# Phase structure of Nf=3 QCD at finite temperature and density by Wilson-Clover fermions

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in collaboration with
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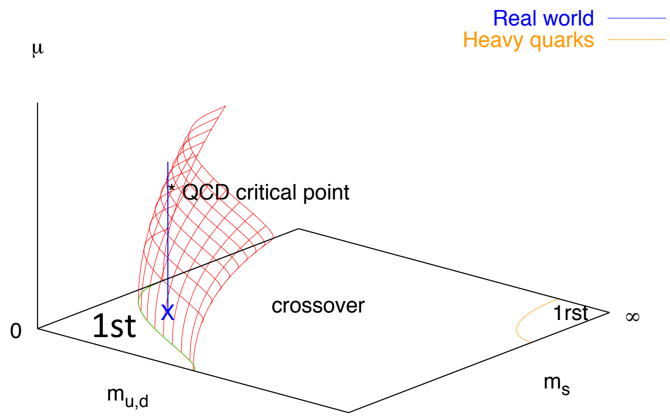
Lattice 2015 in Kobe

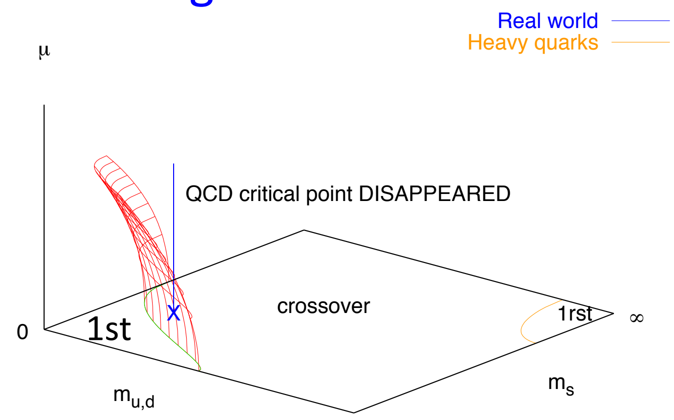
# Goal

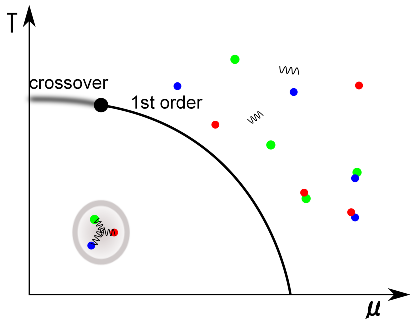
Curvature of critical line (surface) in μ-m plane is +/-?

Positive: Conventional scenario




Negative: Exotic scenario




$$\frac{m_c(\mu)}{m_c(0)} = 1 - 0.7(4) \left(\frac{\mu}{\pi T}\right)^2$$

de Forcrand & Philipsen 2007

For Nf=3

# Goal

Curvature of critical line (surface) in μ-m plane is +/-?

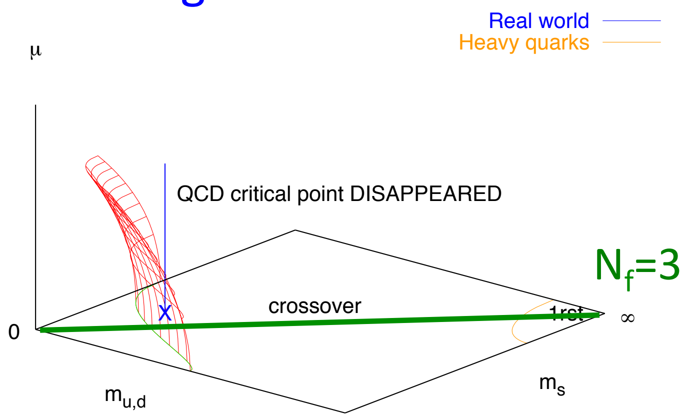
de Forcrand & Philipsen 2007

- Staggered fermions
- Imaginary chemical potential
- at finite lattice spacing: $N_t$=4

OURS

- Wilson-clover fermions
- Phase-reweighting
- at finite lattice spacing: $N_t$=6

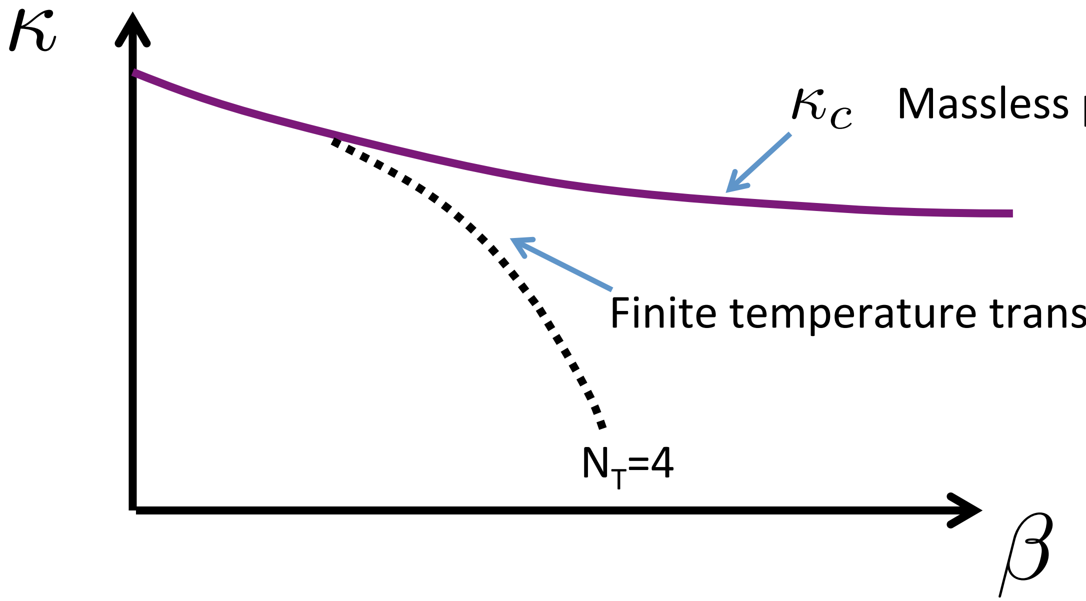
Negative: Exotic scenario



# Strategy

$N_f$=3

$a\mu$=0



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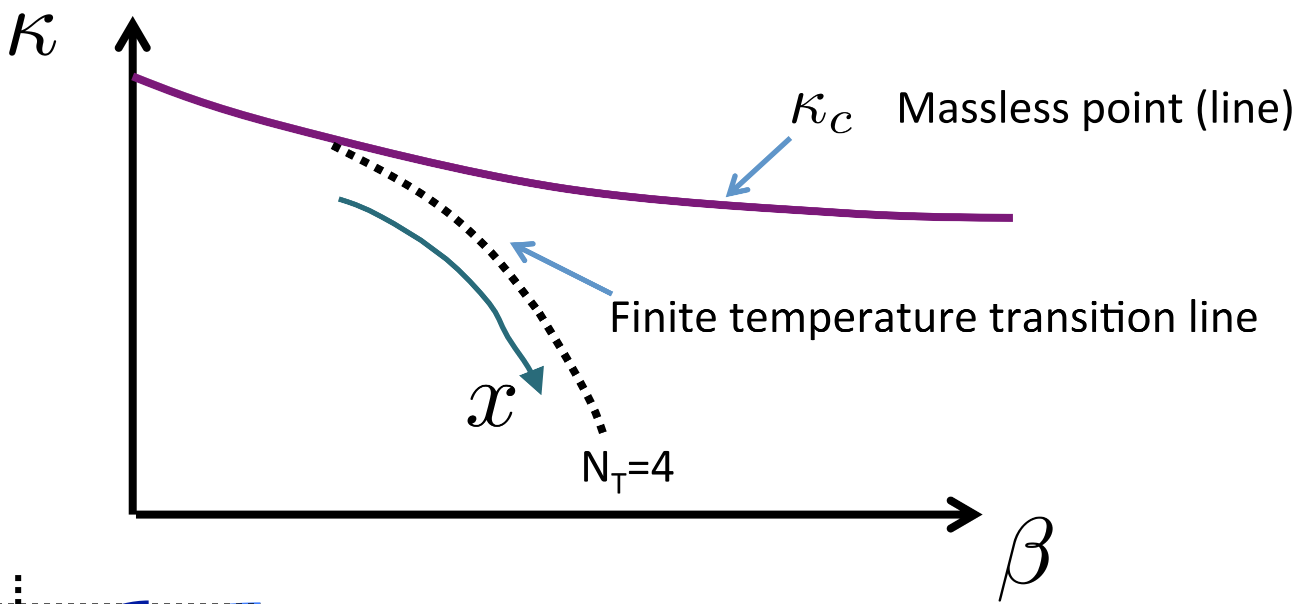
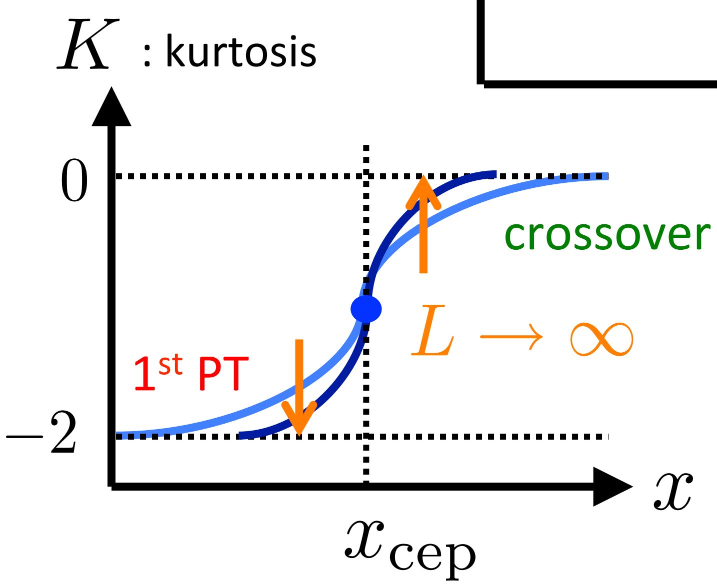


