Polyakov loop and its correlator

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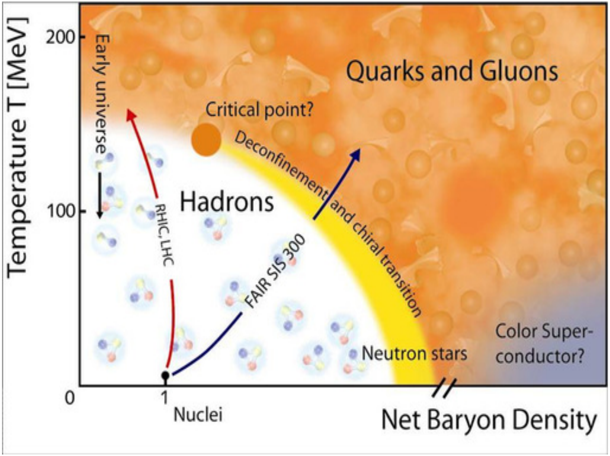
Leibnitz

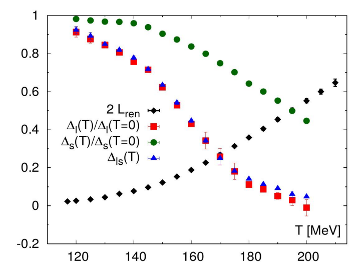
- Overview & introduction
- Polyakov loop
- Polyakov loop correlator
- Summary & outlook

QCD phase diagram



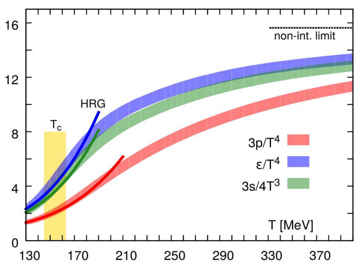
Finite temperature results from lattice QCD

Chiral restoration and deconfinement



A. Bazavov, P. Petreczky, PRD87 (2013) 094505

Equation of State



HotQCD, Bazavov et al, PRD90 (2014) 094503

Pseudocritical temperature:

$$T_c = (154 \pm 9)\,\mathrm{MeV}$$

HotQCD, Bazavov et al, PRD85 (2012) 054503

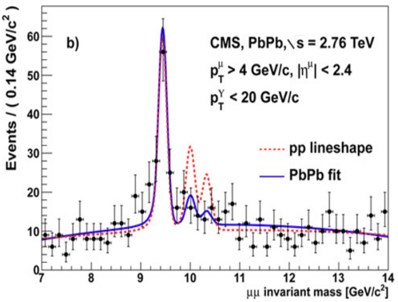
Increase of entropy: deconfinement

Hadron resonance gas fits for low T

Weakly interacting limit not reached

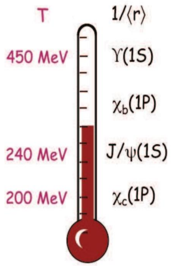
Finite temperature results from heavy ion collisions

Υ Data from CMS



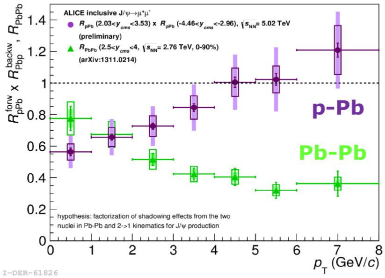
In-medium suppression of quarkonia

- Matsui & Satz in 1986 (PLB 178)
- Dissolution of quarkonia indicates temperature of QGP



Finite temperature results from heavy ion collisions

J/ψ Data from ALICE



In-medium suppression of quarkonia

- Matsui & Satz in 1986 (PLB 178)
- Dissolution of quarkonia indicates temperature of QGP
- Not exclusively hot medium effects in heavy ion collisions . . .
- Different models – but none is excluded by experimental results

