Color screening in 2+1 flavor QCD

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in collaboration with
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(**TUMQCD** collaboration)

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TUM-EFT 81/16; PRD 93 114502 (2016); arXiv:1601:08001 (2016)

First principle description of in-medium quarkonia

- Ingredients: QCD, no models
- Analytic approach: non-relativistic EFTs, dimensionally reduced EFTs
  - Need weak coupling (expansion in $g = \sqrt{4\pi\alpha_s}$)
  - Assume hierarchies between NR and thermal scales $p \sim T$, $p \sim gT$, ...
- For $T < 1\,\mathrm{GeV}$: $\alpha_s \approx 0.4, g \sim 2$
  - Is weak coupling appropriate for realistic temperatures ($g \gtrsim 1$)?
  - Are hierarchies actually realized (for $g \sim 2$) and distinguishable?
- We test weak coupling/hierarchies/regimes using realistic lattice QCD simulations and heavy quarks in the static limit
  - We aim at establishing whether the mechanisms described in EFTs are realized in QCD at the (experimentally) relevant temperatures

Color screening in 2+1 flavor QCD

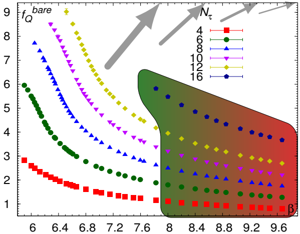
- Overview & Introduction
- Correlators of Polyakov loops
- Comparison to weak coupling
- Summary

What is **new** about the TUMQCD lattices?

$f_Q^{\text{bare}} = -\log \langle P \rangle_T$

Two different volumes and two quark masses:

Controlled **finite volume** and **quark mass** dependence



TUMQCD collaboration, **TUM-EFT 81/16**

Continuum limit with **realistic** quark masses

$N_\tau a(\beta) = 1/T(N_\tau, \beta)$

$T \in [135, 2325]$ MeV with at least four N_τ

- $N_\tau = 4 - 16$: $12 - 30+$ ens. each, $5.9 \leq \beta \leq 9.67$, $a = 0.0085 - 0.25$ fm.
- **HISQ/Tree** action, errors: $\mathcal{O}(\alpha_s a^2, a^4)$; lattice artefacts are reduced.
- Ensembles: $\frac{N_\sigma}{N_\tau} = 4$, $m_l = \frac{m_s}{20} \Leftrightarrow m_\pi = 161$ MeV; $\beta \leq 7.825$, $a \geq 0.04$ fm most from A. Bazavov et al., **PRD 85** 054503 (2012), **PRD 90** 094503 (2014) [HotQCD]
- All $N_\tau < 16$, $m_l = \frac{m_s}{5}$: $3 - 5$ ensembles each, $3 - 10 \times 10^4$ **TU** each, $7.03 \leq \beta \leq 8.4$, $a = 0.025 - 0.083$ fm; $T = 0$ lattices available.
- r_1 scale for $\beta > 8.4$ from non-perturbative β function **PRD 90** 094503 (2014)

Polyakov loops and free energies of static (heavy) quark states

- The *Polyakov loop L* is the gauge-invariant expectation value of the traced propagator of a static quark (P) and related to its **free energy**: $L(T) = \langle P \rangle_T = \langle \mathrm{Tr}\, S_Q(x,x) \rangle_T = e^{-F_Q^{\mathrm{b}}/T}$. L needs renormalization.

  A. M. Polyakov, **PL 72B** (1978); L. McLerran, B. Svetitsky, **PRD 24** (1981)

- The *Polyakov loop correlator* is related to *singlet* & *octet free energies*

  $$C_P(r,T) = e^{-F^{\mathrm{b}}_{Q\bar{Q}}(r,T)} = \frac{1}{9} e^{-F_S^{\mathrm{b}}/T} + \frac{8}{9} e^{-F_A^{\mathrm{b}}/T} = \frac{1}{9} C_S(r,T) + \frac{8}{9} C_A(r,T).$$

  S. Nadkarni, **PRD 33, 34** (1986)

- Meaning of **gauge-dependent** *singlet* & *octet free energies* is unclear.
- C_P is also related to the **gauge-invariant potentials** $V_{S,A}$ of **pNRQCD**

  $$C_P(r,T) = e^{-F^{\mathrm{b}}_{Q\bar{Q}}(r,T)} = \frac{1}{9} e^{-V_S^{\mathrm{b}}/T} + \frac{8}{9} L_A^{\mathrm{b}}\, e^{-V_A^{\mathrm{b}}/T} + \mathcal{O}(g^6) \text{ for } rT \ll 1.$$

