Finite Temperature QCD with Physical (u/d, s, c) Domain-Wall Quarks

Ting-Wai Chiu (趙挺偉)

Academia Sinica
National Taiwan Normal University
National Taiwan University

In collaboration with Yu-Chih Chen and Tung-Han Hsieh

(for the TWQCD collaboration)

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Outline

- Introduction
- Actions and algorithms
- Gauge ensembles
- Hadron masses on the 64^4 lattice with a ~0.064 fm
- Topological charge via the Wilson flow
- Topological susceptibility for T ~ 155--516 MeV
- Remarks

Introduction

- The topologically susceptibility $\chi_t = \lim_{V_4 \to \infty} \langle Q_t^2 \rangle / V_4$ is a vital quantity to measure the quantum fluctations of the topology of ***QCD*** vacuum. For $T < T_c$, χ_t is related to chiral condensate $\Sigma = -\langle \bar{\psi}\psi \rangle$, which is the origin of spontaneous chiral symmetry breaking, giving the majority of the visible (non-dark) mass in the universe today.

- If the Pecci-Quinn machanism is realized in Nature, the evolution of $\chi_t(T)$ from the early universe to T_γ determines the axion relic energy density, a promising candidate of the dark matter.

  axion mass: $m_A(T) = \sqrt{\chi_t(T)} / f_A$, f_A : the scale of breaking the $U(1)_{PQ}$ sym.

- Compute $\chi_t(a,T)$ of 15 ensembles with physical $(u/d,\ s,\ c)$ DW quarks, for $T \approx 155 - 516$ MeV and 3 lattice spacings (0.064, 0.068, 0.075) fm, to extract $\chi_t(T)$ in the continuum limit.

Actions and Algorithms

- Quarks: optimal DWF [TWC, PRL 2003] with $N_s = 16$, $\lambda_{max}/\lambda_{min} = 6.20/0.05$.
  Gluons: plaquette gauge action at $\beta = 6/g^2 = (6.20,\ 6.18,\ 6.15)$
- For the one-flavor, use the Exact One-Flavor pseudofermion Action (EOFA)
  [Y.C. Chen & TWC, Phys. Lett. B738 (2014) 55; TWC, Phys. Lett. B744 (2015) 95]
- For the 2-flavor, use the two-flavor action for DWF.
  [TWC, T.H. Hsieh, Y.Y. Mao, Phys. Lett. B702 (2012) 131]

Optimal Domain-Wall Fermion

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Optimal Lattice Domain-Wall Fermions

Ting-Wai Chiu*
Department of Physics, University of Washington, Seattle, Washington 98195-1560
Department of Physics, National Taiwan University, Taipei, Taiwan 106, Taiwan
(Received 30 October 2002; published 19 February 2003)

I show that the conventional formulations of lattice domain-wall fermion with any finite N_s (in the fifth dimension) do not preserve the chiral symmetry optimally and propose a new action which preserves the chiral symmetry optimally for any finite N_s.

$$\omega_s = \frac{1}{\lambda_{\min}} \sqrt{1-\kappa'^2 sn^2(v_s;\kappa')}, \quad s = 1,\cdots,N_s$$

Effective 4D Dirac op. of the optimal DWF is exactly equal to the Zolotarev optimal rational approx. of the overlap Dirac op.

Optimal DWF with R_5 Symmetry [TWC, Phys. Lett. B 744 (2015) 95-100]

$$N_s = 2n \ (\text{even}) \qquad \omega_s = \omega_{N_s+1-s} = \frac{1}{\lambda_{min}} \sqrt{1-\kappa'^2 \mathrm{sn}^2\left(\frac{(2s-1)K'}{N_s};\kappa'\right)}$$

Gauge Ensembles

- Lattice sizes : $64^3 \times (64,\ 20,\ 16,\ 12,\ 10,\ 8,\ 6)$
- Lattice spacings : $a \simeq (0.064, 0.068, 0.075)$ fm,

$$a^{-1} \approx (3.1, 2.9, 2.6) \text{ GeV}$$

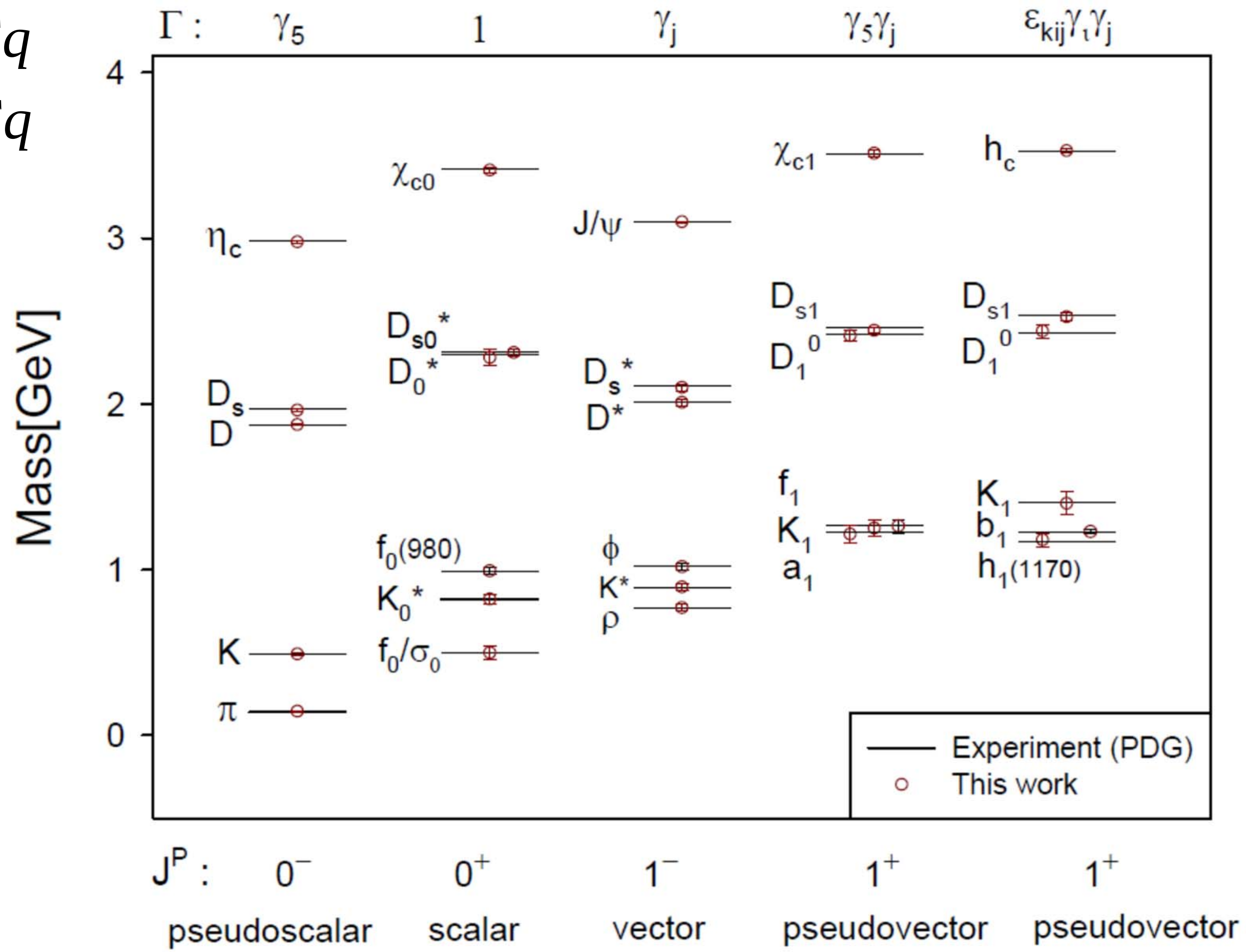
- Spatial volume : $L^3 > (4 \text{ fm})^3, \ M_\pi L > 3$
- Temperatures : $\sim 0 - 520$ MeV
- Statistics : ~$500 - 3000$ configurations per ensemble
- The lattice spacings are determined by the Wilson flow, using $t^2 \langle E \rangle \big|_{t=t_0} = 0.3$ with $\sqrt{t_0} = 0.1416(8)$ fm.
- The masses of s and c quarks are fixed by the masses of $\phi(1020)$ and $J/\psi(3097)$ respectively, while the mass of u/d quarks by $M_\pi(140)$, on the 64^4 lattices.
- The HMC simulations are performed on 10-20 units of Nvidia DGX-1 at 3 institutions/organizations in Taiwan, since January 2018.

