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Importance of closed quark loops for lattice QCD studies of tetraquarks

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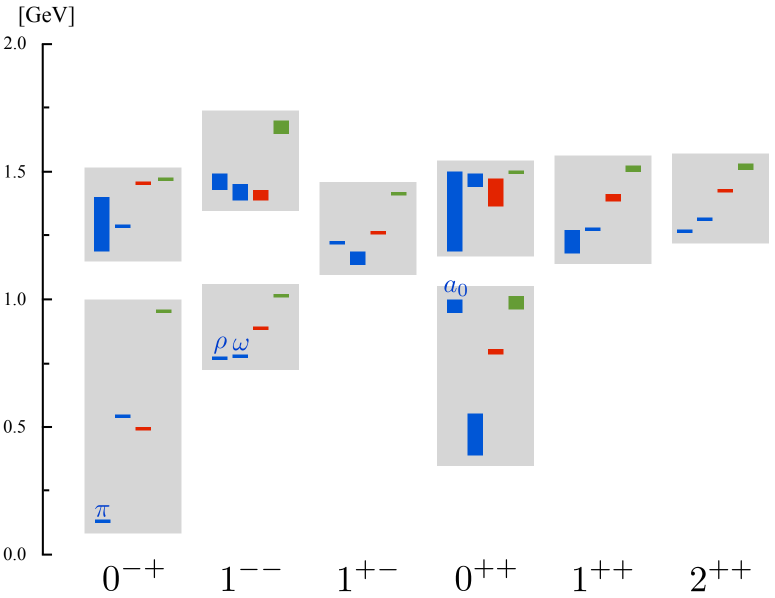
Outline

1. Introduction & Motivation
2. Approach
3. Efficient computation of $C_{jk}(t)$
4. Analysis
5. Summary

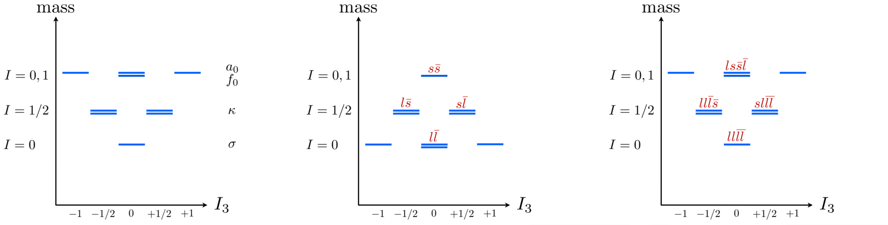
Light mesons



Tetraquark interpretation

Nonet of light scalar mesons ($J^P = 0^+$) still poorly understood

- $I = 1$ (two $u/\bar{d}$ quarks) states (a_0, f_0) are **heavier** than the $I = 1/2$ ($u/\bar{d} + s$ quark) states (κ)
- Tetraquark interpretation resolves the mass ordering of the 0^+ sector naturally
  - $a_0 \equiv us\bar{s}\bar{d}$ and $\kappa \equiv u(u\bar{u} + d\bar{d})\bar{s}$
  - $a_0(980) \longrightarrow K\bar{K}[\bar{s}u][\bar{d}s]$ & $a_0(980) \longrightarrow \eta_s\pi[\bar{s}s][\bar{d}u]$



experimental results | conventional $q\bar{q}$ pairs | tetraquark interpretation

Approach

Study of **effective masses** from mesonic two-quark and four-quark operators.

- Information about possible stable states around threshold
- Composition of states from the solution of the generalized eigenvalue problem
- Relies on large operator basis, in particular 2 meson states

Gauge configurations:

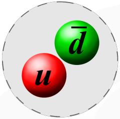
- 2+1 dyamical clover fermions and Iwasaki gauge action
- generated by the PACS-CS Collaboration

  S. Aoki *et al.* [PACS-CS Collaboration], Phys. Rev. D **79** (2009) 034503 [arXiv:0807.1661 [hep-lat]].
- Lattice: $32^3 \times 64$, $a \approx 0.09$fm
- ≈ 500 configurations at $M_\pi \approx 300$MeV

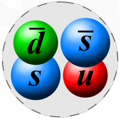
Operator basis

In our study: 6 operators with the quantum numbers of $a_0(980)$.

