RTG 2575:
Rethinking
Quantum Field Theory

Importance of local tetraquark operators for the $T_{cc}(3875)^+$ spectrum

Based on arXiv:2510.26459

Andres Stump
Jeremy R. Green

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Humboldt-Universität zu Berlin

$T_{cc}(3875)^+$ tetraquark

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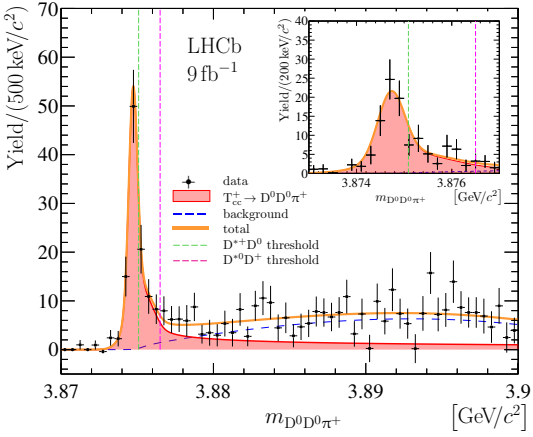

[Aaij et al. 2022]

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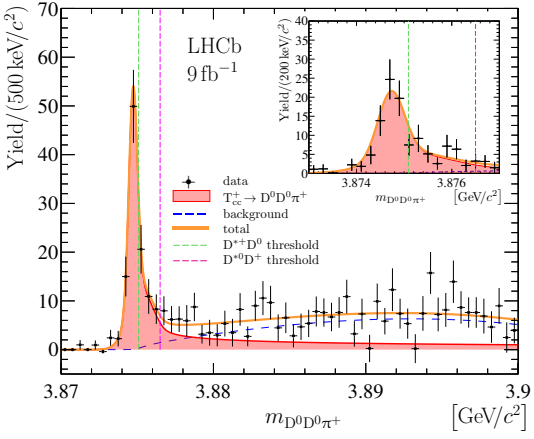

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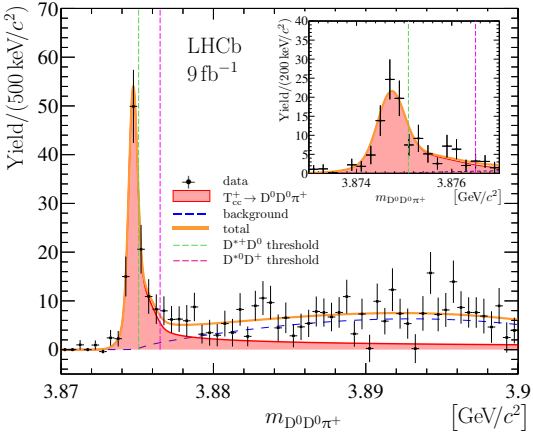
$T_{cc}(3875)^+$ tetraquark

- Exotic hadron discovered at LHCb
- Found in $D^0 D^0 \pi^+$ mass spectrum
  Just below $D^{*+} D^0$ threshold
- Minimal quark content $cc\overline{u}\overline{d}$, $I(J^P) = 0(1^+)$



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Finite-volume T_{cc} spectrum

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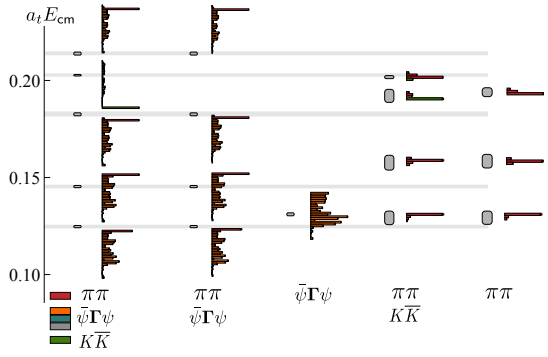

ρ resonance: Diverse operator basis required
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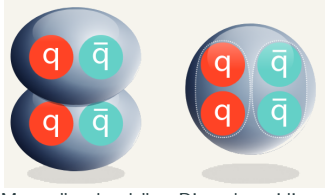
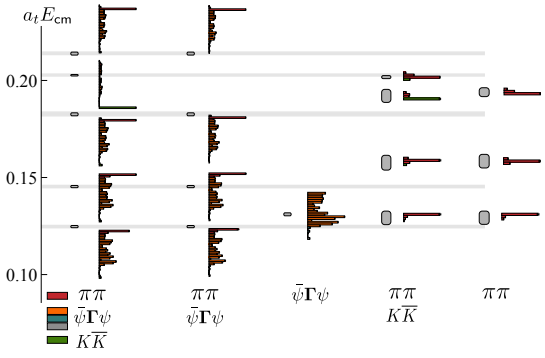
- Are bilocal $D^{(*)}D^*$ scattering operators enough?



Meson "molecule" Diquark-antidiquark



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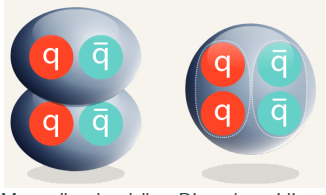
Finite-volume T_{cc} spectrum

How to obtain accurate finite-volume T_{cc} spectrum?

- Insufficiently diverse operator bases can lead to inaccurate spectrum
- Are bilocal $D^{(*)}D^*$ scattering operators enough?
- Do we need local tetraquark operators?



