Critical end point in Nf=3 QCD with finite density and temperature

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in collaboration with
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Study of LQCD thermodynamics

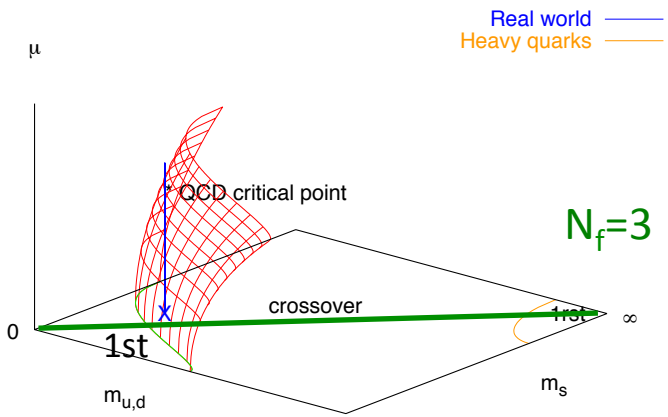
- Staggered fermions are mainly used in both zero and finite density
  - HotQCD, BMW, BNL/Bielefeld,….
- Rooting trick?
- Universality check by solid ground formulation
- We use Wilson-type fermions HERE

Goal

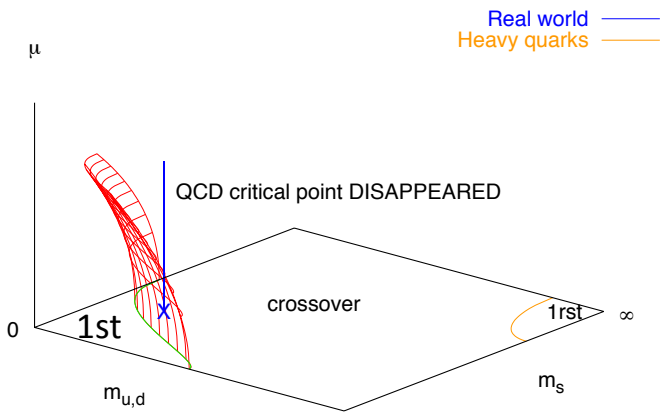
Slope/curvature of critical surface is positive/negative???

de Forcrand & Philipsen 2007

Conventional scenario



Exotic scenario



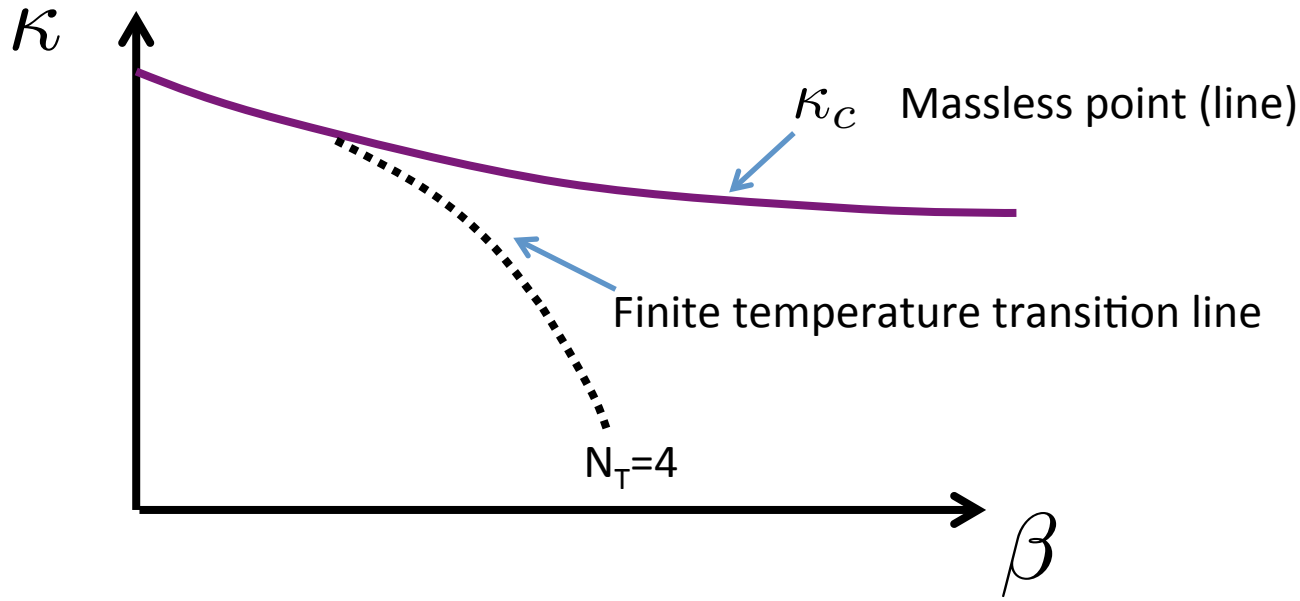
$$\frac{m_c(\mu)}{m_c(0)} = 1 - 0.7(4)\left(\frac{\mu}{\pi T}\right)^2$$

For Nf=3

Strategy

N_f=3

aμ=0



Strategy

N_f=3

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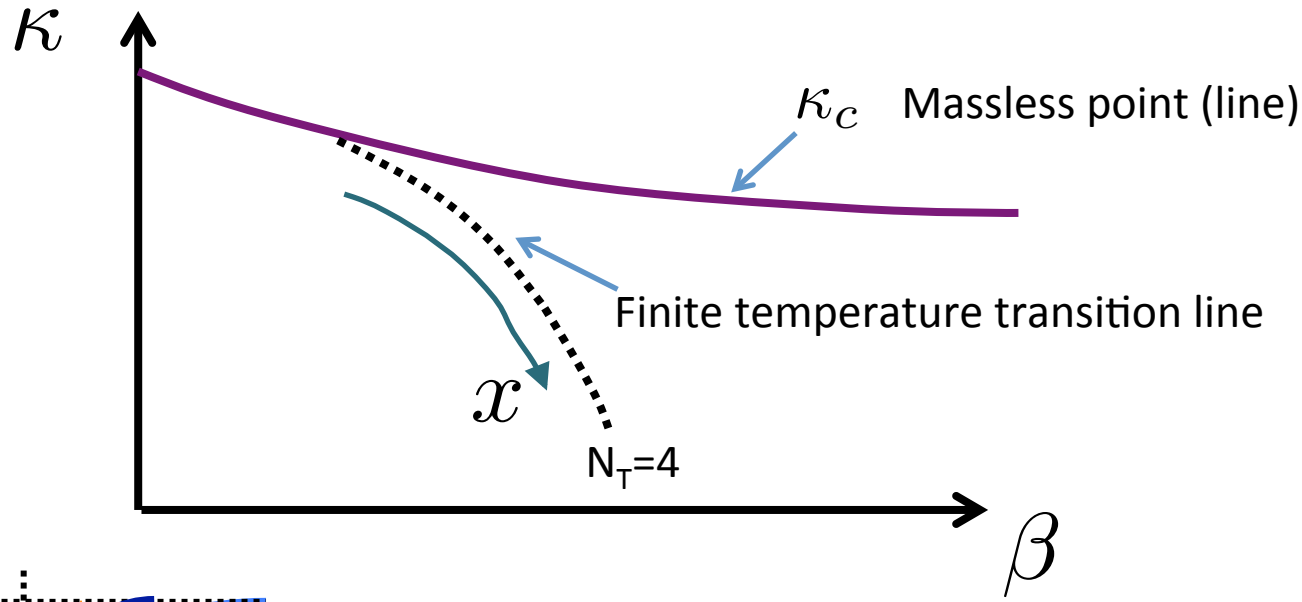
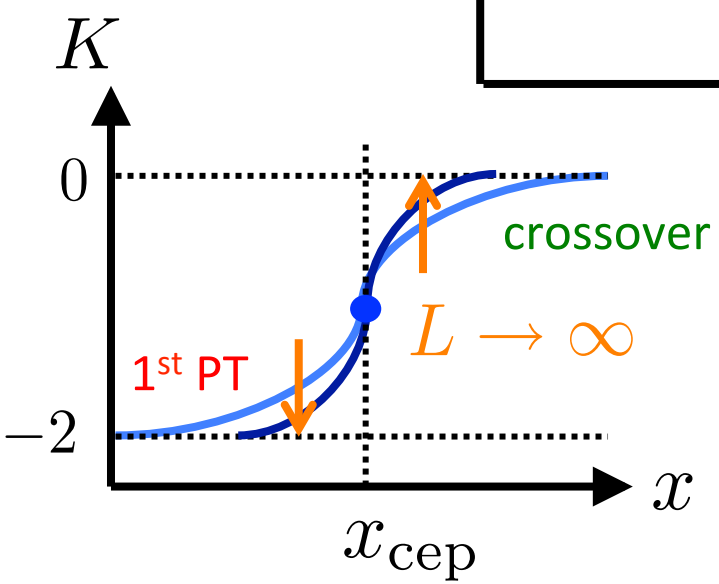