Quarkonia in static approximation

- Temperature in lattice QCD: $T(\beta, N_\tau) = 1/(a(\beta)N_\tau)$
- Static limit of heavy quarks Q: Polyakov lines

$$W_0(\vec{x}) = \prod_{x_0=1}^{N_\tau} U_0(x_0, \vec{x})$$

- Single static quark Q: renormalised Polyakov loop

$$L^{\mathrm{ren}}(T; N_\tau) = e^{-N_\tau c_Q} \left\langle \frac{1}{N_c} \mathrm{Tr}\, W_0(\vec{x}) \right\rangle,$$

vanishes for pure Yang-Mills vacuum, non-zero due to sea quarks

- Static $Q\bar{Q}$ at distance r: renormalised Polyakov loop correlator

$$P_c^{\mathrm{ren}}(T, r; N_\tau) = e^{-2N_\tau c_Q} \left\langle \frac{1}{N_c^2} \mathrm{Tr}\, W_0(\vec{x})\, \mathrm{Tr}\, W_0^\dagger(\vec{x} + \vec{r}) \right\rangle,$$

spectral features of $P_c^{\mathrm{ren}}(T, r)$ correspond to bound states of $Q\bar{Q}$

Polyakov loop (correlator) and free energy

- Free energy of a single static quark Q: renormalised Polyakov loop

$$L^{\mathrm{ren}}(T) = \exp\left[-F_Q/T\right],$$

- Free energy of static $Q\bar{Q}$ pair at distance r: Polyakov loop correlator

$$P_c^{\mathrm{ren}}(T,r) = \exp\left[-F_{Q\bar{Q}}/T\right],$$

  contains arbitrary colour configurations

- Colour singlet part (ground state for $T=0$): singlet free energy

$$\exp\left[-F_s/T\right] = e^{-2N_\tau c_Q} \left\langle \frac{1}{N_c} \mathrm{Tr} \left[W_0(\vec{x})\; W_0^\dagger(\vec{x}+\vec{r})\right]\right\rangle ,$$

  not gauge invariant, have to fix Coulomb gauge

- Alternative gauge-invariant approaches with cyclic Wilson loop

$$W_c^{\mathrm{bare}}(T,r;N_\tau) = \left\langle \frac{1}{N_c} \mathrm{Tr} \left[W_0(\vec{x})\, \mathrm{Tr}\, \mathcal{W}_{\vec{r}}(\vec{x}+\vec{r},N_\tau)\, W_0^\dagger(\vec{x}+\vec{r}) \mathcal{W}_{\vec{r}}^\dagger(\vec{x}+\vec{r},0)\right]\right\rangle$$

  open questions: path dependence, renormalisation, interpretation, ...

Target of our study

- Deconfinement aspect of the QCD crossover
- Screening radii and screening masses in thermal medium
- Comparison between lattice and weak coupling for sufficiently high T
- Non-perturbative $Q\bar{Q}$ potential with remnants of confining forces
- Understand cyclic Wilson loop

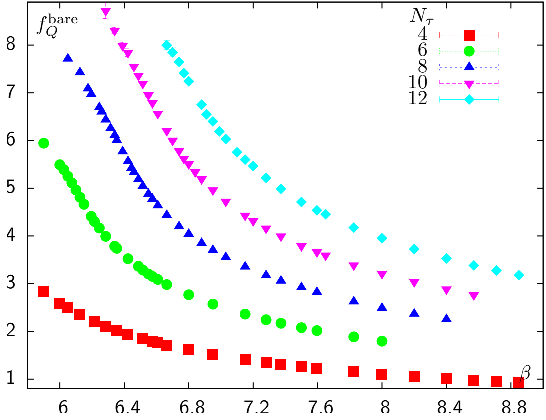
Our lattice setup

- HISQ/Tree action, 2+1 flavours: $N_\tau = 4, 6, 8, 10, 12$, aspect ratio 4
- Temperature range $115\,\mathrm{MeV} \lesssim T \lesssim 2.9\,\mathrm{GeV}$, almost up to $T \lesssim 1\,\mathrm{GeV}$ with five different N_τ
- Physical strange quark, almost physical light quarks ($M_\pi \approx 160\,\mathrm{MeV}$)

Polyakov loop

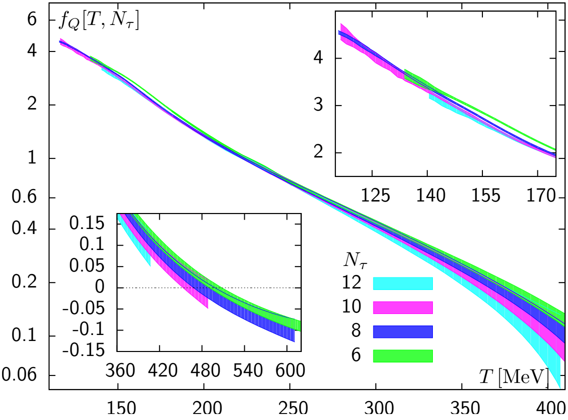
- Single quark free energy F_Q
- Access to higher temperatures through direct renormalisation
- Single quark entropy S_Q

