Symmetries of the Light Hadron Spectrum in High Temperature QCD

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Overview

High-temperature phase of QCD (previous talk by K. Suzuki):

- topological susceptibility consistent with zero (∃ critical quark mass?)
- $U(1)_A$ susceptibility strongly suppressed

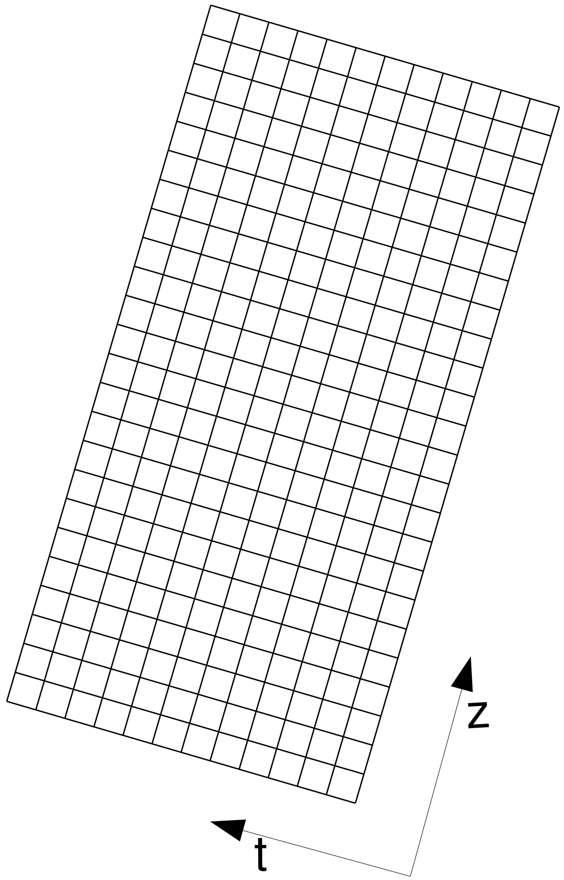
Outline:

- at 1.2 T_c: $U(1)_A$ and $SU(2)_L \times SU(2)_R$ symmetries
  - for mesonic screening spectrum
  - for parity doubling in baryon spectrum
  - for baryonic screening spectrum
- at higher temperature:
  - $SU(2)_{CS}$ chiral spin and SU(4) symmetries

Simulation Setup

- **n_f=2** flavor QCD
- **2.6 GeV** cutoff (1/a)
- **domain wall fermions** with m_{res}< 1 MeV
- quark masses from **m_{ud}= 2.6 MeV** to 26 MeV
- temperatures from **T = 220 MeV** to 1 GeV
  - pseudo-critical temperature: 175 MeV
  - point sources for quark propagators

$N_s^3 \times N_t$	β	T [MeV]	T/T$_c$
$24^3 \times 12$	4.30	220	1.2
$32^3 \times 12$	4.30	220	1.2
$40^3 \times 12$	4.30	220	1.2
$32^3 \times 8$	4.30	330	1.8
$32^3 \times 8$	4.37	220	2.2
$32^3 \times 6$	4.30	440	2.5
$32^3 \times 8$	4.50	480	2.7
$32^3 \times 4$	4.30	660	3.8
$32^3 \times 4$	4.50	960	5.5



Chiral Symmetries at 1.2 T_c

Meson Operators

- local isovector operators: $O_\Gamma(x) = \bar{q}(x)(\vec{\tau} \otimes \Gamma)q(x)$

$$\langle O(t)\bar{O}(0)\rangle \quad \sim \quad e^{-mt} + e^{-m(N_t - t)}$$

- extract effective mass: $m_{eff}(t) = \ln\left|\frac{C(t)}{C(t+1)}\right|$

(or cosh to respect periodicity)

- for screening spectrum: $t \to z, \quad C(n_z) = \sum_{n_x, n_y, n_t} \langle O(n_x, n_y, n_z, n_t)\bar{O}(\mathbf{0})\rangle$

Chiral-Parity Group Rep.	Γ	Abbreviation	Symmetries
$(\frac{1}{2}, \frac{1}{2})_a$	γ_5	PS	$U(1)_A$
$(\frac{1}{2}, \frac{1}{2})_b$	$\mathbb{1}$	S	
$[(0,1)+(1,0)]_a$	$\gamma_k\gamma_5$	$\mathbf{A}$	$SU(2)_A$
$[(0,1)+(1,0)]_a$	γ_k	$\mathbf{V}$	
$(\frac{1}{2}, \frac{1}{2})_a$	$\gamma_k\gamma_3$	$\mathbf{T}$	$U(1)_A$
$(\frac{1}{2}, \frac{1}{2})_b$	$\gamma_k\gamma_3\gamma_5$	$\mathbf{X}$	

