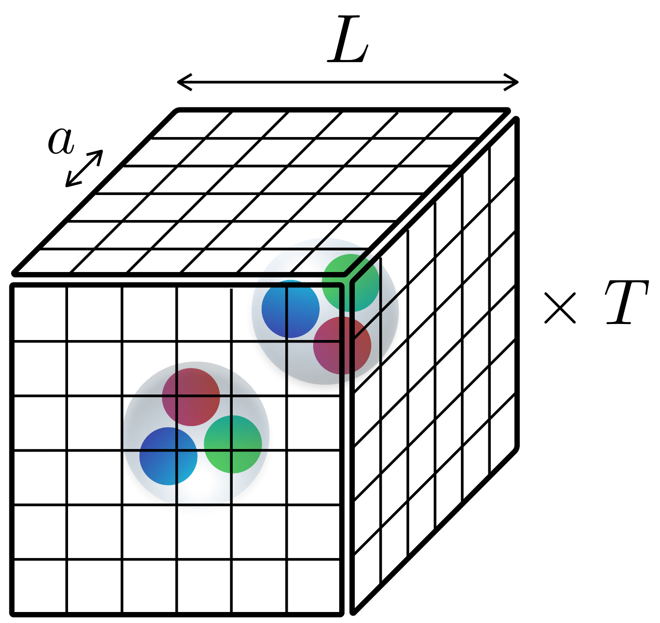
Studying the interactions between hyperons and nucleons from Lattice QCD

Marc Illa

Brief introduction to Lattice QCD

LQCD is a nonperturbative approach based on the path-integral formalism, where QCD is solved on a discretized finite volume



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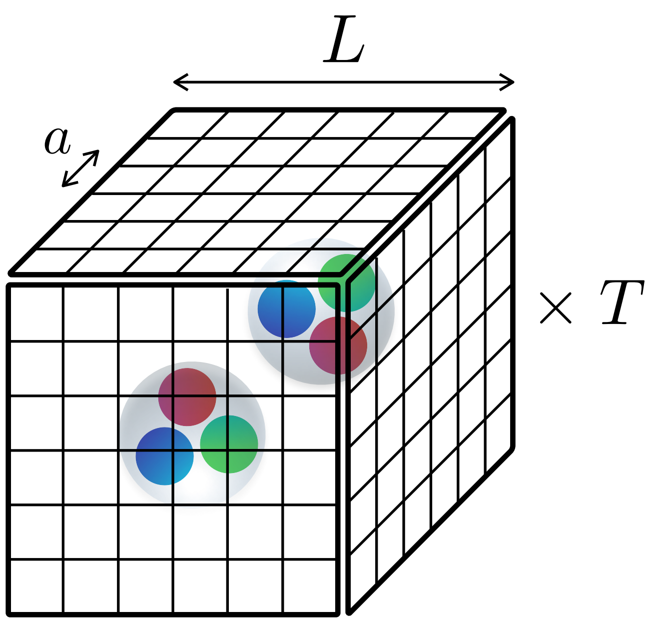


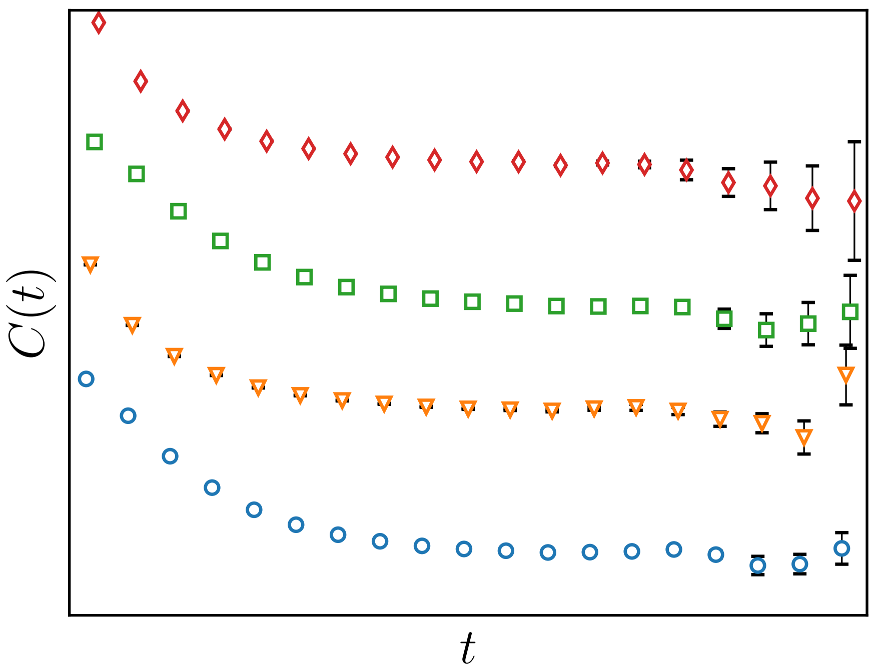
There are two different approaches:

- The potential method
- The direct method

Brief introduction to Lattice QCD

With the direct method, the finite-volume energy levels are extracted from two-point correlation functions

Brief introduction to Lattice QCD

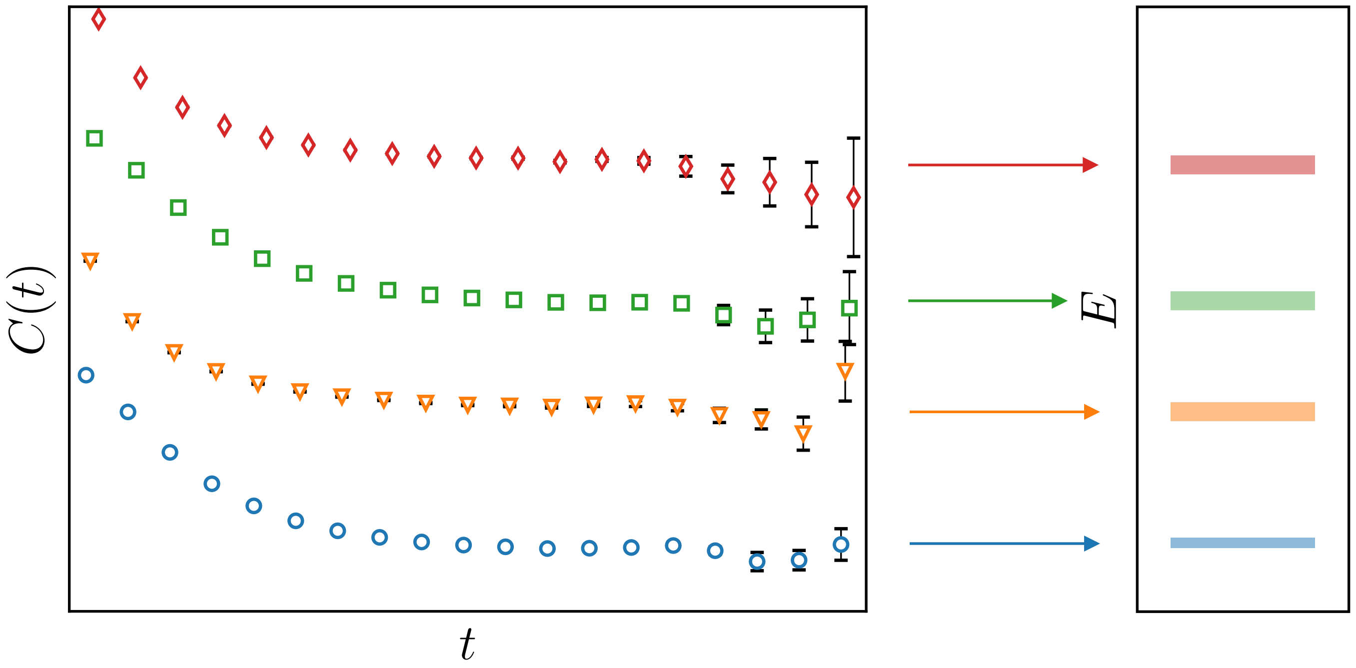


With the direct method, the finite-volume energy levels are extracted from two-point correlation functions

$$C_B(t, \mathbf{p})$$
$$C_{B_1 B_2}(t, \mathbf{p})$$

Input: spatial structure of operators with specific quantum numbers

Brief introduction to Lattice QCD



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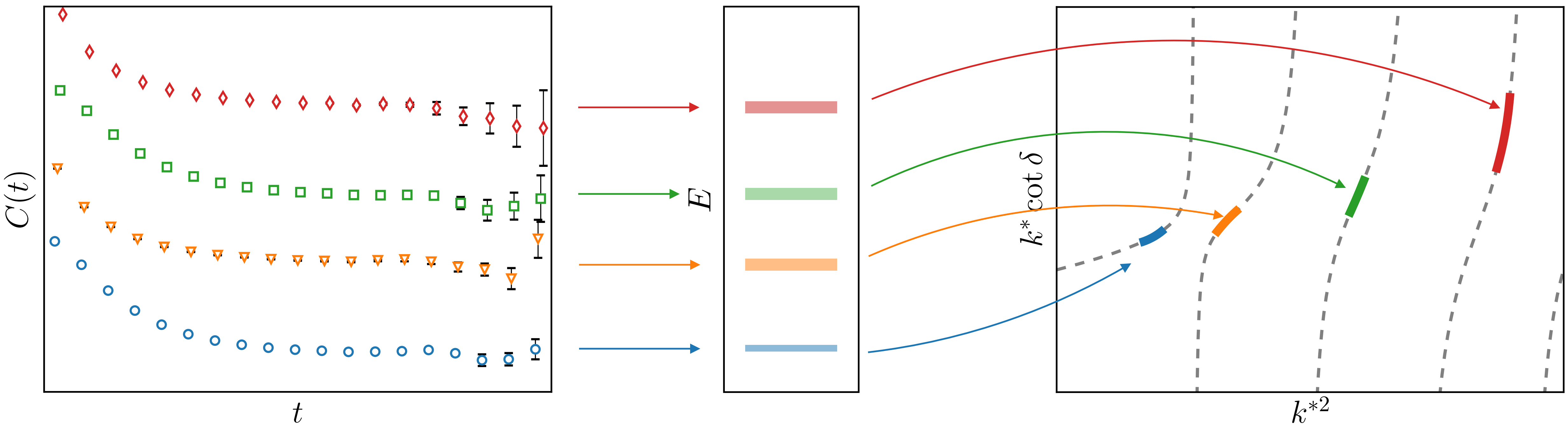
$$C_B(t, \mathbf{p})$$
$$C_{B_1 B_2}(t, \mathbf{p}) \longrightarrow \Delta E$$

