IRFP conformal dynamics in many flavor lattice QCD in the light of thermal chiral phase transition

Kohtaroh Miura

KMI Theory Seminar, April 25, 2013

References

- K. Miura, M. P. Lombardo and E. Pallante, Phys. Lett. B **710** (2012) 676.
- K. Miura and M. P. Lombardo, Nucl. Phys. **B871** (2013) 52-81.

Motivation

QCD with MANY FLAVORs!

Why Many Flavor QCD?

- New Class of The Gauge Theories: The strong interaction may lead to a novel (Quasi-)Conformal Dynamics associated with Infra-Red Fixed Point (IRFP).
- The quasi-conformal dynamics plays an essential role in the Walking Technicolor Model, a modern version of the technicolors admitting composite Higgs with a mass ~ 126 (GeV).

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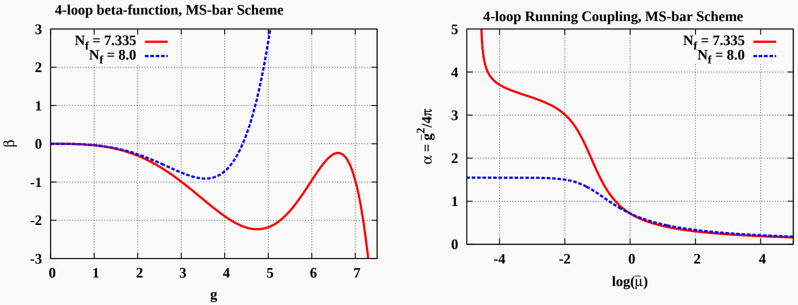
Example, IRFP Conformality in Color SU(3)



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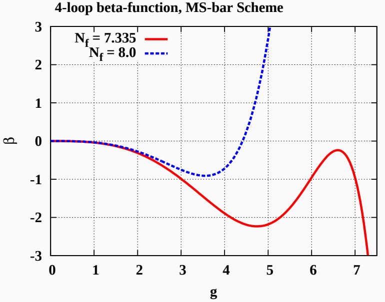

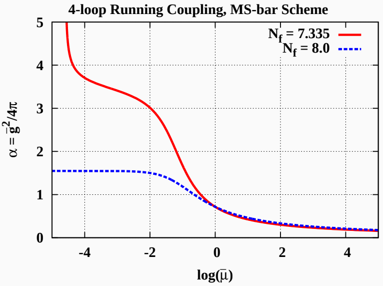

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Status of IRFP-Conformality: Color SU(3) Case

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Lattice: Revies: Ref. [0]

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- **[4] Tsukuba:** $N_f = 7$ may be the lower edge of the conformal window.
- **[5] Colorado:** $N_f = 8$ might be in the conformal window.
- **[6] SanDiego etc.:** No! $N_f = 12$ may be still in the chirally broken phase.

[0] J. Giedt, *PoS* **LAT2012**; E. T. Neil, *PoS* **LAT2011**; L. Del Debbio, *PoS* **LAT2010**; E. Pallante, *PoS* **LAT2009**.

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Our Motivation and Goal

- We evaluate the onset of the conformal window N_f^* by using the lattice Monte-Carlo simulations.
- We investigate the finite T chiral transition as a function of N_f: $T_c(N_f^*) = 0$. The N_f^* estimate beyond a fixed N_f analysis would give a stronger evidence of the existance of the conformal window.
- We particularly investigate the finite T QCD with $N_f = 6$ and 8, which have not been well understood yet but important for the N_f^* hunting.
- The first-order chiral transition which may happen in the multi-flavor QCD can be a potential interst in the scenario of the electroweak baryogenesis.

