The QCD phase diagram at vanishing baryon density

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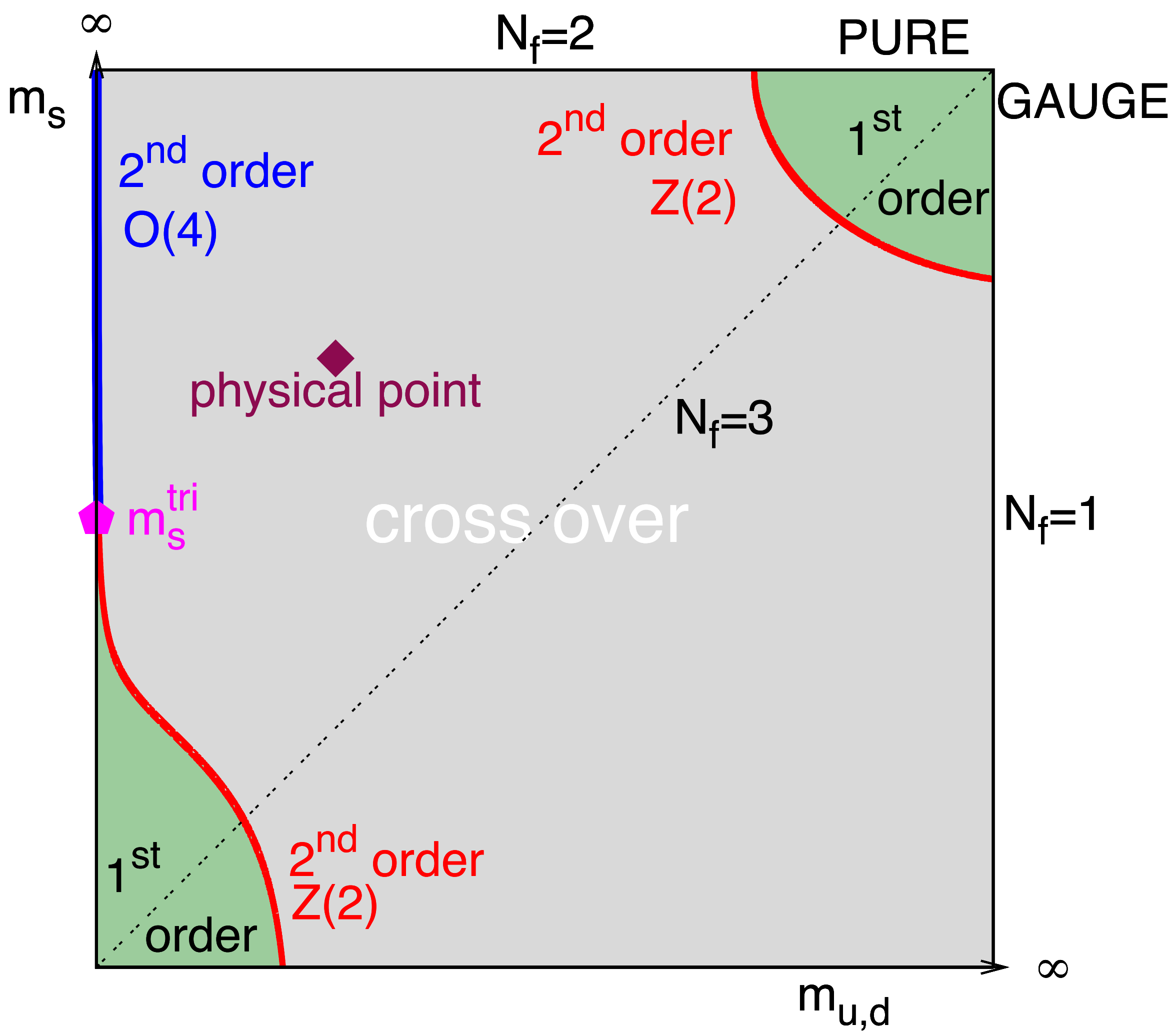
done in collaboration with Alexei Bazavov, Prasad Hegde, Frithjof Karsch, Swagato Mukherjee, Peter Petreczky

arXiv:1111.0185

The QCD phase diagram

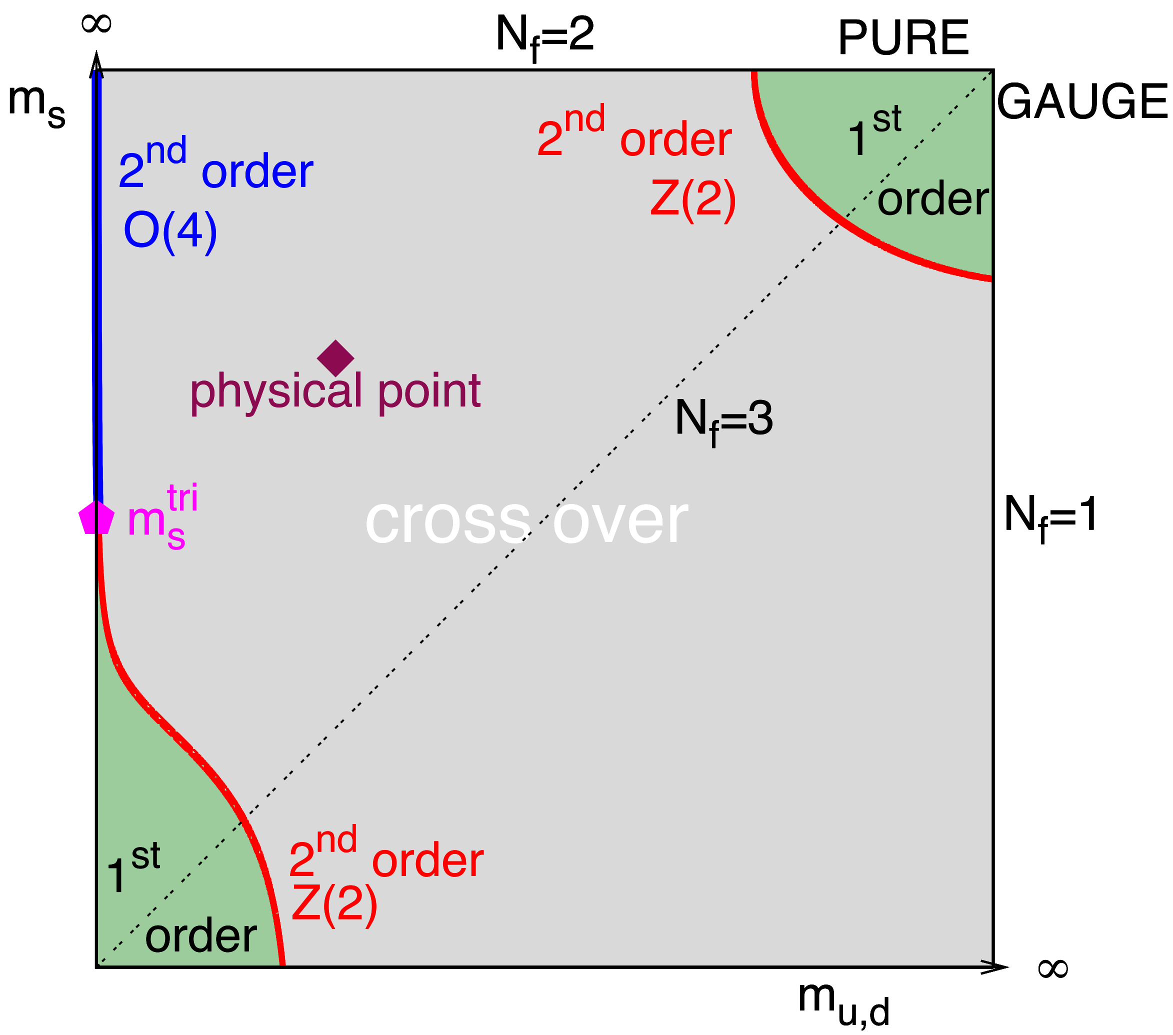


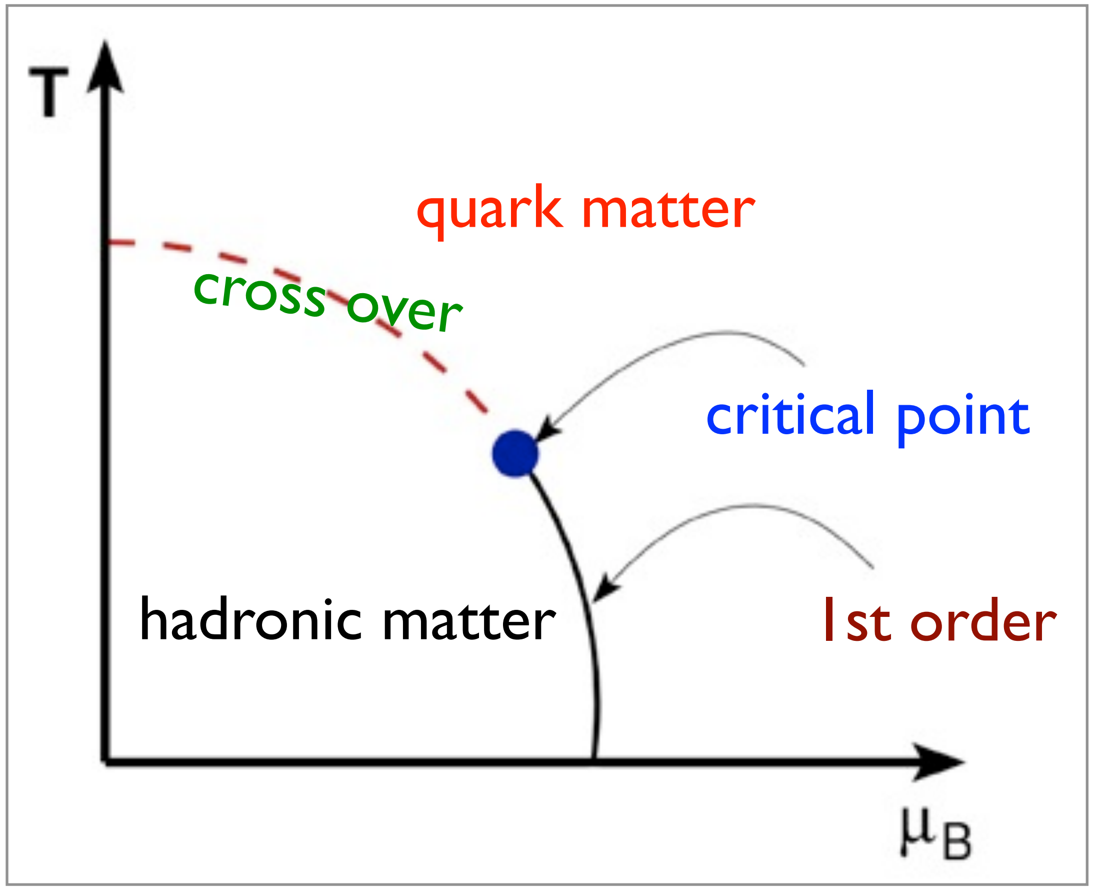
- N_f=2+1 theory: at m=0 or ∞ has a first order phase transition Pisarski, Wilczek PRD '84, Alexandrou et al., PRD'99...
- Intermediate quark mass region an analytic cross over is expected
- At physical quark masses, a cross over is confirmed Bernard et al., PRD '05, Cheng et al., PRD '06, Aoki et al., Nature '06...
- Critical lines of second order transition

