HYP 2022 PRAGUE

14th International Conference on Hypernuclear and Strange Particle Physics

28th June, 2022

Studying the interactions between hyperons and nucleons from Lattice QCD

Marc Illa

STRONG-2020

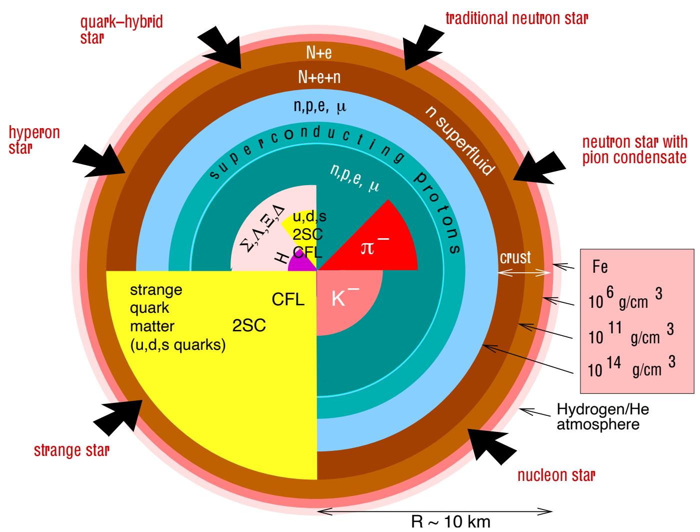
IQuS

QUANTUM SCIENCE CENTER

UNIVERSITY of WASHINGTON

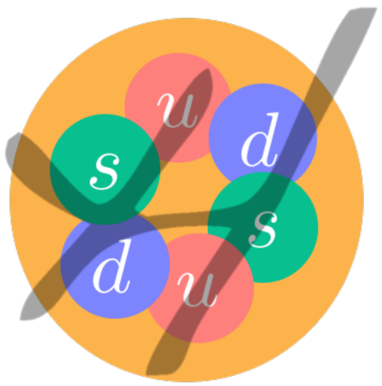
NPLQCD

Introduction

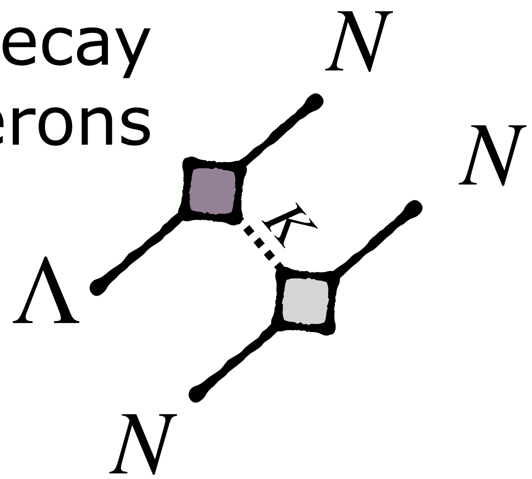


Composition of neutron stars

Spectroscopy



In-medium weak decay
of hyperons



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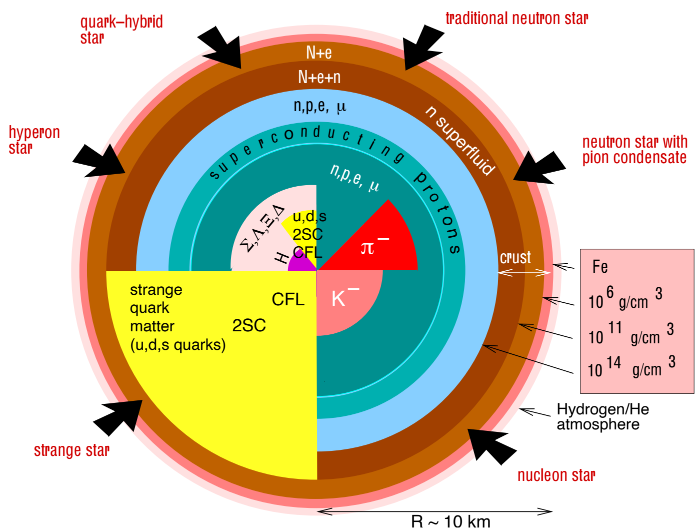

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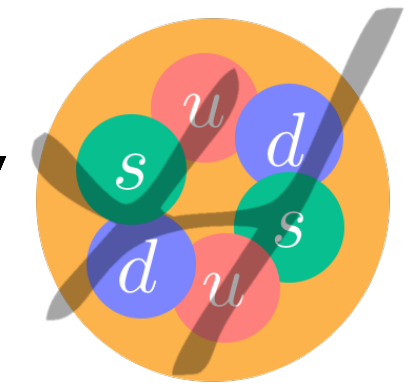

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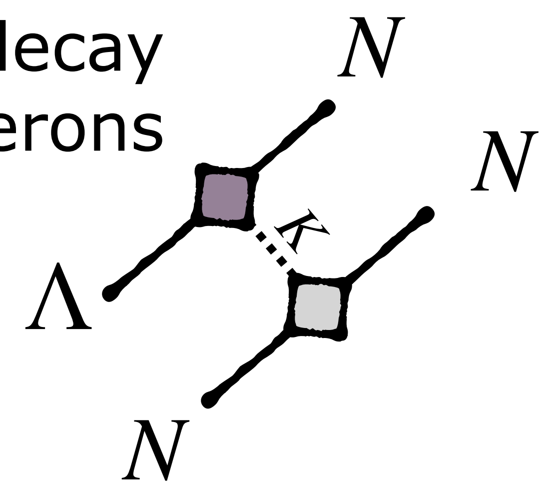

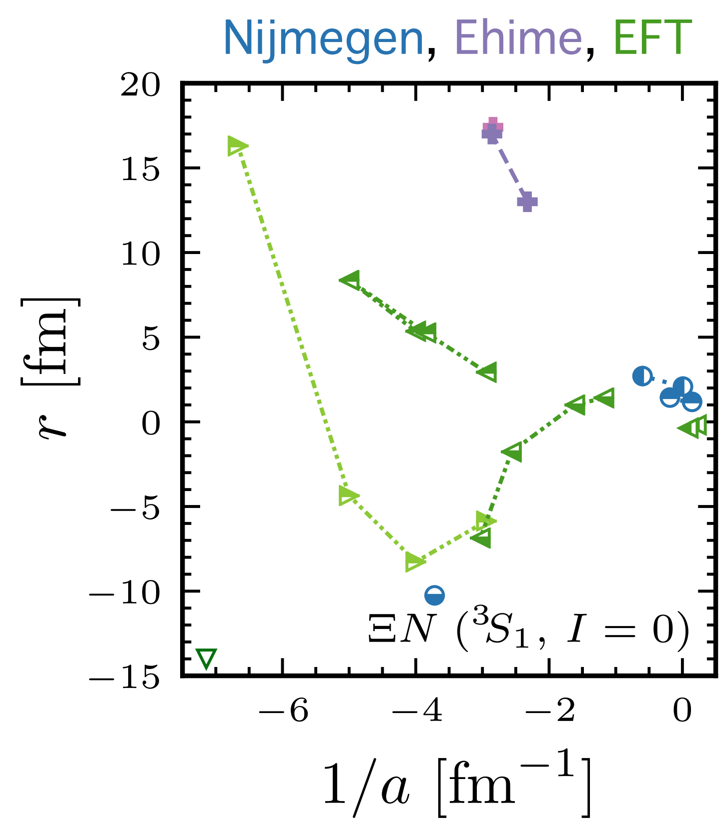

Lack of experimental data to constrain YN and YY interactions

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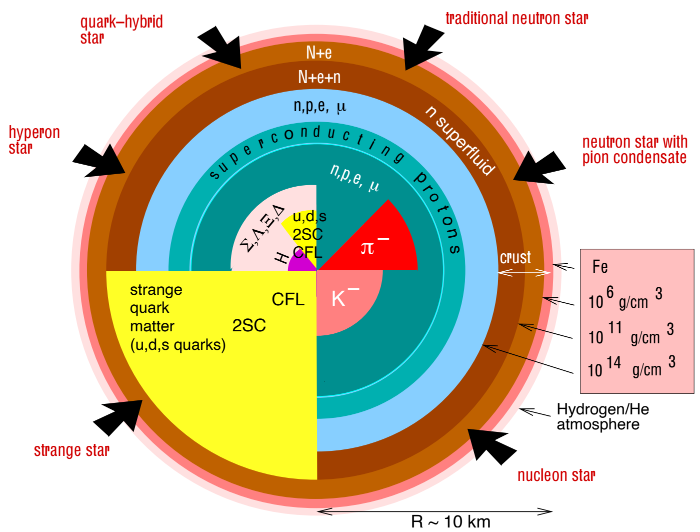

Composition of neutron stars

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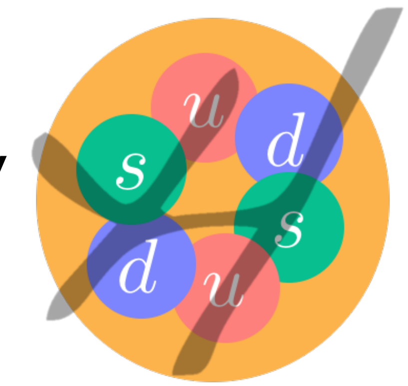

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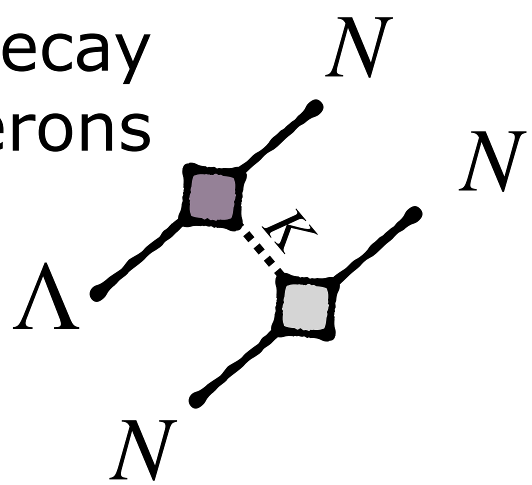
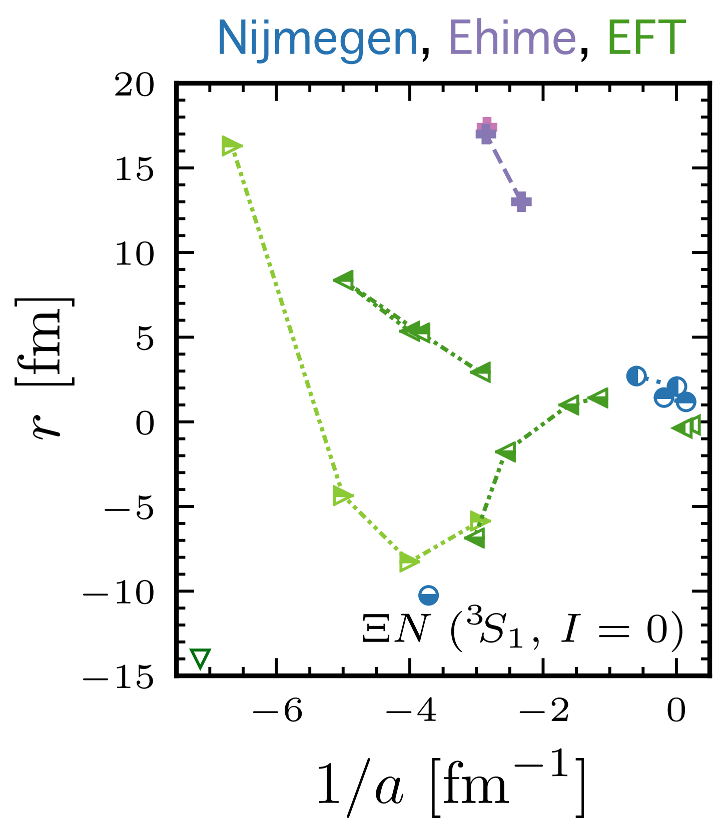


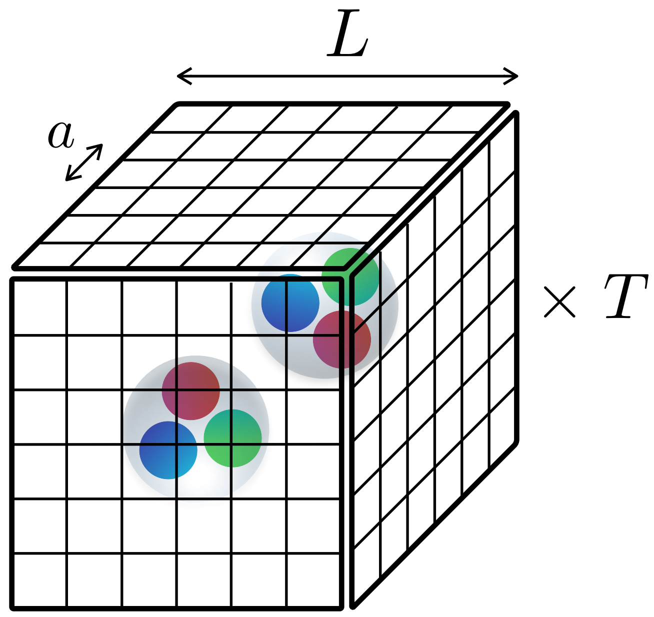


Lack of experimental data to constrain
YN and YY interactions

Lattice QCD can provide complementary information for these channels

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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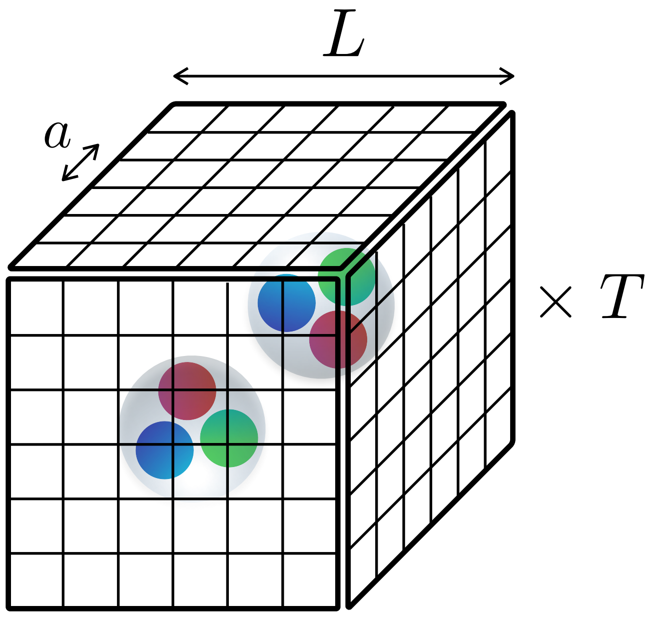


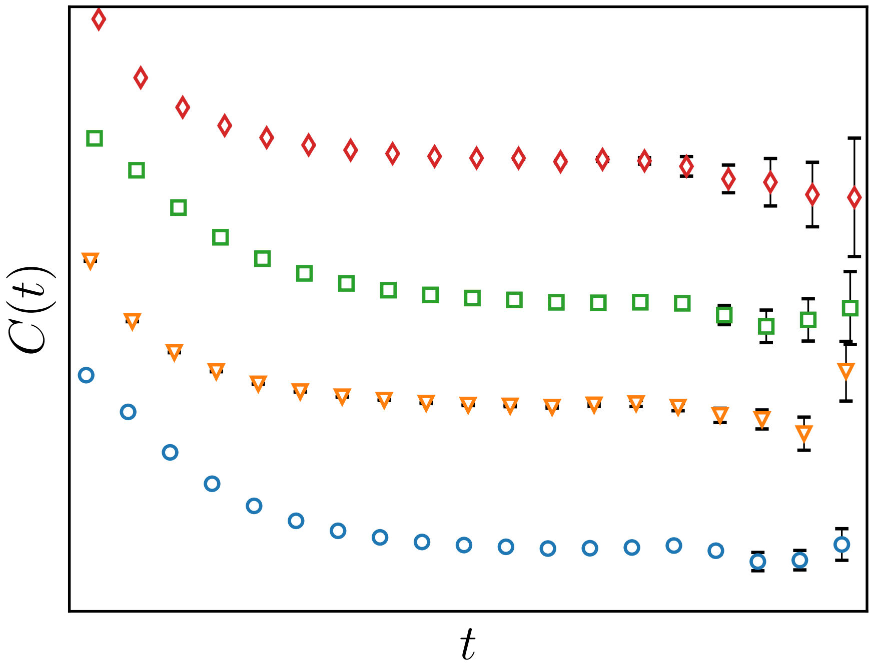
There are two different approaches:

- The potential method (presented by Prof. T. Doi)
- The direct method

Lattice QCD

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

Lattice QCD



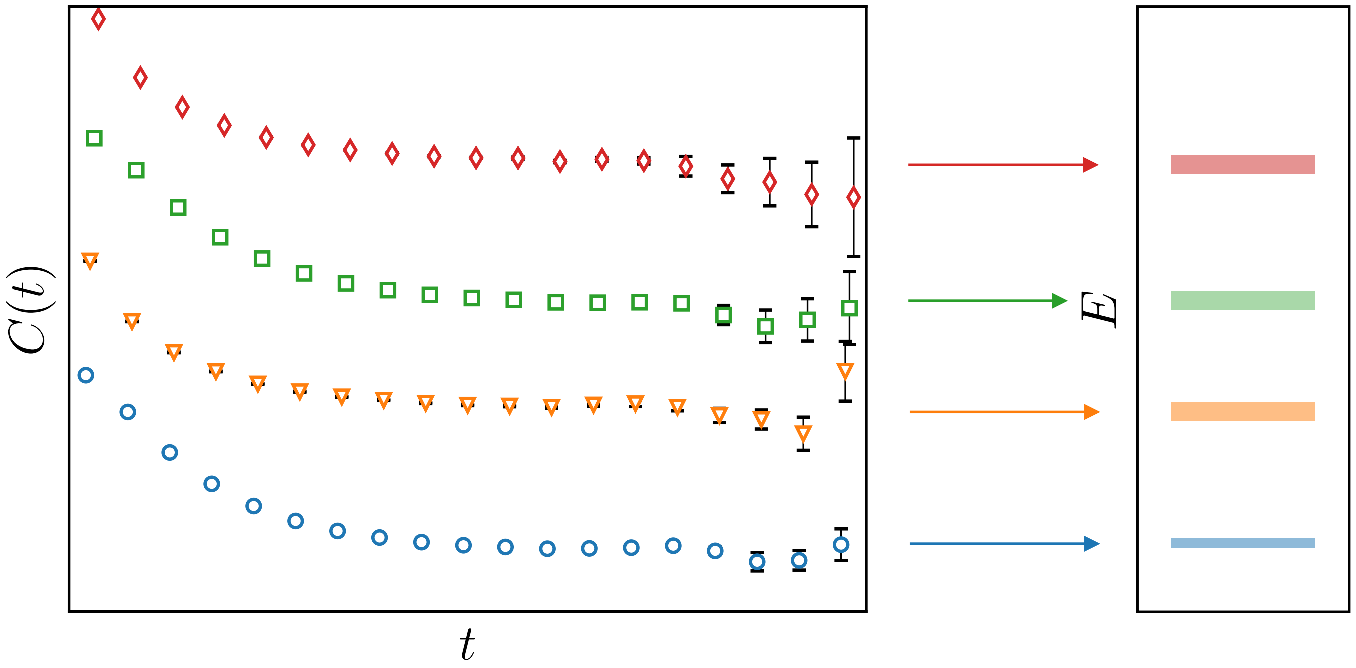
With the direct method, the finite-volume energy levels are extracted from two-point correlation functions

$$C_B(t, \mathbf{p})$$

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

Input: spatial structure of operators with specific quantum numbers

Lattice QCD



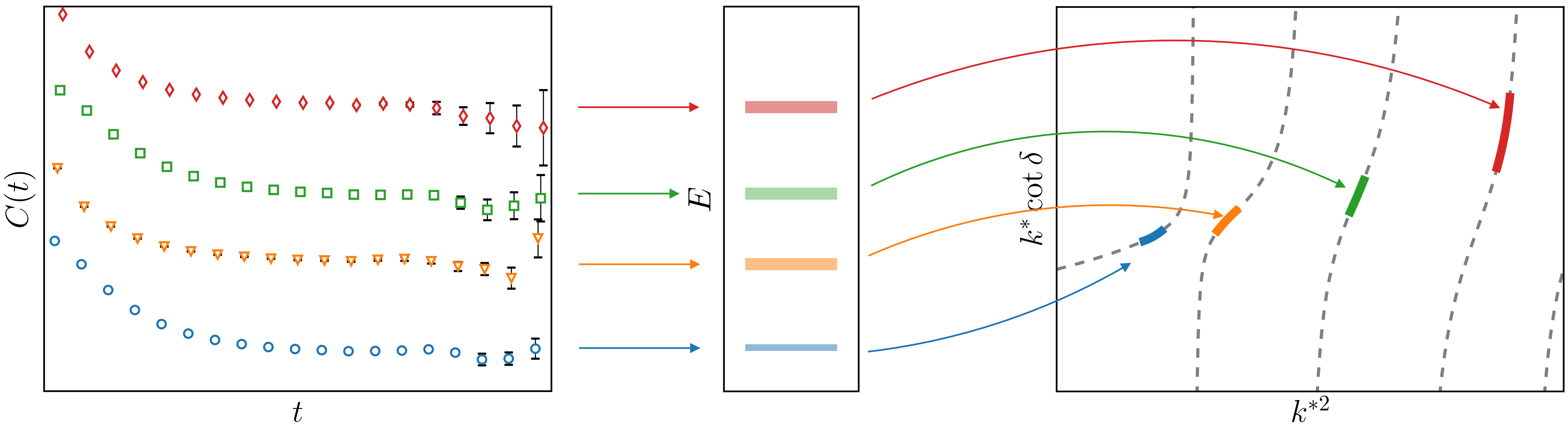
With the direct method, the finite-volume energy levels are extracted from two-point correlation functions

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

Fit temporal dependence

Input: spatial structure of operators with specific quantum numbers

Lattice QCD



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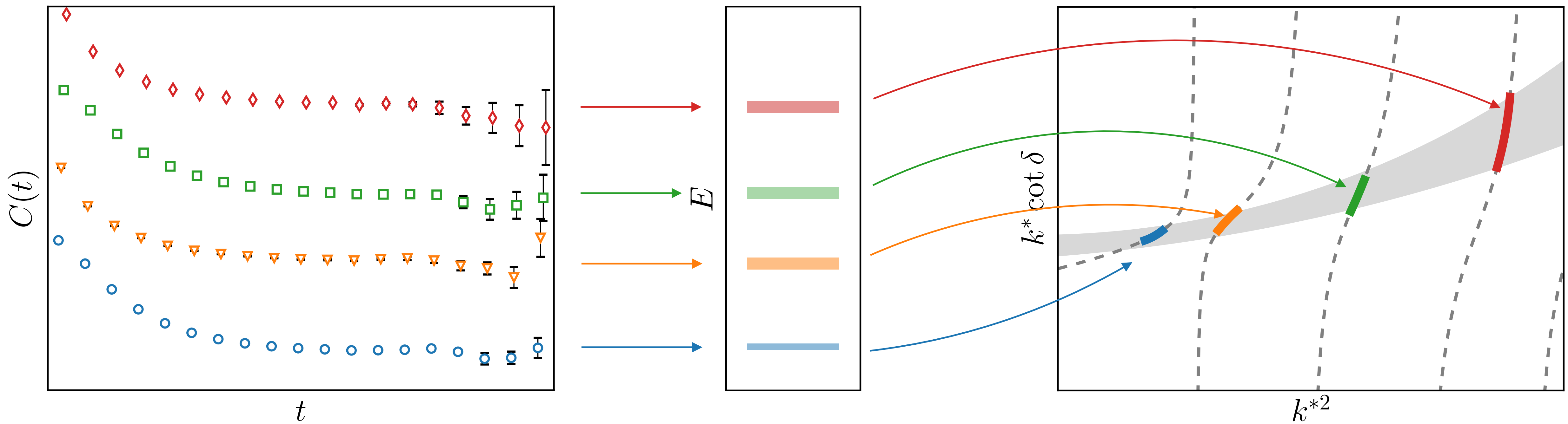
$$C_B(t, \mathbf{p})$$
$$C_{B_1 B_2}(t, \mathbf{p})$$

Input: spatial structure of operators with specific quantum numbers

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

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

Lattice QCD



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

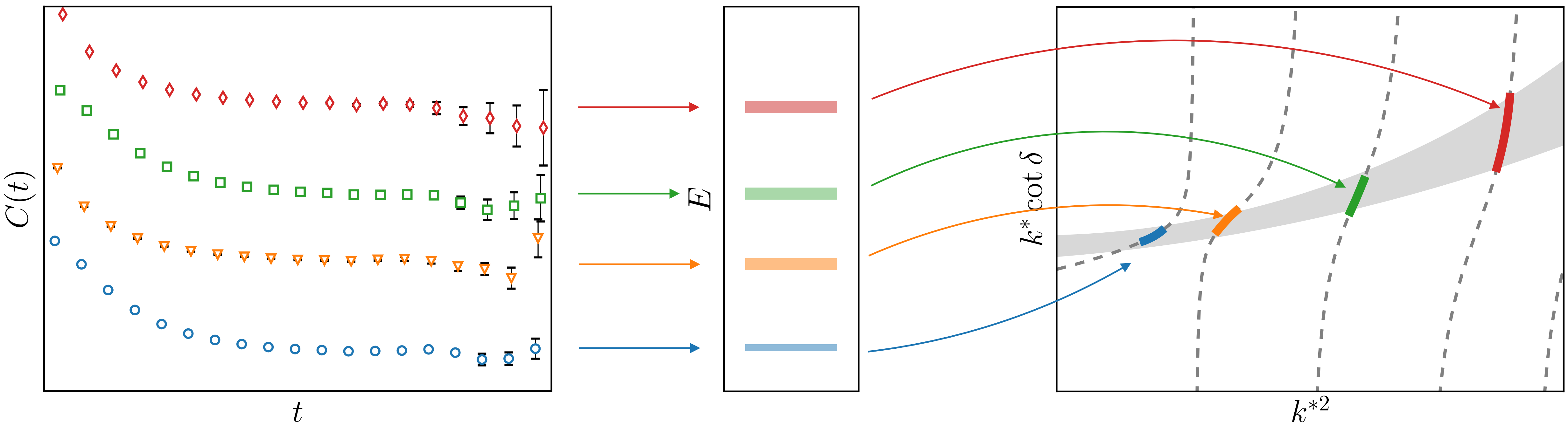
$$\longrightarrow \Delta E \longrightarrow \begin{matrix} k^* \cot \delta \\ B \end{matrix}$$

Fit temporal dependence

Lüscher's method

Input: spatial structure of operators with specific quantum numbers

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

Fit temporal dependence → ΔE

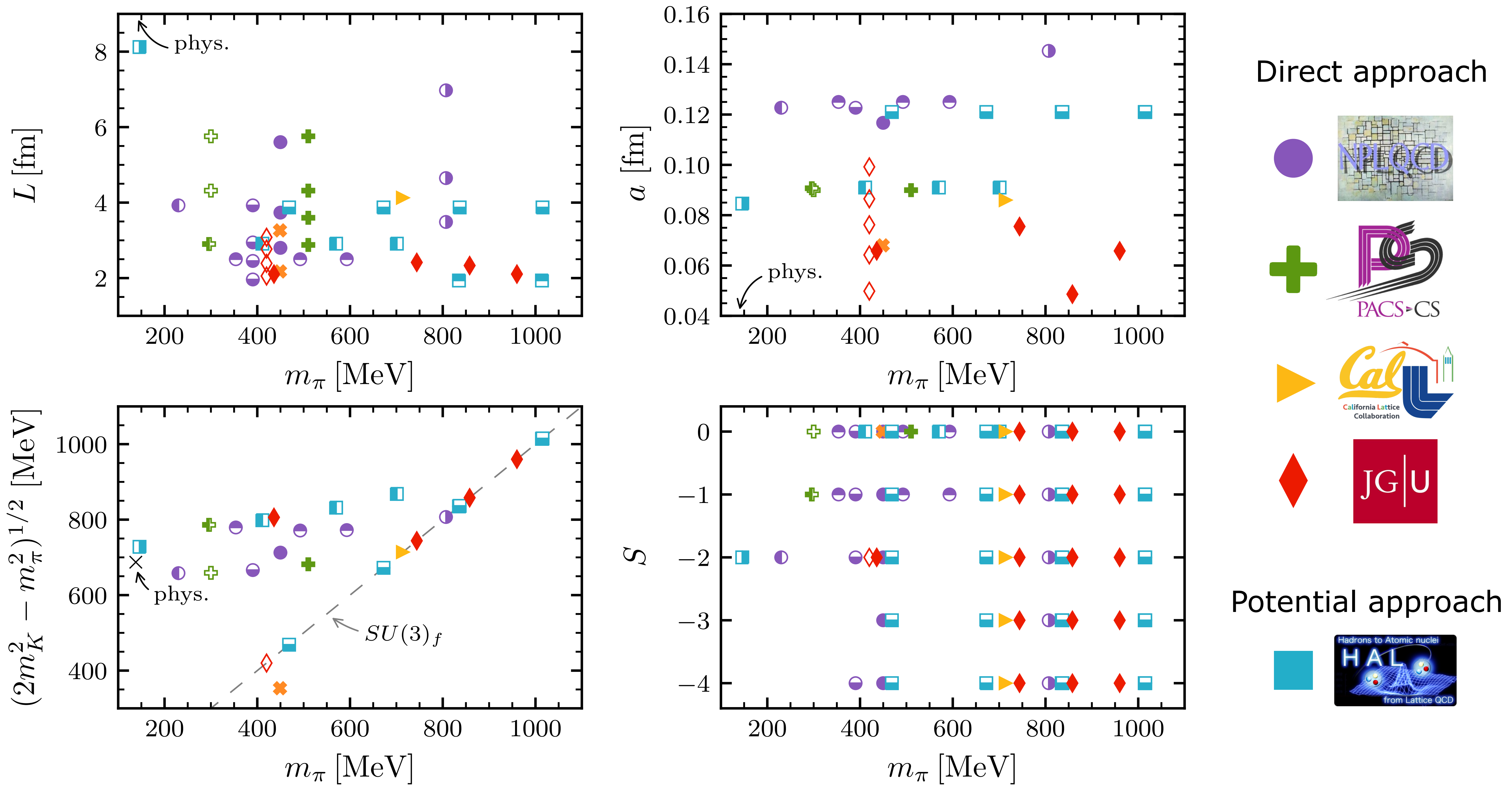
ΔE → Lüscher's method → $k^* \cot\delta$, B

