Correlated Dirac Eigenvalues and Axial Anomaly in Chiral Symmetric QCD

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R-CCS

based on PRL 126 (2021) 082001 & in collaboration with
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Outline

- Motivation
- $\partial^n \rho / \partial^n m_l$ & C_{n+1} and $U_A(1)$ symmetry
- Lattice Setup
- Results
- Summary & Conclusions

Symmetries of QCD

$$\mathcal{L} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a + \sum_{q \in u,d,s,c,b,t} \bar{q}[i\gamma^\mu(\partial_\mu - igA_\mu) - m_q]q$$

$$SU_L(N_f) \times SU_R(N_f) \times U_V(1) \times U_A(1) \quad (m_q = 0)$$

☆ $SU_L(N_f) \times SU_R(N_f)$ chiral symmetry

- SSB in the vacuum: $SU_L(N_f) \times SU_R(N_f) \to SU_V(N_f)$
- Restored at $T \geq T_c$

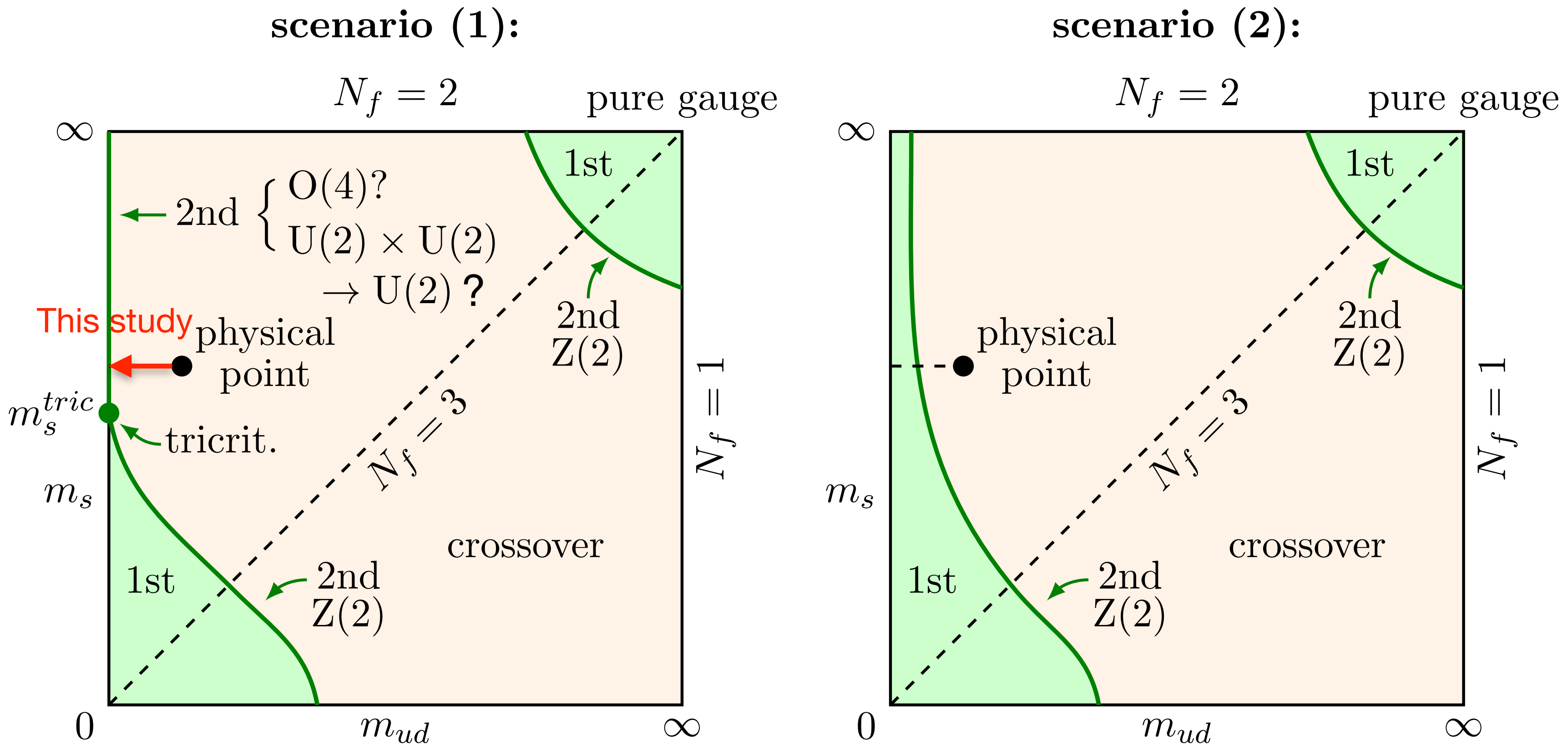
☆ $U_A(1)$ symmetry

- Broken on the quantum level due to ABJ anomaly

$$\partial_\mu j_5^\mu = \frac{g^2 N_f}{16\pi^2} F_a^{\mu\nu} \tilde{F}_{\mu\nu}^a \neq 0 \quad (\tilde{F}_{\mu\nu}^a \equiv \frac{1}{2}\epsilon_{\mu\nu\lambda\rho} F_a^{\lambda\rho})$$

$U_A(1)$ symmetry & Chiral phase transition

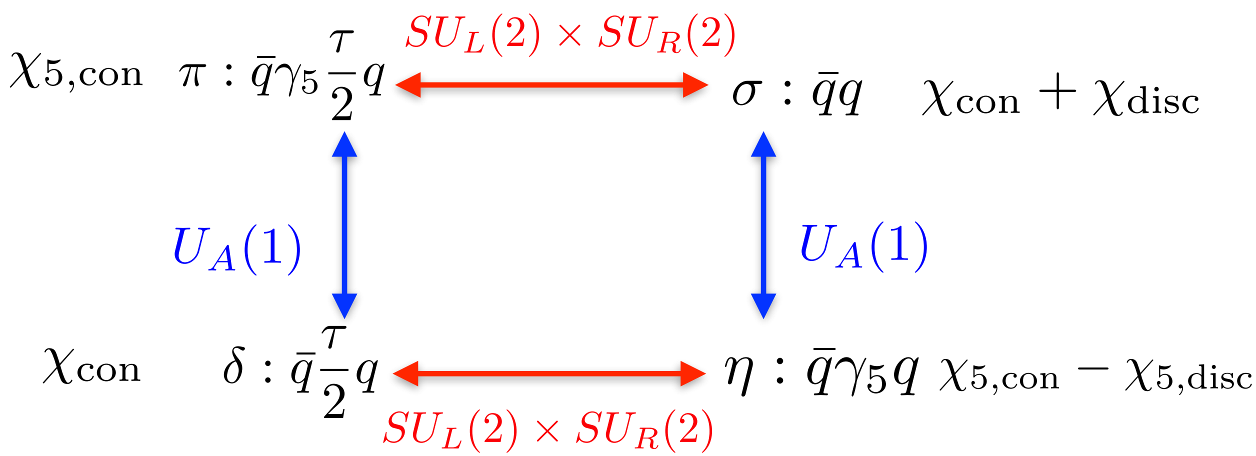
The nature of chiral phase transition depends on
how axial anomaly manifest itself at $T \sim T_c$?



Pisarski, Wilczek PRD 29 (1984) 338
Butti et. al., JHEP 08 (2003) 029
Pelissetto & Vicari, PRD 88 (2013) 105018
Grahl, PRD 90 (2014) 117904

Signatures of symmetry restorations

- Susceptibilities defined as integrated two point correlation functions of the local operators, e.g. $\chi_\pi = \int d^4x \langle \pi^i(x)\pi^i(0) \rangle$ HotQCD PRD 86 (2012) 094503



$SU_L(2) \times SU_R(2)$

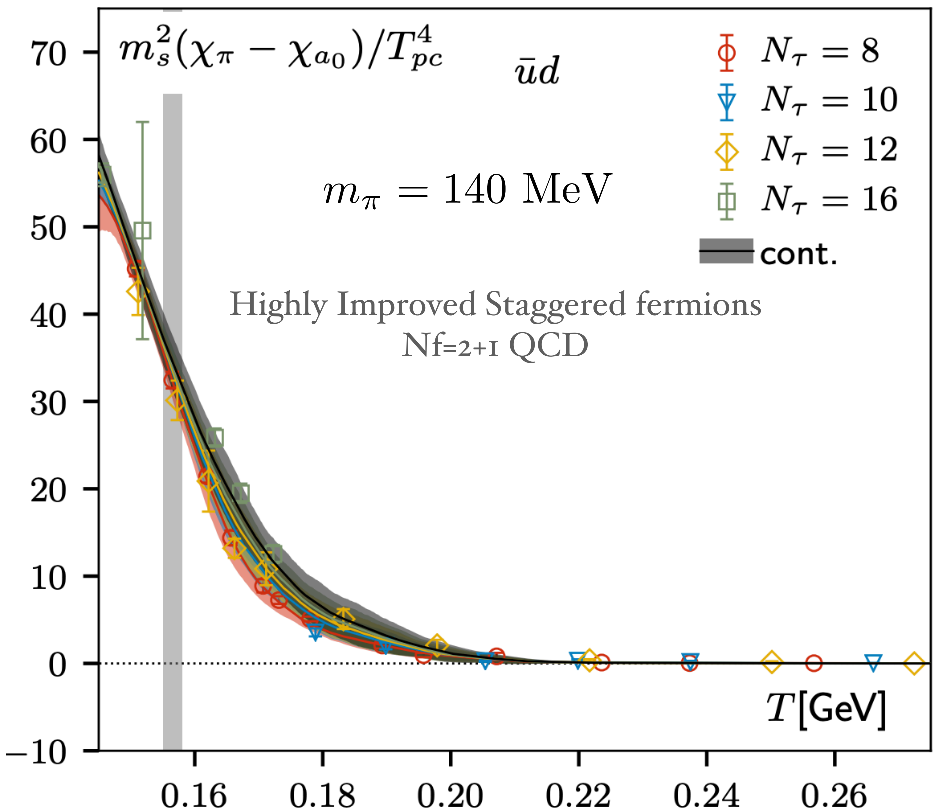
$$\begin{cases} \chi_\pi = \chi_\sigma \\ \chi_\delta = \chi_\eta \end{cases} \Rightarrow \chi_\pi - \chi_\delta = \chi_{\mathrm{disc}}$$

$U_A(1)$

$$\begin{cases} \chi_\pi = \chi_\delta \\ \chi_\sigma = \chi_\eta \end{cases} \Rightarrow \chi_\pi - \chi_\delta = \chi_{\mathrm{disc}} = 0$$

$$\chi_{\mathrm{disc}} = \frac{T}{V} \int d^4x \, \langle [\bar{\psi}(x)\psi(x) - \langle \bar{\psi}(x)\psi(x) \rangle]^2 \rangle$$

Status of lattice studies on axial anomaly



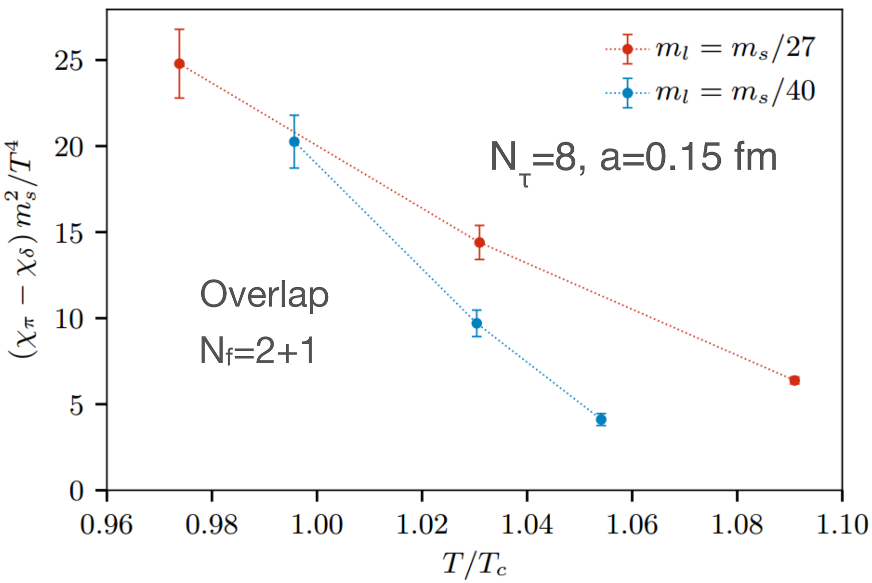
HotQCD, Phys.Rev.D 100 (2019) 094510

- At T$\lesssim$ T_{pc} for physical pion mass axial anomaly remains manifested in $\chi_\pi - \chi_\delta$

  See similar conclusions obtained using chiral fermions:
  HotQCD, PRL 113(2014) 082001, PRD 89 (2014) 054514
  JLQCD, arXiv:2011.01499,…

- What happens in the chiral limit?

