Chiral phase transition of (2 + 1)-flavor QCD

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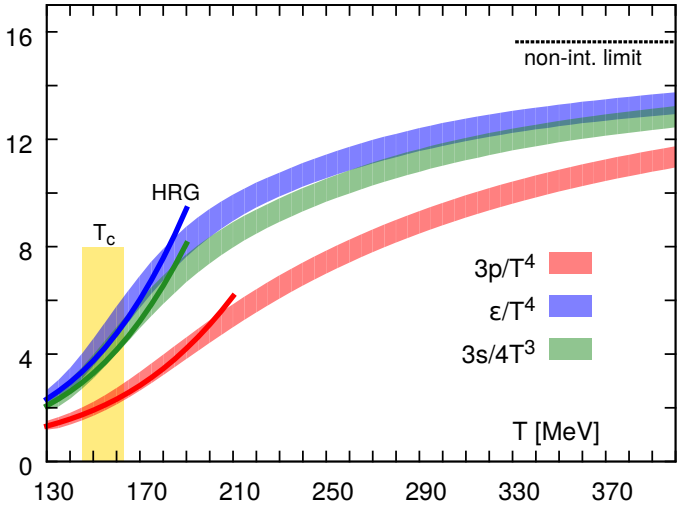
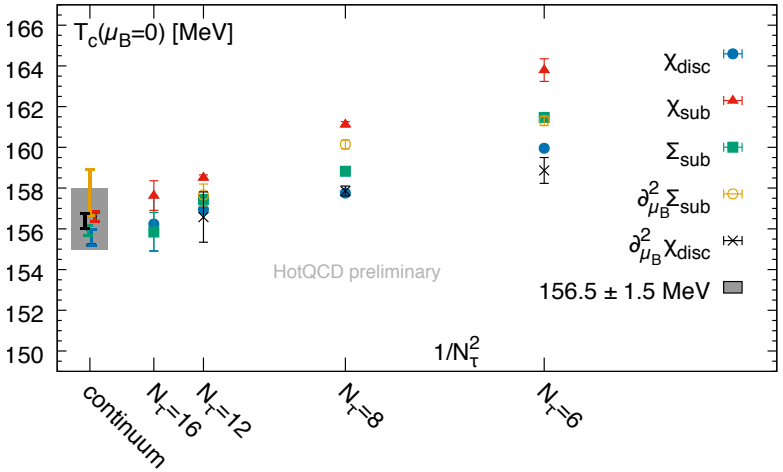
Chiral crossover transition of QCD in the real world



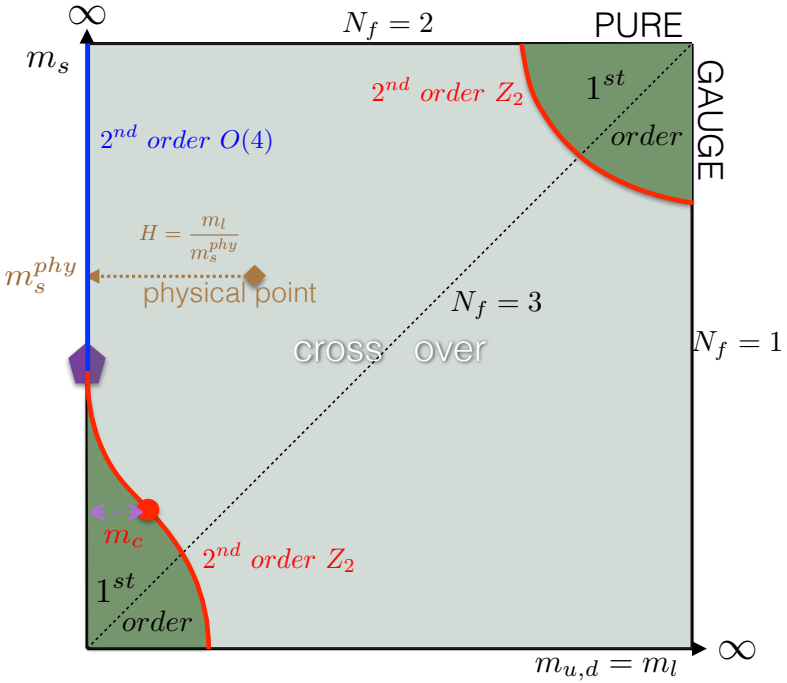
PRD 90, 094503 (2014)