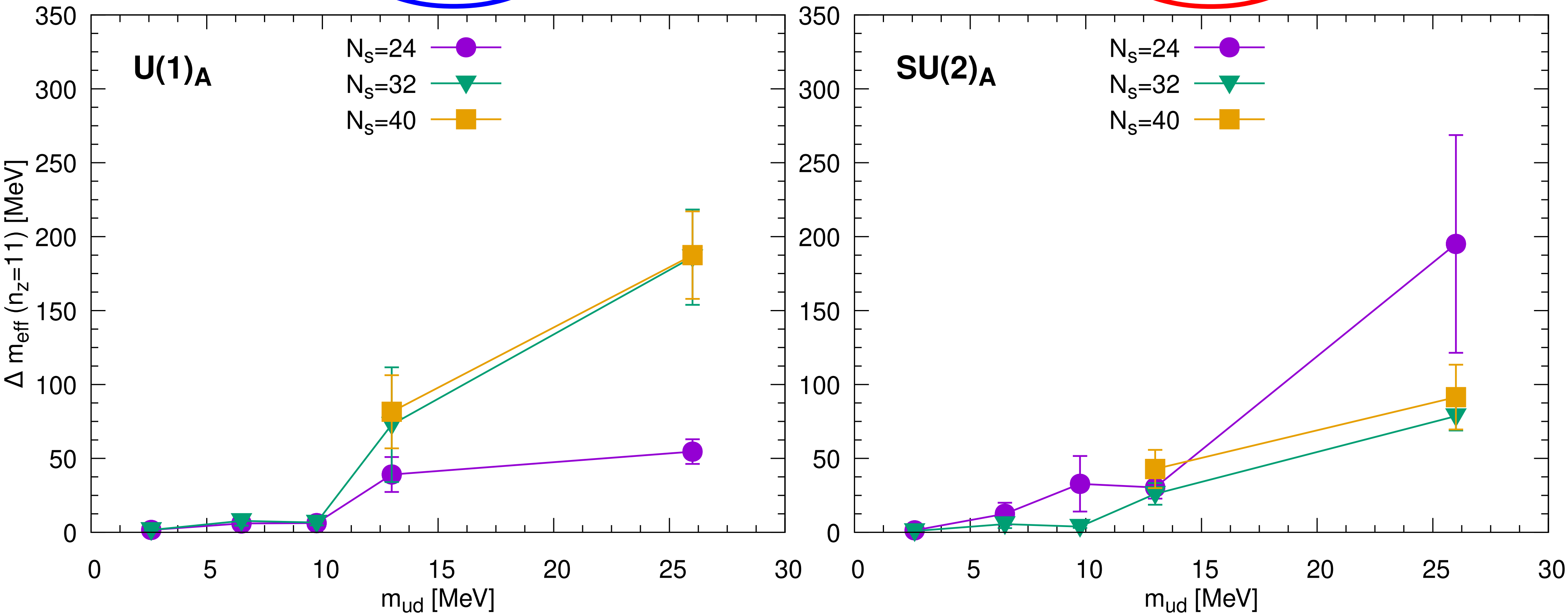
Chiral Symmetry of the Mesons Spectrum

@ 1.2 T_c

→ *extract symmetry violation by comparing* ***screening masses*** *of related interpolating fields*

$$U(1)_A: \quad \Delta m_{eff} = |m_{eff}^{PS} - m_{eff}^{S}|$$

$$PS \longleftarrow e^{i(\gamma_5 \otimes \mathbb{1})\vec{\theta}} \longrightarrow S \qquad V_x \longleftarrow e^{i(\gamma_5 \otimes \vec{\tau})\vec{\theta}} \longrightarrow A_x$$



Baryon Operators

- local nucleon operators (isospin=1/2, spin=1/2)
- parity projection: $N_\pm = \frac{(1 \pm \gamma_4)}{2} N$

$$\langle N^\pm(t)\bar{N}^\pm(0)\rangle \quad \sim \quad e^{-m_\pm t} + e^{-m_\mp (N_t - t)}$$

positive parity forward

negative parity backward

- for screening spectrum: $t \to z, \quad C(n_z) = \sum_{n_x, n_y, n_t} e^{i n_t \omega_0} \langle N^\pm(n_x, n_y, n_z, n_t)\bar{N}^\pm(\mathbf{0})\rangle$

Chiral-Parity Group Rep.	Operator	Abbreviation	Symmetries
$[(0,\frac{1}{2}) + (\frac{1}{2},0)]_a$	$(\tilde{q}q)q$	N_1	$U(1)_A$
$[(0,\frac{1}{2}) + (\frac{1}{2},0)]_b$	$(\tilde{q}\gamma_5 q)\gamma_5 q$	N_2	
$(\frac{1}{2},1) + (1,\frac{1}{2})$	$(\tilde{q}\gamma_\mu q)\gamma^\mu q$	N_3	$SU(2)_A$
$(\frac{1}{2},1) + (1,\frac{1}{2})$	$(\tilde{q}\gamma_\mu \gamma_5 \tau^i q)\gamma^\mu \gamma_5 \tau^i q$	N_4	