ΔE → EFT → B

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

Present status

Landscape for octet-baryon studies



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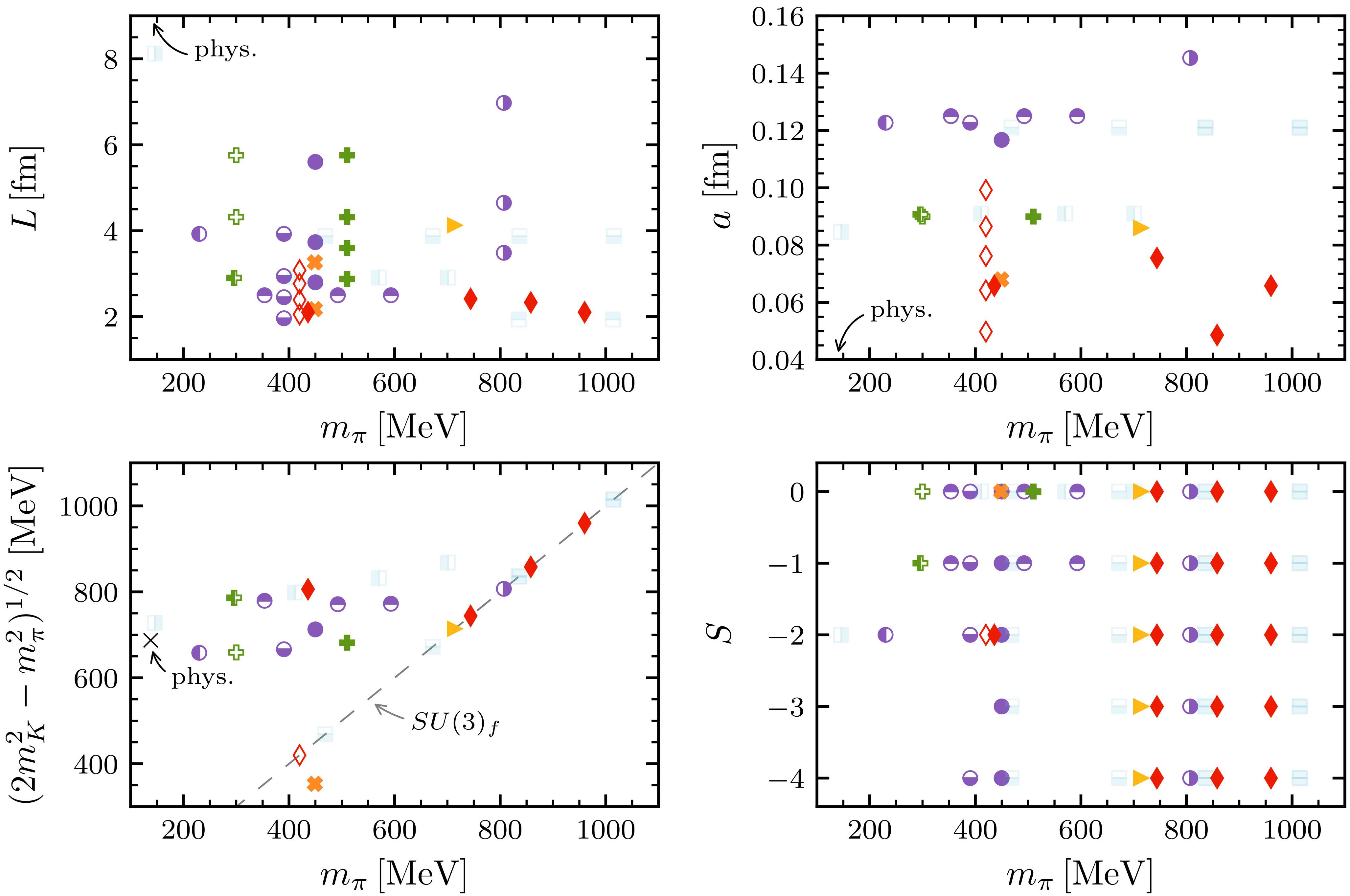
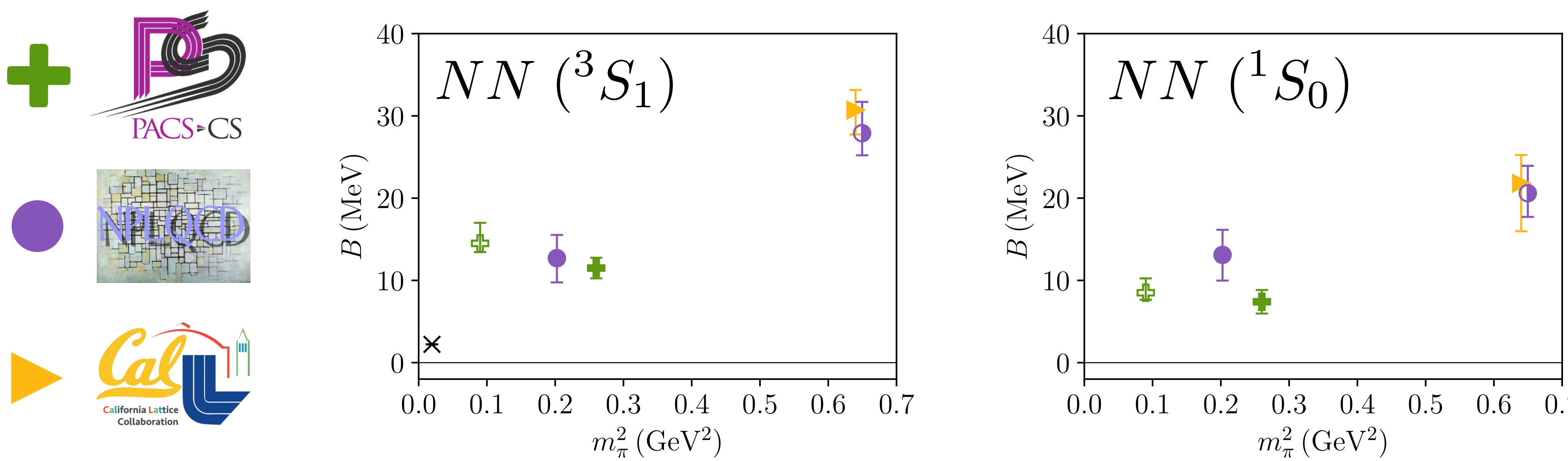


Direct approach

Potential approach

$S = 0$ sector

Traditionally, calculations were performed with asymmetrical correlators (different source and sink operators), leading to bound NN systems



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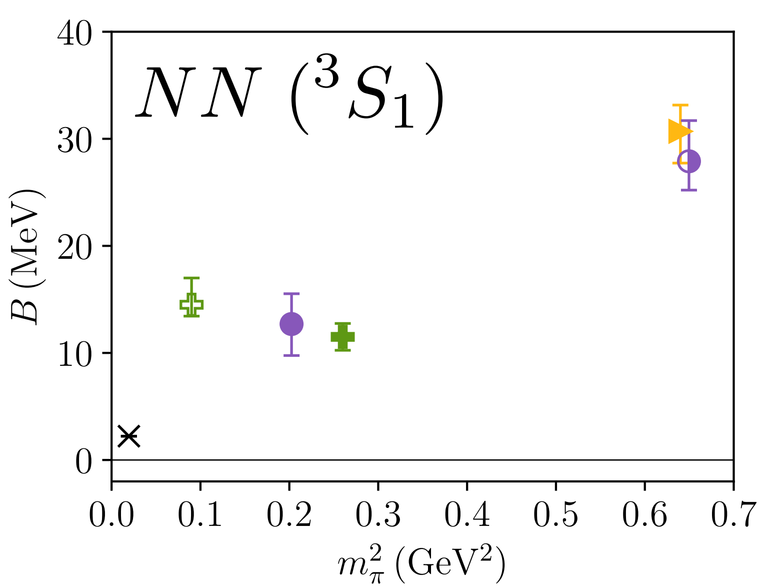
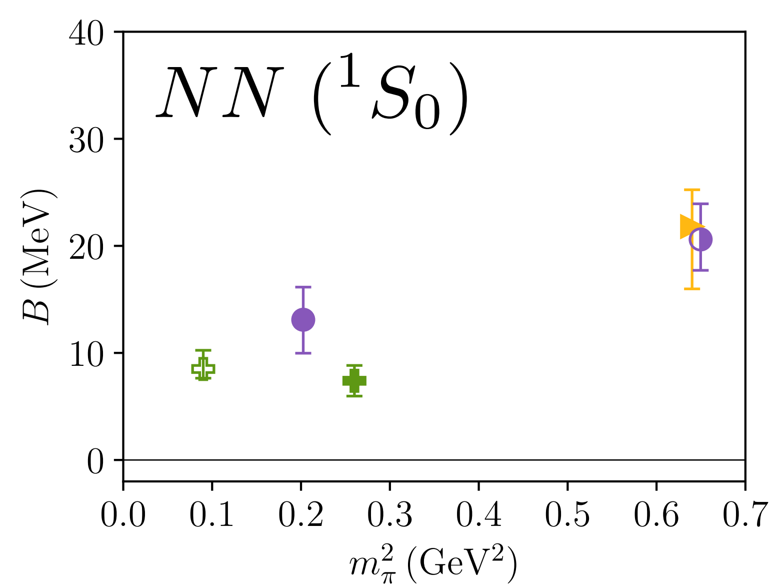
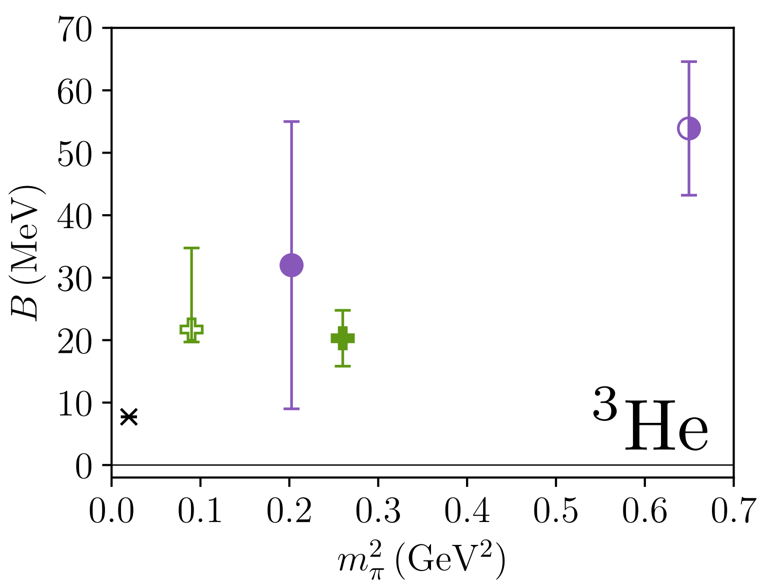
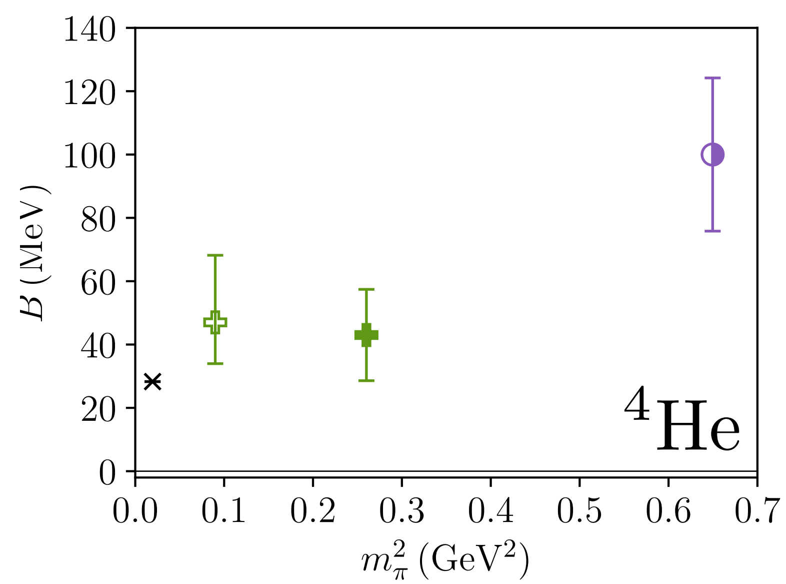




And also 3- and 4-body systems





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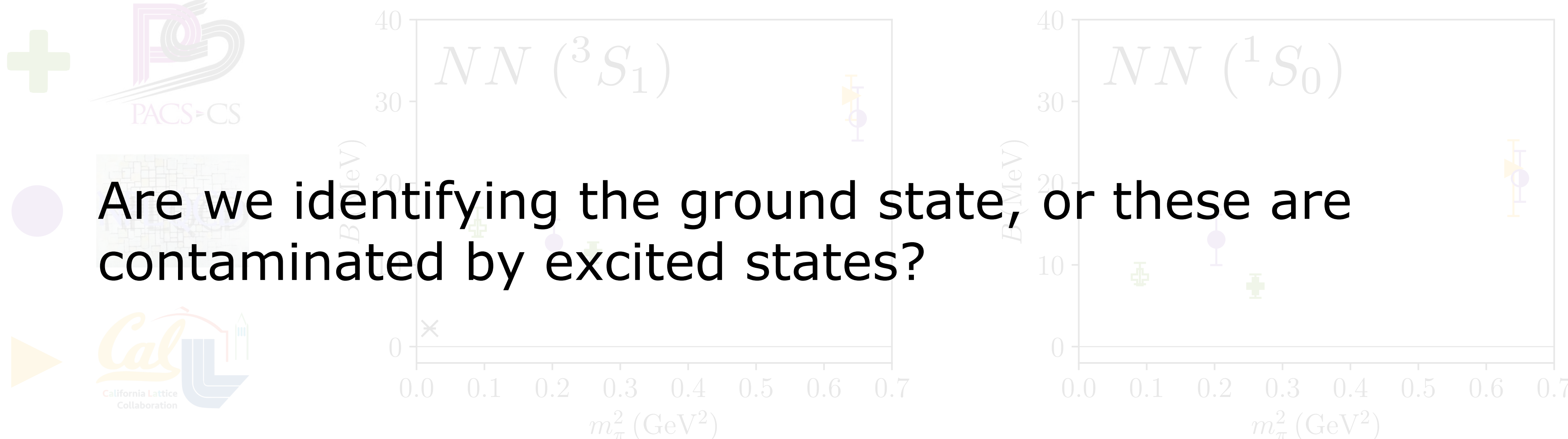
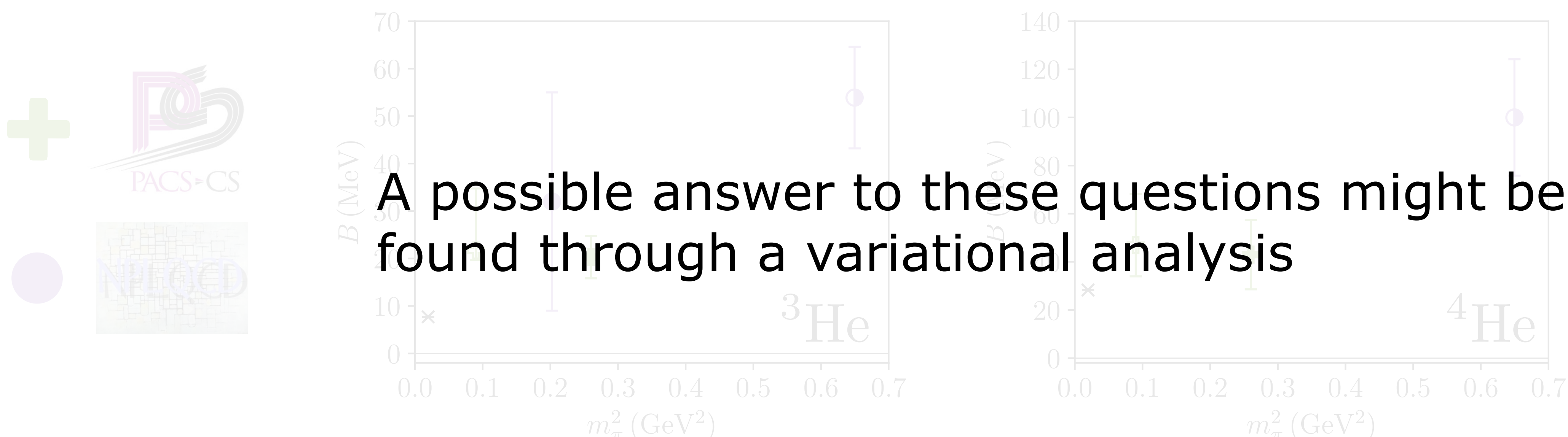


Are we identifying the ground state, or these are contaminated by excited states?

Is there an operator dependence of these energy levels?

