

# Scalar in $N_f = 8$ QCD

倉知 昌史

名古屋大学素粒子宇宙起源研究機構 (KMI)

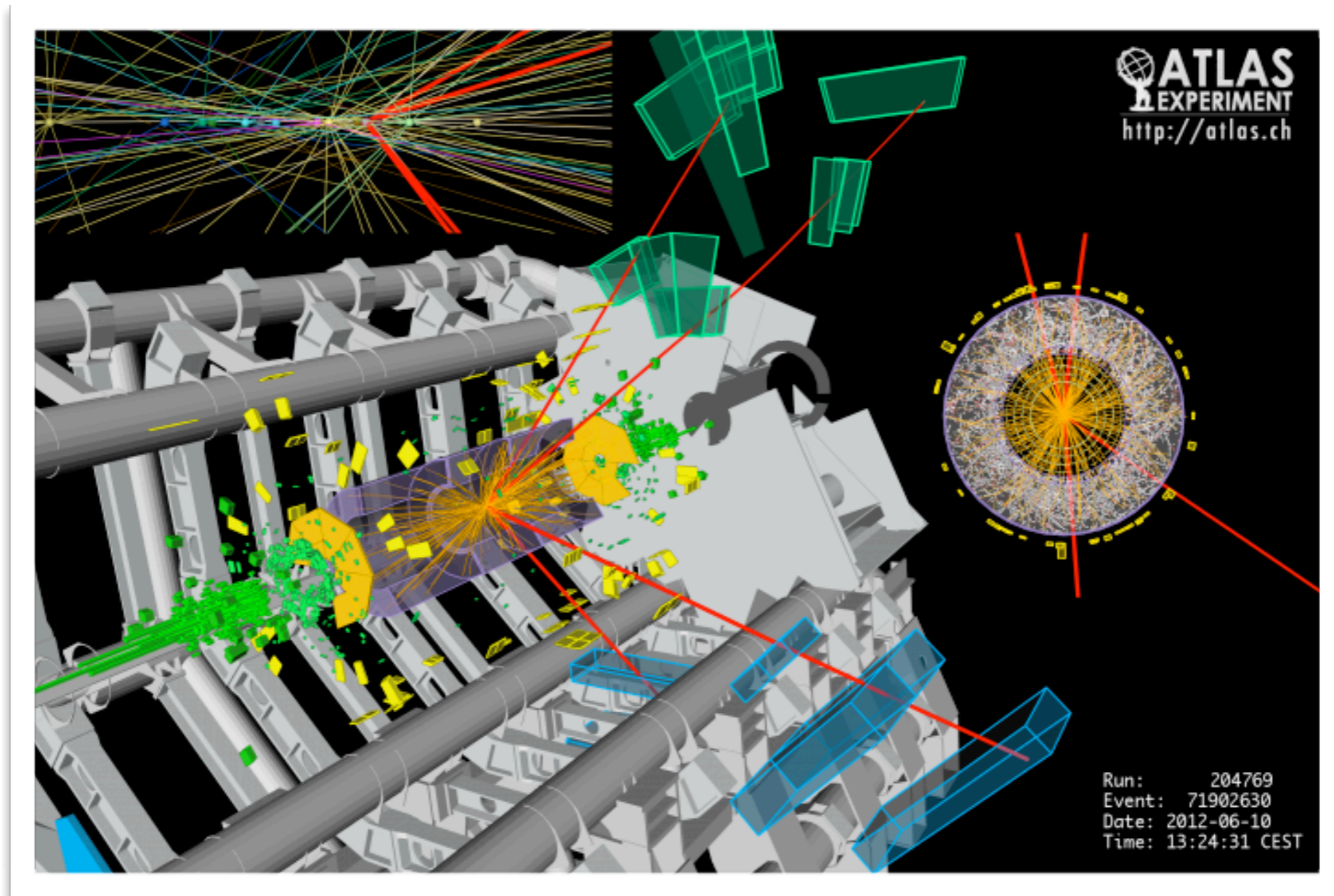
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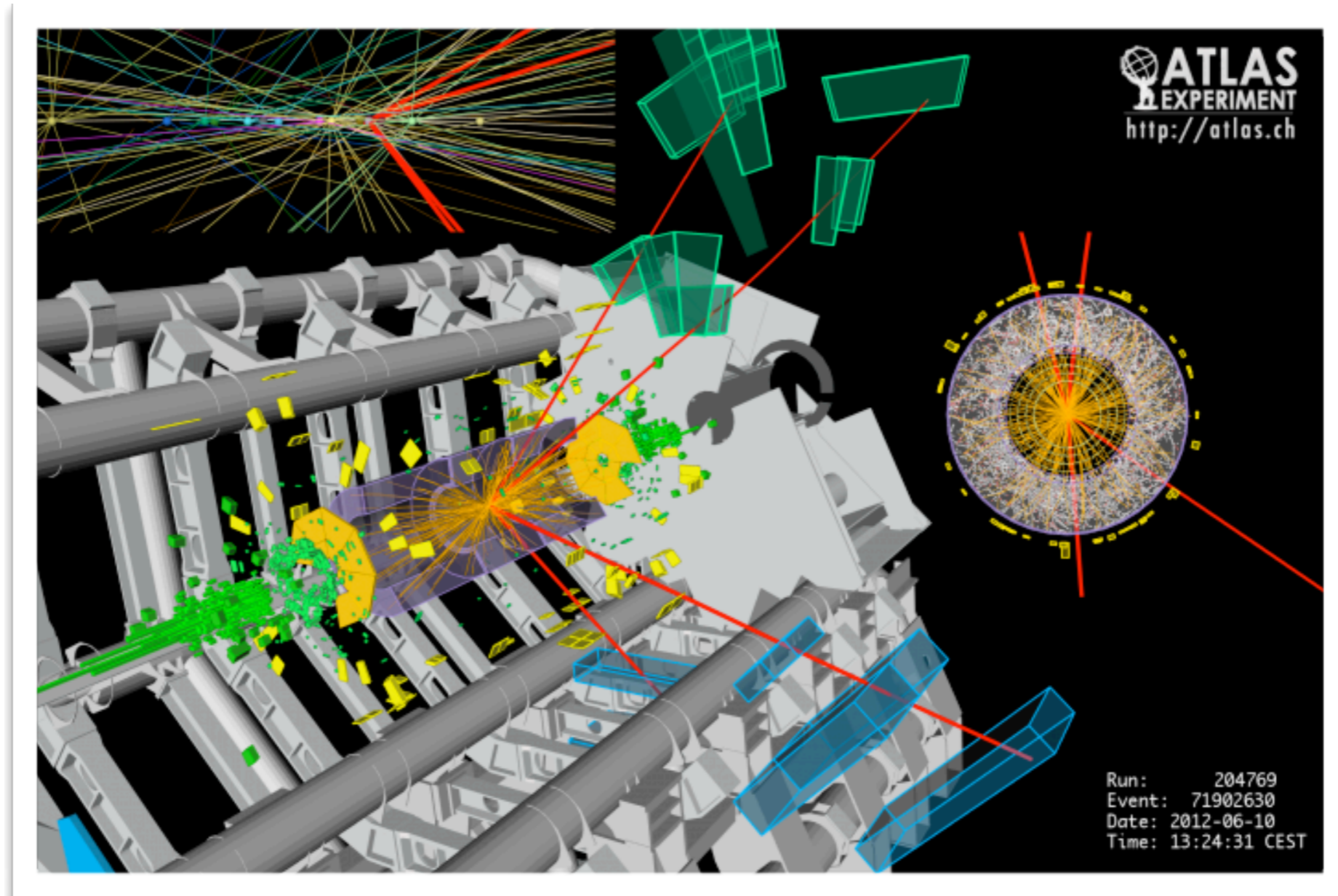
広島大学 東広島キャンパス

Y. Aoki, T. Aoyama, M. Kurachi, T. Maskawa, K.-i. Nagai,  
H. Ohki, E. Rinaldi, A. Shibata, K. Yamawaki, and T. Yamazaki  
(LatKMI Collaboration)

# Higgs(-like) boson の発見！



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電弱対称性の破れの起源は？

SM Higgs ? 強結合ゲージ理論 ?