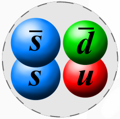
$$\mathcal{O}^{q\bar{q}} = \sum_{\mathbf{x}} \Big(\bar{d}_{\mathbf{x}} u_{\mathbf{x}} \Big)$$



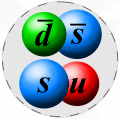
$$\mathcal{O}^{K\bar{K},\text{ point}} = \sum_{\mathbf{x}} \Big(\bar{s}_{\mathbf{x}} \gamma_5 u_{\mathbf{x}} \Big)\Big(\bar{d}_{\mathbf{x}} \gamma_5 s_{\mathbf{x}} \Big)$$



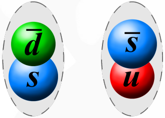
$$\mathcal{O}^{\eta_s\pi,\text{ point}} = \sum_{\mathbf{x}} \Big(\bar{s}_{\mathbf{x}} \gamma_5 s_{\mathbf{x}} \Big)\Big(\bar{d}_{\mathbf{x}} \gamma_5 u_{\mathbf{x}} \Big)$$



$$\mathcal{O}^{Q\bar{Q}} = \sum_{\mathbf{x}} \epsilon_{abc} \Big(\bar{s}_{\mathbf{x},b} (C\gamma_5) \bar{d}^T_{\mathbf{x},c} \Big) \epsilon_{ade} \Big(u^T_{\mathbf{x},d} (C\gamma_5) s_{\mathbf{x},e} \Big)$$



$$\mathcal{O}^{K\bar{K},\text{ 2-part}} = \sum_{\mathbf{x},\mathbf{y}} \Big(\bar{s}_{\mathbf{x}} \gamma_5 u_{\mathbf{x}} \Big)\Big(\bar{d}_{\mathbf{y}} \gamma_5 s_{\mathbf{y}} \Big)$$



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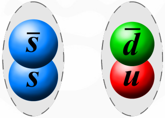
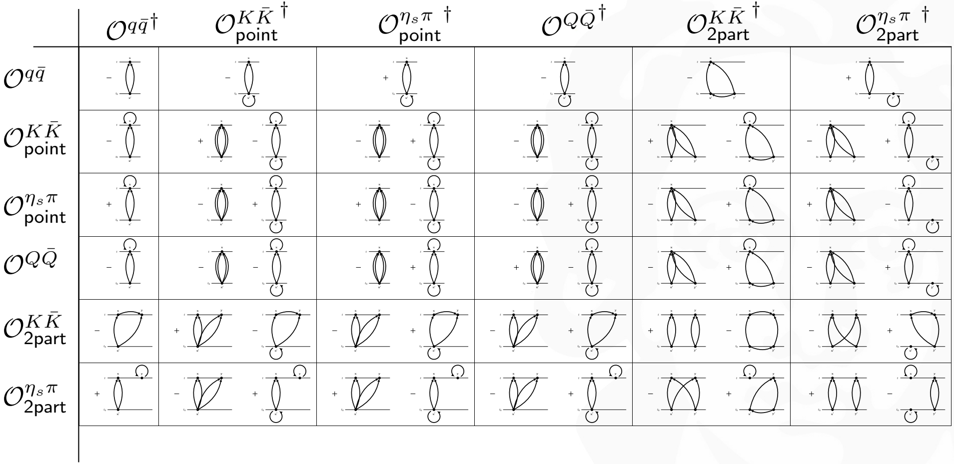
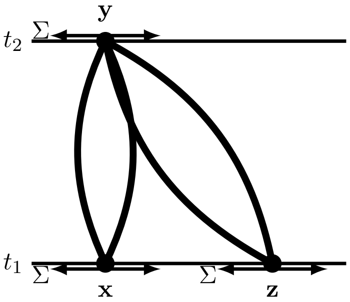


$C_{jk}(t)$

$$C_{jk} = \langle \mathcal{O}_j \mathcal{O}_k^\dagger \rangle$$



Efficiency of methods and combination of methods



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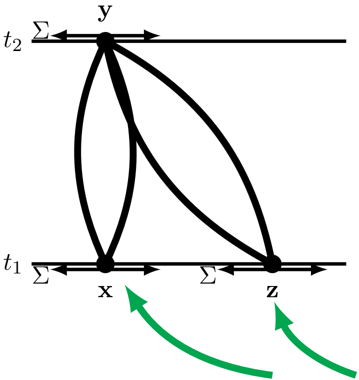

