Chiral phase transition of N_f=3 and 2+1 QCD at μ_B =0

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for the Bielefeld-BNL-CCNU collaboration

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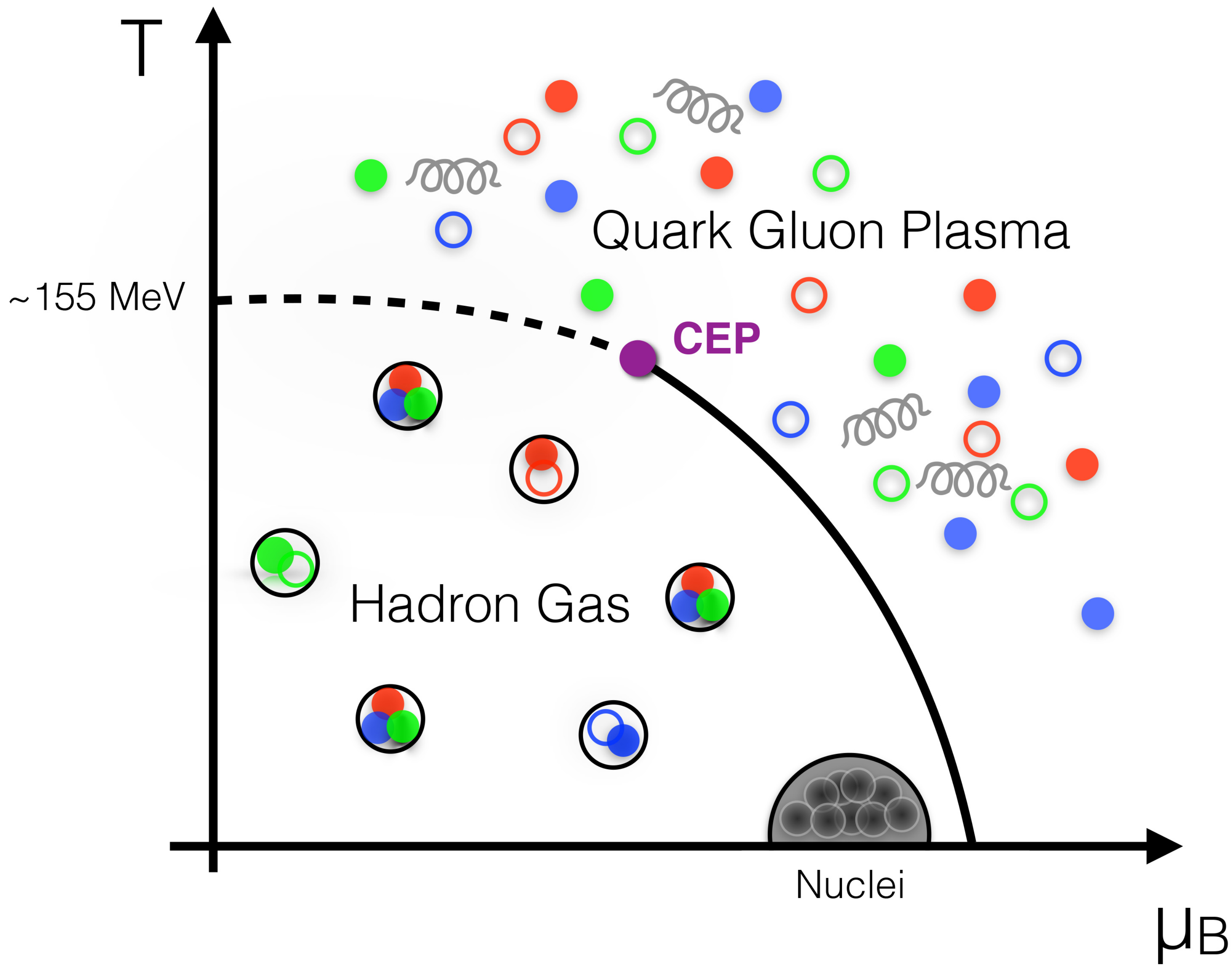
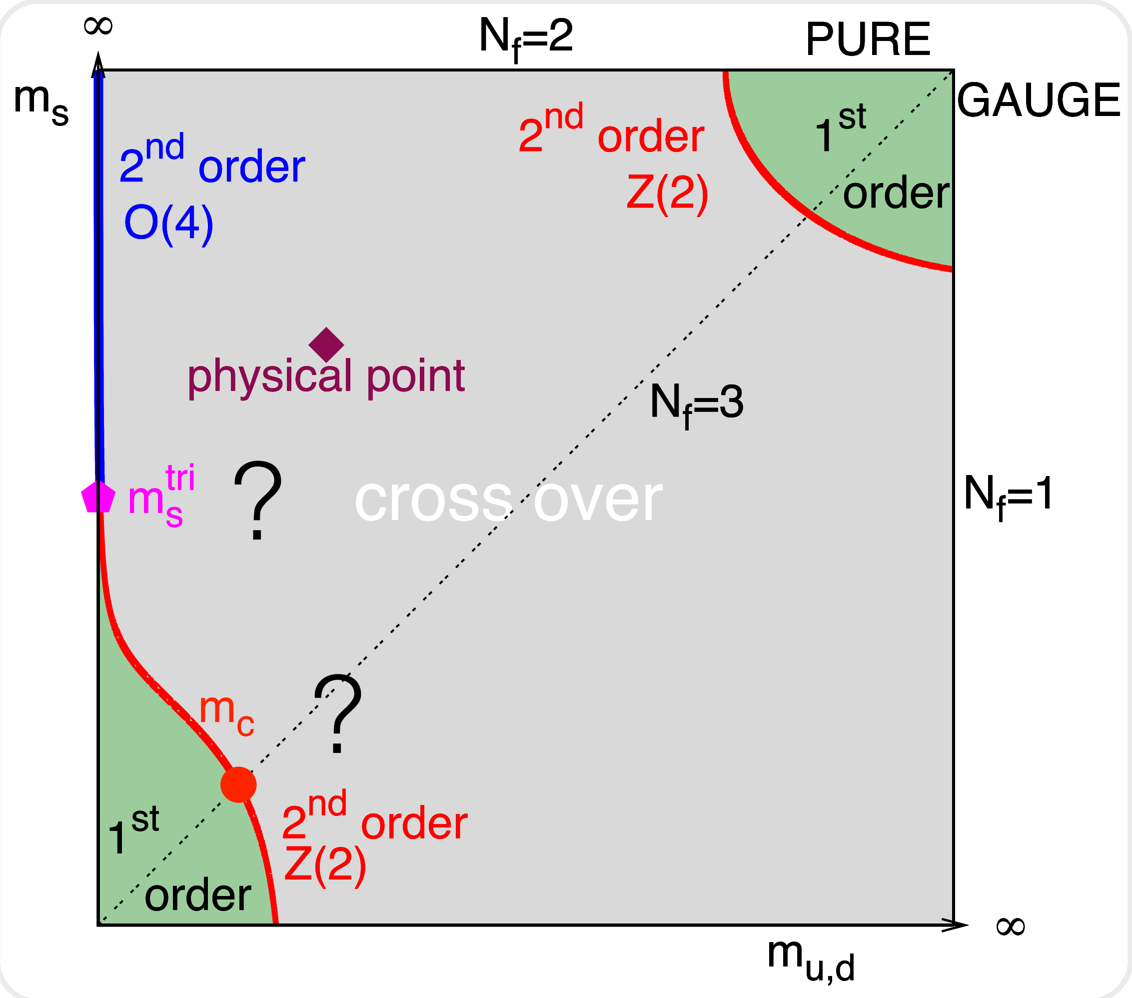
QCD phase diagram



HTD, F. Karsch, S. Mukherjee, arXiv:1504.0527

QCD phase diagram at $\mu_B=0$

columbia plot:

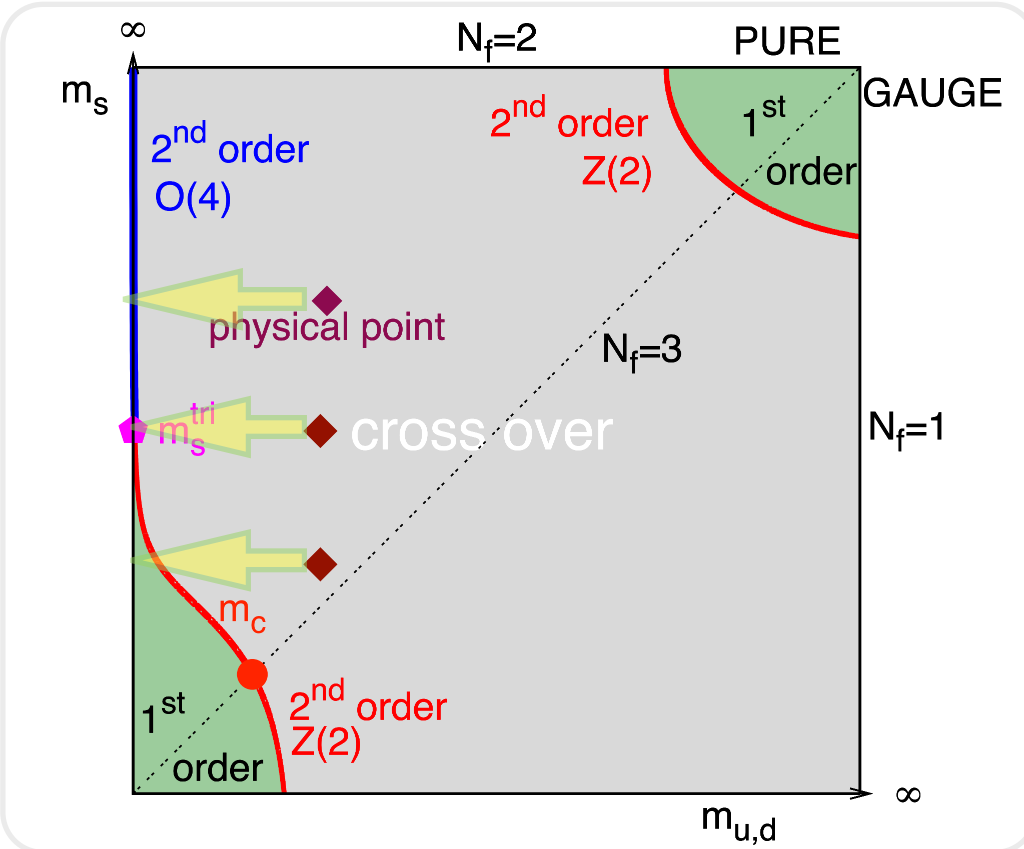


- At physical point: cross over, $T_{pc} \sim 155$ MeV HotQCD '12, BMW '10
- N_f=2(+1): $U_A(1)$ remains broken at $T_{\chi SB}$ JLQCD '13,'14,'15, HotQCD '13,'14
- Critical lines of second order transition
  - N_f=2: O(4) universality class Pisarski & Wilczek PRD '84, Kogut & Sinclair, PRD '06
  - N_f=3: Ising universality class Karsch, Laermann, Schmidt PLB '04,...

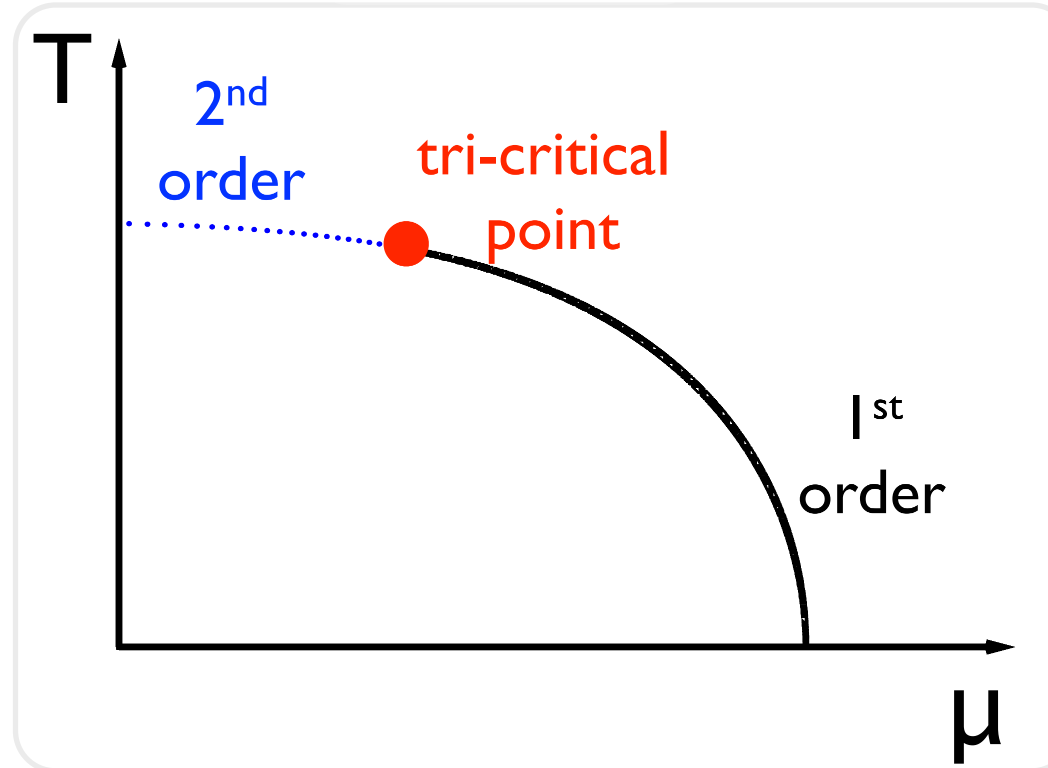
Towards the chiral limit:

- N_f=2+1 QCD: m_s^{tri} ? m_s^{phy}
- N_f=3 QCD: critical mass m_c?

