BSM

—Near Conformal Strong Dynamics—

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- Lattice 2014 -

June 26, 2014

Nagoya University

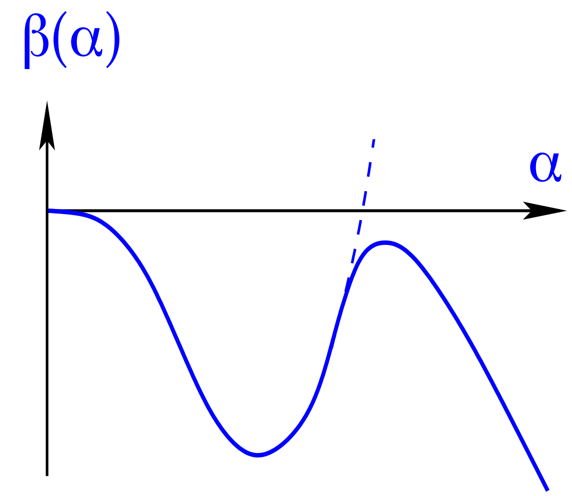
Request from LOC

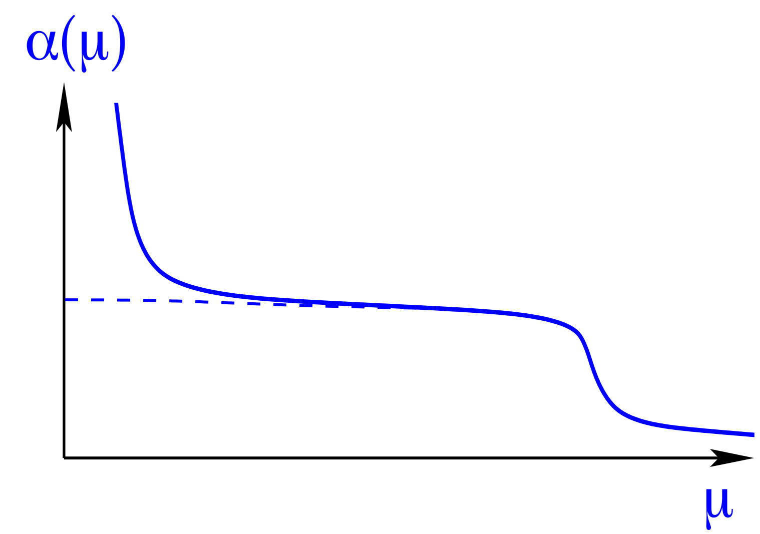
We would like you to give a review talk on the current status of lattice BSM simulations, especially the progress towards a possible light scalar in strongly interacting gauge theories. This could include your recent work, as well as other similar studies.

Walking Technicolor for composite description of Higgs particle

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

[Holdom, Yamawaki-Bando-Matsumoto]





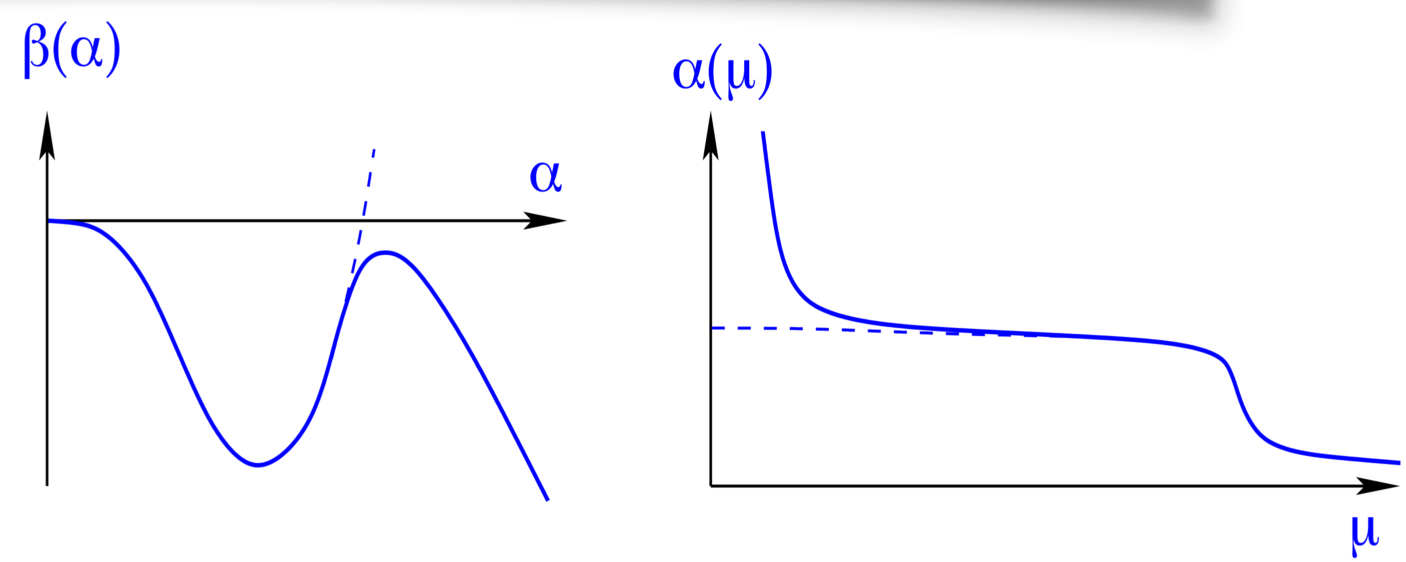
- renormalized gauge coupling
  - to run very slowly (walking)
  - eventually grows at low energies → to produce techni-pions
- mass anomalous dimension
  - large: $\gamma_m \sim 1$

Walking Technicolor for composite description of Higgs particle

- key: t[...]

Is it possible to construct such a theory ?

[...]moto]



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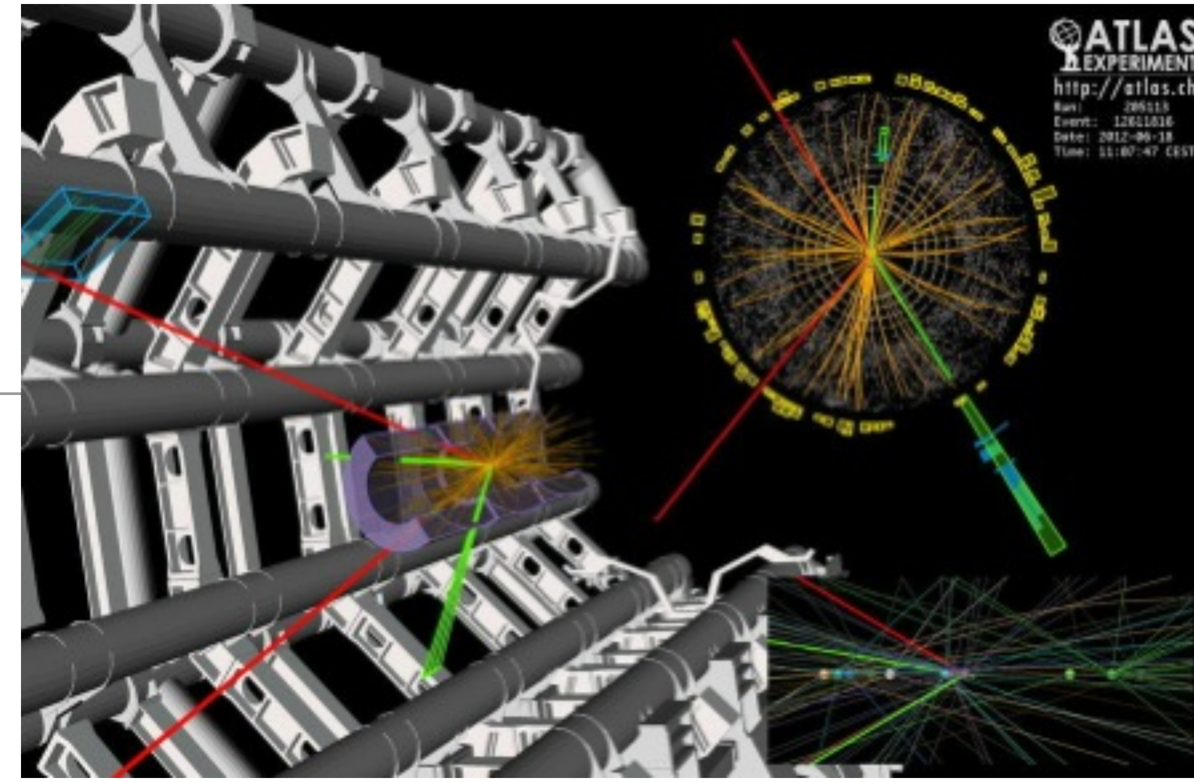
“Higgs boson”



- Higgs boson fund at LHC
- m_H = 125 GeV
- so far consistent with Standard Model Higgs ($J^{PC}=0^{++}$) fundamental scalar
- but it could be different
- one of the possibilities:
    - composite Higgs through strong dynamics
    - SM Higgs is the low energy effective description of that, cf: ChPT ⇔ QCD

after July 4, 2012

- Some people think technicolor is dead (how many times it should die ?)
  - m_H=125 GeV is too light for technicolor (typical composite mass ~ TeV)
- Some think walking technicolor is still OK
  - who ?
    - the authors of PRD 82 014510 (2010)
      - and people well aware the results
    - Yamawaki, Bando, Matumoto, PRL 56 1335 (1986)
      - and who believed that

Higgs as a techni dilaton
[Yamawaki, Bando, Matumoto,   PRL 1986]

- approximate scale invariance in the walking technicolor theory
- spontaneously broken due to chiral symmetry breaking → dynamical mass
- composite Higgs particle behave like pseudo Nambu-Goldstone boson

  ➡light!

- We can test this using lattice QCD tools !
- I will review the progress in this direction and related works in (near) conformal theories on the lattice

Strong gauge dynamics for BSM @ Lattice 2014

- vacuum alignment [Golterman 3F]
- Walking TC / toy model [Akerlund 1C]
- SU(2) gauge
  - Nf=2 fundamental [Rinaldi 2C, Hietanen 2C, Detmold 8C, Drach 8C]
  - Nf=4 fundamental [Matsufuru 1C]
  - Nf=6 fundamental [Matsufuru 1C]
  - Nf=8 fundamental [Huan 1C, Matsufuru 1C, Rantaharju 5C]
  - Nf=2 adjoint [Del Debbio 5C]
  - Nf=2 sextet [Sinclair 1C]

Strong gauge dynamics for BSM @ Lattice 2014

- SU(3) gauge
  - Nf=2+N fundamental [Ejiri P]
  - Nf=4+8 fundamental [Weiberg 2C, Witzel P]
  - Nf=6 fundamental [Nunes da Silva 1C]
  - Nf=8 fundamental [Nunes da Silva 1C, Nagai 9C, Ohki 9C]
  - Nf=12 fundamental [Rinaldi P, Geltzer P, Itou P, Hasenfratz 5C, Lin 5C]
  - Nf=2 sextet [Kuti 2C, Wong 2C, Mondal 8C]
- SU(4) gauge
  - Bosonic composite DM [Buchoff 8C]
  - Nf=2 sextet [Liu 9C]

Other BSM models @ Lattice 2014

- Higgs sector
  - gauge-Higgs unification [Moir 2C, de Forcrand 8C]
  - Higgs-Yukawa with Φ^6 [Nagy 9C]
- Supersymmetry
  - N=1 SYM [Muenster P, Piemonte 6C]
  - N=4 SYM
    [Korcyl P, Joseph 6C, Wenger 6C, Catterall 6C, Giedt 6C, Schaich 6C]
- 4D Quantum Gravity [Laiho P]

BSM QCD matrix elements @ Lattice 2014

- BK with non-SM operators [Hansen 3C]
- nEDM (chromo) [Shindler 3C, Abramczyk]
- N charges [Yoon 4D, Gupta 6D]
- proton decay [Soni P]
- N-Nbar oscillation [Wagman P]

Many thanks to those who let me know the works

G. Schierholz [Horsley, Perit, Rakow, Schierholz, Schiller, PLB 2014]

- numerical stochastic perturbation theory to 20th order in pure gauge QCD
    - combined with 4-loop fermion effect and/or Pade improvement
    - IR fixed point emerges even for Nf=2

M. Della Morte [Della Morte and Hernandez JHEP 1311; Lattice 2013]

- non-perturbative study of massive gauge theories: simplest EWSB

M. Hanada [Hanada, Hyakutake, Nishimura Sience 2014; 2E]

- gauge-gravity duality conjecture is correct to $1/\lambda$ and $1/N$

Thanks to the members of LatKMI collaboration

- YA, T.Aoyama, E, Bennett, M.Kurachi, T.Maskawa, K.Miura,

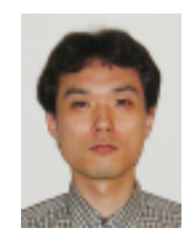





K.Nagai, H.Ohki, K.Yamawaki, T.Yamazaki

名古屋大学



KMi
IMK
KMI

- E. Rinaldi

Lawrence Livermore National Laboratory

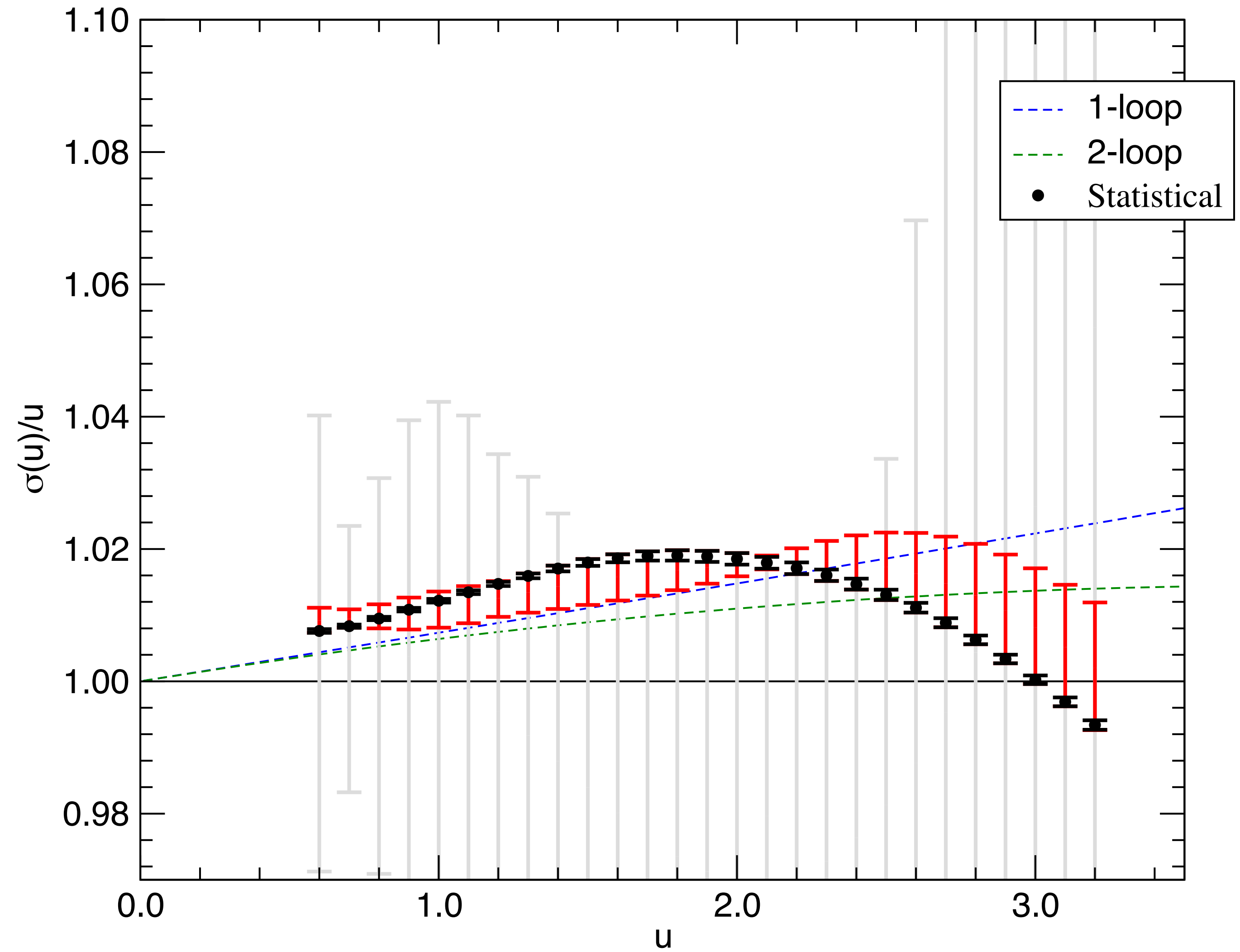
A.Shibata

KEK

Running coupling

running coupling from step scaling: issue of continuum extrapolation

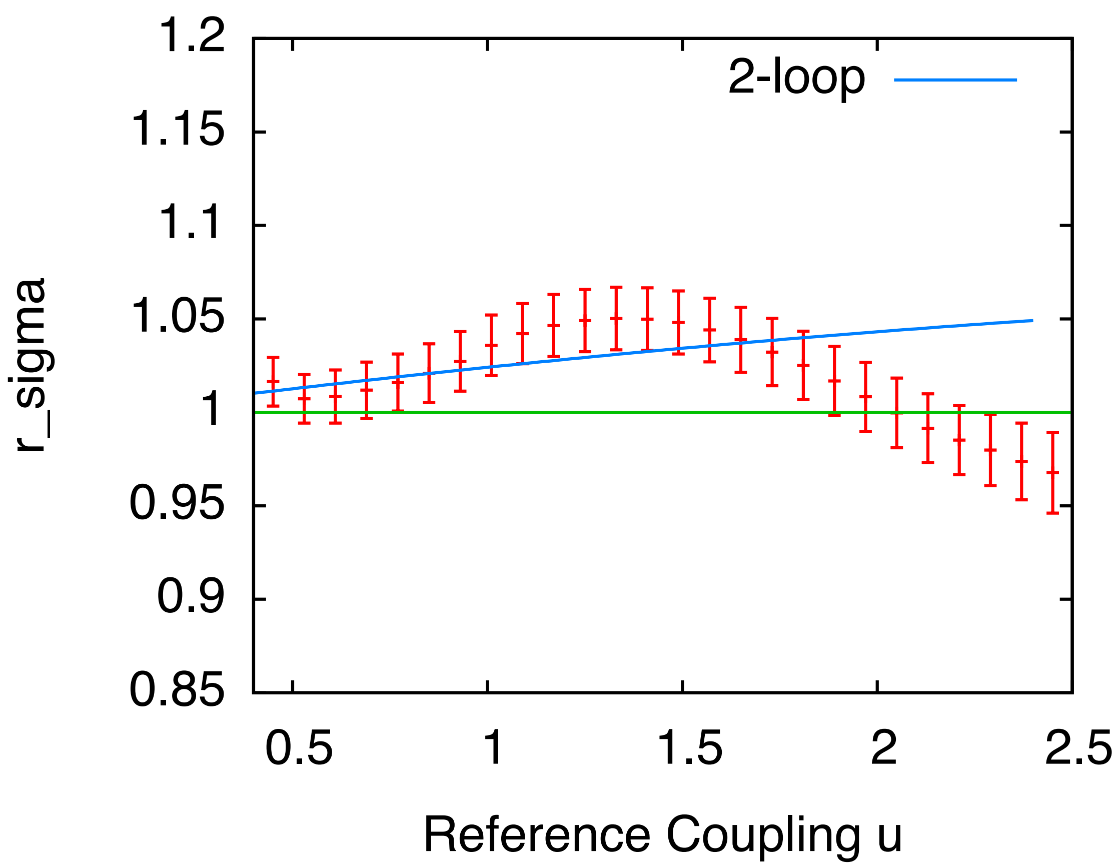
- SU(2) 2 adjoints: SF coupling [Del Debbio 5C]
- grey: "honest estimate of the systematic error"



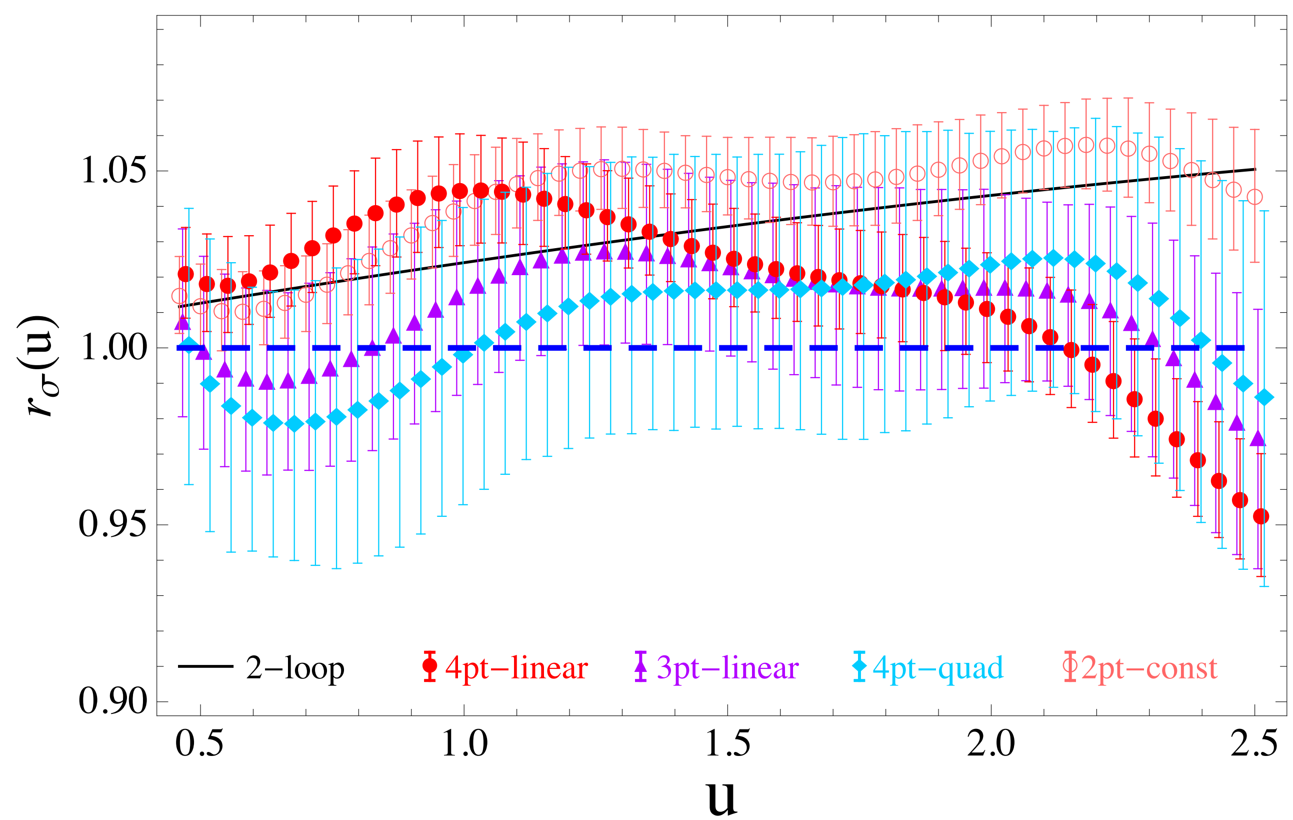
running coupling from step scaling:
issue of continuum extrapolation

C.-J.D.L., K.Ogawa, H.Ohki, E.Shintani, 2012

K.Ogawa, lattice 2013



without (L/a=12 ⟶ L/a = 24)
systematics severely underestimated...



with (L/a=12 ⟶ L/a=24)

- better method needed

SU(3) fundamental Nf=12: running coupling [Hasenfratz 5C]

[Cheng et al JHEP 1405]

- Wilson + adjoint gauge, nHYP smeared staggered
- gradient flow coupling and finite volume $c = \sqrt{8t}/L = 0.2$

SU(3) fundamental Nf=12: running coupling [Hasenfratz 5C]

- Wilson + adjoint gauge, nHYP smeared staggered

[Cheng et al JHEP 1405]

- gradier

Method being tested using MILC HISQ 2+1+1 flavor lattices

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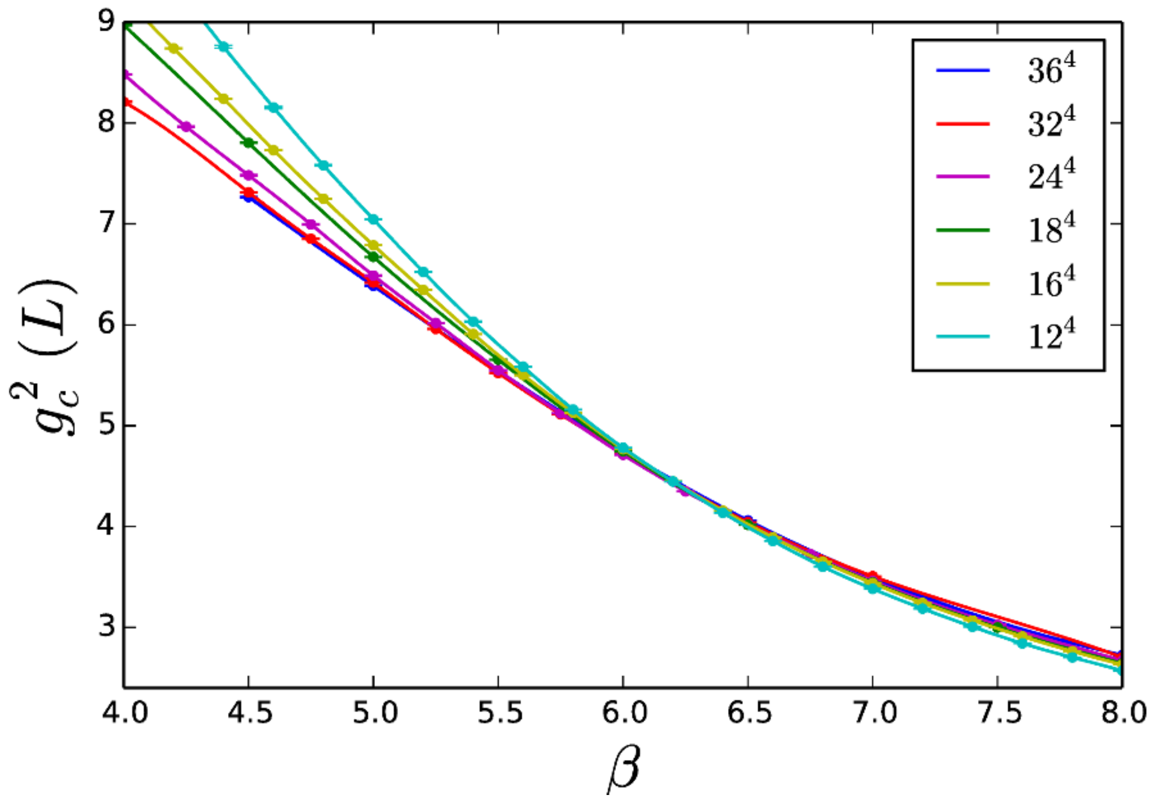

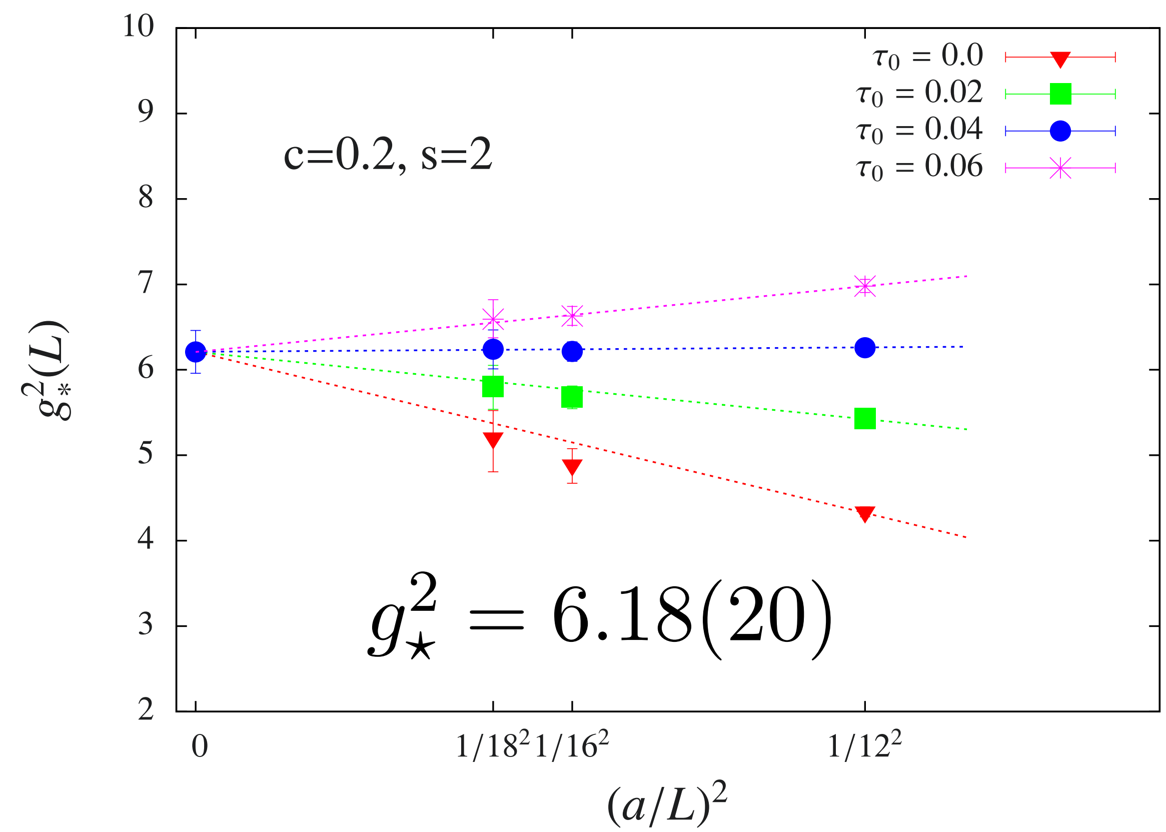

$$g^2_{\mathrm{GF}}(\mu; a) = g^2_{\mathrm{GF}}(\mu; a=0) + a^2\mathcal{C} + \mathcal{O}(a^4[\log a]^n, a^4)$$

$$\widetilde{g}^2_{\mathrm{GF}}(\mu; a) = \frac{1}{\mathcal{N}}\left\langle t^2 E(t + \tau_0 a^2)\right\rangle$$