Status of lattice studies on axial anomaly

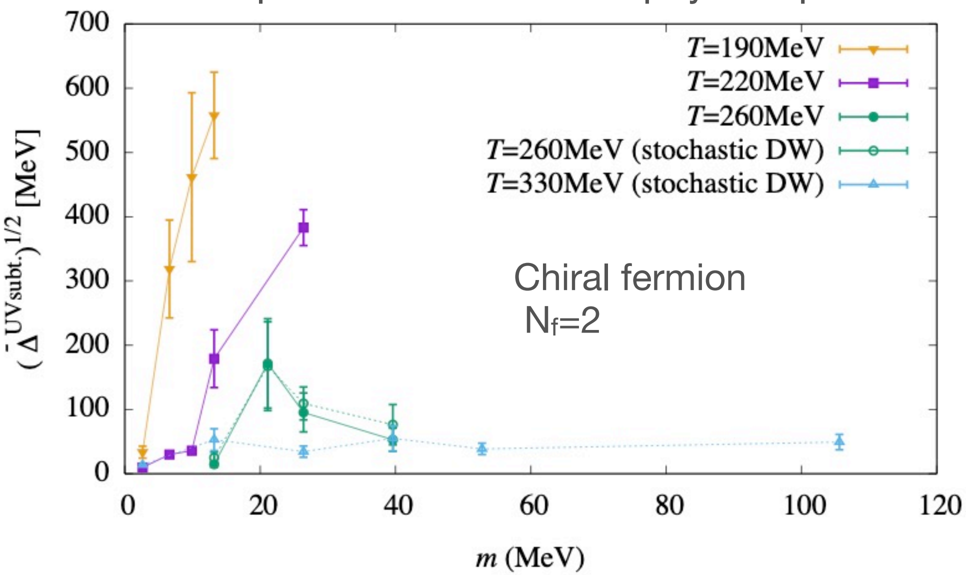


L. Mazur et al., arXiv:1811.08222

Remains manifested for m_π=110 MeV at T<1.1T$_c$

See similar conclusions from
Ohno et al., PoS Lattice 2012 (2012) 095,
Dick et al., PRD 91(2015) 094504,…

a=0.0074 fm
One quark mass below the physical point



JLQCD, PRD 103 (2021) 074506

Seems to disappear at T≥220 MeV

See similar conclusions from
Chiu et al., PoS Lattice 2013 (2014) 165,
Tomiya et al.,[JLQCD] PRD 96 (2017) 034509,…

The fate of U$_A$(1) still unsettled due to the lack of continuum and chiral extrapolations

Signatures of symmetry restorations in ρ

$$\langle\bar{\psi}\psi\rangle = \int_0^\infty \mathrm{d}\lambda \frac{4m_l\rho}{\lambda^2+m_l^2} \qquad \chi_\pi - \chi_\delta = \int_0^\infty \mathrm{d}\lambda \frac{8m_l^2\rho}{(\lambda^2+m_l^2)^2}$$

- Restoration of $SU_L(2)\times SU_R(2)$ symmetry :
  - $\rho(0)=0$ as from Banks-casher relation: $\lim_{m_l\to 0}\langle\bar{\psi}\psi\rangle = \pi\rho(0)$ — Banks and Casher, NPB 169 (1980) 103
  - Partition function is an even function in m_l due to the Z(2) subgroup
- Effective restoration of $U_A(1)$ symmetry :
  - A sizable gap in the near-zero modes, i.e. $\rho(\lambda<\lambda_c)=0$ — Cohen, nucl-th/980106
  - If ρ is analytic in m_l^2 and λ, $U_A(1)$ breaking is absent in up to 6 point correlation functions of π and δ — Aoki, Fukaya and Taniguchi, PRD 86 (2012) 114512

Possible behaviors of ρ making $SU_L(2)\times SU_R(2)$ restored but not $U_A(1)$

- Dilute instanton gas approximation $\rho \sim m^2\delta(\lambda)$ will lead to $U_A(1)$ breaking even in the chiral limit

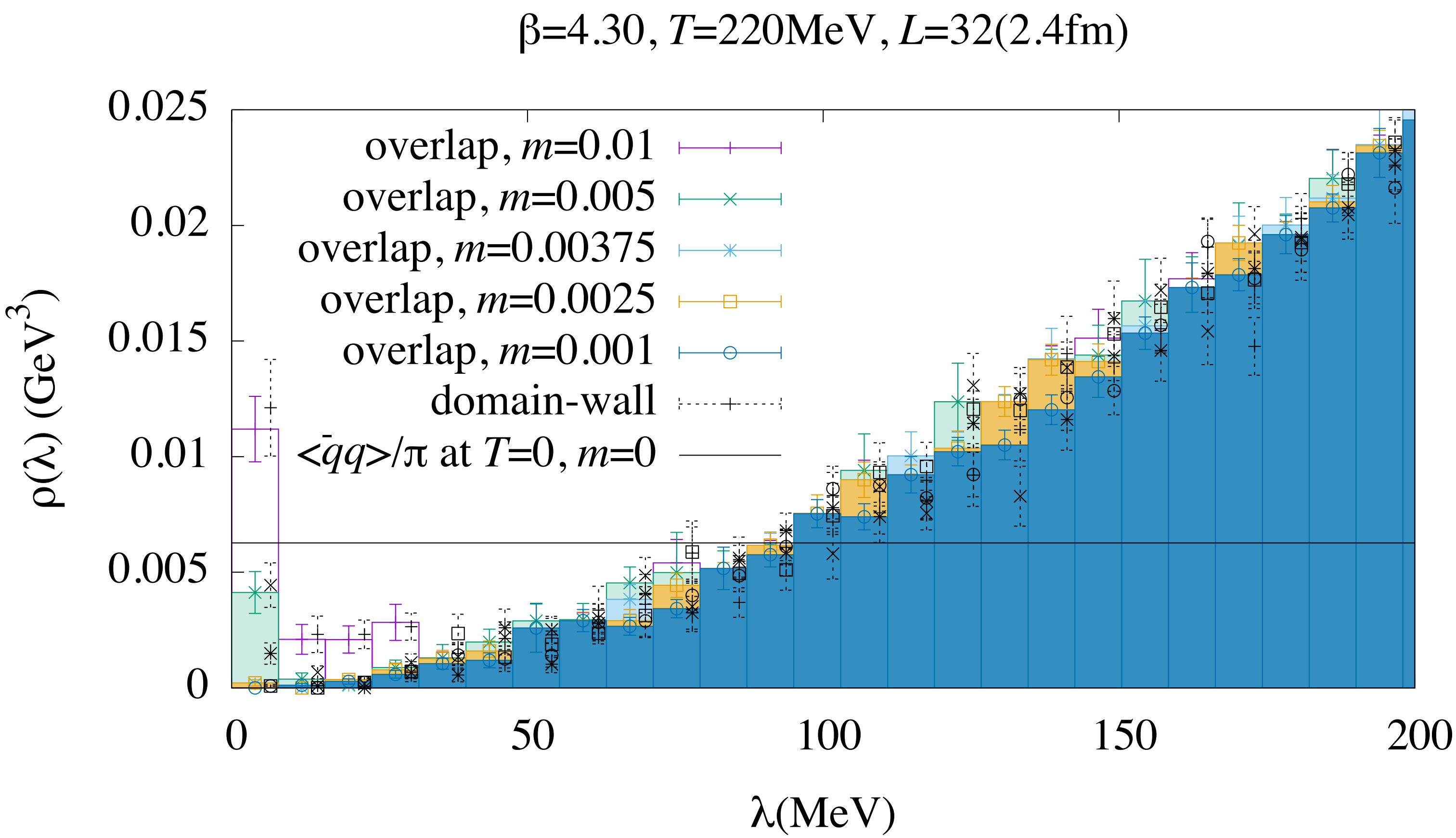
Gross, Yaffe & Pisarski, RMP 81'

- LQCD: At high T for the physical m_l , the T dependence of χ_t follows dilute instanton gas approximation prediction

See a recent review, Lombardo & Trunin, IJMPA 35 (2020) 2030010

Due to $\rho \sim m^2\delta(\lambda)$? what happens for $m_l \to 0$?

Microscopic origin in ρ



JLQCD, PRD 103 (2021) 074506

- No clear gap
- As m_l gets smaller, the infrared enhancement seems disappeared, at $m_l < 0.01$ mass dependence can be hardly seen

Novel relation: quark mass derivative of ρ & C_{n+1}

Eigenvalue spectrum for (2+1)-flavor QCD:

$$\rho(\lambda, m_l) = \frac{T}{VZ[U]} \int D[U] e^{-S_G[U]} \det[\not{D}[U] + m_s] \times (\det[\not{D}[U] + m_l])^2 \rho_U(\lambda)$$

Eigenvalue spectrum for a given configuration: $\rho_U(\lambda) = \sum_j \delta(\lambda - \lambda_j)$

Partition function: $Z[U] = \int D[U] e^{-S_G[U]} \det[\not{D}[U] + m_s] \times (\det[\not{D}[U] + m_l])^2$

$$\det[\not{D}[U] + m_l] = \prod_j (+\mathrm{i}\lambda_j + m_l)(-\mathrm{i}\lambda_j + m_l) = \exp\left(\int_0^\infty \mathrm{d}\lambda \rho_U(\lambda) \mathrm{In}[\lambda^2 + m_l^2]\right)$$

$$\Rightarrow \quad \boxed{\frac{V}{T}\frac{\partial \rho}{m_l} = \int_0^\infty \mathrm{d}\lambda_2 \frac{4 m_l C_2}{\lambda_2^2 + m_l^2}}$$

$$C_2(\lambda, \lambda_2) = \langle \rho_U(\lambda) \rho_U(\lambda_2) \rangle - \langle \rho_U(\lambda) \rangle \langle \rho_U(\lambda_2) \rangle$$

Novel relation: light quark mass derivative of ρ and C_{n+1}

$$\frac{V}{T}\frac{\partial^2\rho}{m_l^2} = \int_0^\infty \mathrm{d}\lambda_2 \frac{4(\lambda_2^2 - m_l^2)\, C_2}{(\lambda_2^2 + m_l^2)^2} + \int_0^\infty \mathrm{d}\lambda_2 \mathrm{d}\lambda_3 \frac{(4m_l)^2\, C_3}{(\lambda_2^2 + m_l^2)(\lambda_3^2 + m_l^2)}$$

... ...

... ...

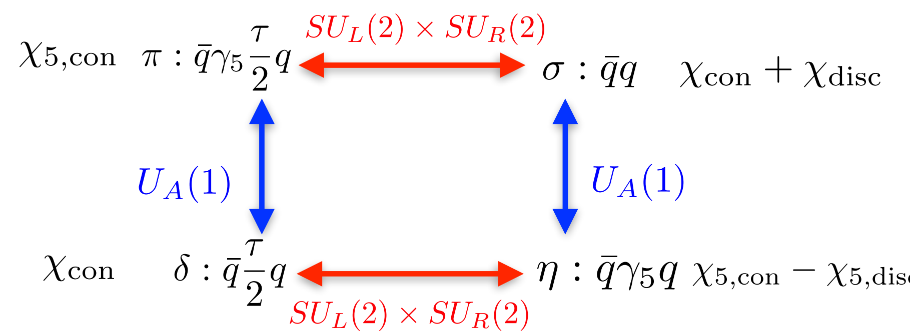
$$C_n(\lambda_1, ..., \lambda_n; m_l) = \left\langle \prod_{i=1}^{n} [\rho_U(\lambda_i) - \langle \rho_U(\lambda_i) \rangle] \right\rangle$$

Signatures of symmetry restorations in ρ

Chiral symmetry restoration: $\chi_\pi - \chi_\delta = \chi_{\rm disc}$

$$\chi_\pi - \chi_\delta = \int_0^\infty d\lambda \frac{8m_l^2 \rho}{(\lambda^2 + m_l^2)^2}$$

$$\chi_{\rm disc} = \int_0^\infty d\lambda \frac{4m_l \partial\rho/\partial m_l}{\lambda^2 + m_l^2}$$



Toublan and Verbaarschot, NPB603 (2001) 343
HotQCD PRD 86 (2012) 094503
Kanazawa & Yamamoto, JHEP 01 (2016) 141

If eigenvalues are uncorrelated, they obey the Poisson statistics:

$$C_n^{\rm Po}(\lambda_1, ..., \lambda_n) = \delta(\lambda_1 - \lambda_2)...\delta(\lambda_n - \lambda_{n-1}) \langle \rho_U(\lambda_1) \rangle + \mathcal{O}(1/N)$$

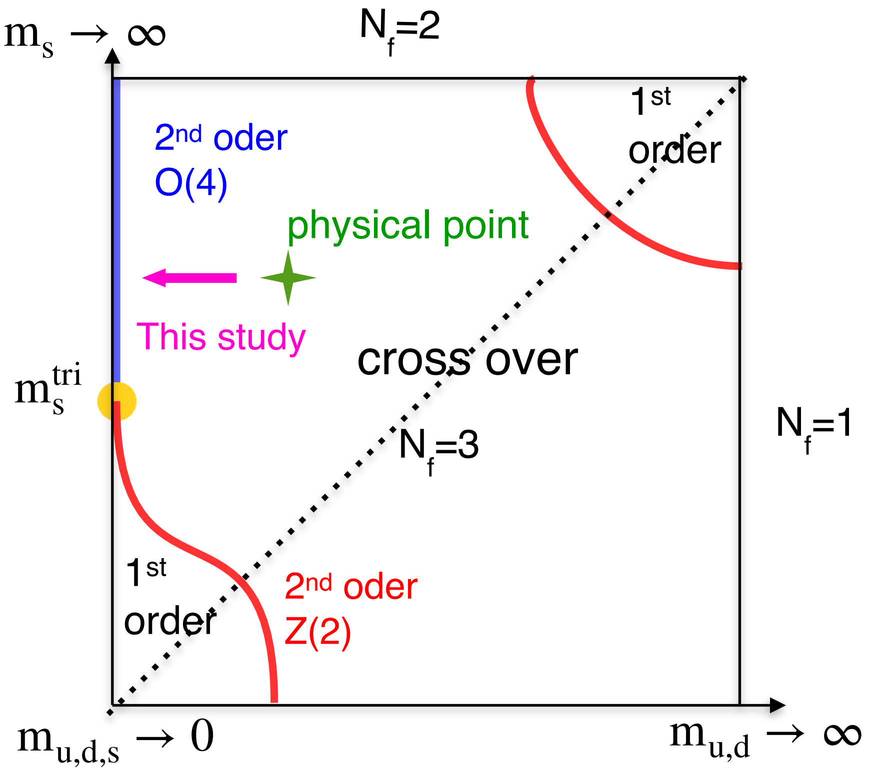
$$\left(\frac{\partial\rho}{\partial m_l}\right)^{\rm Po} = \frac{4m_l\rho}{\lambda^2 + m_l^2} - \frac{V\rho}{TN}\langle\bar{\psi}\psi\rangle \quad \Rightarrow \quad \chi_{\rm disc}^{\rm Po} = 2(\chi_\pi - \chi_\delta)$$

Non-Poisson correlation among eigenvalues are needed for chiral symmetry restoration if $\chi_\pi - \chi_\delta \neq 0$

Kanazawa & Yamamoto, JHEP 01 (2016) 141

Lattice Setup

- At temperature T=205 MeV (1.6 T_c)
- HISQ/tree action
- Nf = 2+1:
  - N_τ=8, 12, 16 (a=0.12,0.08,0.06 fm)
  - m_s^{phy}/m_l = 20, 27, 40, 80, 160
    (m_π =160, 140, 110, 80, 55 MeV)
  - $4 \leq N_s/N_t \leq 9$



