ROCKSTAR: Towards a Roadmap of the Crucial Measurements of Key Observables in Strangeness Reactions for Neutron Stars Equation of State

12th October, 2023

Status of hyperon forces in Lattice QCD

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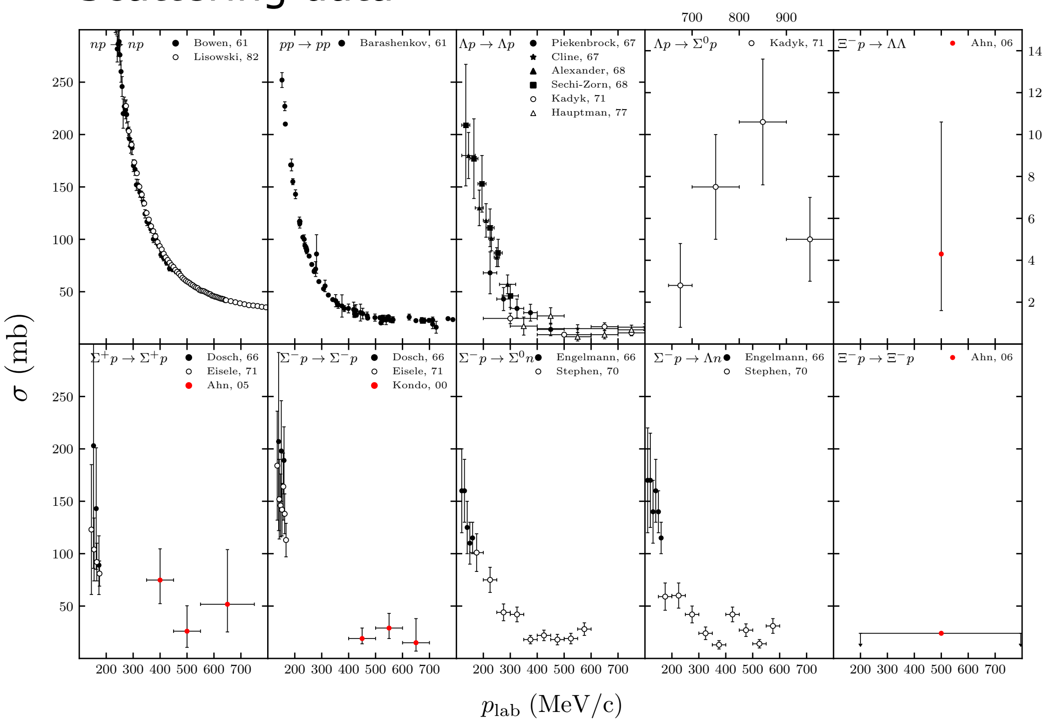
NPLQCD

Experimental status

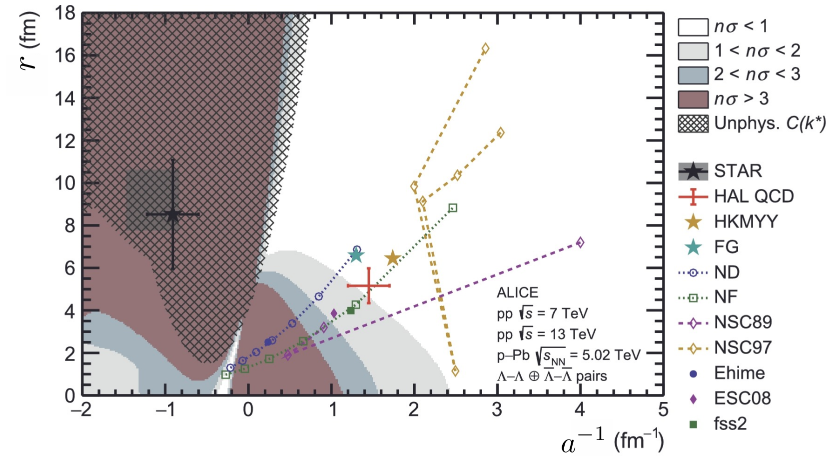
Experimental input to constrain theory

Scattering data



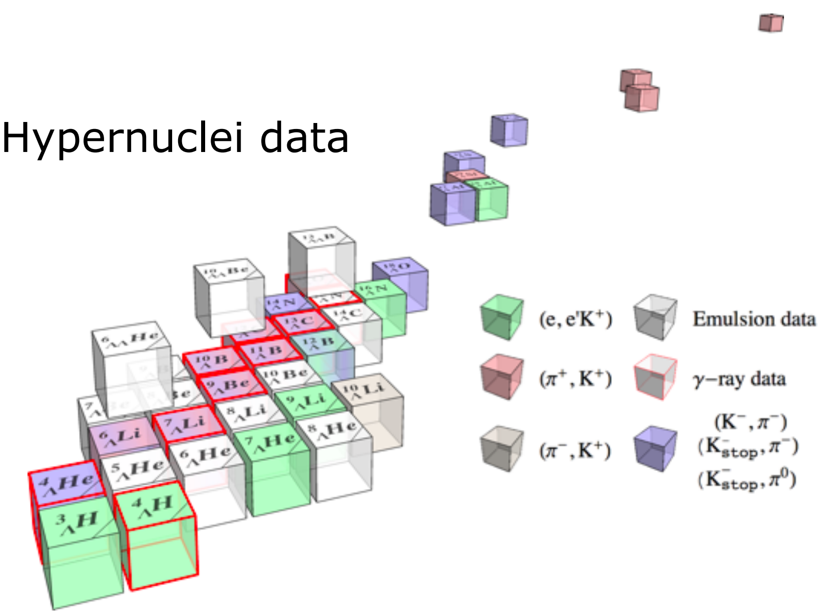
updated from Dover and Feshbach, Ann. Phys. 198 (1990)

Femtoscopy data



ALICE Collaboration, PLB 797 (2019)

Hypernuclei data



Source: Axel Pérez-Obiol

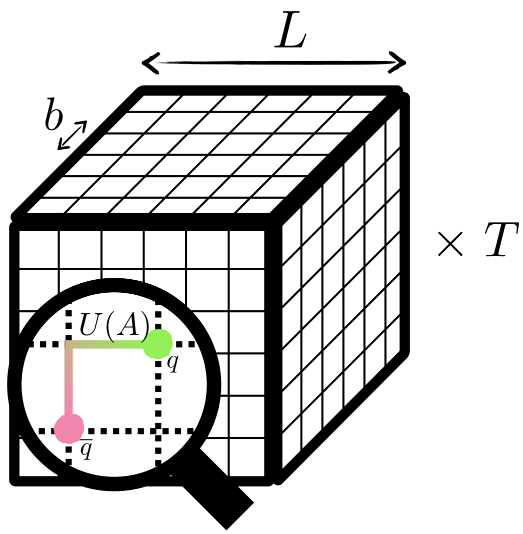
Lattice QCD

$$\langle \hat{\mathcal{O}} \rangle = \frac{1}{Z} \int \mathcal{D}\psi \mathcal{D}\overline{\psi} \mathcal{D}A_\mu \, \hat{\mathcal{O}}[\psi, \overline{\psi}, A] e^{\mathrm{i}S_{QCD}}$$

Finite volume $L^3 \times T$ $\quad L \gg m_\pi^{-1}$

Discretize spacetime $b \ll \Lambda_{QCD}^{-1}$

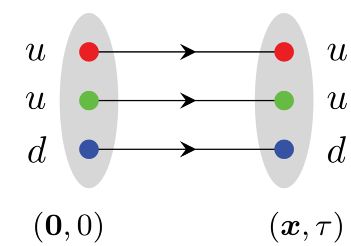
Imaginary time $t \to -\mathrm{i}\tau$



$$\langle \hat{\mathcal{O}} \rangle = \frac{1}{Z} \int \mathcal{D}\psi \mathcal{D}\overline{\psi} \mathcal{D}U_\mu \, \hat{\mathcal{O}}[\psi, \overline{\psi}, U] e^{-S_{QCD}}$$