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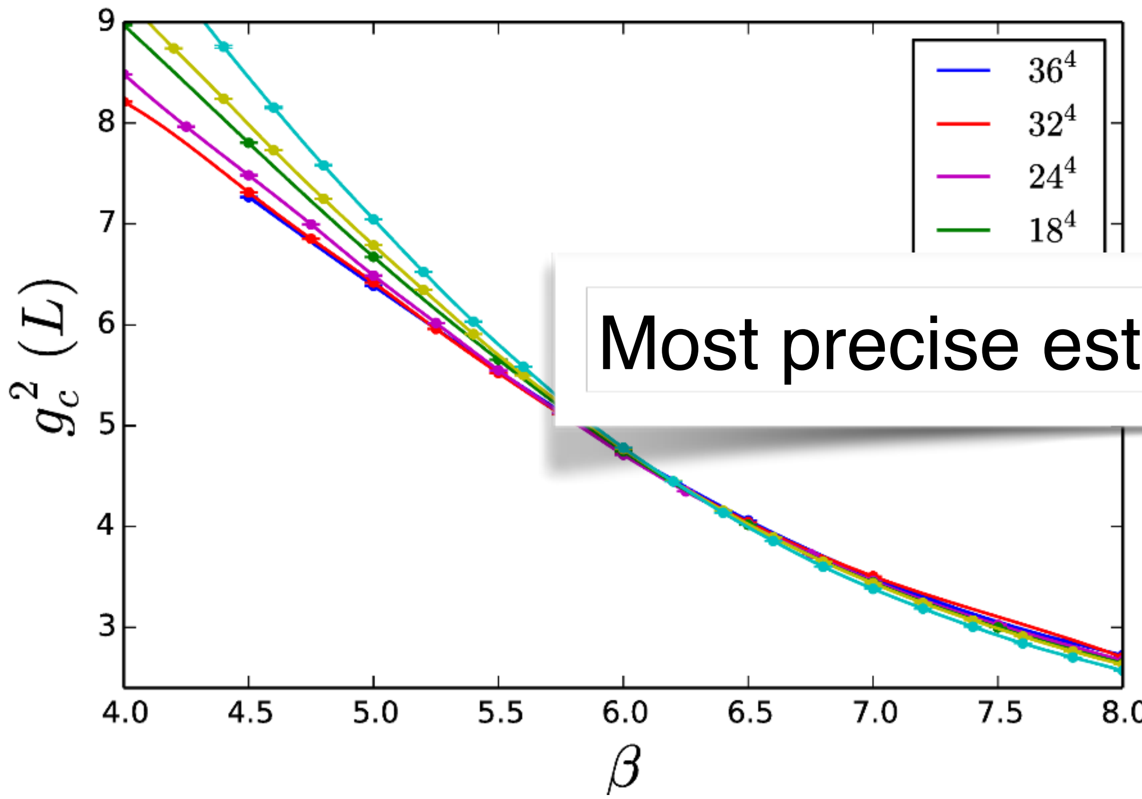
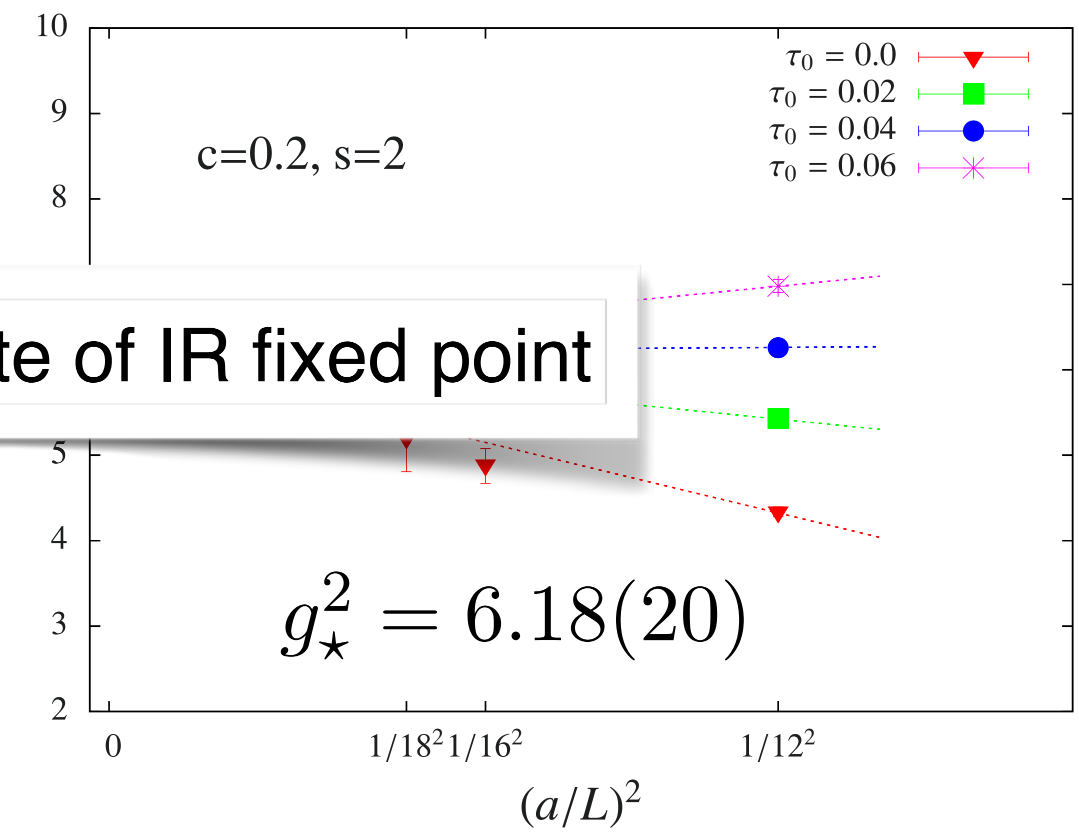


Most precise estimate of IR fixed point



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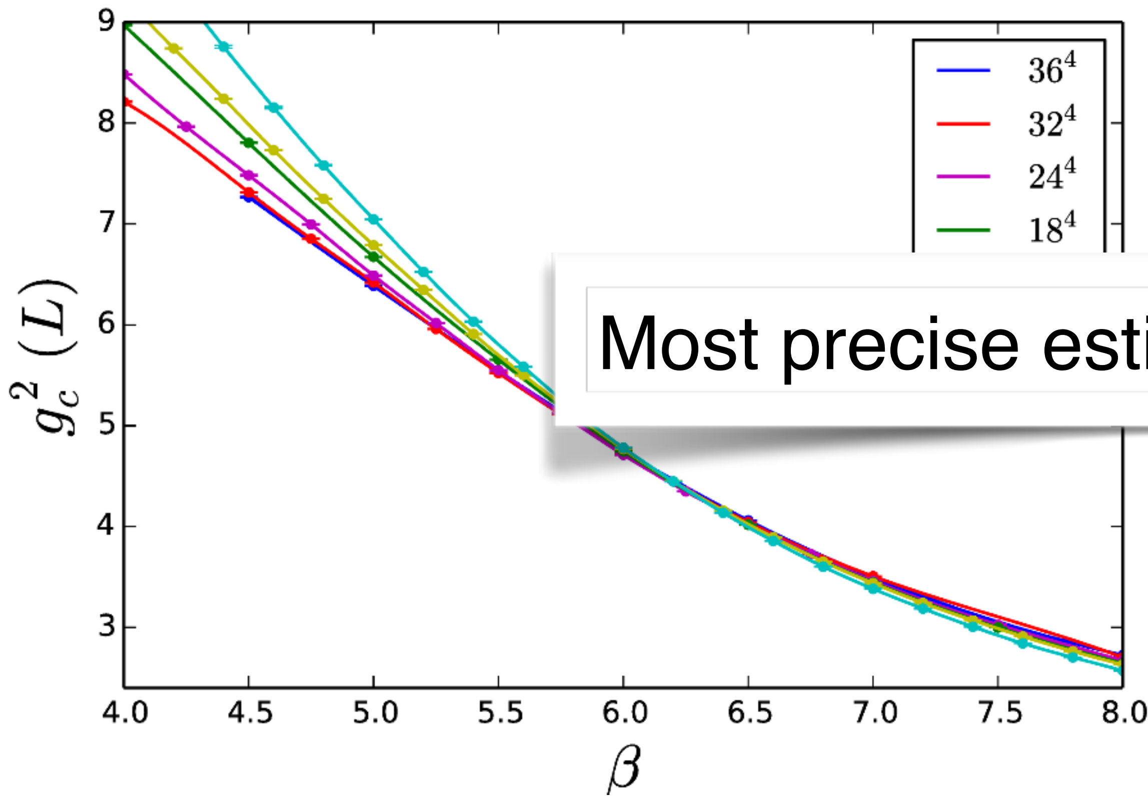

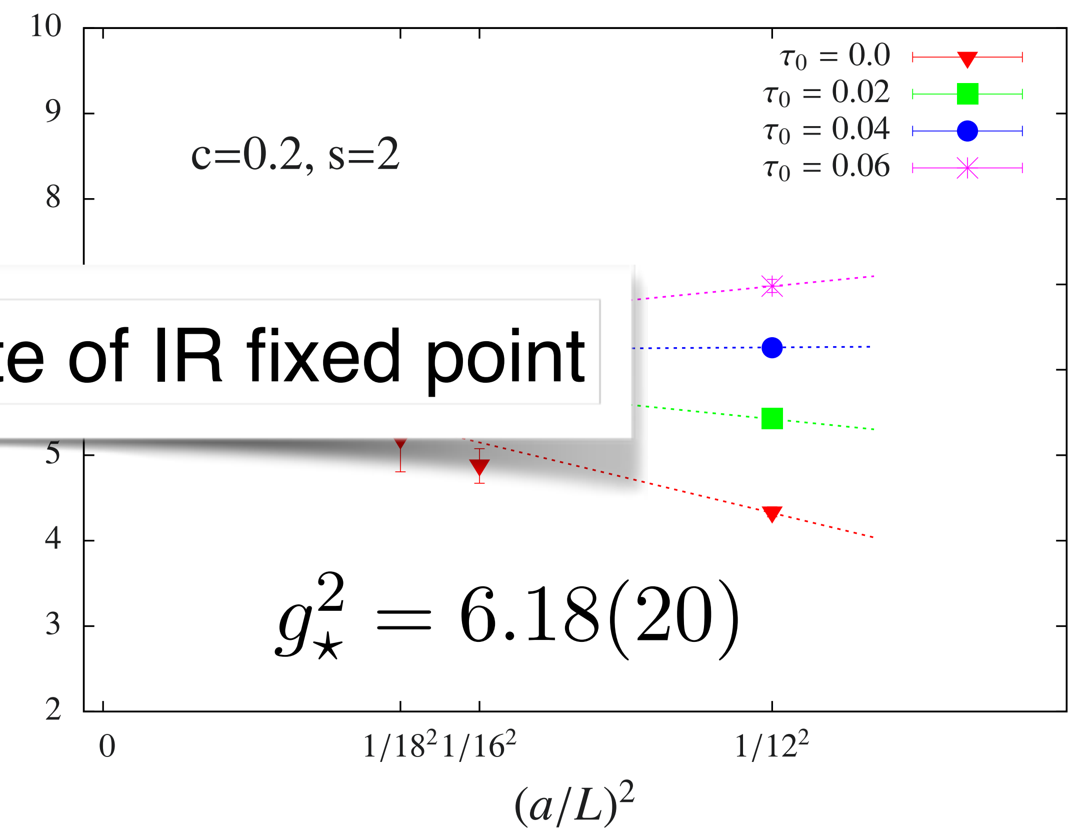

Most precise estimate of IR fixed point

- different c=0.25,, investigated

- robustness is being tested

$$g^2_{\rm GF}(\mu; a) = g^2_{\rm GF}(\mu; a=0) + a^2\mathcal{C} + \mathcal{O}(a^4[\log a]^n, a^4)$$

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SU(3) fundamental Nf=12: running coupling

[Lin 5C]

- Taiwan-Japan collab.: D. Lin et al
- gradient flow coupling and step scaling
- Wilson gauge with twisting x,y
- Naive staggered with twisting
- study palette and clover operators to check the continuum extrapolation
- c=0.25, 0.30, 0.35, 0.40 $c = \sqrt{8t}/L = 0.2$

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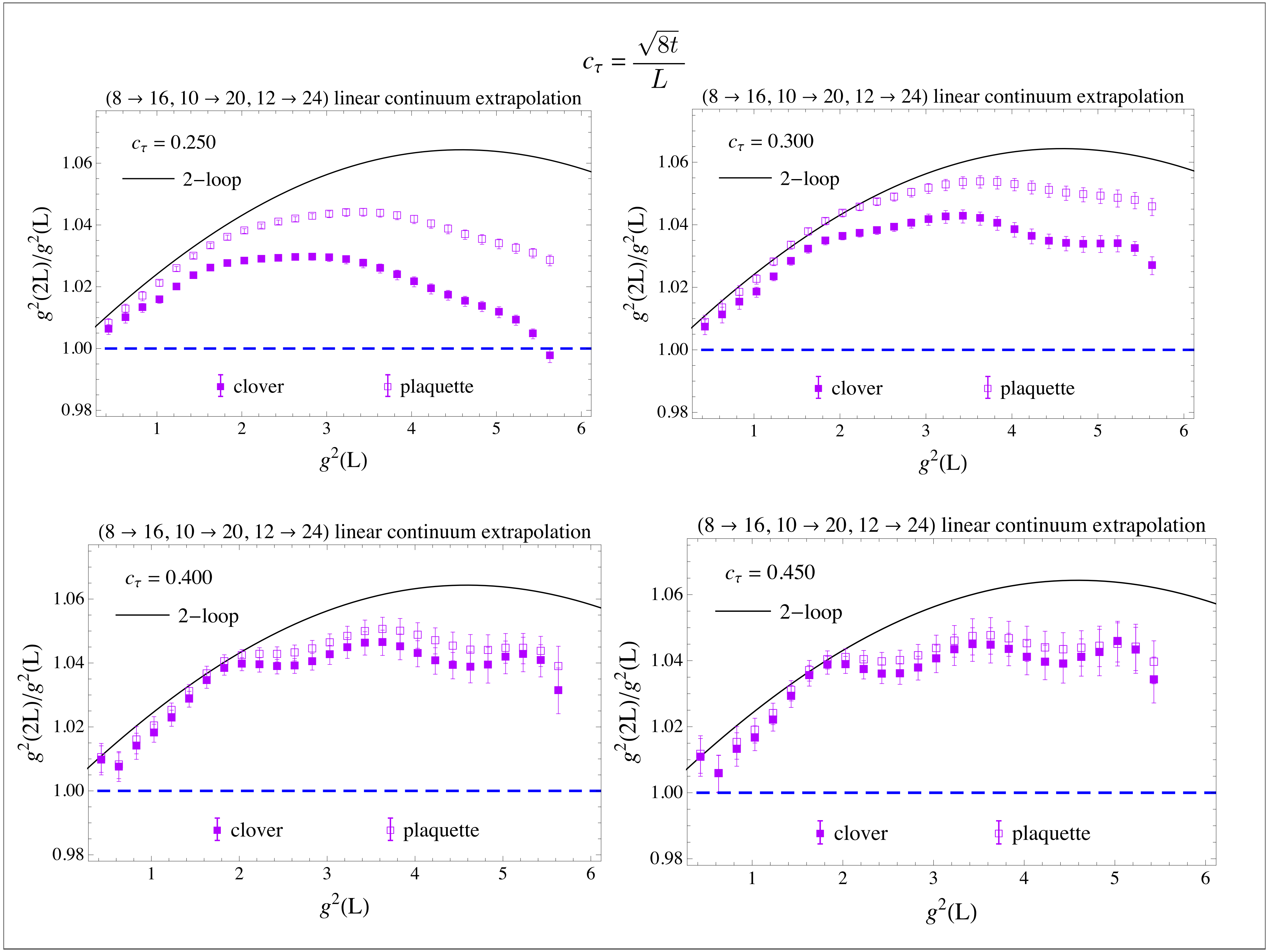

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- Taiwan-Japan collab.: D. Lin et al
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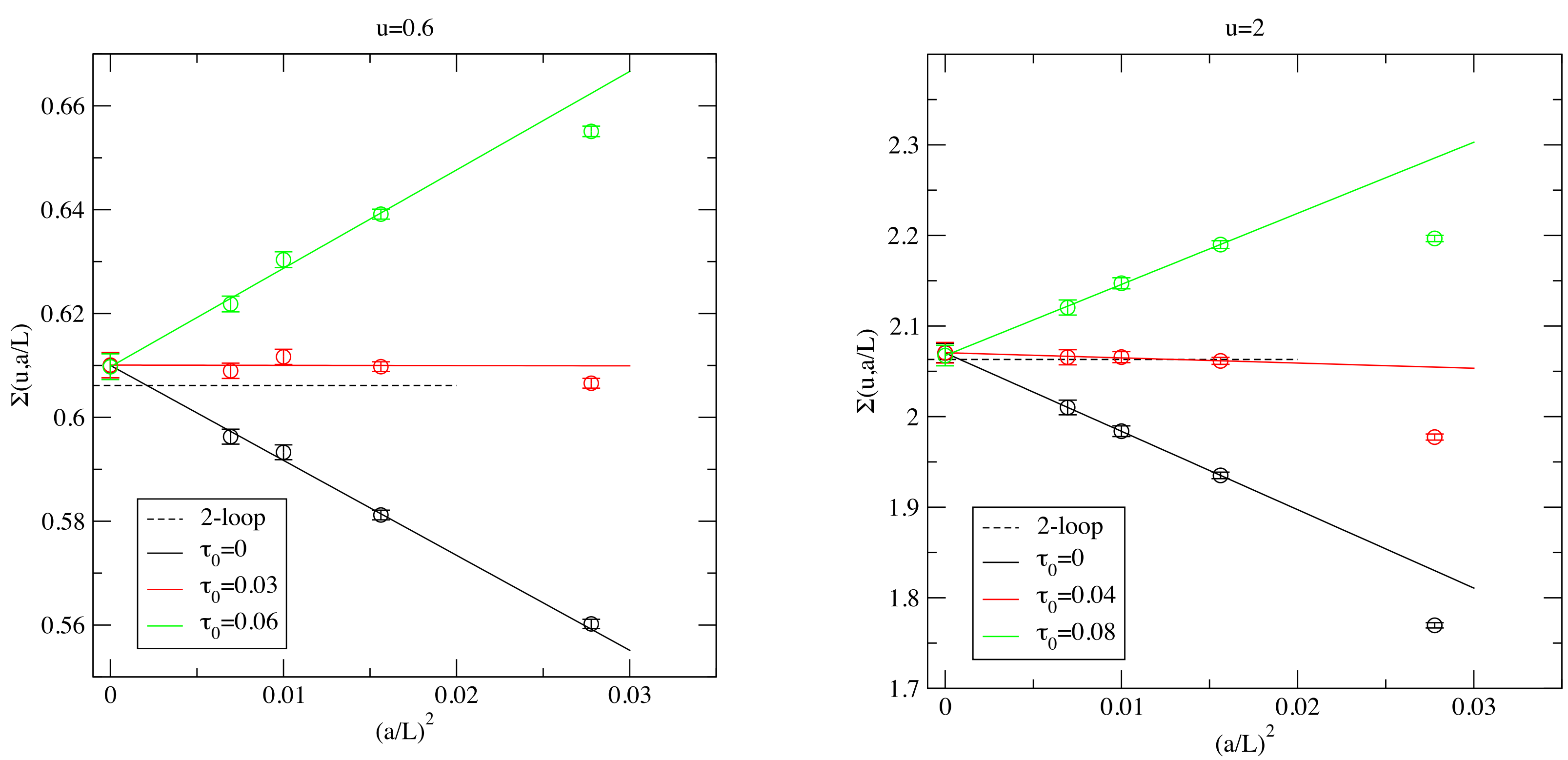
- study palette and clover operators to check the continuum extrapolation
- c=0.25, 0.30, 0.35, 0.40 $c = \sqrt{8t}/L = 0.2$
- inconclusive on existence of IRFP / continuum limit; needs further investigation
  - problem being unfolded through the high precision of gradient flow method
- L=8→24 so far. 32 simulation underway.

SU(2) Nf=8 fundamental: running coupling [Rantaharju 5C]

- HEX smeared O(a) improved Wilson $S = (1 - c_g) S_G(U) + c_g S_G(V) + S_F(V) + c_{SW} \delta S_{SW}(V)$
- t-shift gradient flow (Cheng et al) coupling with SF boundary & step scaling



- Continuum limit with $\Sigma(u, \mathrm{a}/L) = \sigma(u) + c(\mathrm{a}/L)^2$

- Inconclusive on existence of IRFP

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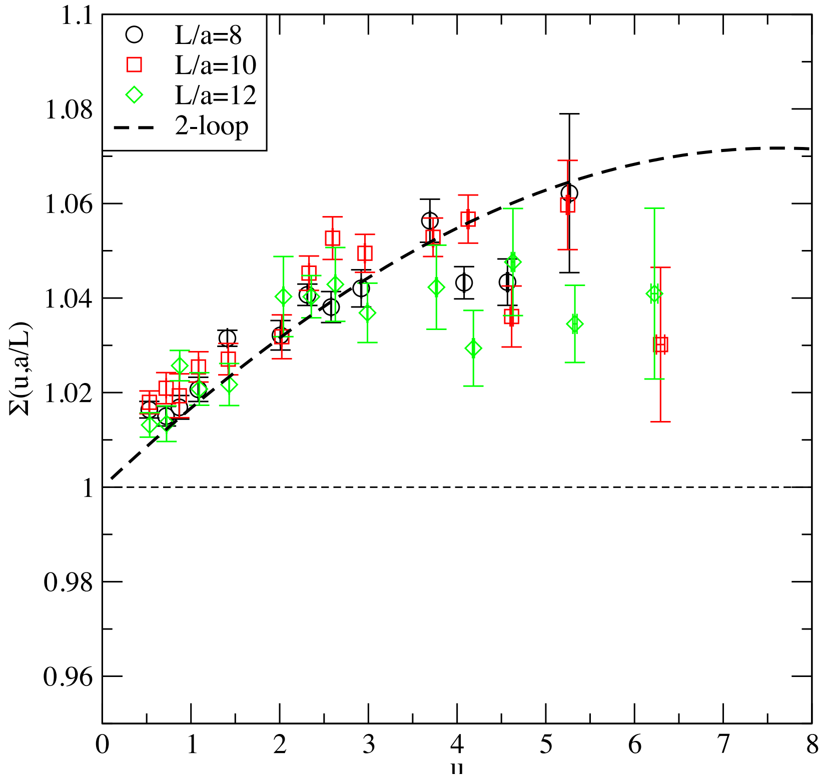
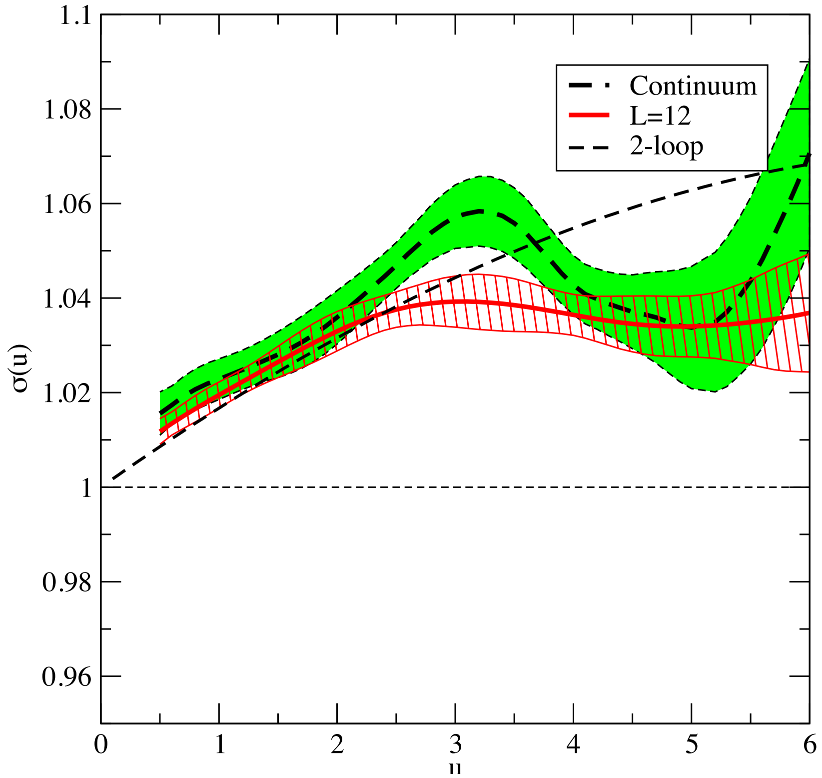


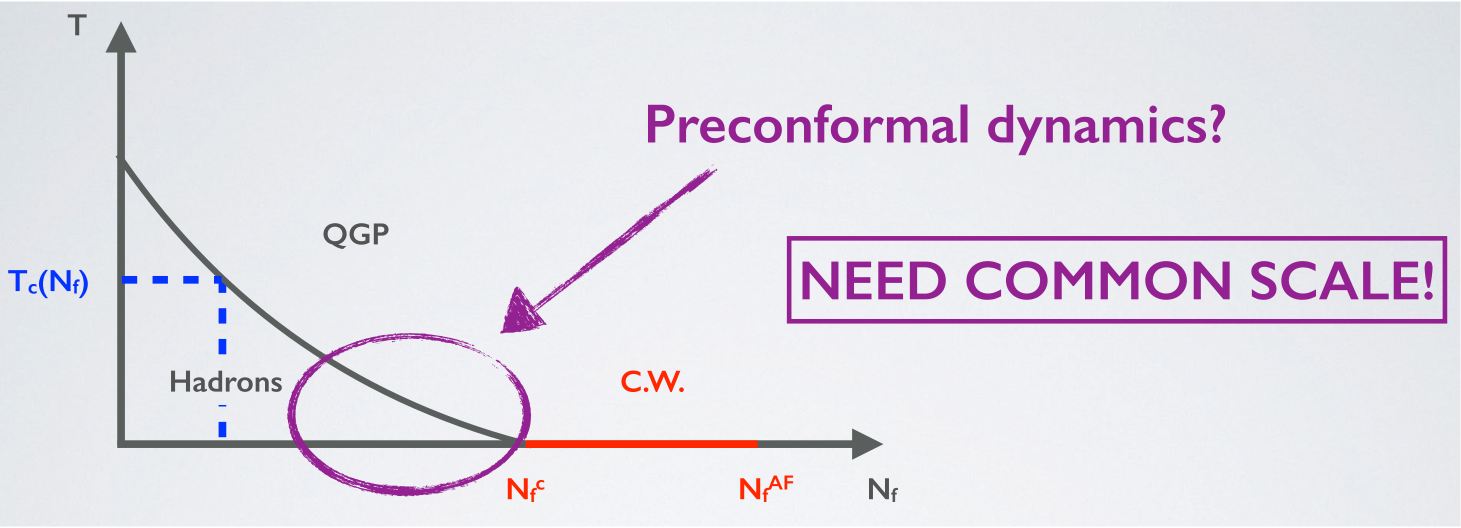


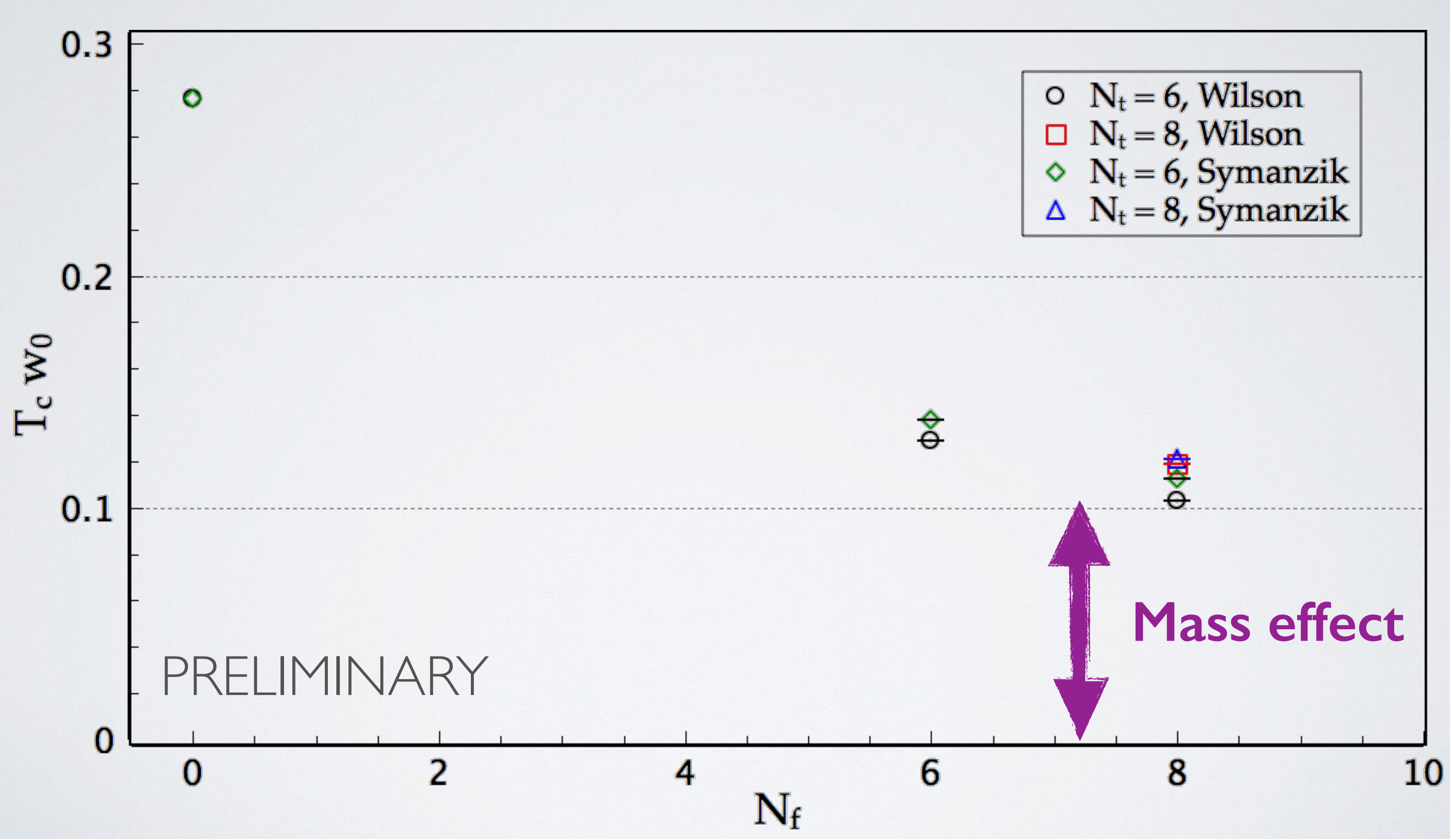
- Inconclusive on existence of IRFP

SU(3) gauge + fundamental fermions Nfc ?