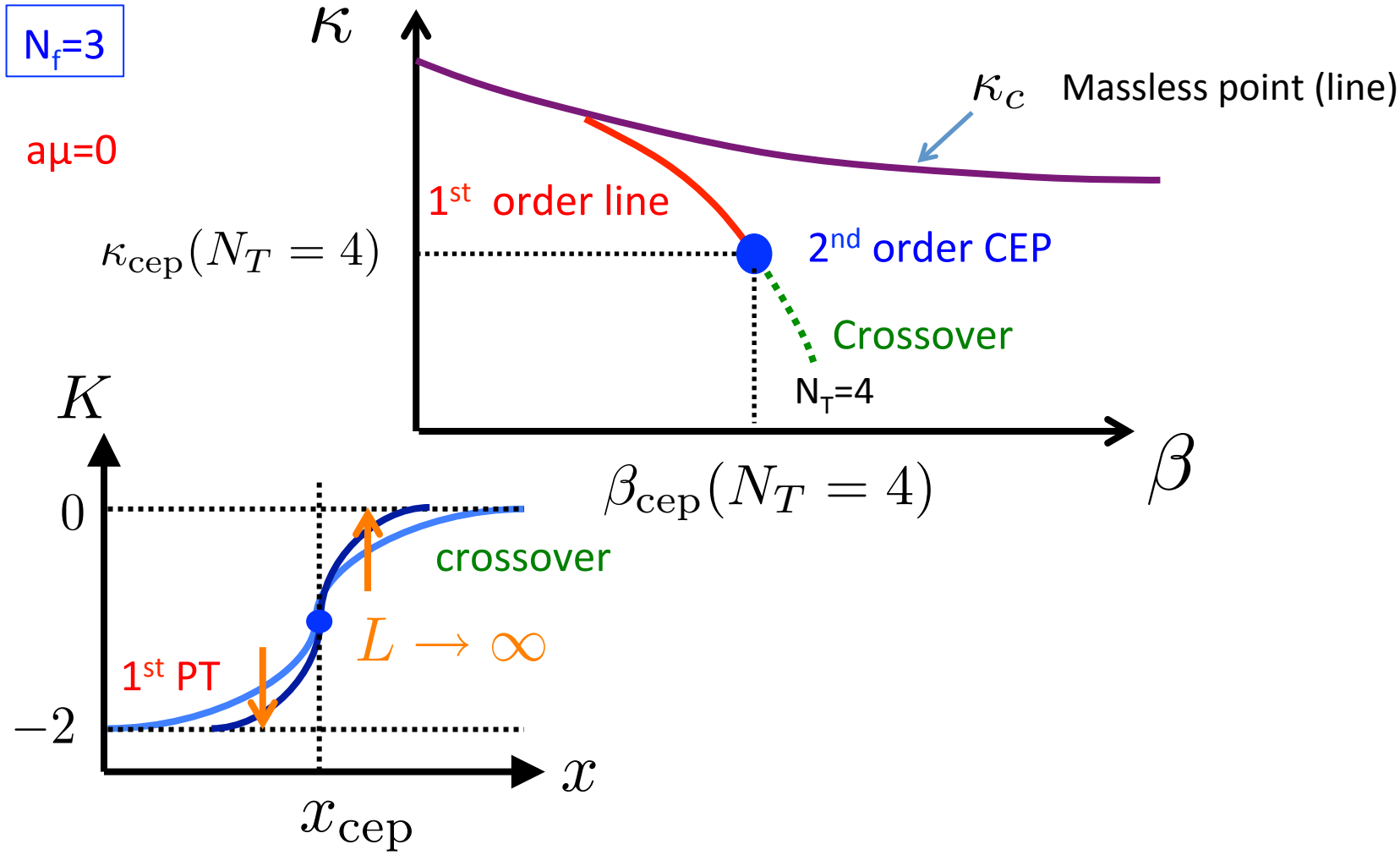


$$K = \frac{\langle (O - \langle O \rangle)^4 \rangle}{\langle (O - \langle O \rangle)^2 \rangle^2} - 3$$