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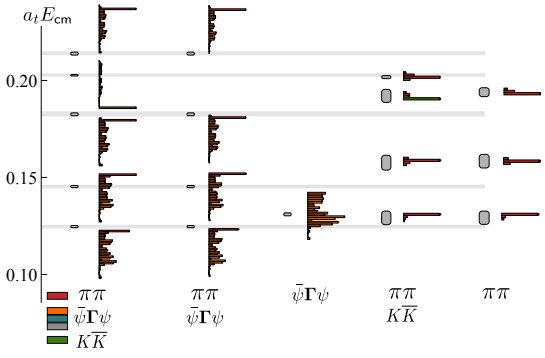

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   - Distillation method
   - Position-space sampling method

2. Results for T_{cc}
   - Operator importance analysis
   - Finite-volume T_{cc} spectrum with and without local tetraquark operators
   - s-wave Lüscher analysis

Local tetraquark operators in distillation

Distillation method [Peardon et al. 2009]

Use Laplacian Heaviside (LapH) smearing for quark fields $\psi_{\mathrm{sm}}(t) = V(t)V(t)^\dagger\psi(t)$ with

$$V(t) = \left(v^{(1)}(t), v^{(2)}(t), \ldots, v^{(N_v)}(t)\right)$$

containing the N_v lowest eigenvectors of $\Delta(t)$

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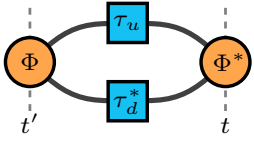
E.g. for pion two-point function we get

$$C(t',t) = \left\langle \mathrm{tr}\left[\Phi(t') \cdot \tau_u(t',t) \cdot \Phi(t)^\dagger \cdot \tau_d(t',t)^\dagger\right]\right\rangle_G$$



$D^{(*)}D^*$ scattering and local tetraquark operators in distillation

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$$\mathcal{O}^{DD^*}(t) \sim (\overline{u}\gamma_5 c)(\boldsymbol{p}_1, t)\ (\overline{d}\gamma_i c)(\boldsymbol{p}_2, t)$$

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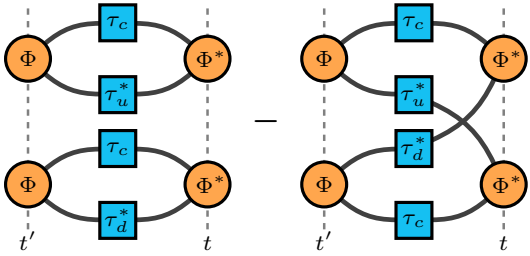

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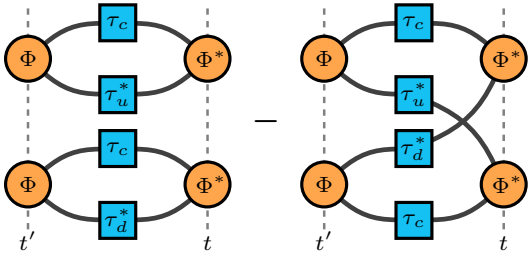

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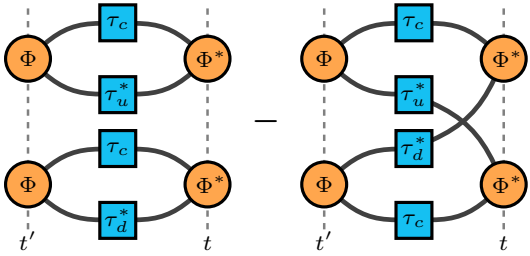

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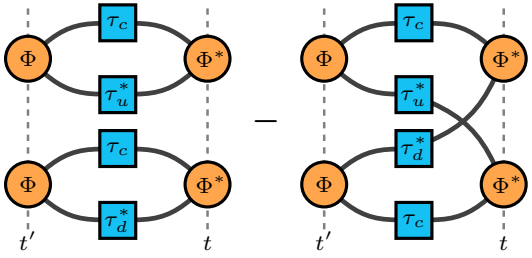

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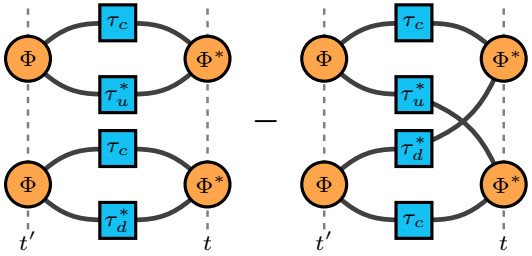

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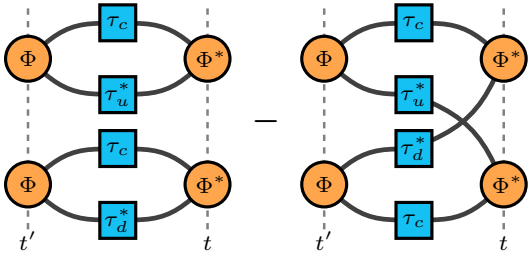

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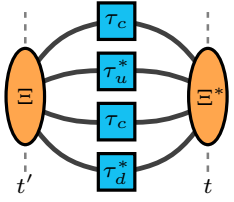

