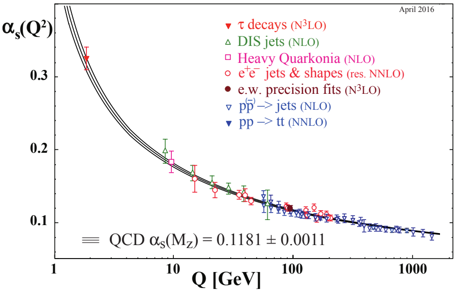
Lattice QCD and baryon-baryon interactions

Jeremy R. Green

Deutsches Elektronen-Synchrotron DESY

Astroparticle and Particle Physics Workshop
DESY, Zeuthen
October 6–8, 2025

QCD is the sector of the Standard Model containing *quarks* and *gluons*.



PDG 2016

In QCD, the strong coupling constant α_s depends on the energy scale at which we study it.

- At high energy, α_s becomes small (*asymptotic freedom*), and perturbation theory works.
- At low energy, α_s is large and perturbation theory breaks down. Need nonperturbative methods such as lattice QCD.

Degrees of freedom for low-energy QCD: *hadrons*. Bound states of quarks and gluons.

Hadrons

Historically, two kinds:

- mesons: quark-antiquark
- baryons: three quarks

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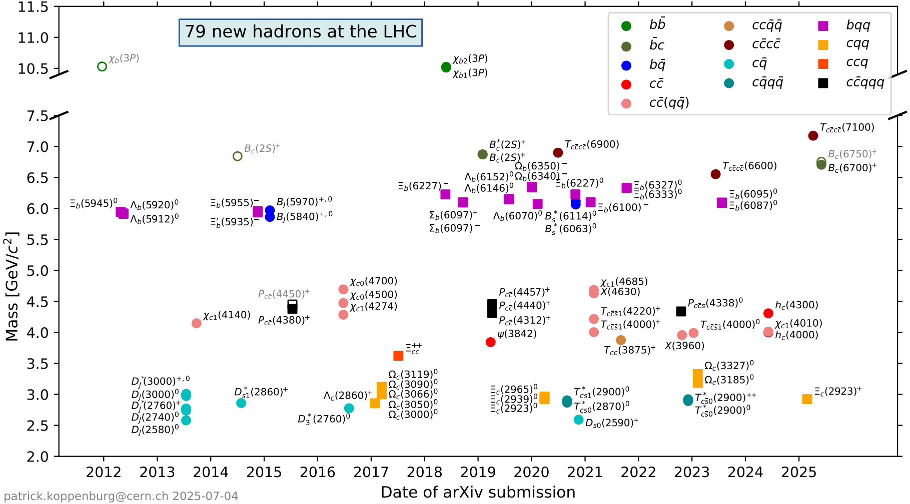
In QCD:

- Some hadrons are stable $\longrightarrow$ exist as asymptotic states.
- Most hadrons are resonances (unstable) $\longrightarrow$ decay to stable hadrons.

Rigorously, resonances appear in partial wave scattering amplitudes of stable hadrons.
Resonances are studied in lattice QCD via 2- and 3-particle scattering amplitudes.

Ordinary and exotic hadrons at the LHC



patrick.koppenburg@cern.ch 2025-07-04

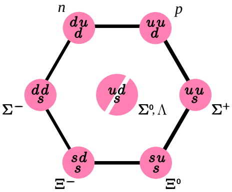
E.g. $T_{cc}(3875)^+$ ($cc\bar{u}\bar{d}$ tetraquark) studied via DD^* or $DD\pi$ scattering.

→ Andres Stump poster

LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and recent updates.

Baryon-baryon interactions

In SU(3) flavour multiplets, lightest baryons are



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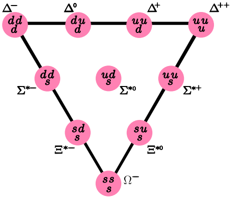

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Well-known $J^P = 1^+$ pn bound state: deuteron (^{2}H nucleus), $m_d \approx 1876.1$ MeV.

