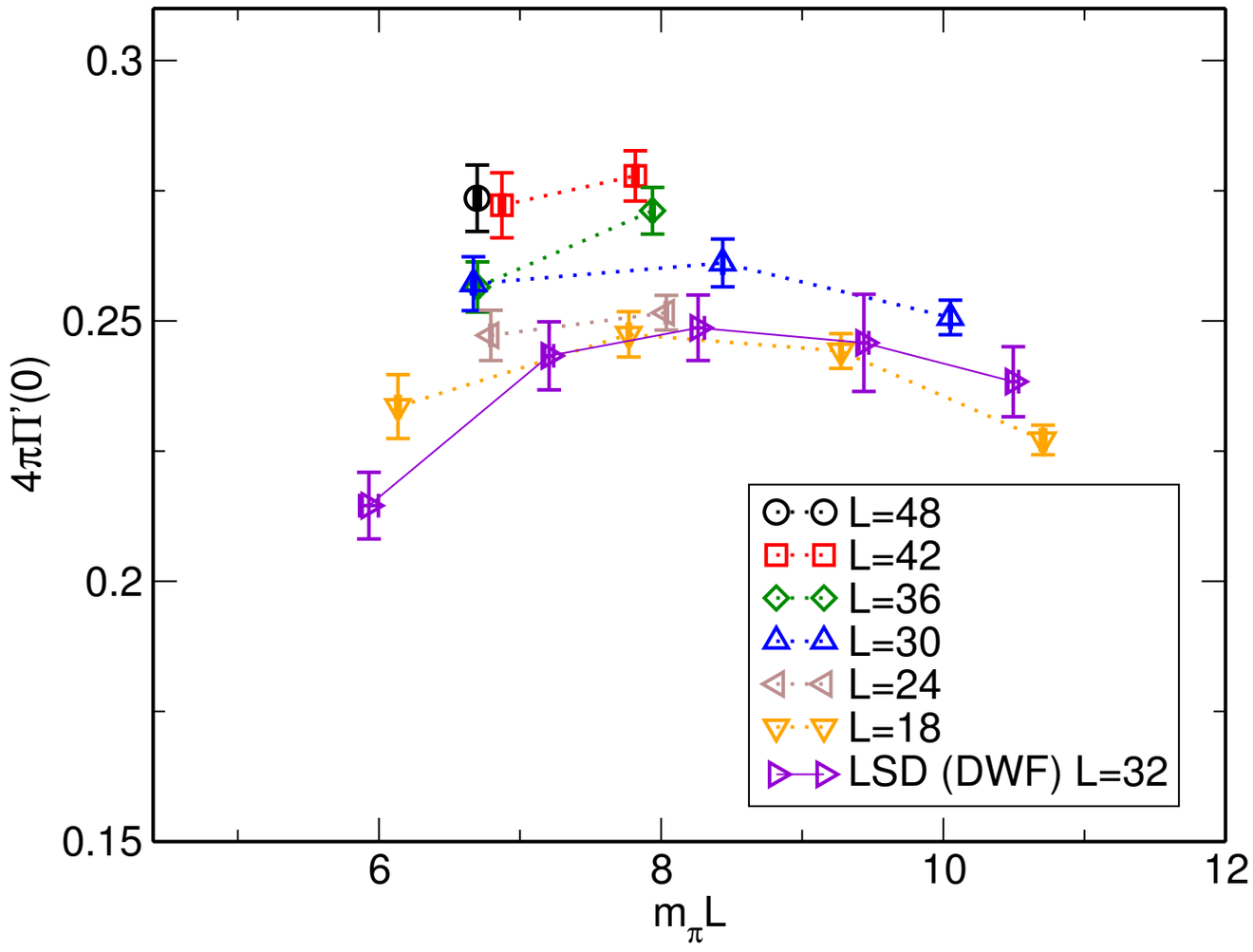
- consistent behavior observed with yet another lattice definition of S
  - through 4d Fourier transformation
  - time moment method through zero-spatial momentum projection

$S(m_\pi L)$: TC contribution per EW doublet (preliminary)



