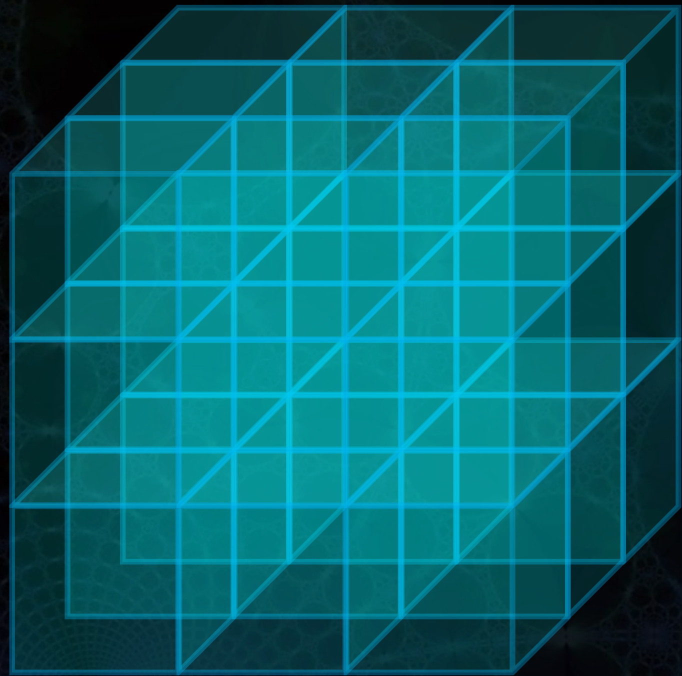
The 40th International Symposium on Lattice Field Theory

Axial U(1) symmetry near the pseudocritical temperature in N_f=2+1 lattice QCD with chiral fermions



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JLQCD Collaboration:
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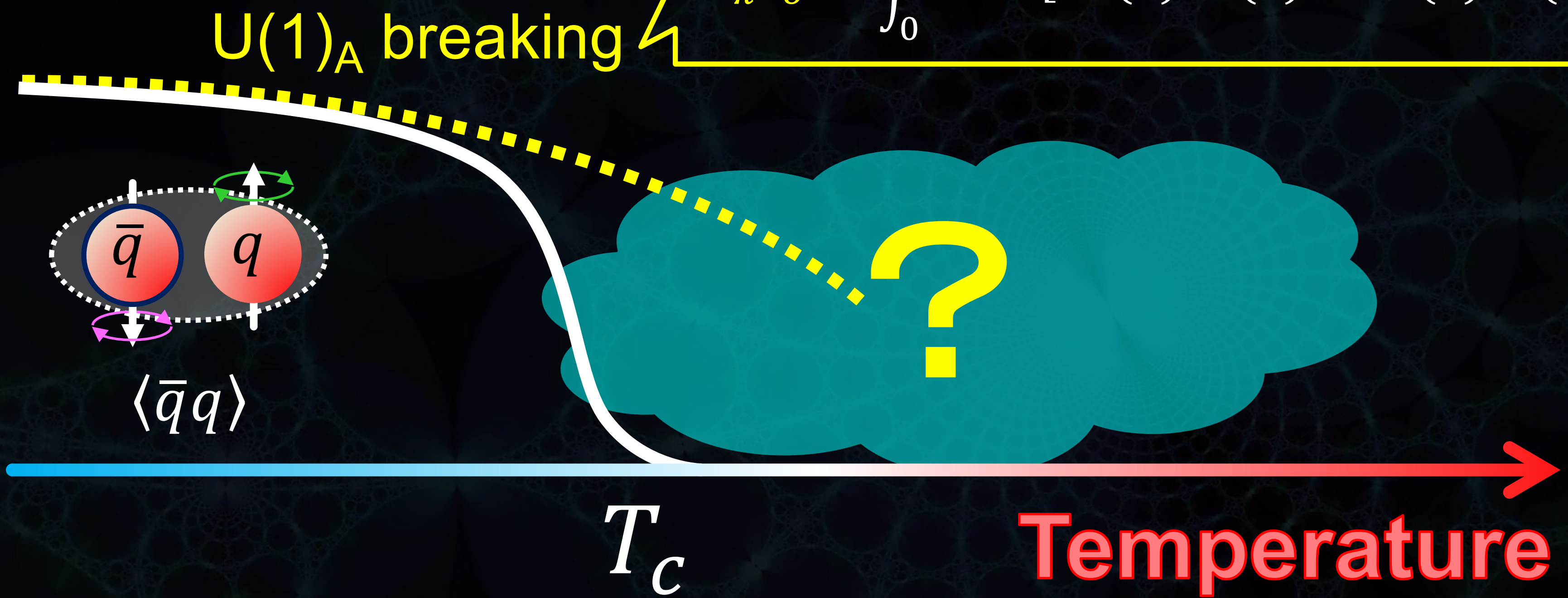
Does the U(1)$_A$ anomaly disappear/survive above T$_c$?

- Above T$_c$, chiral symmetry breaking via $\langle \bar{q}q \rangle$ disappears
  ⇒How about <u>U(1)$_A$ symmetry breaking?</u>

An "order parameter" is, for example,

$$\Delta_{\pi-\delta} = \int_0^\infty d^4x\, [\pi^a(x)\pi^a(x) - \delta^a(x)\delta^a(x)]$$



JLQCD's finite T project

	Quark action	Setup	Remark on $U(1)_A$ anomaly
G. Cossu et al. PRD**87**,114514 (2013)	Overlap fermion(OV)	Nf=2 a=0.1 fm	Topology is fixed.
A. Tomiya et al. PRD**96**, 034509 (2017)	Mobius domain-wall DW(MDW) and (reweighted) OV	Nf=2, 1/a=1.7GeV (a=0.11fm)	MDW and OV are inconsistent due to lattice artifact
S. Aoki et al. PRD**103**, 074506 (2021) PTEP, 023B05 (2022)	MDW and (reweighted) OV	Nf=2, 1/a=2.6GeV (a=0.076fm) (Finer lattice)	MDW and OV are consistent (except for m~0).
JLQCD 2020-present	MDW and (reweighted) OV	Nf=2+1, 1/a=2.453GeV (a=0.08fm)	

Summary of N_f=2 results

(by JLQCD publications in 2012-2021)

- At a~0.1fm, the results for axial U(1) susceptibility with Mobius domain-wall fermion and overlap fermion are inconsistent: precise chiral sym. is crucial.
- At T>=T_c, $U(1)_A$ and topological susceptibilities are strongly suppressed near the physical quark mass [PRD**103** 074506 (2021)]
- At 220<T<500MeV, $SU(2)_{CS}$ (and SU(4)) symmetry emerges. [Glozman 2015, Glozman and Pak 2015, 2017, Rohrhofer et al2017, 2019, 2020]

  ⇒Related talk in Nf=2+1 by D. Ward [Mon.]
- Signal of Chiral susceptibility is dominated by $U(1)_A$ anomaly [PTEP 023B05 (2022)] ⇒Related talk by H. Fukaya [Tue.]

This talk: Preliminary N_f=2+1 results near Tc

Lattice setup

Nf=2+1 Möbius-DW / (reweighted) overlap fermions + Symanzik gauge action

- 1/a=2.453GeV (a~0.08fm)
- L=32 (2.58fm), 40 (3.22fm), 48 (3.86fm)
- T=204MeV (1.3Tc), 175MeV (1.1Tc),
  153MeV (~Tc), 136MeV (0.9Tc)
- m_q=2.5MeV (mass reweighting from 5 MeV),
  5MeV (phys. pt. sim.), 9, 17, 29MeV
- m_s=100MeV (phys. pt.)