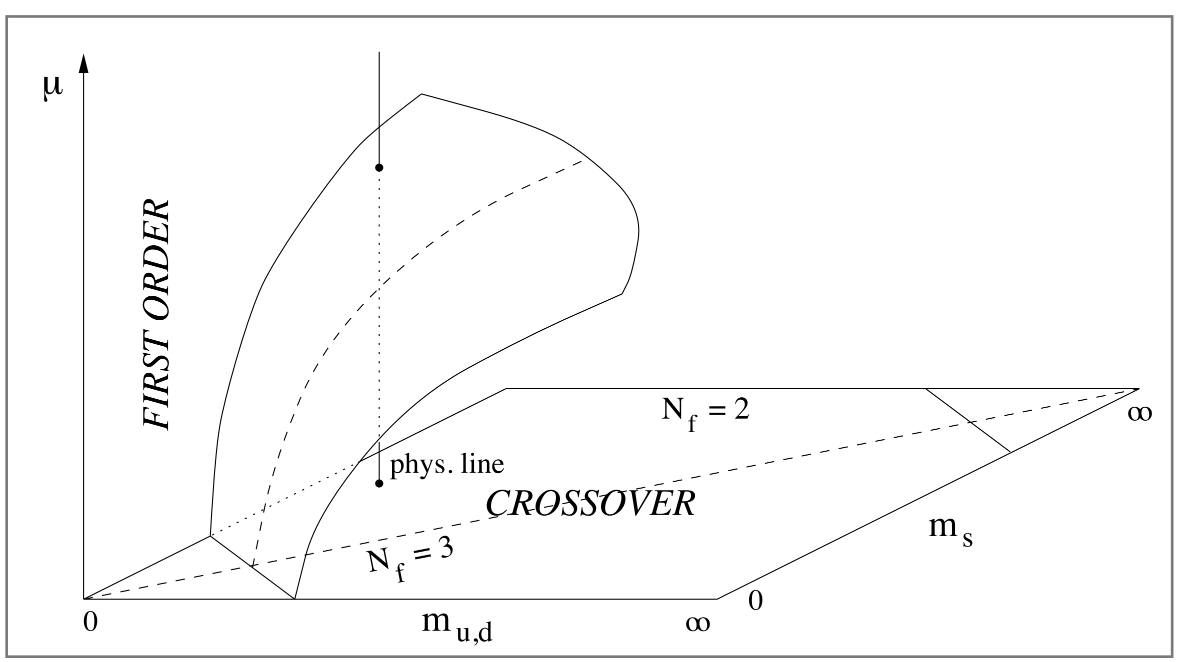
  N_f=2: O(4) universality class Ejiri et al., PRD '09, ...

  N_f=3: Ising universality class Karsch, Laermann, Schmidt PLB '04,...