B_4

Karsch et al. 2001

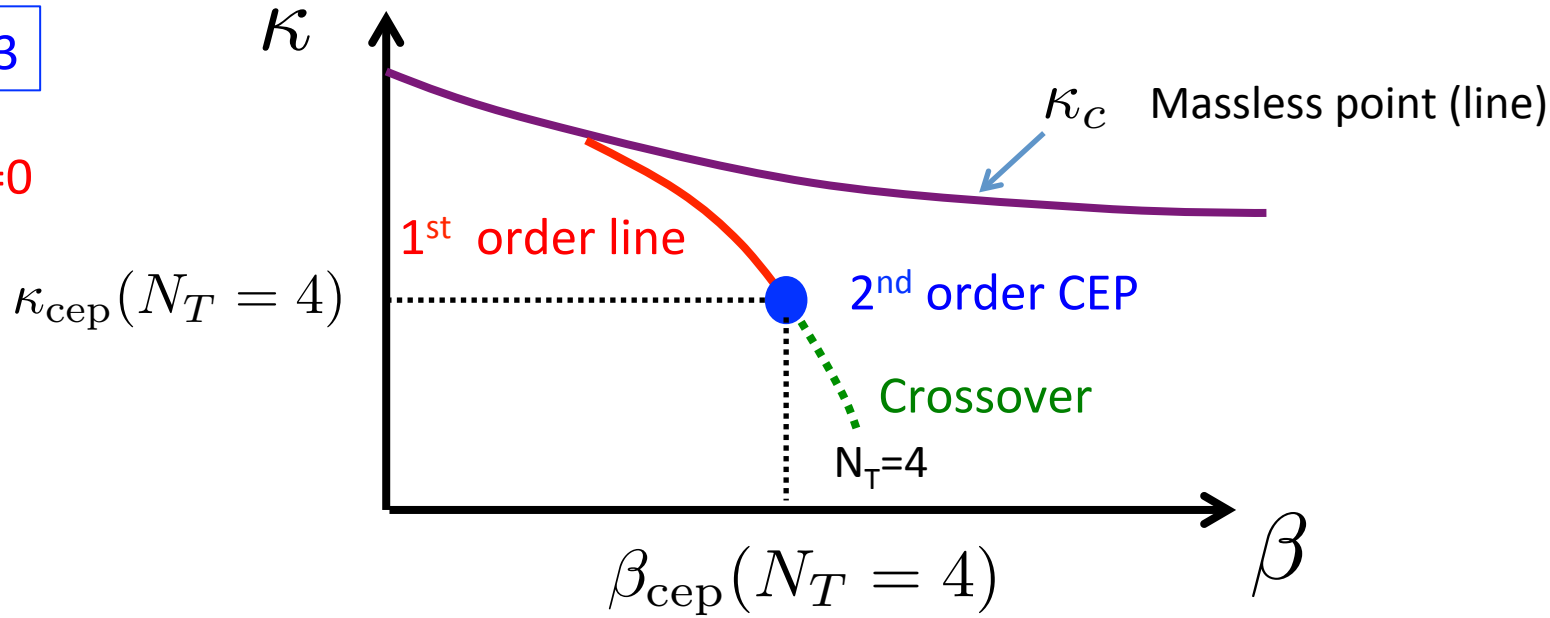
Strategy


N_f=3
aμ=0
κ
κ_c Massless point (line)
1st order line
$\kappa_{\rm cep}(N_T=4)$
2nd order CEP
Crossover
N_T=4
$\beta_{\rm cep}(N_T=4)$
β
K
0
crossover
$L \to \infty$
1st PT
-2
x
$x_{\rm cep}$

Strategy

N_f=3

aμ=0

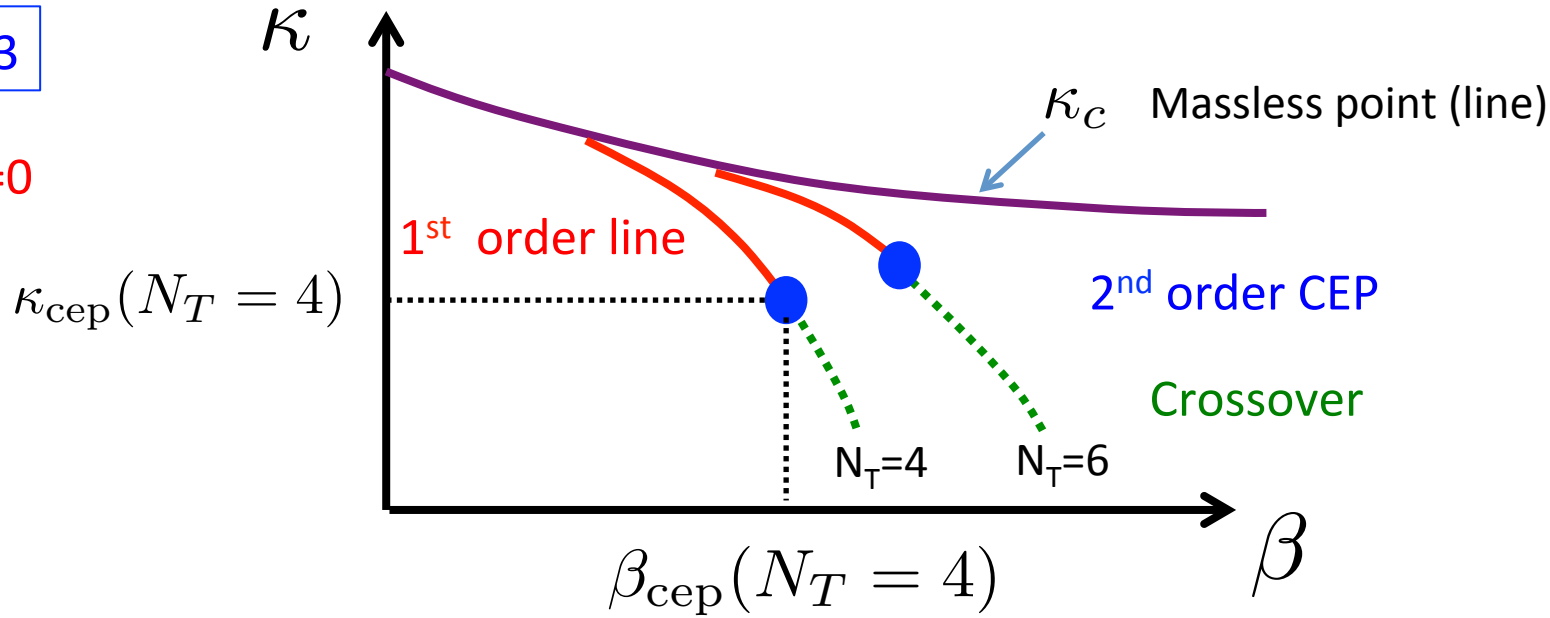


$$\left.\frac{m_{\rm PS}}{m_{\rm V}}\right|_{\kappa_{\rm cep}(N_{\rm T}),\beta_{\rm cep}(N_{\rm T})}$$