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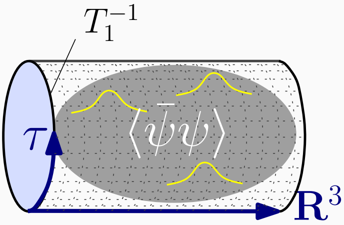
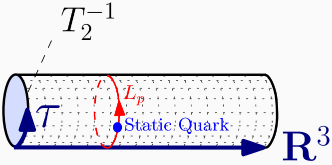
Setups

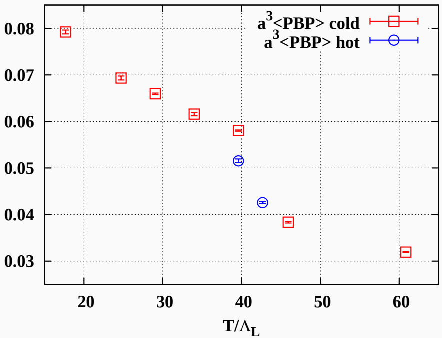




- We measure the chiral condensates $\langle\bar{\psi}\psi\rangle$, the Polyakov loops L_p and their susceptibilities as a function of T.
- We use the Asqtad fermion with Symanzik and Tadpole improved gauge action.
- We use a single lattice fermion mass $ma = 0.02$. We will comment on the chiral and continuum limits later.

Chiral Condensate as a Function of T, $N_f = 8$, $ma = 0.02$, $24^3 \times 8$

Update for Miura-Lombardo Nucl. Phys. B ('13). *c.f.* Deuzeman et.al. Phys. Lett. B ('08).



$$\frac{T_c}{\Lambda_{\rm L}} \propto \frac{1}{N_t} \exp\left[\int_{\infty}^{g_{\rm L}{}^{\rm c}} \frac{dg}{B_{\rm 2loop}(g)}\right] = 39.6 \pm 5.5\ . \quad (1)$$

Polyakov Loop as a Function of T. $N_f = 8$, $ma = 0.02$, $24^3 \times 8$

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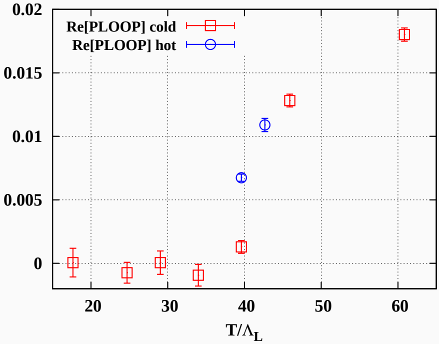

The first-order chiral transition at $T_c/\Lambda_{\rm L} = 39.6 \pm 5.5$

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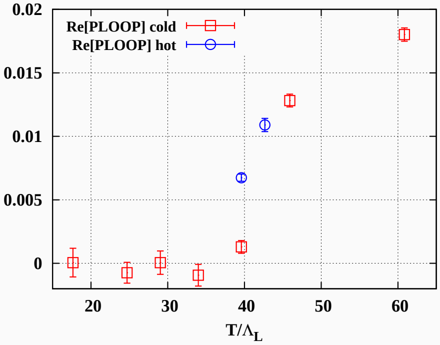

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Two-Loop Asymptotic Scaling

We should confirm the observed transition is not the bulk-transition (lattice artifact) (*c.f.* $N_f = 12$ case: Deuzeman et.al. '09). The bulk-transition strongly breaks the UV (continuum) asymptotic scaling characterized by the beta-function.

- The change of temporal lattice sites N_t gives a scale variation:

$$T_c = \frac{1}{a({g_{\mathrm{L}}}^{c})N_t} = \frac{1}{a({g_{\mathrm{L}}}^{c\prime})N_t'} \,, \quad a(g_{\mathrm{L}}) = \text{Lattice Spacing} \,. \tag{2}$$

- 2-loop renormalization flow:

$$\frac{T_c}{\Lambda_{\mathrm{L}}} = \frac{1}{N_t}\frac{a^{-1}({g_{\mathrm{L}}}^{c}(N_t))}{\Lambda_{\mathrm{L}}} \propto \frac{1}{N_t}\exp\left[\int_{\infty}^{{g_{\mathrm{L}}}^{c}(N_t)} \frac{dg}{B_{2\mathrm{loop}}(g)}\right] \,. \tag{3}$$