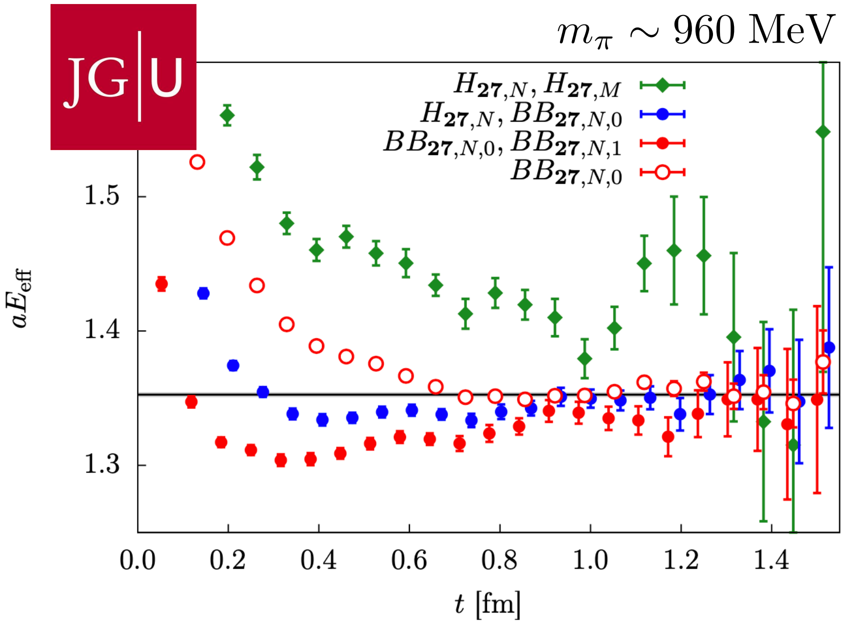
And also 3- and 4-body systems



A possible answer to these questions might be found through a variational analysis

$S = 0$ sector

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., PRD99 (2019)

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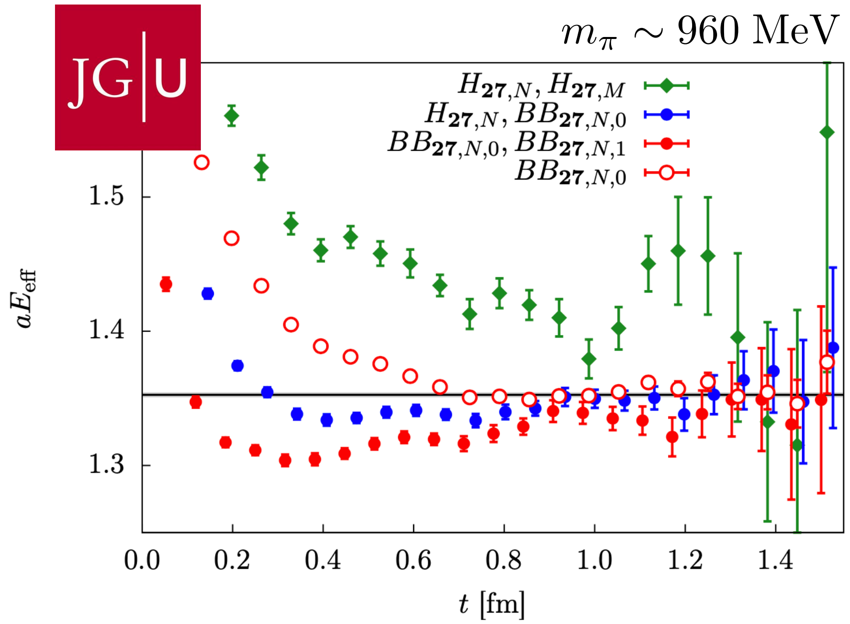

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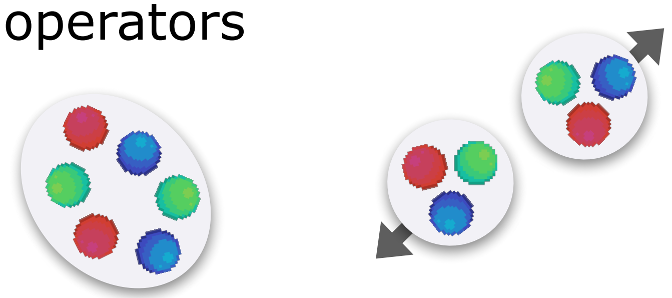
Non-hermitian matrices with hexaquark and dibaryon-like operators

Hermitian matrices with only hexaquark or dibaryon-like operators



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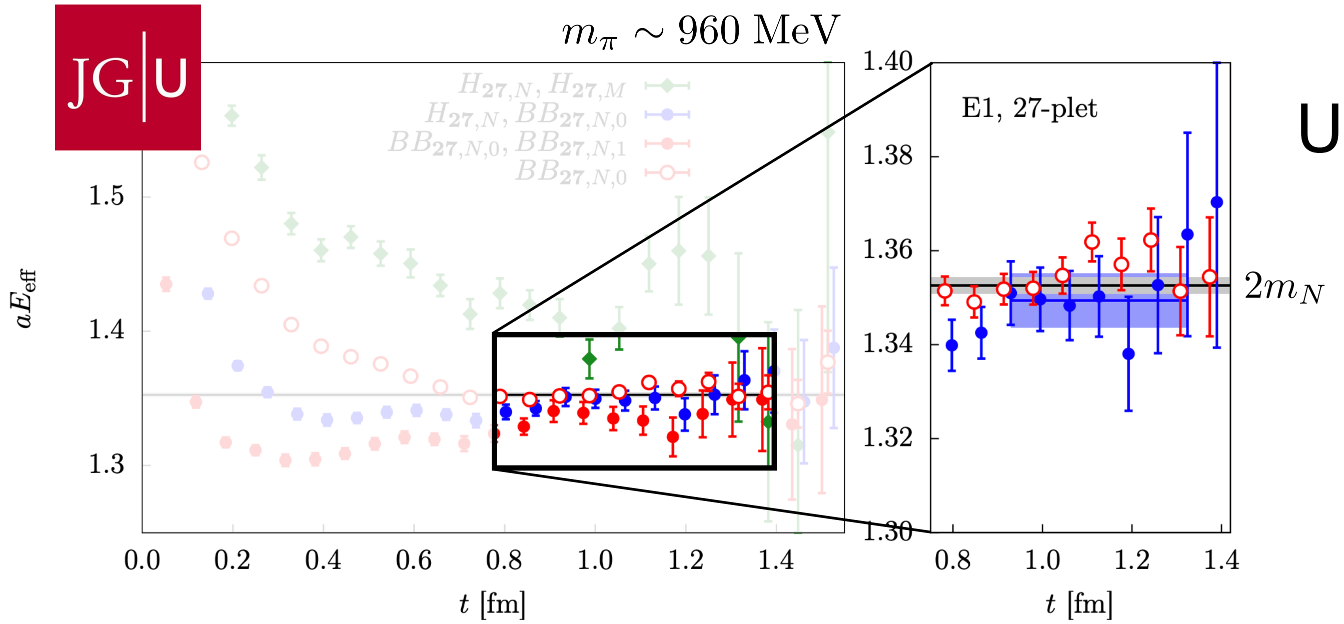

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Unbound NN $(^1S_0)$

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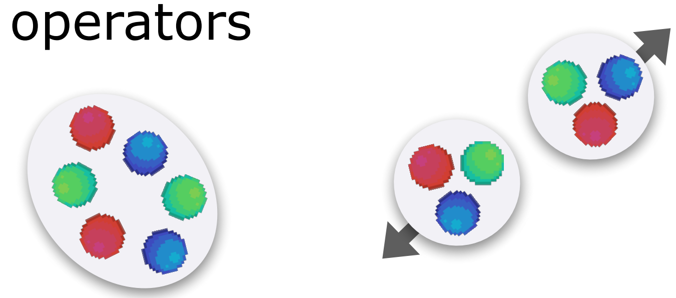

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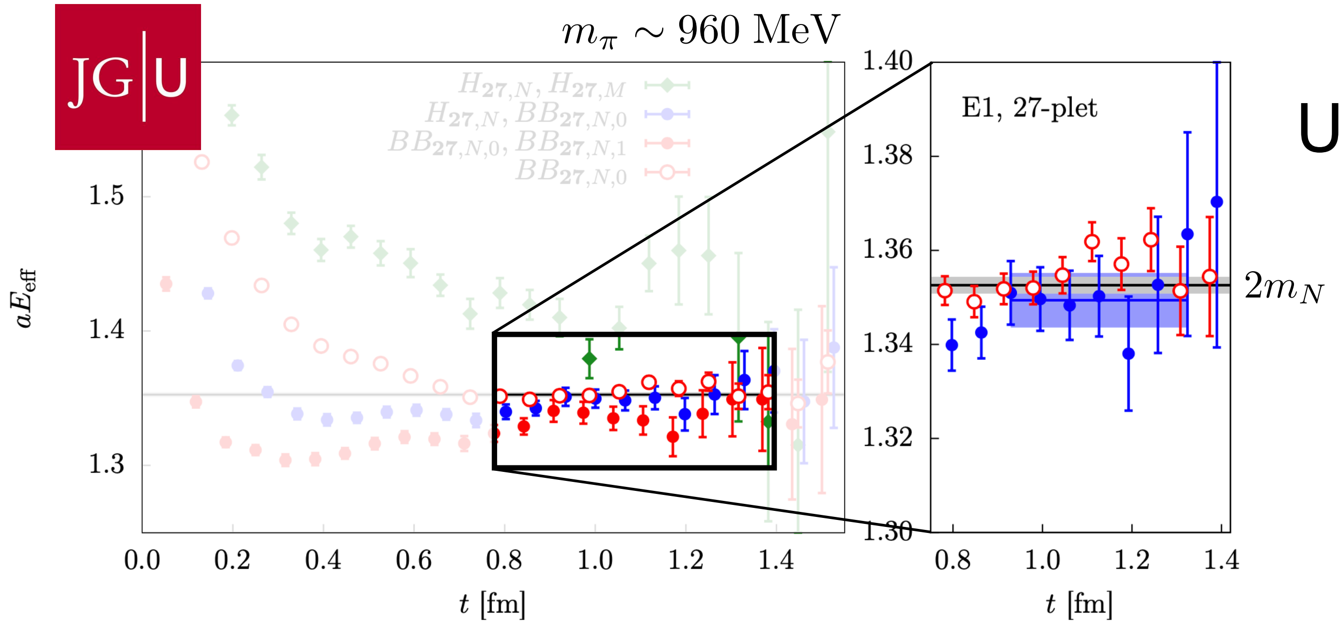

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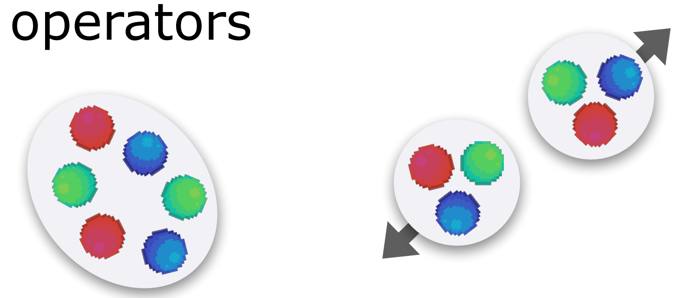

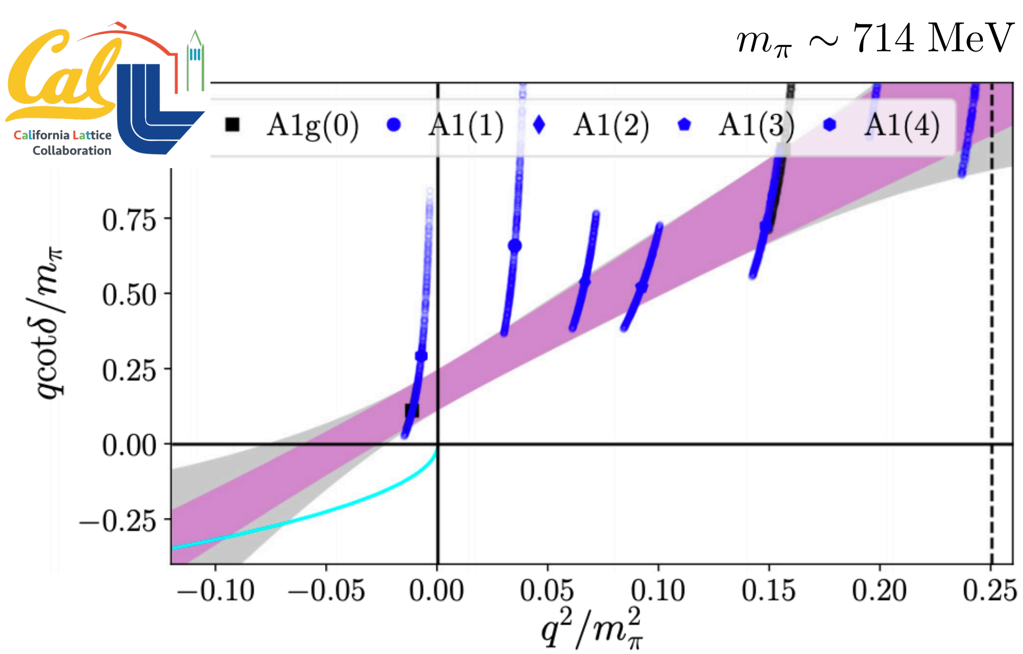

Hörz et al., PRC103 (2021)

Unbound NN $(^1S_0)$

Hermitian matrices with only dibaryon-like operators

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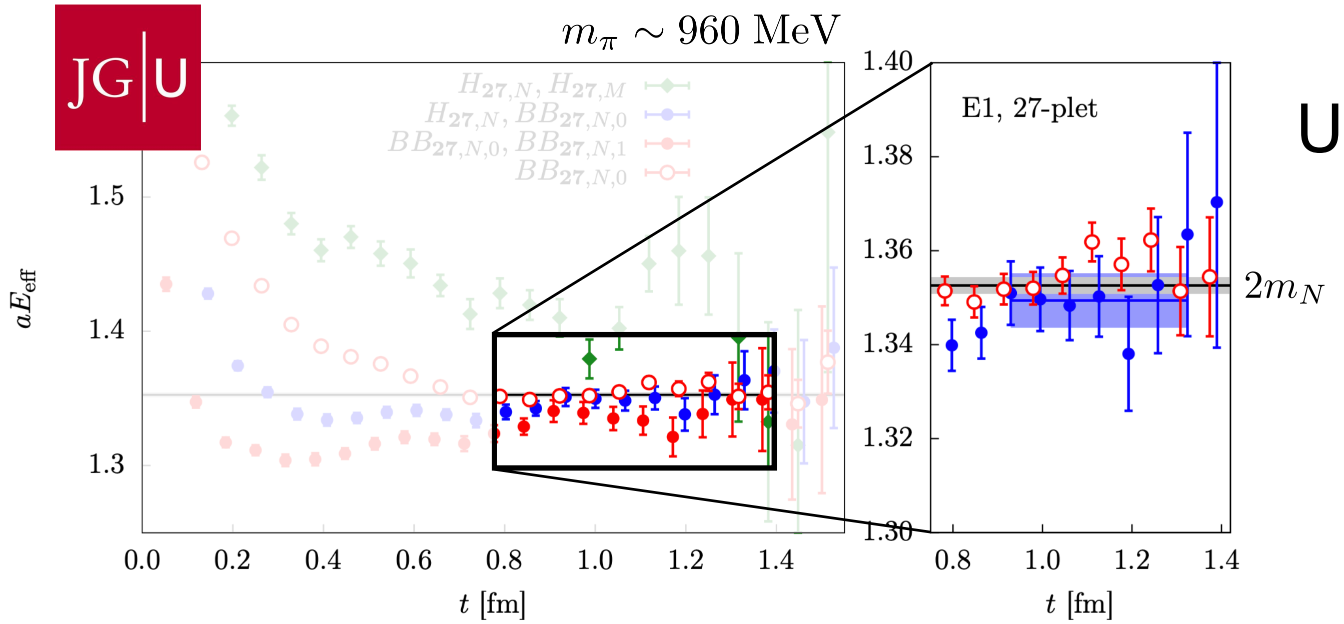

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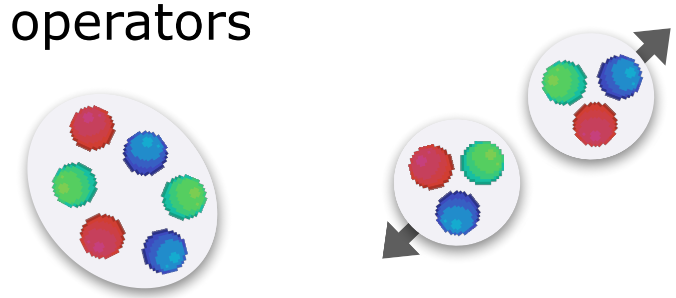