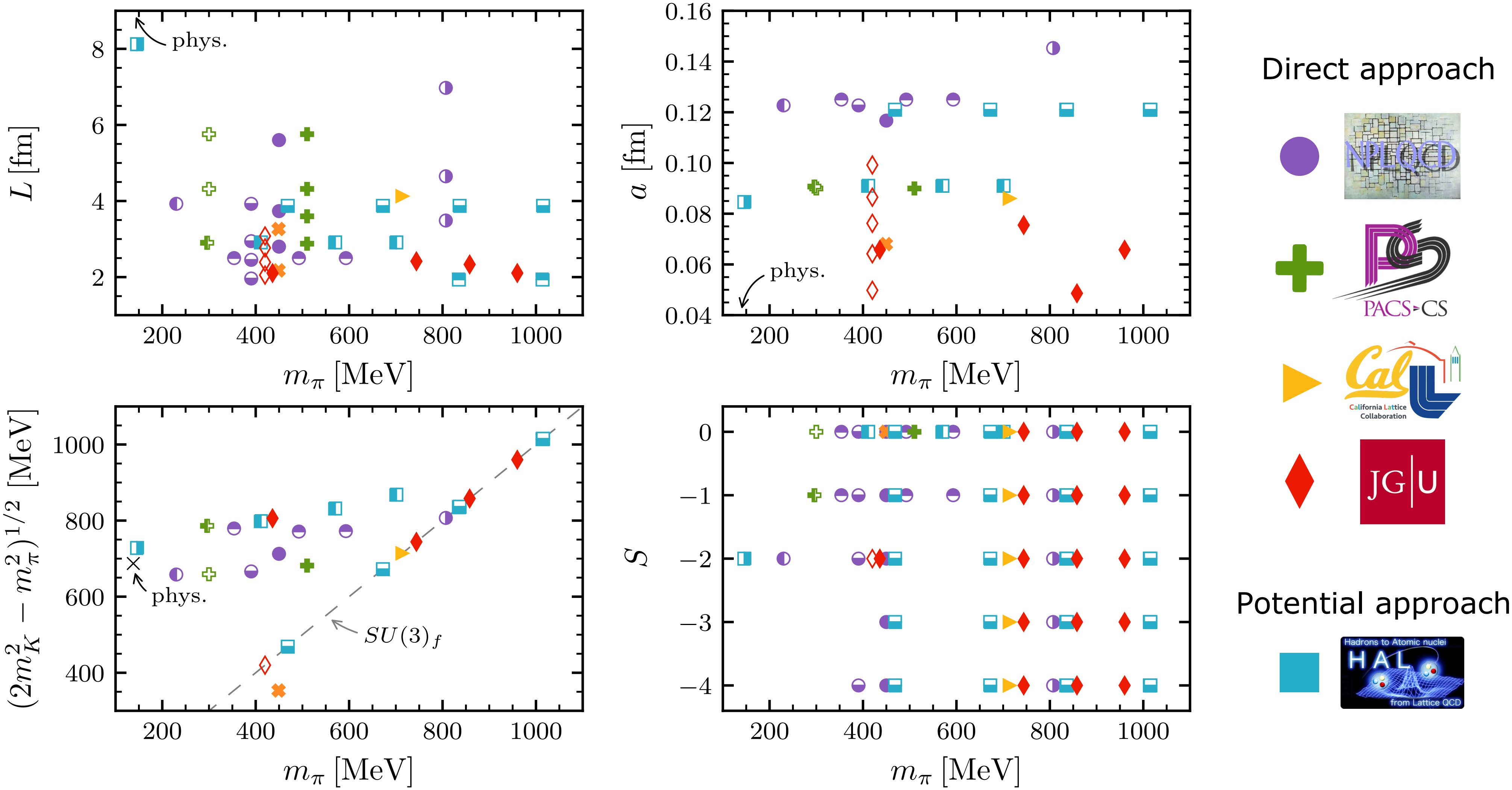
$$\langle \hat{\mathcal{O}} \rangle \approx \frac{1}{N_{\mathrm{cfg}}} \sum_{n=1}^{N_{\mathrm{cfg}}} \hat{\mathcal{O}}(\{U\}_n)$$

$$C_{2pt}(\tau, \boldsymbol{p}) = \sum_{\boldsymbol{x}} e^{-\mathrm{i}\boldsymbol{x}\cdot\boldsymbol{p}} \, \Gamma_{\beta\alpha} \langle \mathcal{X}_\alpha(\boldsymbol{x}, \tau) \bar{\mathcal{X}}_\beta(\boldsymbol{0}, 0) \rangle$$



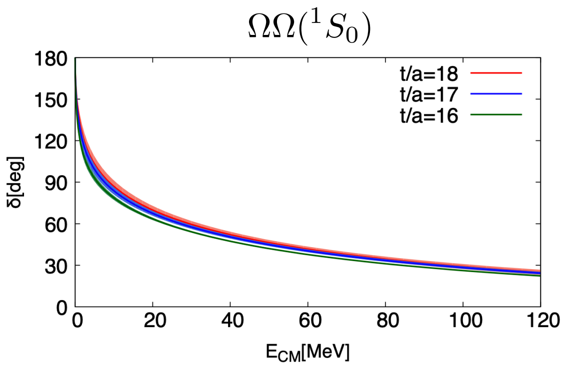
Present status

Landscape for octet-baryon studies

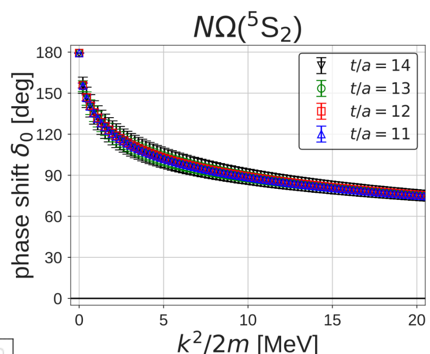


Potential approach

HAL QCD has performed the first LQCD calculations almost at the physical point

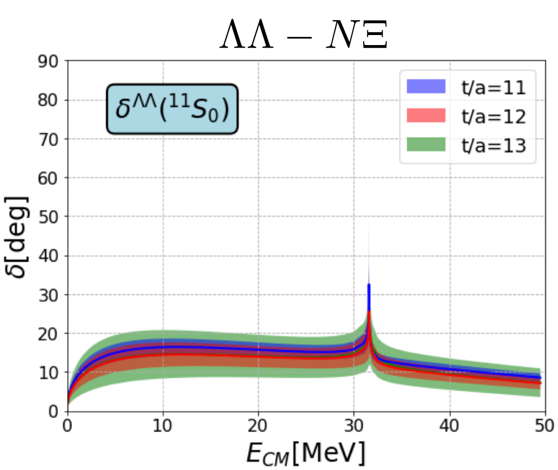


HAL QCD, PRL 120 (2018)

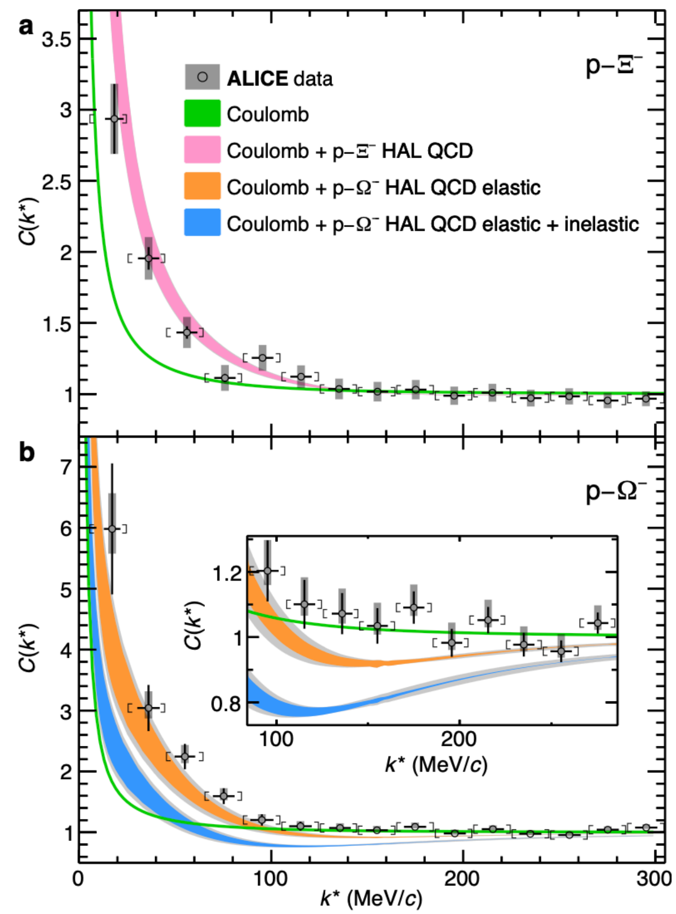


HAL QCD, PLB 792 (2019)