The Spectrum of the Lowest-lying Mesons

$64^4,\ \beta = 6.20,\ a = 0.064$ fm, 400 confs   TWC, arXiv:2020.06126

$\bar{Q}\Gamma q$

$\bar{q}\Gamma q$

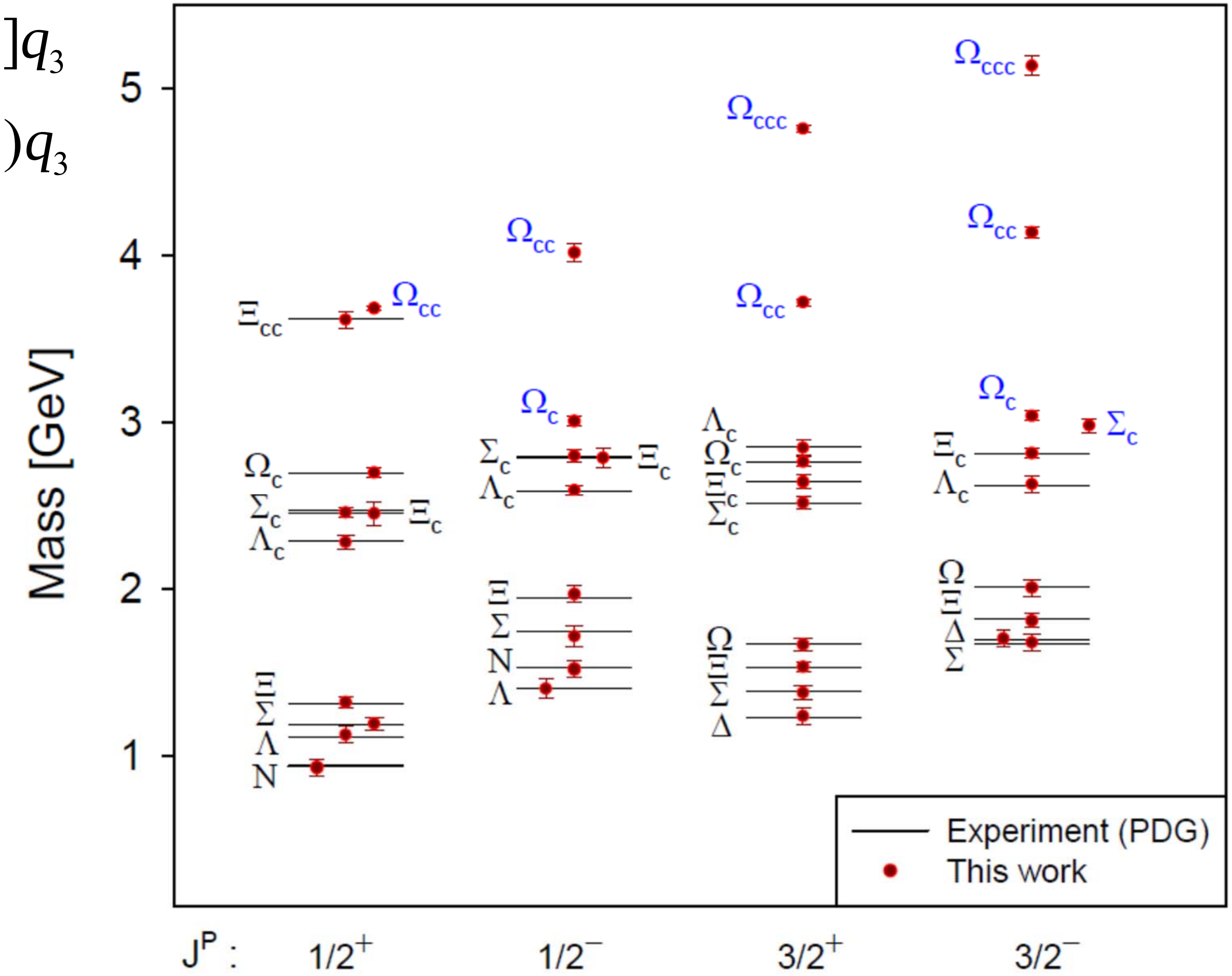


The Spectrum of the Lowest-lying Baryons

$64^4, \ \beta = 6.20, \ a = 0.064$ fm, 400 confs   TWC, arXiv:2020.06126

$[q_1 C\Gamma q_2]q_3$

$(q_1 C\Gamma q_2)q_3$



Topological susceptibility $\chi_t(T)$ of lattice QCD with physical (u/d, s, c) domain-wall quarks

15 Ensembles

β	$a\,[\mathrm{fm}]$	N_x	N_t	$T=(N_t a)^{-1}[\mathrm{MeV}]$	# confs
6.20	0.064	64	6	516	3038
6.20	0.064	64	8	387	2665
6.20	0.064	64	10	310	2547
6.20	0.064	64	12	258	1684
6.20	0.064	64	16	193	2230
6.20	0.064	64	20	155	2491
6.18	0.068	64	6	479	2908
6.18	0.068	64	8	360	2088
6.18	0.068	64	10	288	1629
6.18	0.068	64	12	240	649
6.18	0.068	64	16	180	565
6.15	0.075	64	6	438	2454
6.15	0.075	64	8	329	2109
6.15	0.075	64	10	263	831
6.15	0.075	64	12	219	811

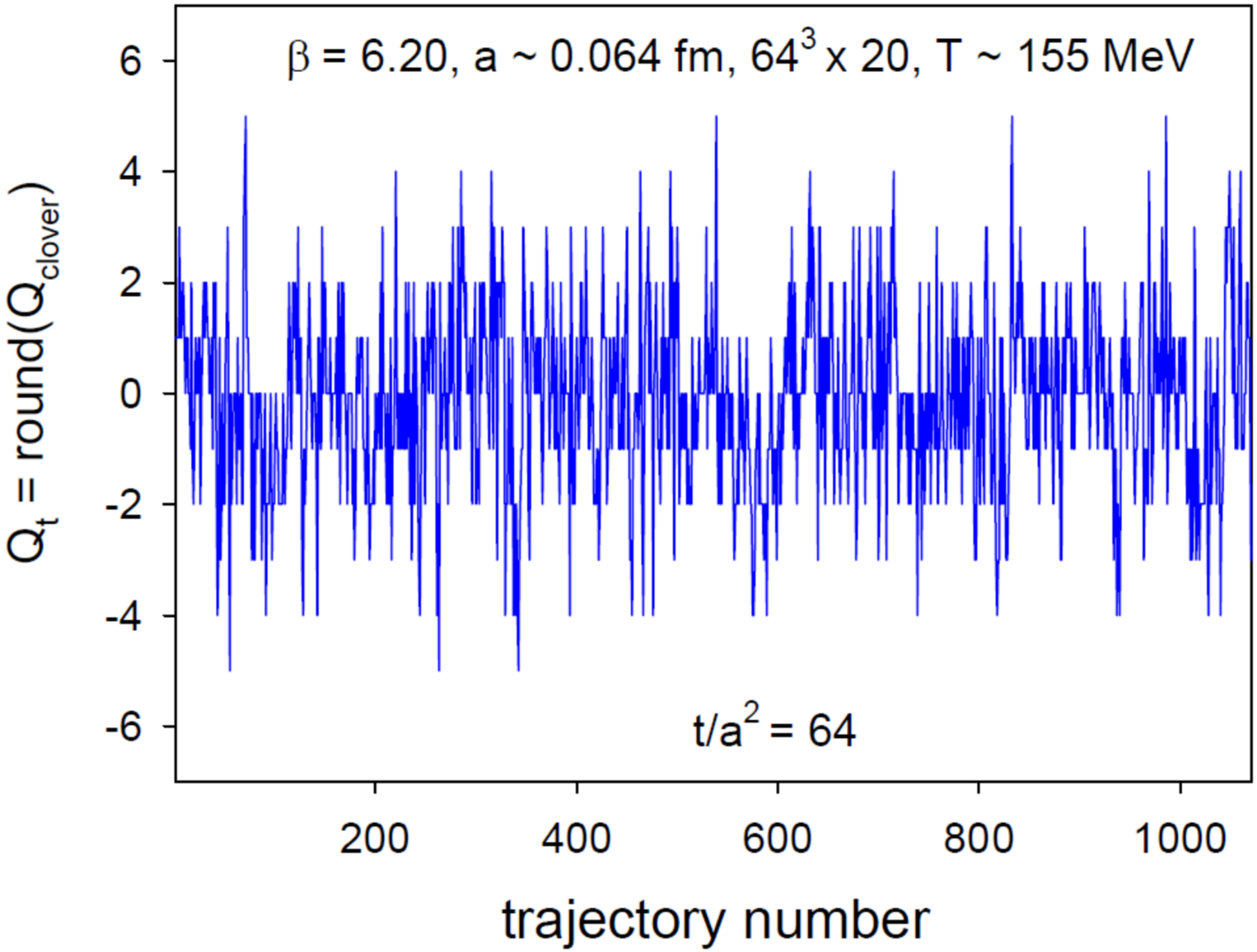
Topological Charge and Topological Susceptibility

- The topological charge Q_t of each configuration is measured via the Wilson flow, using the clover definition.

