From string breaking to quarkonium spectrum

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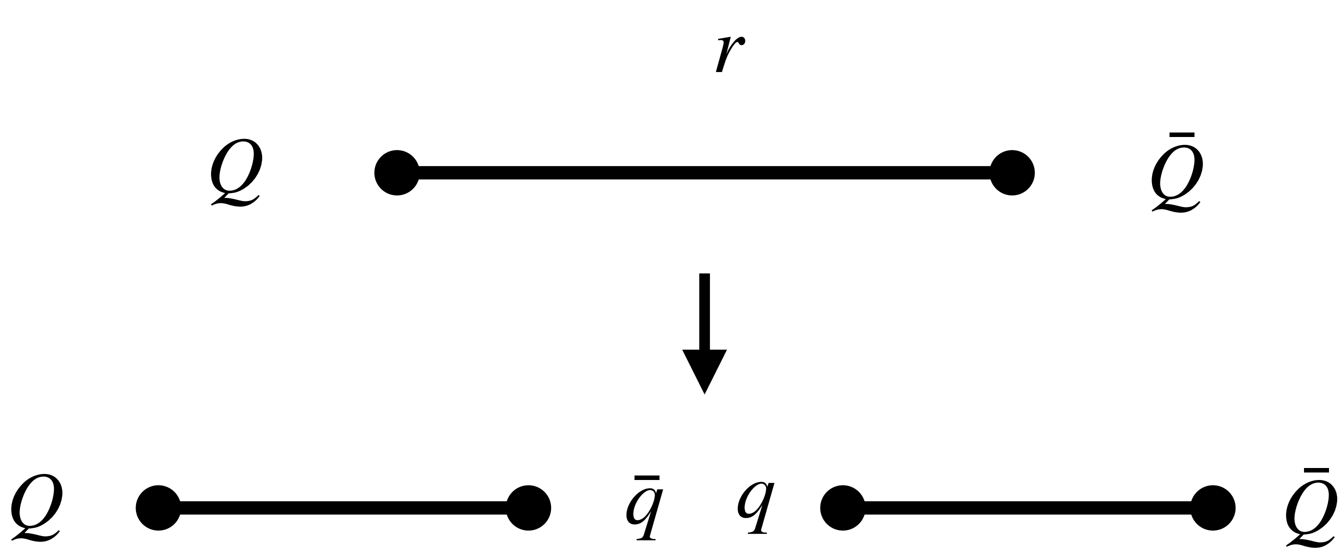
Motivation

- Interested in the quarkonium **bound states** and resonances
- QCD provides a description of quark dynamics, and gives **information on the hadron spectrum**
- **String breaking**: when a quark-antiquark pairs are distant enough than a creation of additional quark and antiquark pairs or mesons is energetically favourable
- **Looking for exotic states** which are not ruled out from QCD: e.g. tetraquarks, pentaquarks …

String breaking

- **String breaking** is something that theoretically should occur when distance among quarks increases (Bali et al. *Phys. Rev.* D71 114513, 2005). In this case it is more convenient for the system to produce other couples quark-antiquark and new bound states appear

- For example for two heavy quark-antiquark $Q\ \bar{Q}$ we have



The method

- Different methods can be implemented in order to study the **string breaking**:

1. Simply evaluating the change of sign of $V(r) - 2E_m$, $V(r)$ is the potential between two static heavy sources $Q\bar{Q}$ and E_m is the mass of a static-light meson, e.g. $q\bar{Q}$ or $\bar{q}Q$

2. Using the approach of the matrix of correlators (Bali et al. *Phys. Rev.* D71,114513, 2005)

$$C(t) = \begin{pmatrix} C_{QQ}(t) & C_{QB}(t) \\ C_{BQ}(t) & C_{BB}(t) \end{pmatrix}$$

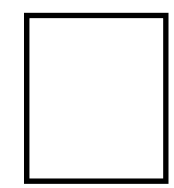
The method

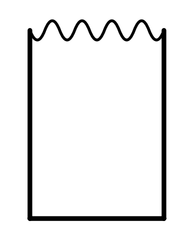
$$C(t) = \begin{pmatrix} C_{QQ}(t) & C_{QB}(t) \\ C_{BQ}(t) & C_{BB}(t) \end{pmatrix}$$