  N. Brambilla et al., **PRD 82** (2010)

Renormalization of free energies

- **Singlet free energy** and **potential** appear to be related for $rm_D \sim 1$:

$$F_S(r,T) = -C_F\alpha_s\left[\frac{e^{-r\,m_D}}{r} + m_D\right] + \mathcal{O}(g^4) = V_S(r) + \mathcal{O}(g^3).$$

N. Brambilla et al., **PRD 82** (2010)

$\Rightarrow$ F_S and V_S share the same renormalization $2C_Q$, which depends on T only through the lattice spacing: $V_S = V_S^b + 2C_Q \Rightarrow F_S = F_S^b + 2C_Q$.

- Use V_S at $T=0$: fix r_1 scale & determine $2C_Q$ using **static energy**.

A. Bazavov et al., **PRD 85** 054503 (2012), **PRD 90** 094503 (2014) [HotQCD]

- Cluster decomposition theorem: $F_{Q\bar{Q}} = F_S = 2F_Q$ for $r \gg 1/T$.

$\Rightarrow$ renormalize as $F_{Q\bar{Q}} = F_{Q\bar{Q}}^b + 2C_Q$ and $F_Q = F_Q^b + C_Q$. $\rightarrow$ **PRD 93 114502 (2016)**

Beyond $C_Q(\beta)$ from $T=0$ lattices – use **direct renormalization** of F_Q
$\Rightarrow$ Infer unknown $C_Q(\beta)$ from known $C_Q(\beta^{\mathrm{ref}})$ using different $N_\tau, N_\tau^{\mathrm{ref}}$

$$C_Q(\beta) = \left\{C_Q(\beta^{\mathrm{ref}}) + F_Q^{\mathrm{b}}(\beta^{\mathrm{ref}}, N_\tau^{\mathrm{ref}}) - F_Q^{\mathrm{b}}(\beta, N_\tau)\right\}$$

$\rightarrow$ S. Gupta et al., **PRD 77** 034503 (2008)

Renormalization of free energies

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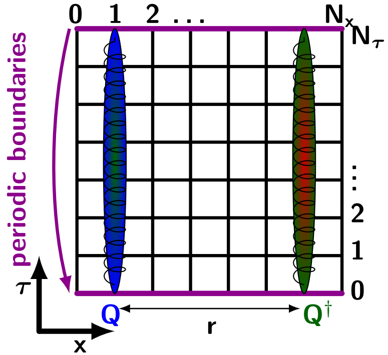
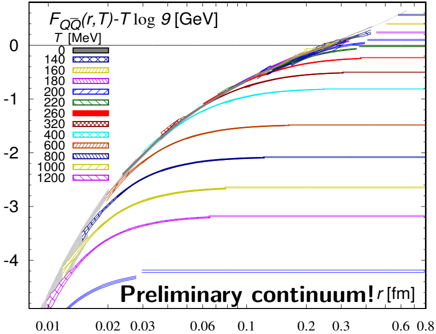
$$C_Q(\beta) = \left\{ C_Q(\beta^{\mathrm{ref}}) + F_Q^{\mathrm{b}}(\beta^{\mathrm{ref}}, N_\tau^{\mathrm{ref}}) - F_Q^{\mathrm{b}}(\beta, N_\tau) + \Delta_{N_\tau, N_\tau^{\mathrm{ref}}} \right\}$$ $\rightarrow$ **PRD 93 114502 (2016)**

Color screening for a static quark-antiquark pair



Polyakov loop correlator and $Q\bar{Q}$ free energy

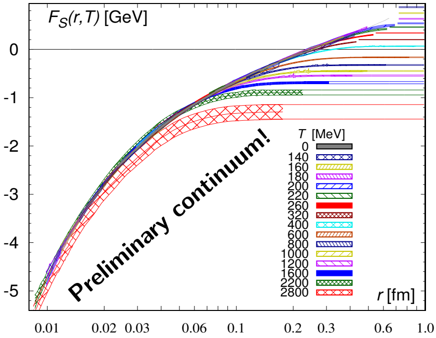


- **Free energy of a $Q\bar{Q}$ pair**, $F_{Q\bar{Q}}$, is also called *color-averaged potential*:

$$C_P^{\rm ren}(r,T) = \langle P(0)P^\dagger(\boldsymbol{r})\rangle_T^{\rm ren} = e^{-\frac{F_{Q\bar{Q}}(r,T)}{T}} = \frac{1}{9}e^{-\frac{F_S(r,T)}{T}} + \frac{8}{9}e^{-\frac{F_A(r,T)}{T}}.$$

