Exploring for the walking technicolor on the lattice

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for the LatKMI collaboration

- Brookhaven Forum 2013 -

May. 2, 2013

LatKMI collaboration

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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

  ➡Techni Dilaton (Yamawaki, Bando, Matsumoto)

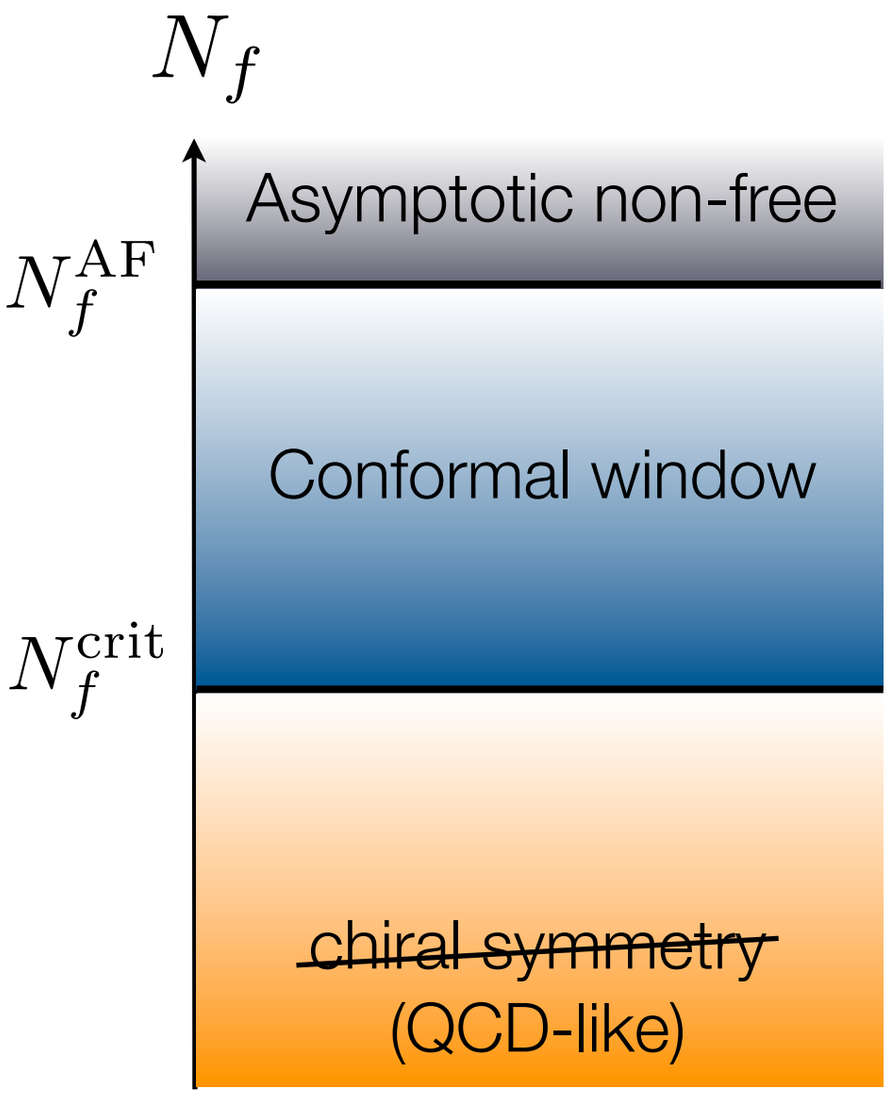
Requirements for the successful WTC theory

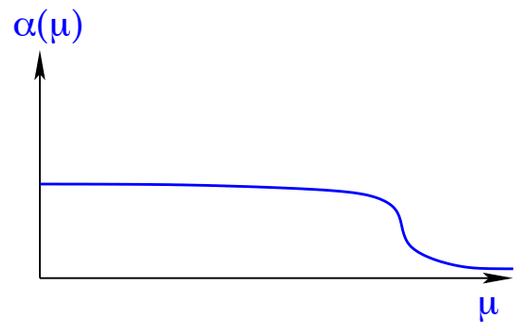
- spontaneous chiral symmetry breaking
- running coupling “walks” = slowly changing with μ → nearly conformal
- large mass anomalous dimension: $\gamma_m \sim 1$
- light scalar 0^{++} (m_H = 126 GeV @ LHC !)
- with input $F_\pi = 246/\sqrt{N}$ GeV (N: # weak doublet in techni-sector)
  - to reproduce $W^\pm$ mass
- typical QCD like theory: $M_{Had} >> F_\pi$ (ex.: QCD: $m_\rho/f_\pi \sim 8$)
  - Naive TC: $M_{Had} \gtrsim 1{,}000$ GeV
  - 0^{++} is a special case: pseudo Nambu-Goldstone boson of scale inv.

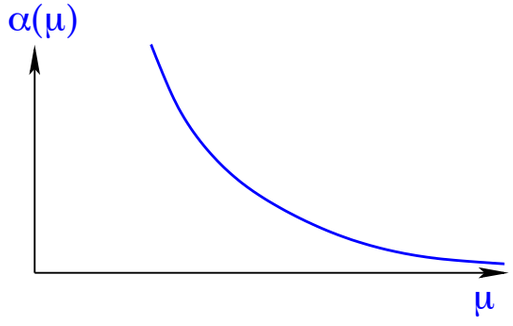
  ➡ is it really so ?

conformal window and walking gauge coupling

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







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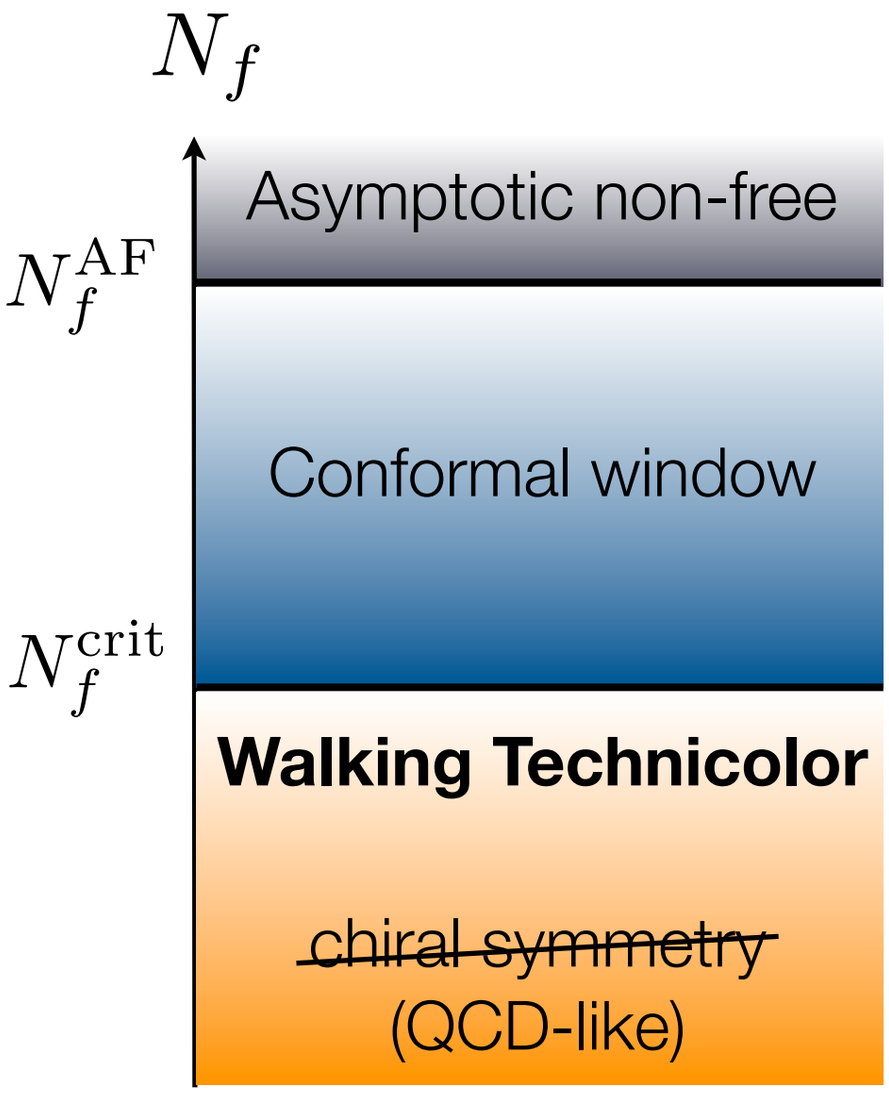

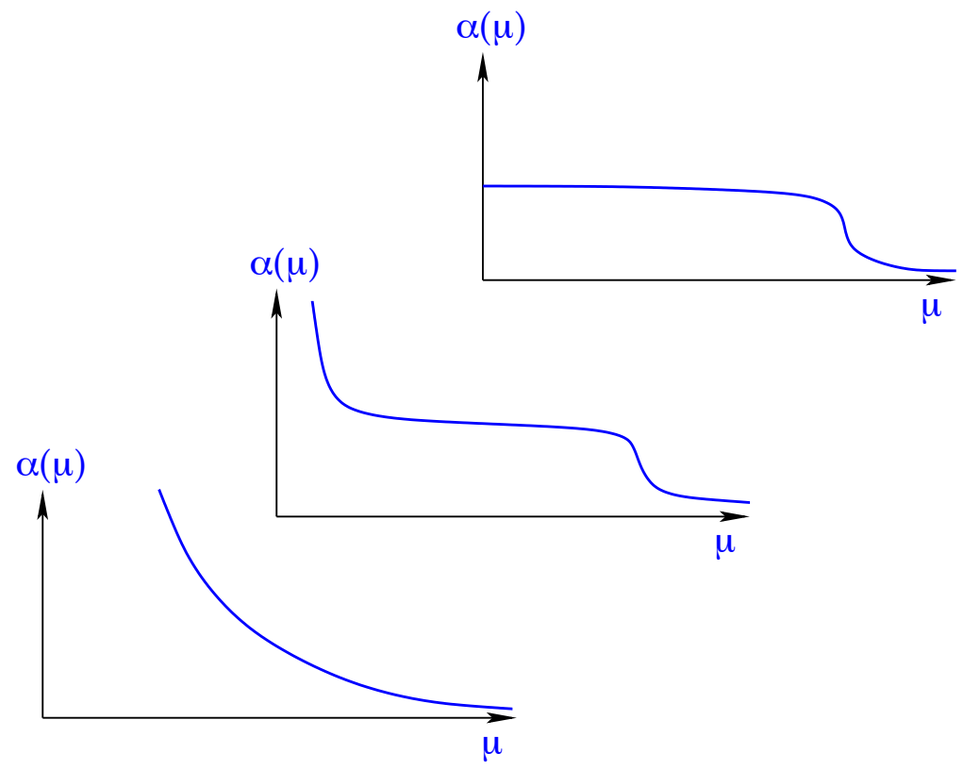

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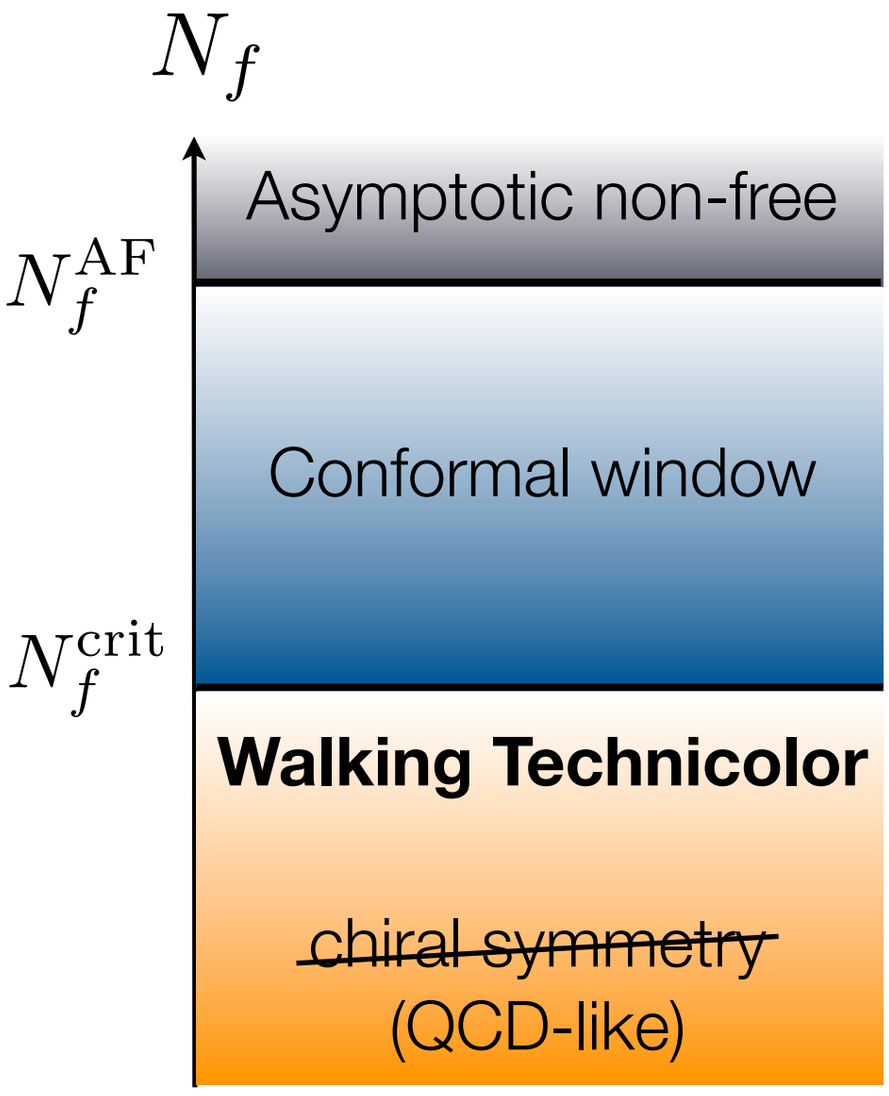