HAL QCD, NPA 998 (2020)

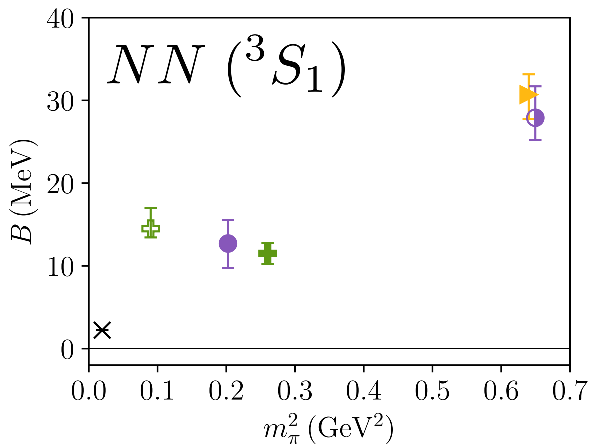


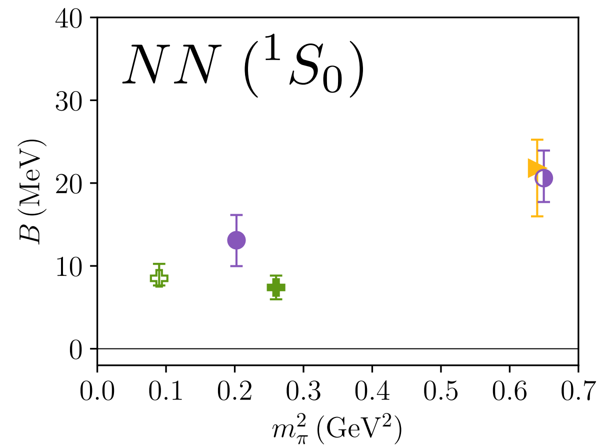
ALICE, Nature 588 (2020)



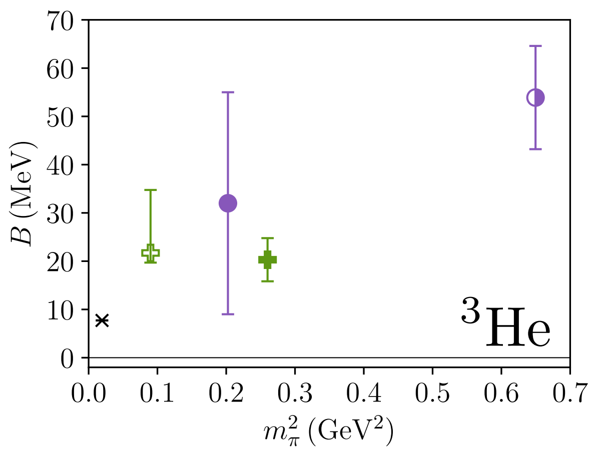
Direct approach

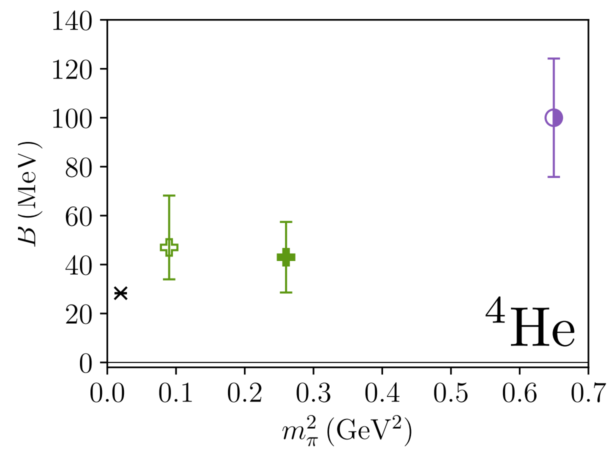
Traditionally, calculations were performed with asymmetrical correlators (different source and sink operators), leading to bound NN systems





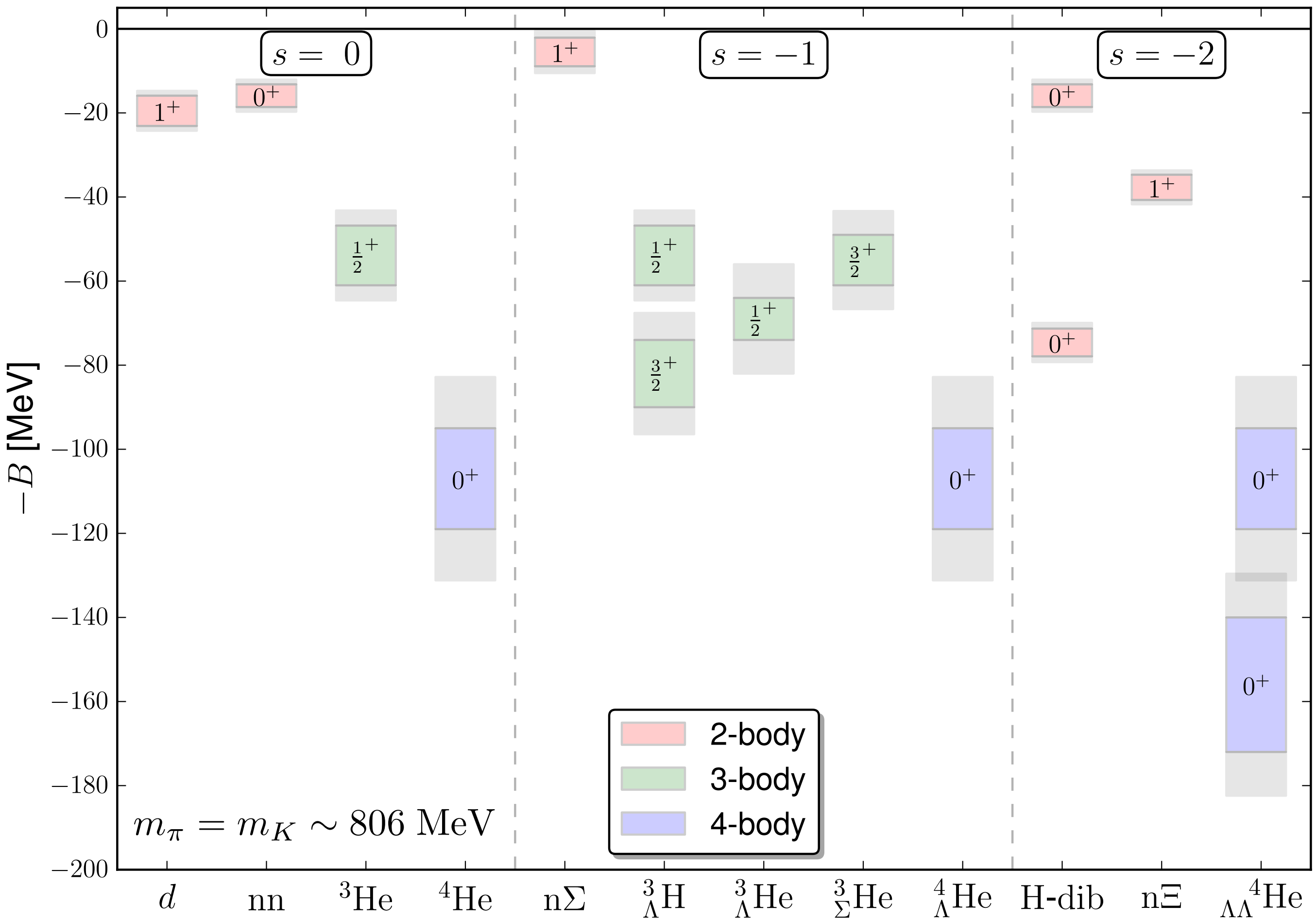
And also 3- and 4-body systems





Direct approach

The systems with hyperons have also been studied



Beane et al. [NPLQCD], PRD 87 (2013)