Strategy

N_f=3

aμ=0

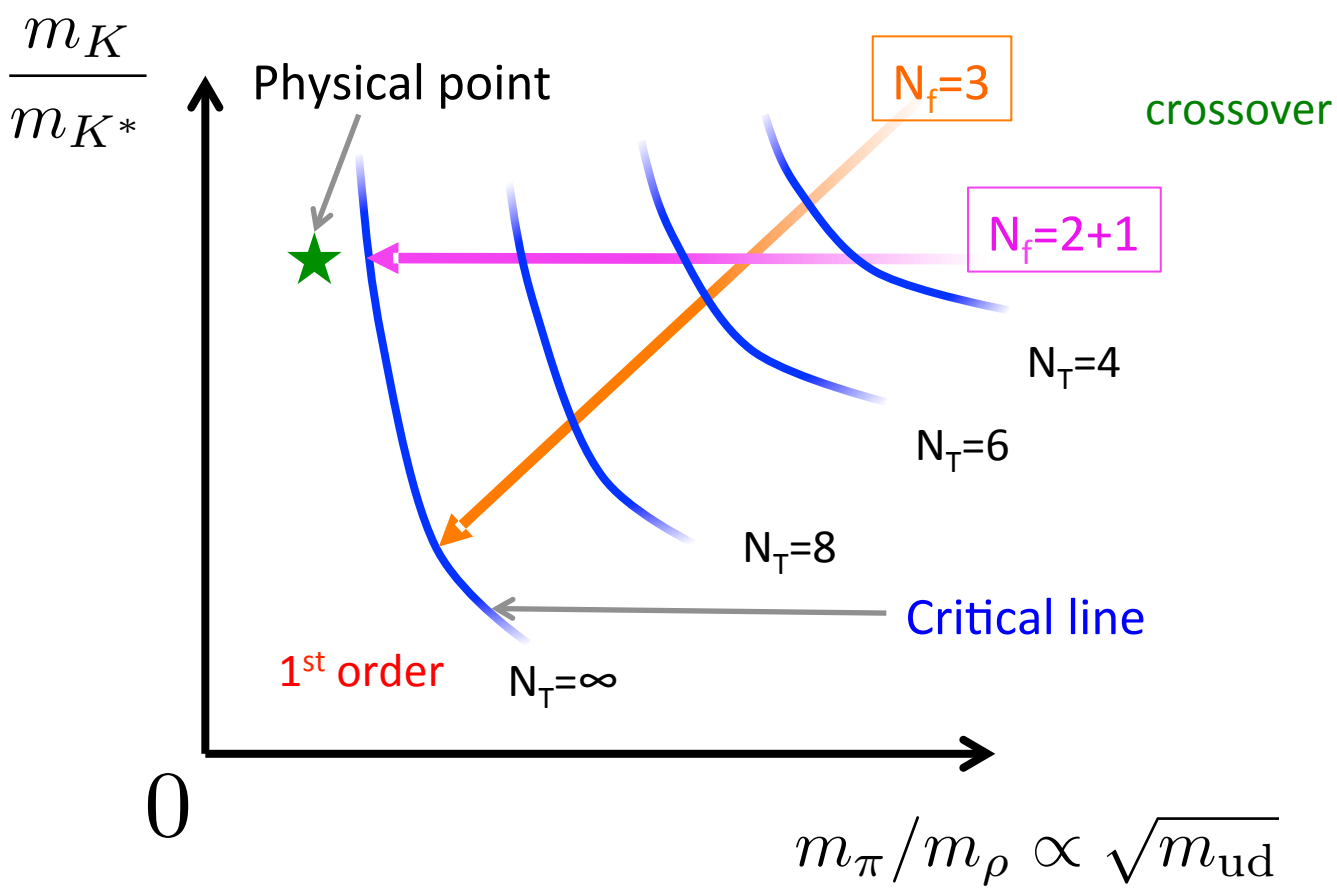


Continuum limit

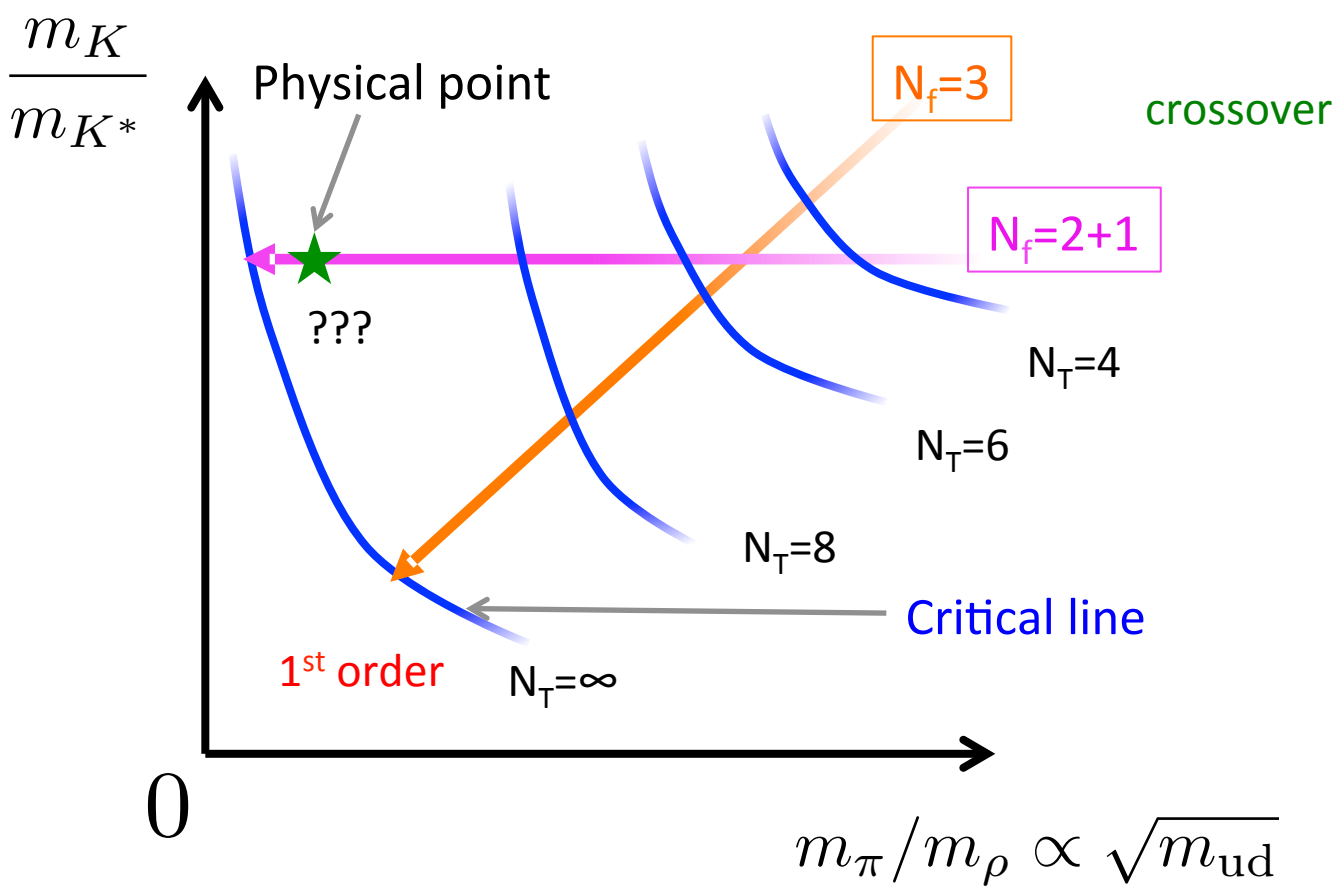
$$\lim_{N_{\rm T}\to\infty} \frac{m_{\rm PS}}{m_{\rm V}}\Bigg|_{\kappa_{\rm cep}(N_{\rm T}),\beta_{\rm cep}(N_{\rm T})}$$