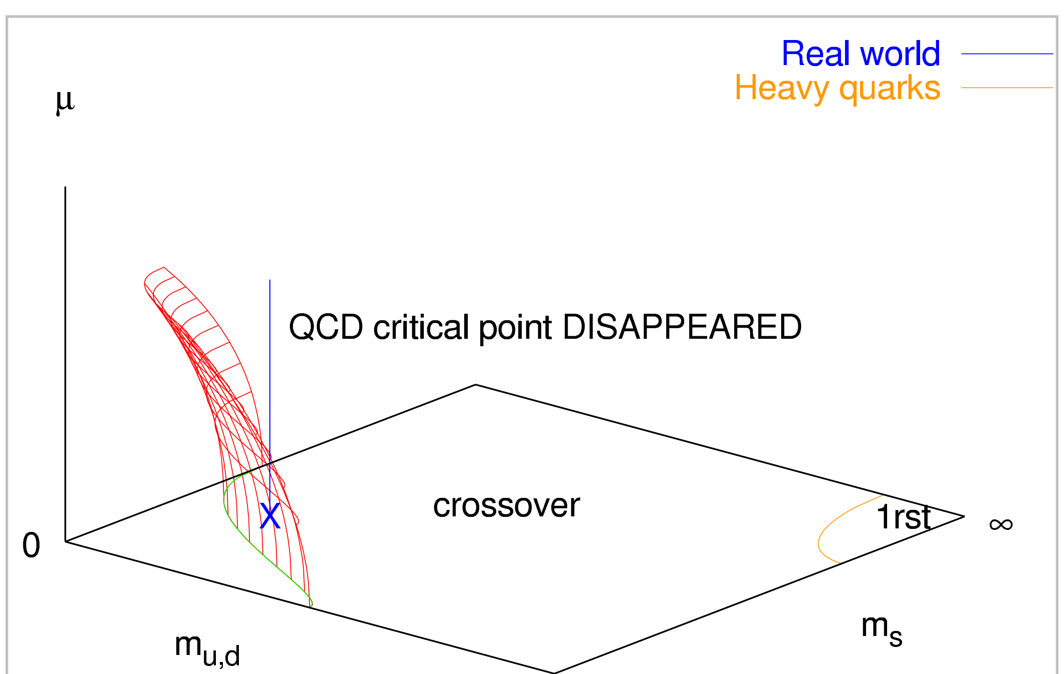
The QCD phase diagram





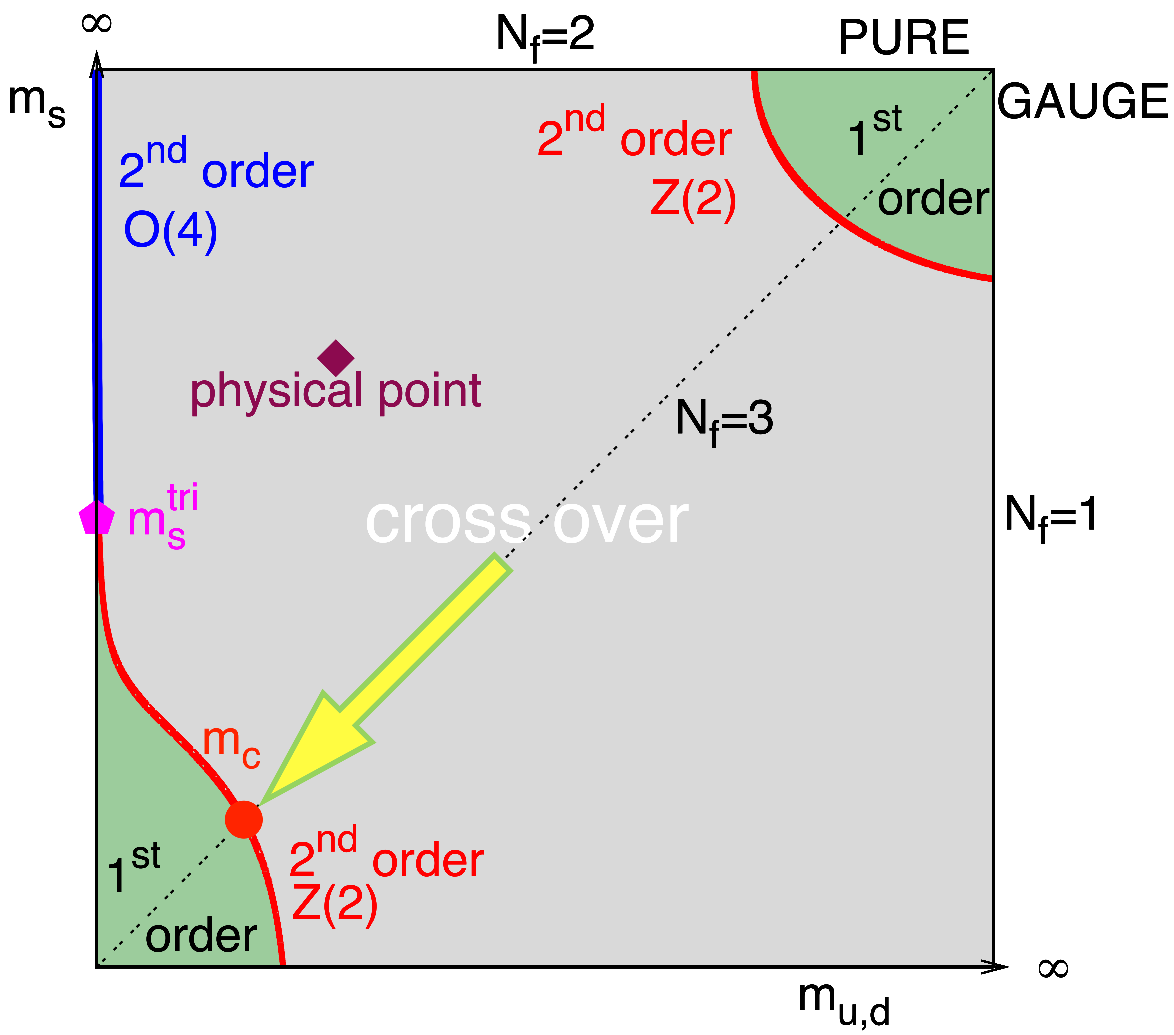


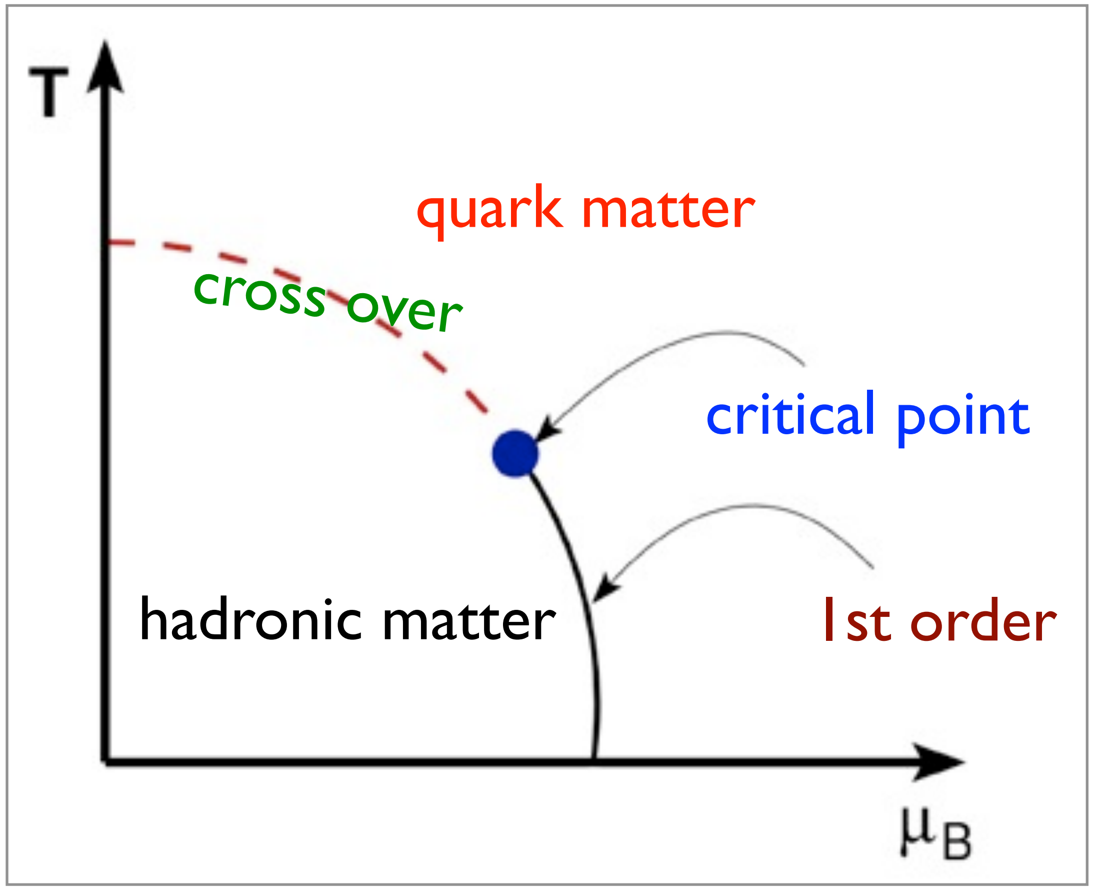
Karsch et al., '03

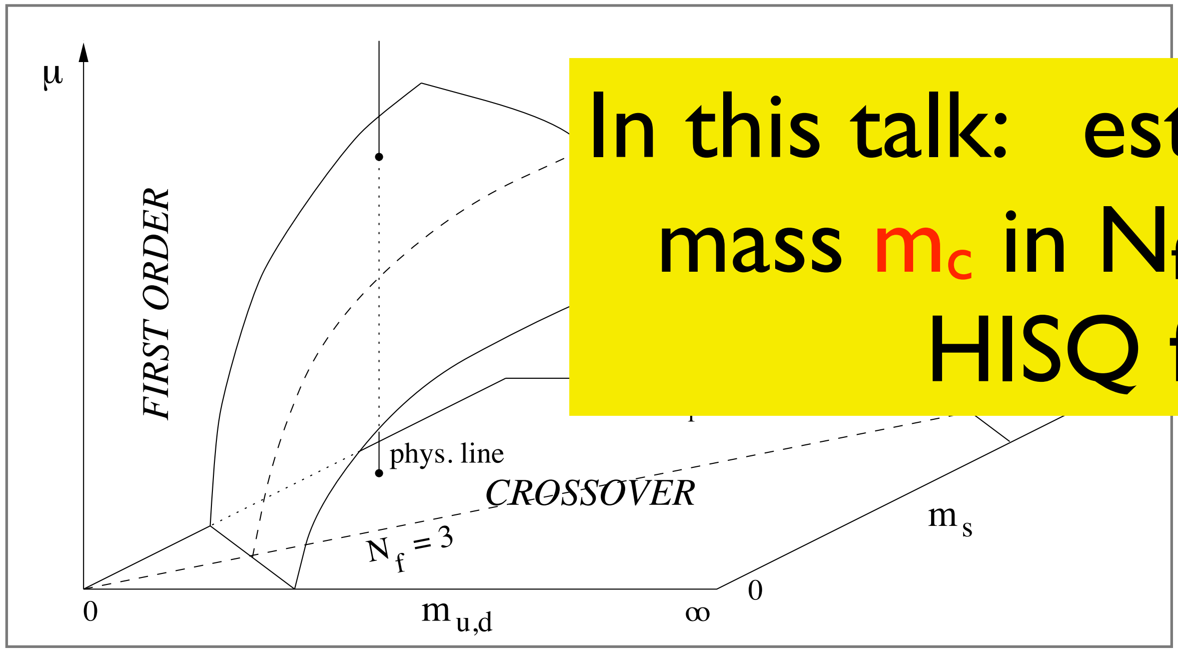


de Forcrand & Philipsen, '07

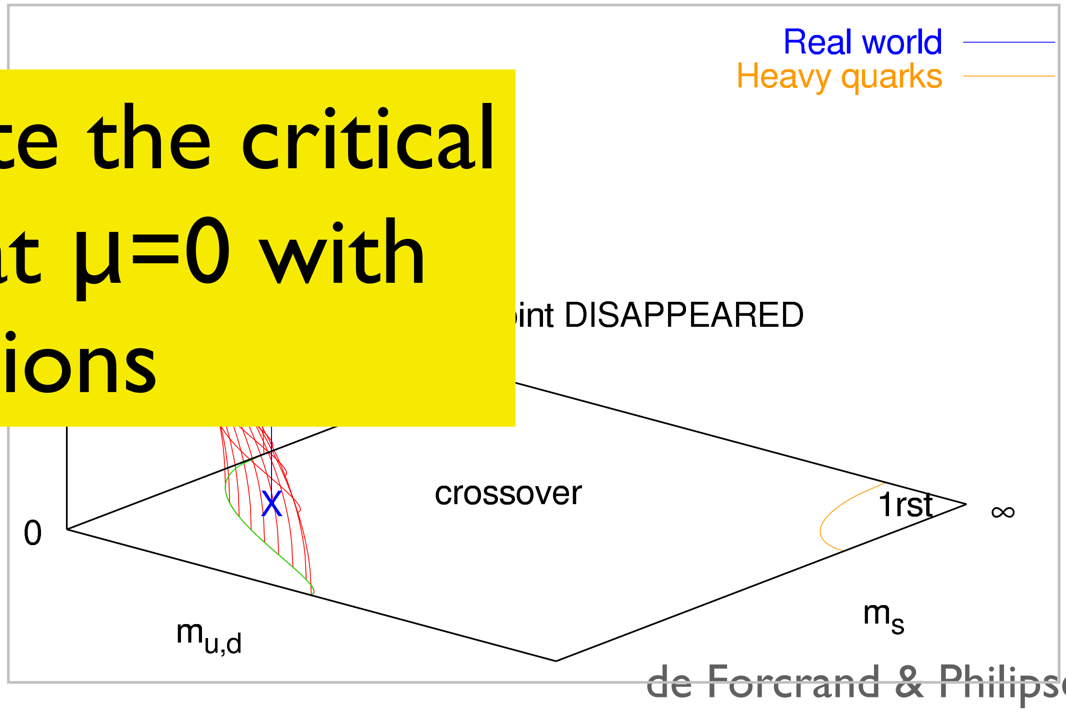
The QCD phase diagram







In this talk: estimate the critical mass m_c in N_f=3 at μ=0 with HISQ fermions



Karsch et al., '03

de Forcrand & Philipsen, '07

Universality class near critical lines

Behavior of the free energy close to critical lines

$$f(m,T)=h^{1+1/\delta} f_s(z) + f_{reg}(m,T)$$

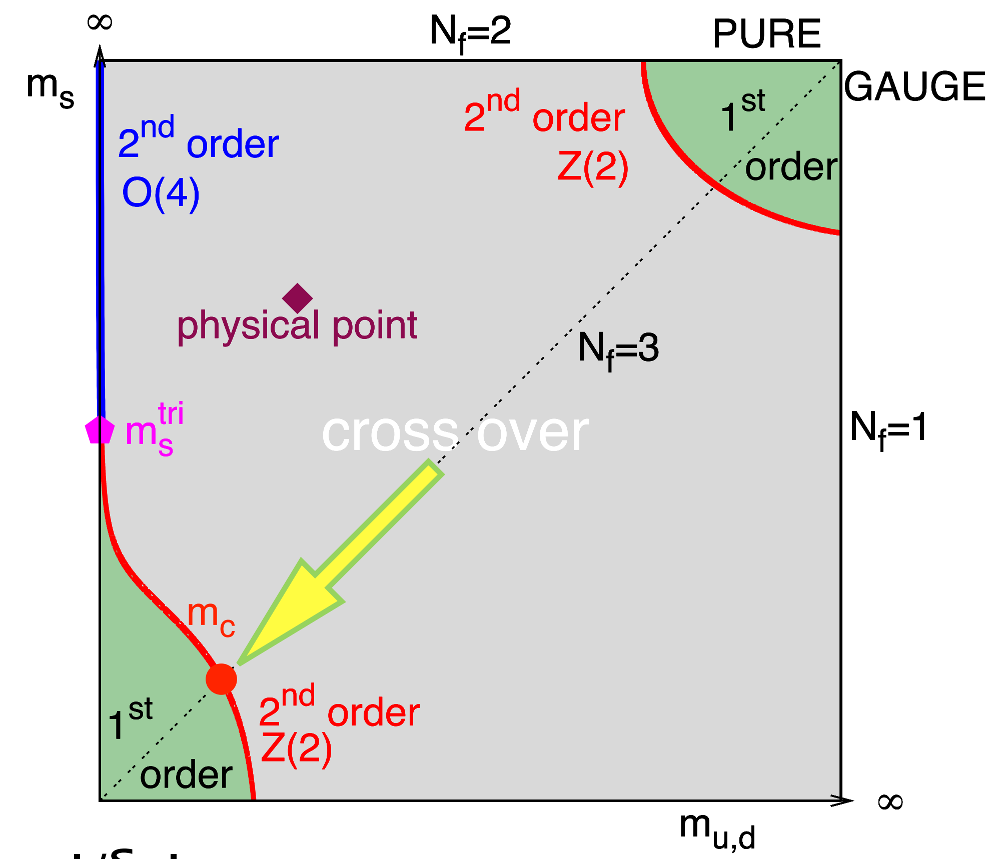
$h \sim m-m_c$

$t \sim T-T_c$

$z=t/h^{1/\beta\delta}$, h: external field, t: reduced scaling variable

$f_s(z)$: universal scaling function, Z(2) etc.