Single quark free energy F_Q



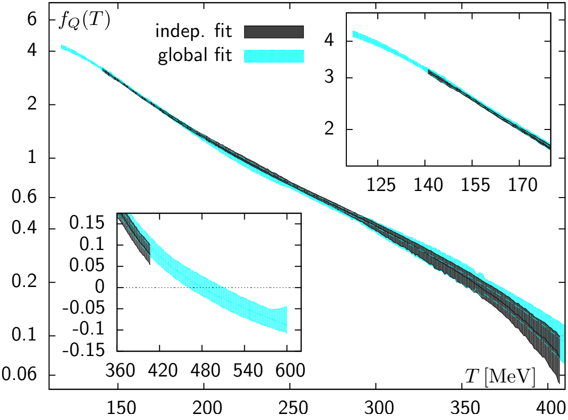
- Bare free energy: $f_Q^{\mathrm{bare}} = -\log L^{\mathrm{bare}}$

Single quark free energy F_Q



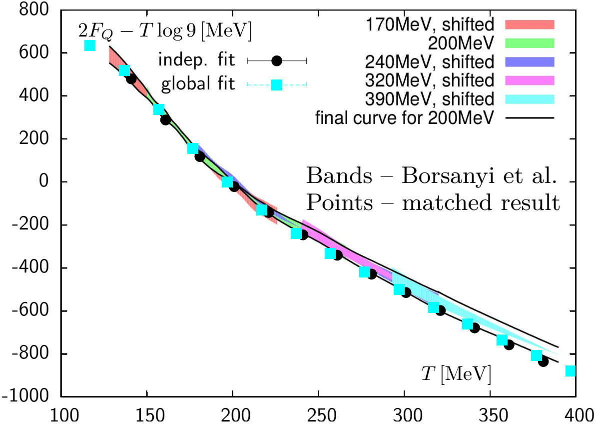
- Renormalised free energy: $F_Q = T(f_Q^{\text{bare}} + N_\tau c_Q)$
- c_Q from QQ procedure limited to $\beta \leq 7.825$

Single quark free energy F_Q



- Independent continuum extrapolation for $140\,\mathrm{MeV} \lesssim T \lesssim 407\,\mathrm{MeV}$
- Extend temperature range with global fit for $117\,\mathrm{MeV} \lesssim T \lesssim 600\,\mathrm{MeV}$

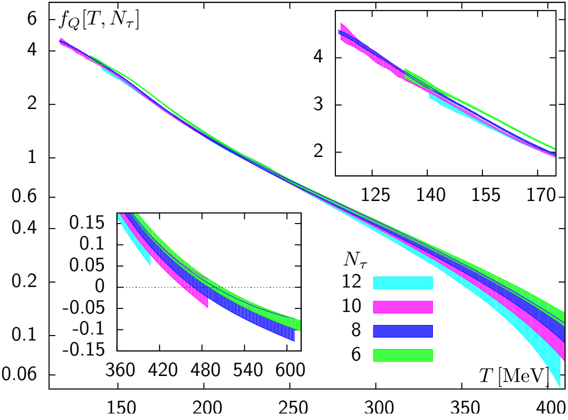
Comparison to recent results



- BW coll. [Borsanyi et al., JHEP **1504** (2015) 138]: smeared Polyakov loops
- Set $F_Q(T, N_\tau)$ to zero for $T = 200$ MeV for all N_τ – cutoff effects?

Access to higher temperatures through direct renormalisation

PRELIMINARY!