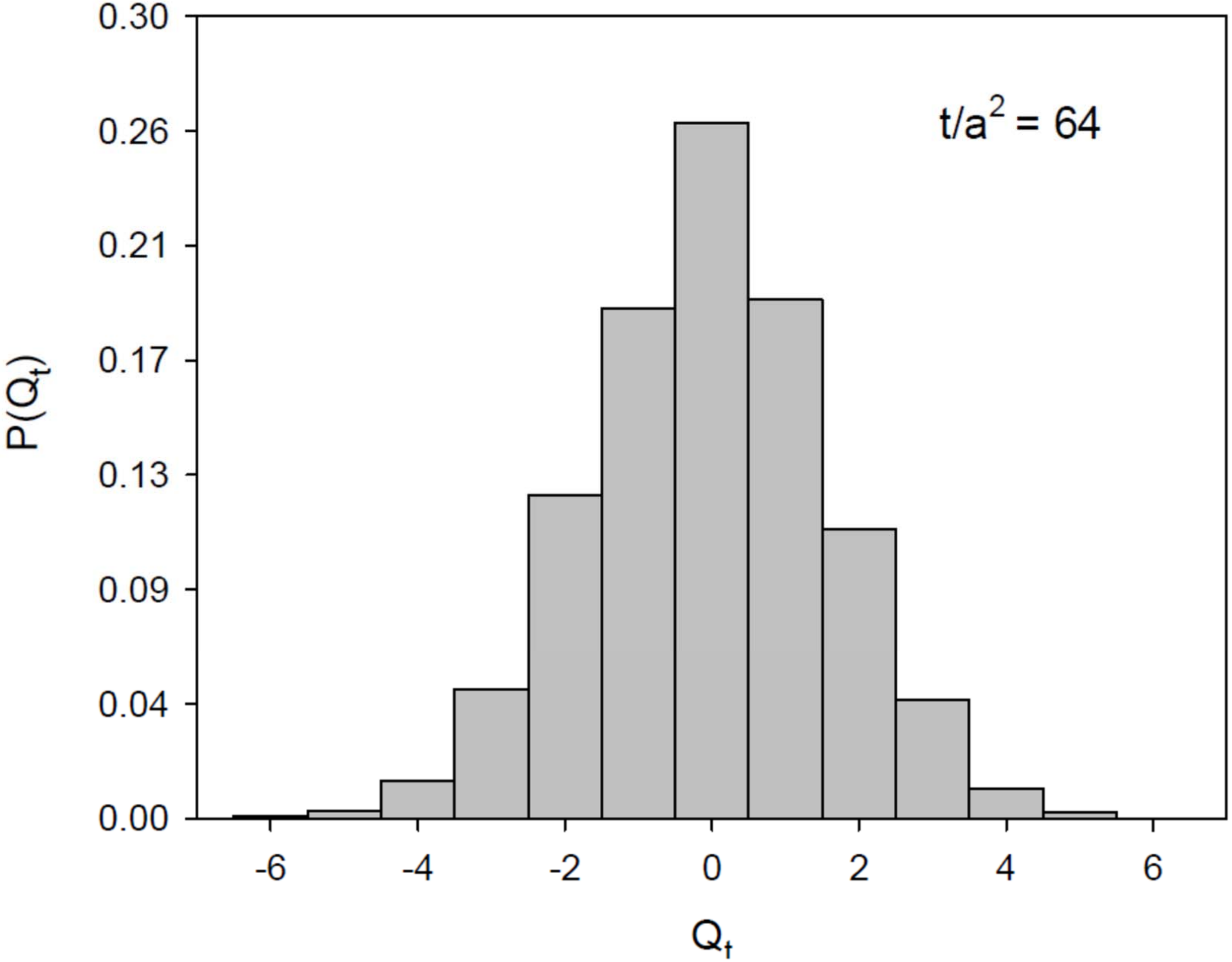
- The Wilson flow equation is integrated from $t/a^2 = 0$ to 256 with the step size $\Delta t / a^2 = 0.01$.

- In order to extrapolate $\chi_t = \langle Q_t^2 \rangle / V_{4D}$ to the continuum limit, Q_t is required to be measured at the same t (in physical units) for all ensembles, which is chosen to be $t = 0.8192 \text{ fm}^2$ in this study.

