Critical endline of the finite temperature phase transition for 2+1 flavor QCD away from the SU(3)-flavor symmetric point

Yoshifumi Nakamura
RIKEN Advanced Institute for Computational Science

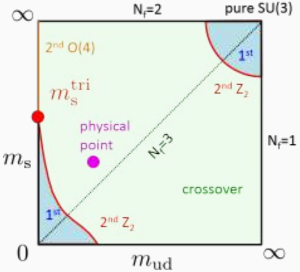
in collaboration with
Y. Kuramashi & S. Takeda

20 Jun. 2017

Lattice 2017 in Granada

Columbia plot

nature of finite temperature phase transition of 2+1 flavor QCD at $\mu = 0$ in the plane of $m_{u,d}$ and m_s

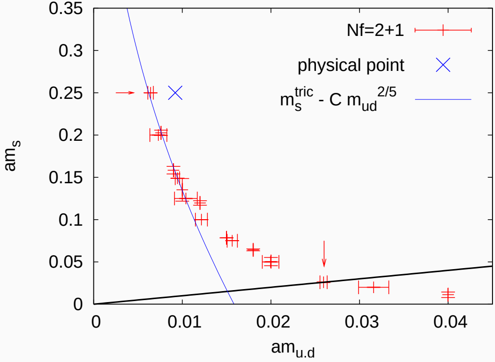


- 1st order : small m_q region [Pisarski, Wilczek, '84]
- 1st order : heavy m_q region
- crossover : medium m_q
- 2nd order (Z_2) : boundary between 1st and crossover

At small m_q region

- critical end point at SU(3) flavor symmetric point, m^{sym}, has not been determined yet [S. Takeda's talk]
- crossover at the physical point [many lattice results]
- critical end line has not been well determined yet

Previous study for critical end line



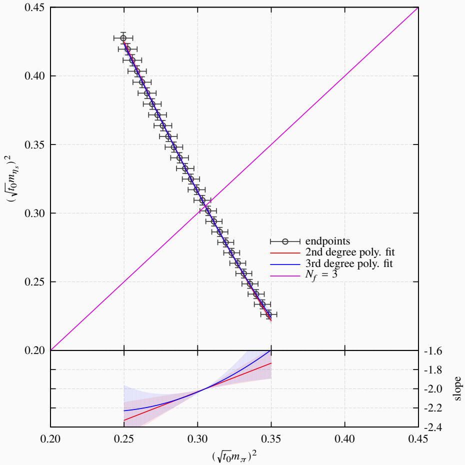
[de Forcrand, Philipsen, '06]

- staggered fermions
- $N_t = 4$, $a \approx 0.3$ fm
- data exhibits that slope at m^{sym} is not - 2
- $am_s^{crit} \approx 0.7$ (roughly **5** times larger than m_s^{phy})

Our recent study for critical end line

[Kuramashi et at., '16]

around $\boldsymbol{m}^{\mathrm{sym}}$

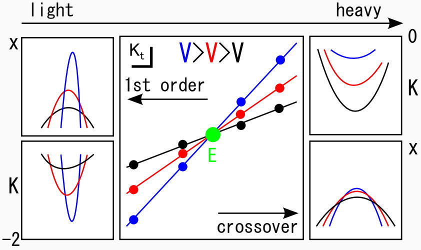


- Wilson-clover fermion
- $\boldsymbol{N_t = 6}$
- $\boldsymbol{a \approx 0.19}$ fm
- we confirmed that slope at $\boldsymbol{m}^{\mathrm{sym}}$ is - 2

We shall extend our study for critical end line away form $\boldsymbol{m}^{\mathrm{sym}}$

Simulations(1/2)

