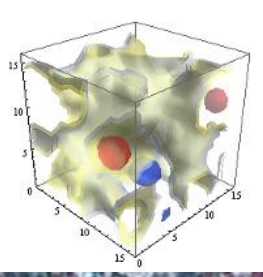
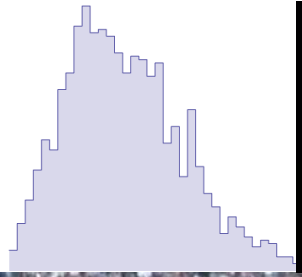
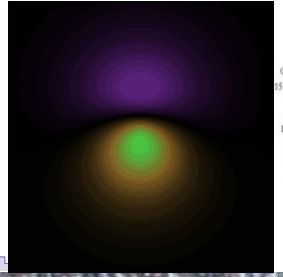
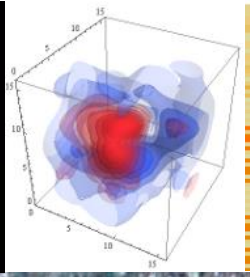
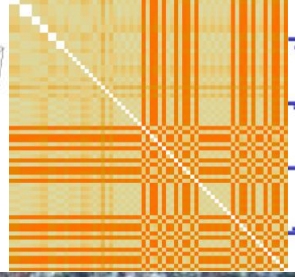
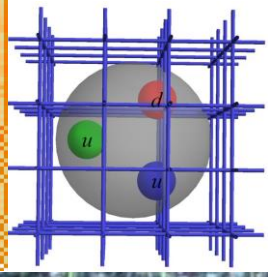


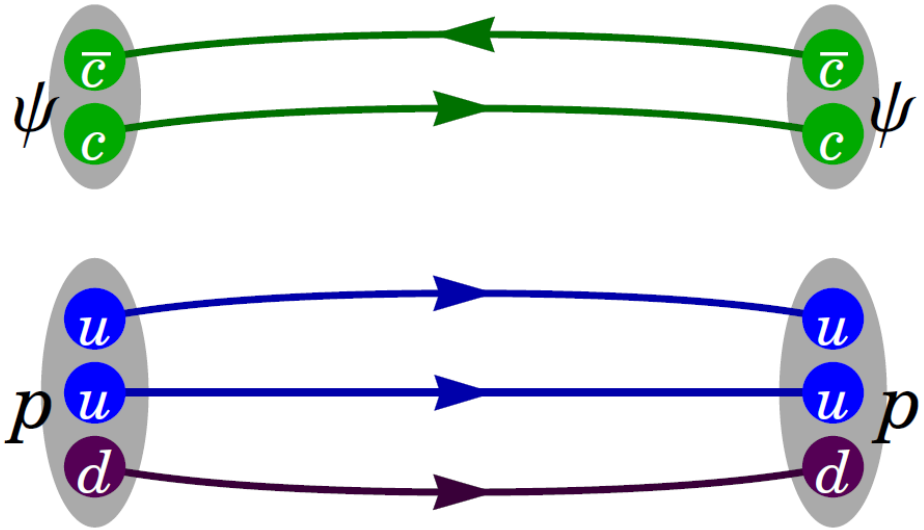
Quarkonium-Nucleus Bound States on the Lattice

Huey-Wen Lin

Motivation

§ Unique Probe for QCD Effects

- Heavy quarkonia share no valence quarks with nuclei
- Normally dominant quark exchange suppressed to second order
- Dominated by two-gluon exchange (color van der Waals)
- Color Stark effect: Chromoelectric field induces dipoles in neutral hadrons that interact