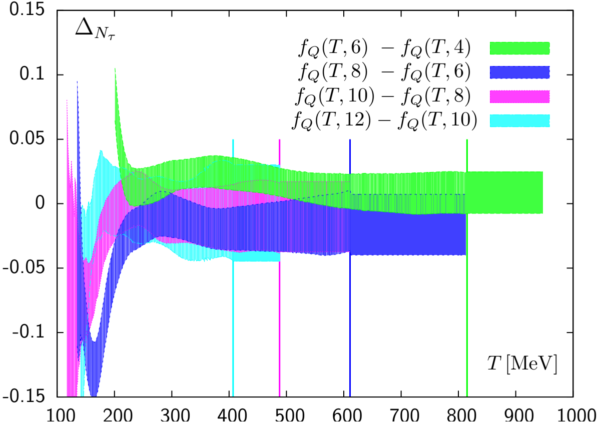


- Direct renormalisation procedure [Gupta et. al., PRD77 (2008) 034503]

$$c_Q(\beta_2) = \frac{1}{N_{\tau_2}} \left\{ f_Q^{\text{bare}}(T(\beta_1, N_{\tau_1}), N_{\tau_1}) - f_Q^{\text{bare}}(T(\beta_2, N_{\tau_2}), N_{\tau_2}) + N_{\tau_1} c_Q(\beta_1) \right\}$$

Access to higher temperatures through direct renormalisation

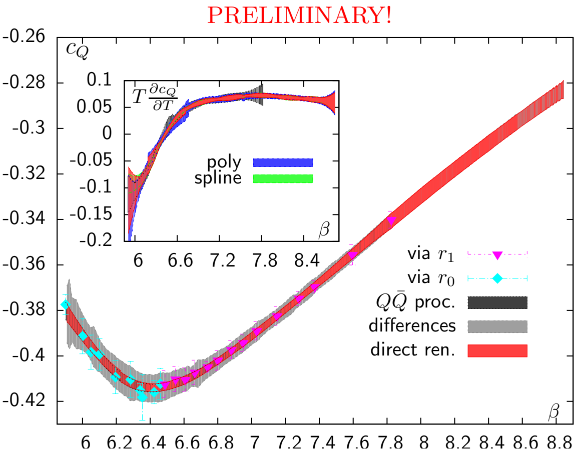
PRELIMINARY!



- Caveat: first subtract residual cutoff effects $\Delta_{N_\tau} = f_Q(T) - f_Q(T, N_\tau)$

$$c_Q(\beta_2) = \frac{1}{N_{\tau_2}} \left\{ f_Q^{\text{bare}}(T, N_{\tau_1}) - f_Q^{\text{bare}}(T, N_{\tau_2}) + \Delta_{N_{\tau_2}} - \Delta_{N_{\tau_1}} + N_{\tau_1} c_Q(\beta_1) \right\}$$

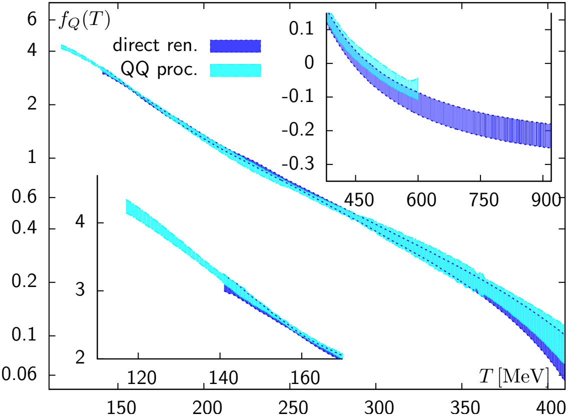
Access to higher temperatures through direct renormalisation



- Obtain $c_Q(\beta_2)$ for all available sets $(N_{\tau_1}, N_{\tau_2}, \beta_1)$
- Check for residual cutoff effects, then average $c_Q(\beta_2)$

Access to higher temperatures through direct renormalisation

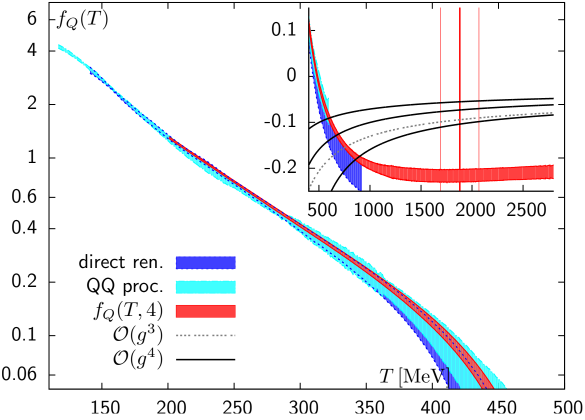
PRELIMINARY!



