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Hadron Structure and Spectroscopy from Lattice QCD

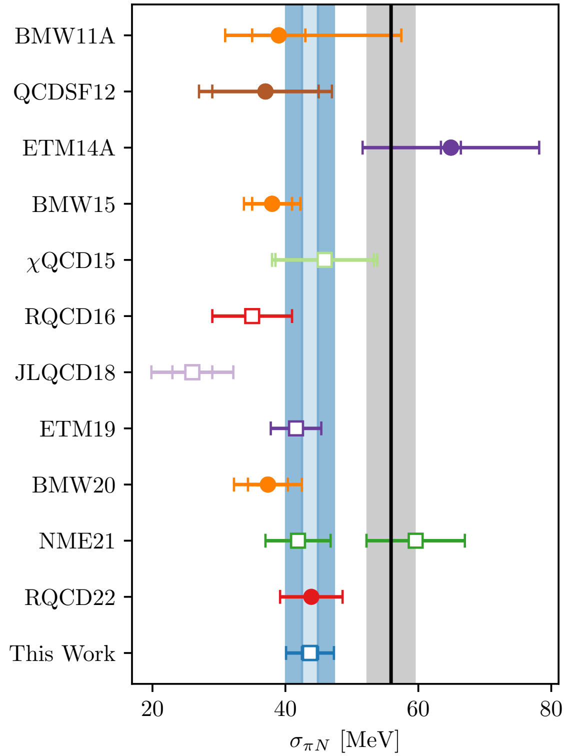
Hartmut Wittig
CML Retreat 2023
4–5 October 2023

Lattice QCD as a first-principles approach

Lattice calculations increasingly competitive:

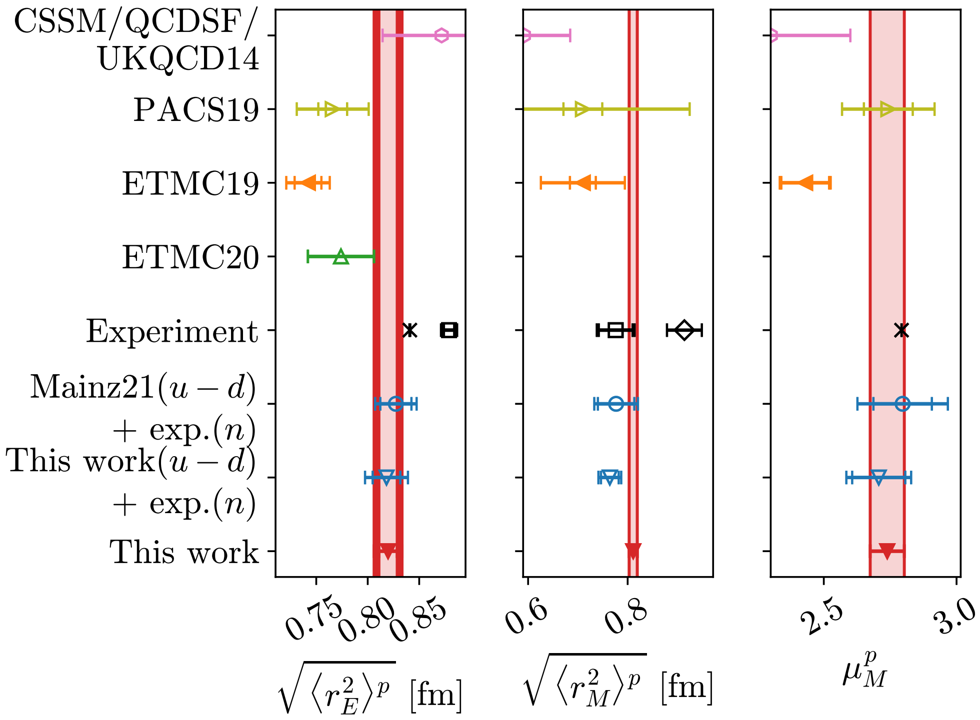
Precise enough to challenge conventional wisdom / phenomenology / experiment

Pion-nucleon σ-term



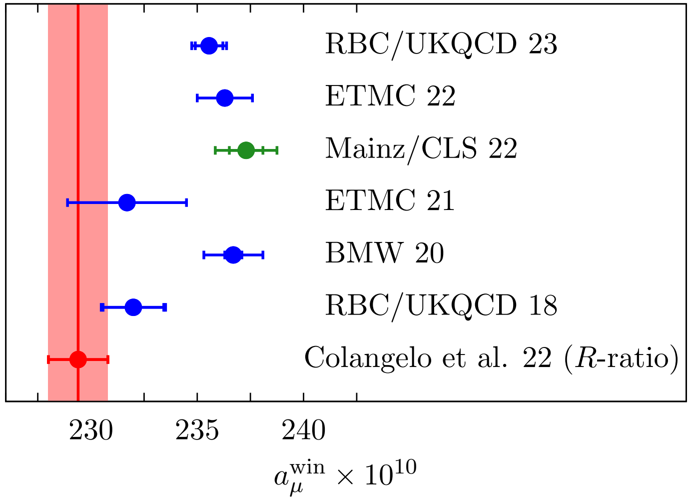
[Djukanovic et al., 2303.08741]