Fit temporal dependence

Input: spatial structure of operators with specific quantum numbers

Brief introduction to Lattice QCD



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$\longrightarrow$ Fit temporal dependence $\longrightarrow$ ΔE $\longrightarrow$ Lüscher's method $\longrightarrow$

$$k^* \cot\delta$$
$$B$$

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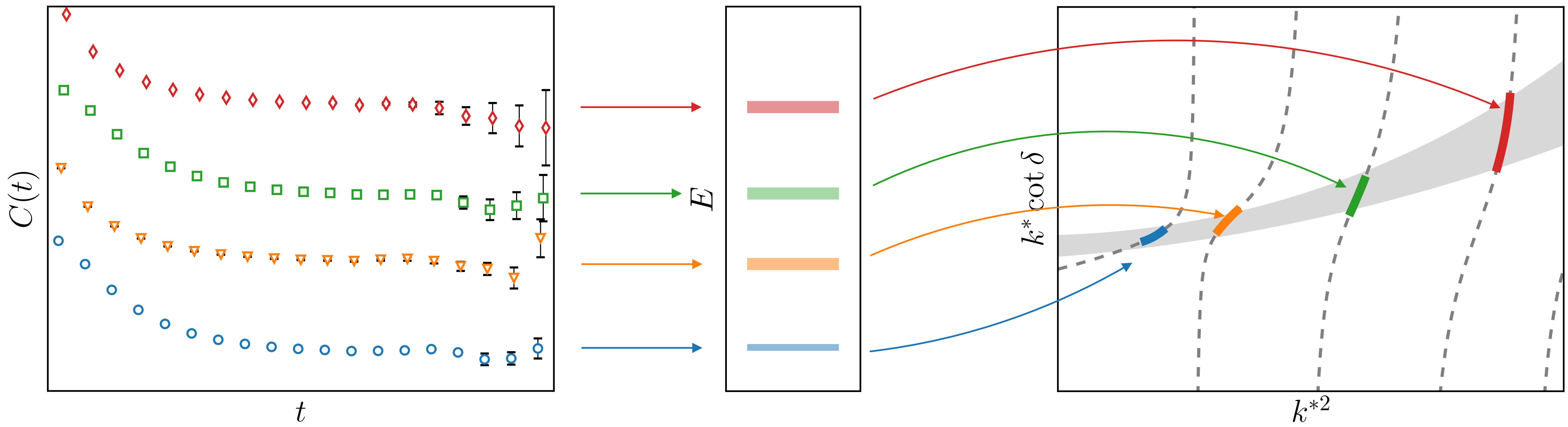

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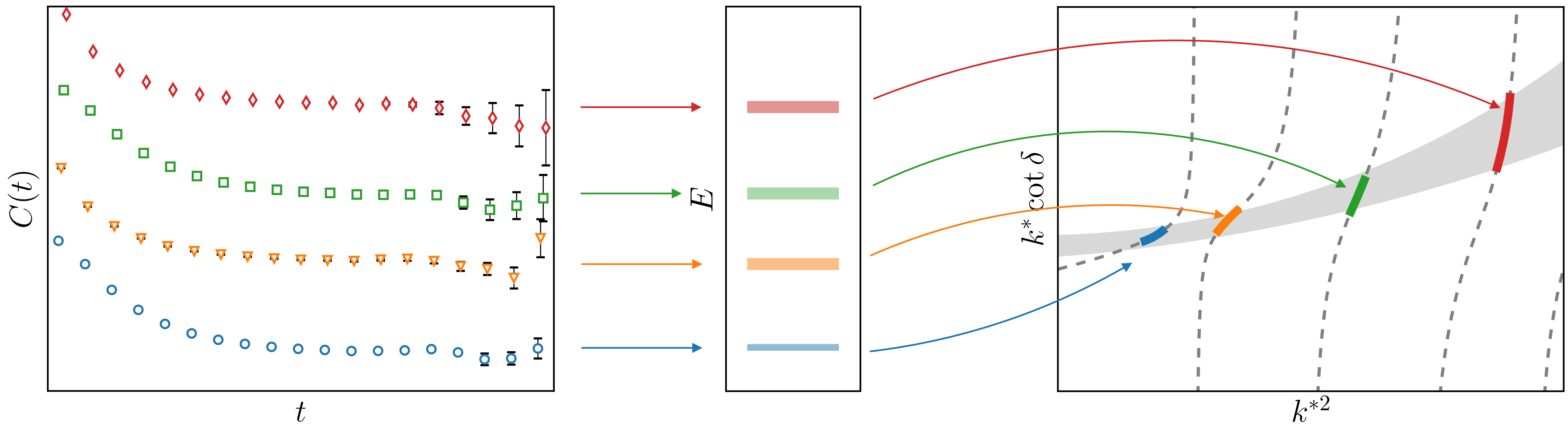

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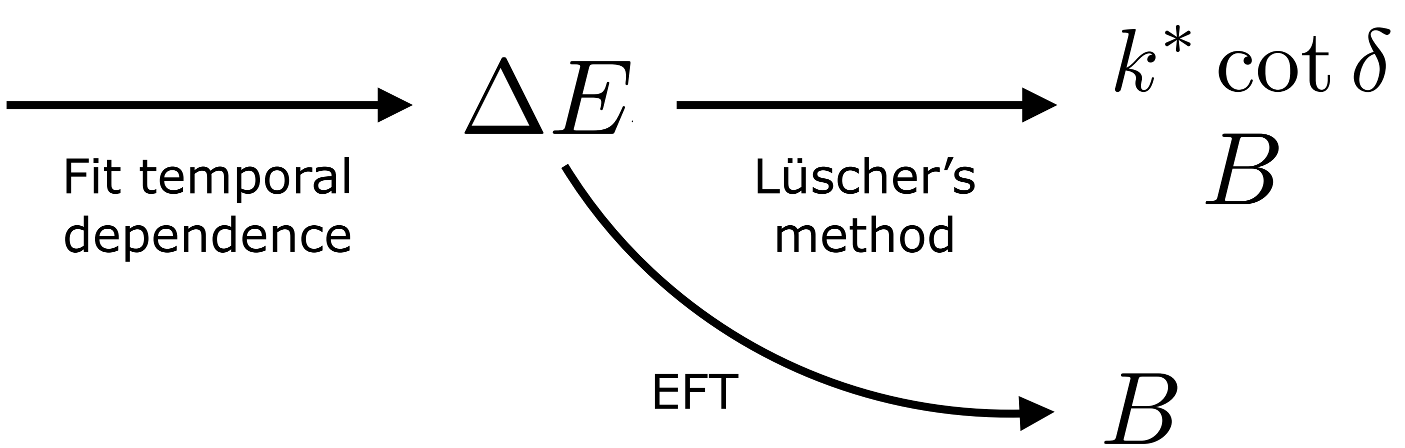
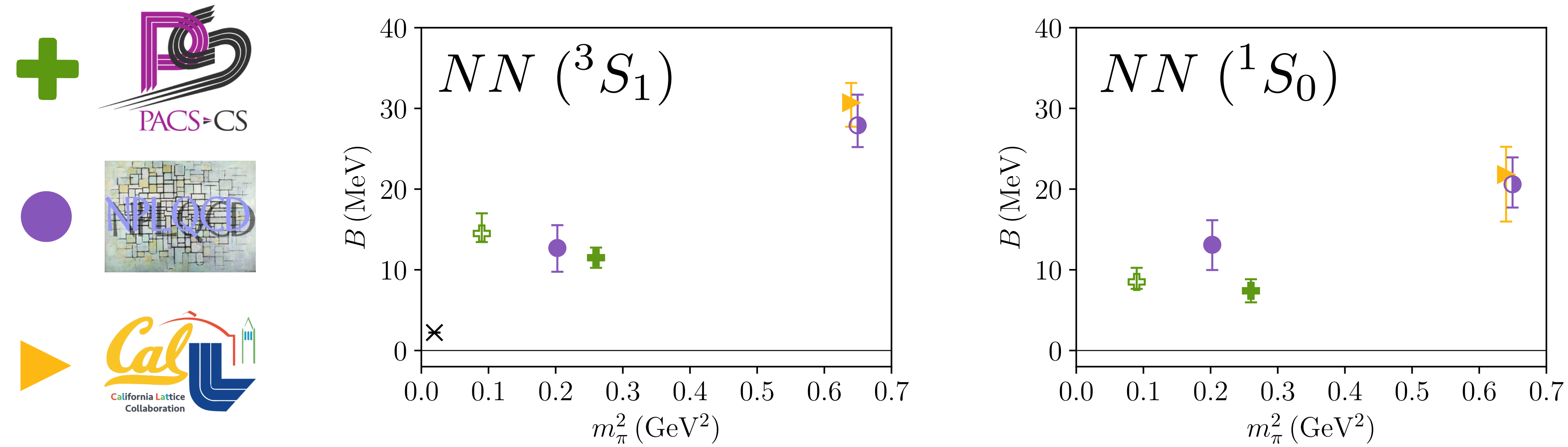


Eliyahu, Bazak and Barnea, PRC102 (2020)
Detmold and Shanahan, PRD103 (2021)

Present status

Traditionally, calculations with the direct approach were performed with asymmetrical correlators (different source and sink operators), leading to bound NN systems with unphysical quark masses



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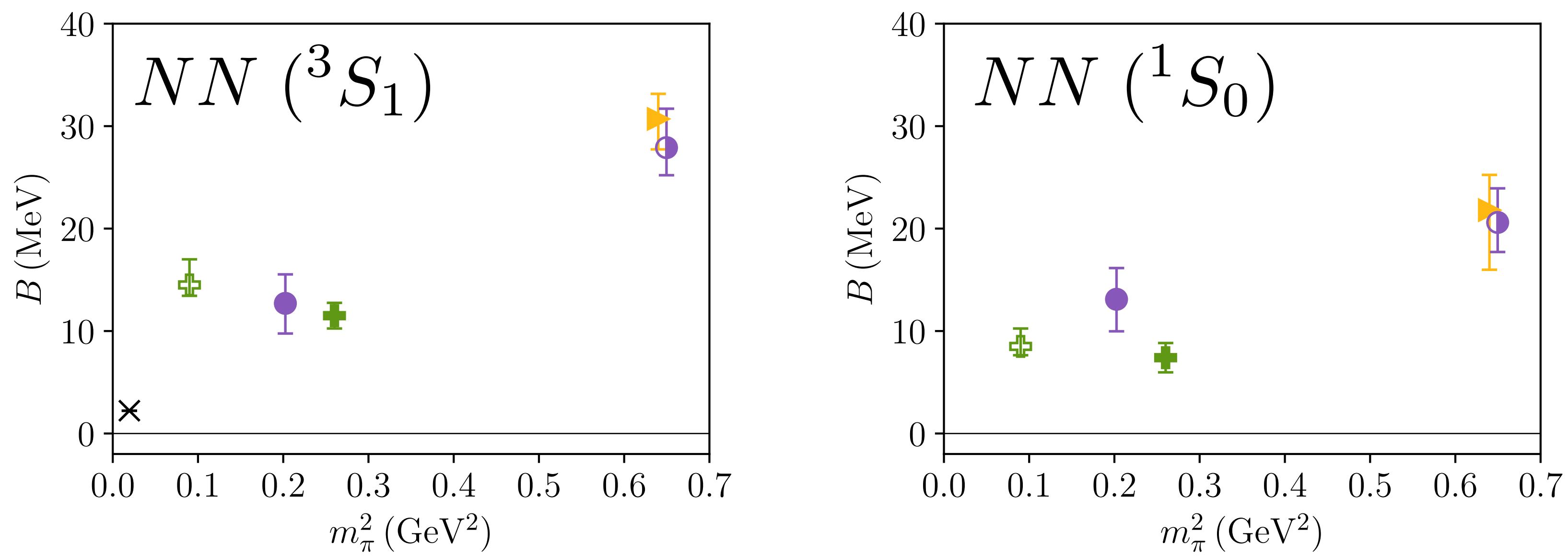
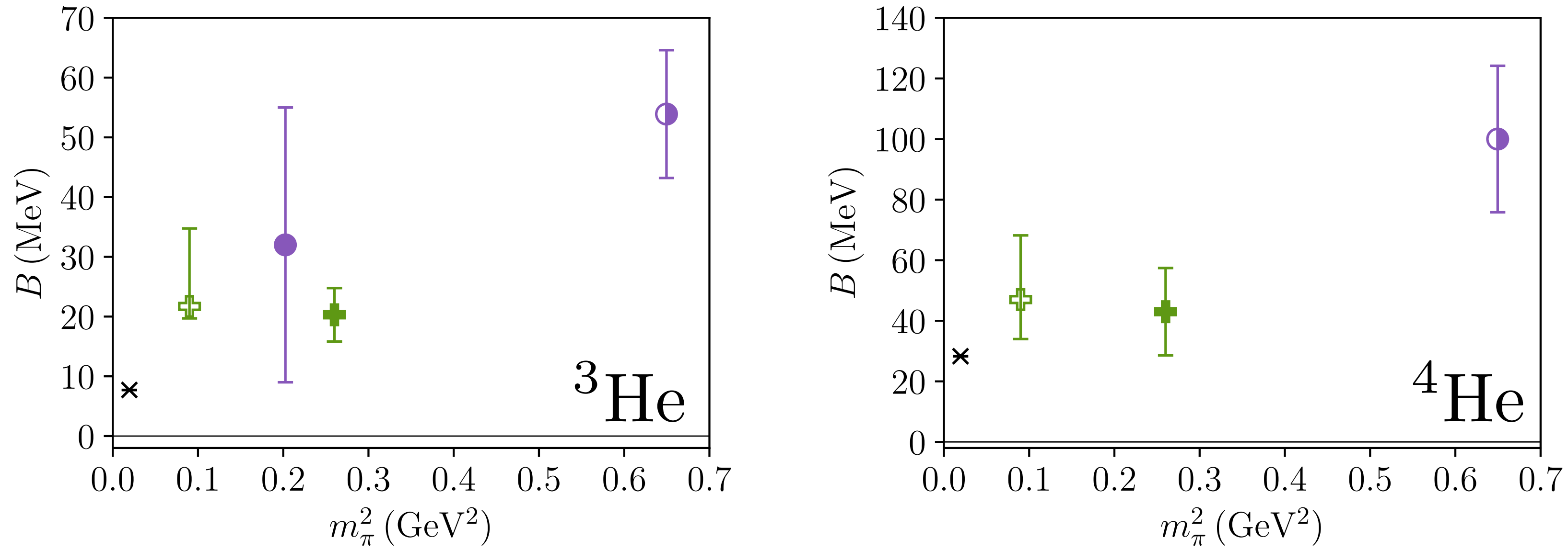