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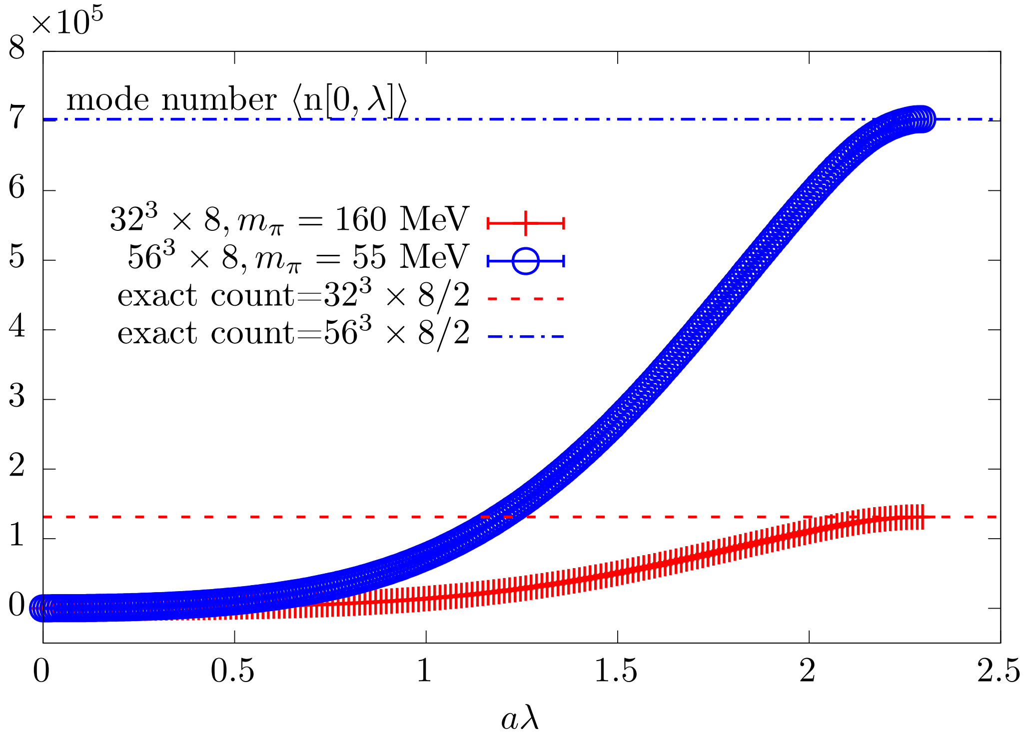
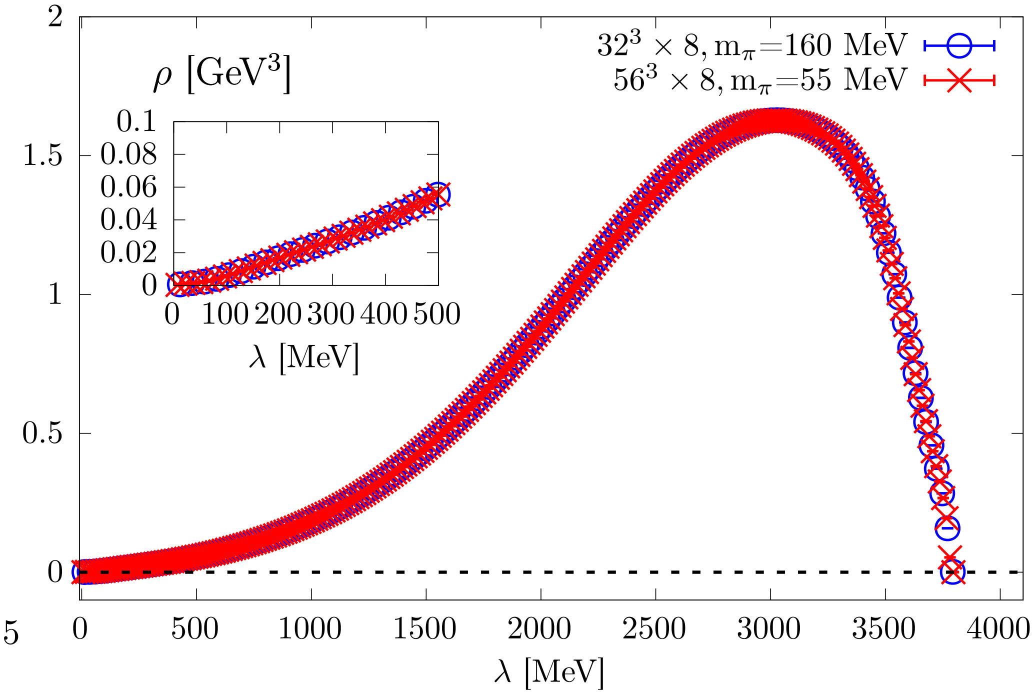
PRL 126 (2021) 082001

Nuclear Science Computing Center at CCNU

Mode number and Complete ρ



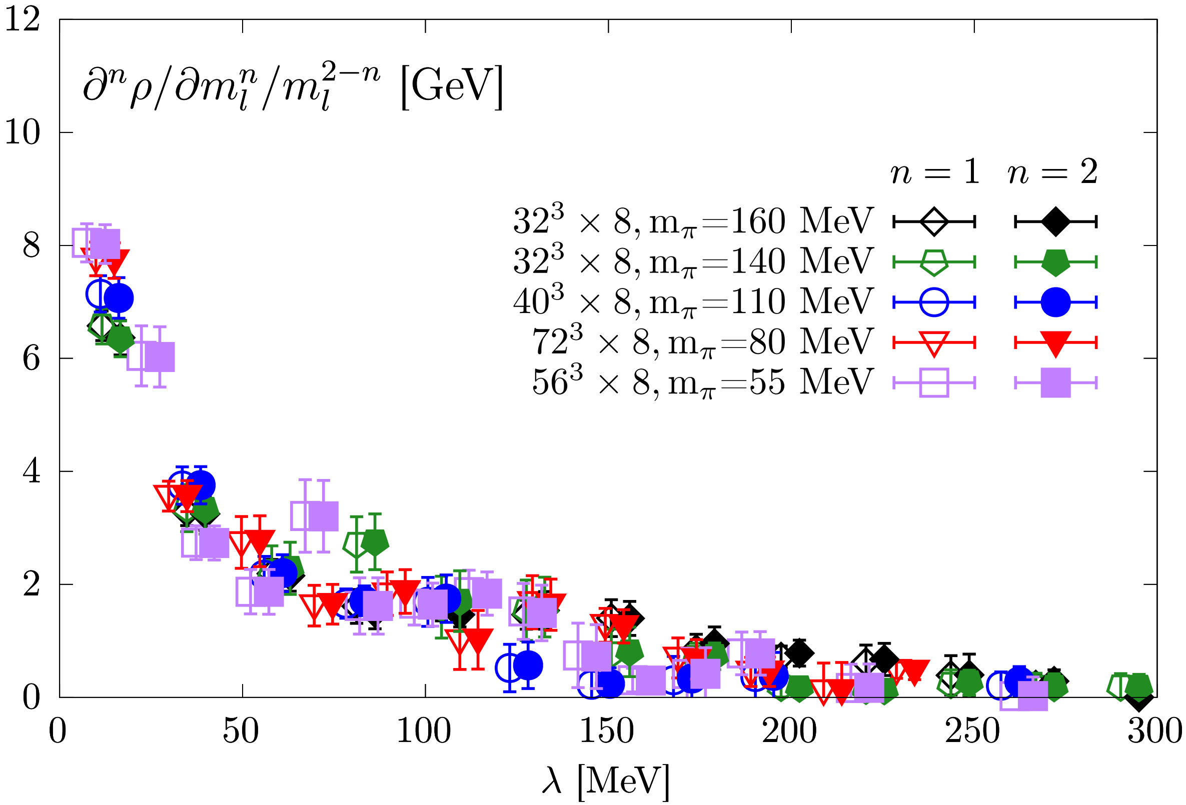


- Converges to the exact count
- Mass dependence can be hardly observed from ρ directly

Utilize the Chebyshev filtering technique combined with a stochastic estimate of the mode number

Giusti and Luscher, JHEP03(2009)013, Patella PRD86(2012)025006, Cossu et al., PTEP 2016(2016)093B06
Fodor et al., arXiv:1605.08091, de Forcrand & Jäger, arXiv: 1710.07305, YuZhang, Lattice19', arXiv:2001.05217

1st and 2nd mass derivative of ρ on N_T =8 lattices



- $m_l^{-1}(\partial\rho/\partial m_l) \approx \partial^2\rho/\partial m_l^2$
- Quark mass independent
- Peaked structure develops at $\lambda \rightarrow 0$ and drops rapidly towards zero for $\lambda/T > 1$

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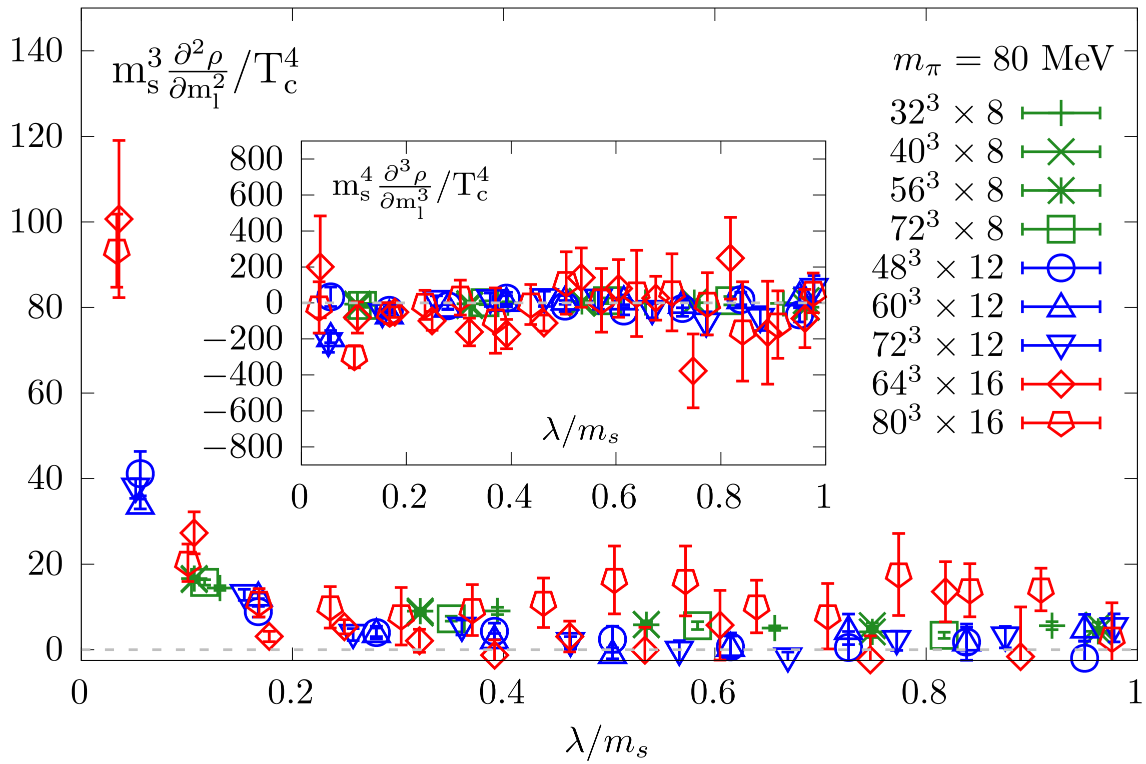
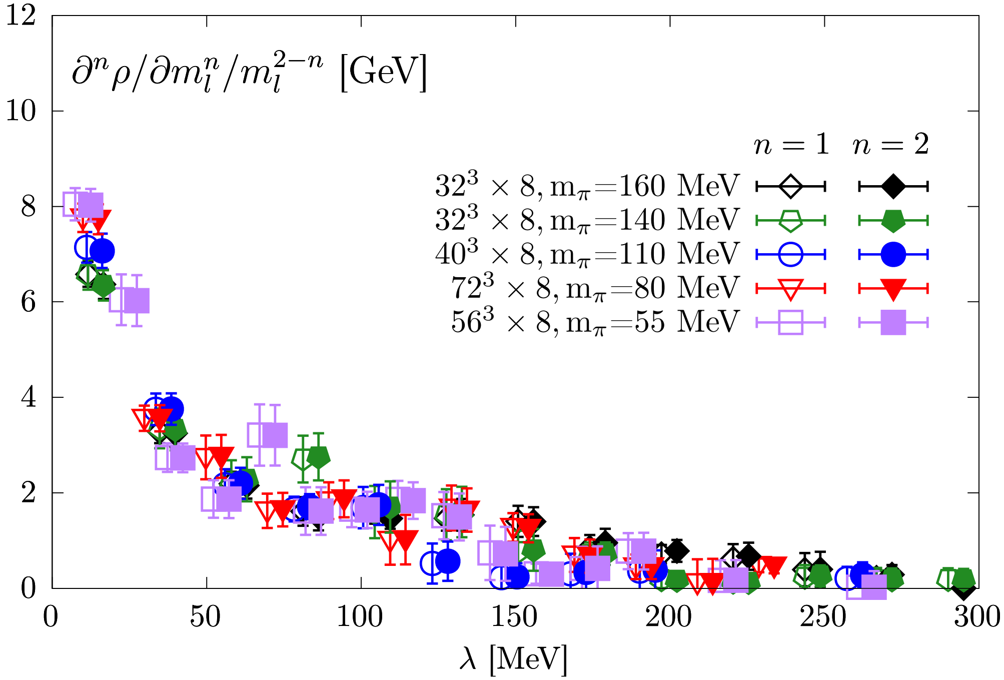
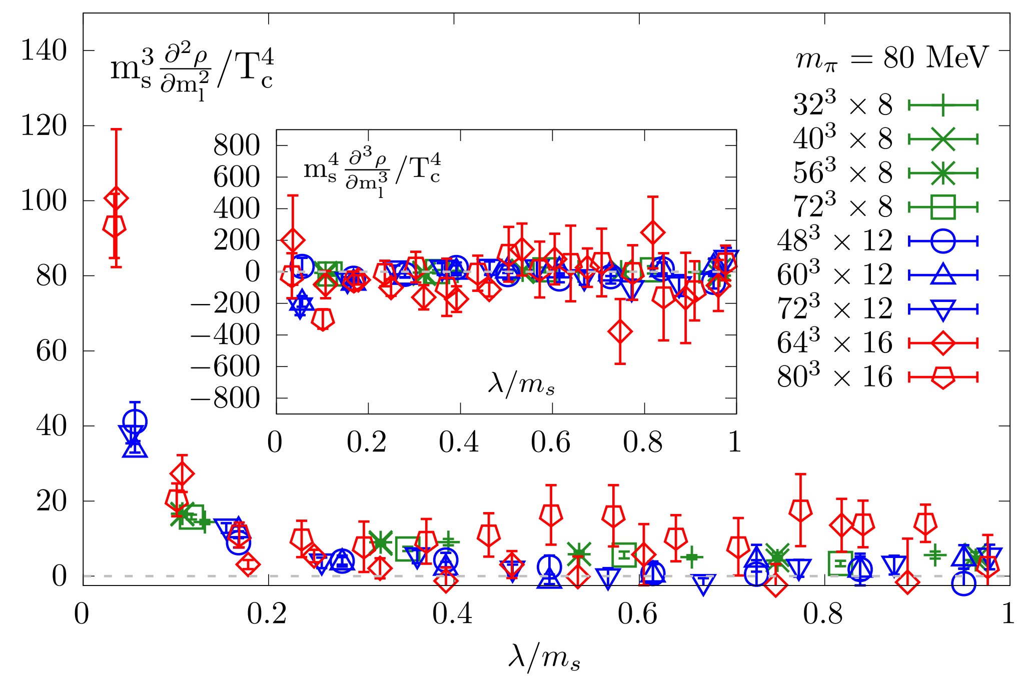
2nd and 3rd mass derivative of ρ: volume and a dependences