scenarios of QCD phase transition at m_l=0



$m_s^{phy} > m_s^{tri}$



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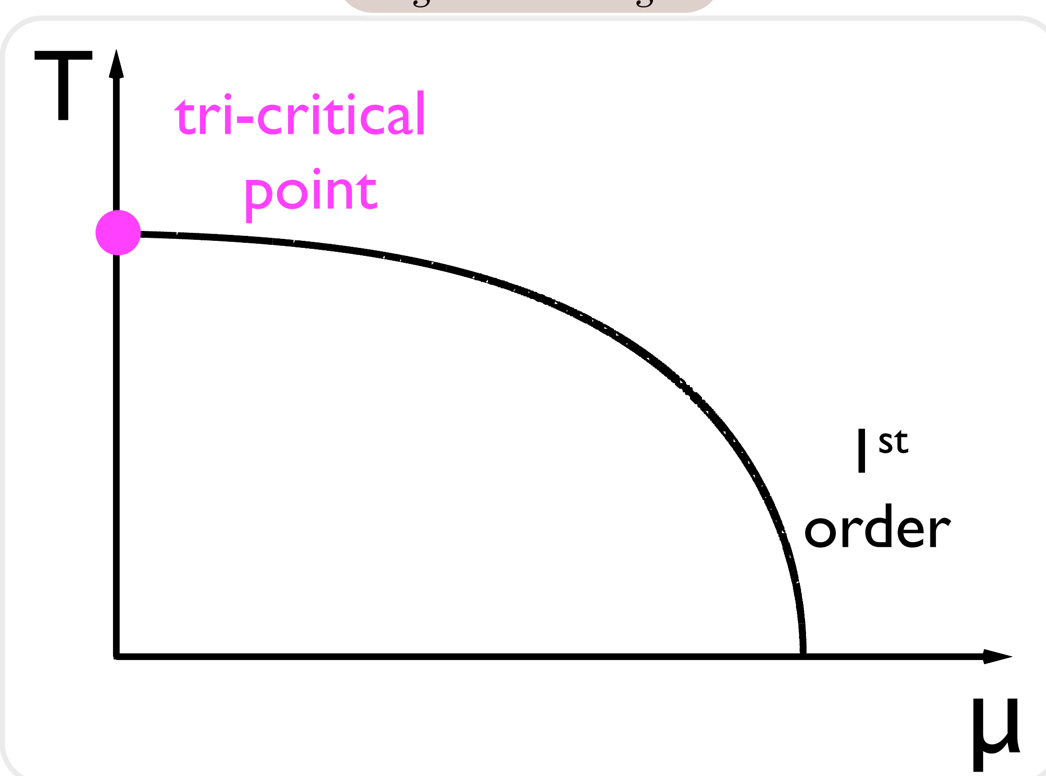
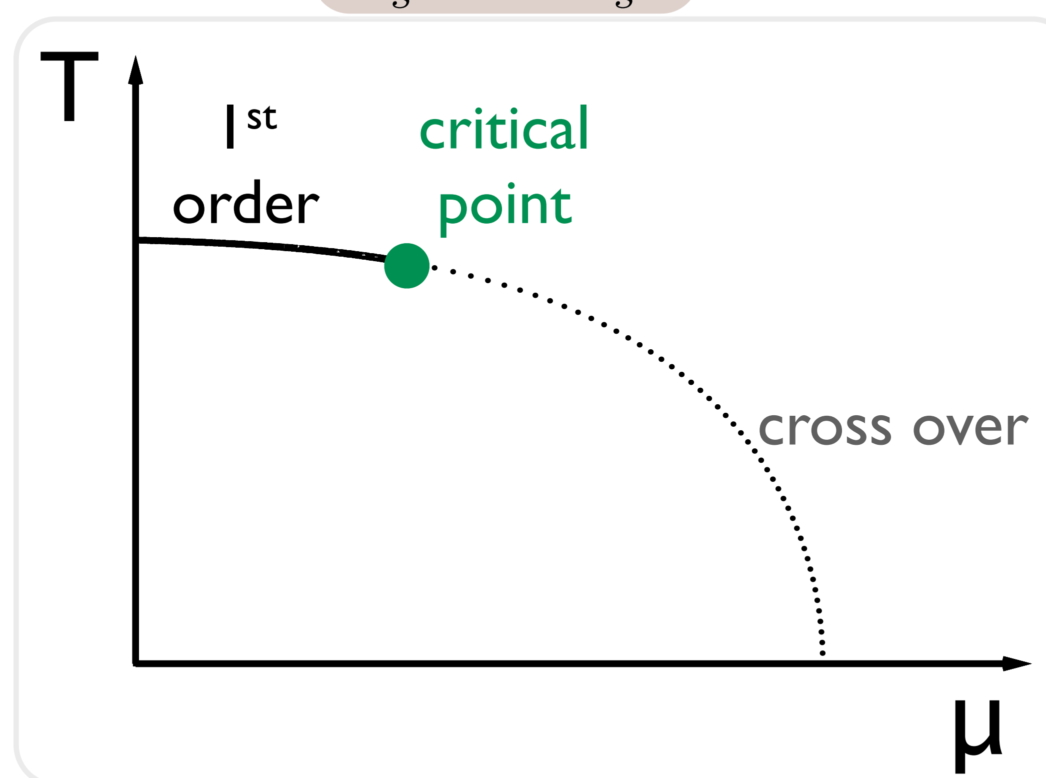
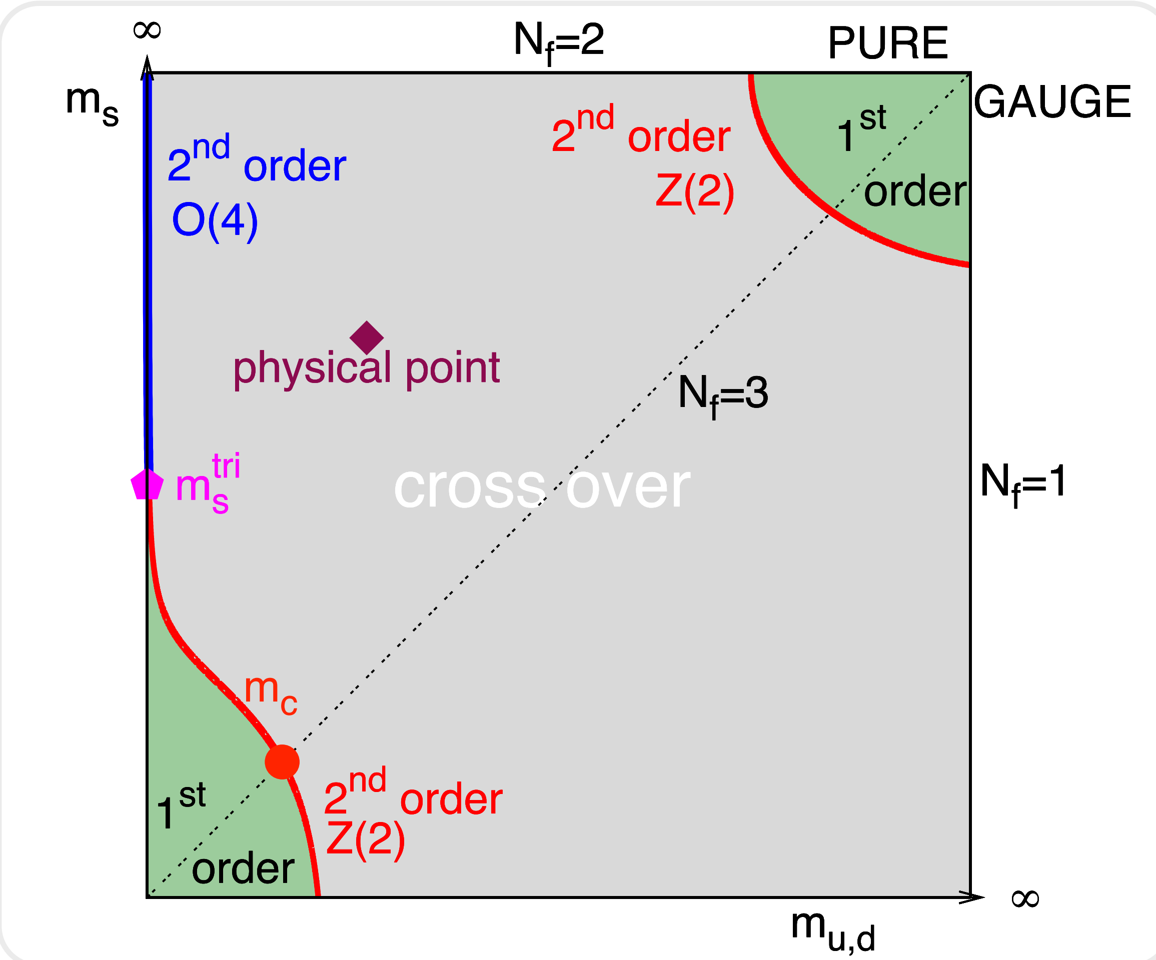
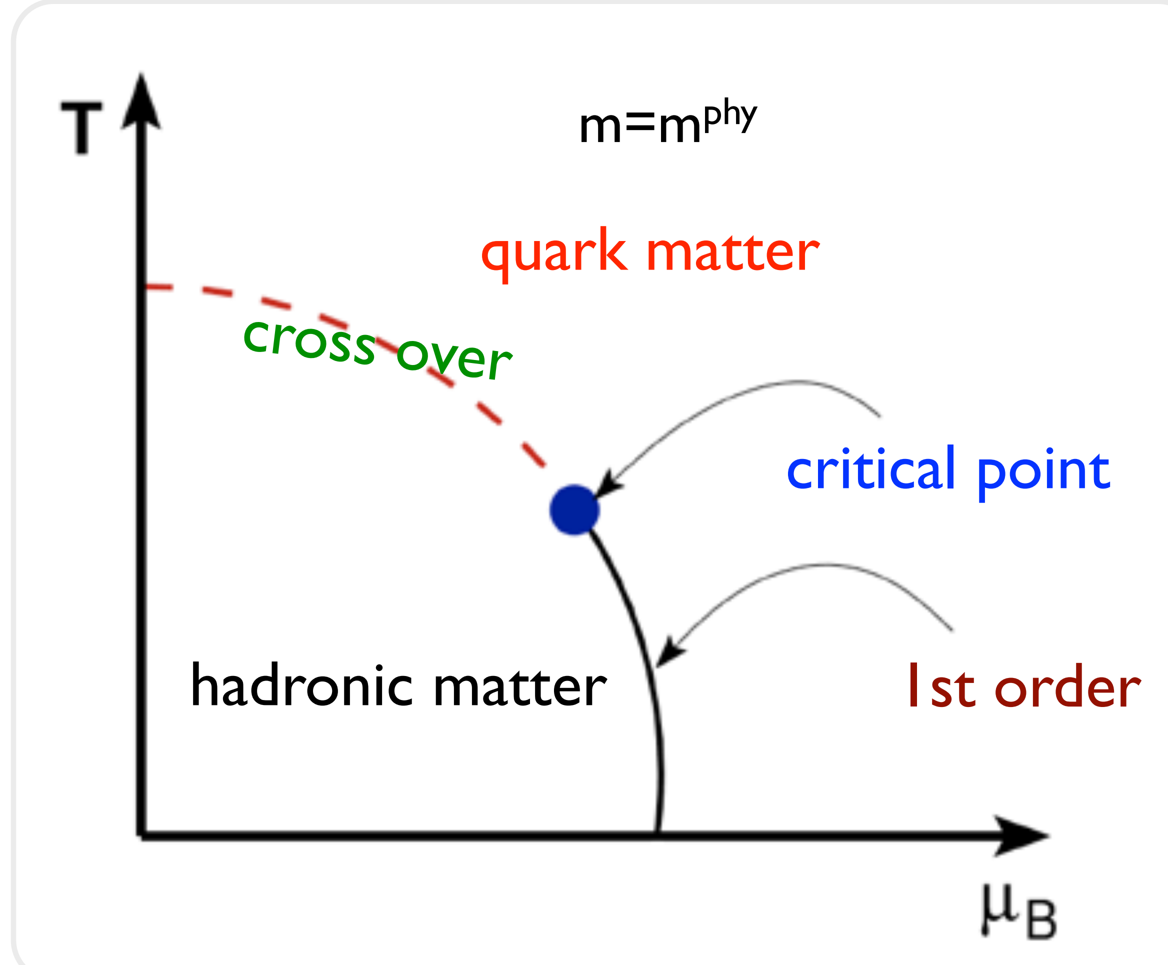


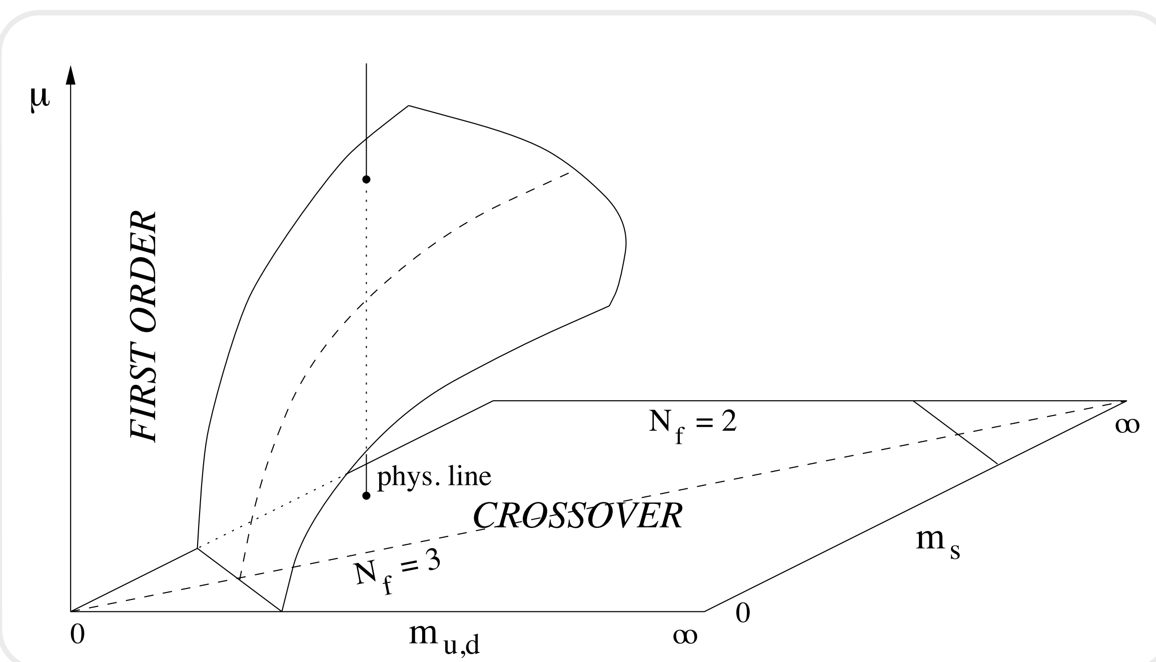
$m_s^{phy} < m_s^{tri}$

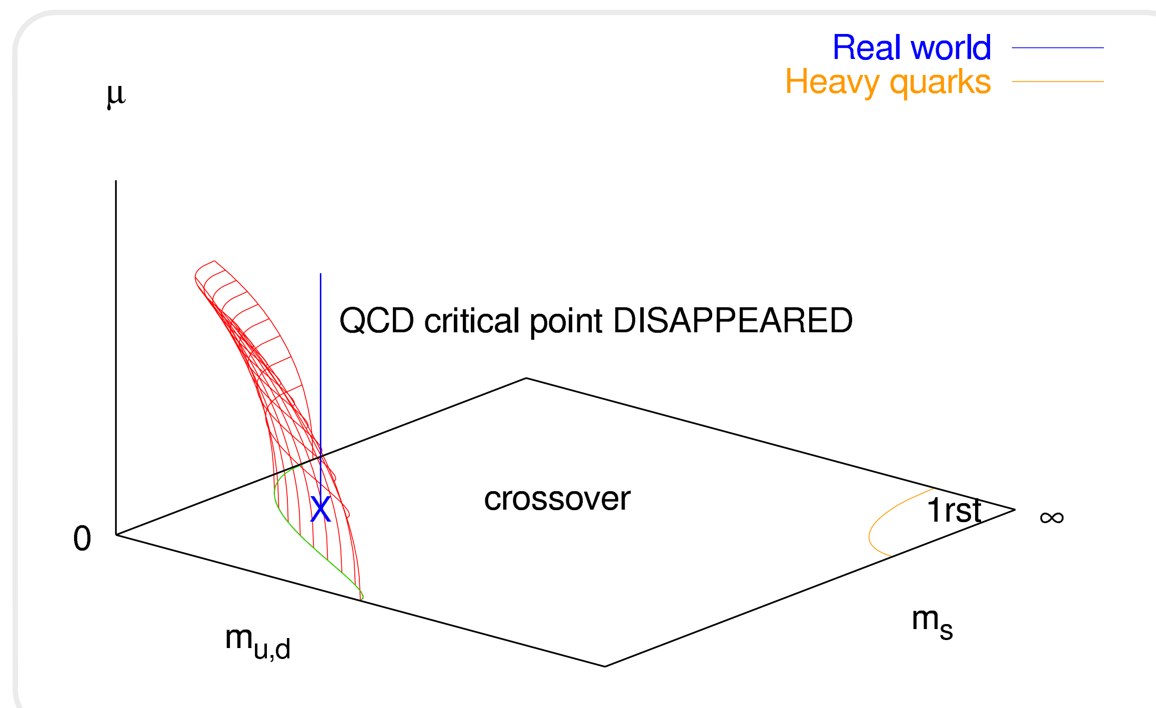


QCD phase transition at the physical point









Karsch et al., '03, X.-Y. Jin et al., '15 , S. Takeda, Tue 15:20-40

de Forcrand & Philipsen, '07

Phase transition in the chiral limit

N_f=2+1:

- standard staggered action: $N_\tau = 4 \Rightarrow m_s^{tri} > m_s^{phy}$
  de Forcrand & Philipsen, JHEP 0701(2007)077
- p4fat3 action: $N_\tau = 4 \Rightarrow m_s^{tri} < m_s^{phy}$
  S. Ejiri et al., Phys.Rev. D80 (2009) 094505