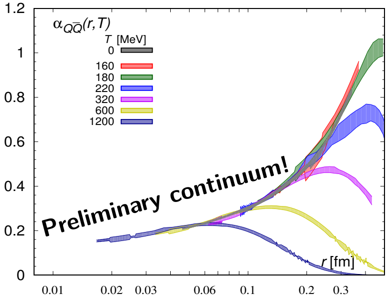
- $F_{Q\bar{Q}} - T\log 9$ is close to the $T=0$ **static energy** V_S for very small rT.

Singlet free energy in Coulomb gauge



- **Singlet free energy:** $C_S^{\mathrm{ren}}(r,T) = \frac{1}{3}\left\langle \sum_{a=1}^{3} W_a(0) W_a^\dagger(\boldsymbol{r}) \right\rangle_T^{\mathrm{ren}} = e^{-F_S(r,T)/T}$
- Wilson line correlator requires explicit **gauge fixing** (Coulomb gauge)
- F_S is numerically close to the $T=0$ **static energy** V_S for $rT \lesssim 0.3$.

Effective coupling: vacuum-like and screening regimes

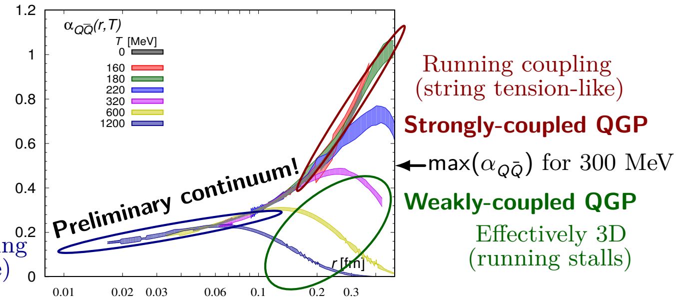


- **Effective coupling** $\alpha_{Q\bar{Q}}(r,T)$ is a proxy for the **force** between Q and $\bar{Q}$.

$$\alpha_{Q\bar{Q}}(r,T) = \frac{r^2}{C_F}\frac{\partial E(r,T)}{\partial r}, \; E = \{F_S(r,T), V_S(r)\}$$

- $\alpha_{Q\bar{Q}}$ clearly distinguishes different regimes at small and large r.
- Is **weak coupling** appropriate for $\alpha_{Q\bar{Q}} \ll 1$? $\Rightarrow$ test quantitatively.

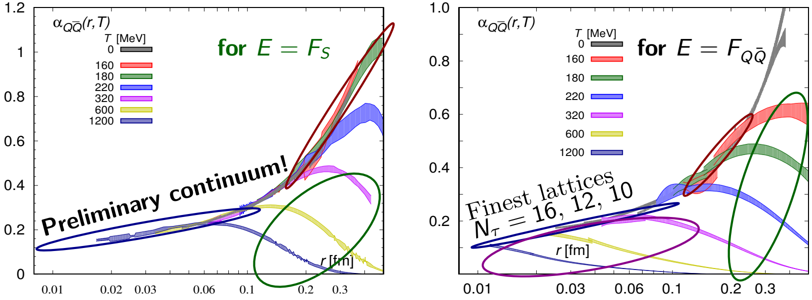
Effective coupling: vacuum-like and screening regimes



Vacuum-like regime	Screening regime	$\max(\alpha_{Q\bar{Q}})$
$rT \lesssim 0.2$	$rT \gtrsim 0.3$	$r_{\max} T \sim 0.4$

- $r_{\max}$ defined through $\max(\alpha_{Q\bar{Q}})$, which is proxy for the **maximal force**.
- For $T \lesssim 300\,\mathrm{MeV}$: $\max(\alpha_{Q\bar{Q}})(T) \gtrsim 0.5$ – **strongly-coupled QGP**.