P. Steinbrecher, 1807.05607

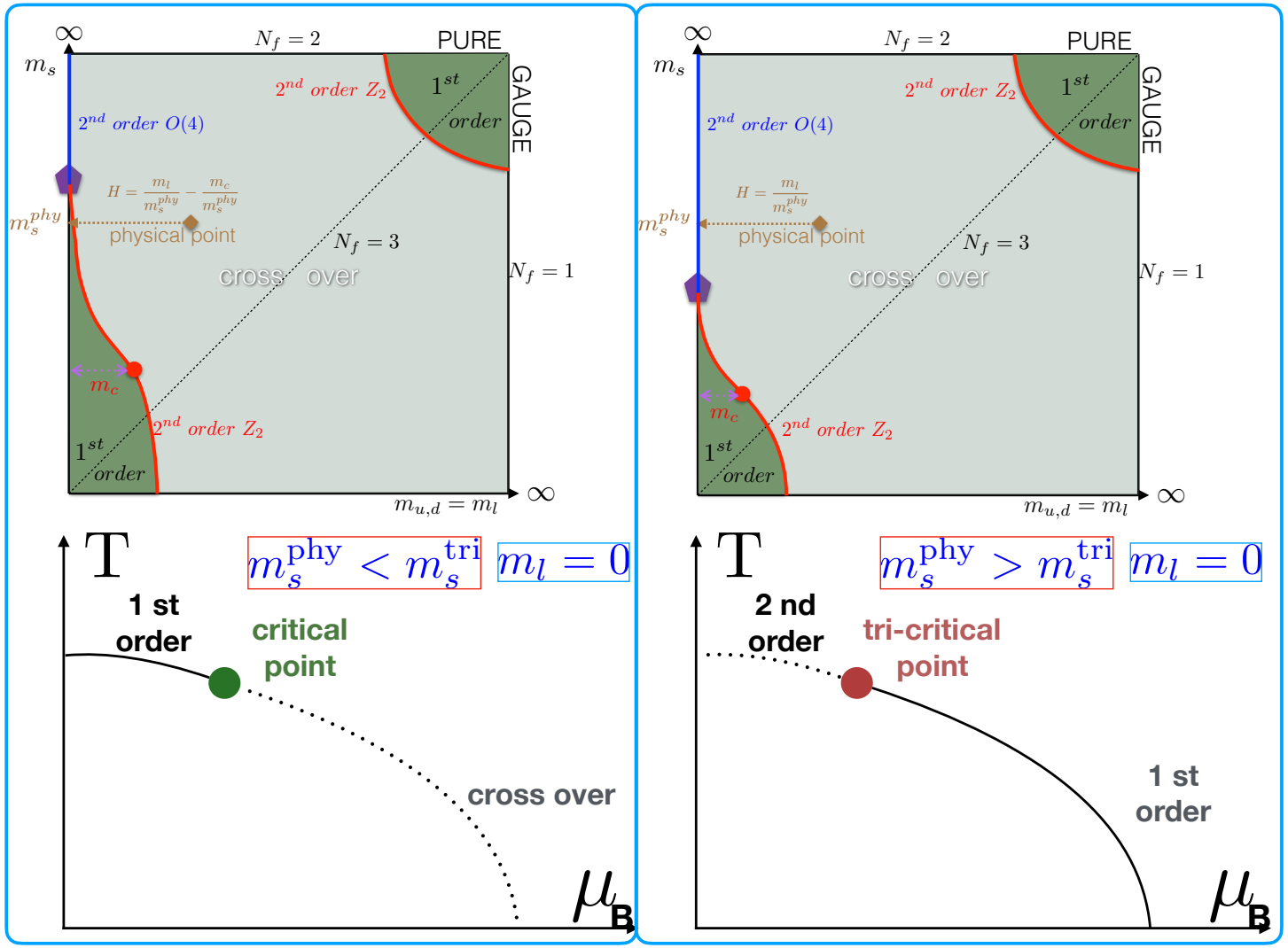
- The transition from Hadronic phase to Quark Gluon Plasma phase at $\mu_B = 0$ is a crossover but NOT a PHASE transition (Y. Aoki .et al, Nature 443 (2006) 675-678 and A. Bazavov et al., Phys.Rev.D85(2012) 054503 and the ref therein)
- Latest results $T_{pc}(\mu_B = 0) = 156.5 \pm 1.5$ MeV ("QCD crossover at zero and non-zero baryon densities" by P. Steinbrecher, Wed. 16:10-16:30)

QCD chiral phase transition



- The real PHASE transition in the chiral limit ?
- The order and universality class of the phase transition ?
- Influence of the criticality in the chiral limit to the thermodynamics at the physical point ?

Two different scenarios at $\mu_B \neq 0$



Magnetic Equation of State (MEOS)

Behaviour of QCD continuous phase transition can be described by the MEOS

$$M(t,h) = h^{1/\delta} f_G(z) + f_{reg} = \frac{m_s}{f_K^4}\left[\langle\bar{\psi}\psi\rangle_l - \frac{2m_l}{m_s}\langle\bar{\psi}\psi\rangle_s\right]$$

$$\chi_M(t,h) = \frac{\partial M}{\partial H} = H^{-1}h^{1/\delta} f_\chi(z) + \frac{\partial f_{reg}}{\partial H} = \frac{m_s^2}{f_K^4}\chi_{subtot} \tag{1}$$

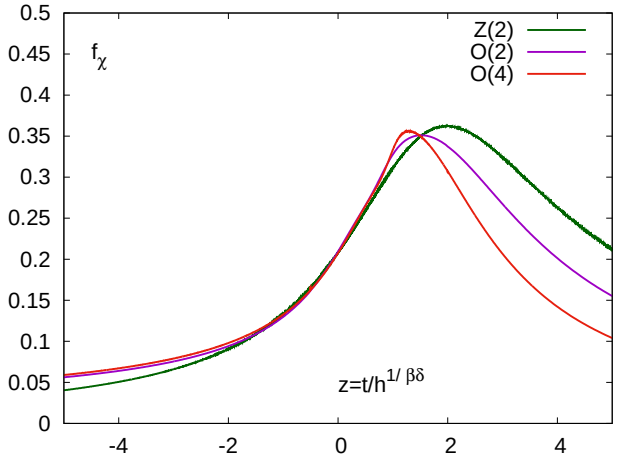
where, $f_{reg} = a_1(T)H + a_3(T)H^3 + ...$