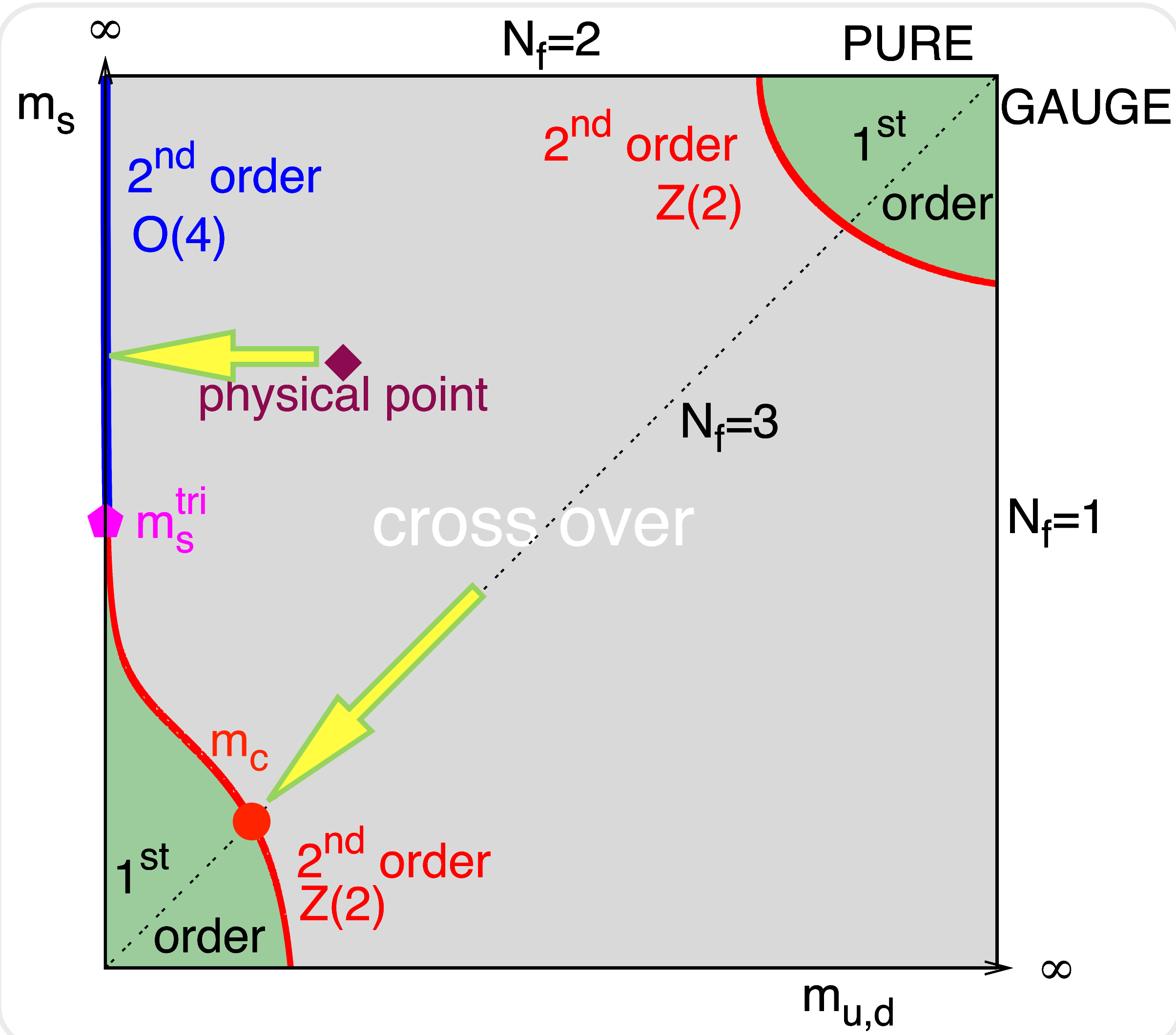
N_f=3:

- Standard staggered action: $N_\tau = 4 \Rightarrow m_\pi^c \approx 290$ MeV
  F. Karsch et al., Nucl.Phys.Proc.Suppl. 129 (2004) 614
- Standard staggered 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
- HISQ action: $N_\tau = 6 \Rightarrow m_\pi^c \lesssim 45$ MeV
  HTD et al., '13
- Wilson-clover fermion: $N_\tau = 4,6,8 \Rightarrow m_\pi^c \approx 304$ MeV
  X.-Y.Jin et al., Phys.Rev. D91 (2015) 1, 014508

N_f=2:

- standard staggered action: $N_\tau = 4 \Rightarrow 1^{st}$ order
  D'Elia et al., Phys.Rev. D72 (2005) 114510
- standard staggered action: $N_\tau = 6 \Rightarrow 2^{nd}$ order, O(2)
  Kogut & Sinclair, Phys.Rev. D73 (2006) 074512

N_f=2+1 & N_f=3 QCD simulations

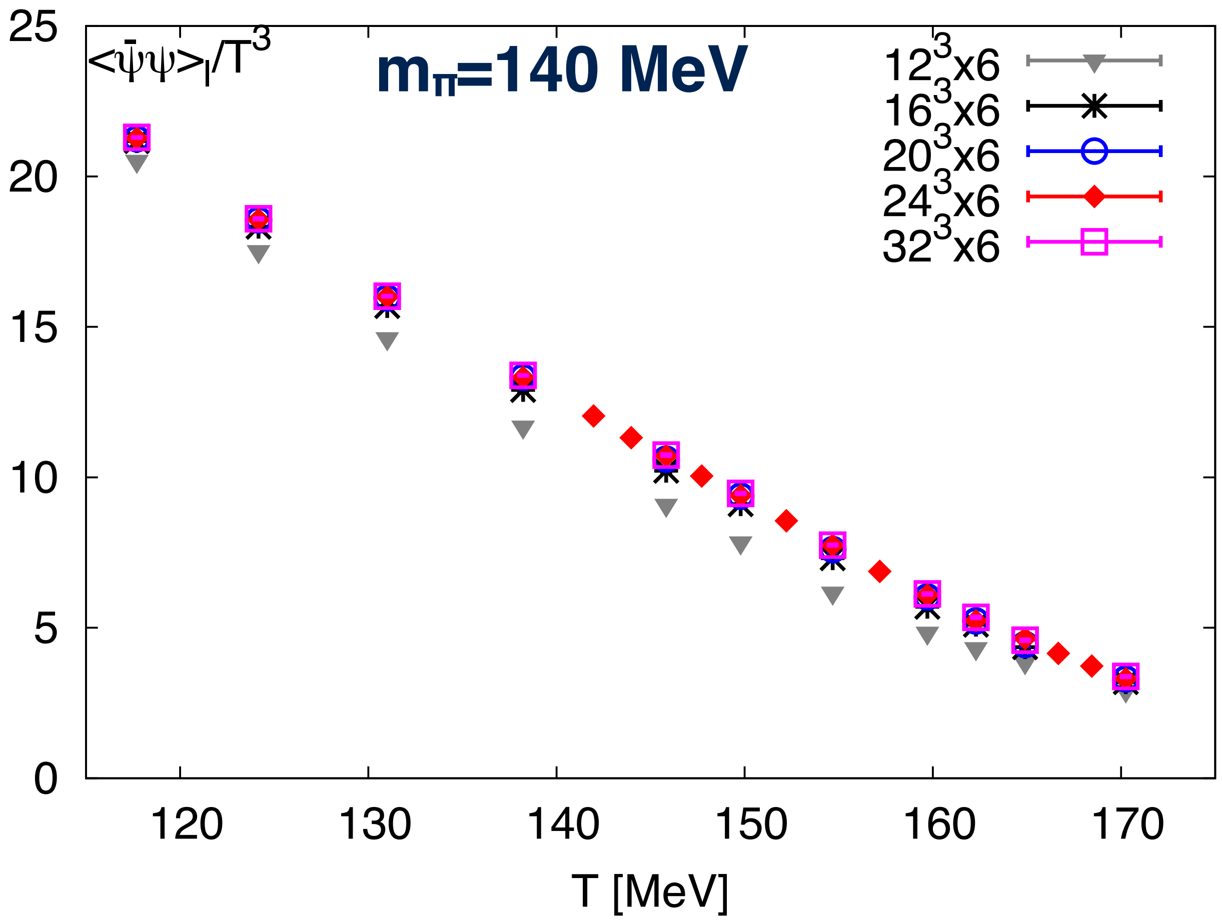


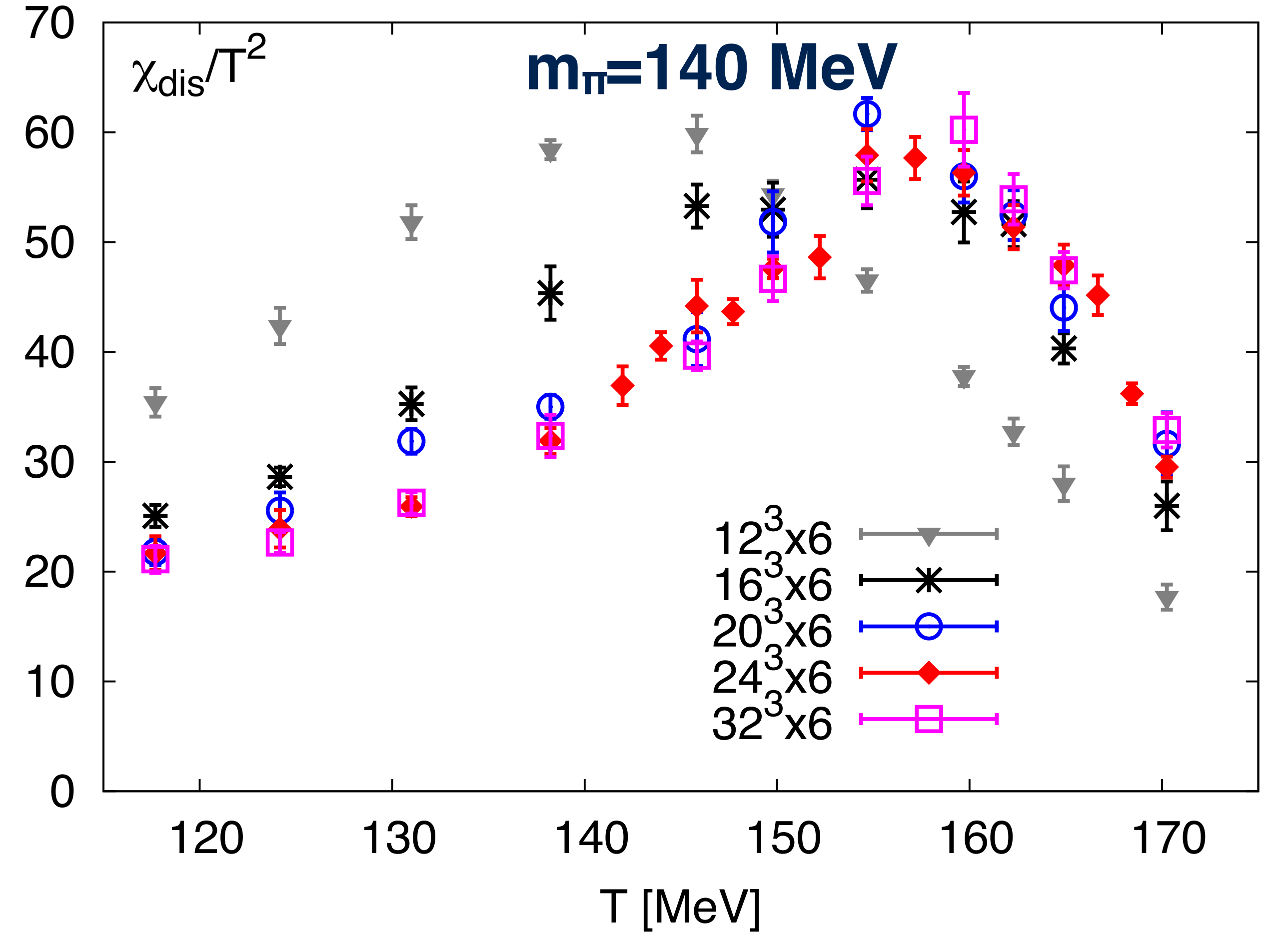
- HISQ/tree action on Nt=6 lattices
- **N_f=2+1:**
  - ☑ $m_s^{phy}/\mathbf{m_l}$ = 20, 27, 40, 60, 80
    $m_\pi \approx$160,140,110,90,80 MeV
  - ☑ $m_\pi L > 3$
- **N_f=3:**
  - ☑ $m_s^{phy}/\mathbf{m_q}$ = 10,20,30,40,60,80
    $m_\pi \approx$230,160,140,110,90,80 MeV
  - ☑ $m_\pi L > 3$