Also evidence of 3^+ resonance $d^*(2380)$. WASA-at-COSY, Phys. Rev. Lett. **112**, 202301 (2014)

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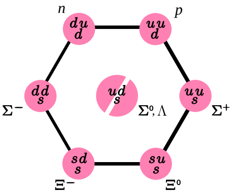

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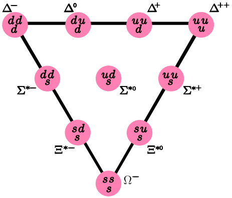

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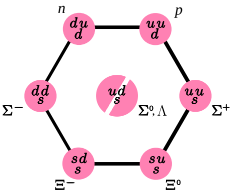

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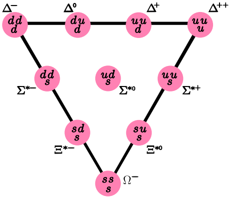

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Data with nonzero strangeness are scarce: hypernuclei and femtoscopy.

What about ab initio QCD?

Dependence on quark masses

NN interaction (and NNN) leads to nuclei.

How fine tuned is the universe? Could Standard Model parameters have changed over time?

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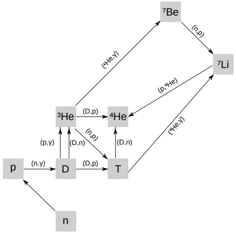

(By Pamputt [CC-BY-SA-4.0], via Wikimedia Commons)

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low deuteron binding energy 2.2 MeV delays onset of nucleosynthesis.
$\rightarrow$ controls abundances of light elements.

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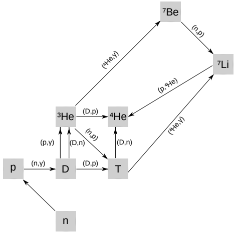

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How strongly does deuteron binding depend on quark masses? H. Meyer and U.-G. Meißner, JHEP **2024**, 74
Could pp or nn bind?

Hyperon interactions

NN interaction thoroughly studied in experiments. What about strange baryons (*hyperons*)?
Hyperon interactions with $S = -1$ or -2 less well known. $\rightarrow$ opportunity for lattice QCD
Also studied in recent years using femtoscopy at ALICE.

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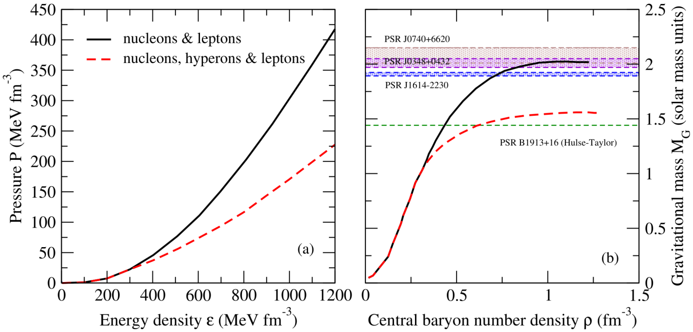

I. Vidaña, EPJ Web Conf. **271**, 09001 (2022)

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Contradicted by detection of neutron stars with $M \approx 2M_\odot$.

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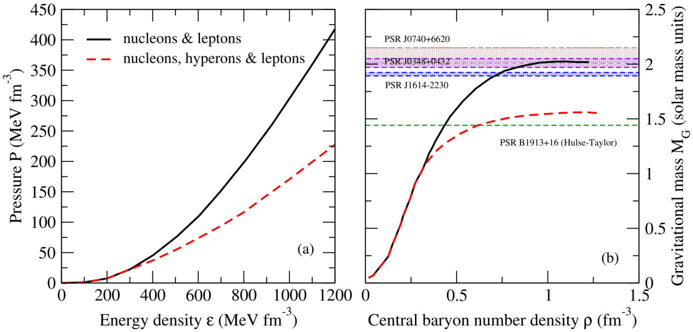

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Do hyperon-hyperon (YY) or NNY interactions play a role?

Nuclei as tools in experiments

In practice, nuclei instead of free nucleons are often used.

- Argon in neutrino experiments (MicroBooNE, DUNE).
- Xenon for dark matter direct detection (XENONnT, LUX-ZEPLIN).