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

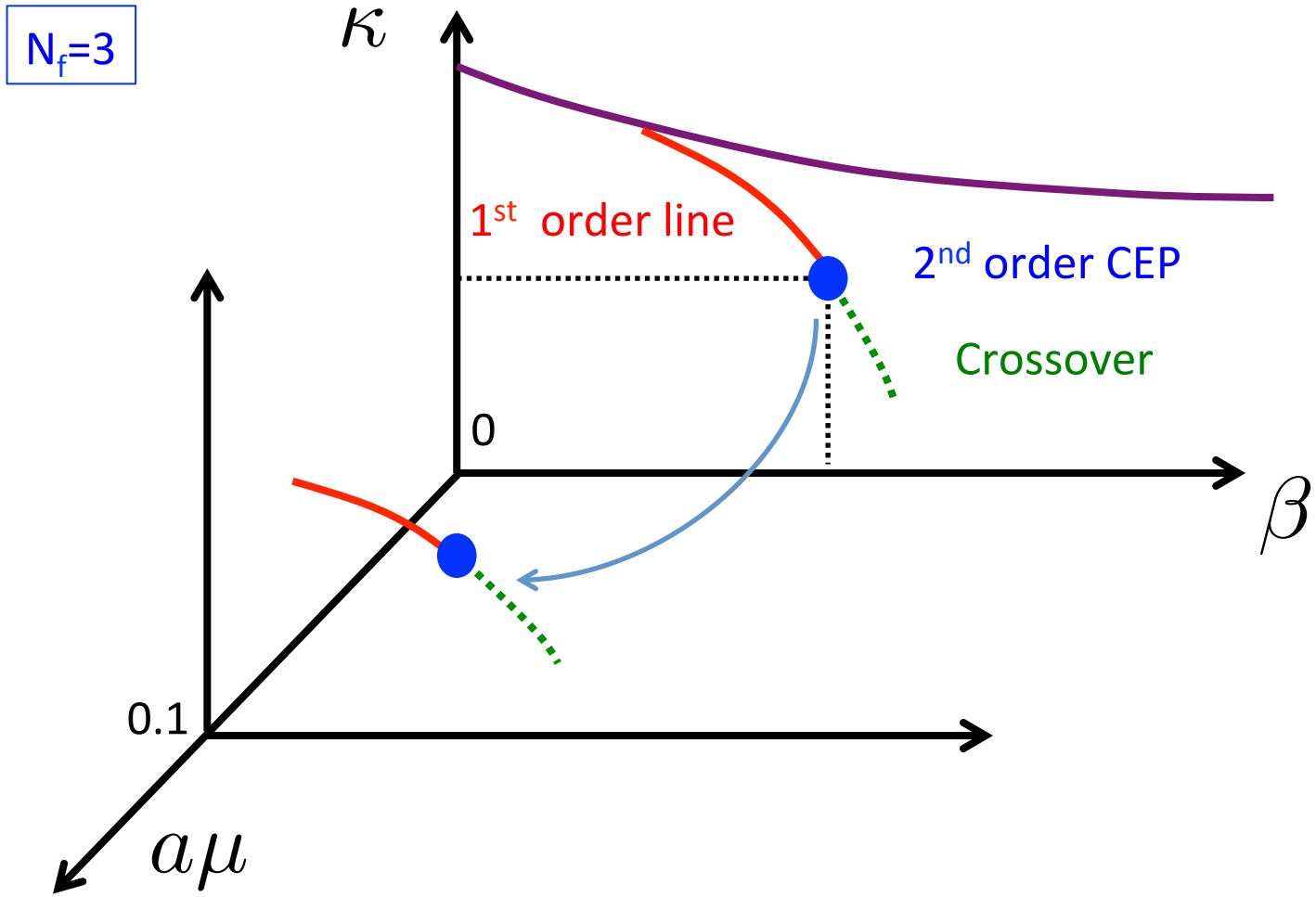
Continuum limit of CEP



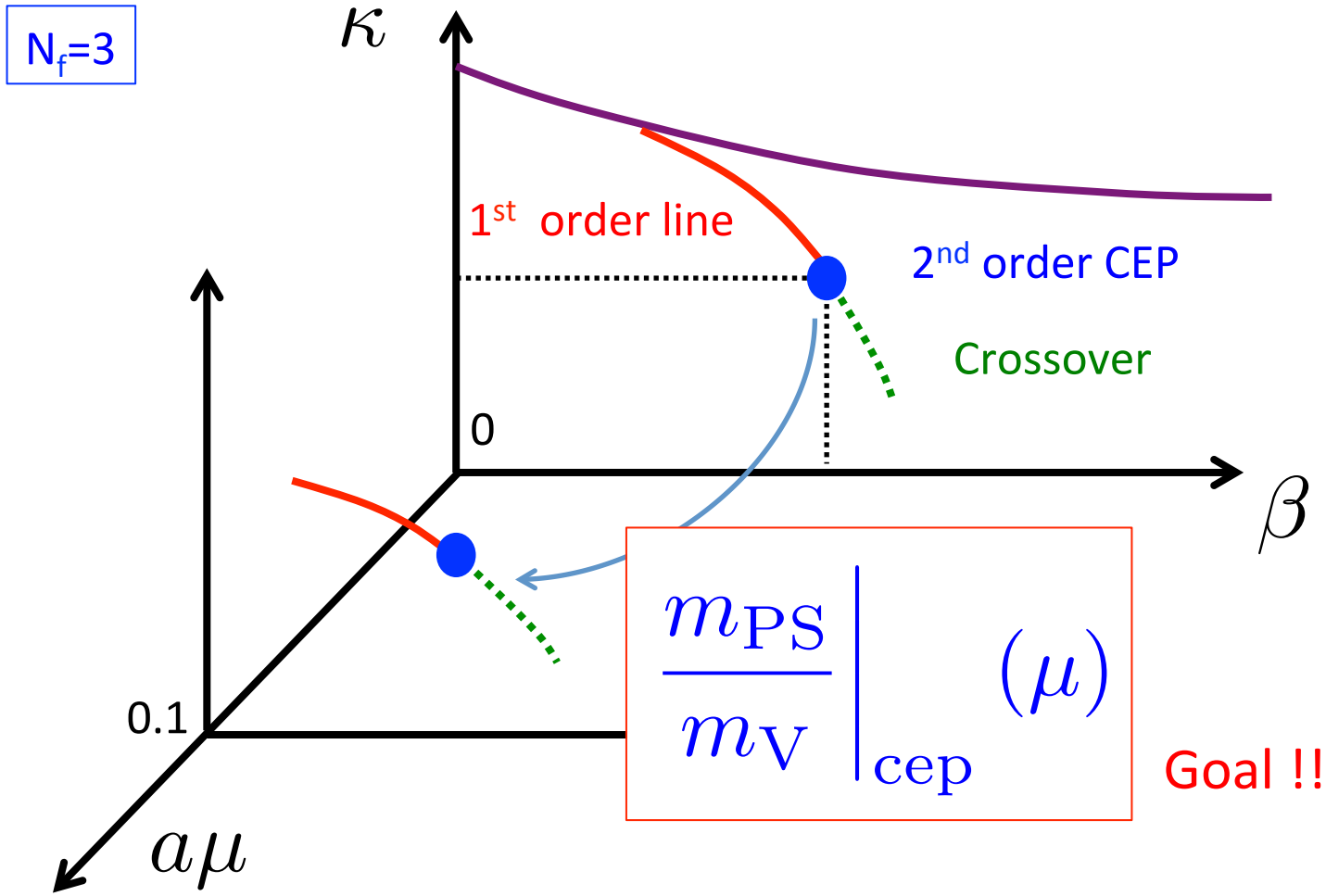
Continuum limit of CEP



For finite density



For finite density



Simulation details

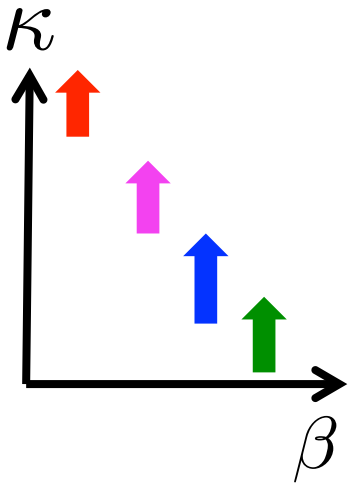
- Nf=3 Clover with NP c_{sw} + Iwasaki gauge
- Phase reweighting
  - Evaluate phase exactly