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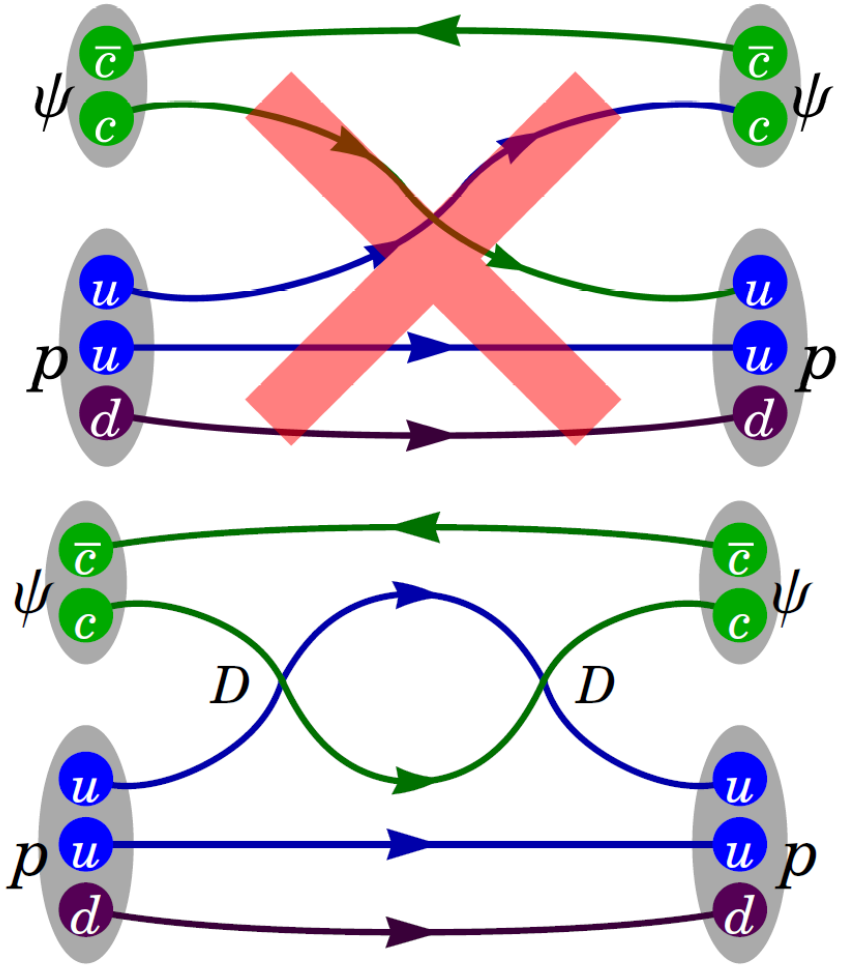

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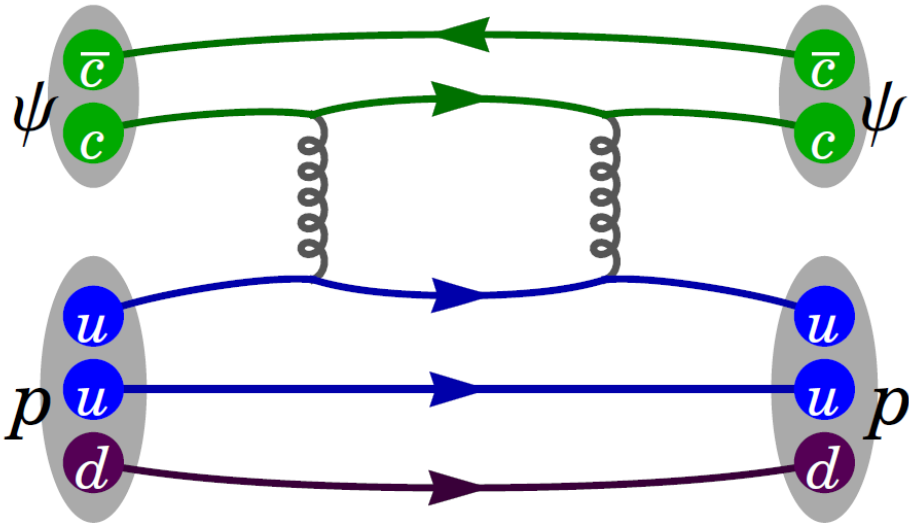
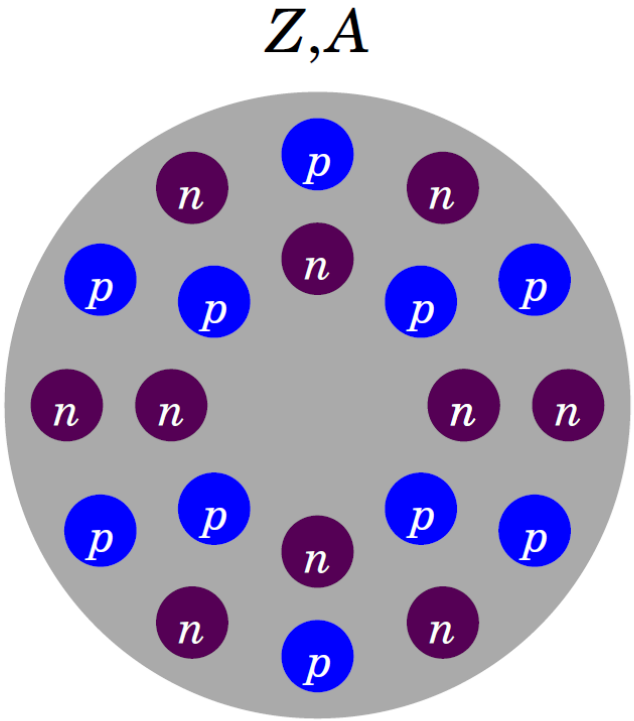