β,δ: universal critical exponents



Magnetic Equation of State (MEoS):

$$M = -\partial f_s(t,h)/\partial h = h^{1/\delta} f_G(z)$$

M: order parameter

- $N_f=2$, $m_c=0$

$$M= \langle\bar{\Psi}\Psi\rangle/T^3\Big|_{\text{fixed } z} \sim m^{1/\delta} \qquad \chi_q/T^2\Big|_{\text{fixed } z} \sim m^{1/\delta-1}$$

- $N_f=3$, $m_c \neq 0$

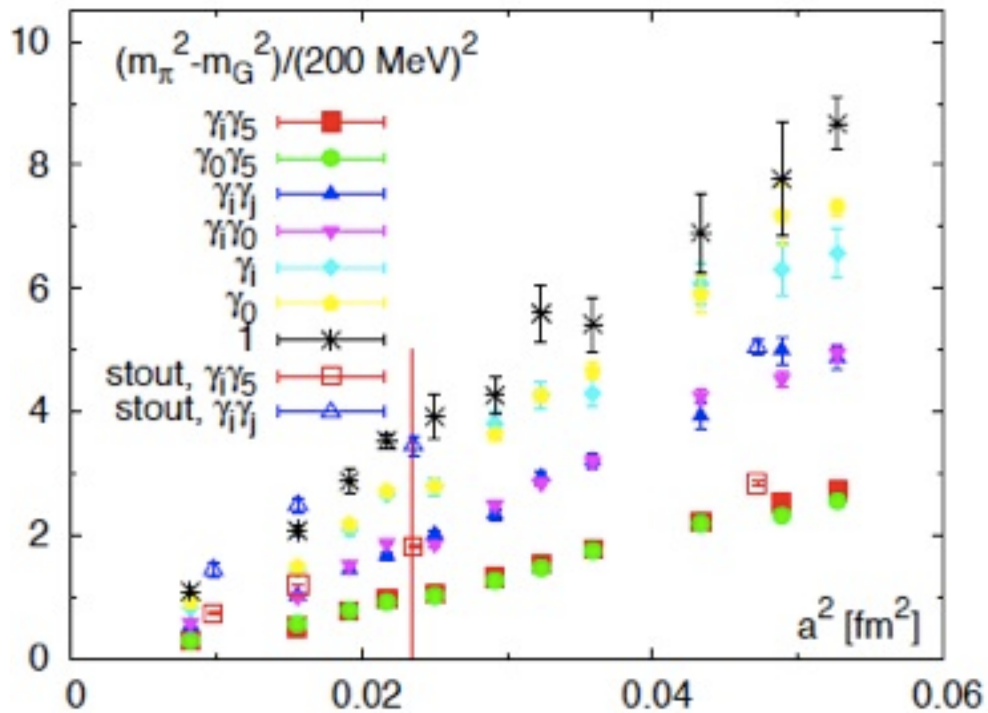
$$M= (\langle\bar{\Psi}\Psi\rangle + r \,\square)\Big|_{T=T_{c},m_c} \sim (m-m_c)^{1/\delta} \qquad \chi_q/T^2\Big|_{T=T_{c},m_c} \sim (m-m_c)^{1/\delta-1}$$

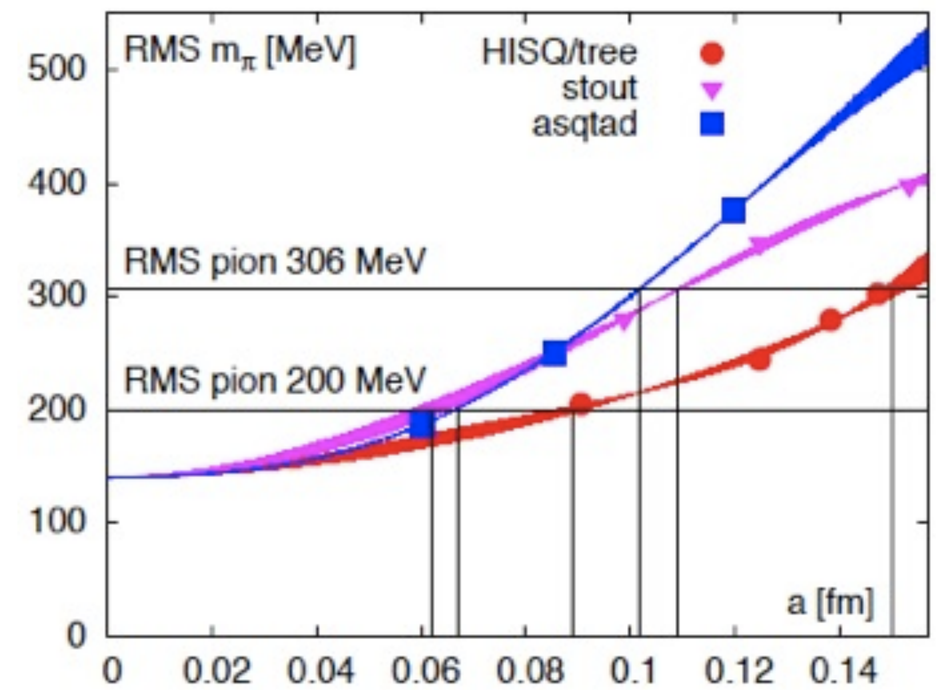
the value of m_π^c investigated so far...

Dependence on the choice of action

- Naive action: $N_\tau = 4 \;\Rightarrow m_\pi^c \approx 290$ MeV F. Karsch et al., Nucl.Phys.Proc.Suppl. 129 (2004) 614
- Naive action: $N_\tau = 6 \;\Rightarrow m_\pi^c \approx 140$ MeV *P. de Forcrand et al, PoS LATTICE2007 (2007) 178*
- p4fat3 action: $N_\tau = 4 \;\Rightarrow m_\pi^c \approx 67$ MeV F. Karsch et al., Nucl.Phys.Proc.Suppl. 129 (2004) 614
- stout action: $N_\tau = 6 \;\Rightarrow m_\pi^c \lesssim 50$ MeV G. Endrodi et al., PoS LAT2007 (2007) 228

Highly Improved staggered quarks (HISQ) used in this work





Bazavov and Petreczky, PoS LAT2010,169(2010)

Lattice data for N_f=3 and N_τ=6

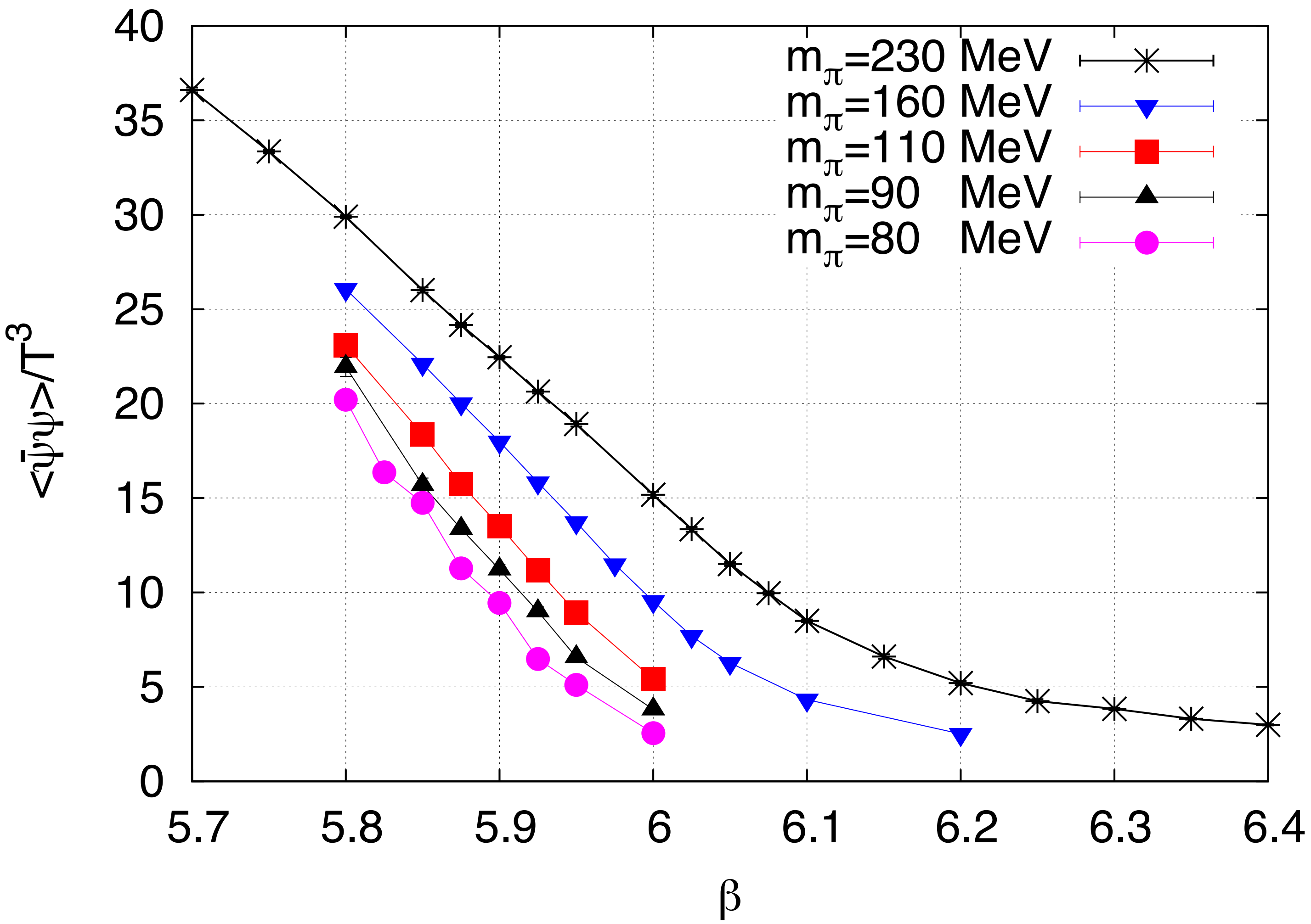
★ Highly Improved staggered fermions/tree action used