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- Hierarchy problem
- Triviality?
- Vacuum stability?
- QCD によるカイラル対称性の破れという  
美しい類似例

# SM Higgs ? 強結合ゲージ理論 ?

- Hierarchy problem
- Triviality?
- Vacuum stability?
- QCD によるカイラル対称性の破れという  
美しい類似例

The most conservative scenario for the EWSB is still

technicolor



# 候補となる強結合理論は？

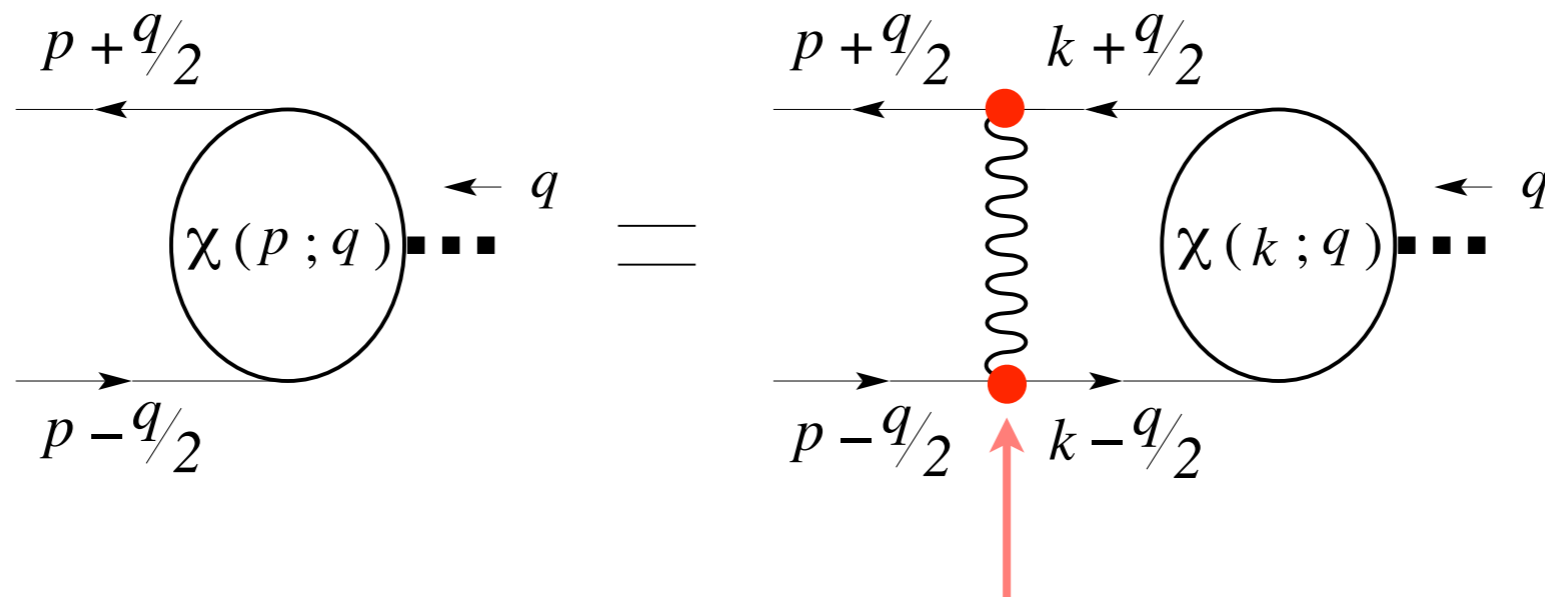
## $N_f=8$ $SU(3)$ ゲージ理論が面白い

- Chiral restoration point 付近にいる可能性
  - 現象論的に求められている walking behavior を持つ  
(長井さんのトーク、[arXiv:1302.6859](https://arxiv.org/abs/1302.6859), LatKMI Collaboration)
- Extended Technicolor 模型に自然に組み込める

