The QCD Phase Transition with Three Physical-Mass Pions

32nd International Symposium on Lattice Field Theory

June 23, 2014

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Lawrence Livermore National Laboratory

LLNL-PRES-641426

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

The QCD phase transition with physical-mass, chiral quarks

(HotQCD Collaboration)

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(Dated: February 18, 2014)

http://arxiv.org/abs/1402.5175

And huge THANKS to Peter Boyle!

Executive Summary

- The 1st study of the QCD phase transition with chirally symmetric lattice fermions and physical pion masses
- The transition is a crossover with T_χ = 155 (1) (8) MeV
  - similar to previous results using staggered fermions
- Anomalous $U(1)_A$ symmetry is thoroughly broken up to T ~ 185 MeV ~ 1.2 T_χ
- The disconnected chiral susceptibility peak doubles when M_π is reduced from 200 to 135 MeV, in rough agreement with O(4) scaling
- ***Demanding*** calculations enabled by cutting edge algorithms (DSDR), software (CPS/BFM), and machines (LLNL BG/Q)

Outline

- the QCD finite-temperature transition
- domain wall fermions
- chiral susceptibilities and chiral symmetry
- chiral susceptibilities and $U(1)_A$
- cutoff effects

The QCD Finite-T Transition

The spontaneous breaking of chiral symmetry

$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$$

is a crucial aspect of the history and present state of our Universe

- studied intensely for over 30 years, experimentally and theoretically
- one outstanding puzzle: role of anomalous $U(1)_A$ axial symmetry

The QCD Finite-T Transition

- $m_q = 0$:
  - $U(1)_A$ thought to be clearly broken at T_χ
    → **4** light d.o.f. (σ, π), O(4)-class 2nd order criticality
  - Pisarski, Wilczek (1984):
    if $U(1)_A$ breaking at T_χ is mild, have **8** light d.o.f.
    → NOT O(4)-class – $SU(2)_L \times SU(2)_R / U(2)_V$?
    → maybe even 1st order

  → $U(1)_A$ of fundamental importance and NOT understood
- m_q physical:
  - transition appears to be analytic crossover

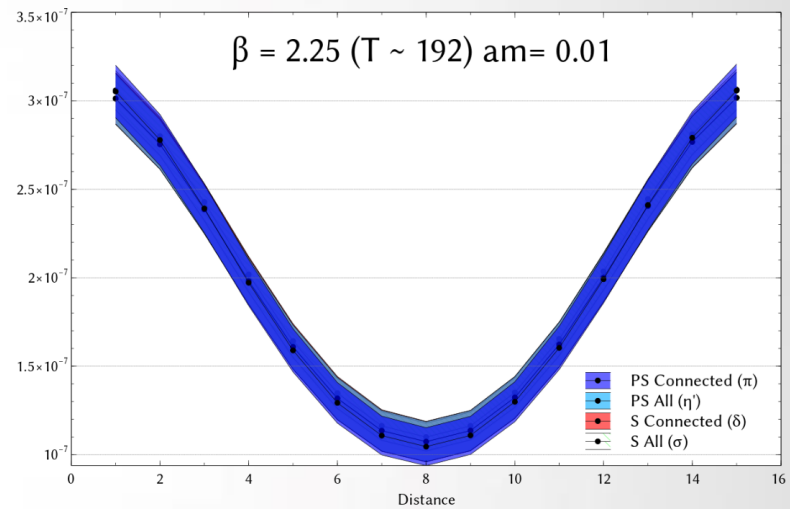
Recent literature - I

G. Cossu et al. (2013) for JLQCD
Disconnected meson diagrams **vanish** at temperatures above T_c

Related: Gap in the Dirac spectrum

Aoki, Fukaya, Taniguchi (2012)
Analytic calculation (Overlap)
Dirac spectrum $\rho(\lambda) \sim c\lambda^3$
Implies **$U(1)_A$ anomaly invisible**

Meson spatial correlators



$$\pi = \delta = \rho = \sigma$$

Restored

credit: Guido Cossu, Lattice 2014

Recent literature - II

Bazavov et al. (2012-13)
Domain wall, several volumes
Dirac spectrum, susceptibilities
NOT restored

Ohno et al., Sharma et al. (2012-13)
Overlap on HISQ configurations
Dirac spectrum
NOT restored

Brandt et al. (2013)
Wilson improved fermions
Screening masses
NOT restored

Our previous study
Exact chiral symmetry (Overlap)
topology fixed
Only 16^3x8 volume
Mass dependence
No continuum limit

credit: Guido Cossu, Lattice 2014

Domain Wall Fermions

- chiral fermions **expensive** but **essential**
- staggered fermions:
  - explicitly break $U(1)_A$ *and* 5/6 of $SU(2)_L$ x $SU(2)_R$
  - very costly continuum limit absolutely necessary
- domain wall fermions:
  - three, degenerate pions *and* exact anomalous current conservation <u>*at finite lattice spacing*</u> (for infinite L_s)
  - near-continuum results expected for sufficiently large L_s
  - still need to control effects of finite a, V, and L_s