And also 3- and 4-body bound systems



Present status

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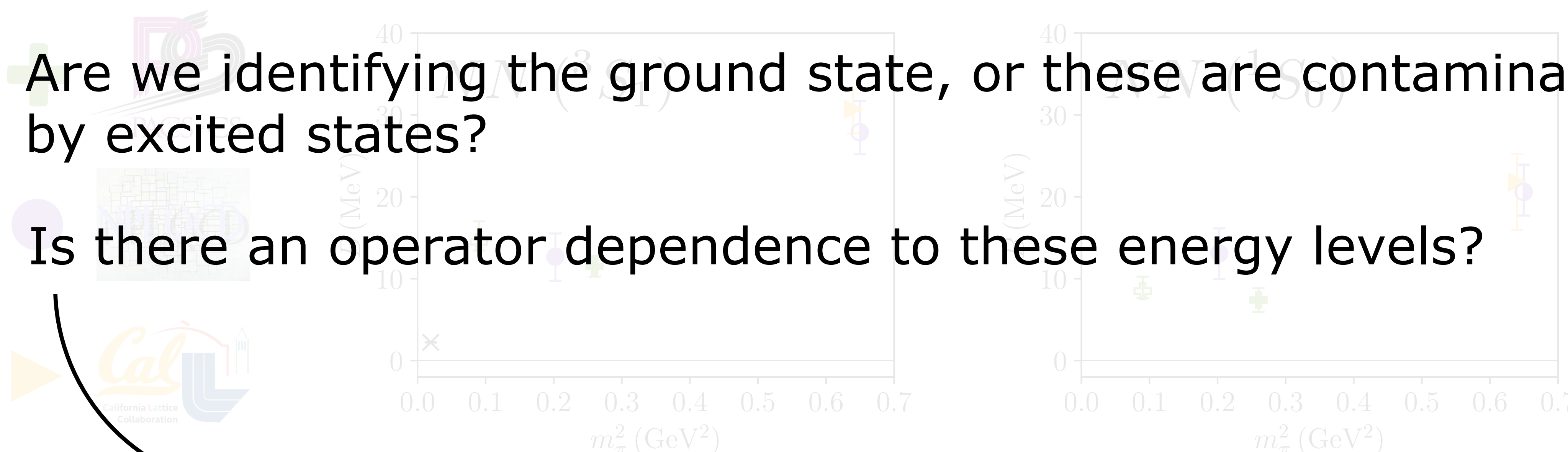
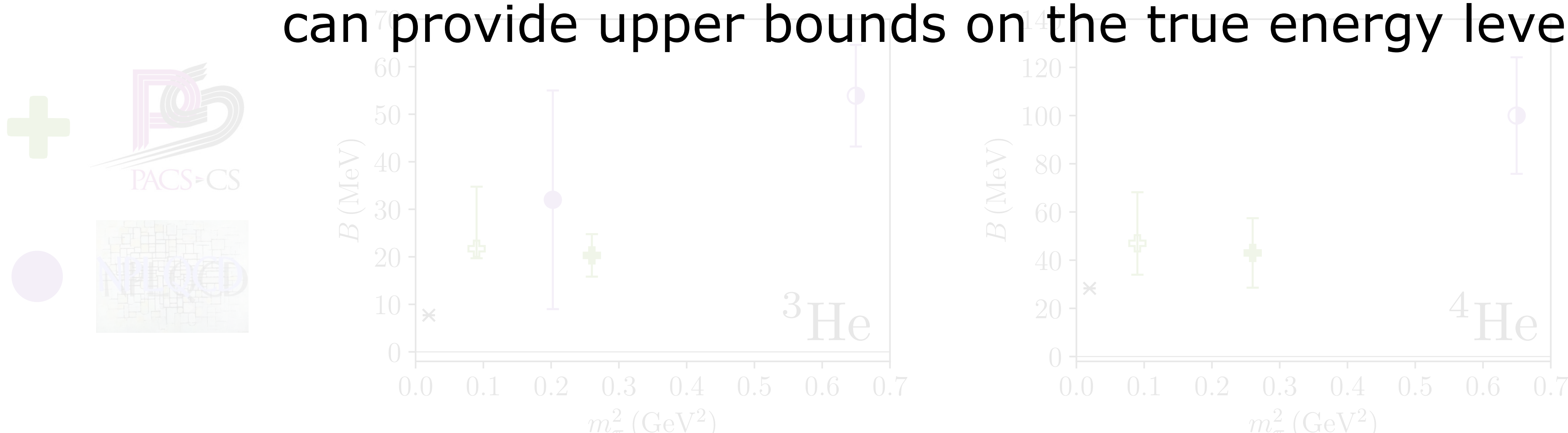
Are we identifying the ground state, or these are contaminated by excited states?

Is there an operator dependence to these energy levels?



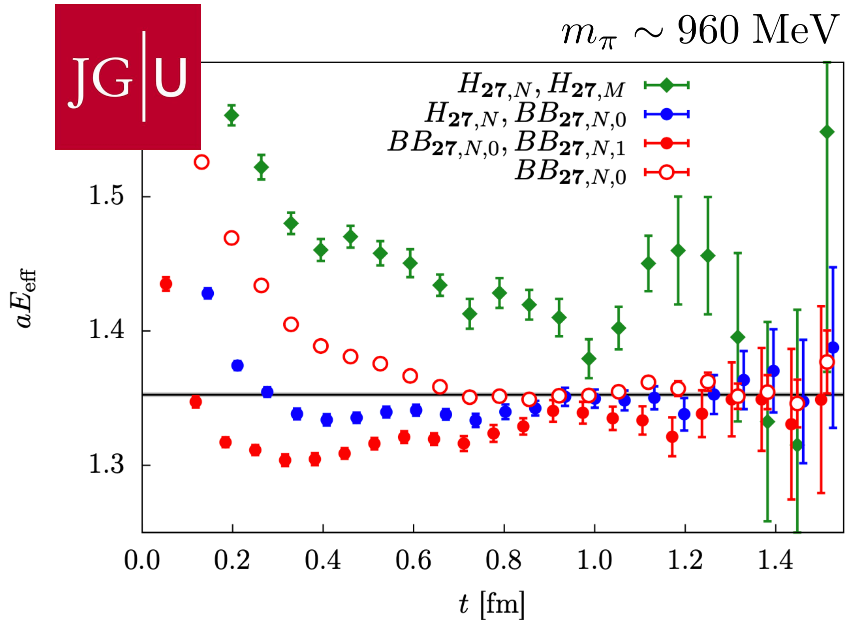
A possible answer to these questions might be found through a variational analysis, where the lattice results can provide upper bounds on the true energy levels

And also 3- and 4-body bound systems



First variational calculations

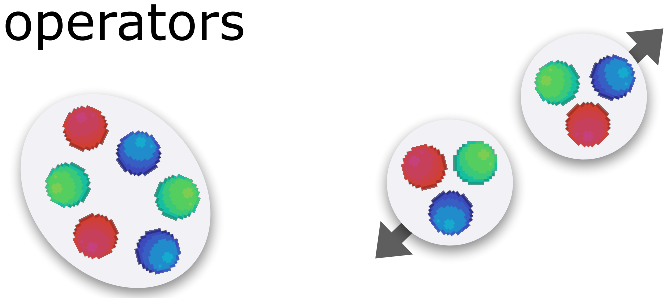
The first variational calculations appeared in 2018 by the Mainz group, and additional studies were performed in 2020-21 by CalLat and NPLQCD



Francis et al., PRD 99 (2019)