Brief History

§ Studied since 1990

- Brodsky et al. [PRL64,1011 (1990)] noted features of pp scattering near open-charm threshold
- No Pauli blocking; no quark-exchange
  $\eta_c h$: 19 MeV, $\eta_c {}^{9}$Be: 407 MeV(!)
- Wasson [PRL67,2237 (1991)] points out the nucleus is not pointlike
- Charm binding saturates for large A
  $\eta_c h$: 0.8 MeV, $\eta_c {}^{208}$Pb: 27 MeV



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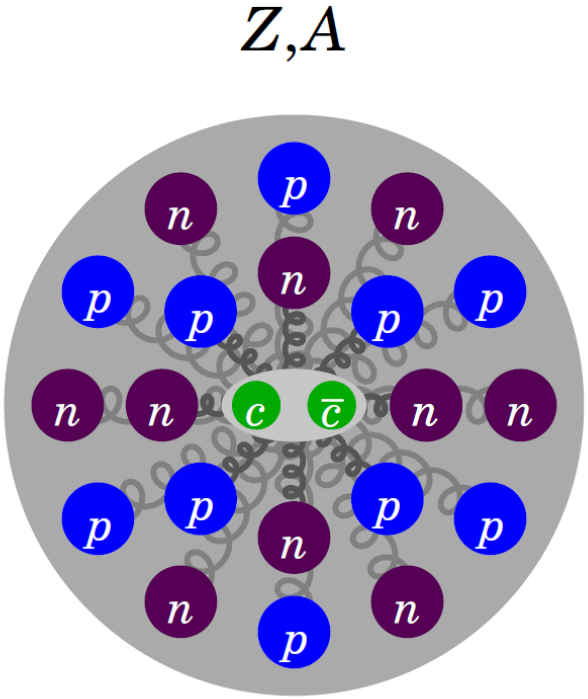

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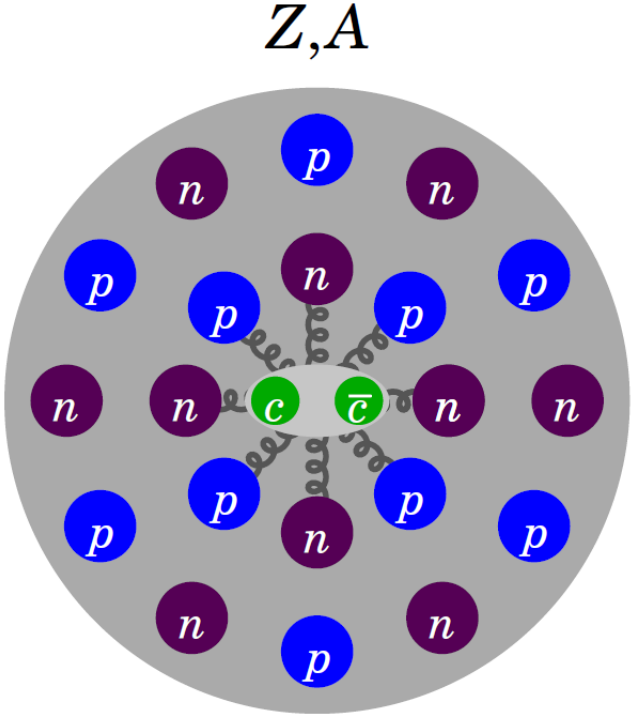