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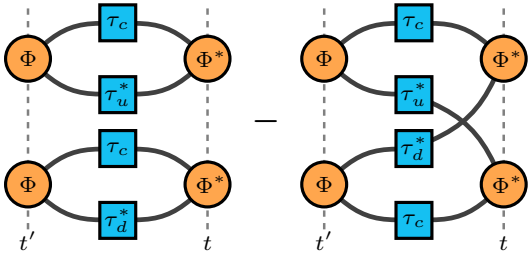

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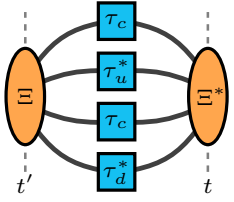

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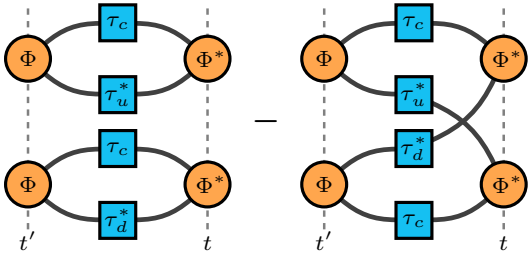

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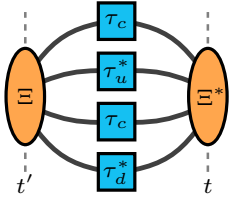
  $\rightarrow$ **Expensive**, especially in large volumes!



Position-space sampling for local tetraquark operators

Usual order of contraction produces rank-4 tensor
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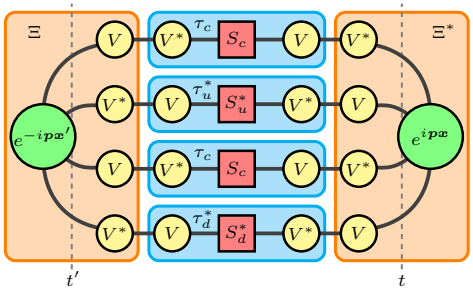

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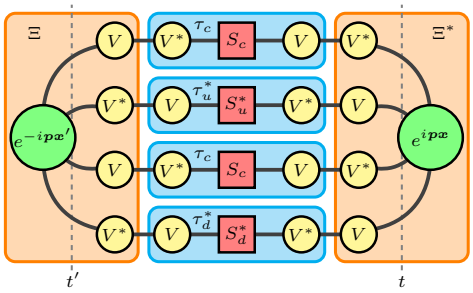

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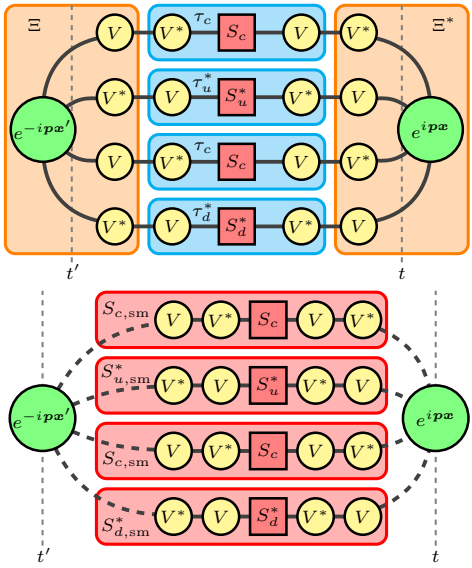

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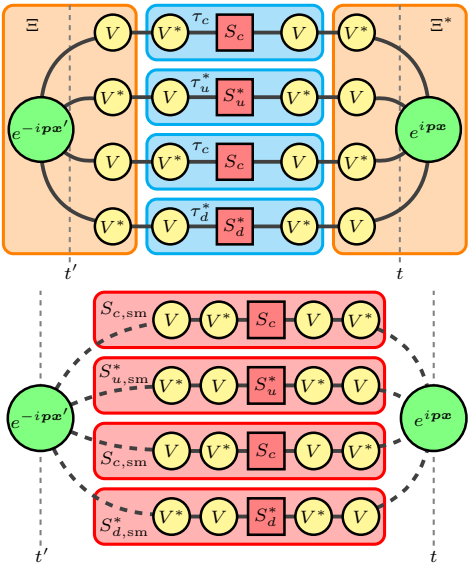

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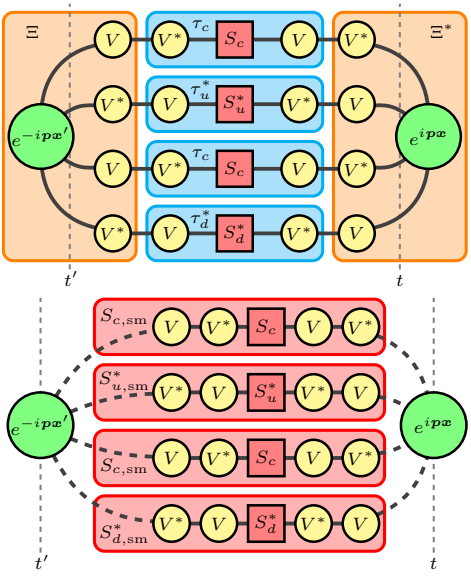