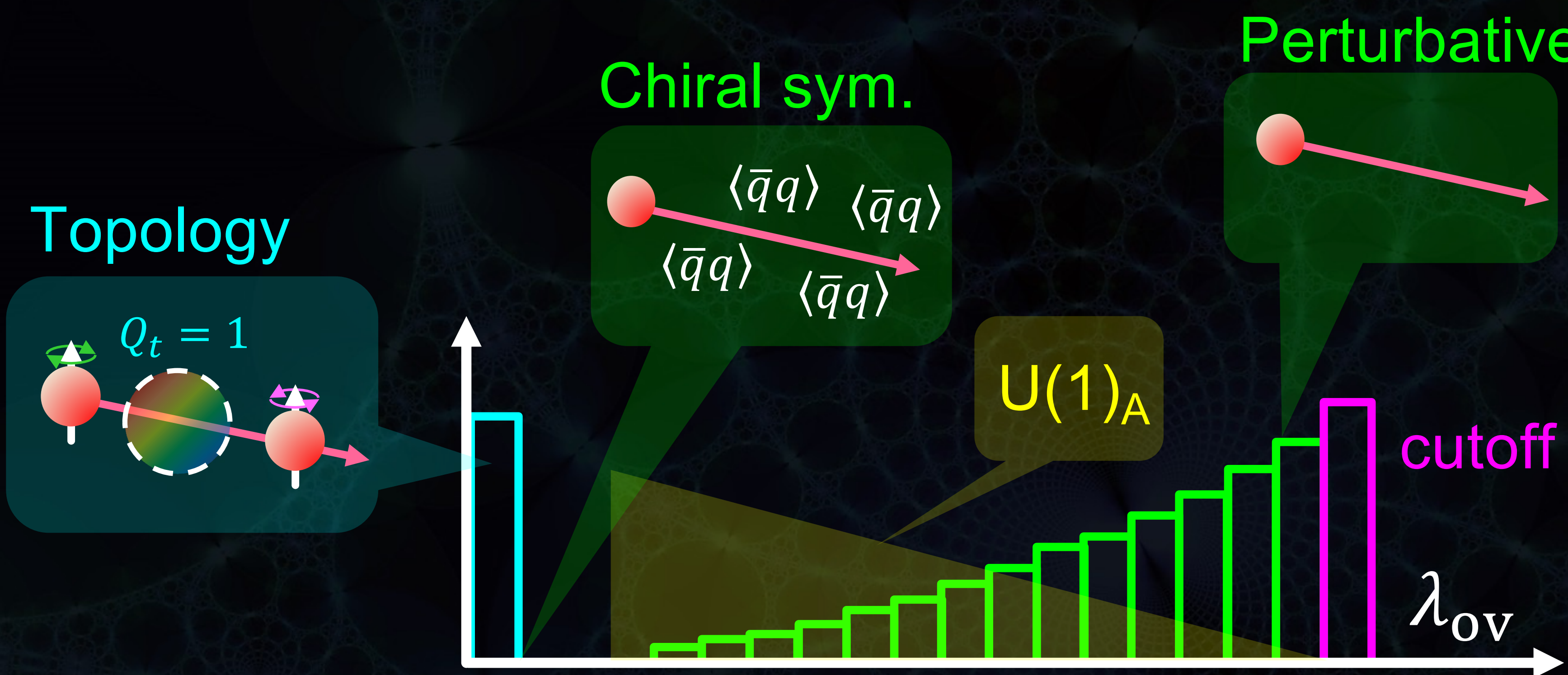
Simulation codes : Irolro++ (https://github.com/coppolachan/Irolro)
Grid (https://github.com/paboyle/Grid)
Bridge++(https://bridge.kek.jp/Lattice-code/)

Acknowledgements

- Fugaku (hp200130, hp210165, hp210231, hp220279)
- Oakforest-PACS [JCAHPC]
    HPCI projects : hp170061, hp180061, hp190090,
        hp200086, hp210104,
    MCRP in CCS, U. Tsukuba : xg17i032 and xg18i023
- Wisteria/BDEC-01 [HPCI: hp220093, MCRP: wo22i038]
- Polarie/Grand Chariot (hp200130)
- Flow at Nagoya U.
- SQUID at Osaka U.
- Program for Promoting Researches on the Supercomputer Fugaku, Simulation for basic science: from fundamental laws of particles to creation of nuclei Joint
- Institute for Computational Fundamental Science (JICFuS)

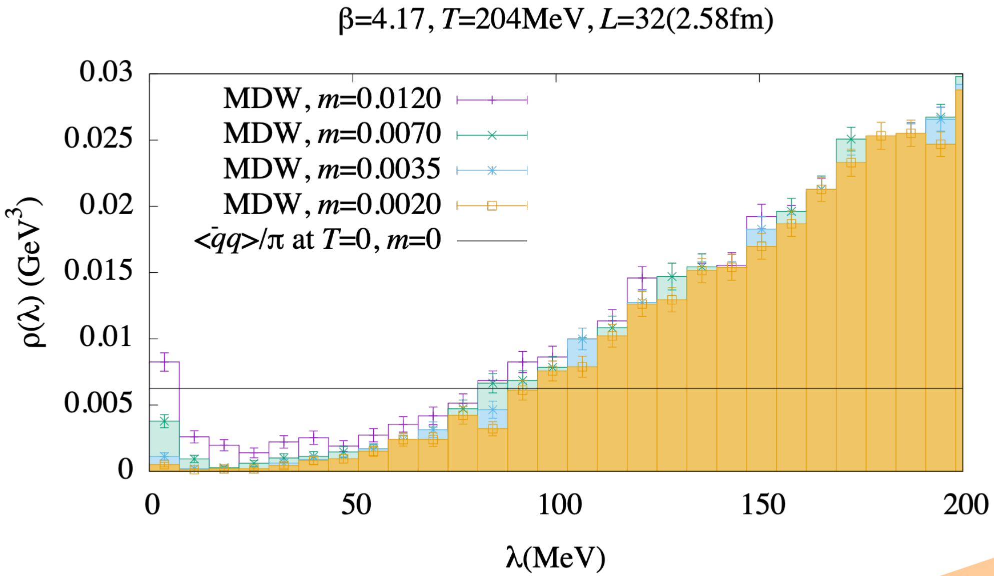
Contents

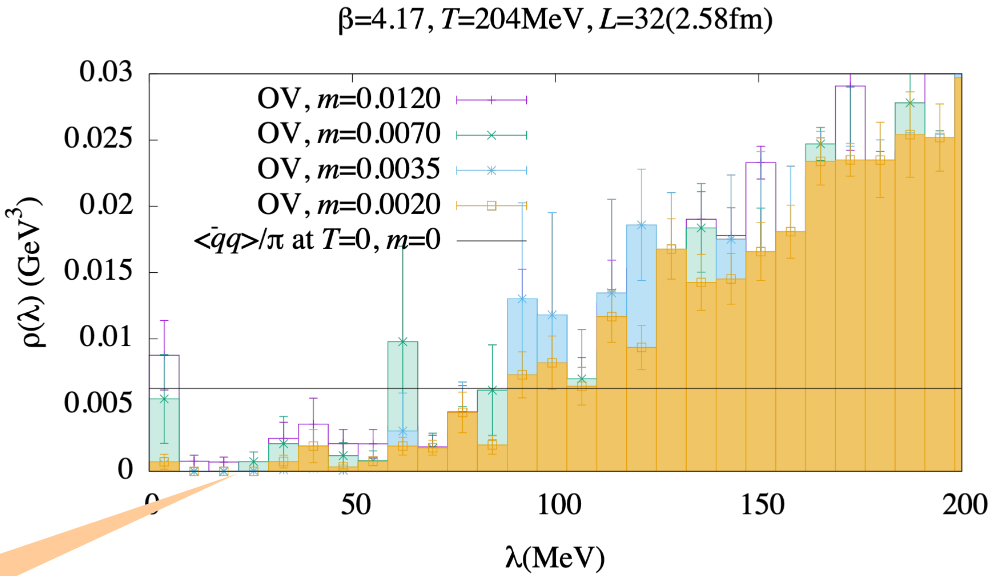
Dirac spectrum and QCD physics at different scales