★ 3 degenerate quarks

★ N_τ=6 lattices

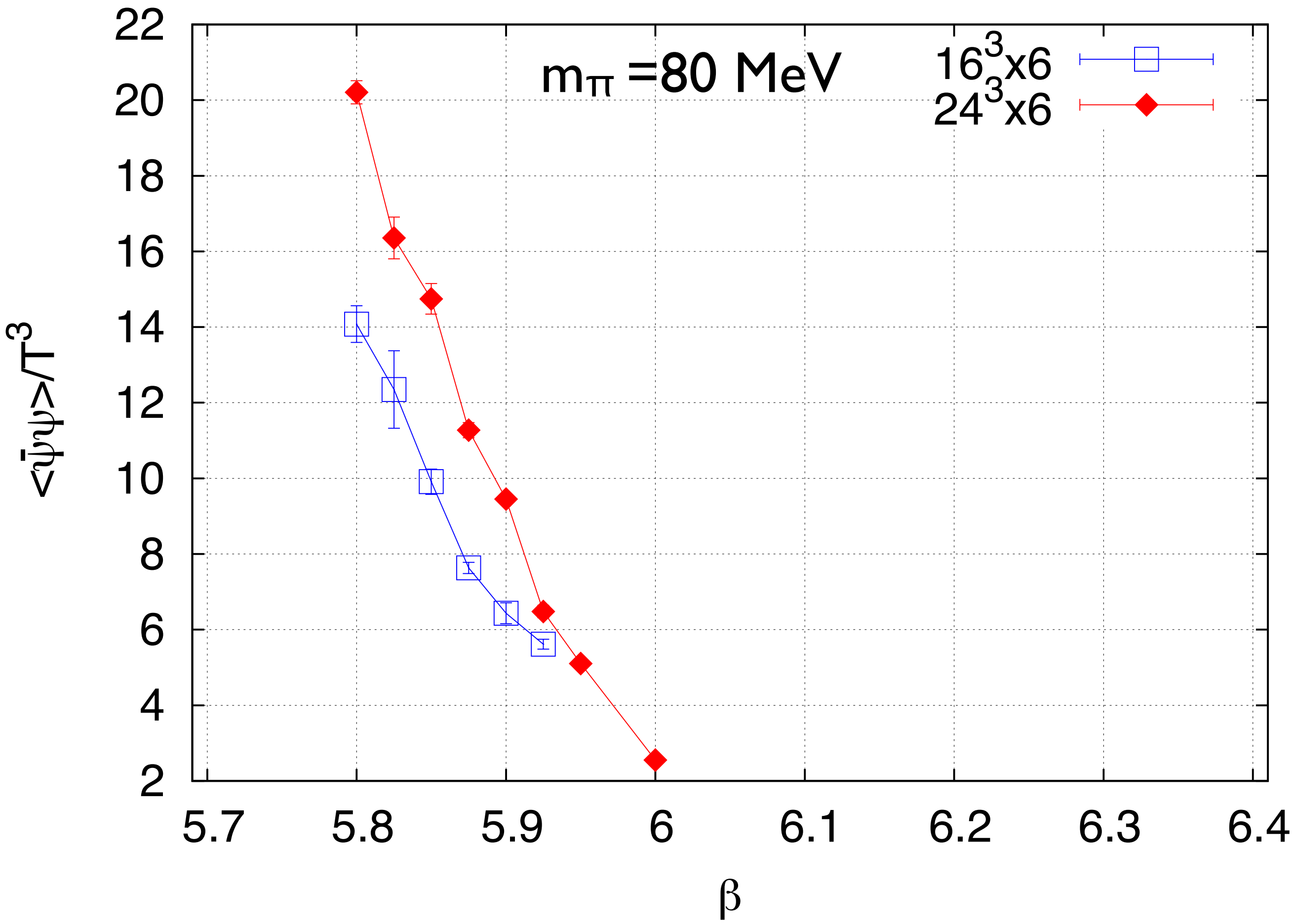
lattice dim	quark mass	m_π	#T	statistics
16^3x6	ma=0.0075	230 MeV	17	~6000
24^3x6	ma=0.00375	160 MeV	12	~8000
24^3x6	ma=0.001875	110 MeV	7	~8000
24^3x6	ma=0.00125	90 MeV	7	~5000
24^3x6	ma=0.0009375	80 MeV	8	~6000
16^3x6	ma=0.0009375	80 MeV	6	~7000

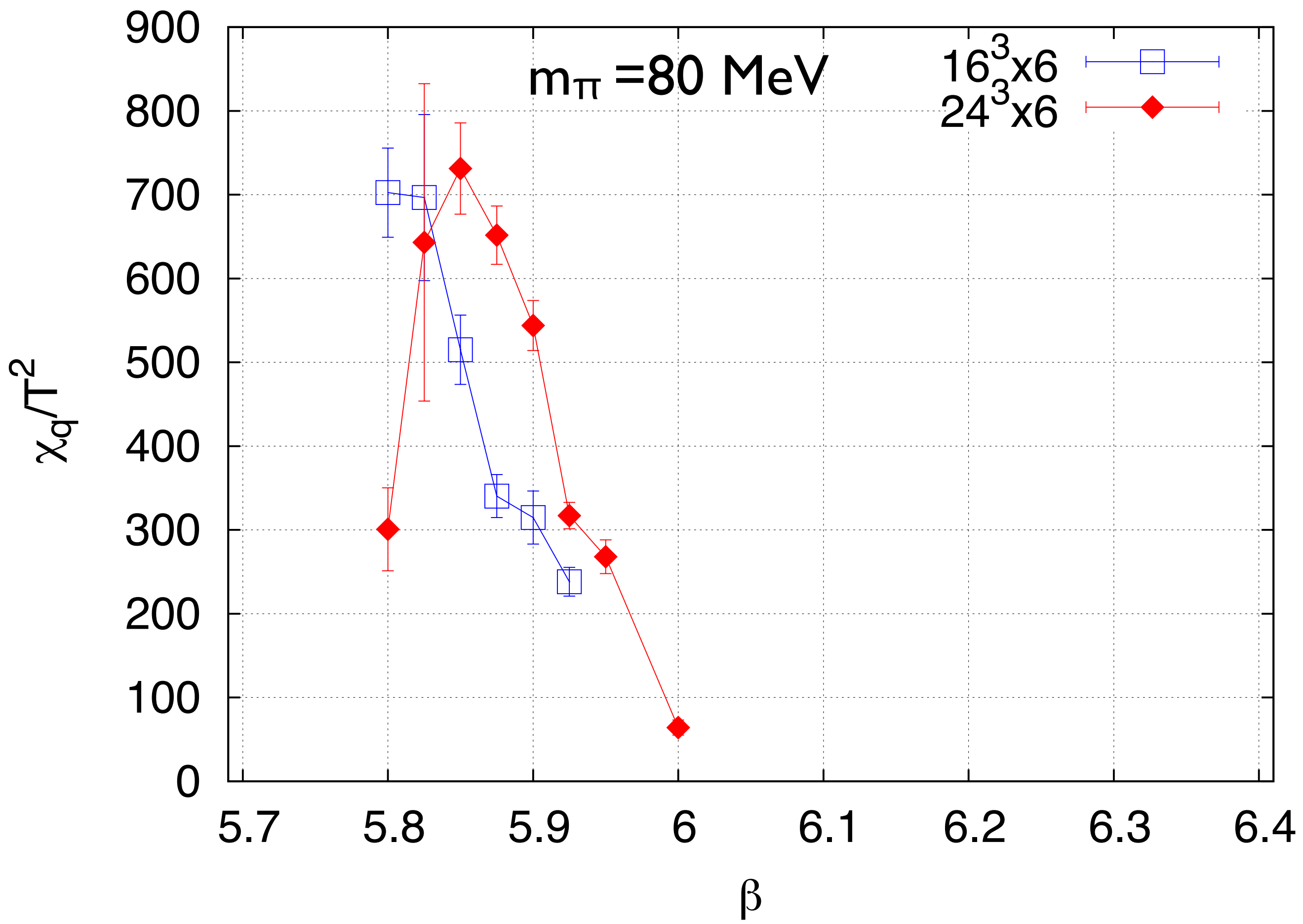
chiral condensate as an approx. order parameter



- No evidence for discontinuity is found

chiral condensate as an approx. order parameter





- finite volume effects bring chiral condensates down
- No evidence of volume scaling from chiral susceptibility