Direct approach

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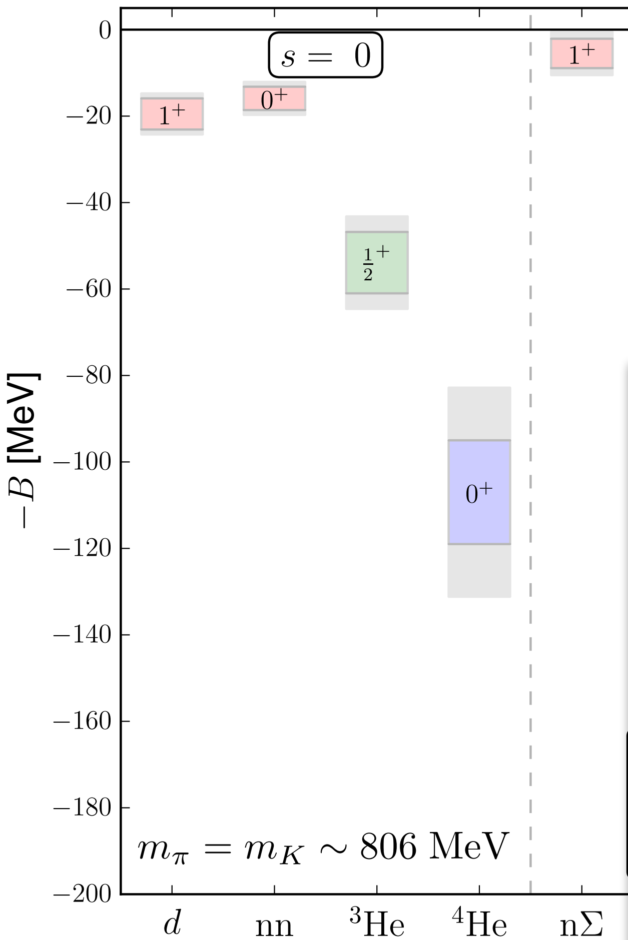
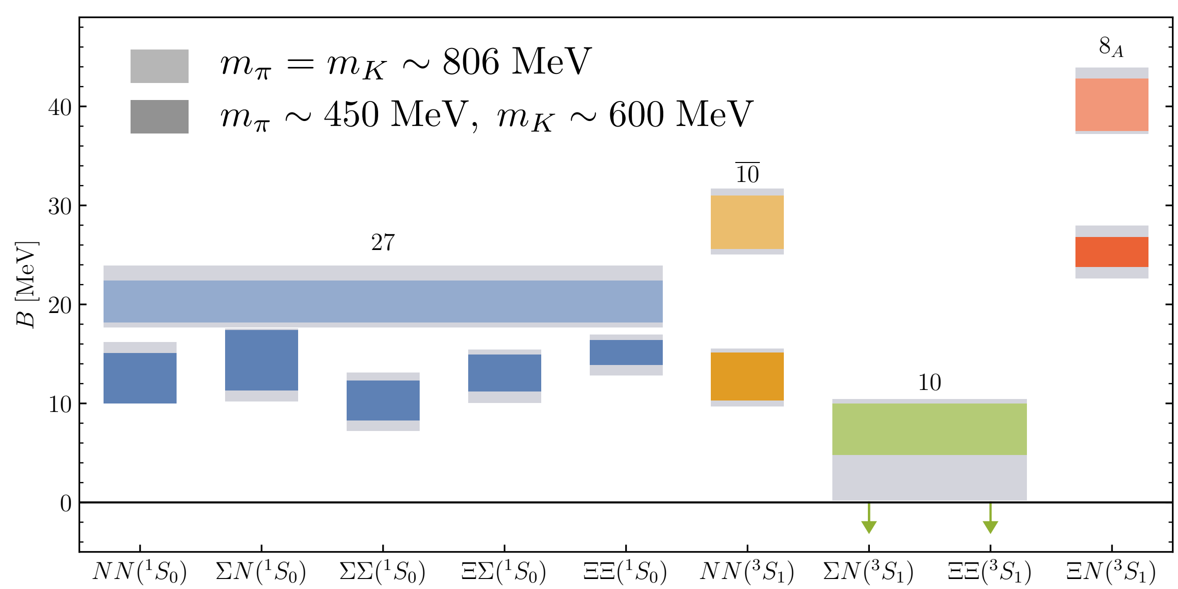


Beane et al. [NPLQCD], PRD 87 (2013)

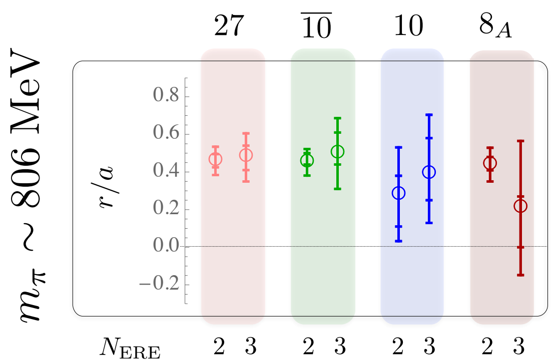


Wagman et al. [NPLQCD], PRD 96 (2017)   Illa et al. [NPLQCD], PRD 103 (2021)

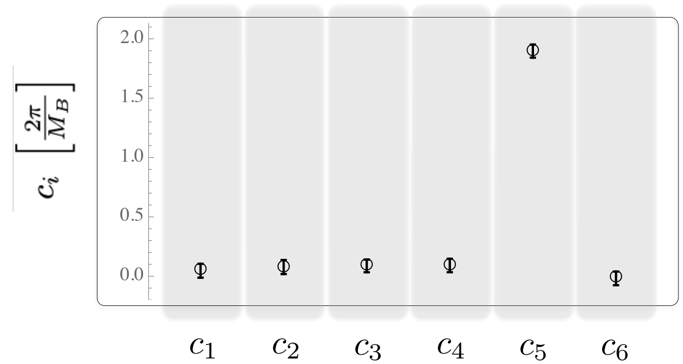
Baryon-baryon interactions

Some insights about their fundamental interactions

Scattering parameters



EFT matching: LO pionless



Wagman et al. [NPLQCD], PRD 96 (2017)

Observe accidental SU(16) symmetry at m_π~800 MeV

(expected an SU(6) from the large-N$_c$ limit)

Why is there an SU(16) symmetry?

Its existance follows from entanglement suppresion in the S-matrix (minimum entanglement power)

Beane et al., PRL 122 (2019)

Interesting to note that the strong force works in the opposite way compared to QED (where one finds that it maximixes entanglement)

Cervera-Lietra et al., SciPost 3 (2017)

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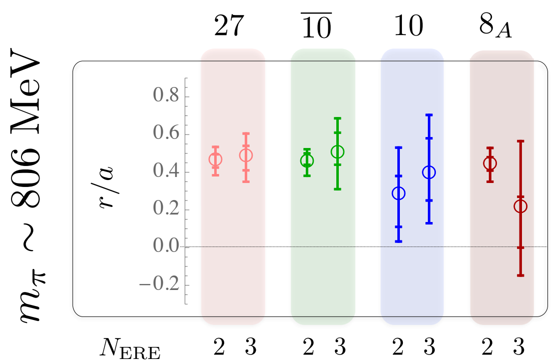

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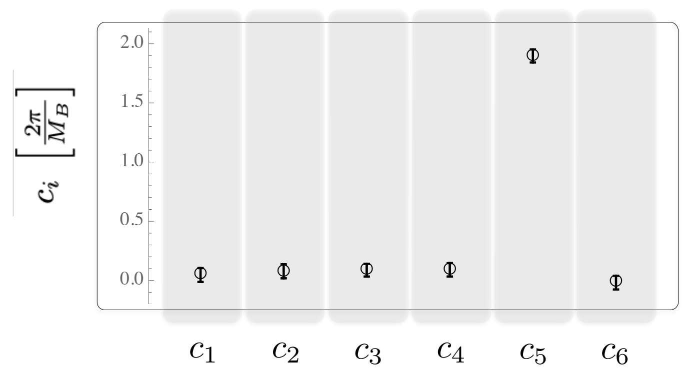