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- Position-space sampling for momentum projection:
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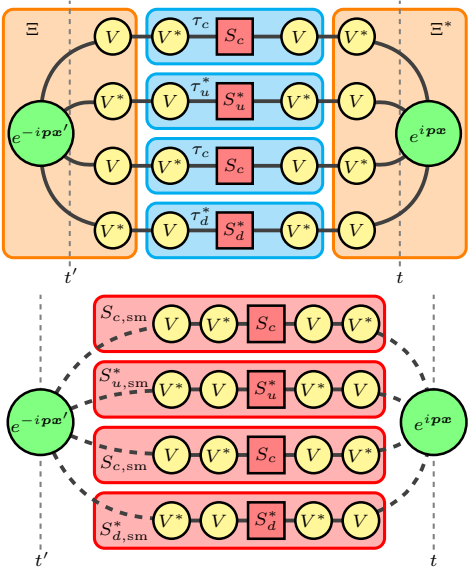
  - Random shift at sink and source: sampling from full lattice
    $\rightarrow$ **Unbiased estimator**



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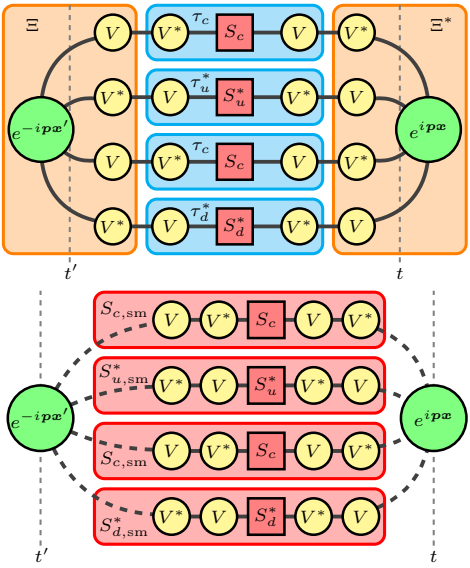
$\rightarrow$ Position-space sampling makes tetraquark operators affordable in distillation!



Results for T_{cc}

Lattice Setup

CLS gauge ensembles (B450, N202):

- $N_f = 3$ Wilson clover fermions
- $SU(3)$-flavour-symmetric point with physical $\frac{1}{3}(m_u + m_d + m_s)$
- $m_\pi \approx 420$ MeV
- Same action for valence charm quark
- c mass tuned to get physical $\frac{1}{3}(m_{D^0} + m_{D^+} + m_{D_s^+})$

Operator importance analysis for T_{cc}

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- 9 bilocal $D^{(*)}D^*$ operators
  - Organized in groups

$$D^{(*)}(\boldsymbol{k}^2)D^*(\boldsymbol{k}^2)\ \{N_{\text{ops}}\} \qquad \text{(integer momentum } \boldsymbol{k} = \frac{L}{2\pi}\boldsymbol{p}\text{)}$$

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- 3 tetraquark operators ($T\ \{3\}$)
  - Diquark-antidiquark ($(\overline{\mathbf{3}}_c \otimes \mathbf{3}_c)_{\mathbf{1}_c}$ color irrep)
  - local DD^* and D^*D^*

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Variational method to extract energies [Blossier et al. 2009]:

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$$D^{(*)}(\boldsymbol{k}^2)D^*(\boldsymbol{k}^2)\ \{N_{\text{ops}}\} \qquad \text{(integer momentum } \boldsymbol{k} = \frac{L}{2\pi}\boldsymbol{p}\text{)}$$

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Variational method to extract energies [Blossier et al. 2009]:

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$$\Delta E_{\text{eff},n}(t) = E_{\text{eff},n}(t) - m^{D}_{\text{eff}}(t) - m^{D^*}_{\text{eff}}(t)$$

  (where all effective energies have plateaued individually)

Operator importance analysis for T_{cc}

Operator basis (rest frame T_1^+):

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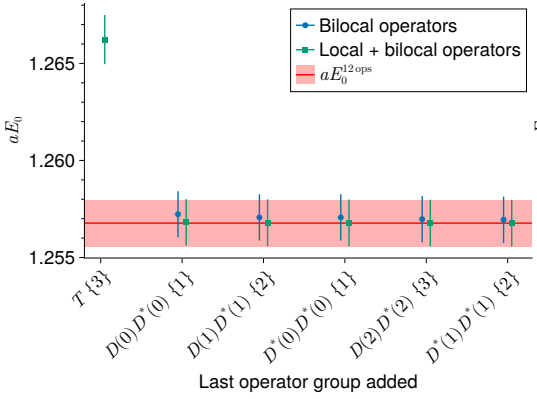