JLQCD, preliminary (2023)

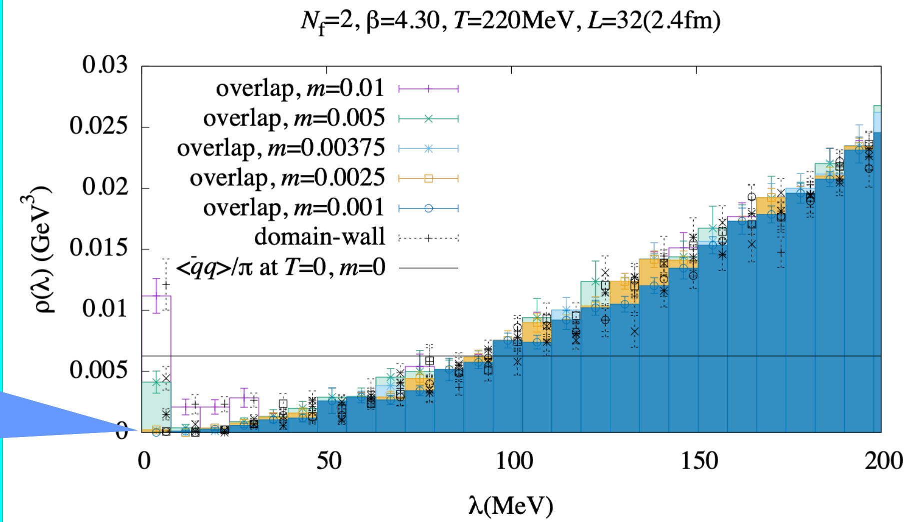
Dirac spectrum <u>at T = 204MeV (1.3Tc)</u>





At physical m_q, lower eigenmodes are strongly suppressed

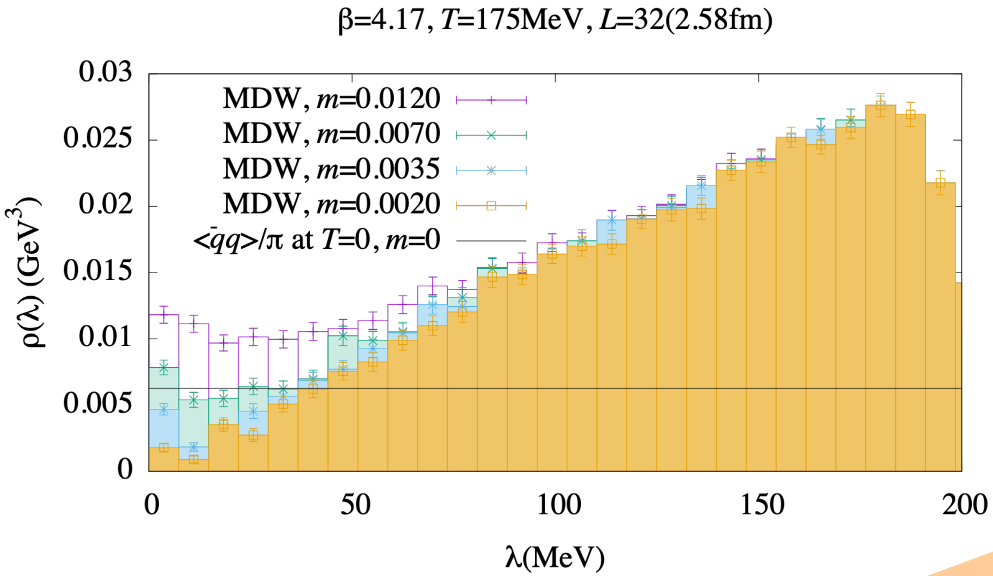
N_f=2+1 is consistent with N_f=2 (T=220MeV)

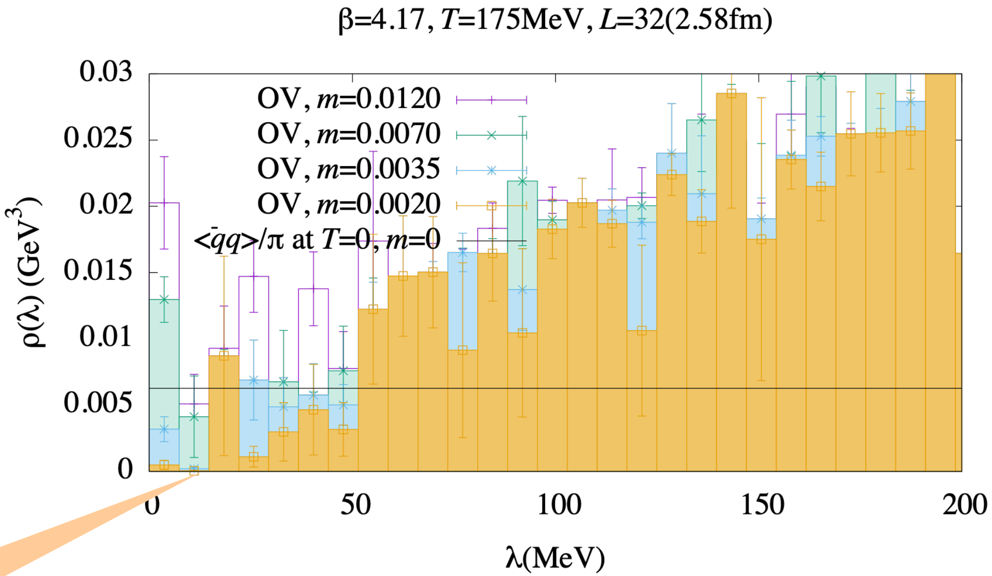


Nf=2, JLQCD, 2011.01499

JLQCD, preliminary (2023)

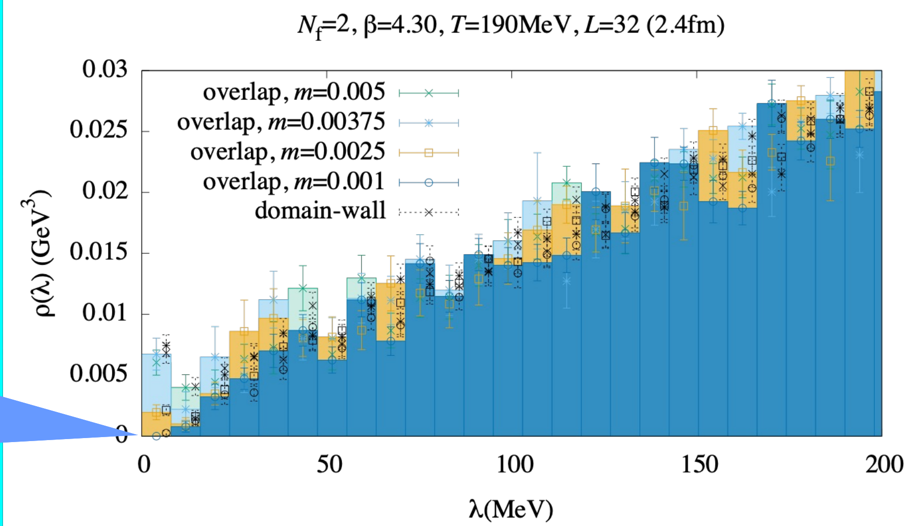
Dirac spectrum at T = 175MeV (1.1Tc)