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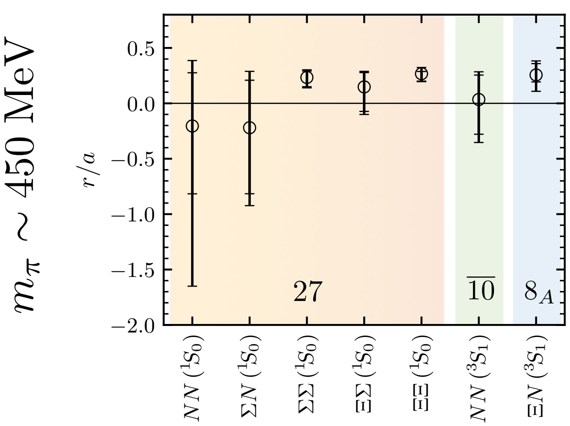
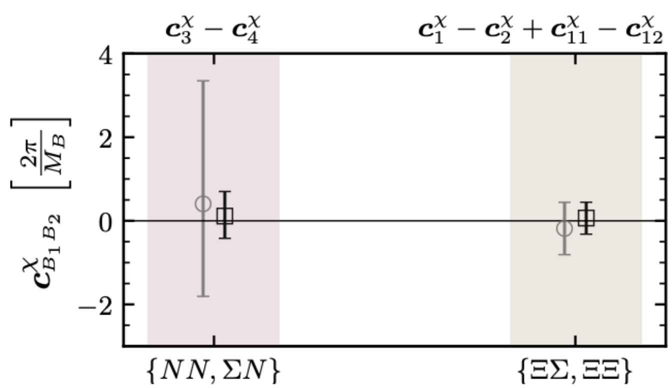


EFT matching: LO+NLO pionless



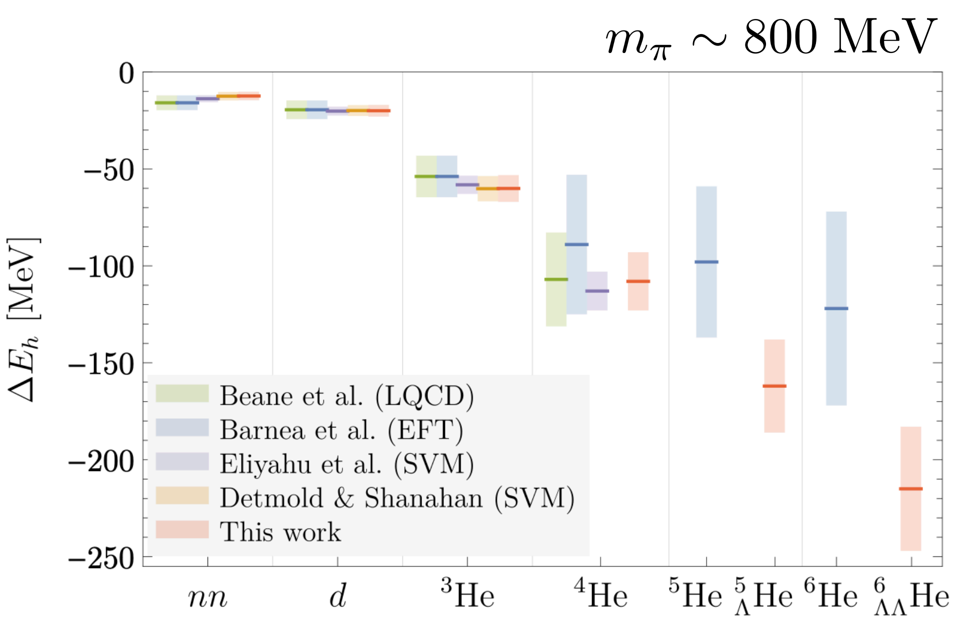
Illa et al. [NPLQCD], PRD 103 (2021)

Don't observe SU(3)f symmetry breaking effects at m_π~450 MeV

Baryon-baryon interactions

Direct fitting to LQCD energies via EFT

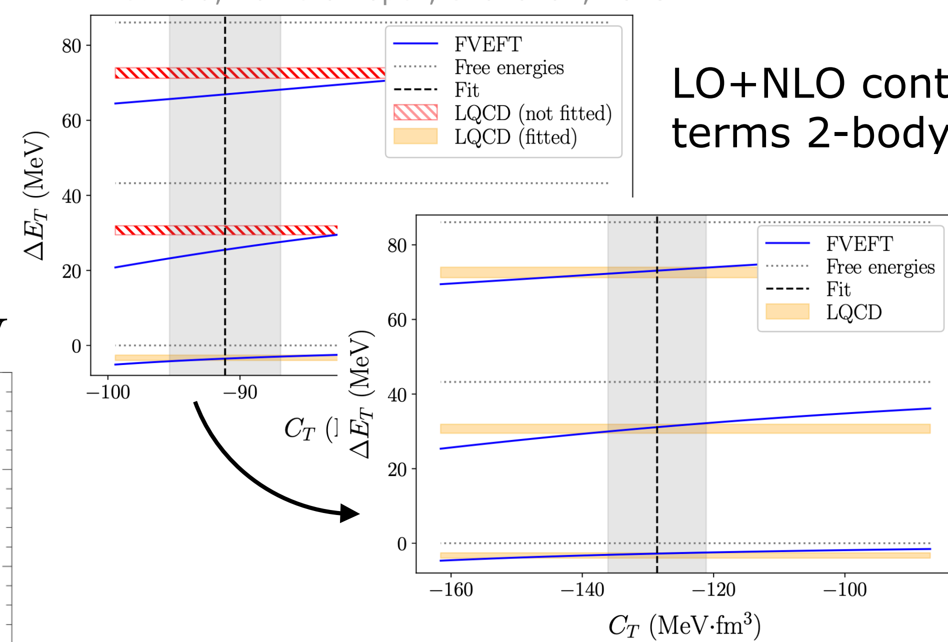
Barnea et al., PRL 114 (2015)
Contessi et al., PLB 07 (2017)
Bansal et al., PRC 98 (2018)
Eliyahu, Bazak, Barnea, PRC 102 (2020)
Detmold, Shanahan, PRD 103 (2021)
Sun, Detmold, Luo, Shanahan, 2022
Detmold, Romero-López, Shanahan, 2023



Sun, Detmold, Luo, Shanahan, 2022

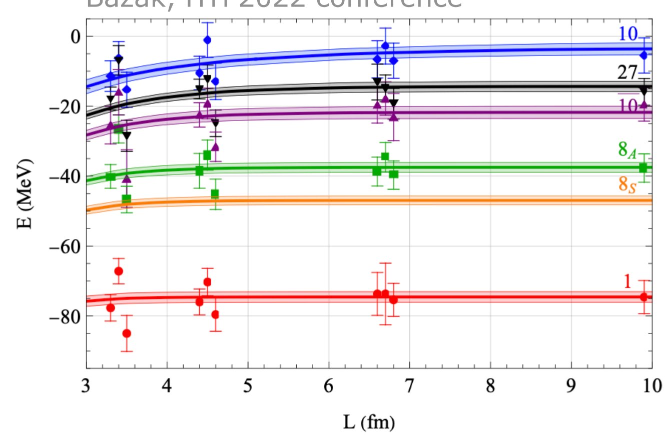
LO contact terms 2-body+3-body

Detmold, Romero-López, Shanahan, 2023



LO+NLO contact terms 2-body

Bazak, HYP2022 conference



Fit to all octet systems

Baryon-baryon interactions

What evidence do we have that these bound states are real?