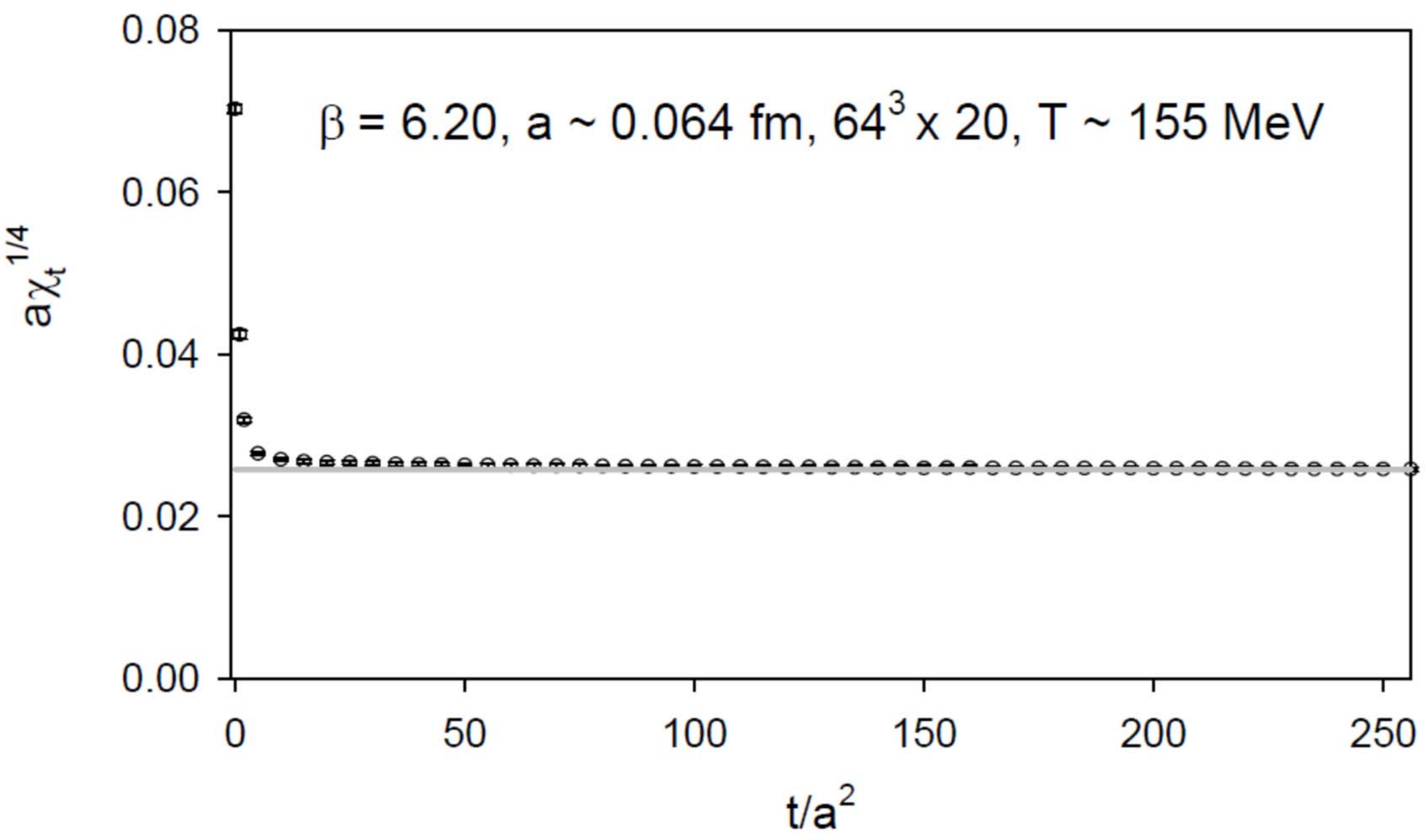
Evolution of Q_t in HMC at T=155 MeV



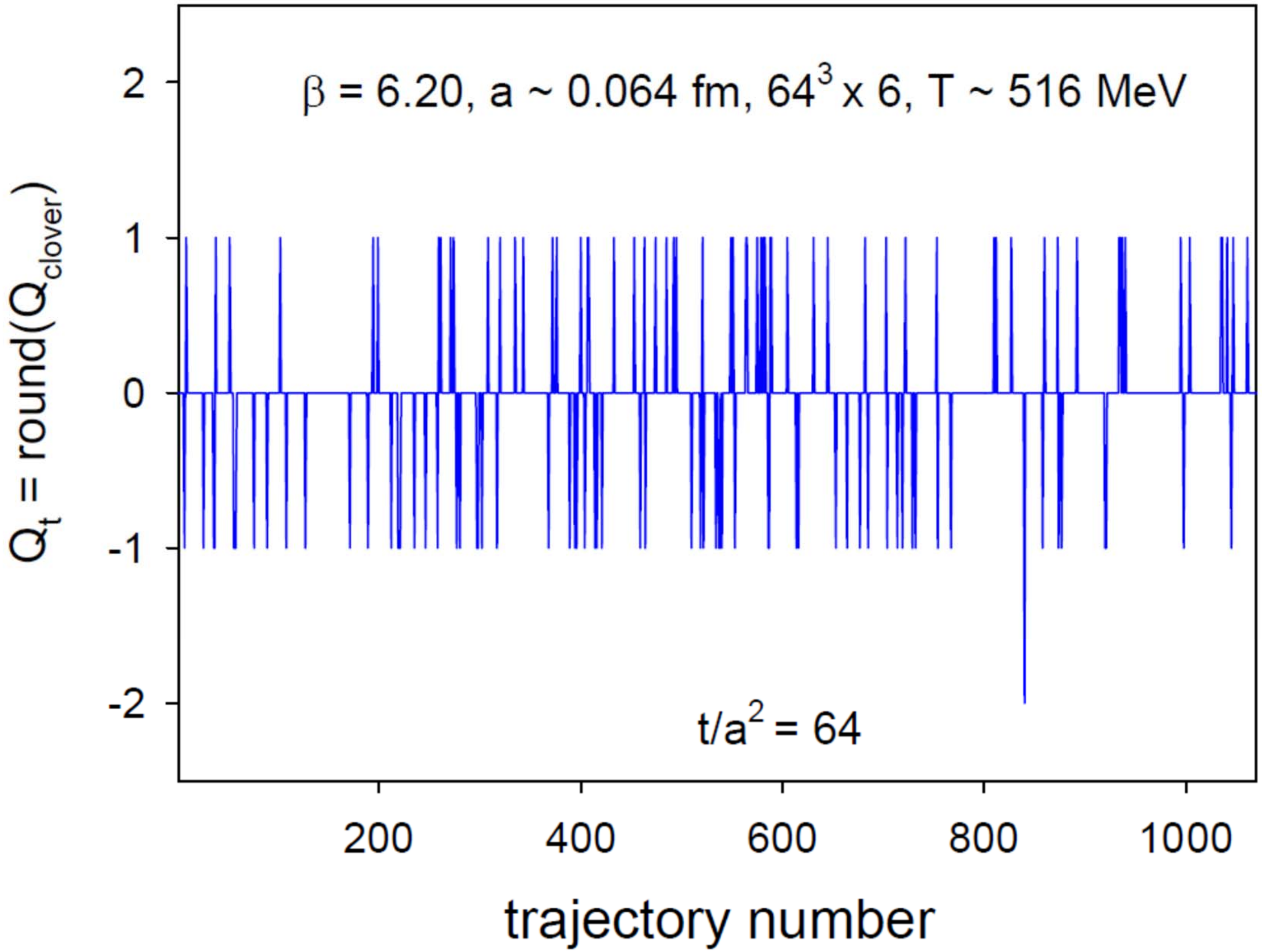
Histogram of Q_t at T=155 MeV



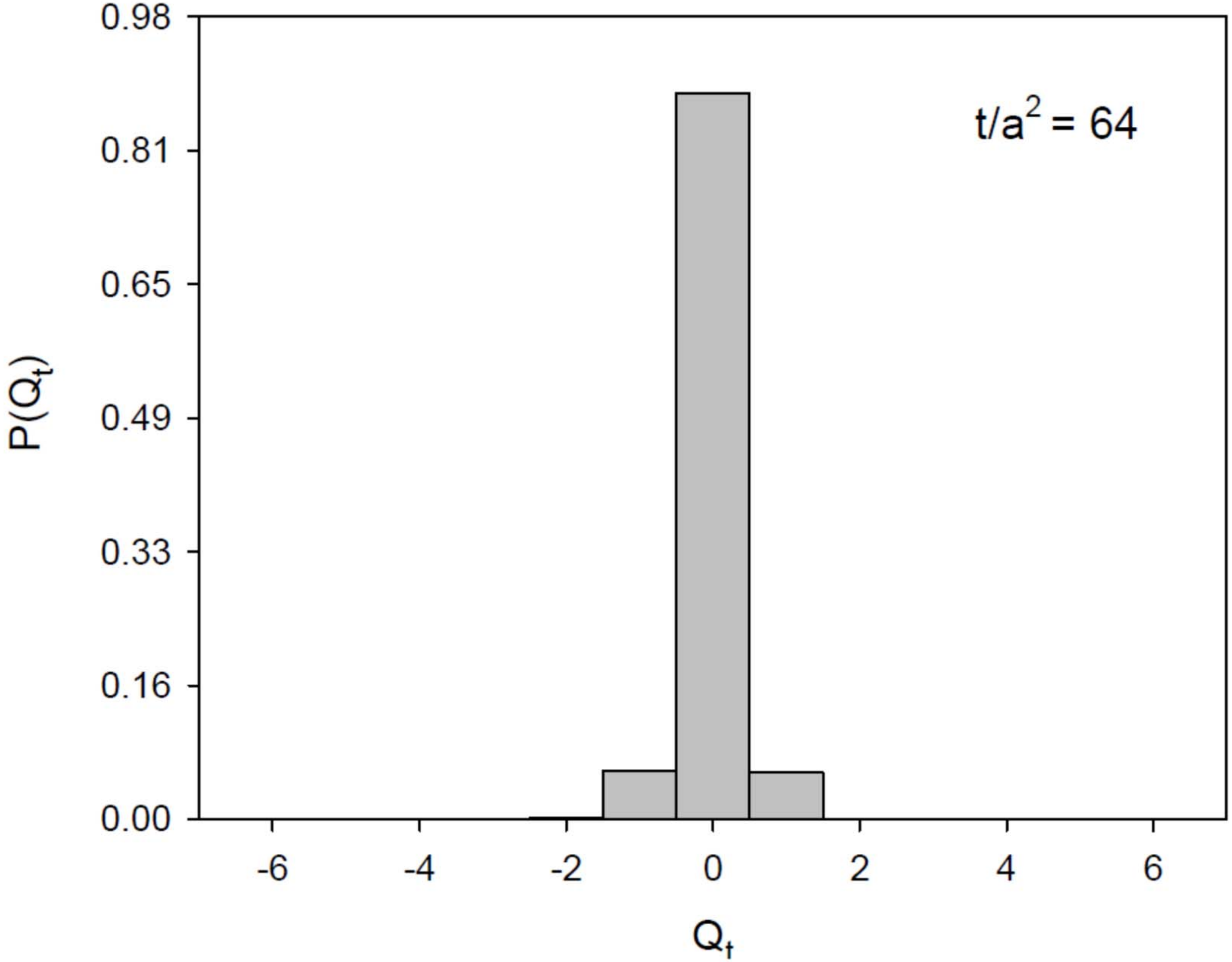
Topological Susceptibility at T=155 MeV



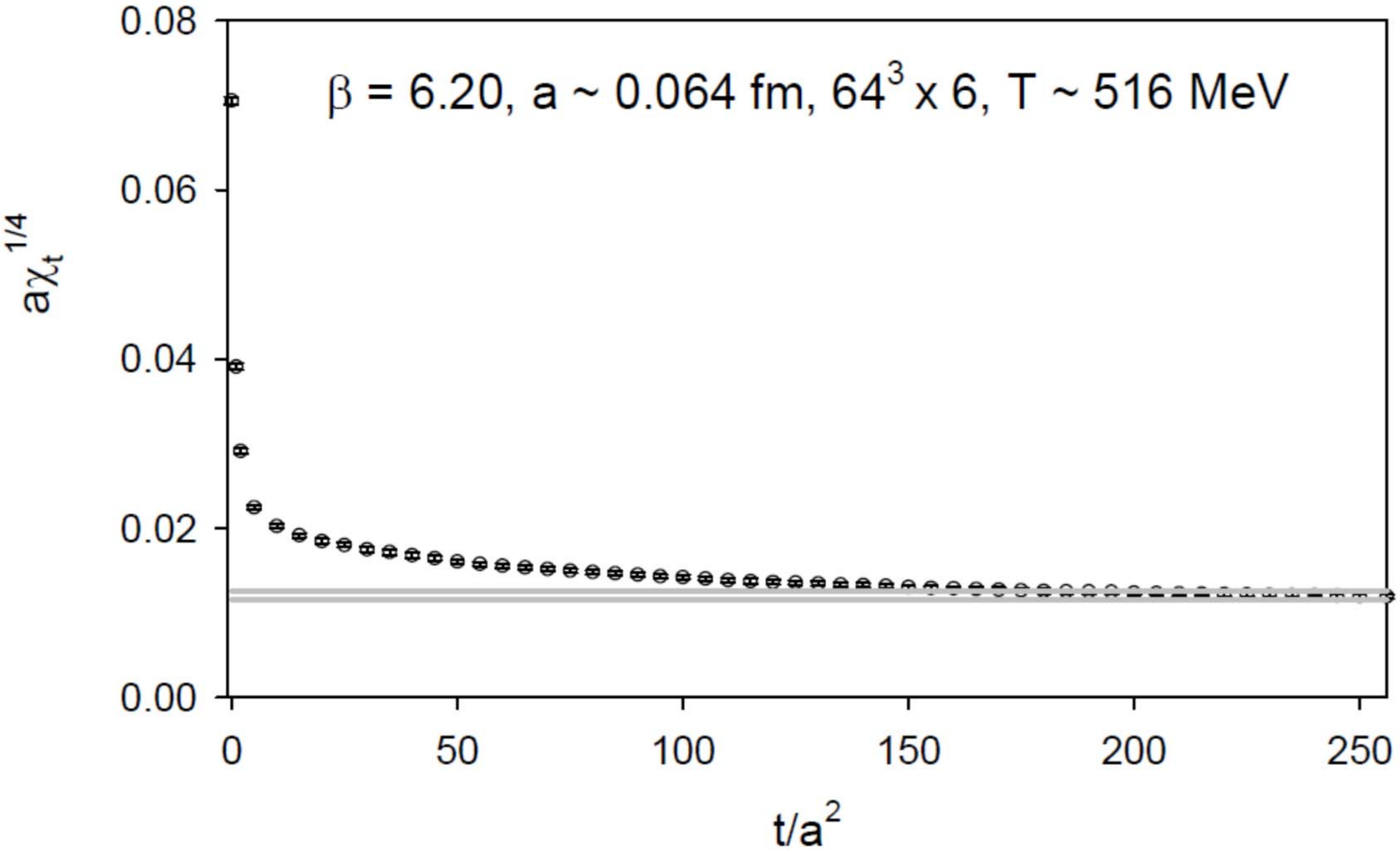
Evolution of Q_t in HMC at T=516 MeV



Histogram of Q_t at T=516 MeV