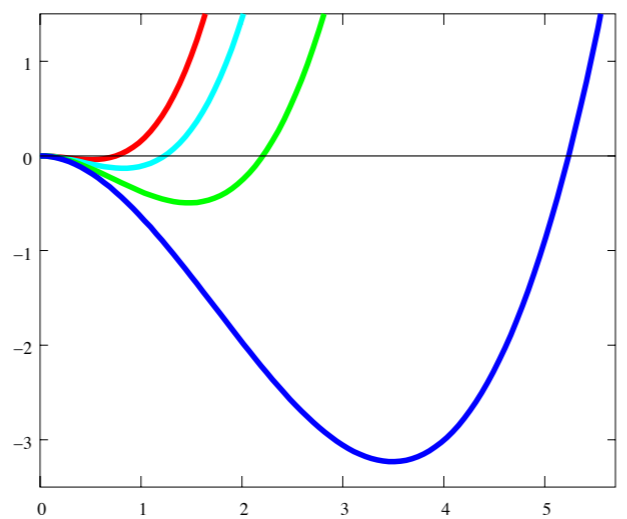
軽い ( $\sim 125$  GeV) スカラー束縛状態が存在するか？

# Ladder picture

Bethe-Salpeter equation for a  $q\bar{q}$  bound state



$\beta(\alpha)$



$\alpha$

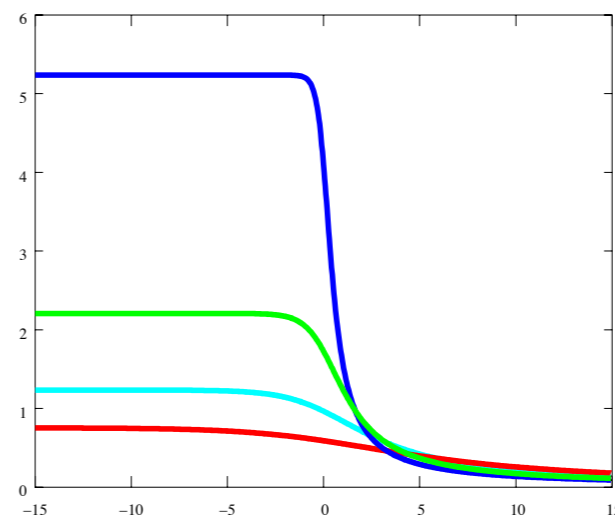
$$N_f = 9$$

$$N_f = 10$$

$$N_f = 11$$

$$N_f = 12$$

$\alpha(\mu)$



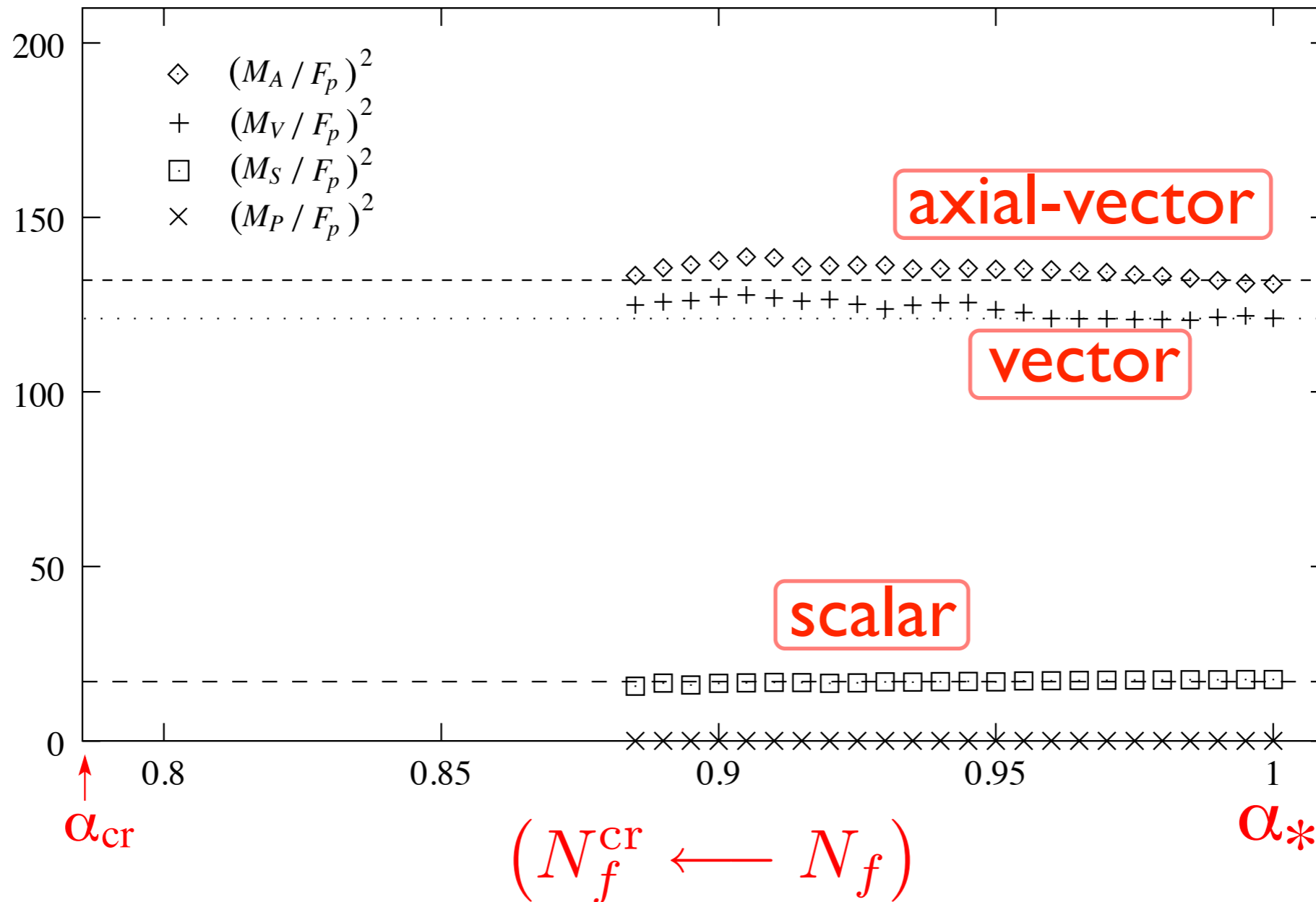
$\log \mu / \Lambda$

Large  $N_f$  2-loop running coupling



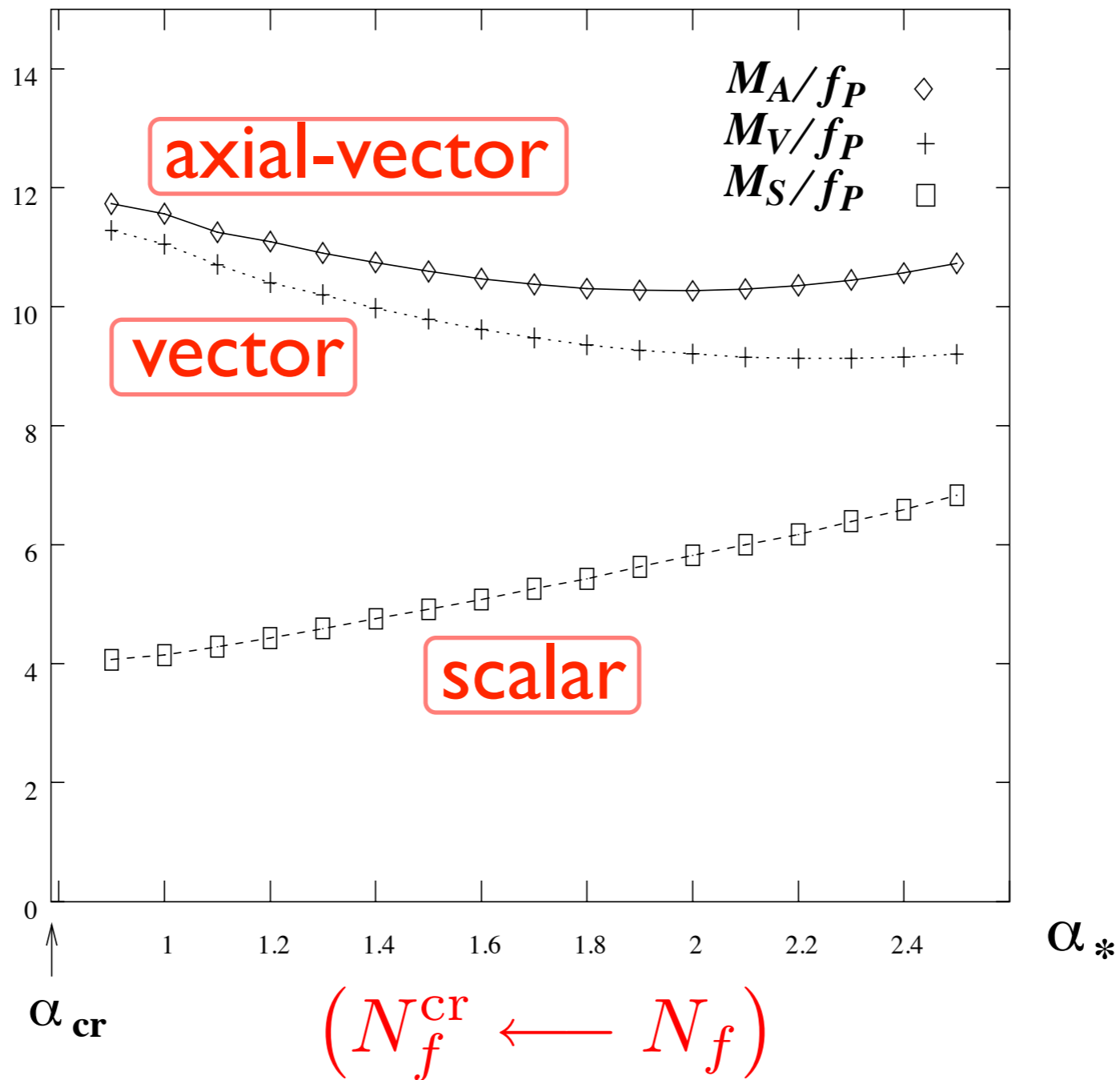
# Ladder picture

$(M_{A,V,S,P} / F_p)^2$  spectrum の  $N_f(\alpha_*)$  依存性

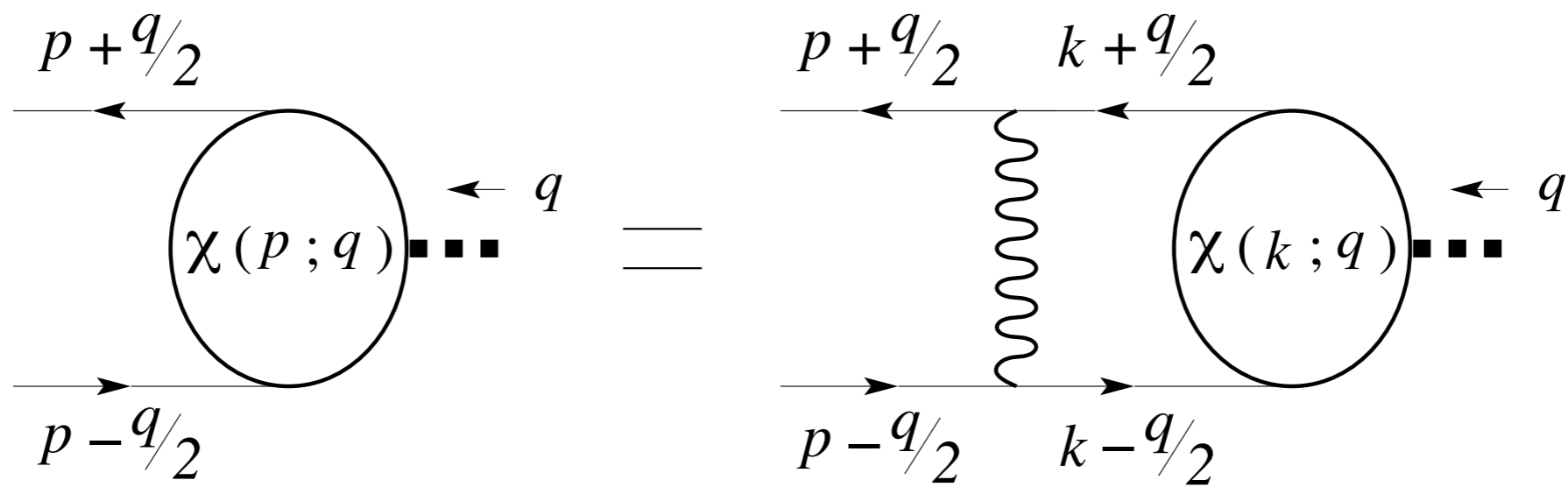


# Ladder picture

$M_{A,V,S}/f_P$  spectrum の  $N_f(\alpha_*)$  依存性



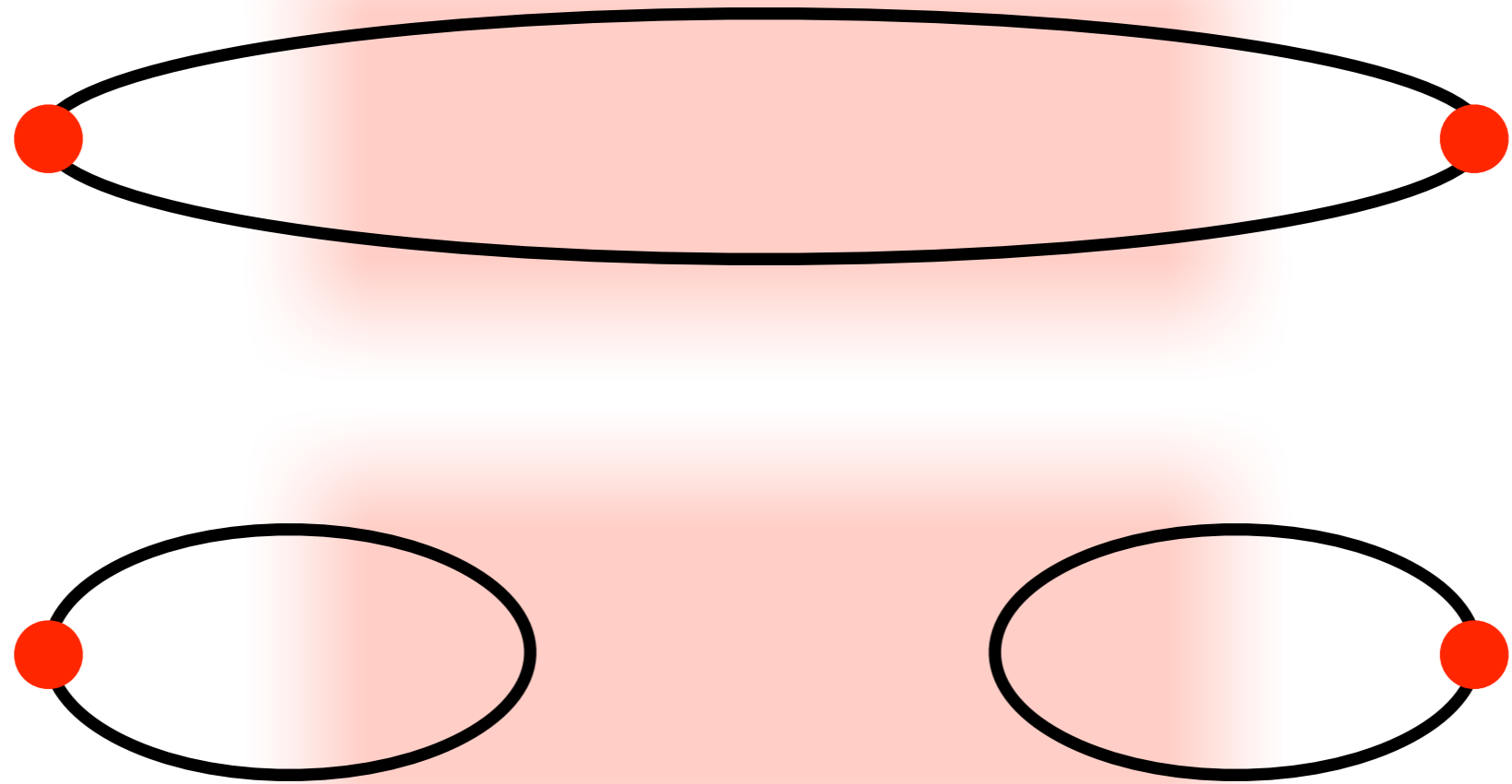
# Ladder picture



Note: Ladder 近似計算はどちらかということ  
**flavor non-singlet mesons** に適した計算

singlet の場合は他の state (例えば glueball) との  
mixing で flavor-singlet scalar がさらに軽くなる可能性あり

# Fully nonperturbative calculation (Lattice!!)



# Lattice setup

- Nf=8, SU(3) gauge theory
- Tree-level Symanzik gauge action
- Highly Improved Staggered Quarks (HISQ)
- Parameter set

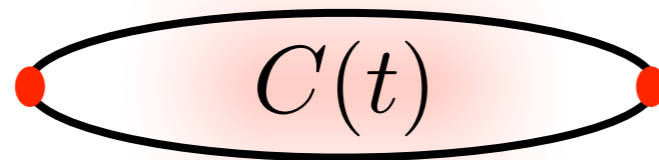
$$\beta(\equiv 6/g^2) = 3.8, \quad m_f = 0.06, \quad V = 24^3 \times 32$$

# Disconnected correlator measurement

- 7600 configurations (from 15200 thermalized trajectories)
- Stochastic estimator with 64 gaussian noises
- Venkataraman-Kilcup variance reduction technique