Proton radii



[Djukanovic et al., 2309.6590, 2309.07491]

Muon $g-2$



[HW @ Moriond, 2306.04165]

Hadron spectroscopy and few-body dynamics

49 new conventional and 23 new exotic hadrons discovered at LHC, Belle,…. since 2012

Finite-volume quantisation ("Lüscher method"): rigorous formalism amenable to Lattice QCD

$$\det\left(\tilde{\mathcal{K}}^{-1}(E_\mathrm{L}) - B(E_\mathrm{L},\, L)\right) = 0$$

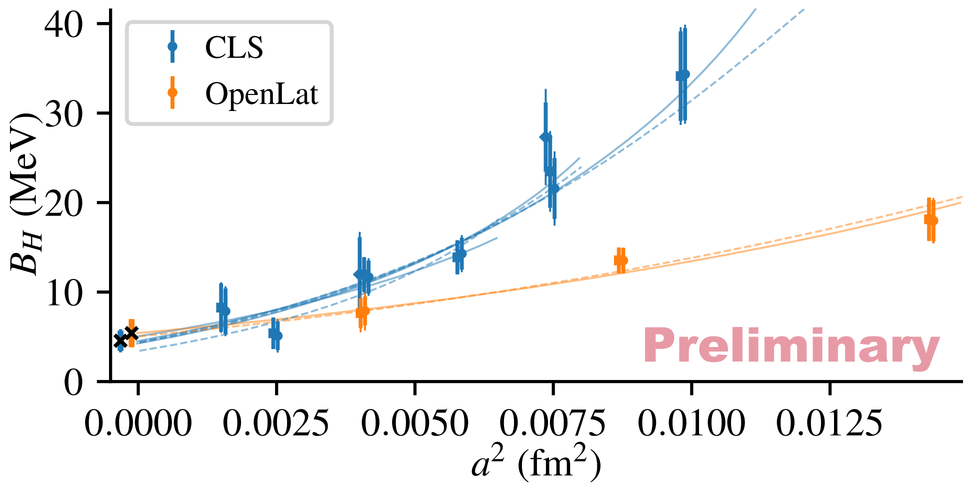
$\tilde{\mathcal{K}}(E_\mathrm{L})$: $2 \to 2$ scattering amplitude

$B(E_\mathrm{L},\, L)$: analytically known function

E_L : multi-particle energy levels in finite volume

Topics / Examples:

- H dibaryon — hyperon-hyperon interactions
- NN scattering and nucleon resonances
- Resonances in charm sector; tetraquarks: T_{cc}^{+}
- Interpretation of the $\Lambda(1405)$
- ….

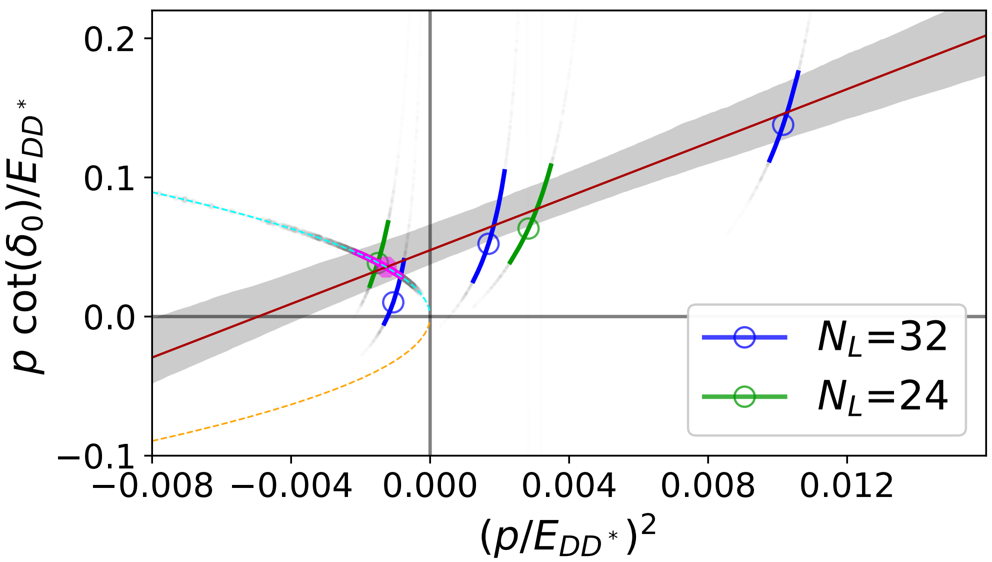


[Green et al., PRL 127 (2021) 242003, and in prep.]