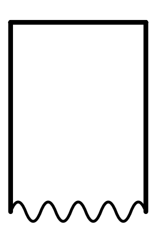
The matrix elements can be obtained from the following operators:

$$\mathcal{O}_Q = Q\bar{Q} \qquad\qquad \mathcal{O}_B = q\bar{Q}$$

→ And using some algebra the matrix elements can be written as

$$C_{QQ}(t) = \left\langle 0 \,|\, \mathcal{O}_Q(t)\bar{\mathcal{O}}_Q(0) \,|\, 0 \right\rangle = 2e^{-2m_Q t} \left\langle tr\left\{ V_t^\dagger(r,0) U_r(t,0) V_0(r,0) U_0^\dagger(t,0) \right\} \right\rangle_U = e^{-2m_Q t}$$ 

$$C_{BQ}(t) = \left\langle 0 \,|\, \mathcal{O}_B(t)\bar{\mathcal{O}}_Q(0) \,|\, 0 \right\rangle = e^{-2m_Q t} \left\langle tr\left\{ P_- \frac{\gamma \cdot r}{r} M^{-1} U_r(t,0) V_0(r,0) U_0^\dagger(t,0) \right\} \right\rangle = e^{-2m_Q t}$$ 

$$= e^{-2m_Q t}$$  $$= C_{QB}(t)$$

V. Koch et al. Phys. Lett. B793 493-498 2019

Bali et al. *Phys. Rev.* D71,114513, 2005

O. Philipsen and H. Wittig Phys. Rev. Lett. 81 (1998) 4056-4059

The method

$$C(t) = \begin{pmatrix} C_{QQ}(t) & C_{QB}(t) \\ C_{BQ}(t) & C_{BB}(t) \end{pmatrix}$$

The matrix elements can be obtained from the following operators:

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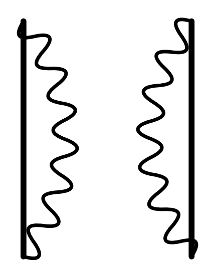
→ And using some algebra the matrix elements can be written as

$$C_{BB}(t) = \left\langle 0 \,|\, \mathcal{O}_B(t)\bar{\mathcal{O}}_B(0) \,|\, 0 \right\rangle = e^{-2m_Q t}\delta_{ij}\left\langle tr\left\{P_- M^{-1}U_r(t,0)\right\} tr\left\{P_+ M^{-1}U_0^\dagger(t,0)\right\}\right\rangle$$

$$-e^{-2m_Q t}\left\langle tr\left\{P_- M^{-1}U_r(t,0)P_+ M^{-1}U_0^\dagger(t,0)\right\}\right\rangle$$

$$= e^{-2m_Q t}\Big(\delta_{ij}$$



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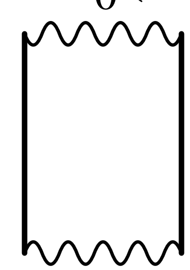


$$\Big)$$

where the straight line consists of gauge link variables and the wavy line are the light quark propagators

Importance in the study of tetraquark bound states

The use of the matrix of correlators can be important also in the study of tetraquark, made by two heavy quark-antiquark and two light quarks.

The potential that one gets from the heavy quark-antiquark system can be plugged in the Schrödinger equation (Born-Oppenheimer approximation):

$$\left(-\frac{1}{2}\mu^{-1}\left(\partial_r^2+\frac{2}{r}\partial_r-\frac{\mathbf{L}^2}{r^2}\right)+V(\mathbf{r})+2m_M-E\right)\psi(\mathbf{r})=0$$

and look e.g. for bottomonium bound states and resonances (P. Bicudo et al. ArXiv:1910.04827), including potential tetraquark resonances