update results of 1312.0119 and 1302.5740

$N_f=2+1$

Volume dependence of chiral observables

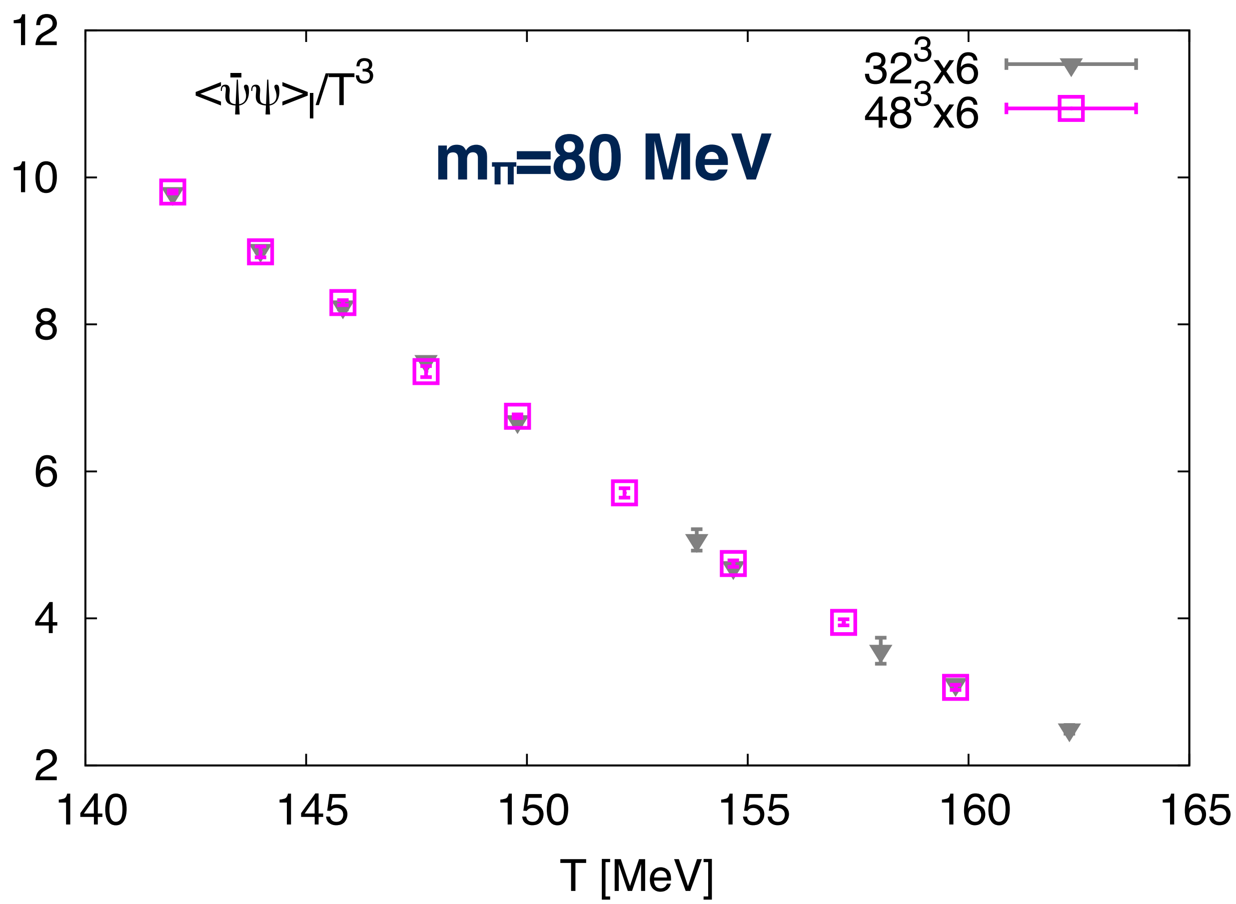


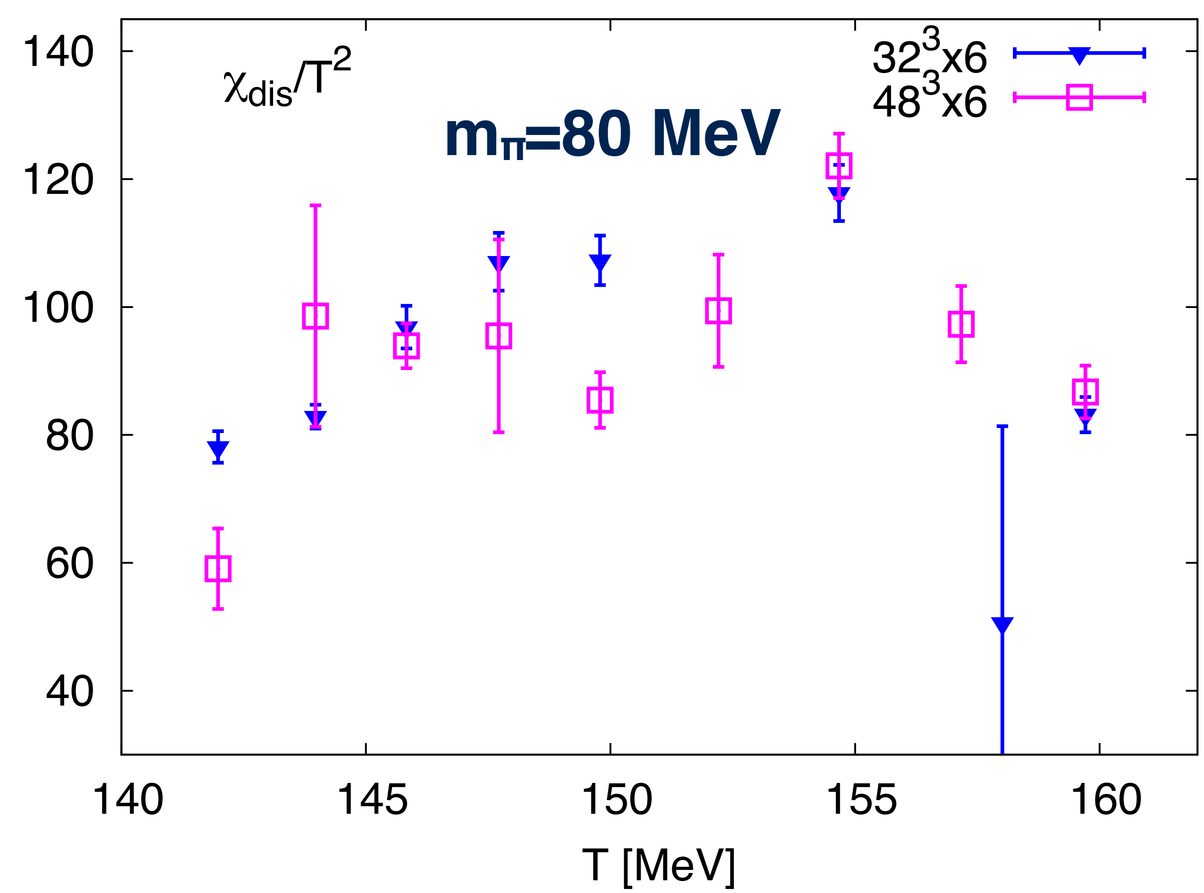


- volume effects are small in 3 largest volume
- $m_\pi L > 4$ is ensured in the following other datasets

  48^3x6 with m_π=80 MeV,
  40^3x6 with m_π=90 MeV,
  32^3x6 with m_π=110 MeV,
  24^3x6 with m_π=160 MeV

Volume dependence of chiral observables





- Mild volume dependence is seen from chiral observables
- No evidence of linear volume scaling as signatures of first order phase transition

chiral phase transition and universal scaling

Behavior of the free energy close to critical lines

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

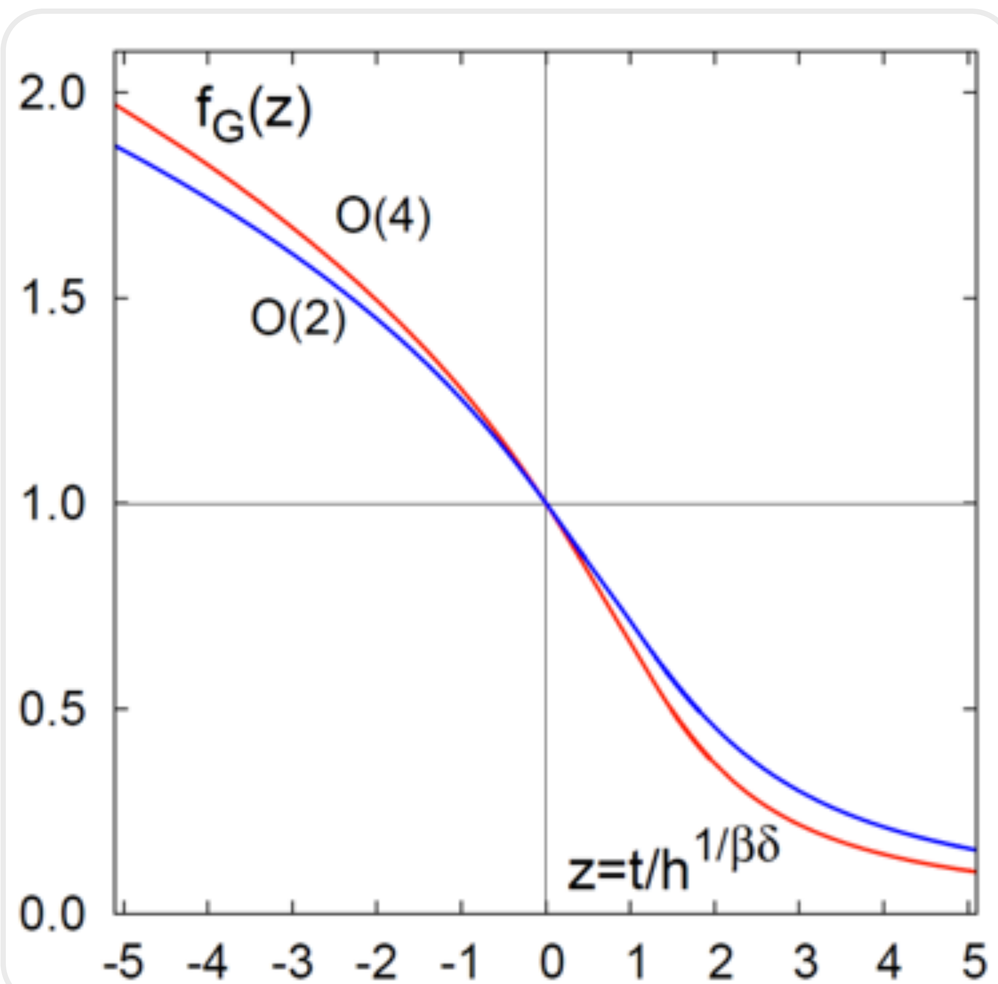
h: external field, t: reduced temperature, β,δ: universal critical exponents

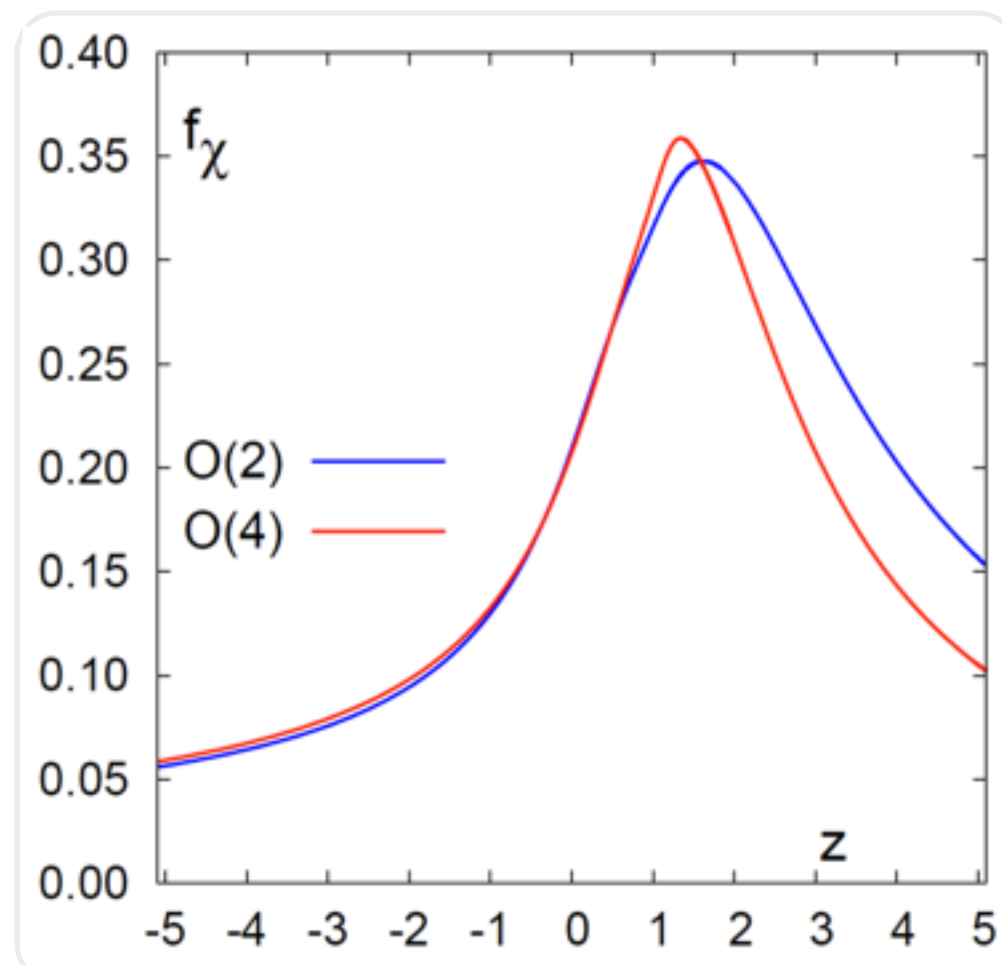
$f_s(z)$: universal scaling function, O(N) etc.

$$h=\frac{1}{h_0}\frac{m_l}{m_s} \qquad t=\frac{1}{t_0}\frac{T-T_c}{T_c}$$

Magnetic Equation of State (MEoS):

$$M = -\partial f_s(t,h)/\partial h = h^{1/\delta}\, f_G(z) \qquad f_\chi(z)=h_0^{1/\delta}(m_l/m_s)^{1-1/\delta}\partial M/\partial h$$





chiral phase transition and universal scaling

Behavior of the free energy close to critical lines

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

h: external field, t: reduced temperature, β,δ: universal critical exponents

$f_s(z)$: universal scaling function, O(N) etc.

$h = \frac{1}{h_0}\frac{m_l}{m_s}$ $\quad t = \frac{1}{t_0}\frac{T-T_c}{T_c}$

Magnetic Equation of State (MEoS):

$M = -\partial f_s(t,h)/\partial h = h^{1/\delta} f_G(z)$ $\quad f_\chi(z) = h_0^{1/\delta}(m_l/m_s)^{1-1/\delta}\partial M/\partial h$

- Comparison with QCD

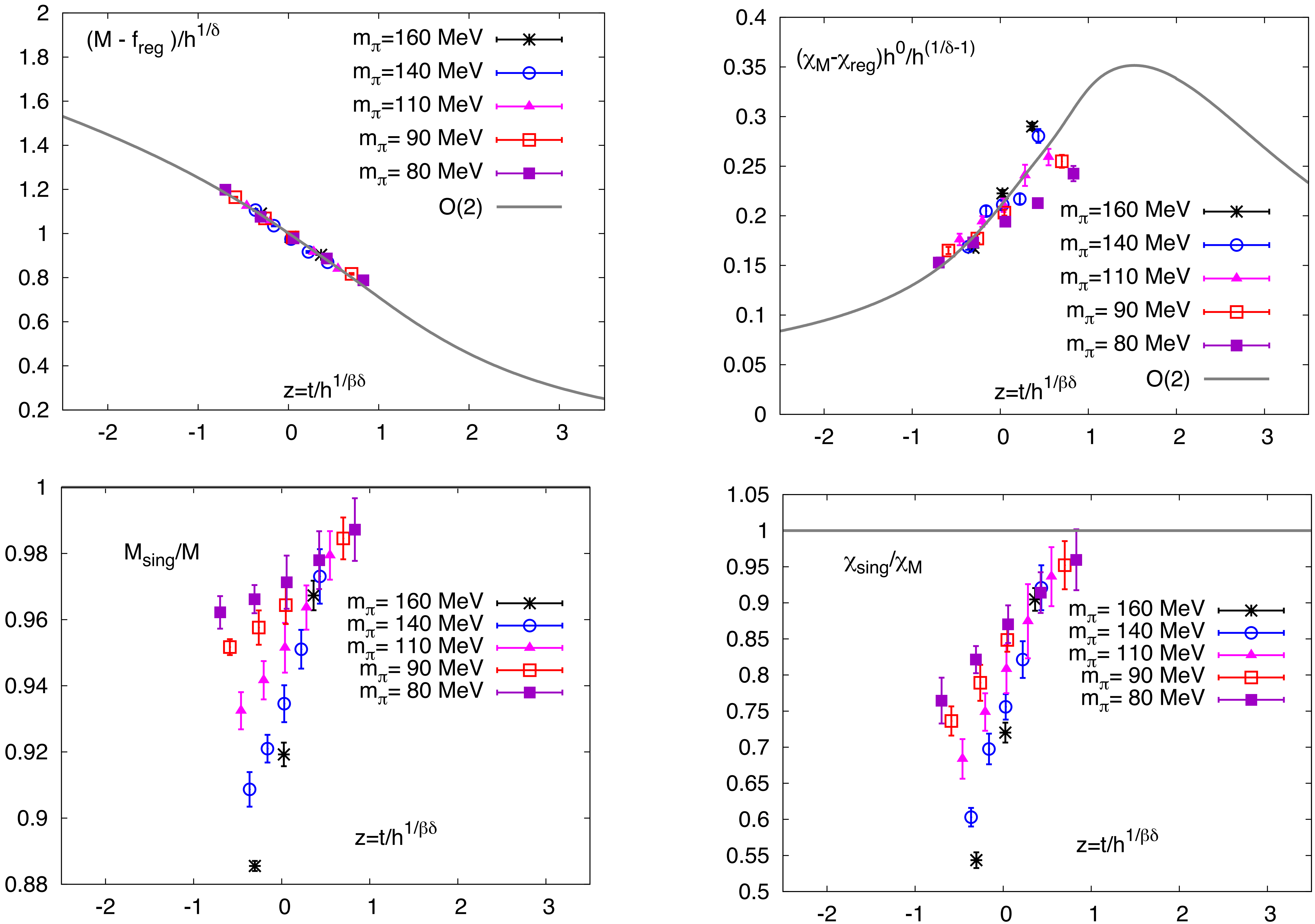
$$M = m_s \langle\bar{\psi}\psi\rangle_l / T^4, \qquad \chi_M = m_s^2 \chi_{tot}/T^4$$