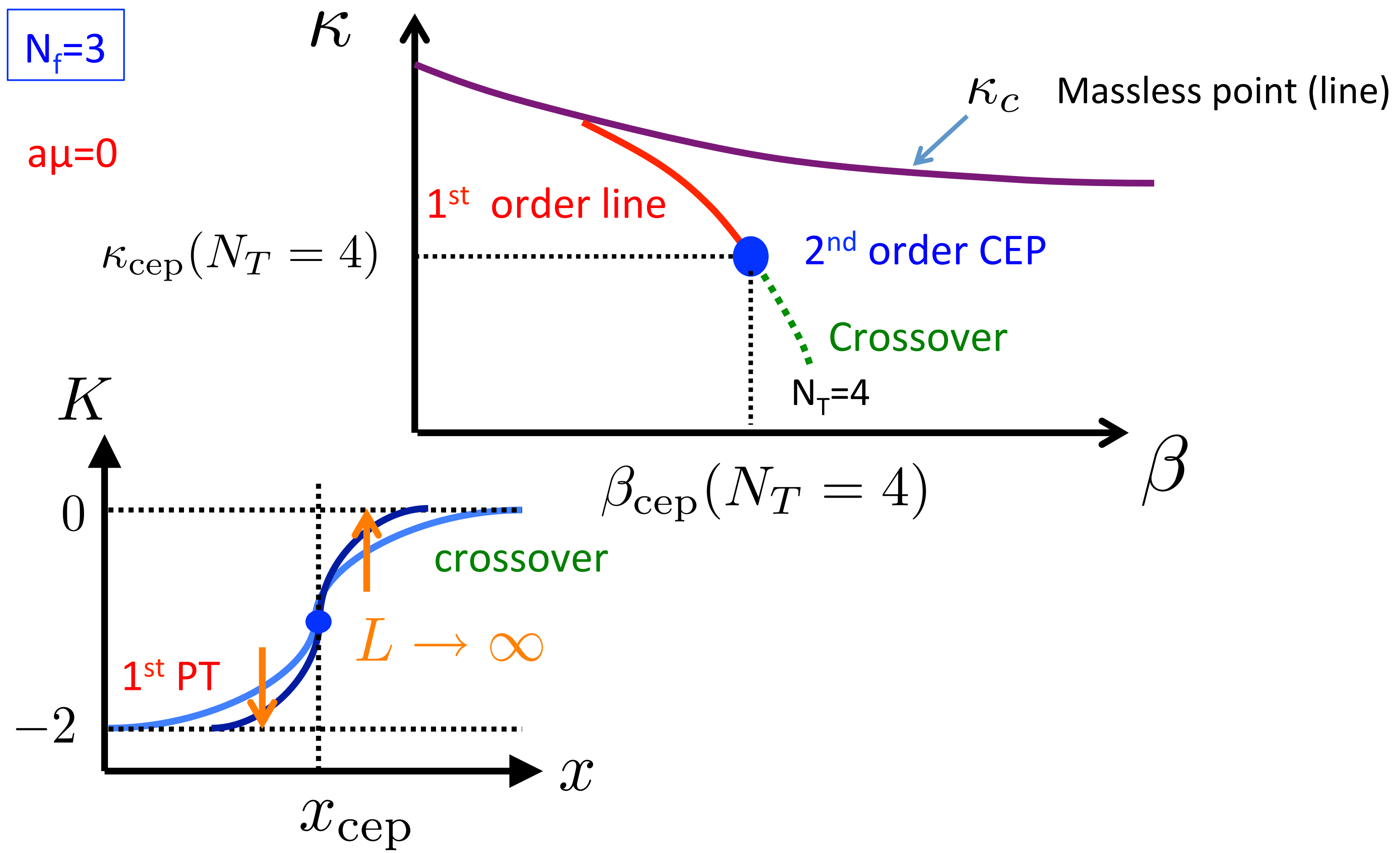




$B_4$: Binder cumulant

$$K = \frac{\langle (O - \langle O \rangle)^4 \rangle}{\langle (O - \langle O \rangle)^2 \rangle^2} - 3$$

Karsch et al. 2001

# Strategy

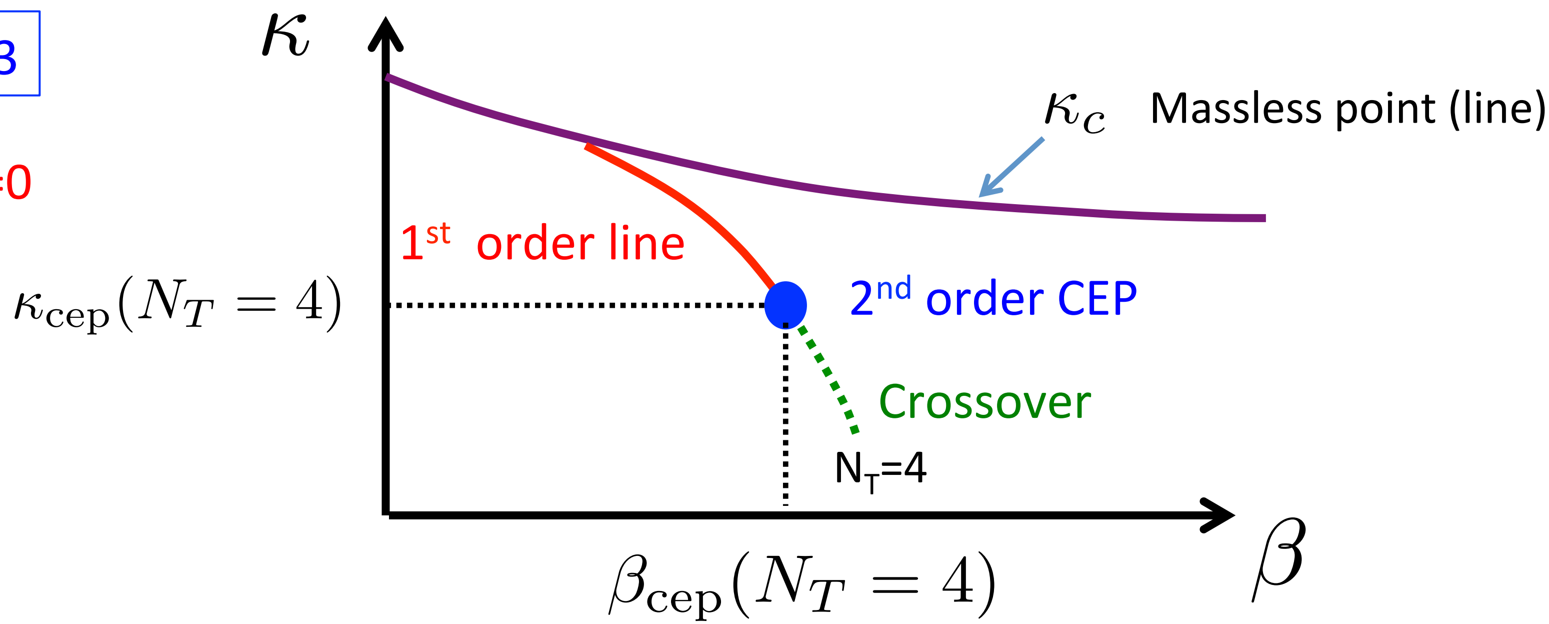


N_f=3
aμ=0
κ
κ_c
Massless point (line)
1st order line
κ_cep(N_T = 4)
2nd order CEP
Crossover
N_T=4
β
β_cep(N_T = 4)
K
0
−2
crossover
L → ∞
1st PT
x
x_cep

# Strategy

$N_f=3$

$a\mu=0$

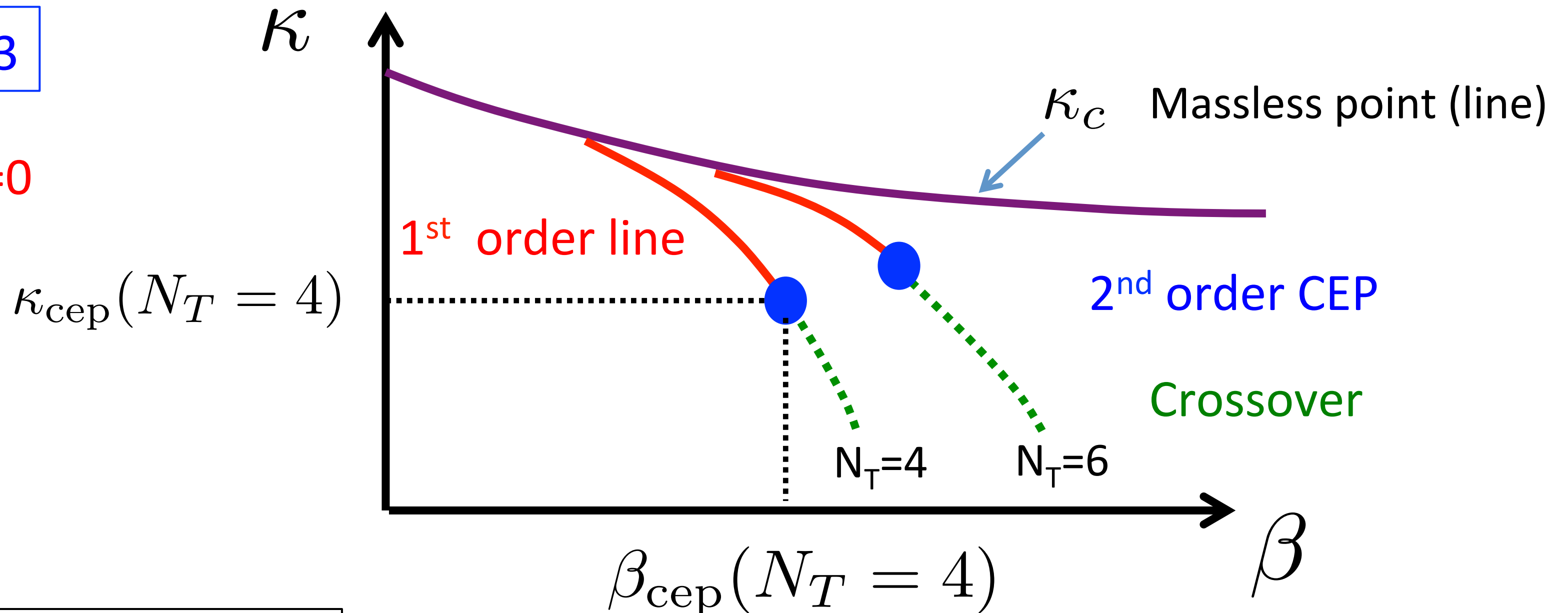



$$\left.\frac{m_{\rm PS}}{m_{\rm V}}\right|_{\kappa_{\rm cep}(N_{\rm T}),\beta_{\rm cep}(N_{\rm T})}$$

# Strategy

$N_f$=3

aμ=0



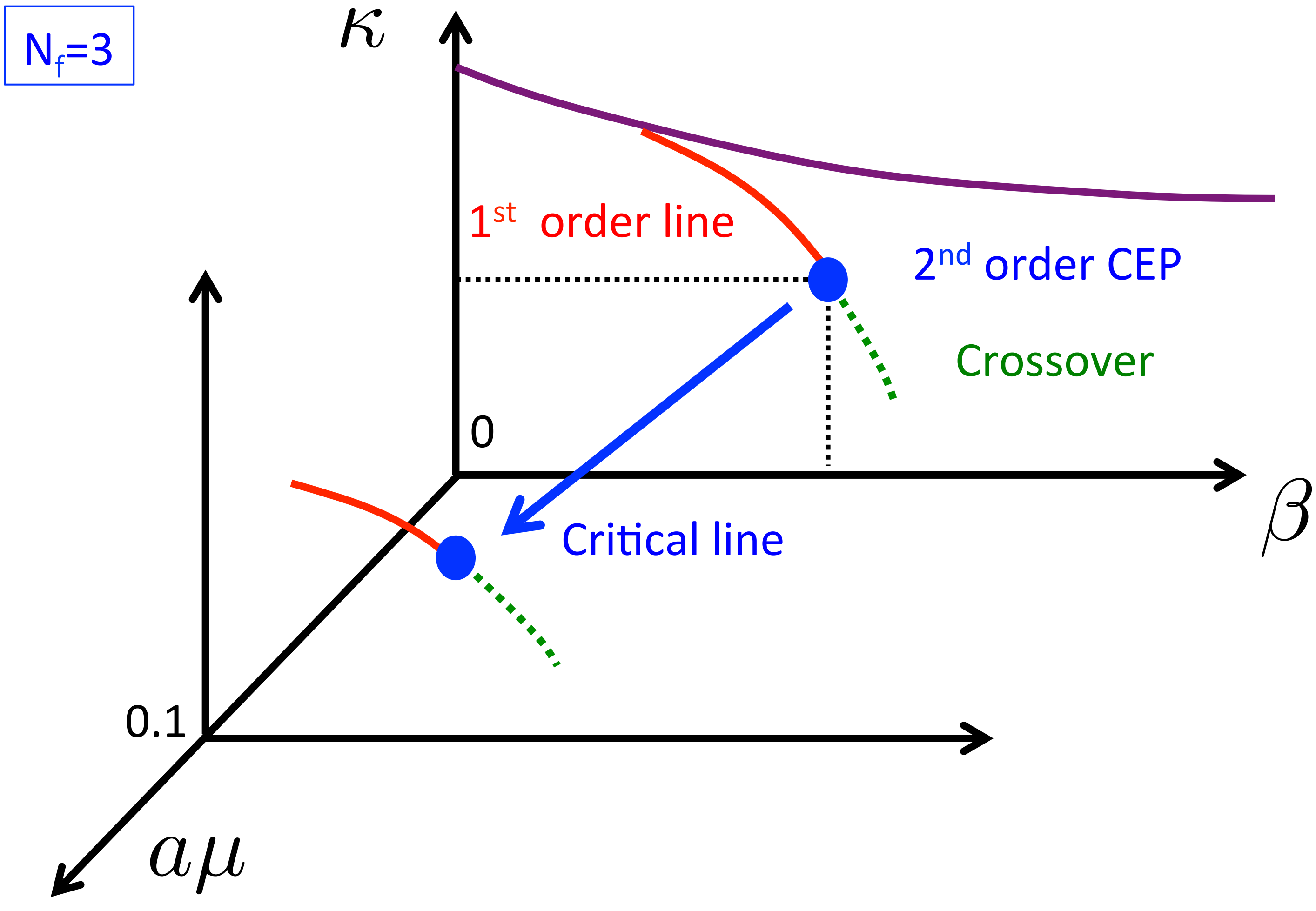

Continuum limit

$$\lim_{N_{\rm T}\to\infty} \frac{m_{\rm PS}}{m_{\rm V}}\bigg|_{\kappa_{\rm cep}(N_{\rm T}),\beta_{\rm cep}(N_{\rm T})}$$