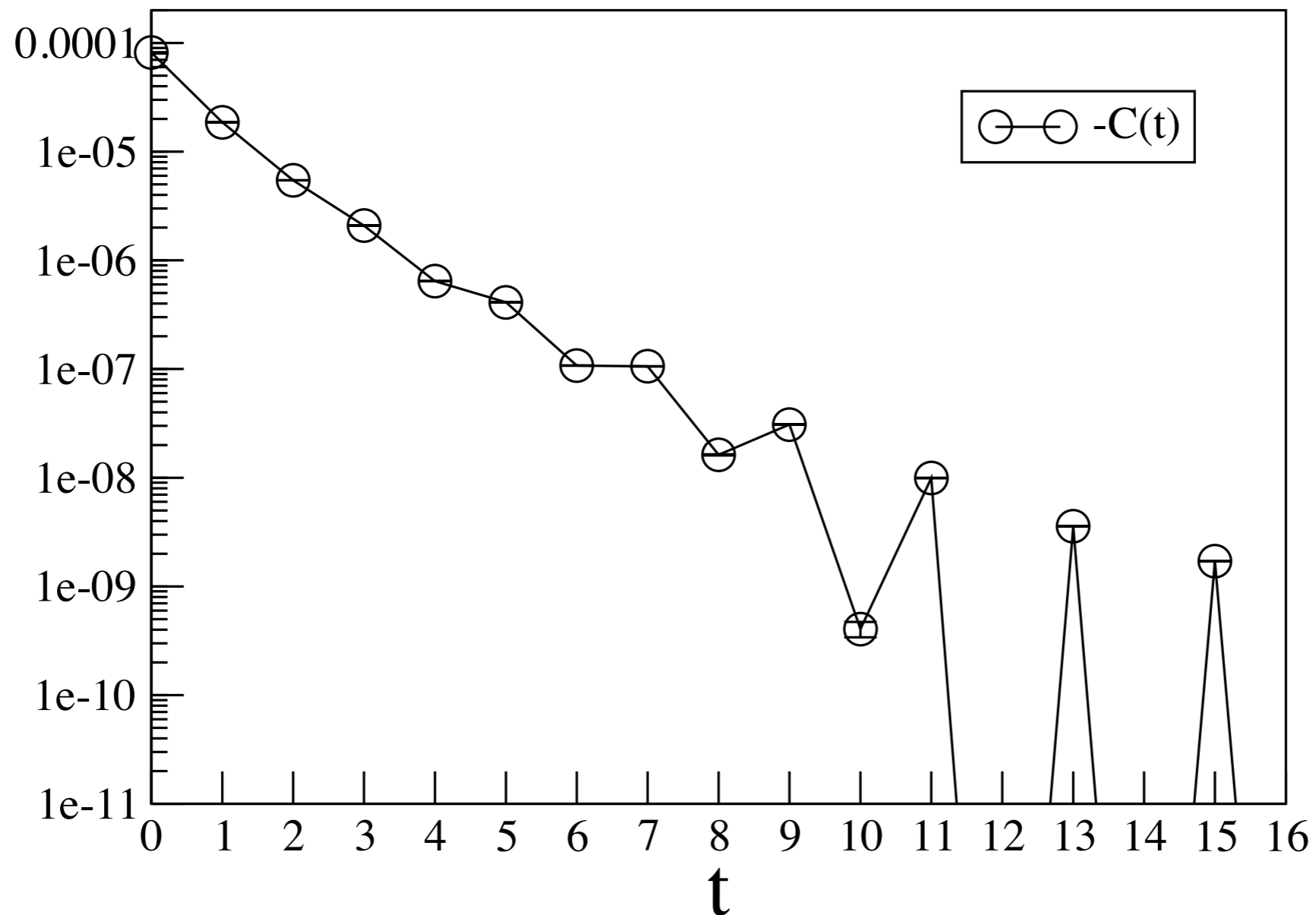
$$N_C = 3, N_f = 8, \beta = 3.8, m_f = 0.06, V = 24^3 \times 32$$