- Contributions from the regular term

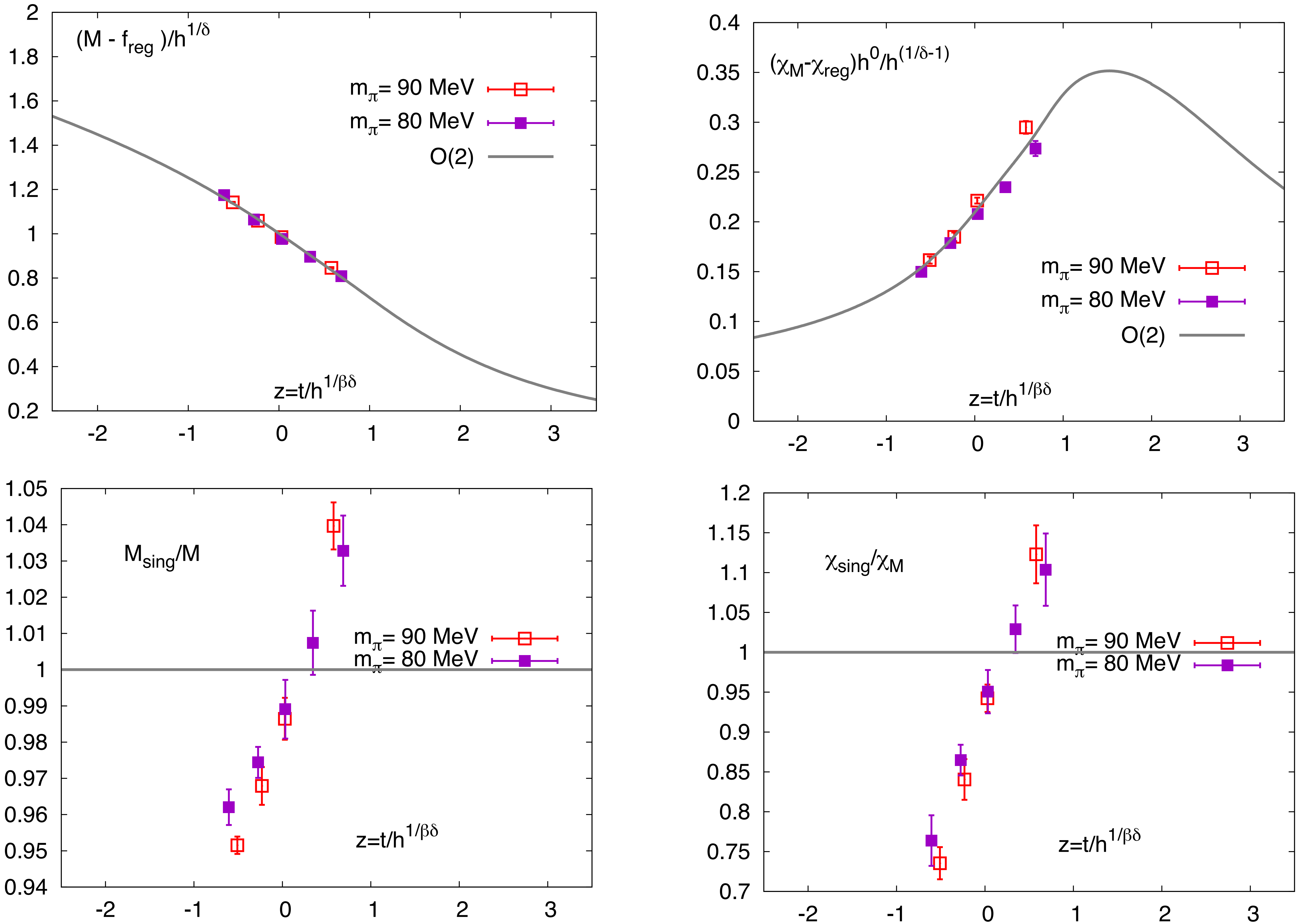
$$M = h^{1/\delta} f_G(z) + f_{reg} \quad , \qquad f_{reg} = \left(a_0 + a_1 \frac{T-T_c}{T_c}\right)\frac{m_l}{m_s}$$

$$\chi_M = h_0^{-1} h^{1/\delta - 1} f_\chi(z) + f'_{reg}, \qquad f'_{reg} = a_0 + a_1 \frac{T-T_c}{T_c}$$

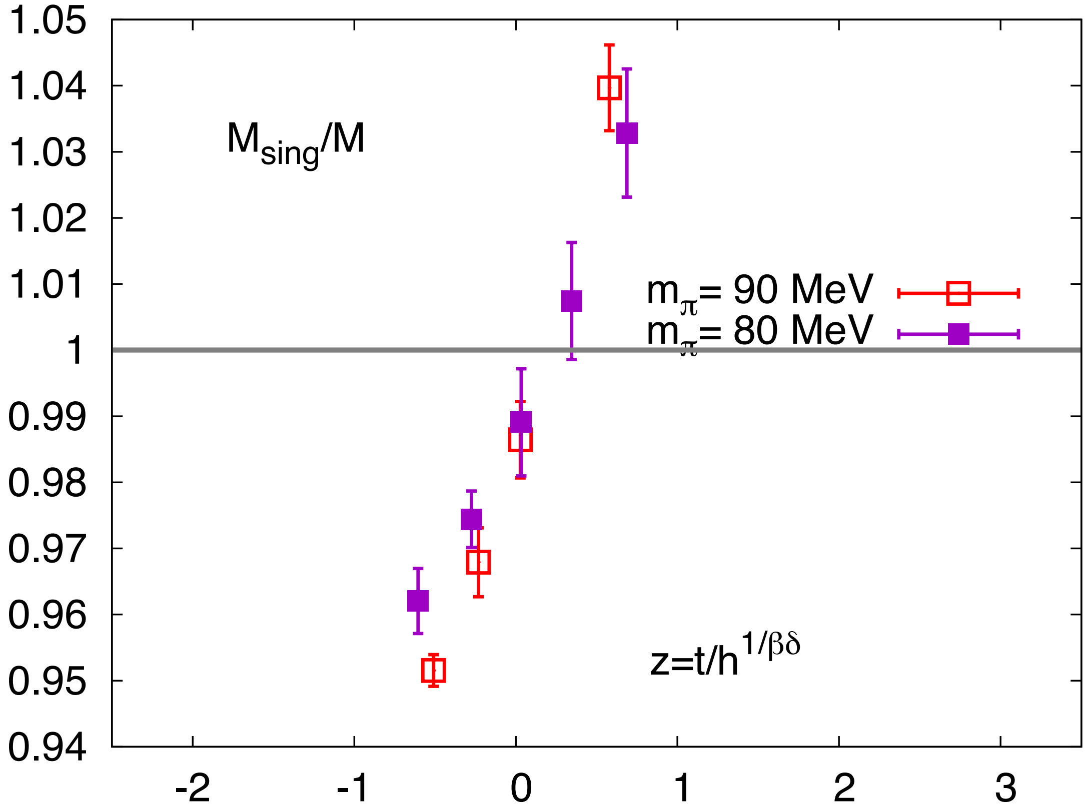
O(2) scaling fit to chiral susceptibilities & condensates

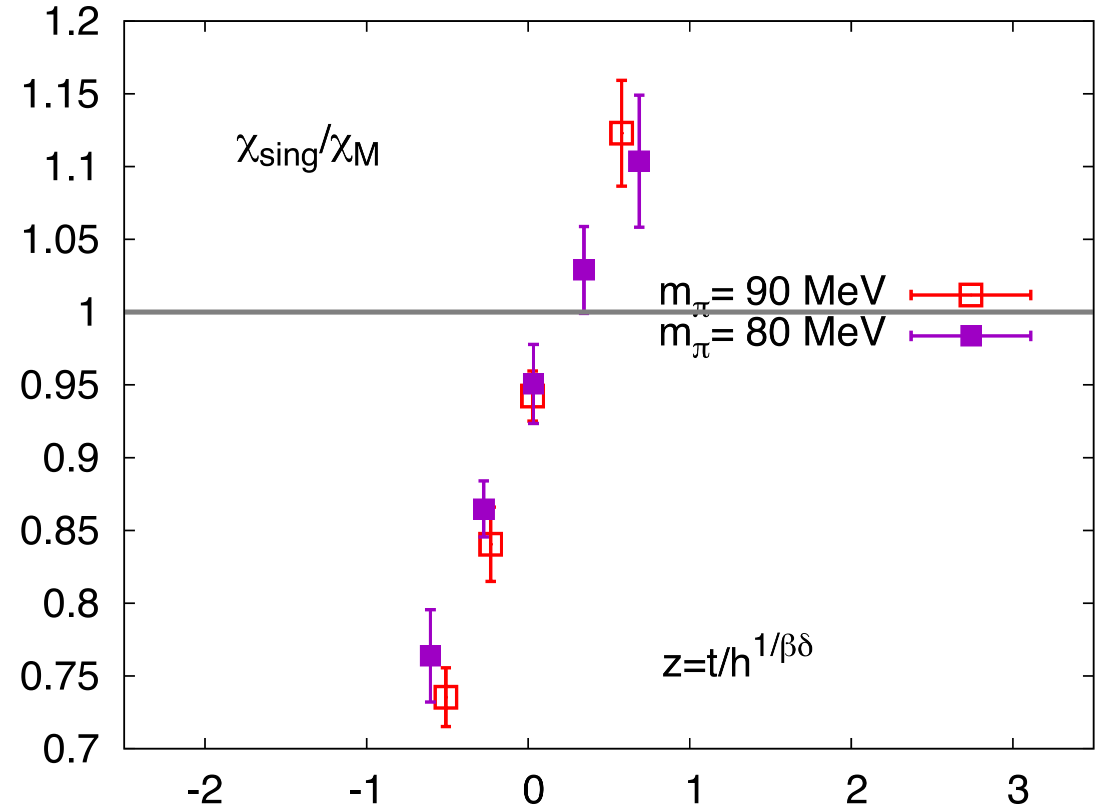


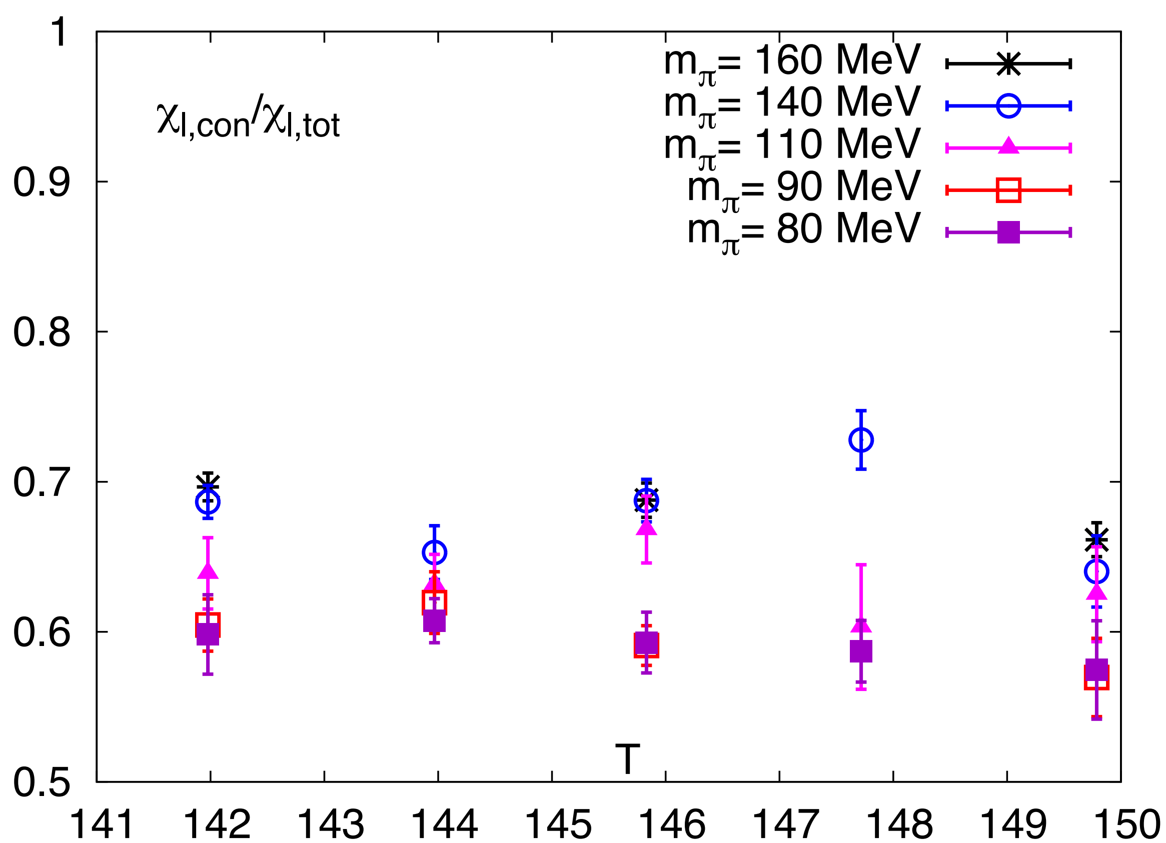
O(2) scaling fit to chiral susceptibilities & condensates