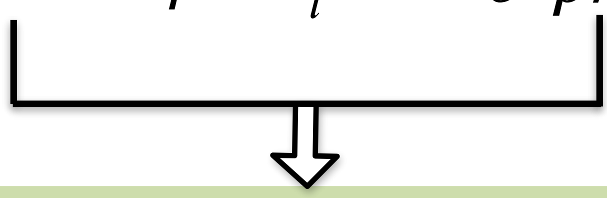
- Peaked structure in 2nd mass derivative of ρ at small λ range becomes sharper towards continuum limit
- Mild volume dependence
- $\partial^3 \rho / \partial m_l^3 \approx 0$

Quark mass derivatives of ρ





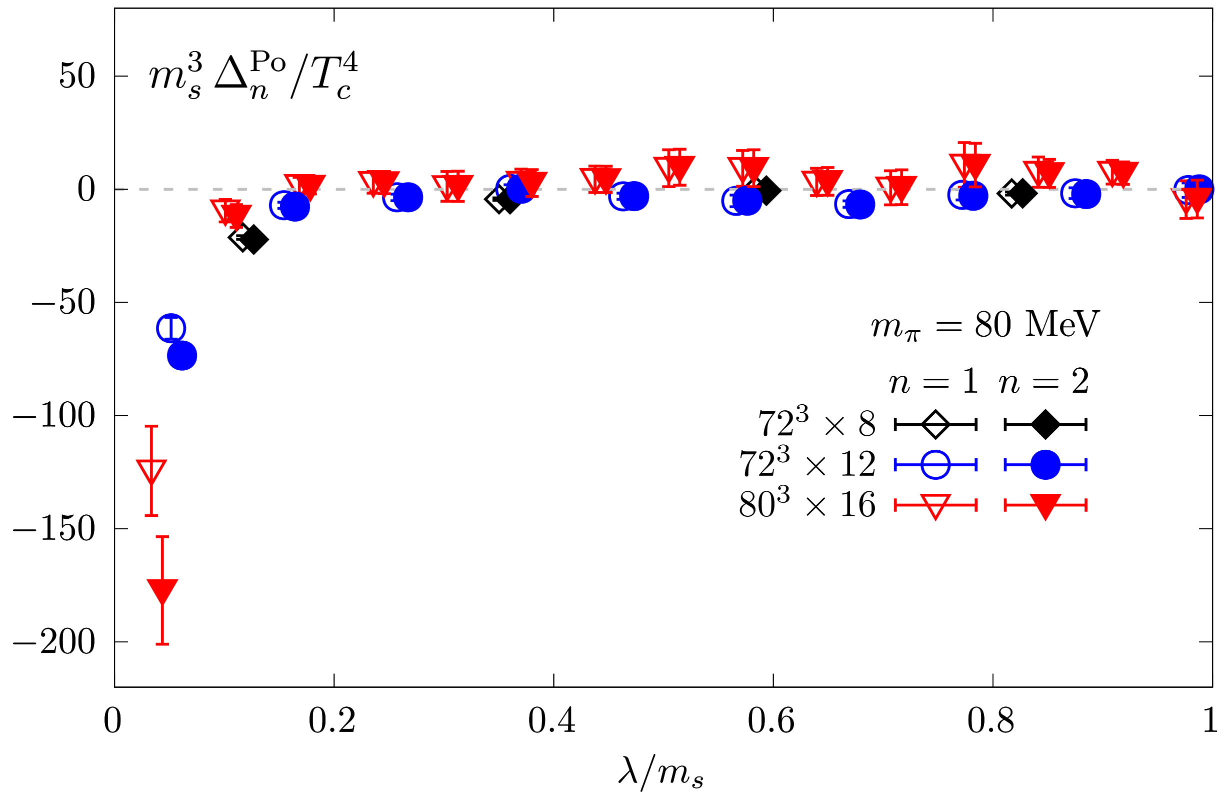
$$m_l^{-1}\left(\partial\rho/\partial m_l\right) \approx \partial^2\rho/\partial m_l^2 \qquad \partial^3\rho/\partial m_l^3 \approx 0$$



$$\rho\left(\lambda\to 0,\ m_l\to 0\right) \propto m_l^2$$

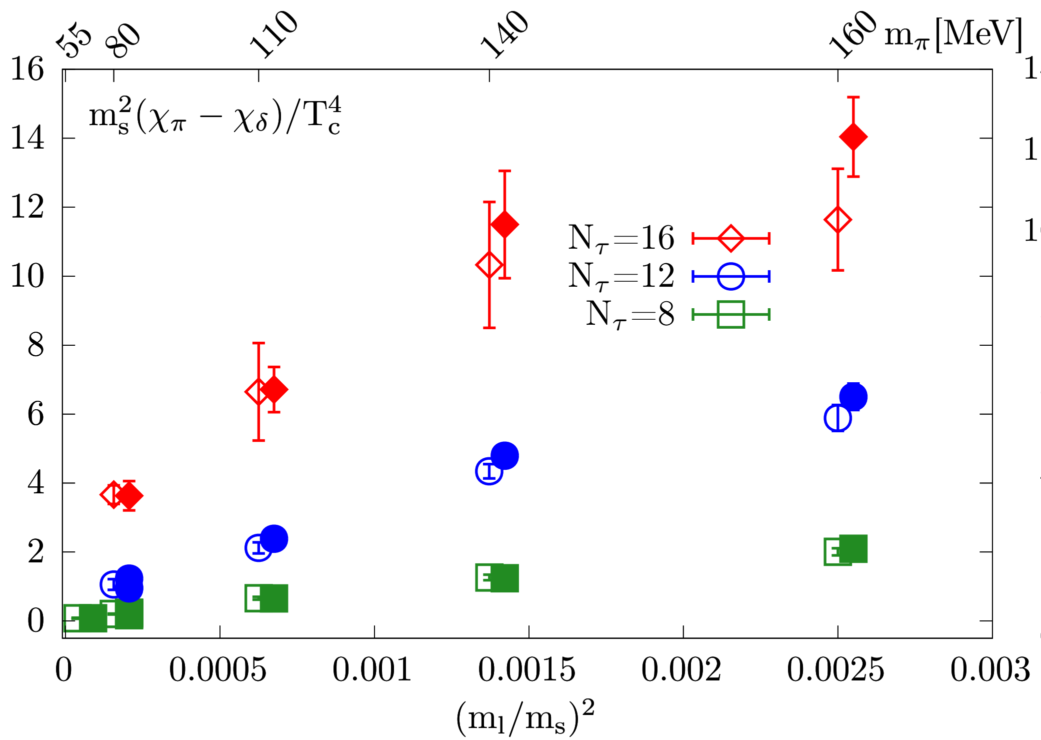
Non-Poisson correlations

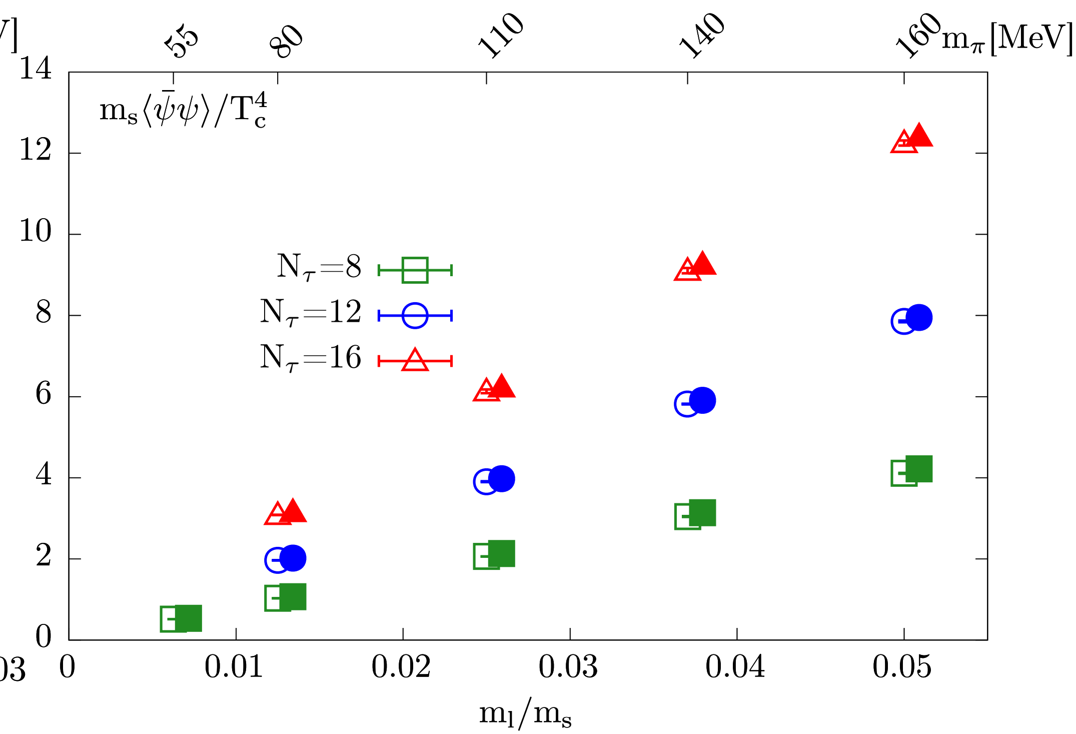
$$\Delta_n^{\mathrm{Po}} = m_l^{n-2}[\partial^n \rho/\partial m_l^n - (\partial^n \rho/\partial m_l^n)^{\mathrm{Po}}]$$



Repulsive non-Poisson correlation at small λ range gives rise to the $\rho(\lambda \to 0)$ peak

Quantities related to ρ



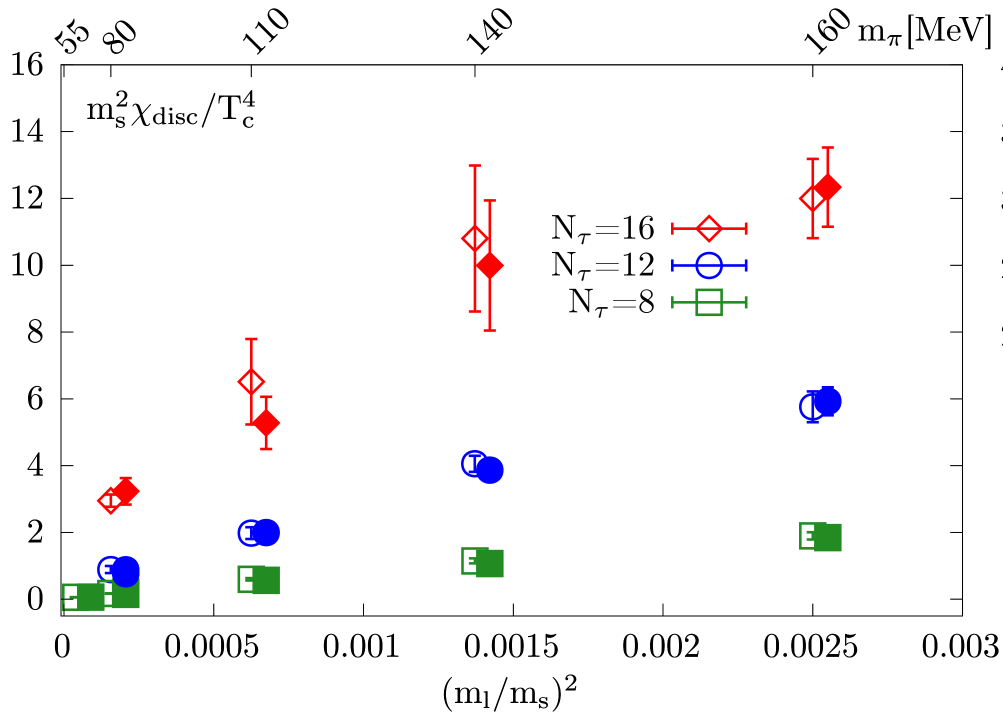


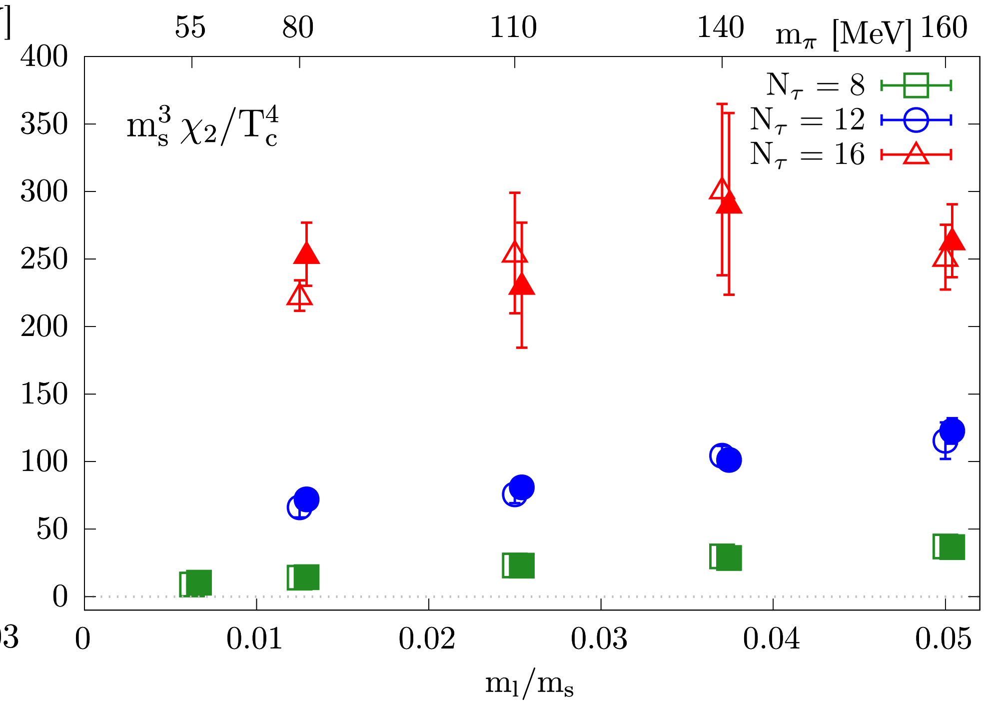
$$\chi_\pi - \chi_\delta = \int_0^\infty \mathrm{d}\lambda \frac{8m_l^2\rho}{(\lambda^2+m_l^2)^2}$$

$$\langle\bar\psi\psi\rangle = \int_0^\infty \mathrm{d}\lambda \frac{4m_l\rho}{\lambda^2+m_l^2}$$