Domain Wall Fermions

- Wilson, w/ chiralities separated in 5th dimension
- LH and RH fields localized on domain walls, x_s=0 and L_s, overlap in bulk for finite L_s
- Want "L_s~∞" – **expensive** but manageable

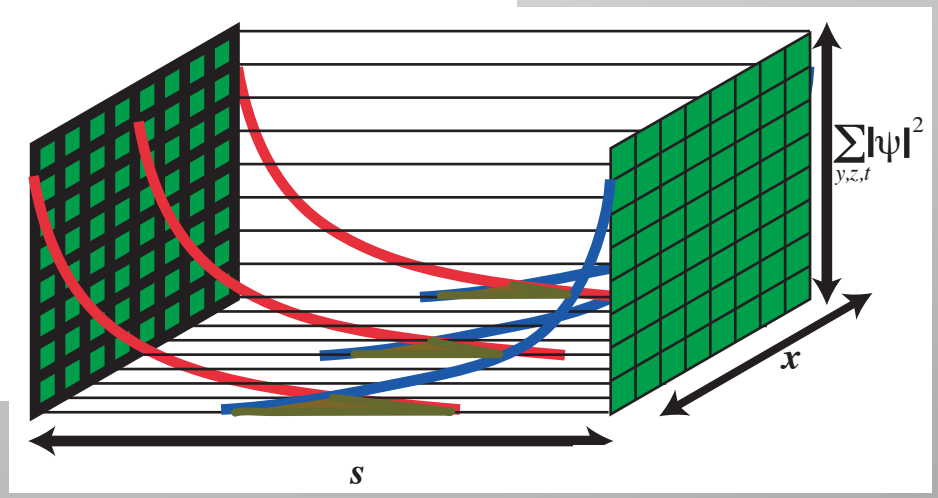
Then there are two chiral zeromode solutions $\Psi_0^{\pm}$ given by

$$\Psi_0^{\pm}(\vec{p}, z) = e^{i\vec{p}\cdot\vec{x}}\phi_{\pm}(s, \vec{p})u_{\pm}$$

where the transverse wavefunctions are given by

$$\phi_+(s, \vec{p}) = e^{-\mu_0|s|}$$

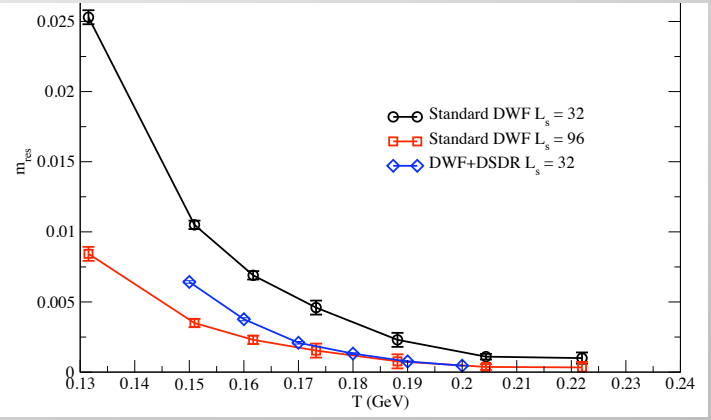
$$\phi_-(s, \vec{p}) = (-1)^{n_s}\phi_+(s, \vec{p}) \ .$$



Domain Wall Fermions

- Substantial cost reductions:
  - Dislocation Suppressing Determinant Ratios (DSDR)
    - introduce ratio of Wilson fermions with negative unphysical mass
    - suppress "dislocations" - low modes due to O(a) effects – without freezing topology
    - achieve target m_{res} at reduced L_s
  - Möbius Formulation
    - generalize Shamir formulation with overall scaling factor
    - improve sign function approximation in low-mode, residual-χSB region
    - achieve target m_{res} at further reduced L_s