- Iwasaki gauge + NP O(a) improved Wilson fermions
- chiral condensate (10 - 20 noises for $\mathrm{Tr}D^{-1,-2.-3,-4}$)
- kurtosis intersection method to determine the critical endpoint
- reweighting method to obtain more critical endpoints
- $N_t = 6$ ($a \approx 0.19$fm)
- $N_l = 10, 12, 16, 20, 24$



symmetric runs

β	κ
1.715	0.140900 – 0.141100
1.73	0.140420 – 0.140450
1.75	0.139620 – 0.139700

Simulations(2/2)

- very heavy m_s runs

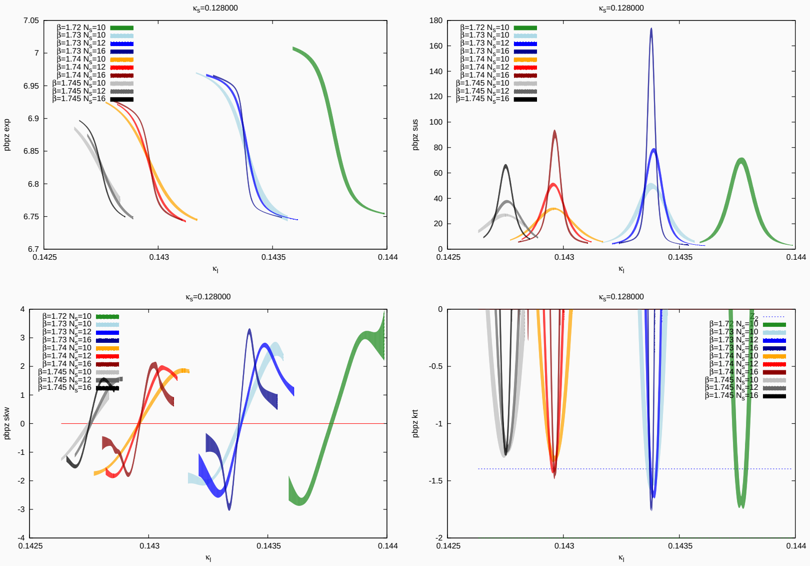
β	κ_l	κ_s
1.72	0.143788	0.128000
1.73	0.143365 – 0.143410	0.128000
1.74	0.142955 – 0.143042	0.128000

- heavy m_s runs

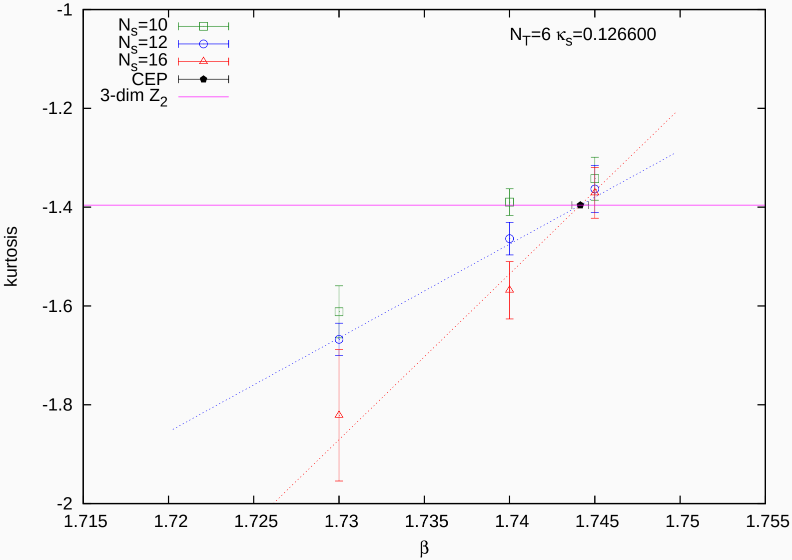
β	κ_l	κ_s
1.72	0.143455	0.132100
1.72	0.143160	0.132800
1.73	0.142702, 0.142750	0.132800
1.74	0.142955 – 0.143042	0.132800