- Independent continuum extrapolation possible for $T \lesssim 920\,\mathrm{MeV}$
- Global fit will extend range to $117\,\mathrm{MeV} \lesssim T \lesssim 970\,\mathrm{MeV}$

Access to higher temperatures through direct renormalisation

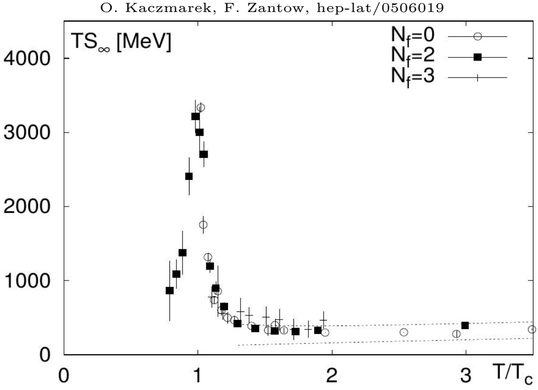
PRELIMINARY!



- Free energy beyond $T \lesssim 1\,\text{GeV}$ currently only with $N_\tau = 4$
- $f_Q(T,4)$ consistent with going through minimum for $T \sim 10\,T_c$

Single quark entropy S_Q

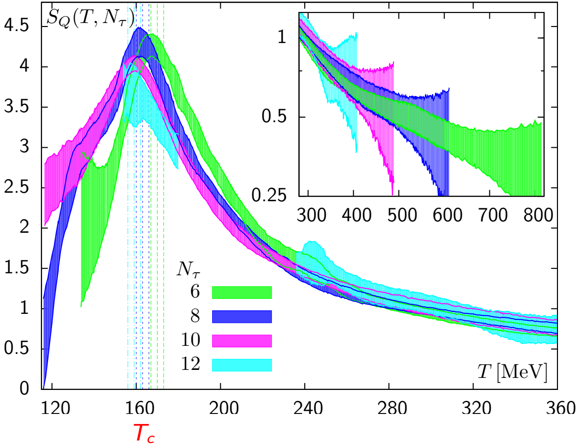
PRELIMINARY!



- Entropy $S_Q = -\left(\frac{\partial F_Q}{\partial T}\right)_V$; not defined for $N_f = 0$ and $T < T_c$
- Center symmetry broken by sea quarks: $S_Q > 0$ for $T < T_c$ and $N_f > 0$

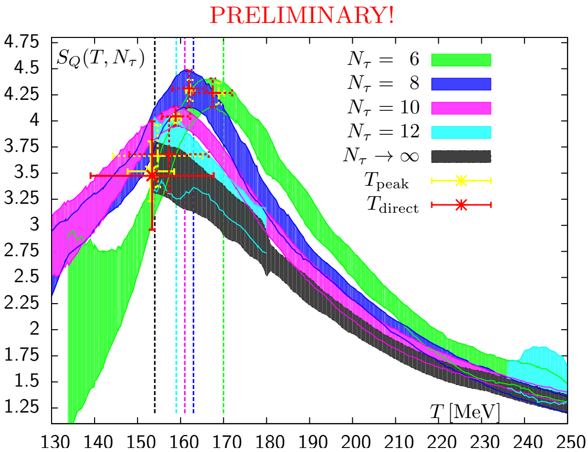
Single quark entropy S_Q

PRELIMINARY!



- $S_Q(T, N_\tau) = -\left(1 + T\frac{\partial}{\partial T}\right)\left(f_Q^{\text{bare}} + N_\tau c_Q\right)$, correlated error analysis
- Derivative from interpolations (model dependence, data quality issues)
- Peak has N_τ dependence similar to chiral crossover temperature T_c

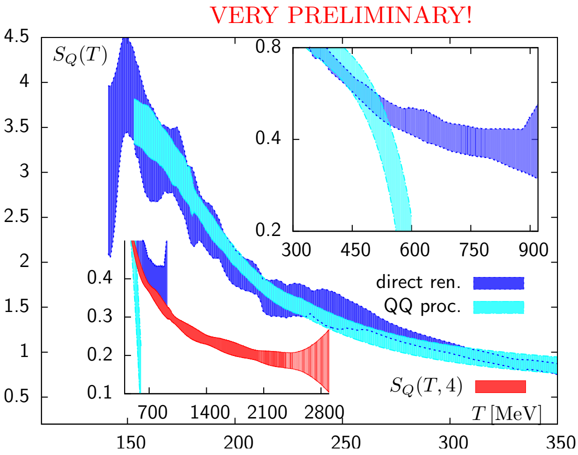
Single quark entropy S_Q



$T_c = 154(9)$ MeV

- Determine peak temperature by eye (T_{direct}) or with fits (T_{peak})
- Continuum limit: $T_{\text{direct}} = 153.4(14.3)$ MeV, $T_{\text{peak}} = 153.1(5.4)$ MeV