PRO

Off-diagonal correlators show plateau for deep states [NPLQCD, CalLat, PACS]

Same state seen in different volumes, hard to find cancellations

EFT matching shows consistency between A = 2, 3 & 4 systems

Extrapolated matrix elements match experimental results (magnetic moments), consitency of sigma terms between slope and direct calculation

GEVP analyses do not see states unless the right operators are included in the set

CON

Variational bounds from GEVP consistent with threshold state [Hörz et al., NPLQCD,Mainz]

HAL QCD potentials do not see bound states

GEVP can reconstruct approximately off-diagonal correlators

Baryon-baryon interactions

All these calculations are still incomplete. The major challenges are:

- Reaching physical quark masses
- Control finite-volume effects
- Reach continuum limit
- Statistically noisy data
- Excited state contamination
- Design operators with large overlap onto ground state

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First steps with the H-dibaryon @ Mainz

Green et al., PRL 127 (2021)

Baryon-baryon interactions

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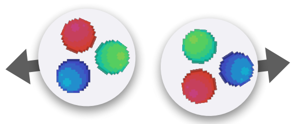
- Design operators with large overlap onto ground state

Ongoing debate if bound states exist at m_{π}~800 MeV

NN sector

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

Mainz and CalLat operator sets only include dibaryon operators: two spatially-separated plane-wave baryons with relative momenta (projected to cubic irreps)



Energy levels are slightly below from non-interacting levels

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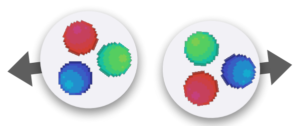
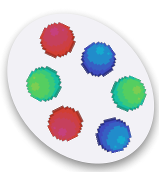
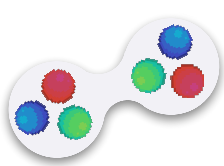


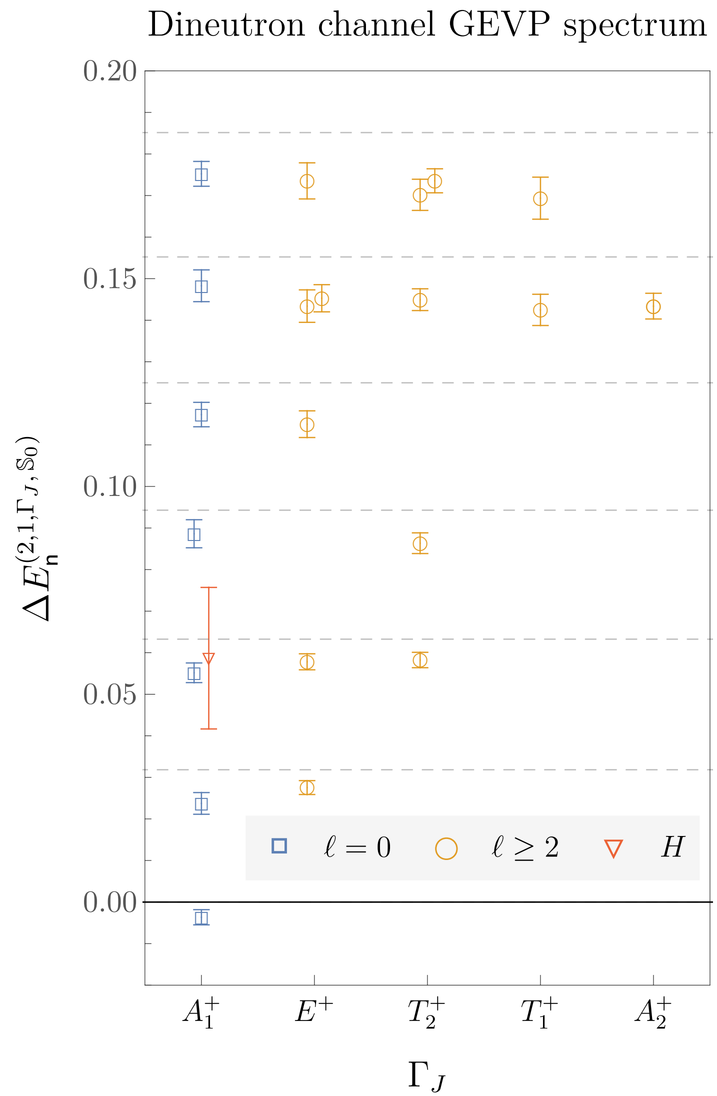
Energy levels are slightly below from non-interacting levels

We also included the hexaquark operators: six quarks at a point



and also quasi-local operators: two exponentially localized baryons (EFT inspired by deuteron wvf)





Amarasinghe et al. [NPLQCD], PRD 107 (2023)

NN sector

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Large interpolating-operator depence is observed

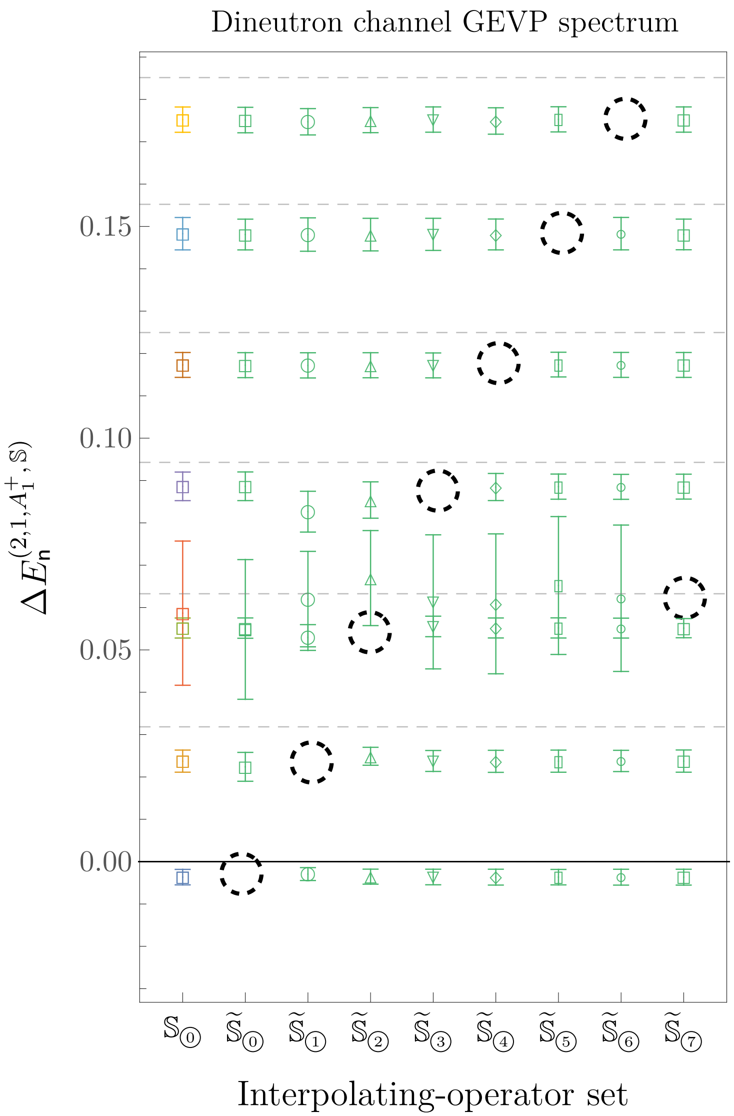
Energy levels disappear when the operator with the corresponding larger overlap is removed

$\pi\pi$ 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?

What about the noisy hex-level?



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

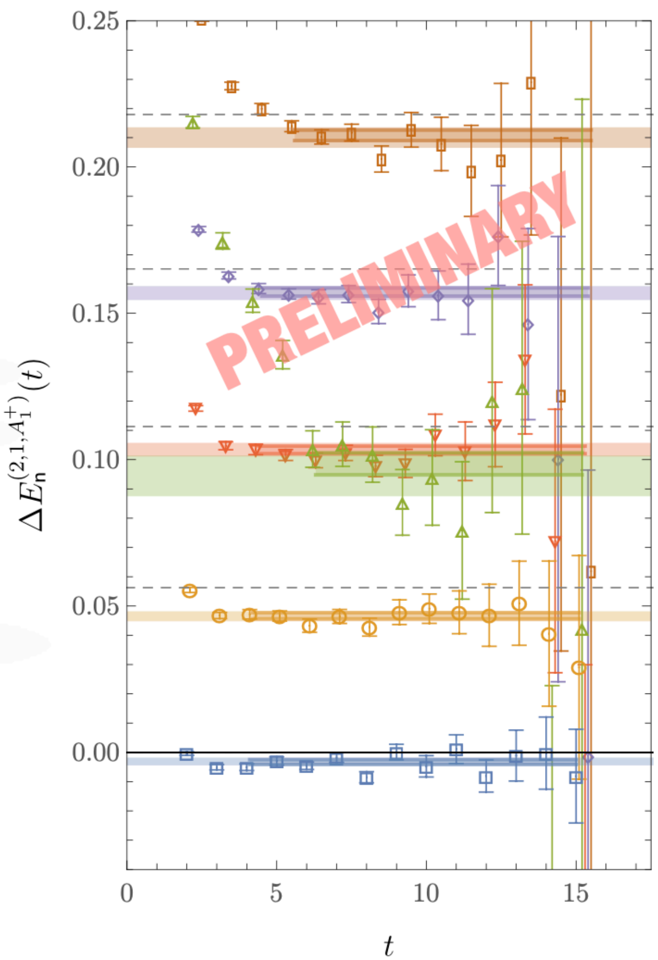
NN sector

What about the noisy hex-level?