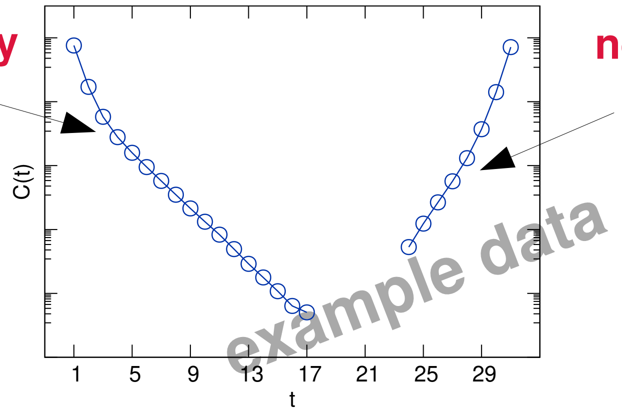
$\tilde{q} = q^T C \gamma_5 (i\tau_2)$

Parity Doubling of Nucleons

→ *extract symmetry violation by comparing*
positive and negative parity states *of same interpolating field*

@ 1.2 T_c

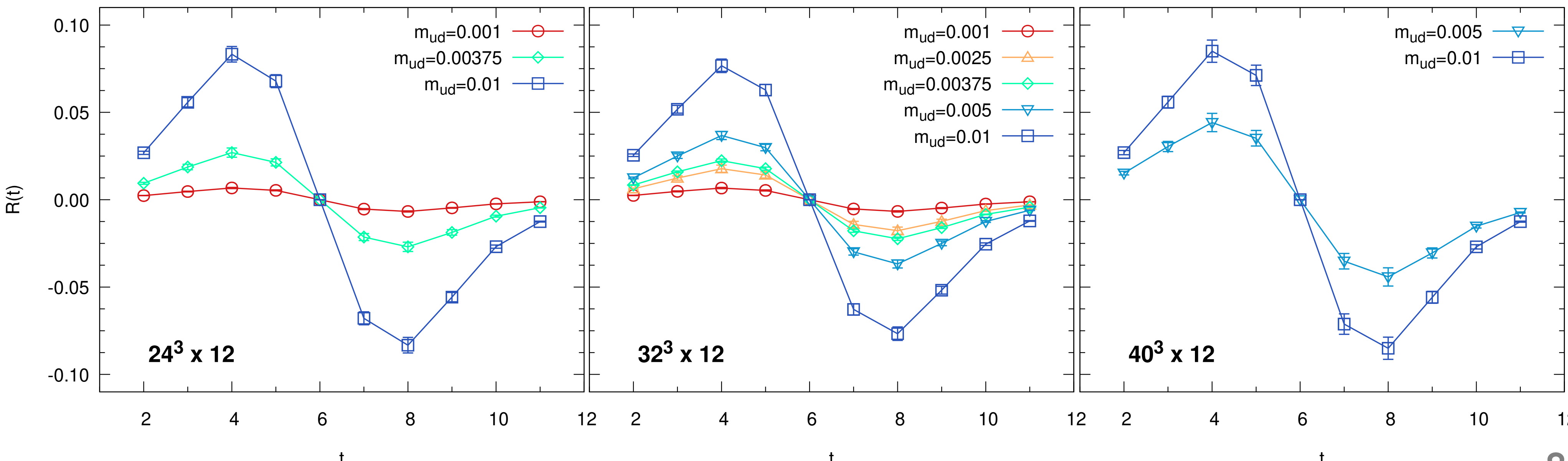
positive parity forward



negative parity backward

'R-parameter':

$$R(t) = \frac{N_1(t) - N_1(N_t - t)}{N_1(t) + N_1(N_t - t)}$$



compare e.g. S.Datta *et al*, JHEP 1302 (2013) 145; G.Aarts *et al*, JHEP 1706 (2017) 34

Parity Doubling of Nucleons

→ *extract symmetry violation by comparing*
positive and negative parity states *of same interpolating field*