Single quark entropy S_Q

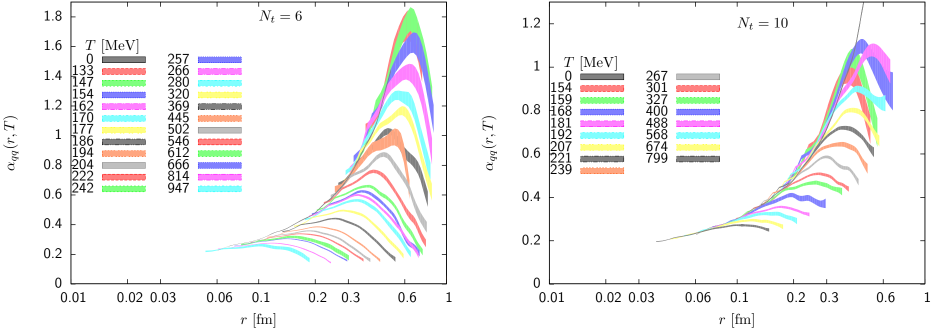


- Direct renormalisation: $S_Q(T)$ decreases logarithmically
- $S_Q(T, N_\tau)$ for $T \gtrsim 1\,\mathrm{GeV}$ only with $N_\tau = 4$: approaches constant?

Polyakov loop correlator

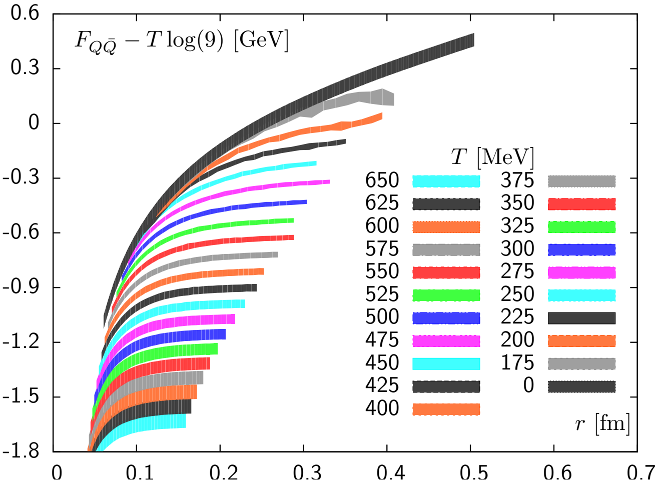
- Remnant confining regime
- Polyakov loop correlator (resp. $F_{Q\bar{Q}}$)
- Singlet free energy

Effective coupling α_{qq}



- Effective coupling $\alpha_{qq} = 3/4r^2 \frac{\partial E(r)}{\partial r}$, $E(r) = \{F_1(T,r), V_0(r)\}$
- Motivated by string potential $V(r) = c + \frac{C_F \alpha_s}{r} + \sigma r$
- $\max \alpha_{qq} \gtrsim 0.5$ for $T \lesssim 300$ MeV indicates strongly coupled plasma
- Regions separated by $r(\max \alpha_{qq})$: vacuum physics or Debye screening

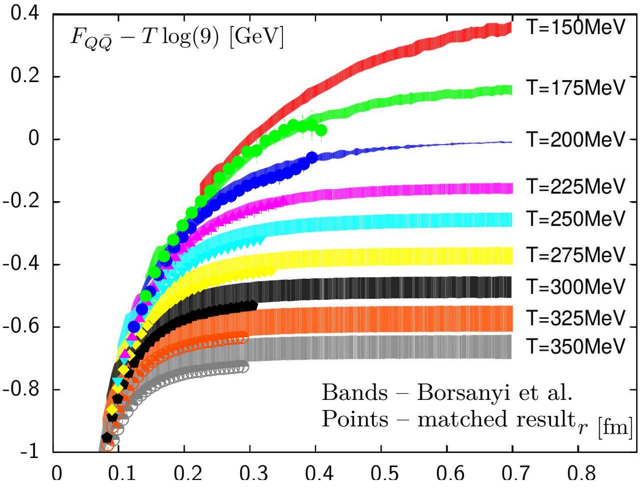
Quark-Antiquark free energy $F_{Q\bar{Q}}$