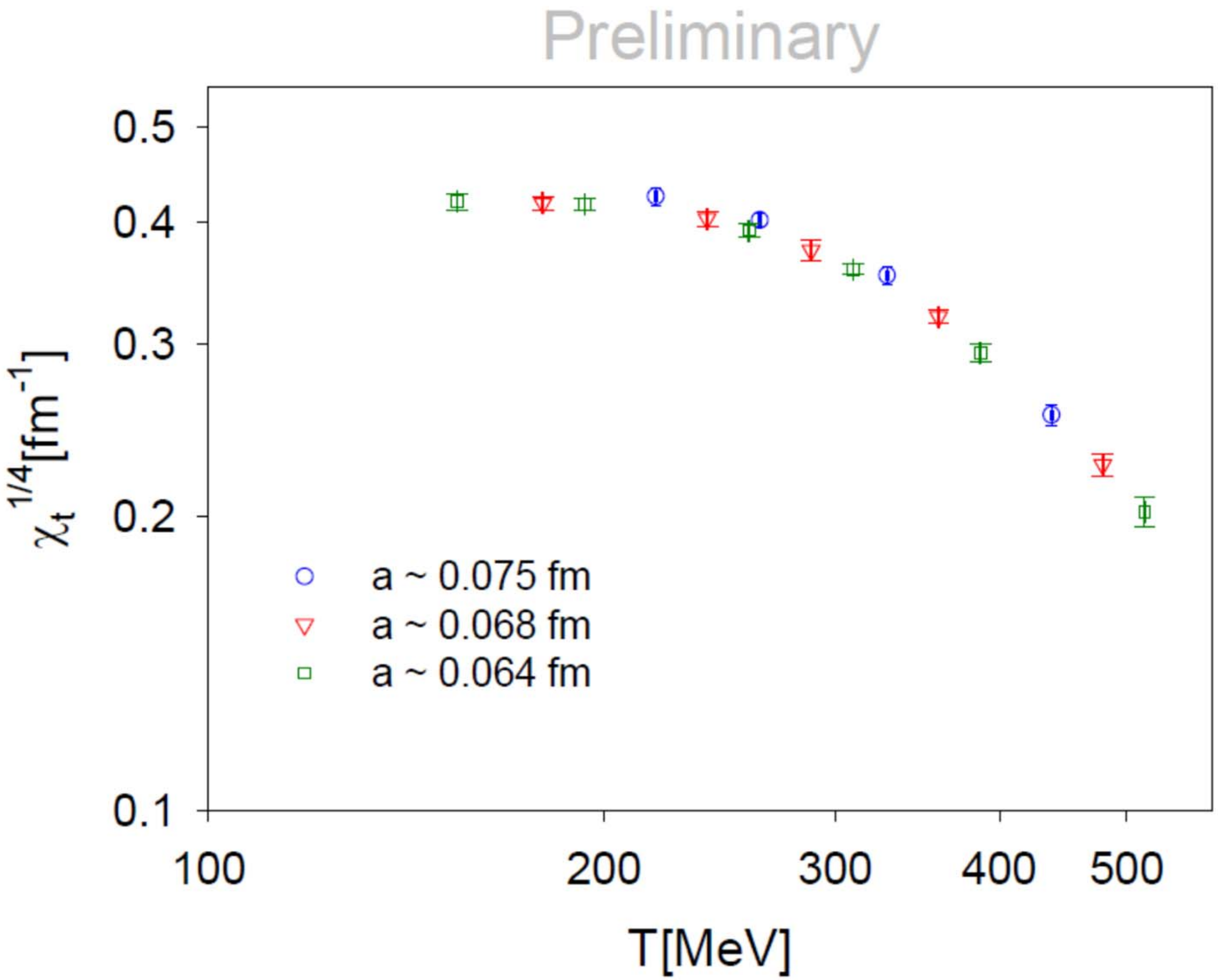


Topological Susceptibility at T=516 MeV



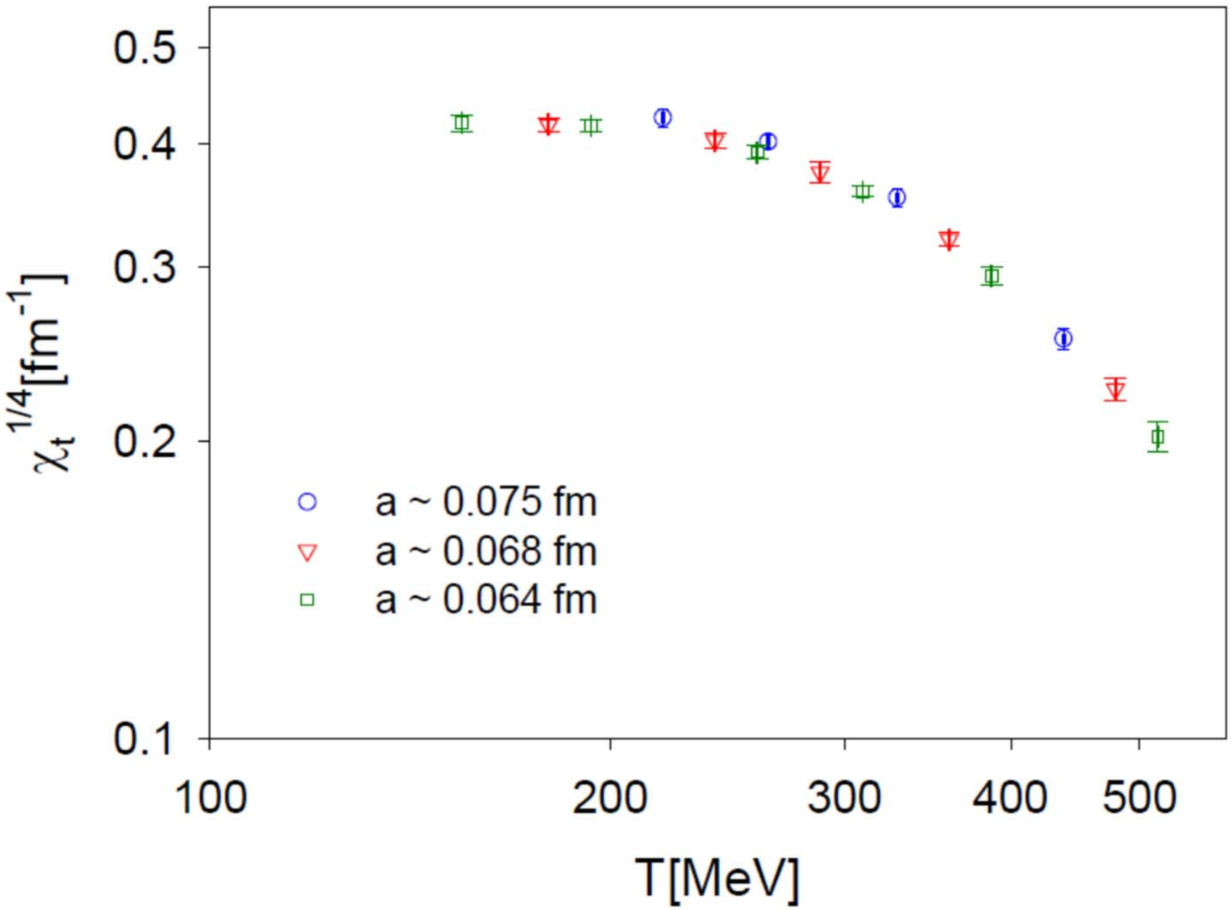
Topological susceptibility $\chi_t(T)$ of lattice QCD with physical (u/d, s, c) domain-wall quarks

How to use the data points of $\chi_t(a,T)$ to extract $\chi_t(T)$ in the continuum limit ?