At physical m_q, lower eigenmodes are strongly suppressed

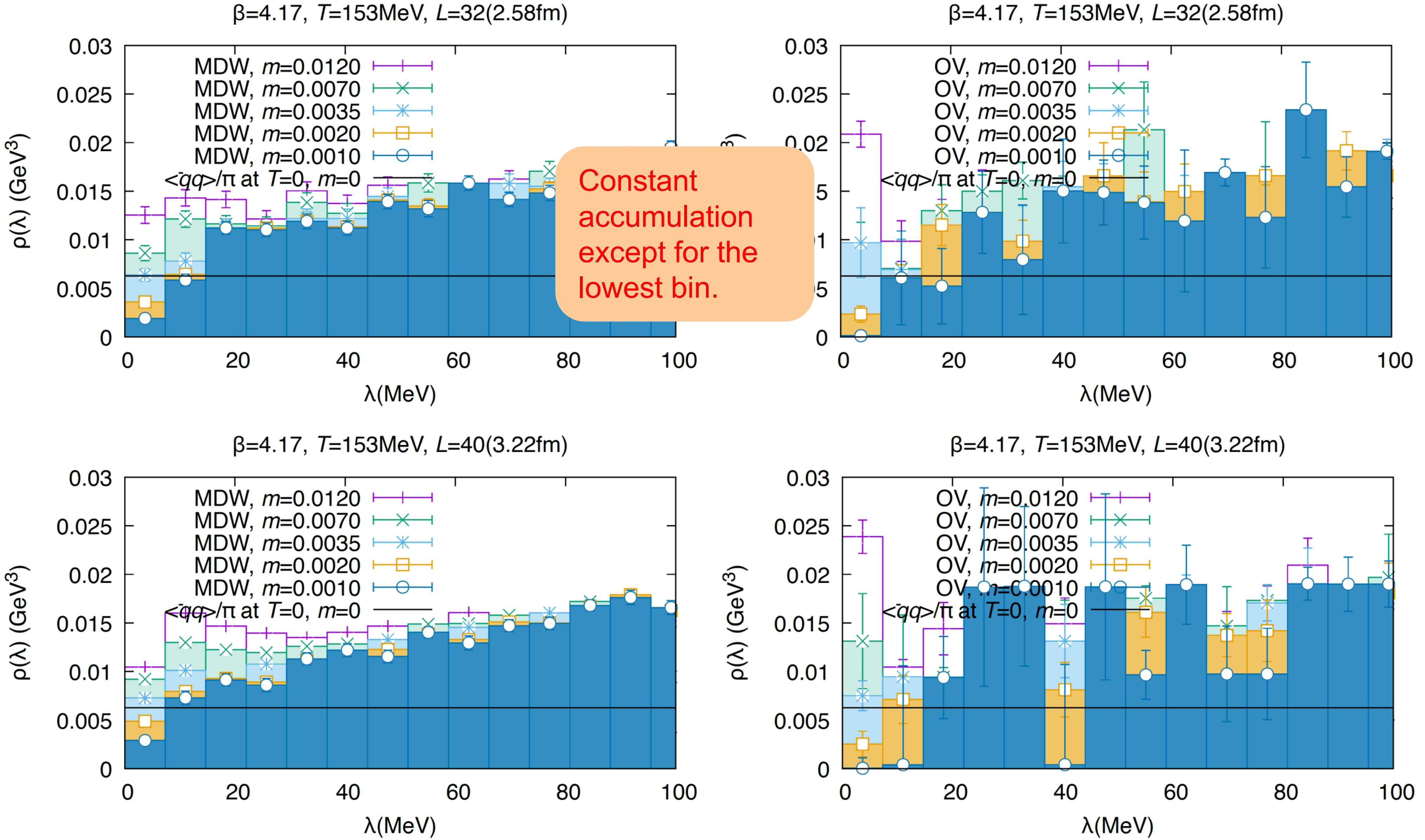
N_f=2+1 is consistent with N_f=2 (T=190MeV)



Nf=2, JLQCD, 2011.01499

JLQCD, preliminary (2023)

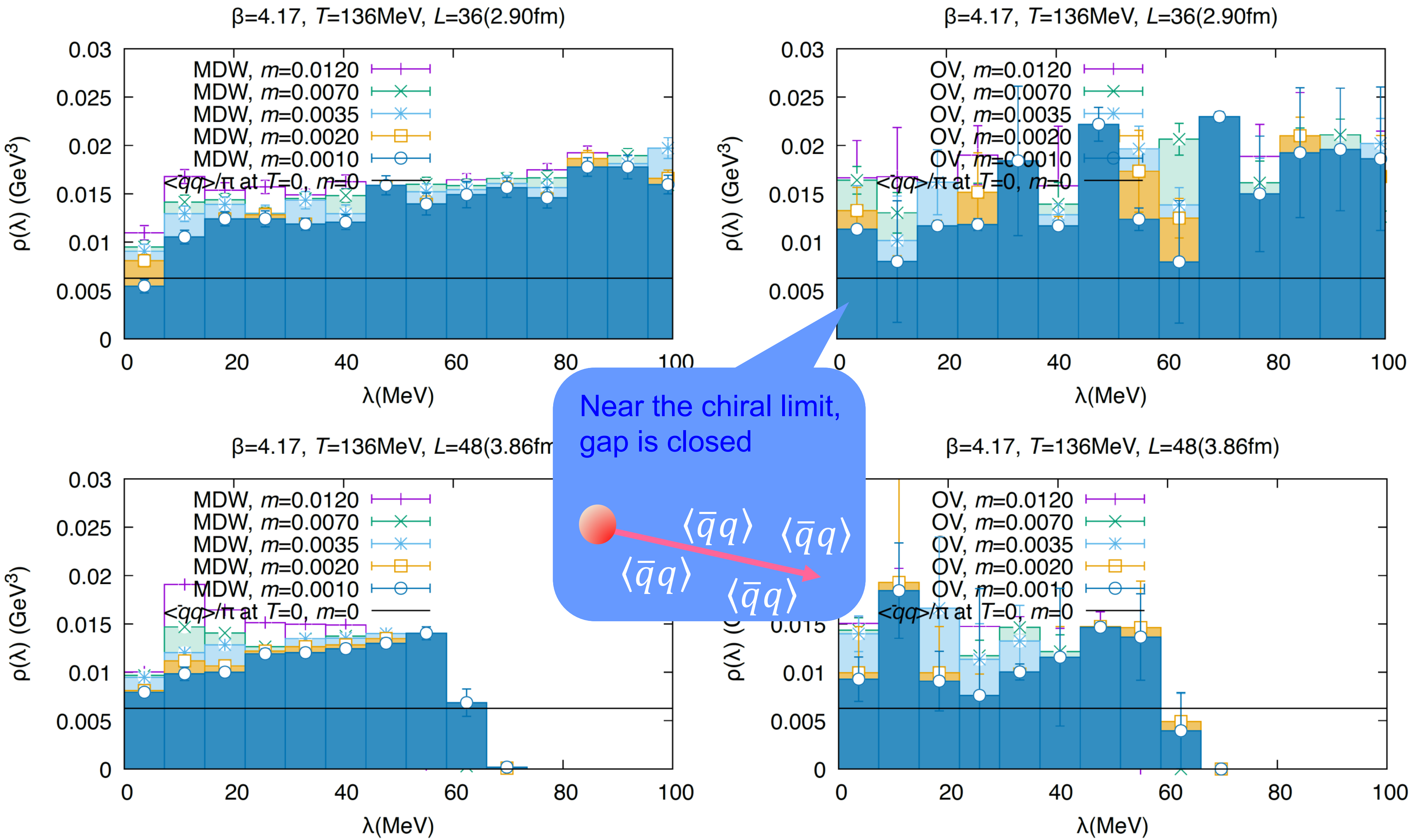
Dirac spectrum at T = 153MeV (~Tc)



Constant accumulation except for the lowest bin.