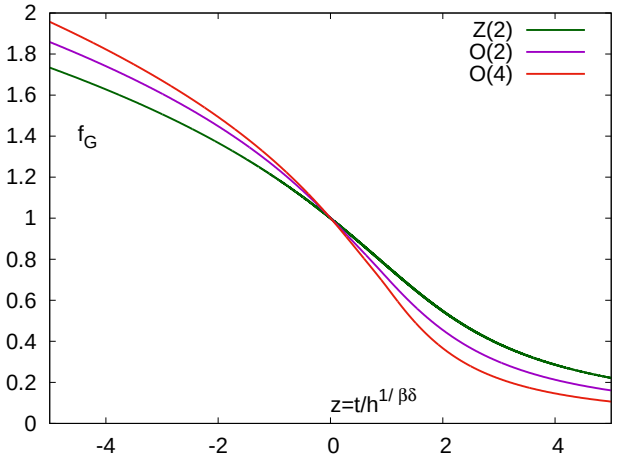
Scaling variables

$$z = t/h^{1/\beta\delta}, \quad t = \frac{1}{t_0}\frac{T - T_c^0}{T_c^0}, \quad h = \frac{H}{h_0} = \frac{1}{h_0}\frac{m_l}{m_s} \tag{2}$$

I. scaling variables, h: external field, t: reduced temperature,
II. β and δ are universal critical exponents.
III. t_0, h_0, T_c^0 are unique parameters from QCD, T_c^0 is the chiral phase transition tempearture and it is a fundamental quantity of QCD

Scaling functions & universal critical exponents





- $m_s^{\rm tri} > m_s^{\rm phy} \rightarrow$ Z(2) at $m_l = m_c$
- $m_s^{\rm tri} < m_s^{\rm phy} \rightarrow$ O(4) at $m_l = 0$
- Staggered$\rightarrow$ O(2)

Model	β	δ
Z(2)	0.3258	4.805
O(4)	0.380	4.824
O(2)	0.349	4.780

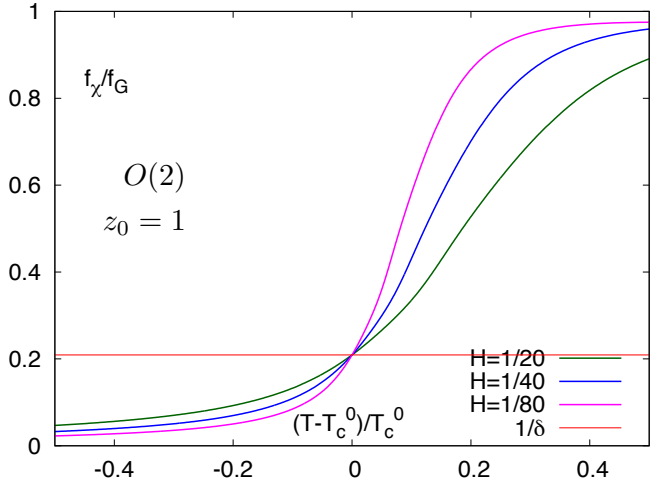
Difficulities:

I. Critical exponents of O(2), Z(2), O(4) are similar

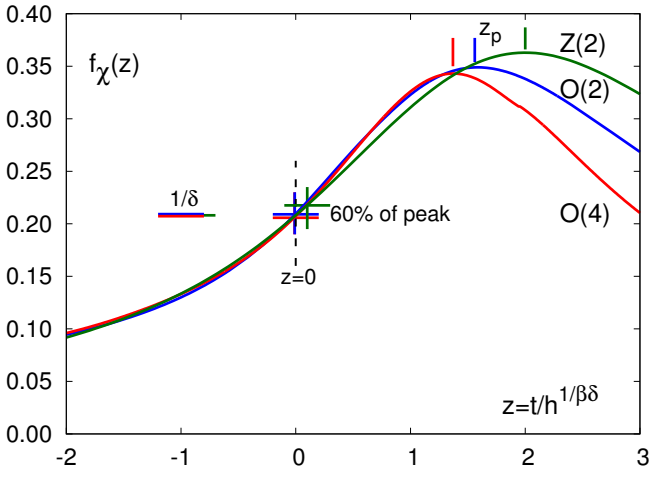
II. Regular contribution from free energy maybe complicated.

A novel way to determine T_c^0

$$\frac{H\chi_M}{M} = \frac{f_\chi(z)}{f_G(z)} = \begin{cases} 0 & z \to -\infty \\ 1/\delta & z = 0 \\ 1 & z \to +\infty \end{cases}$$