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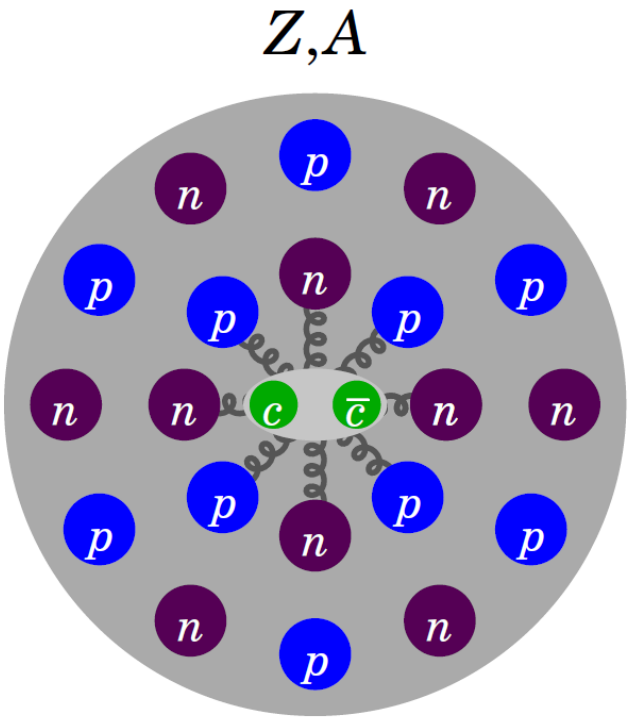
- Luke, Manohar, Savage [PLB288,355 (1992)] use heavy-quark expansion and look at leading Stark effect using OPE
- At saturation:
  ΥA: 4 MeV, $J/\psi A$: 11 MeV
- Induced dipole depends on radius of quarkonium like r^3;
  excited ψ' has huge radius
- Excited state becomes ground state in nuclear matter!
  $\psi'(2s)A$: 700 MeV(!!)



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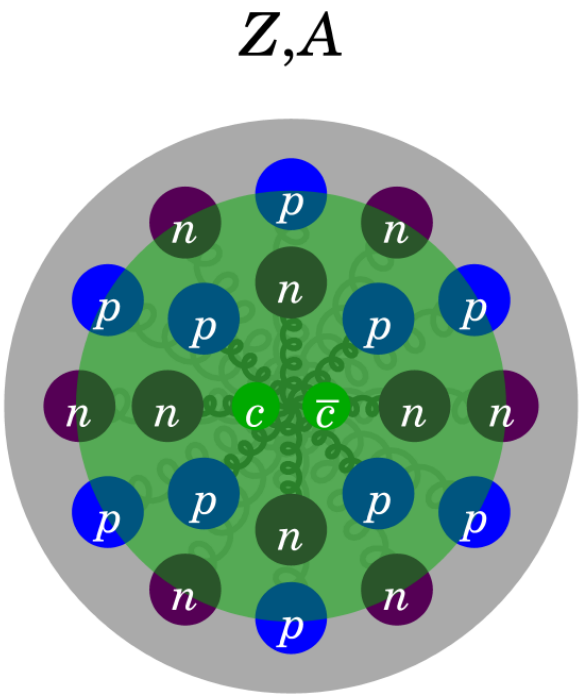


More History

§ Many additional model calculations; small selection shown

- Shevchenko [PLB392,457 (1997)] uses vacuum-correlator method
  No binding(?) except for very large nuclei
- de Teramond, Espinoza, Ortega-Rodriguez [PRD58,034012 (1998)]
  Tune their potential to *pp* spin correlations;
  No binding in light nuclei
  η_c ^{6}Li: 0.1 MeV, η_c ^{208}Pb: 9 MeV
- Lee and Ko [PRC67,038202 (2000)] look again at ψ' at saturation
  J/ψ *A*: 5 MeV, $\psi'(3686)$ *A*: 130 MeV
- Thomas [PRC83,065208 (2011)] uses quark-meson coupling model
  J/ψ α: 5 MeV, J/ψ ^{208}Pb: 18 MeV