- The derivative of the above equation in terms of N_t reads

$$a^{-1}\frac{d{g_{\mathrm{L}}}^{c}}{da^{-1}} = B_{2\mathrm{loop}}\left[1 + N_t\frac{d}{dN_t}\log\frac{T_c}{\Lambda_{\mathrm{L}}}\right] \,. \tag{4}$$

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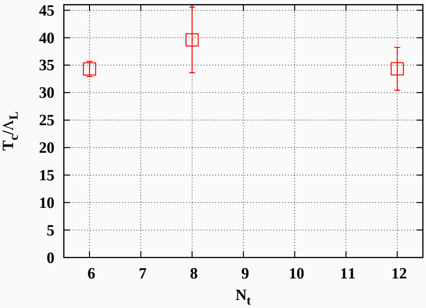
T_c/Λ_{L} as a function of N_t

Update for Miura-Lombardo Nucl. Phys. B ('13). *c.f.* Deuzeman et.al. Phys. Lett. B ('08).



The T_c/Λ_{L} depend on N_t, but within the error bars.

Short Summary for $N_f = 8$

- The observed first-order transition is the physical thermal transition. The QCD with $N_f = 8$ seems to be out side of the conformal window, consistently to the previous work (Deuzeman et.al. '08).
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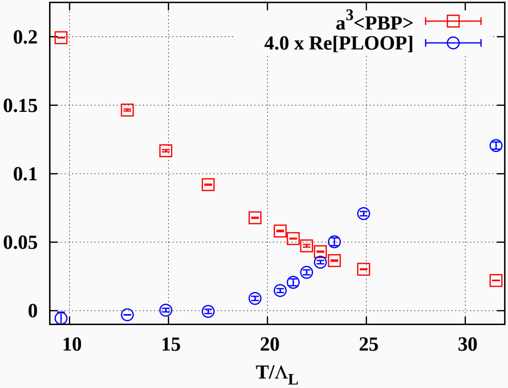
$N_f = 6$ QCD!

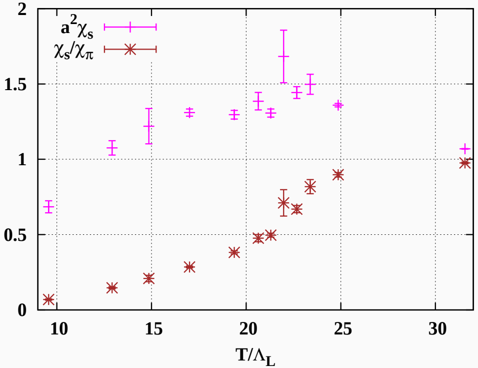
Chiral phase transition for $N_f = 6$, $ma = 0.02$, $24^3 \times 8$

Miura-Lombardo Nucl. Phys. B ('13).



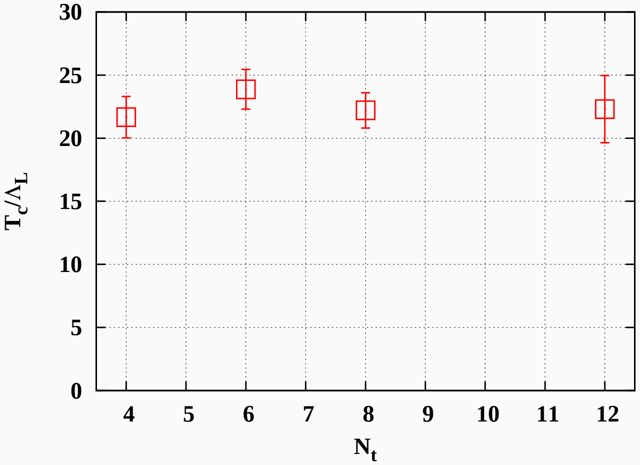
Chiral Susceptibility for $N_f = 6$, $ma = 0.02$, $24^3 \times 8$

Miura-Lombardo Nucl. Phys. B ('13).



$$\frac{T_c}{\Lambda_L} = 22.0 \pm 1.5 \ , \quad \Lambda_L = \text{2-loop Lattice Lambda} \ . \tag{5}$$

