2022/08/??
Lattice 2022
Bonn

Phase structure and critical point in heavy-quark QCD at finite temperature

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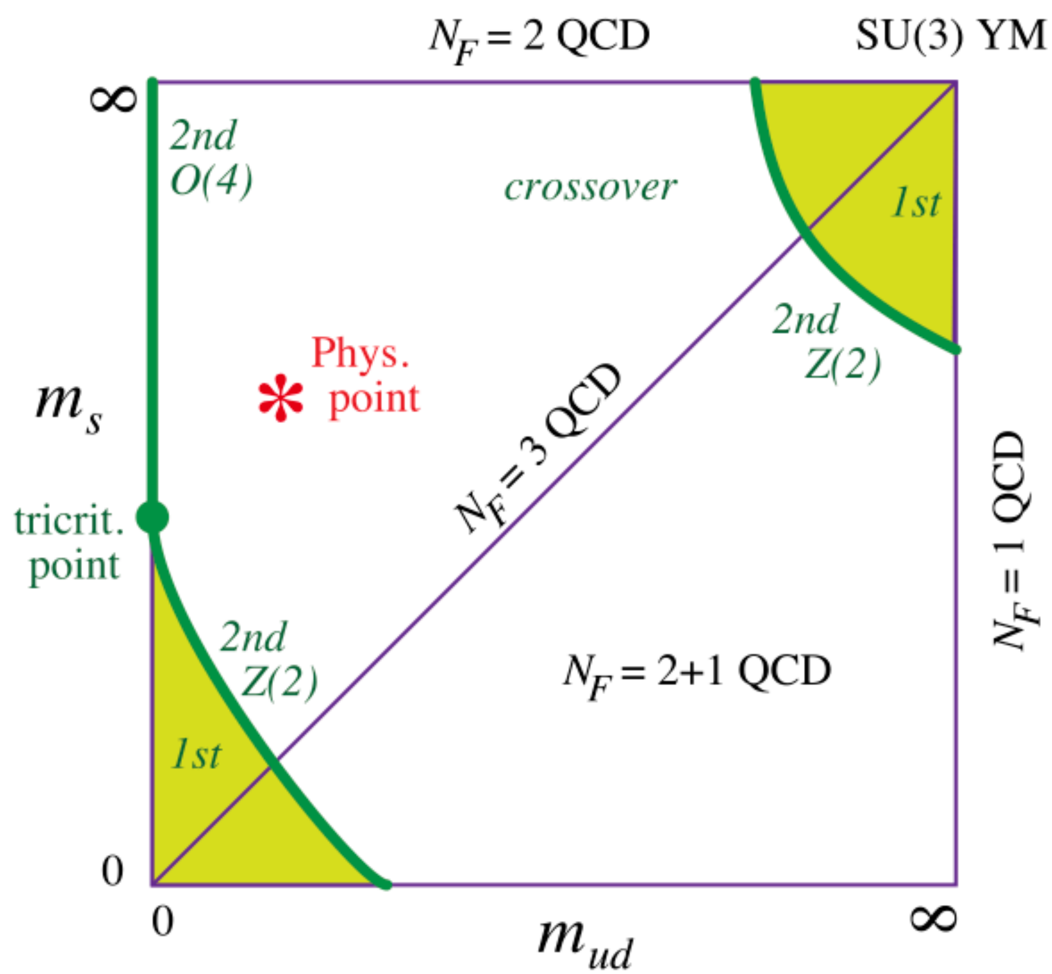
University of Tsukuba

Tomonaga Center for the History of the Universe

Nature of $T > 0$ QCD transition as function of m_q's

The traditional picture given by this Columbia plot



Nature of $T > 0$ QCD transition as function of m_q's

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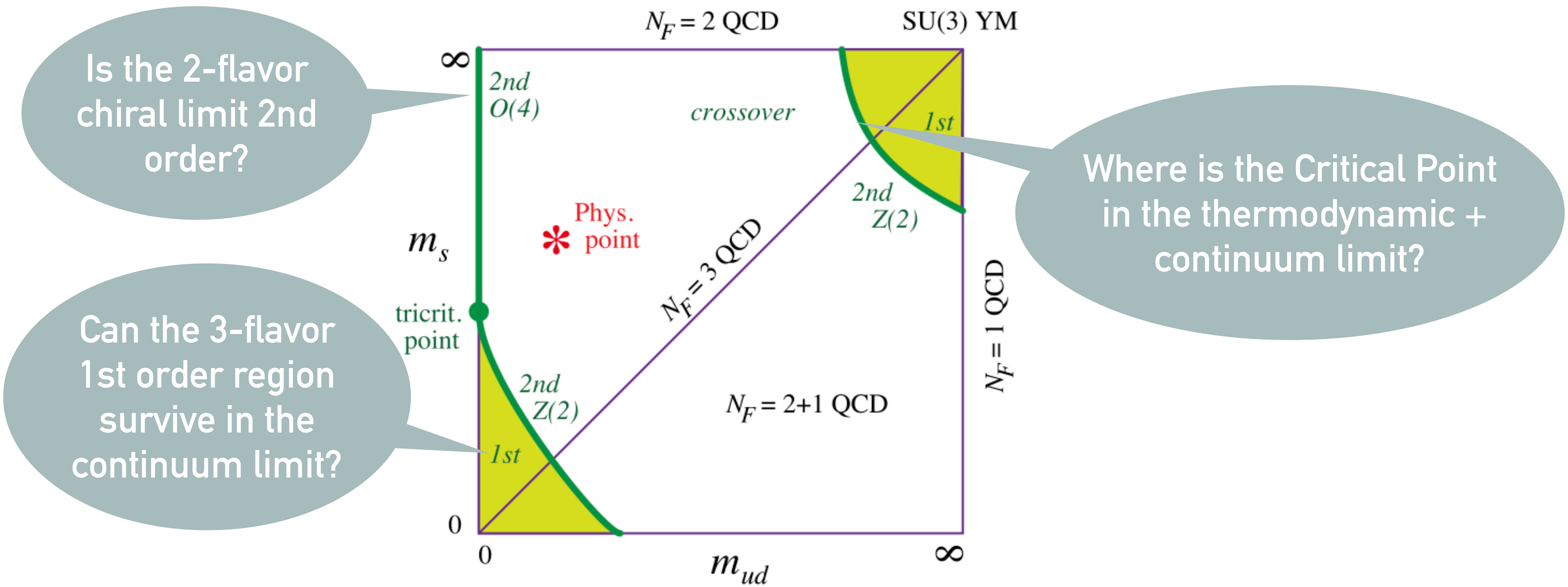
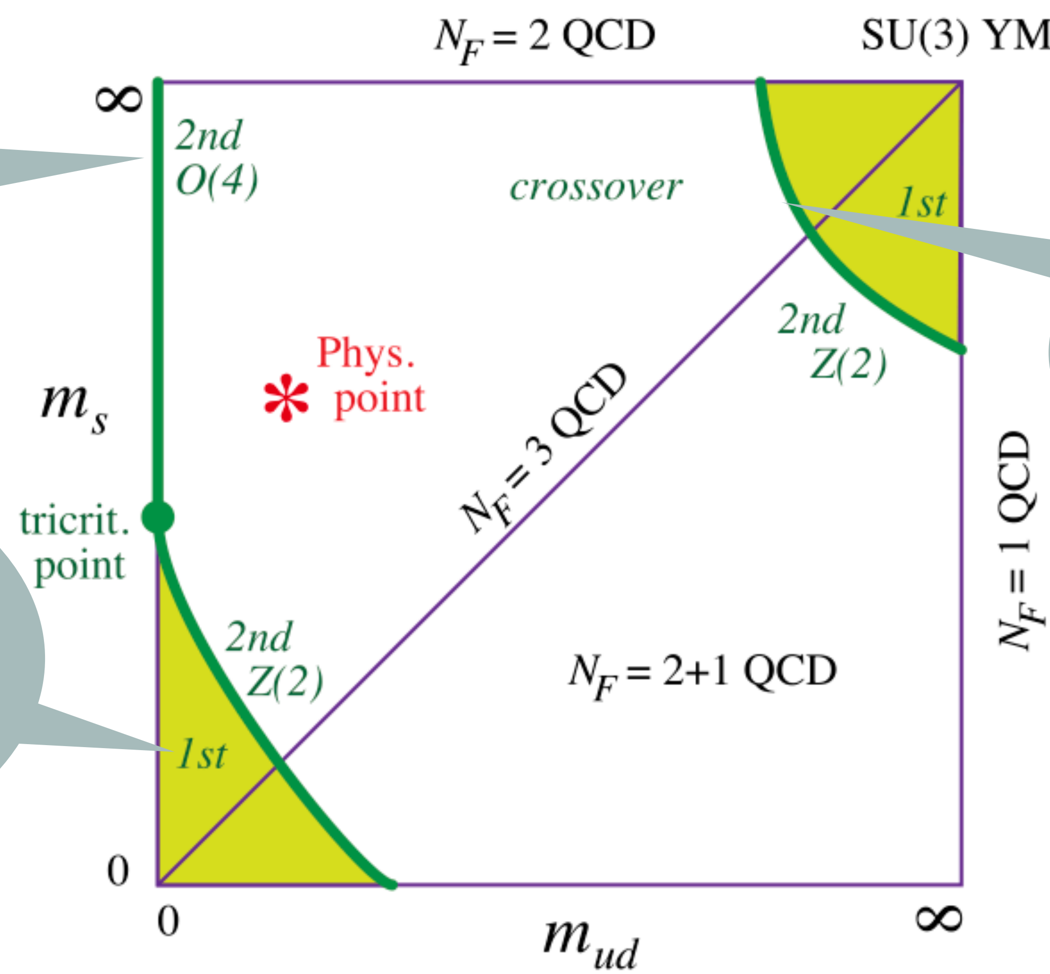


Nature of $T > 0$ QCD transition as function of m_q's

The traditional picture given by this Columbia plot is still under many discussions…

Is the 2-flavor chiral limit 2nd order?

Can the 3-flavor 1st order region survive in the continuum limit?