Experimental Prospects

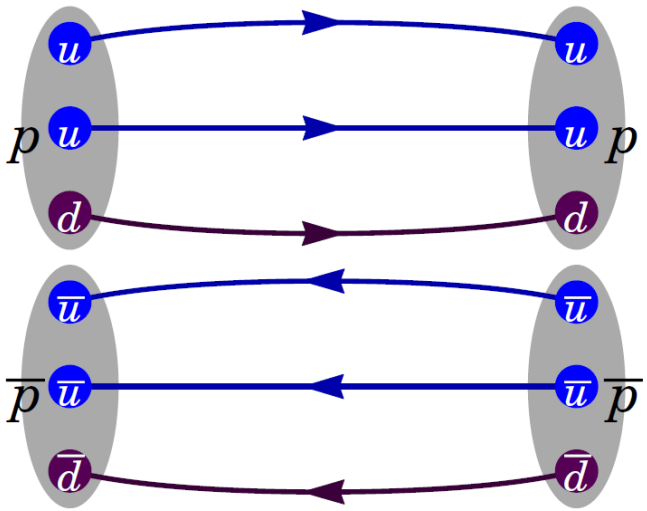
- Long history of proposals to measure charmonium-nucleus binding
  - ATHENNA 12-GeV upgrade at CEBAF (JLab) (ep scattering)
  - PANDA at FAIR (GSI) ($\bar{p}p$ scattering)
- Also attempts to measure nucleus-bound ϕ, ω, η' or η
- ηh: 4(4) MeV(??) at MAMI [PRL92,252001 (2004)]
  not confirmed by COSY; some theoretical problems
- COSY-GEM [PRC79,012201 (2009)] found ${}^{25}_{\eta}$Mg: 12(2) MeV
- Models of other mesic nuclei
  - [PRC34,1845 (1986)]: $A < 12$ unbound, ηA: 17 MeV
  - Thomas predicts ηA: 90 MeV at saturation
  - [Prog.Th.Phys.124,147 (2010)]: ϕA: 4–40 MeV at saturation

What Can LQCD Do?

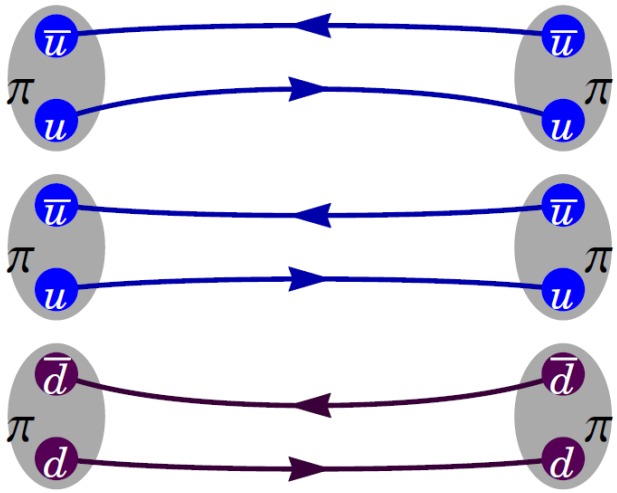
§ Signal-to-noise problem: hard to calculate nuclei

Recall that variance is $\sigma_O^2 = \langle O^2 \rangle - \langle O \rangle^2$.
For a nucleon correlator, our operator is $O \propto qqq(t)\,\bar{q}\bar{q}\bar{q}(0)$

What you want



What you get



$S/N \sim e^{-M_N t}/e^{-2M_N t/2} \sim$ const $\quad \sim e^{-M_N t}/e^{-3M_\pi t/2} \sim e^{-(M_N - \frac{3}{2}M_\pi)t}$

§ For nucleus A $\quad \exp\left[-A(M_N - 3/2m_\pi)t\right]$

What Can LQCD Do?

- Work at the SU(3) symmetric point: $M_\pi \approx 800$ MeV
- NPLQCD Calculation [PRD87,034506 (2012)]
  - Isotropic 2+1-flavor 800-MeV $O(a)$-improved Wilson-clover fermions
  - $a_s = 0.145$ fm
  - 3 volumes: 3.4 fm, 4.5 fm and 6.7 fm
  - Very high statistics:
    72×3822 (3.4 fm), 48×3050 (4.5 fm), 54×1905 (6.7 fm)
- Several sources and smearings available for each correlator