Connected

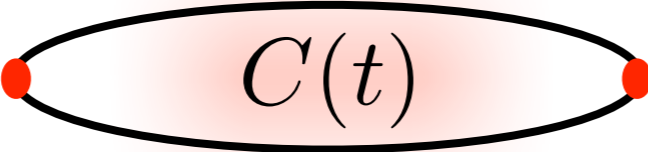


scalar interpolating  $\bar{\chi}\chi$   
operator couples to 2 states

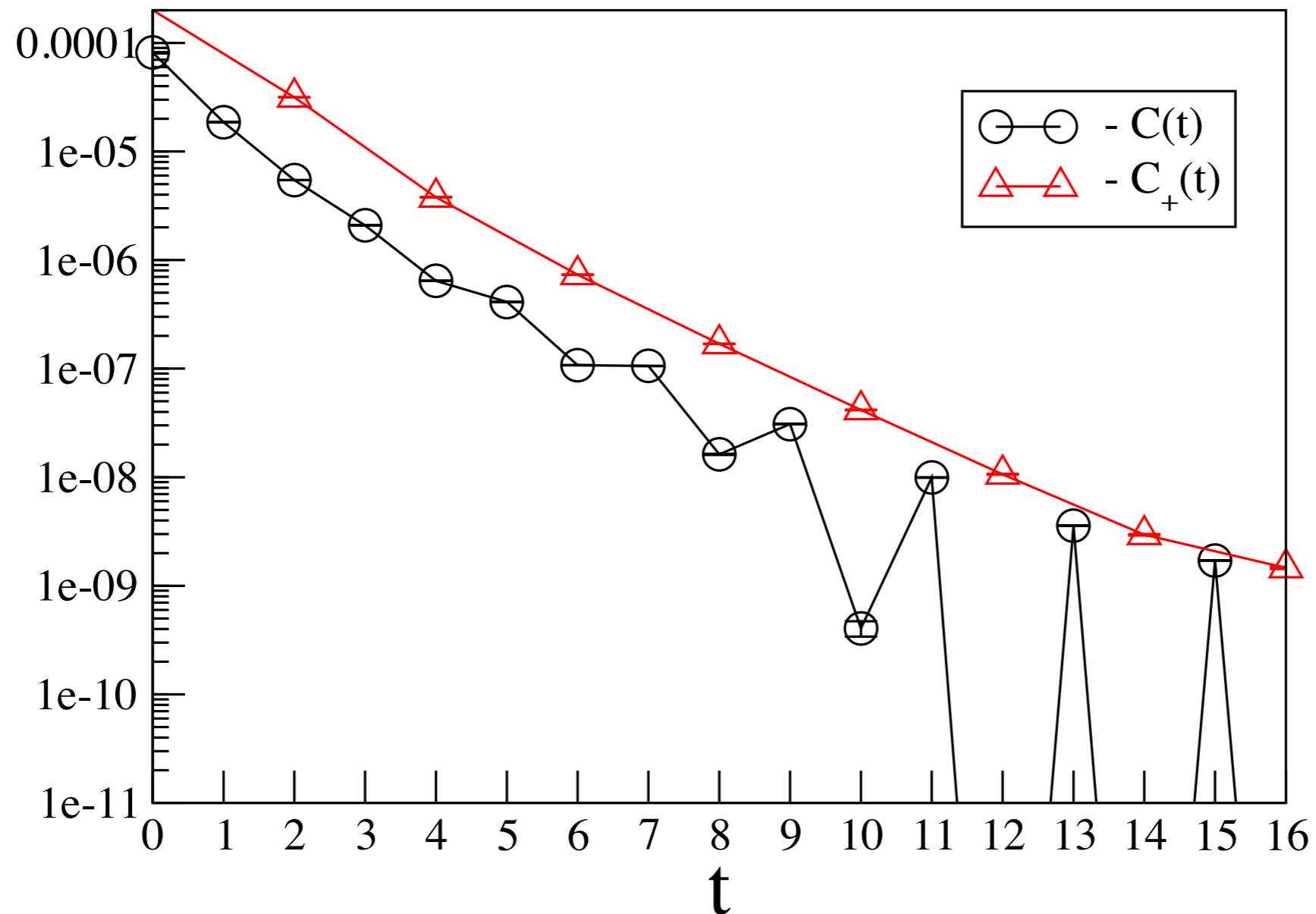
$0^+$   $0^-$



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

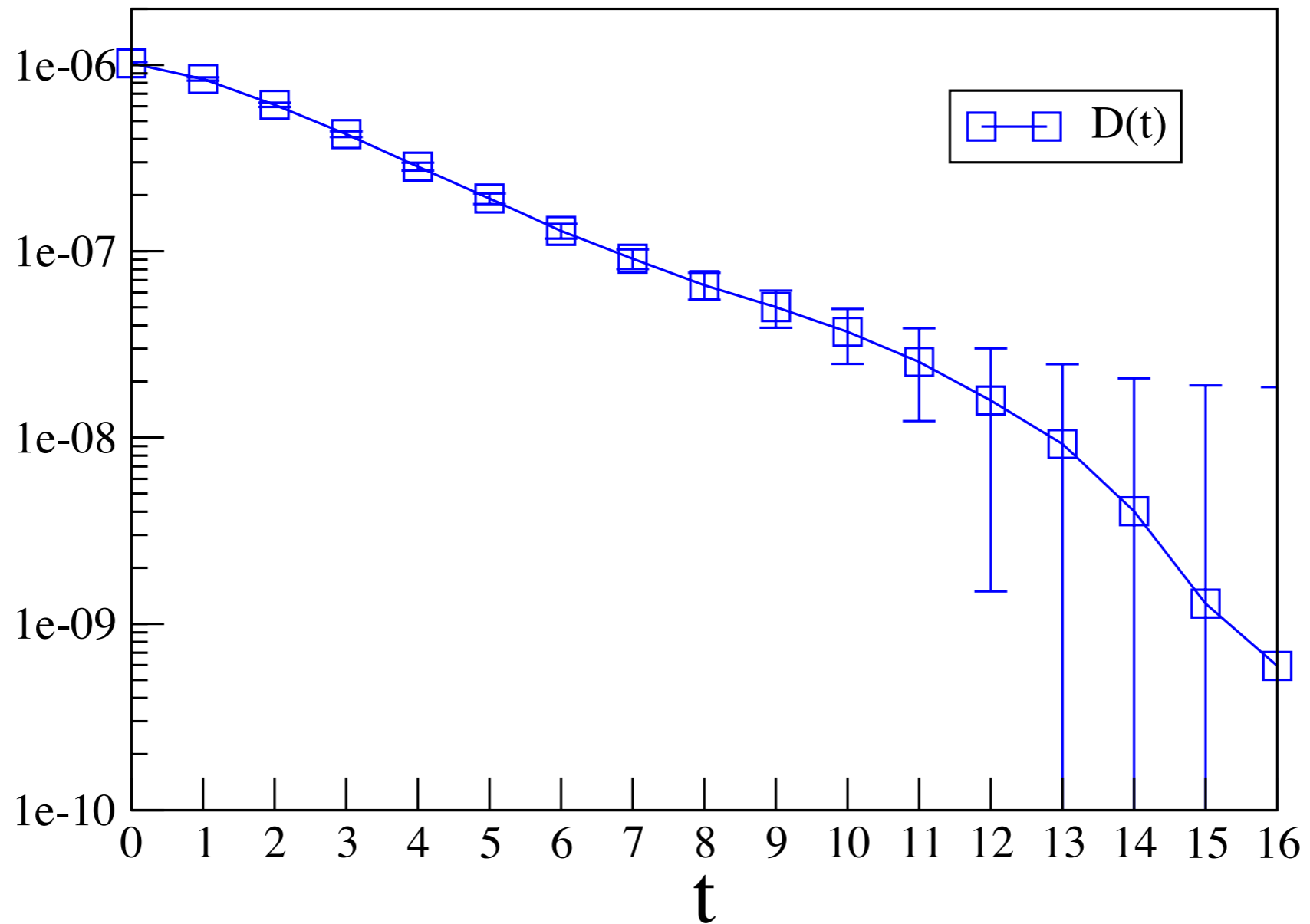
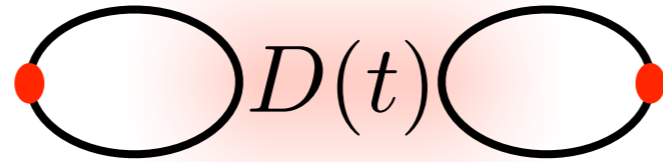
Connected 