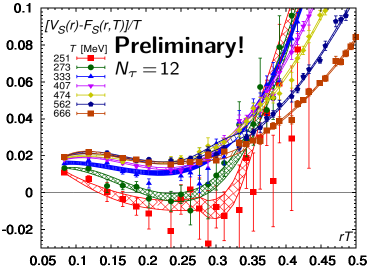
Effective coupling: vacuum-like and screening regimes

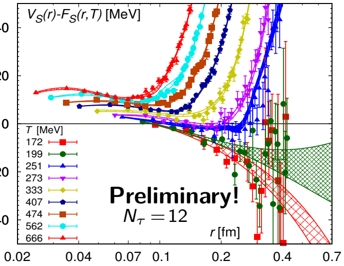


Vacuum-like regime	Color-octet contribution	Screening regime
$rT \lesssim 0.1$	$rT \lesssim 0.3$	$rT \gtrsim 0.3$

- **Coulomb-like regime** dominated by **color singlet**: very small rT.
- Much stronger T dependence due to **color-octet contribution**.

Static energy and singlet free energy (I) - global features

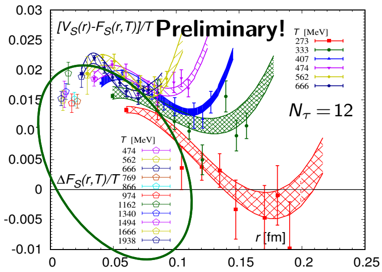


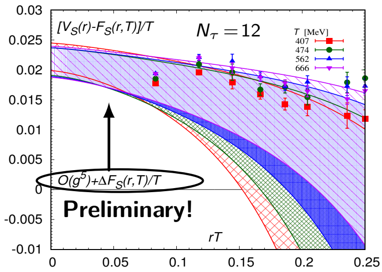


log scale!

- $V_S(T=0) - F_S(T>0)$ up to $\mathcal{O}(\alpha_s^3)$ M. Berwein et al., **PRD 96** 014025 (2017)
- Cancellations in $V_S - F_S$ – smoother for $r/a < 3$, **no renormalization**.
- For $rT \lesssim 0.1$ & $T > 300\,$MeV: $V_S - F_S \sim 0.02\,T$, mild N_τ dependence.
- Mild T dependence for $rT \lesssim 0.25$, **sudden onset of medium effects**.

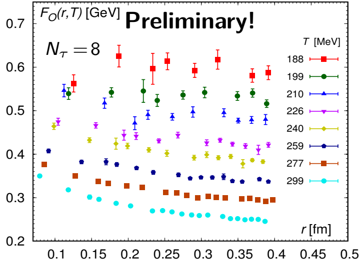
Static energy and singlet free energy (II) – weak coupling





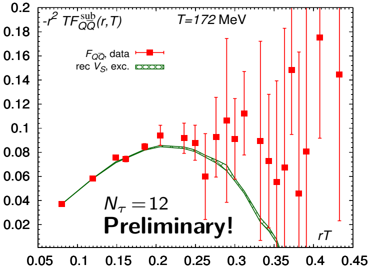
- $V_S(T=0) - F_S(T>0)$ up to $\mathcal{O}(\alpha_s^3)$ M. Berwein et al., **PRD 96** 014025 (2017)
- **Constant term** $\propto \alpha_s^3 T$ in F_S – determine with $T \to 0$ extrapolation $\Delta F_S[T] = \lim_{N'_\tau \to \infty} F_S[T\beta, N'_\tau)] - F_S[T(\beta, N_\tau)]$ using only $N'_\tau \geq 12$.
- $\mathcal{O}(g^5)$ shifted by missing ΔF_S term captures main features of data.
- If $V_A - V_S \gg 1/T$ which corresponds to $rT < \alpha_s(1/r) \to$ thermal effects even exponentially suppressed Brambilla et al., **PRD 78** 014017 (2008)

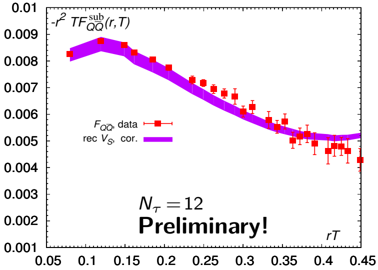
Color octet contribution in the Polyakov loop correlator (I)