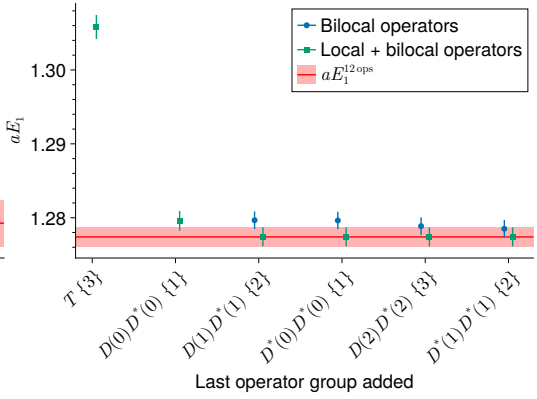

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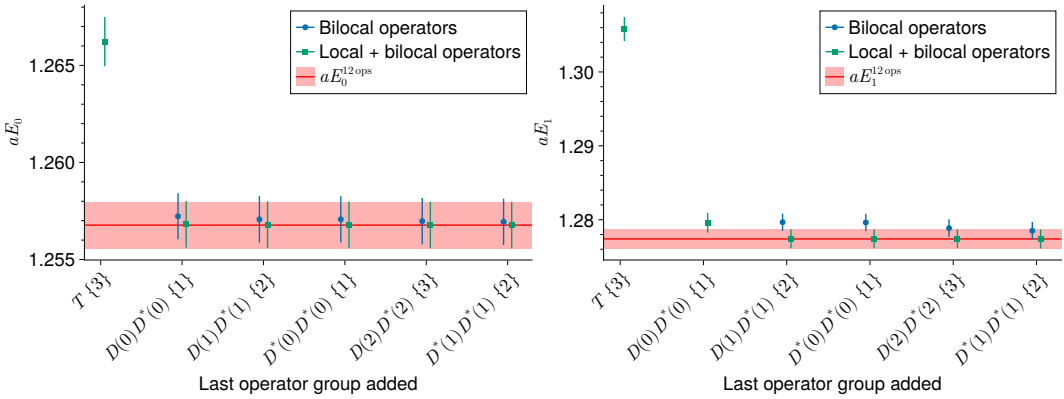

- Negligible effect for ground state

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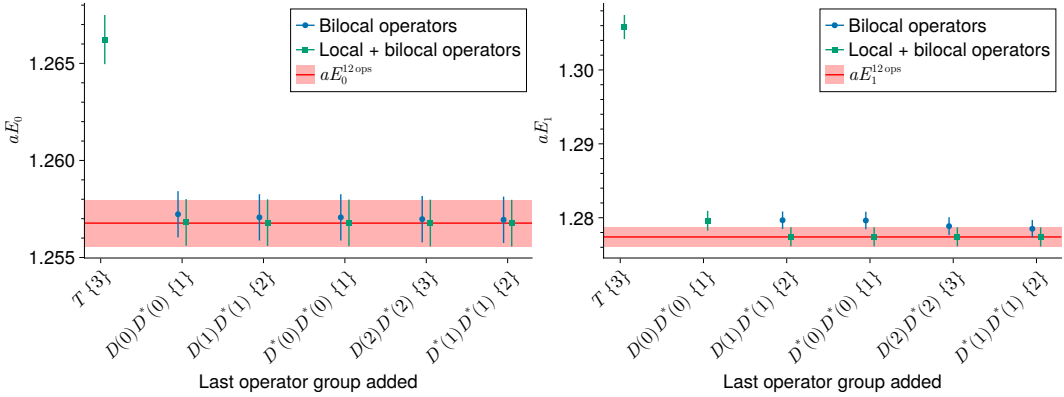

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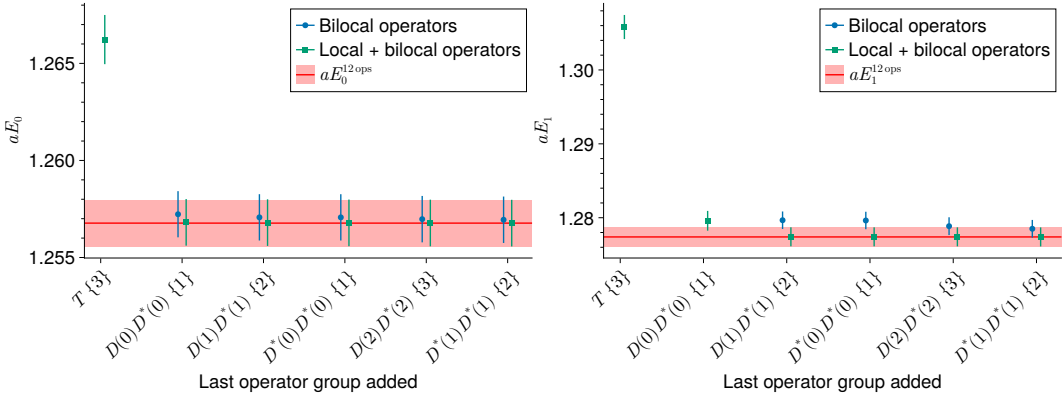

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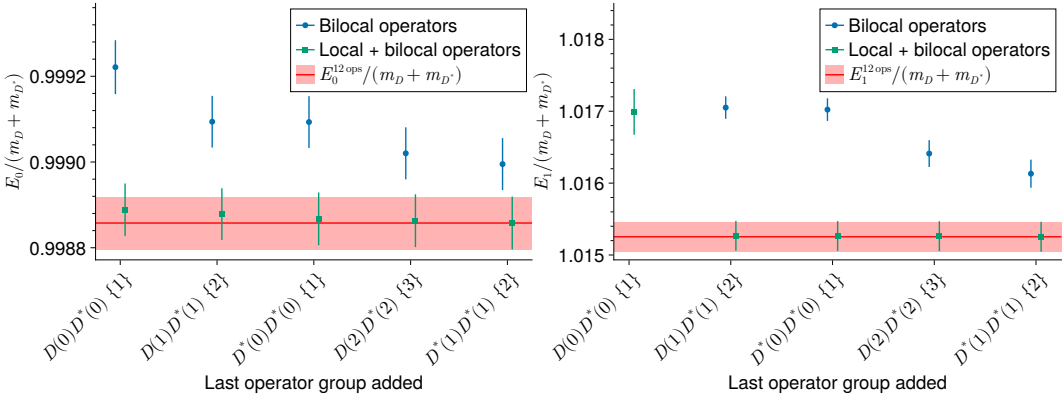
In Lüscher analysis: Correlation with non-interacting energies is relevant!