@ 1.2 T_c

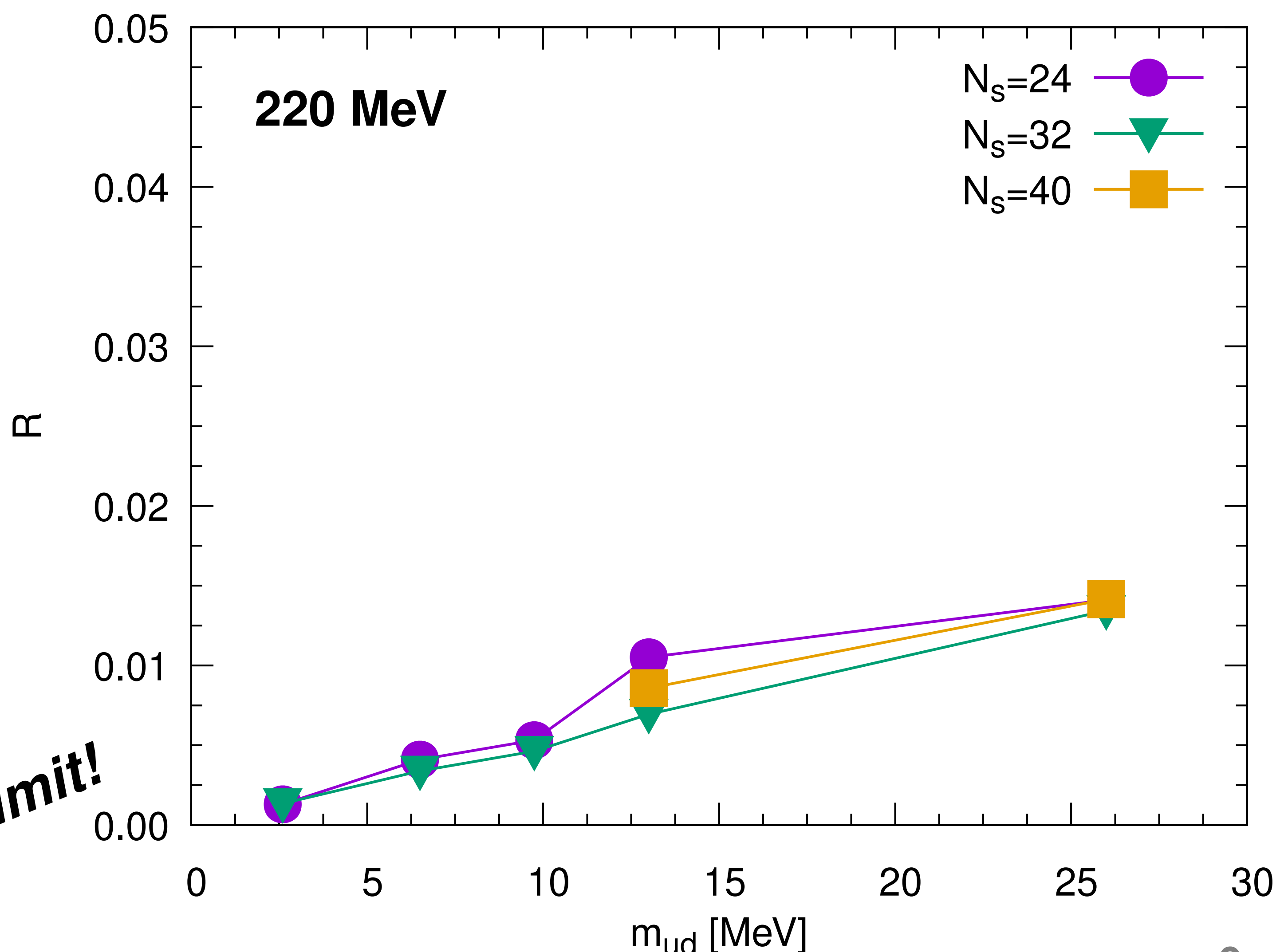
integrated *'R-parameter'*:

$$R = \frac{\sum_{t=1}^{N_t/2} R(t)/\sigma^2(t)}{\sum_{t=1}^{N_t/2} 1/\sigma^2(t)}$$

$R \neq 0$
no parity doubling

$R = 0$
parity doubling

in chiral limit!



compare e.g. S.Datta *et al*, JHEP 1302 (2013) 145; G.Aarts *et al*, JHEP 1706 (2017) 34