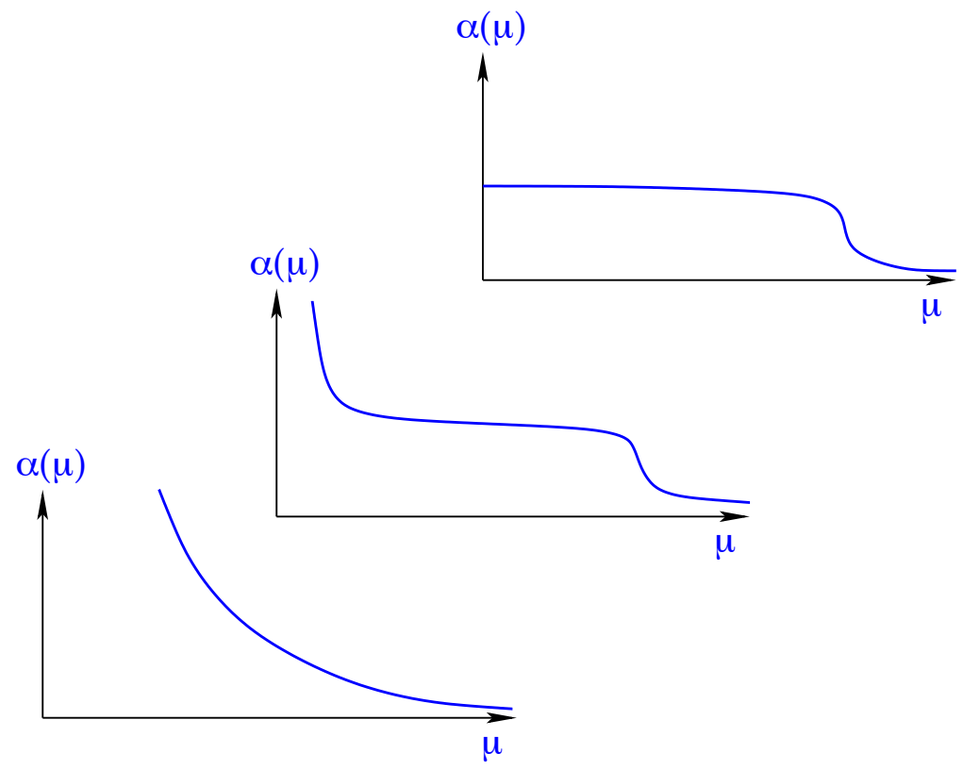

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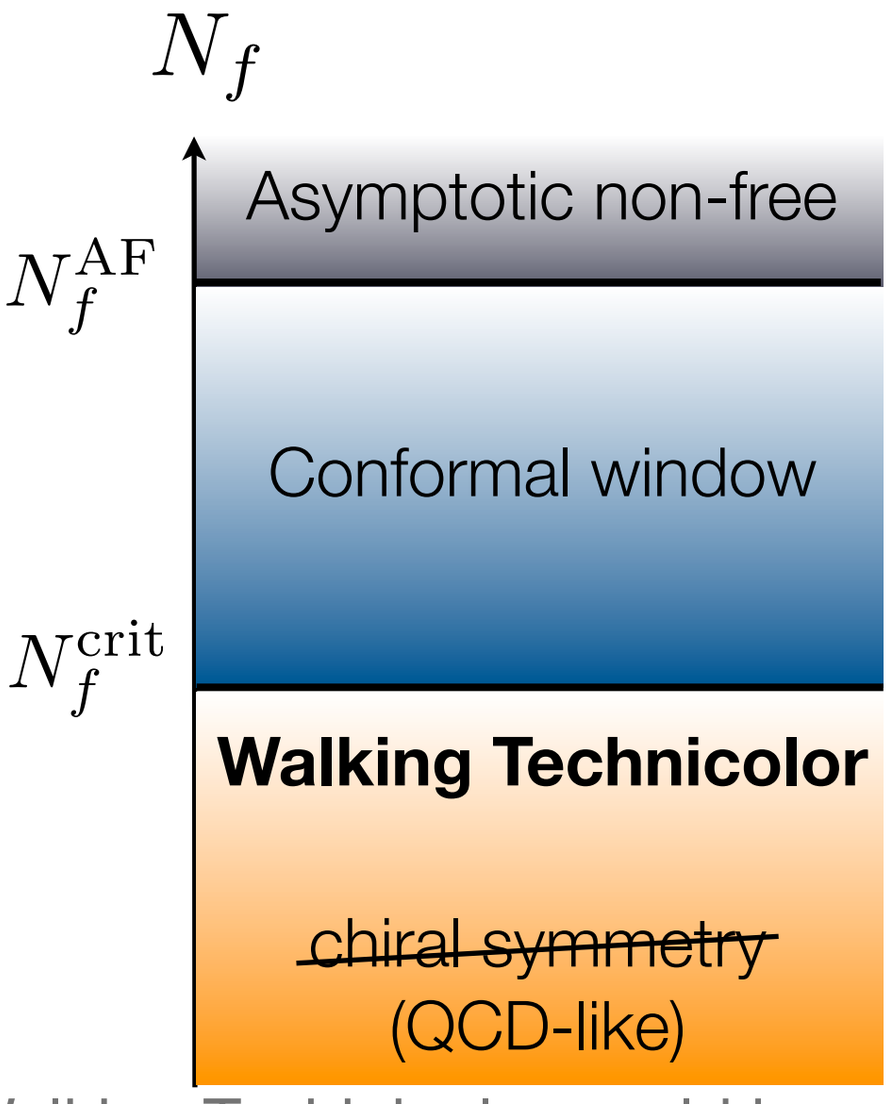

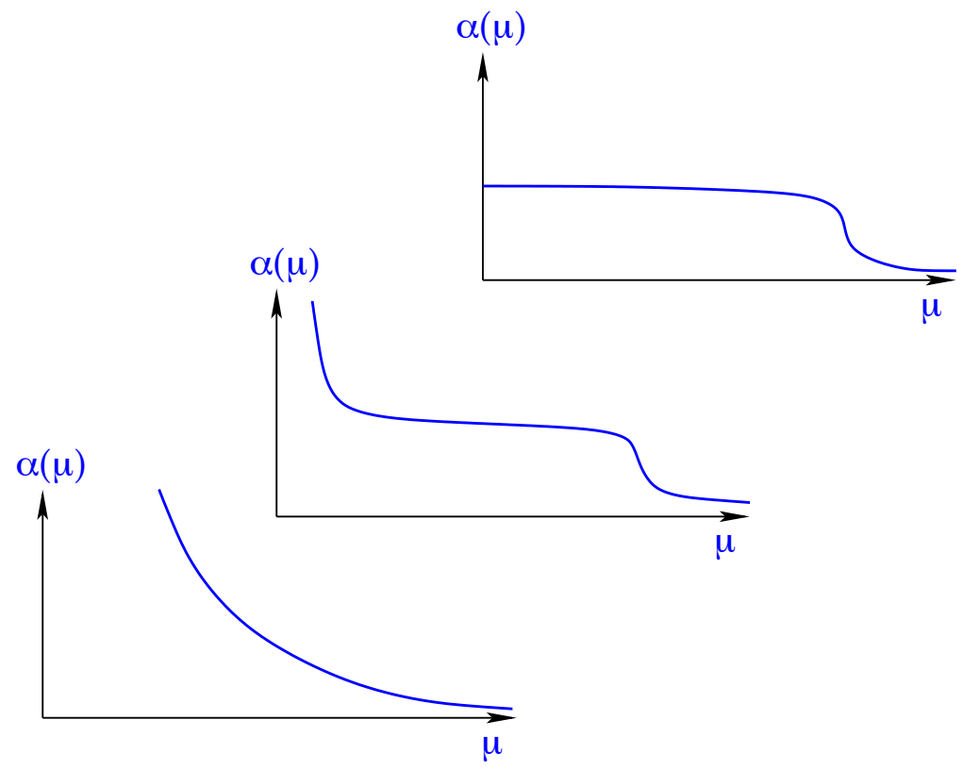

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- crucial information: N_f^{crit} and...

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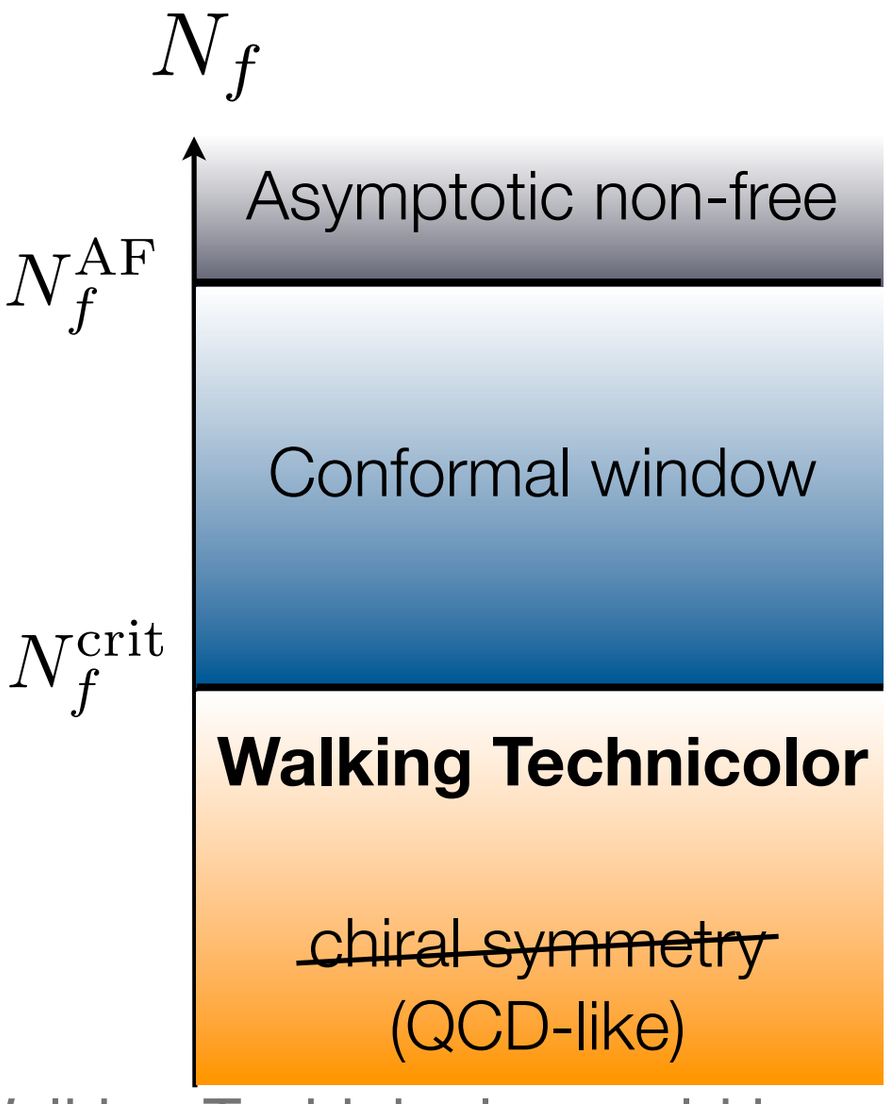
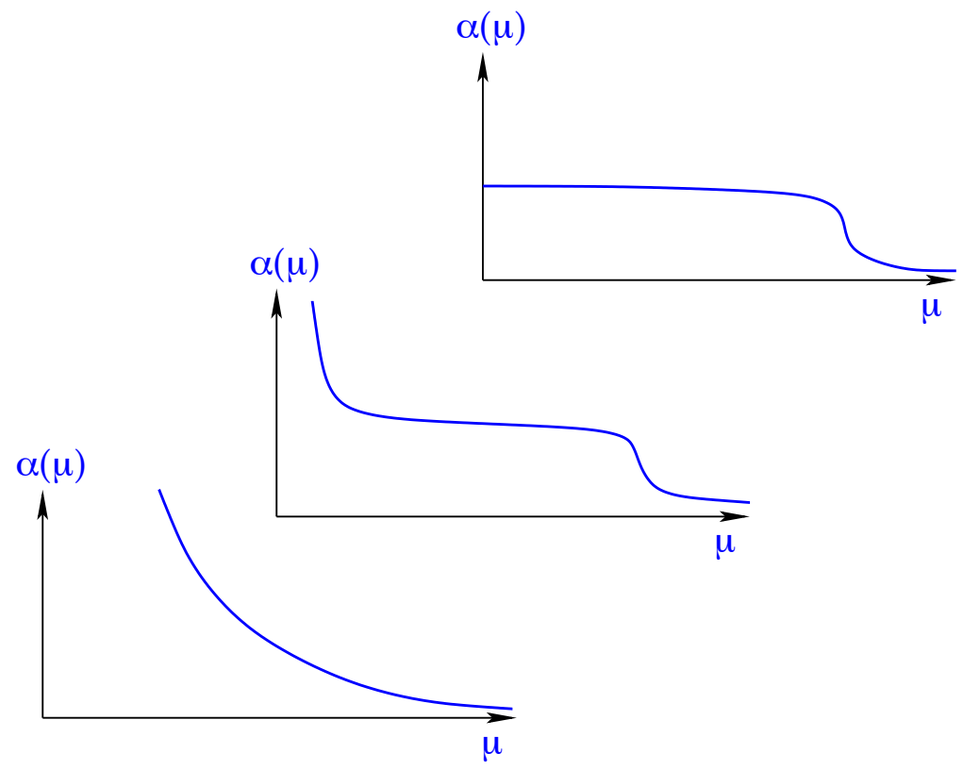