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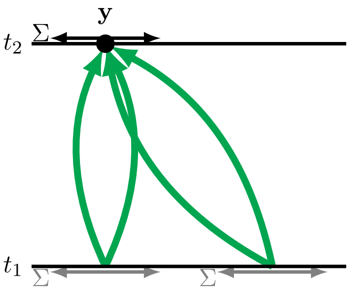
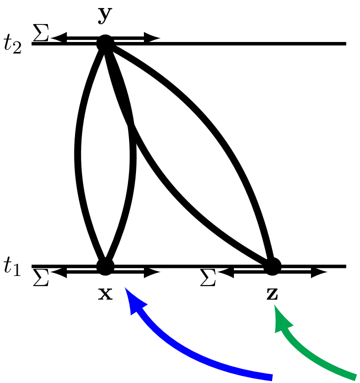
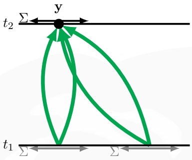


(a)

Efficiency of methods and combination of methods





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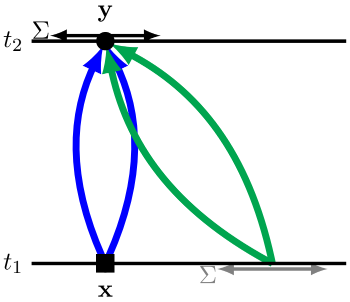

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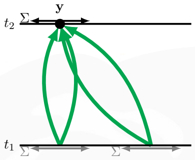

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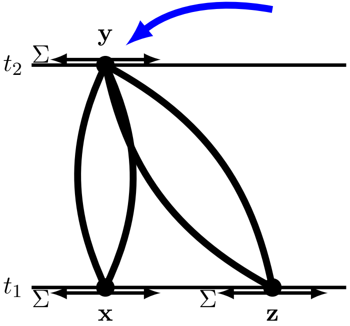

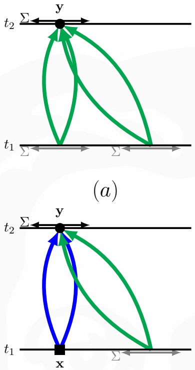

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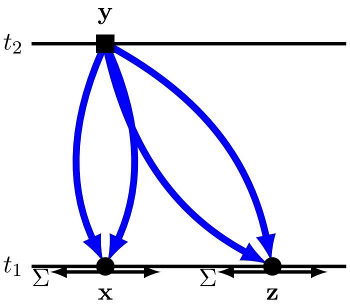
Efficiency of methods and combination of methods



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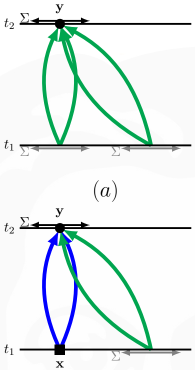

(a)

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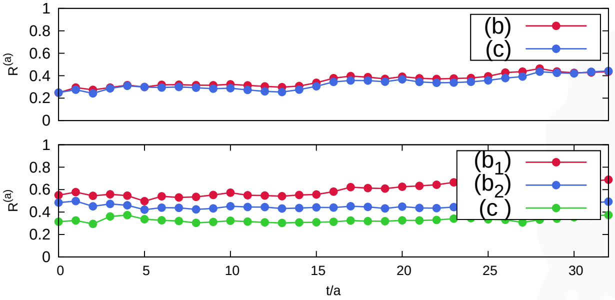
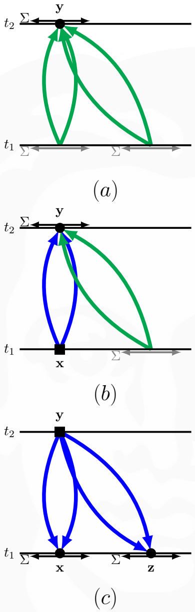
Efficiency of methods and combination of methods