- finite volume effect tends to reduce S
- $m_\pi L \lesssim 7$ finite volume effect begin to develop: $< 10\%$
- $m_\pi L \lesssim 6$ likely affected by finite volume effect: $> 10\%$

$S(m_\pi L)$: TC contribution per EW doublet (preliminary)



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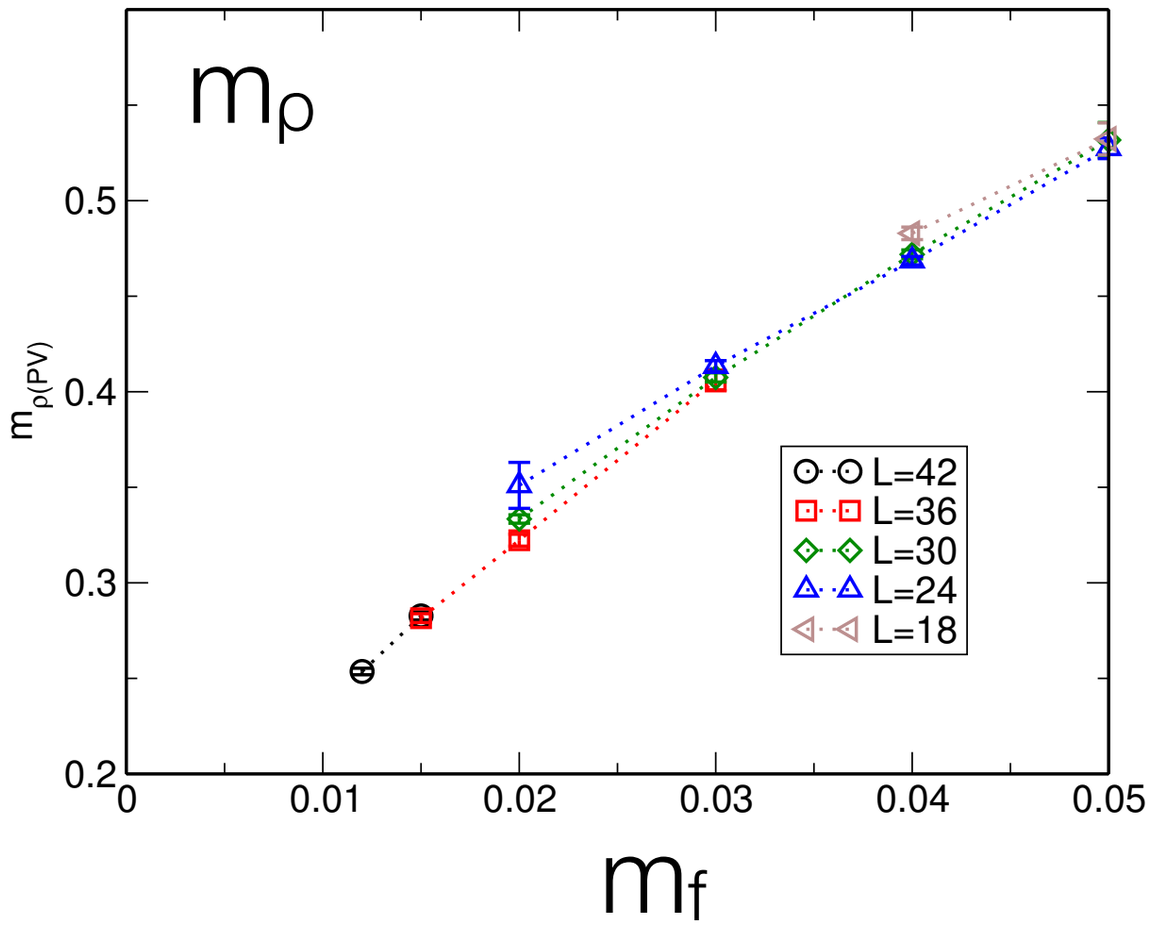
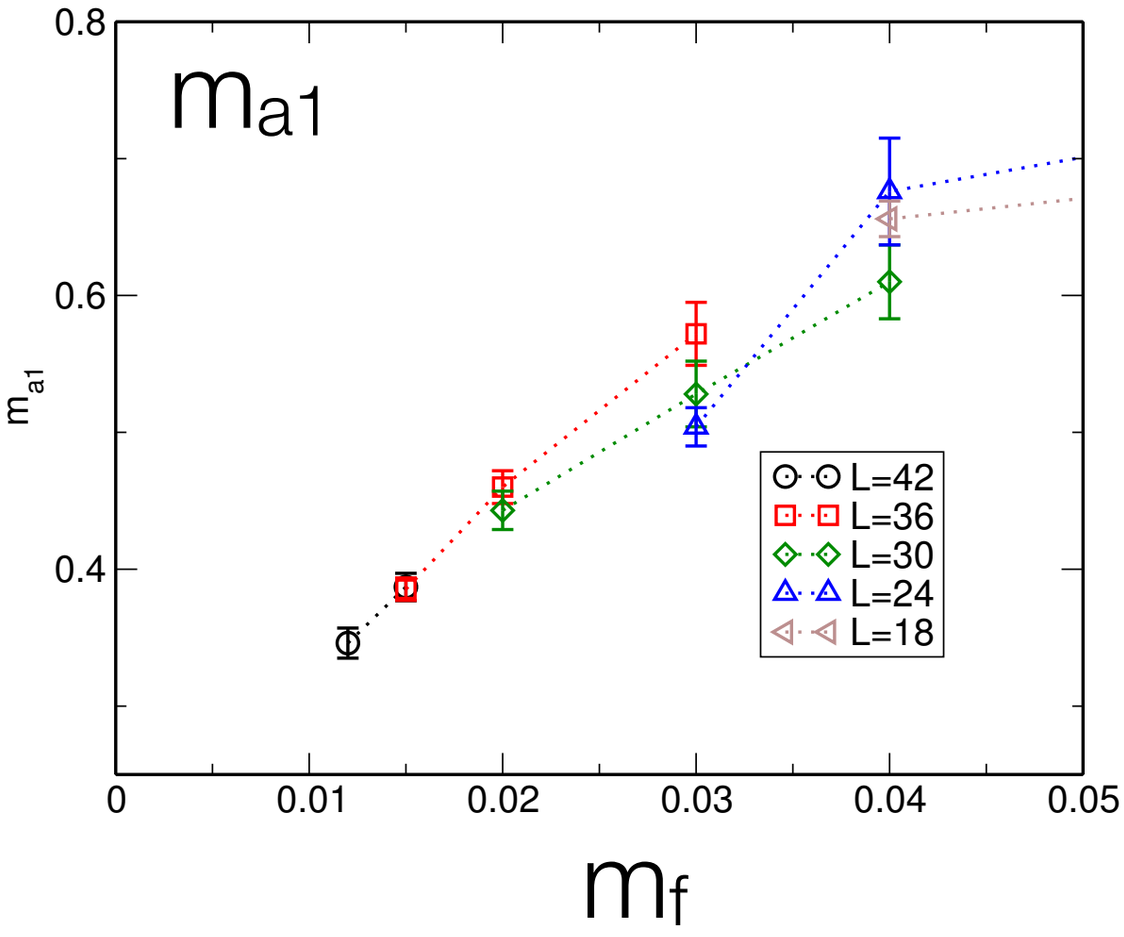
- $m_\pi L \lesssim 6$ likely affected by finite volume effect: $> 10\%$