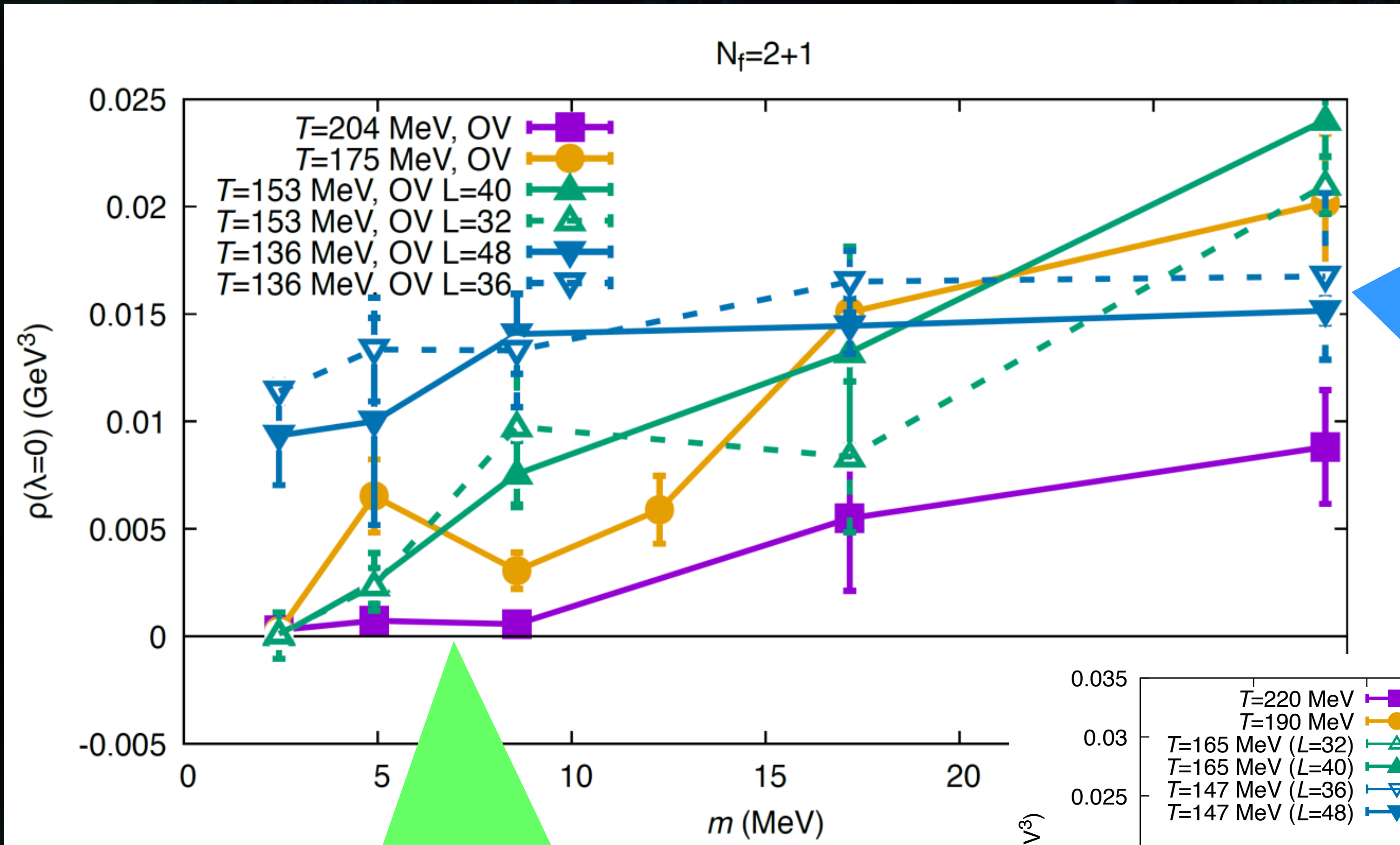
JLQCD, preliminary (2023)

Dirac spectrum at T = 136MeV (0.9Tc)



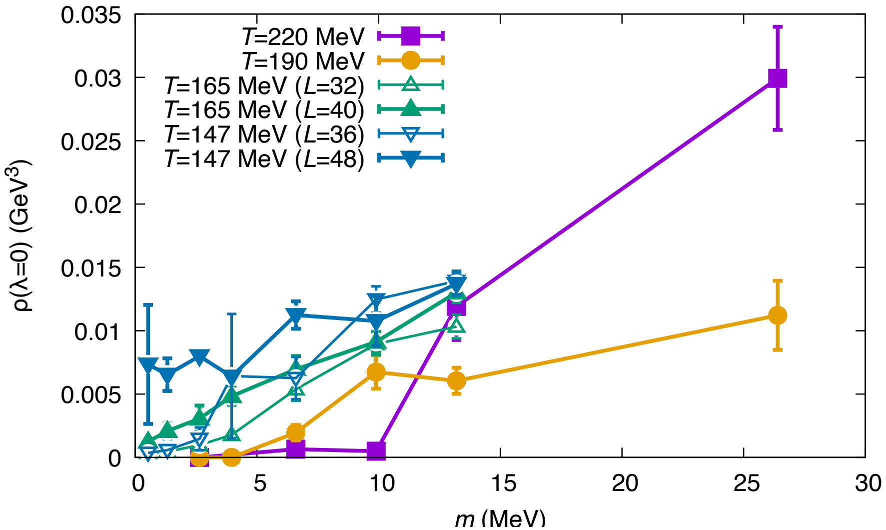
JLQCD, preliminary (2023)

Lowest bin of Dirac spectrum



T=136MeV seems to be in the broken phase (0.9T_c): $\langle\bar{q}q\rangle$ $\langle\bar{q}q\rangle$ $\langle\bar{q}q\rangle$ $\langle\bar{q}q\rangle$

Nf=2, JLQCD, 2011.01499



We estimate T=153MeV ∼T_c but chiral limit may be still in the symmetric phase.

$U(1)_A$ susceptibility

$$\Delta_{\pi-\delta} = \int_0^\infty d^4x\,[\pi^a(x)\pi^a(x) - \delta^a(x)\delta^a(x)]$$