Non-hermitian matrices with hexaquark and dibaryon-like operators

Hermitian matrices with only hexaquark or dibaryon-like operators



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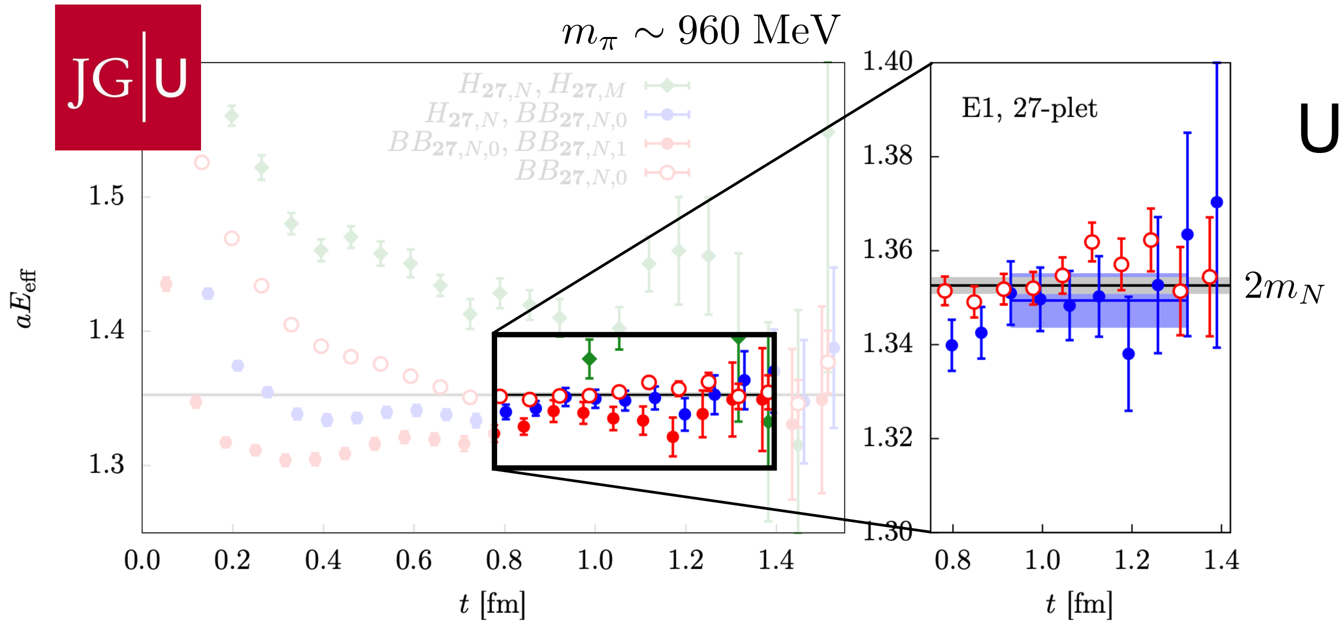

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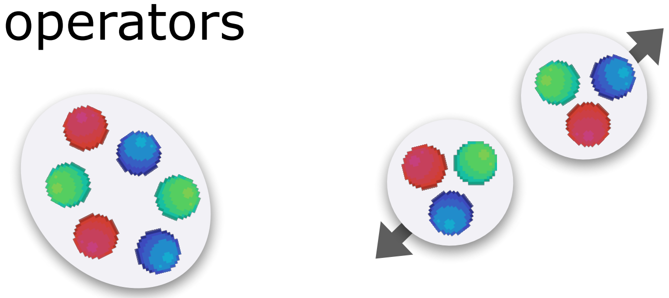

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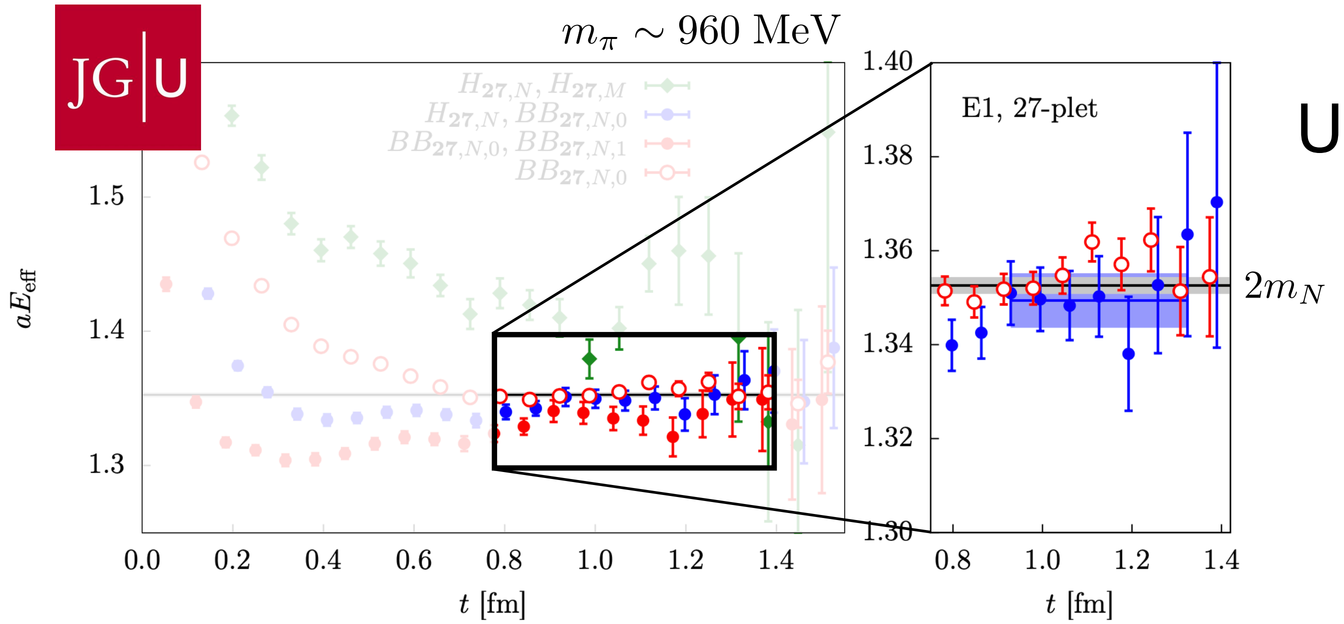

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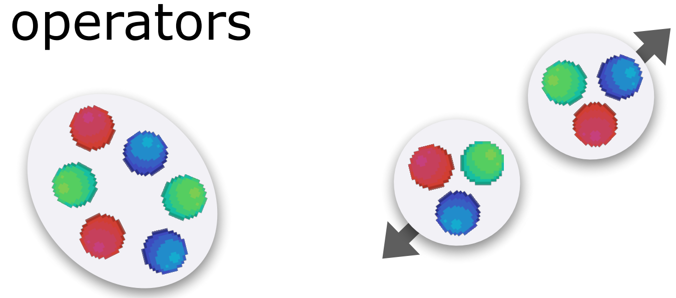

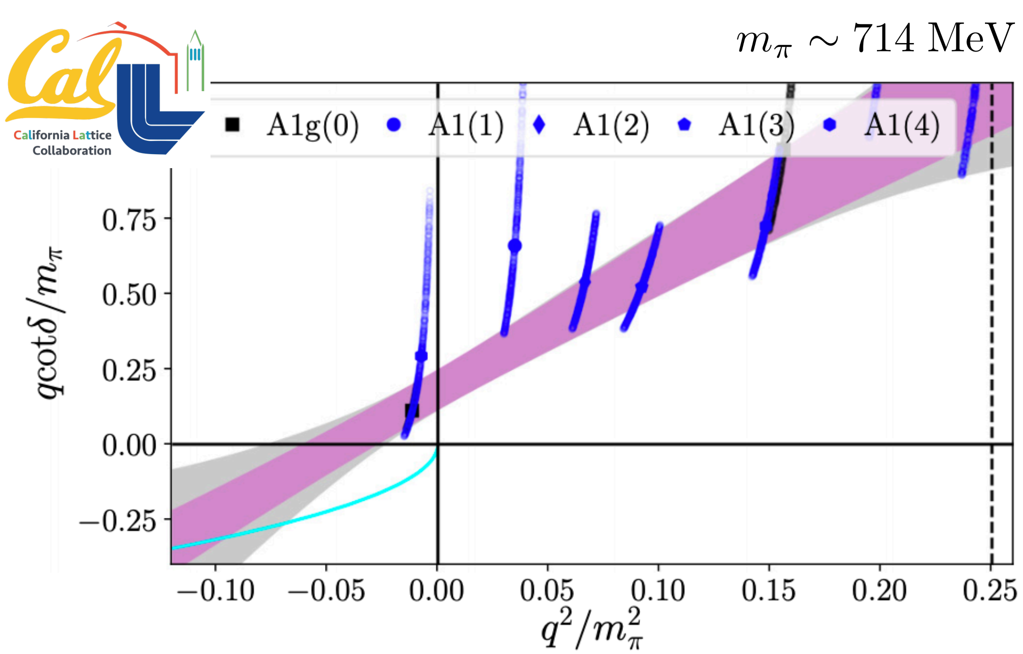

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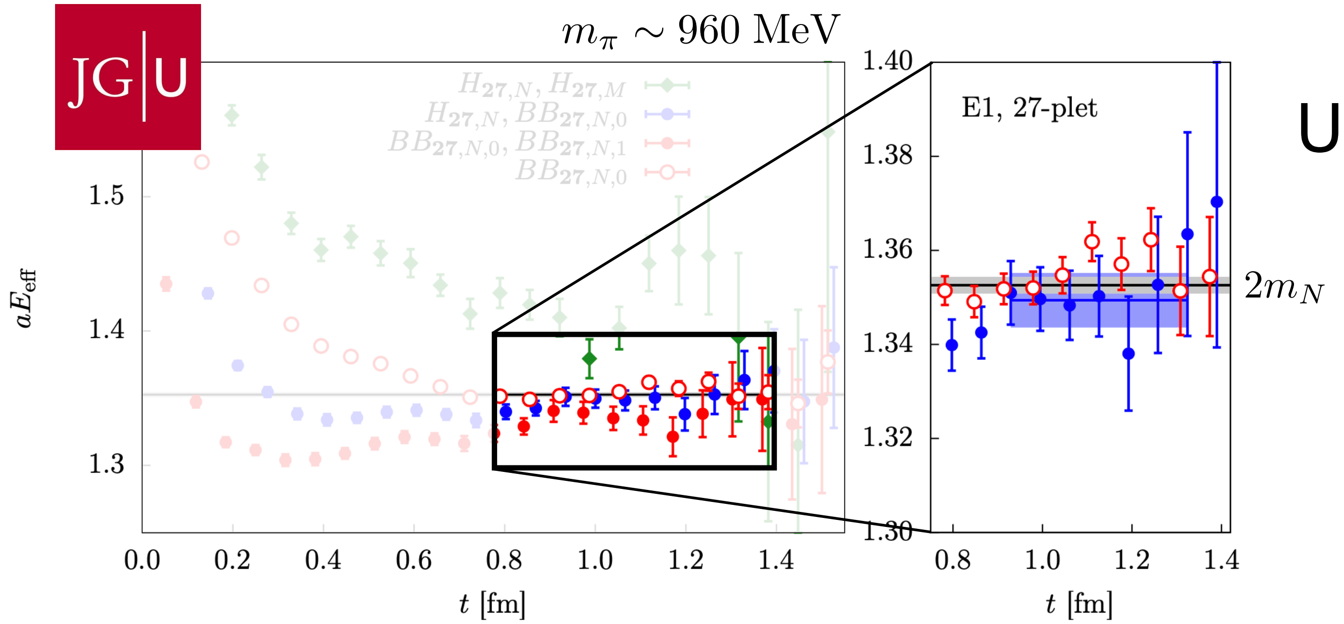

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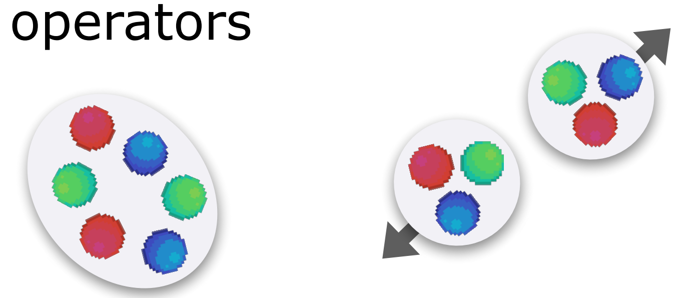