~10X for m_π~135 MeV



additional 2X for m_π~135 MeV

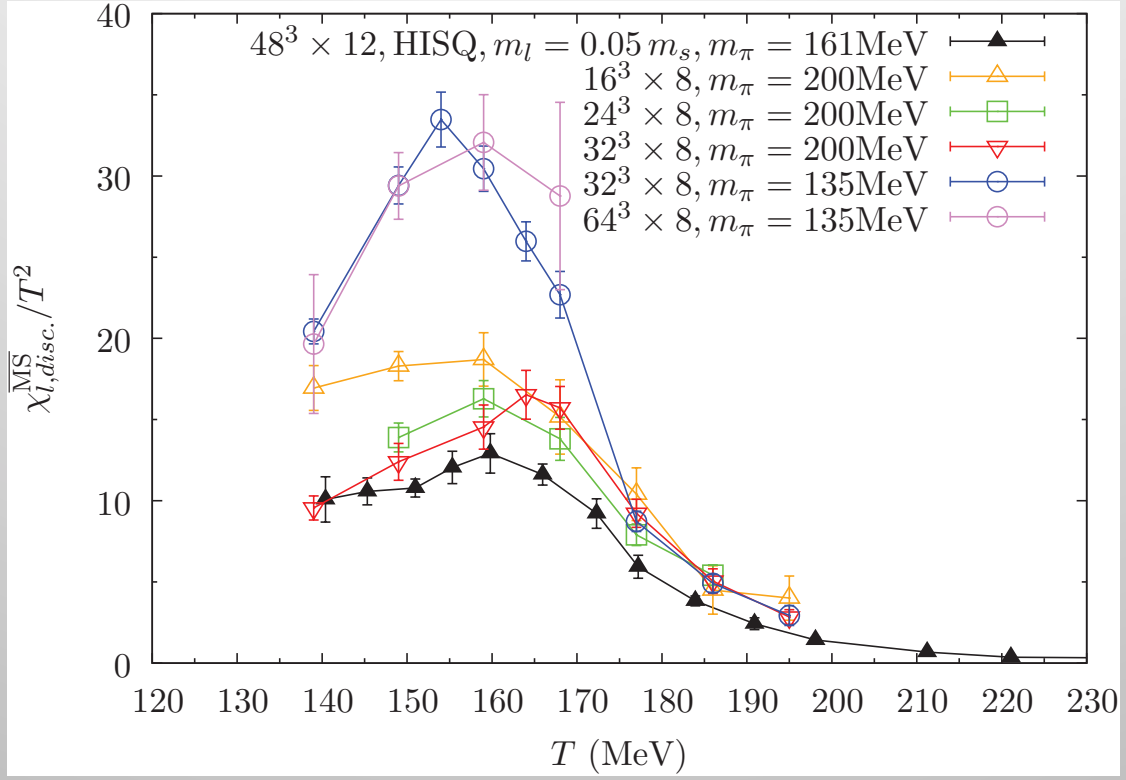
$\chi_{l,\mathrm{disc}}$ and T_χ

- Optimal probe of χSB: disconnected chiral susceptibility

$$\chi_{l,\mathrm{disc}} = \left(\frac{\partial}{\partial m_l}\langle\bar{\psi}\psi\rangle_l\right)_{\mathrm{disc}} = \frac{1}{N_\sigma^3 N_\tau}\left\{\left\langle(\mathrm{Tr}M_l^{-1})^2\right\rangle - \left\langle\mathrm{Tr}M_l^{-1}\right\rangle^2\right\}$$

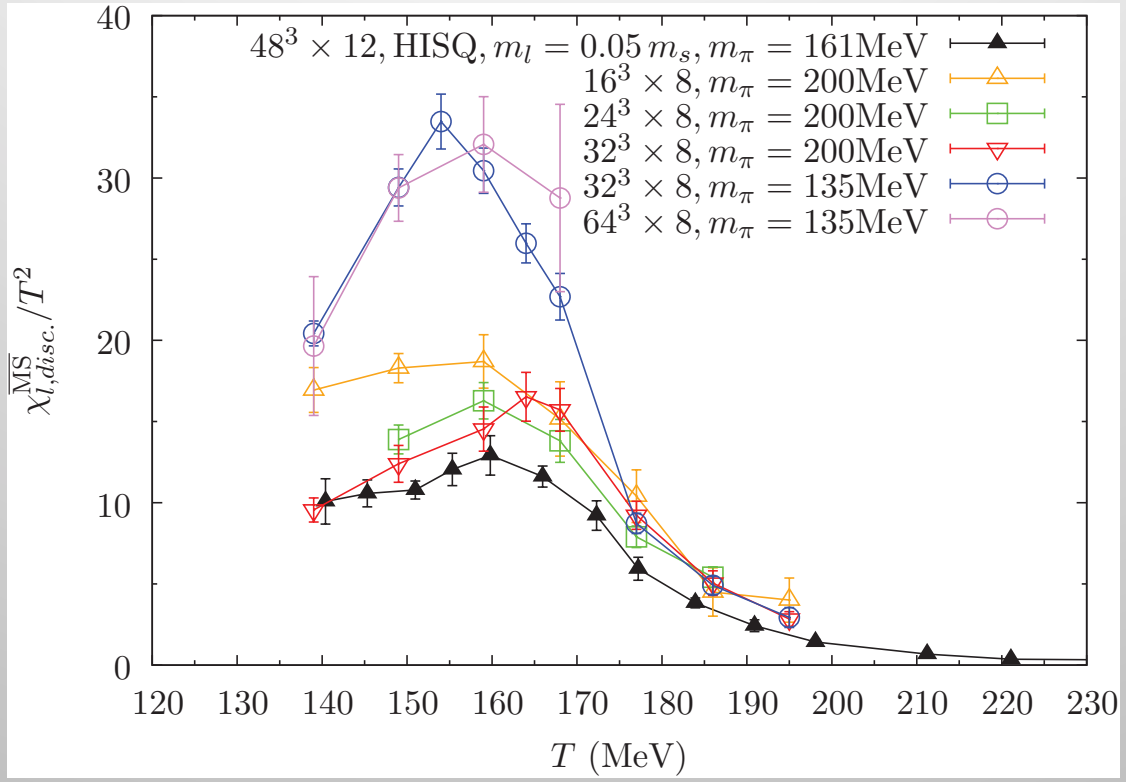
  - clearly peaked at T_χ
  - UV divergence logarithmic and suppressed by m_l^3