Two-Loop Asymptotic Scaling for $N_f = 6$



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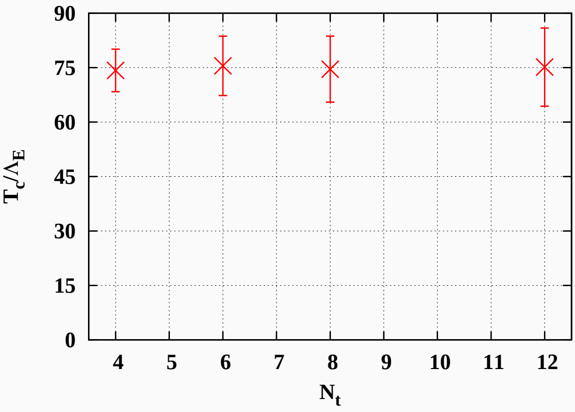

T_c/Λ_{E} is almost N_t independent!! (*c.f.* Gupta ('06)).

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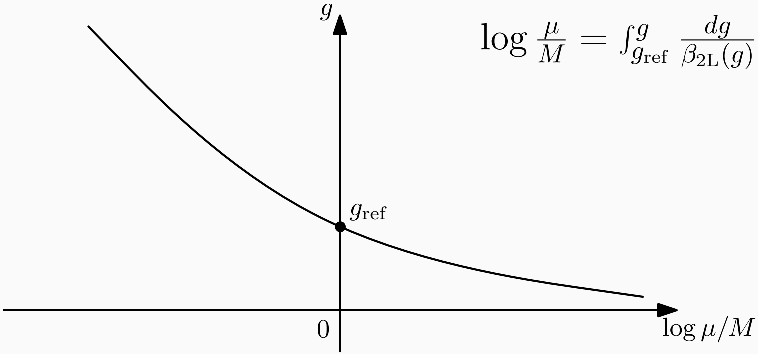

$$\log \frac{\mu}{M} = \int_{g_{\rm ref}}^{g} \frac{dg}{\beta_{2L}(g)}$$

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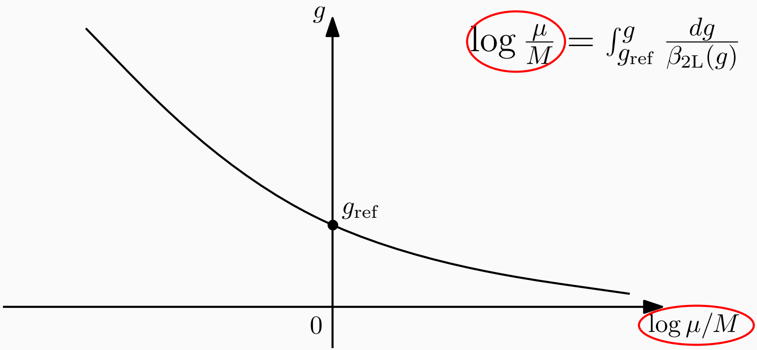

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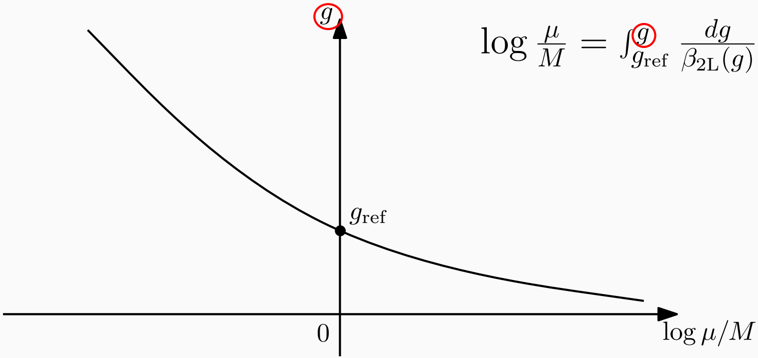