- *pNRQCD*: C_P is given in terms of **potentials** V_S **and** V_A **at** $T=0$ and of the *adjoint Polyakov loop* L_A at $T>0$ N. Brambilla et al., **PRD 82** (2010)
  $C_P(r,T) = e^{-F_{Q\bar{Q}}(r,T)} = \frac{1}{9} e^{-V_S/T} + \frac{8}{9} L_A\, e^{-V_A/T} + \mathcal{O}(g^6)$ for $rT \ll 1$.
- *Gauge-invariant* decomposition of C_P into **color singlet and octet** is defined assuming *weak coupling* – test if it works for lattice as well.
- **Color octet contribution**: define $e^{-F_O/T} \sim \frac{9}{8}\left(e^{-F_{Q\bar{Q}}(r,T)} - \frac{1}{9} e^{-V_S/T}\right)$
- As F_O rapidly decreases for higher T, the **octet** becomes important.

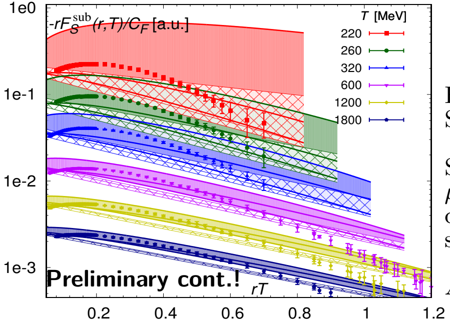
Color octet contribution in the Polyakov loop correlator (II)





- Low $T = 172\,\mathrm{MeV}$: **color singlet** V_S is enough for reconstructing C_P (no sensitivity to **color octet** due to large statistical errors).
- High $T = 666\,\mathrm{MeV}$: cancellation between **color singlet and octet** leads to $1/r^2$ behavior in $F_{Q\bar{Q}}$. We use *pNRQCD*, i.e. $\frac{1}{9} e^{-V_S/T} + \frac{8}{9} L_A\, e^{-V_A/T}$.
- We include **Casimir scaling violation**: $8V_A + V_S = 3\frac{\alpha_s^3}{r}[\frac{\pi^2}{4} - 3] + \mathcal{O}(\alpha_s^4)$.
- $F_{Q\bar{Q}}$ for $rT \lesssim 0.4$ can be understood in terms of **vacuum physics** only.

Confronting weak-coupling predictions in the screening regime (I)



Hashed bands: LO
Solid bands: NLO

Scale uncertainty
$\mu = (1-4)\pi T$
due to resummation
smaller for larger T

$\Lambda_{\rm QCD} = 320\,{\rm MeV}$

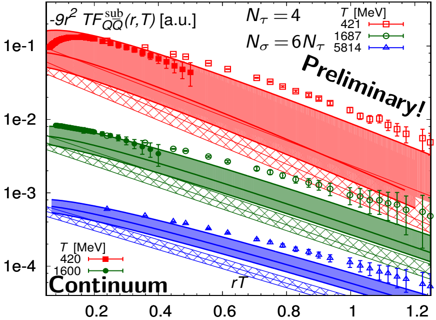
- $F_S(r,T)$ for $rm_D \sim 1$ at **NLO in EQCD** M. Laine et al., **JHEP 0703** 054 (2007)

  $$F_S^{\rm sub} = F_S - 2F_Q = -\frac{C_F\alpha_s e^{-rm_D}}{r}(1+\alpha_s[\delta Z_1(\mu) + rT\, f_1(rm_D)])$$
- $F_S^{\rm sub}$ on the lattice is **compatible with EQCD@NLO** up to $rT \sim 0.6$.

$\Rightarrow$ **Weakly-coupled EQCD** is reasonable in electric screening regime of F_S.

- For $rT > 0.8$: asymptotic screening is inherently non-perturbative.