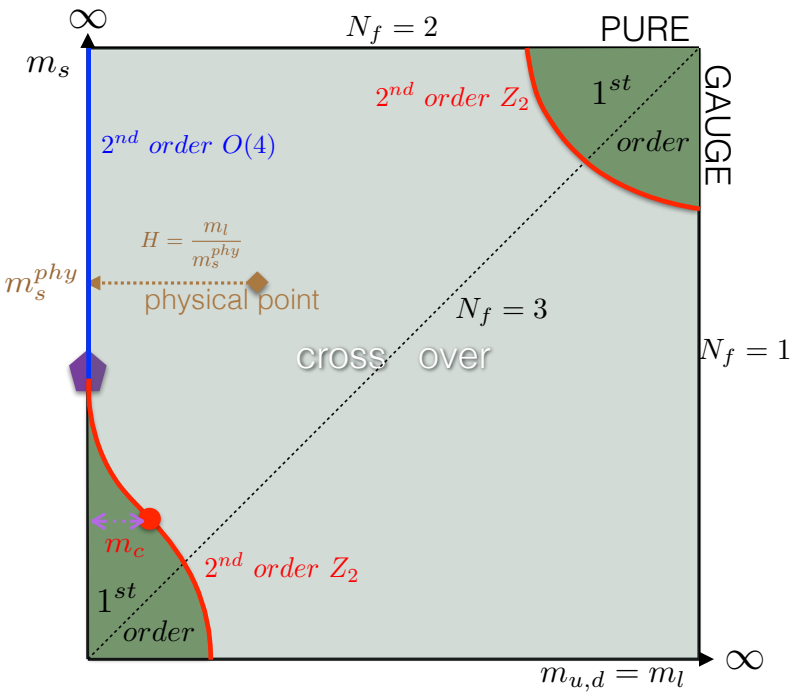
$$T^-_{60\%}(H) = T_c^0 \left(1 + \frac{z^-_{60\%}}{z_0} H^{1/\beta\delta}\right)$$



- The crossing point gives T_c^0 at $H \to 0$
- At $z^-_{60\%}$, $T^-_{60\%} \approx T_c^0$

Model	z_p	$z^-_{60\%}$
Z(2)	2.0	0.1
O(4)	1.37	-0.01
O(2)	1.56	-0.009

Lattice Setup

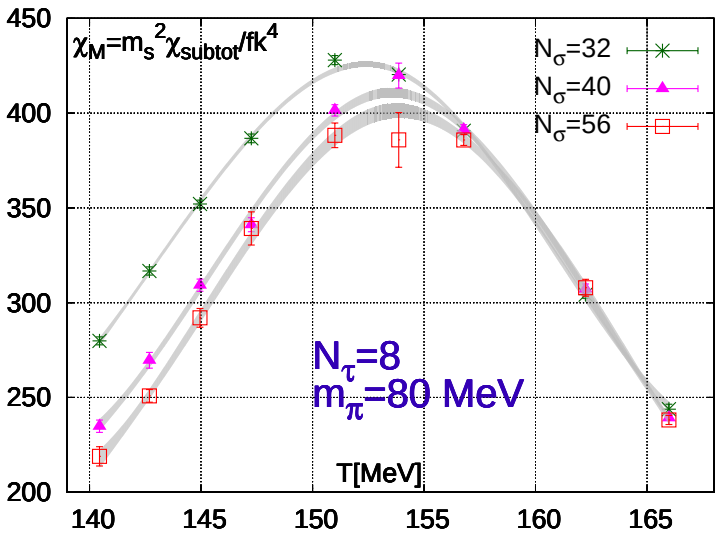


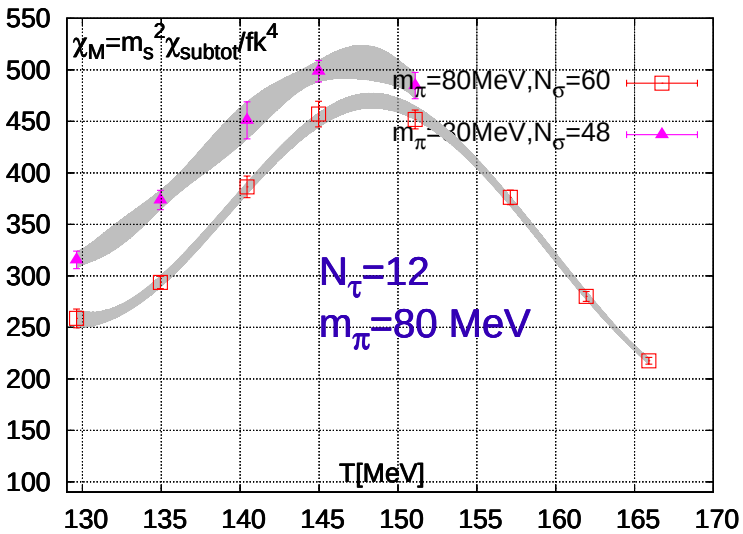
- The strange quark mass is fixed at its physical value
- 4-5 values of quark masses are chosen for $N_\tau = 6$, 8 ,12 to approach the chiral limit
- 55 MeV$\leqslant m_\pi \leqslant$ 160MeV
- $m_l^{\rm phy} = m_s^{\rm phy}/27$

(HISQ/tree) action

N_τ	$m_s^{\rm phy}/m_l$ window	m_π window	N_σ/N_τ window
6	[20, 80]	[80, 160] MeV	[4, 6.7]
8	[20, 160]	[55, 160] MeV	[4, 7]
12	[20, 80]	[80, 160] MeV	[4, 5]