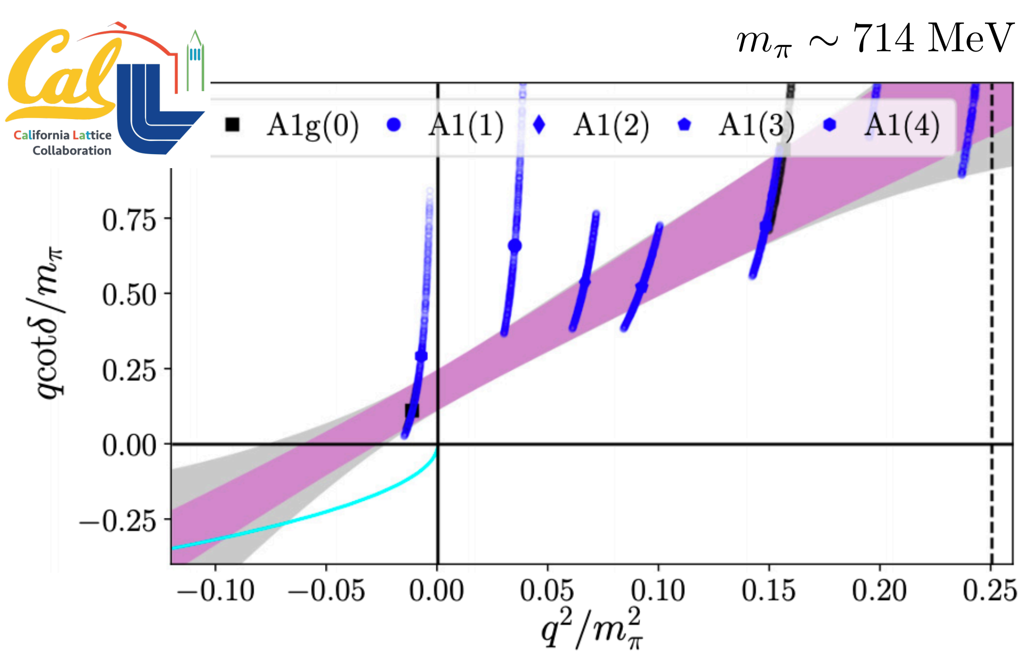

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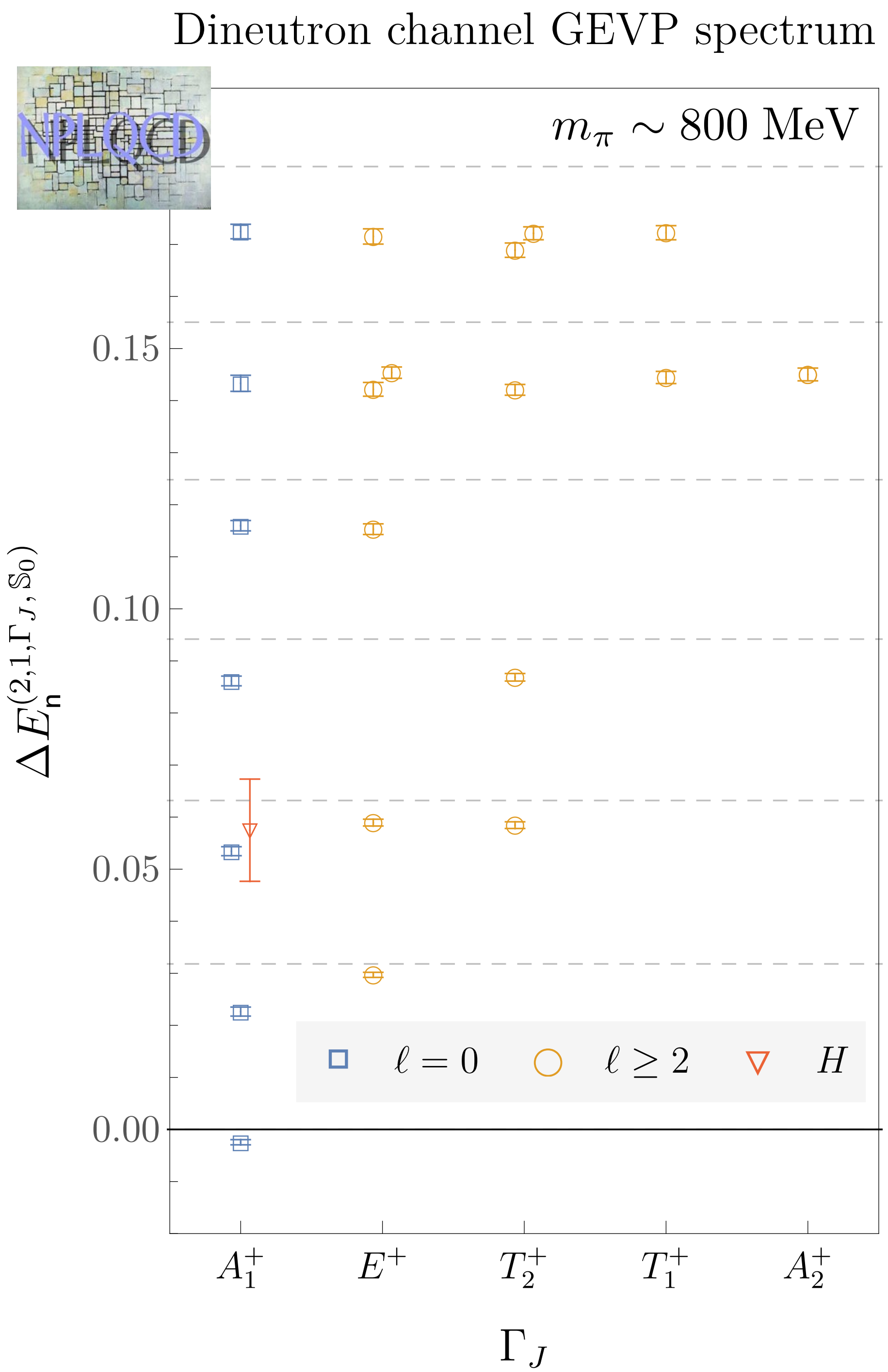
What about the hexaquark operators, which were used to find the bound states?

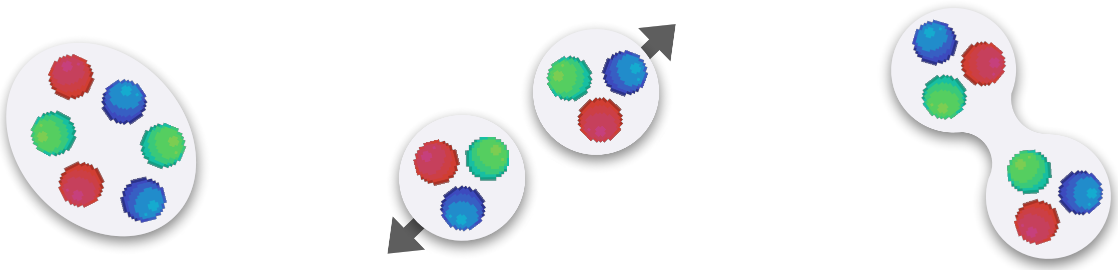
First variational calculations



Amarasinghe et al. [NPLQCD], arXiv:2108.10835 [hep-lat]

Hermitian matrices with three operators:

- Hexaquark
- Dibaryon
- Quasilocal ⟶ EFT inspired, with wavefunction that decays exponentially



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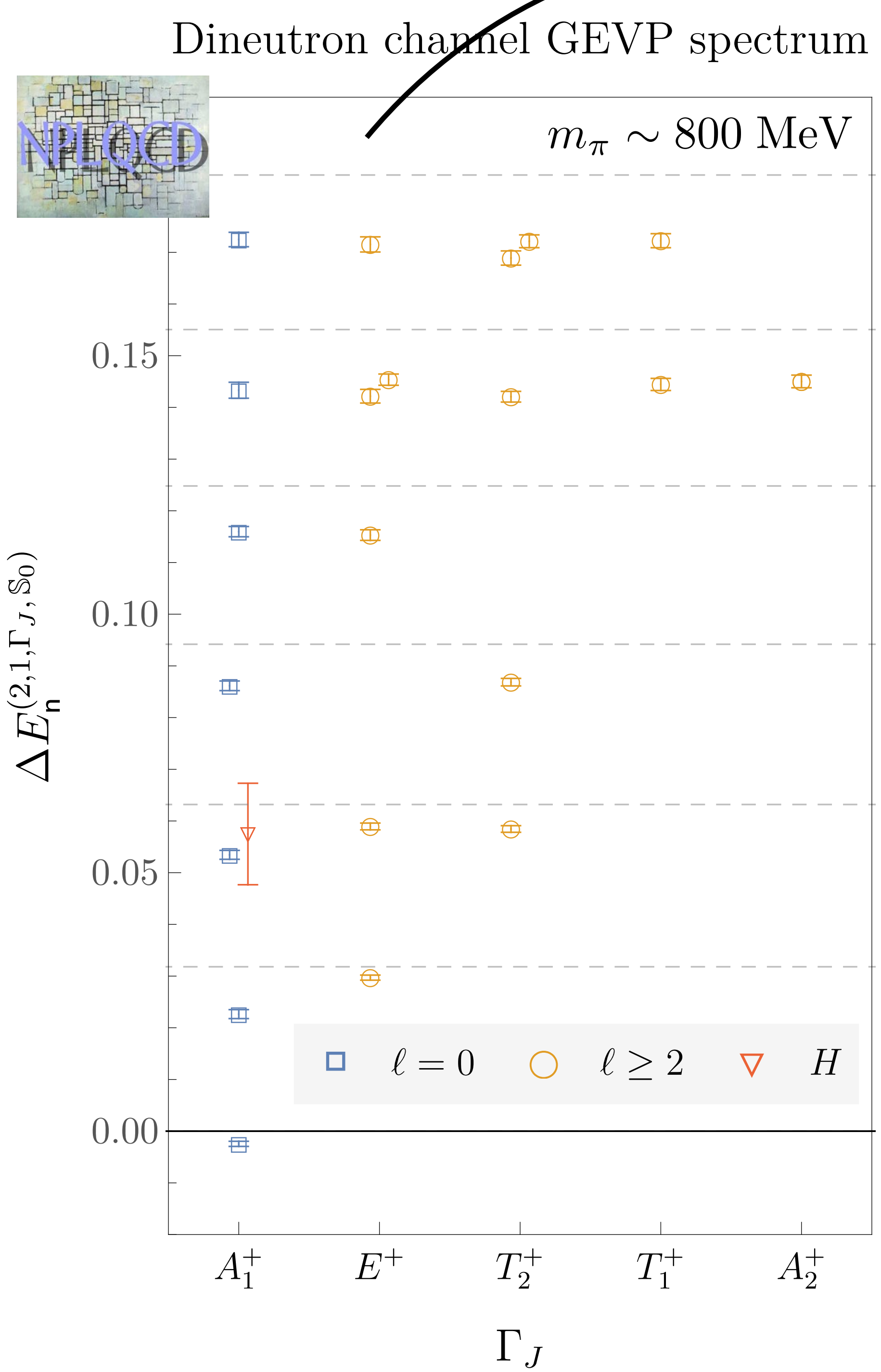