Confronting weak-coupling predictions in the screening regime (II)



Continuum limit with aspect ratio $N_\sigma = 4N_\tau$

Hashed bands: LO
Solid bands: NLO

Scale uncertainty $\mu = (1-4)\pi T$ due to resummation smaller for larger T

$\Lambda_{\rm QCD} = 320\,{\rm MeV}$

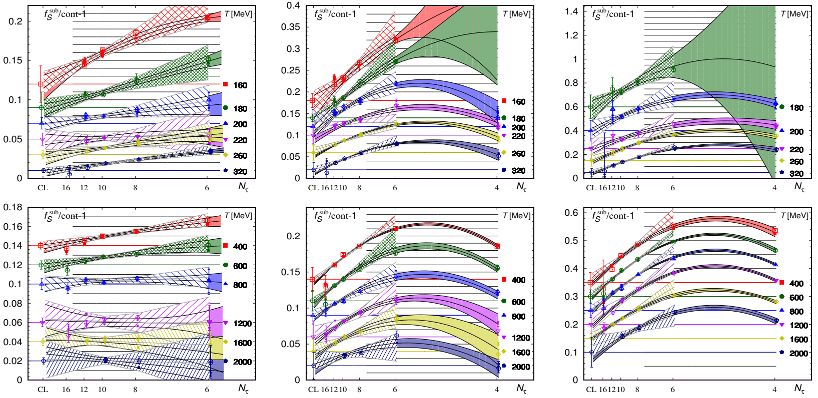
- *Singlet and octet cancel* at LO in $F_{Q\bar{Q}}(r,T) = -\frac{\alpha_s^2}{9}\frac{e^{-2rm_D}}{r^2} + C_F\alpha_s m_D$.
- $F^{\rm sub}_{Q\bar{Q}} = -\frac{\alpha_s^2}{9}\frac{e^{-2rm_D}}{r^2}(1 + \alpha_s[\delta Z_1(\mu) + rT\, f_1(rm_D)])$ S. Nadkarni, **PRD 33** (1986)
- Continuum limit of $F^{\rm sub}_{Q\bar{Q}}$ **agrees with EQCD@NLO** up to $r \sim 1/m_D$.

$\Rightarrow$ **Weakly-coupled EQCD** is reasonable in the electric screening regime of $F_{Q\bar{Q}}$, but non-perturbative (*chromo-magnetic*) effects are stronger .

- We study color screening and deconfinement using the renormalized Polyakov loop correlator and related observables.
- Continuum limit of static quark correlators in $N_f = 2{+}1$ QCD up to $T \sim 2.0\,\mathrm{GeV}$ and down to $r \sim 0.01\,\mathrm{fm}$.
- **Color-singlet correlators** are **vacuum-like up to** $rT \ll 0.3$, exhibit *color-electric screening for* $rm_D \sim 1 \Leftrightarrow 0.3 \lesssim rT \lesssim 0.6$ *compatible with weak coupling* and change to *asymptotic screening for* $rT \gg 0.7$.
- The *Polyakov loop correlator* C_P has a substantial *color adjoint contribution* for $T \gtrsim 200\,\mathrm{MeV}$. For $rT \lesssim 0.4$ weakly-coupled *pNRQCD* describes C_P well in terms of $T = 0$ **potentials** and the *adjoint Polyakov loop* L_A.
- C_P has a *color-electric screening regime* $rm_D \sim 1$. Non-perturbative effects (i.e. the *chromo-magnetic sector*) are much larger.

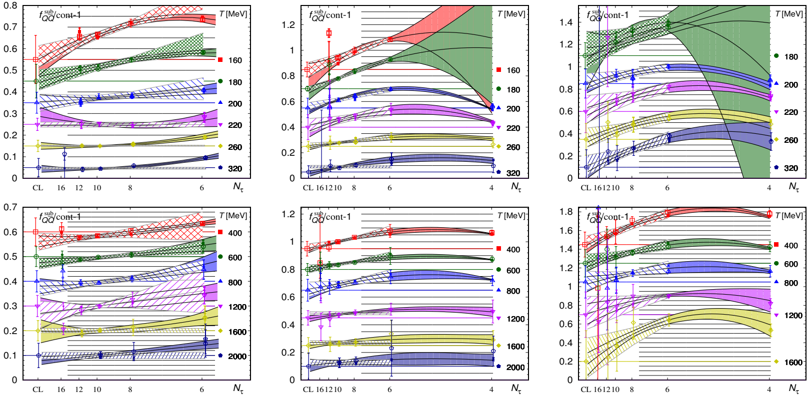
Continuum extrapolations: singlet free energy

$rT = 0.16$ $rT = 0.25$ $rT = 0.45$



Continuum extrapolations: free energy

$rT = 0.16$ $rT = 0.25$ $rT = 0.40$



Continuum extrapolations: effective coupling $\alpha_{Q\bar{Q}}[F_S]$

$rT = 0.16$ $rT = 0.25$ $rT = 0.45$