$\rightarrow$ Look at $E_n/(m_D + m_{D^*})$

Operator importance analysis for T_{cc} (ratio with threshold energy)



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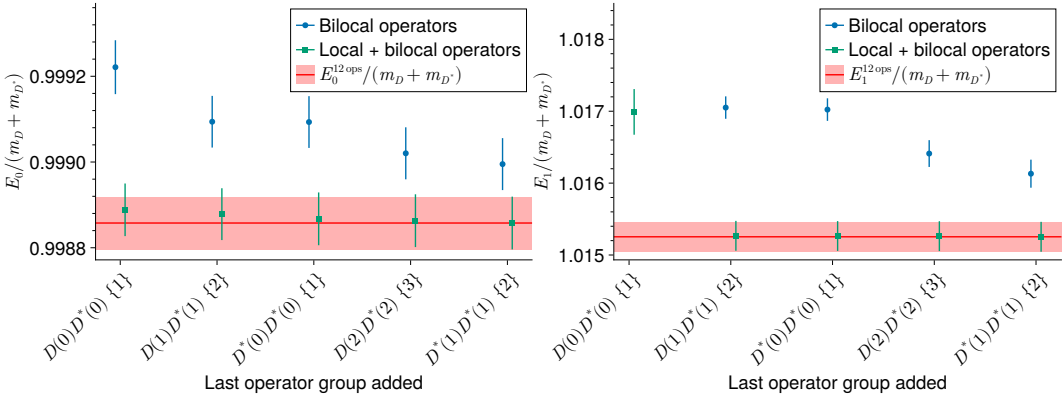

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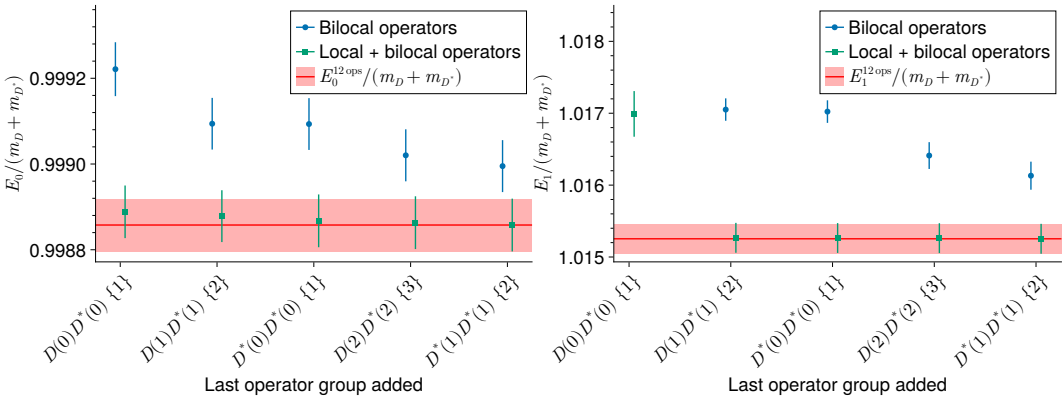

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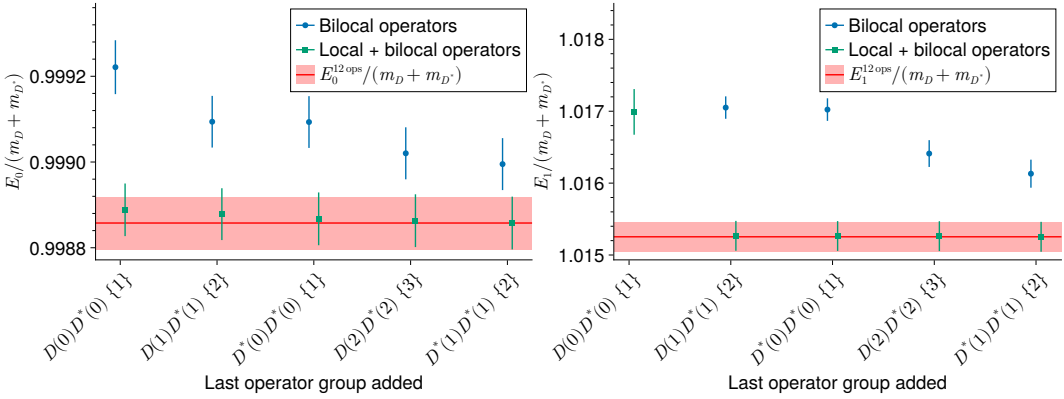

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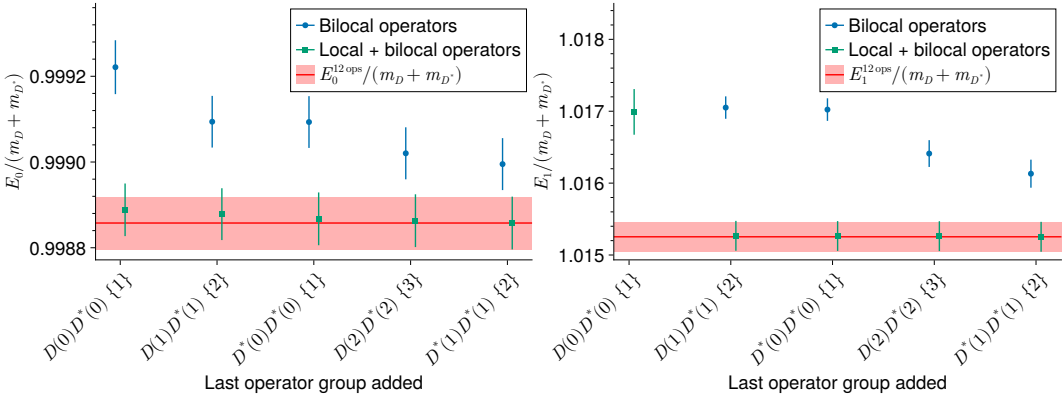