O(2) scaling fit to chiral susceptibilities & condensates





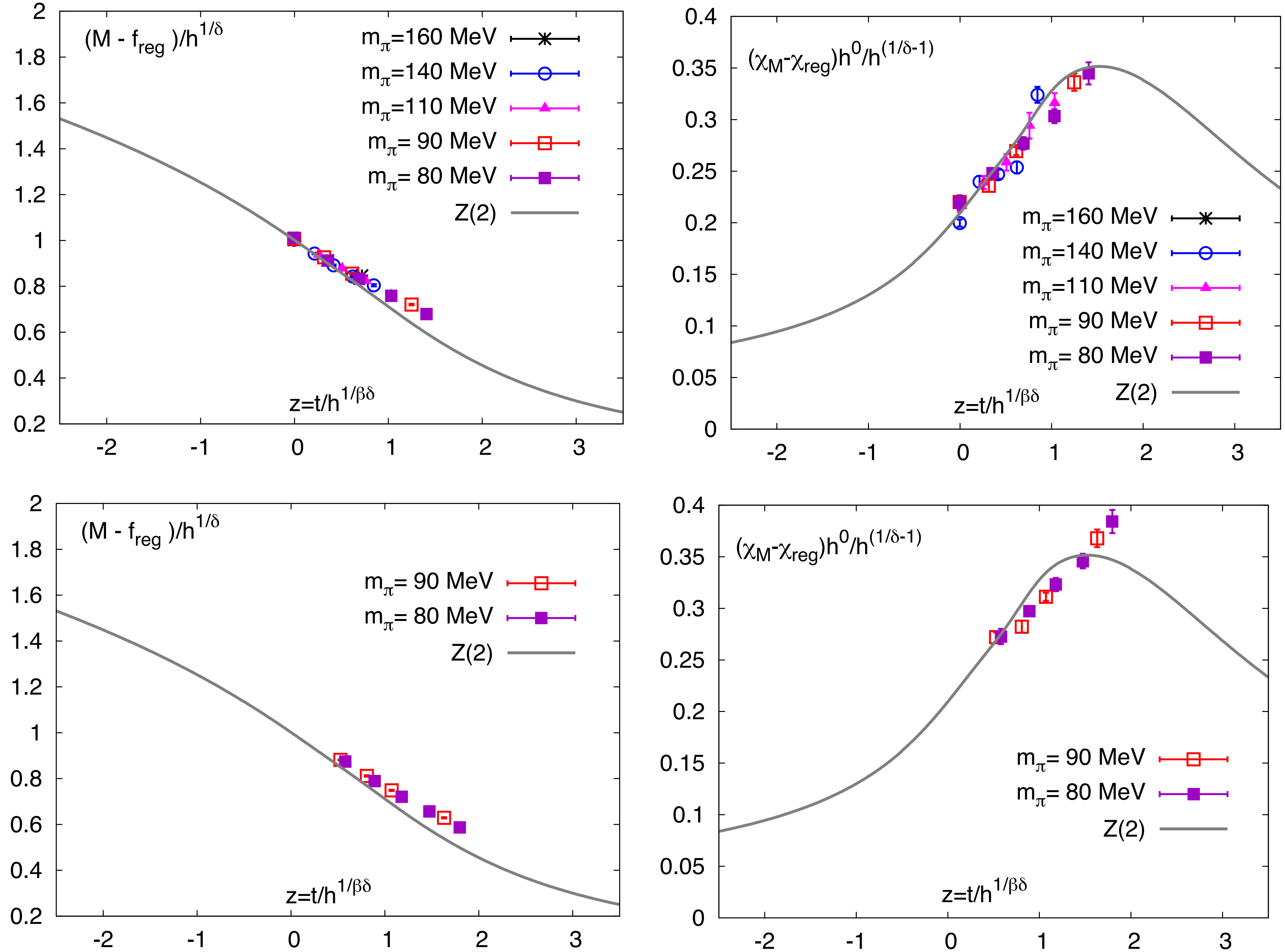


A good fit to chiral observables using O(2) scaling function is obtained

Z(2) scaling fit to chiral susceptibilities & condensates

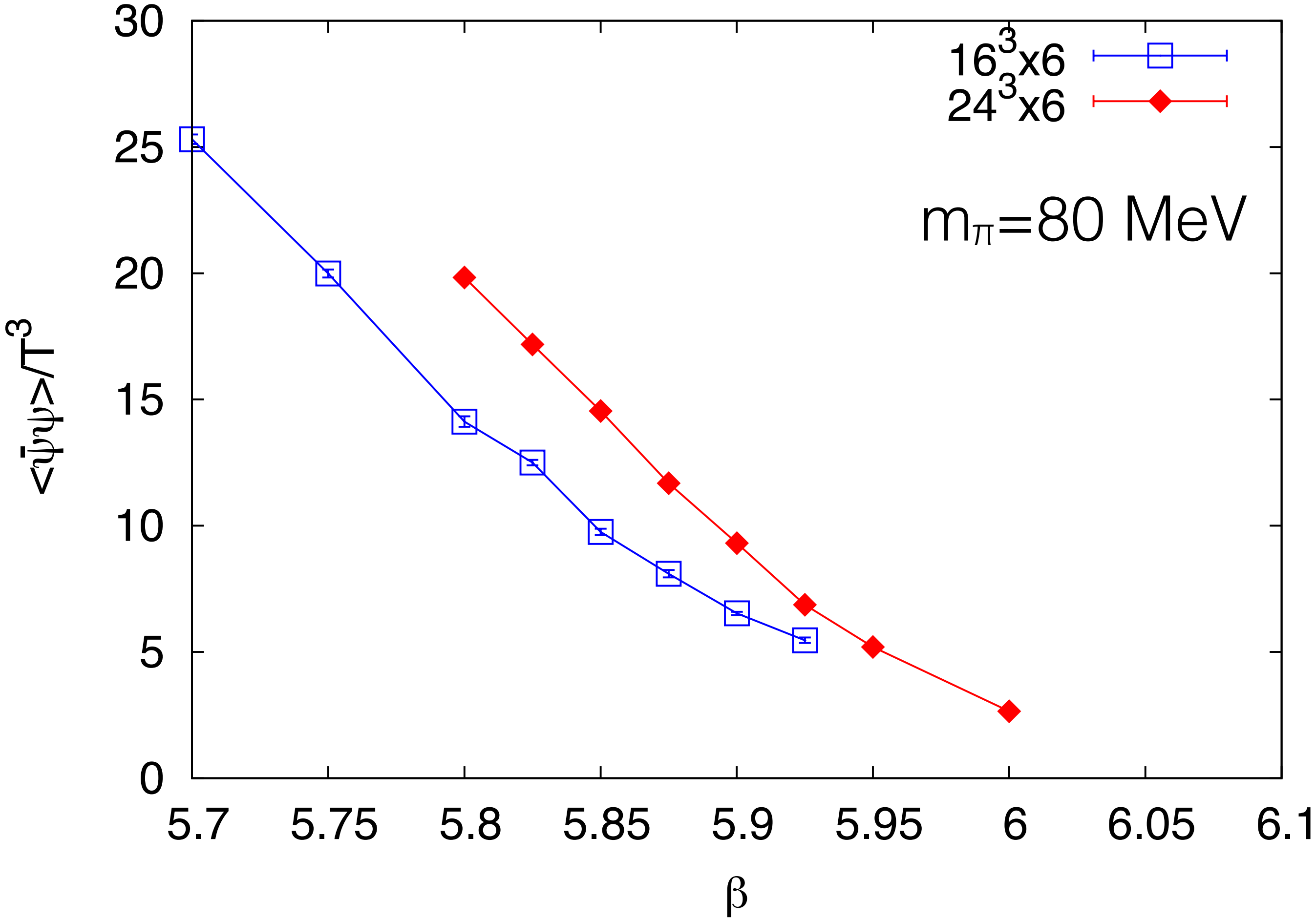
O(2) $h = 1/h_0\, m_l/m_s$ → $h = 1/h_0\, (m_l - m_c)/m_s$ **Z(2)**

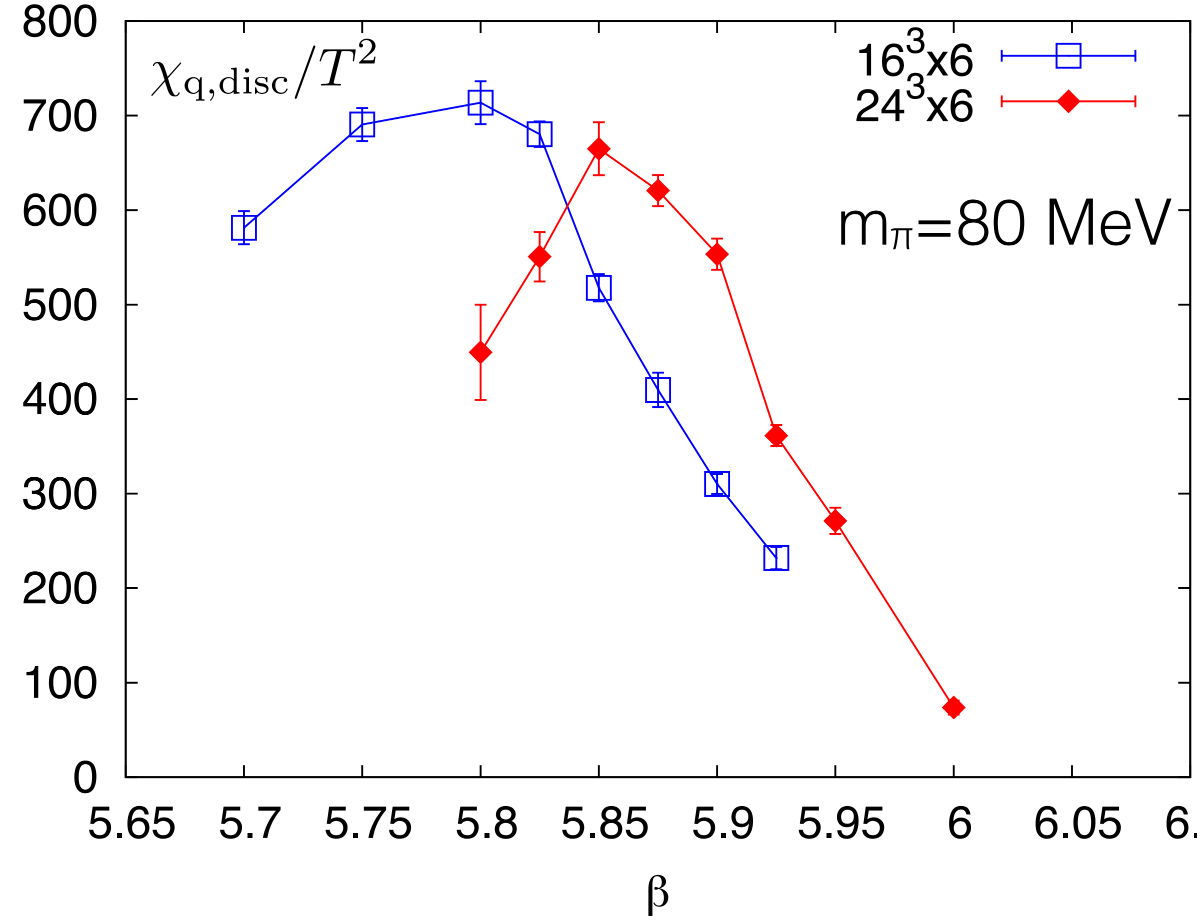
A small and negative value of m_c is favored from fit