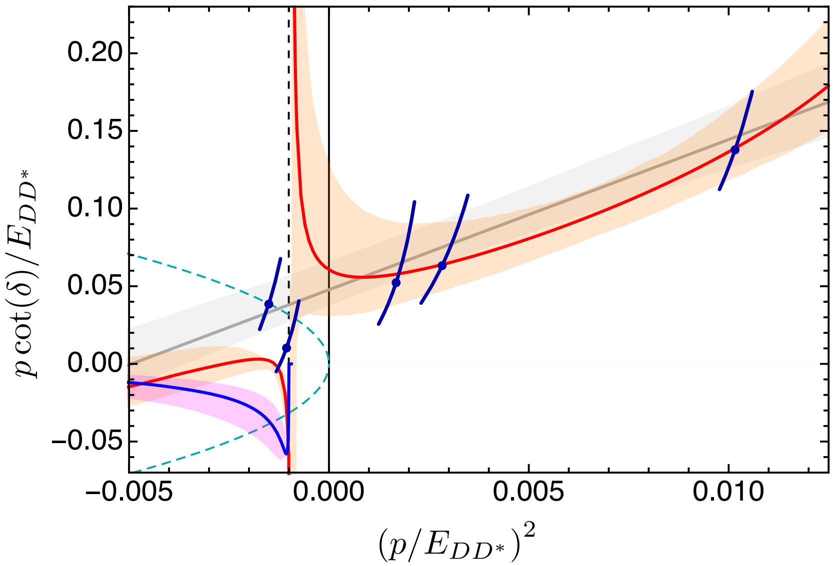
Hadron spectroscopy and few-body dynamics

Current challenges:

- Role of the continuum limit — extrapolation to the physical point
- Perform coupled-channel analyses, incorporate higher partial waves
- Two-particle finite-volume quantisation fails above 3- and 4-particle thresholds and below left-hand cut —> employ and implement 3-particle quantisation conditions



[Padmanath & Prelovšek, PRL 129 (2022) 032002]



[Du et al., PRL 131 (2023) 131903]

Hadron spectroscopy and few-body dynamics

Future plans:

- Comprehensive programme on baryon-baryon, meson-baryon, meson-meson scattering:
- H dibaryon, nucleon-nucleon channels — approach to the physical point: $m_\pi = m_\pi^{\text{phys}}, \quad a \to 0$
- Charmed tetraquarks
- Investigation of left-hand cut — precursor to studying 3-particle quantisation condition

Collaborators:

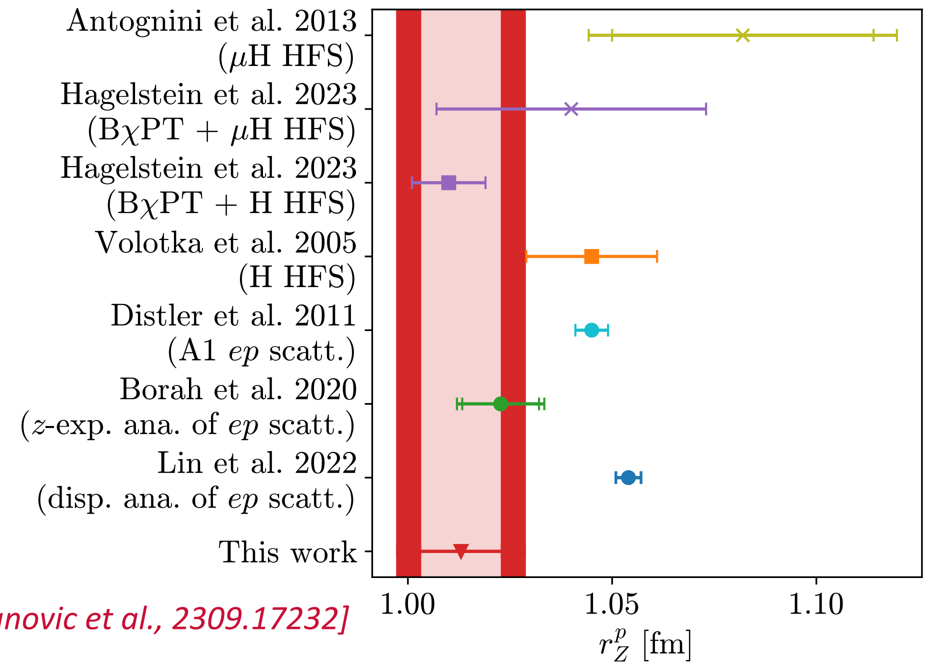
- DESY-Zeuthen (Jeremy Green); GSI, TU Darmstadt (Daniel Mohler)
- BaSc Collaboration [“Baryon Scatterers”] (John Bulava, Colin Morningstar, André Walker-Loud)

Hadron structure observables

Examples for first-principles determinations of nucleon hadronic matrix elements:

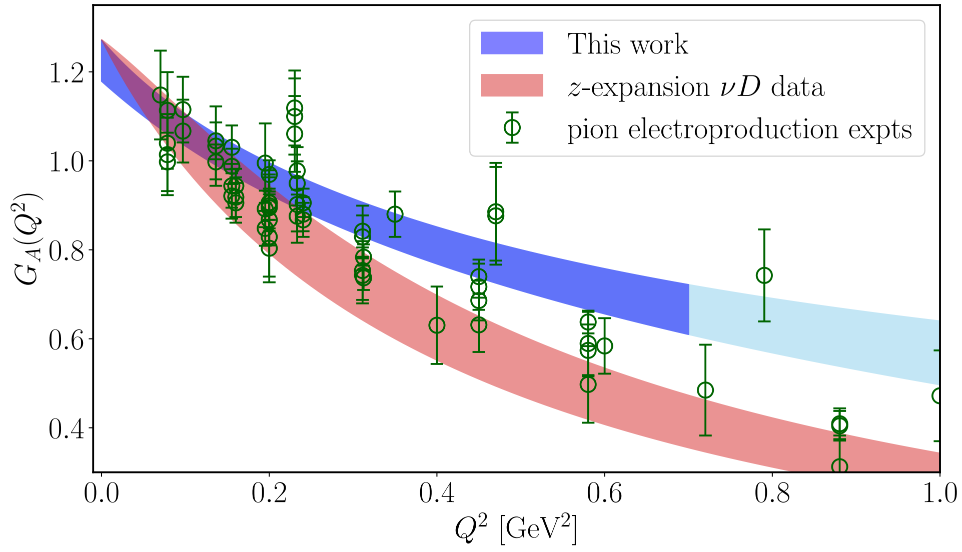
- Axial form factor of the nucleon — input for future neutrino experiments: DUNE, T2HK
- Electric, magnetic and Zemach radii of the proton — final resolution of proton radius puzzle
- PDFs and GPDs — input for EIC

Zemach radius



[Djukanovic et al., 2309.17232]

Nucleon axial form factor

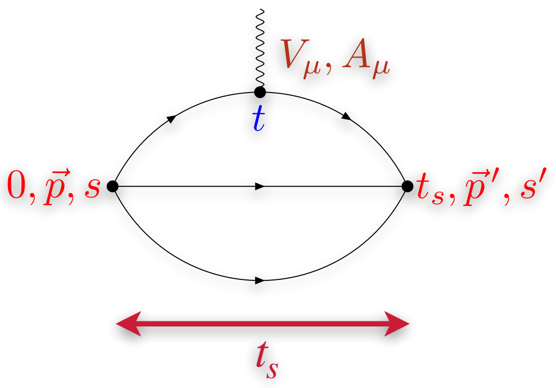


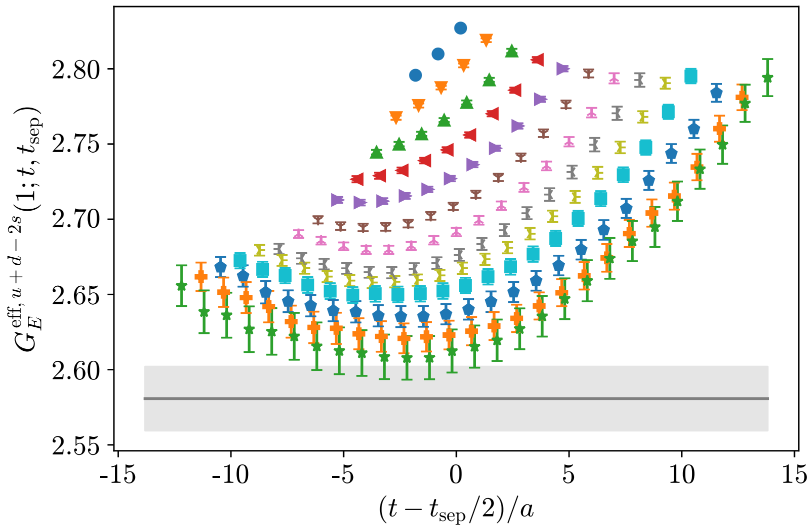
[Djukanovic et al., PRD 106 (2022) 074503]