Lattice setup

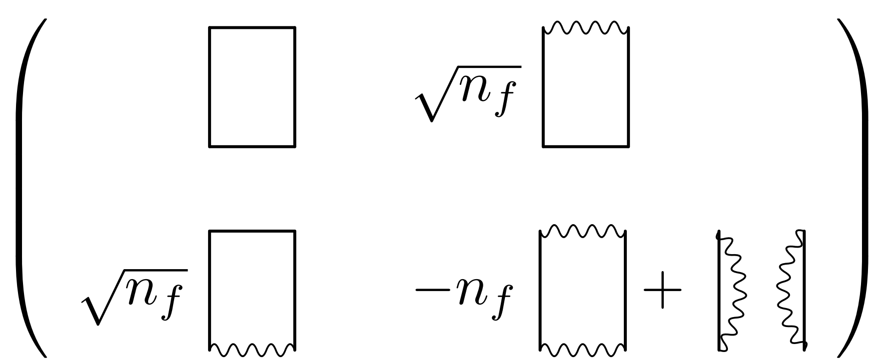
- 36 configurations generated with $N_f = 2$ O(a) improved Wilson fermion action (CLS ensembles)
- Lattice volume: 64x32x32x32
- $m_\pi = 330\ MeV$
- Lattice spacing: $a = 0.0755(11)\ fm$

Computation

We want to compute the elements of the matrix of correlators

$$C(t) = \begin{pmatrix} C_{QQ}(t) & C_{QB}(t) \\ C_{BQ}(t) & C_{BB}(t) \end{pmatrix}$$

$$= e^{-2m_Q t}$$



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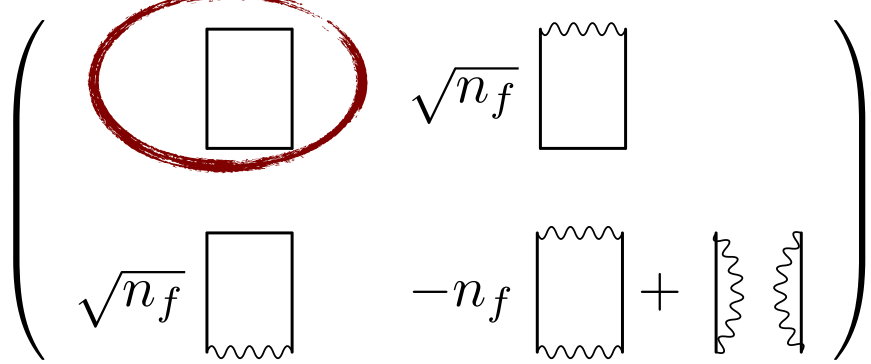


For a start we concentrate on the first element: $C_{QQ}(t)$

Next steps will be the computation of all elements.

A. Hasenfratz et al. Nucl. Phys. Proc. Suppl. 106 (2002)
M. Della Morte et al. Phys. Lett. B581 93-98,2004

HYP smearing

In order to improve the precision of the measurements and reduce the error, it is convenient to smear the link variables. We use the HYP smearing, which consists in 3 steps:

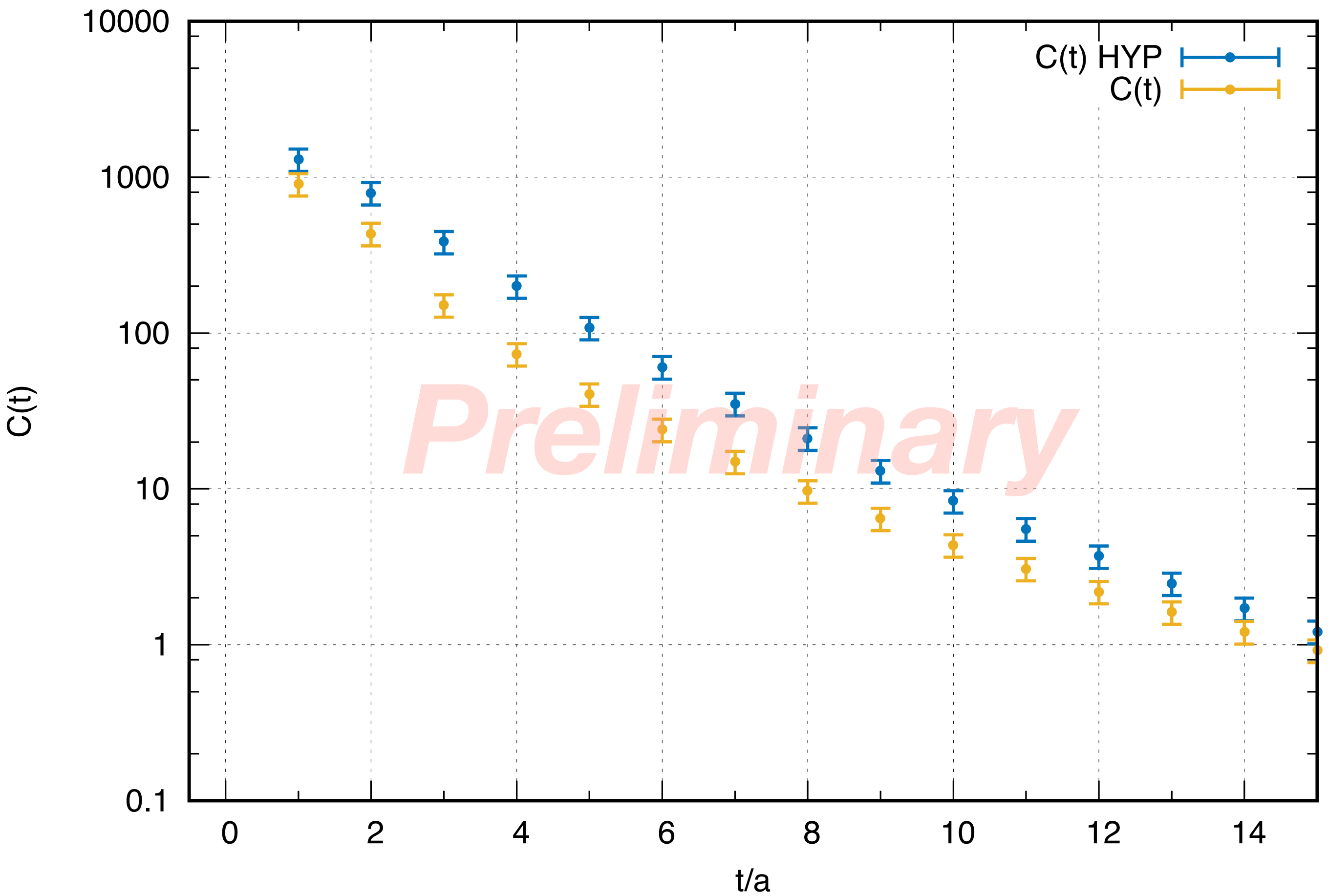
$$\bar{V}_{\mu;\nu\,\rho}(x) = Proj_{SU(3)}[(1-\alpha_3)U_\mu(x) + \frac{\alpha_3}{2}\sum_{\pm\eta=\rho,\nu\mu} U_\nu(x)U_\mu(x+\hat{\eta})U_\eta(x+\hat{\mu}^\dagger)]$$