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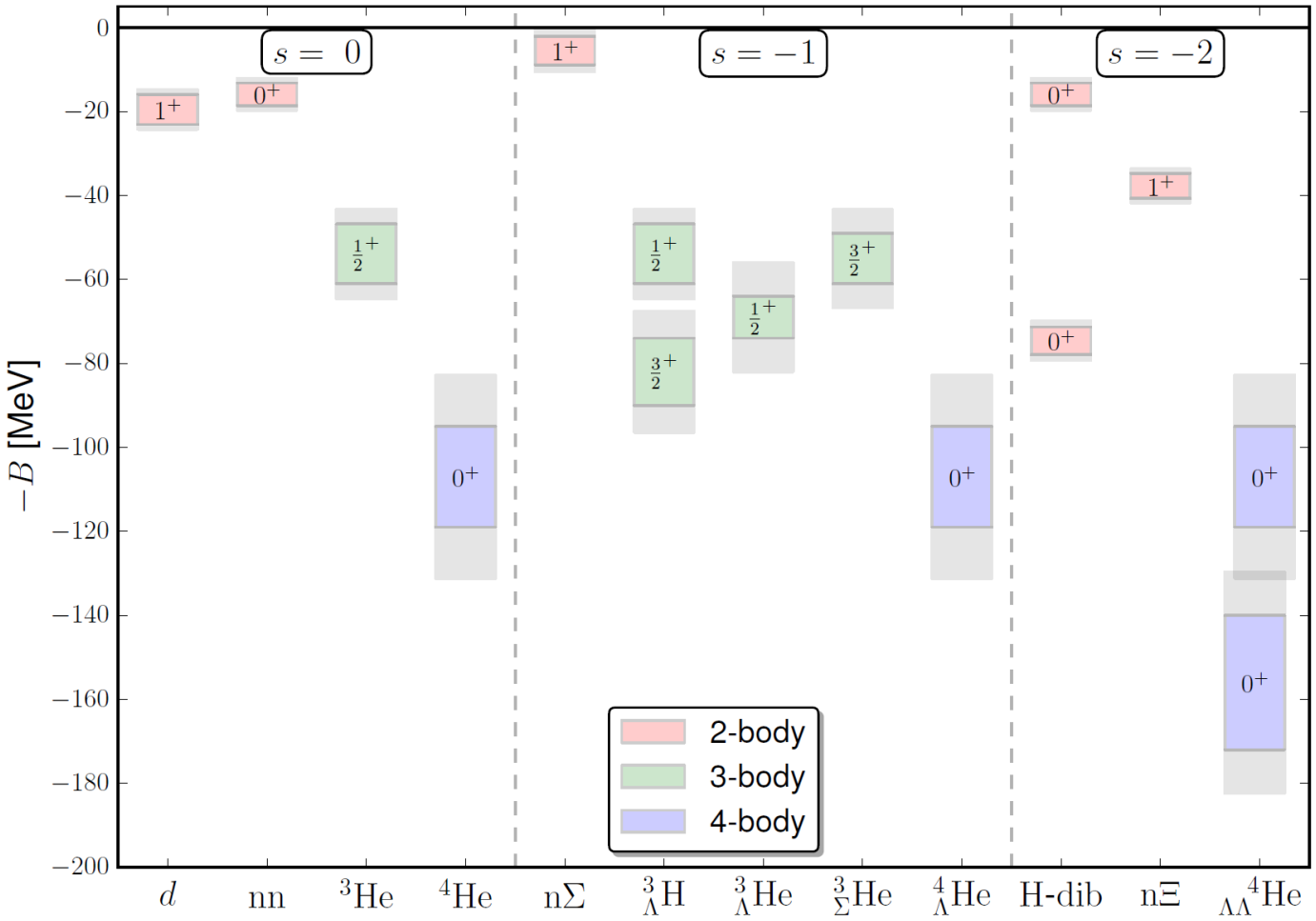
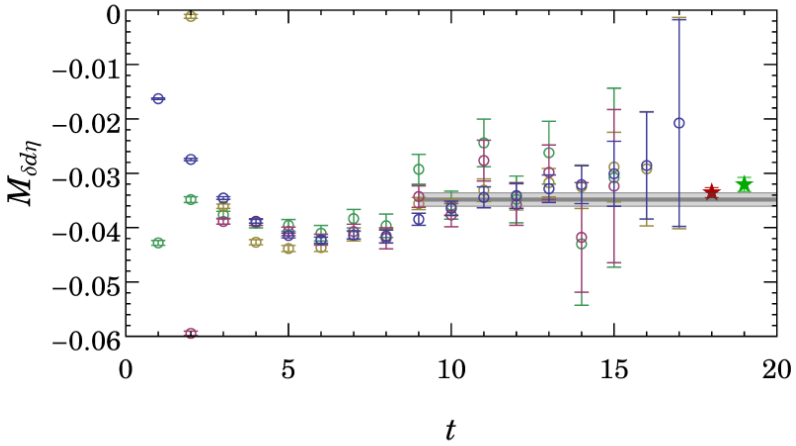