$$= \int_0^\infty d\lambda\,\rho(\lambda)\,\frac{2m^2}{(\lambda^2+m^2)^2}$$

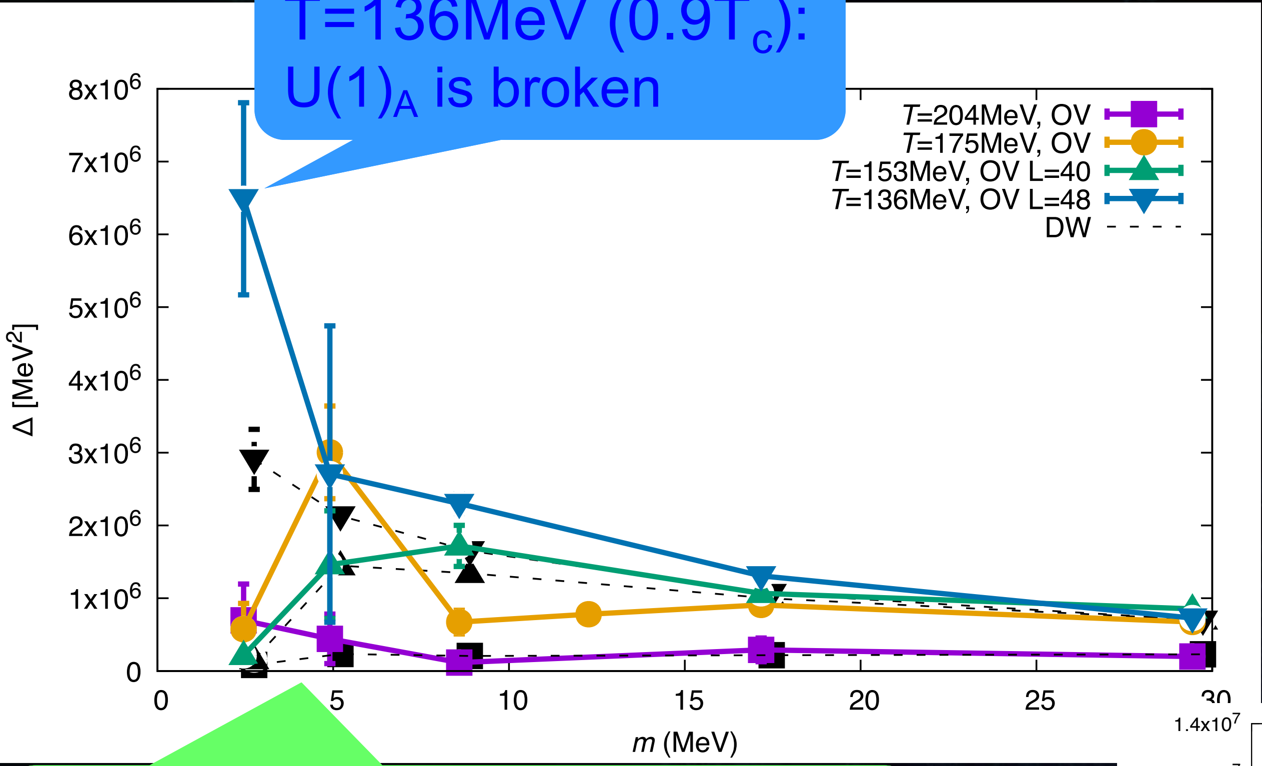
Low mode contribution is enhanced by the factor of $1/\lambda^4$

Cf.) Banks-Casher relation: $\langle \bar{q}q \rangle = \lim_{m\to 0} \int_0^\infty d\lambda\,\rho(\lambda)\,\frac{2m}{\lambda^2+m^2}$

Sensitive to violation of Ginsparg-Wilson relation of the lowmodes.
Gives a dominant contribution to connected chiral susceptibility (Fukaya, Tuesday)

JLQCD, preliminary (2023)