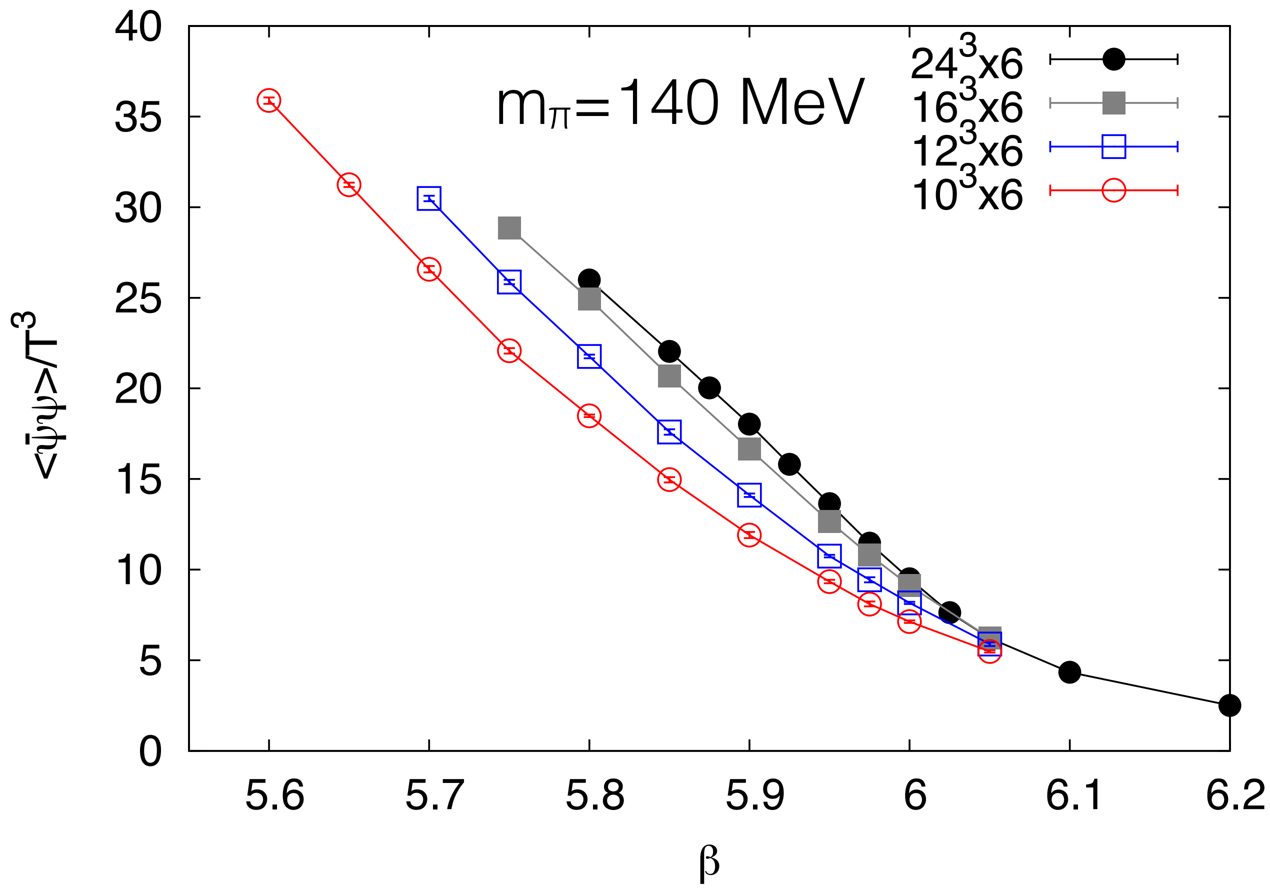


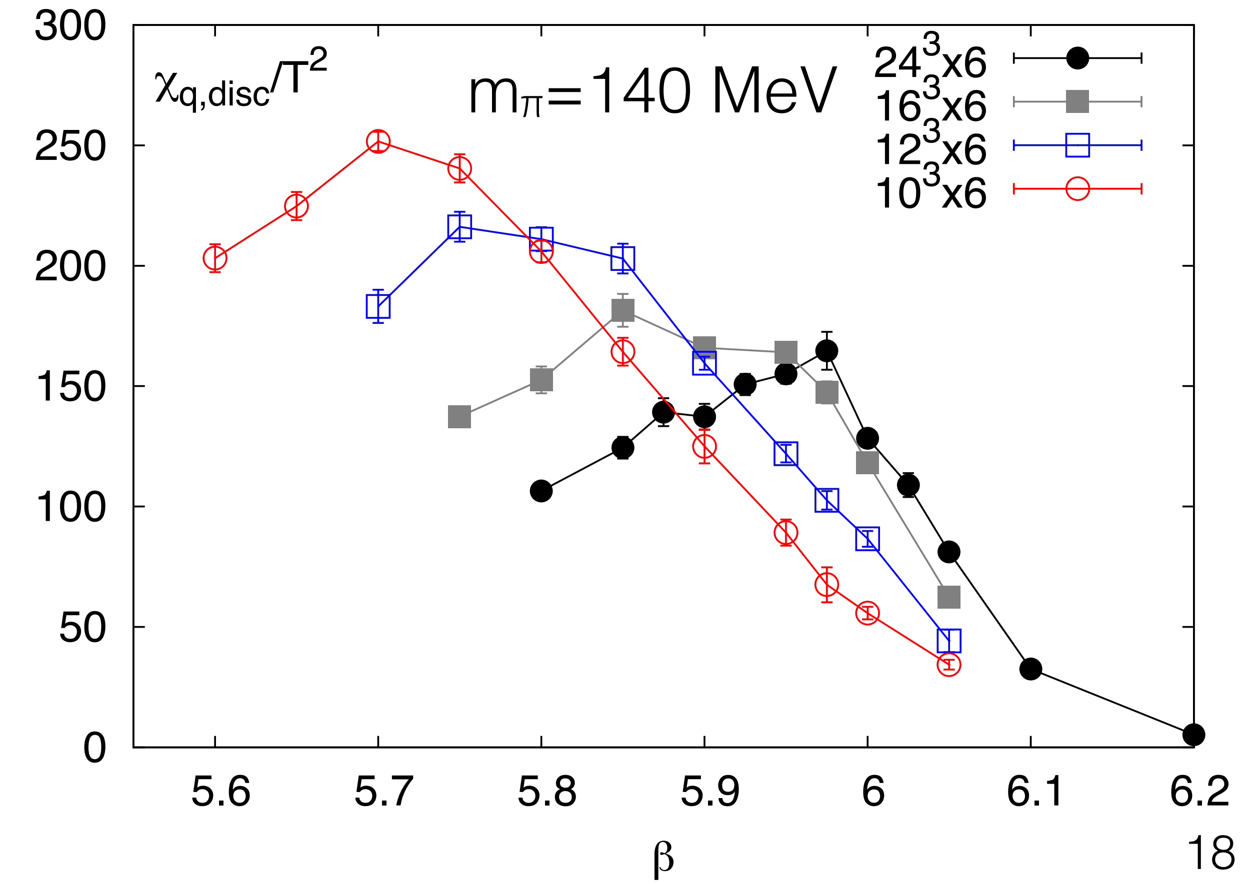
N_f=3

Volume dependence of chiral observables

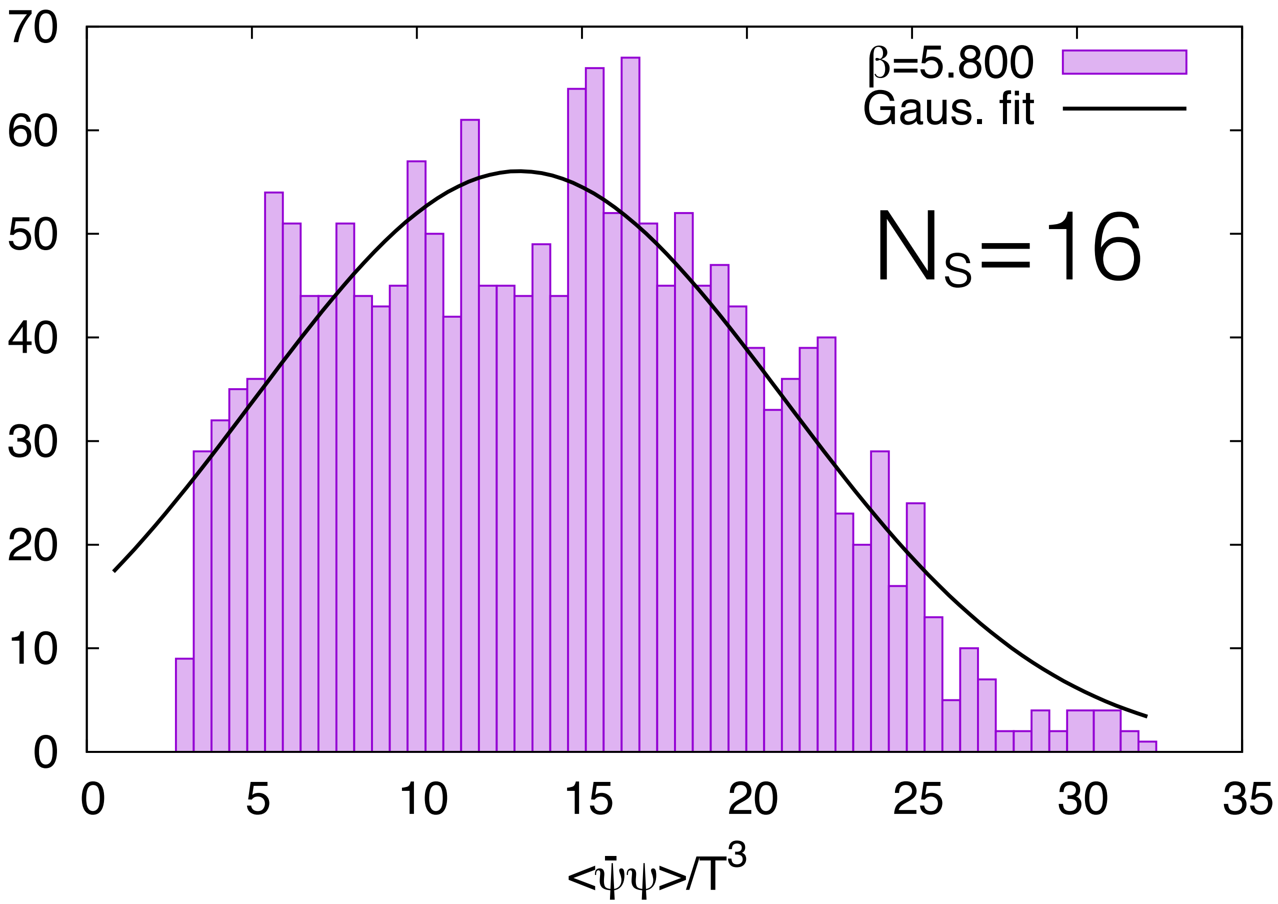


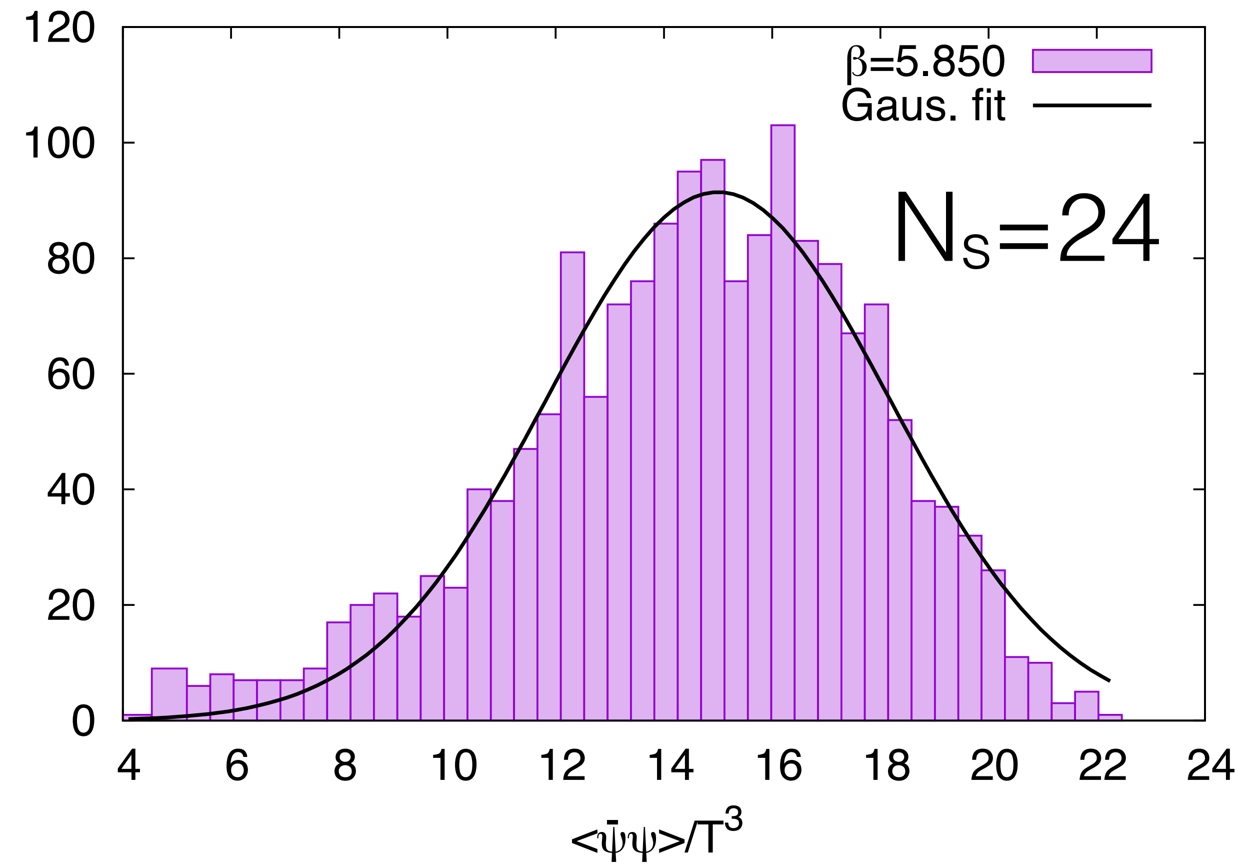






time history of chiral condensate near β_c at lowest quark mass





No double peak structure is observed

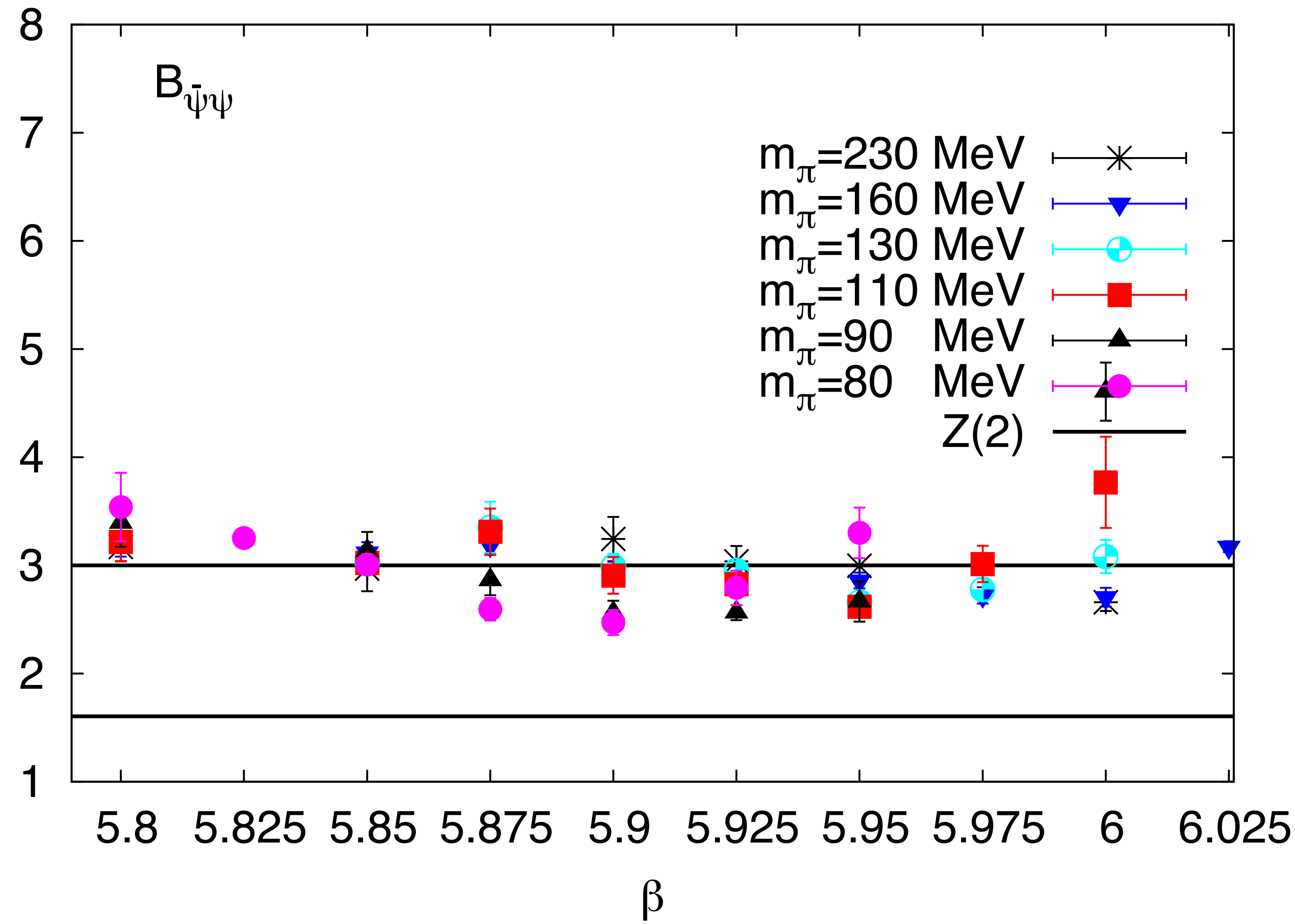
Binder cumulants of chiral condensates

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

In the crossover region B=3

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

1st order transition B=1



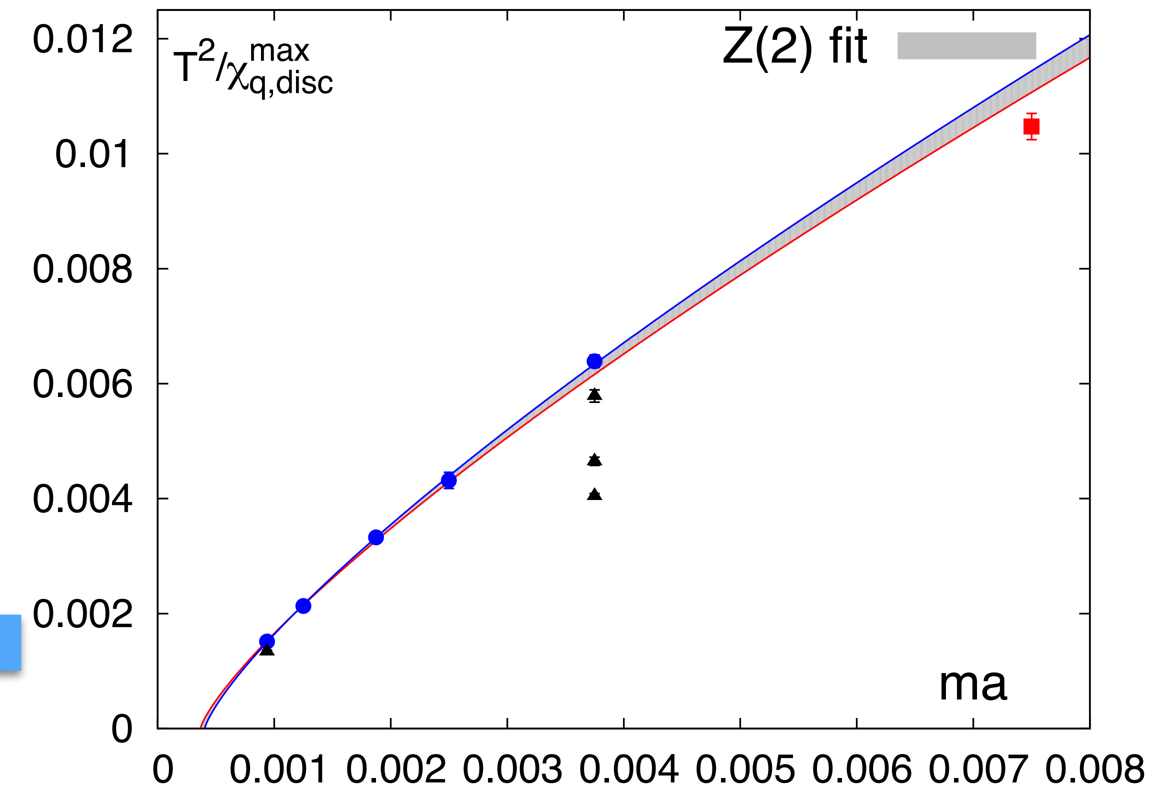
No first order phase transition is observed in the current pion mass window: [80, 230] MeV

estimate of critical mass m_c

At the pseudo critical temperature

$$M_p = h^{1/\delta} f_G(z_p)\ ,\ \ h = (m_q - m_c)/h_0$$

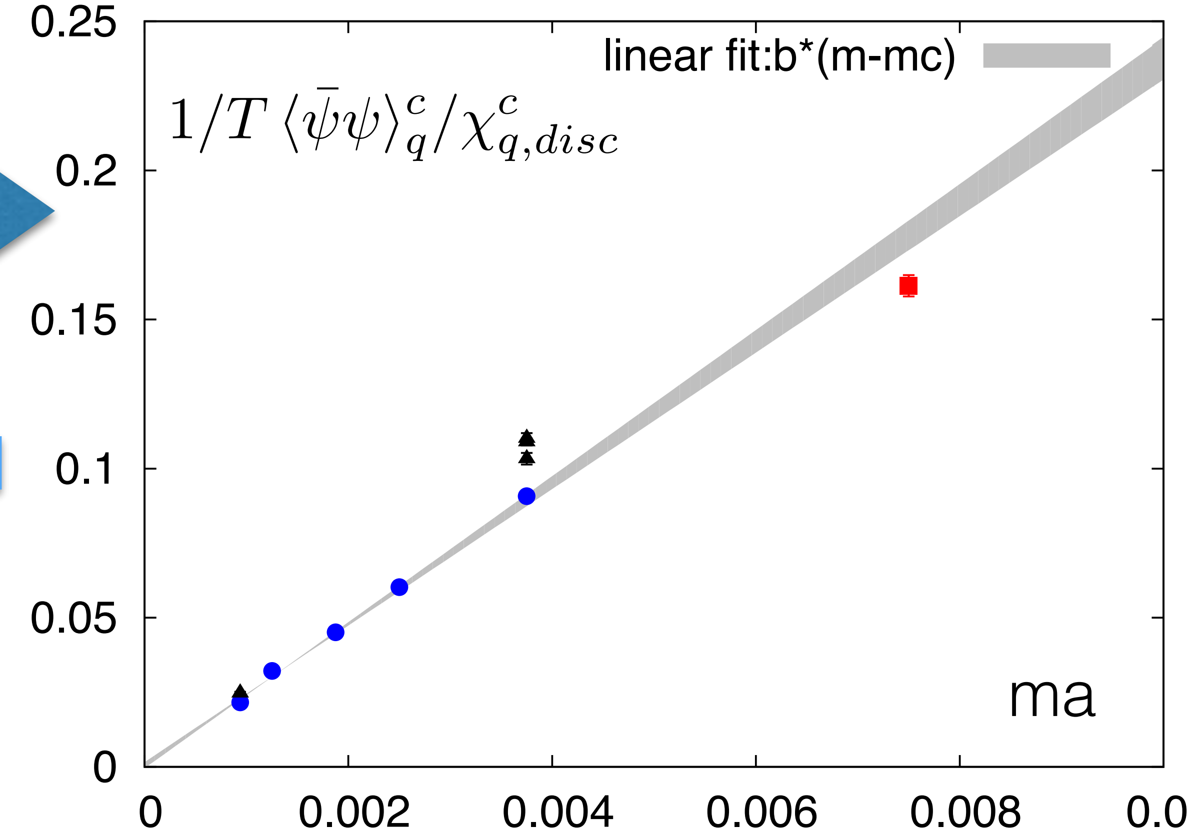
- $$\chi_M^p = h_0^{-1} h^{1/\delta - 1} f_\chi(z_p)$$