spectrum in vector and axialvector channel

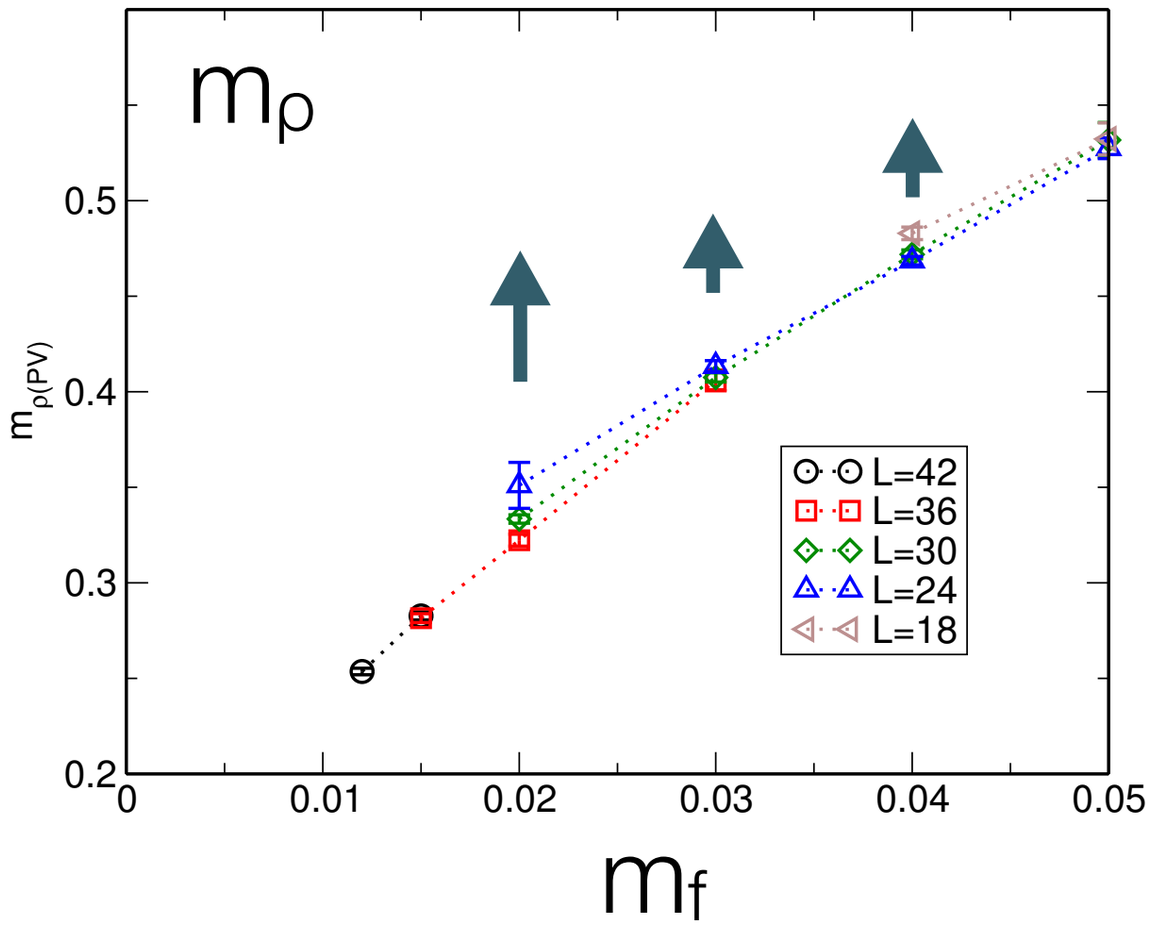


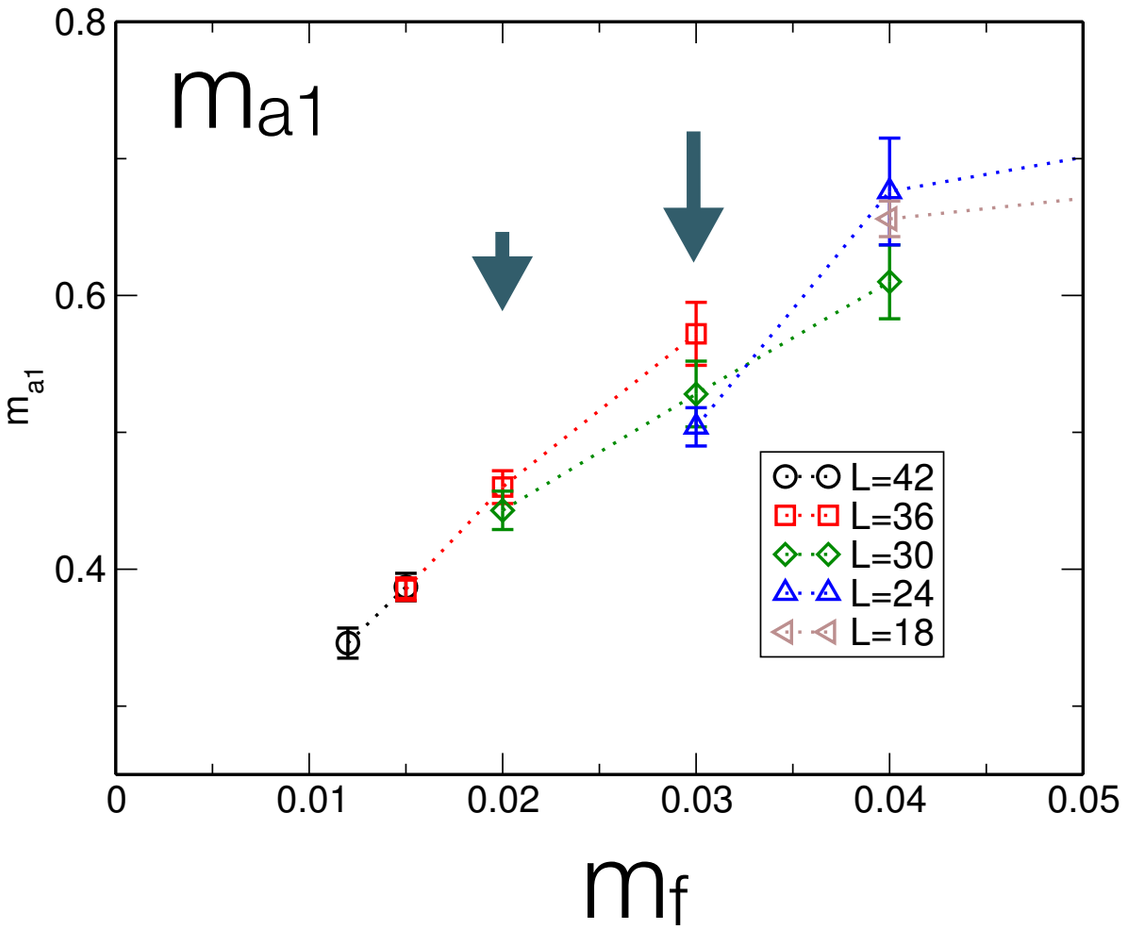


- measured with local operators (spin-taste: PV)
- indicating finite volume effect tends to push towards parity doubling
- decrease of S for lighter mass observed by LSD might just be finite size effect

spectrum in vector and axialvector channel

finite volume effect





- measured with local operators (spin-taste: PV)
- indicating finite volume effect tends to push towards parity doubling
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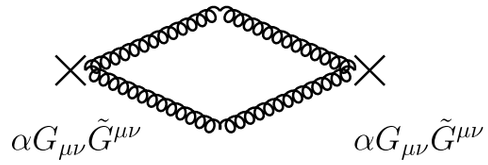
Summary

- N_f=8 QCD investigated with focus on composite spectrum
  - candidate of Walking Technicolor Theory
  - light flavor singlet scalar (Higgs) exists
    - techni rho mass > 1 TeV (minimum; depending on the model)
    - S parameter, suppression due to parity doubling may not be realized
      - ➡ if true, different mechanism for reduction needed, eg, in ETC
- flavor singlet scalar
  - has novel property: strong dependence on N_f
- investigation further continues…

Thank you very much for your attention !

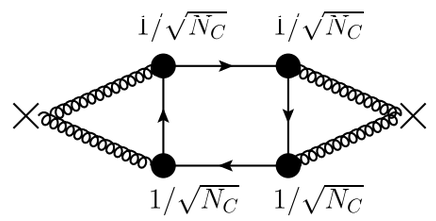
enhancement of $M_{\eta'}$ for larger N_f

- Discussion:
- Usual large Nc argument
  - fix: N_f and $n_c \to \infty$
  - Witten-Venetiano: $\mathbf{M_{\eta'}^2 \sim (N_f/n_c) * \Lambda^2 \to 0}$ for $n_c \to \infty$