- O(100) zero temperature runs at $\beta = \mathbf{1.72, 1.73, 1.74}$ for physical scale setting are covering almost critical endpoints and also transition points of finite temperature simulations

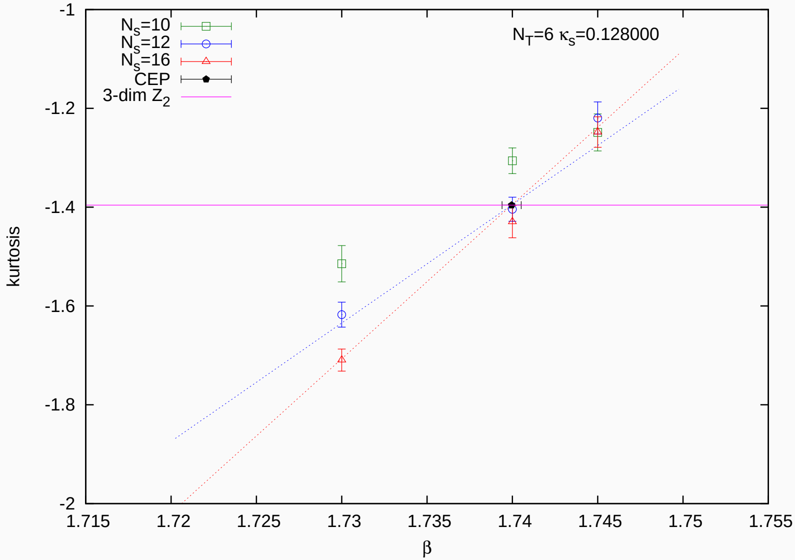
Expectation, susceptibility, skewness and kurtosis (example)