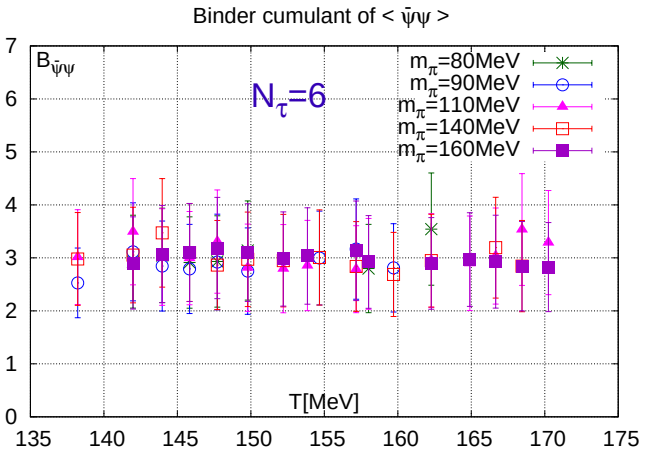
The volume dependence of the chiral susceptibility

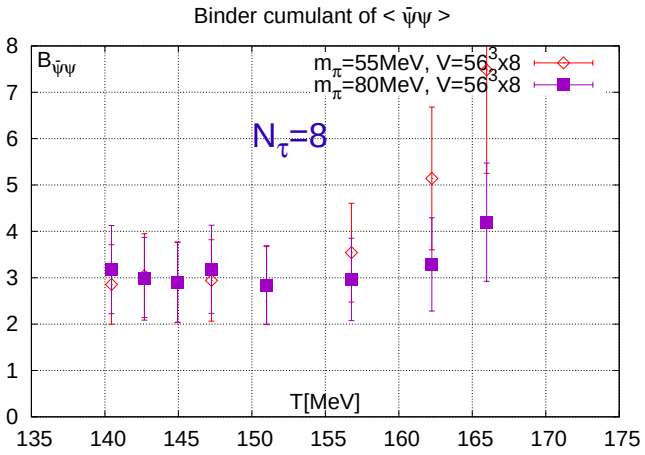


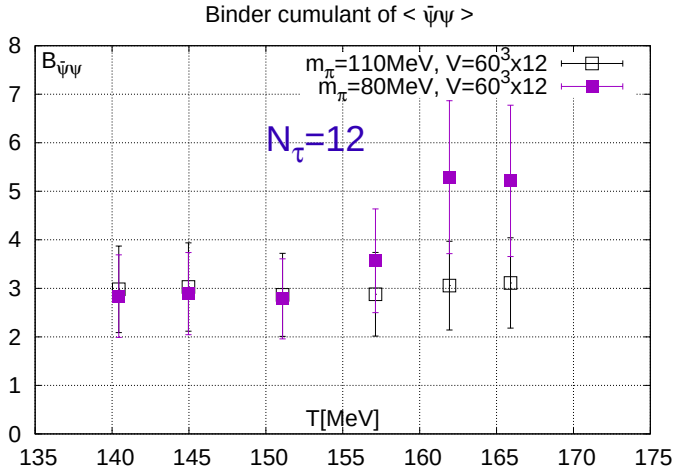


- χ_M does not grow linearly in the volume
- NO evidence for first order phase transition was found in the current pion mass window $m_\pi \geqslant 80$ MeV

Binder cumulant of chiral order parameter



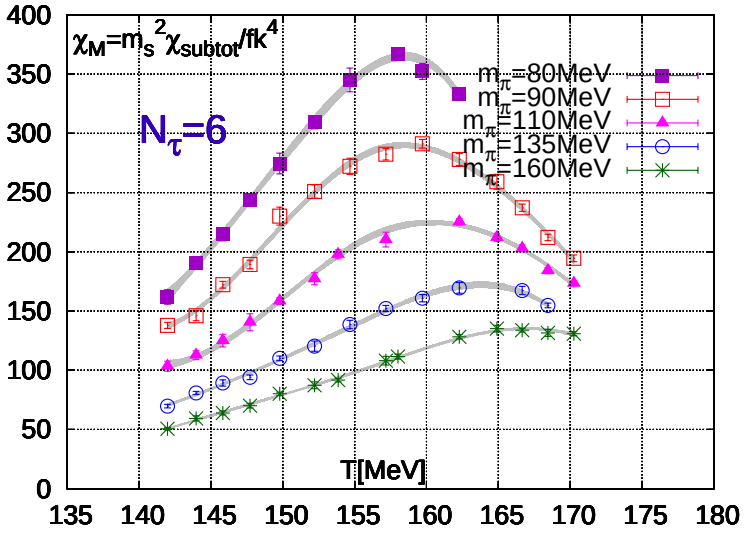


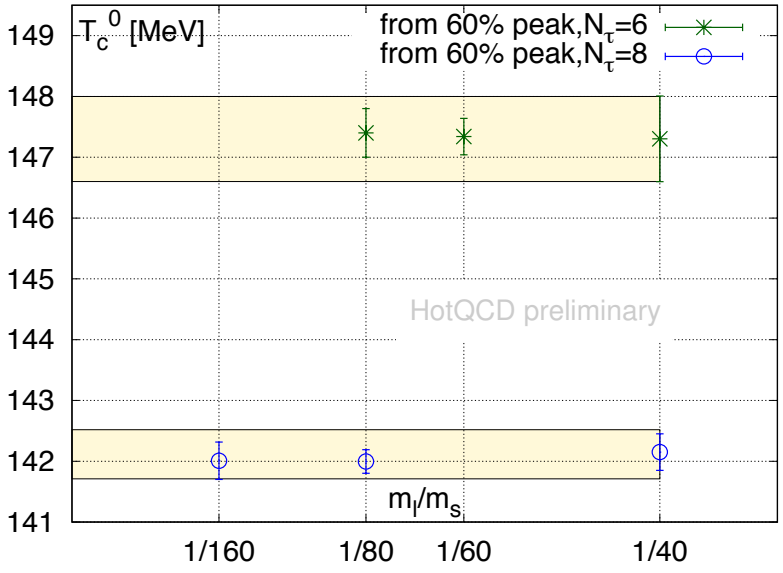


Model	$B_{\bar{\psi}\psi}$
Z(2)	1.604(2)
O(2)	1.242(2)
O(4)	1.092(3)
1 st	1
crossover	3