$\chi_{l,\mathrm{disc}}$ and T_χ



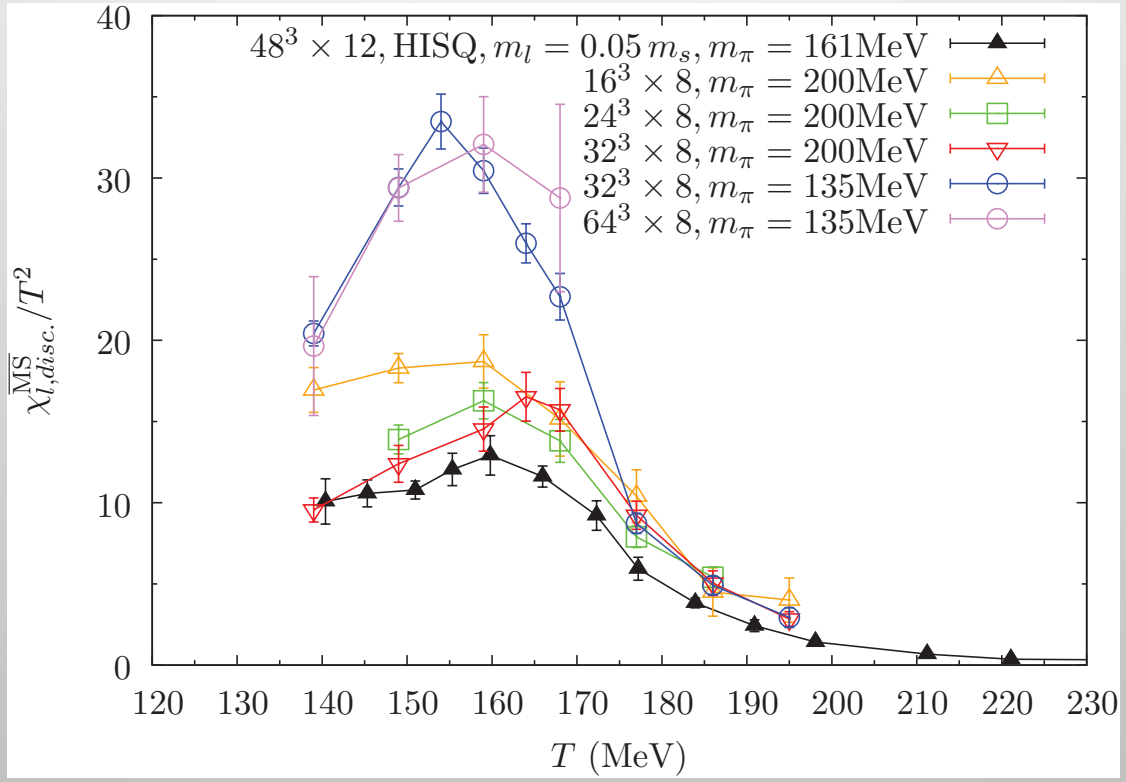
1. T_χ = 155 (1) (8) MeV – good agreement w/ staggered