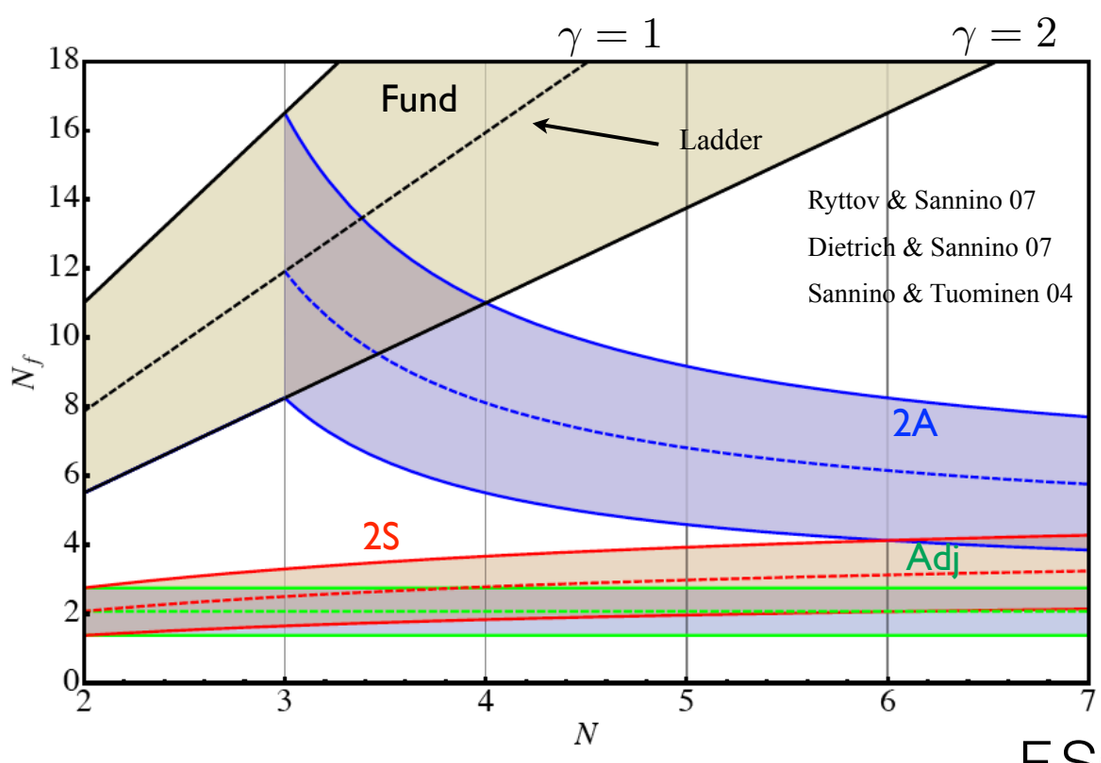


- Walking Techinicolor could be realized just below the conformal window
- crucial information: $N_f^{\rm crit}$ and...
- mass anomalous dimension γ & the composite mass spectrum around $N_f^{\rm crit}$

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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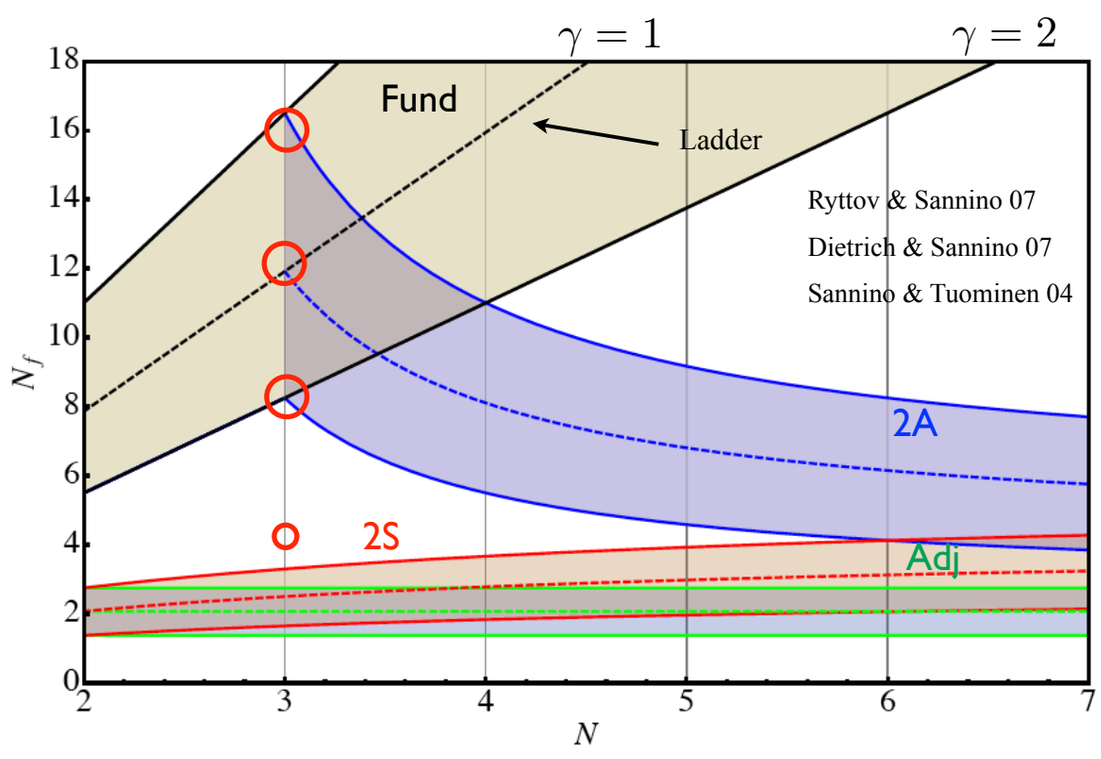

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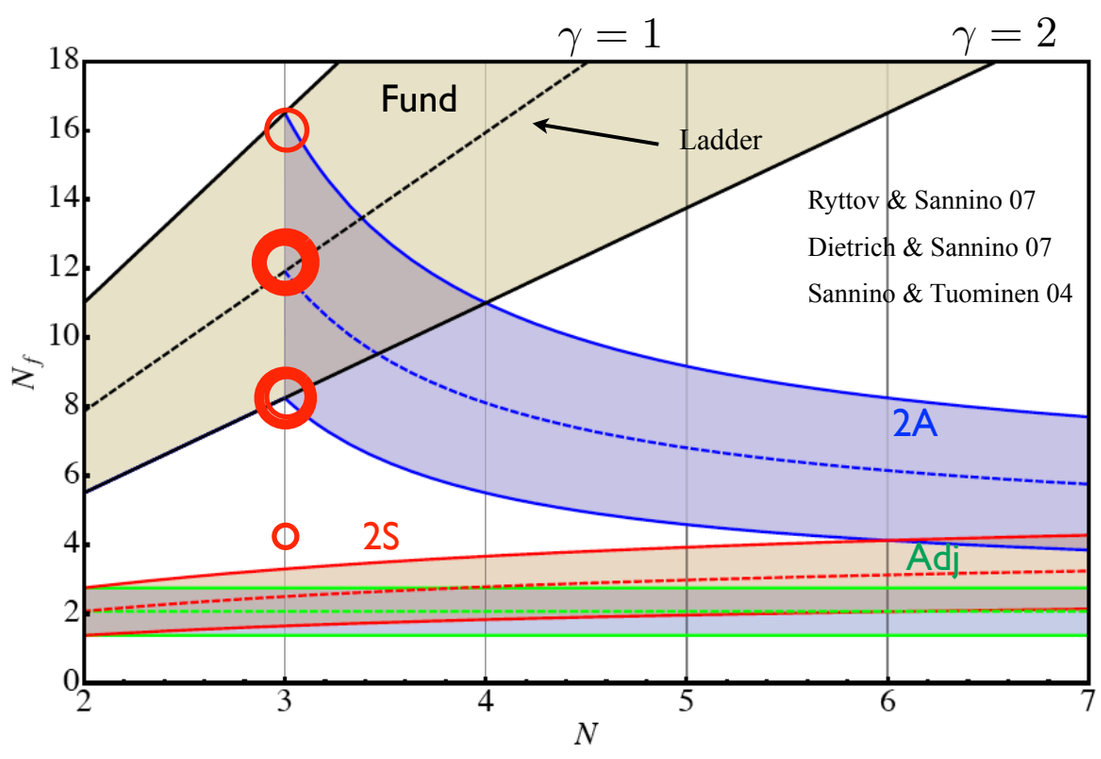
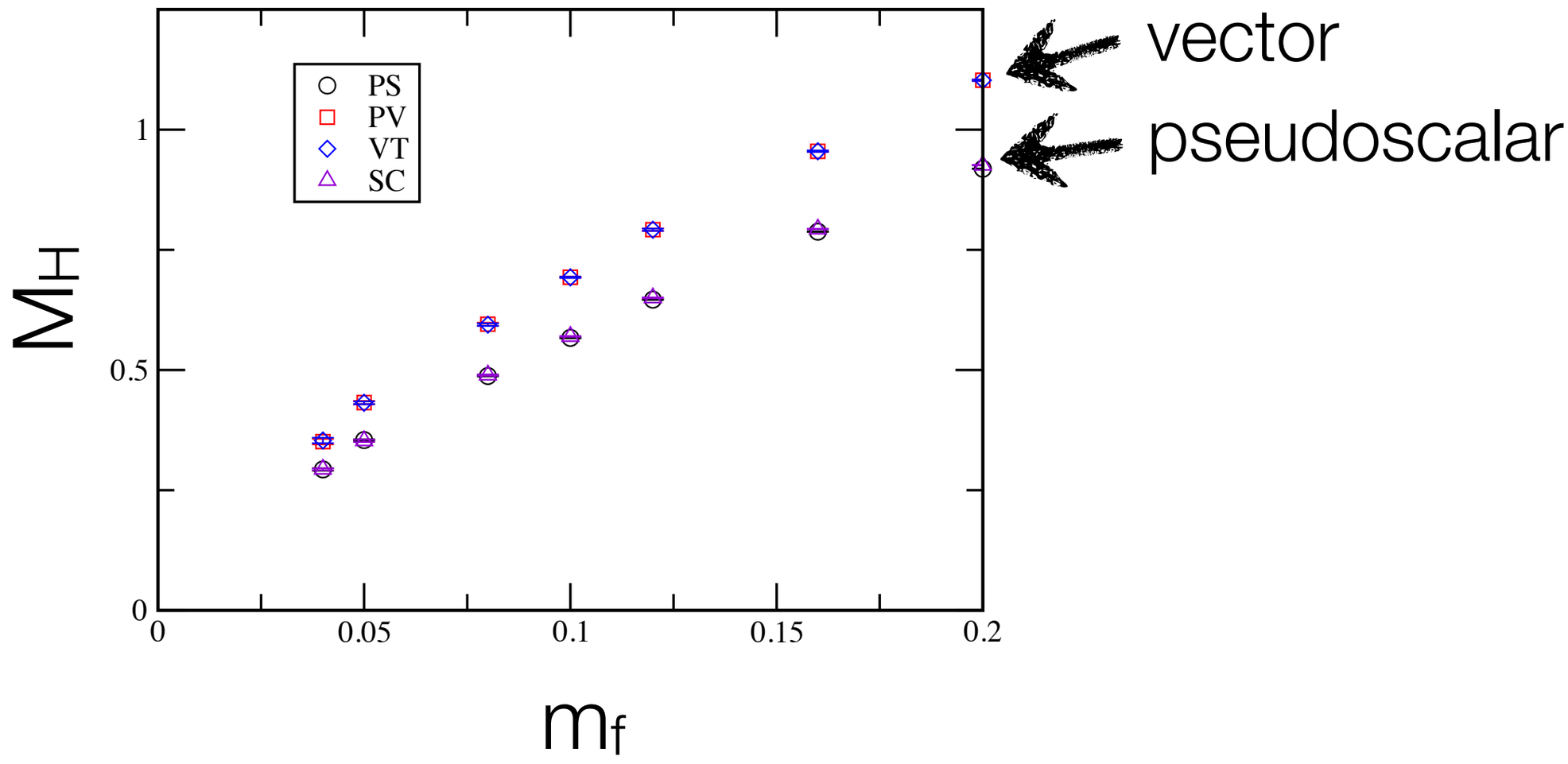