$m_\pi^c \lesssim 50$ MeV ⇐ $m^c a$=3.9(1)e-04

- independent of universal exponents

$$M_p/\chi_M^p = (m_q - m_c)\, f_G(z_P)/f_\chi(z_p)$$



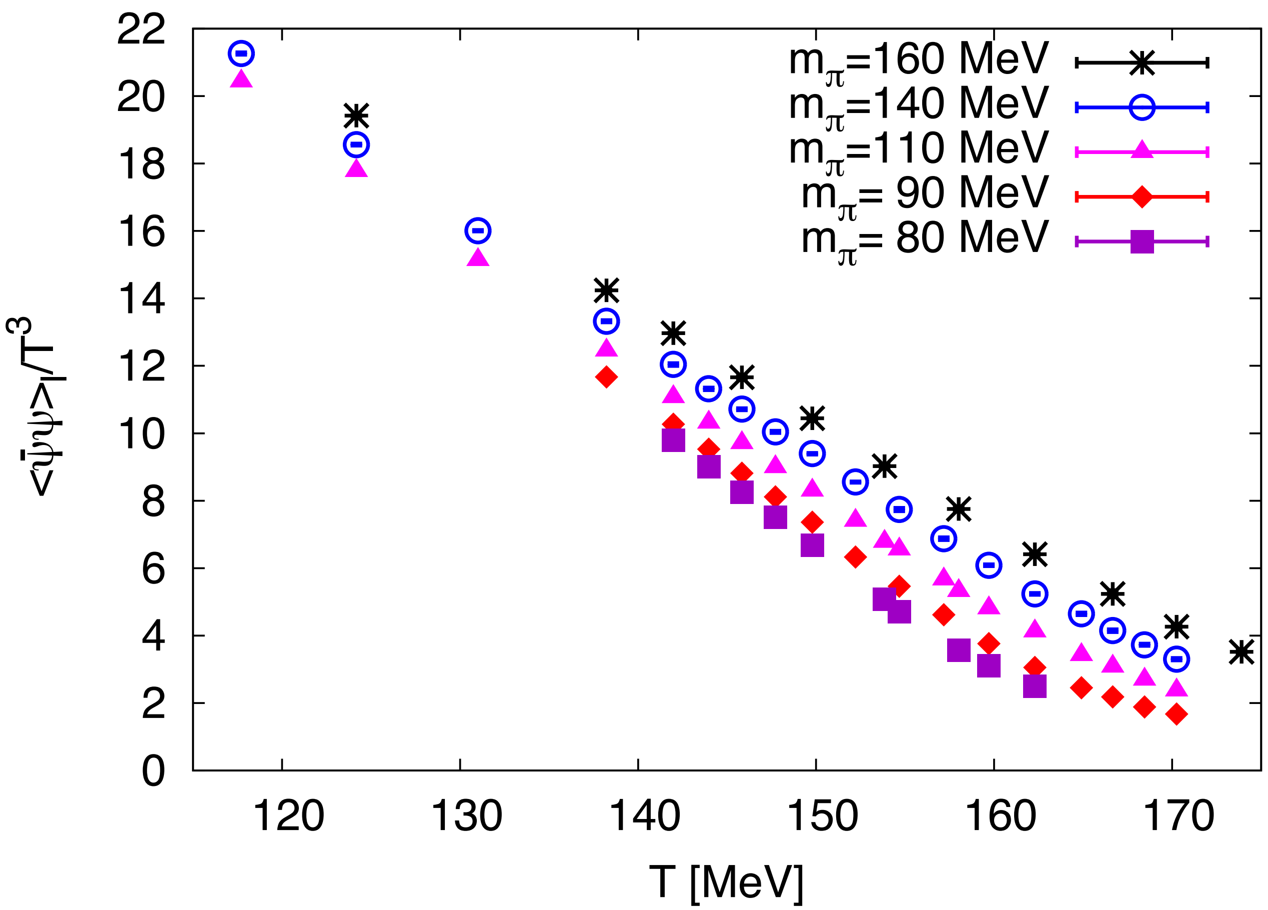
$m^c a$=-6(8)e-05

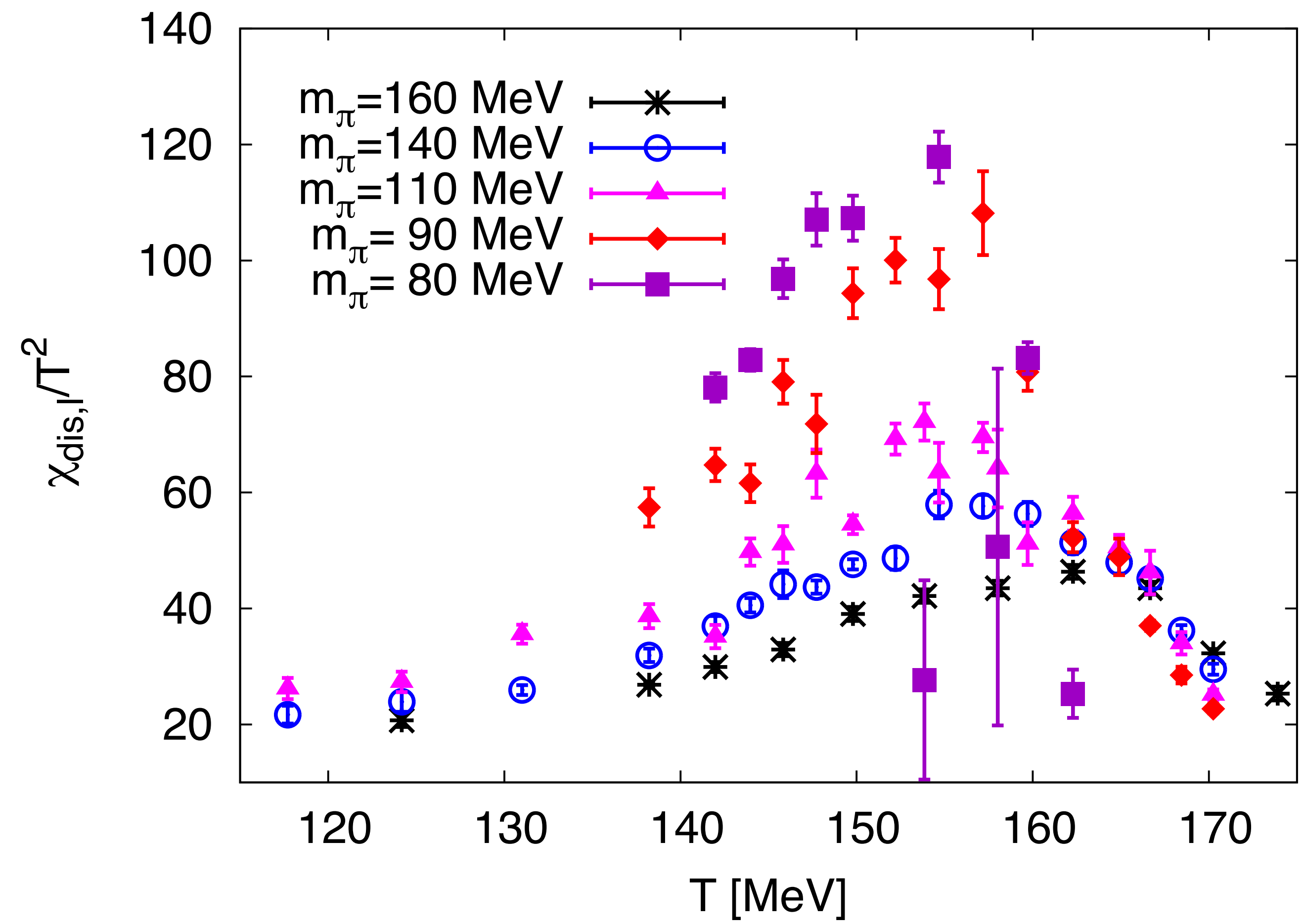
Summary & Outlook

- We have performed simulations on Nt=6 lattices using HISQ/tree action in N_f=2+1 & 3 QCD at 5 & 6 different values of quark masses.
- We found no evidence of a first order phase transition region in 230 MeV $\lesssim m_\pi \lesssim$ 80 MeV in N_f=3 QCD
- Critical pion mass is estimated: $m_\pi \lesssim$ 50 MeV
- A good description of chiral observables in N_f=2+1 QCD is provided by the O(2) scaling function
- Our results indicate $m_s^{tric} < m_s^{phy}$

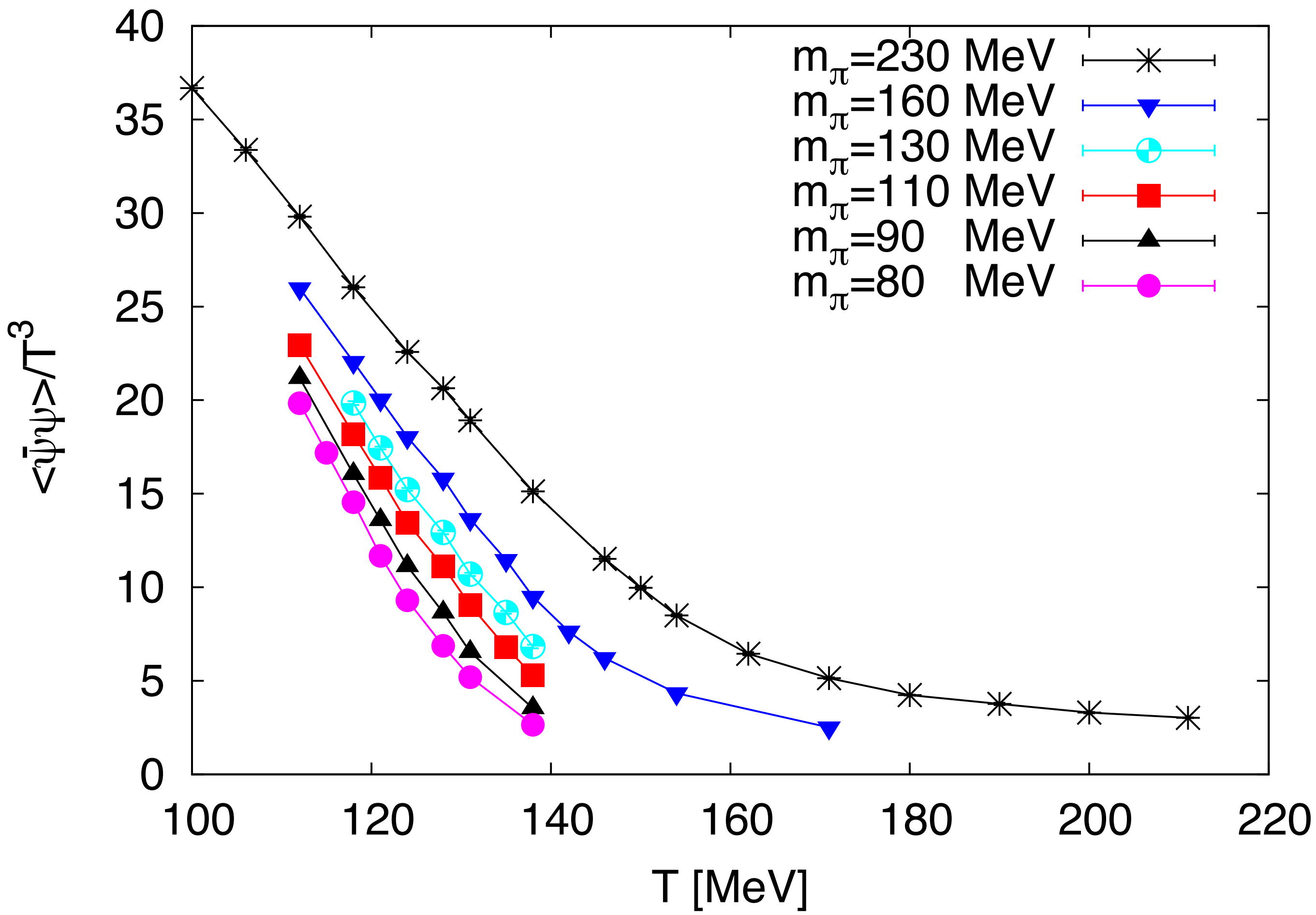
➢ N_τ=8 calculations are on the way

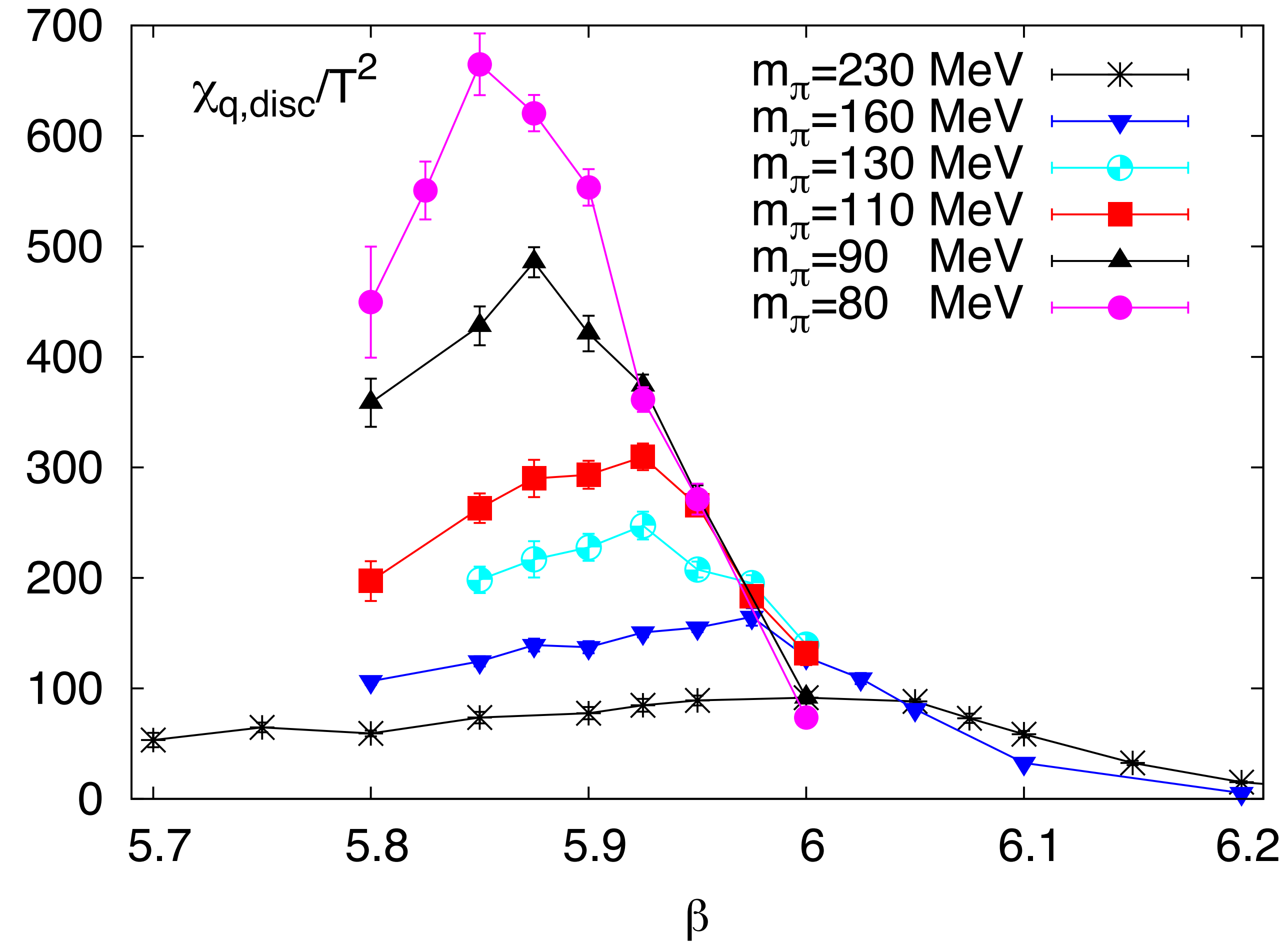
N_f=2+1: chiral condensates and disconnected sus.





N_f=3: chiral condensates & susceptibilities





Nf=3: Binder cumulants of chiral condensates