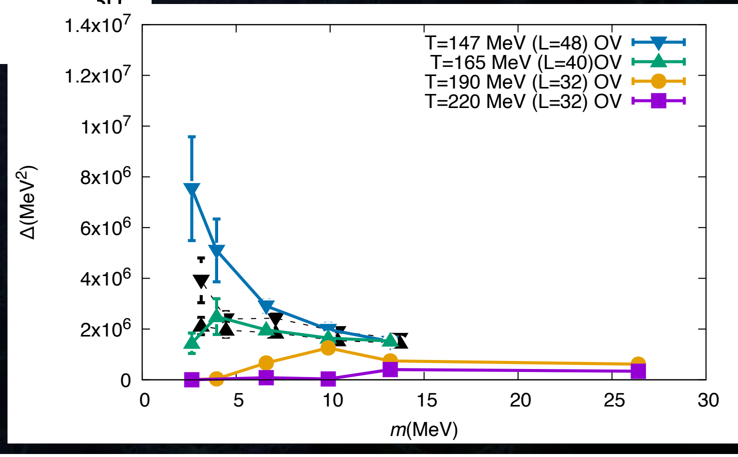
$U(1)_A$ susceptibility



T=136MeV ($0.9T_c$): $U(1)_A$ is broken

For T>= 153MeV, $U(1)_A$ breaking is strongly suppressed near the chiral limit

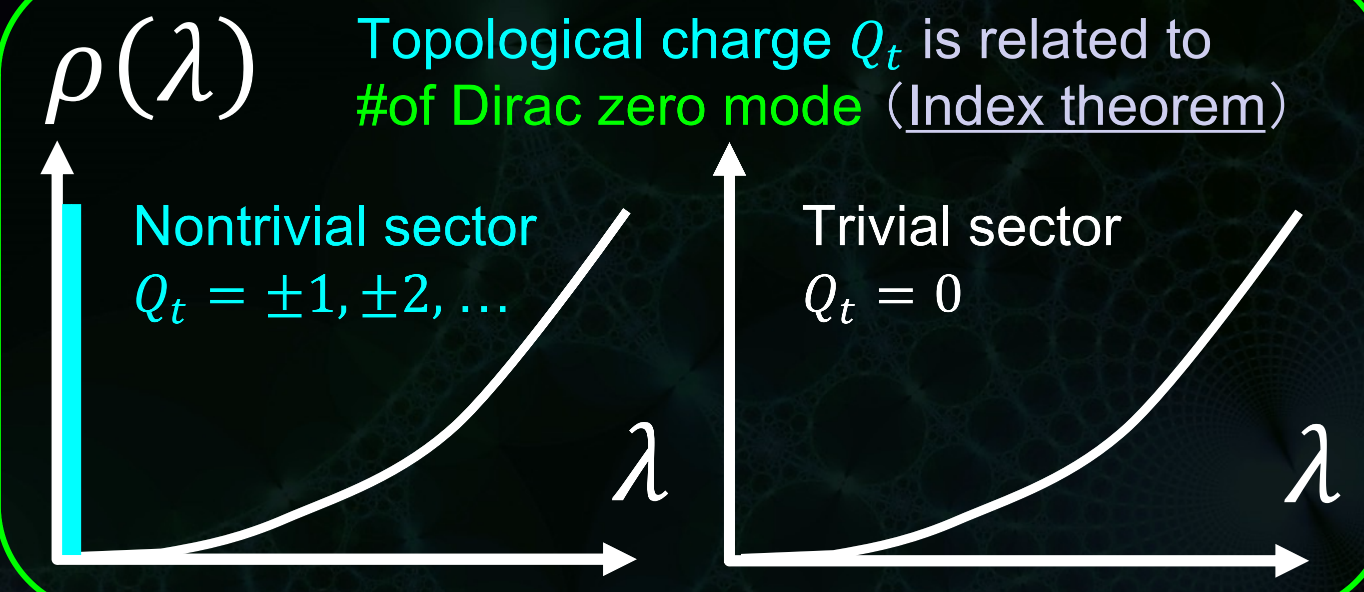
Nf=2, JLQCD, 2011.01499

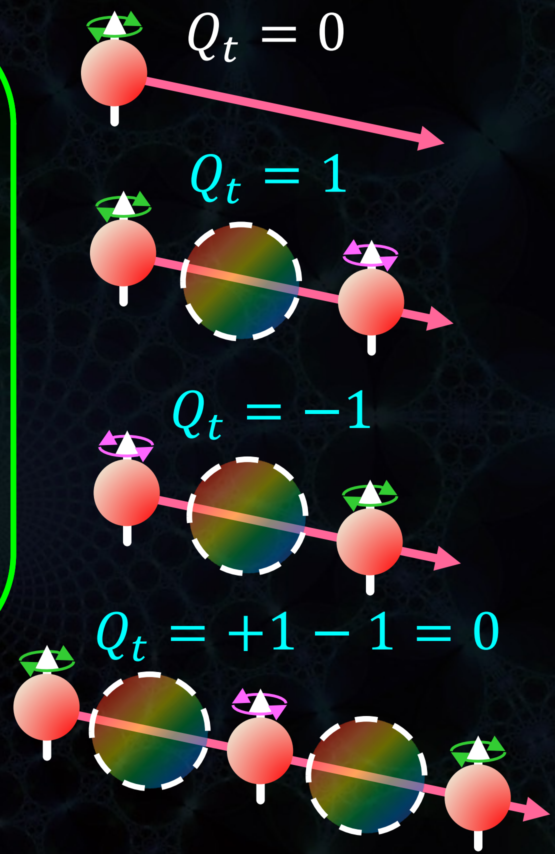


Topological susceptibility and zero mode of Dirac spectra

$$\chi_t \equiv \frac{\langle Q_t^2 \rangle}{V}, \qquad Q_t = n_+ - n_-$$

Topological charge Q_t is related to #of Dirac zero mode（Index theorem）

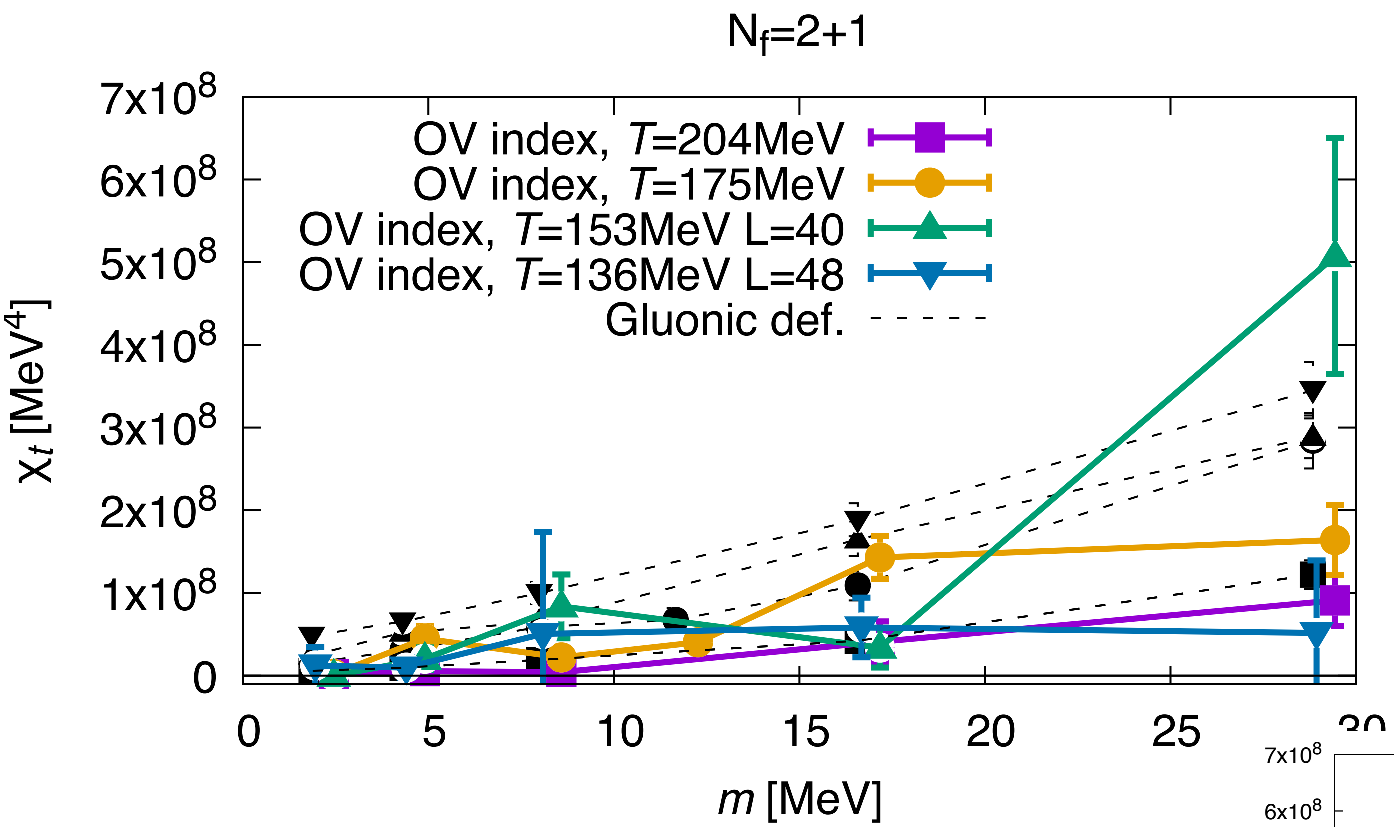




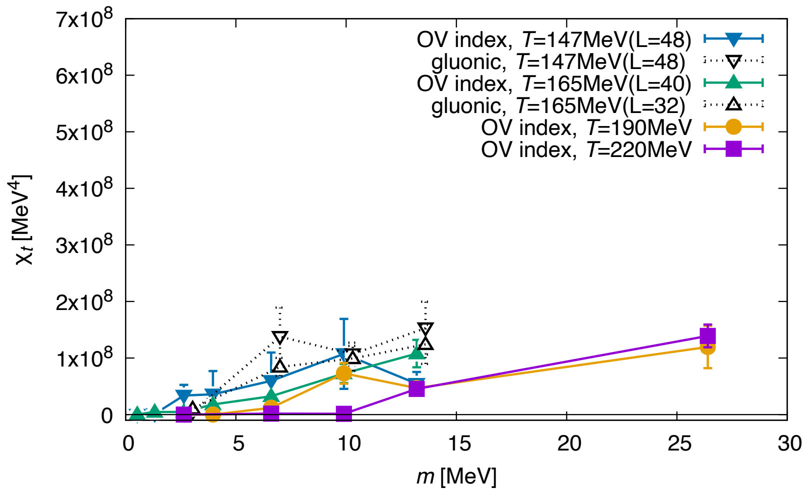
Cf.) Gluonic definition: $Q_t \equiv \frac{g^2}{32\pi^2} \int d^4x \, G^a_{\mu\nu} \tilde{G}^a_{\mu\nu}$

Topological susceptibility

JLQCD, preliminary (2023)