$B_{\bar{\psi}\psi} \approx 3$ suggests that the transition is crossover in the pion mass window 55 MeV $\leqslant m_\pi \leqslant$ 160 MeV

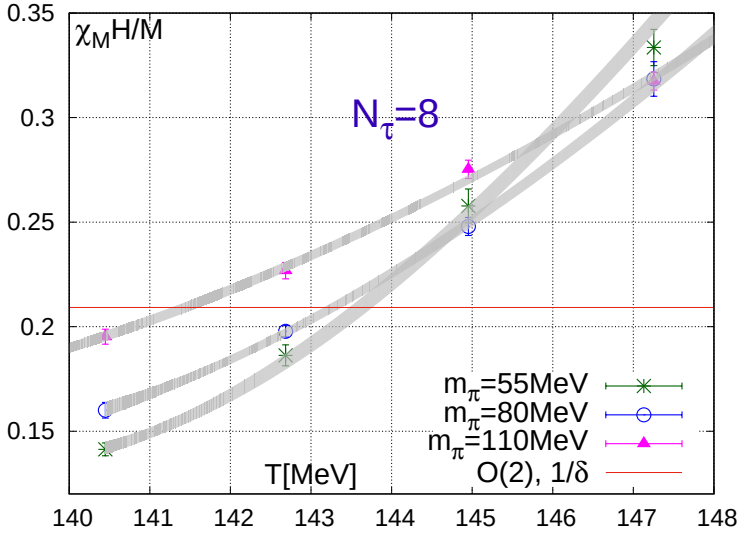
Study T_c^0 by looking at 60% peak of χ_M

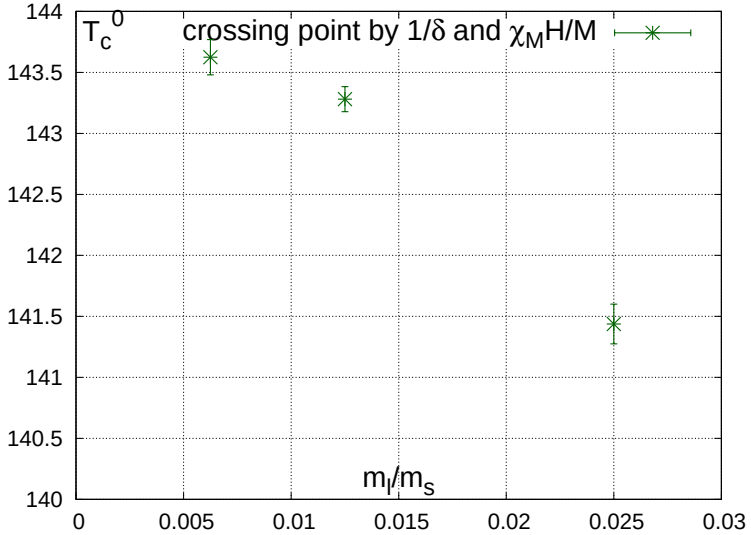




- Current estimation from 60% peak of χ_M: T_c^0 is around 147(2) MeV for N_τ=6, and 142(2) MeV for $N_\tau = 8$ MeV.