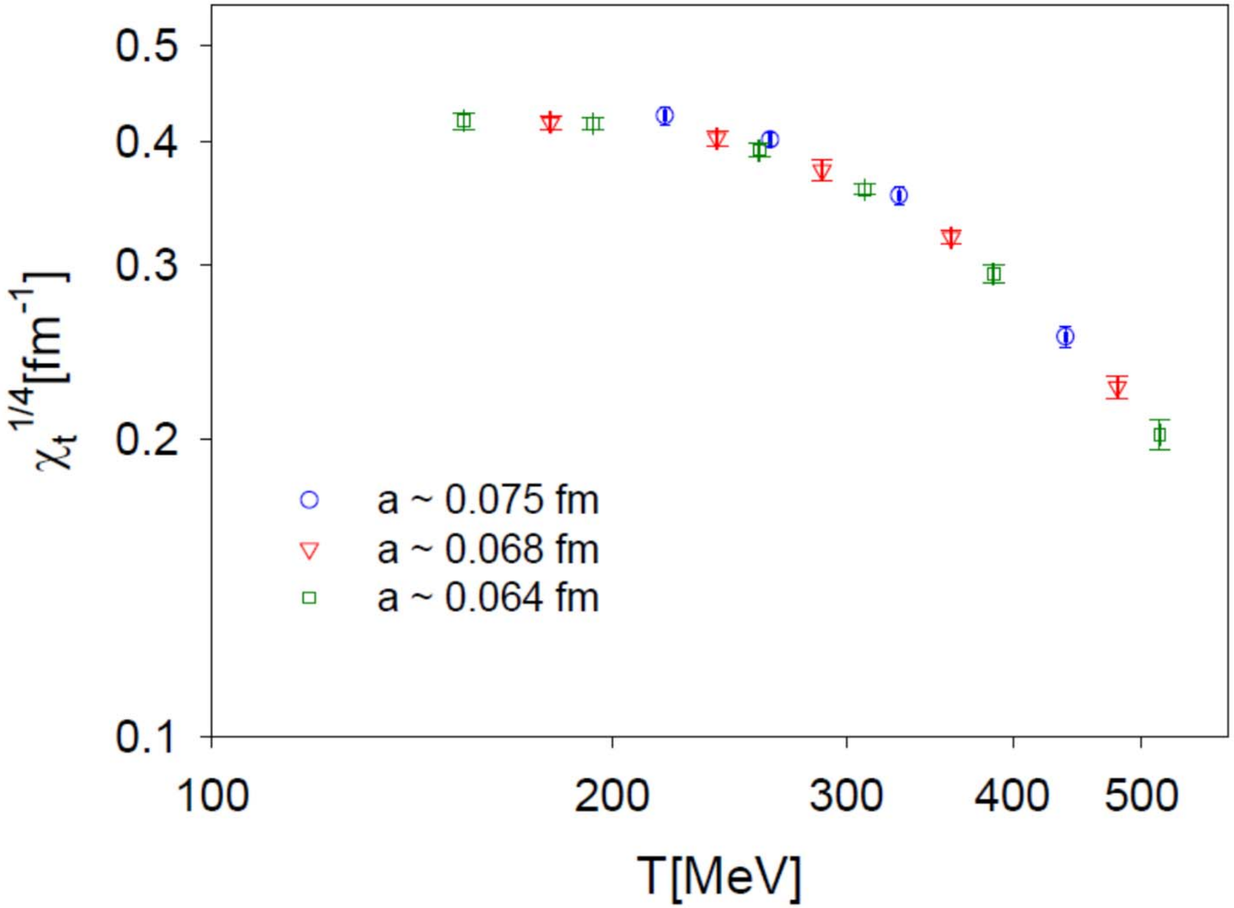
Topological susceptibility $\chi_t(T)$ of lattice QCD with physical (u/d, s, c) domain-wall quarks

power law $\chi_t^{1/4}(a,T) = (c_0 + c_1 a^2)\left(\frac{T_c}{T}\right)^p$ can only fit data points at high T



Topological susceptibility $\chi_t(T)$ of lattice QCD with physical (u/d, s, c) domain-wall quarks

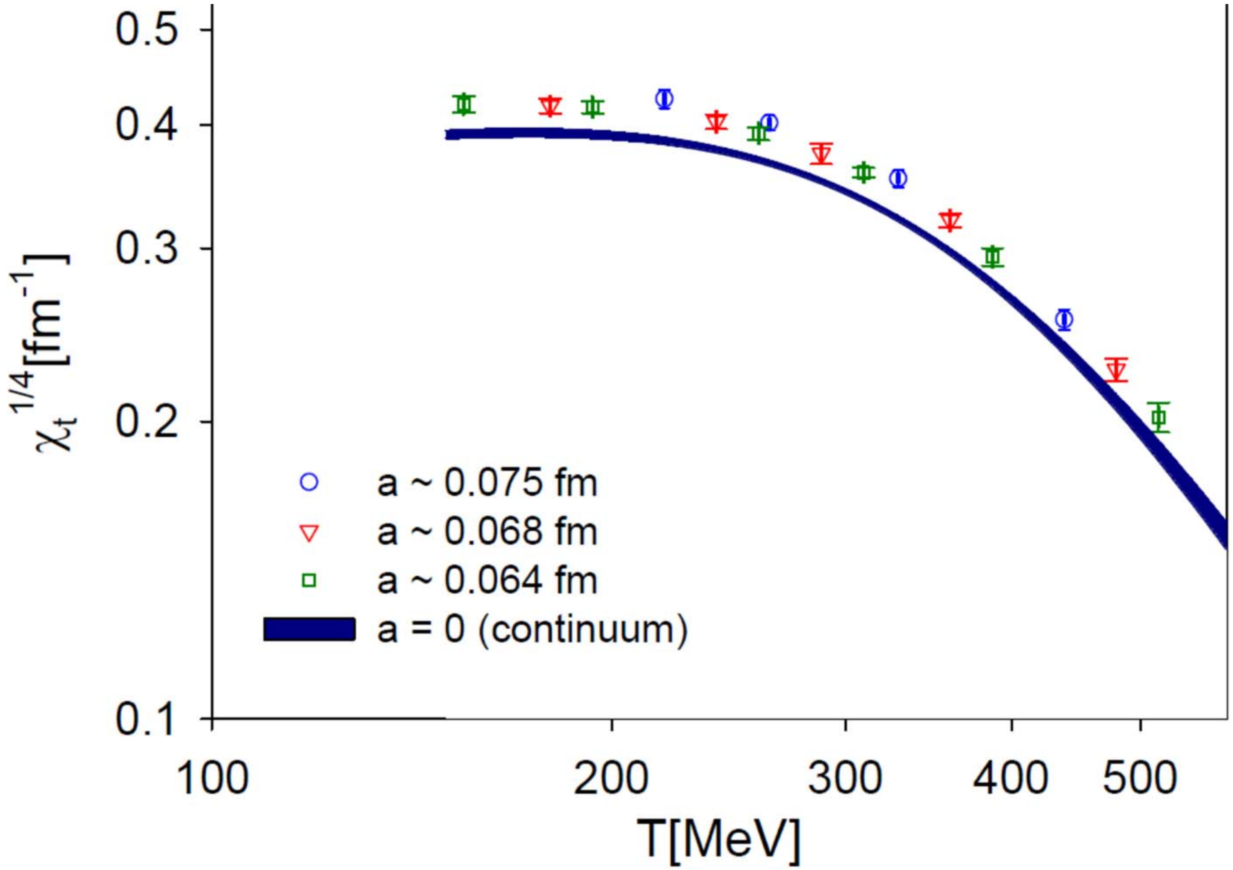
Fitting to $\chi_t^{1/4}(a,T) = (c_0 + c_1 a^2)\dfrac{x^p}{1+bx+cx^2}, \quad x = \dfrac{T_c}{T}, \quad T_c = 155 \text{ MeV}$



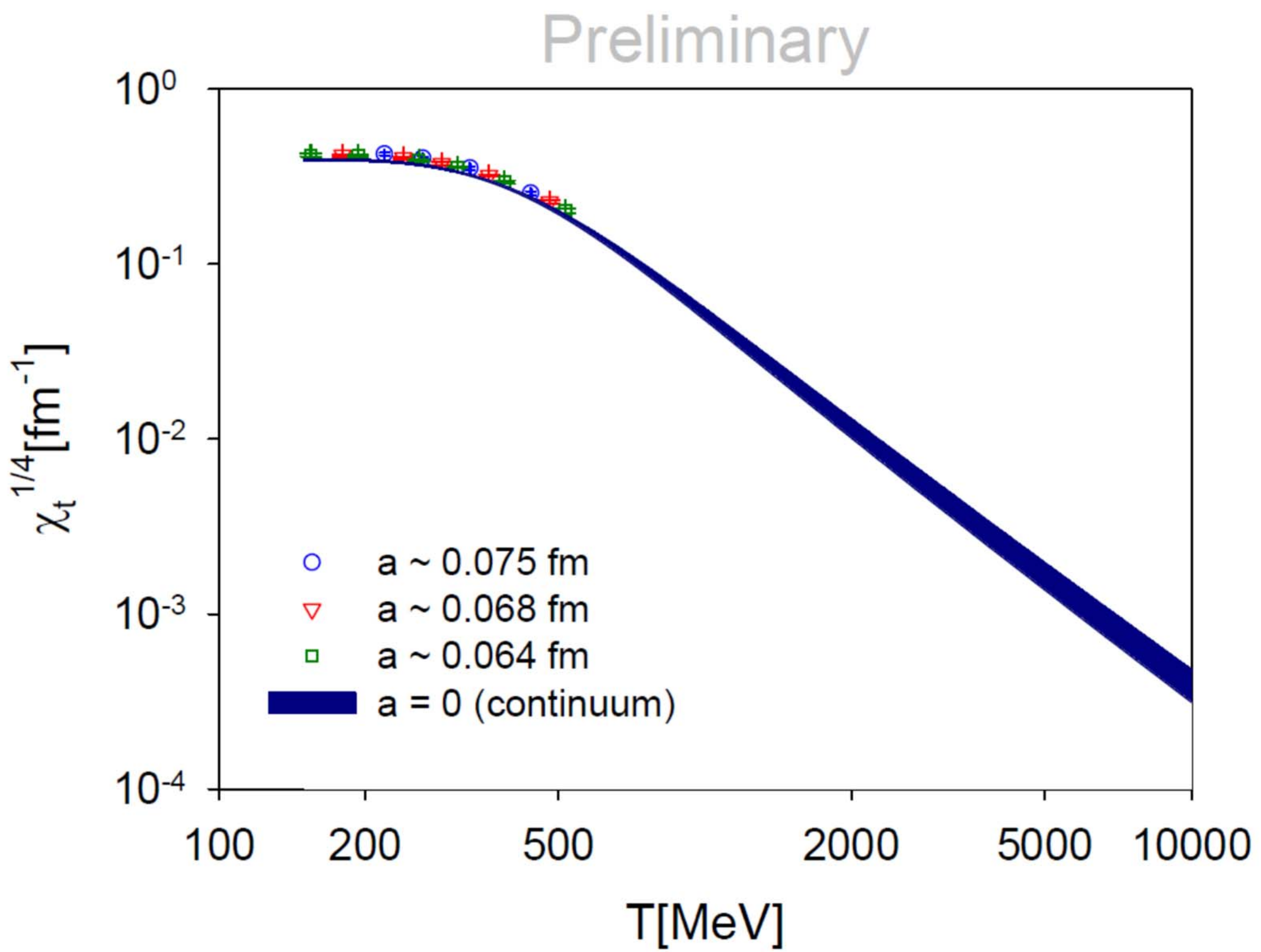
Topological susceptibility $\chi_t(T)$ of lattice QCD with physical (u/d, s, c) domain-wall quarks