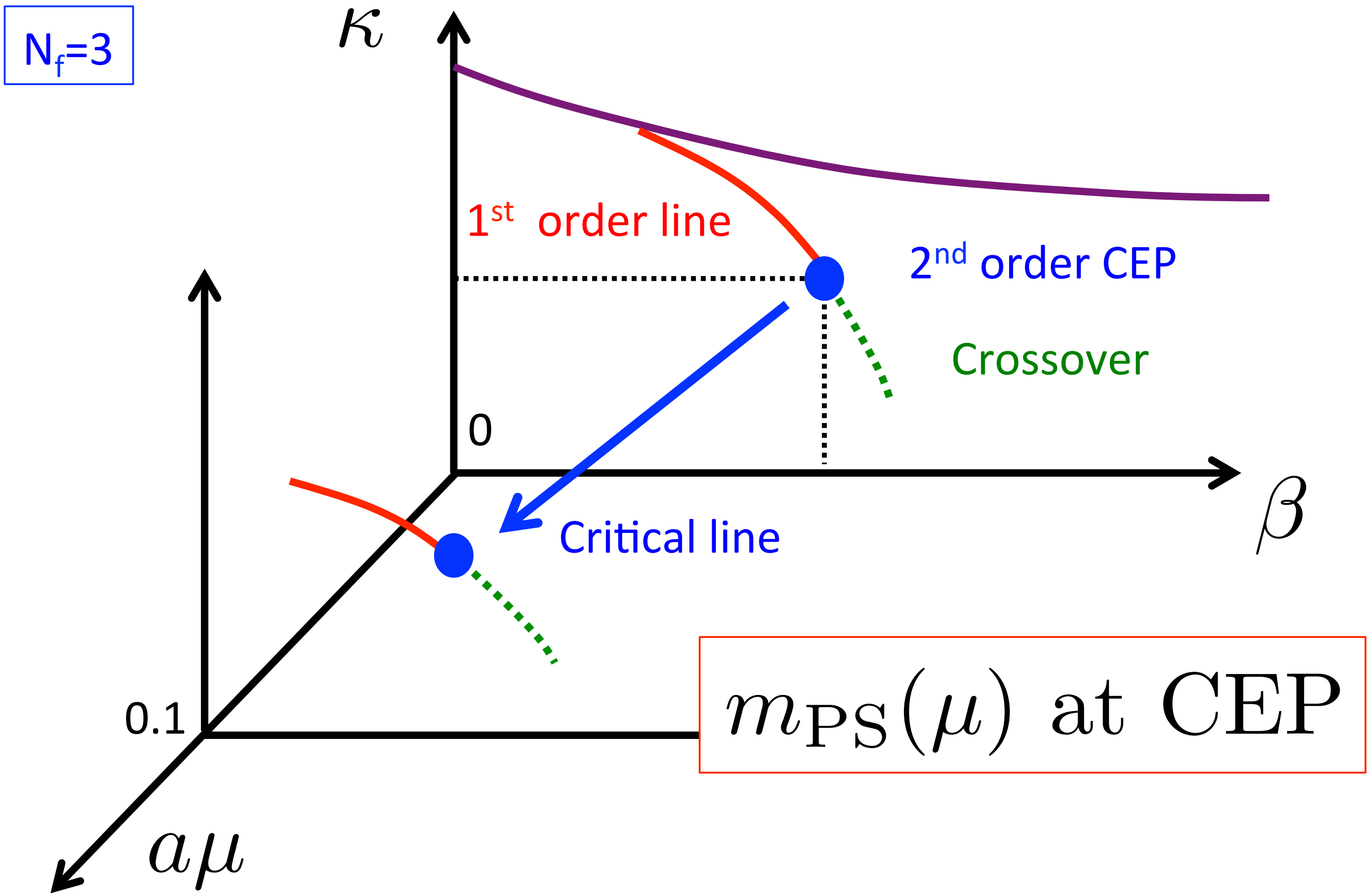
Nakamura-san's talk
PRD91,014508(2015)

$$1/N_{\rm T} = aT_{\rm cep}$$

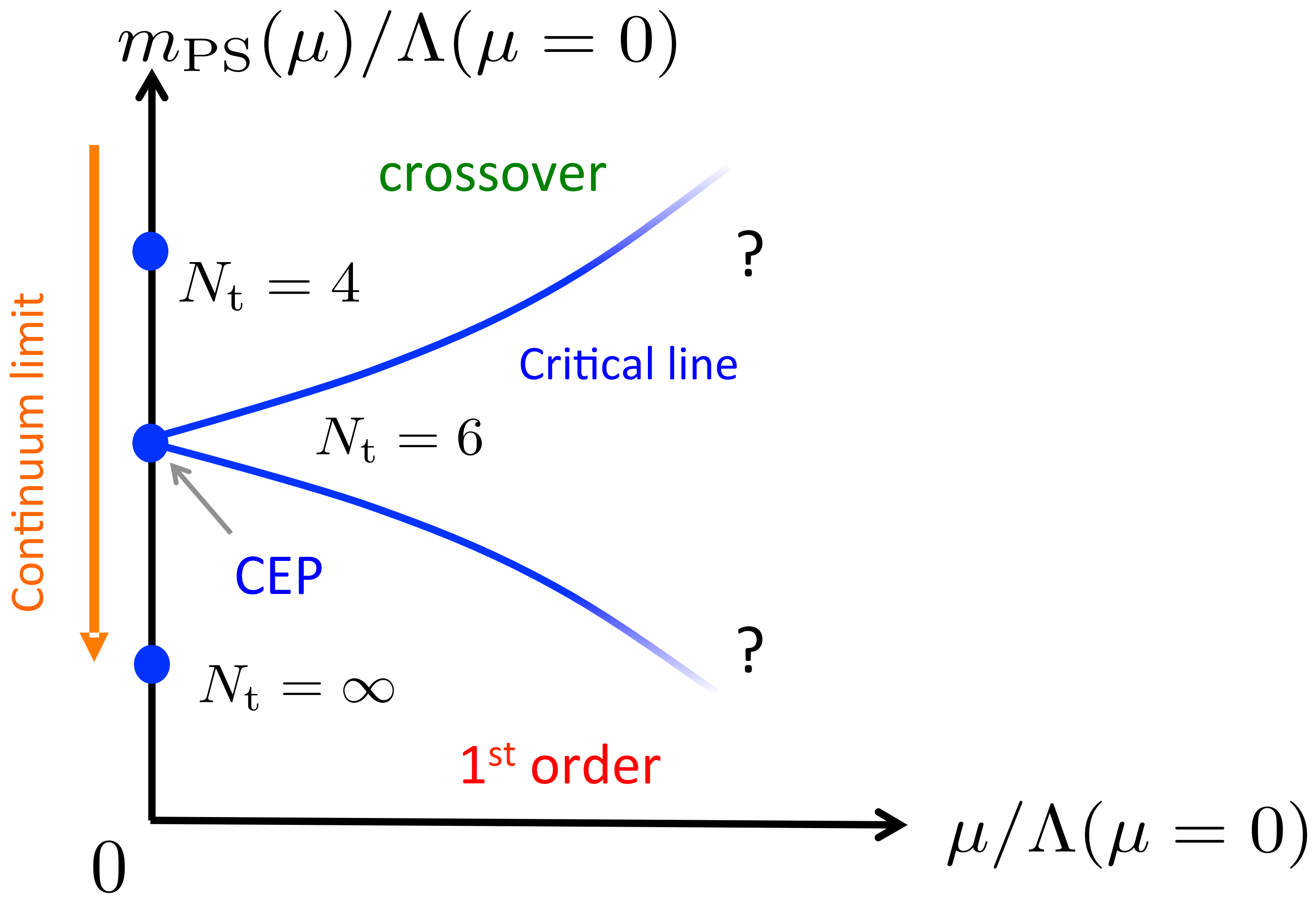
# For finite density



# For finite density



# Critical line in μ-$m_\pi$ plane



# Simulation details

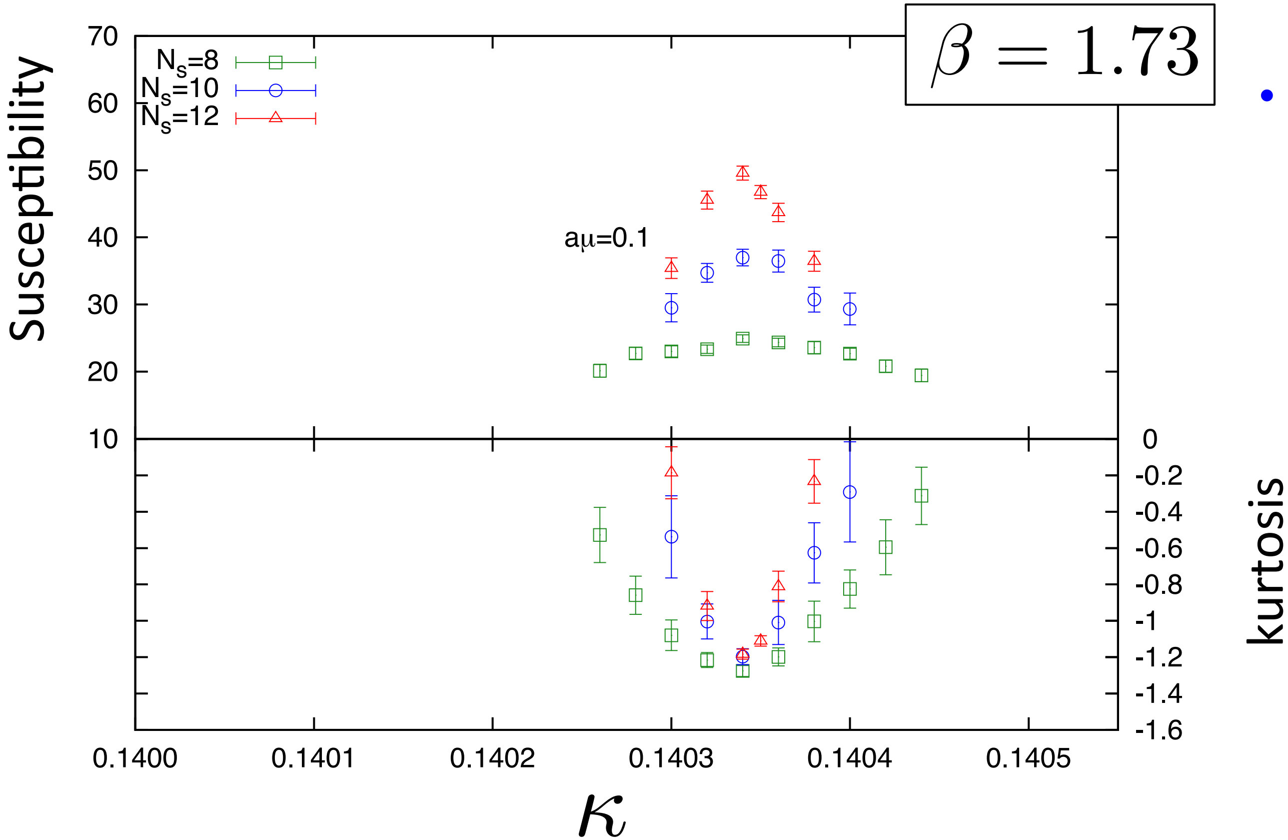
- Nf=3 Clover with NP $c_{sw}$ + Iwasaki gauge
- Phase reweighting
  - Evaluate phase exactly
  - Det. is computed by using reduction method together with LAPACK/GPGPU

$$\langle \mathcal{O} \rangle = \frac{\langle \mathcal{O} e^{iN_{\mathrm{f}}\theta} \rangle_{||}}{\langle e^{iN_{\mathrm{f}}\theta} \rangle_{||}}$$