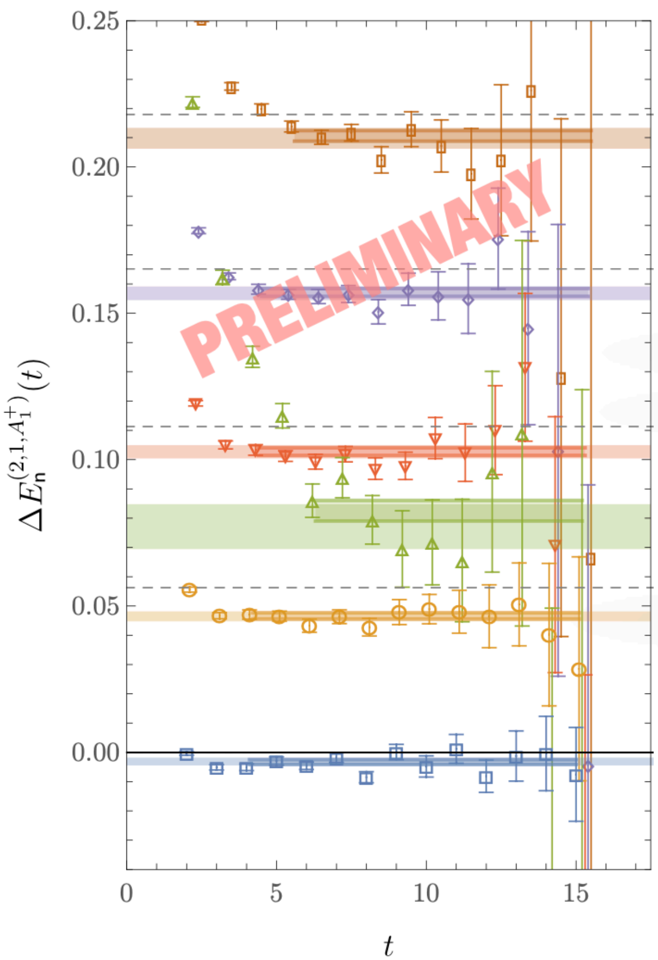
We are running additional hexaquark operators on a smaller volume $L = 4.5\,\mathrm{fm} \rightarrow 3.4\,\mathrm{fm}$

$NN(^1S_0)$

1 hex + 5 dibaryon



16 hex + 5 dibaryon



Will it keep going down?

Or is it another state? d*?

H-dibaryon (S=-2)

The H-dibaryon (coupled $\Lambda\Lambda - \Sigma\Sigma - N\Xi$ I=0 channel) was first predicted by Jaffe to be deeply bound (80 MeV) Jaffe, PRL 38 (1977)

Experimental searches find upper bound from ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ (7 MeV)

Takashi et al., PRL 87 (2001); Nakazawa et al., NPA 835 (2010); Ahn et al., PRC 88 (2013)

New results from femptoscopy (possibly bound)

STAR (2015), ALICE (2019)

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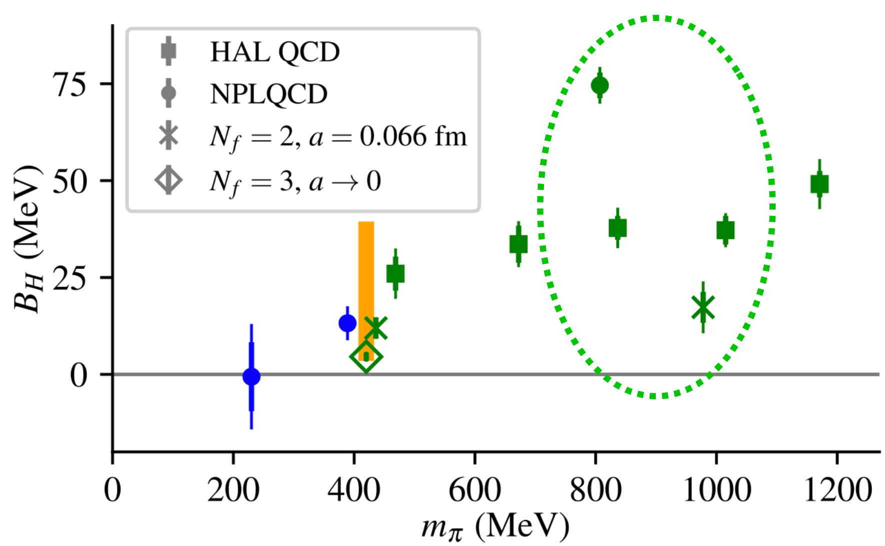
From the LQCD side, there is some tension around 800 MeV

→ perliminary variational results

Green et al., PRL127 (2021)



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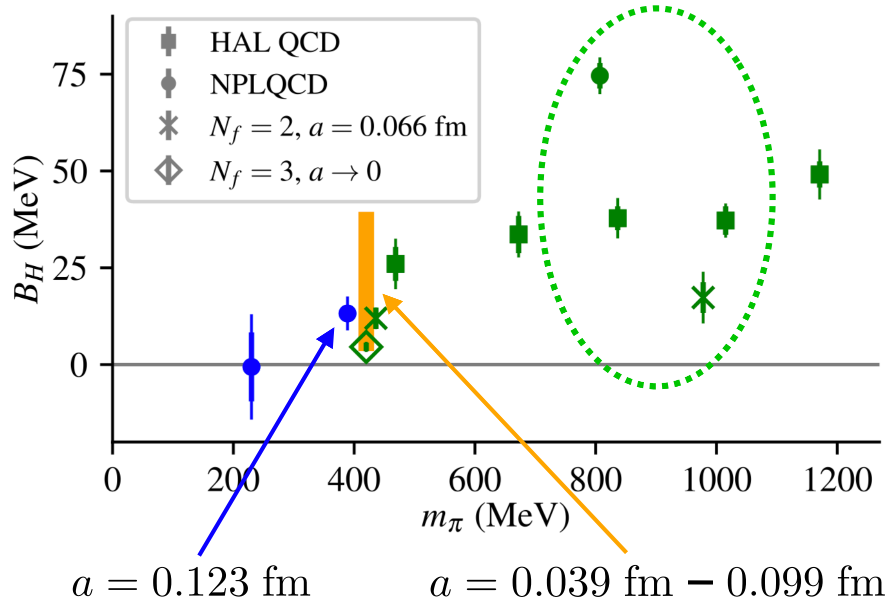
Also, some differences at around 400 MeV (lattice spacing effects?)