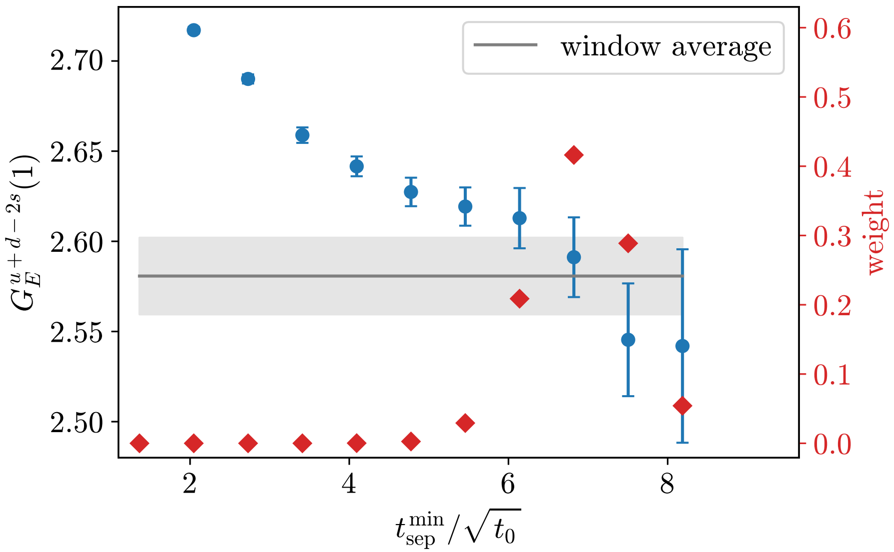
Hadron structure observables

Current challenges:

- Noise problem: exponential growth of signal-to-noise ratio in baryonic correlators
- Related problem: unsuppressed contributions from excited states: $N\pi$, $N\pi\pi$
- GPDs, PDFs: complicated renormalisation of bilocal operators; inverse problem
- Incorporation of isospin-breaking corrections





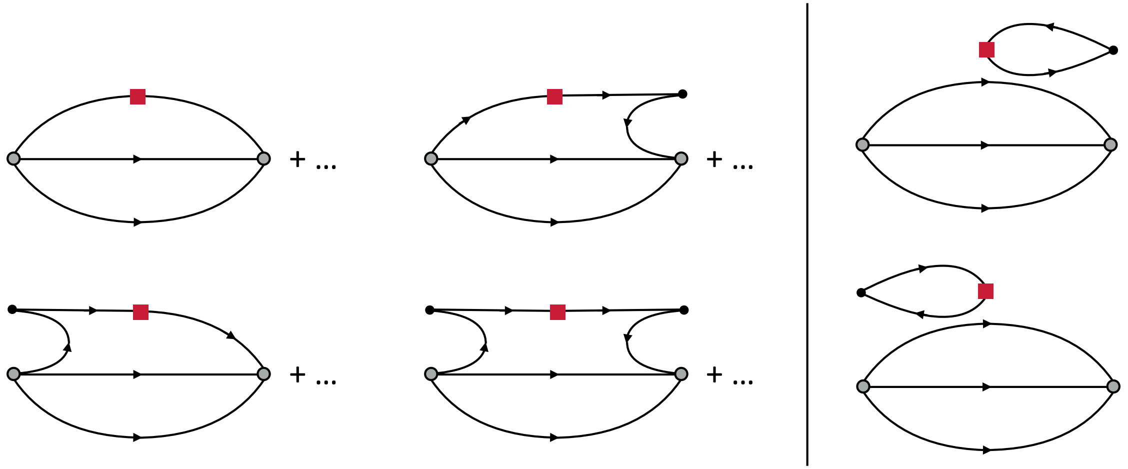


Hadron structure observables

Future plans:

- Comprehensive programme to study electromagnetic, axial and strangeness form factors
- Determine nucleon charges (g_A, g_S, g_T), σ-terms, and moments of structure functions
- Novel noise-reduction technology: multi-particle interpolating operators, machine-learning techniques

Nucleon 3-point function with explicit $N\pi$ interpolators:



Cost-efficient observables via trained networks:

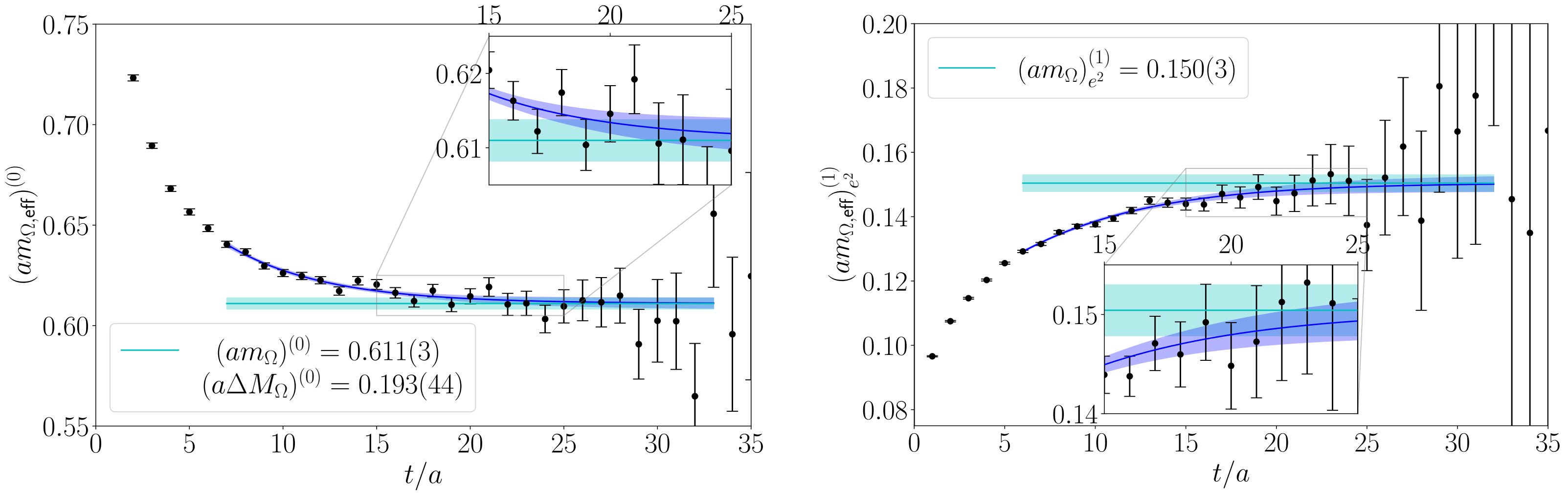
$$\langle O \rangle = \langle O \rangle_{\text{approx}} + \Big\langle (O - O_{\text{approx}}) \Big\rangle$$