Gattringer 2010, Takeda et al., 2012

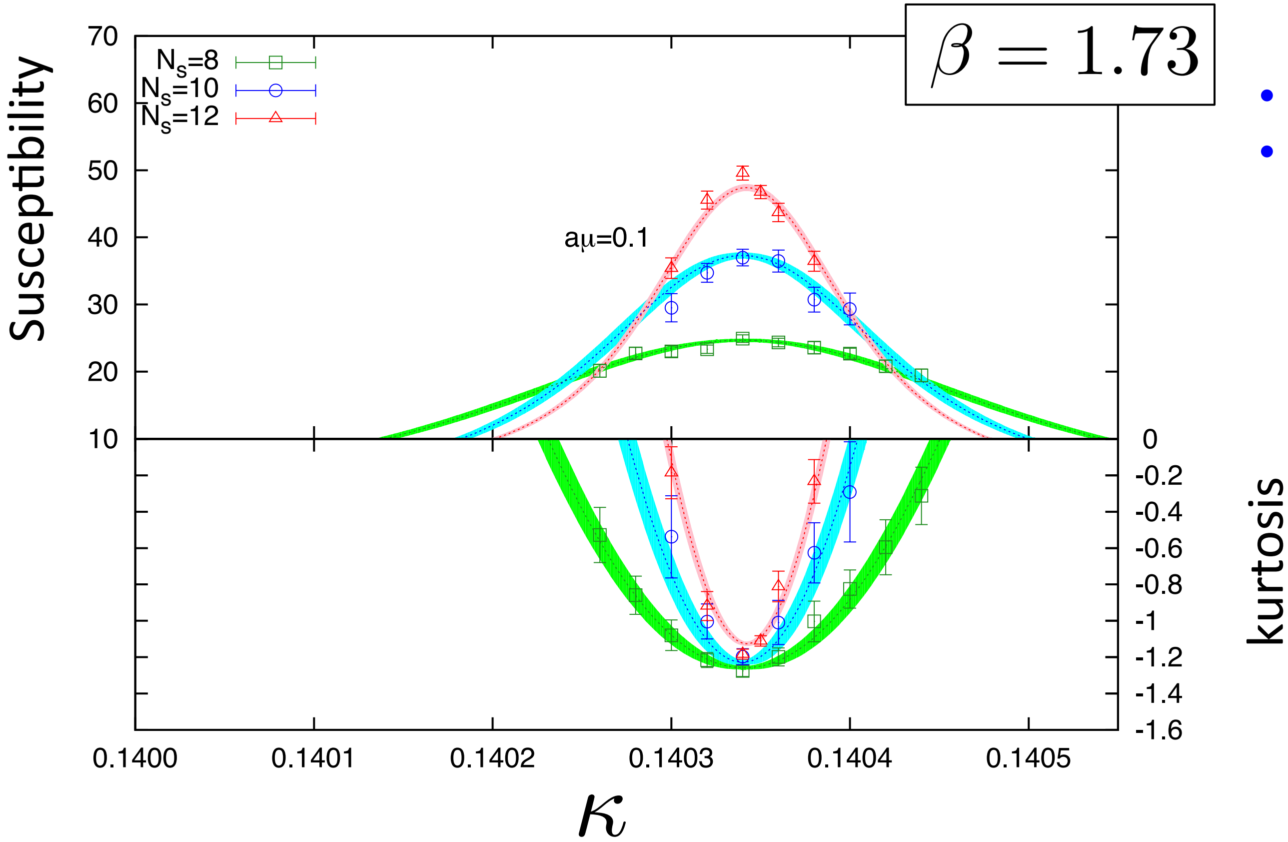
- Parameters:
  - $N_T$=6 & aμ=0.1 ⇒ μ/T=0.6
  - V=$8^3$, $10^3$, $12^3$
  - β=1.70-1.77, κ=0.1386-0.1415
  - configurations = O(10k) for each parameter set