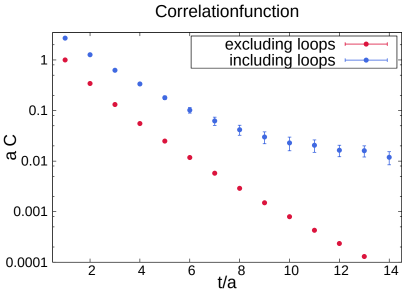


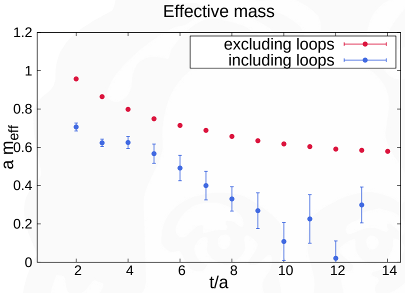


$$R^{(a),(b)} = \frac{\Delta C^{(a)}(t)\cdot\sqrt{\tau^{(a)}}}{\Delta C^{(b)}(t)\cdot\sqrt{\tau^{(b)}}}$$

Evidence for the relevance of closed quark loops

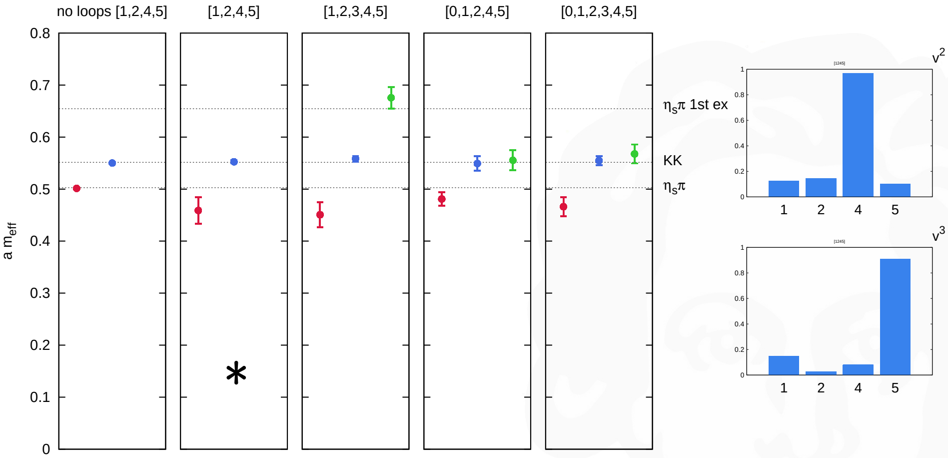
- closed fermion loops not only required to include $\mathcal{O}^{q\bar{q}}$ to the operator basis





- several matrix elements experience distinct changes in their characteristics (not only an addition of stochastic noise)
    - e.g. the correlationfunction for $\mathcal{O}^{Q\bar{Q}}$

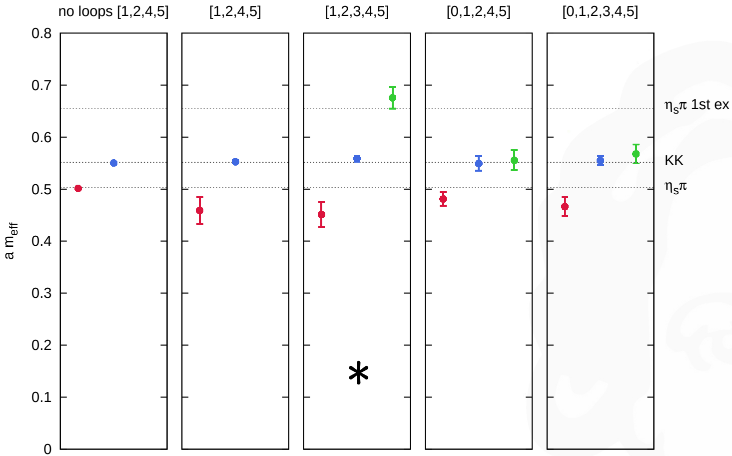
Analysis

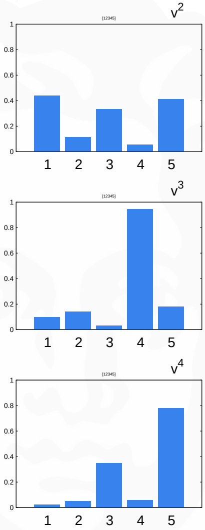


$$0 \mathrel{\hat{=}} \mathcal{O}^{q\bar{q}}, \quad 1 \mathrel{\hat{=}} \mathcal{O}^{K\bar{K}}_{\text{point}}, \quad 2 \mathrel{\hat{=}} \mathcal{O}^{\eta_s \pi}_{\text{point}}, \quad 3 \mathrel{\hat{=}} \mathcal{O}^{Q\bar{Q}},$$