Where is the Critical Point in the thermodynamic + continuum limit?

this talk

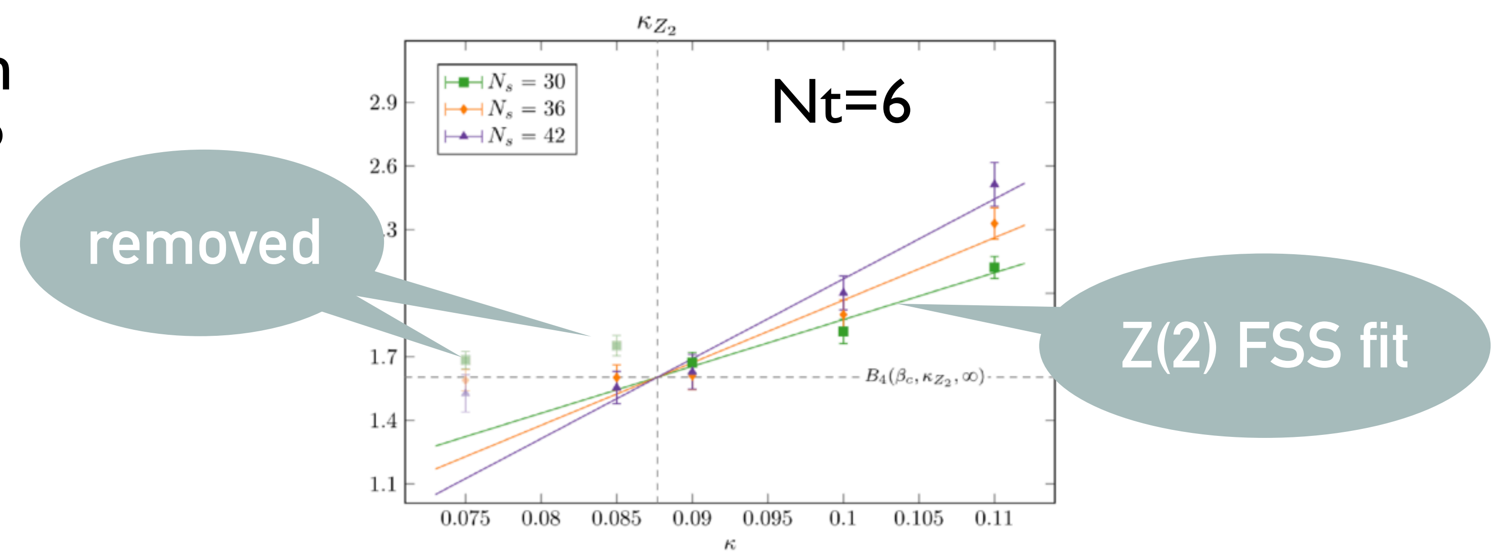
- Recent studies on the location of CP in heavy-quark QCD
  - Saito+ (WQHOT-QCD), *PRD* (2011/2014): HPE LO, Nt=4, Ns/Nt=6
  - Ejiri+ (WHOT-QCD), *PRD* (2020): HPE eff-NLO, Nt=6, Ns/Nt=4–6; Nt=8, Ns/Nt=3
  - Cuteri+, *PRD* (2021): Nf=2, fullQCD, Nt=6,8,10, Ns/Nt=4–7(10)

=> We still have strong cutoff & spatial volume dependences.

Motivations

- Binder cumulant analysis based on the Z(2) FSS expected around CP

  So far, however, identification of the Z(2) FSS is not a simple task
  --- removal of many high-T data required / correction terms to the FSS introduced.



(a) Fit e.6.1 at $N_\tau = 6$.

Cuteri+, *PRD* (2021)

These make the analyses slightly ambiguous & call careful systematic error estimations.

Motivations

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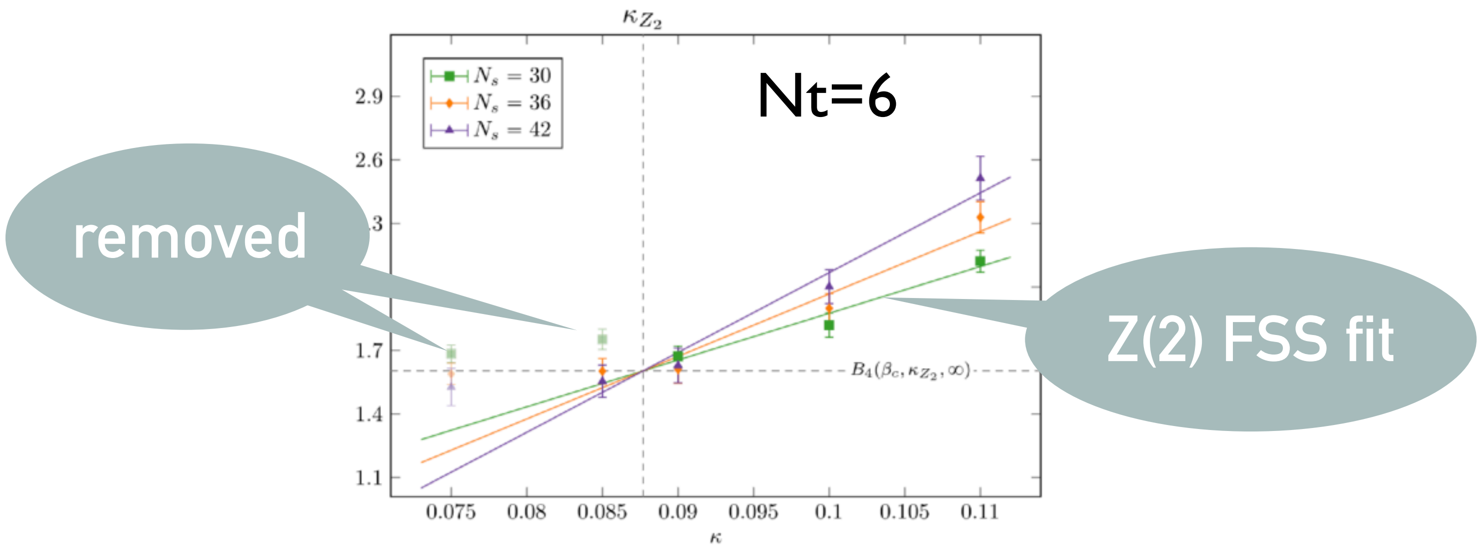


(a) Fit e.6.1 at $N_\tau = 6$.

Cuteri+, *PRD* (2021)

These make the analyses slightly ambiguous & call careful systematic error estimations.

=> Simulations with larger spatial volumes & high statistics to identify the FSS more clearly.
=> Multi-point reweighting to vary coupling parameters continuously.

This talk is based on

- Kiyohara+ (WQHOT-QCD), *Phys.Rrev.D* (2021) [DOI: 10.1103/PhysRevD.104.114509]
- Wakabayashi+ (WHOT-QCD), *Prog.Theor.Exp.Phys.* (2022) [DOI: 10.1093/ptep/ptac019]
- Ashikawa+ (WHOT-QCD), *ongoing*

We first revisit the Nt=4 case to increase the spatial volume [Kiyohara+, *PRD* ('21)].

Lattice setup

- Action: plaquette gauge + standard Wilson quarks
- Kernel for each flavor: $M_{xy}(\kappa) = \delta_{xy} - \kappa \sum_{\mu} \left[(1-\gamma_\mu) U_{x,\mu} \delta_{y,x+\hat{\mu}} + (1+\gamma_\mu) U^\dagger_{y,\mu} \delta_{y,x-\hat{\mu}} \right]$

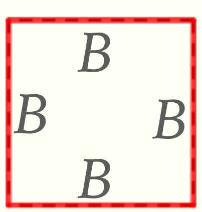
  $= \delta_{xy} - \kappa B_{xy}$ ← hopping term $\qquad \kappa = \dfrac{1}{2am_q + 8}$

- Quark contribution to the effective action: $\ln \det M(\kappa) = -\dfrac{1}{N_{\rm site} n} \sum_{n=1}^{\infty} \mathrm{Tr}[B^n] \kappa^n$
  - closed loops of B with $\kappa^{\text{[loop length]}}$

- Hopping Parameter Expansion to reduce simulation cost for large spatial volumes

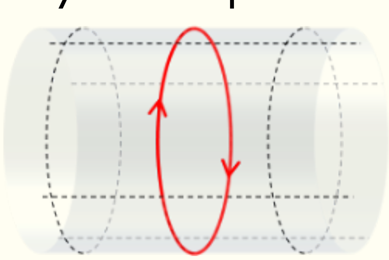
LO:

plaquette



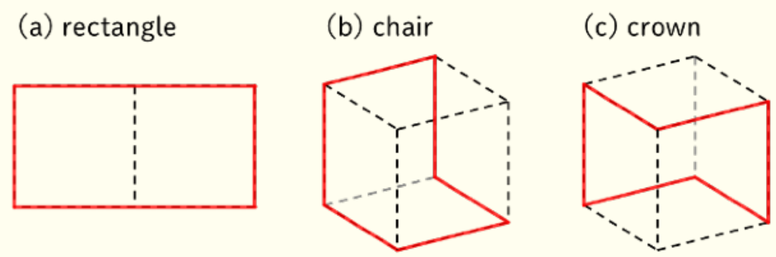
κ^4

Polyakov loop Ω



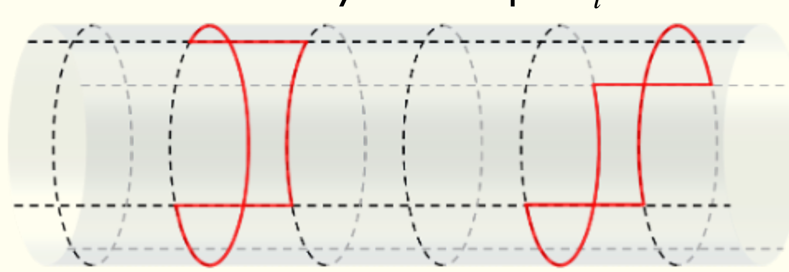
κ^{N_t}

NLO:



κ^6

bent Polyakov loops Ω_i



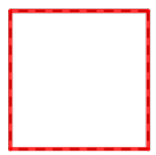
κ^{N_t+2}

  - HPE $\approx 1/(am_q)$ expansion
  - HPE worsens with $a \to 0$ $(N_t \to \infty)$ => higher order terms required with $N_t \to \infty$.