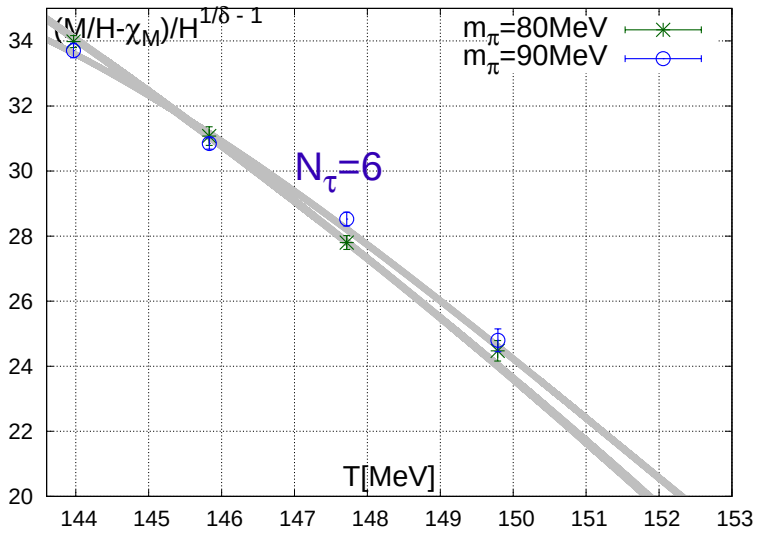
Sanity check for T_c^0

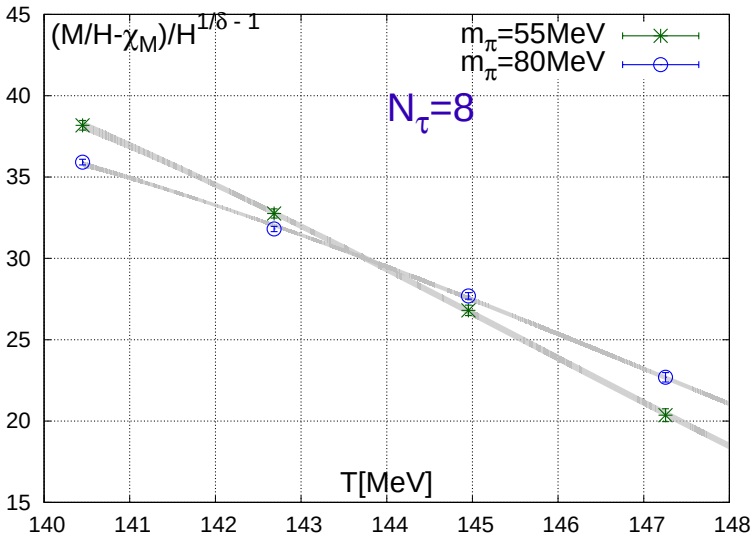




Current estimation from $\chi_M H/M = 1/\delta,\ H \to 0$ shows the chiral phase transition temperature $T_c^0 \approx 144$ MeV for $N_\tau = 8$.

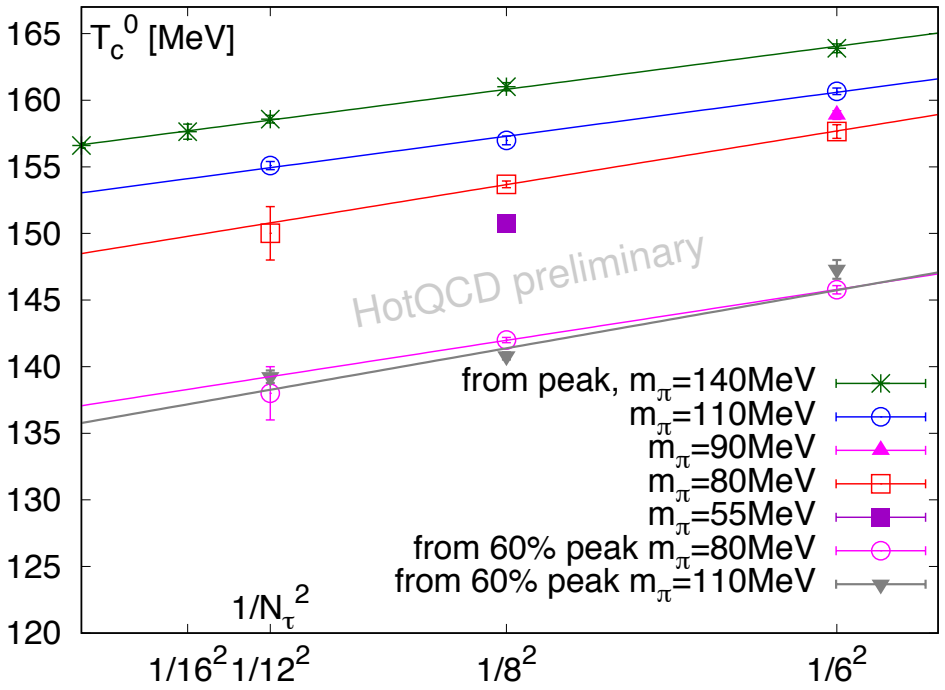
Sanity check for T_c^0





Crossing point by two lightest quarks gives an estimate of T_c^0.

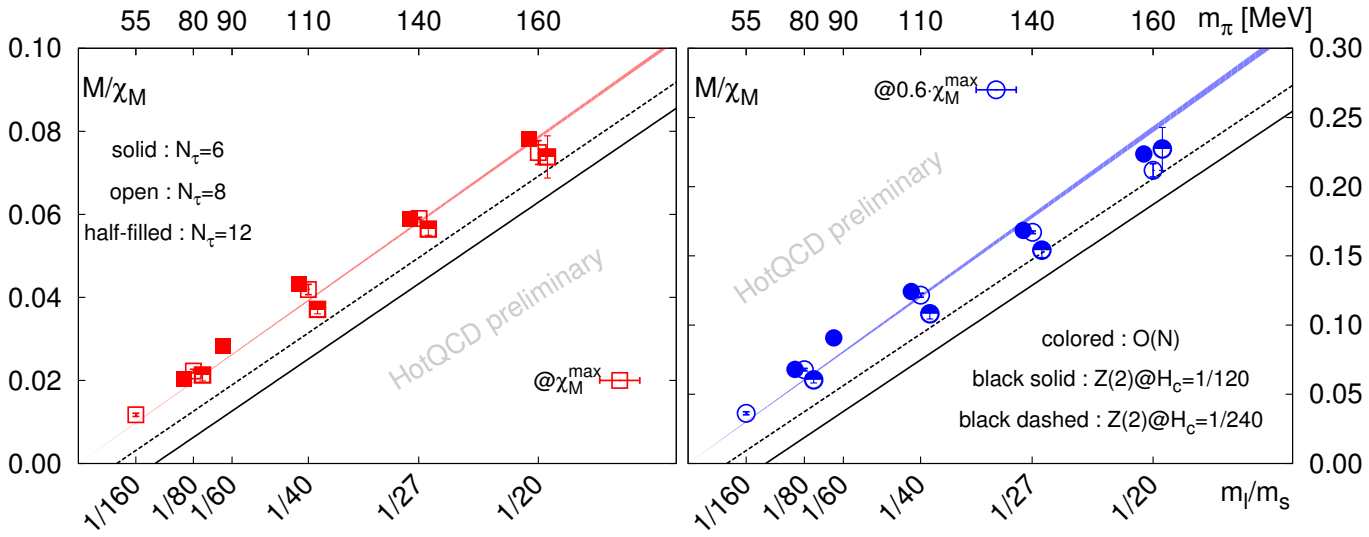
Towards the continuum limit



m_s/m_l	T_c^0 towards continuum limit[MeV]
40	136(3)
80	137(3)