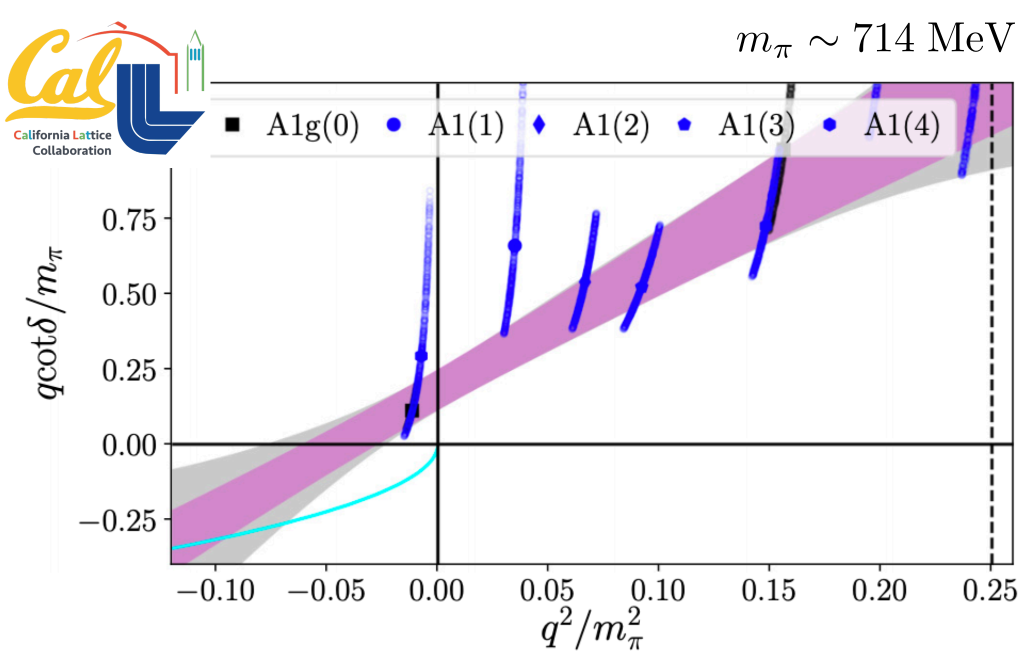

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Unbound NN $(^1S_0)$

Hermitian matrices with only dibaryon-like operators

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

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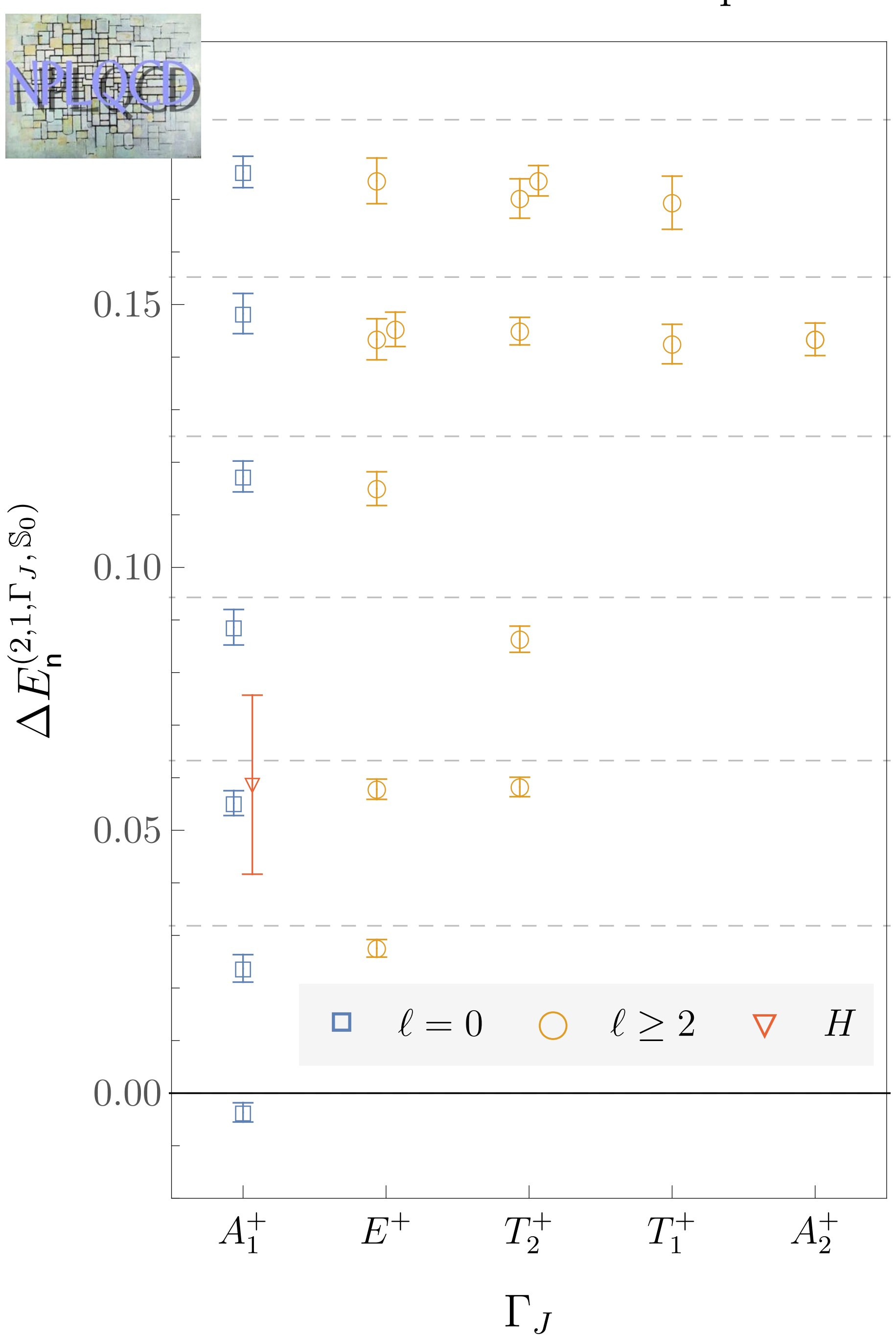
Dineutron channel GEVP spectrum

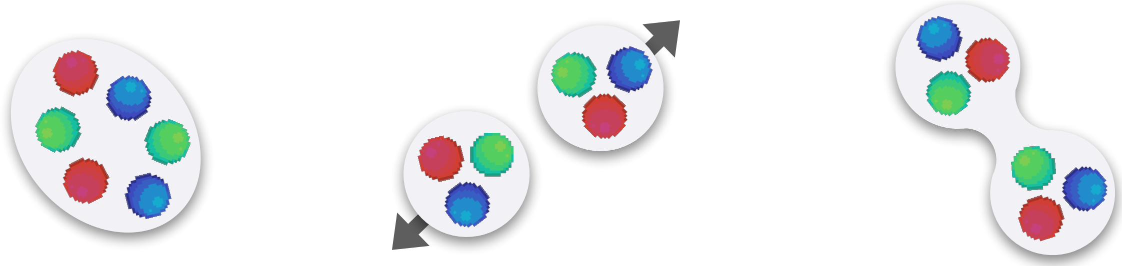


Amarasinghe et al. [NPLQCD], arXiv:2108.10835 [hep-lat]

Unbound $NN\ ({}^1S_0)$

Hermitian matrices with three operators:

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



$S = 0$ sector

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

Large interpolating-operator depence is observed

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

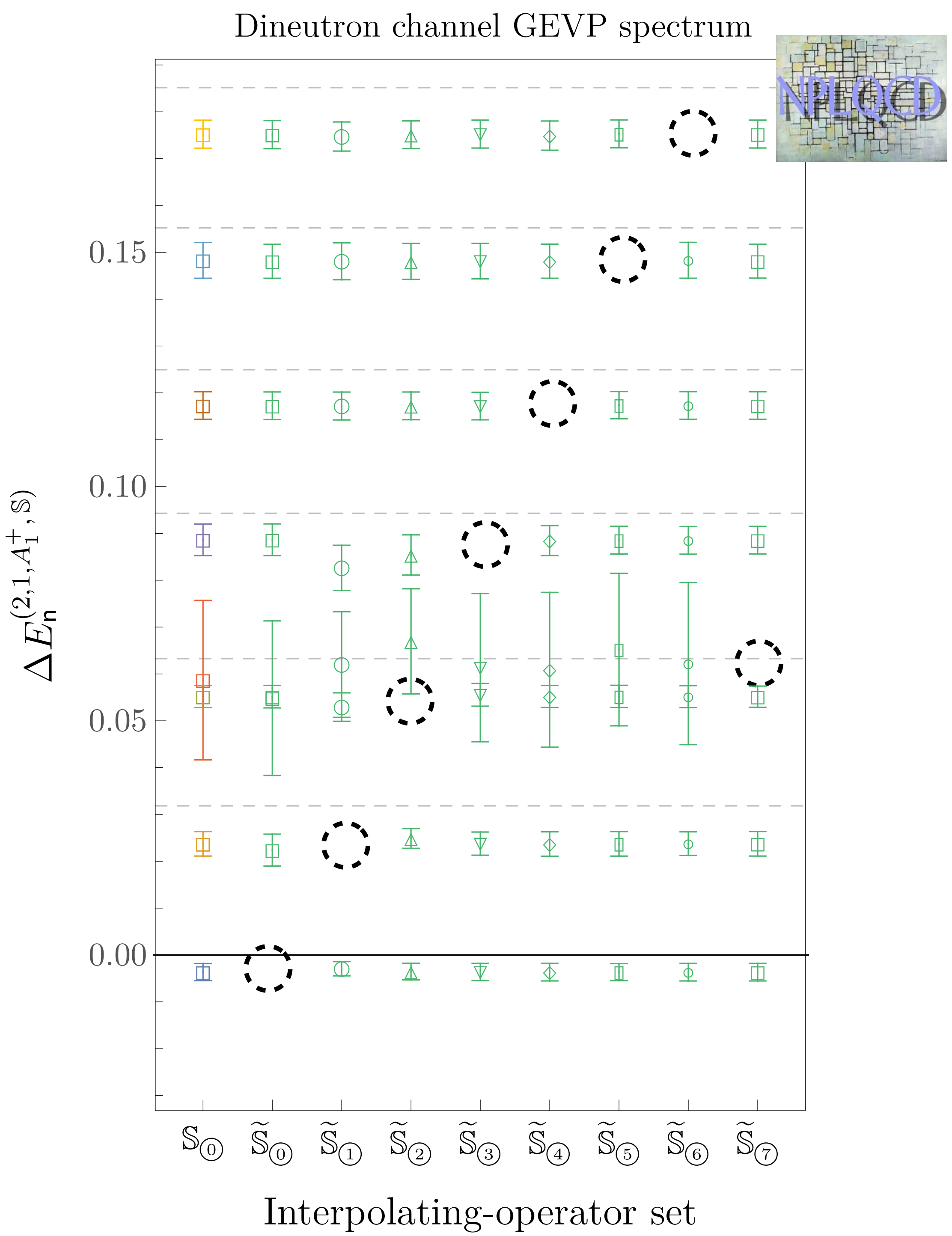
$\pi\pi$ Dudek et al. [HadSpec], PRD87 (2013)

Wislon et al. [HadSpec], PRD92 (2015)

$N\pi$ Lang, Verduci, PRD87 (2013)

Kiratidis et al., PRD91 (2015)

Are we still missing operators?



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

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]

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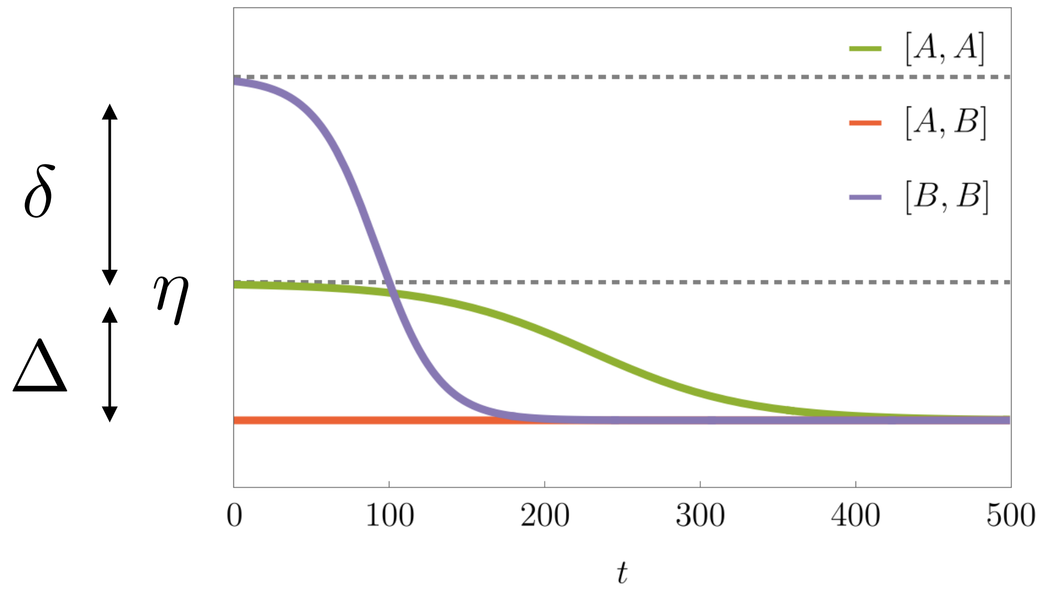

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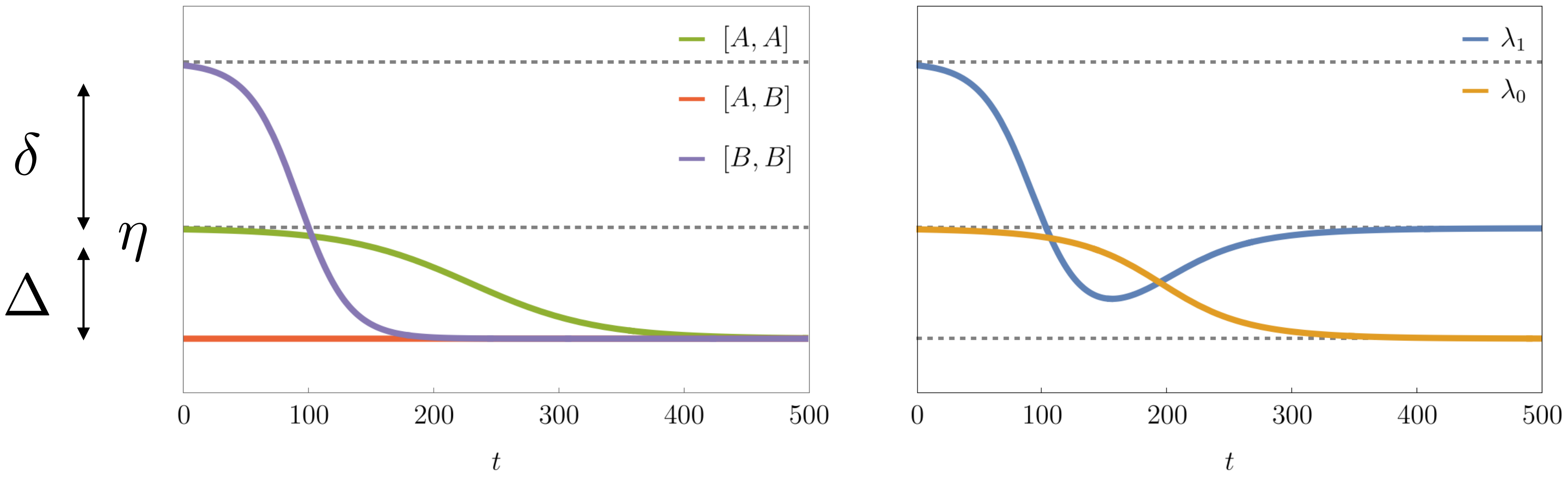

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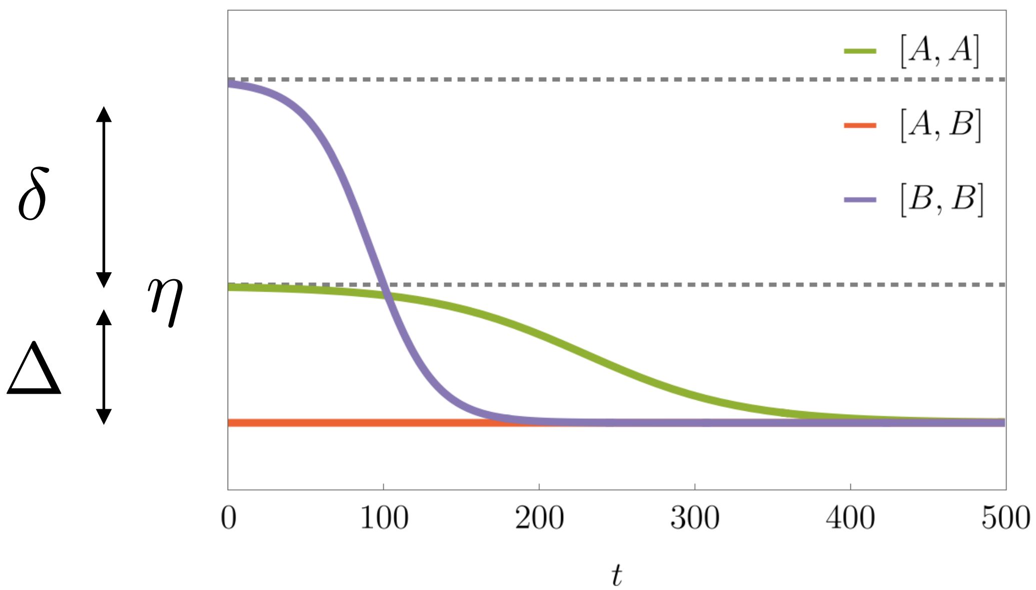

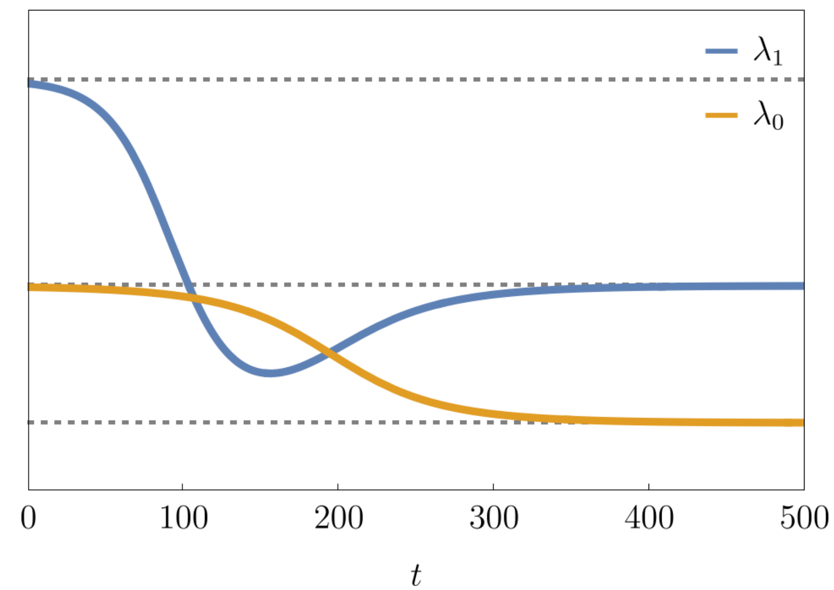

Option b) There is no deep-bound state, however...