$\langle\bar\psi\psi\rangle$ be reproduced very well from ρ

Quantities related to 1st and 2nd mass derivative of ρ



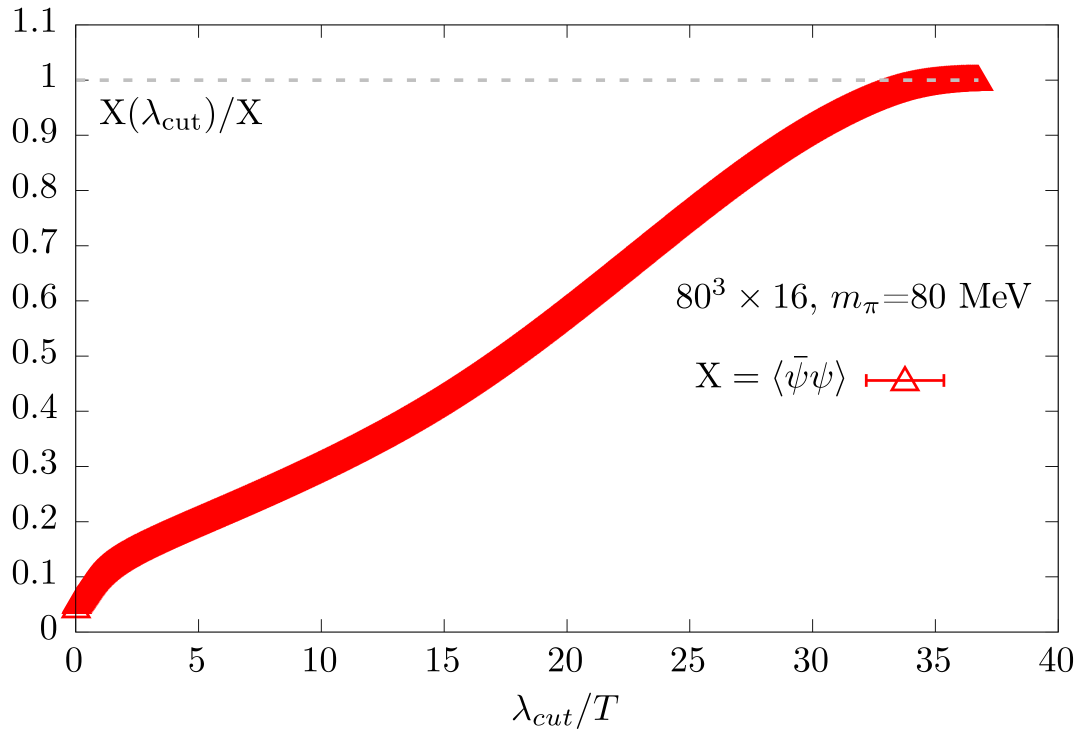


$$\chi_{\text{disc}} = \int_0^\infty \mathrm{d}\lambda \frac{4m_l \partial\rho/\partial m_l}{\lambda^2 + m_l^2}$$

$$\chi_2 = \int_0^\infty \mathrm{d}\lambda \frac{4m_l \partial^2\rho/\partial m_l^2}{\lambda^2 + m_l^2}$$

1st and 2nd mass derivative of ρ can successfully reproduce directly measured χ_{disc} and χ_2

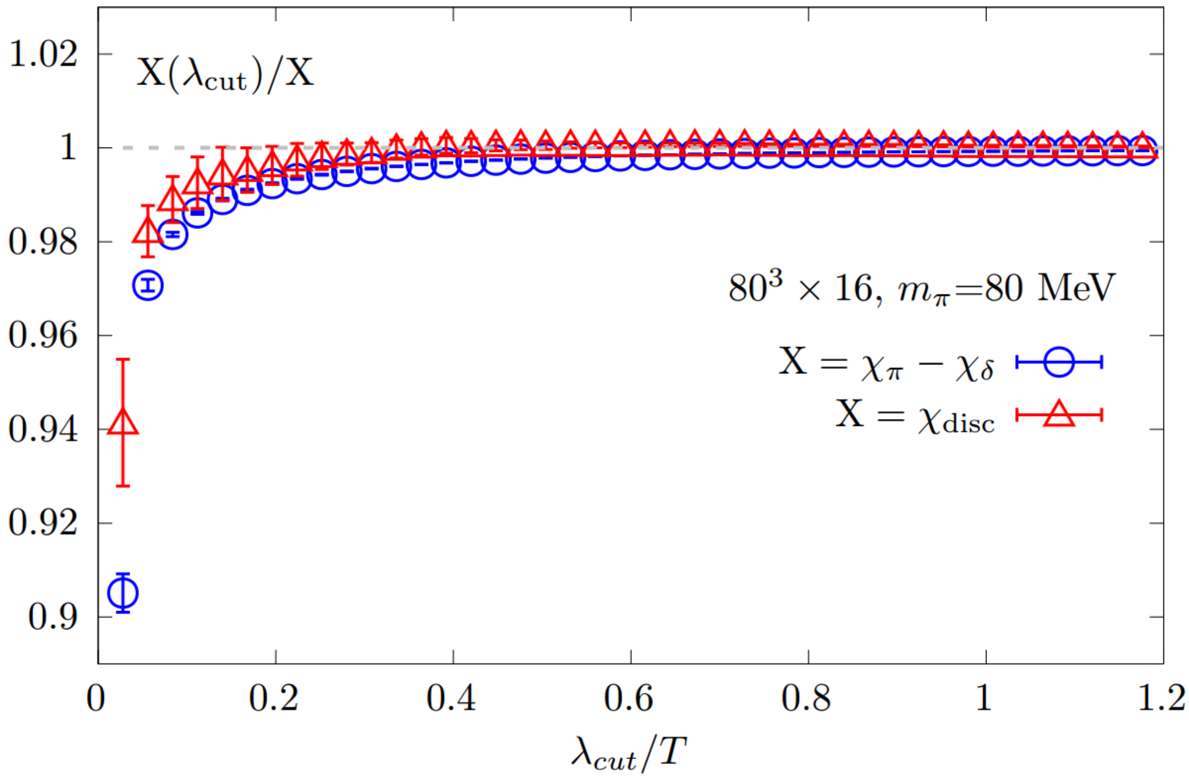
UV divergence of chiral condensate



$$\langle\bar{\psi}\psi\rangle(\lambda_{cut}) = \int_0^{\lambda_{cut}} d\lambda \frac{4m_l\rho}{\lambda^2 + m_l^2}$$

Full ρ is needed for reproduction of chiral condensate

Infrared contribution to two $U_A(1)$ measures

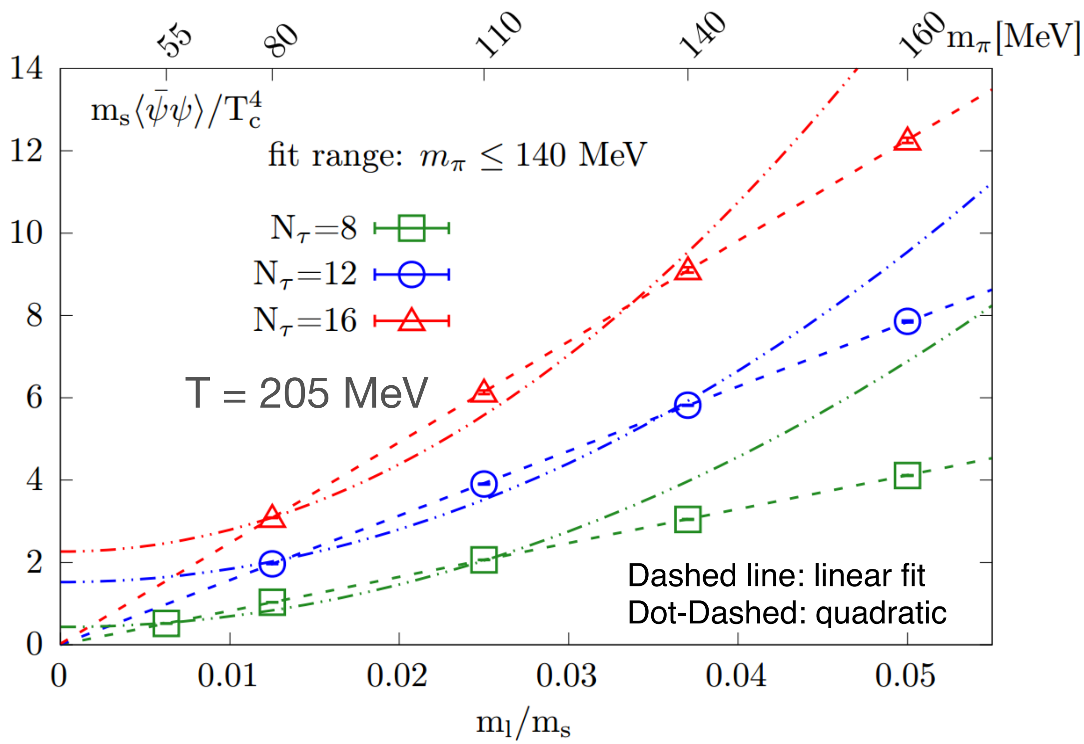


$$(\chi_\pi - \chi_\delta)(\lambda_{cut}) = \int_0^{\lambda_{cut}} d\lambda \frac{8m_l^2 \rho}{(\lambda^2 + m_l^2)^2}$$

$$\chi_{\rm disc}(\lambda_{cut}) = \int_0^{\lambda_{cut}} d\lambda \frac{4m_l \partial\rho/\partial m_l}{\lambda^2 + m_l^2}$$

Only infrared part of ρ and $\partial\rho/\partial m_l$ are needed for the reproduction

$SU_L(2)xSU_R(2)$ symmetry restoration



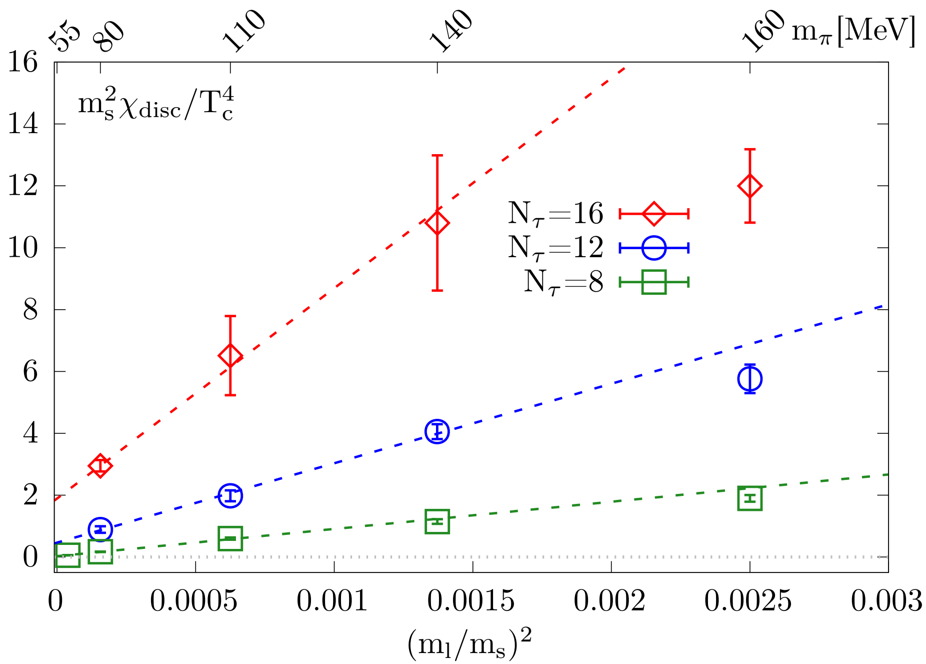
	χ^2/dof	
N_τ	Linear fits	Quadratic fits
8	0.43	13972.7
12	4.4	1504.0
16	0.1	198.5