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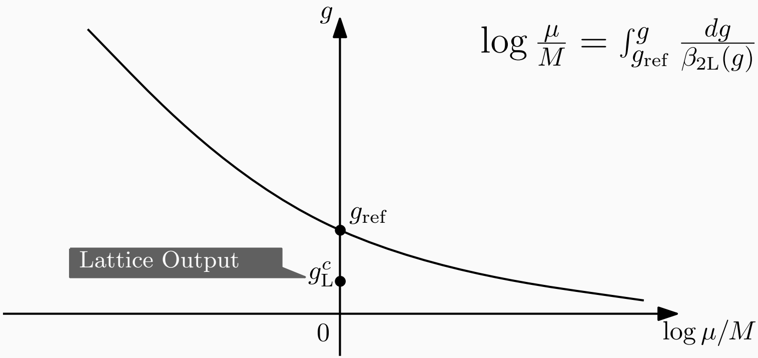
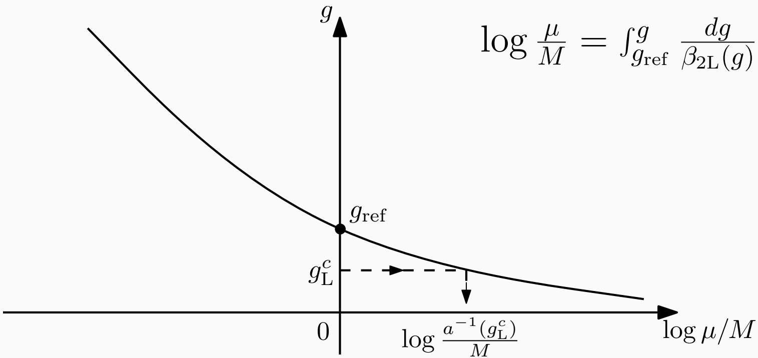
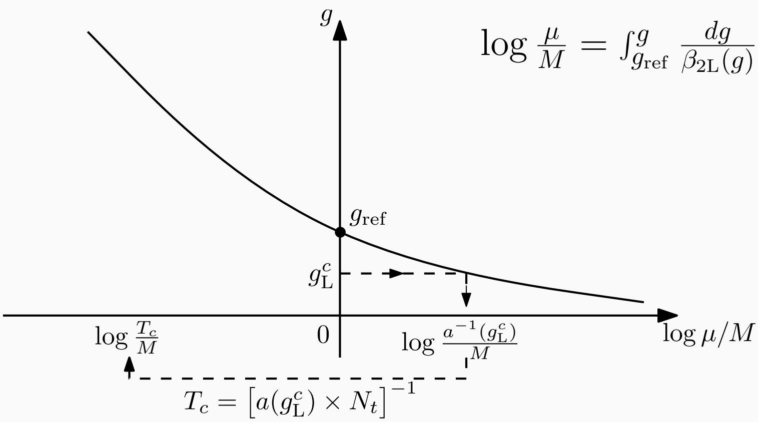


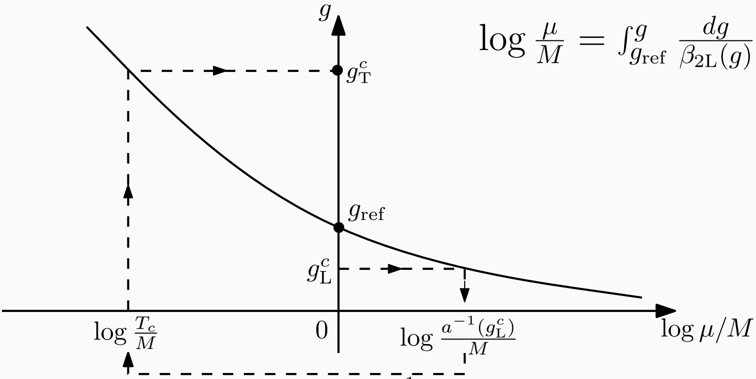
UV Cut-off Scale $a^{-1}(g_{\mathrm{L}}{}^{\mathrm{c}})$