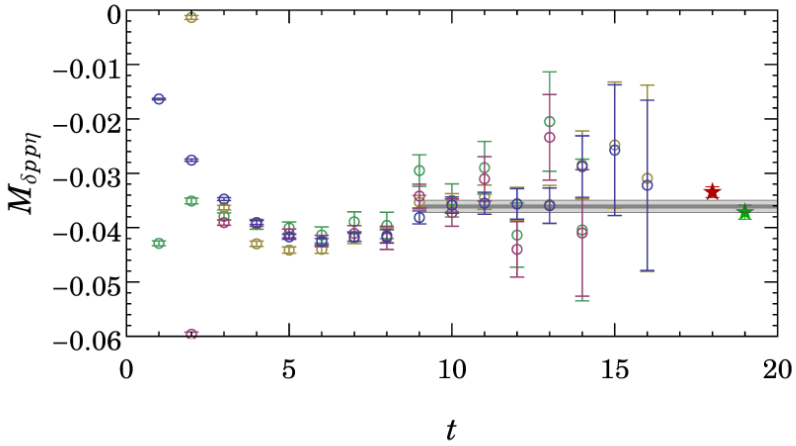
Lattice-QCD Results

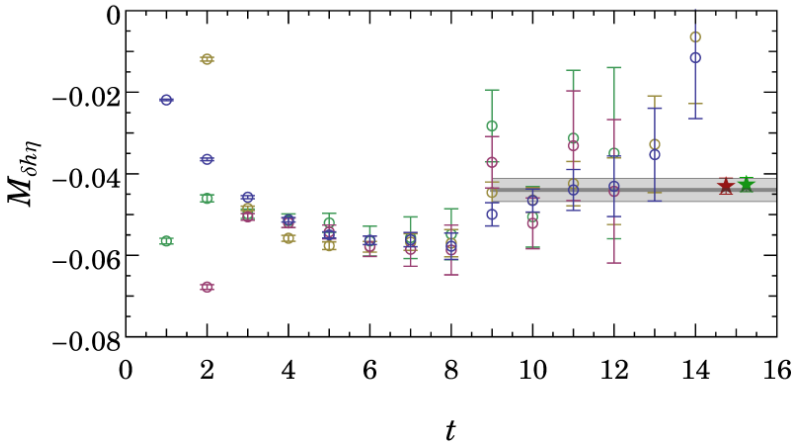
η_s-A Binding Effective Masses

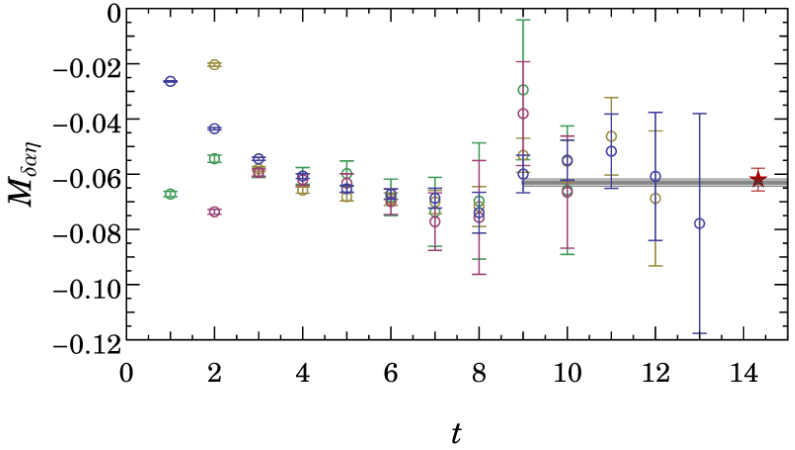
$$\mathcal{R}(t) = \frac{C_{\mathcal{AB}}(t)}{C_{AB}(t)C_{\overline{Q}\Gamma Q}(t)} \to Ze^{-(E_{12}-(E_1+E_2))(t_f-t_i)}$$