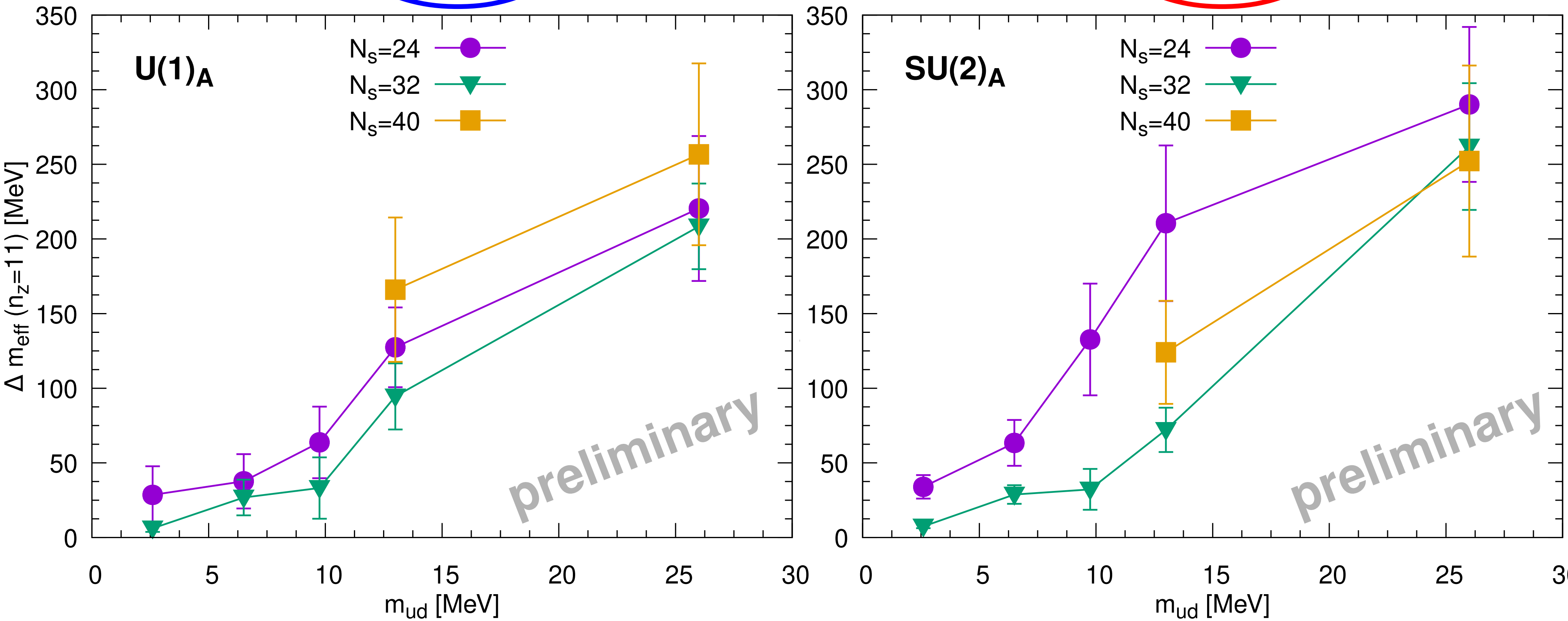
Chiral Symmetry of the Baryon Spectrum

@ 1.2 T_c

→ *extract symmetry violation by comparing* ***screening masses*** *of related interpolating fields*

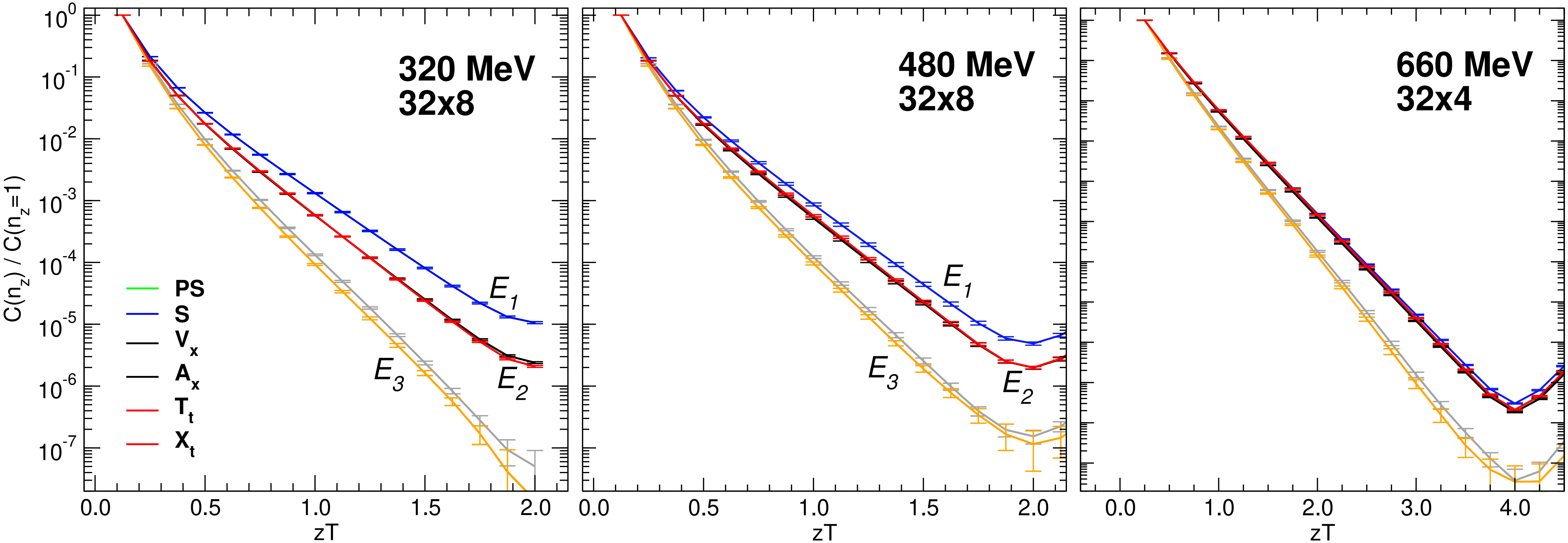
$$U(1)_A: \quad \Delta m_{eff} = |m_{eff}^{N_1^+} - m_{eff}^{N_2^+}|$$

$$N_1^+ \xleftarrow{\quad} e^{i(\gamma_5 \otimes \mathbb{1})\vec{\theta}} \xrightarrow{\quad} N_2^+ \qquad\qquad N_3^+ \xleftarrow{\quad} e^{i(\gamma_5 \otimes \vec{\tau})\vec{\theta}} \xrightarrow{\quad} N_4^+$$



Symmetries at Higher Temperature

Temperature Evolution of Meson Spectrum



states of different chirality connected by **chiral spin**:

$$\mathrm{SU}(2)_{CS}$$

$$\{\gamma_2, -i\gamma_5\gamma_2, \gamma_5\} \quad \Rightarrow \quad A_x \leftrightarrow T_t \leftrightarrow X_t$$

minimal group containing **chiral spin** and **chiral symmetry**:

$$\mathrm{SU}(4)$$

$$V_x \leftrightarrow T_t \leftrightarrow X_t \leftrightarrow A_x \qquad \leftarrow E_2$$

$$V_t \leftrightarrow T_x \leftrightarrow X_x \leftrightarrow A_t \qquad \leftarrow E_3$$

L.Glozman and M.Pak, Phys.Rev. D92 (2015) no.1, 016001
Phys.Rev. D96 (2017) 094501 [arxiv:1707.01881]

Is High Temperature QCD *'more'* symmetric?