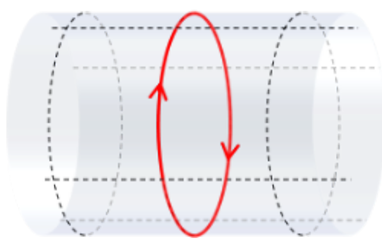
Simulation incorporating LO + NLO meas.'s

Kiyohara, Kitazawa, Ejiri, KK (WHOT-QCD), *PRD* 104 (2021)

- LO incorporated in the configuration generation



$$\beta \;\rightarrow\; \beta^* = \beta + 48 N_f \kappa^4$$



$\lambda \sum_{\mathbf{x}} \Omega(\mathbf{x})$ term in the effective action $\quad (\lambda = 48 N_f N_t \kappa^4$ for Nt=4)

can be incorporated in PHB+OR parallel simulation efficiently

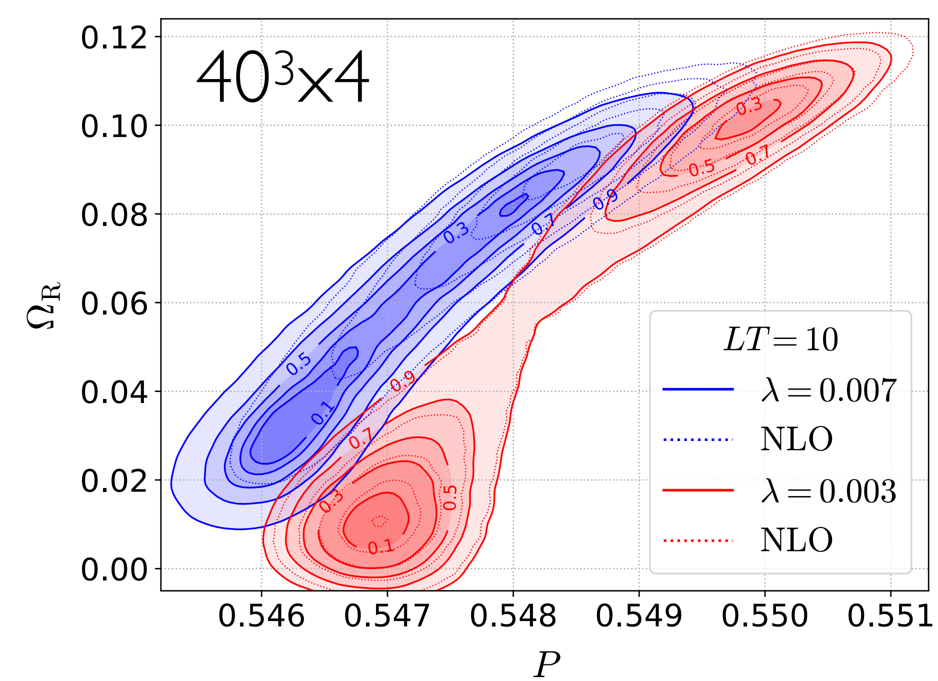
by keeping all temporal sites within a node

- NLO incorporated in the measurements through multi-point reweighting

$$\langle \hat{O}(U) \rangle^{\rm NLO}_{\beta,\lambda} = \frac{\langle \hat{O}(U)\, e^{-\delta S_{\rm LO} - S_{\rm NLO}(\beta,\lambda)} \rangle^{\rm LO}_{\tilde{\beta},\tilde{\lambda}}}{\langle e^{-\delta S_{g+{\rm LO}} - S_{\rm NLO}(\beta,\lambda)} \rangle^{\rm LO}_{\tilde{\beta},\tilde{\lambda}}}$$

$$\delta S_{g+{\rm LO}} = S_{g+{\rm LO}}(\beta,\lambda) - S_{g+{\rm LO}}(\tilde{\beta},\tilde{\lambda})$$

- Simulations at several $(\tilde{\beta}^*, \tilde{\lambda})$ => measure at (β^*, λ)
- Overlap problem resolved by the inclusion of LO in configuration generations <= essential on spatially large lattices in this study

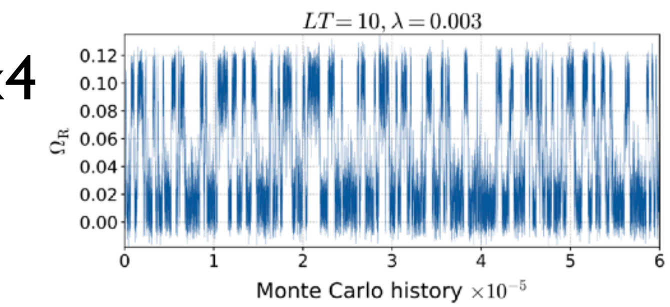


Study on $N_t = 4$ lattices

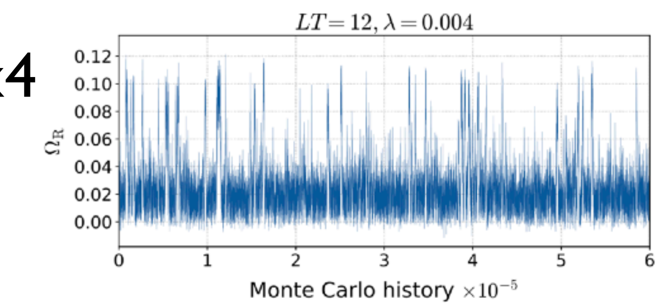
Kiyohara, Kitazawa, Ejiri, KK (WHOT-QCD), *PRD* 104 (2021)

- Simulations: Nt=4, Ns/Nt = LT = 6, 8, 9, 10, 12, each 3-6 x [$(\tilde{\beta}^*, \tilde{\lambda})$ with ~10^6 meas.] around the transition line L = spatial lattice size, $\lambda = 48 N_f N_t \kappa^4$ for Nt=4

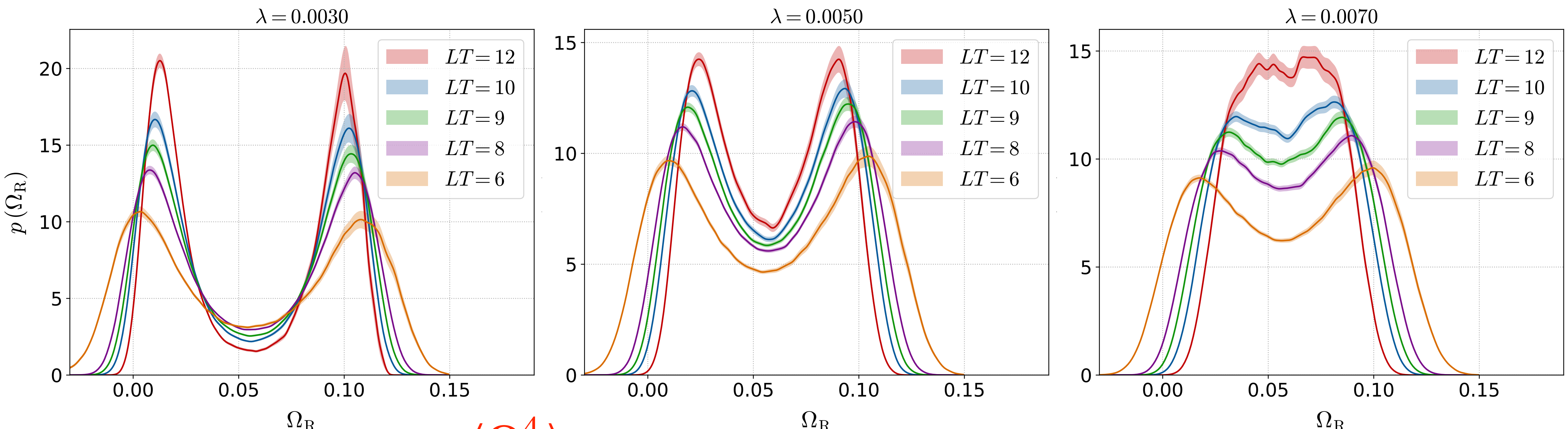
- History of $\Omega_{\rm R} = {\rm Re}\Omega$ 40^3x4



48^3x4



- Distribution of $\Omega_{\rm R}$ on the transition line

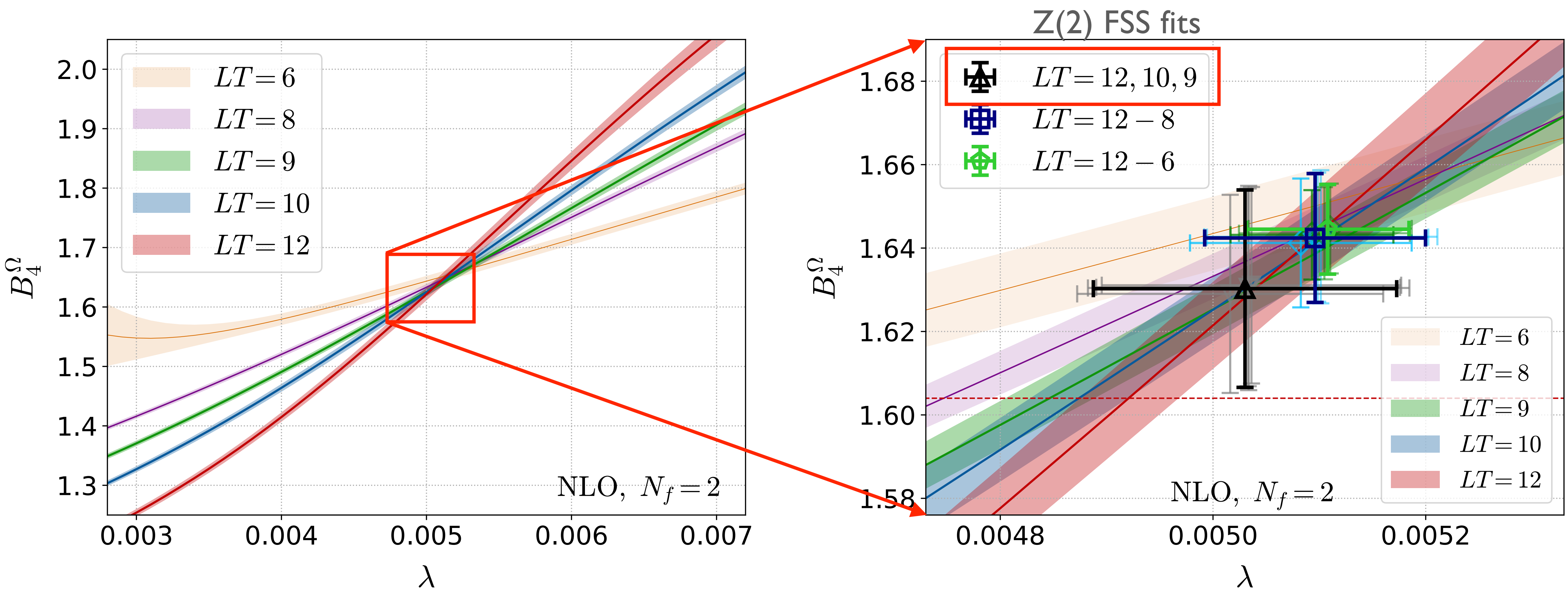


=> Binder cumulant $B_4^{\Omega} = \dfrac{\langle \Omega_{\rm R}^4 \rangle_c}{\langle \Omega_{\rm R}^2 \rangle_c^2} + 3$ along the transition line