Simulation

- 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: $\beta=6/g^2=3.7$, $V=L^3xT$: L/T=2/3; L=12, 16
- N_f=8: $\beta=6/g^2=3.8$, $V=L^3xT$: L/T=3/4; L=18, 24, 30, 36
- N_f=12 (two lattice spacings): [LatKMI collab. PRD86 (2012) 054506]
  - $\beta=6/g^2=3.7$, $V=L^3xT$: 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, $0.05 \leqq m_f \leqq 0.24$
- 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:
response to mass (m_f) deformation

- 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)

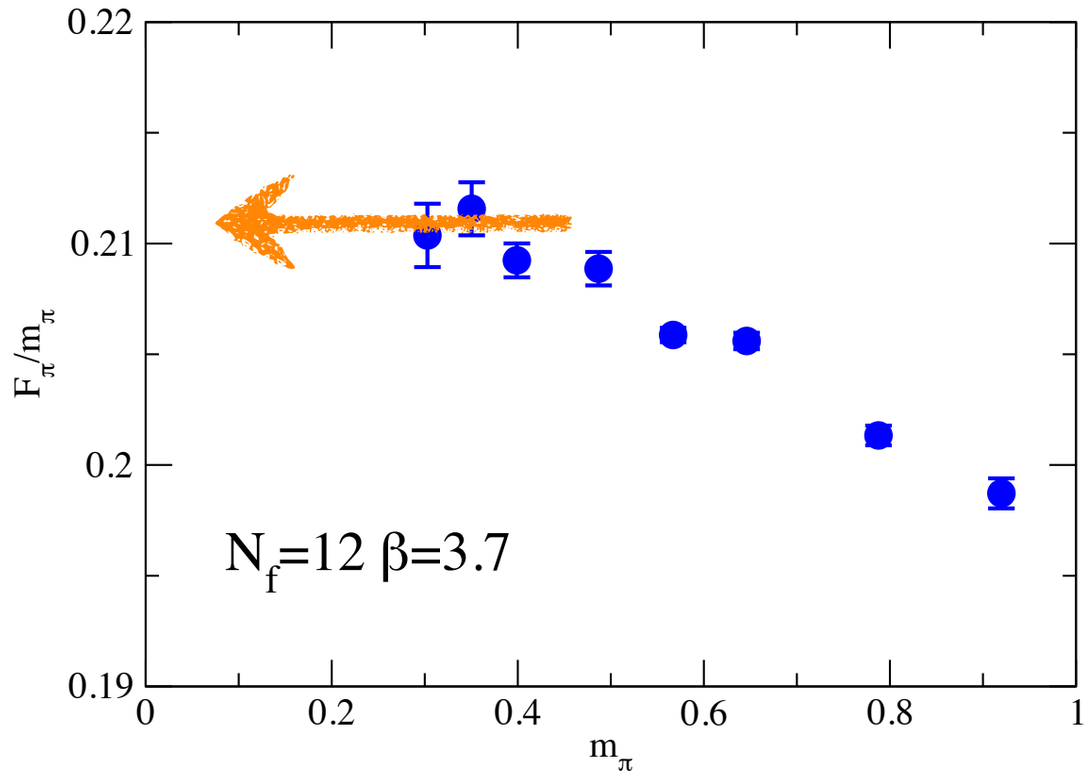
- S χ SB phase:
  - ChPT
  - at leading: $M_\pi^2 \propto m_f$, ; $F_\pi = F + c\, m_f$

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
  - ★ $F_\pi/M_\pi \to$ const. for small m_f
  - ★ $M_\rho/M_\pi \to$ const. for small m_f

a crude analysis: F_π/M_π vs M_π

N_f=12



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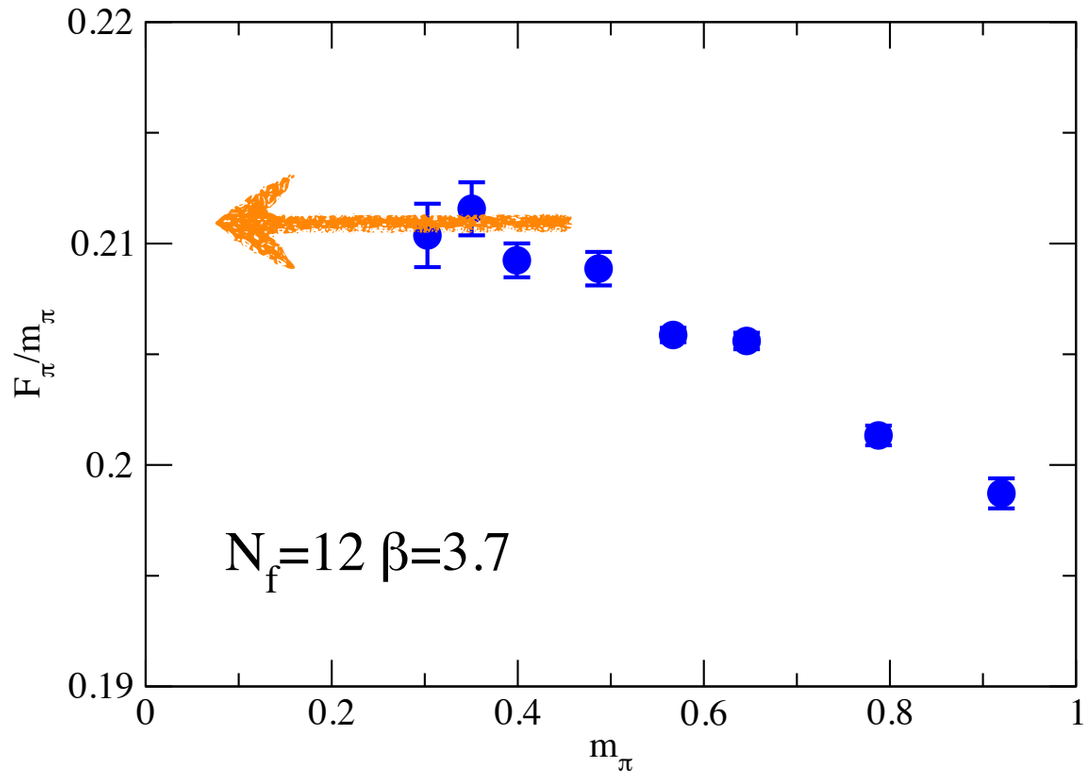


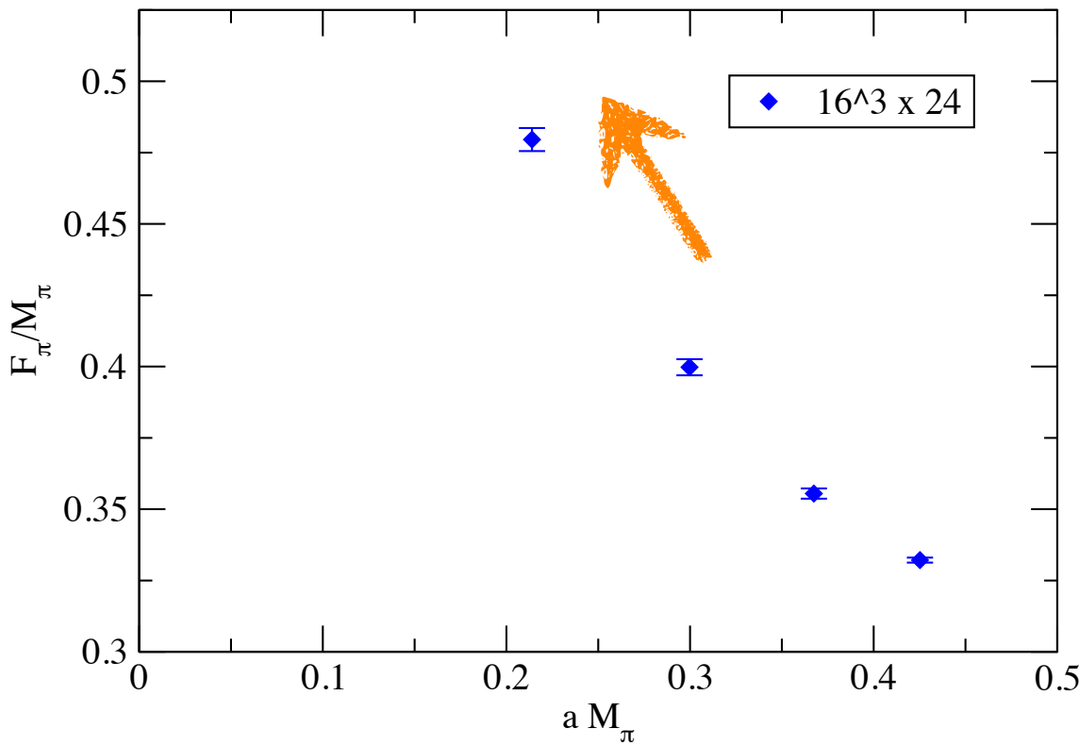
- small mass region: flat ⇔ hyperscaling ⇔ consistent with conformal scenario

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
  - ★ $F_\pi/M_\pi \to$ 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 $m_f \to 0$

a crude analysis: F_π/M_π vs M_π

$N_f=4$



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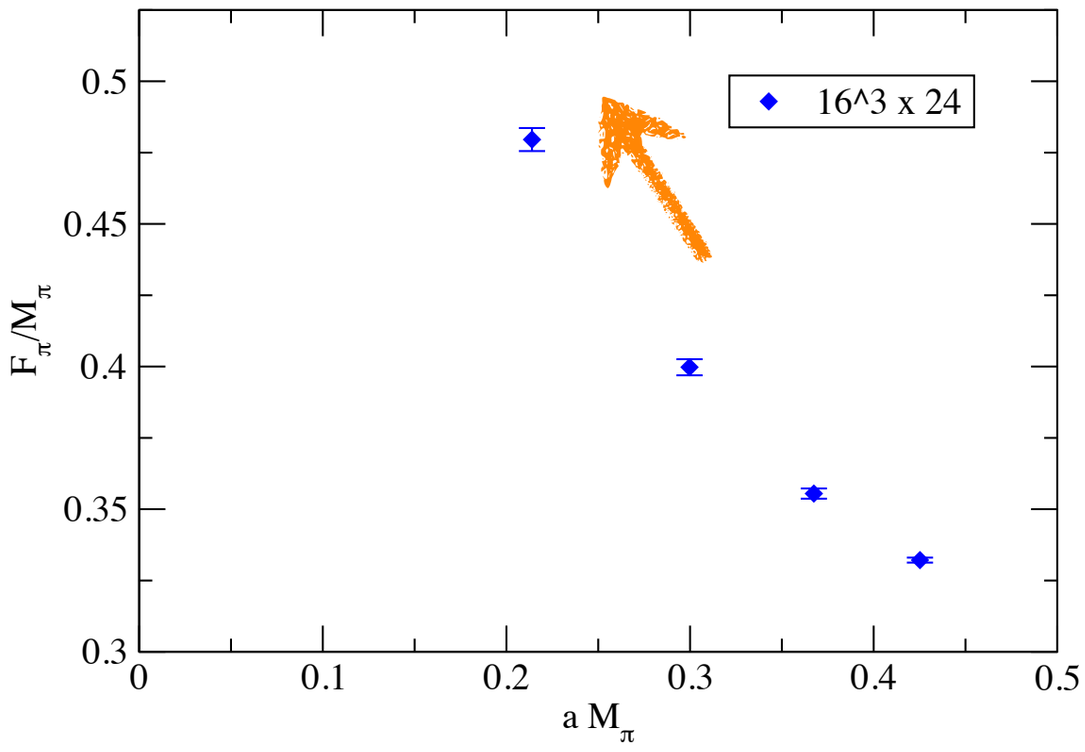