$\sim \alpha^2 N_C^2$

    - checked by lattice (χ_t @ Quench: Del Debbio, Giusti, Pica 2005)
- Walking regime: need to keep (N_f/n_c) non-vanishing
  - "Anti-Venetiano-limit": keep $(N_f/n_c)>1$ fixed & $n_c \to \infty$
  - Matsuzaki-Yamawaki: $\mathbf{M_{\eta'}^2 \sim (N_f/n_c)^2 * \Lambda^2}$ [JHEP 2015]



$\sim \alpha^2 N_F N_C$

  - this could be responsible for the observed ratio 1:2:3 for $M_{\eta'}$

a method for flavor singlets

- statistical technique for these noisy correlation functions
- use purely gluonic operators and sample exact all to all with Gradient Flow
- zero momentum projection is not very efficient

$$\cancel{\sum_{x,y,z} G(x,y,z,t) \to G(t)}$$

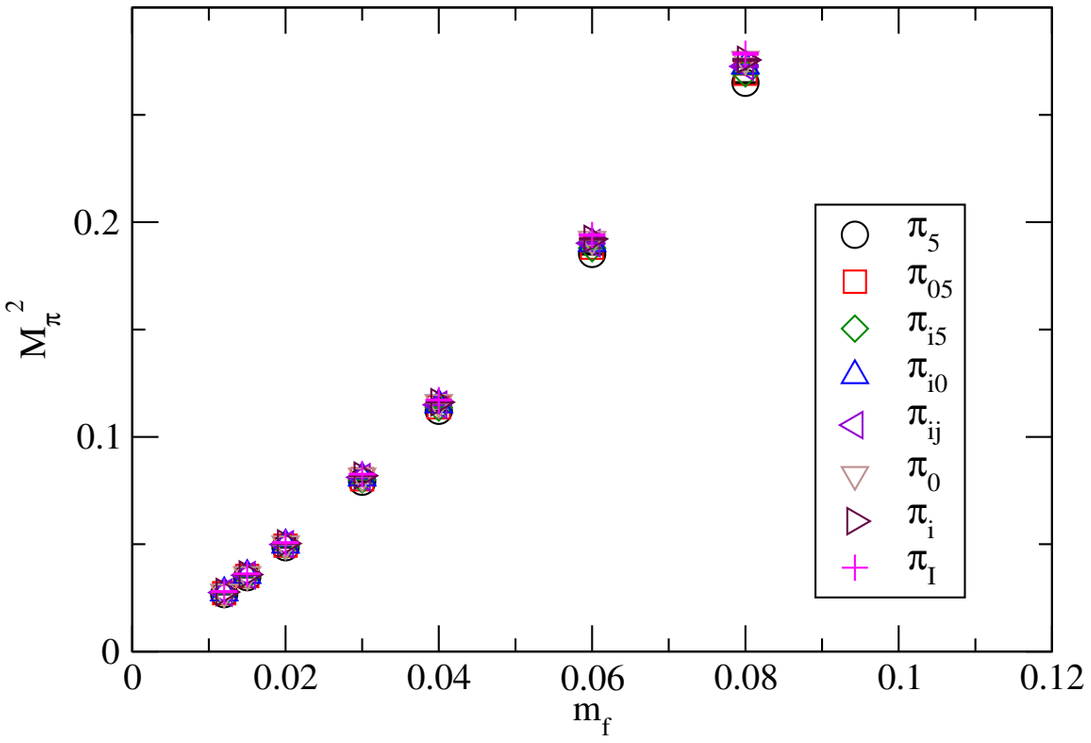
- average to all direction will help

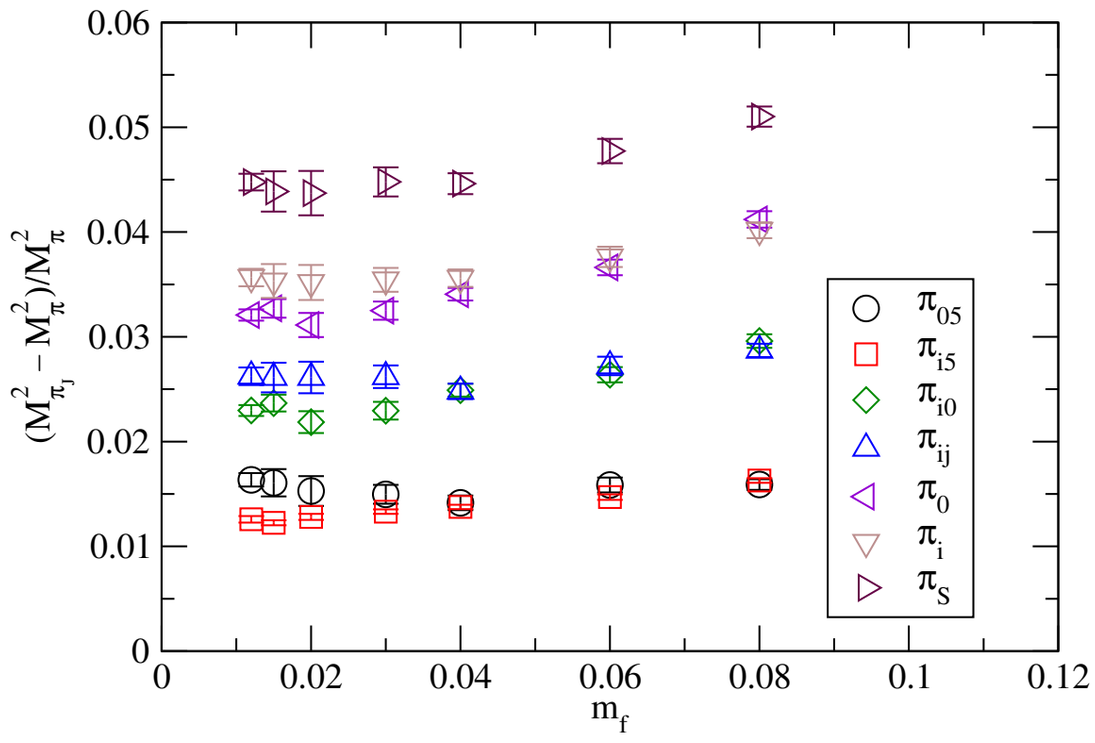
$$\sum_{r:\text{fixed}} \sum_{x,y,z,t} G(x,y,z,t) \to G(r); \;\; r^2 = x^2 + y^2 + z^2 + t^2$$

- Successful applications
  - 0+- glueball @ N_f=0 by Chowdhury, Harindranath, Maiti, PRD 2015