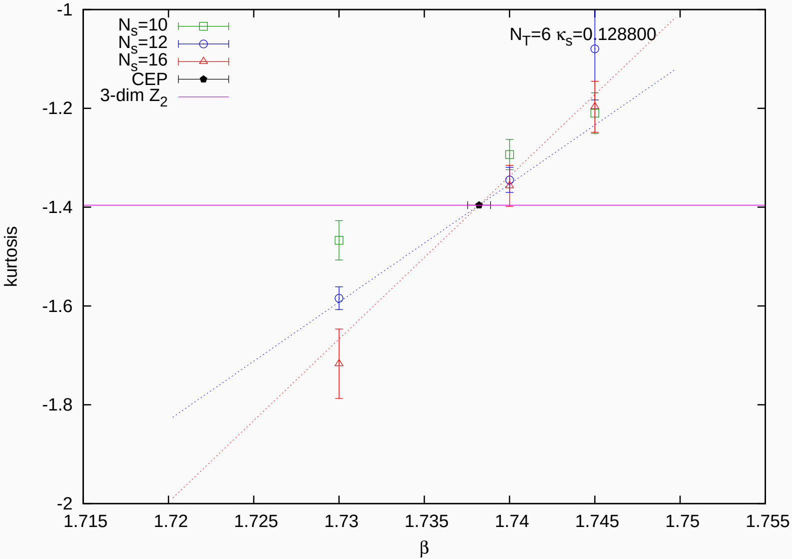
Kurtosis intersection plot 1



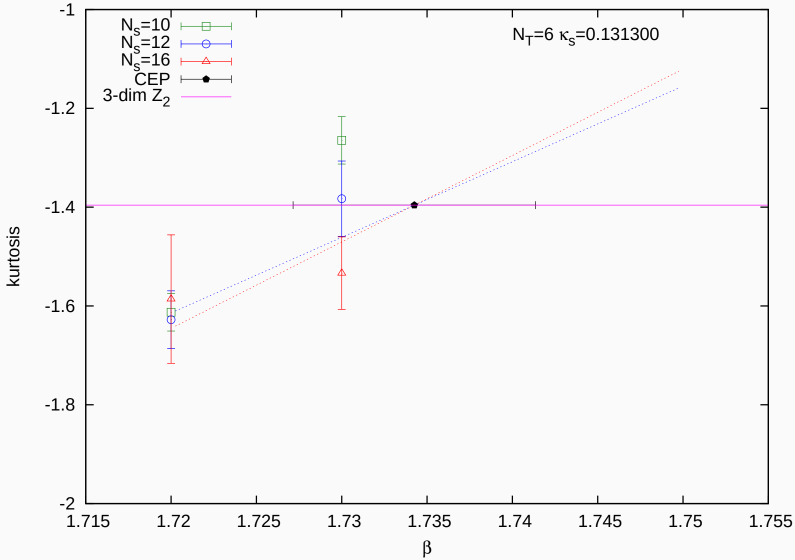
Kurtosis intersection plot 2



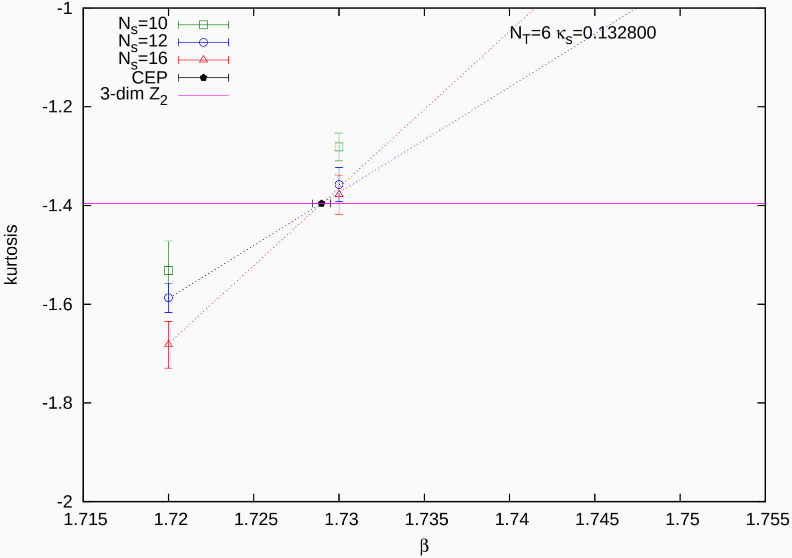
Kurtosis intersection plot 3



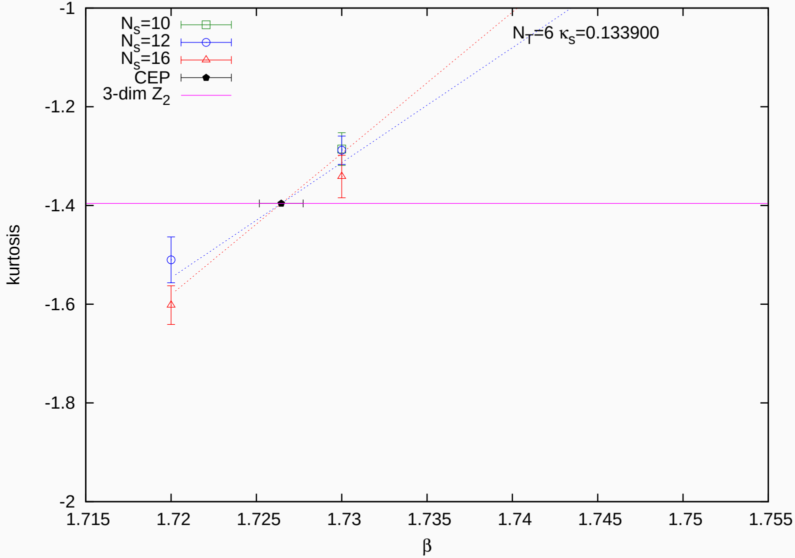
Kurtosis intersection plot 4



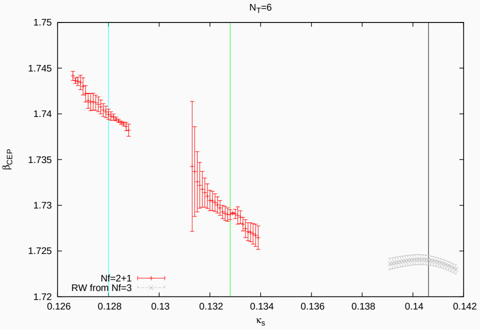
Kurtosis intersection plot 5

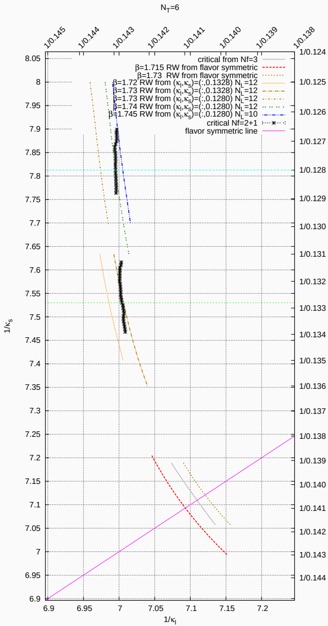


Kurtosis intersection plot 6