The order of the chiral phase transition

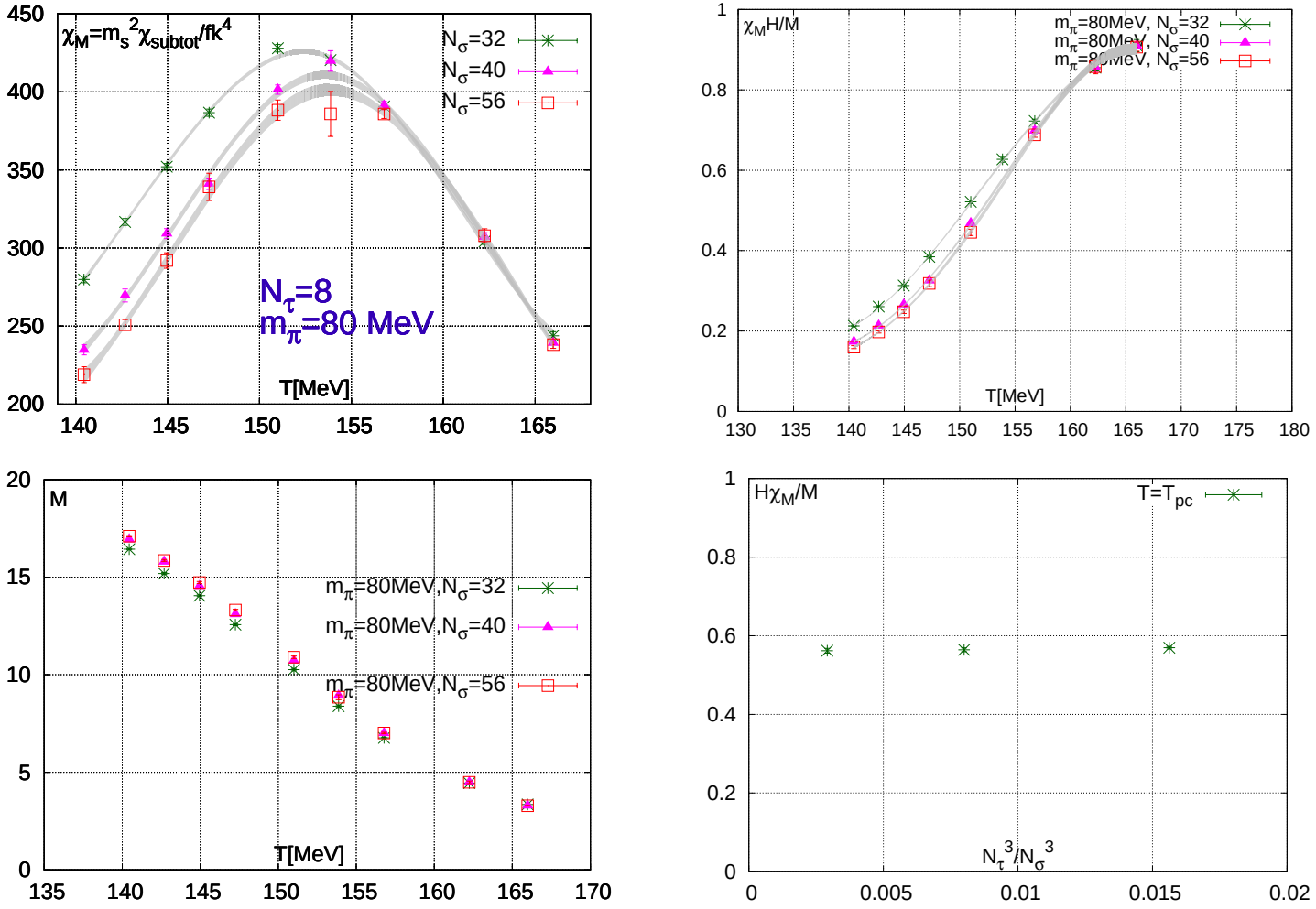
$$\frac{M}{\chi_M} = \frac{m_l - m_c}{m_s} \frac{f_G(z)}{f_\chi(z)} \tag{3}$$



Summary and outlook

- ✓ We have performed simulations on $N_\tau = 6, 8, 12$ lattice using the HISQ action with five different values of light quark masses towards the chiral limit
- ✓ No first order phase transition is observed in our current pion mass window (55MeV $< m_\pi <$ 160MeV)
- ✓ Our scaling analyses suggest that $m_s^{\rm phy} > m_s^{\rm tri}$
- ✓ The chiral phase transition temperature $T_c^0 = 138(5)$ MeV at $a \to 0, V \to \infty, m \to 0$.

Volume dependence of chiral observables



Volume correction to $T^{-}_{60\%}$