Introducing T_c



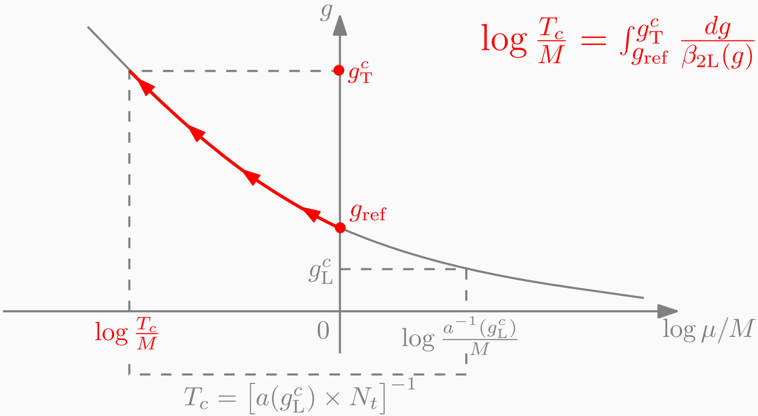
Thermal Critical Coupling $g_T{}^c$



$$\log \frac{\mu}{M} = \int_{g_{ref}}^{g} \frac{dg}{\beta_{2L}(g)}$$

$$T_c = \left[a(g_L^c) \times N_t\right]^{-1}$$

Consider Flow g_{Ref} to $g_{\mathrm{T}}{}^{\mathrm{c}}$



$$\log \frac{T_c}{M} = \int_{g_{\mathrm{ref}}}^{g_{\mathrm{T}}^c} \frac{dg}{\beta_{2\mathrm{L}}(g)}$$

UV Physics at Initial Boundary is N_f INDEP.

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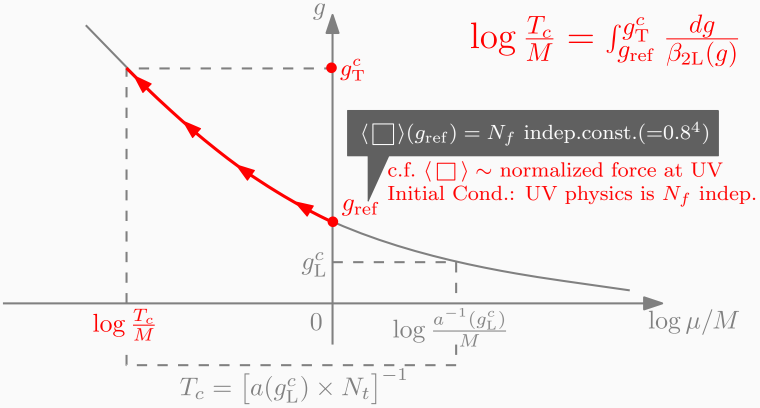
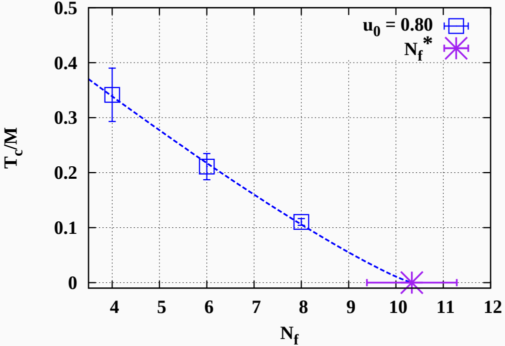


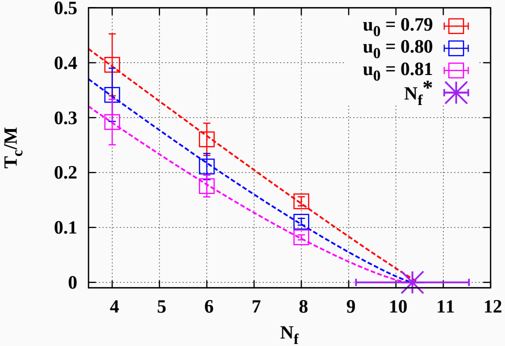
N_f^* Estimate From Vanishing T_c/M $u_0 = \langle\Box\rangle^{1/4} = 0.8$



$$\frac{T_c}{M}(N_f) = \exp\left[\int_{g_L{}^{\mathrm{ref}}(N_f)}^{g_T{}^{c}(N_f)} \frac{dg}{\beta_{2L}(g, N_f)}\right] \quad (6)$$