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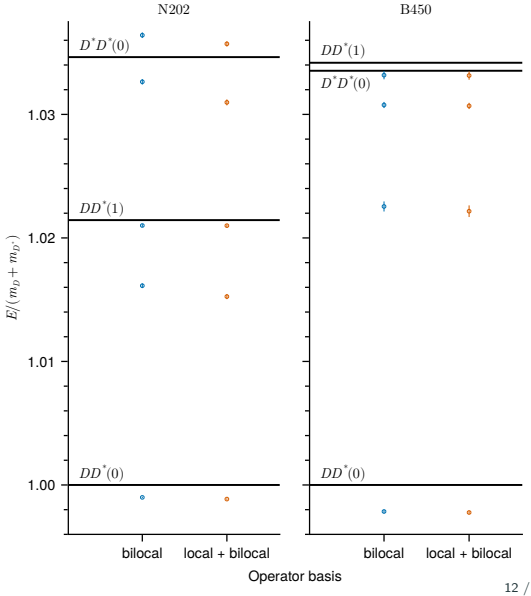
  - Fast convergence when including local operators
  - Step-like decreases without them

Finite-volume T_{cc} spectrum with and without local tetraquark operators

Rest frame T_1^+ spectrum



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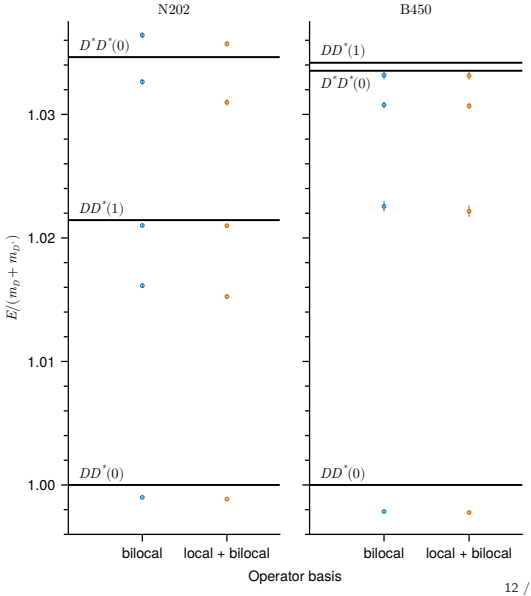

Finite-volume T_{cc} spectrum with and without local tetraquark operators

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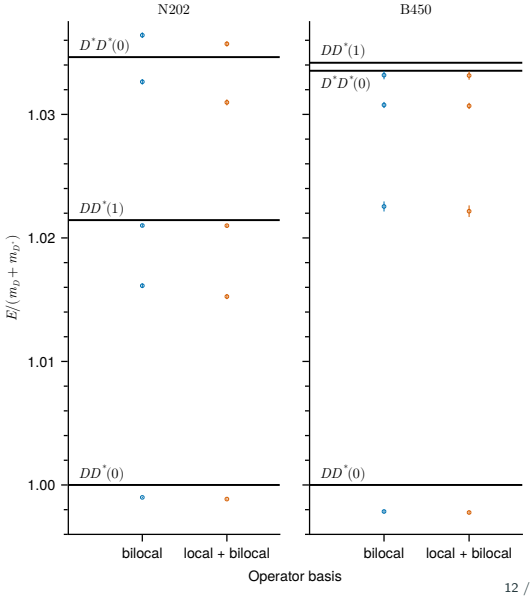

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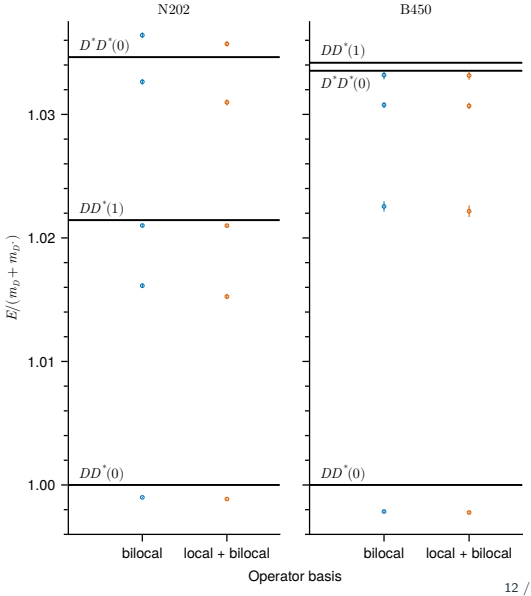