“Pick up”  $0^+$  state:  $C_+(2t) \equiv 2C(t) + C(t+1) + C(t-1)$



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

Disconnected

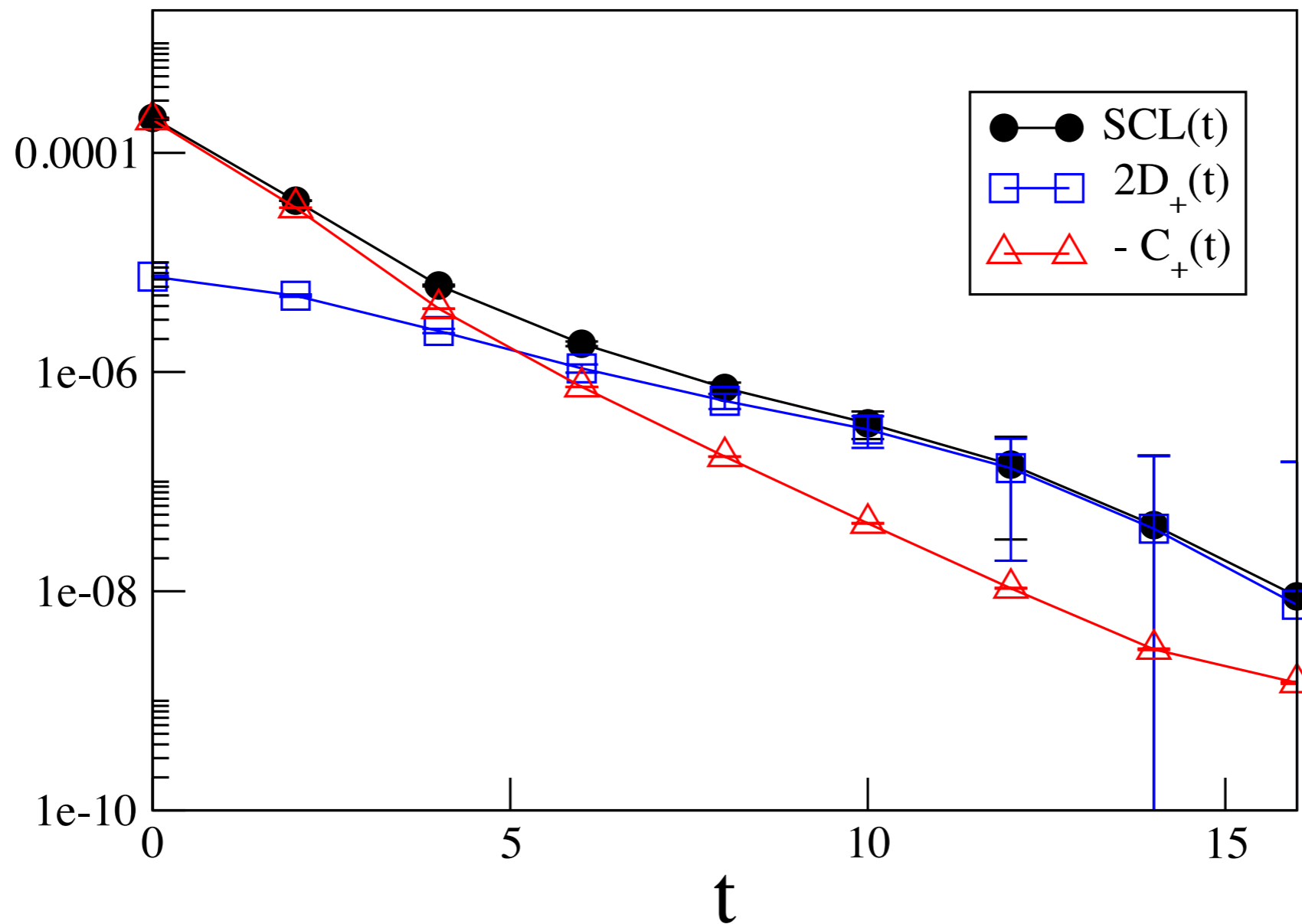




$$N_C = 3, N_f = 8, \beta = 3.8, m_f = 0.06, V = 24^3 \times 32$$

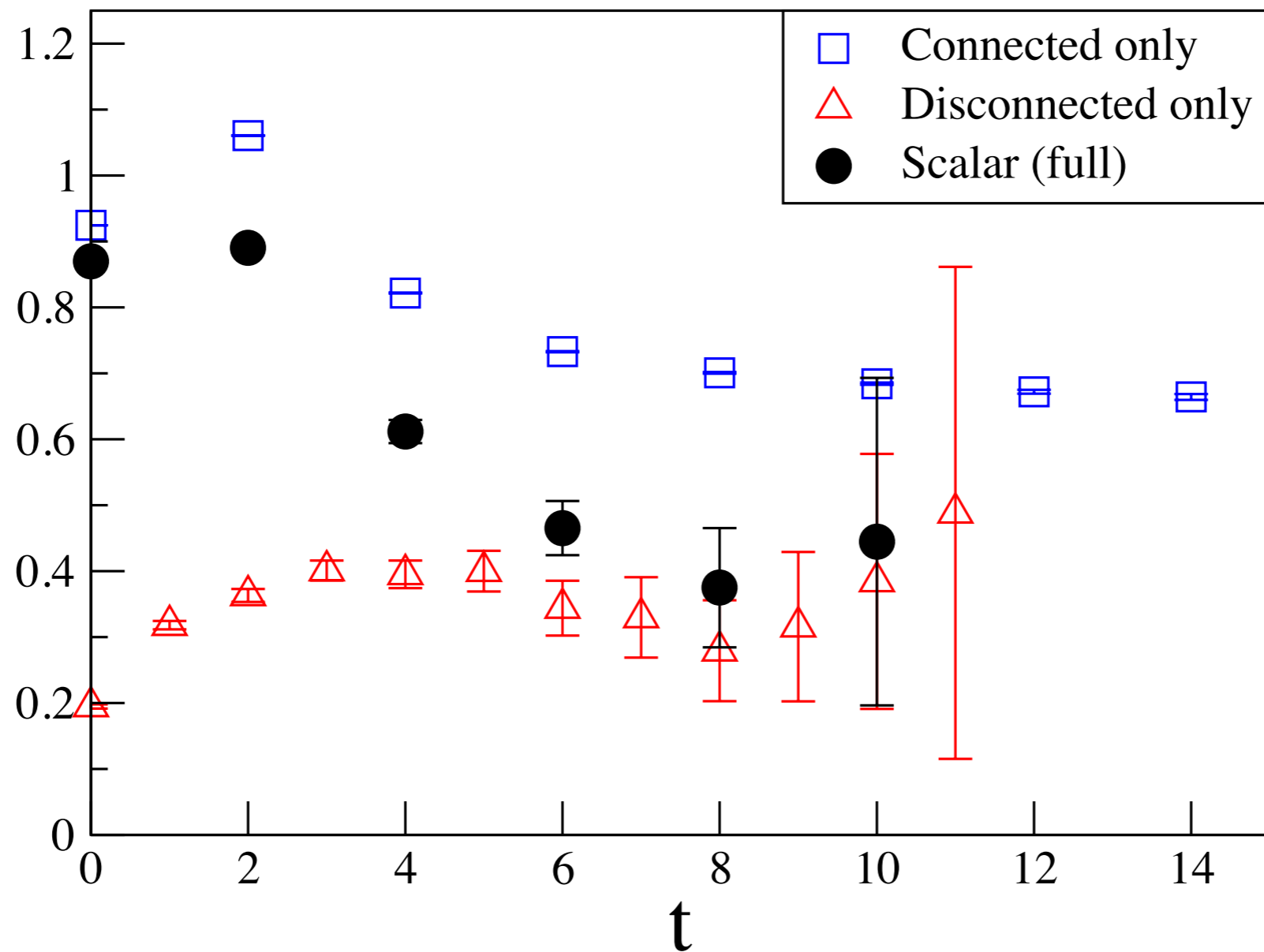
**Full scalar correlator**  $\sim SCL(t) = -C_+(t) + 2D_+(t)$

where  $D_+(2t) \equiv 2D(t) + D(t+1) + D(t-1)$



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

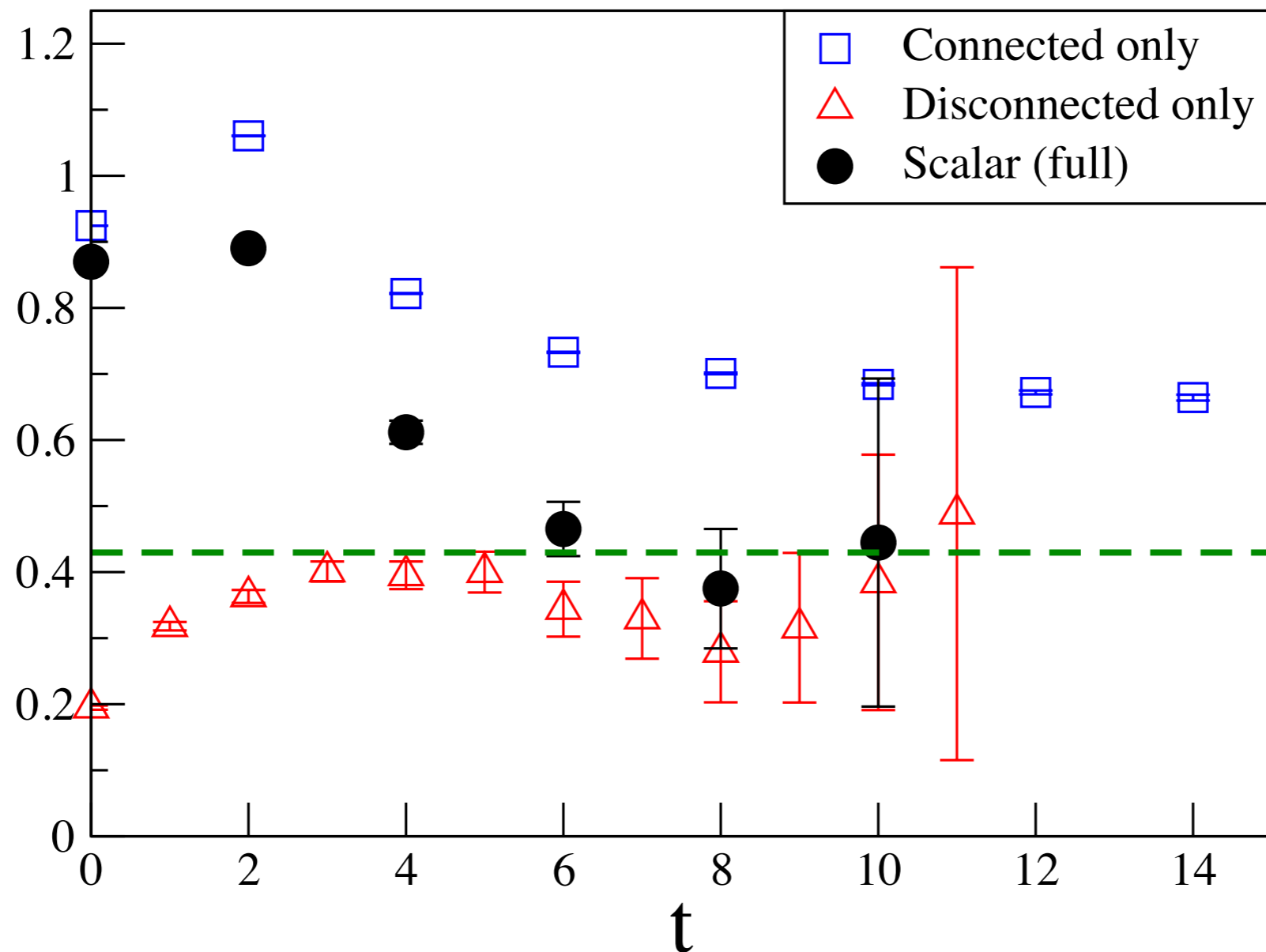
## Effective mass plot



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

## Effective mass plot

NG boson と同程度の軽いスカラーの存在を示唆



$M_\pi$   
arXiv:1302.6859[hep-lat]  
LatKMI Collaboration  
( $F_\pi \sim 0.1$ )