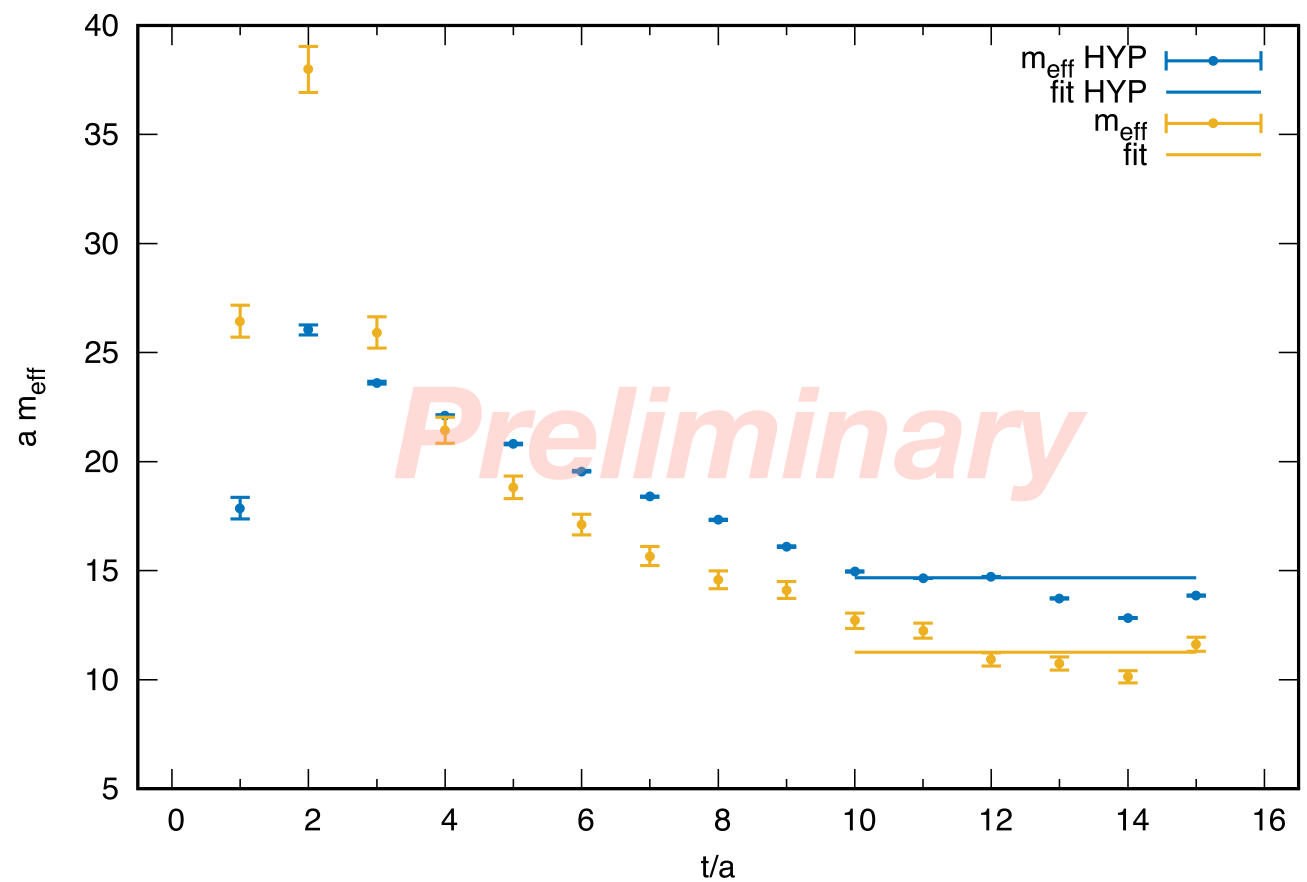
$$\tilde{V}_{\mu;\nu}(x) = Proj_{SU(3)}[(1-\alpha_2)U_\mu(x) + \frac{\alpha_2}{4}\sum_{\pm\rho=\nu\mu} \bar{V}_{\rho;\nu\mu}(x)\bar{V}_{\mu;\rho\nu}(x+\hat{\rho})\bar{V}_{\rho;\nu\mu}(x+\hat{\mu})^\dagger]$$

$$V_\mu(x) = Proj_{SU(3)}[(1-\alpha_1)U_\mu(x) + \frac{\alpha_1}{6}\sum_{\pm\nu=\mu} \tilde{V}_{\nu;\mu}(x)\tilde{V}_{\mu;\nu}(x+\hat{\nu})\tilde{V}_{\nu;\mu}(x+\hat{\mu}^\dagger)]$$