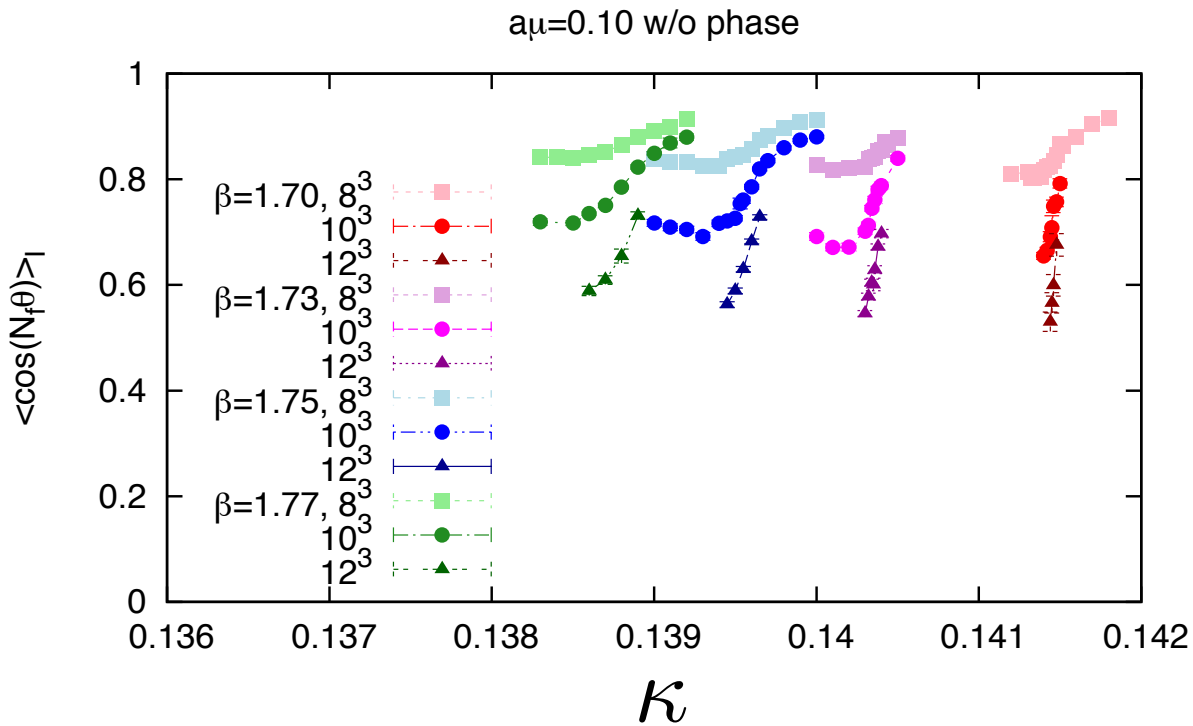
$$\langle \mathcal{O} \rangle = \frac{\langle \mathcal{O} e^{iN_{\rm f}\theta} \rangle_{||}}{\langle e^{iN_{\rm f}\theta} \rangle_{||}}$$

Gattringer '10

  - Det. is computed by using reduction method together with LAPACK&GPGPU
- 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