E_1, E_2, E_3 *groups show **multiplet** structure..*

define '***kappa'*** parameter

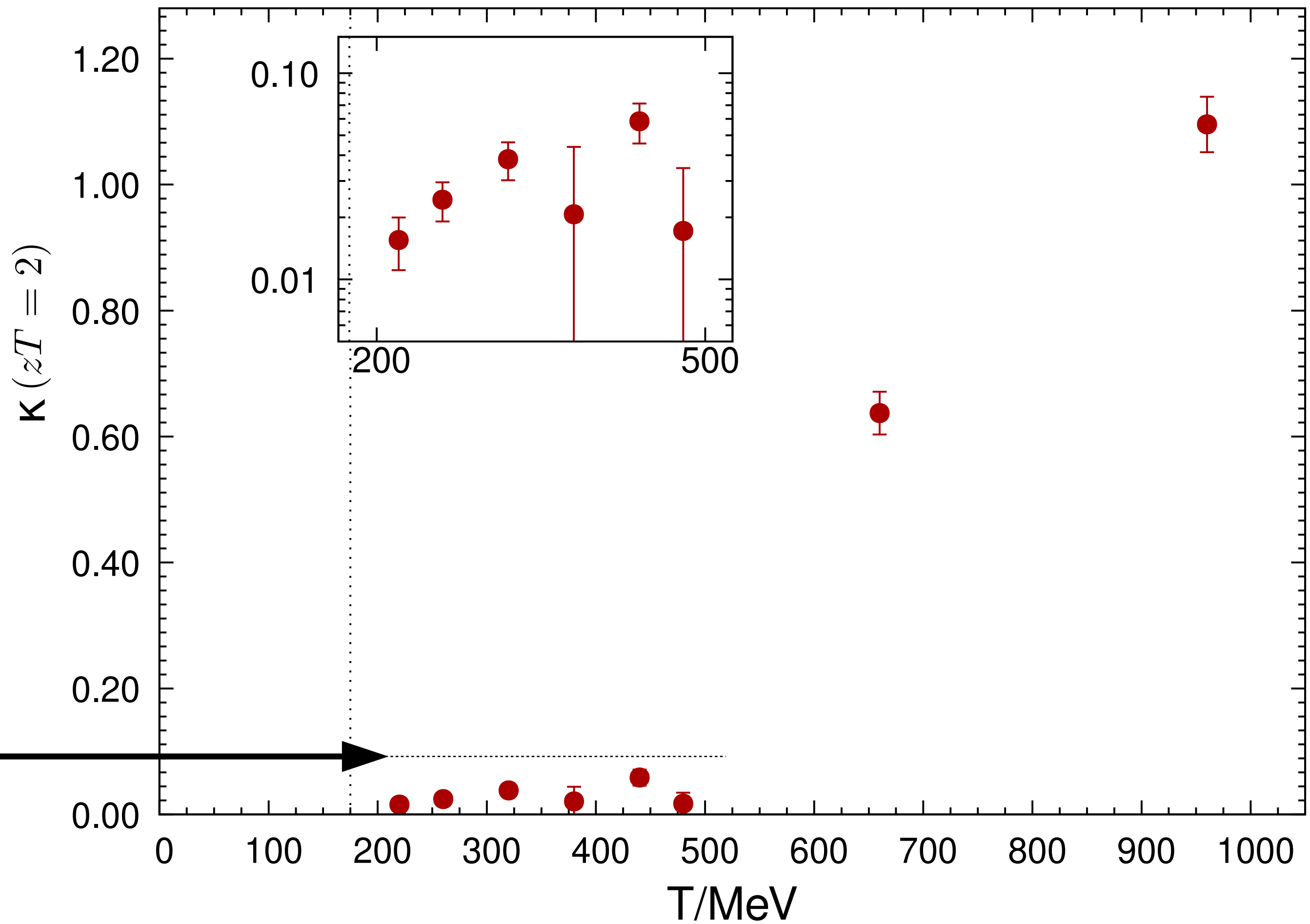
$$\kappa = \frac{|C_{A_x} - C_{T_t}|}{|C_{A_x} - C_S|}$$

as intuitive symmetry measure!

(distance ***within*** a multiplet relative to the distance ***between*** multiplets)