We use $(\alpha_1, \alpha_2, \alpha_3) = (1,1,\frac{1}{2})$

$Q\bar{Q}$ correlators

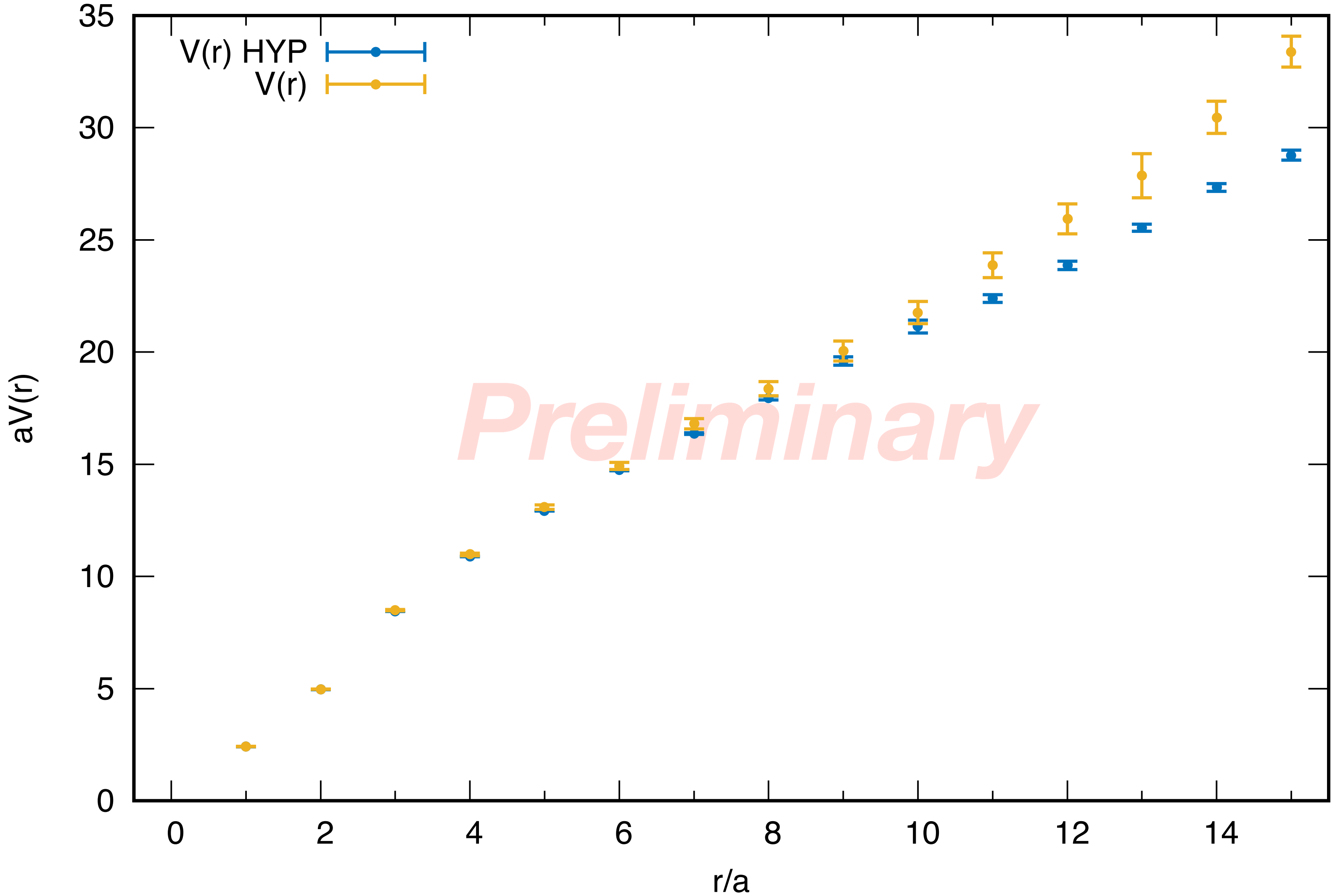




$$C_{QQ}(t) = e^{-2m_Q t} \boxed{}$$

$$m_{eff} = -\lim_{t\to\infty} \frac{1}{a} \log\left(\frac{C(t+a)}{C(t)}\right)$$

Potential



For small distances, there is no difference between smeared and not smeared potential.

Outlooks

- Obtain remaining elements of the correlator matrix (renormalise the potential, include mixing effects) to get the info on the string breaking

- Use the Born-Oppenheimer approximation approach (P. Bicudo et al. ArXiv:1910.04827)
  - ➡ to get the spectrum with increased precision (cross-check), and look for exotic bound states
  - ➡ to get explain new experimental states **[see talk by S. Prelovsek, Wed. 16.30]**

- Repeat calculation for different gauge ensembles (continuum limit for string breaking with dynamical quarks still missing in the literature)

- Systematical study of the noise-reduction techniques (different stochastic methods, distillation, multi-level approach, smoothening techniques …)

- Use the setup to obtain static potentials with C* boundary conditions

Thank you!