Study on $N_t = 4$ lattices

Kiyohara, Kitazawa, Ejiri, KK (WHOT-QCD), *PRD* 104 (2021)

- Results at Nt=4 with HPE up to NLO



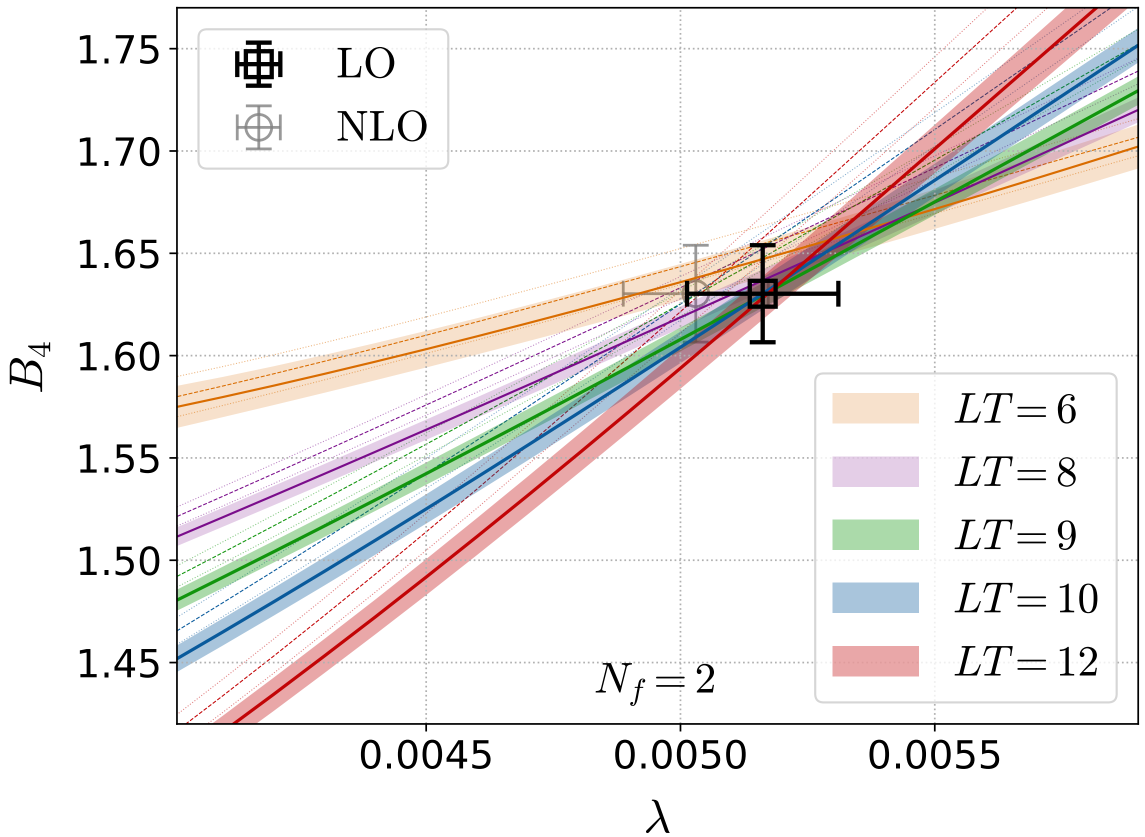
- ☆ Precision much improved over previous studies
- ☆ Ns/Nt = LT ≥ 9 required for Z(2) FSS
- ☆ $B_4^\Omega = 1.630(24)(2)$ using Ns/Nt ≥ 9, consistent with Z(2) value 1.604 within $\approx 1\sigma$
- ☆ $\lambda_c = 0.00503(14)(2)$ [$\kappa_c = 0.0603(4)$] for Nt=4, Nf=2

(cf.) Ejiri+ PRD(2020): $\kappa_c = 0.0640(10)$ with eff. NLO

Study on $N_t = 4$ lattices

Kiyohara, Kitazawa, Ejiri, KK (WHOT-QCD), *PRD* 104 (2021)

- Comparison with LO analysis => effects of NLO corrections



☆ LO ≈ NLO with Ns/Nt=LT ≥ 9

☆ Shift due to NLO is small ($\approx 2.6\%$), suggesting LO dominance around κ_c for Nt=4

=> previous Nt=4 LO results seems OK

Scope and convergence of HPE

Wakabayashi, Ejiri, KK, Kitazawa (WHOT-QCD), *PTEP* (2022)

Are the effects of further higher orders of HPE really negligible?

Scope and convergence of HPE

Wakabayashi, Ejiri, KK, Kitazawa (WHOT-QCD), *PTEP* (2022)

Are the effects of further higher orders of HPE really negligible?

- Quark contribution to the effective action:

loops of length n

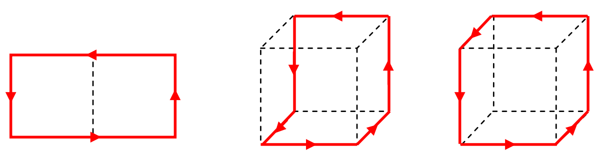
noise average

$$\ln \det M(\kappa) = N_{\rm site} \sum_n D_n \kappa^n, \qquad D_n = \frac{-1}{N_{\rm site} n} {\rm Tr}[B^n] \approx \frac{-1}{N_{\rm site} n} \langle\langle \eta^\dagger B^n \eta \rangle\rangle_{\rm noises}$$

$$B_{xy} = \sum_\mu \left[(1-\gamma_\mu) U_{x,\mu} \delta_{y,x+\hat{\mu}} + (1+\gamma_\mu) U^\dagger_{y,\mu} \delta_{y,x-\hat{\mu}} \right]$$

Wilson-type loops

$$W(4) = 96 N_c \hat{P}, \quad W(6) = 256 N_c (3\hat{W}_{\rm rec} + 6\hat{W}_{\rm chair} + 2\hat{W}_{\rm crown})$$

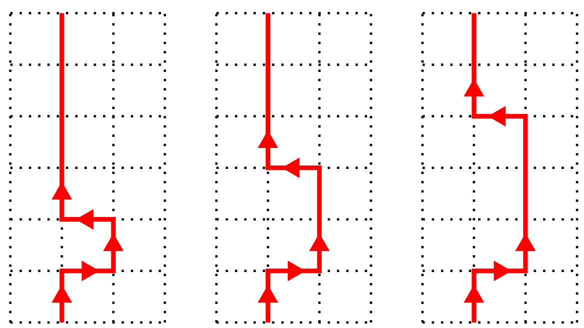


$$D_n = W(n) + \sum_m L_m(N_t, n) = W(n) + L(N_t, n)$$

Polyakov-type loops with m-windings

$$L_1(N_t, N_t) = \frac{4 N_c 2^{N_t}}{N_t} {\rm Re}\hat{\Omega}$$

$$L_1(N_t, N_t+2) = 12 N_c 2^{N_t} \sum_k {\rm Re}\hat{\Omega}_k$$



We developed a method to separately evaluate $W(n)$ and $L_m(N_t, n)$ from D_n by combing the results with various twisted boundary conditions.

Scope and convergence of HPE

Wakabayashi, Ejiri, KK, Kitazawa (WHOT-QCD), *PTEP* (2022)

- $\hat{W}_i, \hat{P}_j$ in $W(n)$ and $L_m(N_t, n)$ take their maximum value 1 when we set $U_{x,\mu} = 1$

  In this case, we can calculate $W(n)$ and $L_m(N_t, n)$ analytically up to high orders.

=> Worst convergent case of HPE can be studied by combining them.