exact ↑ $\langle O \rangle$ — "cheap" ↑ $\langle O \rangle_{\text{approx}}$ — correction ↑ $\langle (O - O_{\text{approx}}) \rangle$

Ancillary calculations

Precision scale setting

- Lattice scale from lowest-lying octet and decuplet baryon masses including isospin-breaking effects



Precision of $\lesssim 0.5\,\%$ in Ω-baryon mass;

Isospin-breaking effects smaller than statistical error

[Segner, Hanlon, Risch, HW, arXiv:2212.07176]

Pion-pion scattering and pion form factor

- Constrain long-distance behaviour of correlator for precision observables (e.g. $(g-2)_\mu$, $\Delta\alpha_{\mathrm{had}}$)

Pion mass-dependence of octet baryons

- Alternative determination of σ-terms via Feynman-Hellmann theorem

QCD Thermodynamics: Photon emissivity of QGP

Differential photon emission rate per unit volume in hot QCD matter:

$$\frac{d\Gamma^{\gamma}}{d\omega} = \frac{\alpha_{\mathrm{e.m.}}}{\pi} \frac{2\omega\,\sigma(\omega)}{e^{\omega/T} - 1} + \mathrm{O}(\alpha_{\mathrm{e.m.}}^2)$$

$\sigma(\omega)$: in-medium spectral function;

ω : photon energy

Perform first-principles determination of properties of the thermal medium

Can determine $\sigma(\omega)$ via dispersion relation without numerically ill-posed inverse problem

[Cè, Harris, Krasniqi, Meyer, Török, 2309.09884]

Summary & PoF V Outlook

Rich research programme in hadron structure & spectroscopy, and QCD thermodynamics