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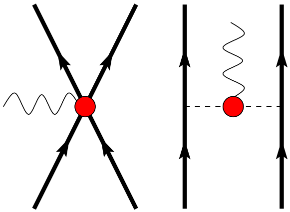
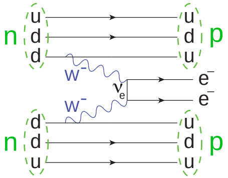
For precision physics, need *meson-exchange currents* to understand interaction of probe with > 1 nucleon, i.e. go beyond *impulse approximation*.

e.g. EMC effect:
distribution of quarks is different inside nucleus compared with proton and neutron



Neutrinoless double beta decay



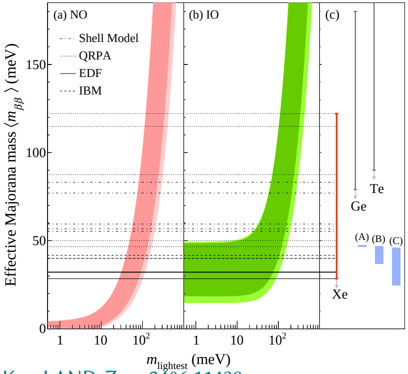
Are neutrinos Majorana?

Violation of lepton number conservation.

Large nuclear modelling uncertainty.

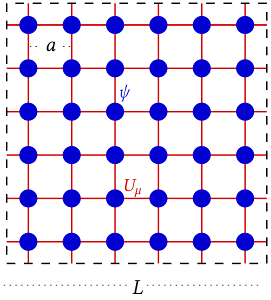
Need QCD for precise interpretation of experimental constraints.

Long-term goal for the lattice.



KamLAND-Zen, 2406.11438

Lattice QCD



Regularize QCD by discretizing space and imaginary time on 4d lattice:

- lattice spacing a: systematic error $O(a^2)$
- periodic box size L: systematic error $O(e^{-m_\pi L})$

Needs minimal experimental input: quark masses and reference scale.

Typical lattice size varies from 48×24^3 to 256×128^3. Can need large compute cluster.

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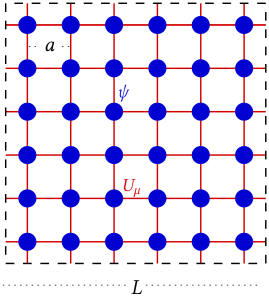

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Need to accommodate range of scales

$$L^{-1} \ll m_\pi \ll m_N \ll a^{-1}.$$

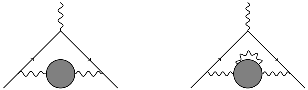
Since $m_\pi^2 \propto m_u + m_d$, small m_u, m_d in nature make simulations difficult.
$\longrightarrow$ Simpler calculations with heavier (unphysical) $m_u = m_d$.

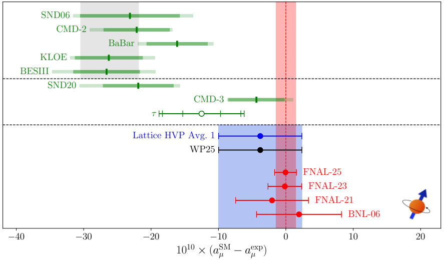
Local lattice QCD activities

QCD+QED (Agostino Patella / RC$*$ collaboration)

For QCD observables at high precision $\sim 1\%$, need to include QED corrections.

E.g. hadronic contributions to muon $g-2$.





Muon $g-2$ Theory Initiative, Phys. Rept. 1143 (2025)

Glueballs (Stefan Schaefer / DFG Research Unit FOR5269)

Hadrons made of gluons. Challenging problem:

- Mixing with $\bar{q}q$ degrees of freedom $\longrightarrow$ start from theory without quarks.
- Severe statistical fluctuations $\longrightarrow$ new numerical techniques.

Choice of quark masses

Physical quark masses necessary for connection with experiment.

Why use unphysical quark masses?

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- Larger $m_u = m_d$ makes simulations numerically easier.
- Larger m_π exponentially reduces noise, particularly for multi-nucleons.
- Larger m_π closes some decay channels and makes some resonances stable (Δ, D^*, ...).
- Can make some approximate symmetries exact: SU(3) flavour, heavy quark spin symmetry.