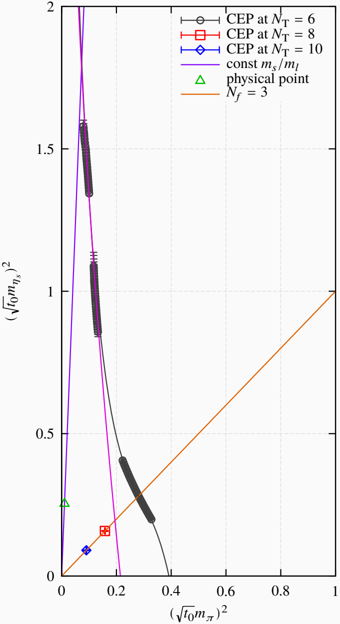


Critical endpoints in bare parameter plane





Critical endline at $N_t = 6$



$$m_s - m_s^{\text{tric}} \sim m_l^{2/5}$$

[Rajagopal '95]

Fitting endpoints

$x = (\sqrt{t_0} m_{\pi,\text{E}})^2 \propto m_l$

$y = (\sqrt{t_0} m_{\eta_s,\text{E}})^2 \propto m_s$

Fit 1 [all range]

$y = a_0 + a_1 x^{2/5} + a_2 x^2 + a_3 x^3$

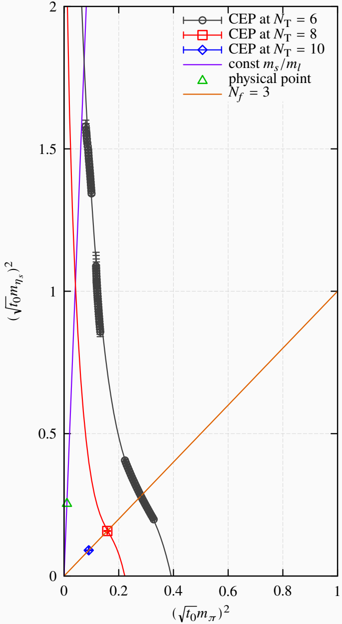
$\chi^2/\text{dof} = 2.32$

Fit 2 [$x < 0.15$]