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 ✓

Are we missing operators?

Symbiotic relationship between LQCD and EFT

Constrain 2 and 3-body nuclear forces, compare 4-body system as a check, and predict larger nuclei

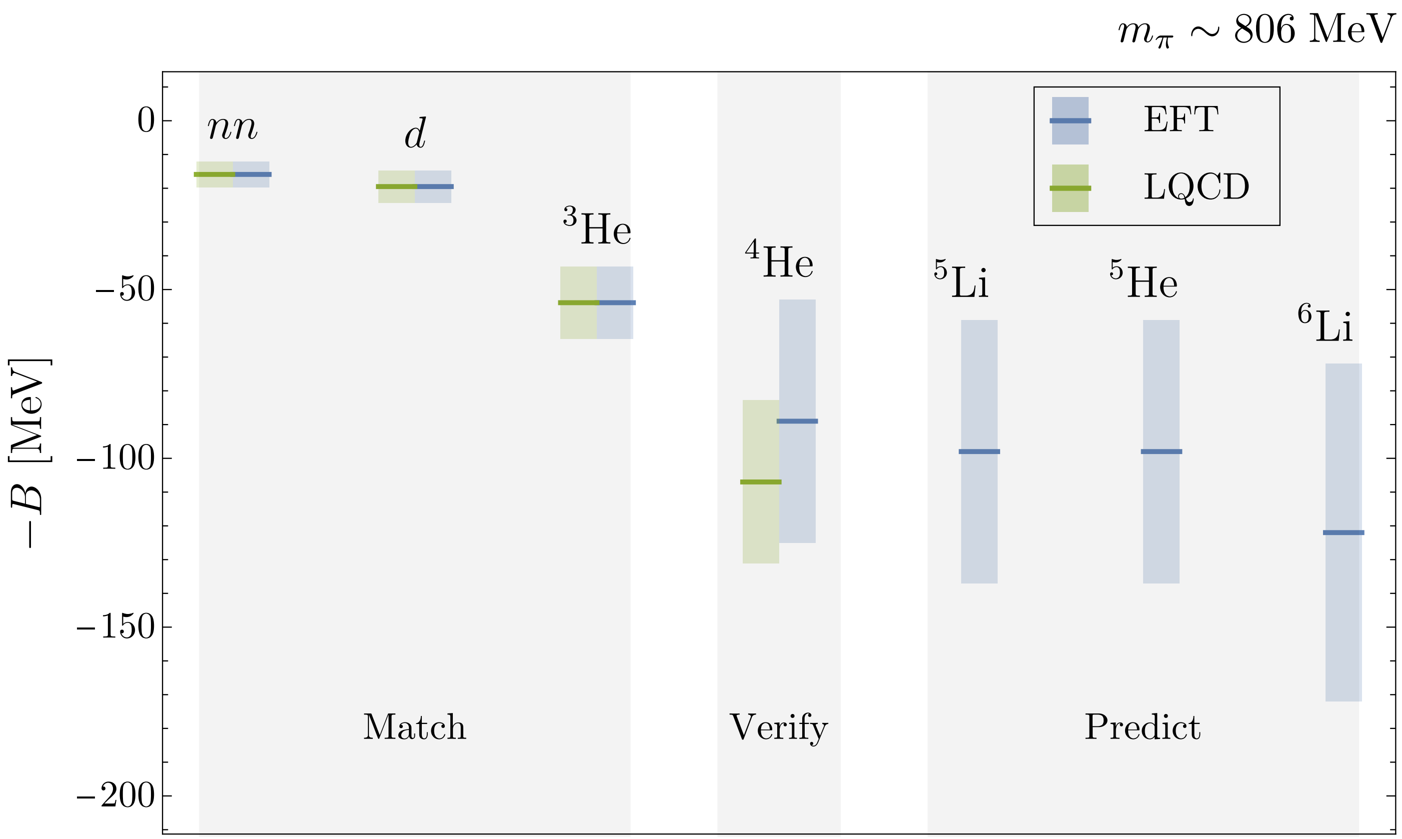

Figure from Davoudi et al., Phys. Rep. 900 (2020)
Data from Beane et al. [NPLQCD], PRD87 (2013) and Barnea et al., PRL114 (2015)

Extensions to ^{16}O and ^{40}Ca

Contessi et al., PLB772 (2017)

Bansal et al., PRC98 (2018)

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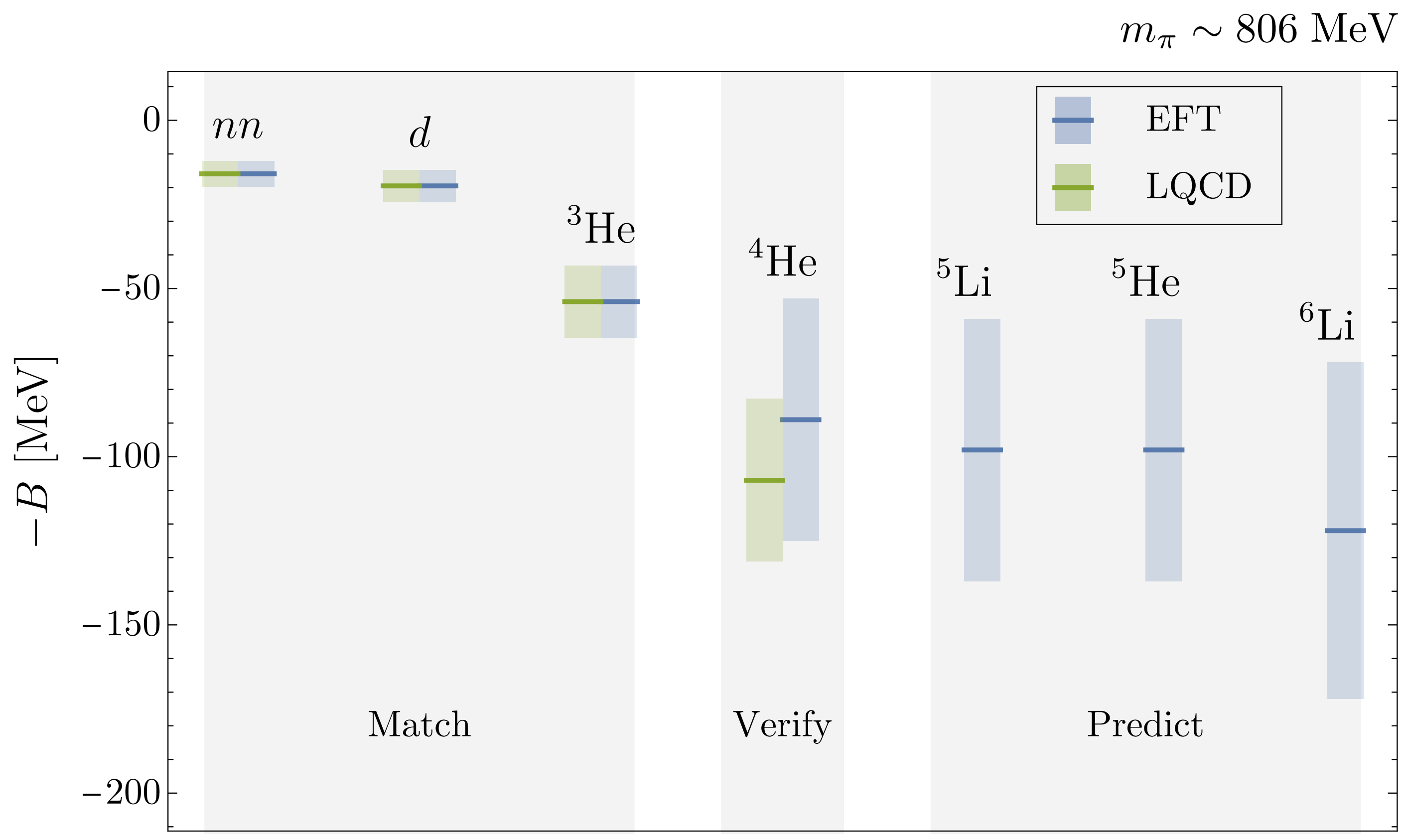

Figure from Davoudi et al., Phys. Rep. 900 (2020)
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Extensions to ^{16}O and ^{40}Ca ⟶ Possible to do the same with hypernuclei once ΛN and ΛNN are extracted

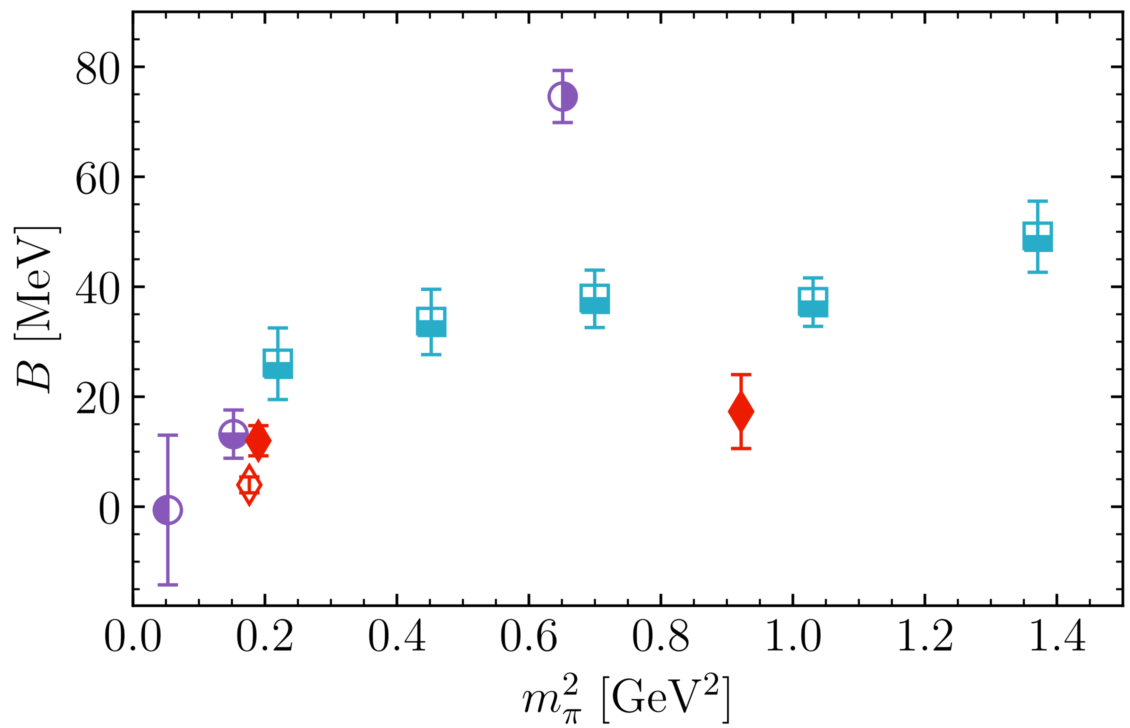
Contessi et al., PLB772 (2017)

Bansal et al., PRC98 (2018)

Are we missing operators?

Option c) These discrepancies arise from lattice spacing effects

With the direct method, only NPLQCD had performed calculations of the H-dibaryon channel unitl 2018 (the others were performed by HALQCD)



NPLQCD

Hadrons to Atomic nuclei HAL from Lattice QCD

JG|U → first application of variational approach to BB

(with only dibaryon-like operators)

Are we missing operators?

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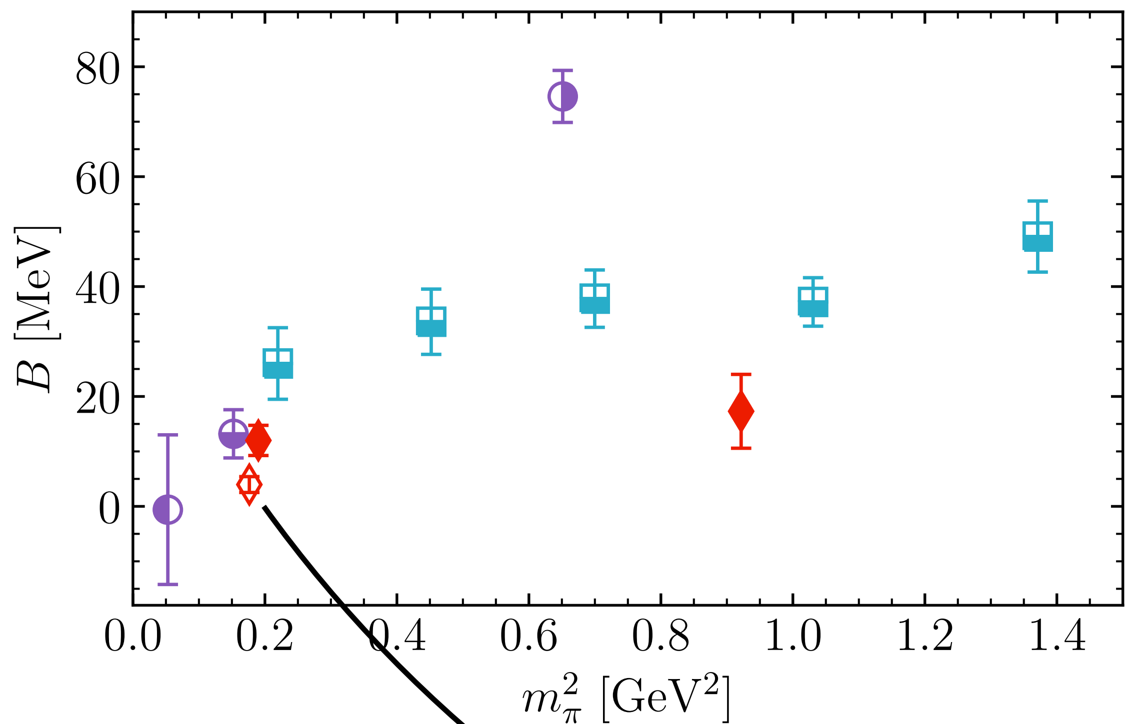
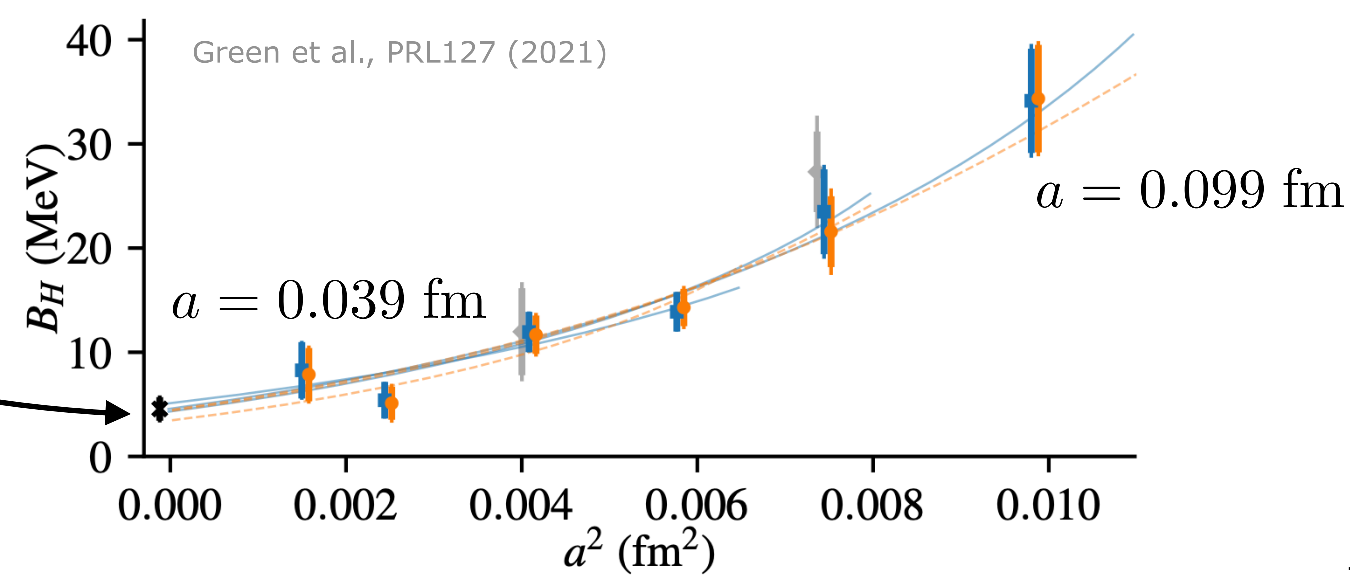