$\chi_{l,\mathrm{disc}}$ and T_χ



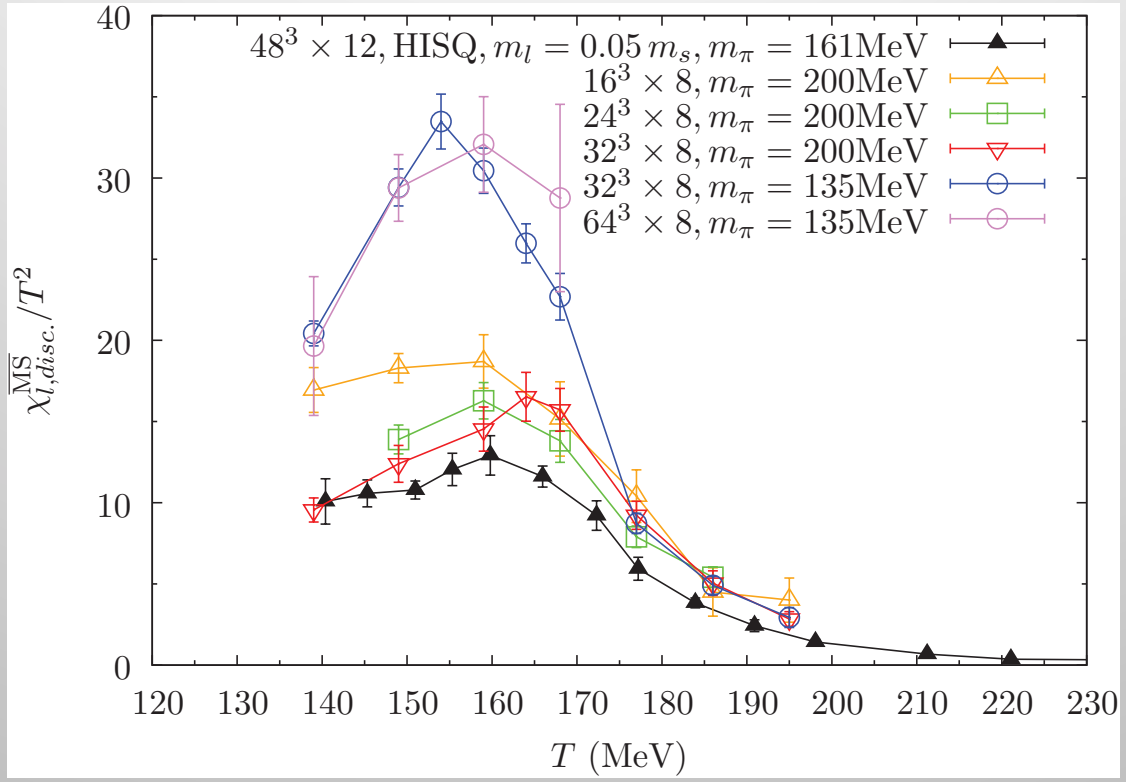
2. 64^3x8 results agree well w/in errors – f.v. effects are minor
   (f.v. effects should ***decrease*** as *T* increases, higher stats needed but ***hard***)

$\chi_{l,\mathrm{disc}}$ and T_χ



3. peak height for M_π = 135 MeV about 2x that for M_π = 200 MeV – agrees with O(4) scaling, but not conclusive