$y = b_0 + b_1 x^{2/5}$

$\chi^2/\text{dof} = 2.02$

Critical endline at $N_t = 6, 8$



assuming same shape for CEL at $N_t = 8$ as at $N_t = 6$

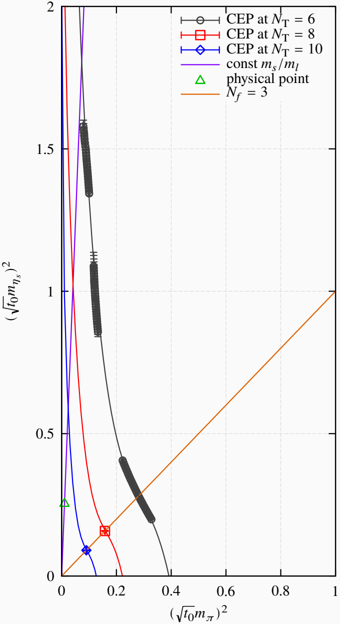
$\rightarrow$

scaling $\sqrt{t_0} m_{\pi,\mathrm{E},6}$ and $\sqrt{t_0} m_{\eta_s,\mathrm{E},6}$ by $\sqrt{t_0} m^{\mathrm{sym}}_{\mathrm{PS,E},8} / \sqrt{t_0} m^{\mathrm{sym}}_{\mathrm{PS,E},6}$

Fit : $a_0 + a_1 x^{2/5} + a_2 x^2 + a_3 x^3$

χ^2/dof =2.32

Critical endline at $N_t = 6, 8, 10$



assuming same shape for CEL at $N_t = 10$ as at $N_t = 6$

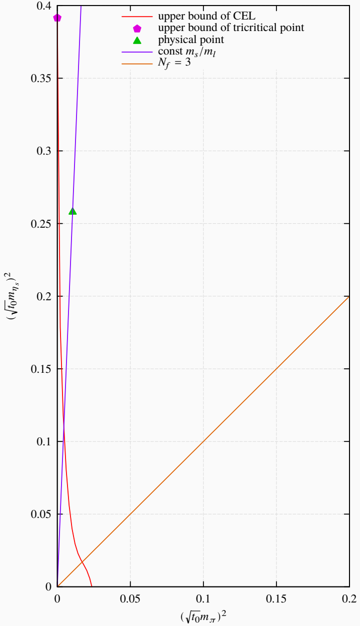
$\rightarrow$

scaling $\sqrt{t_0} m_{\pi,\mathrm{E},6}$ and $\sqrt{t_0} m_{\eta_s,\mathrm{E},6}$ by $\sqrt{t_0} m^{\mathrm{sym}}_{\mathrm{PS,E},10} / \sqrt{t_0} m^{\mathrm{sym}}_{\mathrm{PS,E},6}$

Fit : $a_0 + a_1 x^{2/5} + a_2 x^2 + a_3 x^3$

χ^2/dof =2.32

Critical endline at $N_t = \infty$ (estimated upper bound)



assuming same shape for CEL in the continuum limit as at $N_t = 6$
$\rightarrow$
scaling $\sqrt{t_0}m_{\pi,\mathrm{E},6}$ and $\sqrt{t_0}m_{\eta_s,\mathrm{E},6}$ by $\sqrt{t_0}m^{\mathrm{sym}}_{\mathrm{PS,E},\infty}$ / $\sqrt{t_0}m^{\mathrm{sym}}_{\mathrm{PS,E},6}$

we have only determined upper bound of $\sqrt{t_0}m^{\mathrm{sym}}_{\mathrm{PS,E}}$ in the continuum limit [S. Takeda's talk]

Fit : $a_0 + a_1 x^{2/5} + a_2 x^2 + a_3 x^3$
χ^2/dof =2.32

Summary

We have determined the critical endline away from the SU(3)-flavor symmetric point at $N_t = 6$ with NP O(a) improved Wilson fermions and presented preliminary results for the critical end lines at $N_t = 8, 10$ and in the continuum limit

We find

- 3 series of multi-ensemble, multi-parameter re-weighting determines well the critical end line
- critical end line at $N_t = 6$ is nice agreement with $m_s - m_s^{tri} \sim m_l^{2/5}$ in small m_l region
- $m_s^{tri} < 1.52\, m_s^{phy}$ (very preliminary!!)

Future plans

- larger N_t for the continuum limit