- Small distance and low T: reproduce static energy ($T = 0$)

$\Rightarrow$ Remnants of vacuum $Q\bar{Q}$ singlet interaction for $r \lesssim r(\max \alpha_{qq})/2$

Quark-Antiquark free energy $F_{Q\bar{Q}}$



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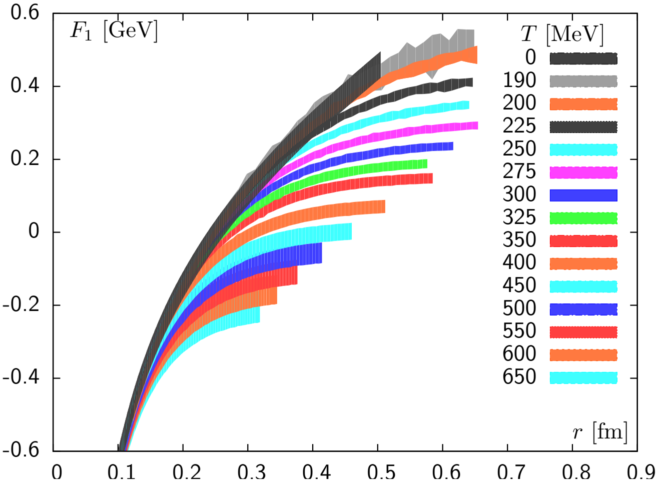
- Set $F_Q(T, N_\tau)$ to zero for $T = 200\,\mathrm{MeV}$ for all N_τ – cutoff effects?

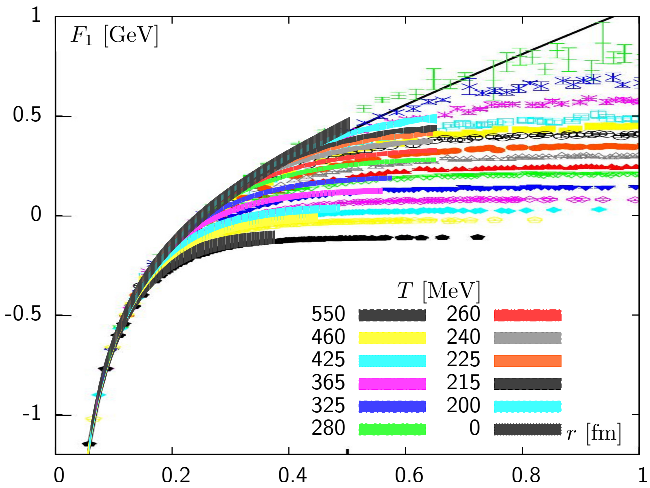
Singlet free energy F_1



- Larger distances & higher T: reproduce static energy $(T = 0)$

$\Rightarrow$ Remnants of vacuum $Q\bar{Q}$ singlet interaction for $r \lesssim r(\max \alpha_{qq})$

Singlet free energy F_1



- RBC coll [Kaczmarek, PoS CPOD **07** (2007) 043], $N_\tau = 4, 6$, $M_\pi \sim 220\text{MeV}$
- Our continuum results are higher: chiral or cutoff effects?

Summary

- Continuum limit of free energy of static quark up to $T \lesssim 1\,\mathrm{GeV}$
  - Renormalised Polyakov loop consistent with maximum for $T \sim 10\,T_c$ resp. ratio of free energy over temperature has minimum
  - Perturbative regime not reached for $T \sim 15\,T_c$
- Continuum limit of entropy of static quark:
  - Find deconfinement temperature $T_{\mathrm{peak}} = 153.1(5.4)\,\mathrm{MeV}$ and pseudocritical temperature $T_c = 154(9)\,\mathrm{MeV}$: very compatible
  - Entropy approaches positive constant at high T logarithmically
- Continuum limit of $Q\bar{Q}$ free energy up to $T \lesssim 650\,\mathrm{MeV}$
  - Remants of confining forces seen up $r(\max \alpha_{qq})$ in (singlet) free energy

Outlook

- Full $Q\bar{Q}$ potential in thermal medium
- Cyclic Wilson loop