$\chi_{l,\mathrm{disc}}$ and T_χ

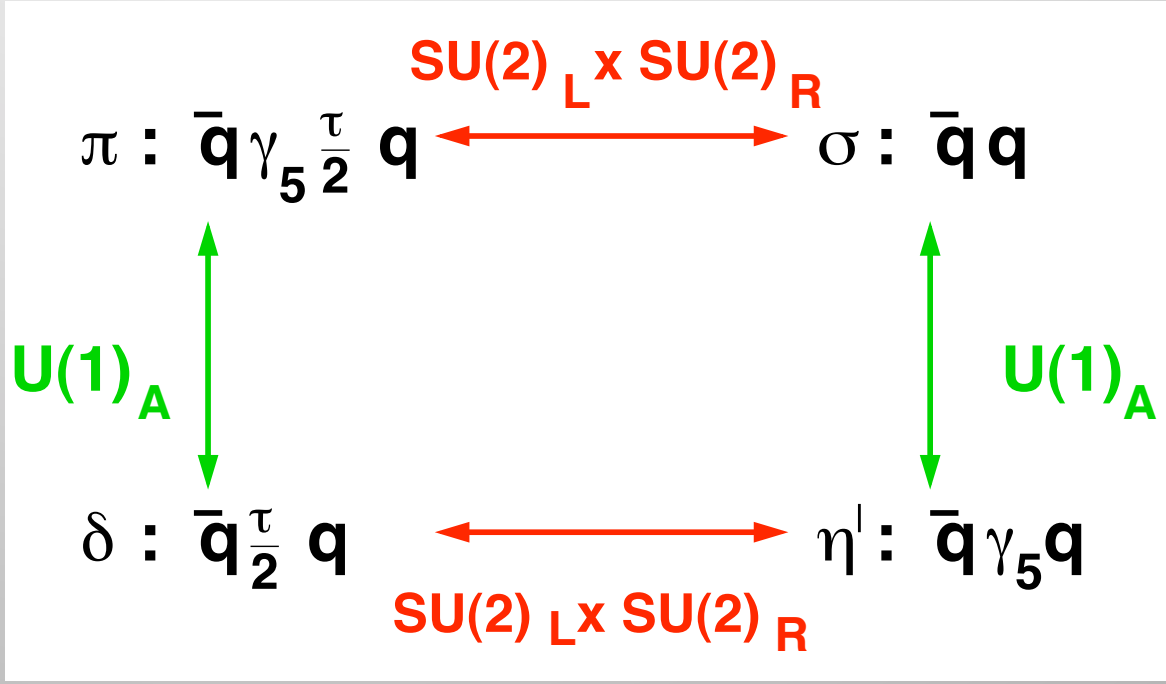


4. N_t=12, M_π=161 MeV HISQ looks like N_t=8, M_π>200 MeV DWF, but need continuum limits for serious comparison

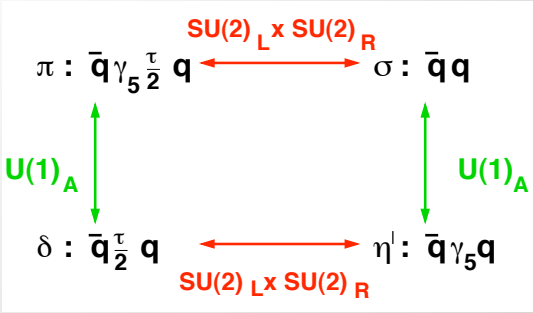
More Chiral Susceptibilities

- pseudo-/scalar, non-/singlet susceptibilities

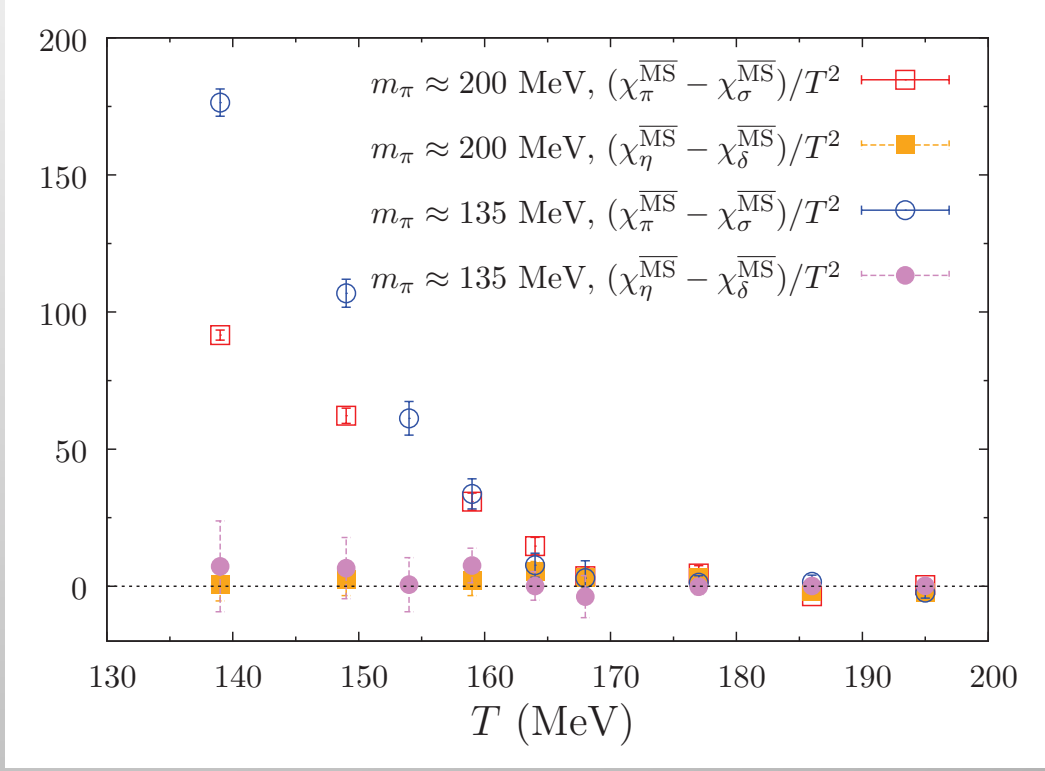
  - more sensitive than condensate
  - probe chiral and $U(1)_A$ symmetries
  - precision boost from random Z_2 wall source
  - renormalized to $\overline{\text{MS}}$ simply using $Z_{m\to\overline{\text{MS}}}$