SU(3) fundamental: N_{fc} from $T_c(Nf)$ [Nunes da Silva 1C]

- Comparing Tc for different Nf
- requires common scale
- IR scale would not be good
- as a UV scale ω_0 is used
- Nt=6, 8 simulation
  - 1 loop Symazik gauge
  - Naik & tadpole improvement
- mass effect under investigation



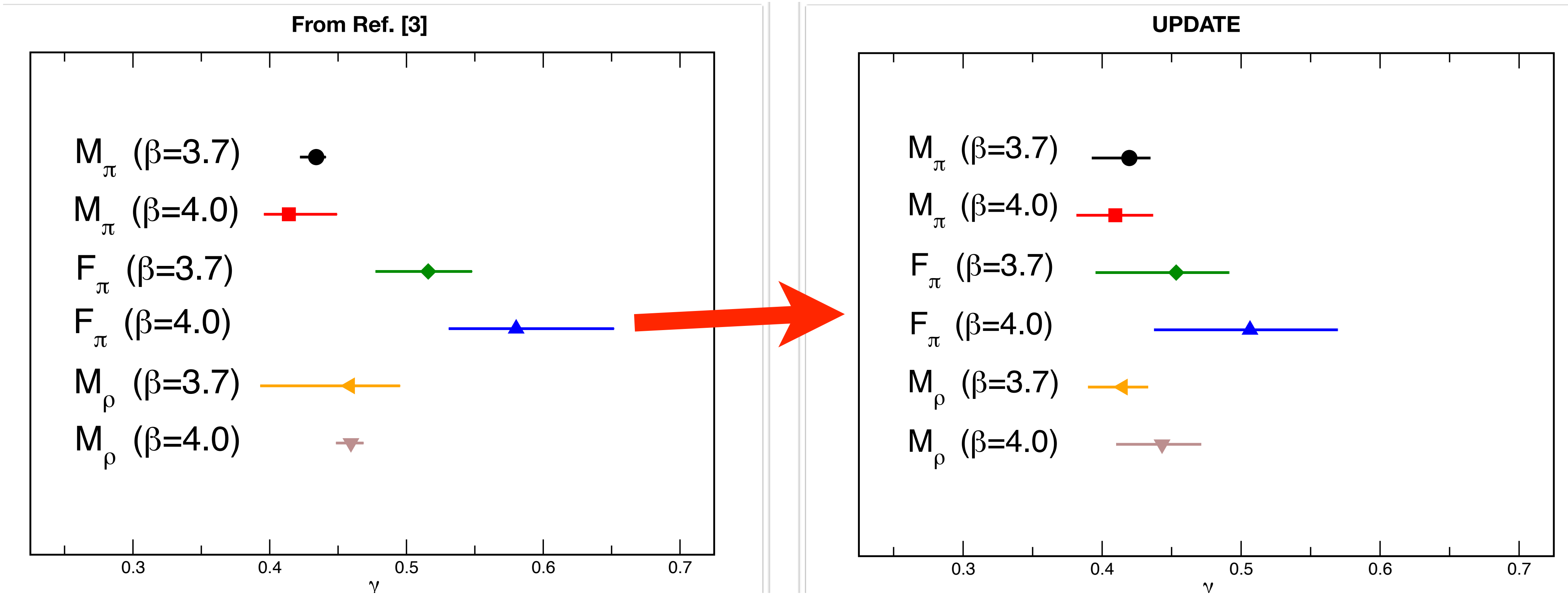


SU(3) fundamental Nf=12 spectrum vs m_f

LatKMI update of conformal scaling study [Rinaldi P]

$$x = Lm^{1/(1+\gamma_\star)}$$

$$\xi = L \cdot M_H = f_M(x)\,, \quad \xi = L \cdot F_H = f_F(x)$$



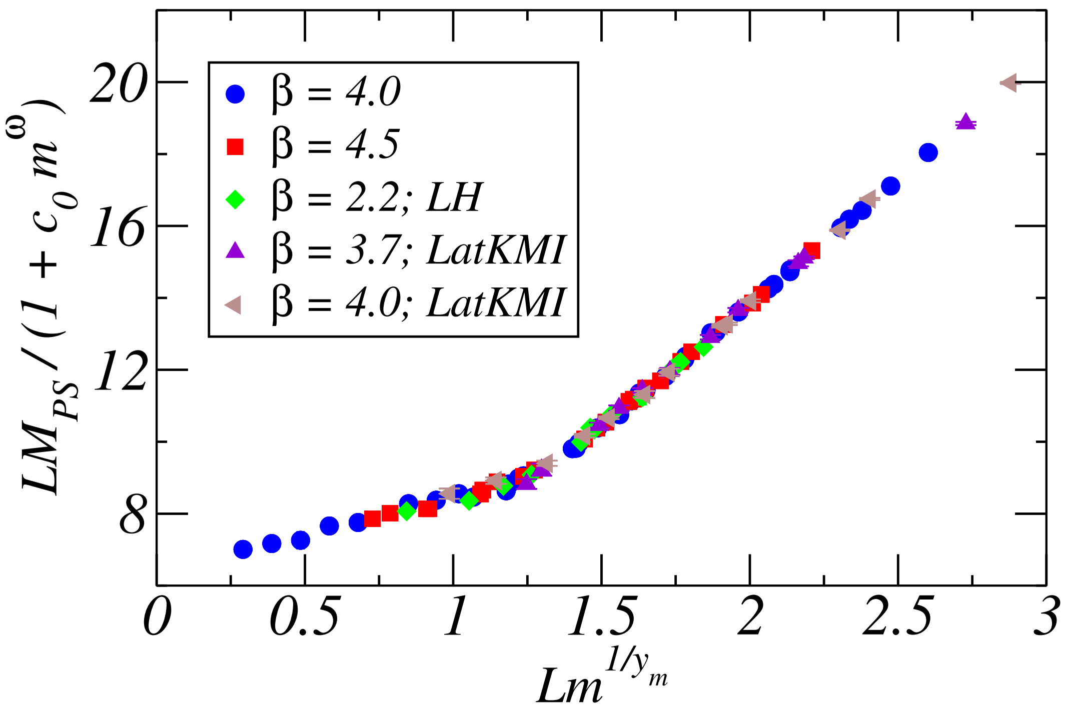
Coupling ➡ β	Lattice Size ➡ L×T	Fermion Mass ➡ m
3.7	18x24, 24x32, 30x40, 36x48	0.03 ➪ 0.2
4.0	18x24, 24x32, 30x40, 36x48	0.04 ➪ 0.2

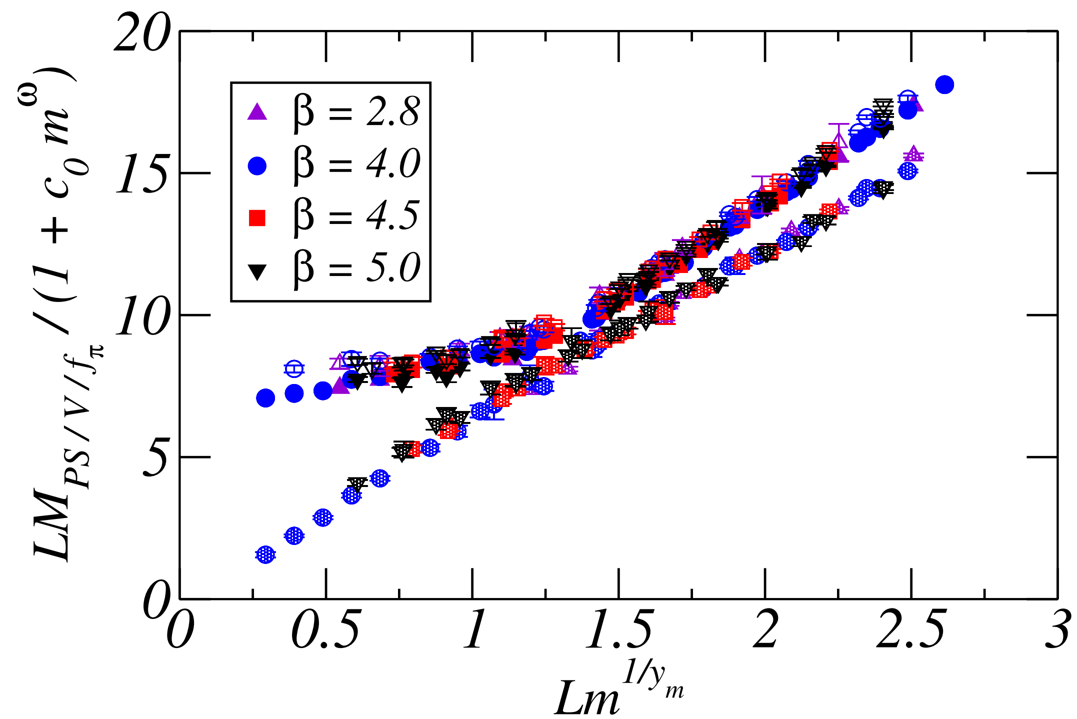
- γ^* : 0.4-0.5 (same as before)

Including the effect of near-marginal operator [Cheng et al 2014]

$$\frac{LM_H}{1 + c_G g_0 m^{\omega}} = F_H(x)$$

[arXiv:1401.0195]





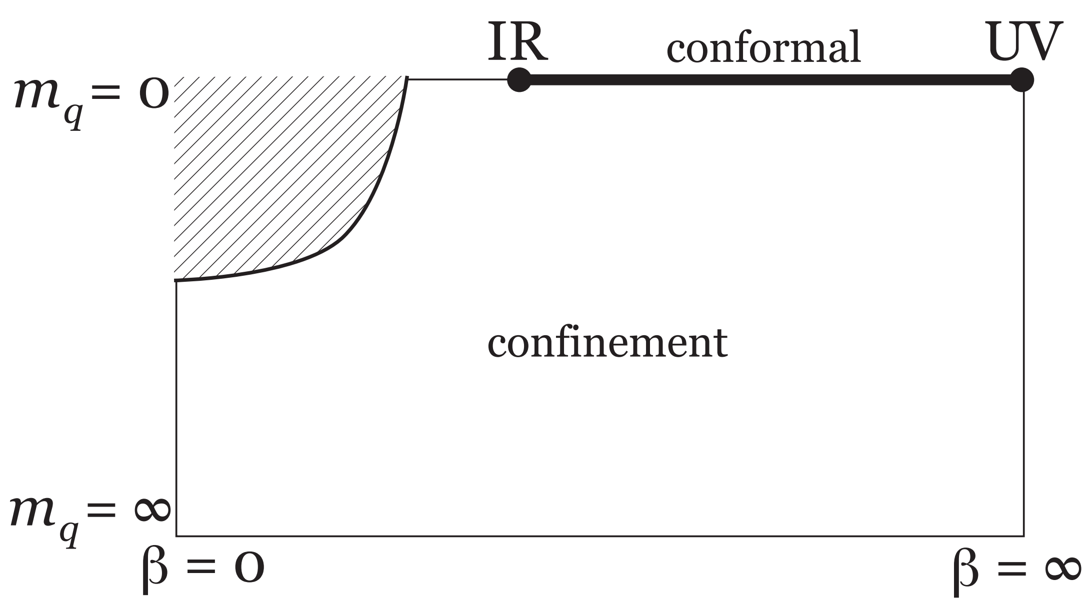
- data from three collaborations (different actions) well aligned with single γ
- 2 segments seem to be observed: separated at x~1.3 for all quantities
- suggesting abrupt change of environment ?

Conformal theory with IR cutoff
[Iwasaki/Ishikawa Lattice 2013]

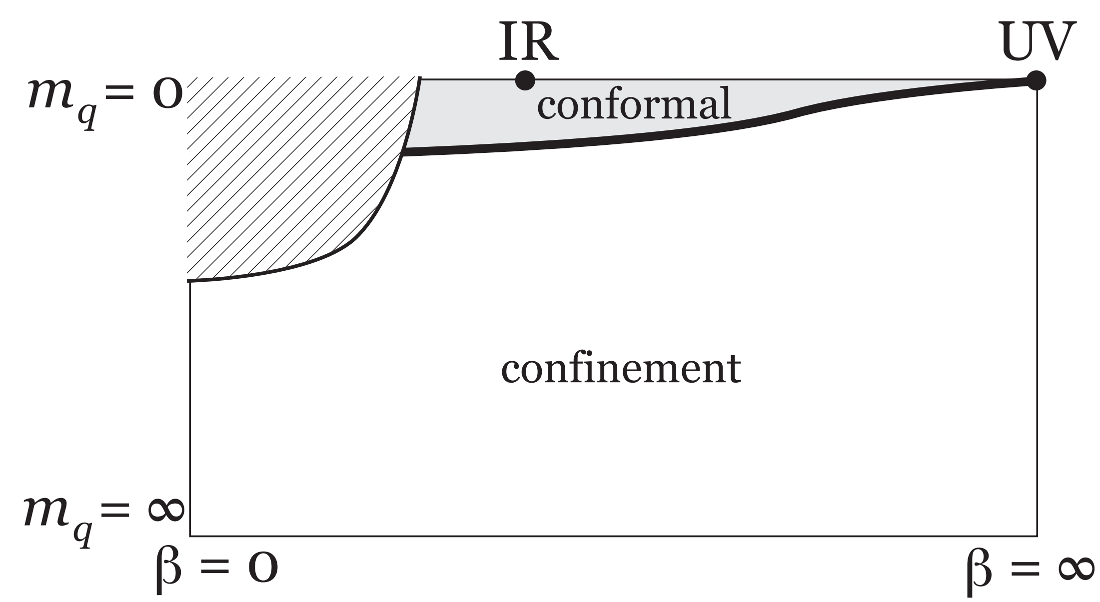
- phase diagram of theories which has IR fixed point

[Ishikawa, Iwasaki, Nakayama, Yoshie PRD87 2013, PRD89 2014]

V=∞



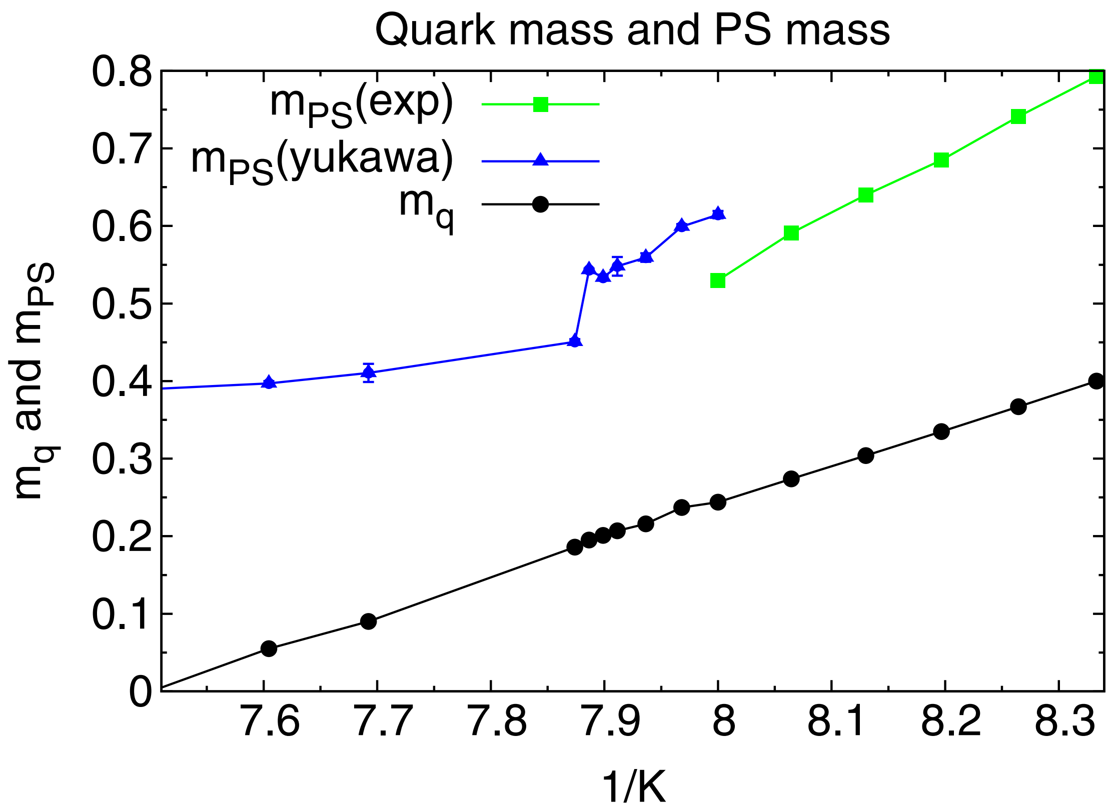
finite V (conjectured)



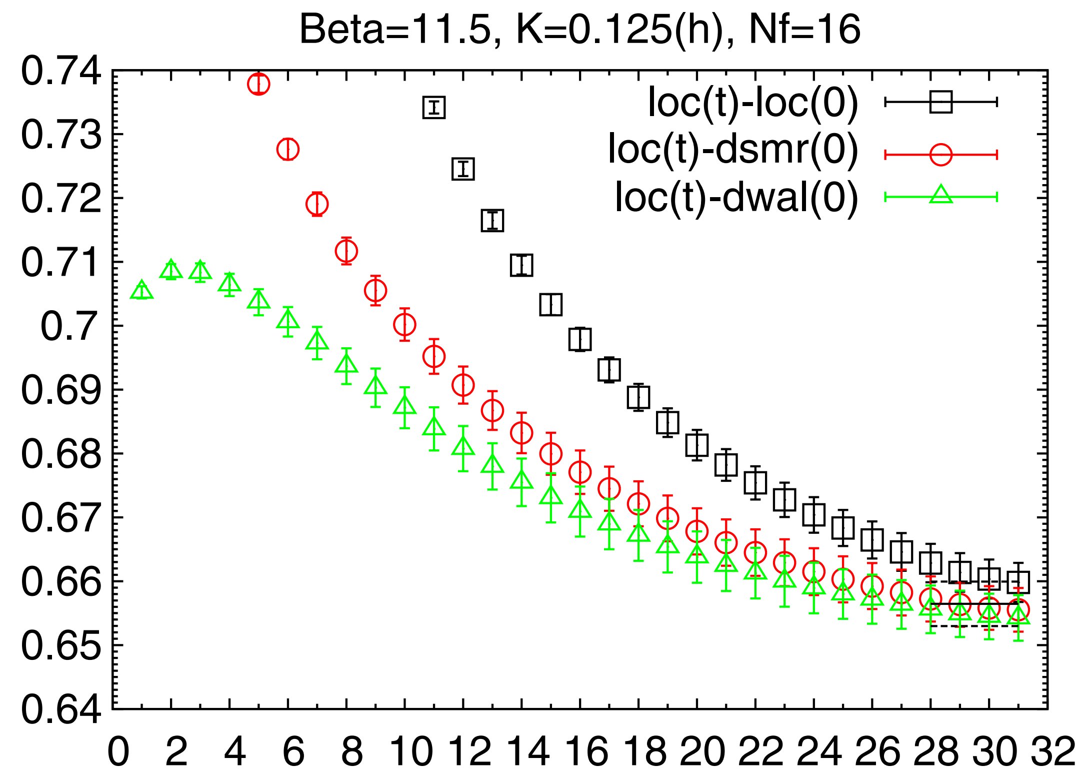
- finite V
  - conformal <-> confinement: separated by 1st order phase transition
  - power low correction to the exponential decay of 2pt function in conformal

Conformal theory with IR cutoff

Nf=16



pion effective mass



- finite V
  - conformal <-> confinement: separated by 1st order phase transition
  - power low correction to the exponential decay of 2pt function in conformal
    - ➡ counter argument (investigating a 2 d toy model) [Akerlund 1C]

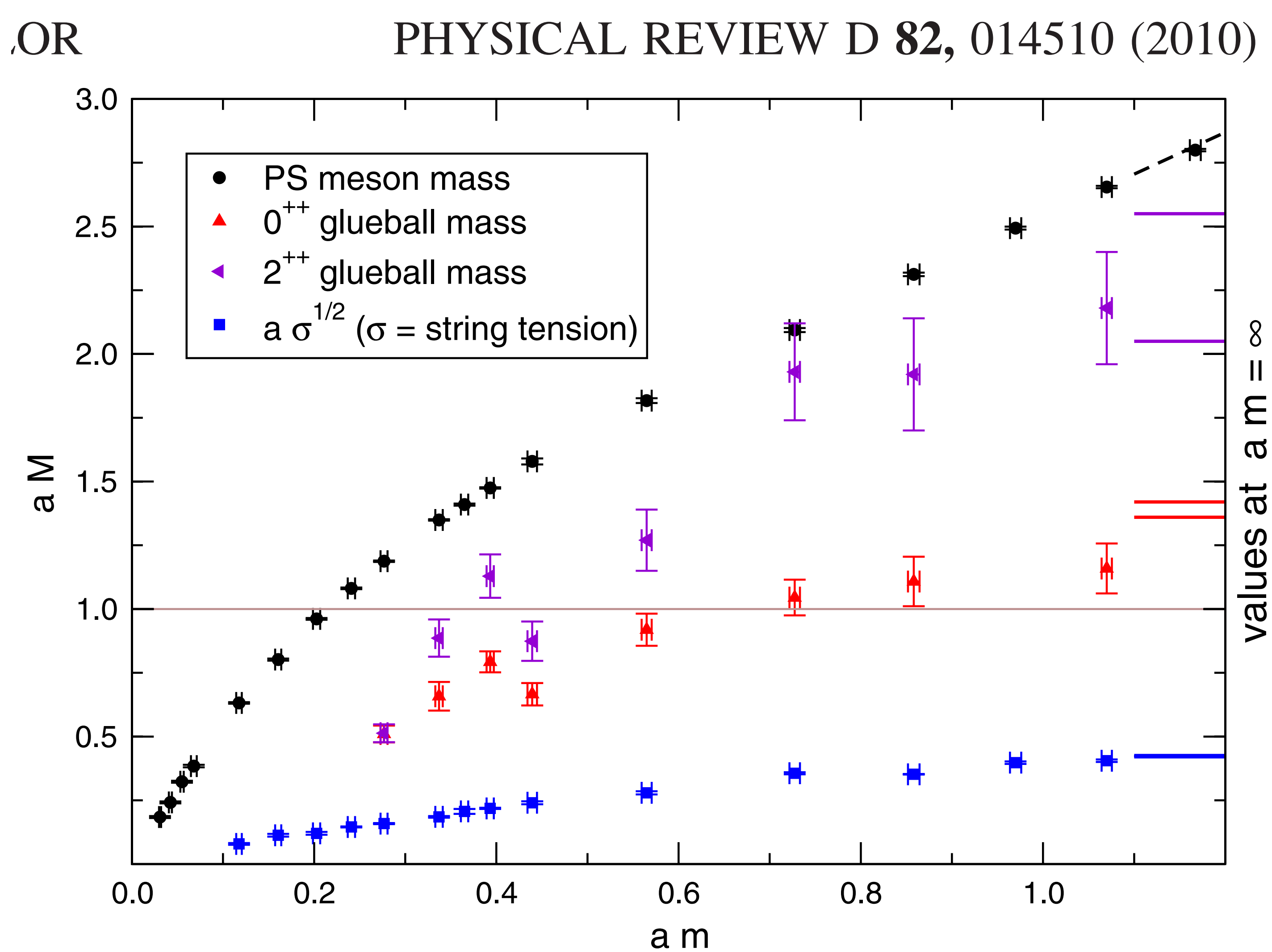
mass anomalous dimension

- scaling near IRFP of composite spectrum (mass deformed theory)
  - LatKMI 0.4-0.5 KMI data: right segment of the scaling figure
  - Cheng et al 0.235(15) ω correction, using all data, both segments
- eigenmode number
  - Cheng et al 0.32(3) mf=0 simulation [JHEP 1307 061]
- twisted Polyakov loop scheme, step scaling
  - [Itou and Tomiya P] 0.081(18)(+25-0) mf=0 simulation
- needs better understanding of the difference

flavor singlet composite scalar (Higgs inposter)

SU(2) Nf=2 adjoint glueball spectrum
[Del Debbio et al PRD2010]

- Likely in conformal window
- $0.16 < \gamma^* < 0.28$
- light 0++ is observed
- $M_{0++} < M_{\pi}$
- novel spectrum pattern

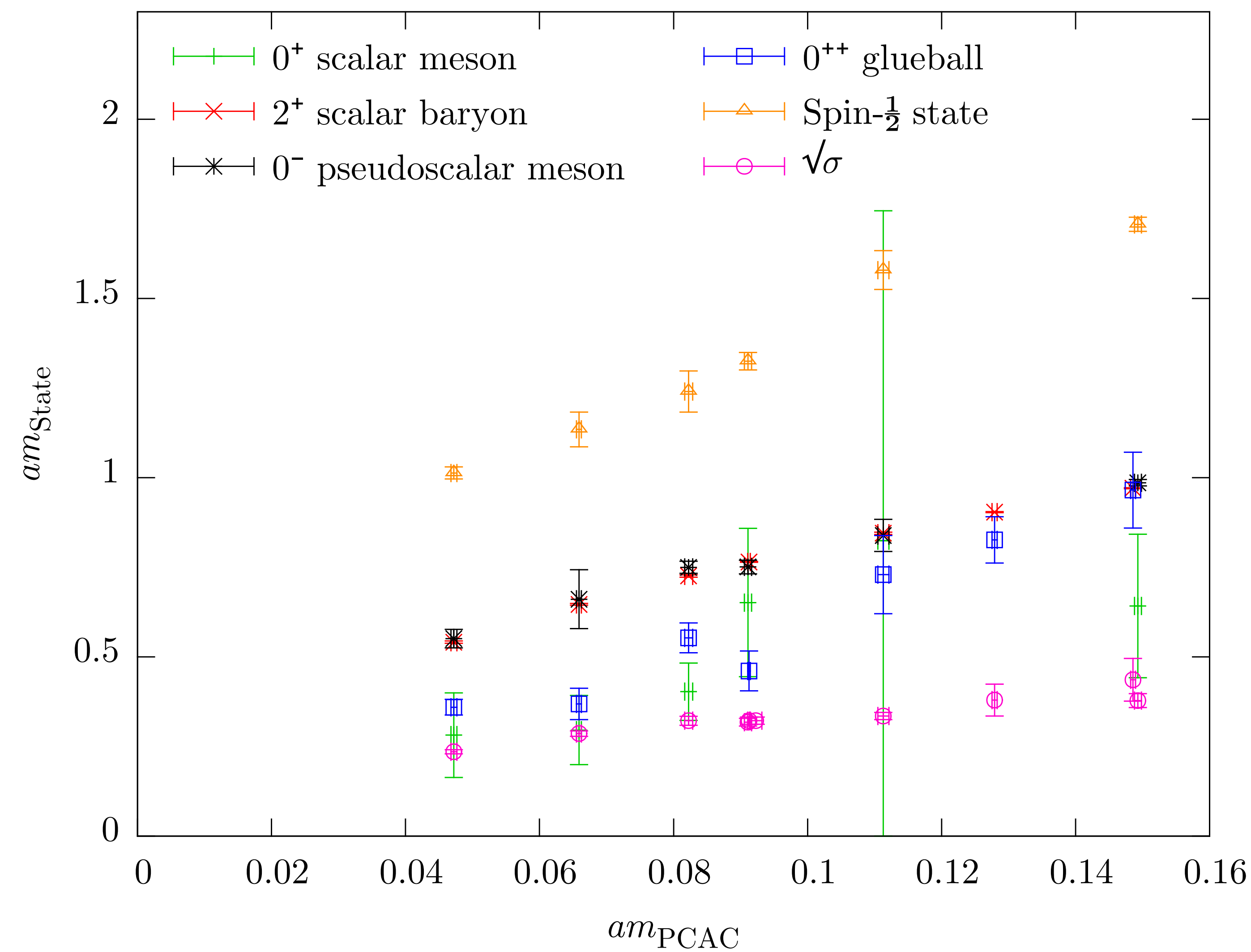


- hint of possible light composite Higgs in near conformal theories

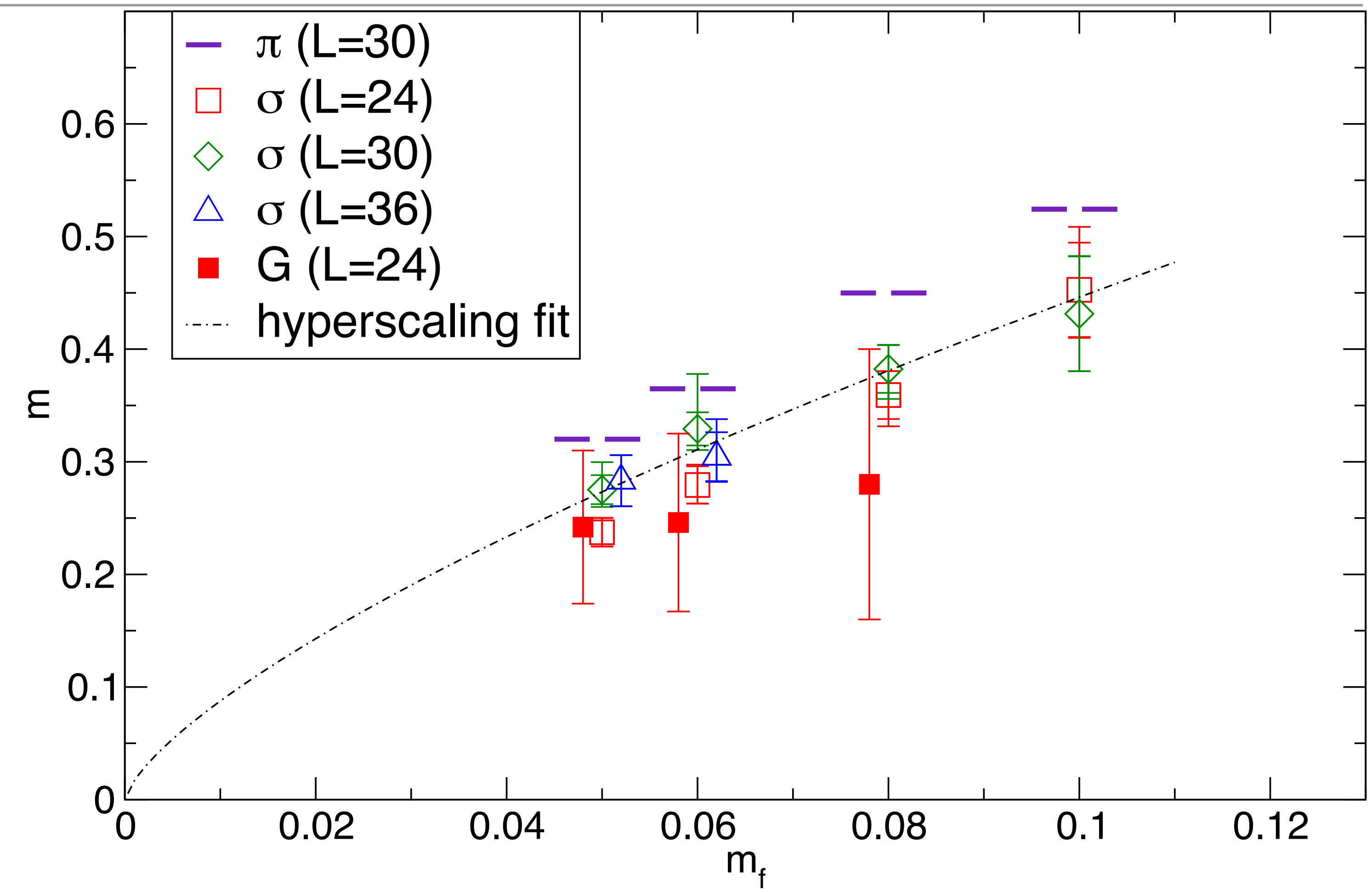
SU(2) Nf=1 adjoint

[Athenodorou et al Lattice 2013]

- conformal or near-conformal
- 0.9 < γ* < 1.0 from mf-scaling of chiral condensate
- γ*=0.92(1) from Dirac spectrum eigen mode number
- 2 pions : not enough for EWSB
- $M_{f0} \leq M_{\pi}$
- similar spectrum pattern as N_f=2
- glueball ↔ **fermion bilinear** ops consistent



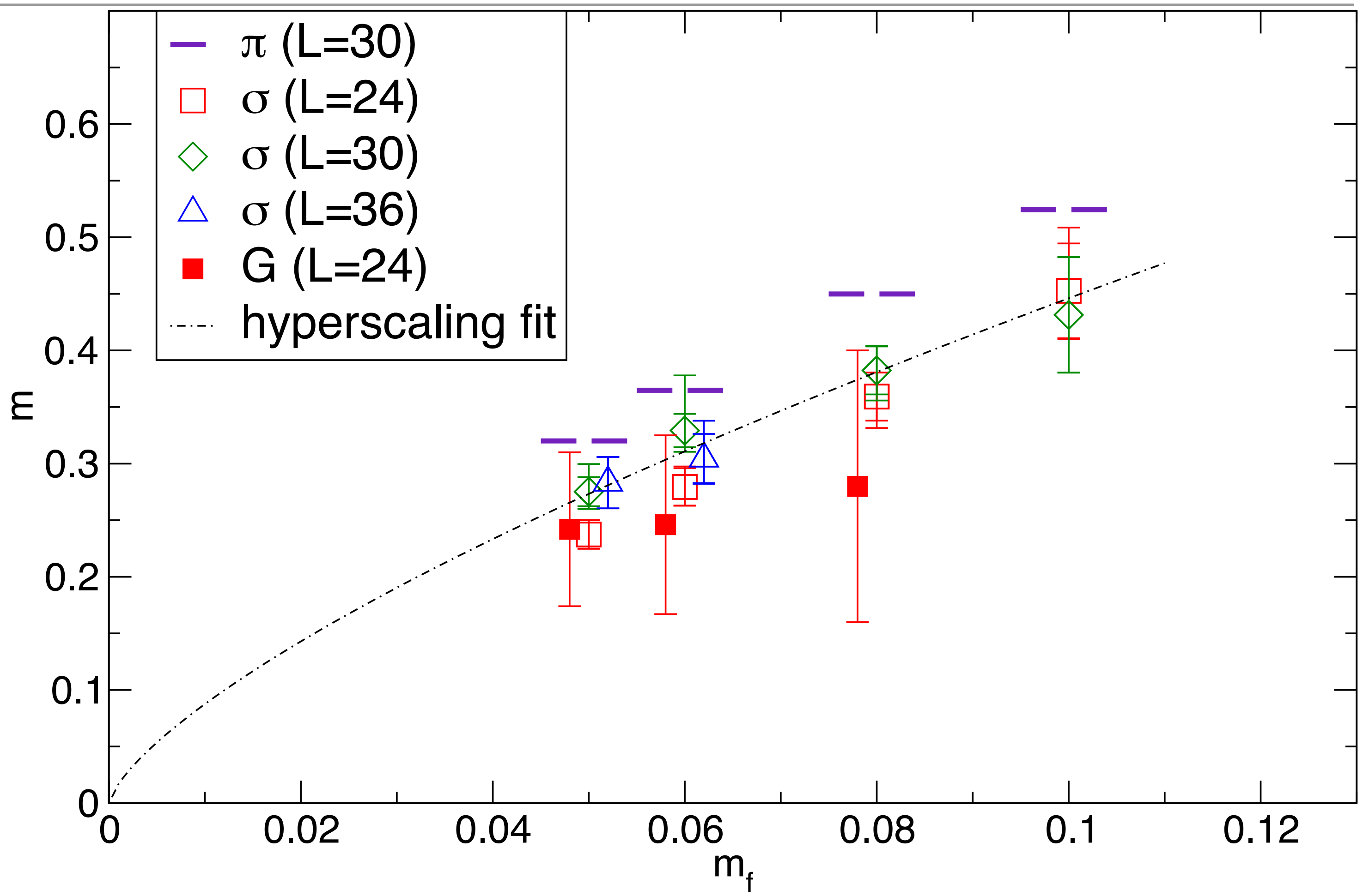
SU(3) Nf=12 flavor singlet scalar spectrum [LatKMI: PRL2013; Aoki&Ronaldi P]