- tends to diverge towards the chiral limit ($M_\pi \to 0$)

a crude analysis: F_π/M_π vs M_π

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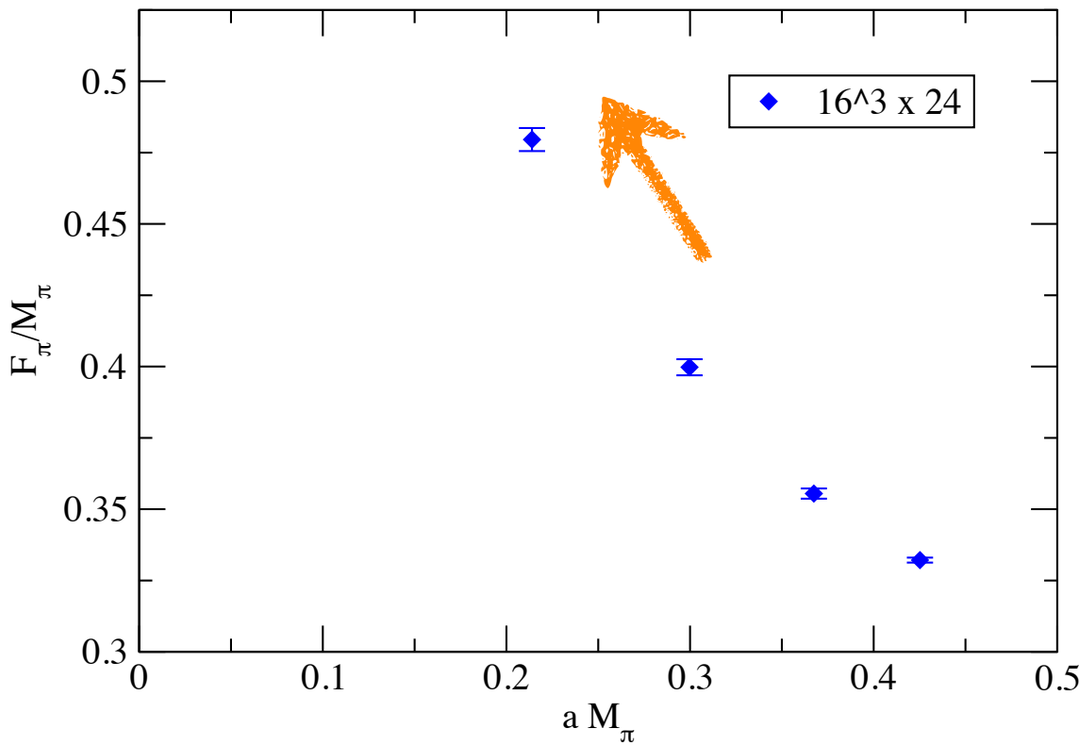
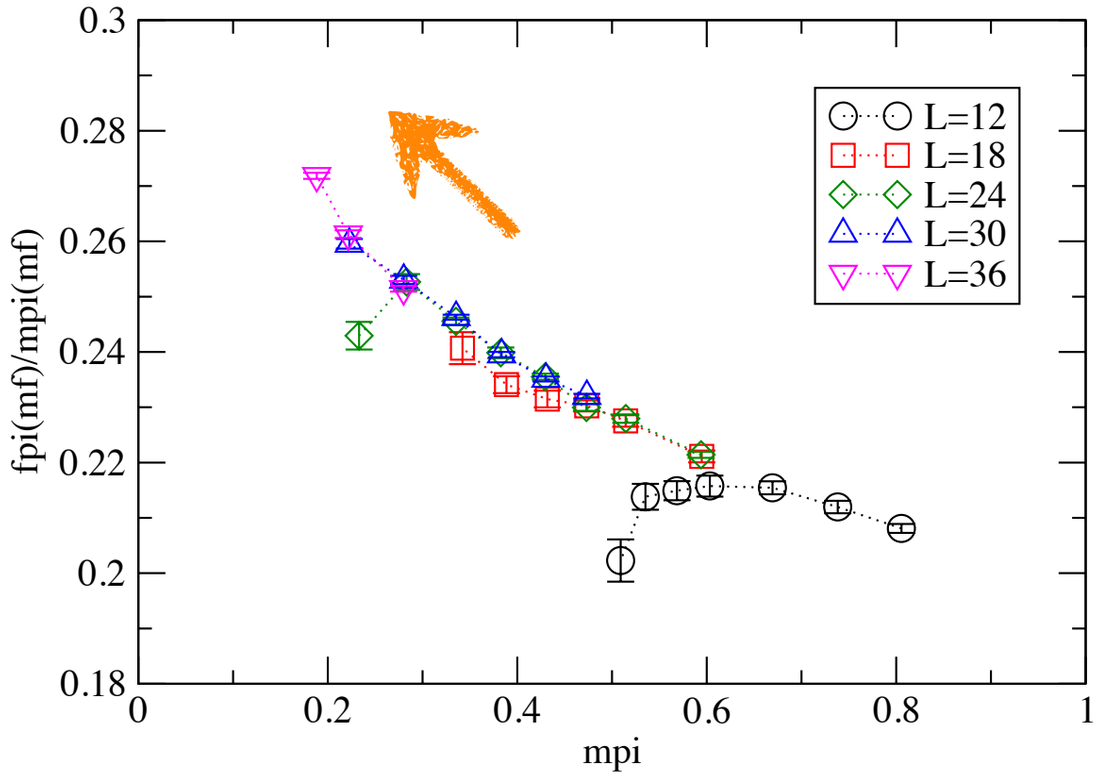


- tends to diverge towards the chiral limit ($M_\pi \to 0$)
- spontaneous chiral symmetry breaking

a crude analysis: F_π/M_π vs M_π

$N_f=8$



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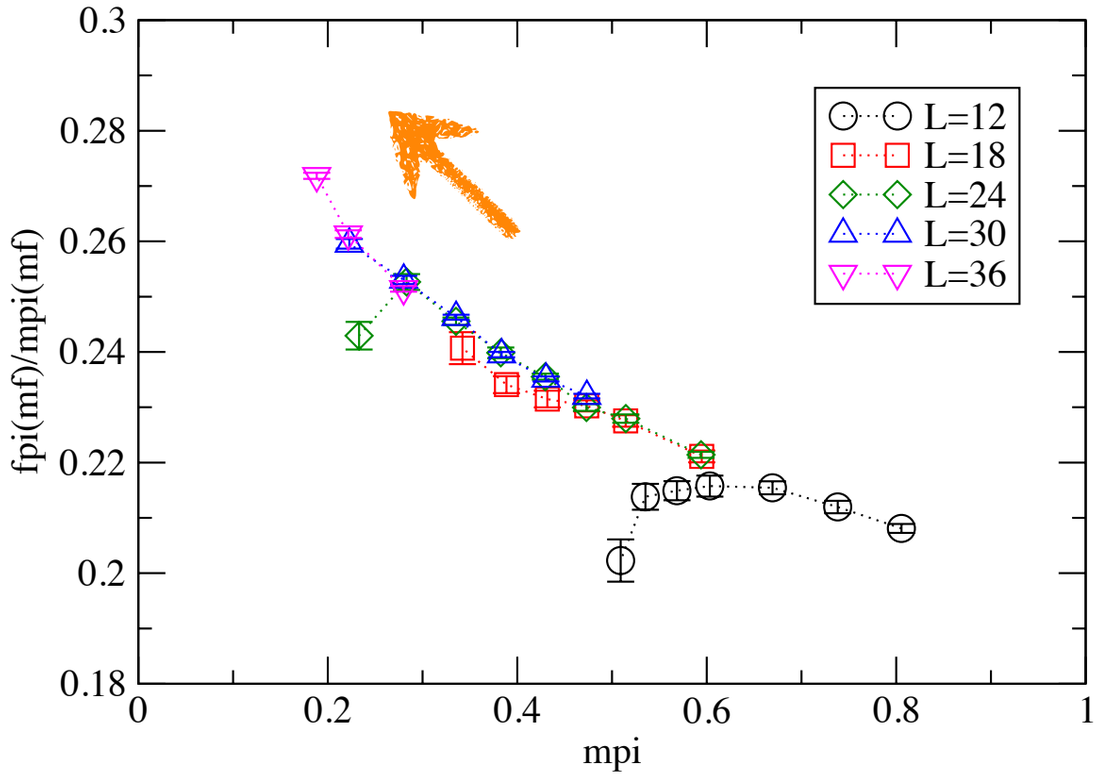

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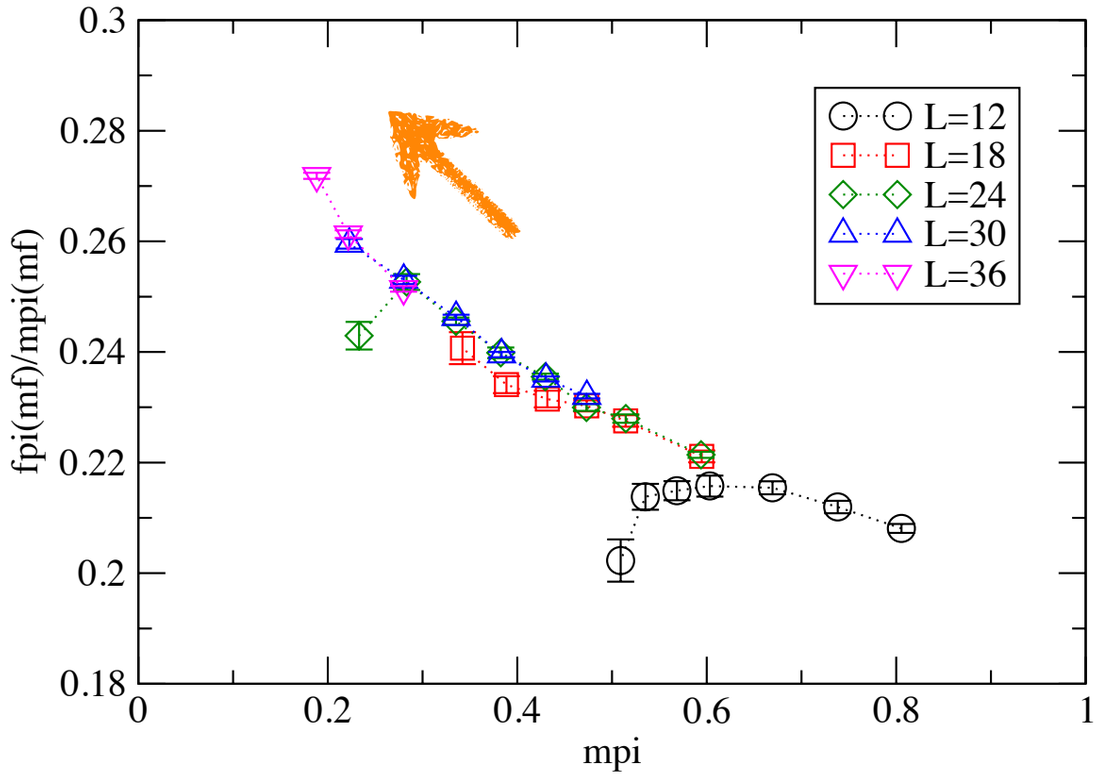
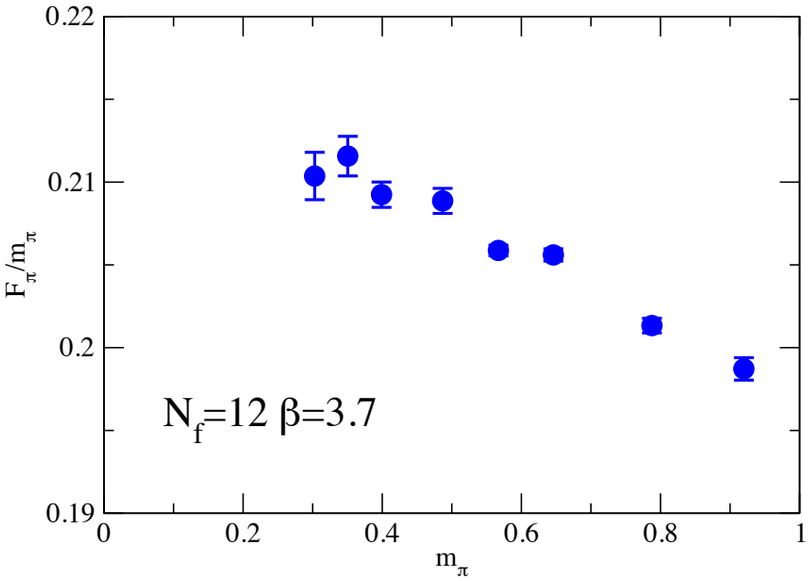


- tends to diverge towards the chiral limit ($M_\pi \to 0$)
- spontaneous chiral symmetry breaking, likely

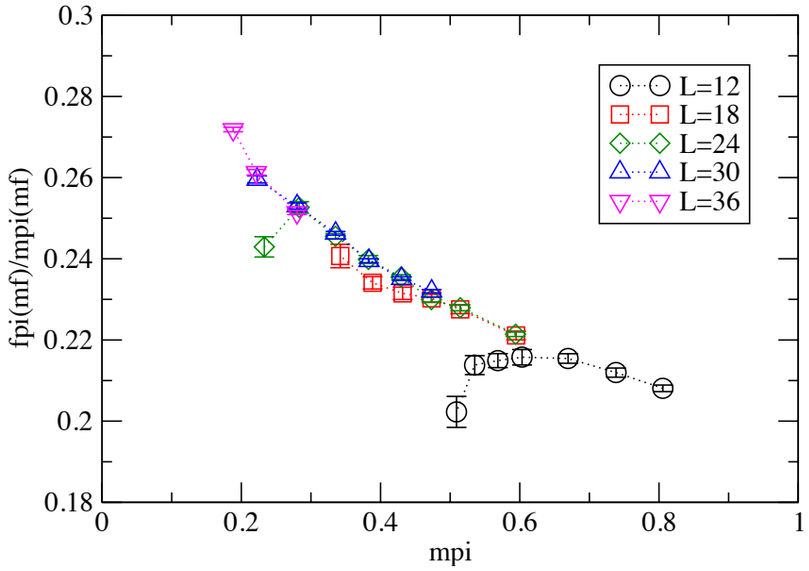
a crude analysis: F_π/M_π vs M_π leads to a likely scenario