Nf=2, JLQCD, 2011.01499

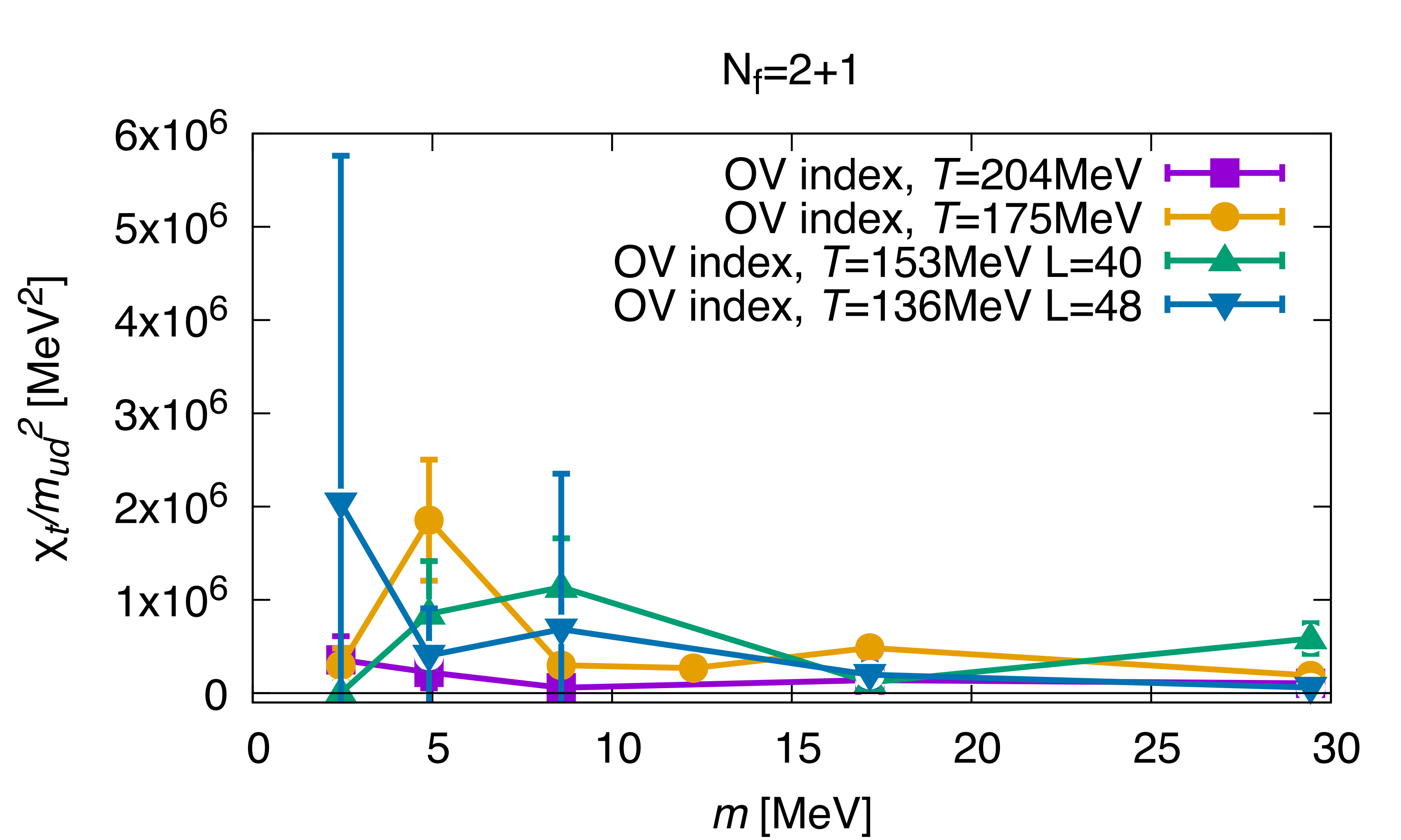


NOTE: chiral limit is zero even at zero temperature:

$$\chi_t = m\langle\bar{q}q\rangle/2$$

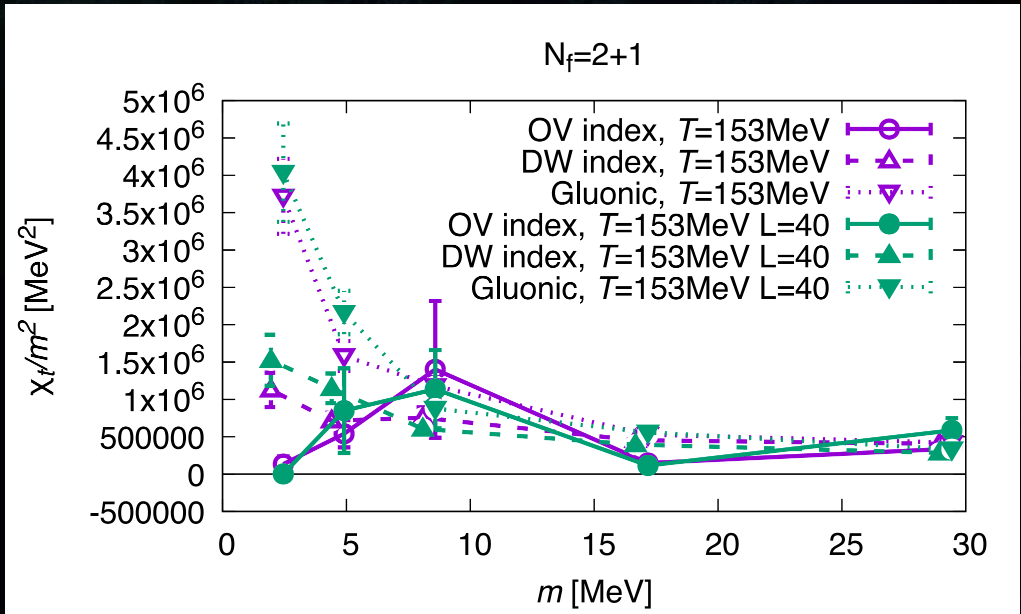
JLQCD, preliminary (2023)

Topological susceptibility divided by m^2

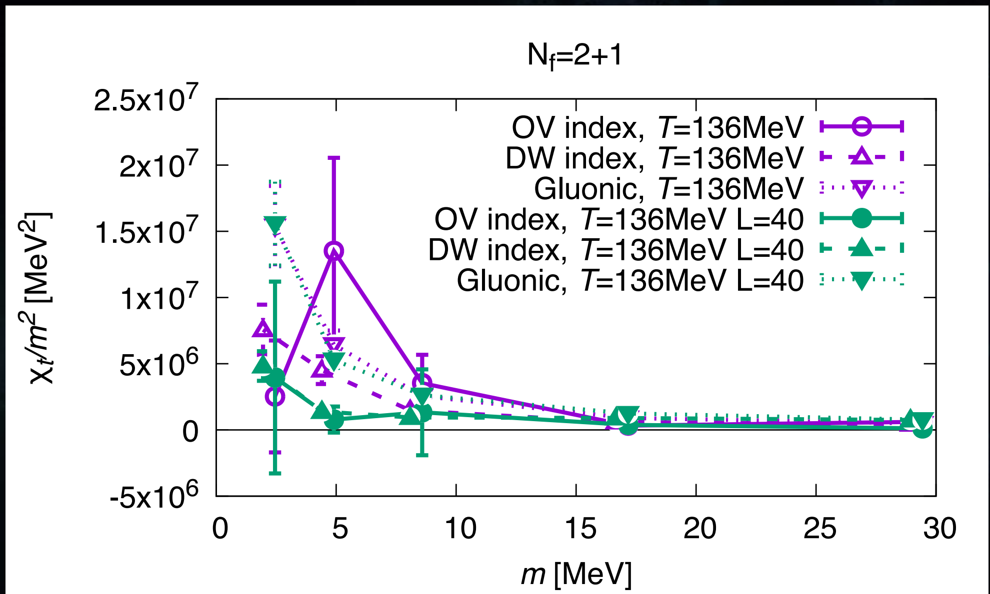


This gives a dominant contribution to disconnected chiral susceptibility (Fukaya, Tuesday)

Volume dependence and OV vs. DW



At T=153MeV (~Tc)
2 Volumes (L=32,40) are consistent .
DW and OV differ at lightest two quark masses.



At T=136MeV (~0.9Tc)
2 Volumes (L=32,40) show difference.
DW and OV differ at lightest two quark masses.

Summary

- We simulate N_f=2+1 QCD at high temperatures with chiral fermions at physical quark mass point.

	$0.9T_c$	Near T_c
ρ(0) or SU(2)xSU(2) breaking	Nonzero	suppressed in the chiral limit
$U(1)_A$ susceptibility	Nonzero	suppressed in the chiral limit
Top. susceptibility/m^2	Nonzero	suppressed in the chiral limit

- $SU(2)_L xSU(2)_R$ and $U(1)_A$ are correlated very much.

Backup