SU(3) Nf=12 flavor singlet scalar spectrum [LatKMI: PRL2013; Aoki&Ronaldi P]

- with very high statistics
- and a variance reduction

➡reasonable signal



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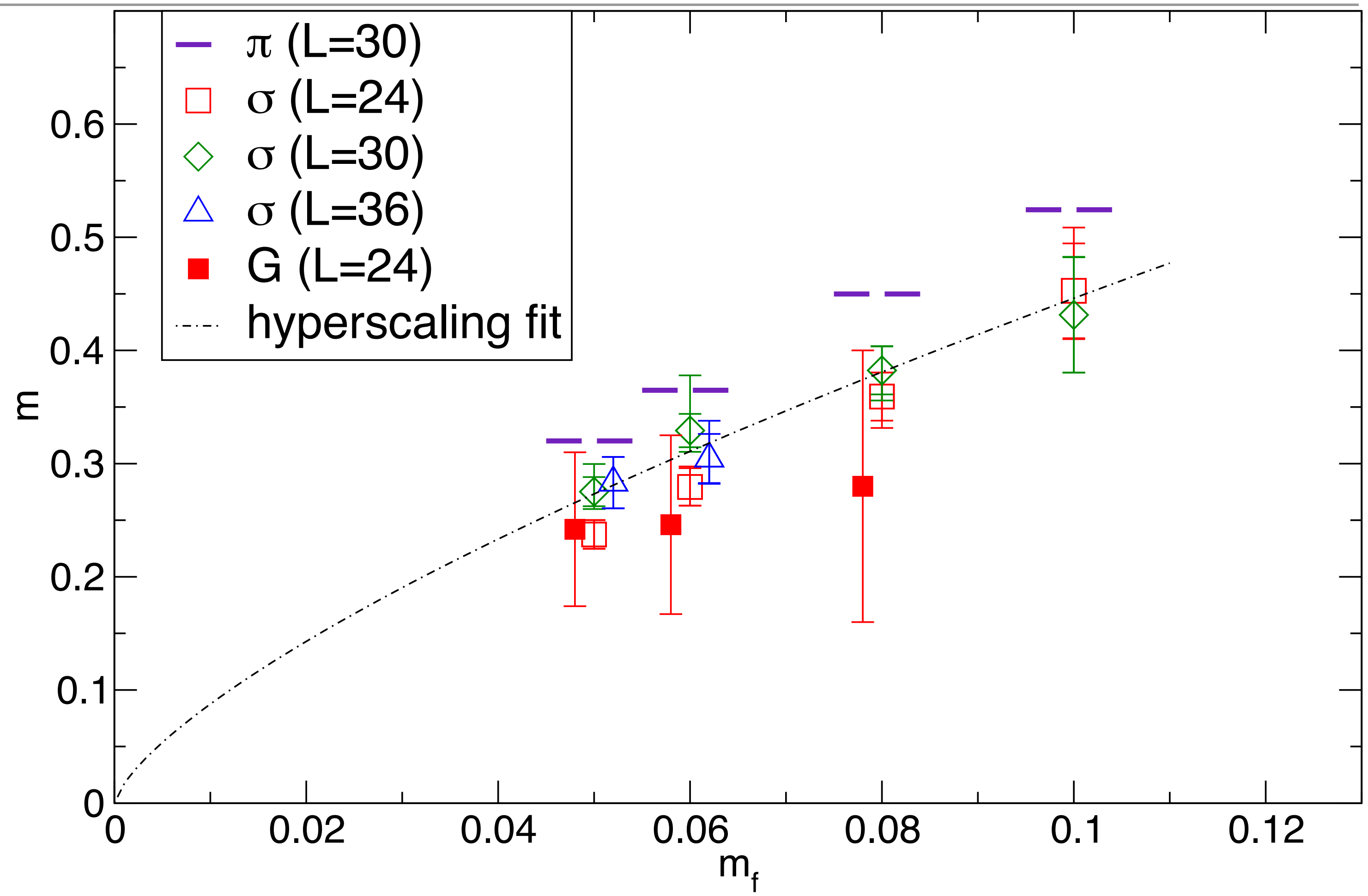
✳π was lightest in QCD (Nf=2)



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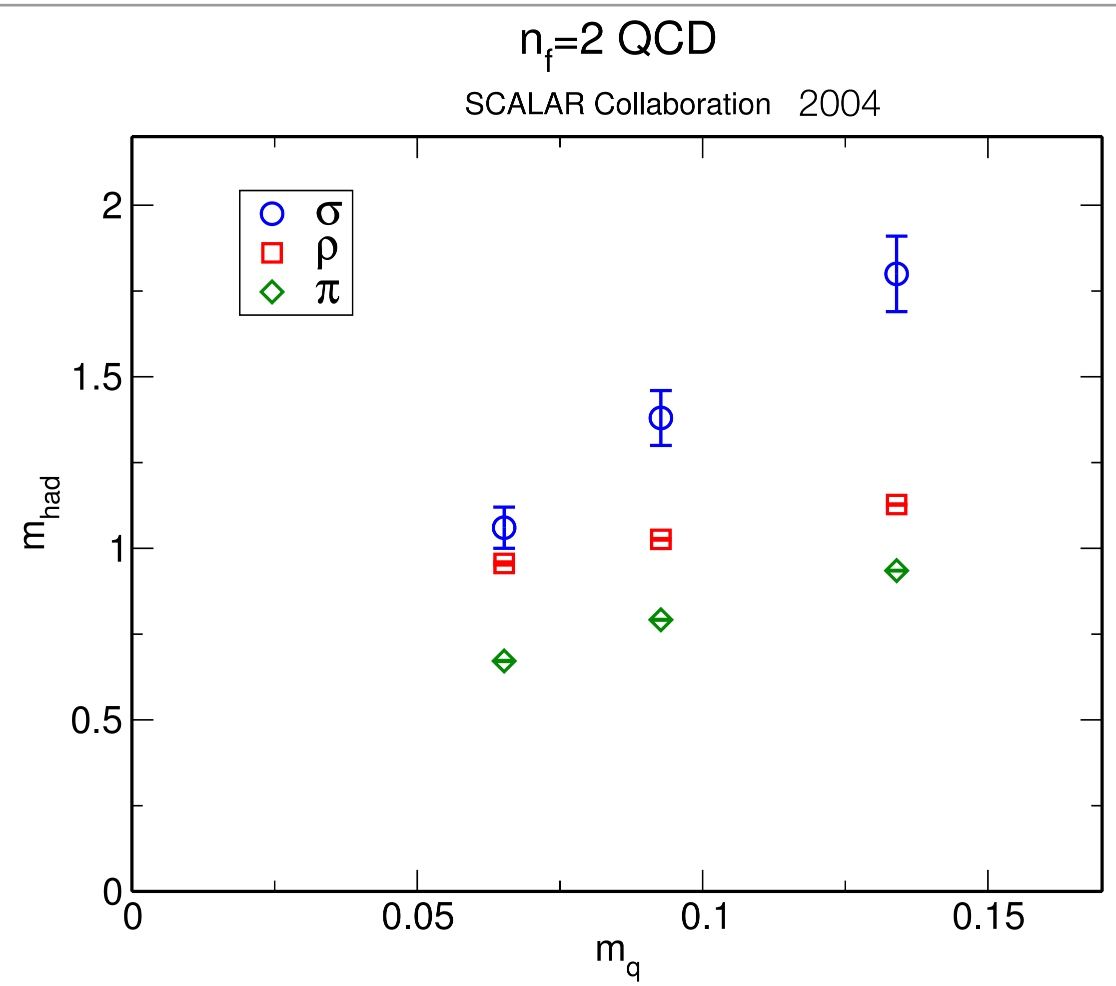
  - results by SCALAR Collab.



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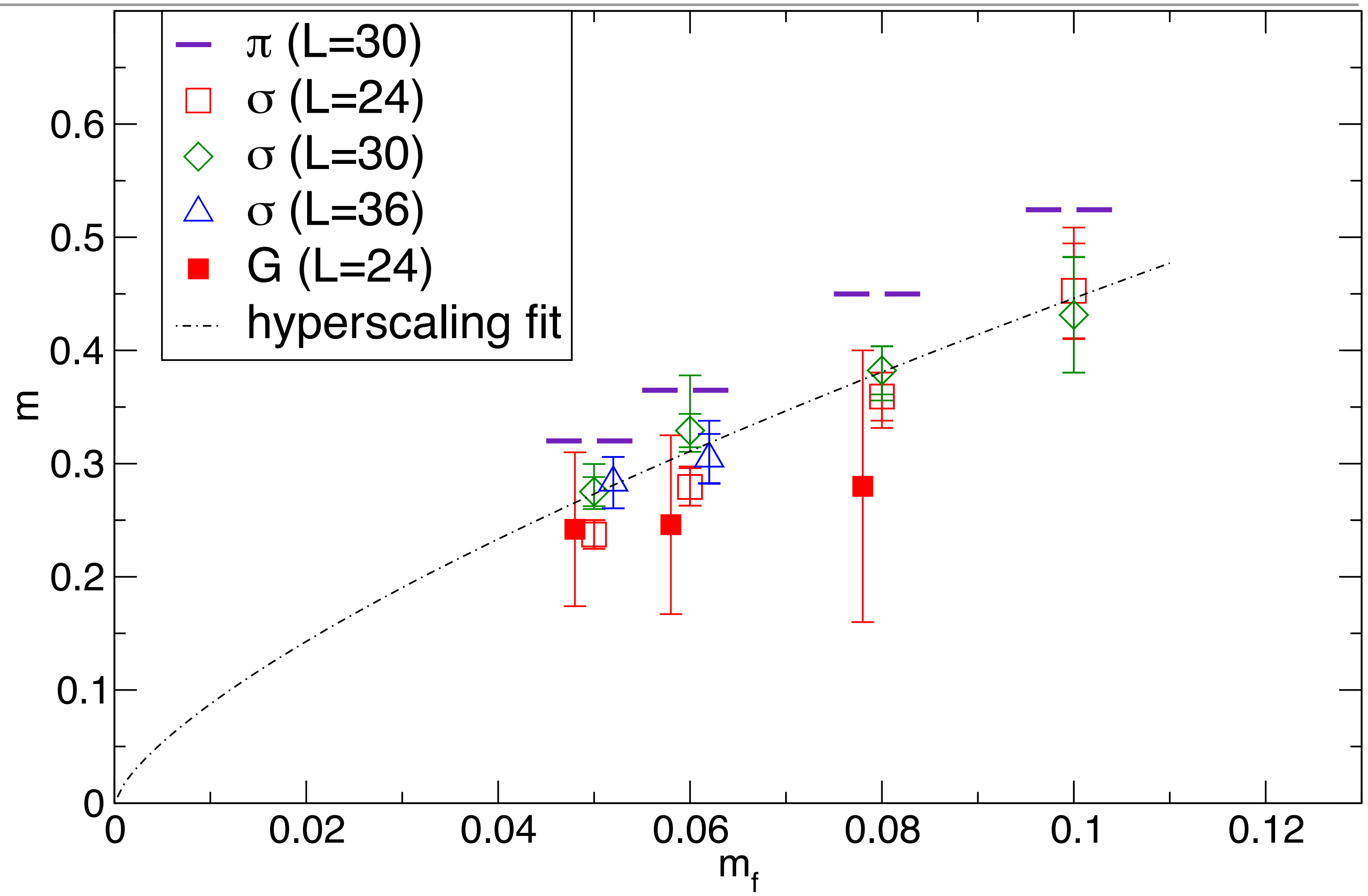
- σ is lightest for Nf=12 SU(3):



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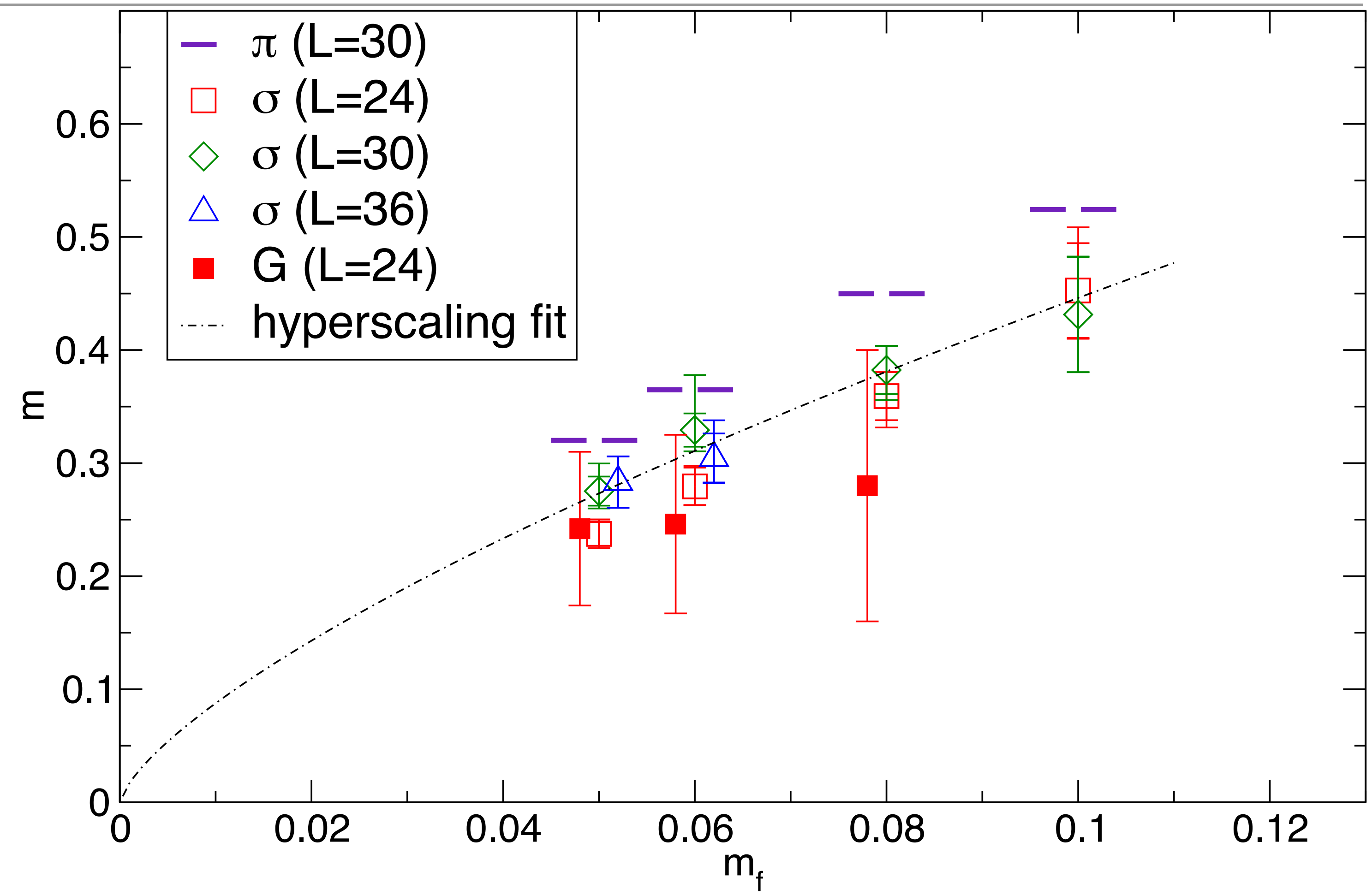
- σ is lightest for Nf=12 SU(3):

  - 0++ glueball is lightest for SU(2) Nf=2 adjoint



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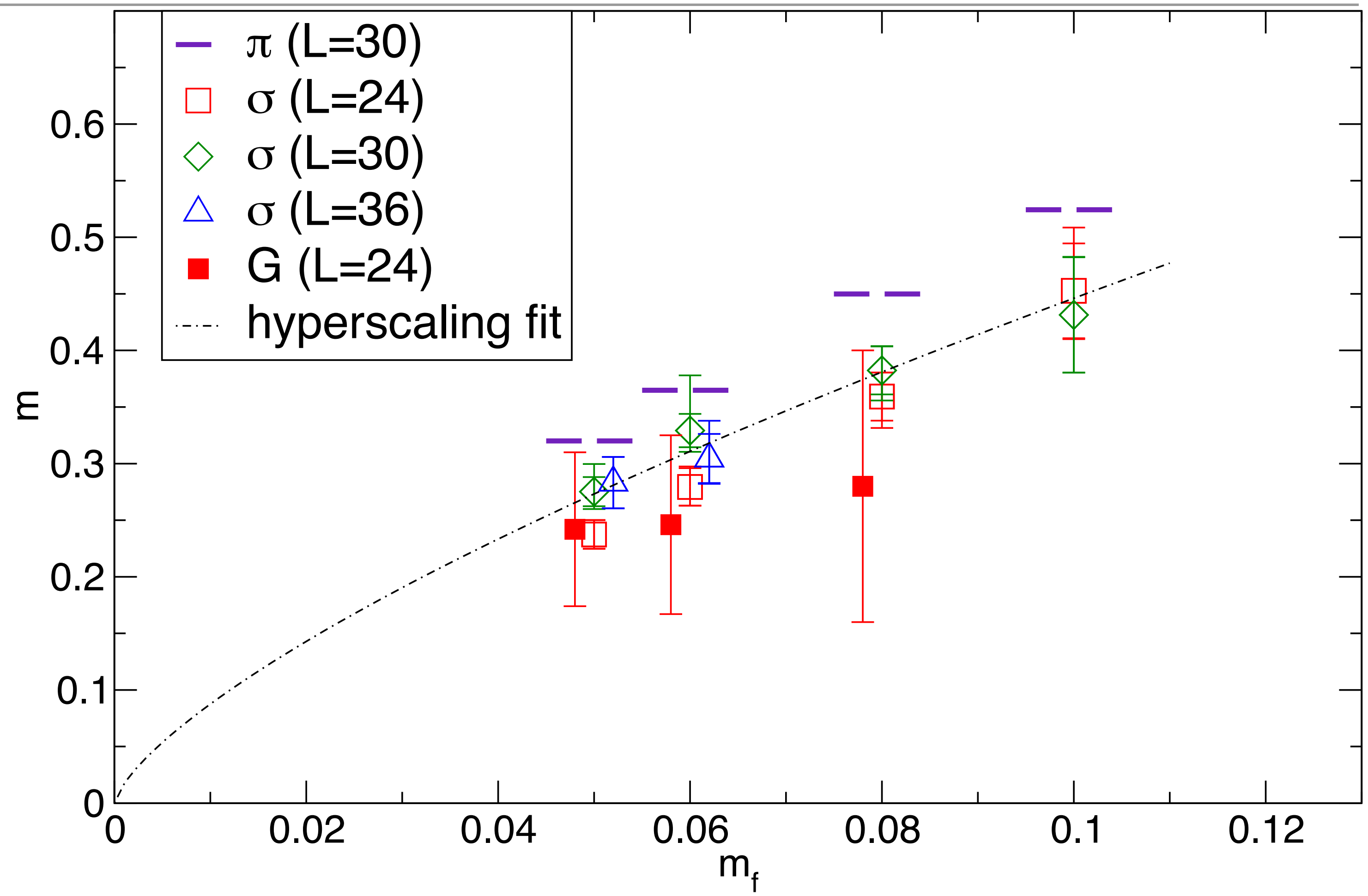
  - results by SCALAR Collab.

- σ is lightest for Nf=12 SU(3):
  - 0++ glueball is lightest for SU(2) Nf=2 adjoint
  - 0++ glueball/σ is lightest for SU(2) Nf=1 adjoint



SU(3) Nf=12 flavor singlet scalar spectrum [LatKMI: PRL2013; Aoki&Ronaldi P]

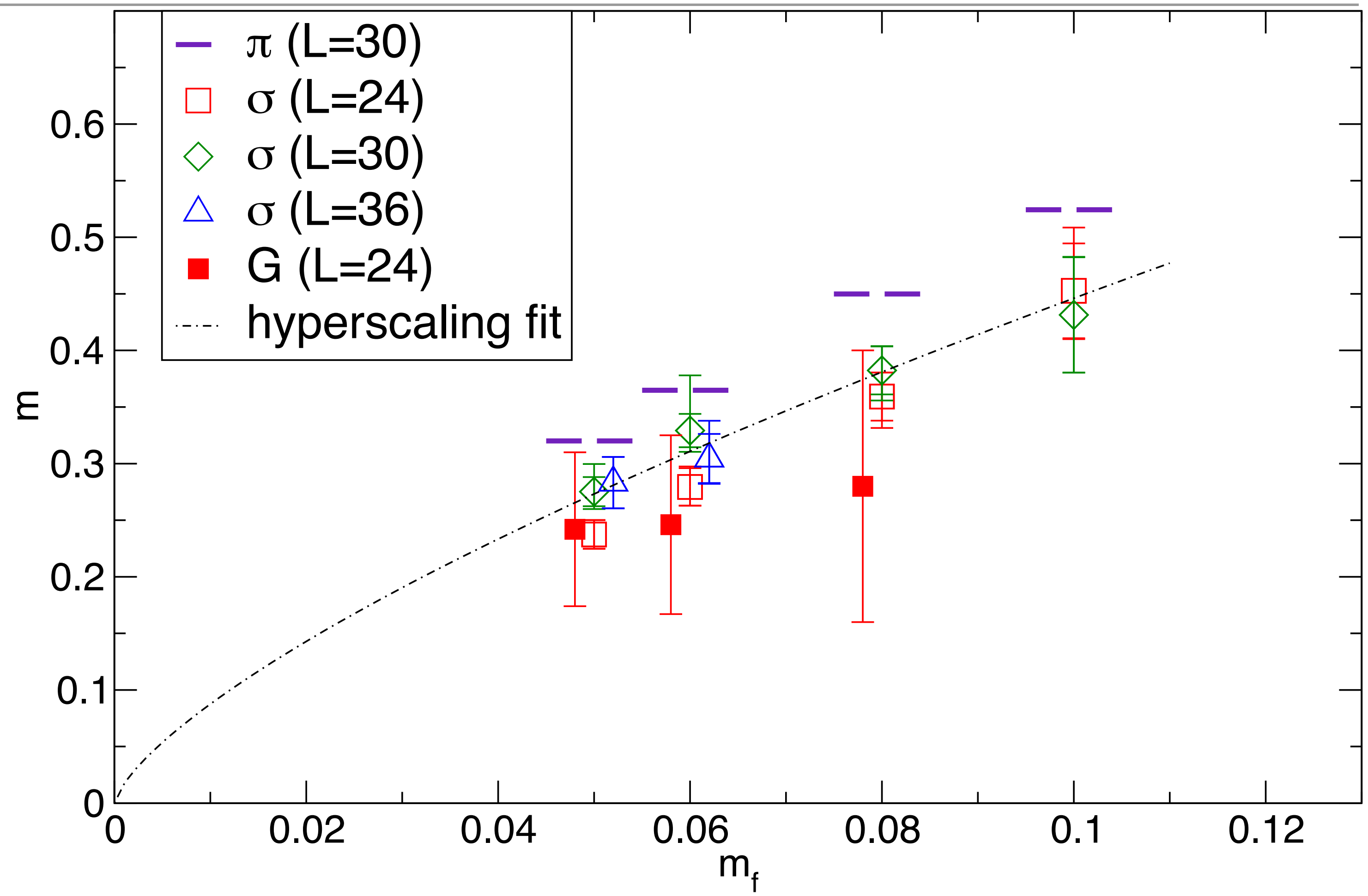
- with very high statistics
- and a variance reduction

➡reasonable signal

✳π was lightest in QCD (Nf=2)

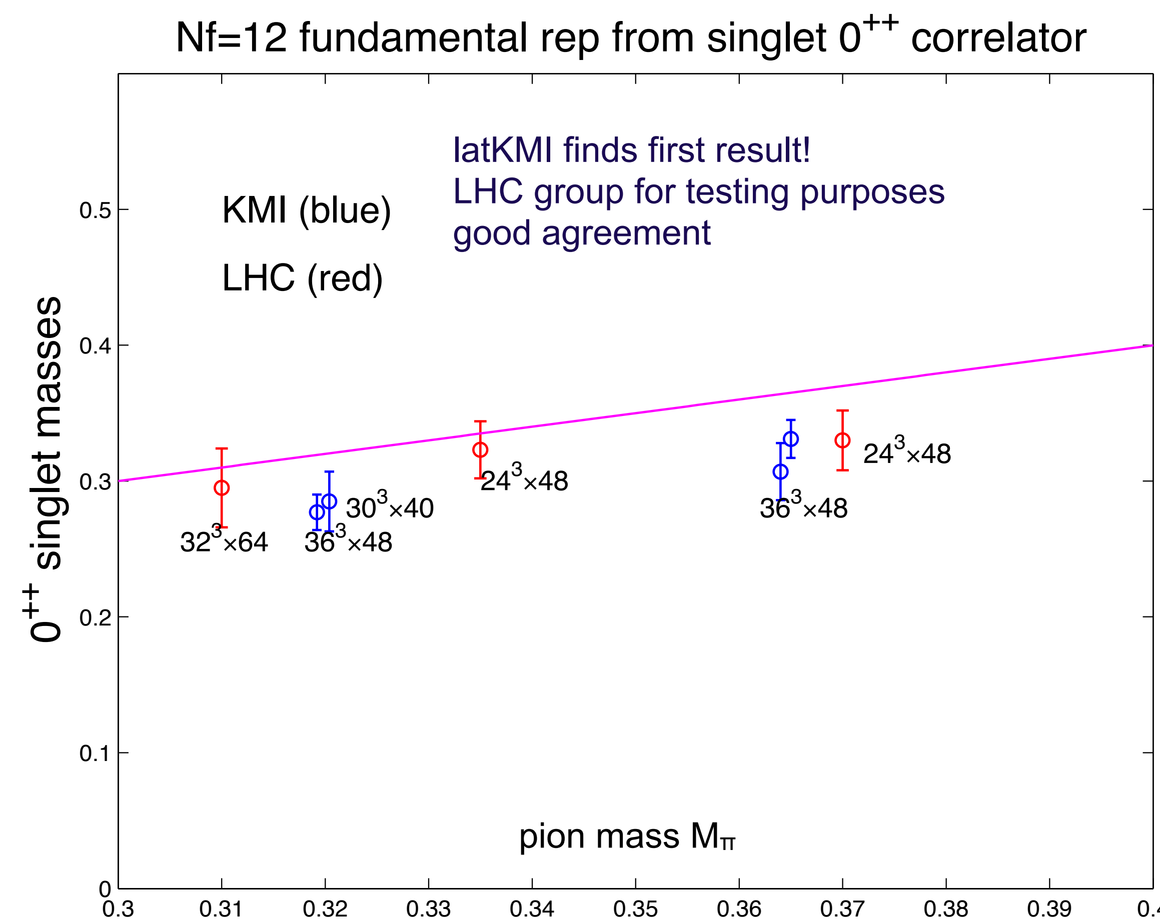
  - results by SCALAR Collab.