N_f=12



- conformality

N_f=8



- ~~chiral symmetry~~

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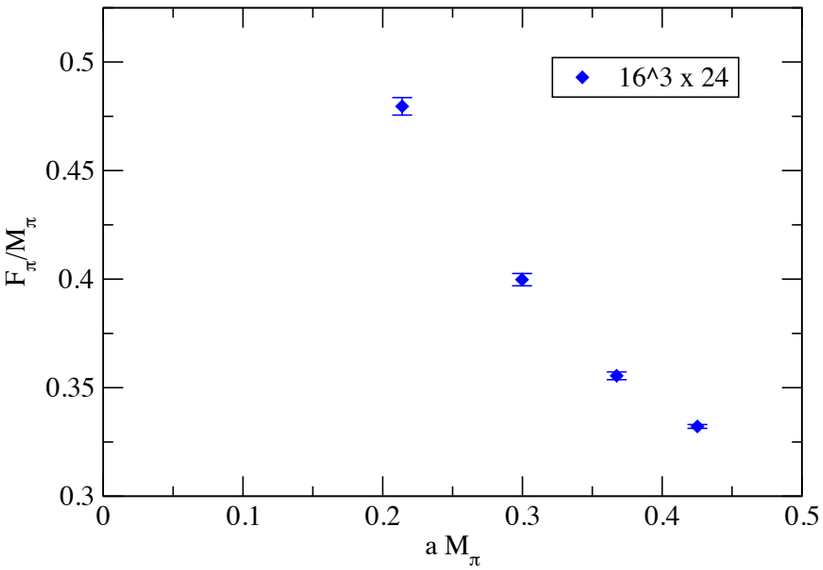

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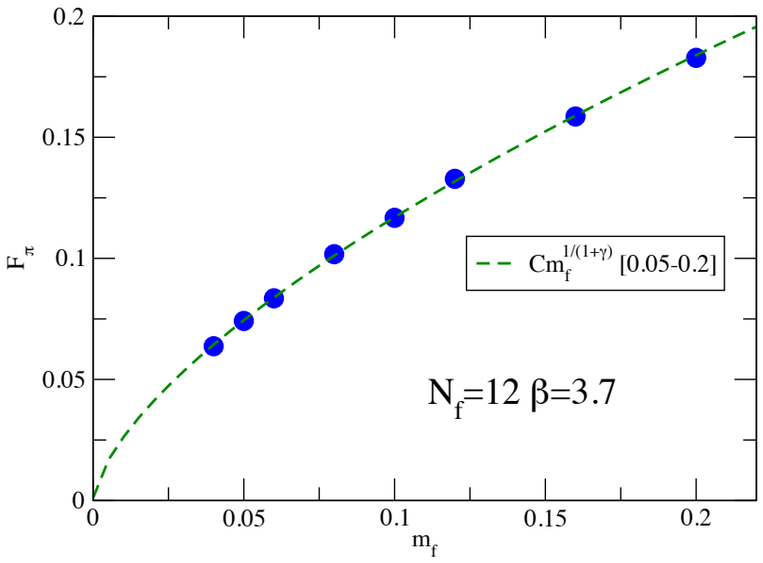
Detailed analysis of F_π vs m_f

N_f=12



- conformality
- $F_\pi \to C m_f^{1/(1+\gamma)}$
- γ~0.5

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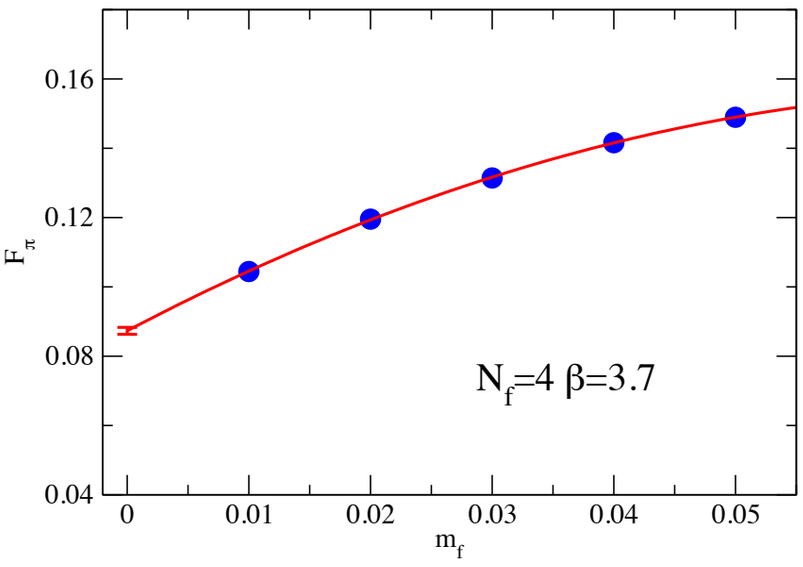

- ~~chiral symmetry~~
- $F_\pi \to F \neq 0$

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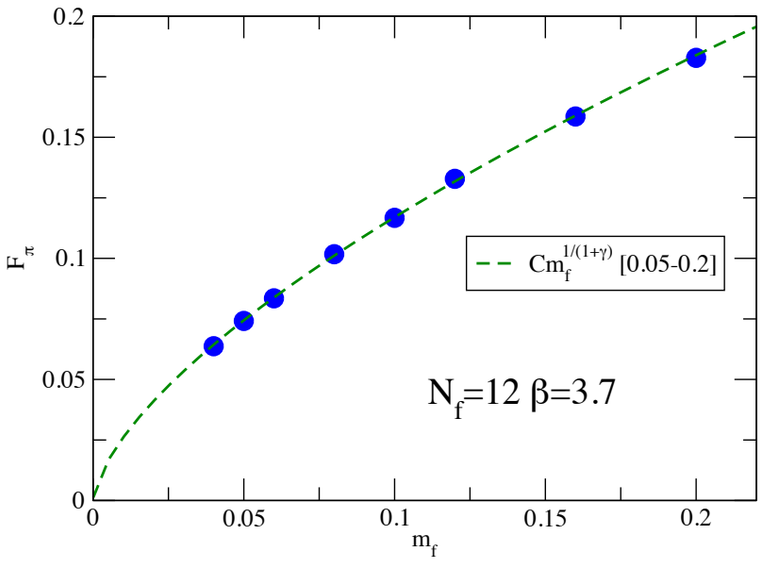

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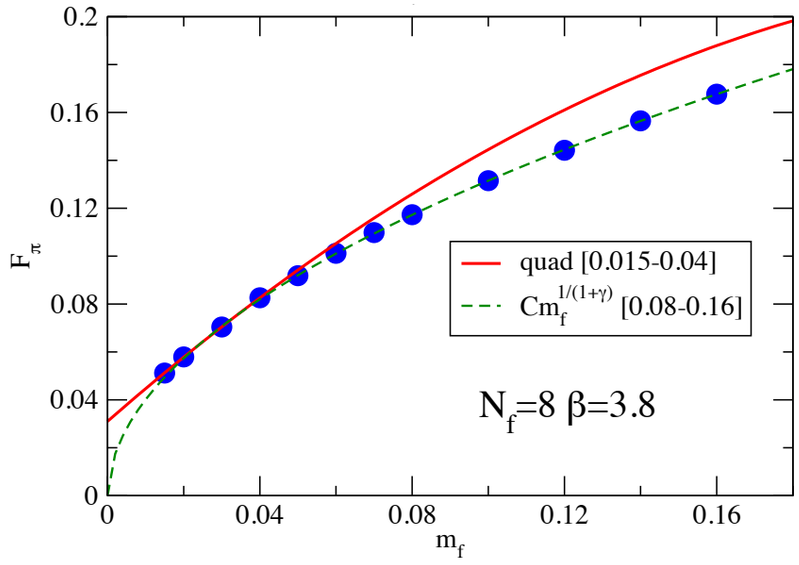

- ~~chiral symmetry~~
- $F_\pi \to F \neq 0$ $m_f \to 0$
- $F_\pi \to C m_f^{1/(1+\gamma)}$ intermediate m_f
- γ~0.9

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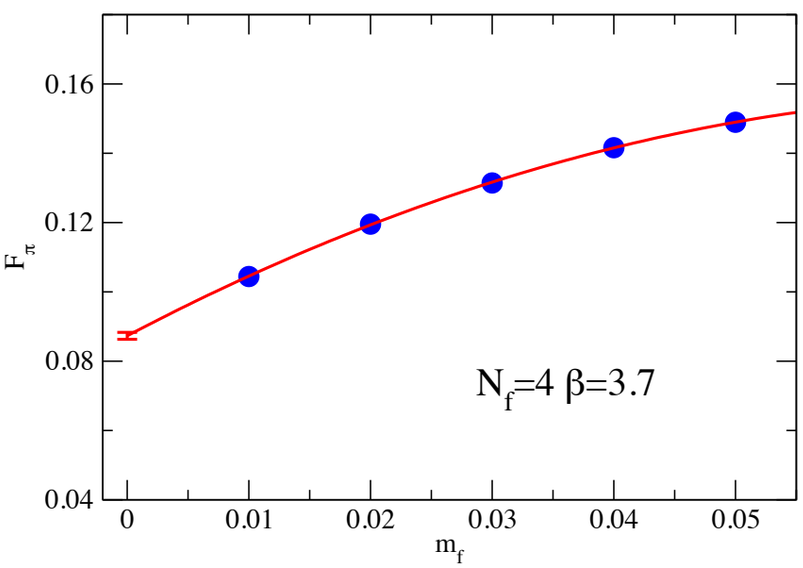

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N_f=8: an interpretation

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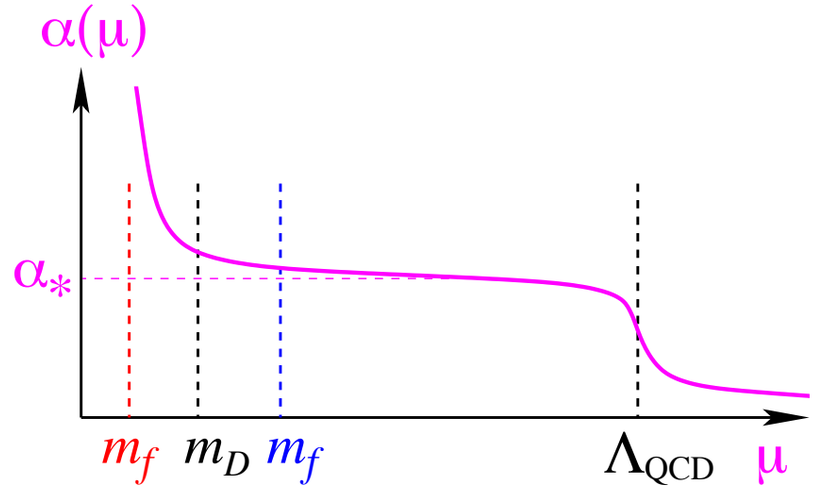

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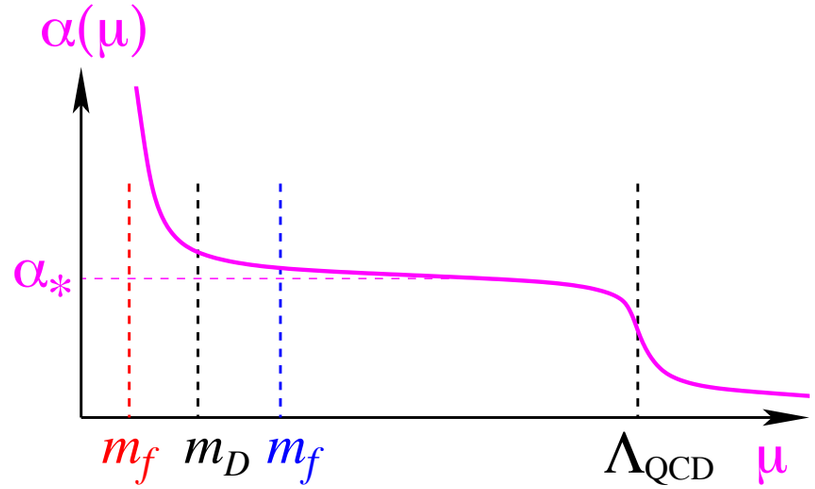