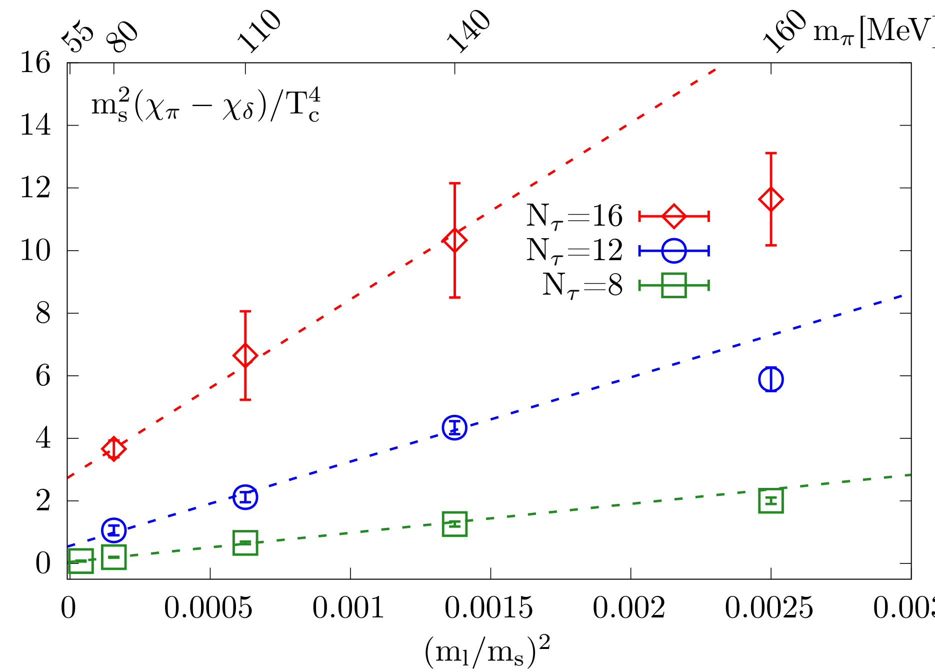
Due to the restoration of Z(2) subgroup of $SU_L(2)\times SU_R(2)$ symmetry, partition function is even function of m_l

$$\langle\bar{\psi}\psi\rangle \propto m_l \text{ as } m_l \to 0$$

$$\chi_{\text{disc}} \propto m_l^2 \text{ as } m_l \to 0$$

Two $U_A(1)$ measures





- Linear in m_l^2 at $m_\pi \lesssim 140$ MeV

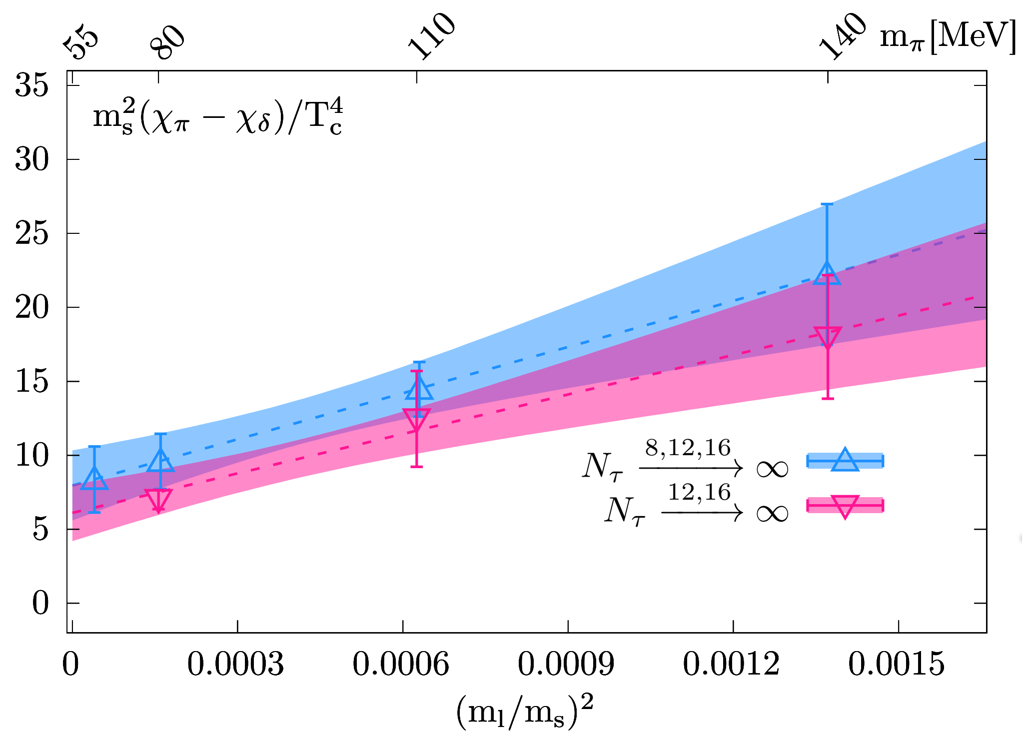
Linear fits for $m_\pi \lesssim 140$ MeV data at each N_τ yield values at m_l=0:

N_τ	$m_s^2\chi_{disc}/T_c^4$	$m_s^2(\chi_\pi - \chi_\delta)/T_c^4$
8	0.0030(7)	0.05(1)
12	0.47(8)	0.6(2)
16	1.9(1)	2.8(1)

In the chiral symmetric phase, $\chi_\pi - \chi_\delta$ should equal to χ_{disc} at m_l=0

→ Continuum extrapolations are crucial!

Continuum and chiral extrapolations



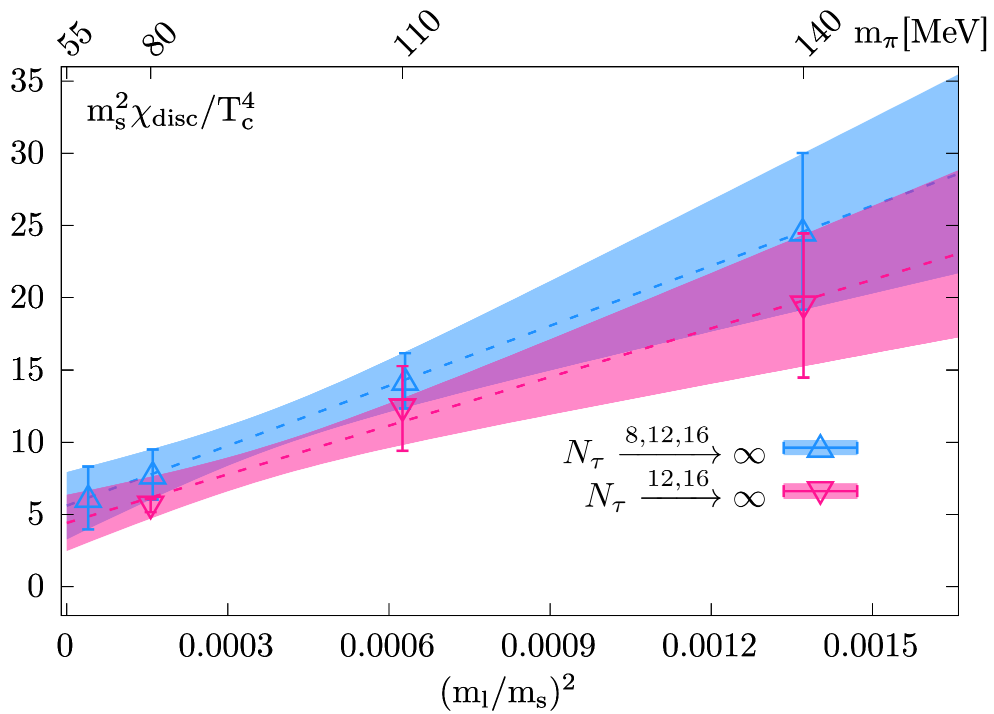
- **Joint fit:** simultaneous fits
  - Continuum: $c_0 + c_1/N_\tau^2 + c_2/N_\tau^4$
  - Chiral: quadratic in quark mass

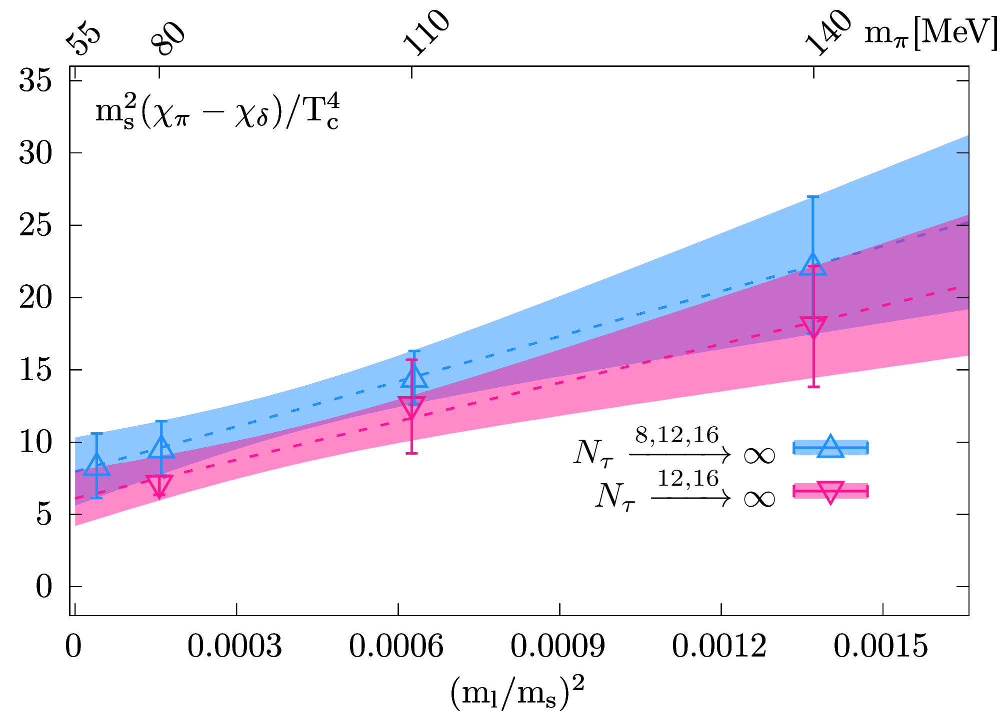
Value at $N_\tau \to \infty$ and $m \to 0$:
8.0 ± 2.4

- **Sequential fit:** first continuum and then chiral extrapolations
  - Continuum: quadratic in $1/N_\tau$ with N_τ=12&16
  - Chiral: quadratic in quark mass

Value at $N_\tau \to \infty$ and $m \to 0$:
6.1 ± 1.9

Continuum and chiral extrapolations





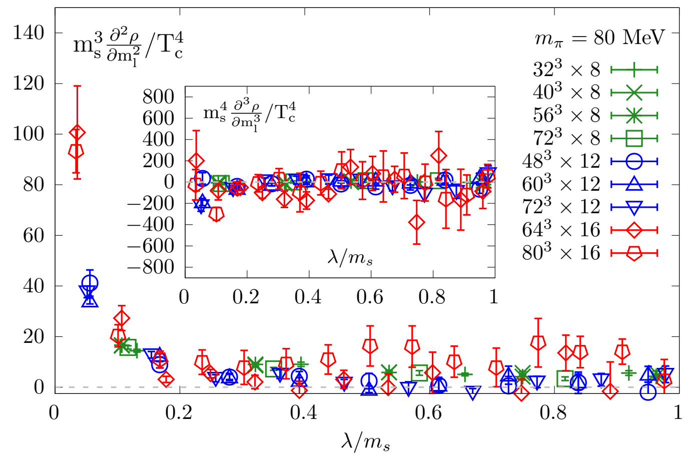
$N_\tau \to \infty$ and $m \to 0$	$m_s^2\chi_{disc}/T_c^4$	$m_s^2(\chi_\pi - \chi_\delta)/T_c^4$
Joint fit	5.6 ± 2.3	8.0 ± 2.4
Sequential fit	4.4 ± 1.9	6.1 ± 1.9

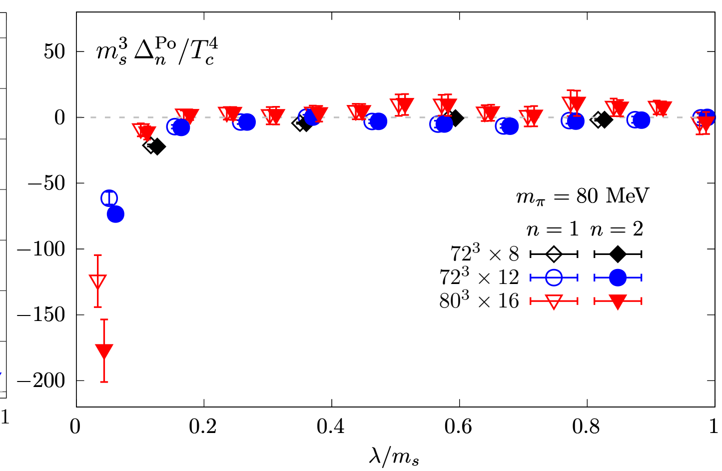
Axial anomaly remains manifested in the two $U_A(1)$ measures even in the chiral limit at 2-3 sigma level for $T \sim 1.6T_c$

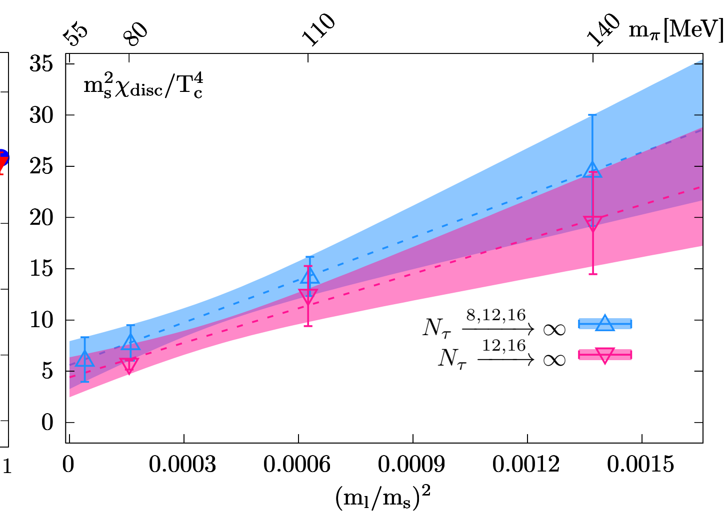
Summary & Conclusions

☑ We established novel relations between $\partial^n \rho / \partial^n m_l$ & C_{n+1}

In N_f=2+1 QCD at T~1.6T_c







Summary & Conclusions

Our study suggests:

- At T≥1.6T_c the microscopic origin of axial anomaly is driven by the weakly interacting instanton gas motivated $\rho(\lambda \to 0, m_l \to 0) \propto m_l^2 \delta(\lambda)$
- N_f=2+1 QCD: 2nd order chiral phase transition belongs to 3-d O(4)

Outlook:

- The methodology would be useful for other discretization schemes

Backup

Calculation of eigenvalue spectrum

- Commonly used method: Lanczos algorithm to calculate the individual low-lying eigenvalues

- Here we utilized the Chebyshev filtering technique combined with a stochastic estimate of the mode number

mode number:

$$\overline{n}[s,t] \approx \frac{1}{N_r} \sum_{r=1}^{N_r} \sum_{j=0}^{p} g_j^p \gamma_j \langle \xi_r^\dagger T_j(A) \xi_r \rangle$$