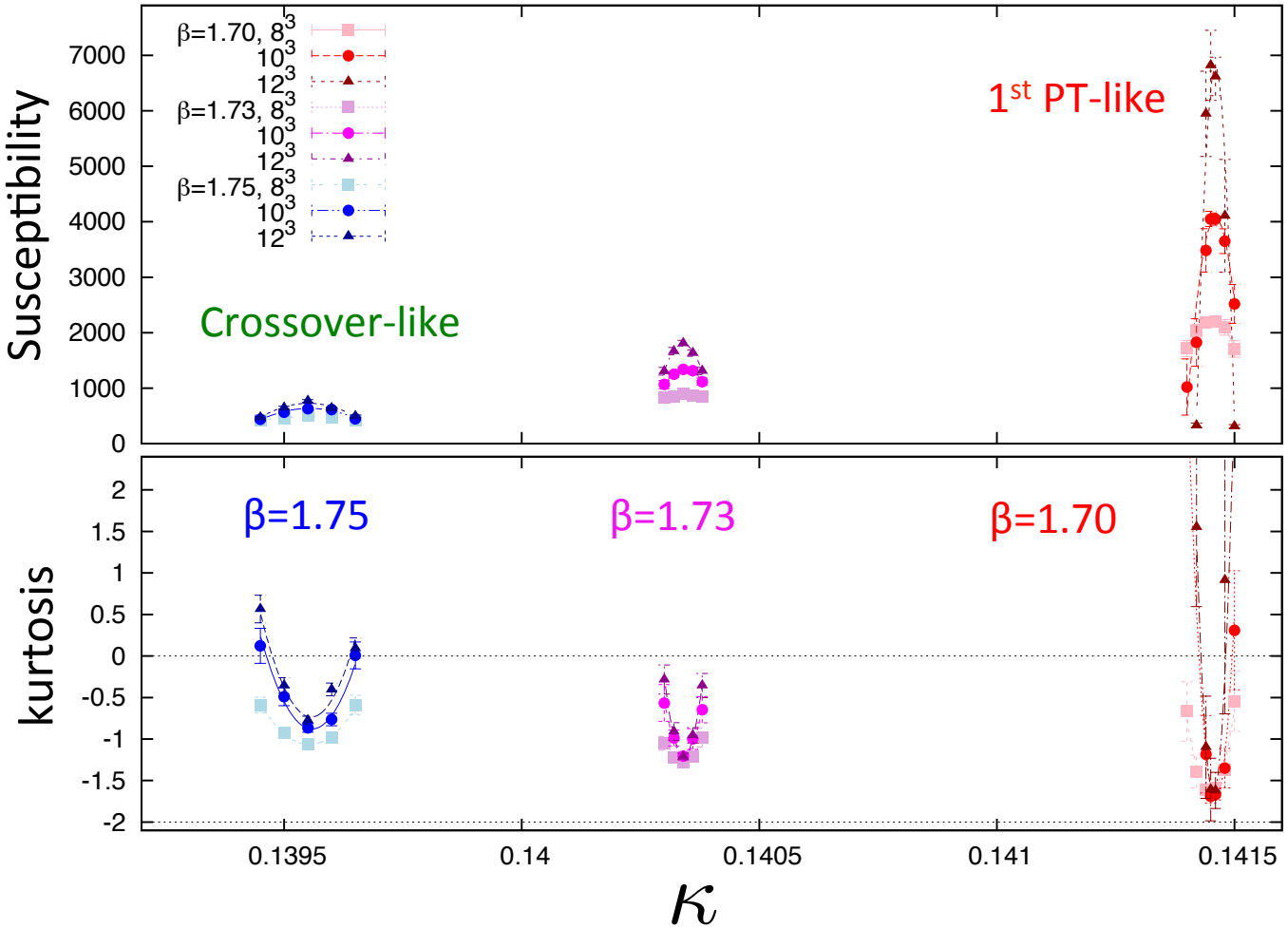
Phase re-weighting factor



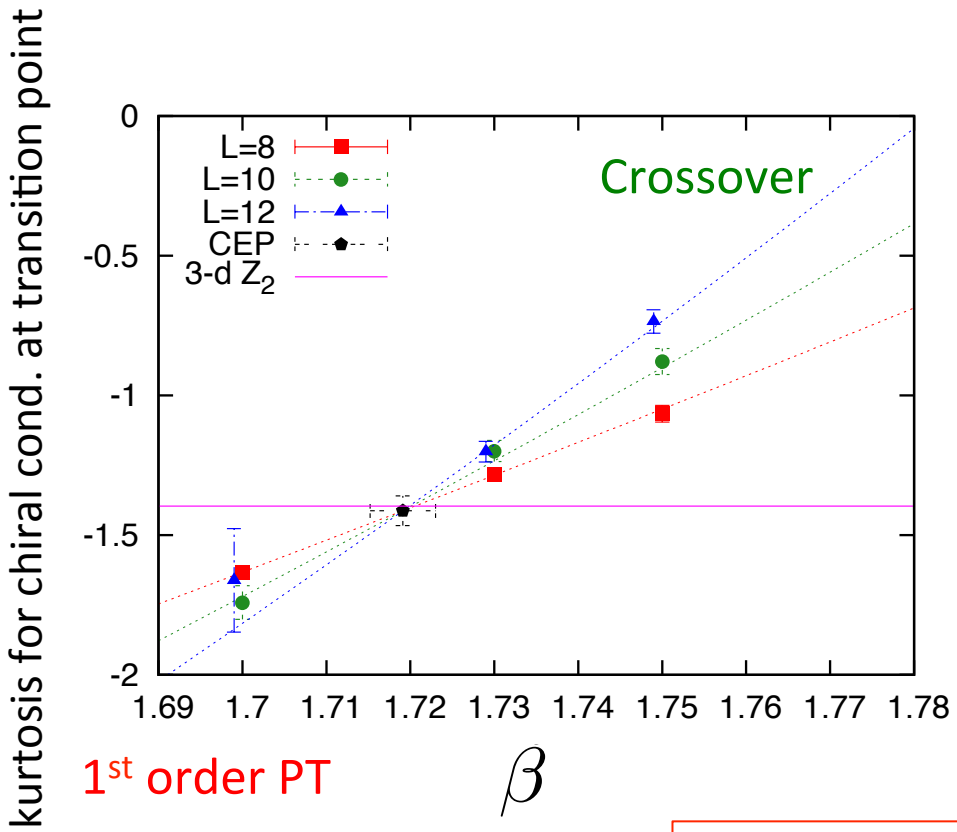


Sign problem is under controlled

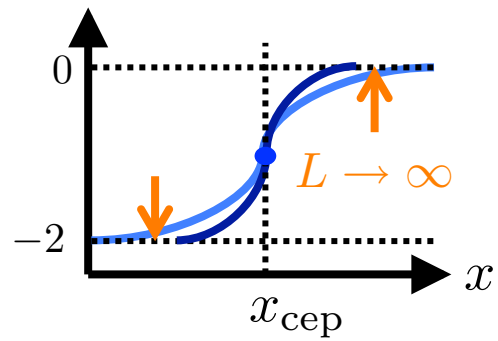
Cumulant of chiral condensate



Kurtosis intersection for chiral cond.



Karsch et al. 2001



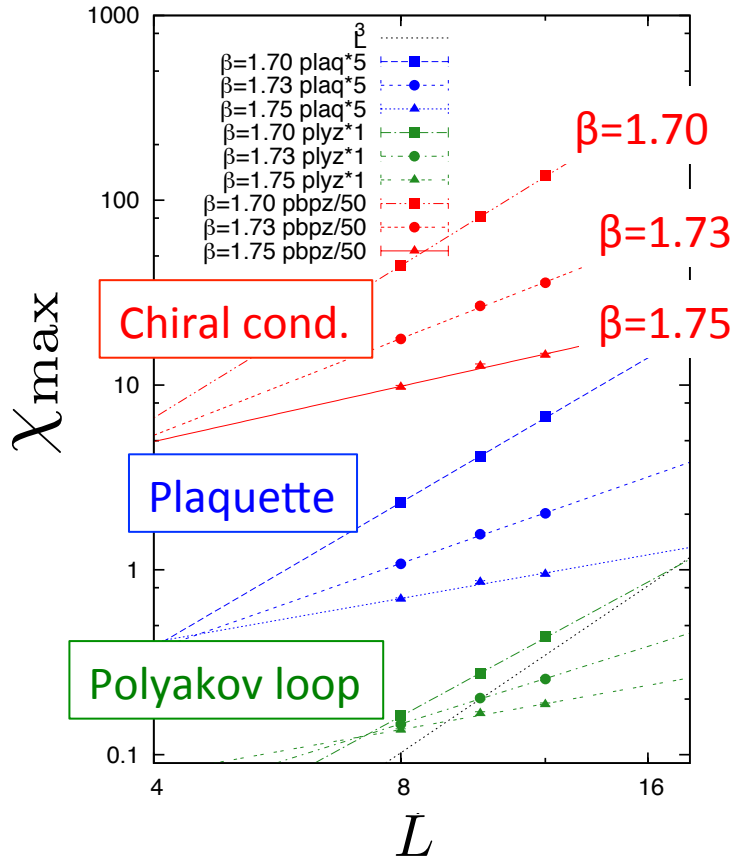
$$K = K_0 + AL^{1/\nu}(\beta - \beta_{\mathrm{CEP}})$$