Scope and convergence of HPE

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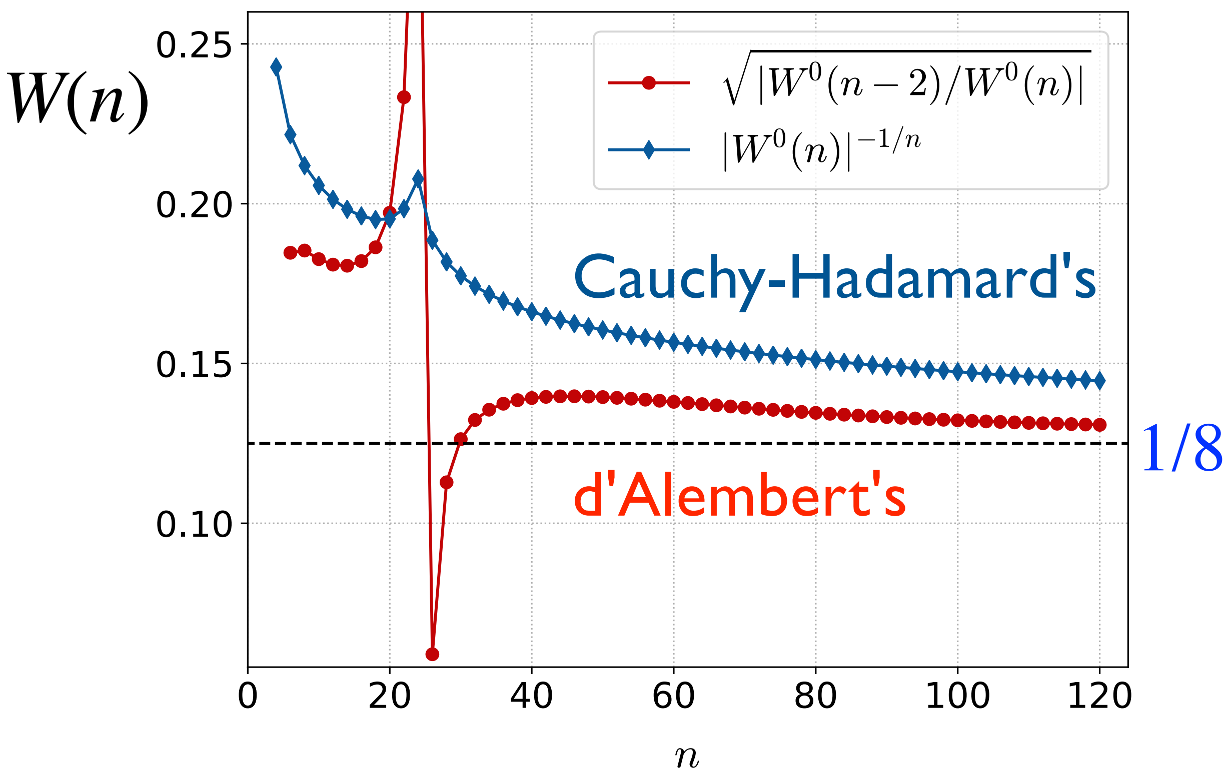
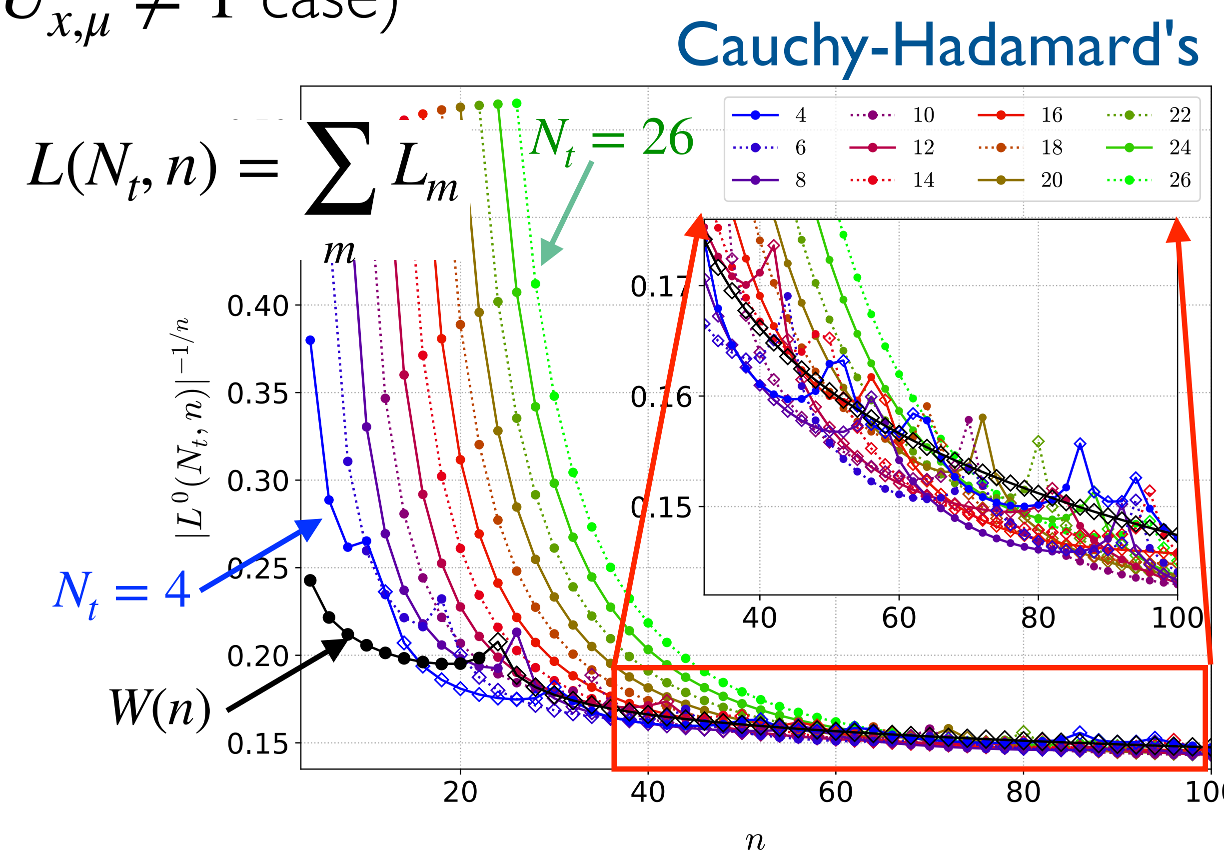
  In this case, we can calculate $W(n)$ and $L_m(N_t, n)$ analytically up to high orders.

=> Worst convergent case of HPE can be studied by combining them.

- **Convergence radius** (lower bound for the $U_{x,\mu} \neq 1$ case)





☆ Convergence radius $\underset{n \to \infty}{\longrightarrow}$ $1/8$, i.e. convergent up to the chiral limit.

<= free Wilson quarks when $U_{x,\mu} = 1$

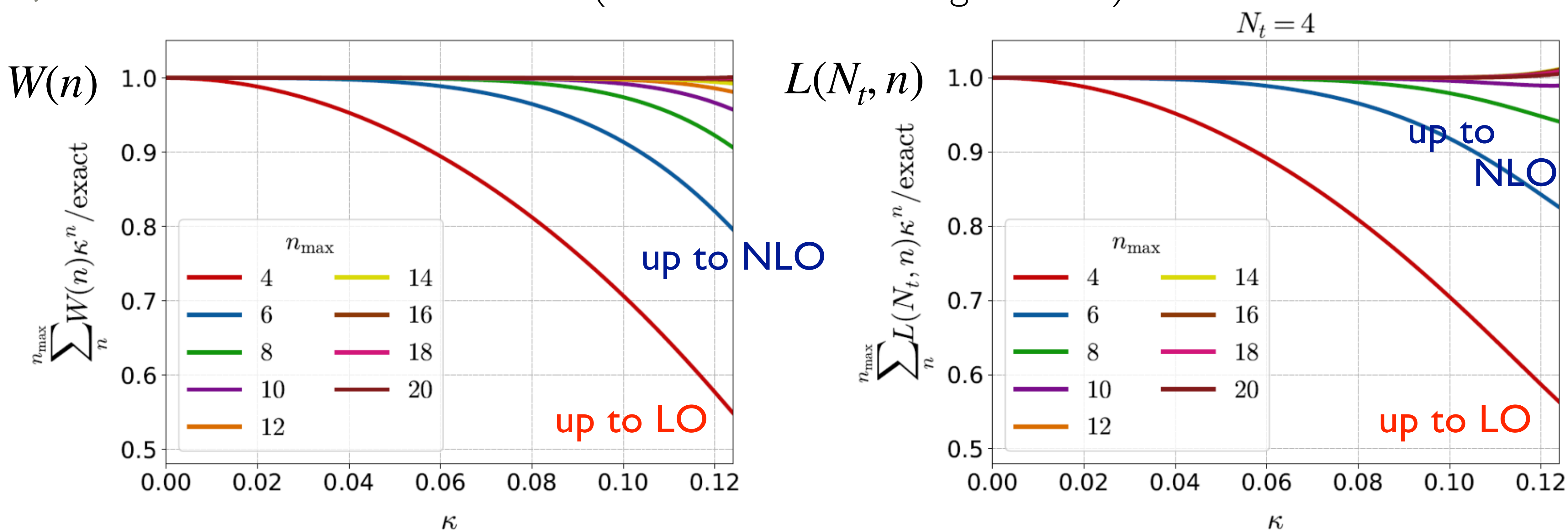
=> **HPE reliable up to the chiral limit when sufficiently high orders are taken.**

Scope and convergence of HPE

Wakabayashi, Ejiri, KK, Kitazawa (WHOT-QCD), *PTEP* (2022)

To which order we need to incorporate? <= *depends on the value of* κ

- **Deviation due to truncation** (in the worst convergent case):



- For Nt=4: $\kappa_c = 0.0603(4)$ [Kiyohara+ ('21)]
  => LO may have at worst ≈10% error, NLO good enough

- For Nt=6: $\kappa_c = 0.0877(9)$ [Cuteri+ ('22)], $0.1286(40)$ [Ejiri+ ('20) using eff. pot.]
  => NLO is ≥93% accurate. remaining error can be removed by NNLO or higher

- For Nt=8: $\kappa_c = 0.1135(8)$ [Cuteri+ ('22)] => NNLO needed for ≥95% accuracy

Effective method to incorporate high orders

Wakabayashi, Ejiri, KK, Kitazawa (WHOT-QCD), *PTEP* (2022)

Calcuration of high order term becomes quickly difficult with increasing n.