  - η’ meson @ N_f=2+1 by JLQCD (Fukaya et al) PRD 2015
    - no pion “contamination” due to no use of fermion correlators

staggered flavor (taste) symmetry for N_f=8 HISQ

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





- excellent staggered flavor symmetry, thanks to HISQ

One-family ETC model

$$\begin{pmatrix} u \\ d \\ u \\ d \\ u \\ d \\ e \\ \nu_e \end{pmatrix} \begin{pmatrix} c \\ s \\ c \\ s \\ c \\ s \\ \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} t \\ b \\ t \\ b \\ t \\ b \\ \tau \\ \nu_\tau \end{pmatrix} \begin{pmatrix} U_1 \\ D_1 \\ U_1 \\ D_1 \\ U_1 \\ D_1 \\ E_1 \\ N_1 \end{pmatrix} \cdots \begin{pmatrix} U_{N_{\rm TC}} \\ D_{N_{\rm TC}} \\ U_{N_{\rm TC}} \\ D_{N_{\rm TC}} \\ U_{N_{\rm TC}} \\ D_{N_{\rm TC}} \\ E_{N_{\rm TC}} \\ N_{N_{\rm TC}} \end{pmatrix}$$

$$SU(3+N_{\rm TC}) \xrightarrow{\Lambda_1} SU(2+N_{\rm TC}) \xrightarrow{\Lambda_2} SU(1+N_{\rm TC}) \xrightarrow{\Lambda_3} SU(N_{\rm TC})$$

8-flavor $\mathrm{SU}(N_{\rm TC})$ technicolor