temperature range

$T \sim 220 - 500 \text{ MeV}$



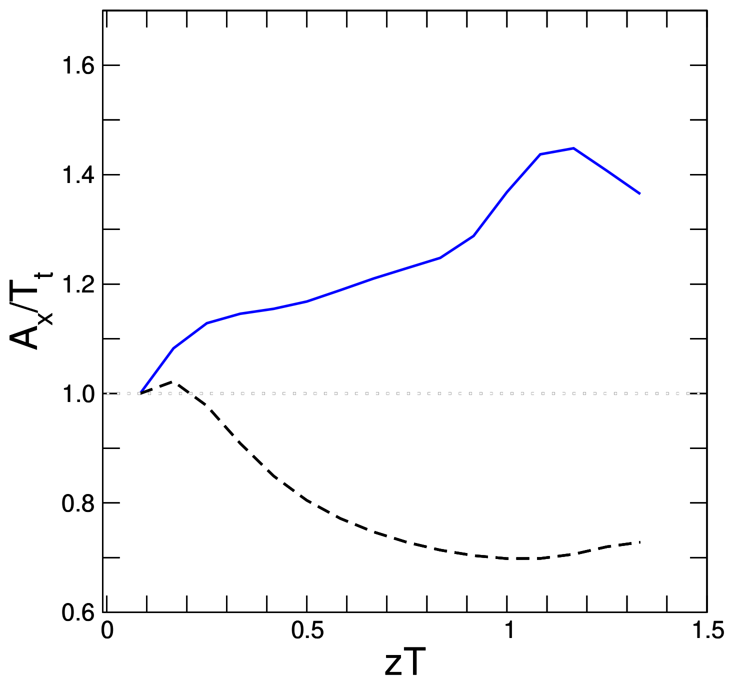
Chiral Spin and the Lagrangian

$$\Psi \xrightarrow{\mathrm{SU}(2)_{CS}} e^{i\vec{\Sigma}\vec{\theta}/2}\Psi \qquad \vec{\Sigma} = \{\gamma_k, -i\gamma_5\gamma_k, \gamma_5\}$$

free, massless fermions: $\mathcal{L} = \bar{\Psi} i \partial\!\!\!/ \Psi$

covariant derivative: $D_\mu = \partial_\mu - igA_\mu$

interacting, massless fermions: $\mathcal{L} = \bar{\Psi} i D\!\!\!\!/ \Psi = \bar{\Psi} i\gamma^0 D_0 \Psi + \bar{\Psi} i\gamma^i D_i \Psi$

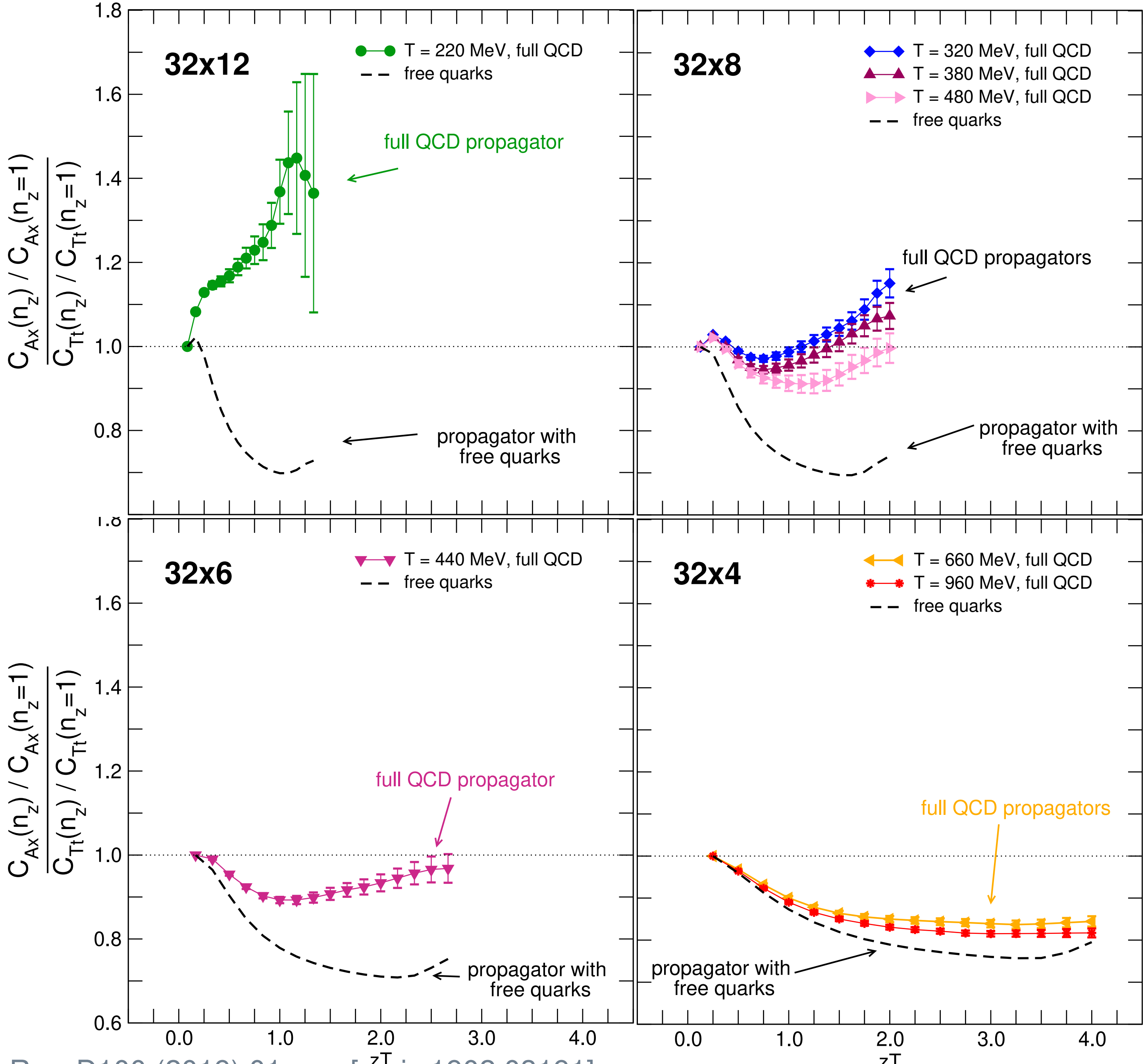


- **kinetic** term breaks chiral spin
- **electric** term is invariant
- **magnetic** term breaks chiral spin