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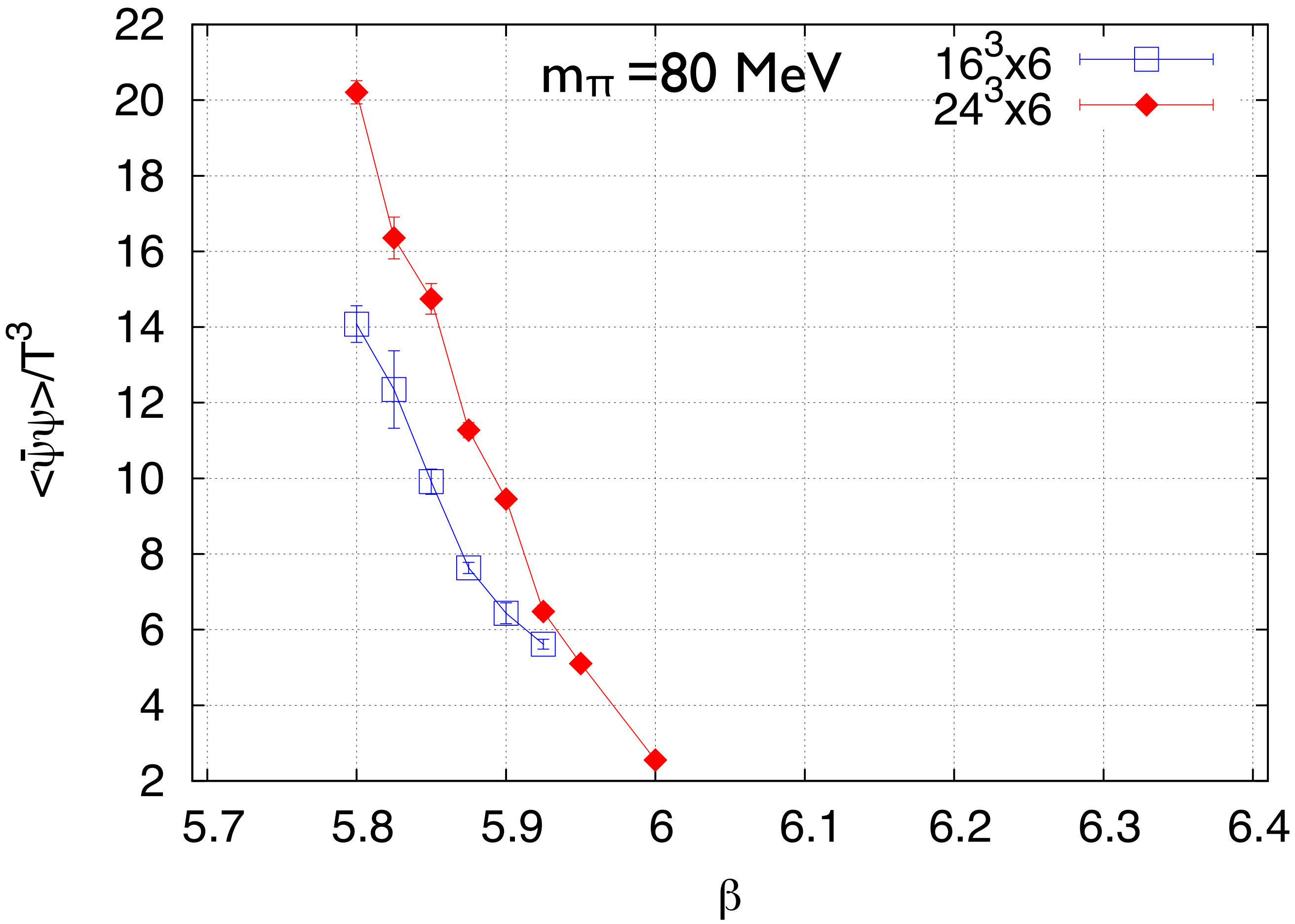
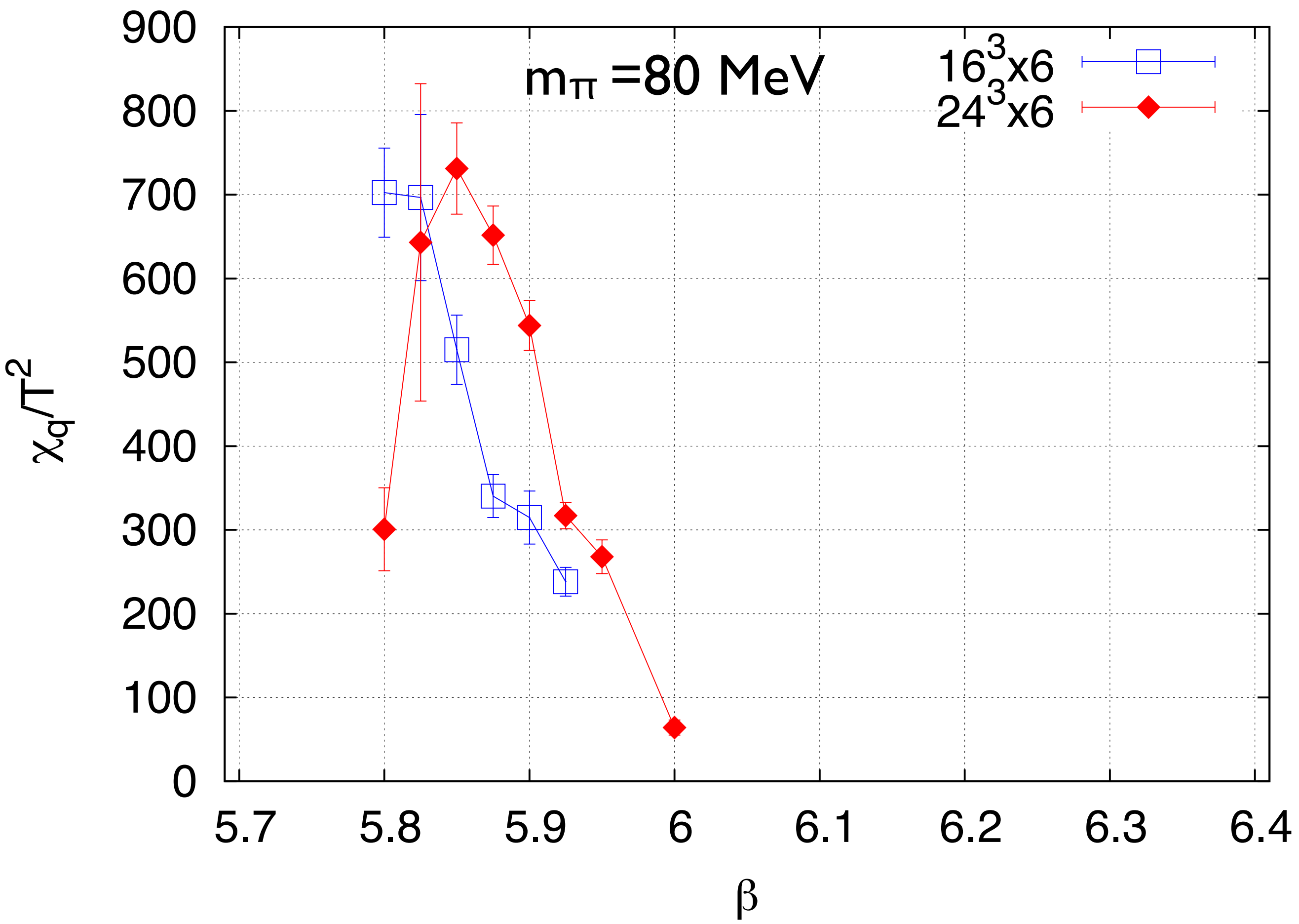
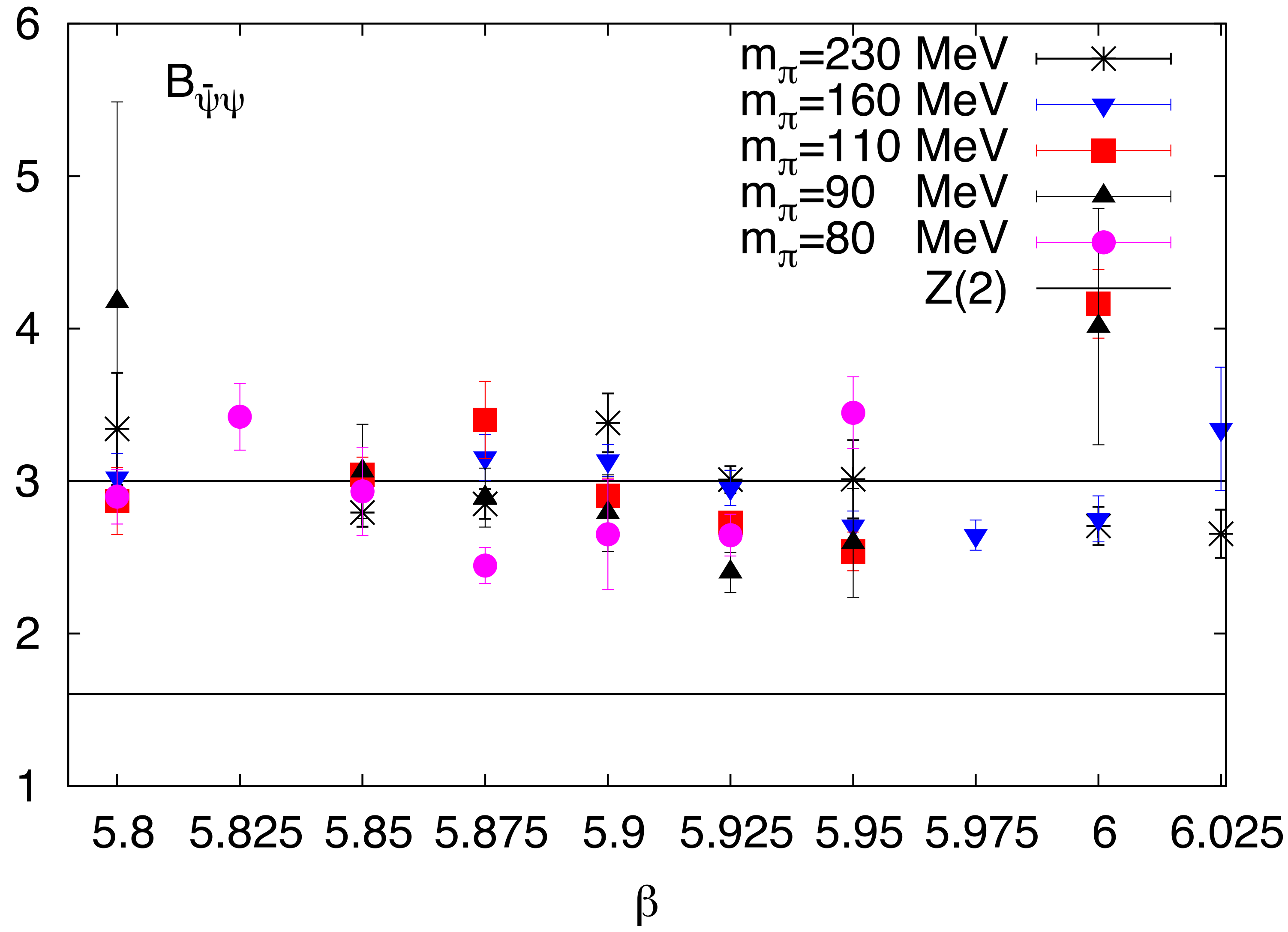




- finite volume effects bring chiral condensates down
- No evidence of volume scaling from chiral susceptibility
- With $230 \geq m_\pi \geq 80$ MeV, no direct signal of first order phase transition is found

Binder cumulant of chiral consendate

$$B_{\bar{\psi}\psi} \equiv \frac{\langle(\delta\bar{\psi}\psi)^4\rangle}{\langle(\delta\bar{\psi}\psi)^2\rangle^2}$$