State-of-the-art calculations

Innovative methodology to turn Lattice QCD into a precision tool

Crucial requirement: High-performance computing

Dedicated resources of ≈ 500 Mcore-hours p.a. required

Major new investment at HIM: **HIMSTER-3 — 1.88 M€**

Shared with experimentalists in EMP, SPECF

Procurement planned in Q4/2024 — Q1/2025

Will need replacement during latter half of PoF V

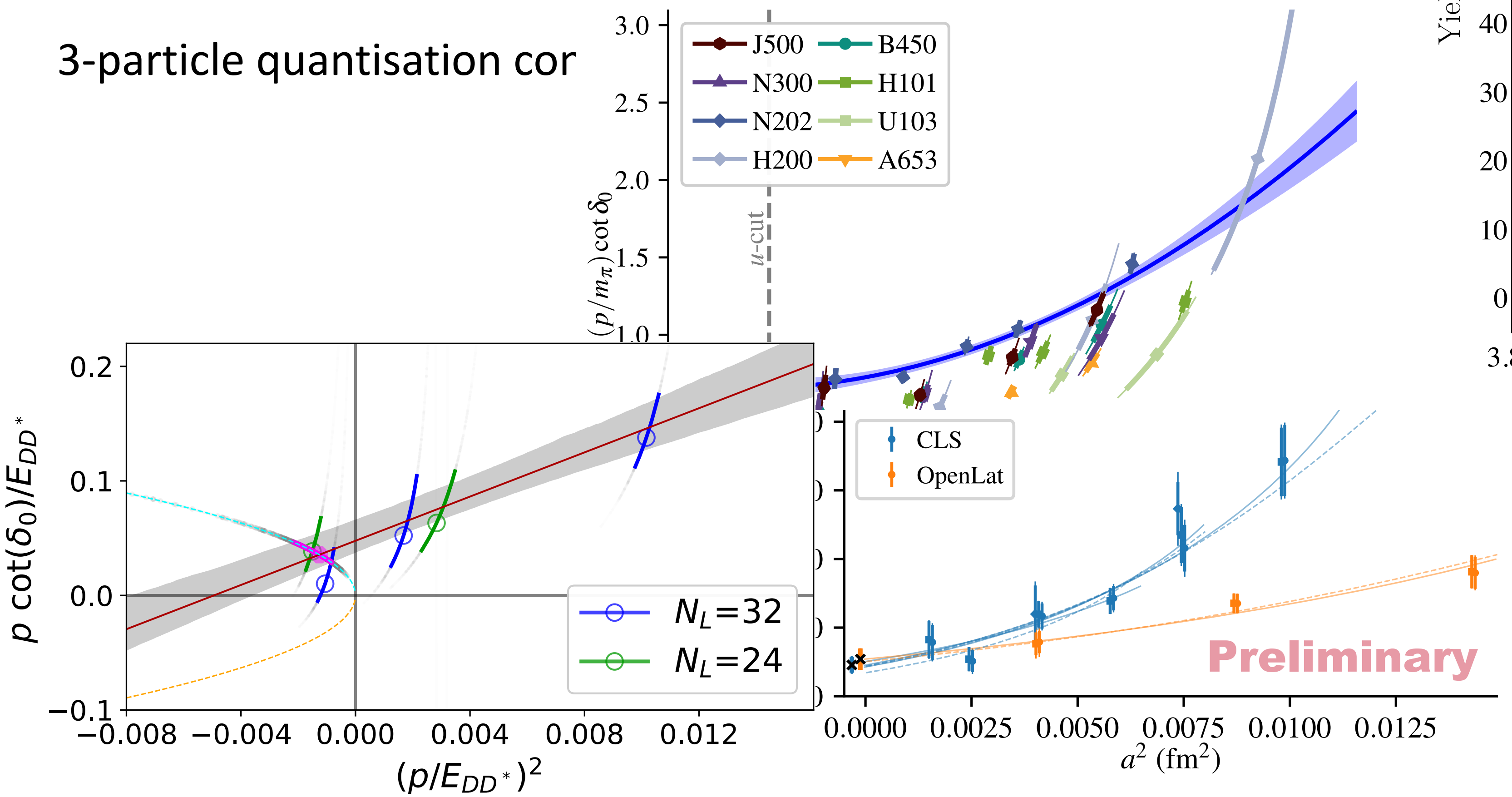
Thank you!

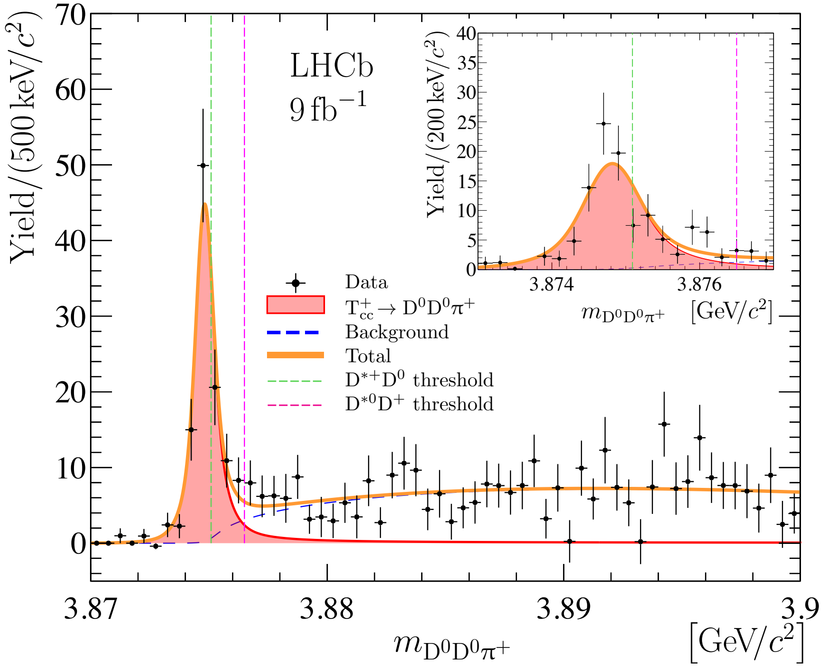
Hadron spectroscopy and few-body dynamics

Issues:

Role of the continuum limit

3-particle quantisation cor





[LHCb, Nature Phys. 18 (2022) 751]