Fitting to $\chi_t^{1/4}(a,T) = (c_0 + c_1 a^2)\dfrac{x^p}{1+bx+cx^2}, \quad x = \dfrac{T_c}{T}, \quad T_c = 155$ MeV

$c_0 = 1.89(3), \; c_1 = 32.2(6.8), \; p = 2.03(5), \; b = -2.42(19), \; c = 6.25(14)$

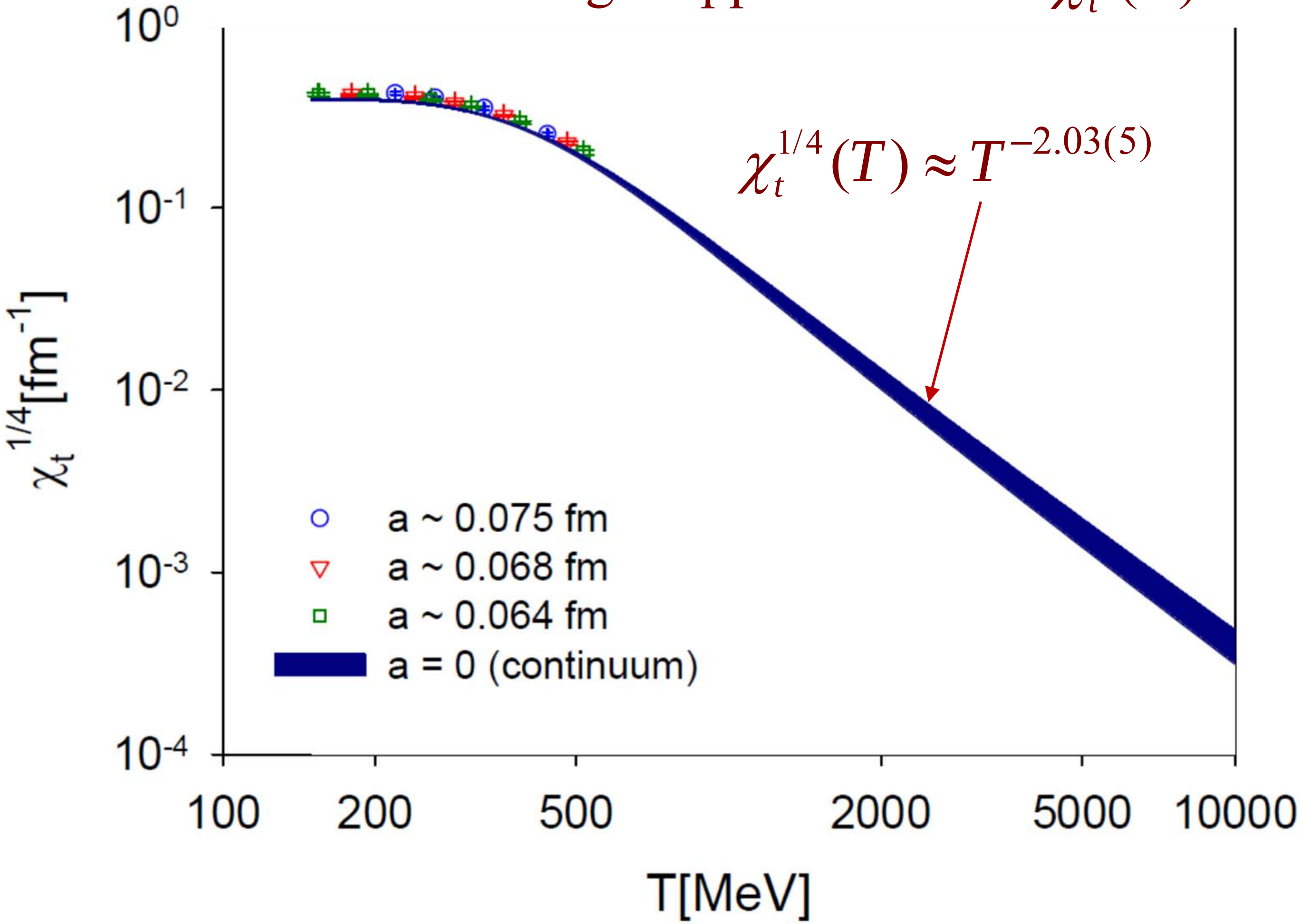


Topological susceptibility $\chi_t(T)$ of lattice QCD with physical (u/d, s, c) domain-wall quarks

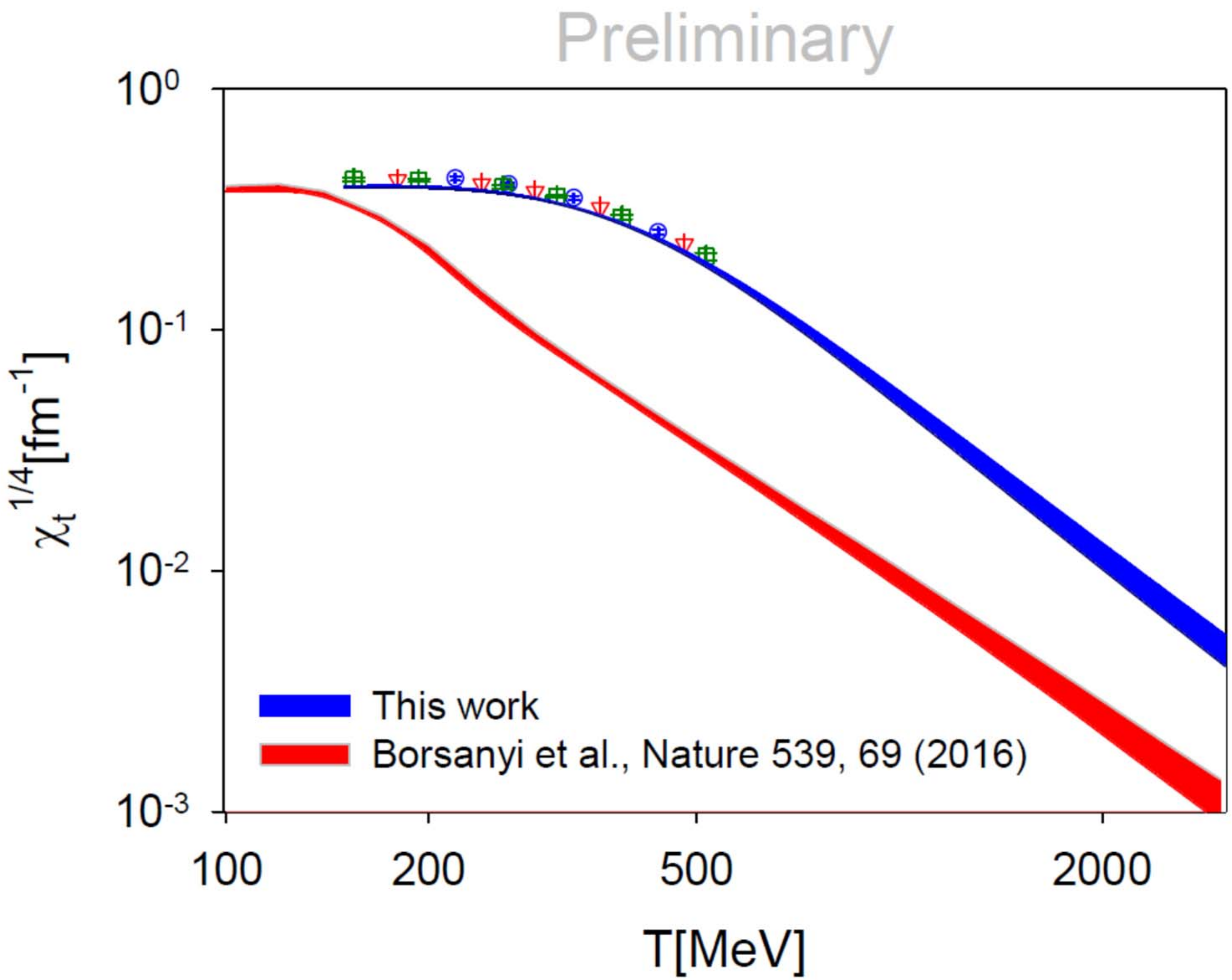


Topological susceptibility $\chi_t(T)$ of lattice QCD with physical (u/d, s, c) domain-wall quarks

For $T \gg T_c$, its T depenence agrees with dilute instanton gas approximation: $\chi_t(T) \approx T^{-8}$



Comparison with other lattice QCD results with physical (u/d, s, c) quarks



Remarks

What would be the causes for the discrepancy between this work and Borsanyi et al., Nature 539, 69 (2016) ?

- Different lattice fermions ?