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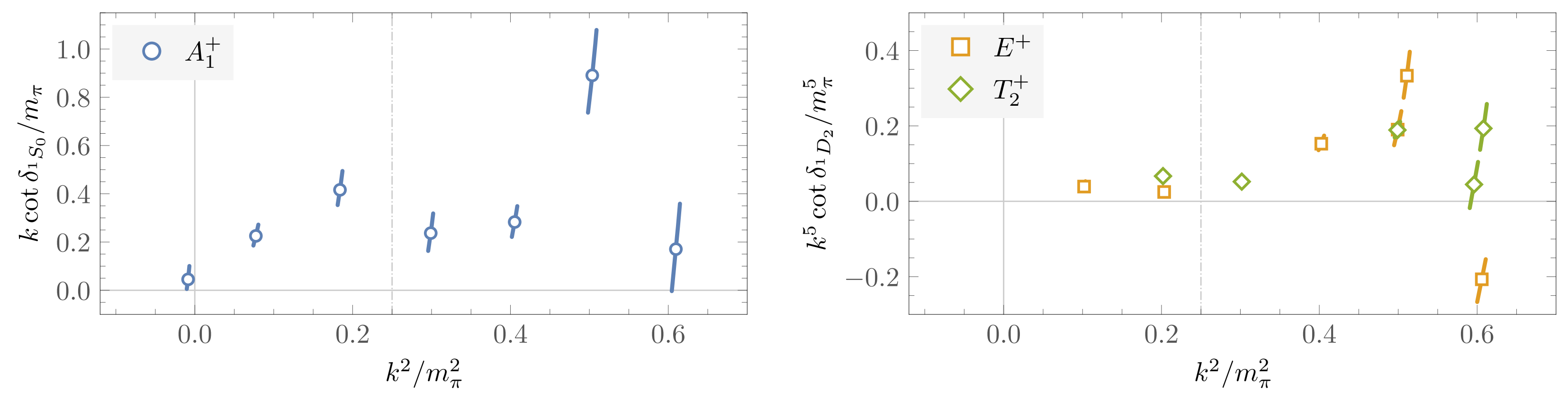
Using generalizations of Lüscher's QC

Luu and Savage, PRD83 (2011)
Briceño, Davoudi and Luu, PRD88 (2013); +Savage, PRD88 (2013)

(without mixing for now)



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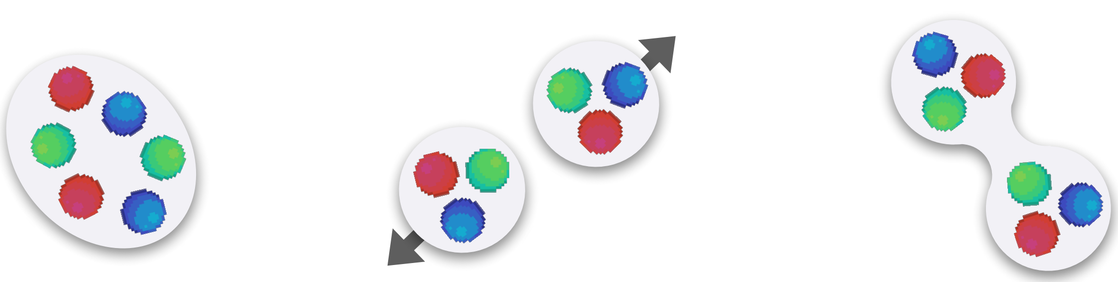


Robustness of variational approach

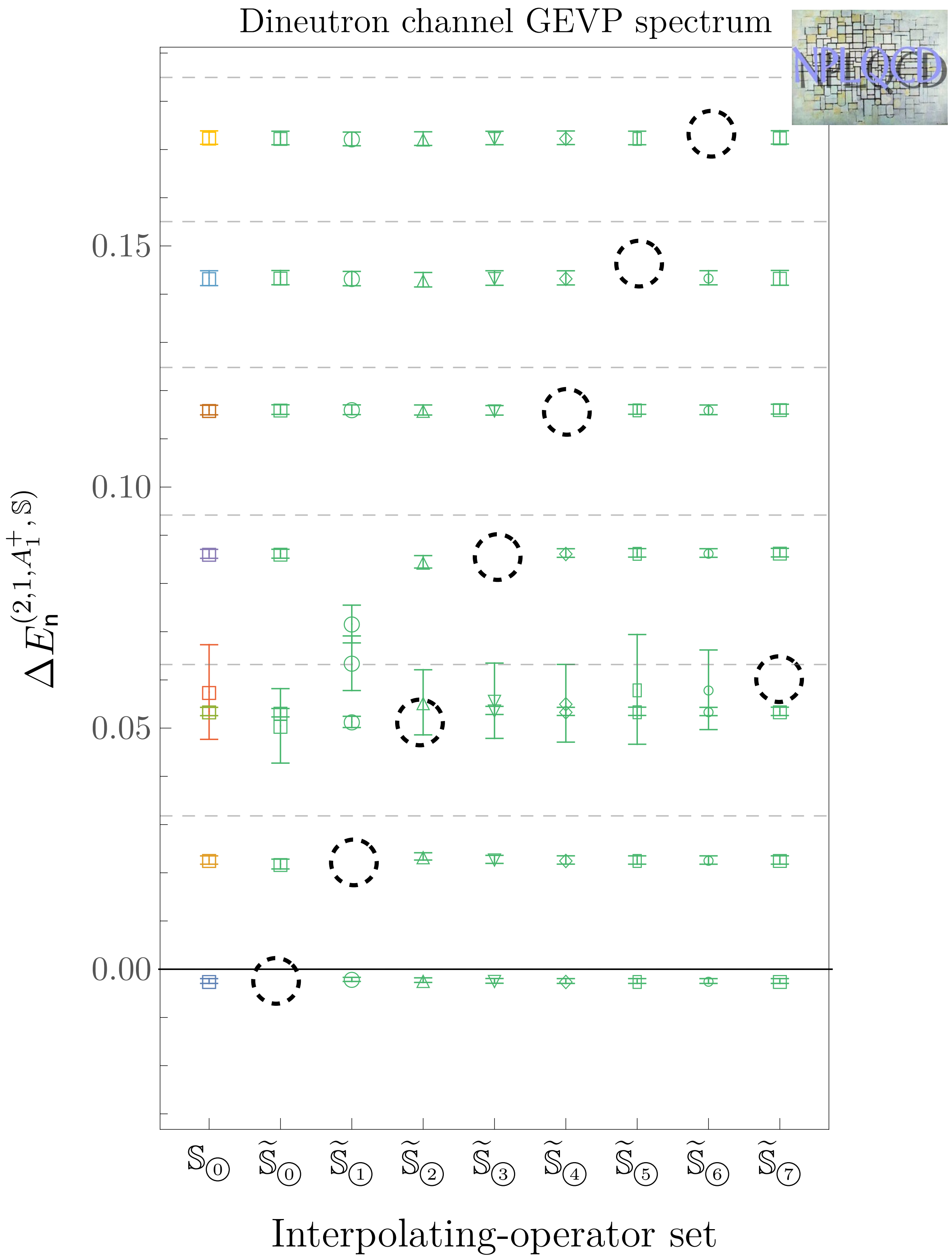
Large interpolating-operator depence is observed

Energy levels disappear when the operator with the corresponding larger overlap is removed

$\pi\pi$ Dudek et al. [HadSpec], PRD87 (2013)
Wislon et al. [HadSpec], PRD92 (2015)

$N\pi$ Lang, Verduci, PRD87 (2013)
Kiratidis et al., PRD91 (2015)

Are we still missing operators?



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Are we missing operators?

Option a) There is a deep-bound state, but the current operators have a small overlap Amarasinghe et al. [NPLQCD], arXiv:2108.10835 [hep-lat]

$$E_0^{(AB)} = \eta - \Delta \qquad E_1^{(AB)} = \eta \qquad E_2^{(AB)} = \eta + \delta$$

$$Z_n^{(A)} = (\epsilon, \sqrt{1-\epsilon^2}, 0) \qquad Z_n^{(B)} = (\epsilon, 0, \sqrt{1-\epsilon^2})$$

$$\lambda_0^{(AB)} = e^{-(t-t_0)\eta} \qquad \lambda_1^{(AB)} = e^{-(t-t_0)(\eta+\delta)}$$

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Option b) There is no deep-bound state, however…

Volume independence of the ground state

Analysis of the phase-shifts and checks on scattering parameters

Consistency in scalar ME extraction between different methods

Agreement with large-N_c predition of an SU(6) symmetry

Agreeing values for the magnetic moments and $np \to d\gamma$ cross section

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Coincidence?

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Are we missing operators?

Hexaquark operators are expected to have large overlap to deep bound state

→ Large number of operators

$$H \sim T_{abcdef}(q_a^T C\Gamma_1 F_1 q_b)(q_c^T C\Gamma_2 F_2 q_d)(q_e^T C\Gamma_3 F_3 q_f)$$

color — spin — flavor

5 x 32 x 5 (9) = 800 (1440)

ways to create a color singlet — spin operators with correct parity — flavor operators with isospin 0 (1)

↓ symmetries

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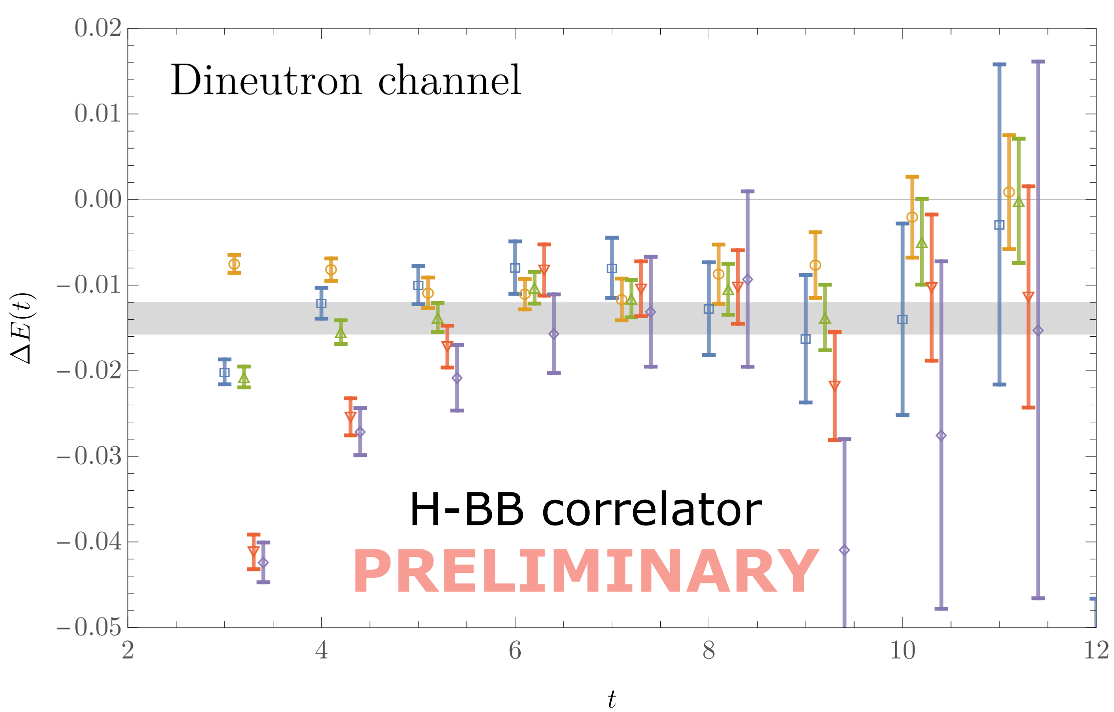
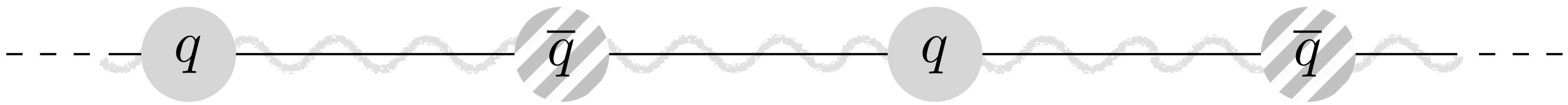