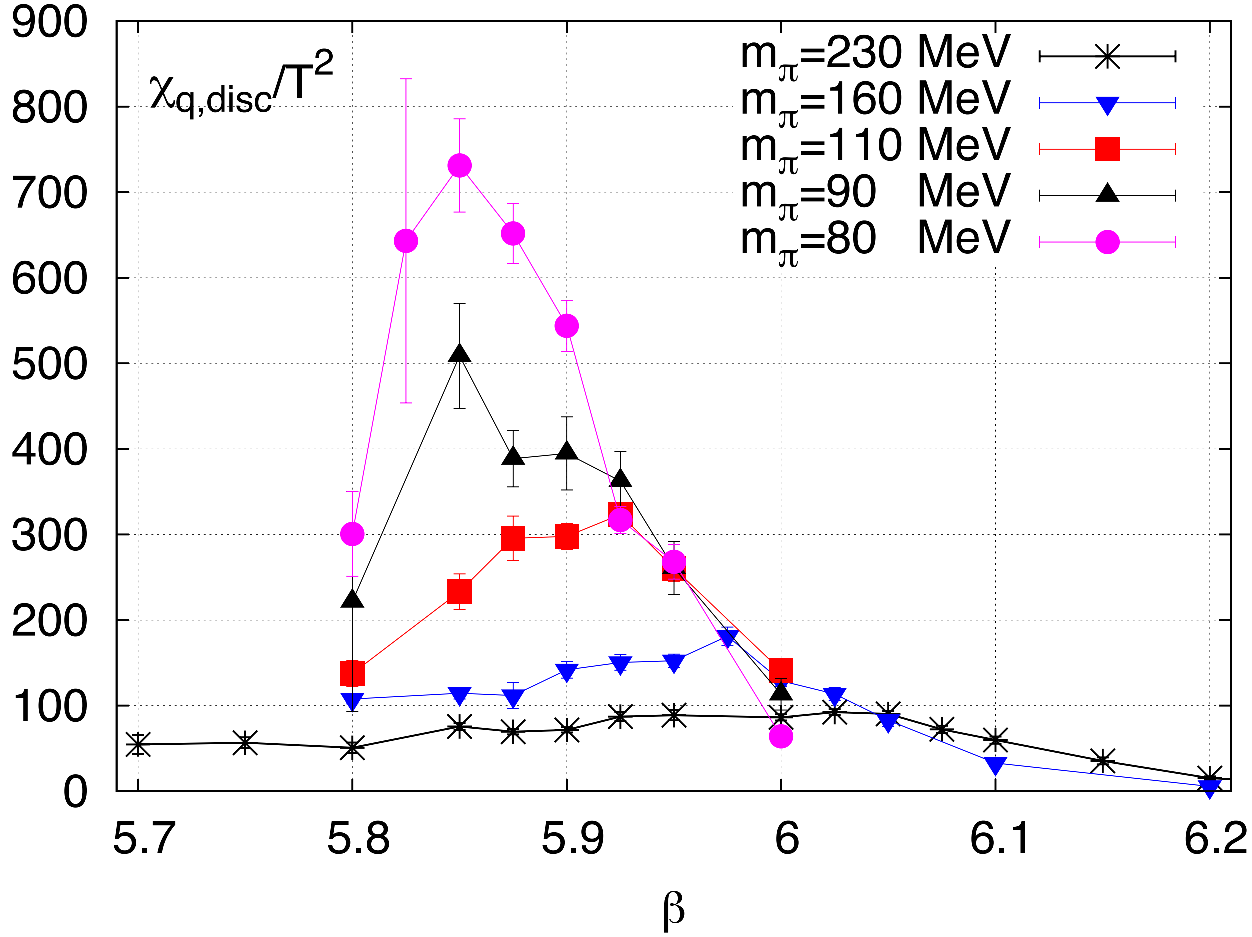


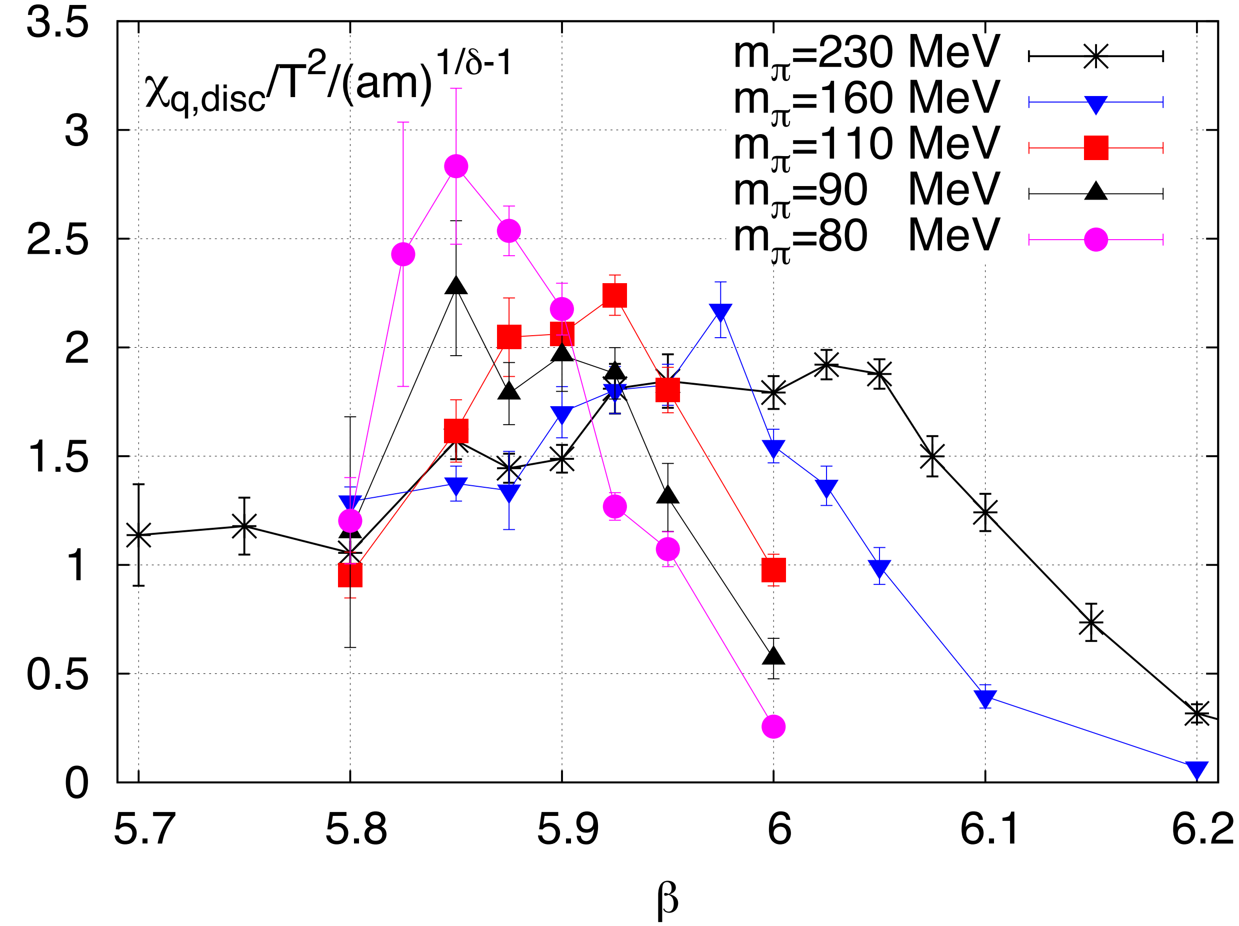
In the crossover region B=3

2nd order transition in the Ising universal class B=1.604

1st order transition B=1

chiral susceptibilities



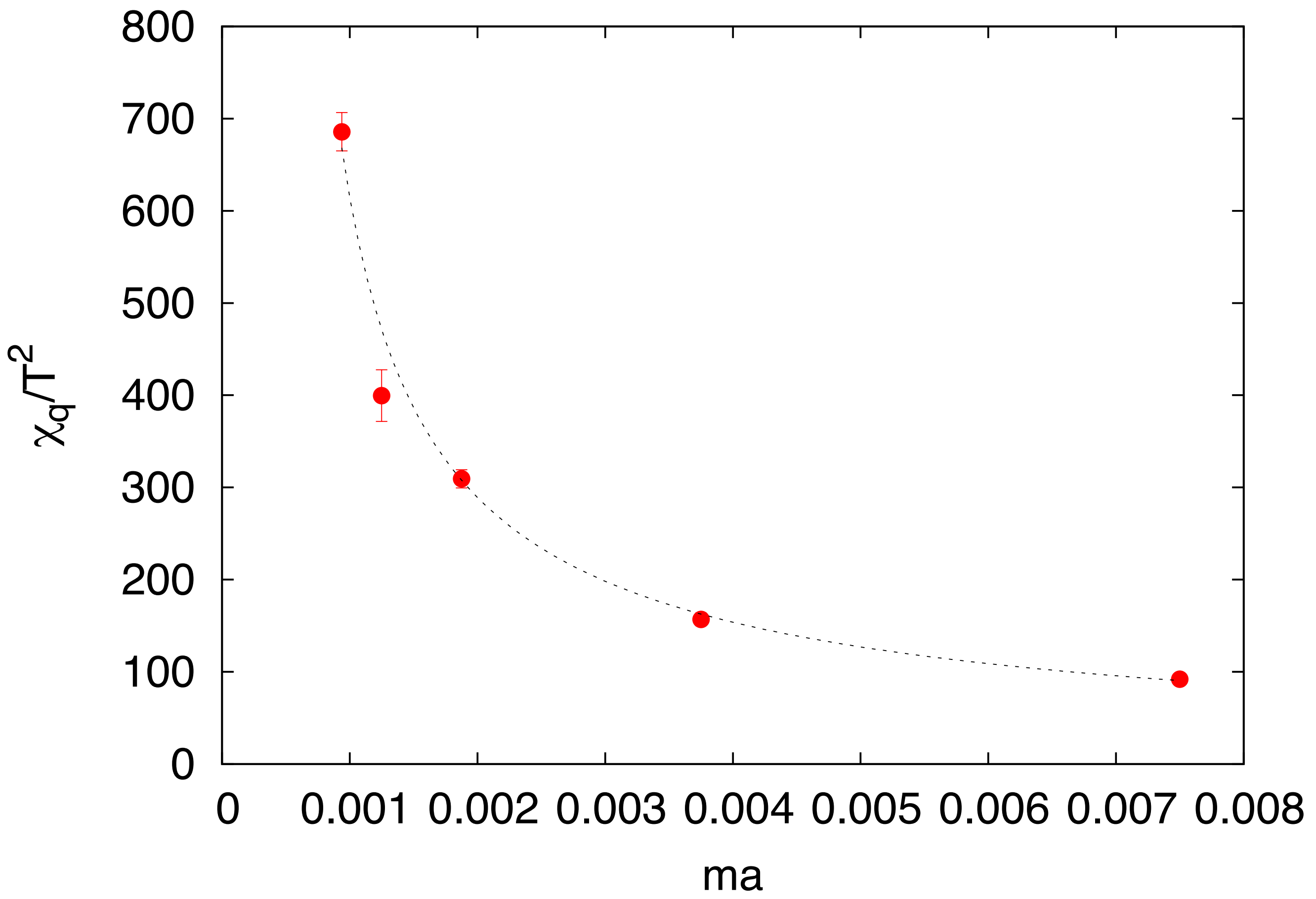


- peak locations in chiral susceptibilities shift to lower temperature with decreasing quark mass