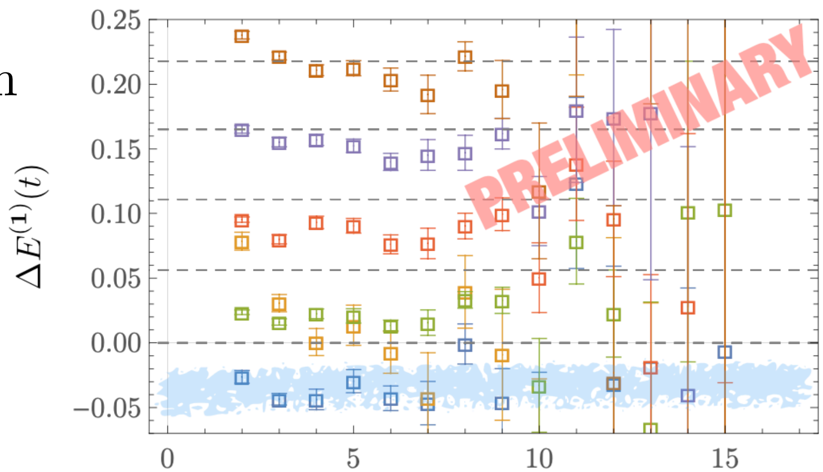
Green et al., PRL127 (2021)



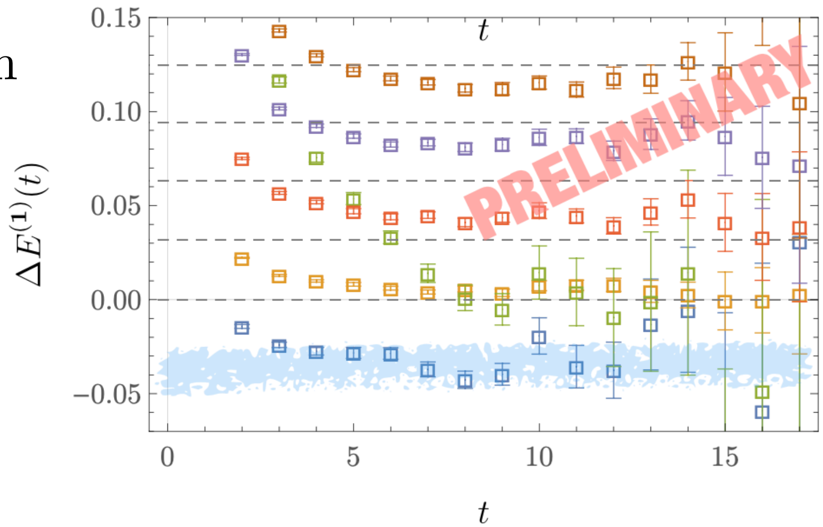
H-dibaryon (S=-2)

Preliminary variational results at 800 MeV

$L = 3.4$ fm
(40 cfgs)

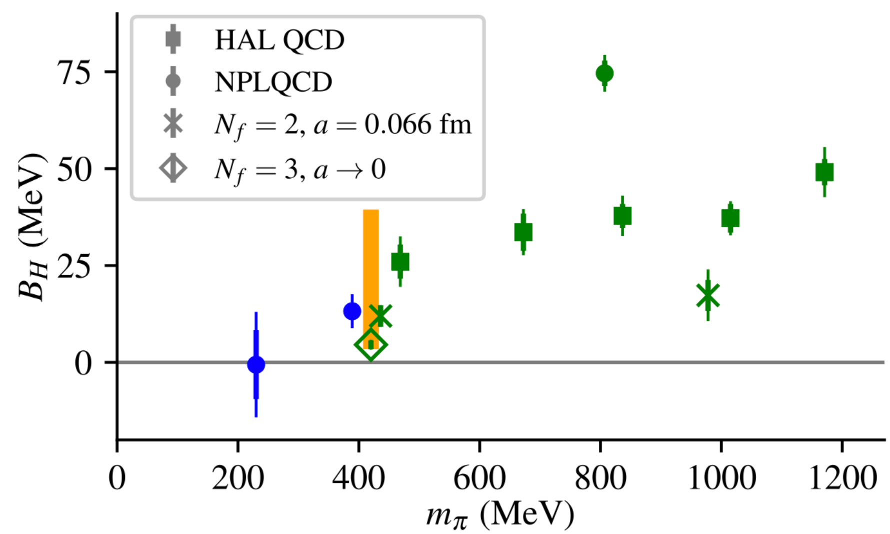


$L = 4.5$ fm
(100 cfgs)



Consistent variational bound on binding energy in both volumes, ~54 MeV

Green et al., PRL127 (2021)



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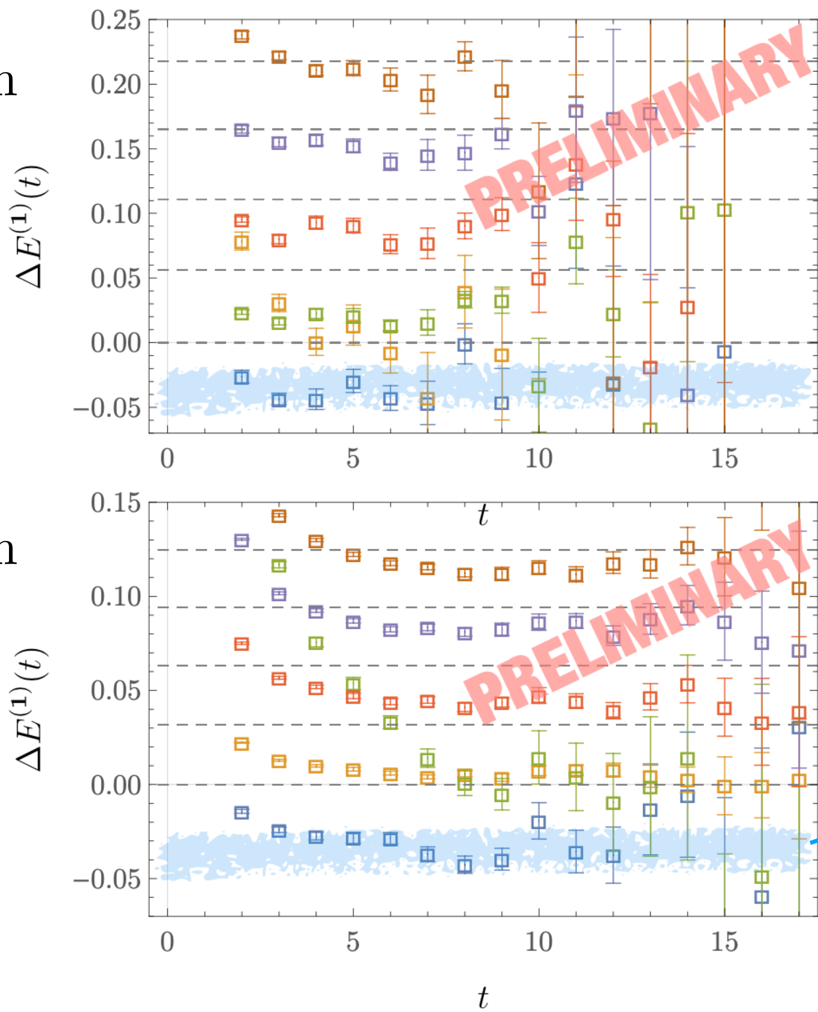

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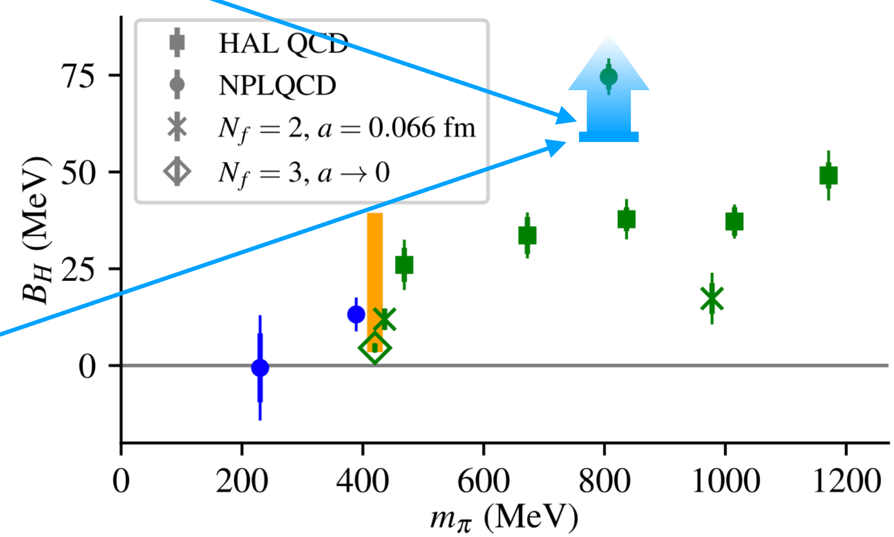

Summary, open questions and future directions

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

- Need to understand extra hex-level
- Are we missing other operators?

Variational bounds for H-dibaryon agree with old asymmetric result, interesting tension with newer results

Starting production for different baryon-baryon systems closer to the physical point ($m_\pi \sim$170 MeV) with different volumes

- Most interesting ones are $S = -1$. Can we provide more data to constrain theory models (like EFT)?

Thank you