Preliminary results show that after diagonalization, no bound state is found, but different off-diagonal correlators see the deep-bound state

Quantum simulations of QCD

Very recently, the first quantum simulations of QCD with quarks have been performed (although in 1+1 dimensions) Farrell, Chernyshev, Powell, Zemlevskiy, Illa, Savage arXiv:2207.01731 [quant-ph]

$$H = H_{kin} + H_m + H_{el} + H_{\mu_B} + H_{\mu_I}$$



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IQuS

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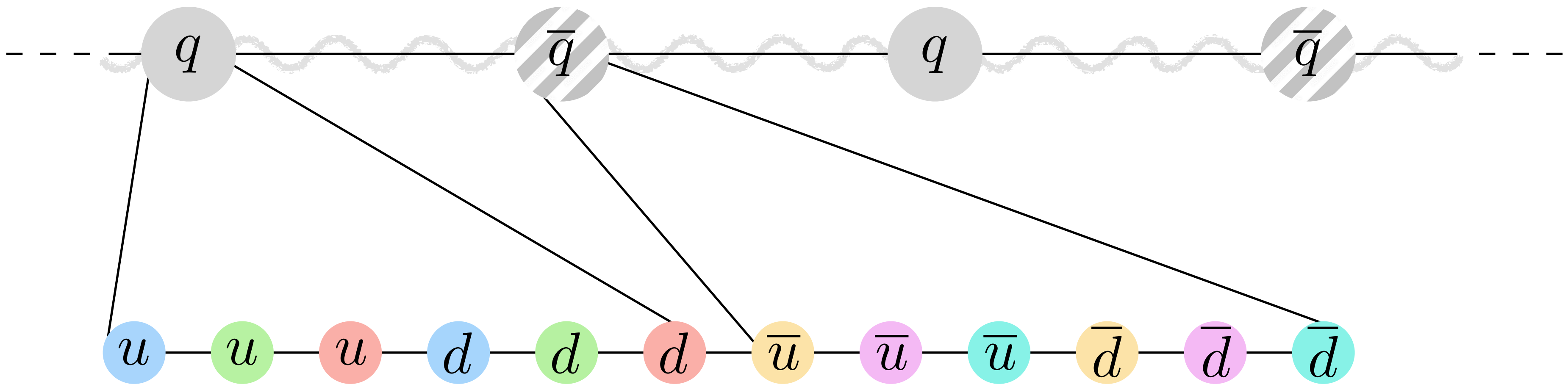

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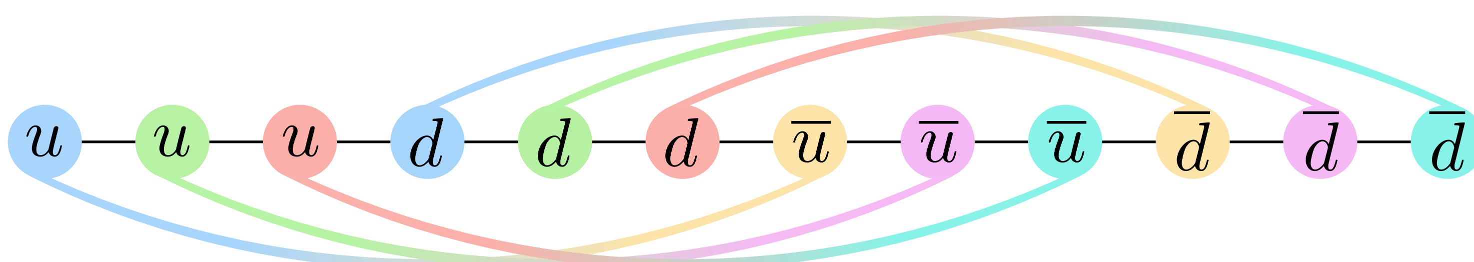

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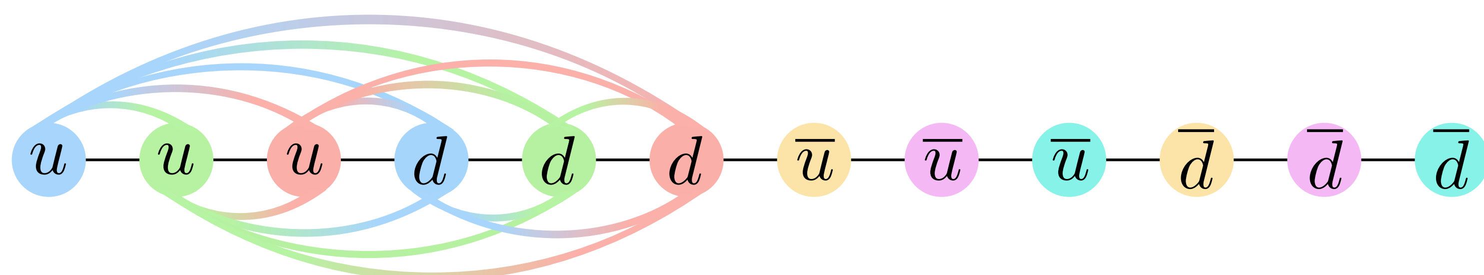

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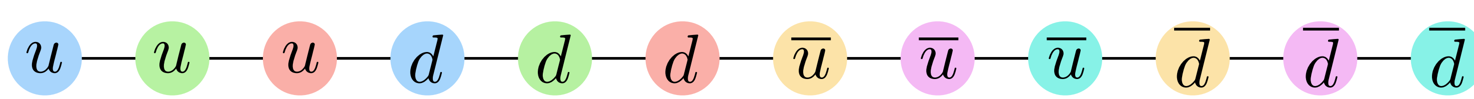
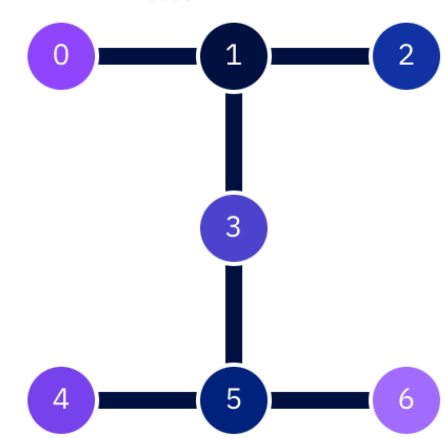


12 qubits

114 CNOT gates

ibm_perth

ibmq_jakarta



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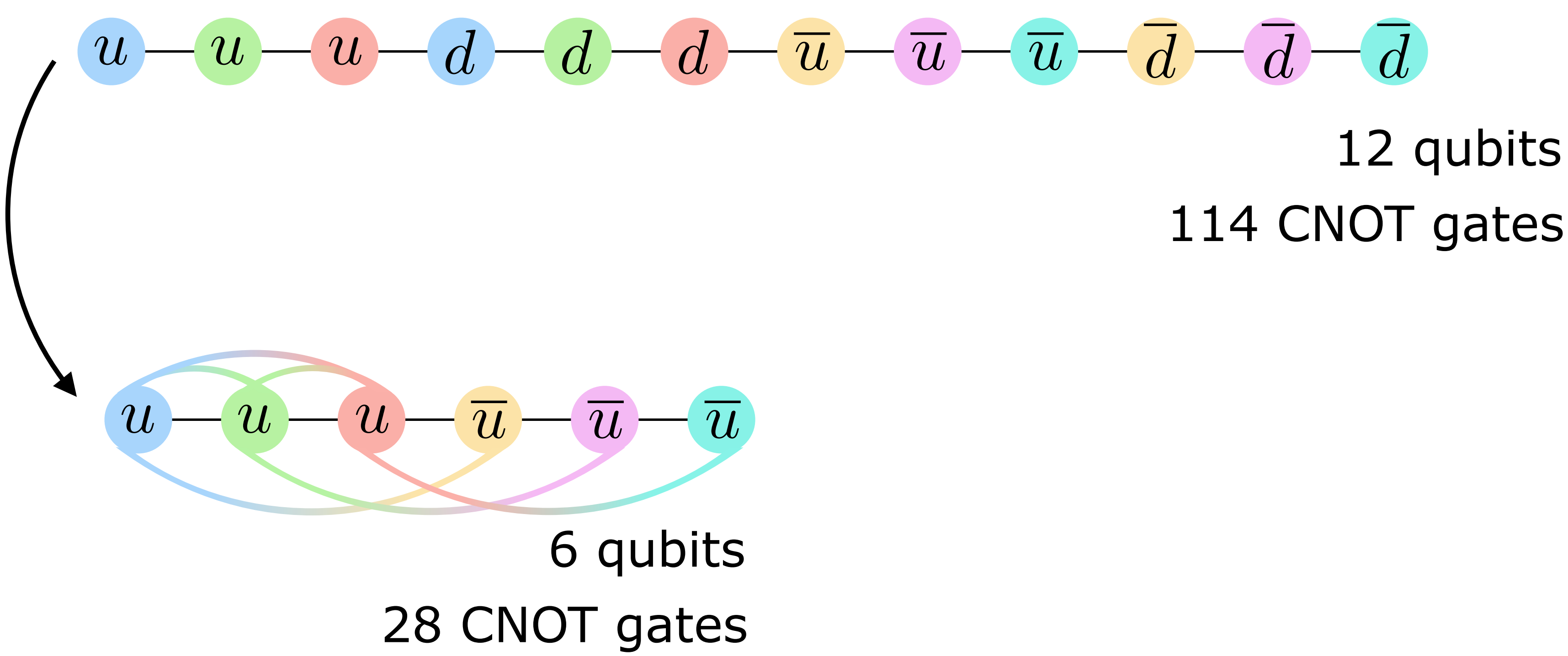

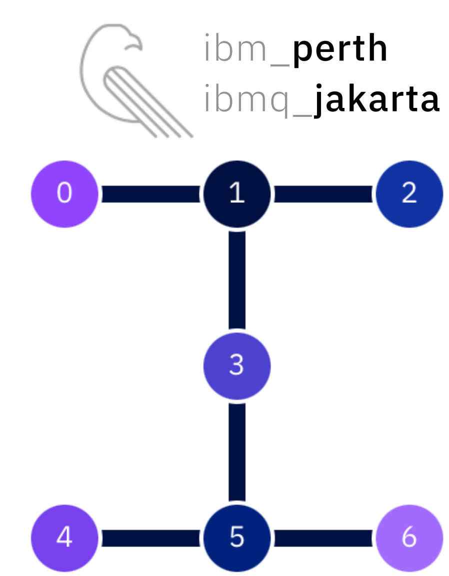

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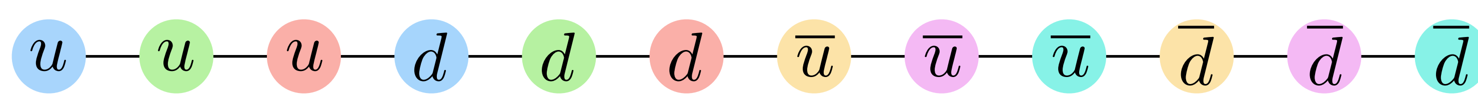