- peak heights in chiral susceptibilities grow faster than $(am)^{1/\delta-1}$: indication of a non-zero critical mass m_c

estimate of the critical mass

Fitting ansatz: $\chi_q/T^2 = c\,(m-m_c)^{1/\delta-1}$

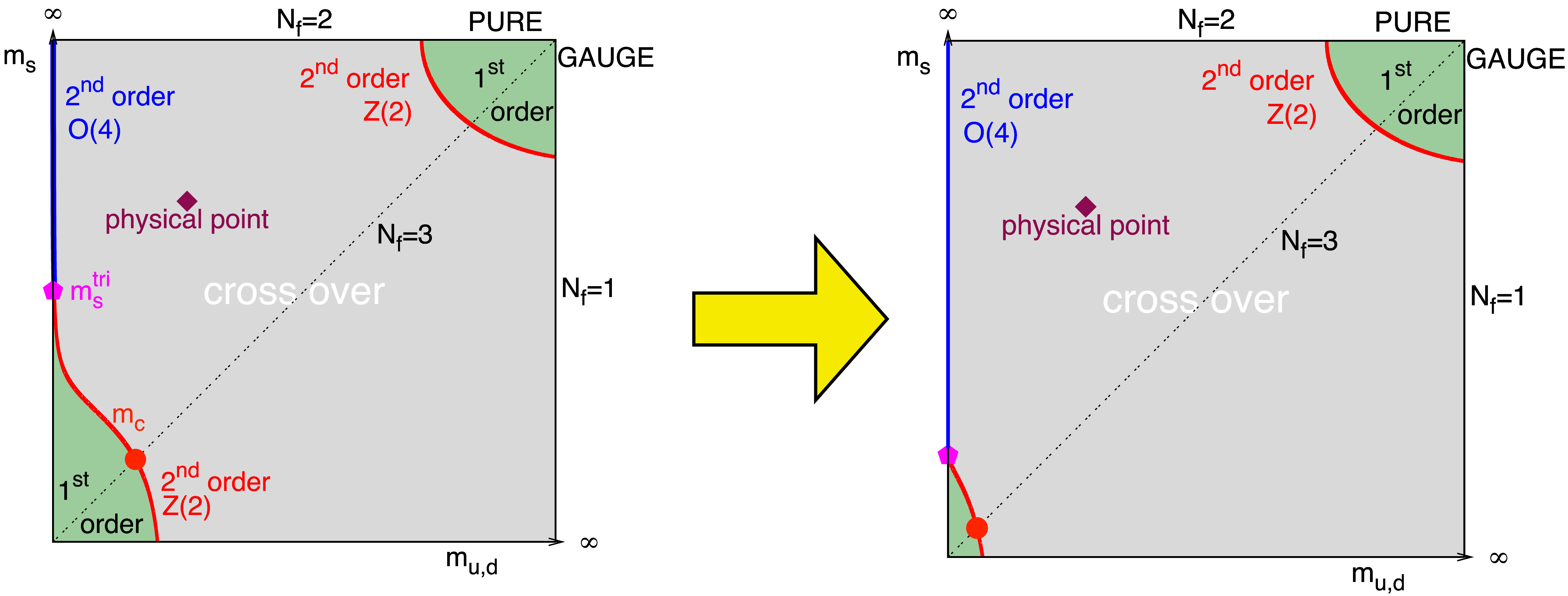


Navigation: am=0.0009375 ⇔ m_π =80 MeV

$am_c \approx 0.00037 \qquad m_\pi^c \approx 45$ MeV

finite V effects

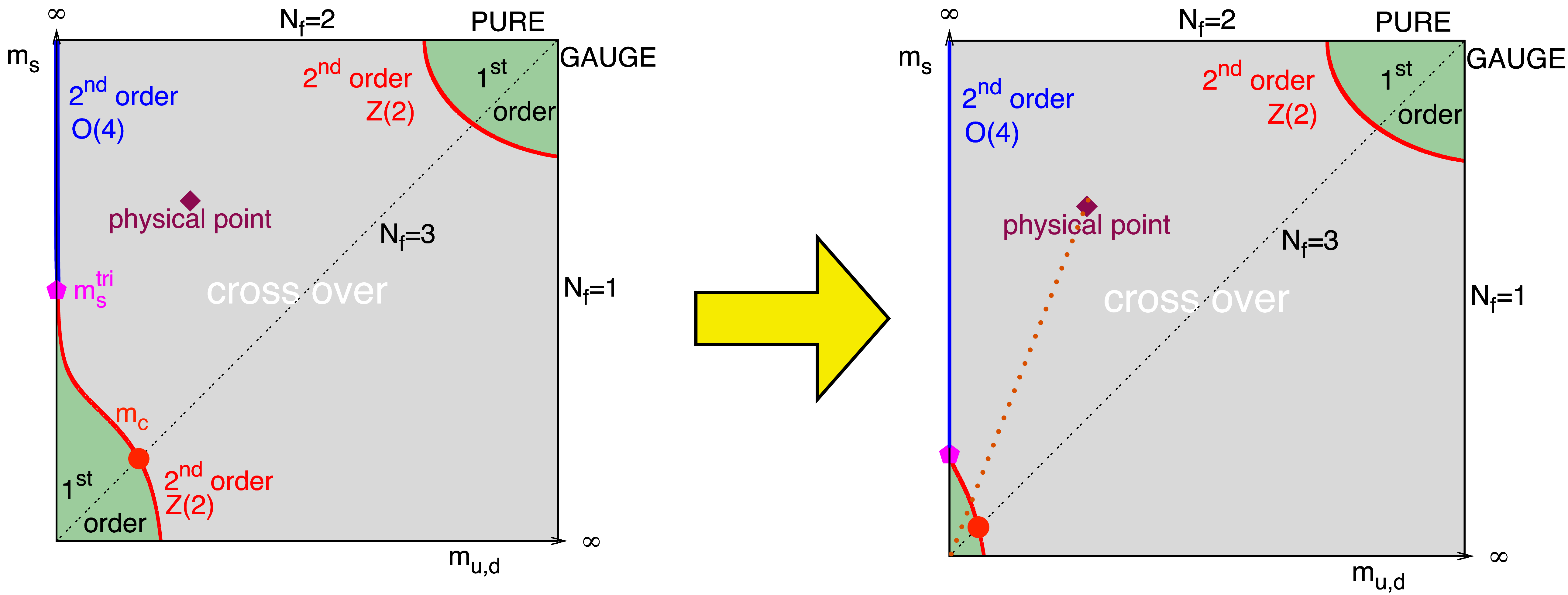
$m_\pi^c \lesssim 45$ MeV



coordinates of the physical point: $(\overline{m}_s/27, \overline{m}_s)$

3 degenerate quarks: coordinates of $m^c_{max} \approx (\overline{m}_s/270, \overline{m}_s/270)$

the first order phase transition region revisited



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non-degenerate quarks: coordinates of $m^c_{max} \approx (\overline{m}_s/225, \overline{m}_s/8)$ Endrodi et al.,'07

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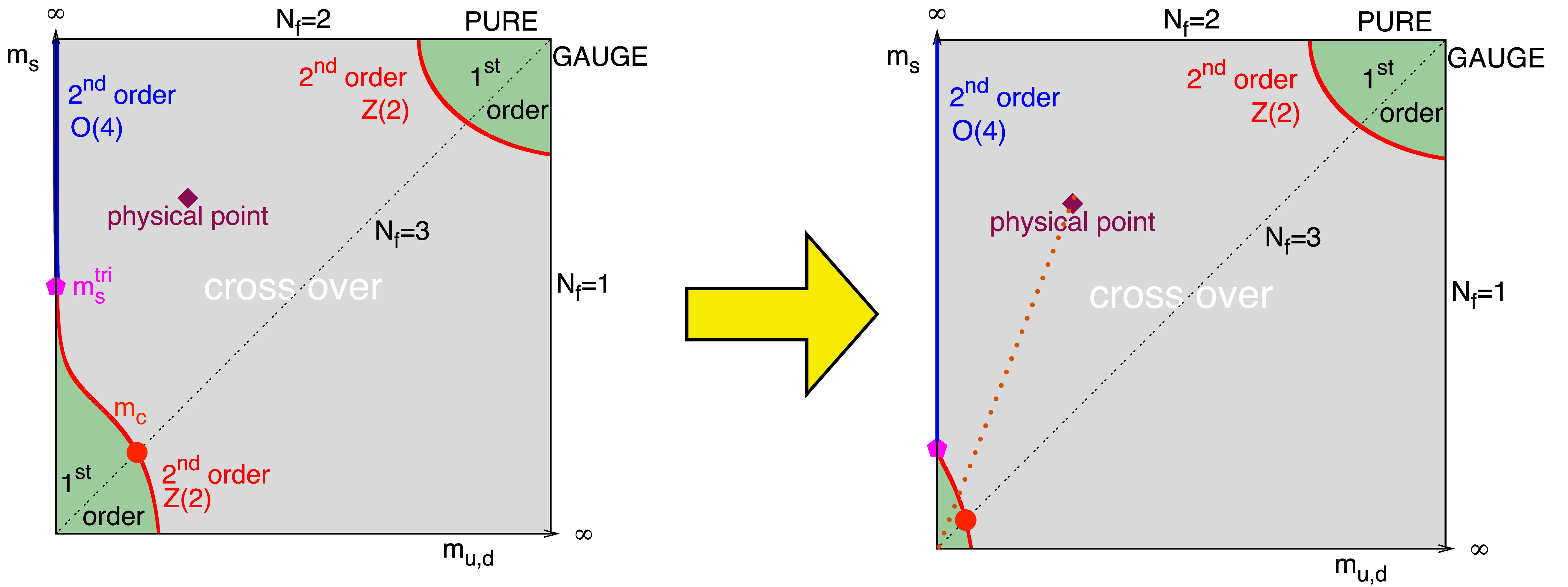

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Consequences: to have a critical point at small μ, the critical surface has to bend towards to the physical point with a very large curvature

Summary & Outlook

- We study the direct signal for first order phase transition with m_π from 230 MeV down to 80 MeV for N_f=3 on N_τ=6 lattices using the HISQ action

- No evidence for first order phase transition is found with 230 MeV $\geq m_\pi \geq$ 80 MeV

- From scaling analysis on chiral susceptibility, current estimation gives $m_\pi^c \lesssim$ 45 MeV, which indicates the first order chiral phase transition region is far away from the physical point