- σ is lightest for Nf=12 SU(3):
  - 0++ glueball is lightest for SU(2) Nf=2 adjoint
  - 0++ glueball/σ is lightest for SU(2) Nf=1 adjoint
- **hint of possible light composite Higgs** in near conformal theories for SU(3)



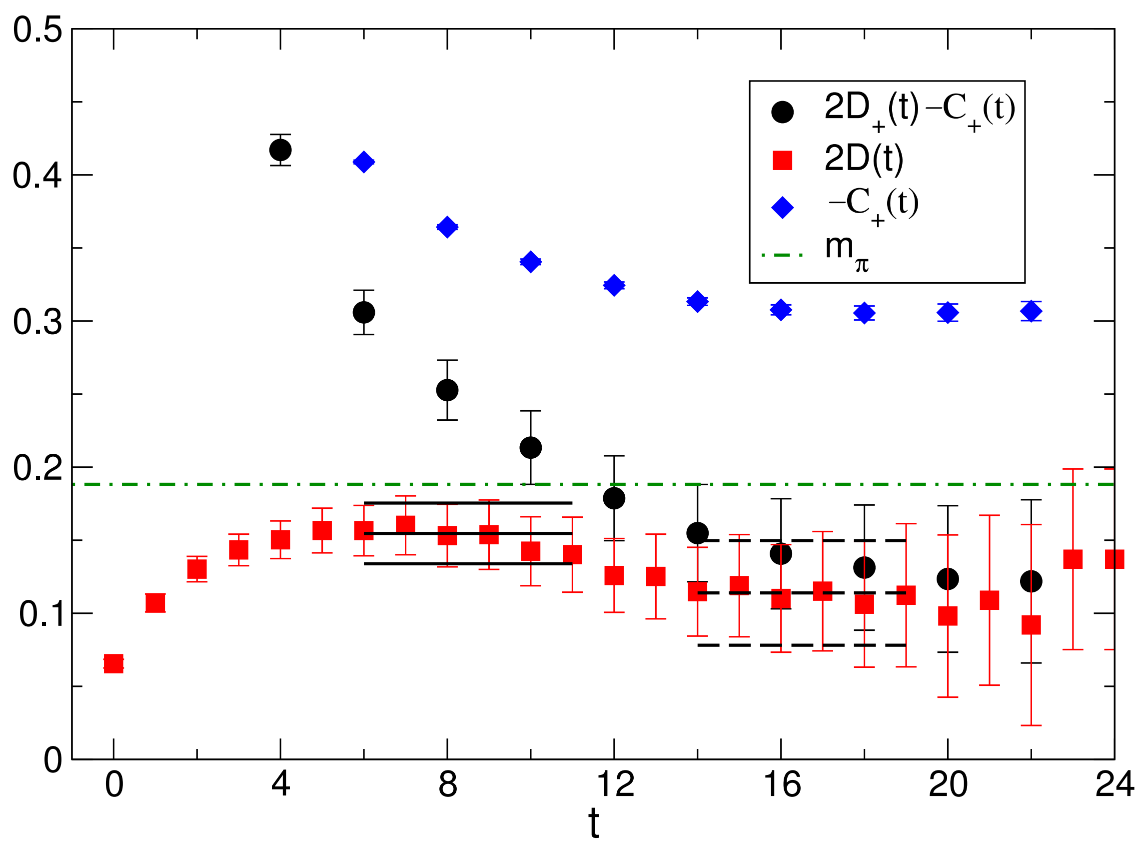
SU(3) Nf=12 flavor singlet scalar spectrum LatKMI↔LSD [Kuti Lattice 2013]

- LatKMI: HISQ
- LSD: stout staggered
  - consistent spectrum



SU(3) Nf=8 flavor singlet scalar spectrum
[LatKMI: PRD2014; Nagai 9C]

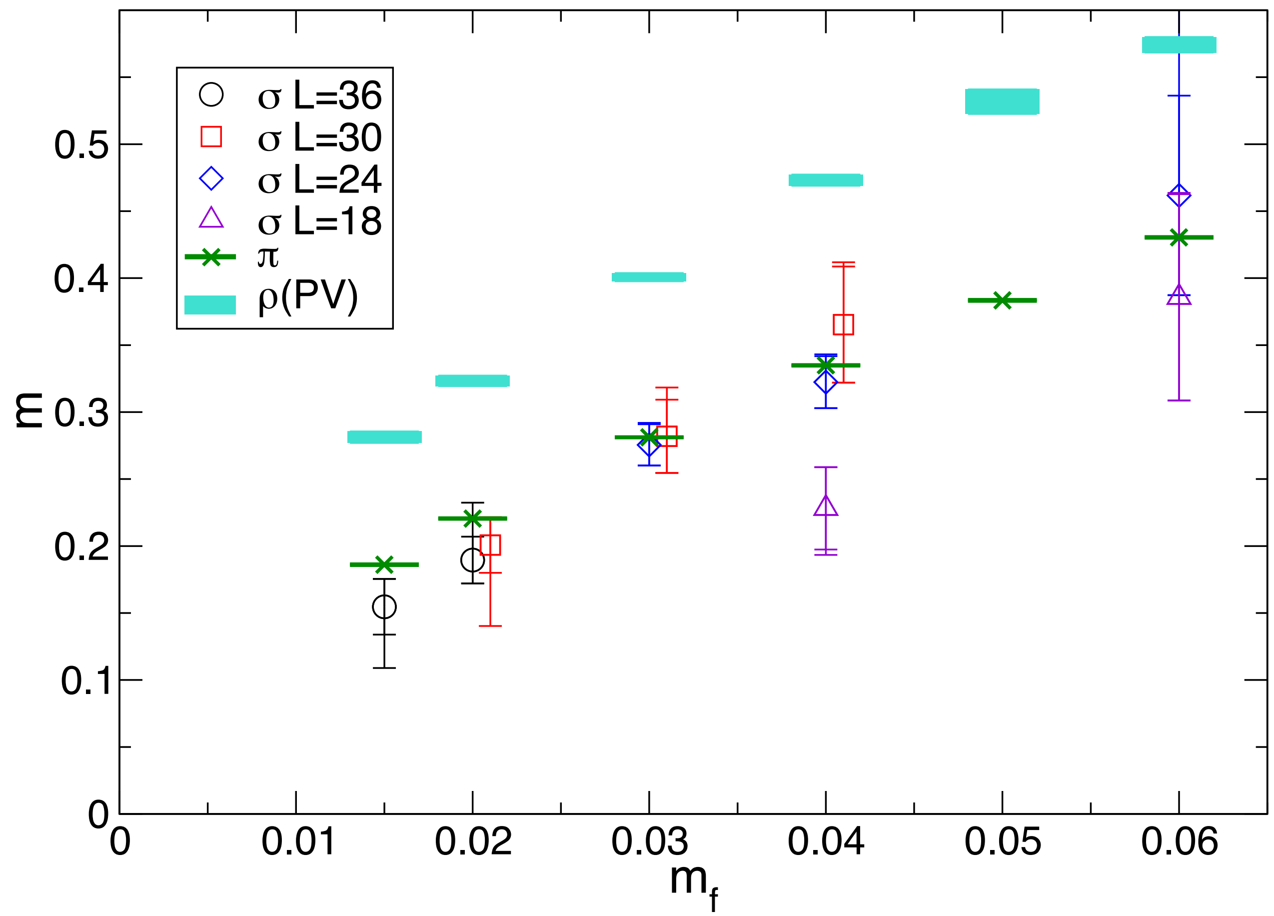
- very high statistics ~ 10,000 configurations
- with variance reduction method
- example of effective mass



m_f	$L^3 \times T$	$N_{\rm cf}[N_{\rm st}]$
0.015	$36^3 \times 48$	3200[2]
0.02	$36^3 \times 48$	5000[1]
0.02	$30^3 \times 40$	8000[1]
0.03	$30^3 \times 40$	16500[1]
0.03	$24^3 \times 32$	36000[2]
0.04	$30^3 \times 40$	12900[3]
0.04	$24^3 \times 32$	50000[2]
0.04	$18^3 \times 24$	9000[1]
0.06	$24^3 \times 32$	18000[1]
0.06	$18^3 \times 24$	9000[1]

[LatKMI arXiv:1403.5000]

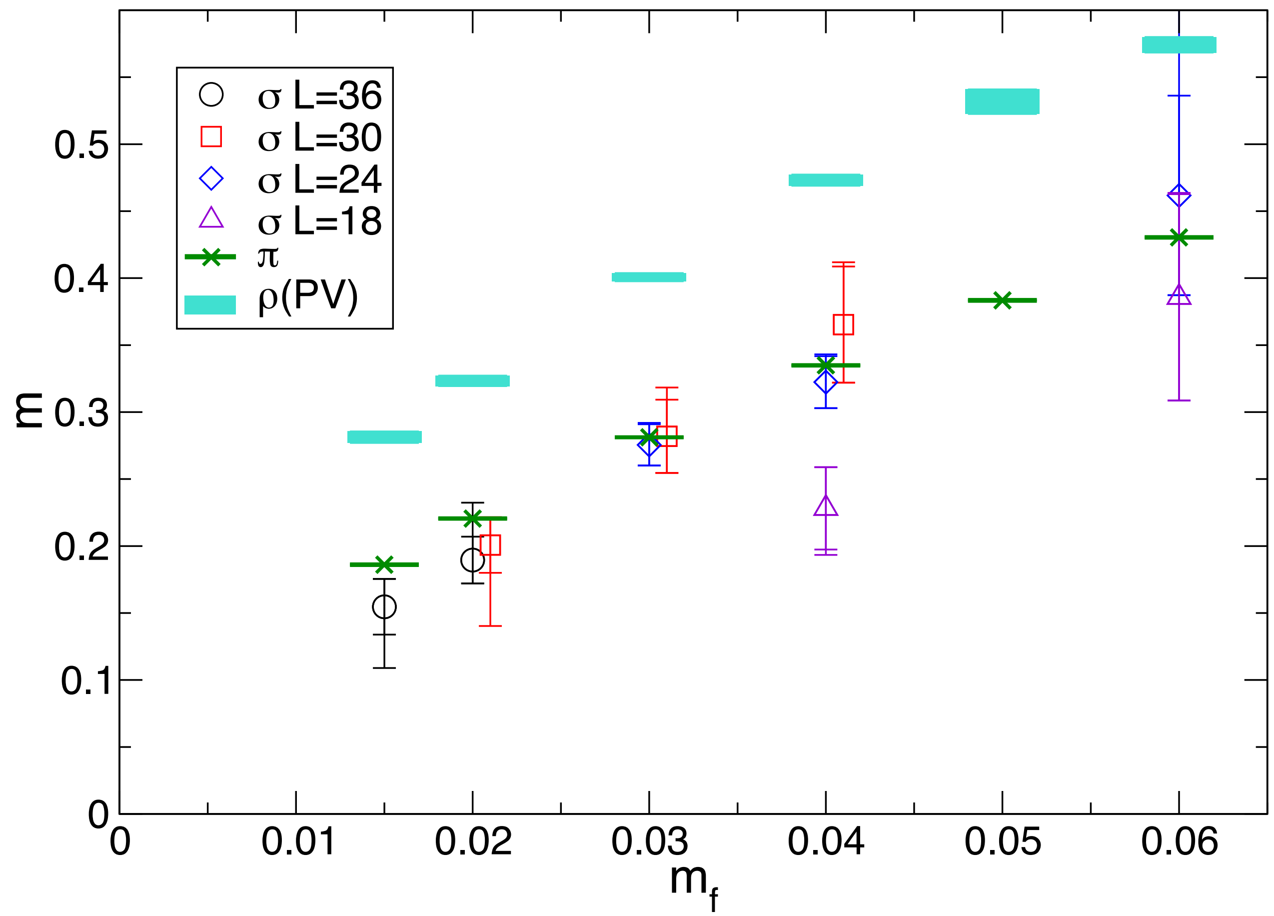
SU(3) Nf=8 flavor singlet scalar spectrum [LatKMI: PRD2014; Nagai 9C]



[LatKMI arXiv:1403.5000 (to appear in PRD)]

SU(3) Nf=8 flavor singlet scalar spectrum [LatKMI: PRD2014; Nagai 9C]

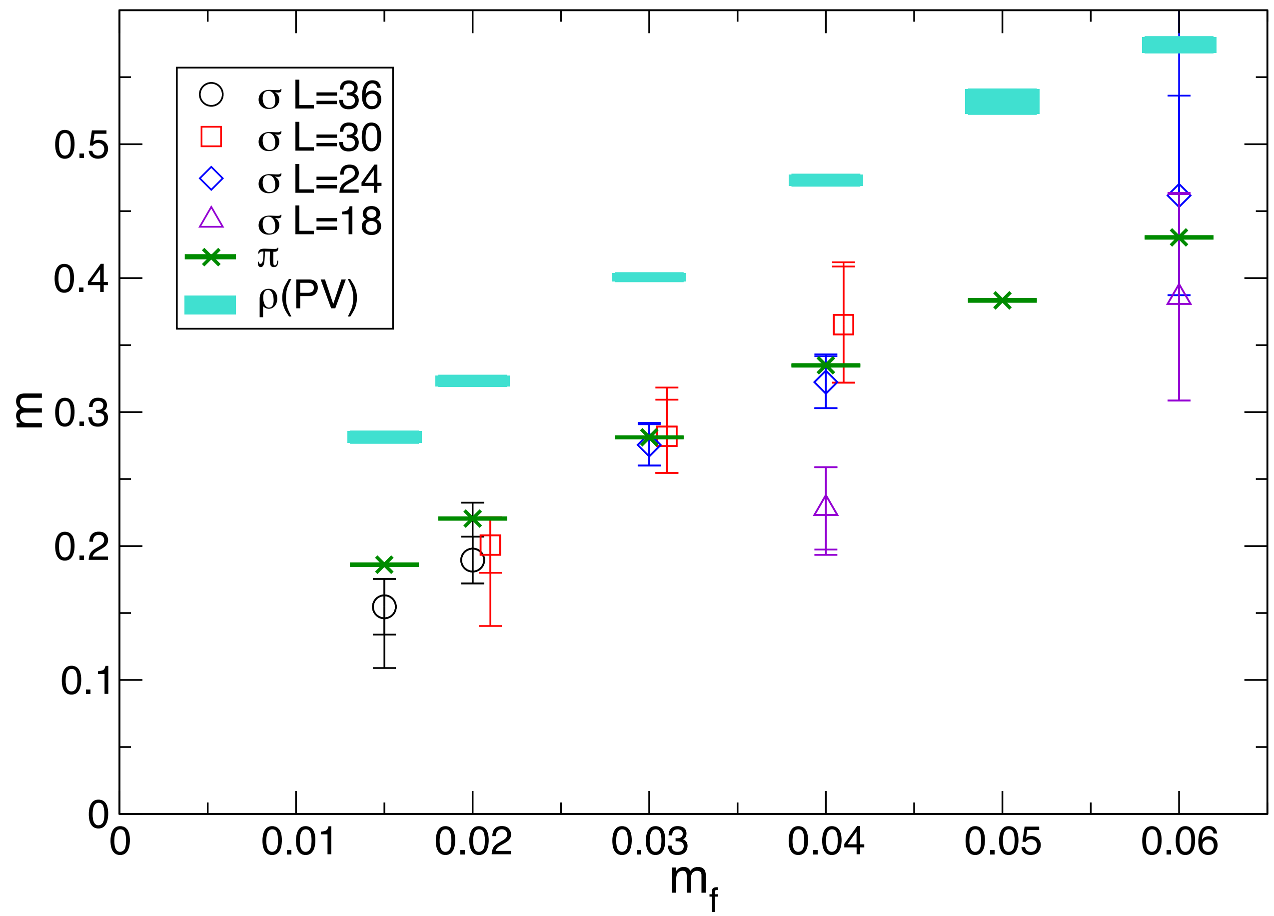
- scalar as light as π



[LatKMI arXiv:1403.5000 (to appear in PRD)]

SU(3) Nf=8 flavor singlet scalar spectrum [LatKMI: PRD2014; Nagai 9C]

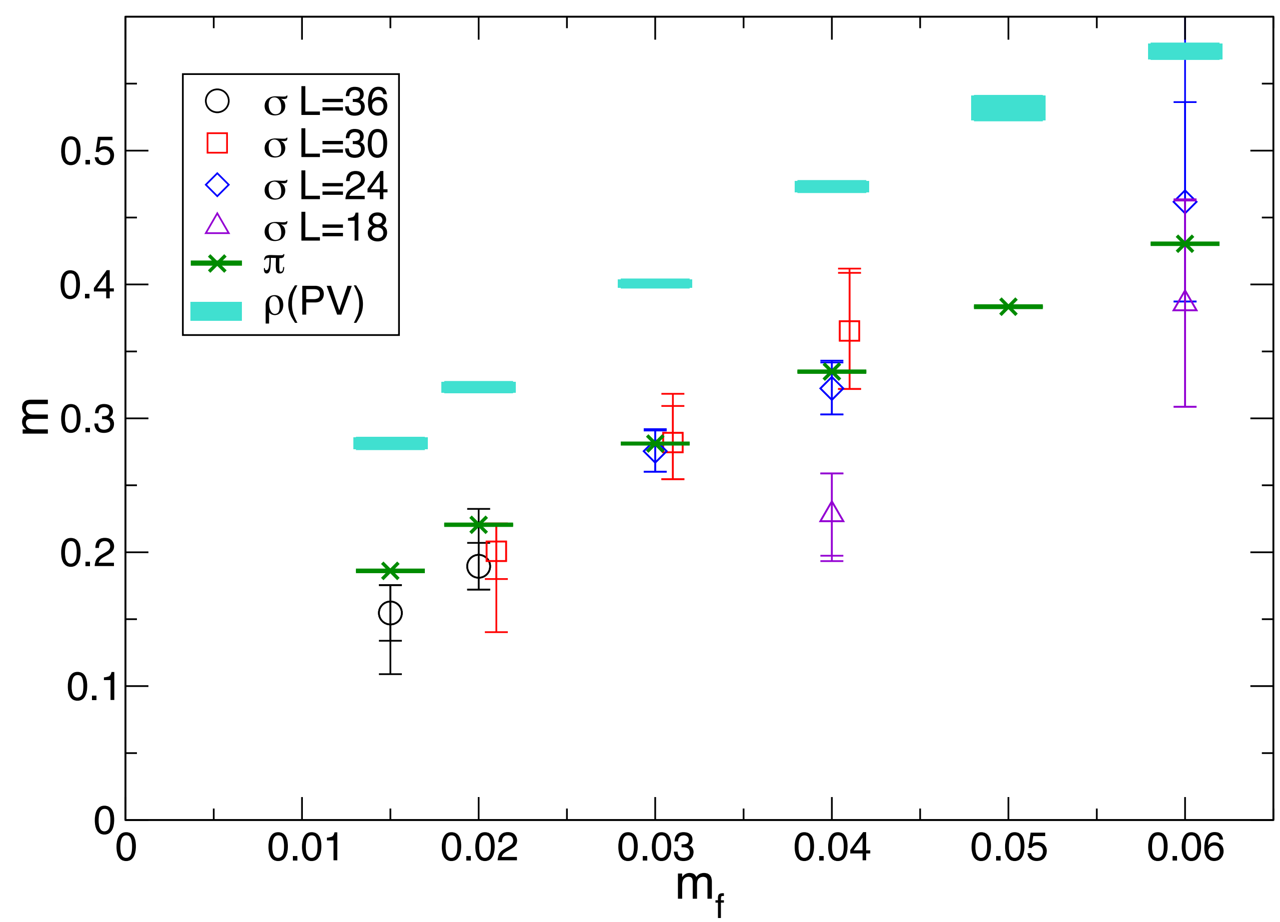
- scalar as light as π
- clearly lighter than ρ



[LatKMI arXiv:1403.5000 (to appear in PRD)]

SU(3) Nf=8 flavor singlet scalar spectrum [LatKMI: PRD2014; Nagai 9C]

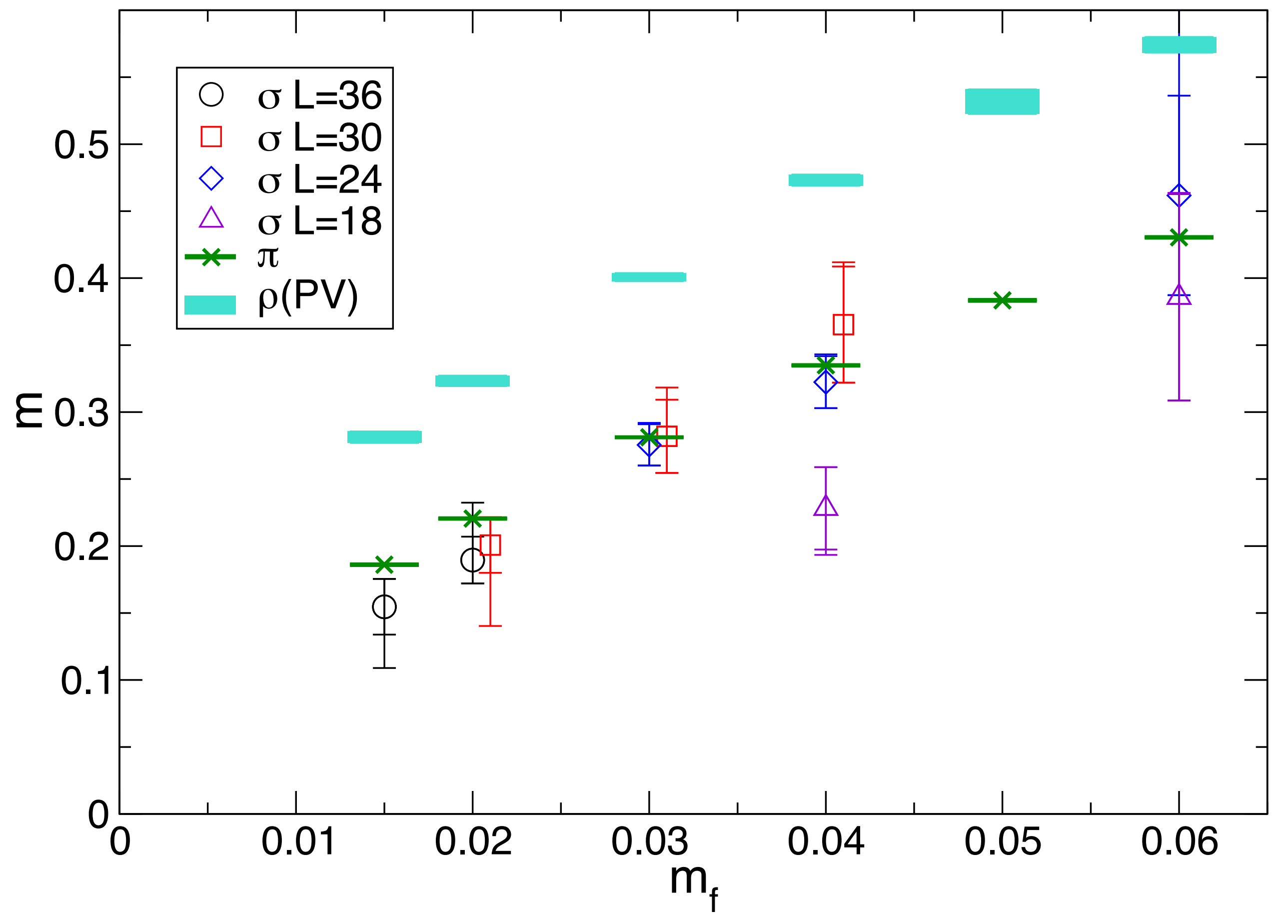
- scalar as light as π
- clearly lighter than ρ
  - ➡ far from heavy quark limit



[LatKMI arXiv:1403.5000 (to appear in PRD)]

SU(3) Nf=8 flavor singlet scalar spectrum [LatKMI: PRD2014; Nagai 9C]

- scalar as light as π
- clearly lighter than ρ
  - ➡ far from heavy quark limit
- light scalar:



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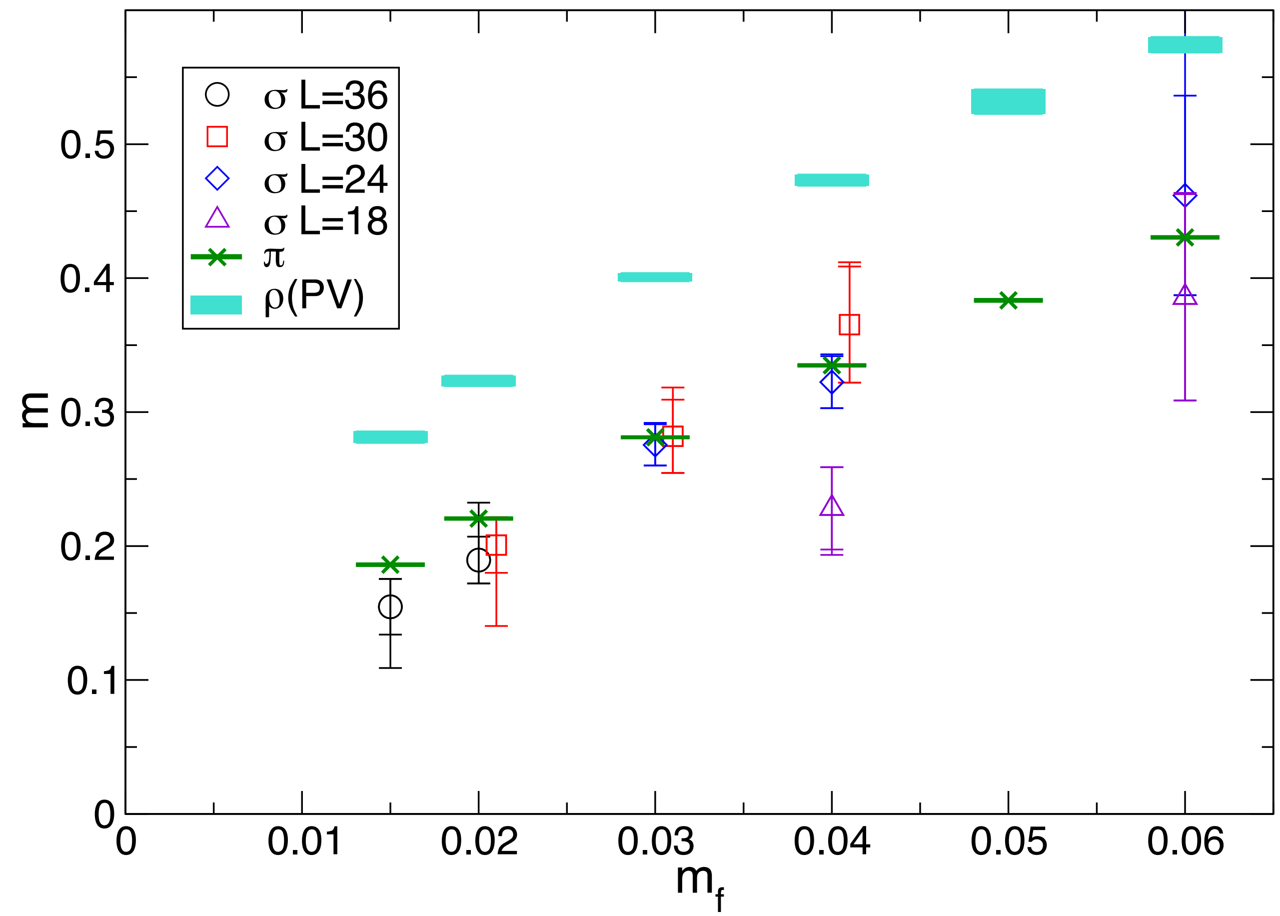
SU(3) Nf=8 flavor singlet scalar spectrum [LatKMI: PRD2014; Nagai 9C]

- scalar as light as π
- clearly lighter than ρ
  ➡ far from heavy quark limit
- light scalar:
  - similar property with Nf=12



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SU(3) Nf=8 flavor singlet scalar spectrum [LatKMI: PRD2014; Nagai 9C]

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- light scalar:
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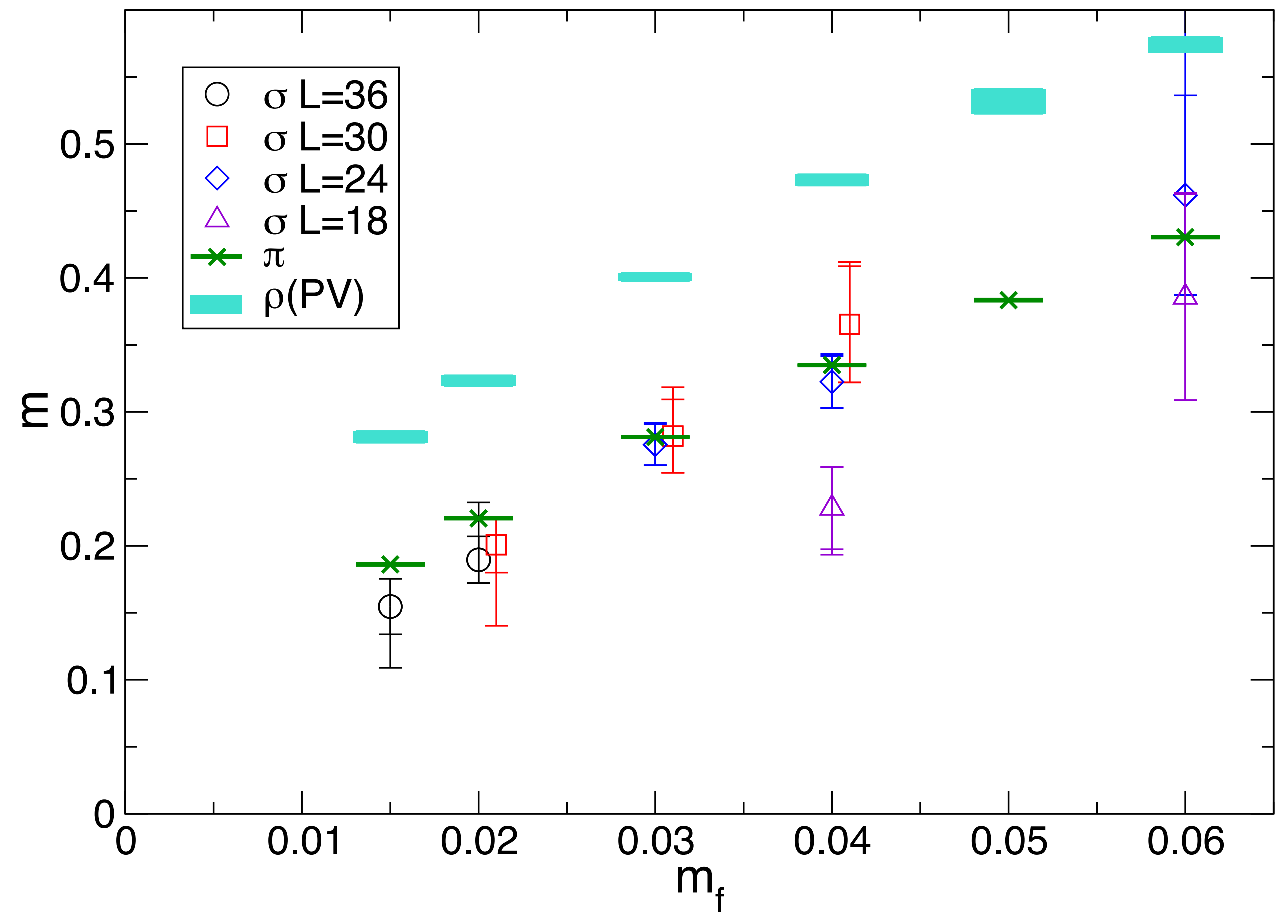
  ➡likely due to (near) conformality



[LatKMI arXiv:1403.5000 (to appear in PRD)]

SU(3) Nf=8 flavor singlet scalar spectrum [LatKMI: PRD2014; Nagai 9C]

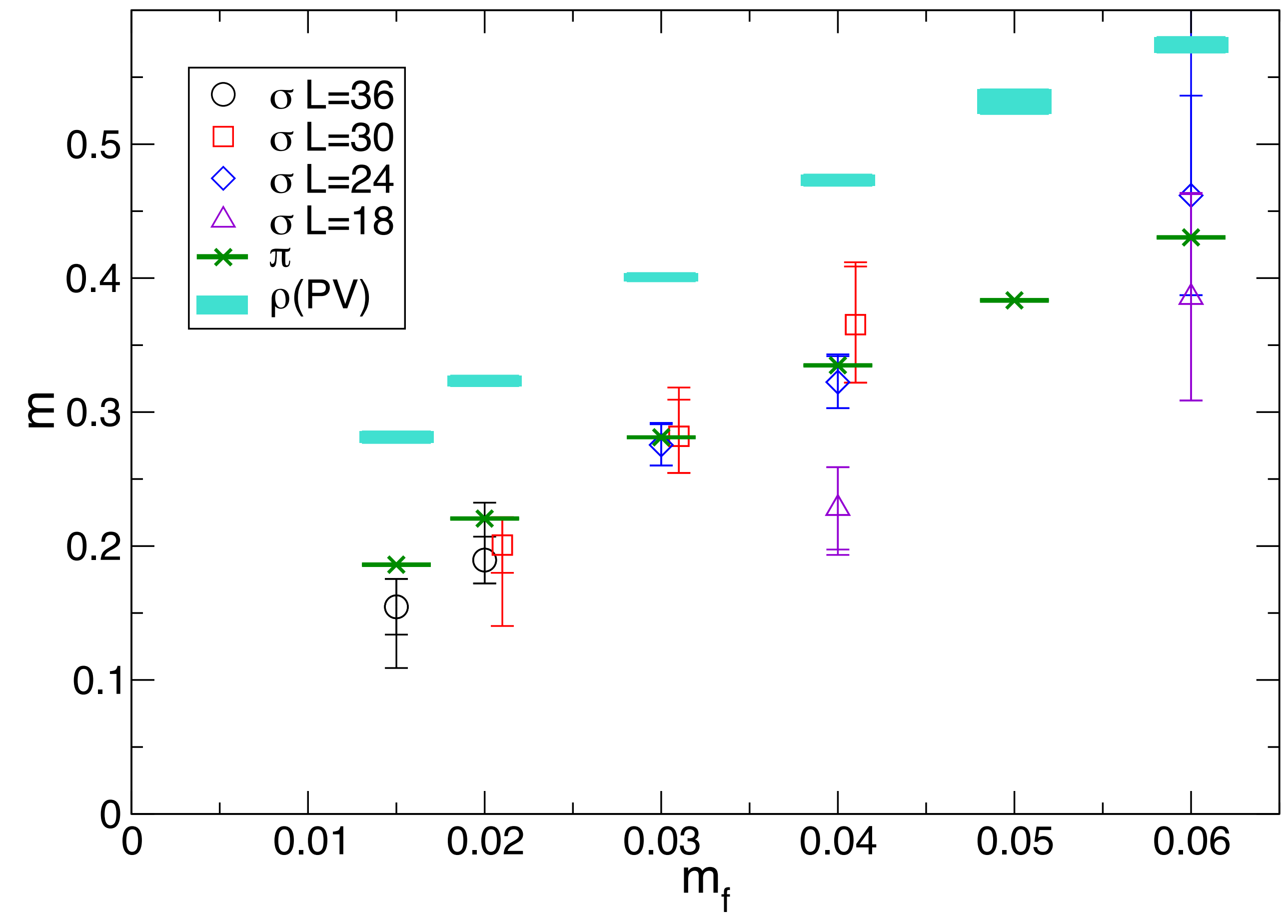
- scalar as light as π
- clearly lighter than ρ