T_j : Chebyshev polynomial

γ_j: coefficient

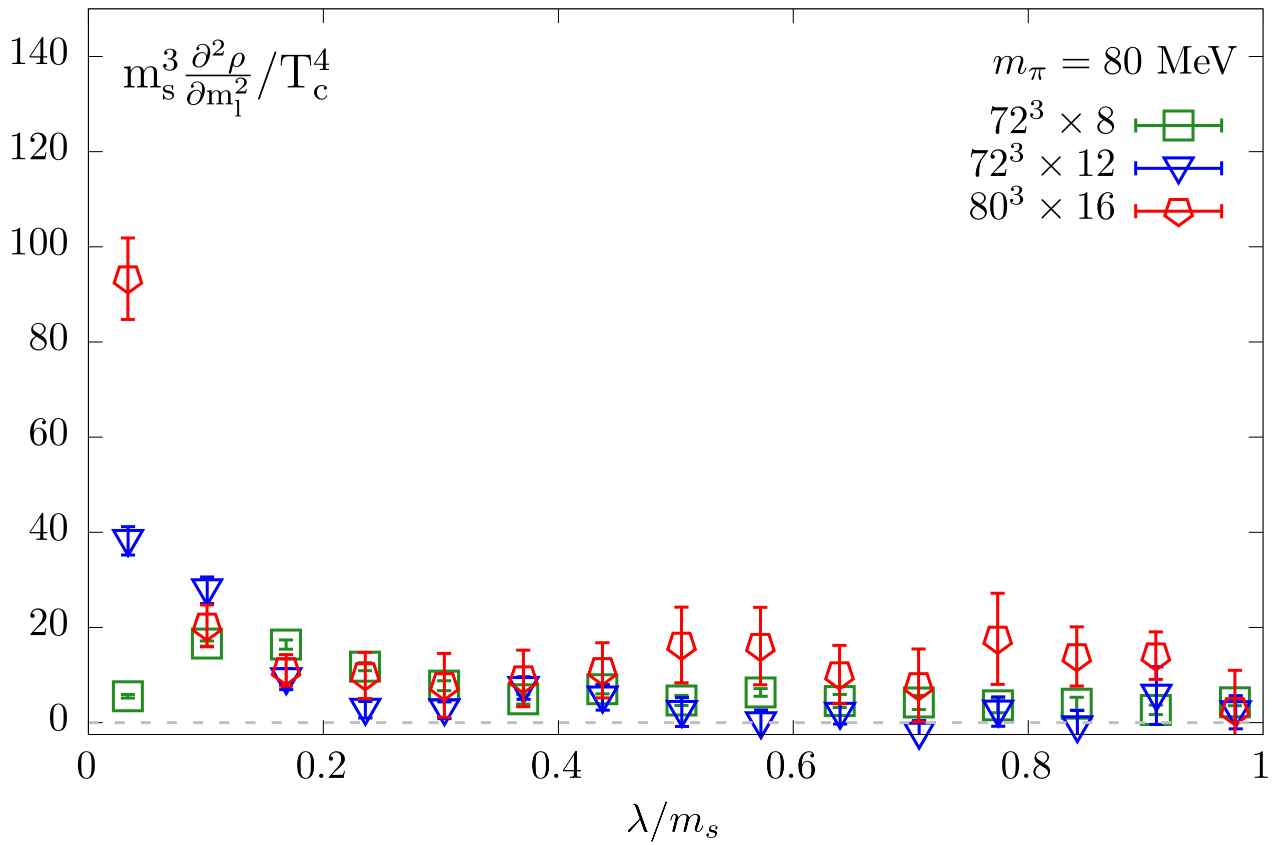
p: polynomial order

Spectrum:

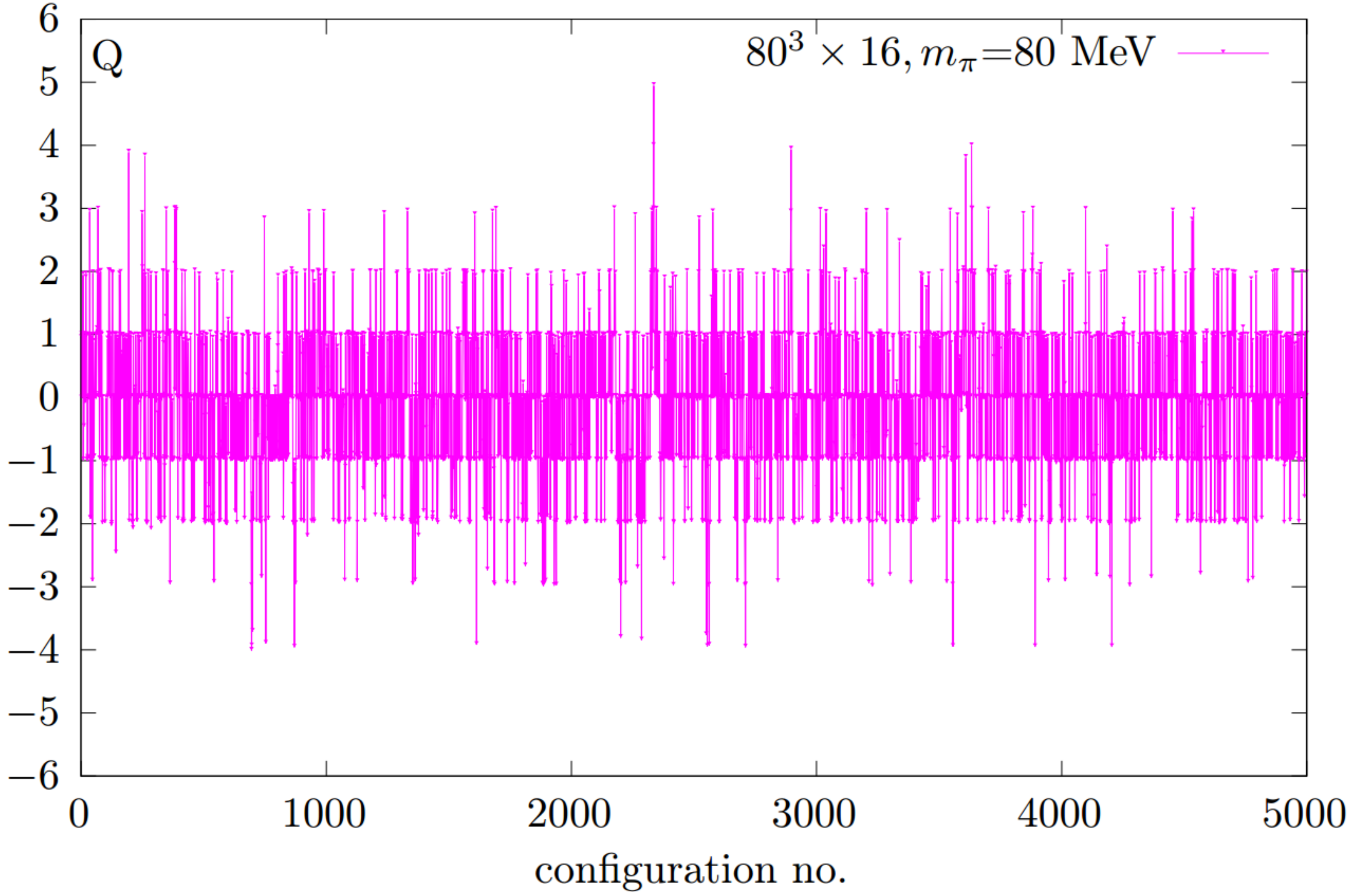
$$\rho(\lambda,\delta) = \frac{1}{V} \frac{\overline{n}[\lambda-\delta/2, \lambda+\delta/2]}{\delta} \qquad (\lambda \geq \delta/2)$$

YuZhang, Lattice19',arXiv:2001.05217
Giusti and Luscher, arXiv:0812.3638
A.Patela, arXiv:1204.432
DiNapoli et al.,arXiv: 1308.4275
Itou et al, arXiv:1411.1155
Fodor et al.,arXiv:1605.08091
Cossu et al.,arXiv:1601.074

2^{nd} mass derivative of ρ



Time history of the topological charge



Poisson distribution

$$C_2(\lambda,\lambda') = \langle \rho_u(\lambda)\rho_u(\lambda')\rangle - \langle \rho_u(\lambda)\rangle\langle \rho_u(\lambda')\rangle$$

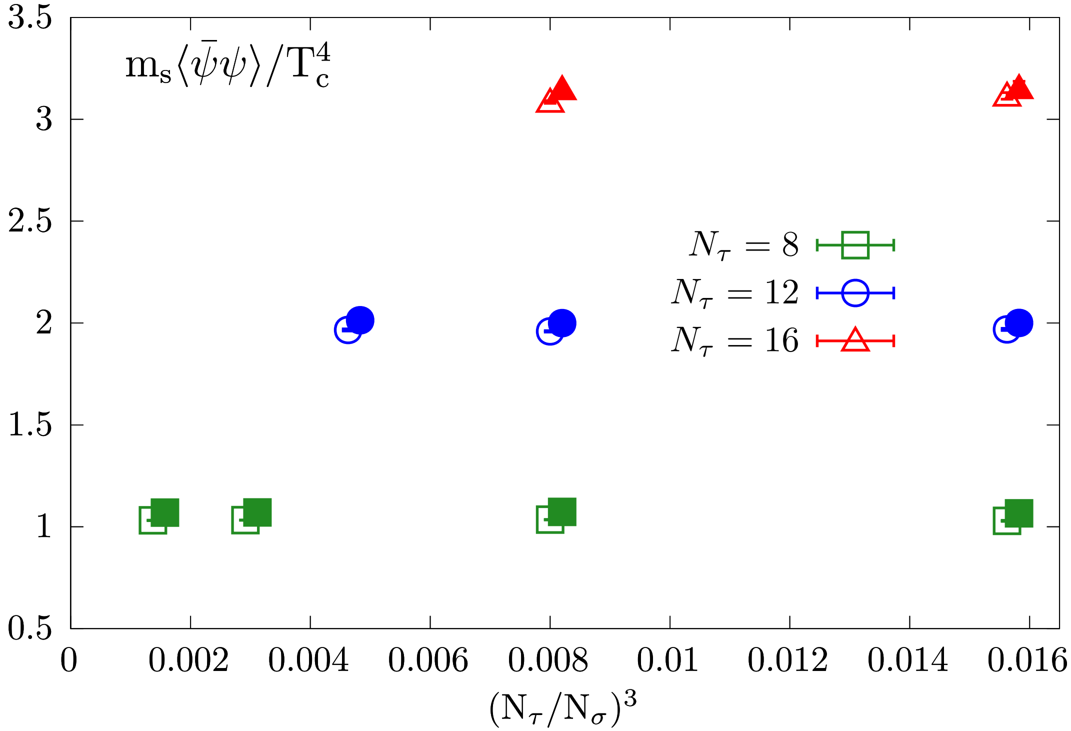
$$= (\frac{1}{V})^2 \left\langle \sum_{k=1}^{N} \delta(\lambda-\lambda_k) \sum_{l=1}^{N} \delta(\lambda'-\lambda_l) \right\rangle - \langle \rho_u(\lambda)\rangle\langle \rho_u(\lambda')\rangle$$

$$= (\frac{1}{V})^2 \left\langle \sum_{k=1}^{N} \delta(\lambda-\lambda_k)\delta(\lambda'-\lambda_k) \right\rangle + (\frac{1}{V})^2 \left\langle \sum_{k=1}^{N} \delta(\lambda-\lambda_k) \sum_{l\neq k} \delta(\lambda'-\lambda_l) \right\rangle - \langle \rho_u(\lambda)\rangle\langle \rho_u(\lambda')\rangle^{(1)}$$

$$= \frac{1}{V}\langle \rho_u(\lambda)\rangle \delta(\lambda-\lambda') + (\frac{1}{V})^2 \left\langle \sum_{k=1}^{N} \delta(\lambda-\lambda_k) \right\rangle \left\langle \sum_{l\neq k} \delta(\lambda'-\lambda_l) \right\rangle - \langle \rho_u(\lambda)\rangle\langle \rho_u(\lambda')\rangle$$

$$\frac{1}{V} \left\langle \sum_{l\neq k} \delta(\lambda'-\lambda_l) \right\rangle = \frac{N-1}{N}\langle \rho_u(\lambda')\rangle \qquad (N = V/2)$$

$$C_2(\lambda,\lambda') = \frac{1}{V}\langle \rho_u(\lambda)\rangle \delta(\lambda-\lambda') - \frac{1}{N}\langle \rho_u(\lambda)\rangle\langle \rho_u(\lambda')\rangle$$

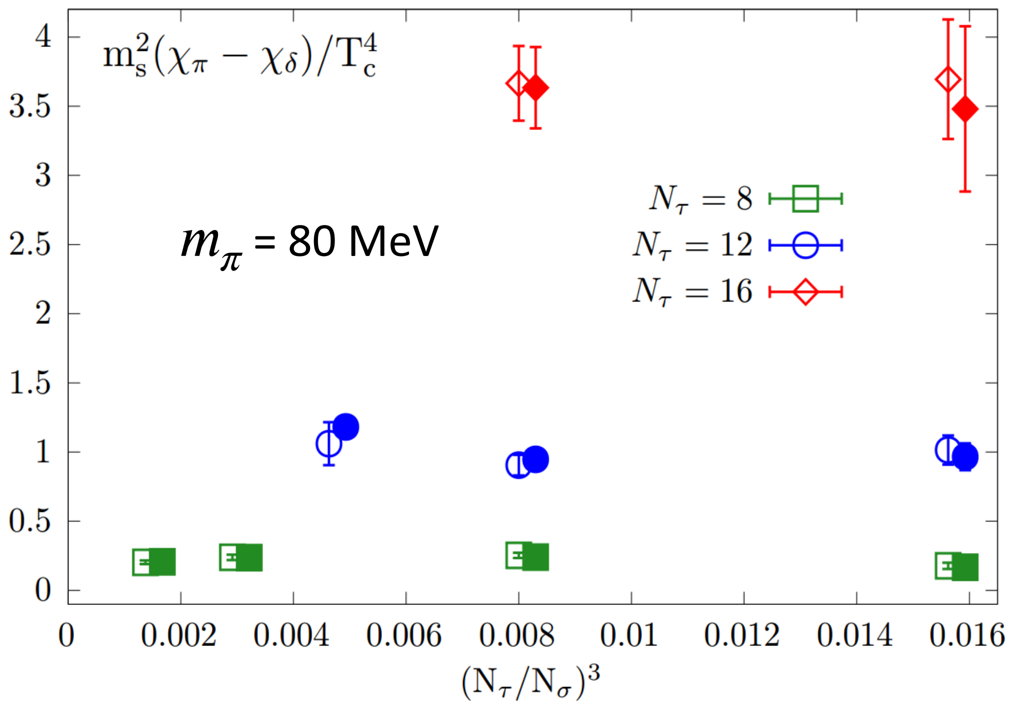


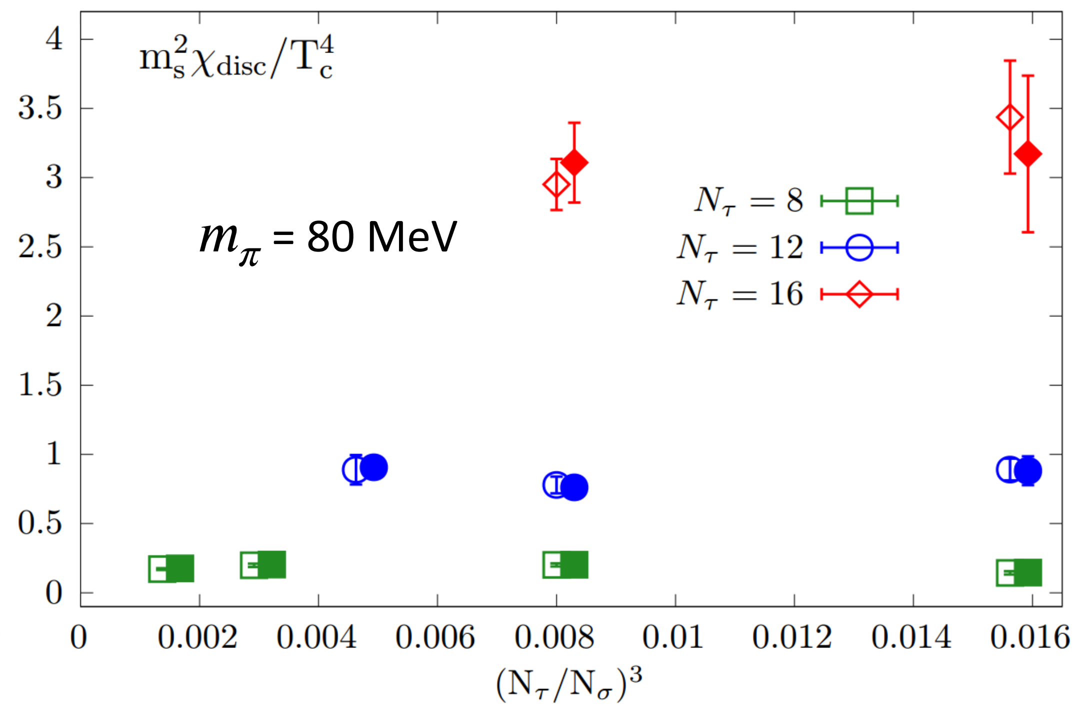
$$\langle\bar\psi\psi\rangle = \int_0^\infty d\lambda \frac{4m_l\rho}{\lambda^2+m_l^2} + \frac{2T}{V}\frac{\langle|Q_{\rm top}|\rangle}{m}$$