# Cumulant of chiral condensate



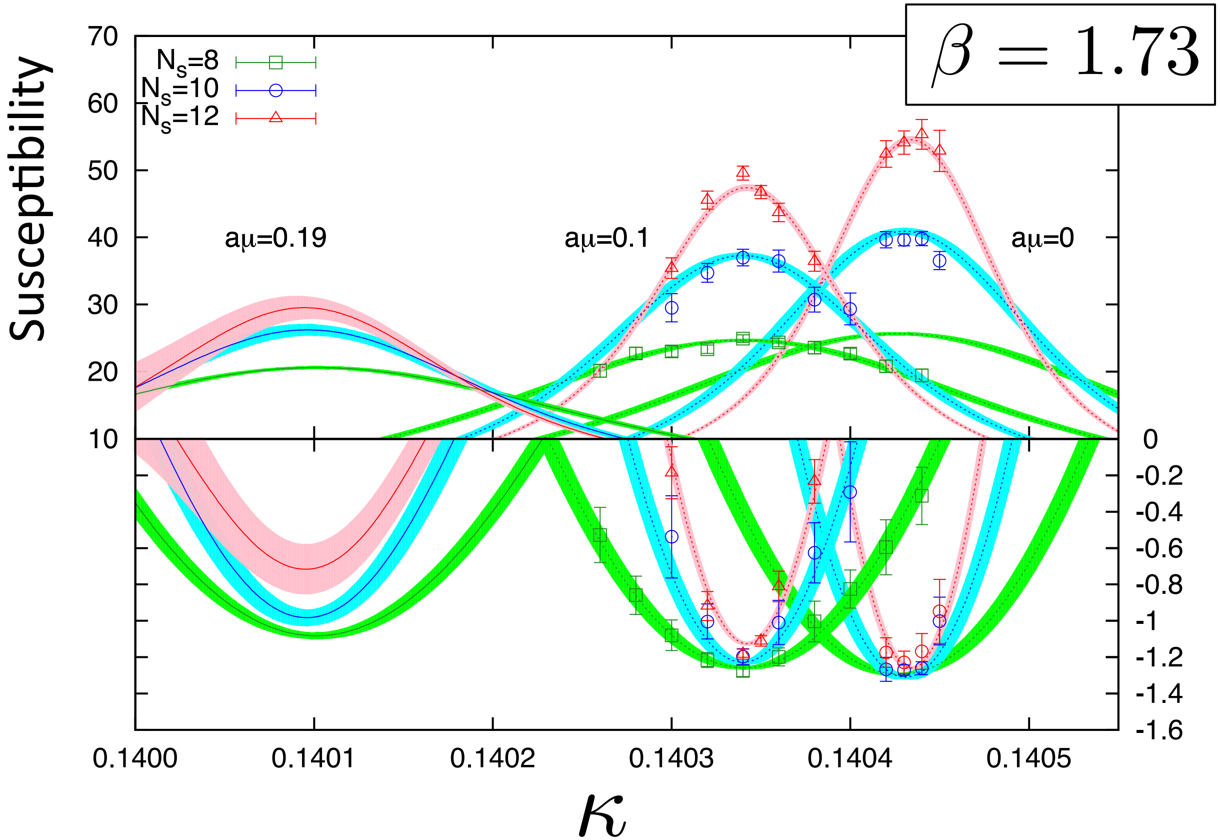

- phase RW

# Cumulant of chiral condensate



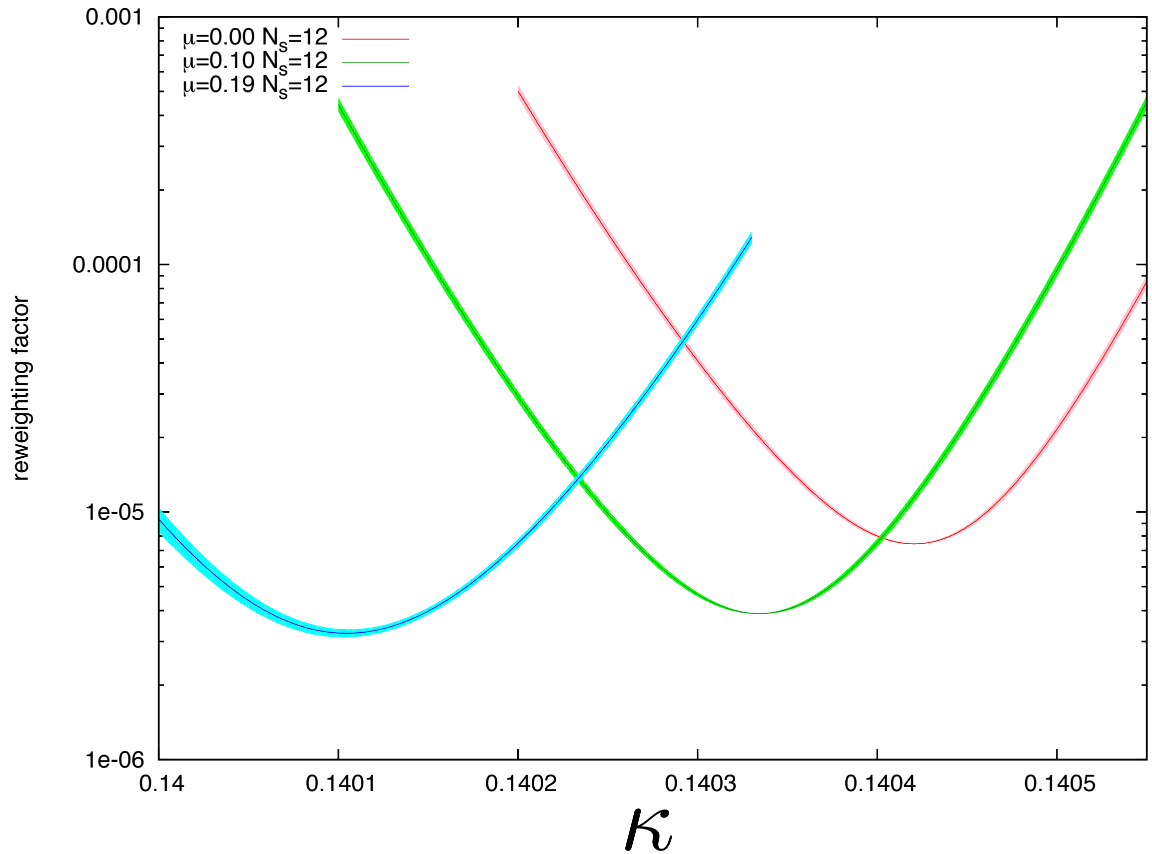

- phase RW
- multi-ensemble RW

# Cumulants of chiral condensate




- phase RW
- multi-ensemble RW
- multi-parameter RW
  κ & μ

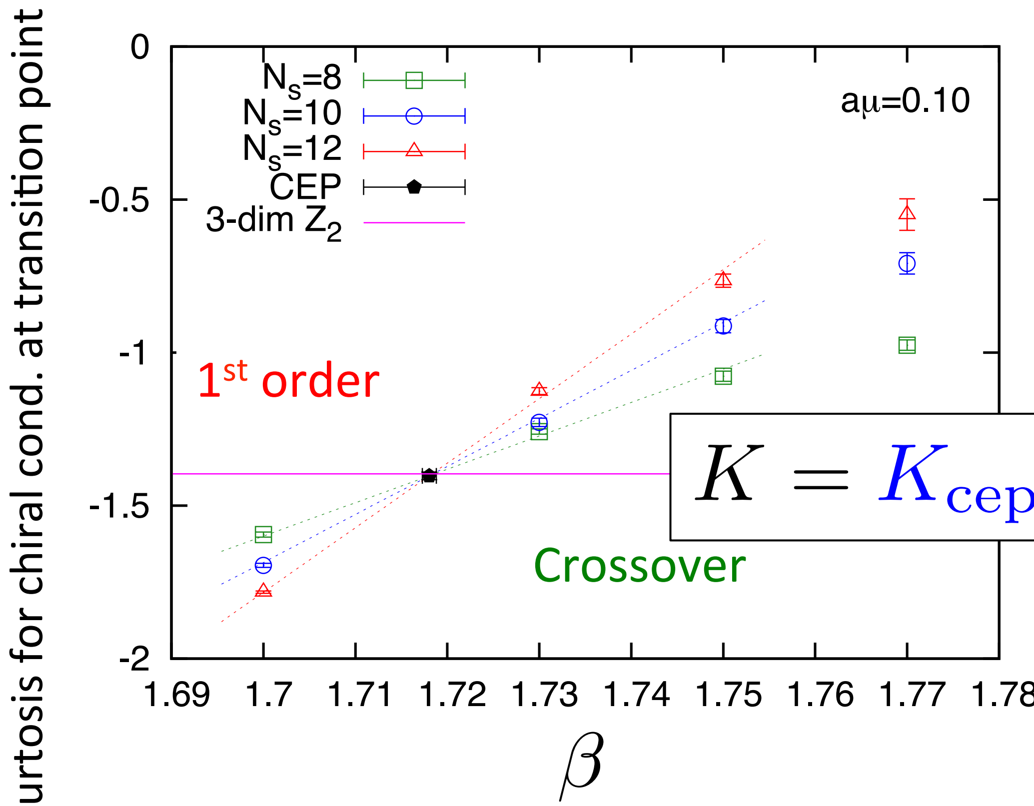
# Re-weighting factor

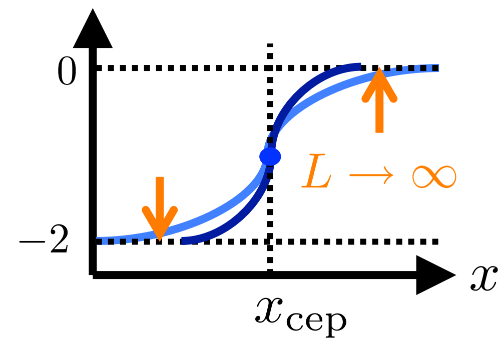



$\beta = 1.73$

The sign problem is under controlled

# Kurtosis intersection for chiral cond.




de Forcrand et al. 2007

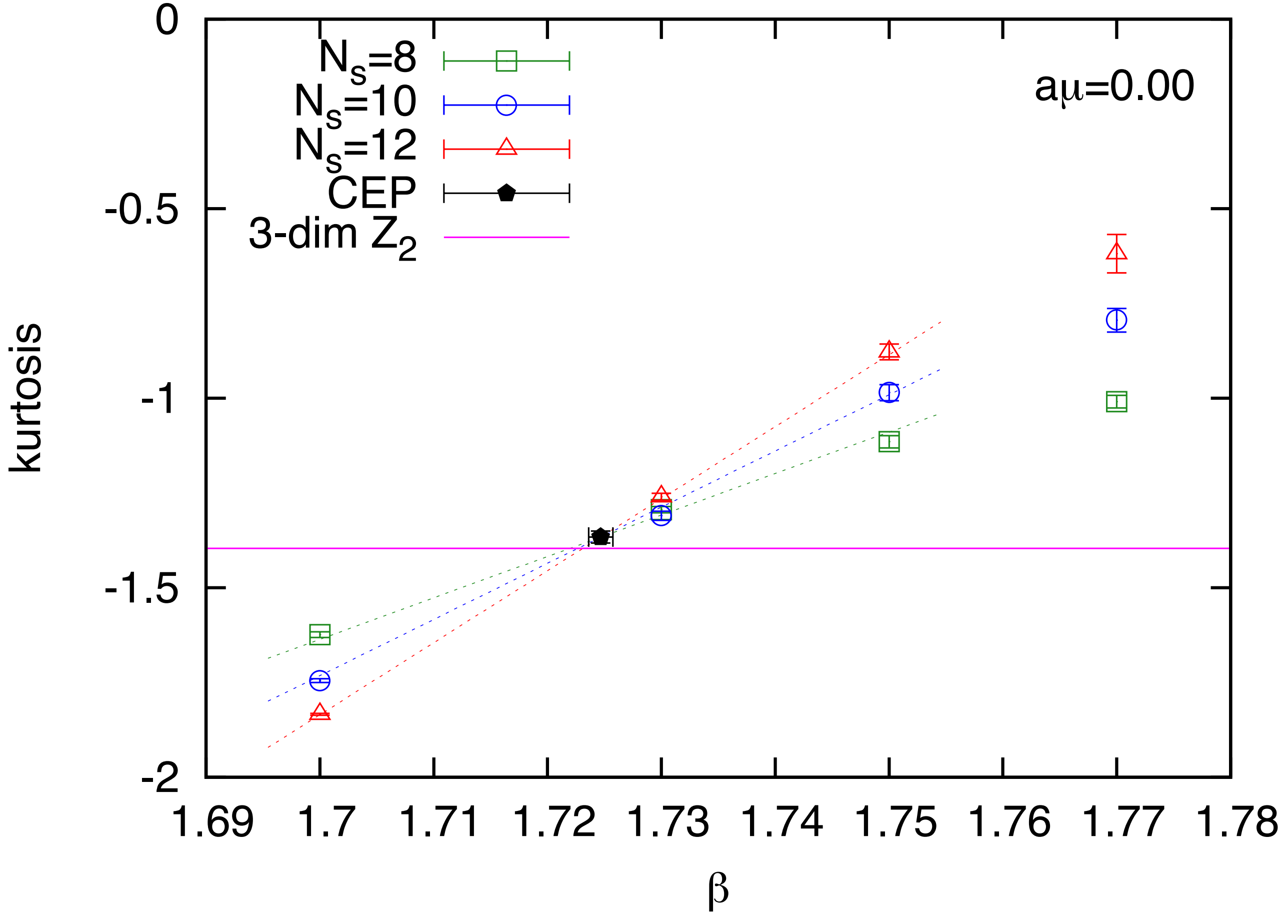
$$K = K_{\rm cep} + A N_{\rm s}^{1/\nu} (\beta - \beta_{\rm cep})$$

$$\nu = 0.615(27)$$

0.63 for 3-dim $Z_2$

3-dim $Z_2$ Universality class is favored

# By changing μ



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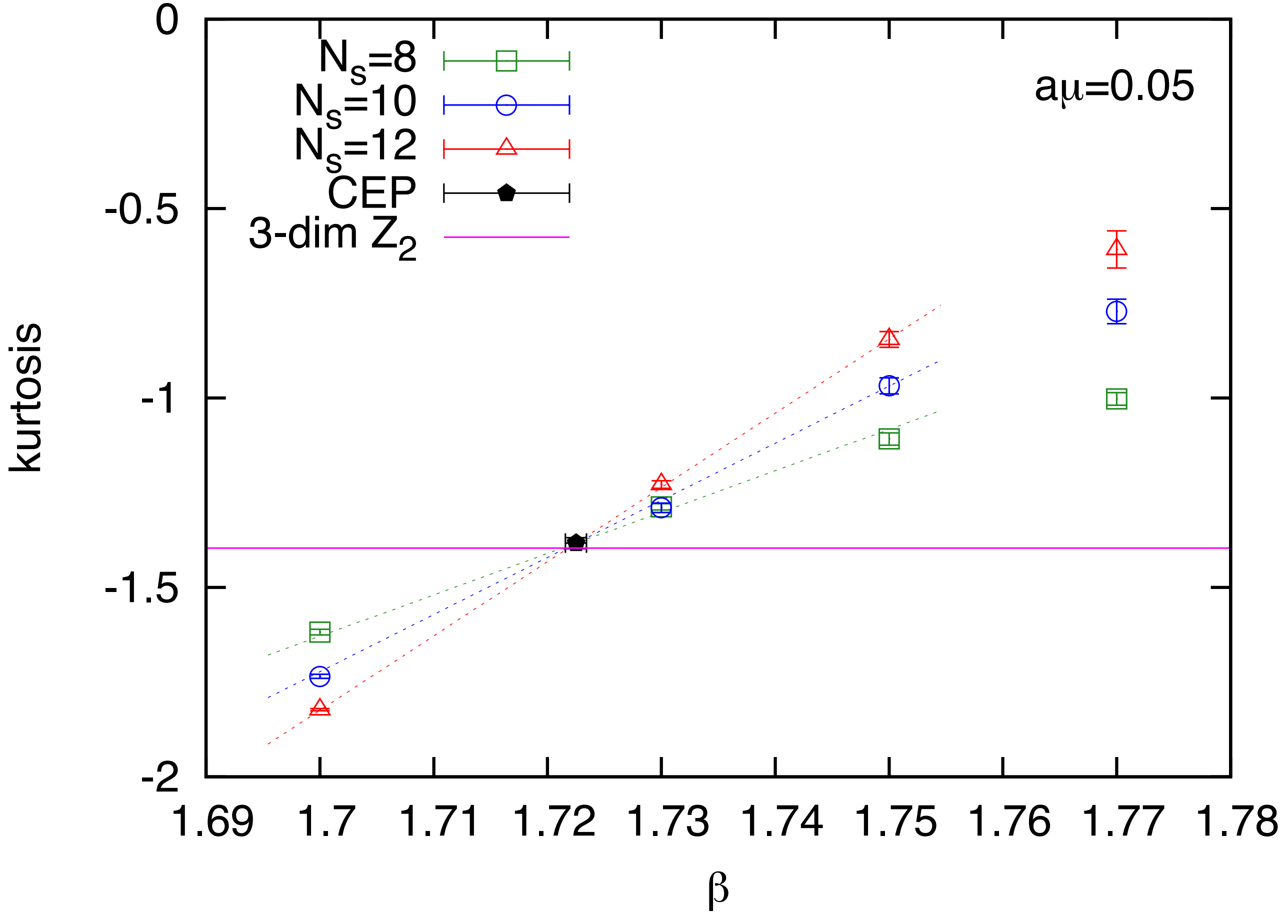