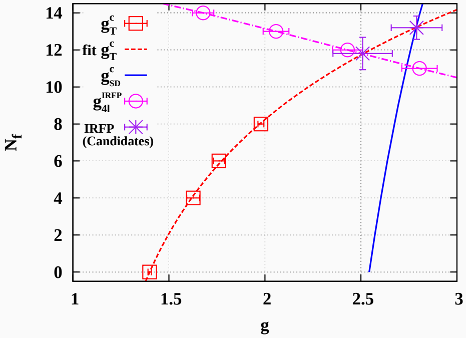
$$\sim K(N_f^* - N_f)^{-(2b_0^2/b_1)(N_f^*)} \quad \text{(c.f. Braun-Gies,'11)} \quad (7)$$

T_c/M for several $u_0 = \langle\Box\rangle^{1/4}$



$$N_f^* = 10.4 \pm 1.2 \text{ for } u_0 = 0.79 - 0.81.$$

$g_{\mathrm{T}}{}^{\mathrm{c}}$ VS g_{SD}^{c} and $g_{4\mathrm{l}}^{\mathrm{IRFP}}$



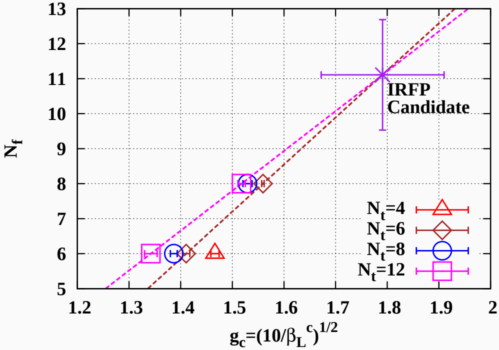
$g_{\mathrm{T}}{}^{\mathrm{c}}(N_f)$: Thermal Critical Coupling, Lattice Results (8)

$g_{\mathrm{SD}}^{c}(N_f)$: (Vacuum Critical Coupling, 2loop SD-Eq. Appelquist et al, '99)(9)

$g_{4\mathrm{l}}^{\mathrm{IRFP}}(N_f)$: (4-loop IRFP, Ryttov-Shrock '12) (10)

Coincidence of them indicates $N_f^* \sim 12.5 \pm 1.6$.

Step scalings in Miransky-Yamawaki Diagram



$$\left[g_{\mathrm{L}}{}^{\mathrm{c}\prime}(N_f)|_{N_t'=12} - g_{\mathrm{L}}{}^{\mathrm{c}}(N_f)|_{N_t=6} \right] \to 0 \, , (N_f \to 11.1 \pm 1.6) \, . \qquad (11)$$

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- Lattice Setups
- $N_f = 8$
- $N_f = 6$

3 Estimate of N_f^*
- N_f^* from Vanishing of T_c
- N_f^* from Thermal Critical Coupling $g_{\mathrm{T}}{}^{\mathrm{c}}$
- N_f^* from Vanishing of Step Scaling

4 Summary

Summary

- Motivated by the Walking Technicolor Model as well as the electroweak baryogenesis, we have investigated the chiral phase transition in the multi-flavor QCD by using Monte-Carlo simulations.
- The QCD with $N_f = 8$ shows the first-order chiral transition, and seems to be outside of the conformal window.
- The QCD with $N_f = 6$ shows the chiral crossover for the bare fermion mass $ma = 0.02$.
- We have estimated the onset of the conformal window as

$$N_f^* \sim \begin{cases} 10.4 \pm 1.2 & (\text{the vanishing of } T_c/M \text{ for } u_0 = 0.79 - 0.81) \,, \\ 12.5 \pm 1.6 & (\text{the approach of } g_{\mathrm{T}}{}^{\mathrm{c}} \text{ to } g_{\mathrm{SD}}^{c} \text{ and } g_{41}^{\mathrm{IRFP}}) \,, \\ 11.1 \pm 1.6 & (\text{the vanishing thermal scaling of } g_{\mathrm{L}}{}^{\mathrm{c}}) \,. \end{cases} \quad (12)$$