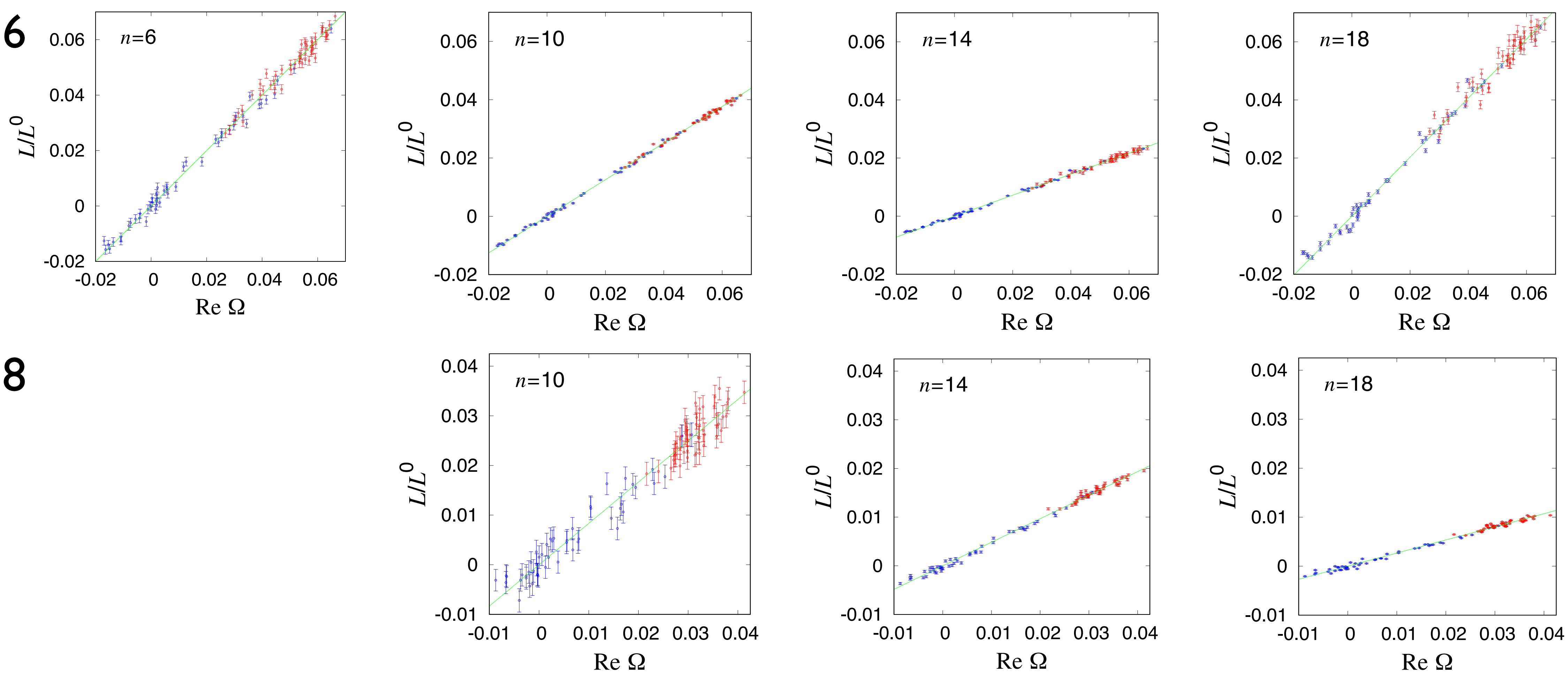
We extend the idea of the effective NLO method [Ejiri+ ('20)] to high orders.

Basic observation: **strong correlation of Wilson/Polyakov-type loops among different n.**

- Distribution of $L(N_t, n)$ vs. the Polyakov loop Ω
  - qQCD simulation on 32^3x(6, 8), blue/red slightly below/above β_{trans}
  - normalized by the Uxμ=1 result L^0

Nt=6

Nt=8



Effective method to incorporate high orders

Wakabayashi, Ejiri, KK, Kitazawa (WHOT-QCD), *PTEP* (2022)

This linear correlation suggests us to approximate

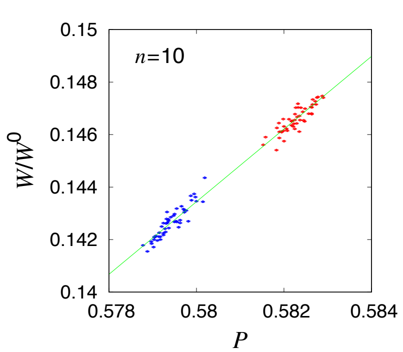
☆ $L(N_t, n) \approx L^0(N_t, n)\, c_n\, \mathrm{Re}\hat{\Omega}$

known from $U_{x\mu}=1$

our MC results:

	$N_t = 6$	$N_t = 8$
c_6	1	
c_8	0.8112(20)(7)	1
c_{10}	0.6280(15)(3)	0.8327(114)(95)
c_{12}	0.4736(29)(15)	0.6408(36)(27)
c_{14}	0.3609(26)(11)	0.4841(22)(10)
c_{16}	0.3106(25)(10)	0.3616(21)(6)
c_{18}	1.0159(90)(33)	0.2679(16)(3)
c_{20}	−0.02771(57)(13)	0.2020(13)(2)

☆ $W(n) \approx W^0(n)\,(d_n \hat{P} + f_n)$



though the correlation weaker than L(Nt,n)

n	$d_n(N_t = 6)$	$f_n(N_t = 6)$	$d_n(N_t = 8)$	$f_n(N_t = 8)$
4	1	0	1	0
6	1.3625(73)(12)	−0.4070(42)(7)	1.3366(66)(8)	−0.3922(39)(5)
8	1.4644(123)(11)	−0.6089(72)(6)	1.4256(96)(8)	−0.5869(57)(5)
10	1.3835(156)(10)	−0.6590(91)(6)	1.3433(117)(8)	−0.6367(70)(5)
12	1.2140(178)(9)	−0.6235(103)(5)	1.1752(130)(7)	−0.6025(78)(4)
14	1.0256(196)(9)	−0.5533(114)(5)	0.9825(141)(7)	−0.5303(85)(4)
16	0.8607(219)(9)	−0.4811(127)(5)	0.8052(153)(8)	−0.4512(92)(5)
18	0.7481(258)(10)	−0.4296(150)(6)	0.6698(173)(9)	−0.3870(103)(5)
20	0.7290(337)(12)	−0.4275(196)(7)	0.6071(219)(12)	−0.3606(131)(7)

=> Higher order effects can be effectively incorporated in the LO simulation by

$$\beta \;\to\; \beta^* = \beta + \frac{1}{6} N_f \sum_{n=4}^{n_{\max}} W^0(n)\, d_n\, \kappa^n \qquad \lambda \;\to\; \lambda^* = N_f N_t \sum_{n=N_t}^{n_{\max}} L^0(N_t, n)\, c_n\, \kappa^n$$

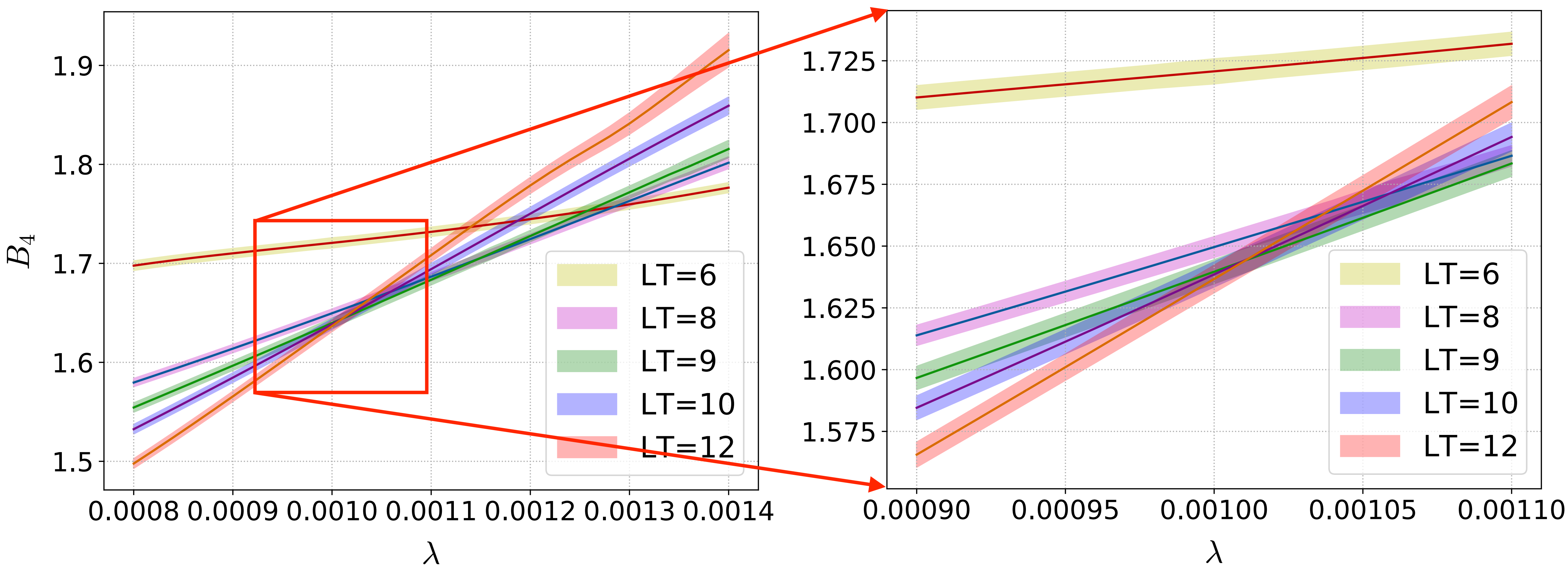
Extension to non-degenerate cases (Nf=2+1 etc.) straightforward.

Study on N_t = 6 lattices

Ashikawa+ (WHOT-QCD), *ongoing*

- Nt=6, Ns/Nt = LT = 6, (7,) 8, 9, 10, 12, (15) *ongoing*
- Status of B_4^Ω with NLO:

$\lambda = 128 N_f N_t \kappa^6$ for Nt=6, Nf=2, NLO



Preliminary:

☆ $B_4^\Omega \sim 1.63 - 1.64$ with Ns/Nt ≥ 9 (cf.) Z(2) value = 1.604

☆ $\lambda_c \sim 0.00101$ => $\kappa_c \sim 0.093$ NLO => $\kappa_c \sim 0.0905$ eff. including up to 20th order

looks consistent with $\kappa_c = 0.0877(9)$ by a full QCD simulation [Cuteri+ ('22)]

Conclusion & outlook

- **HPE provides us with a reliable and powerful way to study QCD with heavy quarks**
  - ☑ Convergent up to chiral limit + enable large Ns/Nt simul.'s + analytic in Nf
  - ☑ up to κ_c of Nt=4, Nf=2 : LO: ≥90% / NLO: ≥99% accurate
  - ☑ around κ_c of Nt=6, Nf=2 : NLO: ≥93% accurate

  Higher orders needed to remove remaining truncation error and for Nt≥8.
- **At Nt=4, Ns/Nt≥9 needed for Z(2) FSS**

  => NLO study of B_4^{Ω} : $\kappa_c = 0.0603(4)$ for Nf=2
- At Nt=6 with Ns/Nt≥9, $\kappa_c \sim 0.090$ including high orders (preliminary) looks consistent with a full QCD study [Cuteri+ ('22)]
- At Nt=6, more statistics & larger Ns/Nt : ongoing
- Continuum extrapolation => large Nt => high orders must be taken.
- **We developed an effective method to incorporate high orders**

  => easy to implement in LO PHB simulations => used in Nt=6 study
- HPE powerful also at **finite densities** : in progress (cf.) Chabane on Monday

We miss our best friend+collaborator

Yusuke Taniguchi

who passed away silently on July 22, 2022.