→ first application of variational approach to BB (with only dibaryon-like operators)



first extrapolation to the continuum for BB systems

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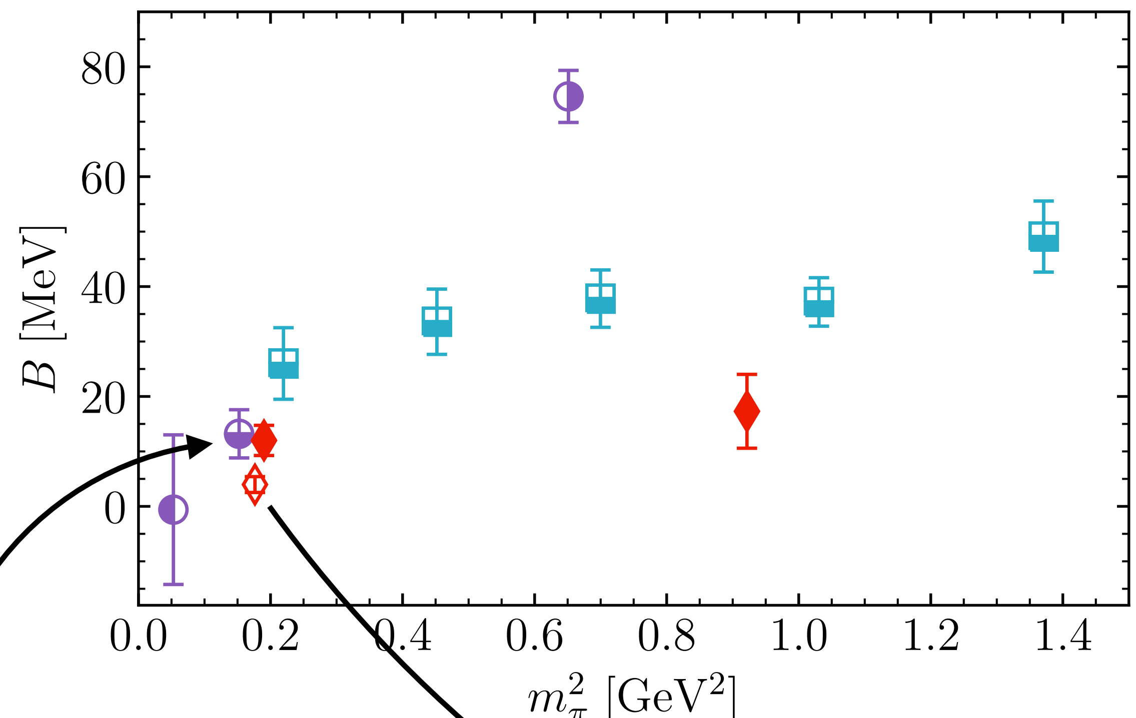
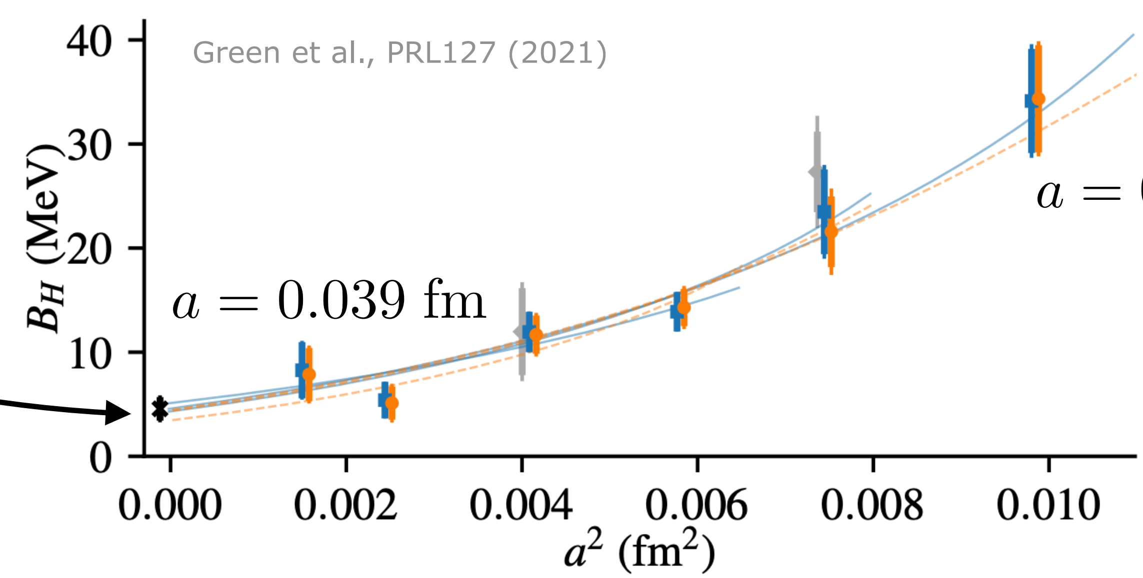


NPLQCD

HAL — Hadrons to Atomic nuclei from Lattice QCD

JGU → first application of variational approach to BB (with only dibaryon-like operators)

$a = 0.123$ fm



$a = 0.099$ fm

$a = 0.039$ fm

first extrapolation to the continuum for BB systems

Summary

We can use LQCD to reach systems that are difficult for experimentalists (like strange systems)

It is still not clear what the best operators are to include in a variational analysis for two-baryon systems

- Ongoing study with additional operators and additional volumes at $m_\pi \sim 806$ MeV
- Starting production for different baryon-baryon systems closer to the physical point ($m_\pi \sim 170$ MeV) with different volumes

Beyond spectroscopy, matrix elements relevant for current experiments are being pursued (momentum fraction, β-decay and $\beta\beta$-decay, scalar and tensor ME,...)

Thank you

This project has received funding from the Helmholtz Institute Mainz and the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093.

Are we missing operators?

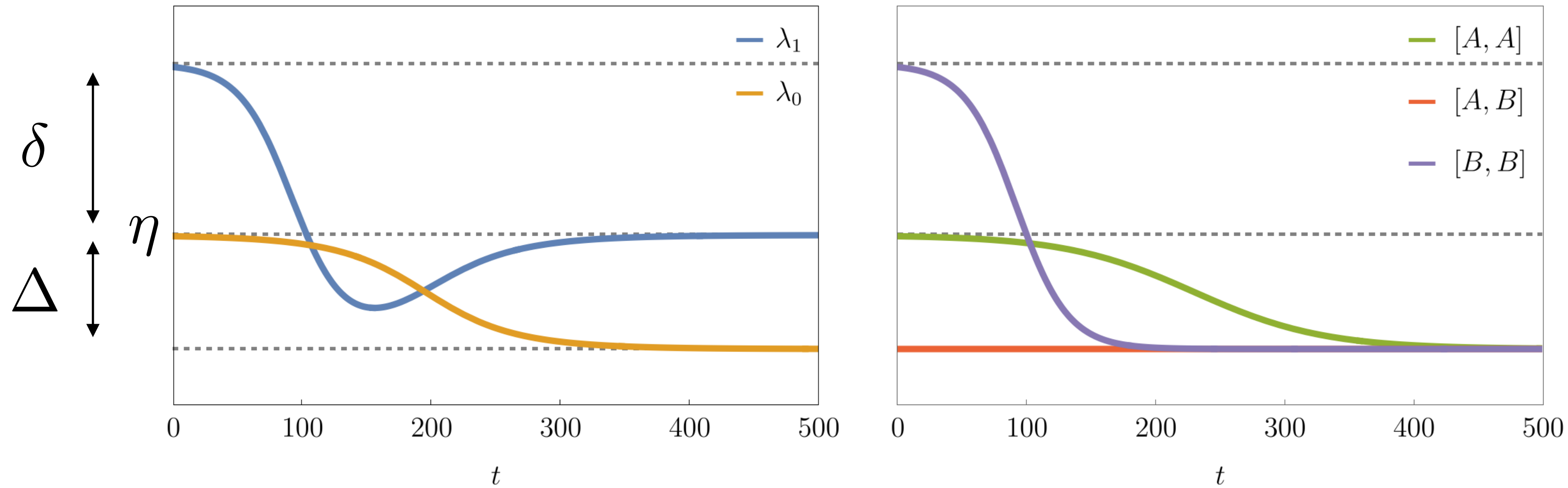
Option a) There is a deep-bound state, but the current operators have a small overlap

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

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

$$\lambda_0^{(AB)} = e^{-(t-t_0)\eta}[1 + \epsilon^2(e^{t\Delta} - e^{t_0\Delta}) + \mathcal{O}(\epsilon^4)]$$

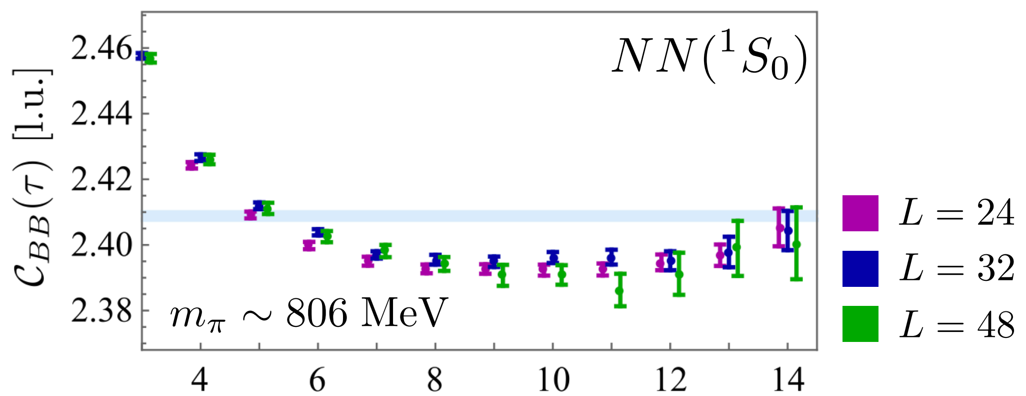
$$\lambda_1^{(AB)} = e^{-(t-t_0)(\eta+\delta)}[1 + \epsilon^2(e^{t(\Delta+\delta)} - e^{t_0(\Delta+\delta)}) + \mathcal{O}(\epsilon^4)]$$



Are we missing operators?

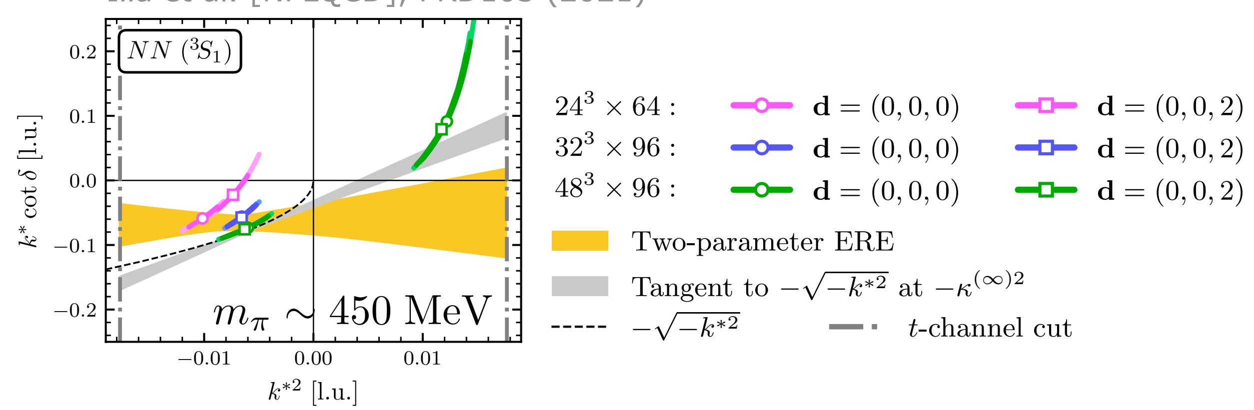
Option b) There is no deep-bound state, however...