  But, presumably, in the continuum limit, they should give consistent results, if they are both in the same universality class of Dirac fermion.

- Borsanyi et al. used the eigenvalue reweighting and the fixed sector integral techniques rather than direct simulations.

  It is unclear to what extent these techniques are valid ?

- To clarify these issues, independent studies using the DWF are needed, as well as direct simulations with the staggered fermion.

Thank you for your attention !

Acknowledgement

TWGrid ASGC

A Member of NARLabs
National Center for High-performance Computing

MOST 科技部
Ministry of Science and Technology

NCTS
National Center for Theoretical Sciences

Academia Sinica

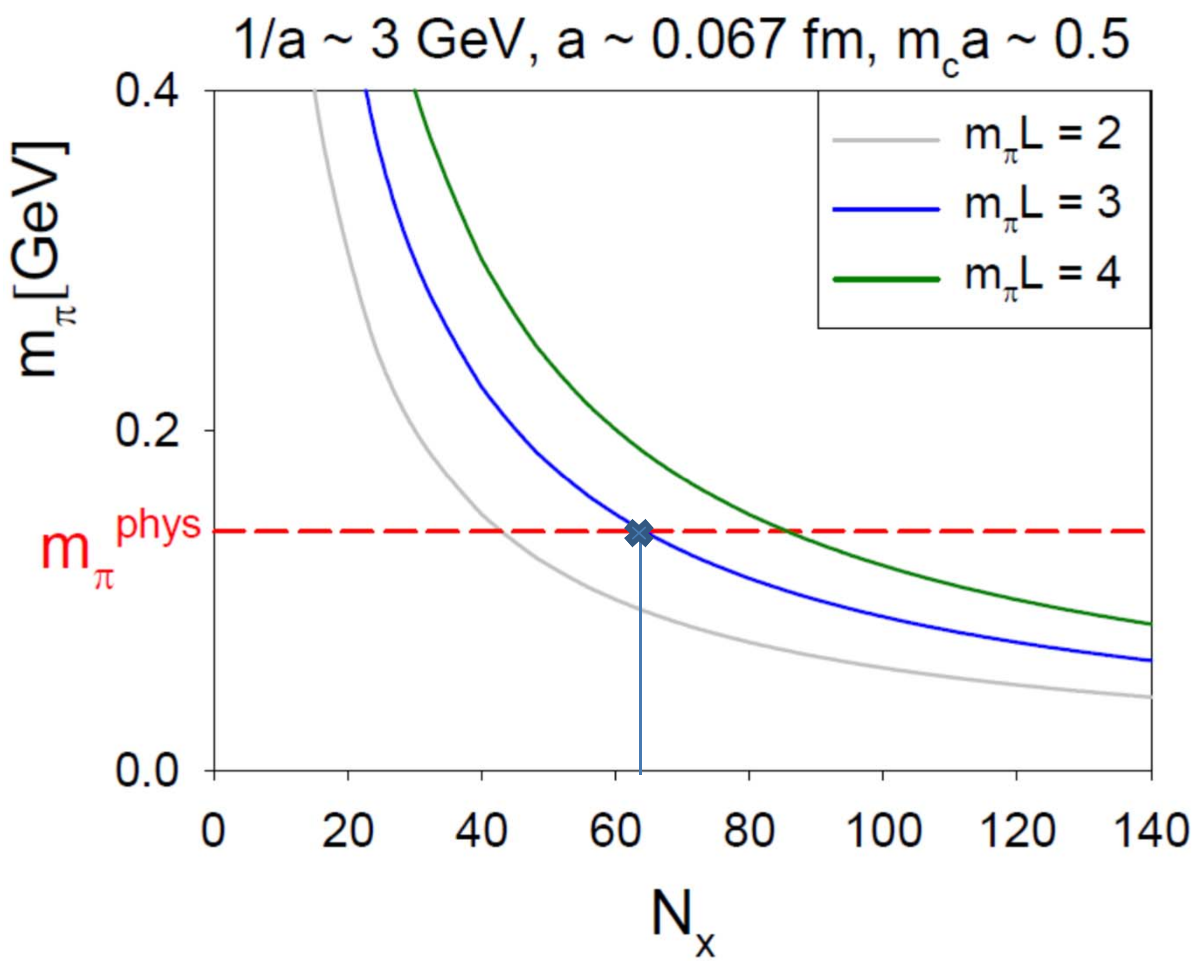
National Taiwan Normal University

National Taiwan University

Backup Slides

Design lattice QCD with physical (u,d,s,c) quarks

TWC, arXiv:1811.08095



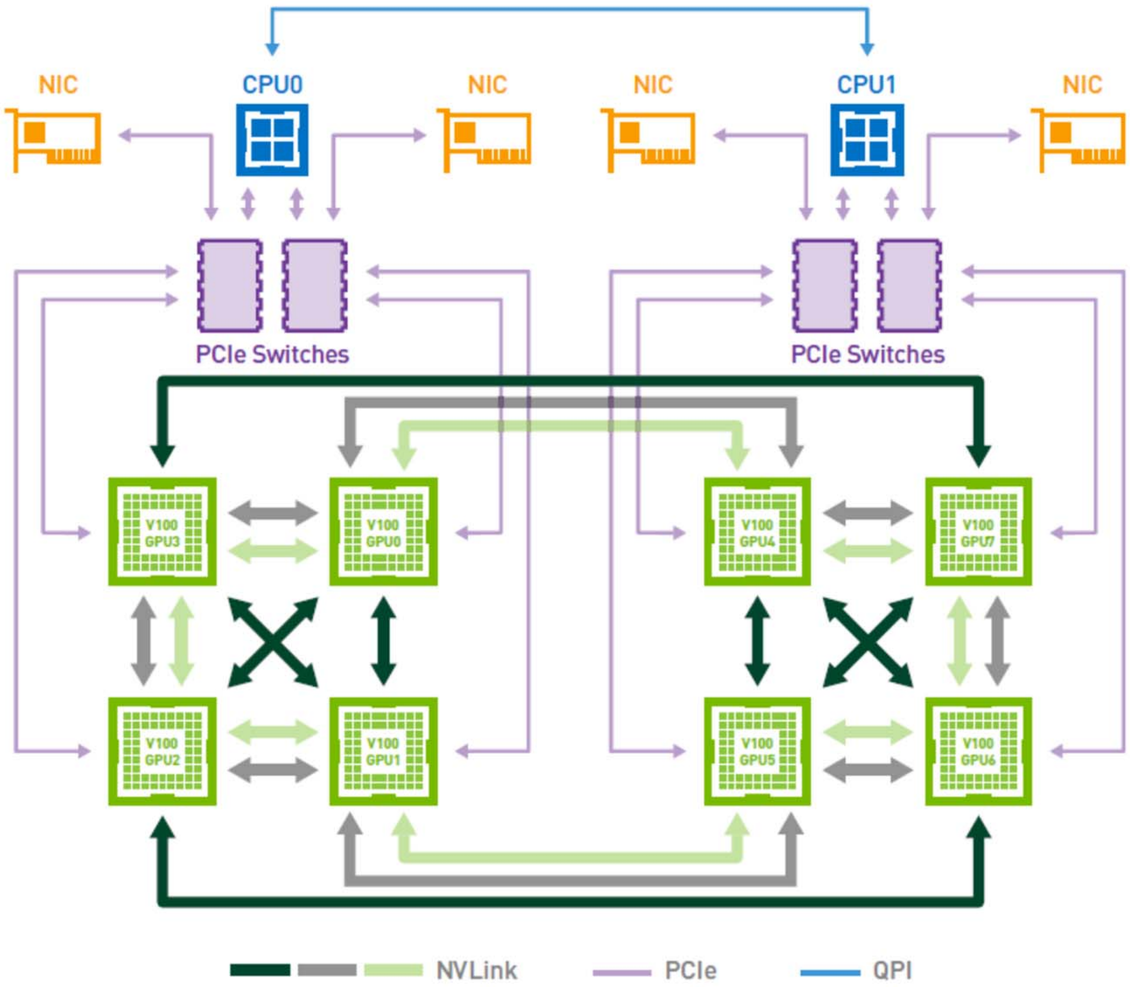
For the $64^3 \times 64$ lattice, $M_\pi L \approx 3$, $M_\pi \approx 140$ MeV, $L \approx 4.3$ fm

Nvidia DGX-1

- Jan 2018 – Oct 2018, the DGX-1 in the Nvidia Taipei office is used for the initial thermalization of the 64^4 lattice at $\beta = 6.20$ with a=0.064 fm.
- Since Dec 2018, 4 units of DGX-1 (HP clone) at Academia Sinica Grid Computing are used for production runs.
- From 2019-2020, used 10-20 units of DGX-1 in Taiwania 2 at NCHC for production runs.

Nvidia DGX-1(8 V100+NVLink)

Figure taken from the White Paper
NVIDIA DGX-1 With Tesla V100 System Architecture



NVLink 2.0, data rate ~ 300 GB/s

臺灣杉二號（TAIWANIA 2）

A Member of NARLabs
National Center for High-performance Computing

2,016 NVIDIA Tesla V100 32GB GPU = 252 units of DGX-1

TOP500 #28 (9 PFLOPS) Green500 #19 (11.285 GFLOPS/W)

Topological Susceptibility of Lattice QCD with Physical (u/d, s, c) DW quarks at zero temperature

TWC, arXiv:2002.06126