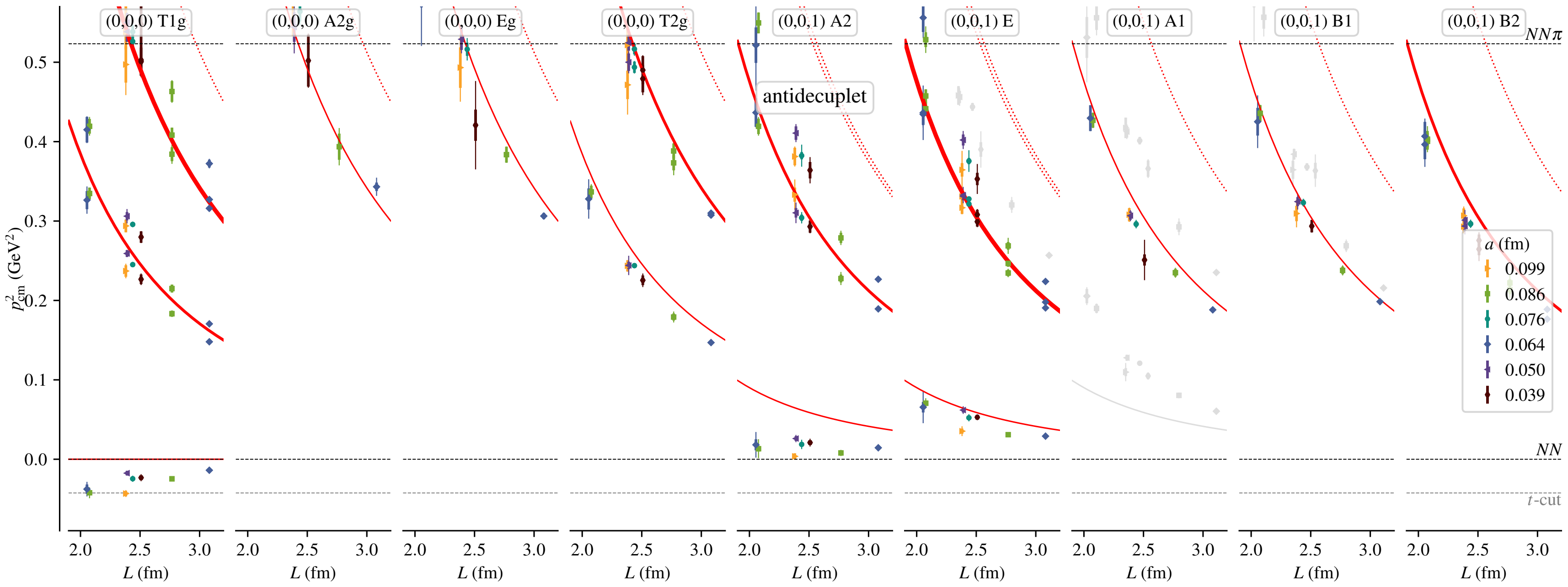
Hadron spectroscopy: Nucleon-nucleon interactions

[Green, Hanlon, Junnarkar, HW, arXiv:2212.09587]

Disagreement over existence of NN-bound states at heavier-than-physical pion mass

Perform scaling study for NN-states at $m_\pi = m_K \simeq 420\,\mathrm{MeV}$ — $\overline{10}$ (deuteron) and 27plet (dineutron)

Antidecuplet, $S = 1,\, I = 0$ (deuteron):



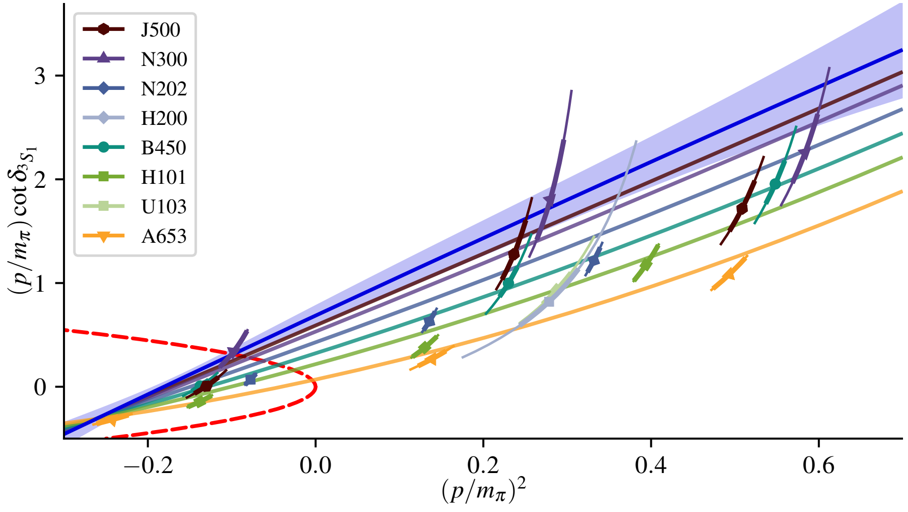
- 300 different energy levels resolved — sensitivity to higher partial waves

Hadron spectroscopy: Nucleon-nucleon interactions

[Green, Hanlon, Junnarkar, HW, arXiv:2212.09587]

Antidecuplet, $I = 0,\ ^3S_1$ phase shift analysis

(mixing with $^3D_1$ neglected)



- NN-interaction weakens as $a \to 0$
- Virtual bound state observed
- No bound deuteron at $m_\pi = m_K \simeq 420\,\mathrm{MeV}$

Include higher partial waves in the fits