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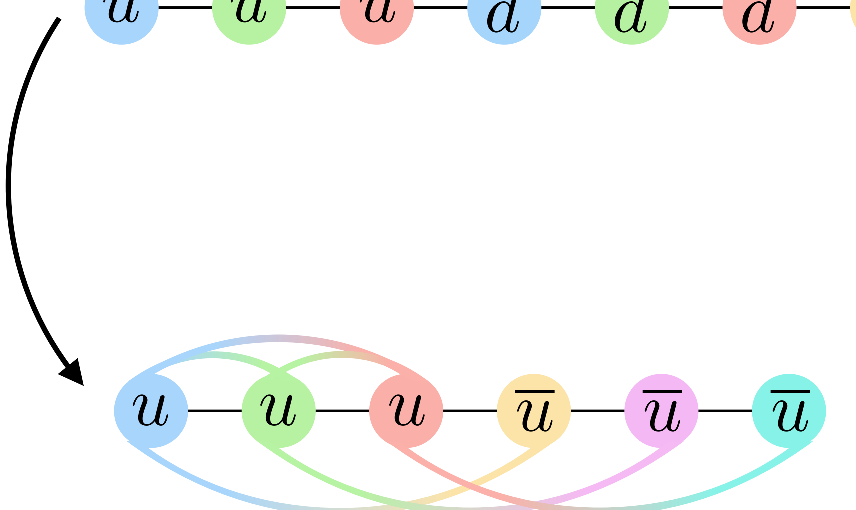
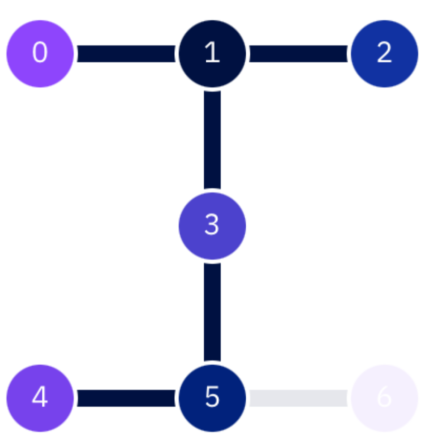


6 qubits

28 CNOT gates ⟶ 34 CNOT gates (after compiling the circuit to have the right connectivity)

ibm_perth
ibmq_jakarta



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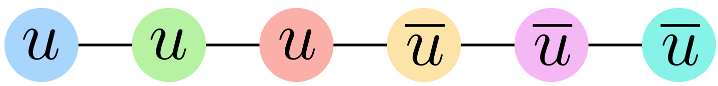
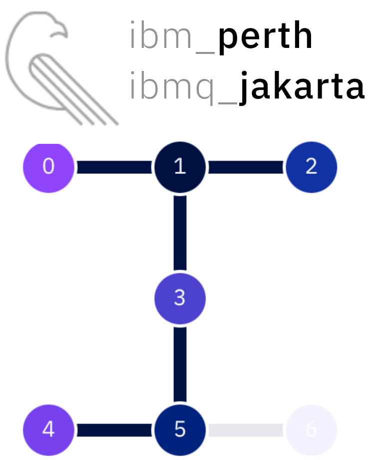
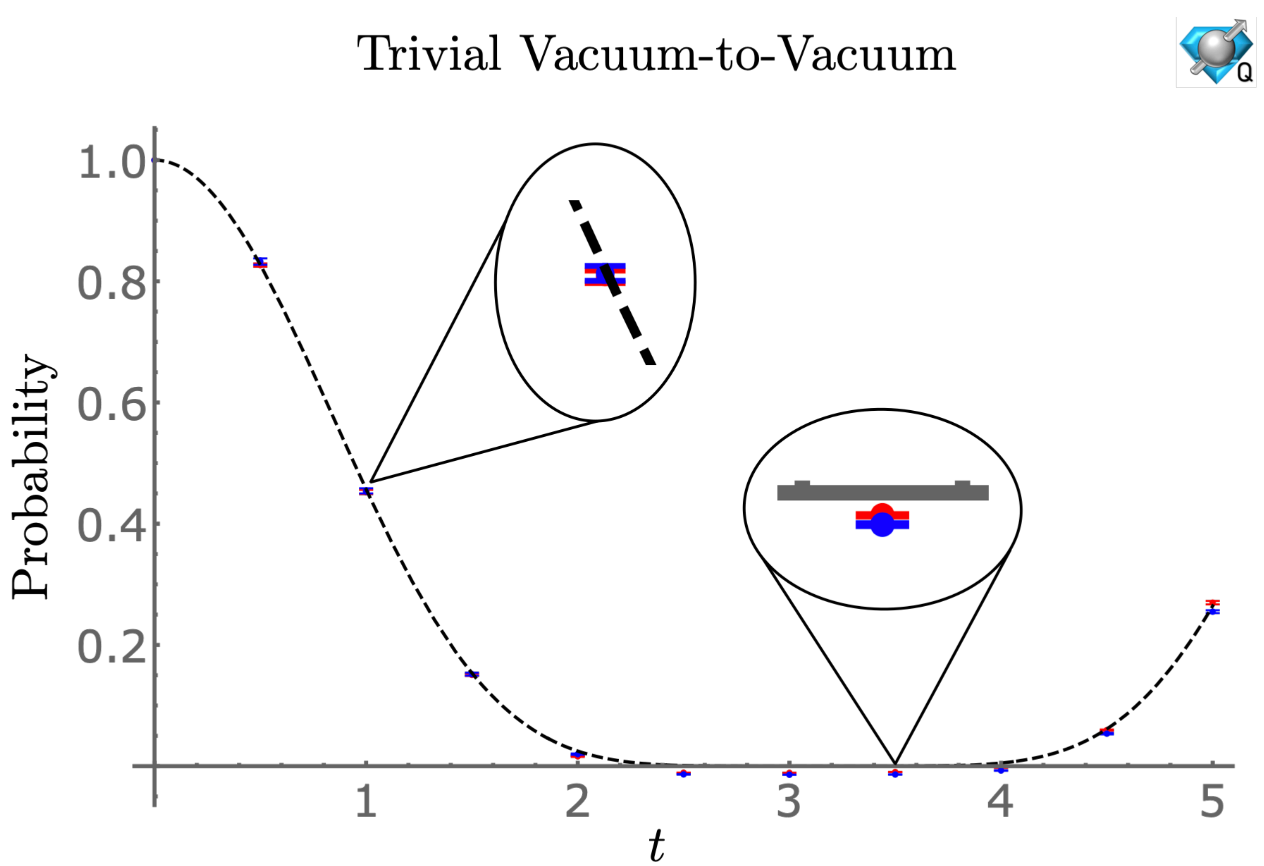
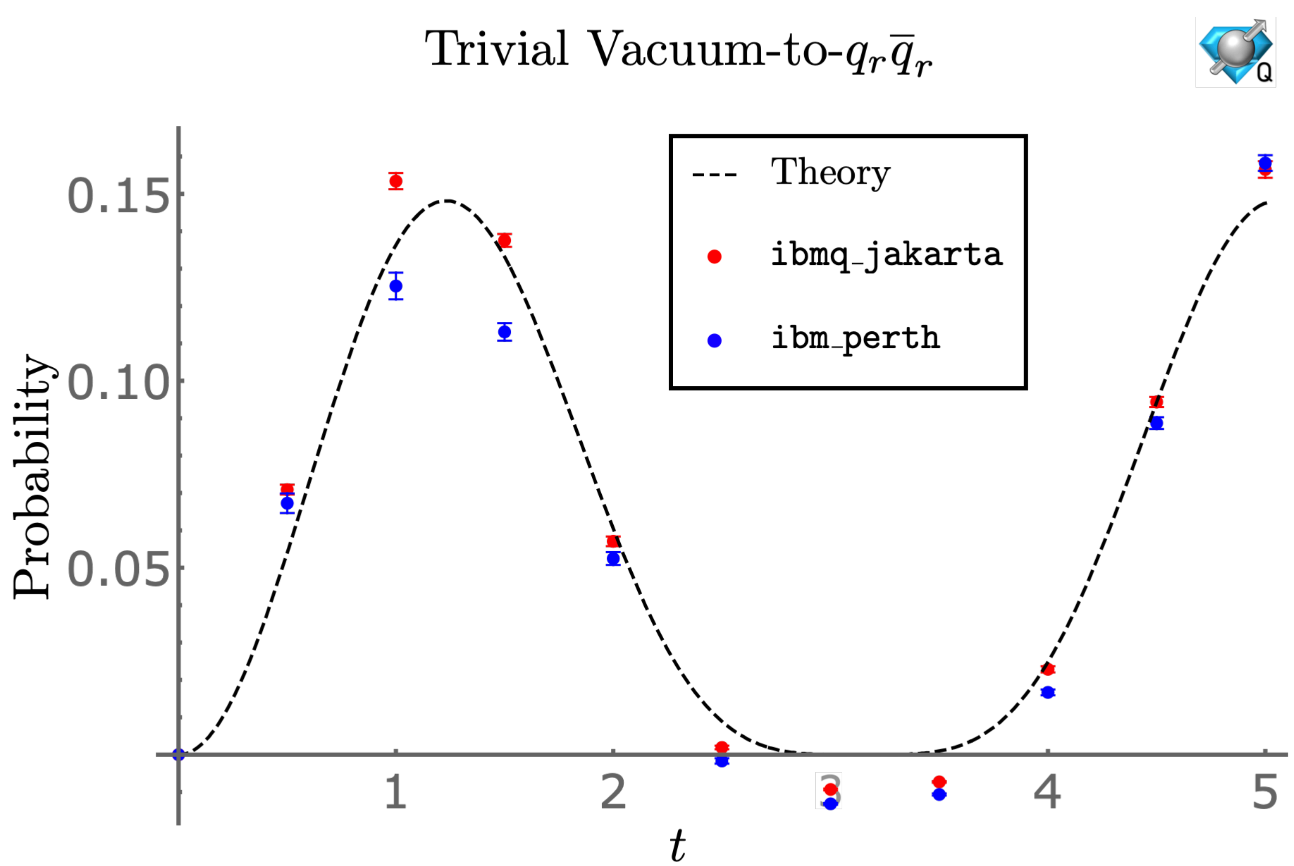




Error mitigation techniques:

- Randomized compiling (Pauli twirling)
- Measurement error mitigation
- Post-selection on physical states





Summary

It is still unclear what the best operators are to include in a variational analysis for NN systems (significant interpolating-operator dependence)

While variational methods can provide reliable upper bounds on the energy levels, they don't rule out the excistence of deep-bound states:

- Ongoing study with additional operators and additional volumes at $m_\pi \sim$ 800 MeV for NN system
- Ongoing production for different baryon-baryon systems, specifically the H-dibaryon system

The first steps to simulate time-dependent QCD processes are being taken with preliminary calculations that include both matter and gauge fields, although limited by current quantum devices.