  ➡ far from heavy quark limit

- light scalar:
  - similar property with Nf=12

  ➡likely due to (near) conformality

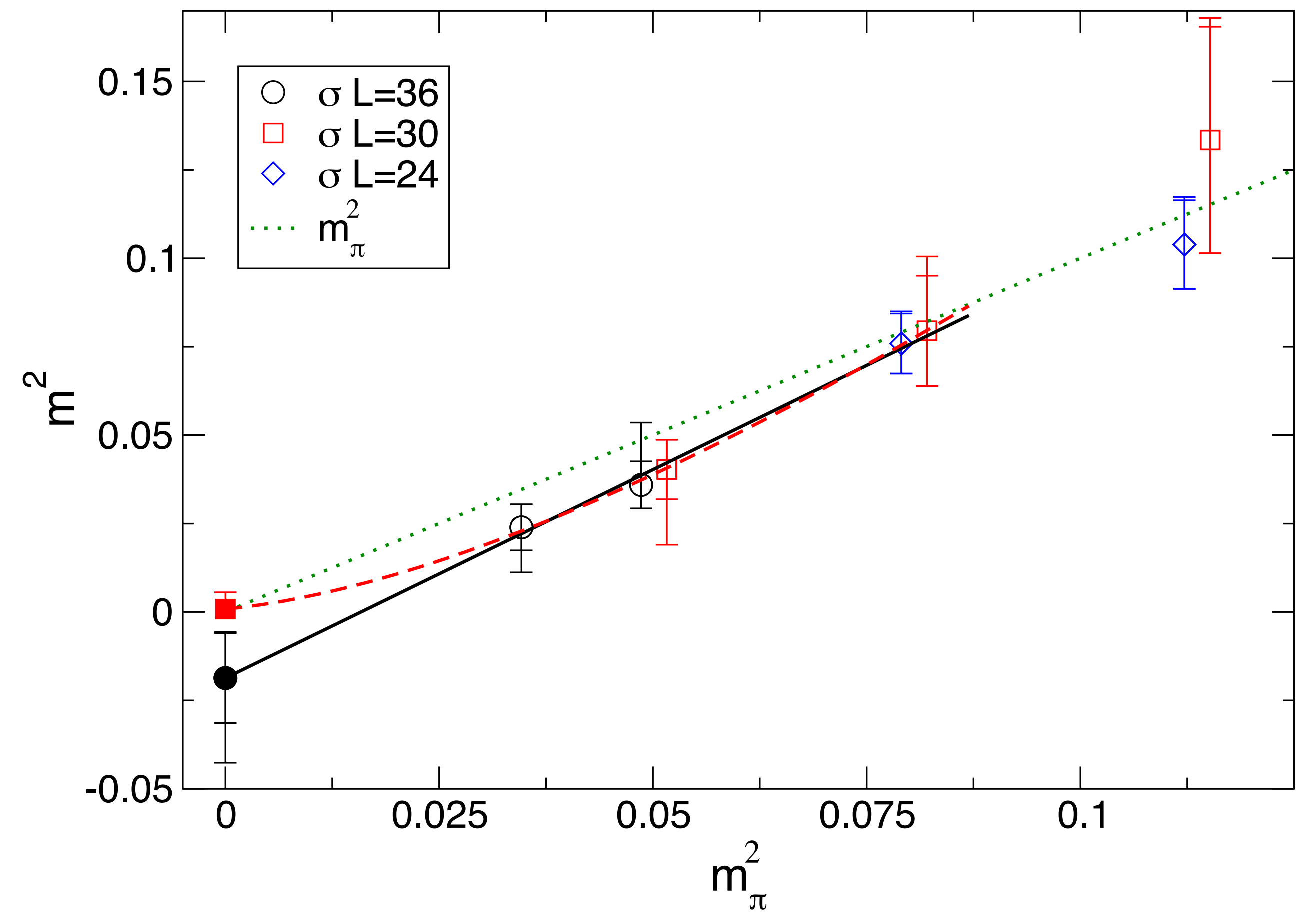
- main result of Nf=8 scalar spectrum from LatKMI



[LatKMI arXiv:1403.5000 (to appear in PRD)]

trial chiral extrapolation for N_f=8 SU(3) m_σ [LatKMI: PRD2014; Nagai 9C]

- though it is too far, so far
- 2 ways:
  - naive linear $m_\sigma = c_0 + c_1 m_f$
  - dilaton ChPT $m_\sigma^2 = d_0 + d_1 m_\pi^2$ (Matsuzaki-Yamawaki 2013)
  - differ only at higher order
- possibility to have ~125GeV Higgs
  - $F/\sqrt{2}$=123 GeV one-family model
- lighter mass data needed!



c_0 = 0.029(39)(+8-72)

d_0 = −0.019(13)(+3-20)

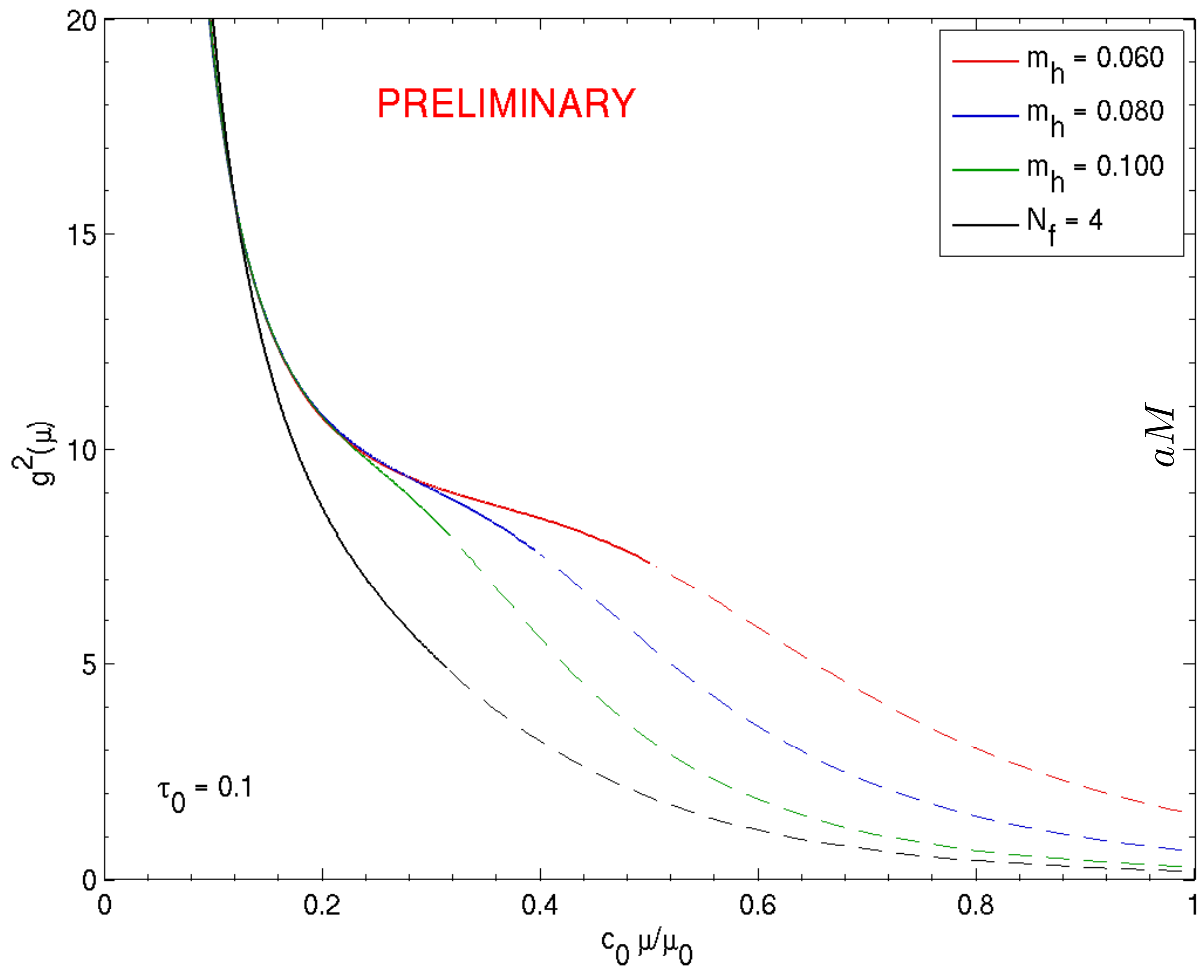
c.f. $m_\sigma \simeq F/\sqrt{2} \rightarrow c_0 \simeq 0.014 \parallel d_0 \simeq 0.0002$

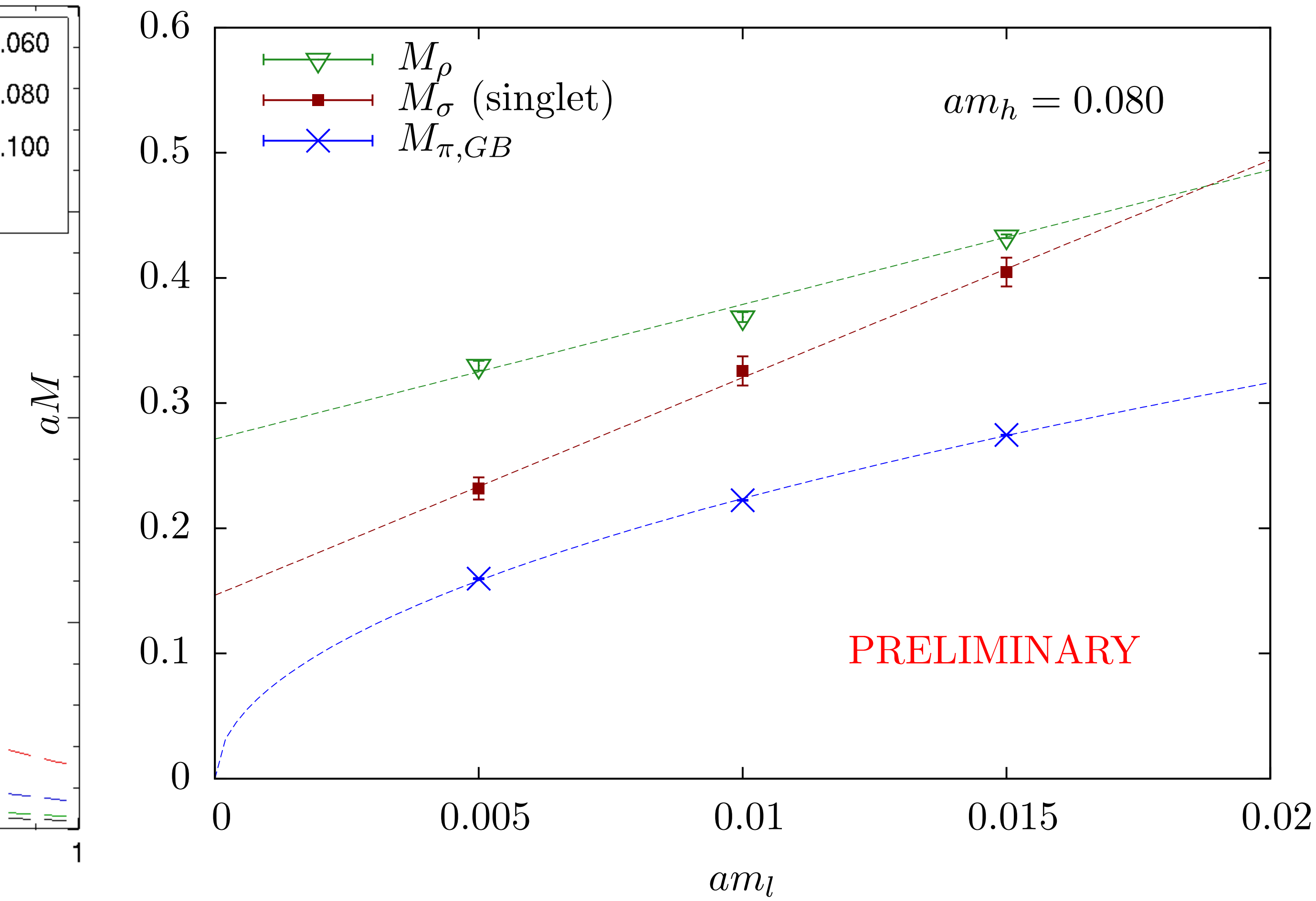
d_1 = 1.18(24)(+35-7)

c.f. $d_1 \sim 1$ (holographic: $F_\sigma \sim \sqrt{N_f} F$) [Matsuzaki & Yamawaki 2012]

Transition from QCD like to walking: SU(3) Nf=4+8 [Weinberg 2C, Witzel P]

- 4 light quarks and varying 8 flavor mass: continuously move from Nf=4 to 12
- gradient flow coupling and spectrum



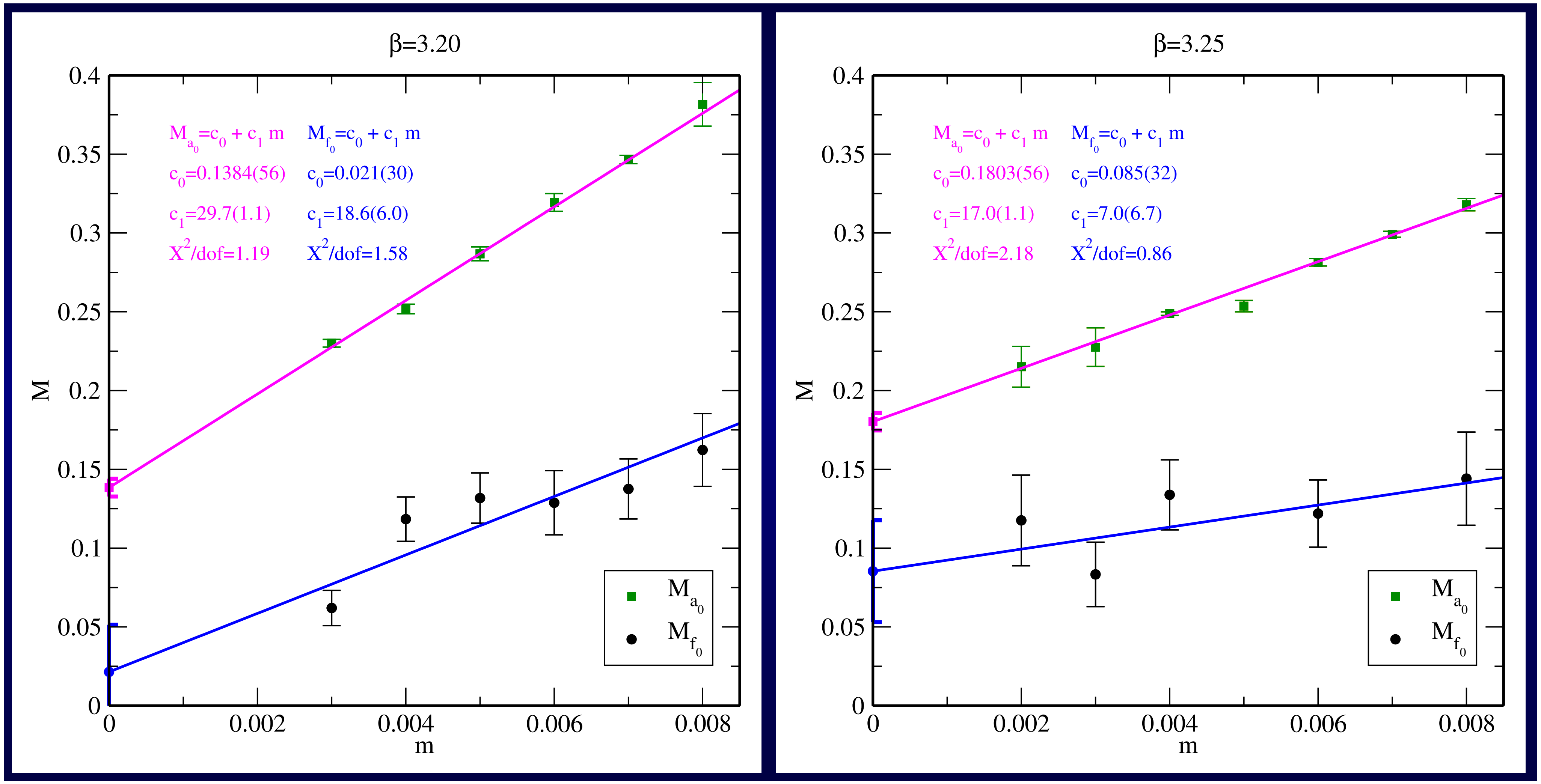


spectrum for mh=0.060 underway

SU(3) Nf=2 sextet

[LatHC: Kuti, Wong 2C]

- extended calculation with 2 beta's and up to 48^3x96

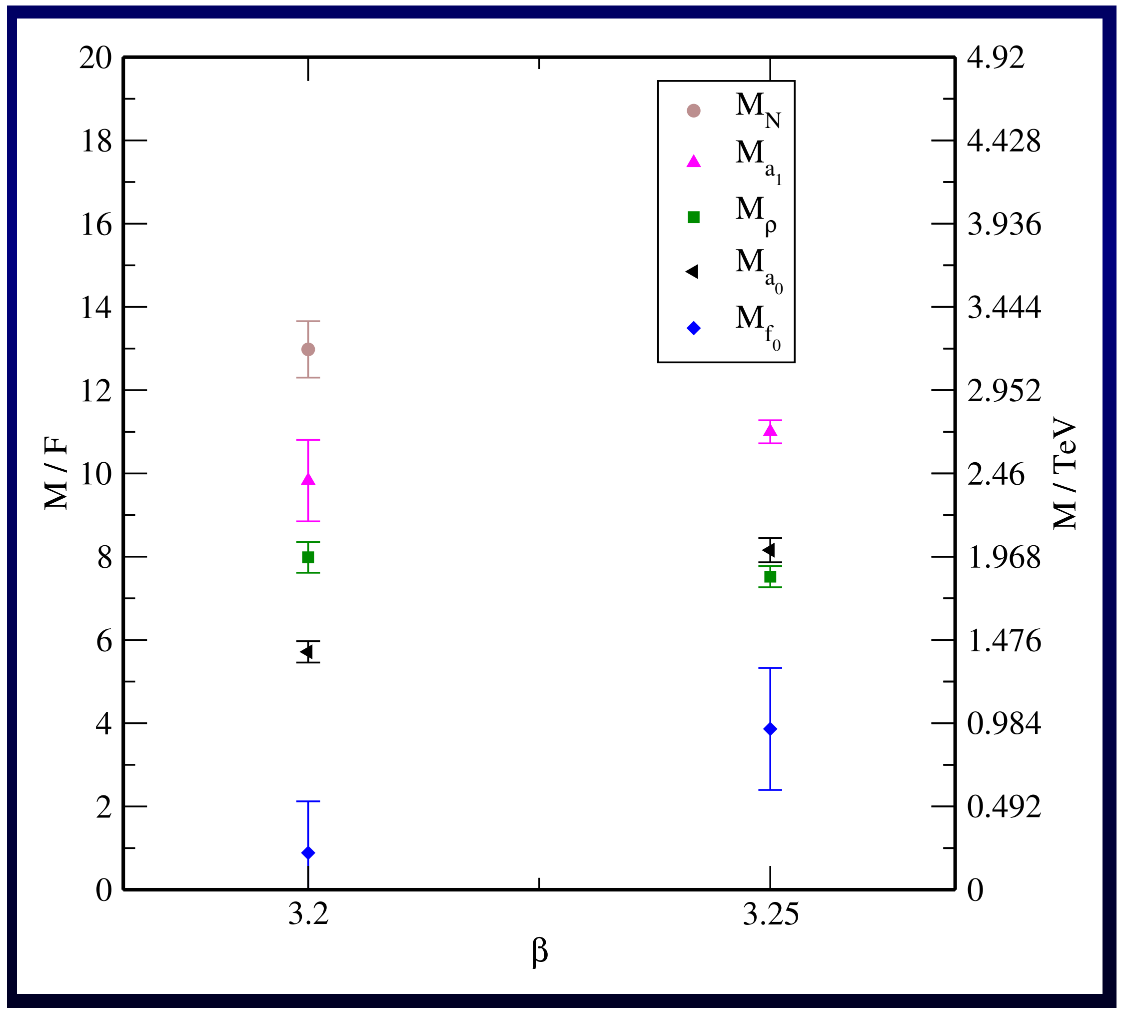


- $M_{f0} \leq M_\pi$

SU(3) Nf=2 sextet

[LatHC: Kuti, Wong 2C]

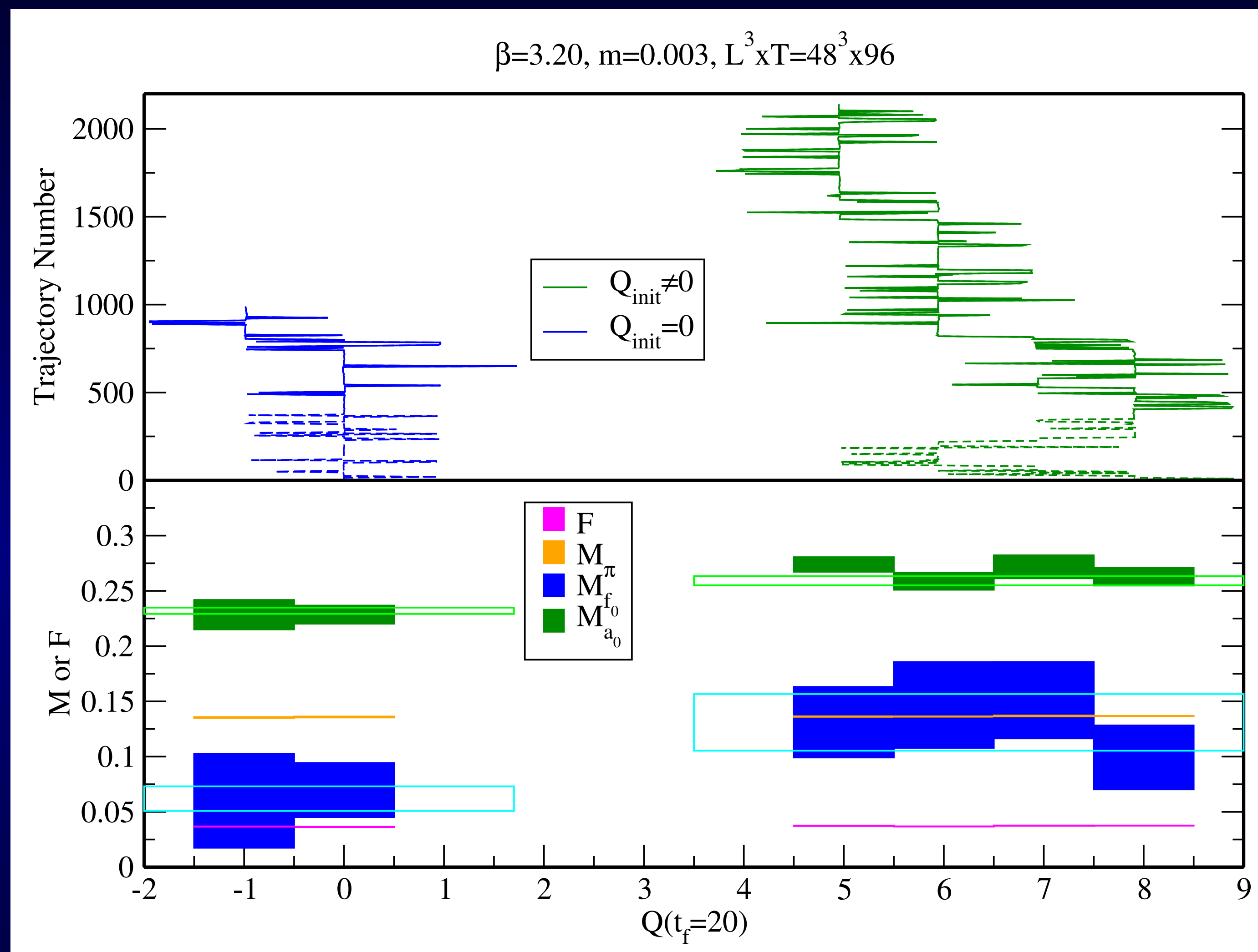
- spectrum at the chiral limit



- Systematic error under investigation

SU(3) Nf=2 sextet: effect of topology on spectrum [LatHC: Kuti, Wong 2C]

- Two separate runs with very different Q values

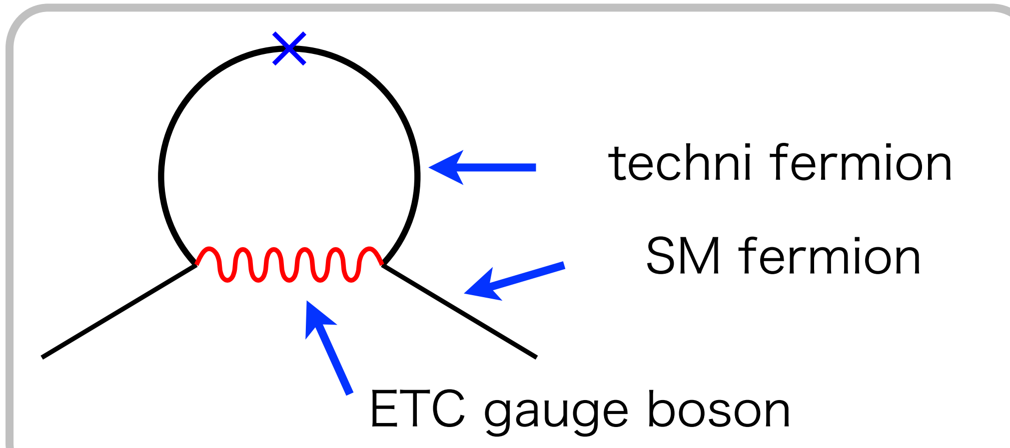


- About $1-\sigma$ effect is observed in M_{a_0} and M_{f_0}, less significant in M_π and $F \Rightarrow$ More controls are needed
- Other studies on topological effects are undergoing (more details in Julius Kuti's talk)

Composite Higgs: other quantities

Extended Technicolor (ETC)

- fermion masses → extended technicolor (ETC)
- New strong interaction of SU(N_{ETC}): N_{ETC}>N_{TC}, T_{ETC}=(T, f): T∈TC, f∈SM
- SSB: SU(N_{ETC})→SU(N_{TC}) x SM @ Λ_{ETC} (≫Λ_{TC})
- $$\frac{1}{\Lambda_{ETC}^2}\overline{T}T\overline{f}f \to m_f = \frac{\langle\overline{T}T\rangle_{ETC}}{\Lambda_{ETC}^2}$$
- $$\frac{1}{\Lambda_{ETC}^2}\overline{f}f\overline{f}f$$ FCNC



- FCNC should be small ⇔ top or bottom quark mass should be produced

➡ enhancement of TC chiral condensate → walking TC γ^*_m~1

[Yamawaki et al, Holdom, Akiba & Yanagida, Appelquist]

enhancement of php

[LSD PRL2010; arXiv:2014]

- ratio of Σ/F³

$$R_8^{(IJ)} = \frac{X^{(IJ)}(N_f = 8)}{X^{(IJ)}(N_f = 2)},$$

$$X^{(CF)} = \frac{\langle\overline{\psi}\psi\rangle_m}{F_P^3}$$

$$X^{(CM)} = \frac{(M_P^2/2m)^{3/2}}{\langle\overline{\psi}\psi\rangle_m^{1/2}}$$

$$X^{(FM)} = \frac{M_P^2}{2mF_P}.$$

- domain-wall fermions
- β tuned so $1/a = M_\rho(m_f=0)$

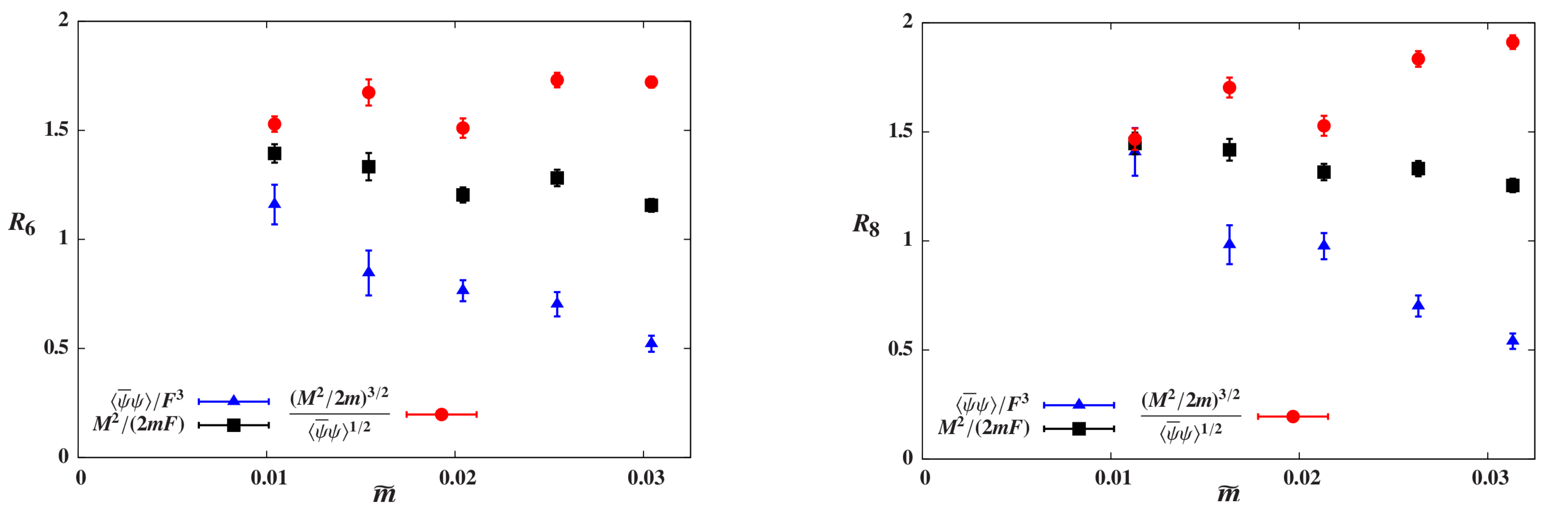
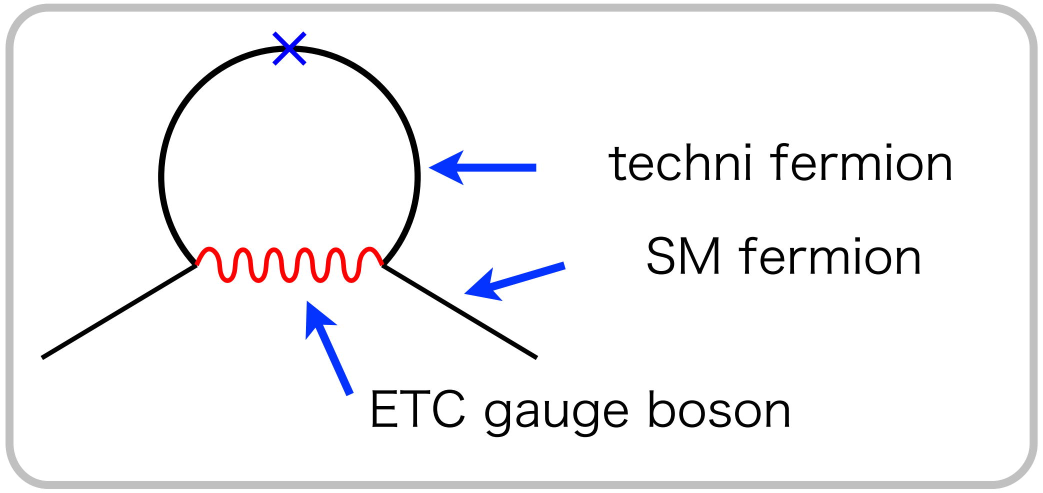


FIG. 10. Ratios $R_{N_f}^{(IJ)}$ of the three observables $X^{(IJ)}$ in Eq. (16) that reduce to $\langle\overline{\psi}\psi\rangle/F^3$ in the chiral limit, for $N_f = 6$ normalized by $N_f = 2$ (left) and $N_f = 8/N_f = 2$ (right). The horizontal axis is the geometric mean $\widetilde{m} = \sqrt{m_{N_f=2}m_{N_f=6,8}}$.