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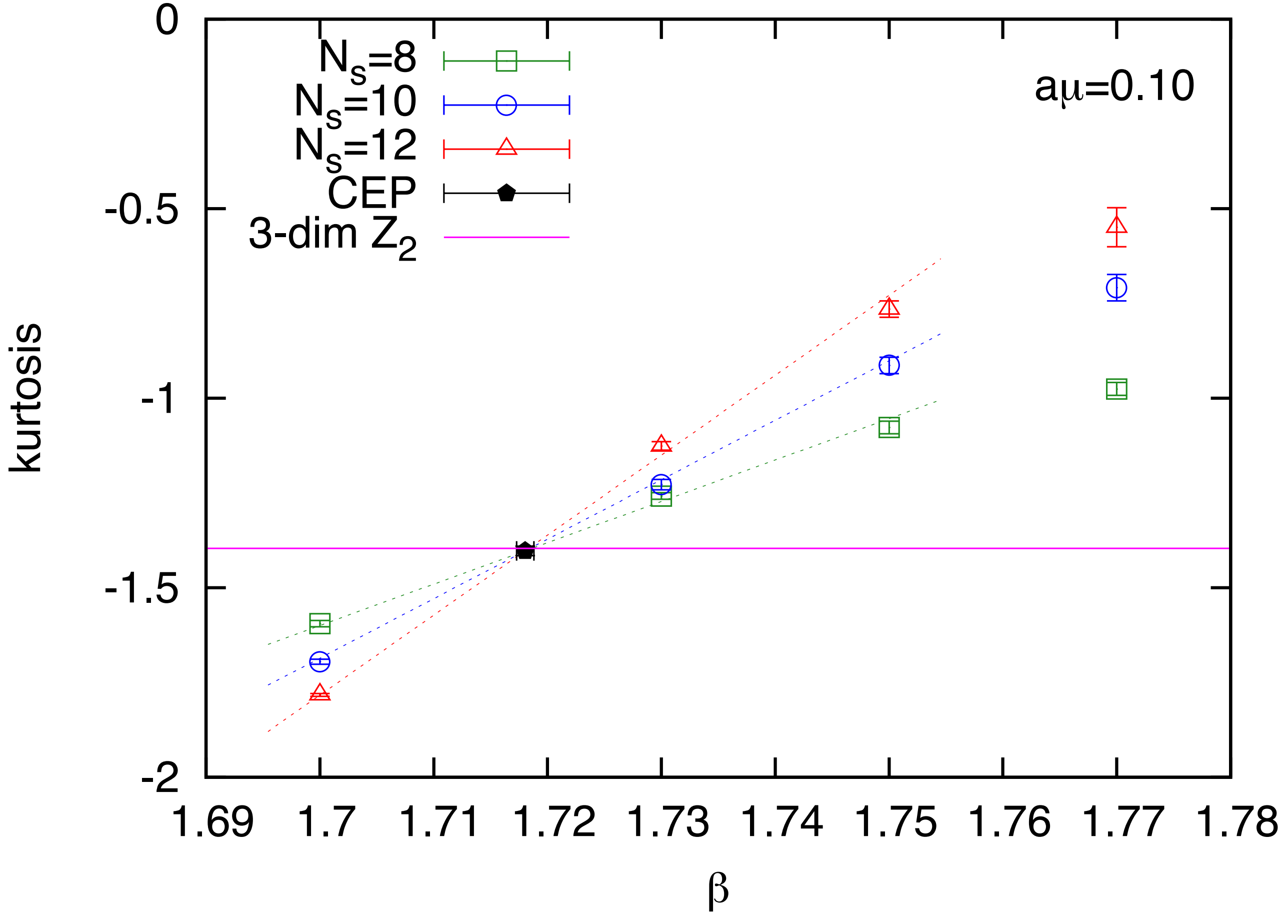

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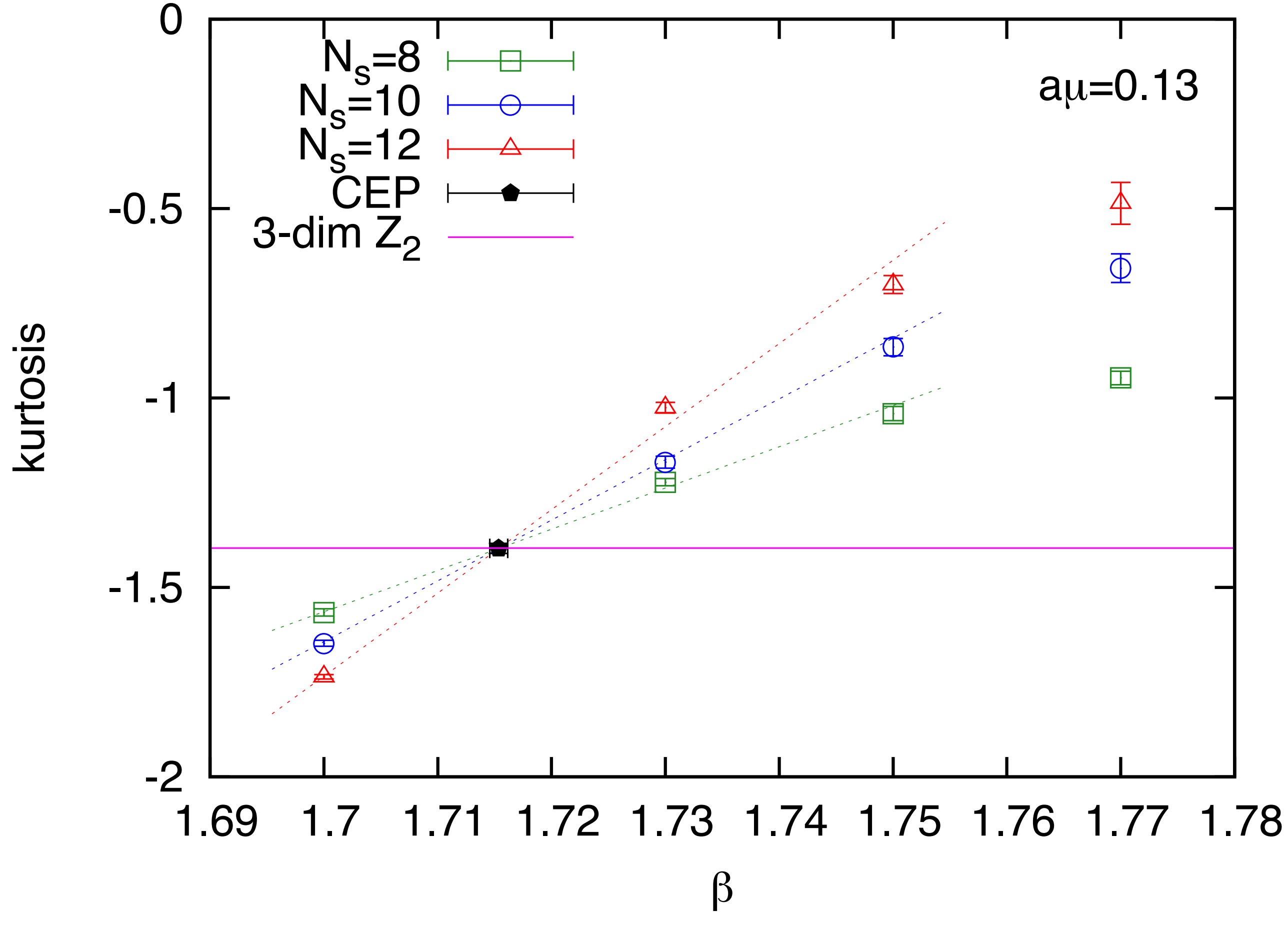

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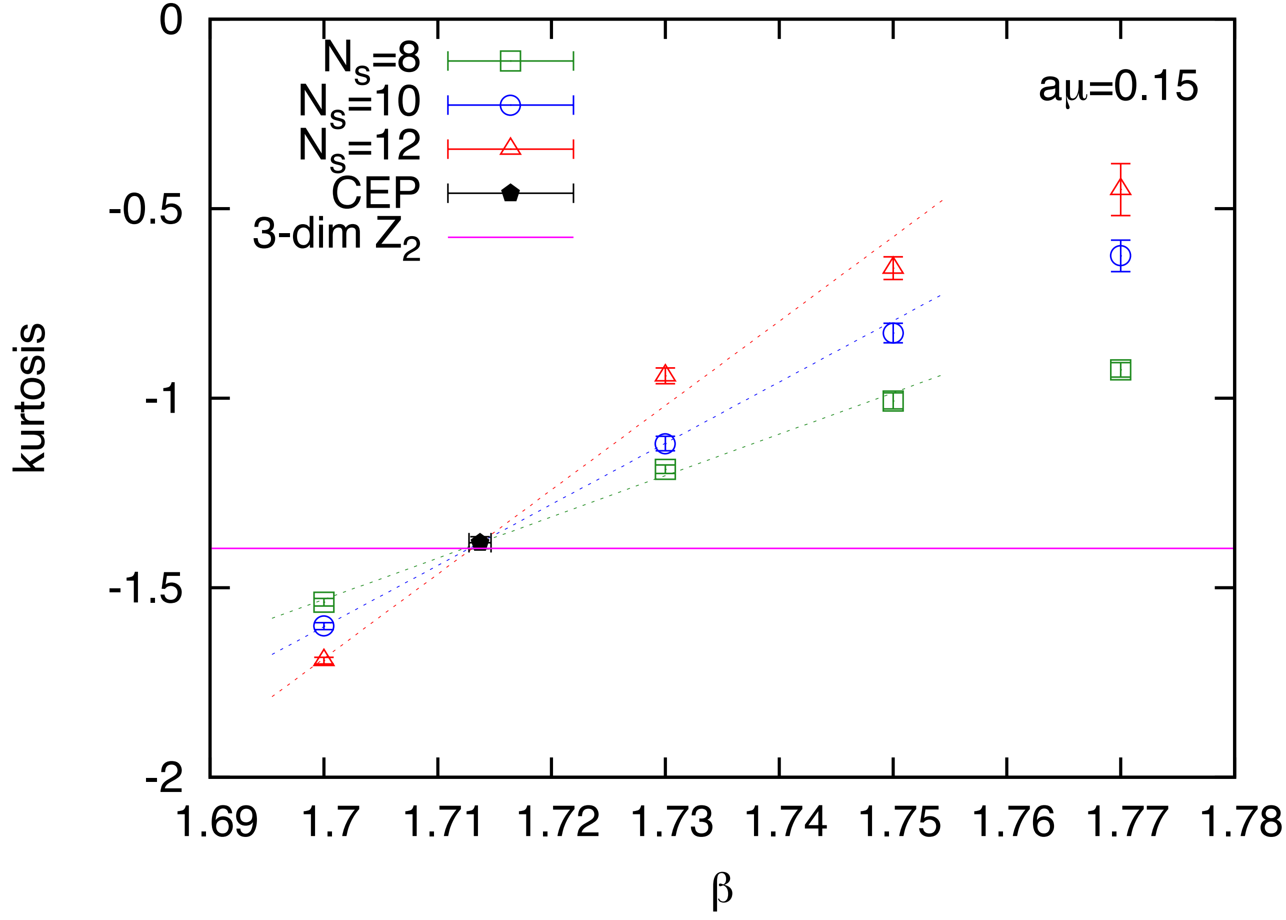

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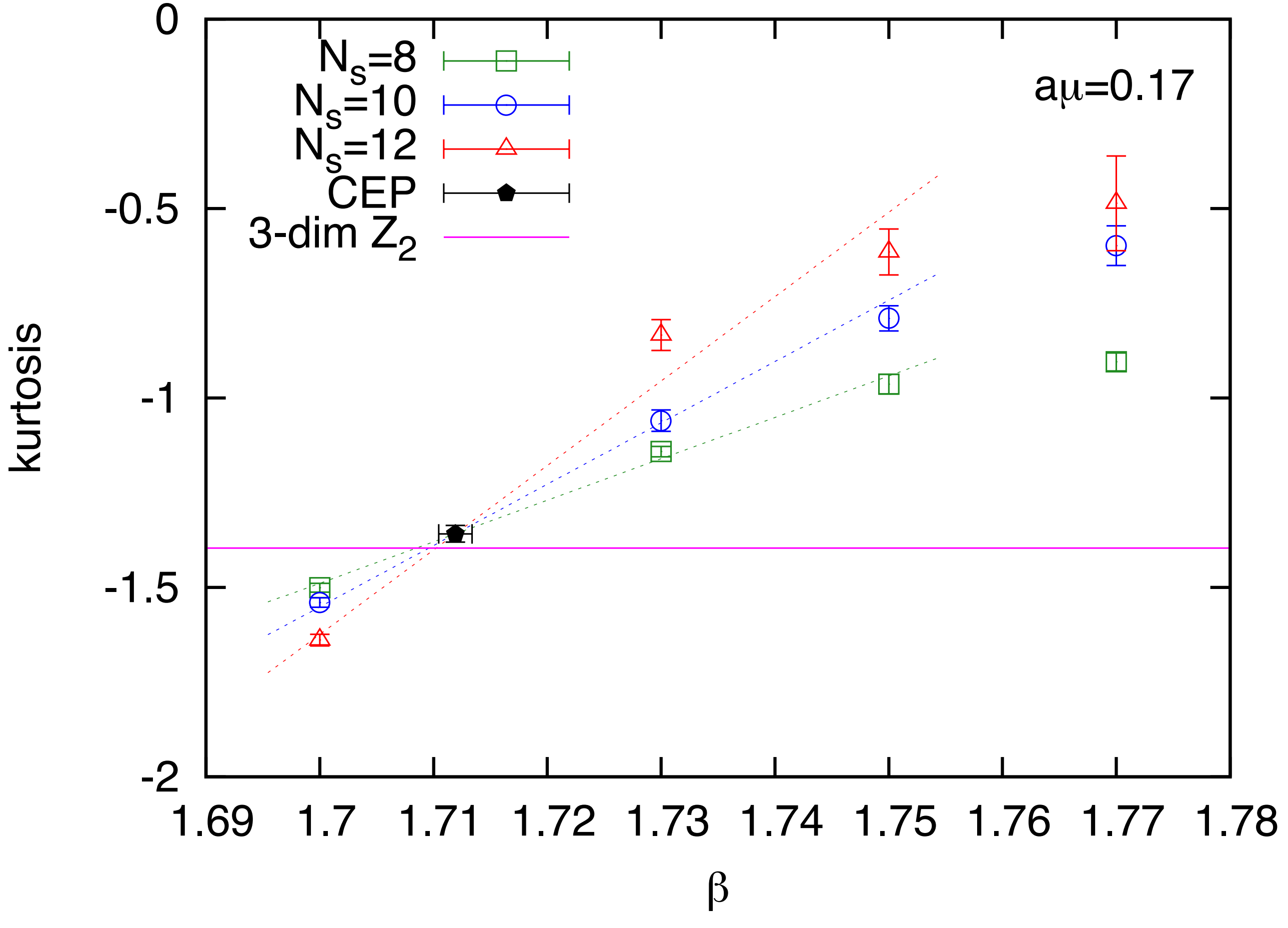