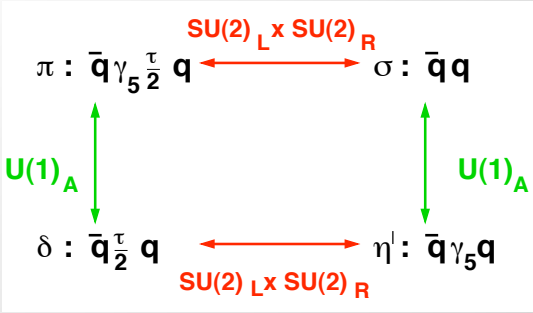
Susceptibilities and T_χ



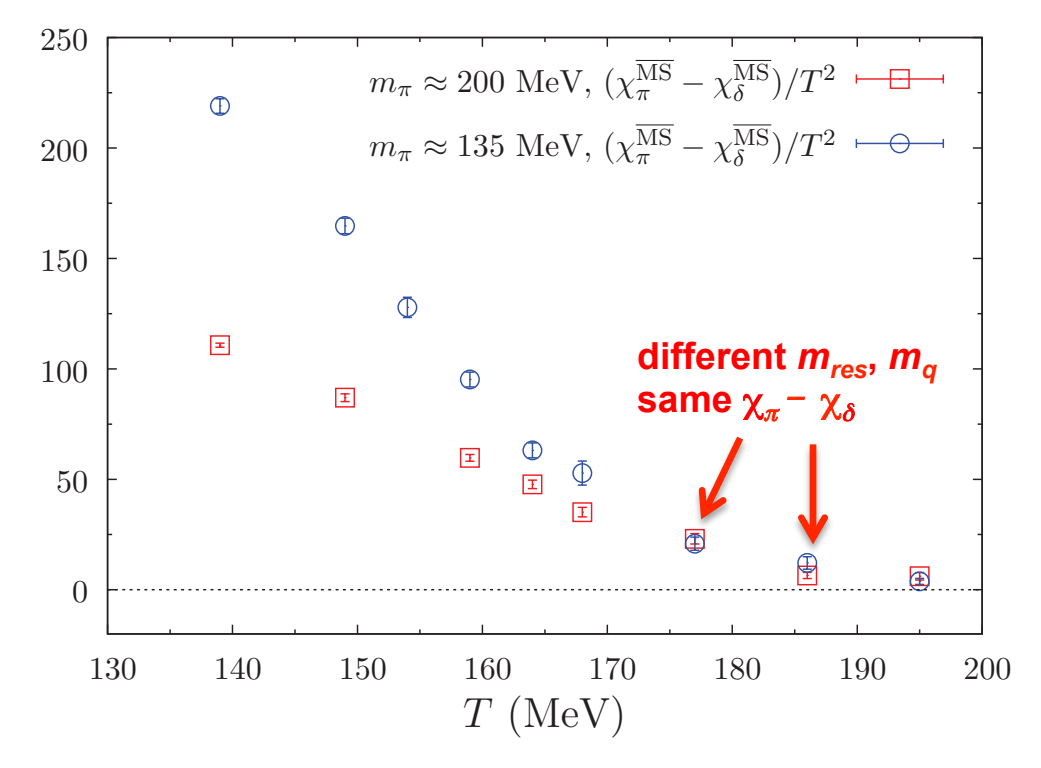
- $\chi_\pi - \chi_\sigma$, $\chi_\eta - \chi_\delta$
  - → zero when chiral symmetry is restored
  - → $\chi_\eta - \chi_\delta$ always near-zero
  - → $\chi_\pi - \chi_\sigma$ near-zero for T > 160 MeV
  - → very little M_π dependence
  - → no significant volume dependence (not shown)