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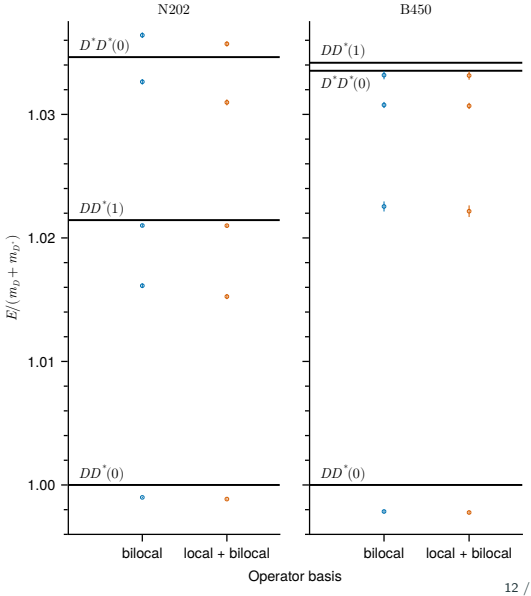
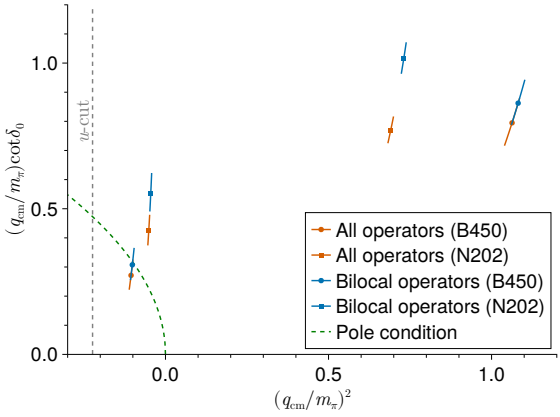
→ **Considerable systematic error** without local operators!



s-wave Lüscher analysis

s-wave DD^* scattering phase shift:



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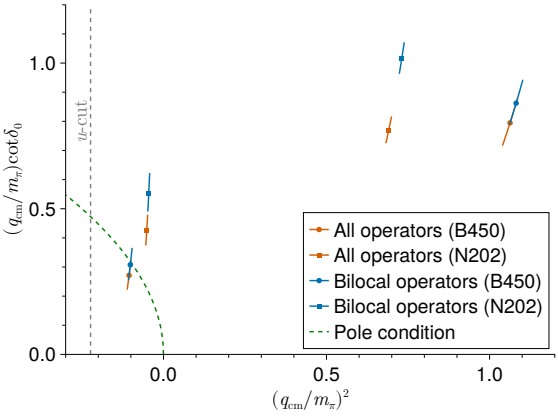

s-wave Lüscher analysis

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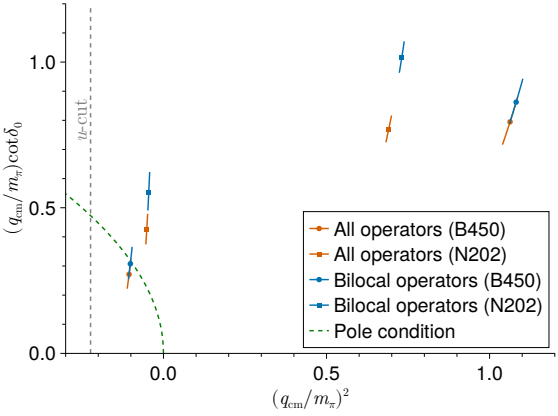
- Shifts also appear in scattering phase shift



Conclusion

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Thank you for your attention!

References

References

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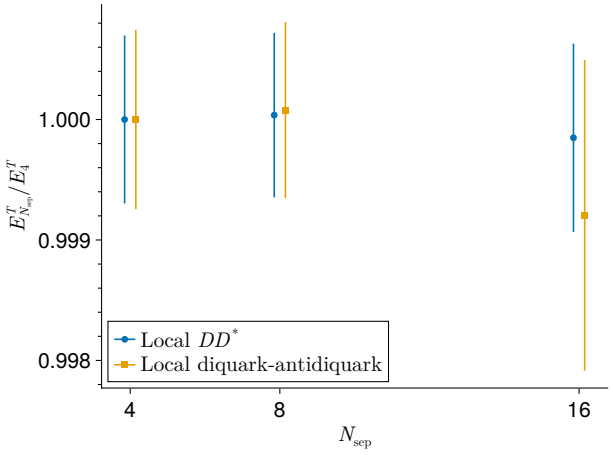
Backup slides

N_{sep} analysis



Plateau values $E^T_{N_{\text{sep}}}$ from plateau fits to the effective energy of the local DD^* and diquark-antidiquark two-point functions vs. the point separation N_{sep}. The plateau values are normalized with the $N_{\text{sep}} = 4$ value E^T_4.

CLS gauge ensembles

Ensemble	$N_s^3 \times N_t$	β	a [fm]	$\kappa_u = \kappa_d = \kappa_s$	κ_c	N_{cfg}	N_{src}	N_v	N_{sep}
B450	$32^3 \times 64$	3.46	0.0749	0.136890	0.126243	1612	8	32	8
N202	$48^3 \times 128$	3.55	0.0633	0.137000	0.128423	899	8	68	8

- $N_f = 3$ Wilson clover fermions
- $SU(3)$-flavour-symmetric point with physical $\frac{1}{3}(m_u + m_d + m_s)$
- $m_\pi \approx 420$ MeV
- Same action for valence charm quark
- c mass tuned to get physical $\frac{1}{3}(m_{D^0} + m_{D^+} + m_{D_s^+})$