$$\langle|Q_{\rm top}|\rangle \propto \sqrt{V}$$

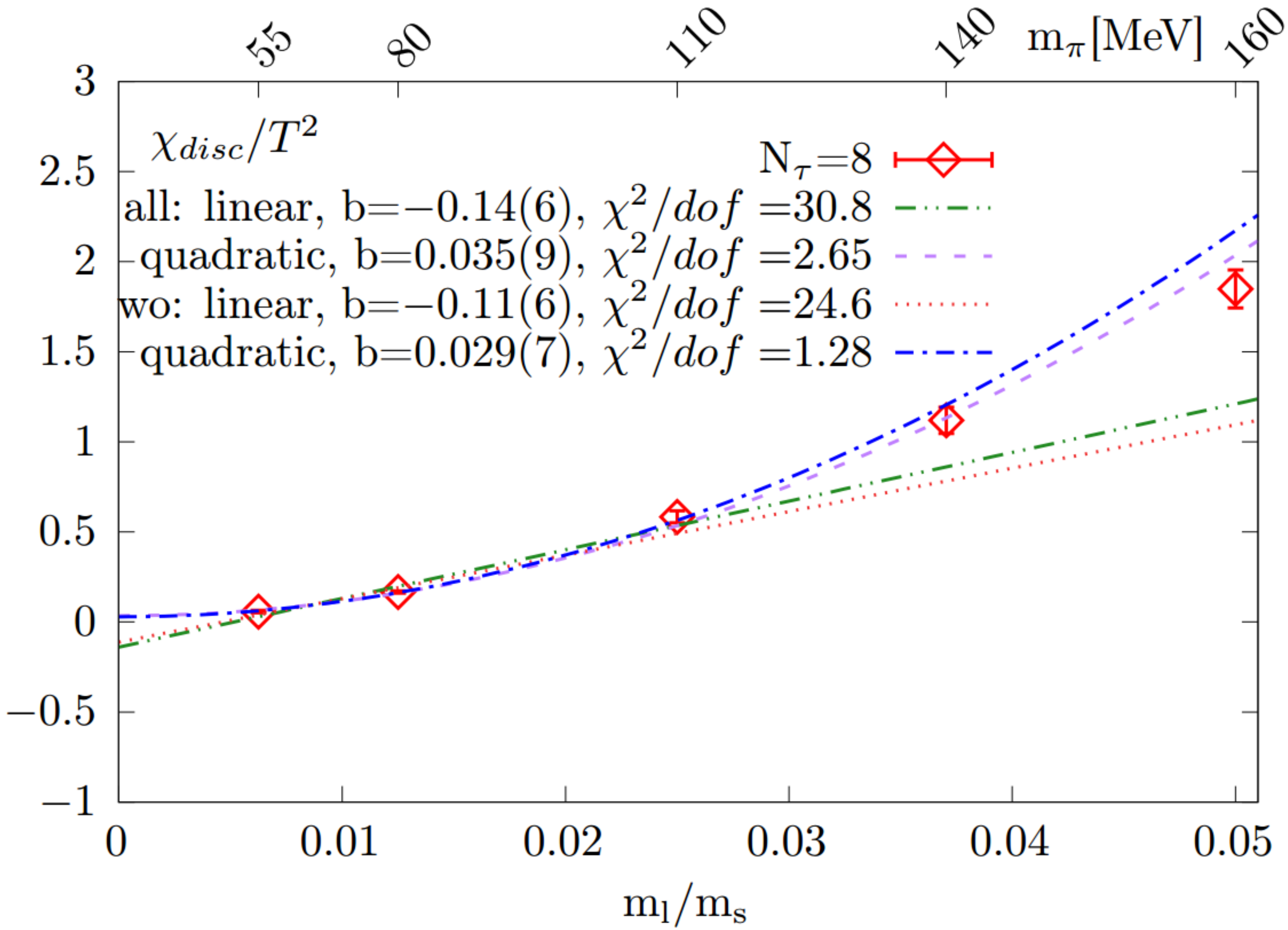
Zero mode contribution vanishes in the thermodynamical limit

Volume dependence of two $U_A(1)$ measures





Volume dependences is very small



55
80
110
140
m_π[MeV]
160
χ_{disc}/T^2
N_τ=8
all: linear, b=−0.14(6), χ^2/dof =30.8
quadratic, b=0.035(9), χ^2/dof =2.65
wo: linear, b=−0.11(6), χ^2/dof =24.6
quadratic, b=0.029(7), χ^2/dof =1.28
3
2.5
2
1.5
1
0.5
0
−0.5
−1
0
0.01
0.02
0.03
0.04
0.05
m_l/m_s

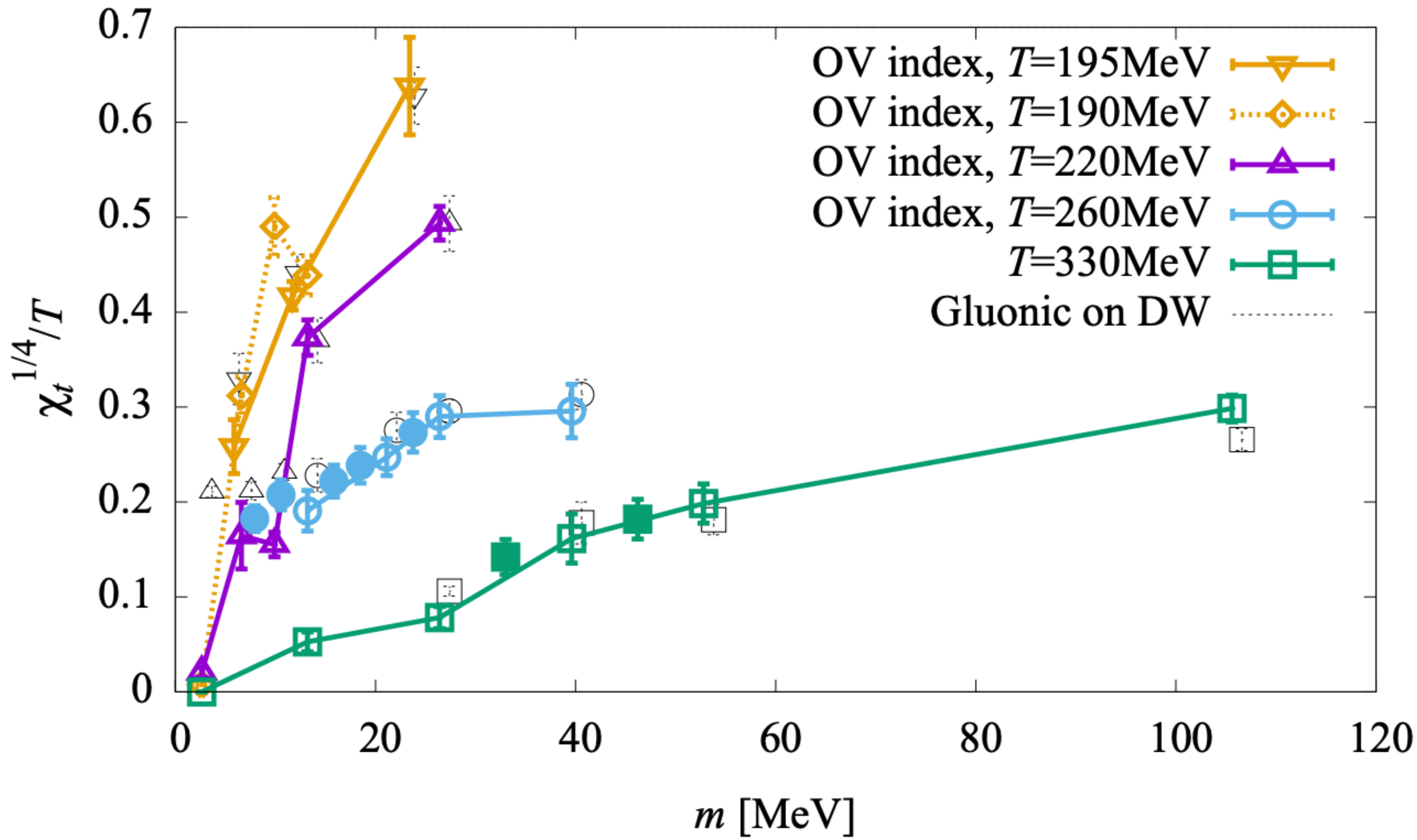
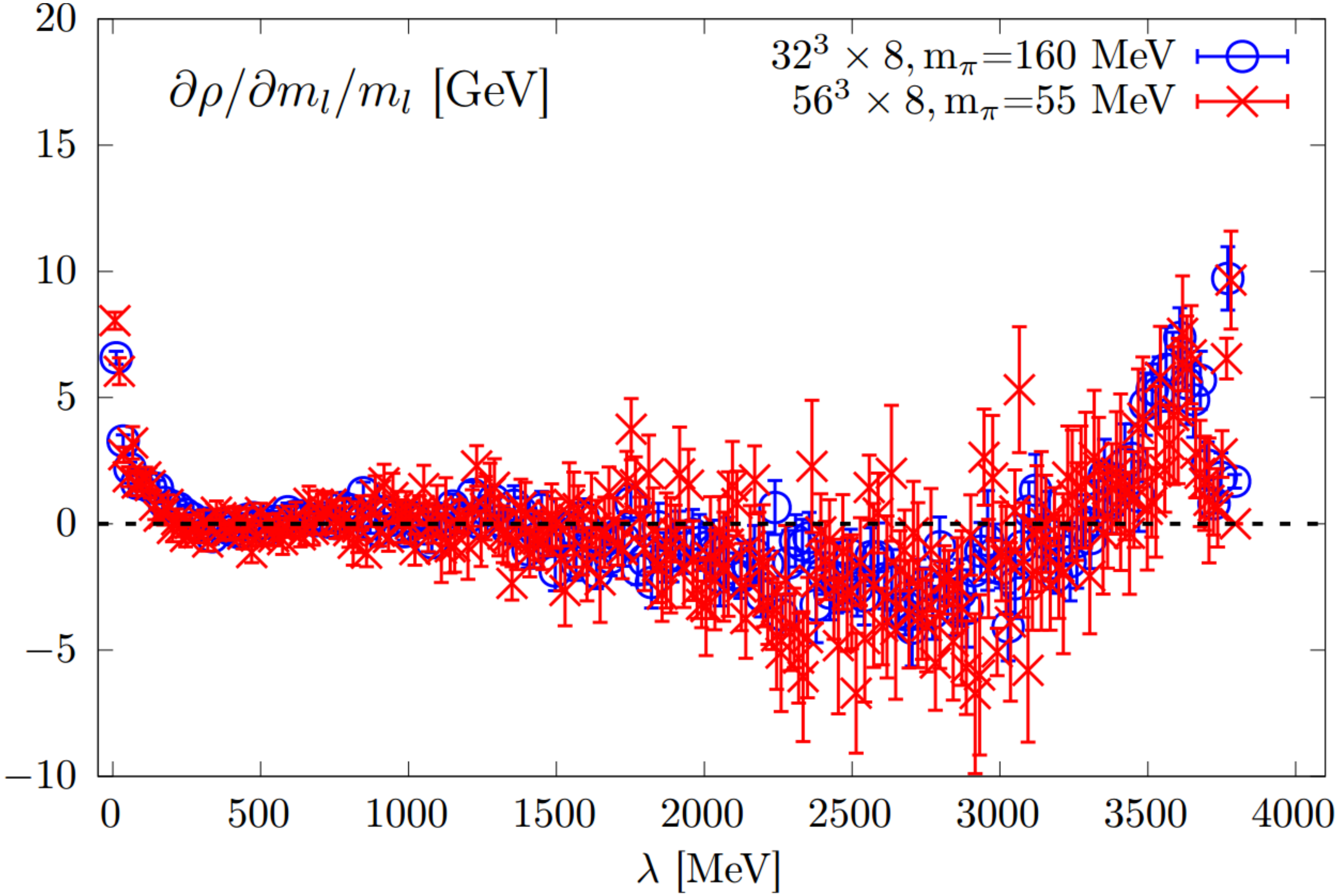


FIG. 8: The same as Fig. 7 but the fourth root is taken and normalized by T. The data suggest that the topological susceptibility near the chiral limit is suppressed to the level of < 10 MeV as $\chi_t^{1/4}/T \sim m$.

Aoki et al., [JLQCD], arXiv:2011.01499

Quark mass dependence of $m_l^{-1}\left(\partial\rho/\partial m_l\right)$



Quark mass dependence of $\partial^2\rho/\partial m_l^2$