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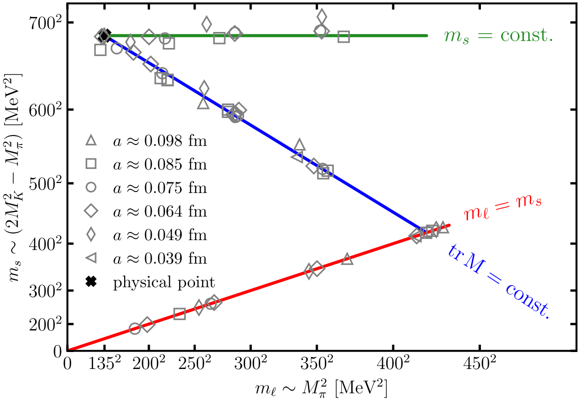
SU(3)-symmetric point with $m_u = m_d = m_s \approx \frac{1}{3}(m_u^{\text{phys}} + m_d^{\text{phys}} + m_s^{\text{phys}})$ has been a useful testing ground.

Coordinated Lattice Simulations (CLS)

European effort for lattice QCD simulations

- Using a particular formulaton of LQCD.
- Sharing computing time, storage, and person effort.
- Leading role played by DESY.



G. Bali @ CLS Workshop

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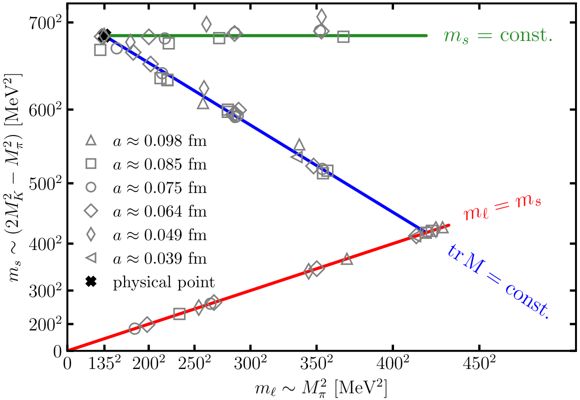

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Investigations of possible new lattice QCD action for CLS ongoing at DESY.

Stefan Schaefer, Jorge Baeza Ballesteros

$\longrightarrow$ set direction for next decade of CLS.

Hyperon-hyperon interactions: H dibaryon

Conjectured $uuddss$ hexaquark state: $\Lambda\Lambda$ bound by 80 MeV in MIT bag model. R. L. Jaffe, 1977

Limits on existence imposed by $^{6}_{\Lambda\Lambda}$He double-hypernucleus produced at KEK and by $\Lambda\Lambda$ femtoscopy at ALICE.

JRG *et al.*, Phys. Rev. Lett. **127**, 242003 (2021)

Calculation at unphysical SU(3) point.

First $a \to 0$ limit for dibaryon system.

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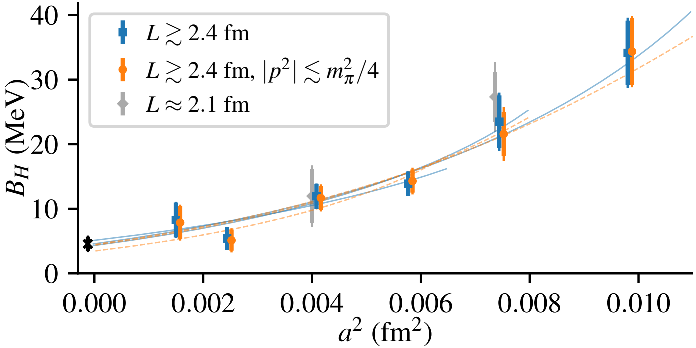