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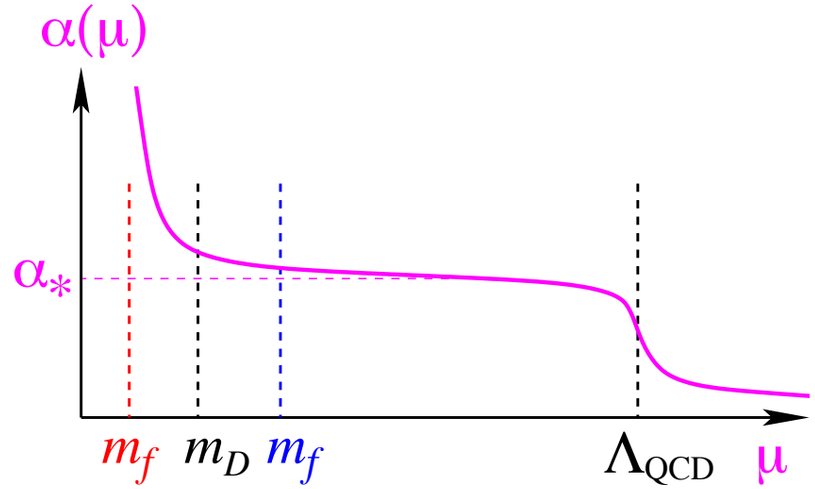

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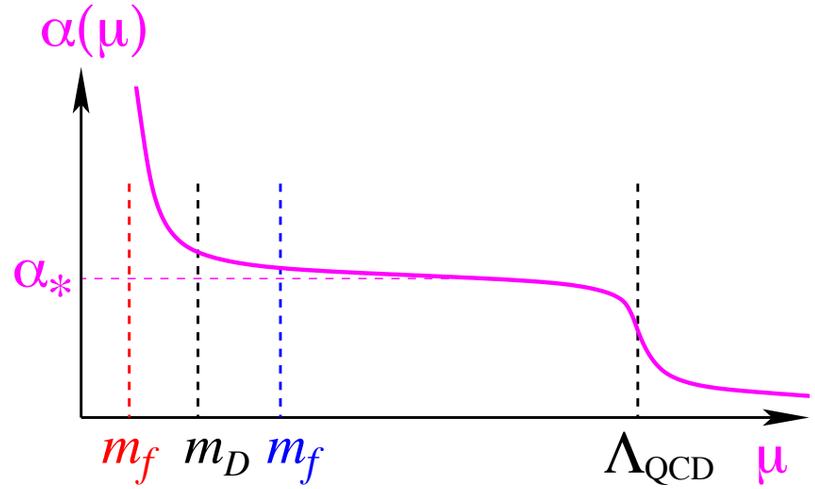
  - spectrum ?



N_f=8 spectrum

- with input F_π = 246 /√N GeV (N: # weak doublet in techni-sector)
- prediction: $M_\rho/F_\pi = 7.7(1.5)(^{+3.8}_{-0.4})$ (with only technicolor dynamics)
  - for example: $M_\rho = 970(^{+515}_{-195})\ \mathrm{GeV}$ for one family model: N=4
- Higgs mass ?
  - 0++: one of the difficult quantities on the lattice
  - multi-faceted nature of N_f=8 adds another difficulty: delicate chiral extrapl.

➡ first analyze simpler N_f=12, which shares “conformality” → techni dilaton

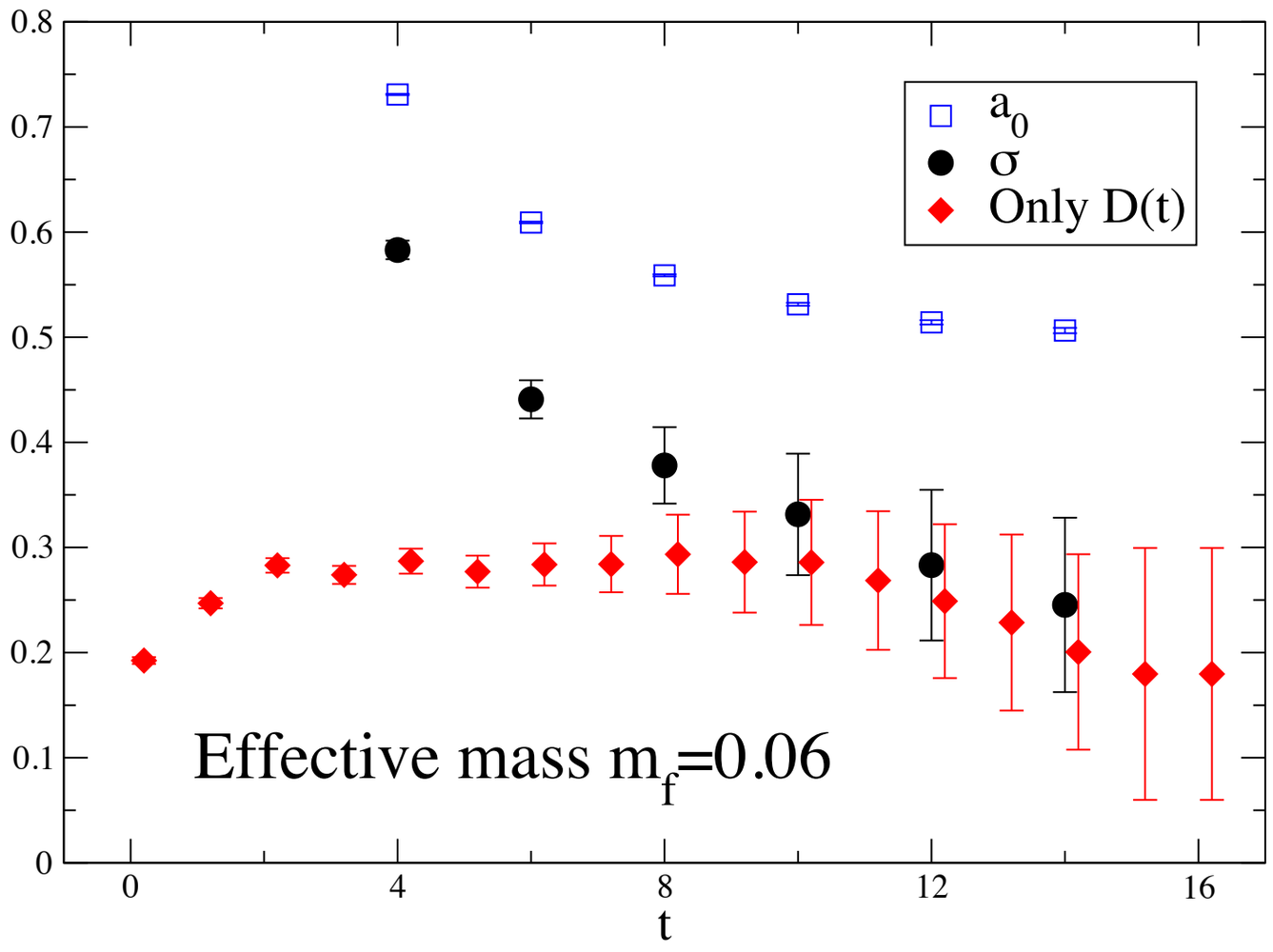
➡Is 0++ state light in (mass deformed) N_f=12 theory

0++ state for N_f=12: fermion bilinear operator

- technique developed staggered fermions in QCD for disconnected diagrams
  - use of Ward-Takahashi identity (Kilcup-Sharpe, NPB(1987)493)
    - large reduction of noise than simple application of stochastic method
      - ~10 times efficient in computation effort
  - already applied to
    - real QCD: N_f=2+1: Gregory et al, η’
    - N_f=12: Jin & Mawhinney, 0++ at bulk transition boundary
- high statistics
  - ~10k configurations

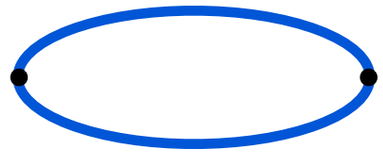
Effective mass in $N_f = 12$ ($m_f = 0.06, 24^3 \times 32$ with $N_{\text{conf}} = 14000$, Preliminary)

$$m_{\text{eff}}(t) = \log(C_H(t)/C_H(t+1)) \xrightarrow{t \gg 1} m_H$$



Nonsinglet scalar

a_0: $-C_+(2t)$



Singlet scalar

σ: $D_+(2t) - C_+(2t)$

$m_\sigma < m_{a_0}$

Only $D(t)$

Consistent m_σ

Smaller error

$$X_+(2t) = 2X(2t) + X(2t+1) + X(2t-1)$$

Good signal of m_σ from $D(t)$

0++ state for N_f=12: through glueball operator

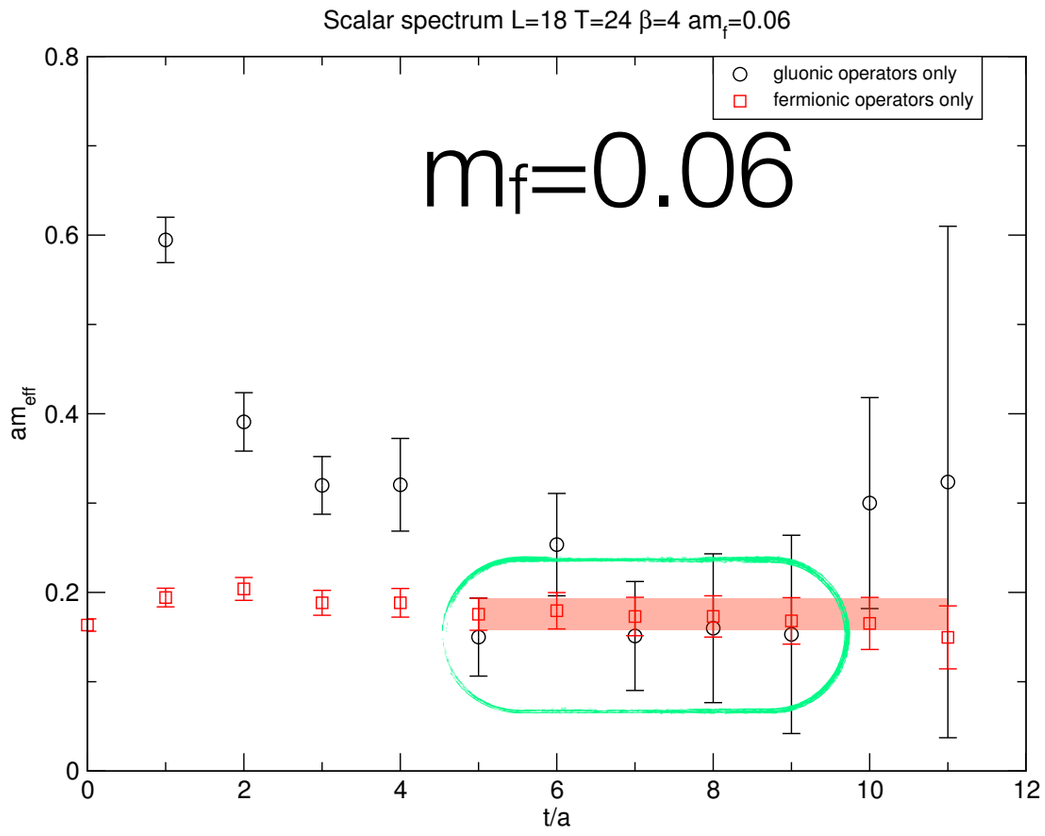
- technique developed in QCD
  - optimization of the operator (Lucini, Rago, Rinaldi, JHEP08(2010)119)
    - multi-shapes
    - multi-level smearing
    - variational analysis
  - for the first time applied to many flavor system
- high statistics
  - ~10k configurations

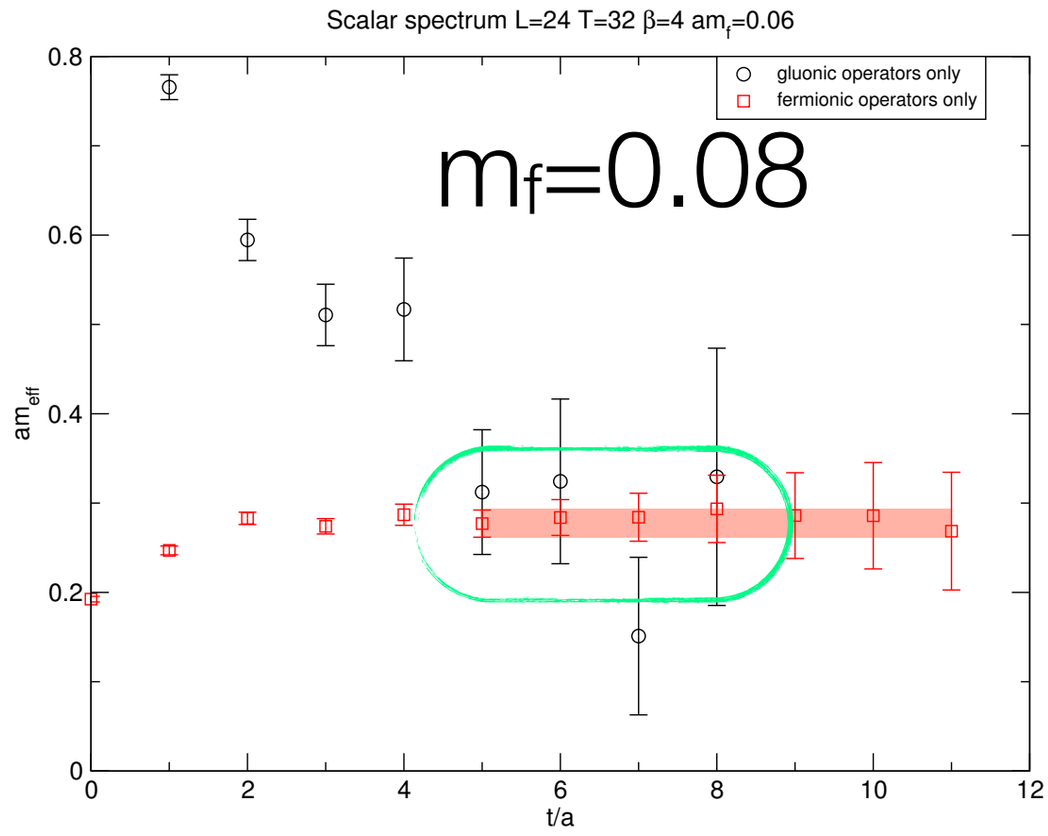
Comparison of effective mass in $N_f = 12$