- similar enhancement of Σ/F³ observed for Nf=6 and 8

Extended Technicolor (ETC)

- fermion masses → extended technicolor (ETC)
- New strong interaction of SU(N_{ETC}): N_{ETC}>N_{TC}, T_{ETC}=(T, f): T∈TC, f∈SM
- SSB: SU(N_{ETC})→SU(N_{TC}) x SM @ Λ_{ETC} ($\gg\Lambda_{TC}$)
- $$\frac{1}{\Lambda_{ETC}^2}\bar{T}T\bar{f}f \to m_f = \frac{\langle \bar{T}T\rangle_{ETC}}{\Lambda_{ETC}^2}$$
- $$\frac{1}{\Lambda_{ETC}^2}\bar{f}f\bar{f}f$$ FCNC



- FCNC should be small ⇔ top or bottom quark mass should be produced

➡ enhancement of TC chiral condensate → walking TC $\gamma^*_m \sim 1$

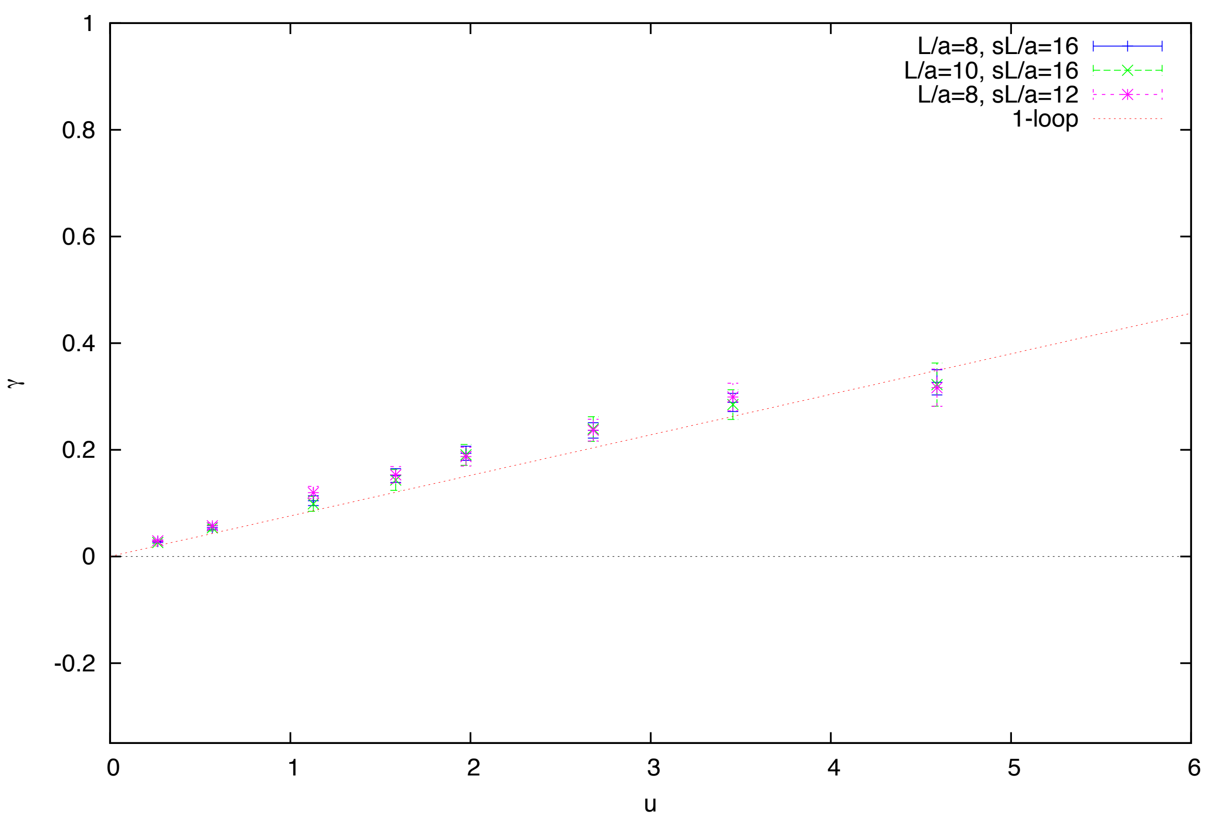
➡ in tern could generate a relevant 4 fermi op $\bar{T}T\bar{T}T$ → fine tuning problem

[Sannino 04, Luty 04, Rattazzi et al 08]

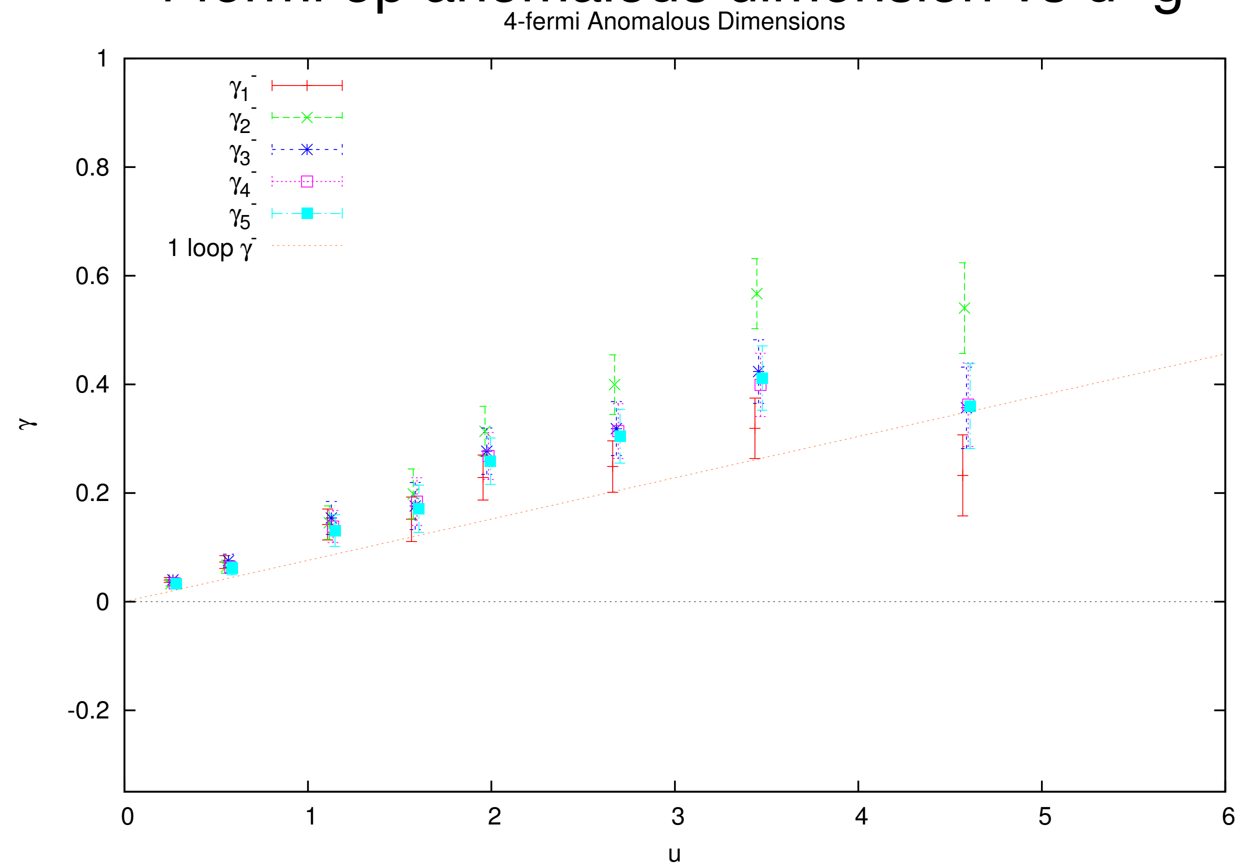
anomalous dimension of 4 fermi operators [Del Debbio 5C]

- SF step scaling set up for SU(2) Nf=2 adj.
- multiplicatively ren. op combination

mass anomalous dimension vs u=g²



4 fermi op anomalous dimension vs u=g²



$$L/a = 8 \to L/a = 16$$

Scheme-independence: system in a neighbourhood of a fixed point?

S parameter

- Ciucini et al JHEP1308 106 (M_H=126GeV)

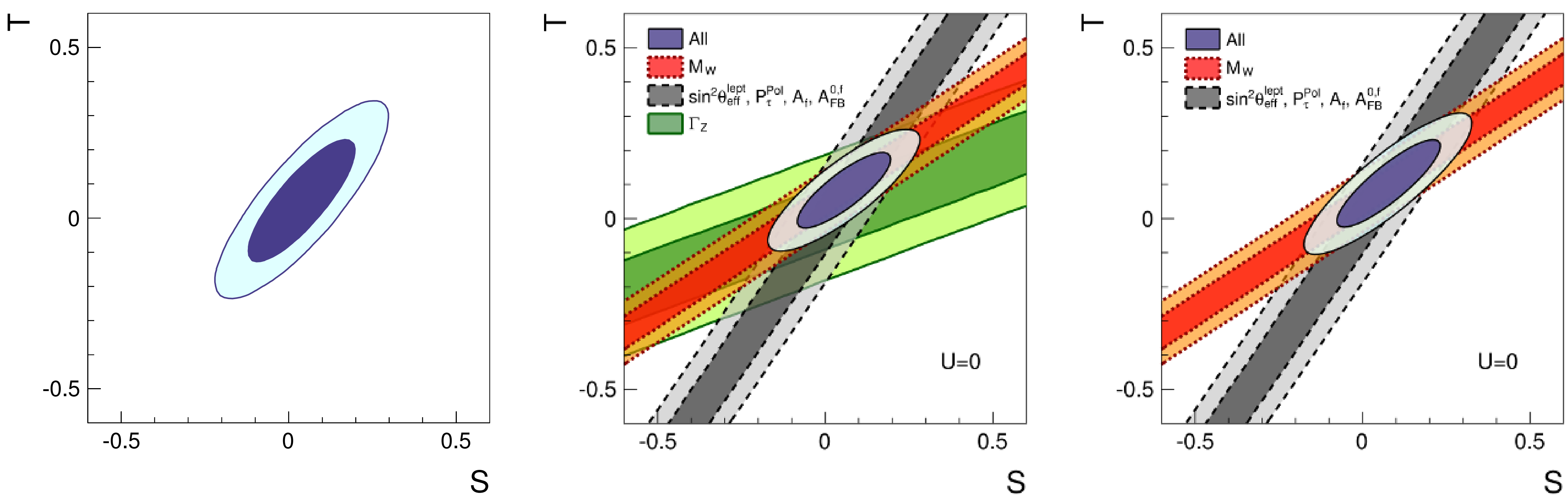


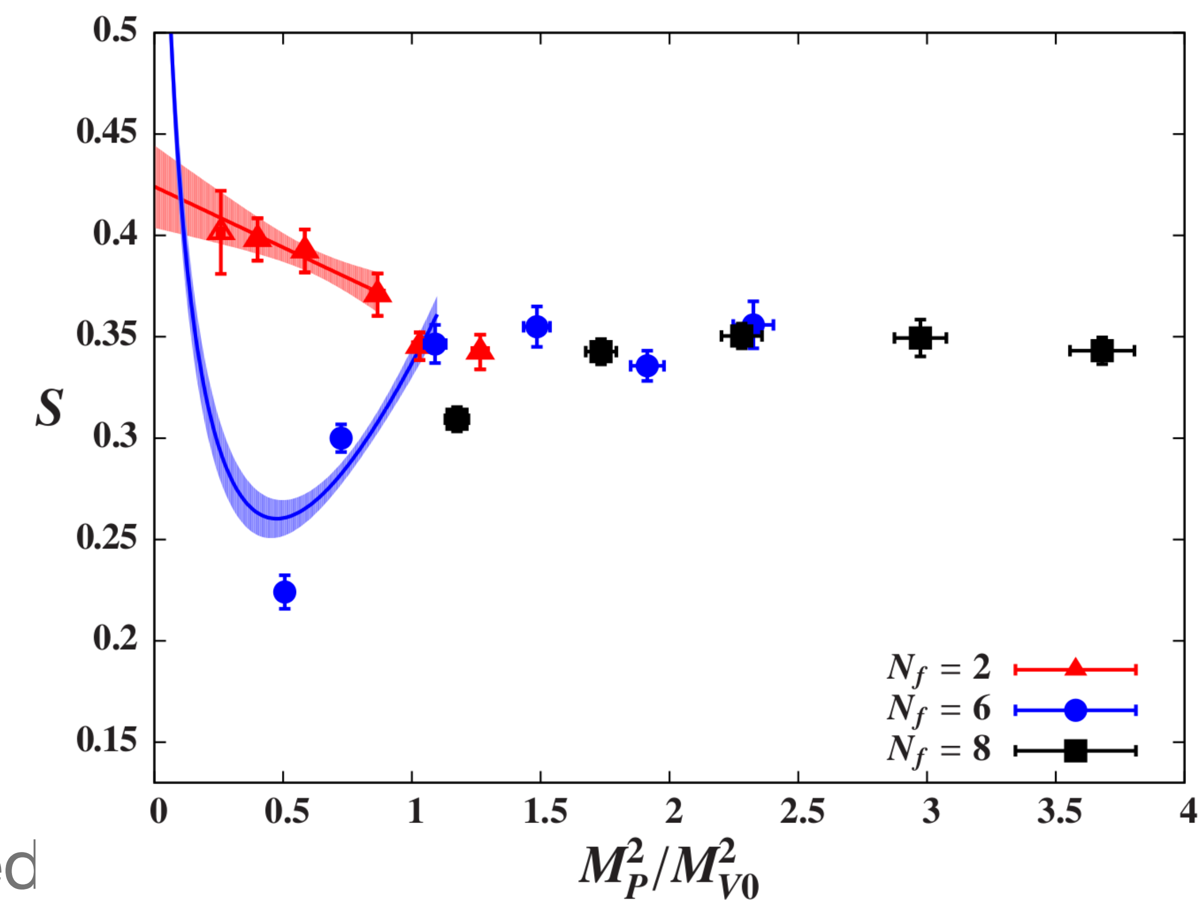
Figure 4. Left: two-dimensional probability distribution for the oblique parameters S and T obtained from the fit with S, T, U and the SM parameters, with the large-m_t expansion for the two-loop fermionic EW corrections to ρ_Z^f. Center: two-dimensional probability distribution for the oblique parameters 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

- calculated through vacuum polarization function of flavor non-singlet currents
- lattice calculation suffers from power divergence without exact chiral symm.
- so far, overlap and domain-wall fermion methods are reported
- Overlap
  - Nf=2 SU(3) [JLQCD Shintani et al PRL 2008]
- Domain-wall
  - Nf=2+1 SU(3) [RBC/UKQCD Boyle et al PRD 2010]
- Staggered   (utilizing exact non-siglet symmetry due to multiple fields)
  - Nf=4n system setup on HISQ [Aoki (LatKMI) Lattice 2013]

S parameter with SU(3) fundamental fermions [LSD, PRL 2011; arXiv:2014]

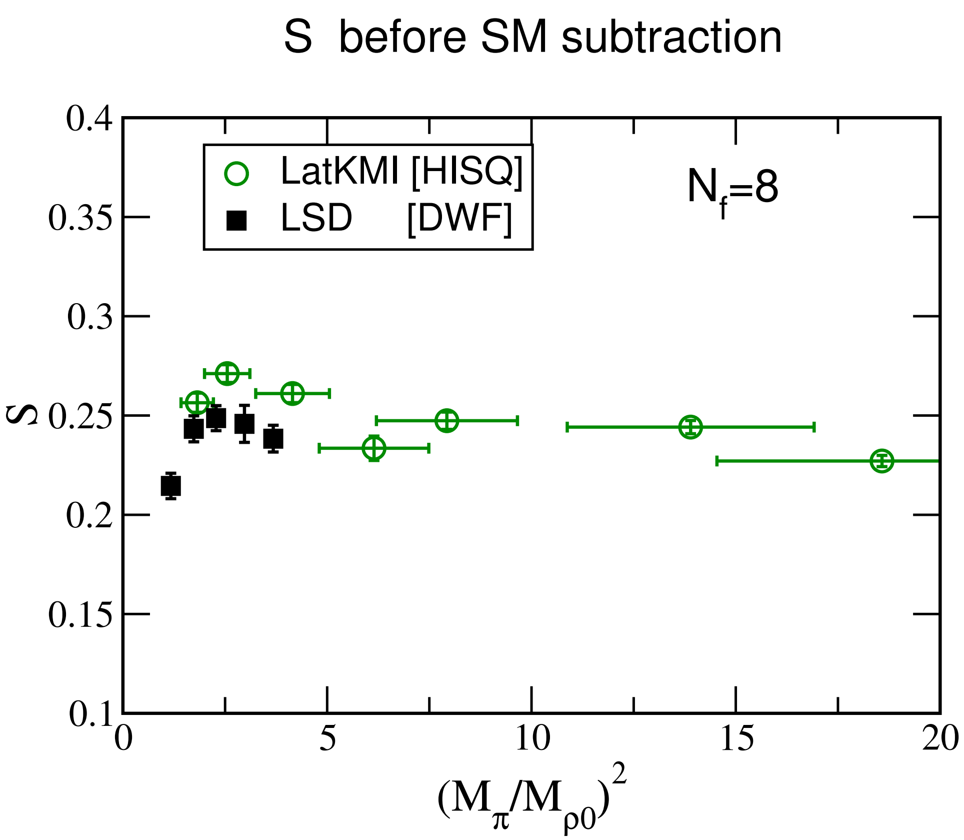
- domain wall fermions with Nf=2,6,8
- one doublet has EW charge →
- Nf=6
  - decreases as m_f enters chiral regime
  - turns up after chiral log sets in
  - low value of S possible for unabsorbed massive pions

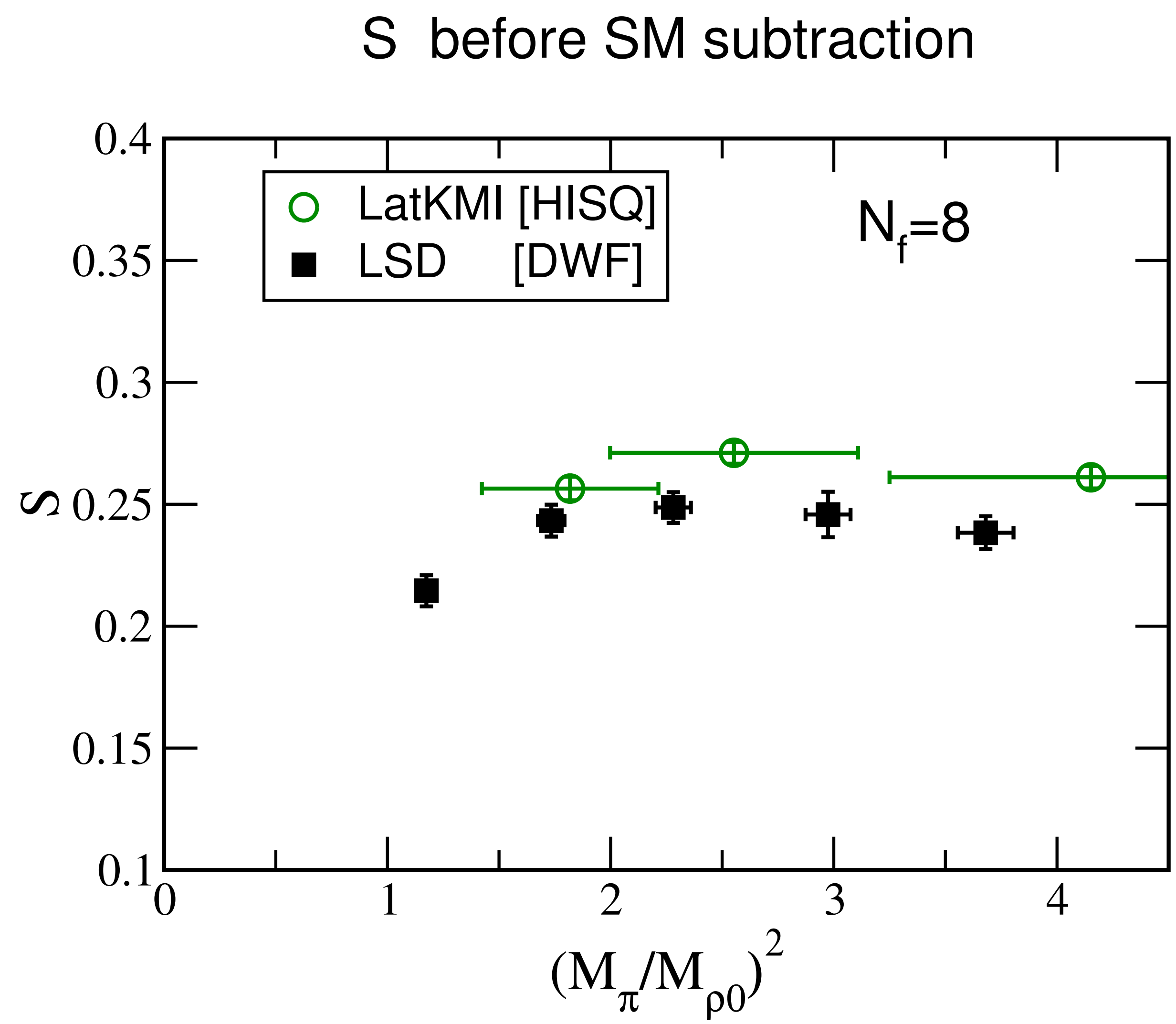


- Nf=8
  - similar trend as Nf=6, but not conclusive

S parameter for SU(3) Nf=8

[LatKMI: Ohki 9C]





- S parameter calculated with HISQ (preliminary), same ballpark as LSD
- More volumes, lighter mass calculations underway

➡check the trend of bending down

Dilaton decay constant

[Ohki 9C]

- F_σ for composite Higgs, like F for pion, gives coupling to other particles
- using continuum Ward-Takahashi identity
- expressing everything with finite quantities on the lattice
- F_σ can be calculated
- Those who interested should come to 214 Pupin at 17:50- on Friday

SUMMARY

- Development on method
  - Running coupling is getting much precise through gradient flow
    - would allow robust evidence of the IRFP
  - S parameter can be calculated in Nf=4n (n>1) staggered fermions
  - a method to calculate dilation decay constant proposed
- Common feature of (near) conformal theories
  - $m_{0++}(m_f) < m_\pi(m_f)$ for the range of m_f so far investigated
  - challenging task $m_f \rightarrow 0$ for walking theory: level crossing and 2π threshold

SUMMARY

- SU(3) Nf=12 fundamental
  - growing evidence of the existence of IRFP
  - different action / scheme being tested to get robust answer
  - mass anomalous dimension: needs more study
- SU(3) Nf=8 fund.: (near) conformal, large anomalous dimension, **Light 0++**
  - could be a candidate of walking technicolor (WTC) theory
  - needs further study (lighter mass, larger V)
- SU(3) Nf=2 sextet: **Light 0++**, could be a candidate of WTC
  - spectrum most extensively studied so far
  - 0++ suffers from topology sampling: systematic study underway

We are heading forward, steadily…

We are heading forward, steadily…

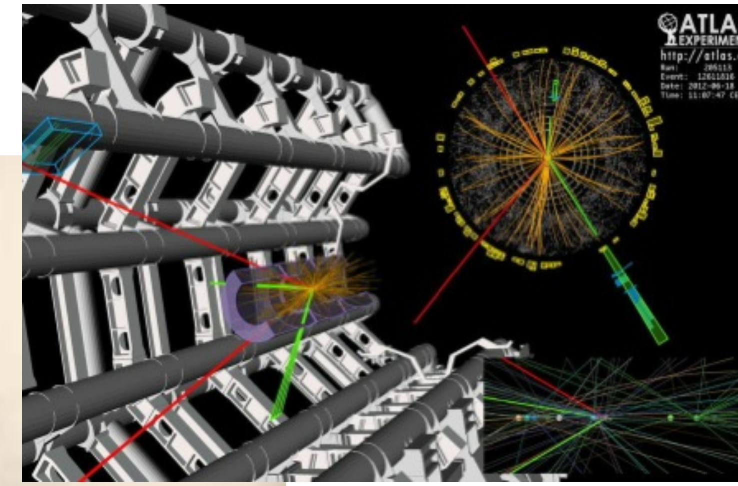
some path may lead to Berlin-wall [© Ukawa]…

We are heading forward, steadily…

some path may lead to Berlin-wall [© Ukawa]…

We will do our best, and may be it will lead to …

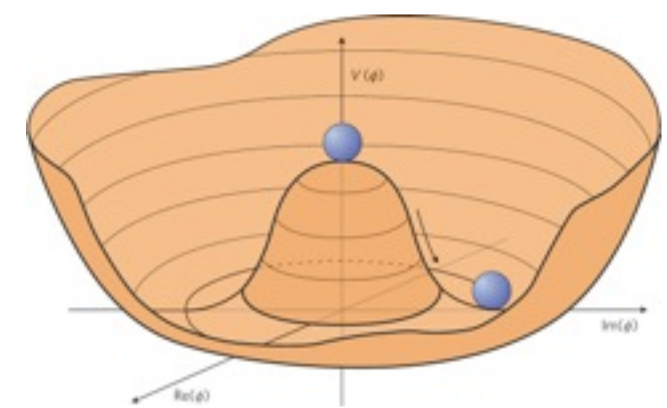
bridge to the new world



Thank you very much for your attention !

Higgs mechanism (cf. Farhi & Susskind)

- Higgs potential : $V=\mu^2 |\phi|^2 + \lambda|\phi|^4$ with $\mu^2<0$: “wine bottle”
  - rotating: m=0 mode
  - radial: $m\neq0$: Higgs particle



- weak doublet: 4 fields: 1 massive Σ, 3 massless
- massless: $\Pi^{\pm}$, Π^0 : Nambu-Goldstone boson (rotational symm. br.)
- have coupling to weak current: $\langle 0|J_\mu^{\pm}|\Pi^{\pm}\rangle = F\, p_\mu$; $F = \langle 0|\phi|0\rangle = 246$ GeV
- make a massless pole in the vacuum polarization
- cancels massless pole of original $W^{\pm}$ propagator → massive gauge boson

$\langle 0|J_\mu^\pm|\Pi^\pm\rangle = F\, p_\mu$

- Isn't it familiar ? : $\langle 0|J_\mu^\pm|\Pi^\pm\rangle = F\, p_\mu$ with massless boson $\Pi^\pm$
- pion decay: $\langle 0|A_\mu^\pm|\pi^\pm\rangle = f\, p_\mu$
  - $\pi^\pm$ π^0 Nambu-Goldstone boson made of u, q quarks due to
  - $SU(2)_L x SU(2)_R \to SU(2)_V$: spontaneous chiral symmetry breaking
  - f=93 MeV ⇔ F=246 GeV
- axial current $A_\mu^\pm$ is a part of weak current $J_\mu^\pm$: (V-A)
- Even if there is no Higgs, weak boson gets mass due to chiral br. in QCD

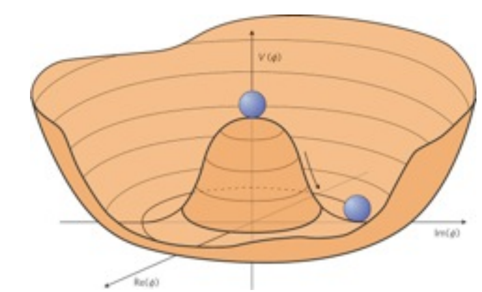
Technicolor (TC)

- $\langle 0|J_\mu^\pm|\Pi^\pm\rangle = F\, p_\mu$
- realize this with a new set of
    - **massless** quarks (techni-quarks)
    - which have coupling to weak bosons,
    - and interact with techni-gluons
    - which breaks the chiral symmetry in the techni-sector,
    - produces techni-pions which have decay constant

➡$F = 246/\sqrt{N}$ GeV: scale up version of QCD (N: # weak doublet from new techni-sector)

Technicolor ⇔ SM Higgs

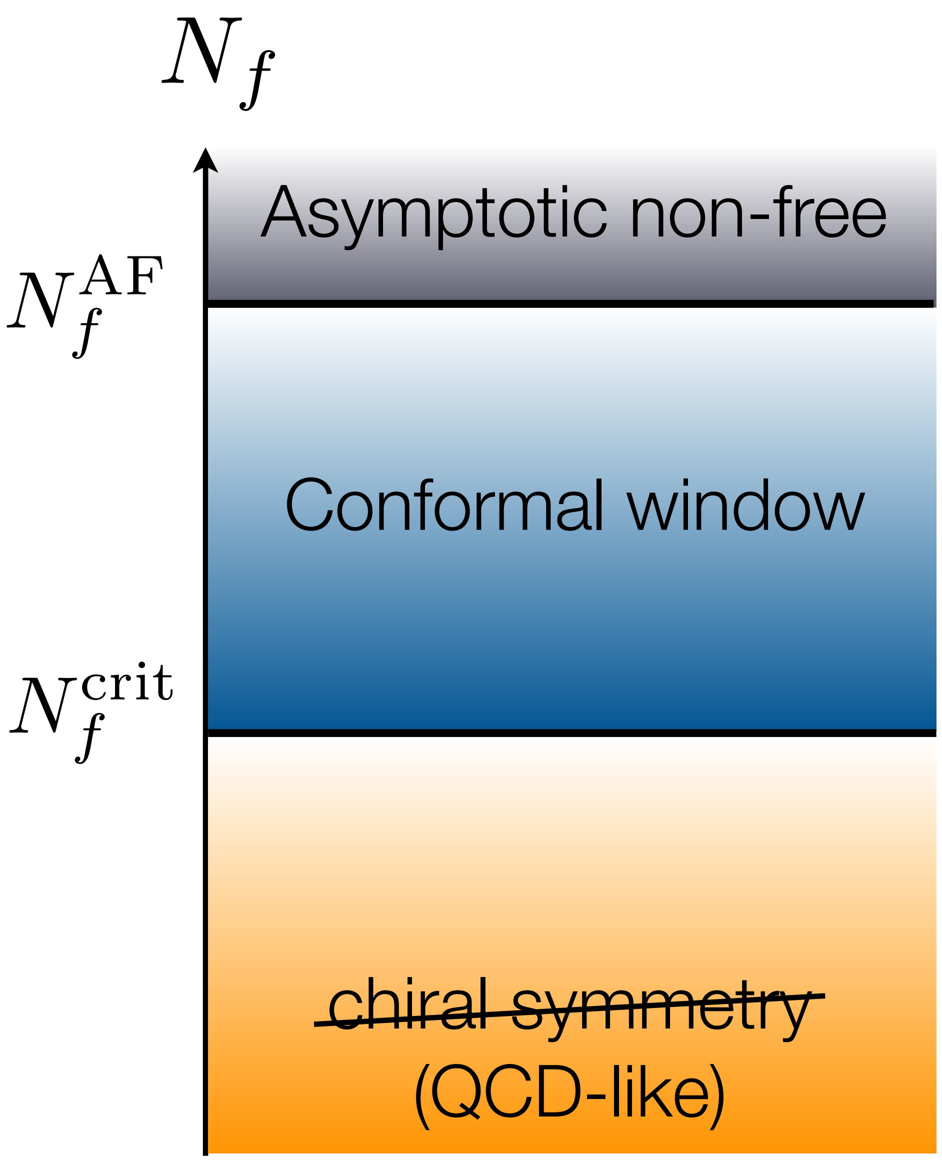
- success of technicolor
  - explaining the origin of EW symmetry breaking
    - dynamics of gauge theory ⇔ $\mu^2 < 0$
  - evading the gauge hierarchy problem: naturalness problem
    - due to logarithmic UV divergence ⇔ power divergence