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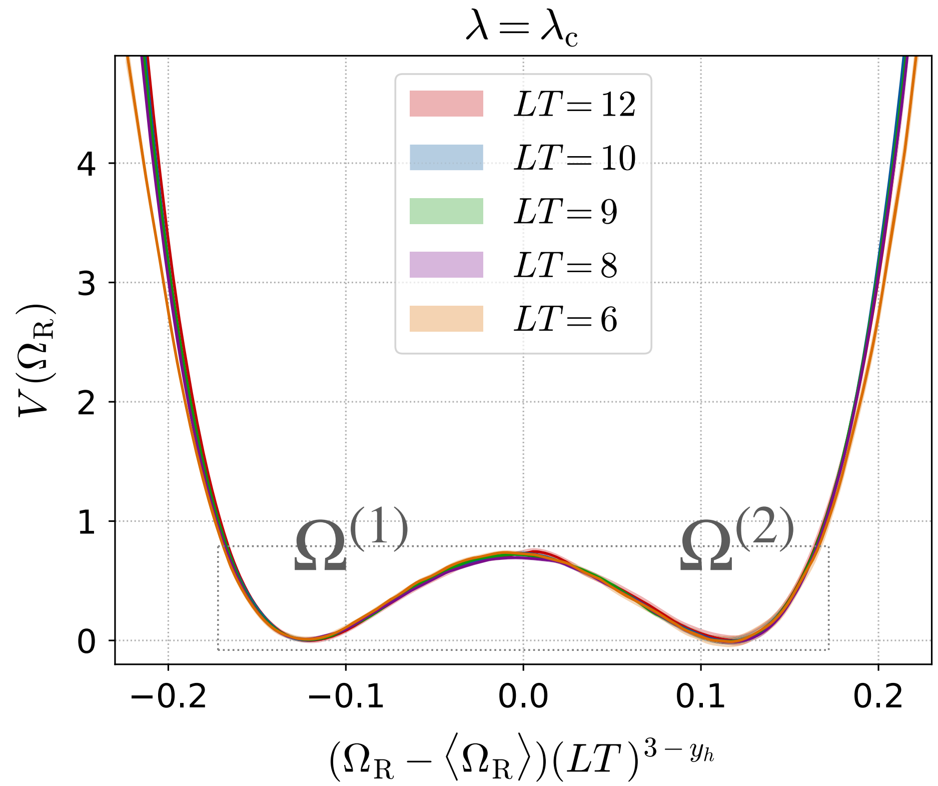
Kiyohara, Kitazawa, Ejiri, KK (WHOT-QCD), *PRD* 104 (2021)

$$V(\Omega_{\rm R};\lambda,LT) = -\ln p(\Omega_{\rm R})_{\lambda,LT},$$



$$\Delta\Omega = \Omega^{(2)} - \Omega^{(1)}. \tag{46}$$

According to Eq. (15), this quantity should behave around the *CP* as

$$\Delta\Omega(\lambda,LT) = (LT)^{y_h-3}\Delta\tilde{\Omega}((\lambda-\lambda_c)(LT)^{1/\nu}), \tag{47}$$

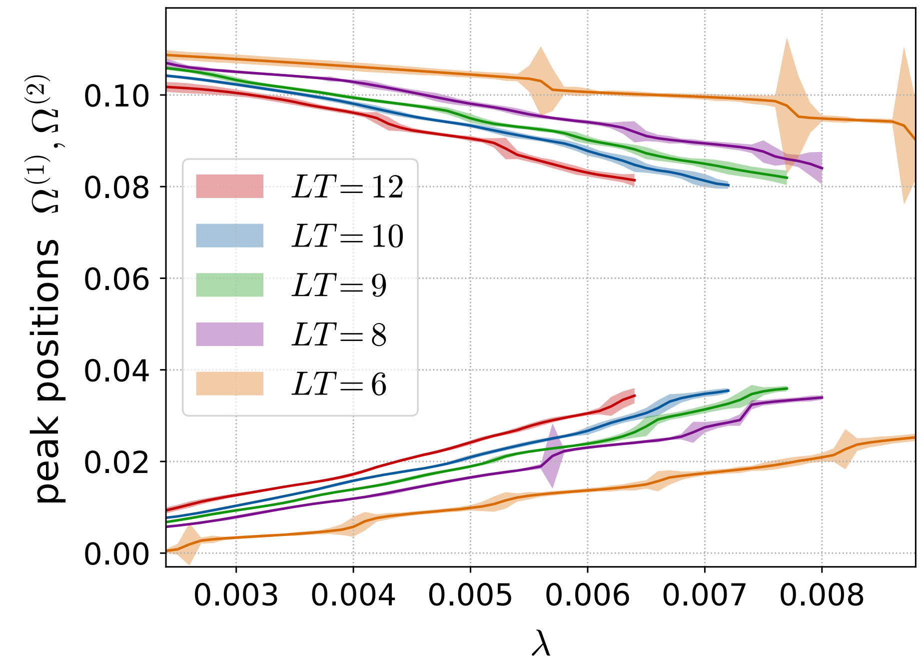
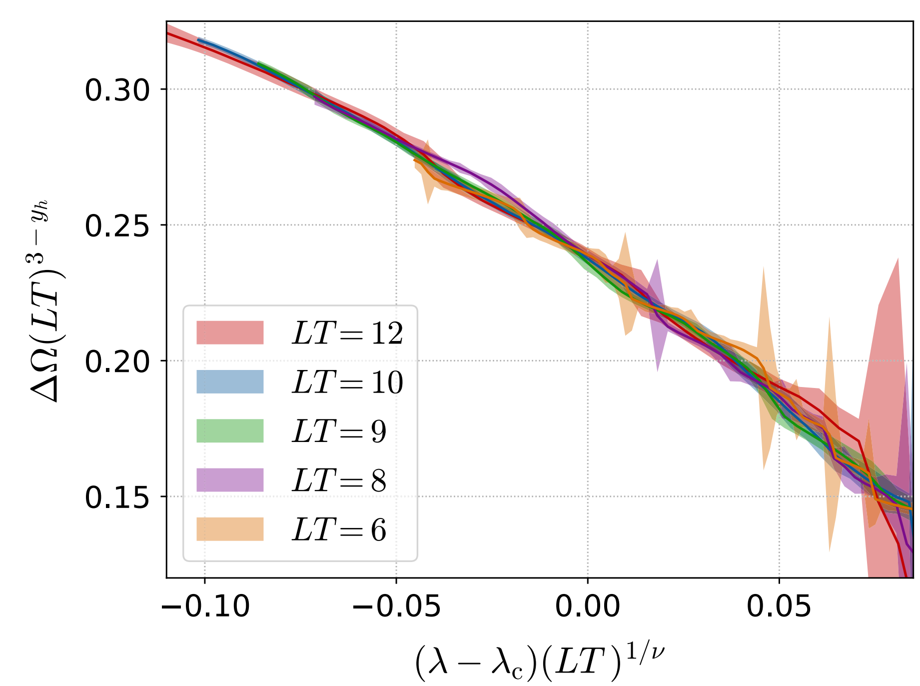


FIG. 13. Positions of peaks of the distribution function $p(\Omega_R)$ measured on the transition line.



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Wakabayashi, Ejiri, KK, Kitazawa (WHOT-QCD), *PTEP* (2022)

$W^0(4)$	288	$W^0(20)$	$1.54422361 \times 10^{14}$	$W^0(36)$	$-5.58410362 \times 10^{27}$
$W^0(6)$	8448	$W^0(22)$	$2.83682900 \times 10^{15}$	$W^0(38)$	$-2.91018925 \times 10^{29}$
$W^0(8)$	245952	$W^0(24)$	$-2.40028584 \times 10^{16}$	$W^0(40)$	$-1.50223497 \times 10^{31}$
$W^0(10)$	7372800	$W^0(26)$	$-6.88836562 \times 10^{18}$	$W^0(42)$	$-7.71380102 \times 10^{32}$
$W^0(12)$	225232896	$W^0(28)$	$-5.41133954 \times 10^{20}$	$W^0(44)$	$-3.95168998 \times 10^{34}$
$W^0(14)$	6906175488	$W^0(30)$	$-3.39122203 \times 10^{22}$	$W^0(46)$	$-2.02386871 \times 10^{36}$
$W^0(16)$	208431502848	$W^0(32)$	$-1.93668514 \times 10^{24}$	$W^0(48)$	$-1.03783044 \times 10^{38}$
$W^0(18)$	$6.00259179 \times 10^{12}$	$W^0(34)$	$-1.05424635 \times 10^{26}$	$W^0(50)$	$-5.33468075 \times 10^{39}$