($m_f = 0.06$, $18^3 \times 24$ with $N_{\text{conf}} = 5000$, $24^3 \times 32$ with $N_{\text{conf}} = 14000$, Preliminary)

$$m_{\text{eff}}(t) = \log(C_H(t)/C_H(t+1)) \xrightarrow{t \gg 1} m_H$$

Glueball correlator and meson $D(t)$





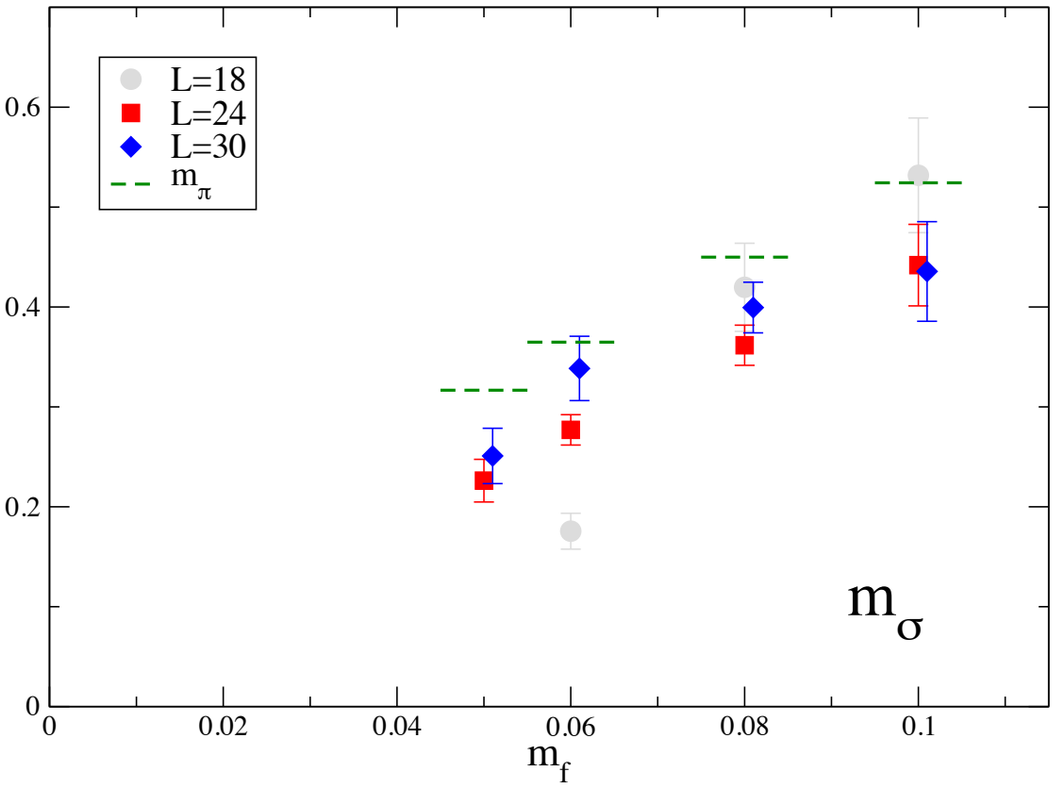
Larger error in glueball correlator

Reasonably consistent in large t

→ will show only fermion bi-linear results

m_f dependence in $N_f = 12$ (Preliminary)

m_σ from effective mass of $D(t)$ at $t = 5$



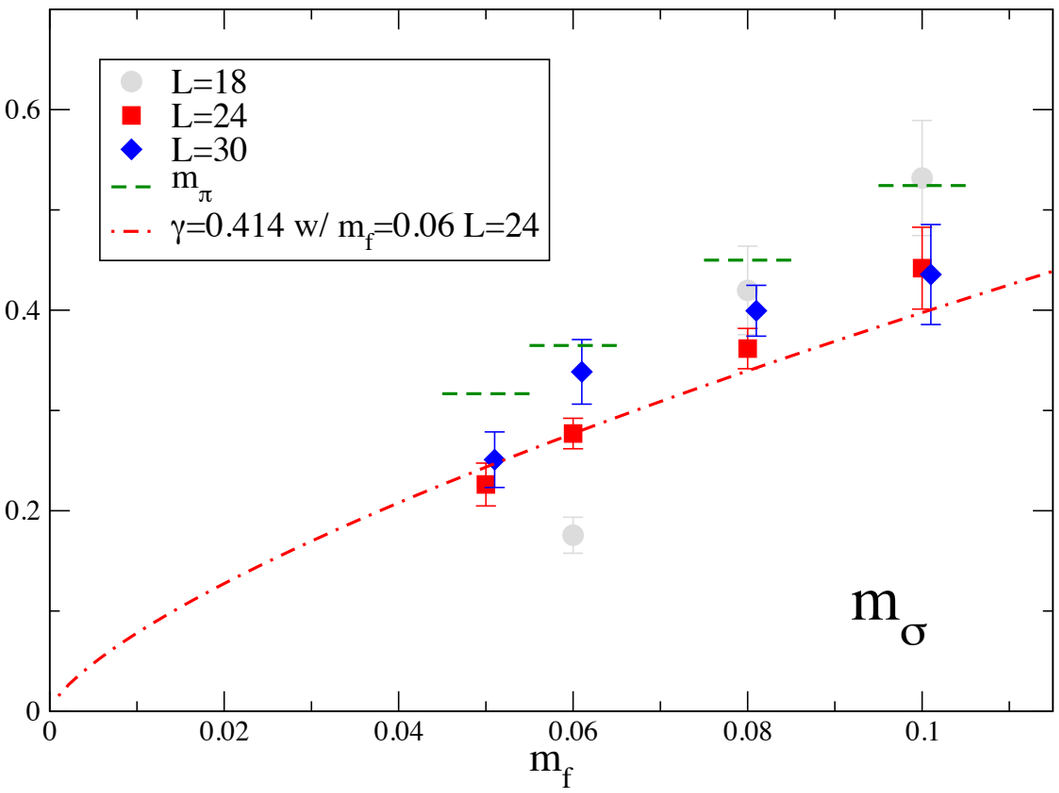
Flavor-singlet scalar is relatively light?

Lighter than π

Hyperscaling is seen as in m_π?

m_f dependence in $N_f = 12$ (Preliminary)

m_σ from effective mass of $D(t)$ at $t = 5$



Flavor-singlet scalar is relatively light?

Lighter than π

Hyperscaling is seen as in m_π?

$m_\sigma = C m_f^{1/(1+\gamma)}$ with $\gamma = 0.414$ from hyperscaling of m_π

N_f=12, 0++: summary of PRELIMINARY results

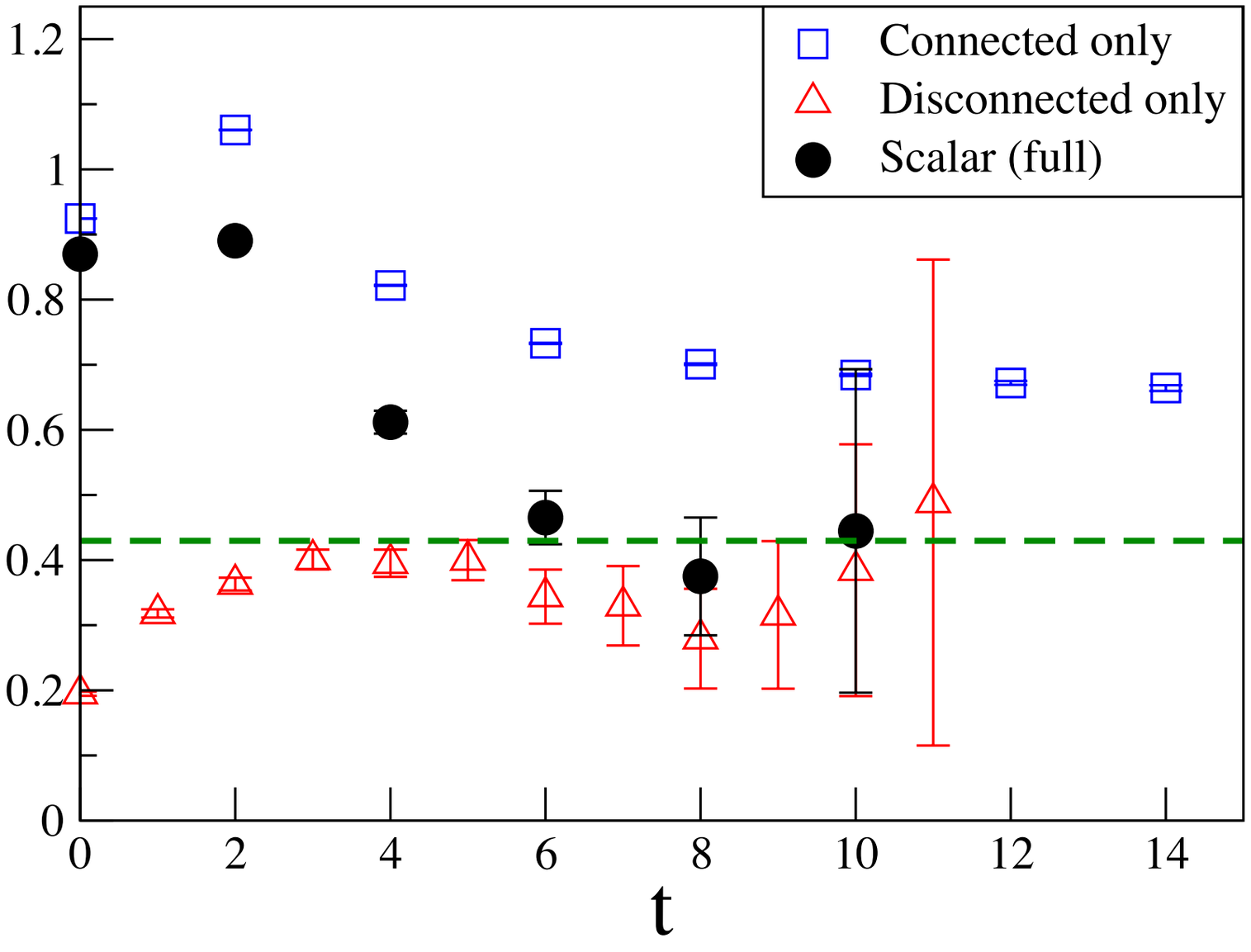
- consistent mass observed for both glueball and fermion bilinear operators
- σ is light! : lighter than pion
  - promising indication for walking theory realized in near Nf: cf, N_f=8
- σ mass more of less consistent with conformal hyperscaling
- to be tested with higher statistics and careful analysis...

- what about N_f=8 ?
  - we have a PRELIMINARY result at one m_f point

$$N_C = 3,\ N_f = 8,\ \beta = 3.8,\ m_f = 0.06,\ V = 24^3 \times 32$$

Effective mass plot

indicating σ as light as π



M_π

arXiv:1302.6859[hep-lat]
LatKMI Collaboration

$(F_\pi \sim 0.1)$

Summary and Outlook

- SU(3) gauge theory with N_f fundamental fermions is studied with HISQ
- summary
  - Nf=12 [LatKMI PRD86(2012)054506]
    - consistent with conformal with small γ_m
  - Nf=8 [LatKMI arXiv:1302.6859]
    - spontaneous chiral symmetry breaking
    - conformal scaling @ intermediate mass indicating largish γ_m
    - candidate of walking technicolor theory
    - ➡ needs further check at smaller m_f

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    - spontaneous chiral symmetry breaking
    - prediction: $M_\rho/F_\pi = 7.7(1.5)(^{+3.8}_{-0.4})$ (with only technicolor dynamics)
      - for example: $M_\rho = 970(^{+515}_{-195})\ \mathrm{GeV}$ for one family model: N=4

➡ needs further check at smaller m_f

Summary and Outlook

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Summary and Outlook

- summary of PRELIMINARY results
  - Nf=12
    - successfully extracted light 0++ state: lighter than pion
    - consistency checked : glueball operator ⇔ fermion bilinear

    ➡ to be tested with higher statistics and careful analysis
- Nf=8
  - light 0++ state observed for one mf: as light as pion
  - interesting candidate of WTC with light Higgs

  ➡ needs further in-depth study

Thank you for your attention