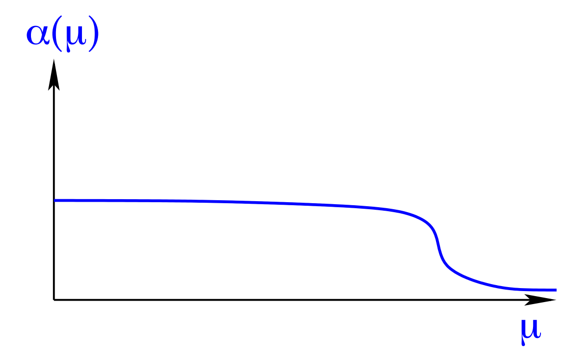


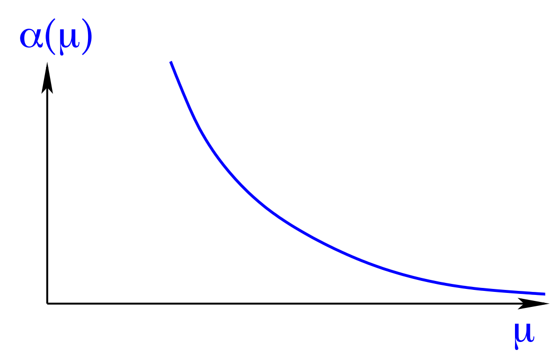
- fermion masses ?
  - ETC effective 4 Fermi interaction ⇔ fermion-Higgs Yukawa coupling
  - produced by introducing interaction: techni-quarks and SM fermions

conformal window and walking gauge coupling

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

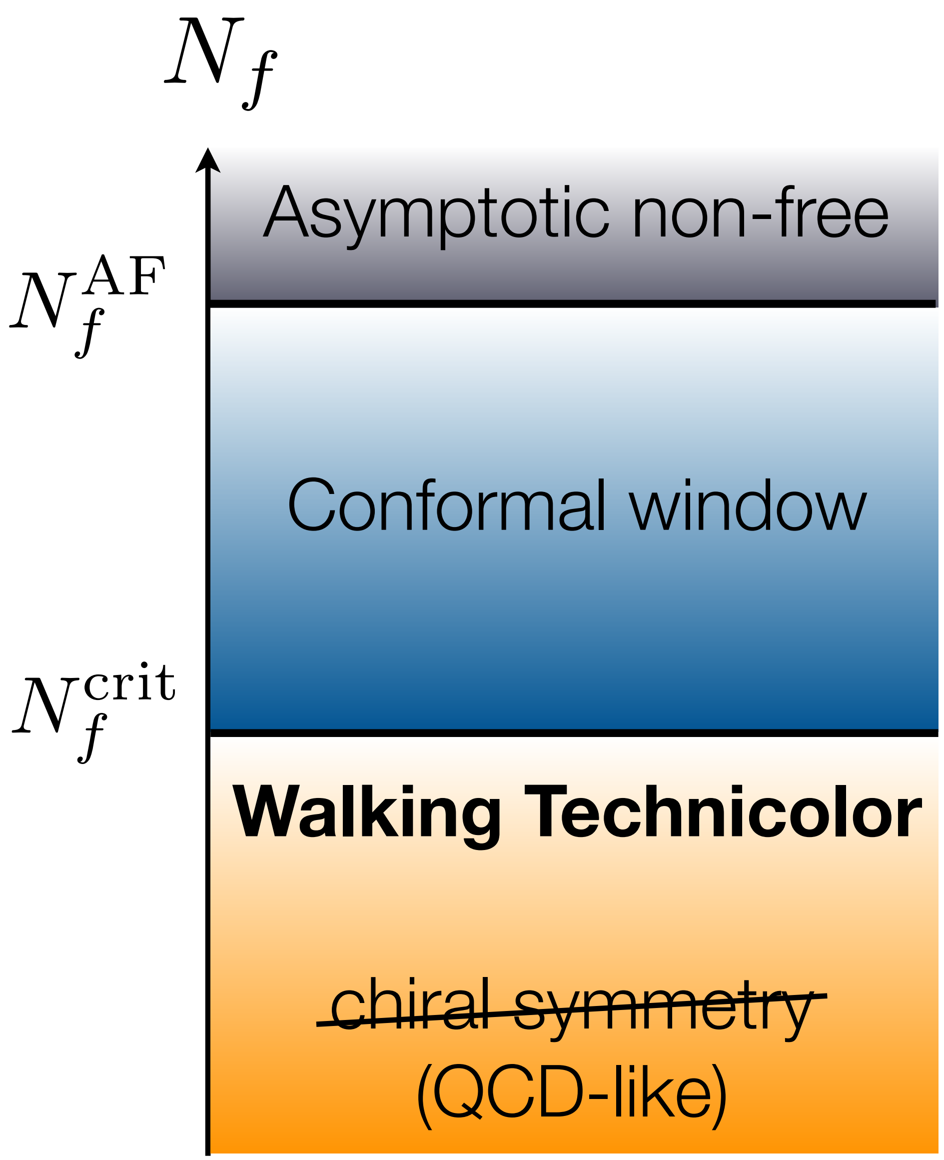


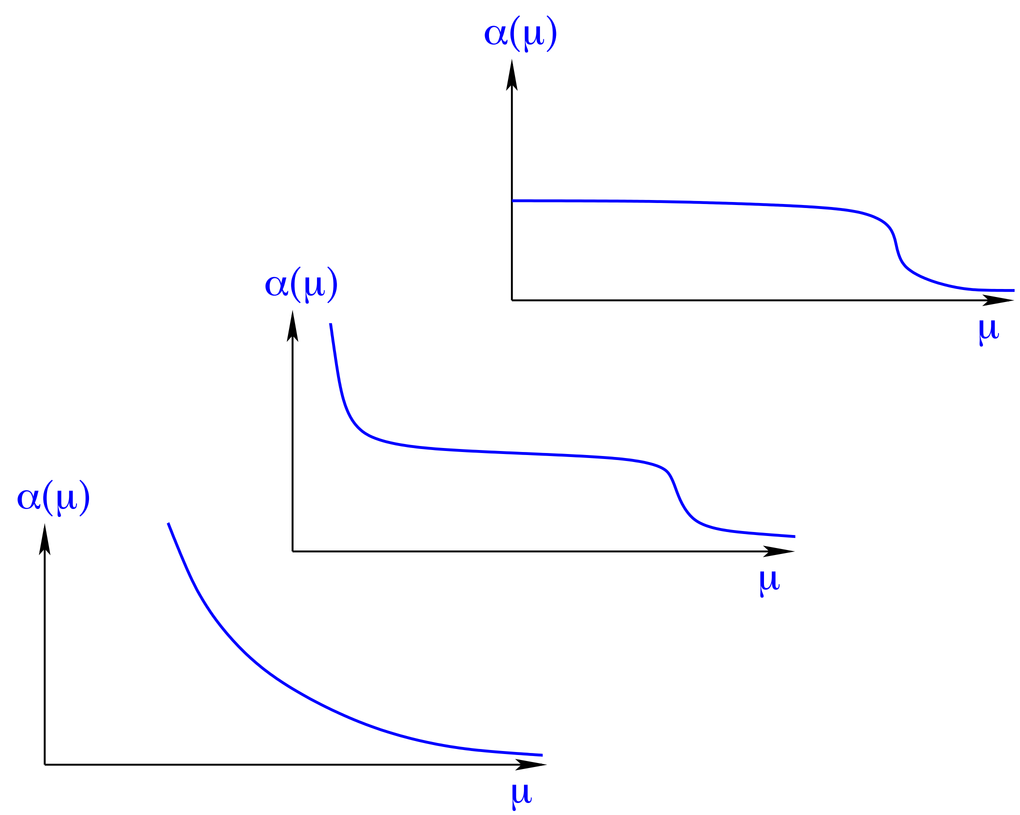




conformal window and walking gauge coupling

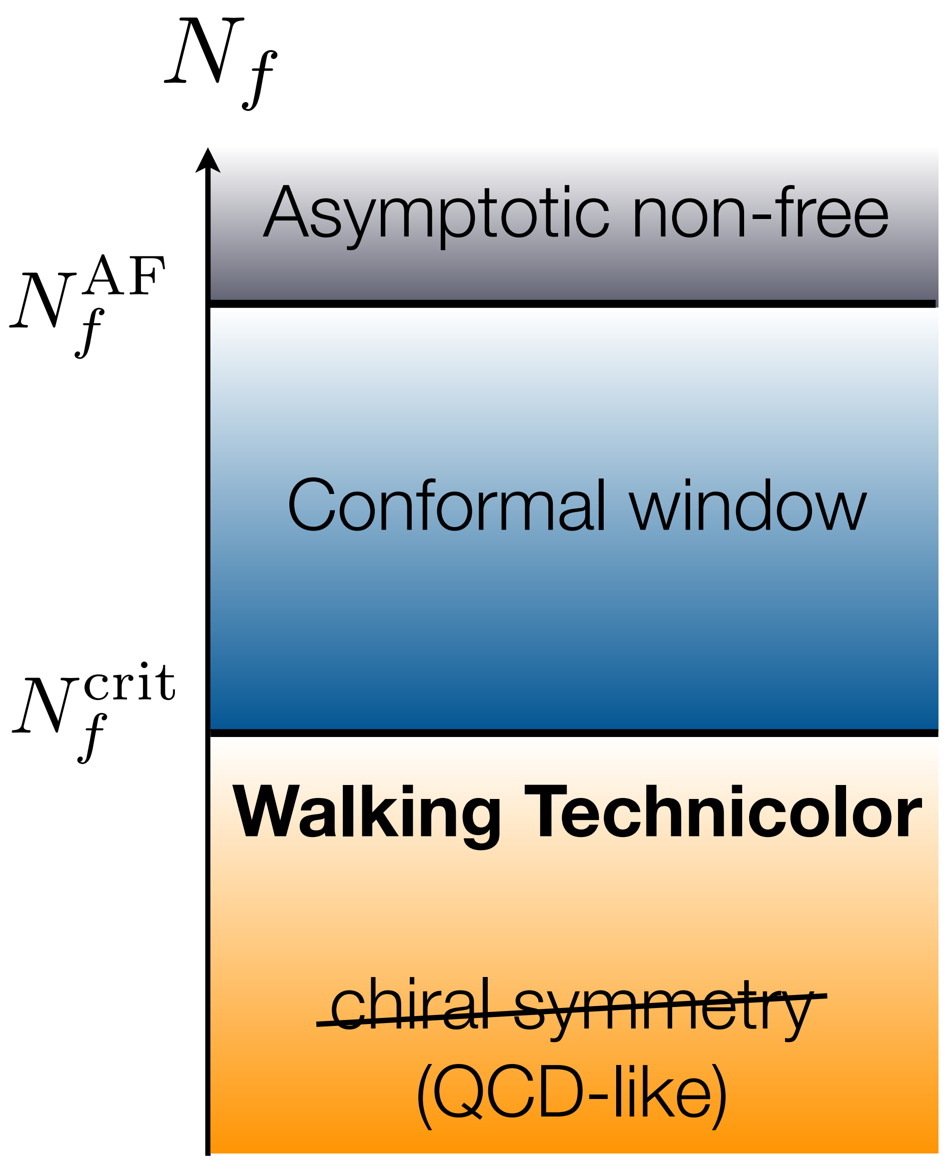
- non-Abelian gauge theory with N_f *massless* fermions -

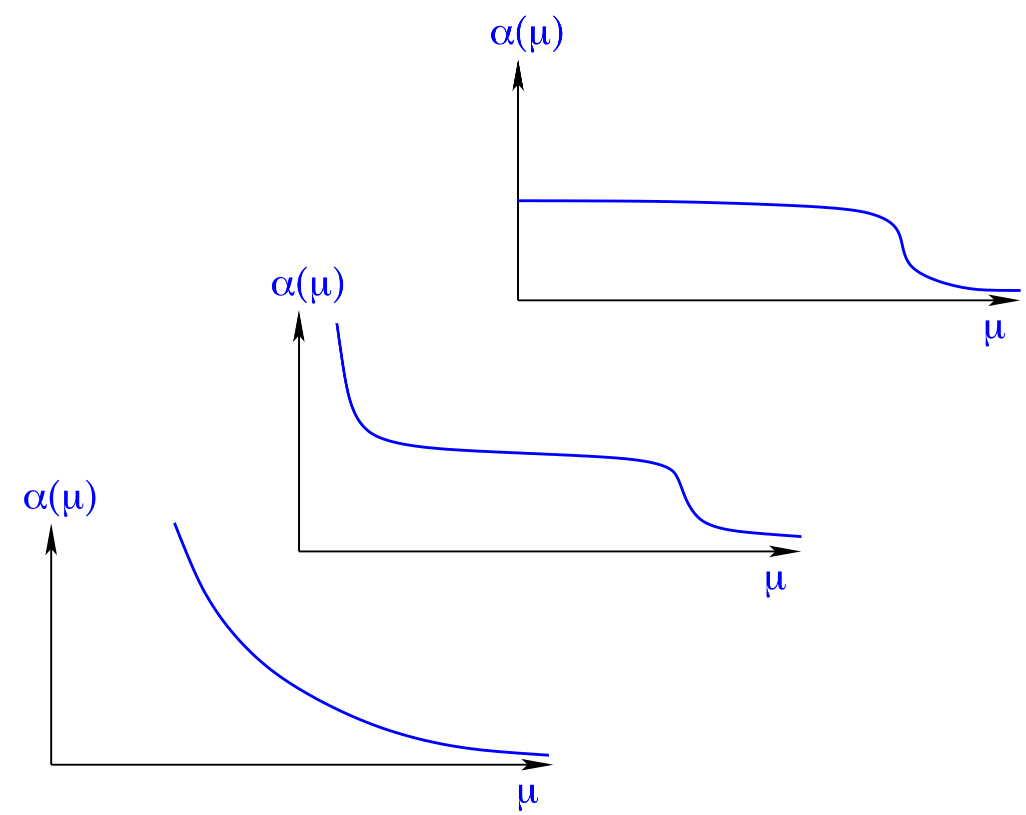




conformal window and walking gauge coupling

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





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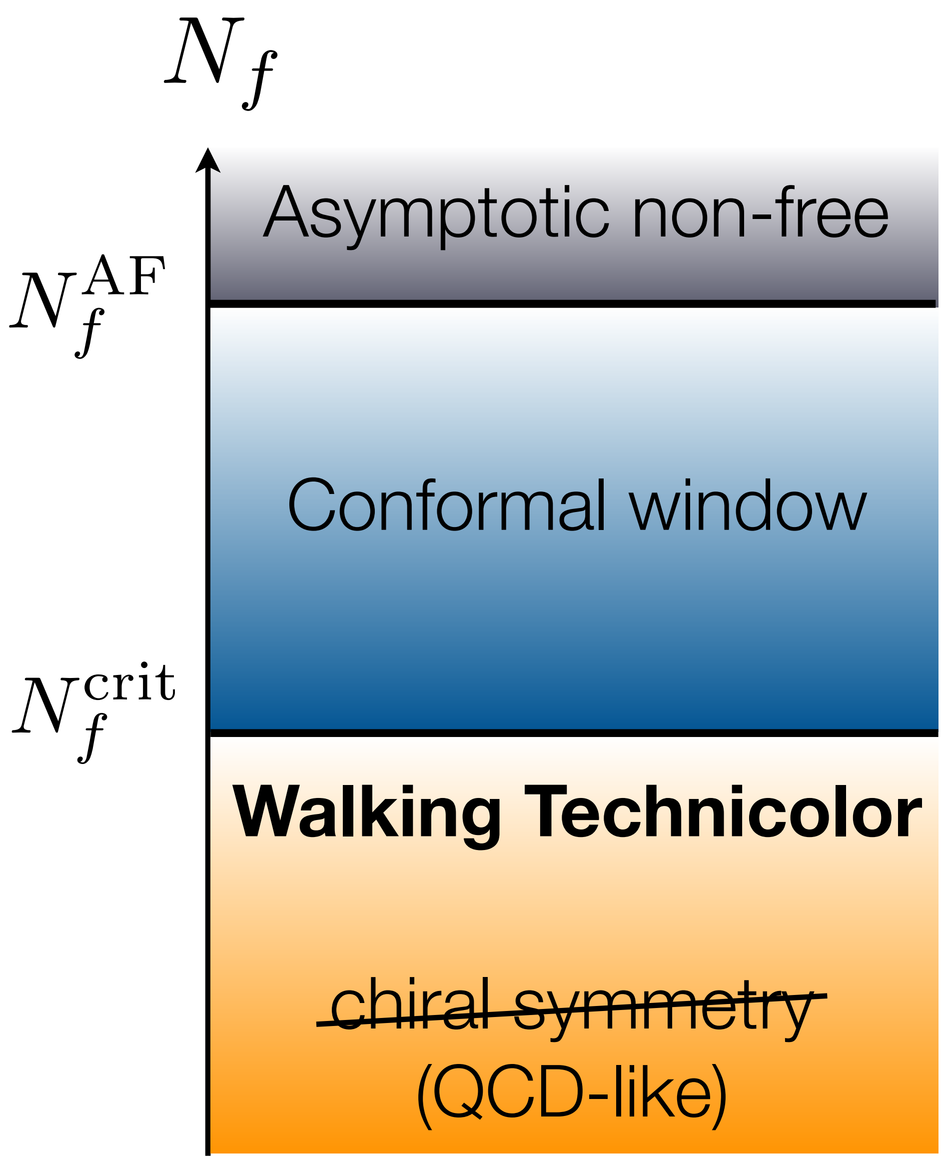

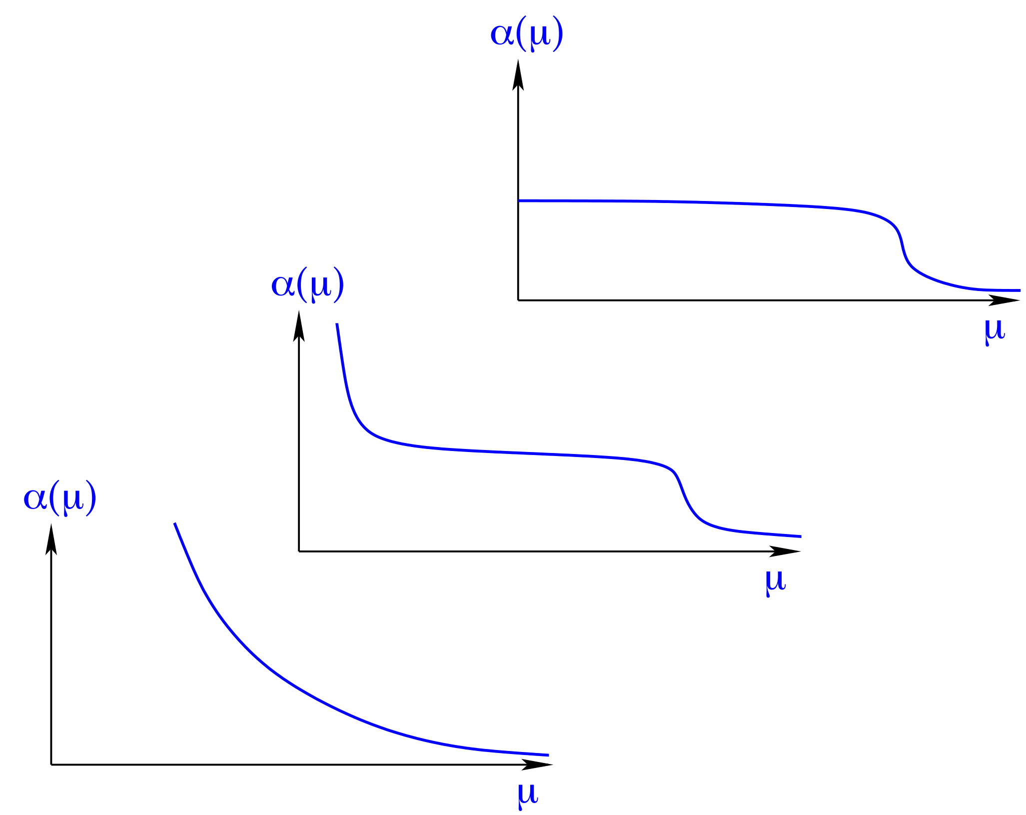

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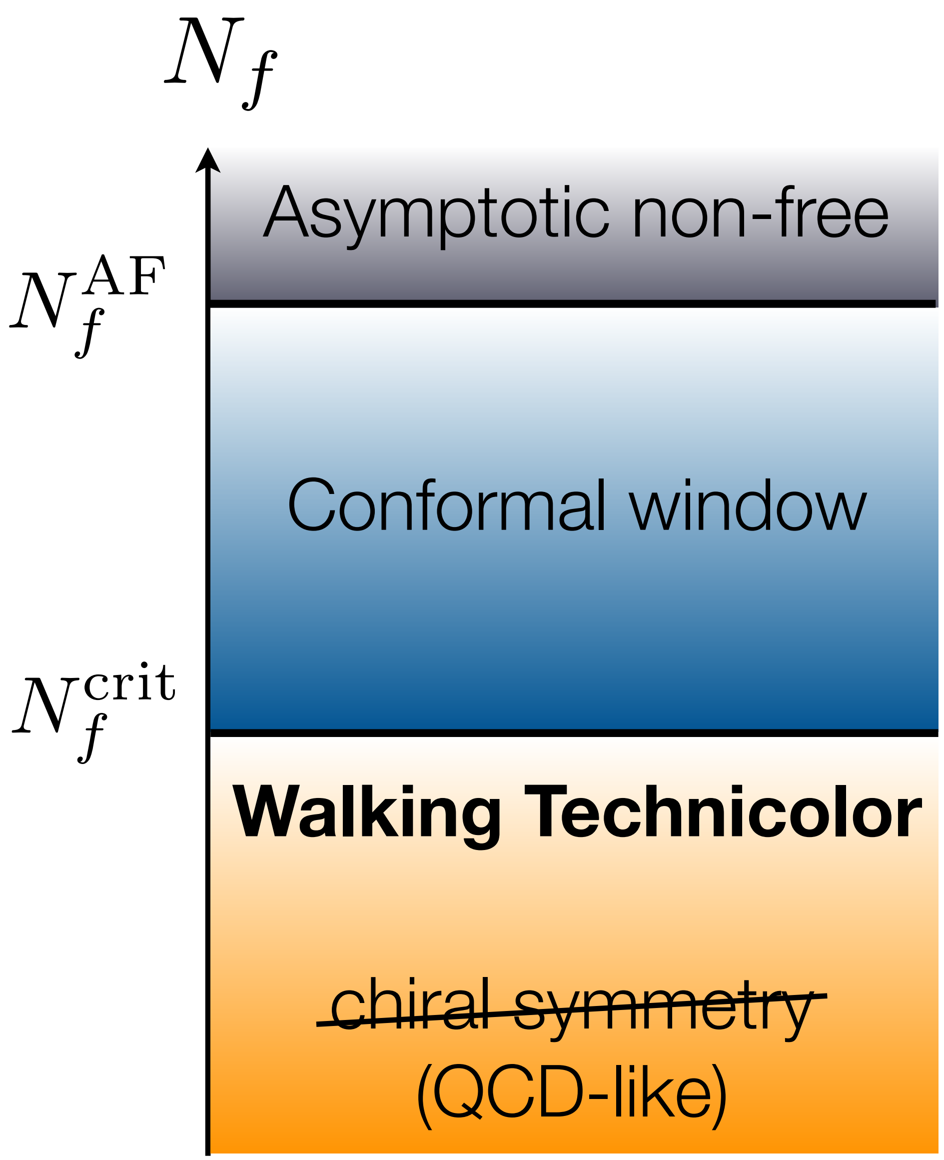

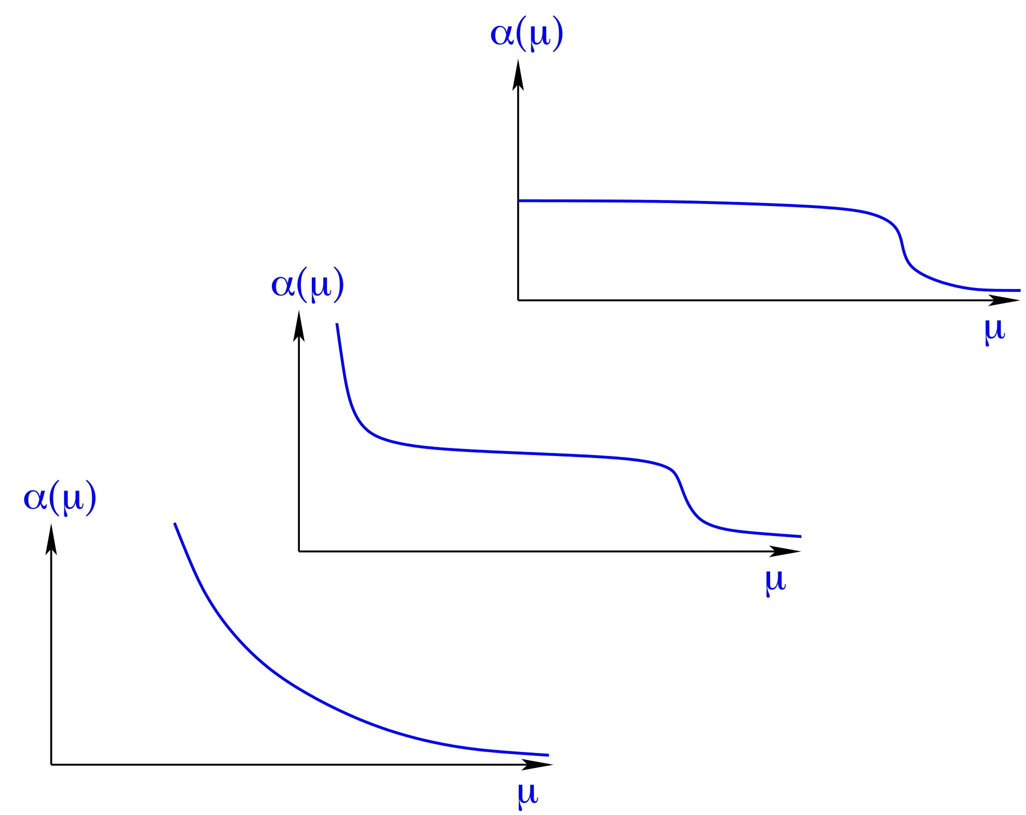

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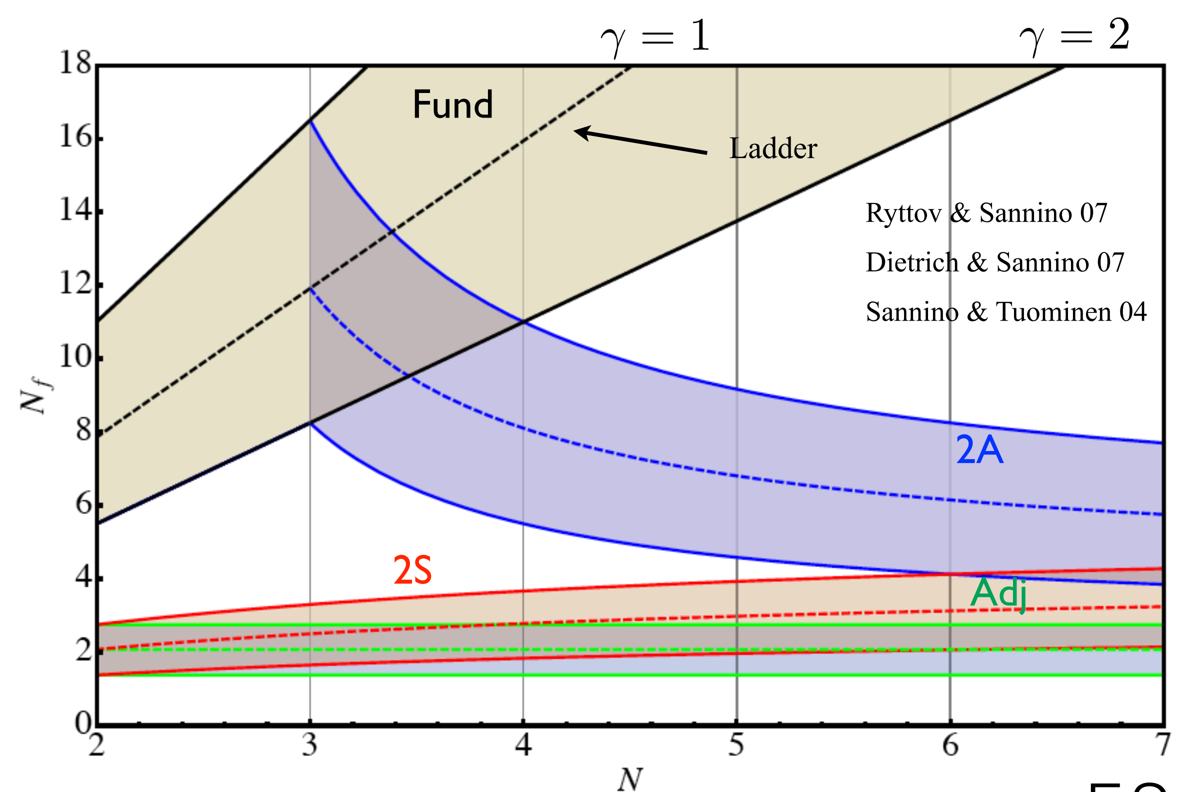
- crucial information: N_f^{crit} and...
- mass anomalous dimension γ & the composite mass spectrum around N_f^{crit}

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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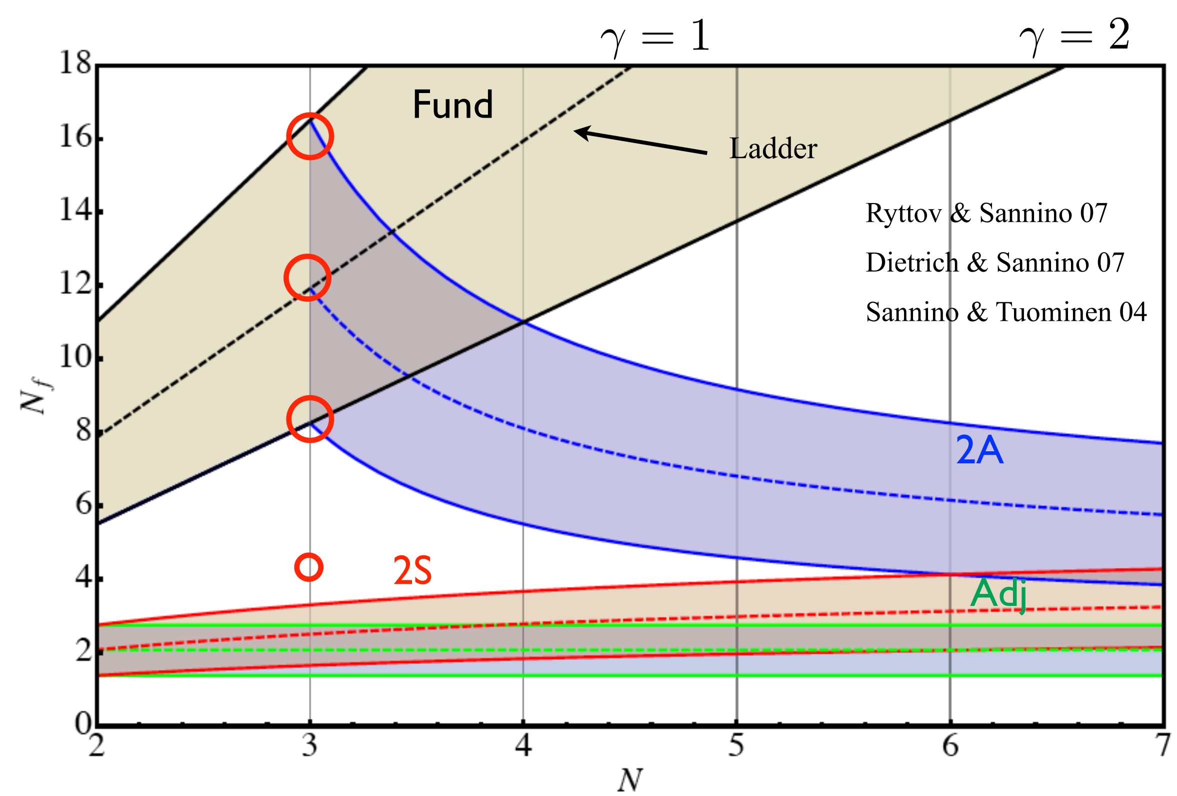

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