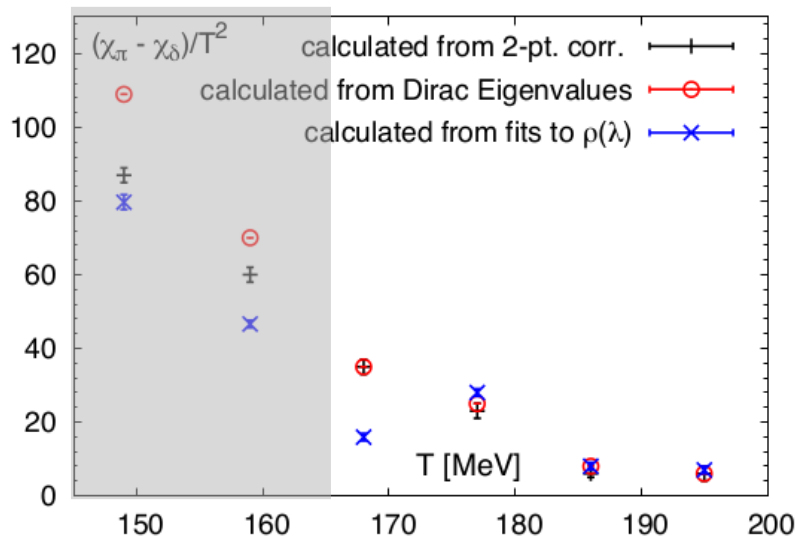
Susceptibilities and $U(1)_A$

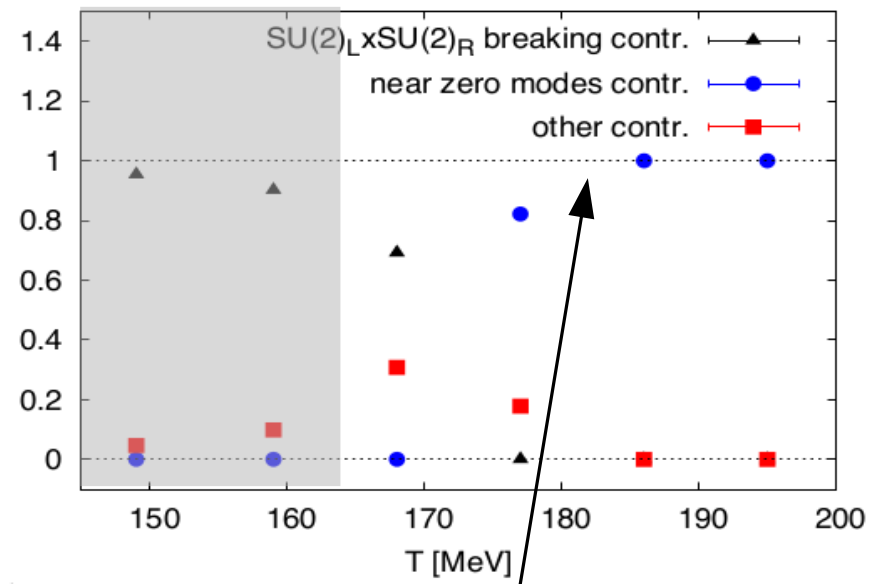


- $\chi_\pi - \chi_\delta$
  - → near-zero when $U(1)_A$ is near-restored
  - → near-zero for T > 185 MeV, well above T_χ
  - → little M_π dependence
  - → no significant volume dependence (not shown)



Axial symmetry breaking from Dirac spectra: DWF





$$\chi_\pi - \chi_\delta = \int_0^\infty d\lambda \, \frac{4m^2\rho(\lambda)}{(m^2+\lambda^2)^2}$$

$$\rho(\lambda \to 0) = a_0 + a_1\lambda + a_2 m^2 \delta(\lambda)$$

$$\chi_\pi - \chi_\delta = a_0 \pi/m + 2a_1 + 2a_2$$

almost the entire contribution to the axial symmetry breaking measure $\chi_\pi - \chi_\delta$ comes from near-zero modes $m^2\delta(\lambda)$ for $T \gtrsim 1.2T_c$

credit: Swagato Mukherjee, XQCD 2014

Cutoff Effects

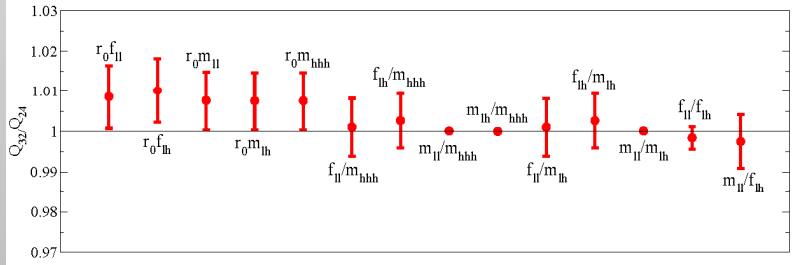
- Published results are all for N_t=8
- Calculation with N_t=12, N_s=64, and one temperature T~T_χ underway -- preliminary results are not yet available
- Zero-T spectrum results suggest cutoff effects of ~5% **<u>but</u>** quantifying cutoff effects at finite T is necessary!

TABLE II. Results at $\beta = 1.633$ and $T = 0$ (in lattice units and MeV) from 50 configurations separated by 10 time units. We use M_Ω to determine the scale. Also listed are the experimental values.

	$1/a$	MeV	Expt.(MeV)
m_π	0.11824(49)	129.53	135
m_K	0.42301(51)	463.39	495
m_Ω	1.5267(55)	1672.45	1672.45
$T = \frac{1}{8a}$	0.125	136.93	
f_π	0.12640(25)	138.47	130.4
f_K	0.14852(48)	162.70	156.1
$m_{\rm res}$	0.002167(16)	—	—

Scaling: 1.73 GeV (24^3) – 2.28 GeV (32^3)

(Chris Kelly)



Ratios of dimensionless combinations of physical quantities computed using $1/a$ = 1.73 and 2.28 GeV.

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Thank you for your attention!

Thanks to the organizers for 15 minutes of fame.

Thanks to all my collaborators for their hard work.

Thanks to LLNL and BNL for HPC resources and support.

Thanks to the DOE and NSF for funding this work.