A *and* ***T*** *mix under chiral spin transformations:*
use ratio to measure breaking ***within*** *multiplet!*

Phys.Rev. D100 (2019) 01xxxx [arxiv:1902.03191]

Interaction within SU(4) multiplets



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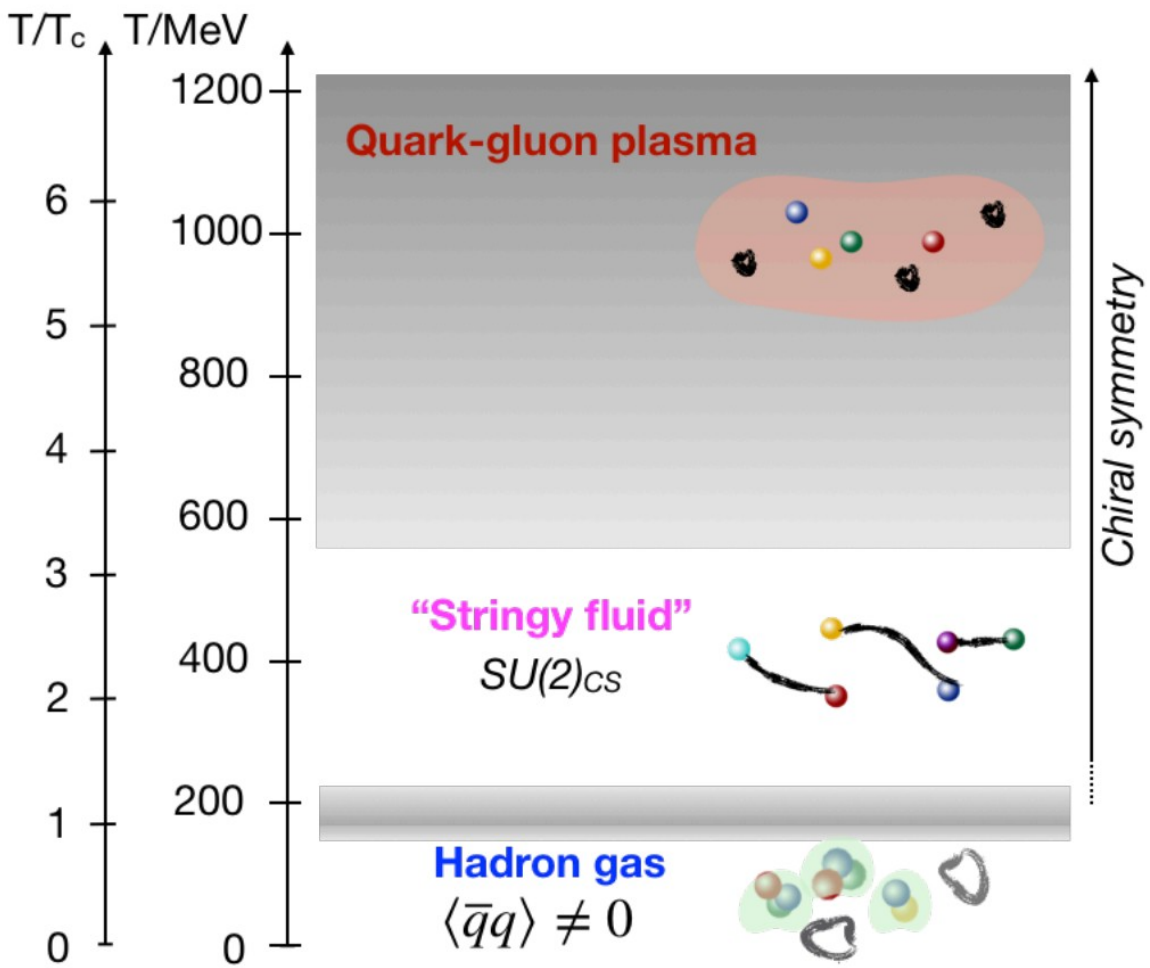
Sketch of a ‘*new*’ Phase Diagram



strongly interacting matter

between

chiral transition

and

weakly interacting **QGP**

Chemical potential does not change picture:

$$S = \int_0^{1/T} \int d^3x \;\; \bar{\Psi}[\gamma_\mu D_\mu + \mu\gamma_4]\Psi$$

*‘**stringy fluid**’ regime at experimental accessible temperatures!*

Phys.Rev. D100 (2019) 01xxxx [arxiv:1902.03191]

Conclusions

Above chiral transition at 220 MeV:

- **$SU(2)_L$ x $SU(2)_R$** restored
- **$U(1)_A$** effectively restored
- **parity doubling** for baryons

At temperatures up to 500 MeV:

- QCD matter approximately **SU(4)** symmetric
- favors **color-electric** degrees of freedom
- chiral symmetry restoration ≠ deconfinement