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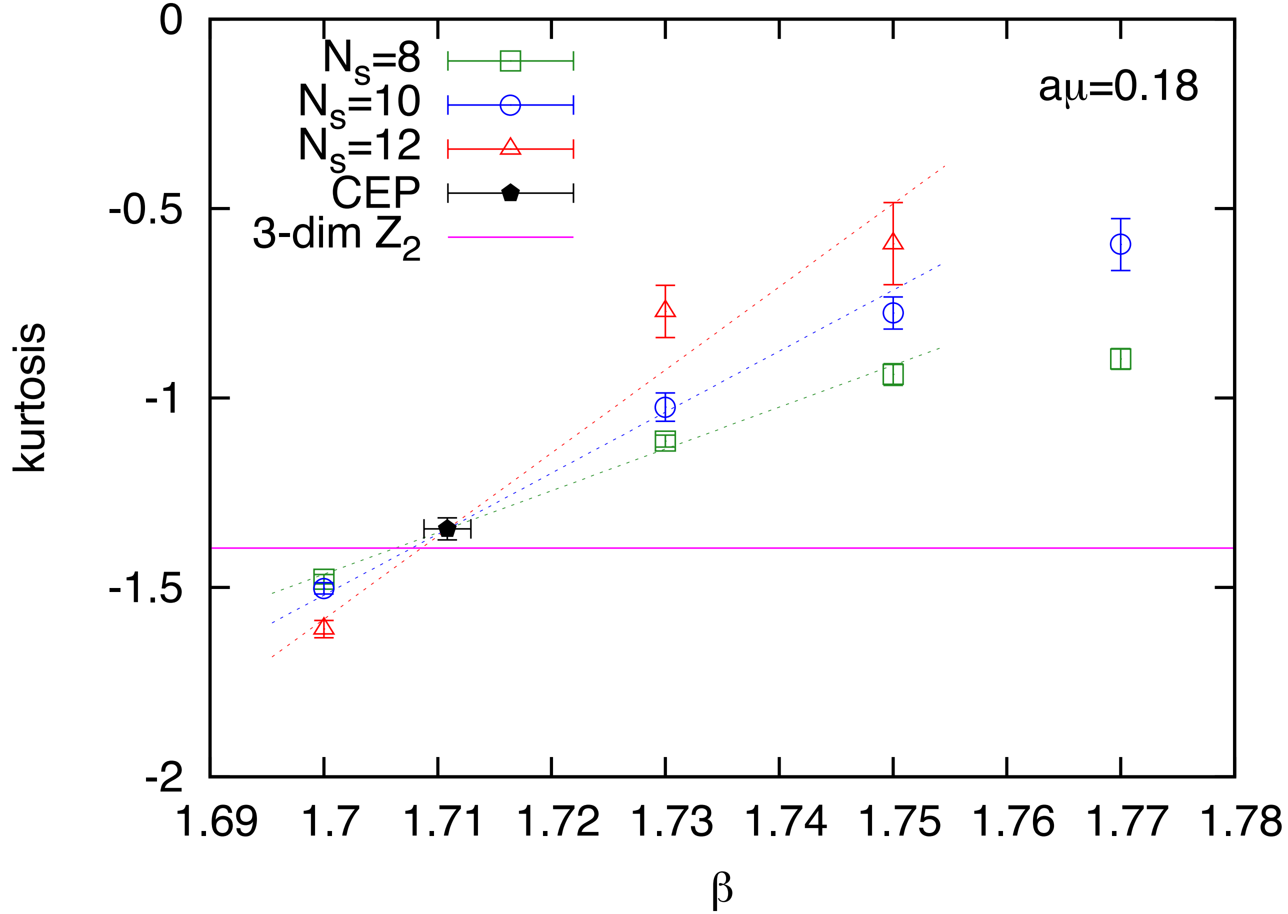

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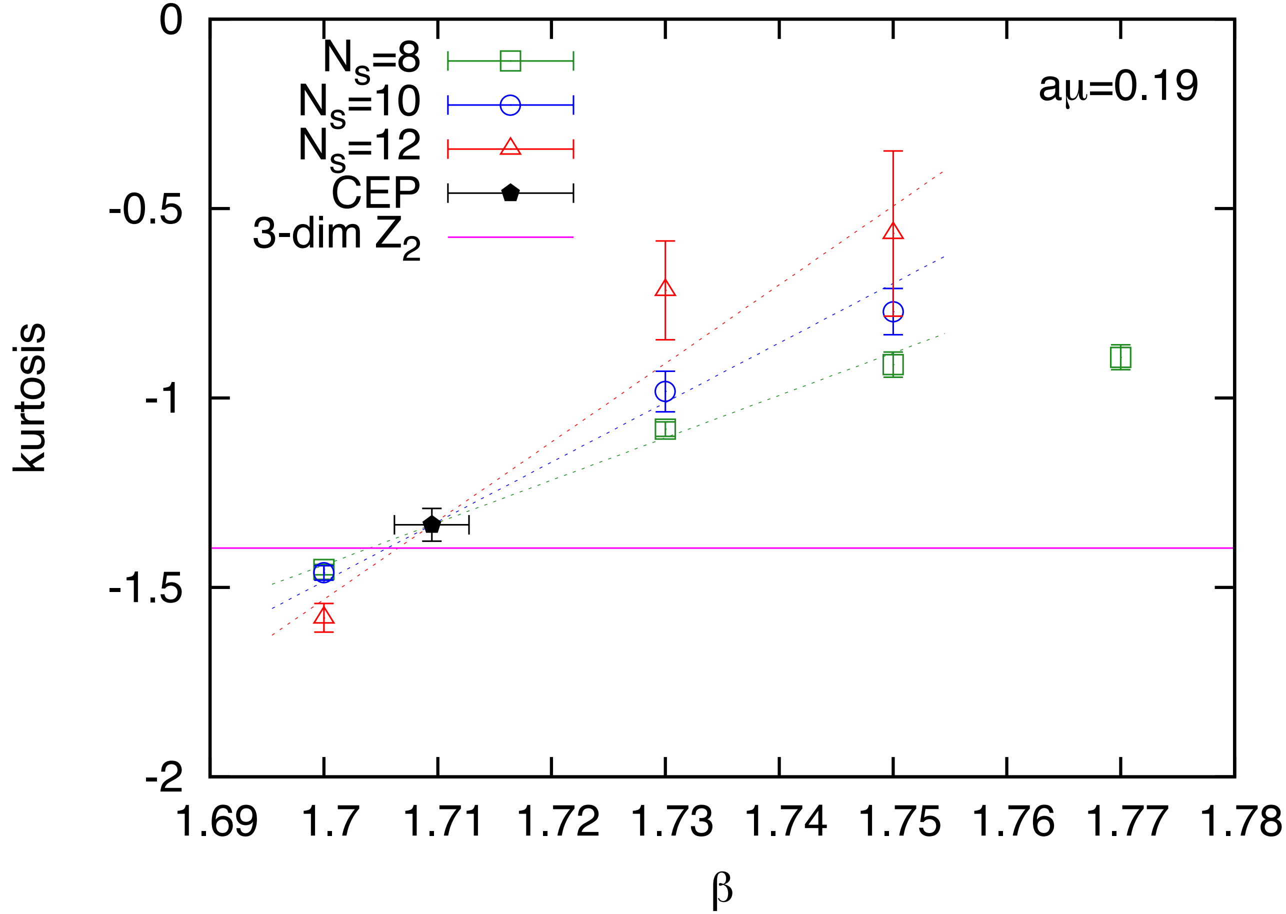
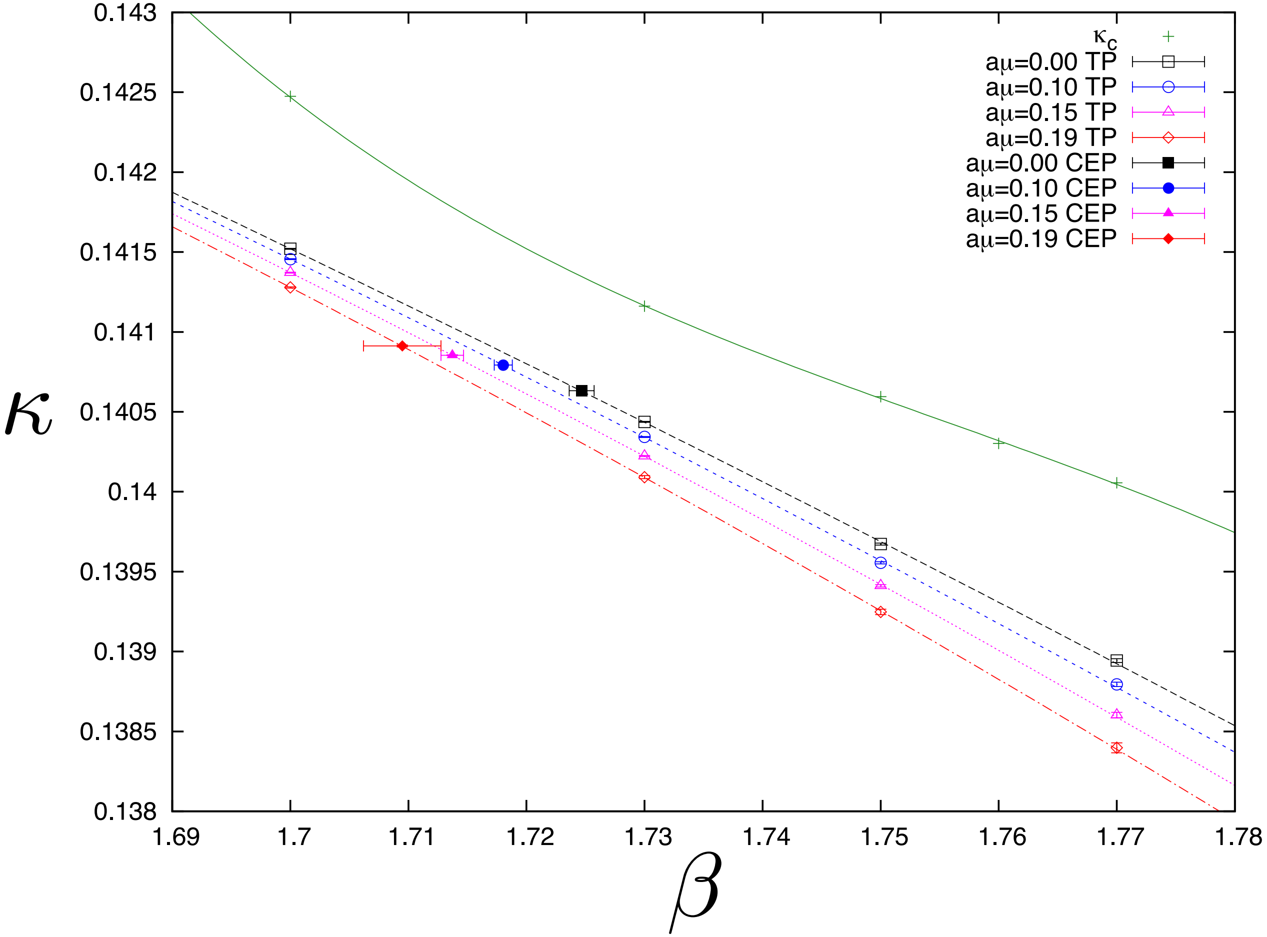