Wagman et al. [NPLQCD], PRD96 (2017)



Volume independence of the ground state

Illa et al. [NPLQCD], PRD103 (2021)



Analysis of the phase-shifts and checks on scattering parameters

$$\sigma_{B;\pi A} = \sigma_{\pi A} - A\sigma_{\pi p}$$

Chang et al. [NPLQCD], PRL120 (2018)

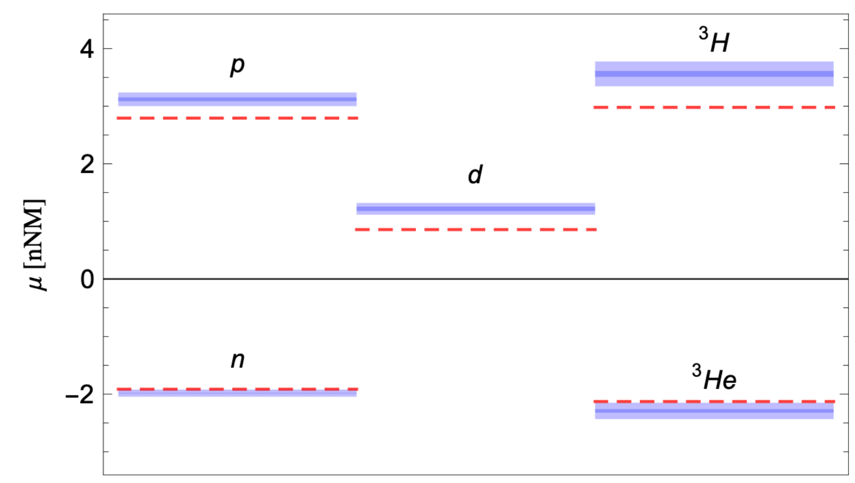
Beane et al., PRD89 (2014)

	Direct calculation	Feynman-Hellmann approach
d	$-7(14)$	$-9.1(6.0)$
^{3}He	$-40(22)$	$-50.8(11.8)$

$m_\pi \sim 806$ MeV

Consistency in scalar ME extraction

Beane et al. [NPLQCD], PRL113 (2014)

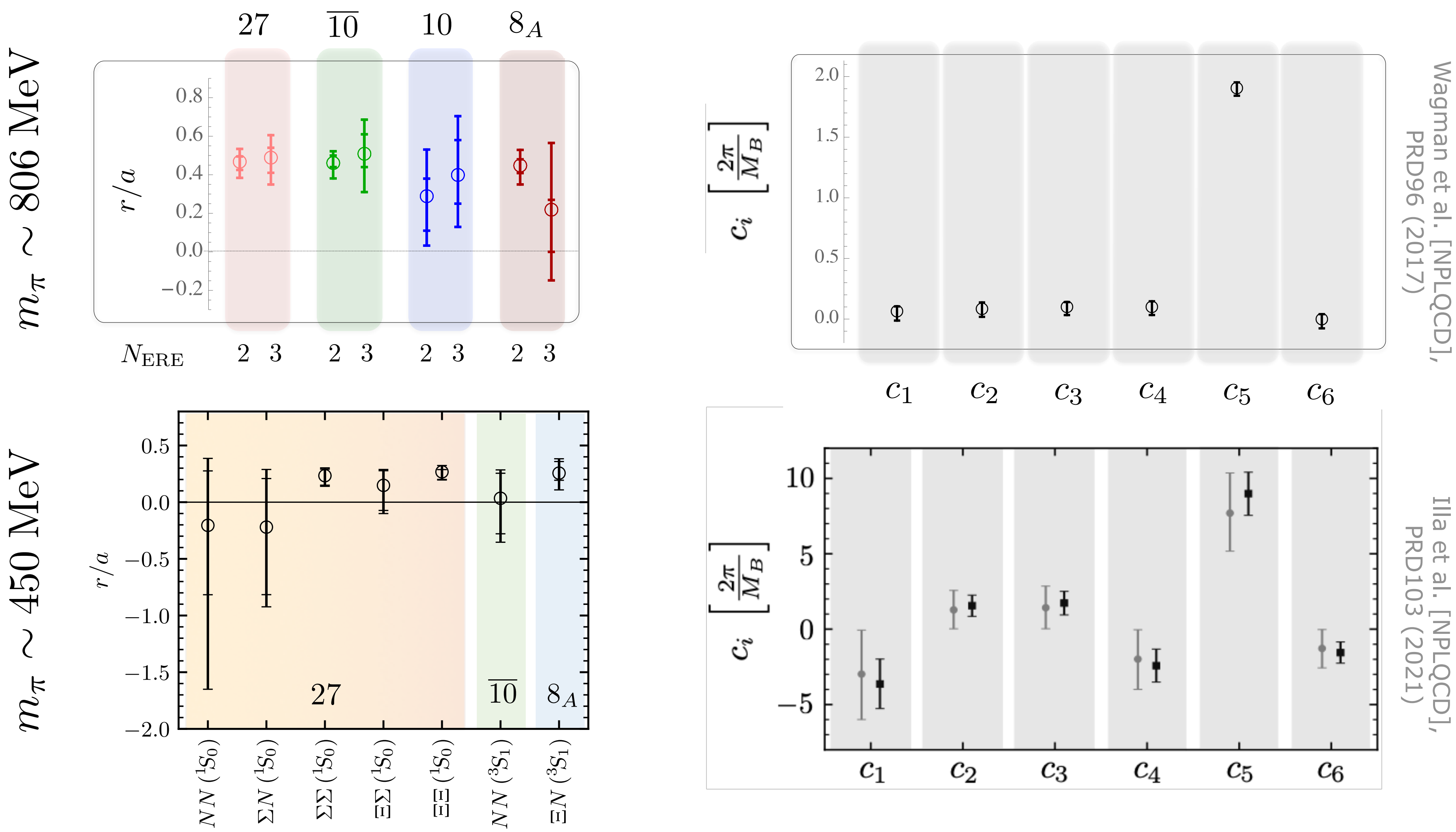


Magnetic moments of light nuclei

Are we missing operators?

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

Scattering parameters → EFT matching

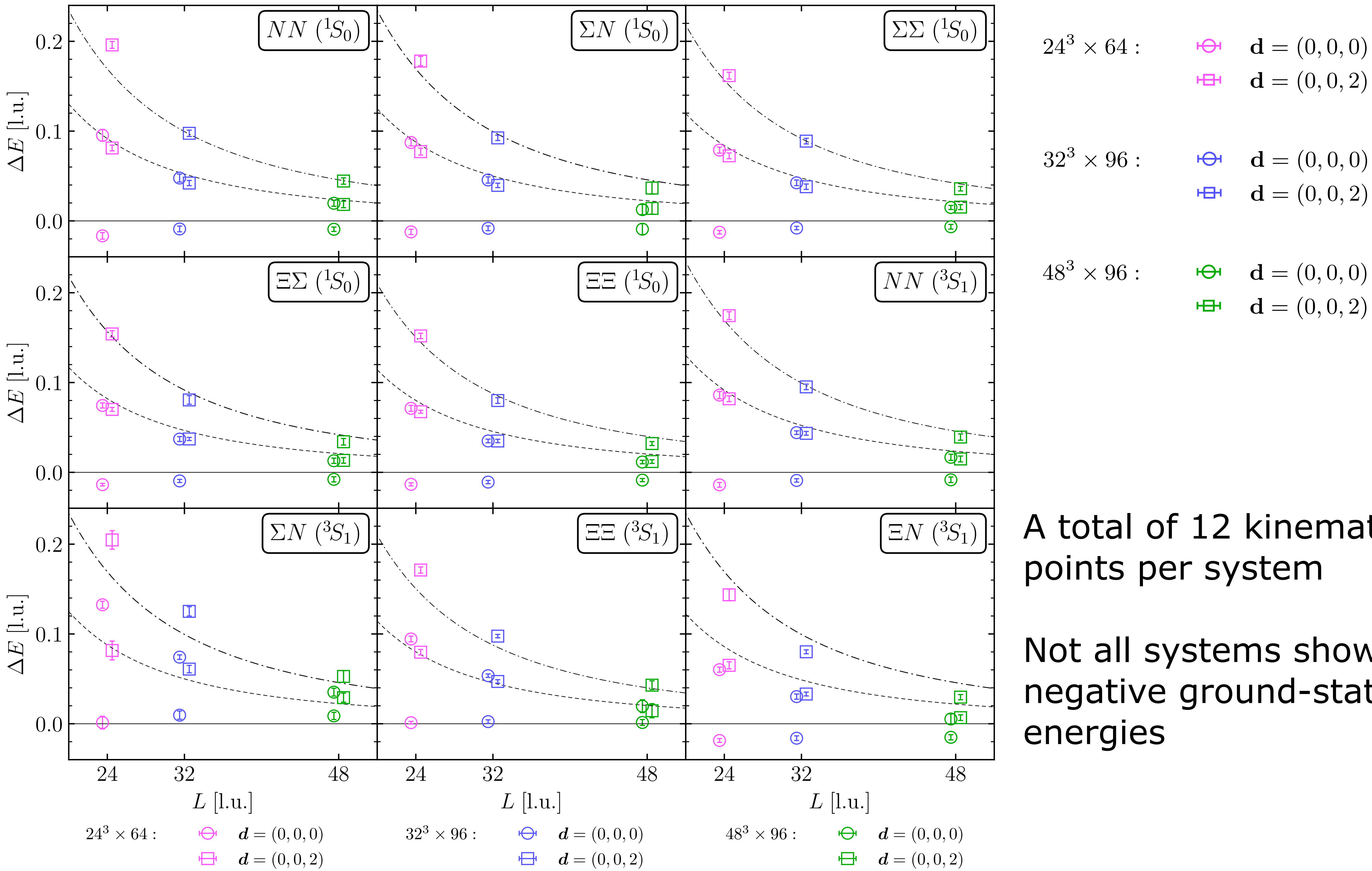


Agreement with large-N_c predition of an SU(6) symmetry, and a larger SU(16) symmetry predicted by the conjecture that entanglement is minimized in low-energy processes Beane, Kaplan, Klco, Savage, PRL122 (2019)

Studying the BB interaction

Illa et al. [NPLQCD], PRD103 (2021)

$m_\pi \sim 450$ MeV

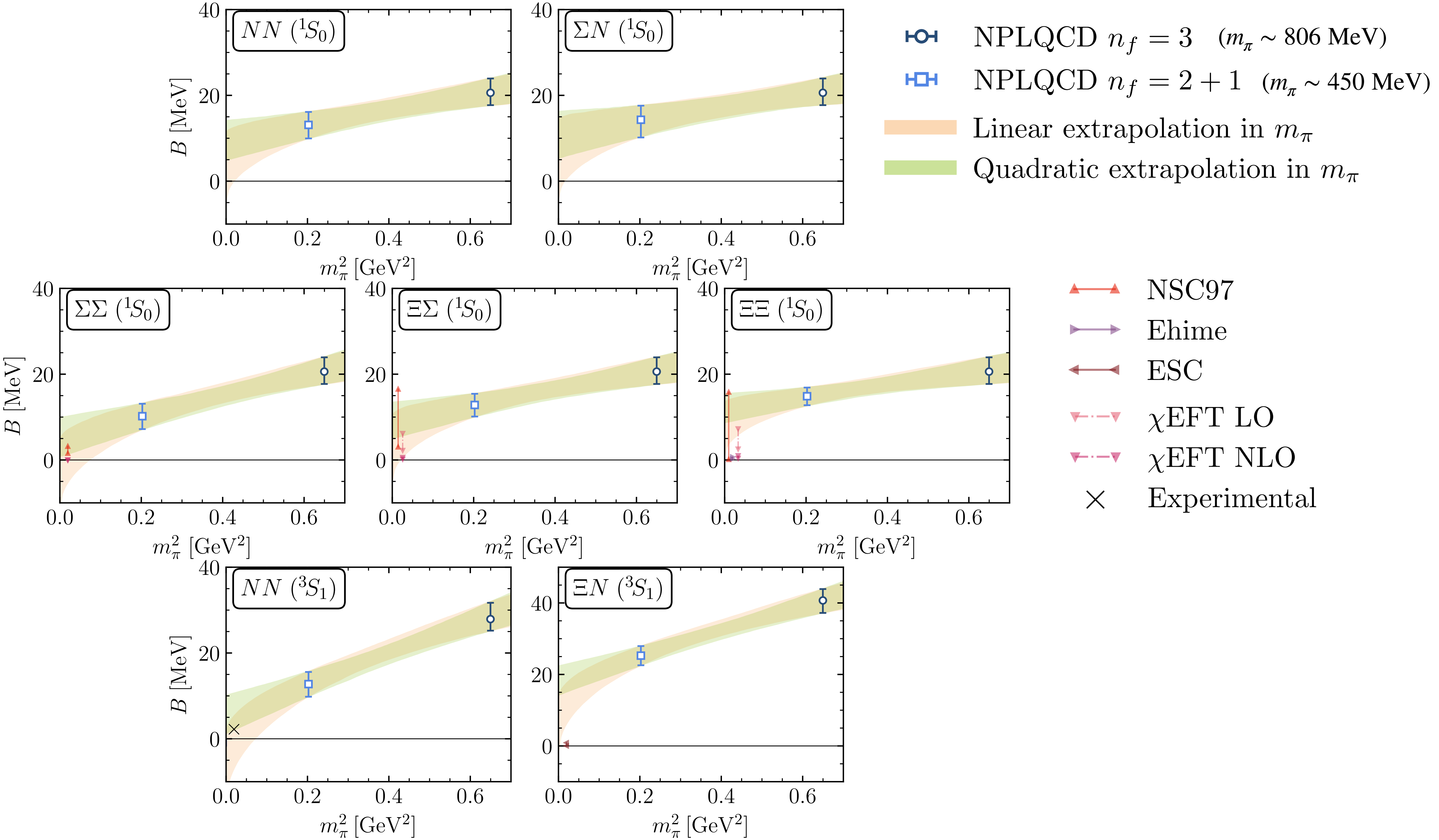


A total of 12 kinematic points per system

Not all systems show negative ground-state energies

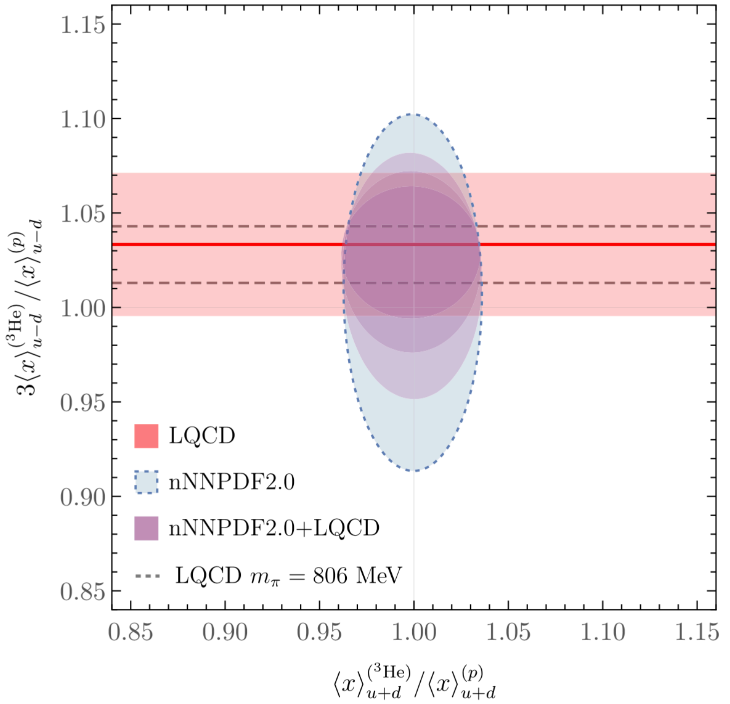
Studying the BB interaction

Illa et al. [NPLQCD], PRD103 (2021)



Matrix elements for nuclear physics

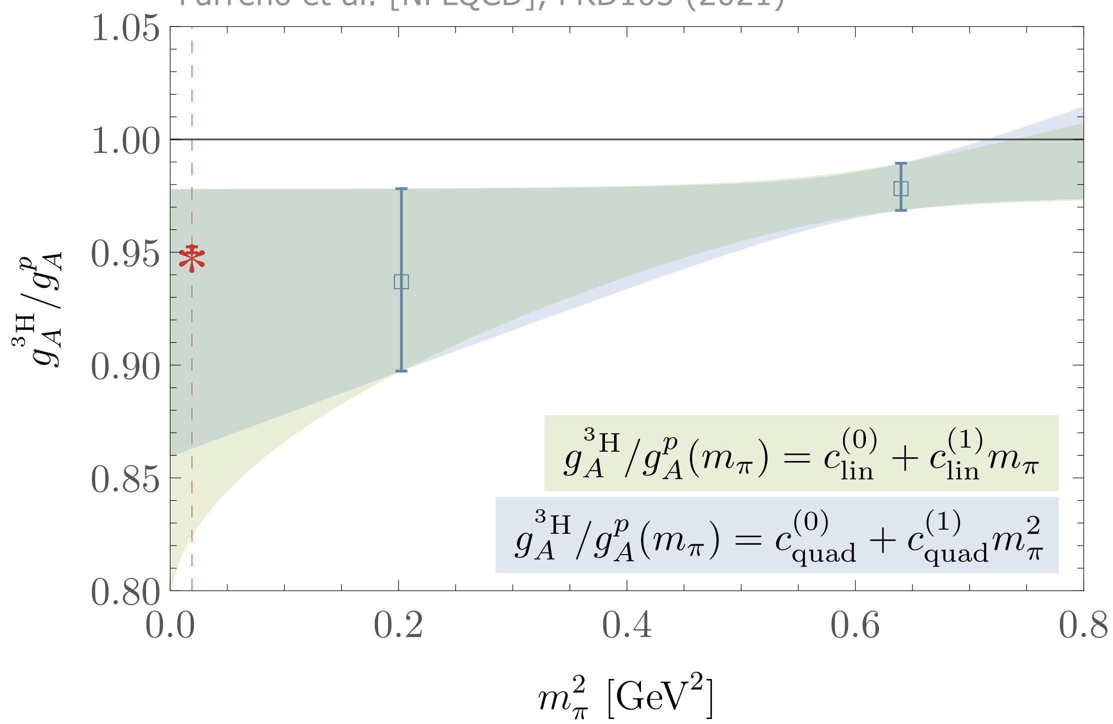
Detmold et al. [NPLQCD], PRL126 (2021)



Extraction of the momentum fraction of $u-d$ in light nuclei

It can help constrain current experimental values, showing the potential for future calculations closer to the physical pion mass

Parreño et al. [NPLQCD], PRD103 (2021)



The axial charge of the triton can be extrapolated to the physical point

Pionless EFT was used to extrapolate the finite-volume lattice result to infinite volume