$$\nu = 0.66(13)$$

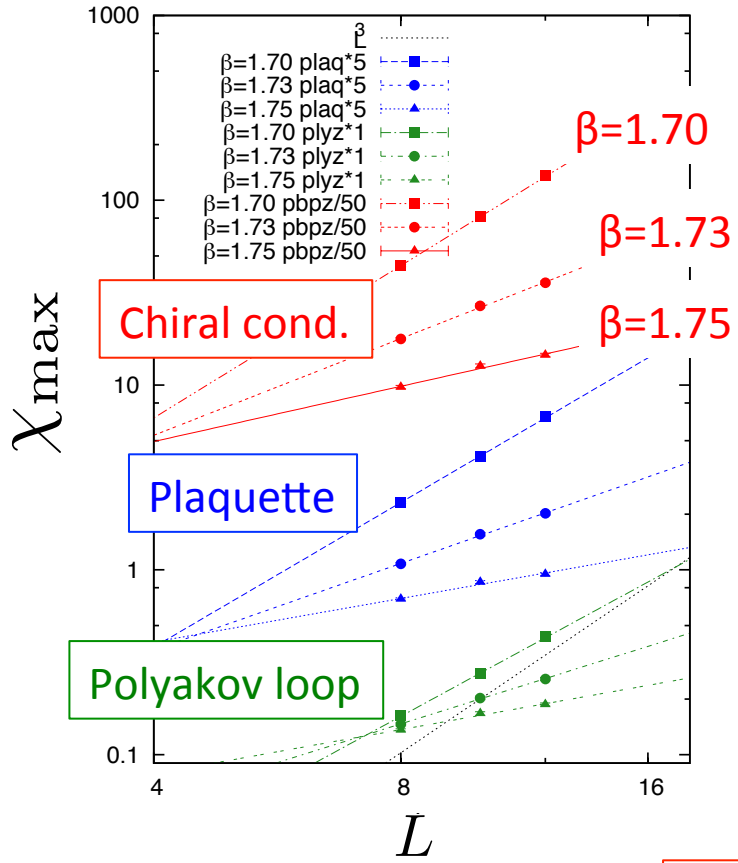
0.63 for 3-d Z_2

3-d Z_2 Universality class is favored

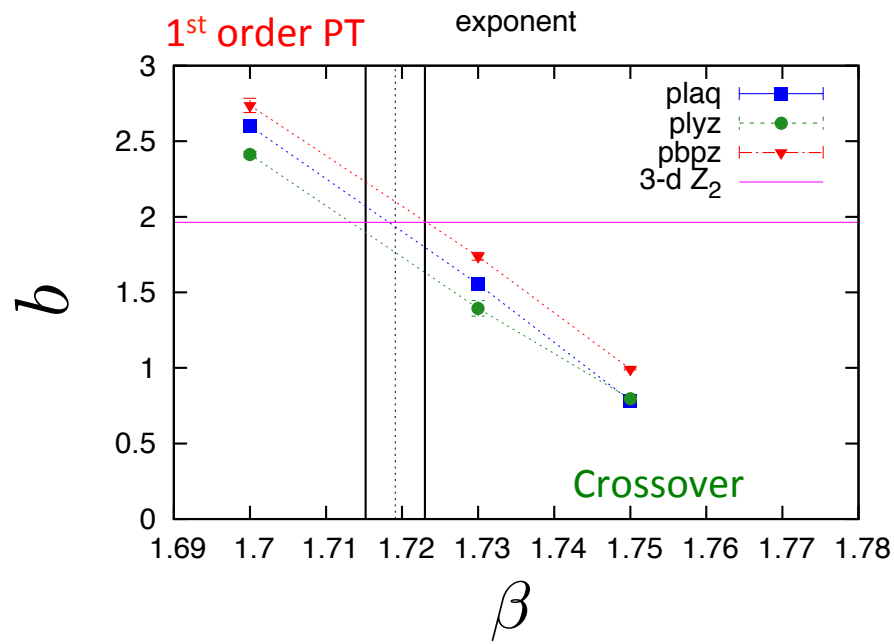
Another critical exponent γ/ν



Another critical exponent γ/ν



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



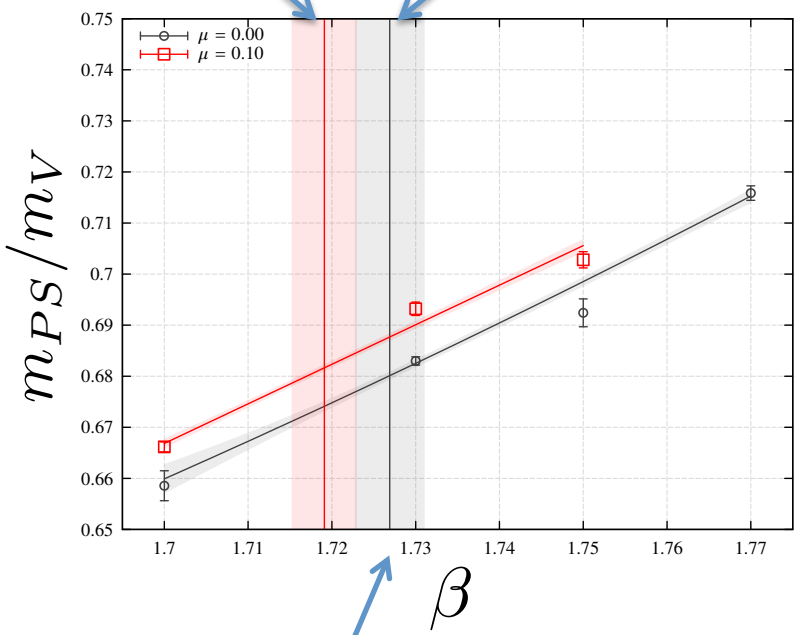
$b = \gamma/\nu = 1.963$ at critical point for 3-d Z_2

Consistent with 3-d Z_2 Universality class

μ-dependence of CEP

CEP for aμ=0.1

CEP for aμ=0

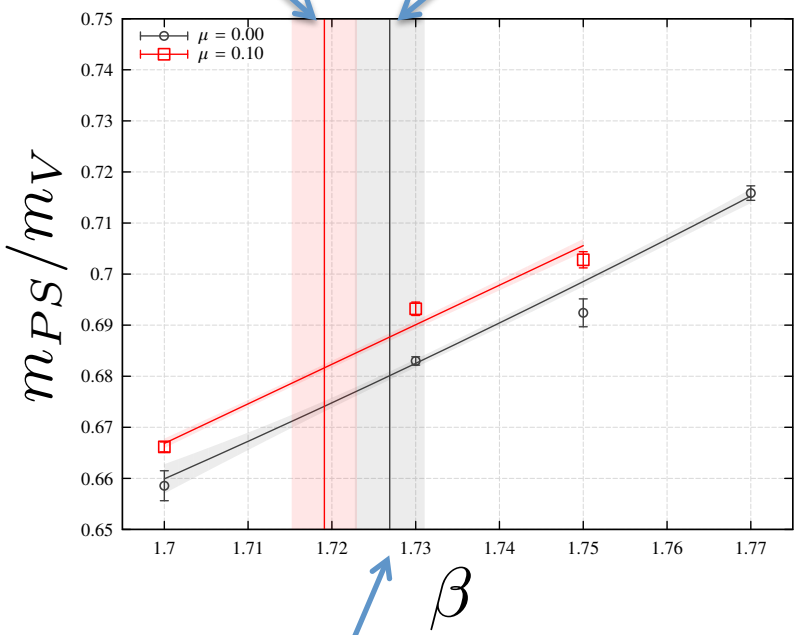


Nakamura-san's talk

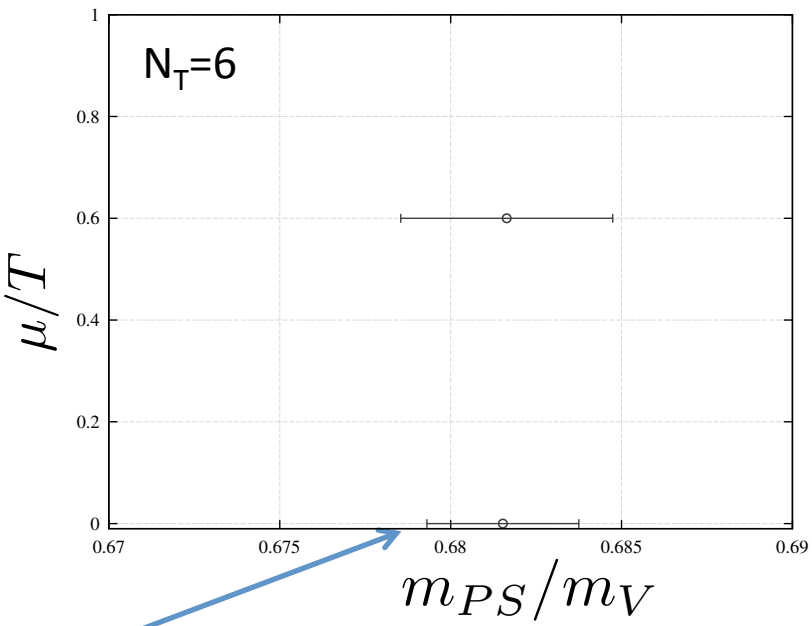
μ-dependence of CEP

CEP for aμ=0.1

CEP for aμ=0



small slope!!!



Nakamura-san's talk

Summary

- Z_2 universality class is favored
- Very small slope of critical end line at $\mu/T=0.6$

Outlook

- Exploring large μ region by β/μ reweighting
- Mixed observable analysis to reduce FSE
- Continuum limit is not taken so far (only $N_T=6$)
  - Challenging to increase $N_T=8,10,\ldots$
- 2+1 flavor with $N_T=6$

BACKUP SLIDES

Zoom of moments of chiral cond.