## Summary

- First lattice study of the flavor-singlet scalar in Nf=8 QCD
- Several techniques + high statistics → シグナル
- $\beta(\equiv 6/g^2) = 3.8$ ,  $m_f = 0.06$ ,  $V = 24^3 \times 32$  で  
NG boson と同程度の軽いスカラー

## Future direction

- Larger volumes, smaller fermion masses  
(chiral limit での振る舞い:  $M_\sigma \rightarrow F$  ?)
- Gluonic operator も含めた study  
(lightest scalar が meson 的か、glueball 的か、その mix か。)

**backups**

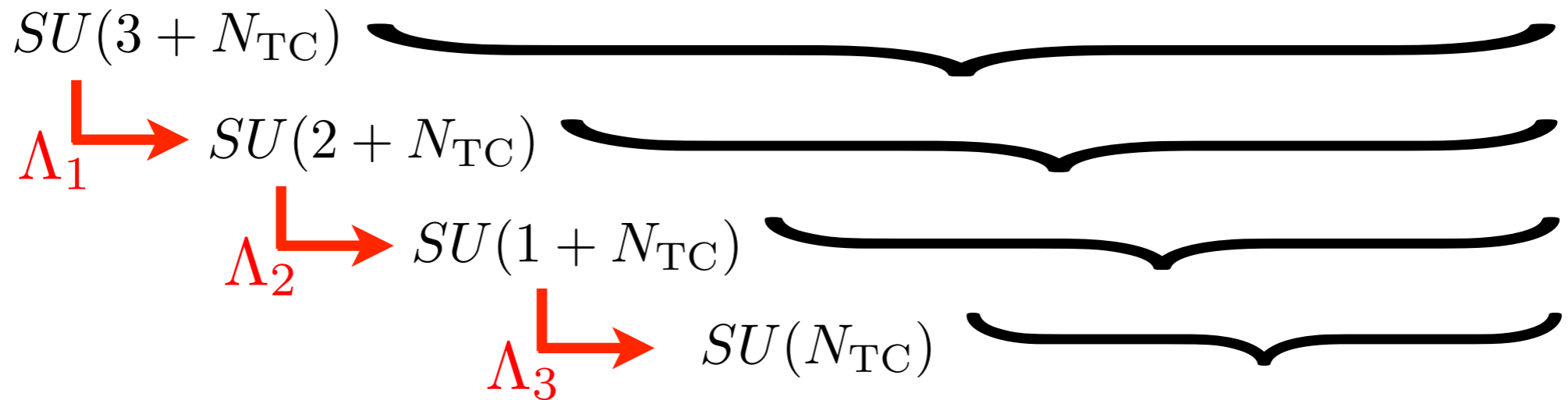
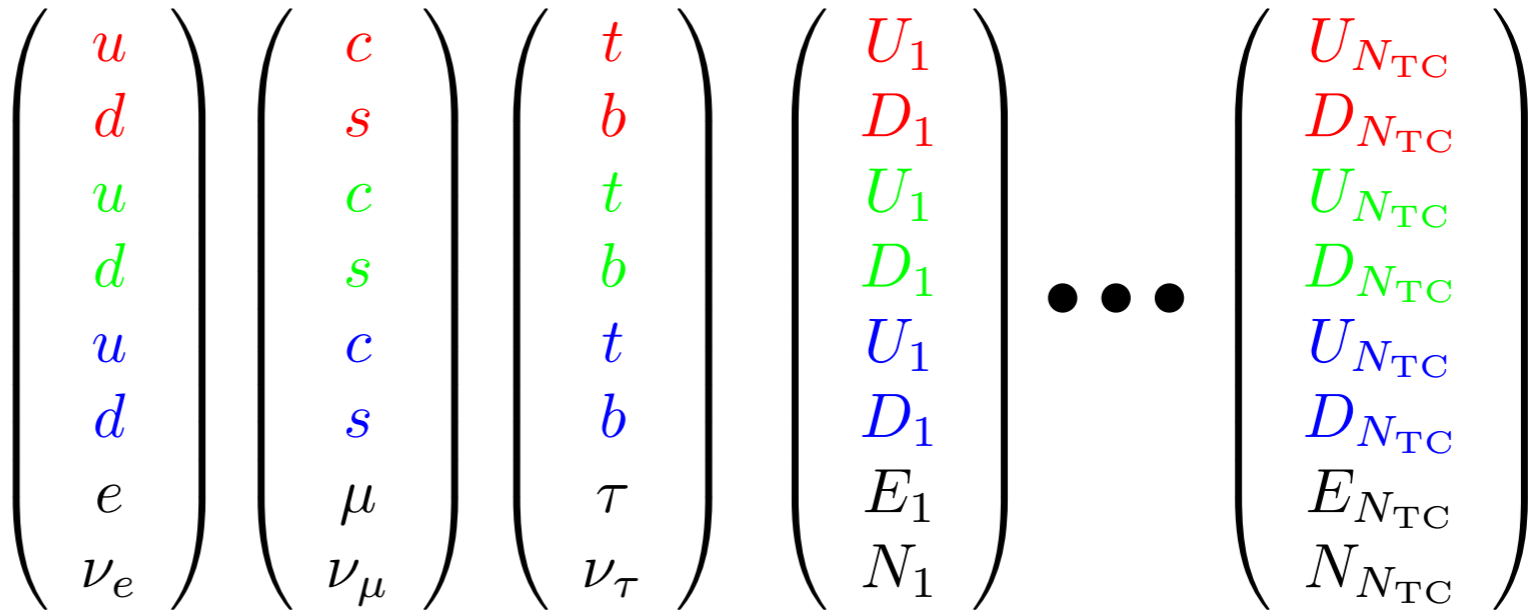
# Spectrum other than flavor-singlet scalar

arXiv:1302.6859[hep-lat], LatKMI Collaboration

$$\beta(\equiv 6/g^2) = 3.8, \quad m_f = 0.06, \quad V = 24^3 \times 32$$

$m_f$	$N_{\text{trj}}$	$F_\pi$	$M_\pi$	$M_{SC}$	$M_{\rho(PV)}$	$M_{\rho(VT)}$	$\langle\bar{\psi}\psi\rangle$
0.02	744	0.0566(8)	0.2330(25)	0.2367(37)	0.3508(117)	0.3461(111)	0.01188(3)
0.03	728	0.0715(4)	0.2832(14)	0.2851(14)	0.4044(96)	0.4018(101)	0.01746(2)
0.04	864	0.0823(2)	0.3353(7)	0.3382(7)	0.4678(57)	0.4693(57)	0.02290(1)
0.05	752	0.0918(5)	0.3826(10)	0.3851(11)	0.5274(54)	0.5228(53)	0.02825(2)
0.06	1848	0.1012(3)	0.4295(6)	0.4327(6)	0.5742(58)	0.5826(55)	0.03345(2)
0.07	864	0.1088(3)	0.4731(6)	0.4767(7)	0.6288(74)	0.6345(75)	0.03853(1)
0.08	816	0.1173(3)	0.5145(8)	0.5187(8)	0.6783(81)	0.6795(71)	0.04357(2)
0.10	948	0.1315(3)	0.5940(5)	0.5987(6)	0.7790(65)	0.7760(68)	0.05334(1)

One-family  
ETC 模型



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