Along the critical line, 3-dim $Z_2$ universality class is maintained

# Phase structure in bare parameter space



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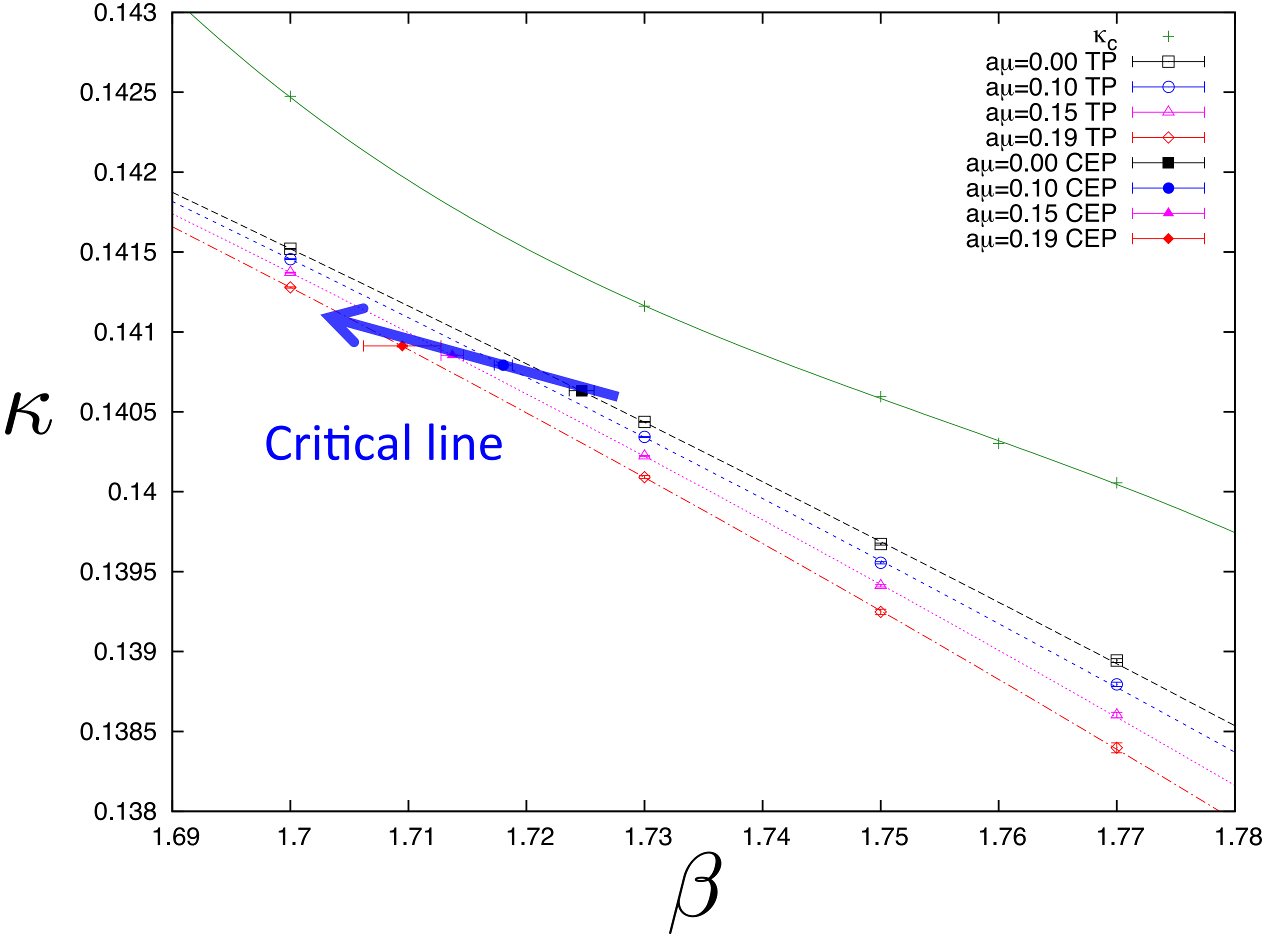
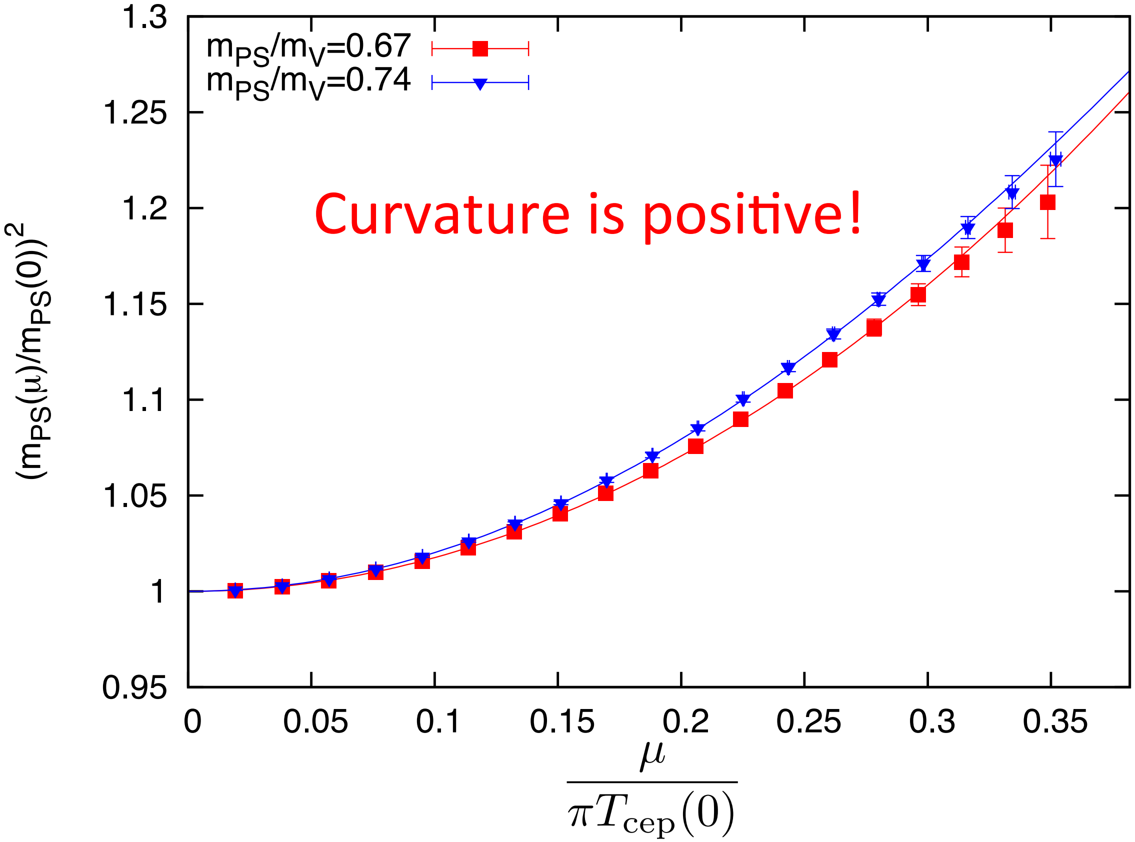


# Critical line on μ-$m_\pi$ plane

$$\left(\frac{m_{\rm PS,cep}(\mu)}{m_{\rm PS,cep}(0)}\right)^2 = 1 + \alpha_1 \left(\frac{\mu}{\pi T_{\rm cep}(0)}\right)^2 + \alpha_2 \left(\frac{\mu}{\pi T_{\rm cep}(0)}\right)^4$$



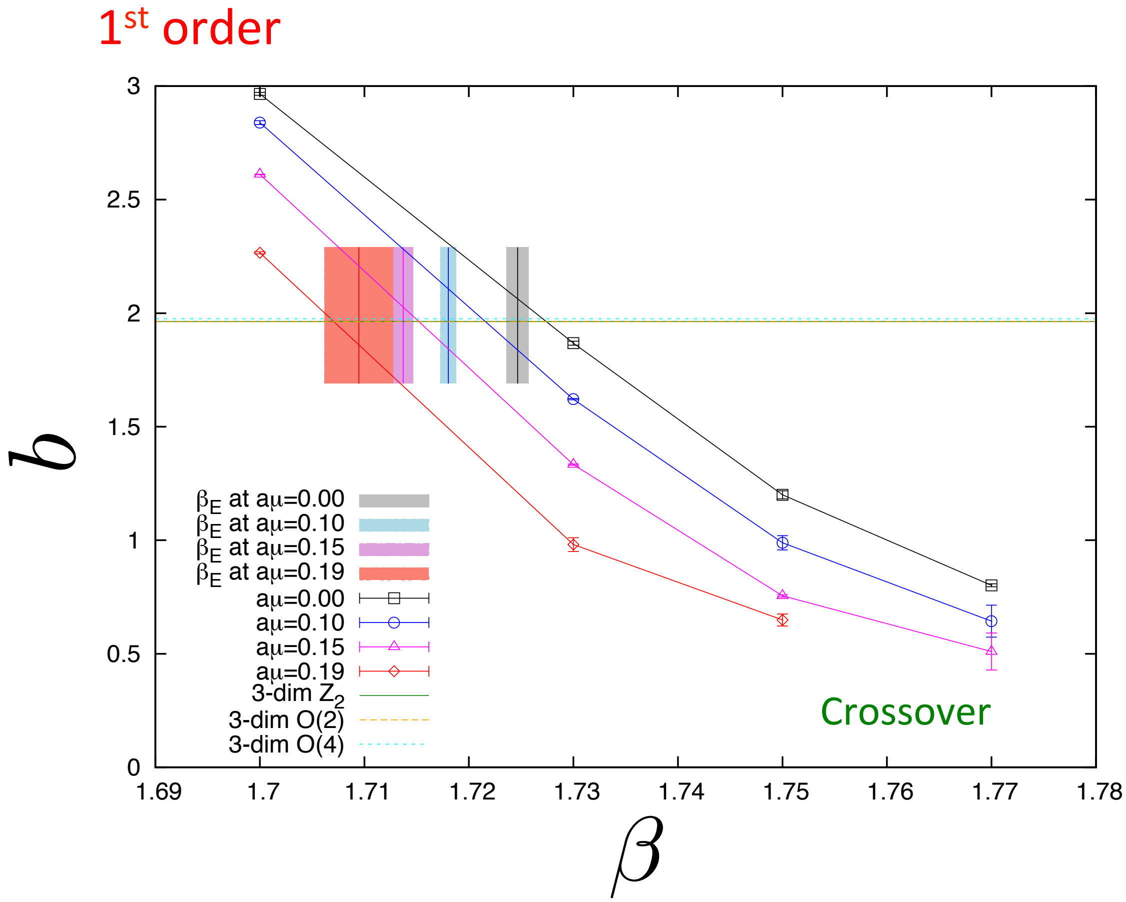

$\alpha_1 \approx 2$

# Summary

- 3-dim $Z_2$ universality class is favored along the critical line
- Curvature is positive in contrast to staggered results (negative). Why?
- Lattice artifact can be large
- One has to take the continuum limit to draw a clear conclusion
- Larger $N_T$=8,10,…, it is hard….
- New strategy is desired

# BACKUP SLIDES

# Critical exponent $\gamma/\nu$




$$\chi_{\max} = CL^b$$

$$b = \gamma/\nu = 1.963$$

at critical point for 3-dim $Z_2$

Consistent with 3-dim $Z_2$ Universality class

# Cumulants of quark condensate