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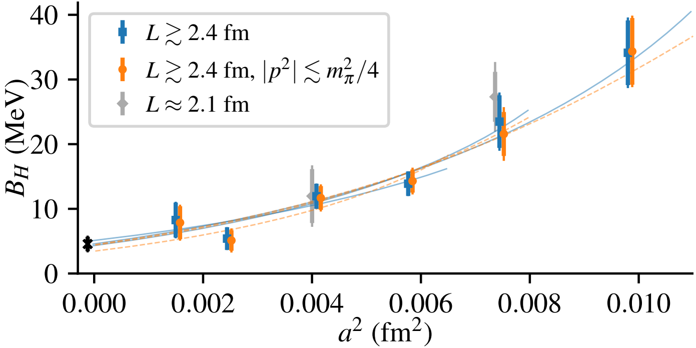
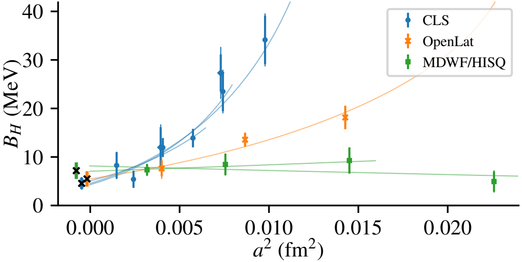


Small binding energy at SU(3)-symmetric point $\implies$ probably no bound state in nature.

Why are lattice spacing effects so large?



In preparation: comparison of different lattice actions.

JRG, BaSc collaboration

universality: expect common $a \to 0$ limit

H dibaryon: follow-up work

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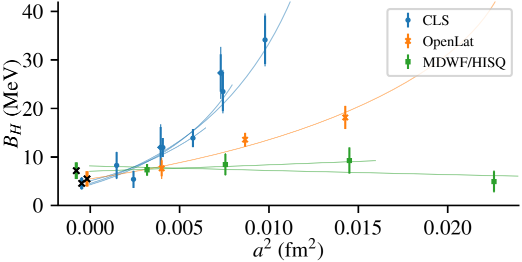

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Longest-distance interaction in finite volume

Two baryons can exchange a pion $\longrightarrow$ sets breakdown point of finite-volume quantization conditions used to interpret lattice data. Problem also occurs in DD^* for $T_{cc}(3875)$ tetraquark.

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Effect on H dibaryon under investigation. JRG, Jorge Baeza Ballesteros

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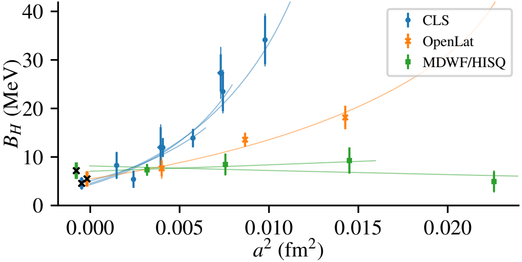

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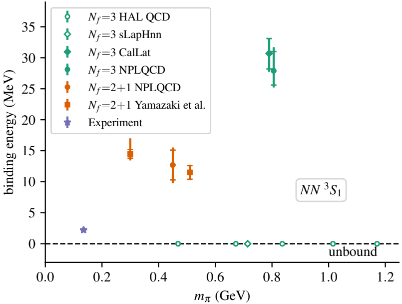
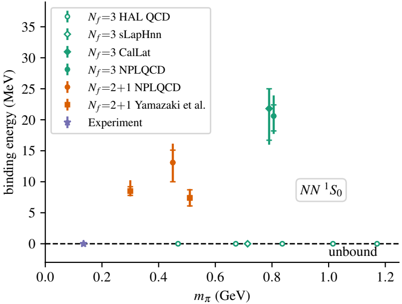
Lighter pion masses with broken SU(3) symmetry JRG, BaSc collaboration

Nucleon-nucleon interaction from LQCD: past calculations

Decade-long controversy over presence of bound states at heavy quark masses.



deuteron



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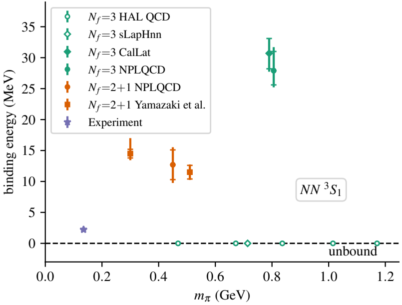

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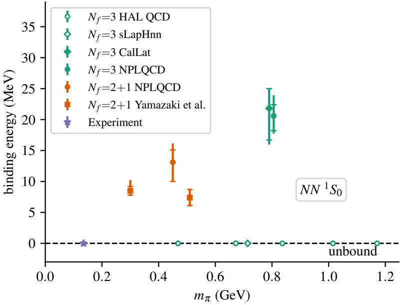

dineutron

Disagreement about simplest warm-up problem for nuclear physics on the lattice.