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Future Plan

- Static Potential Measurement.
- Techni-Baryon Dark Matter in QCD with $N_f = 8$.
- Phase Diagram in $T - m$ plane in QCD with $N_f = 8$.

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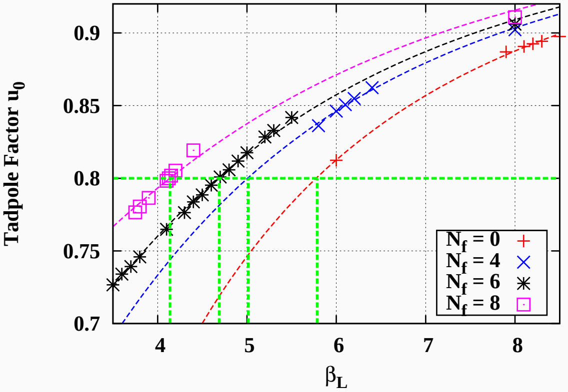
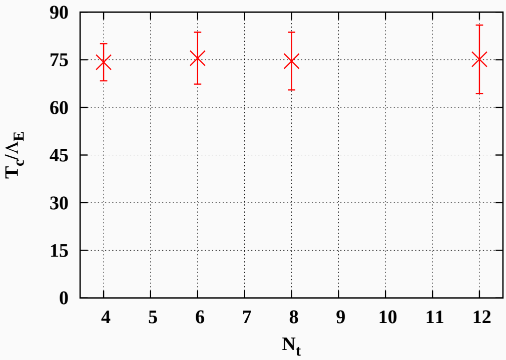
5 Buckups

Tadpole Factor $u_0 = \langle \Box \rangle^{1/4}$

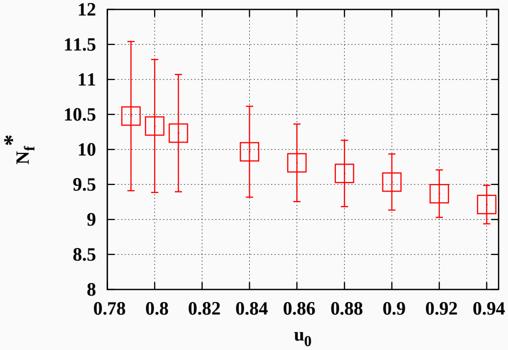


Two-Loop Asymptotic Scaling at $N_f = 6$



$T_c/\Lambda_{\rm E}$ is almost N_t independent!! (*c.f.* Gupta ('06)).

u_0 dependences of N_f^*



Thermal step scalings in MY Diagram

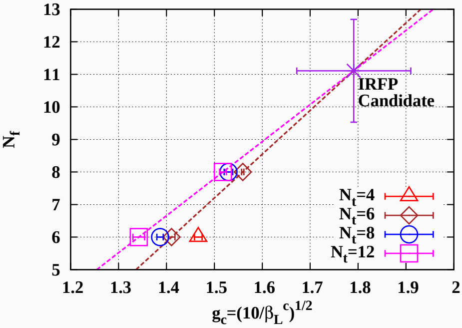


Figure: $T_c = [N_t \; a(g_{\rm L}{}^{\rm c})]^{-1} = [N'_t \; a(g_{\rm L}{}^{\rm c}{}')]^{-1}$ should hold at each N_f.

- By using $N_f = 6, 8$ data, $N_t = 6$ and 12 lines get into the intersection at $N_f^* \sim 11.1 \pm 1.6$.
- We also observe the enhanced fermion screenings at larger N_f (*c.f.* Kogut et al. ('85)).