$$4 \mathrel{\hat{=}} \mathcal{O}^{K\bar{K}}_{\text{2part}}, \quad 5 \mathrel{\hat{=}} \mathcal{O}^{\eta_s \pi}_{\text{2part}}.$$

Analysis





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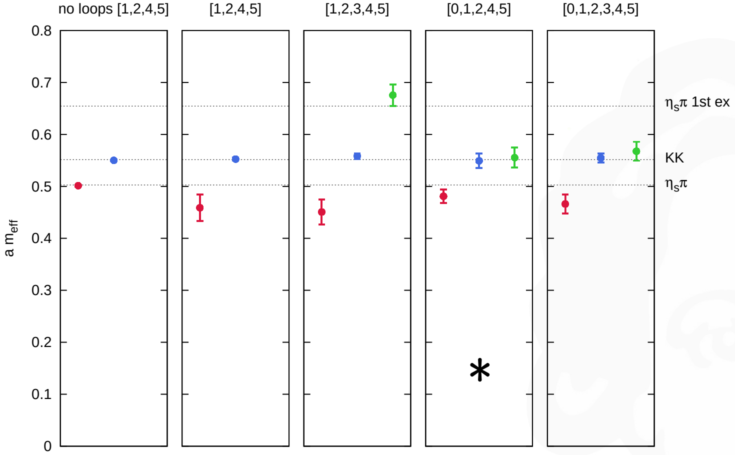

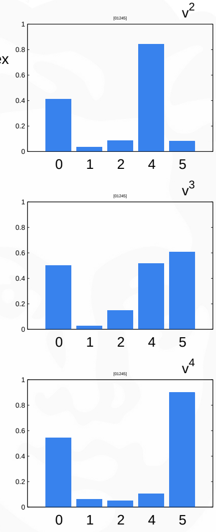

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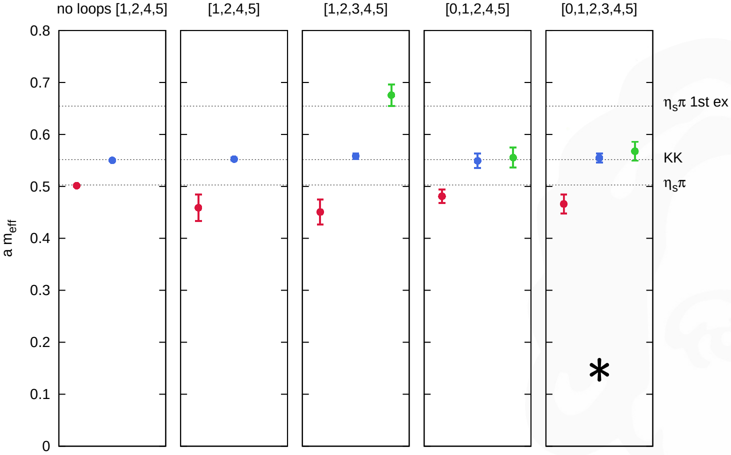

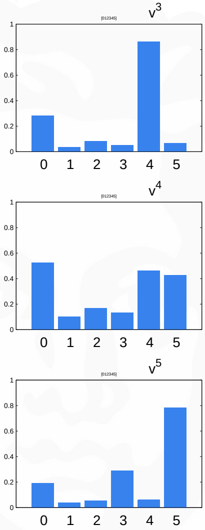

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Summary

- Study of **effective masses** from mesonic two-quark and four-quark operators.

- Investigation of methods and combination of methods to find the **optimal strategy** to compute each diagram of the correlation matrix

- Computation of closed fermion loops expensive, but **essential**

- Analysis of states around the two particle threshold reveals **evidence for an additional state** (a_0, likely of $q\bar{q}$ structure)