Experiment: $B_d \approx 2.2$ MeV known for 90 years. J. Chadwick and M. Goldhaber, Nature **134**, 237–238 (1934)

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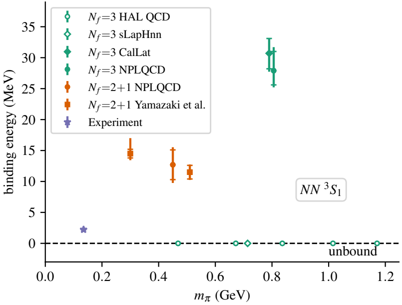

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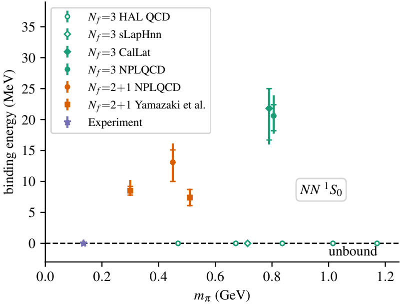

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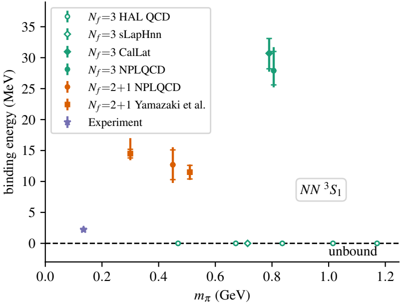

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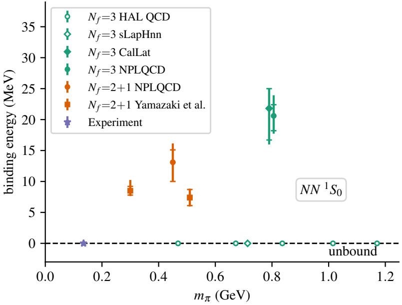

dineutron

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Serious doubt has been cast on methodology used by all calculations that obtain bound states.

Nucleon-nucleon: work in progress

More reliable calculations:

- Adapt methods from years of successful meson-meson calculations.
- Recognize one lattice spacing is insufficient.
- Study amplitudes, not just binding energies.

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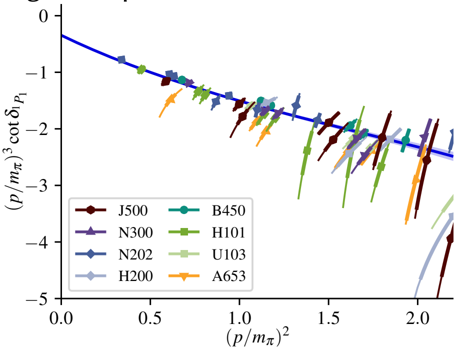
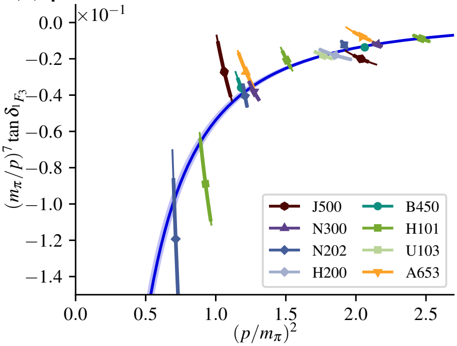
e.g. NN spin-zero P and F waves at SU(3) point JRG, PoS **CD2024** 019 [2502.15546]





Data lie along consistent curve: very nontrivial consistency check.

Outlook

- Hyperon interactions will be where lattice first impacts baryon-baryon phenomenology.
  $\longrightarrow$ better input for hyperon puzzle in neutron stars.
- Extrapolation to physical point needs help from chiral EFT.
  $\longrightarrow$ deuteron binding energy from QCD will be milestone.
- Plans underway for exploring external probe: e.g. start with pp fusion.
- Studying three-baryon interaction is possible but much more difficult than baryon-baryon.
  - Very challenging numerically.
  - Three-body formalism only partially available.
- Dataset is being reused for exotic hadrons such as $T_{cc}(3875)$.