$L_1^0(4, 4)$	48	$L_1^0(10, 10)$	1228.8	$L_1^0(18, 18)$	174762.67
$L_1^0(4, 6)$	1728	$L_1^0(10, 12)$	331776	$L_1^0(18, 20)$	160432128
$L_1^0(4, 8)$	45792	$L_1^0(10, 14)$	52862976	$L_1^0(18, 22)$	75497472000
$L_1^0(4, 10)$	645120	$L_1^0(10, 16)$	6258180096	$L_1^0(18, 24)$	2.36626×10^{13}
$L_1^0(4, 12)$	−26224128	$L_1^0(10, 18)$	5.99330×10^{11}	$L_1^0(18, 26)$	5.50232×10^{15}
$L_1^0(4, 14)$	−3201067008	$L_1^0(10, 20)$	4.87727×10^{13}	$L_1^0(18, 28)$	1.01809×10^{18}
$L_1^0(4, 16)$	-2.14087×10^{11}	$L_1^0(10, 22)$	3.47446×10^{15}	$L_1^0(18, 30)$	1.57315×10^{20}
$L_1^0(4, 18)$	-1.19007×10^{13}	$L_1^0(10, 24)$	2.20156×10^{17}	$L_1^0(20, 20)$	629145.6
$L_1^0(4, 20)$	-6.00757×10^{14}	$L_1^0(10, 26)$	1.24531×10^{19}	$L_1^0(20, 22)$	717225984
$L_1^0(4, 22)$	-2.84486×10^{16}	$L_1^0(10, 28)$	6.20798×10^{20}	$L_1^0(20, 24)$	4.11140×10^{11}
$L_1^0(4, 24)$	-1.28105×10^{18}	$L_1^0(10, 30)$	2.59861×10^{22}	$L_1^0(20, 26)$	1.54445×10^{14}
$L_1^0(4, 26)$	-5.50874×10^{19}	$L_1^0(12, 12)$	4096	$L_1^0(20, 28)$	4.24543×10^{16}
$L_1^0(4, 28)$	-2.25576×10^{21}	$L_1^0(12, 14)$	1622016	$L_1^0(20, 30)$	9.17892×10^{18}
$L_1^0(4, 30)$	-8.69402×10^{22}	$L_1^0(12, 16)$	360603648	$L_1^0(22, 22)$	2287802.18
$L_1^0(6, 6)$	128	$L_1^0(12, 18)$	57416810496	$L_1^0(22, 24)$	3170893824
$L_1^0(6, 8)$	11520	$L_1^0(12, 20)$	7.19497×10^{12}	$L_1^0(22, 26)$	2.17478×10^{12}
$L_1^0(6, 10)$	716544	$L_1^0(12, 22)$	7.51820×10^{14}	$L_1^0(22, 28)$	9.64167×10^{14}
$L_1^0(6, 12)$	35891712	$L_1^0(12, 24)$	6.80443×10^{16}	$L_1^0(22, 30)$	3.09123×10^{17}
$L_1^0(6, 14)$	1464910848	$L_1^0(12, 26)$	5.46987×10^{18}	$L_1^0(24, 24)$	8388608
$L_1^0(6, 16)$	43817011200	$L_1^0(12, 28)$	3.96931×10^{20}	$L_1^0(24, 26)$	13891534848
$L_1^0(6, 18)$	3.17933×10^{11}	$L_1^0(12, 30)$	2.62442×10^{22}	$L_1^0(24, 28)$	1.12307×10^{13}
$L_1^0(6, 20)$	8.54676×10^{13}	$L_1^0(14, 14)$	14043.43	$L_1^0(24, 30)$	5.80075×10^{15}

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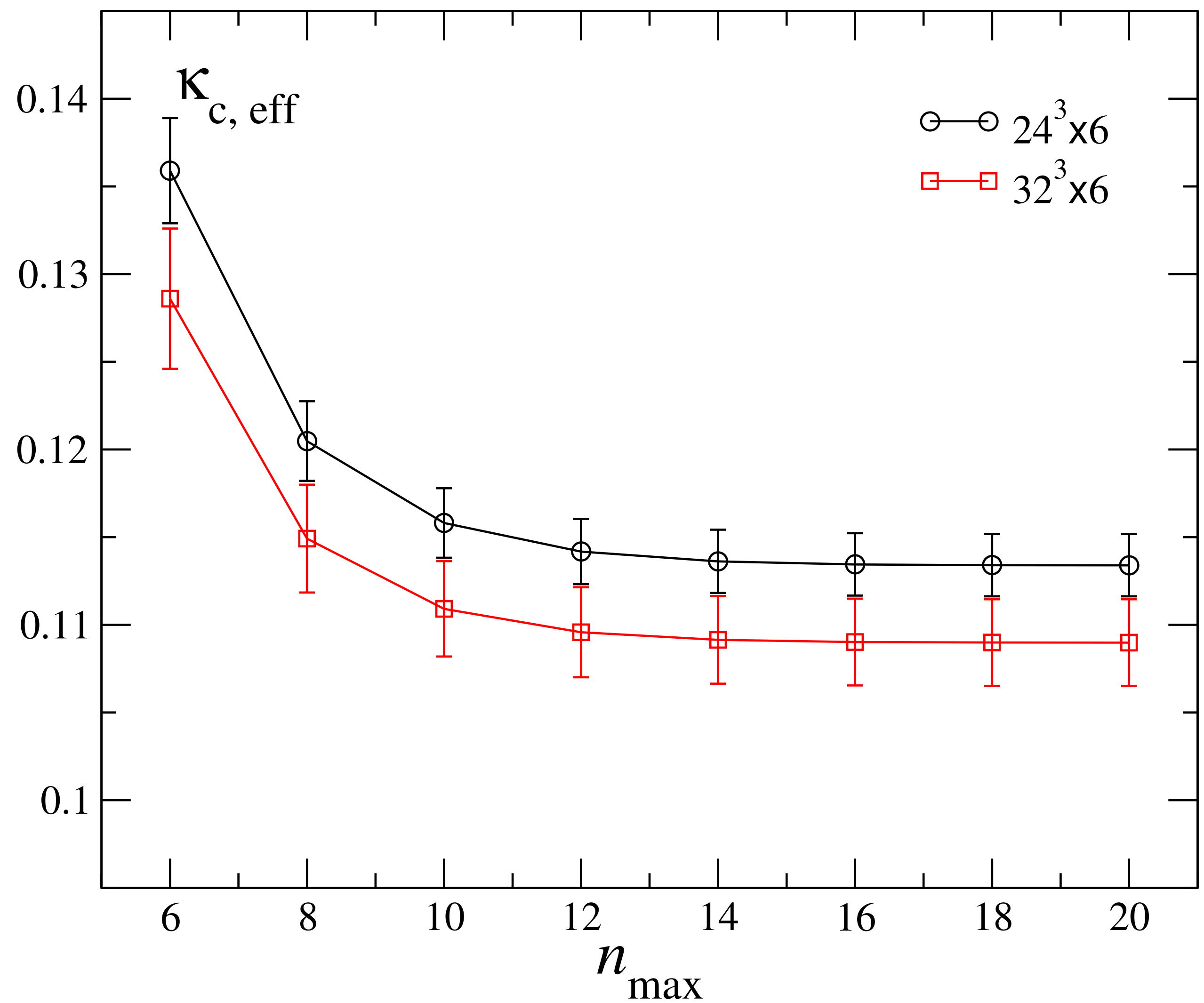

Fig. 11. Effective critical point $\kappa_{\rm c,\,eff}$ in two-flavor QCD for $N_t = 6$ as a function of $n_{\rm max}$. The black circle and red square symbols are for $\kappa_{\rm c,\,LO}$ obtained on a $24^3 \times 6$ and a $32^3 \times 6$ lattice, respectively.

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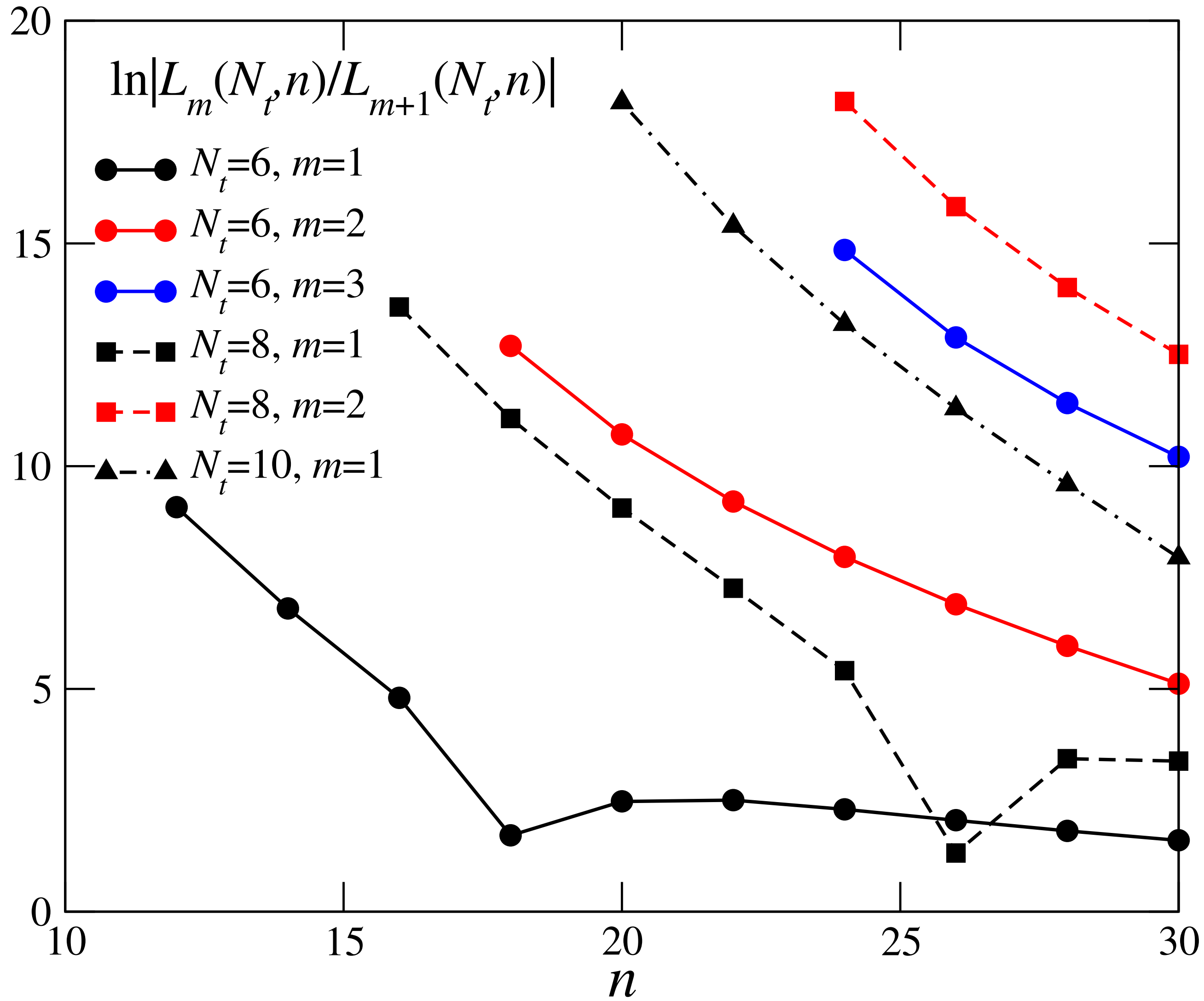

Fig. 14. Upper bound of μ/T such that higher-m terms are small, as given in Eq. (71).

$$\frac{\mu}{T} < \ln\left|\frac{L^0_m(N_t, n)}{L^0_{m+1}(N_t, n)}\right|$$