NPLQCD, 1410.7069, Phys. Rev. D 91, 114503 (2015)





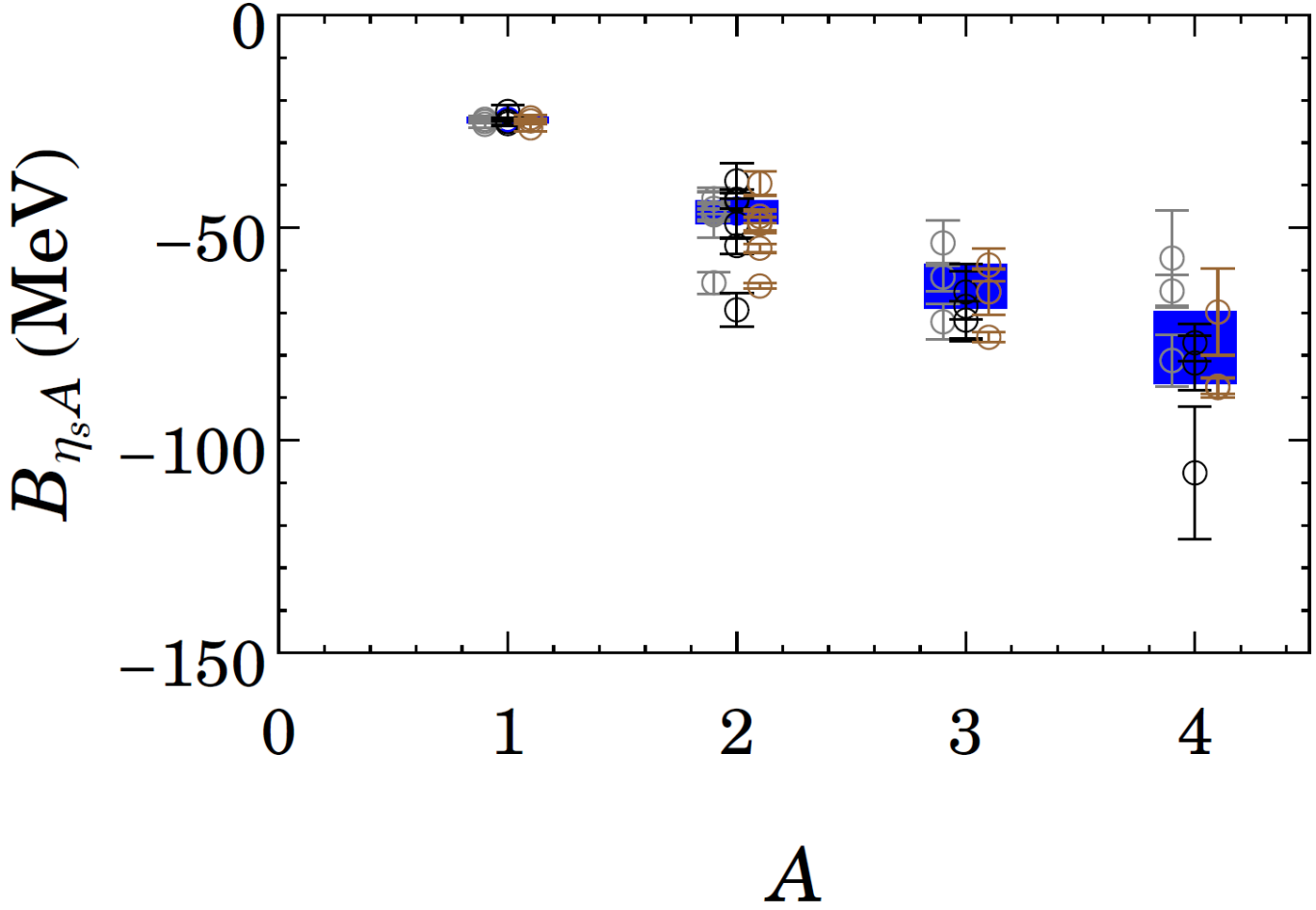




Lattice-QCD Results

§ Estimate systematic errors

NPLQCD, 1410.7069, Phys. Rev. D 91, 114503 (2015)



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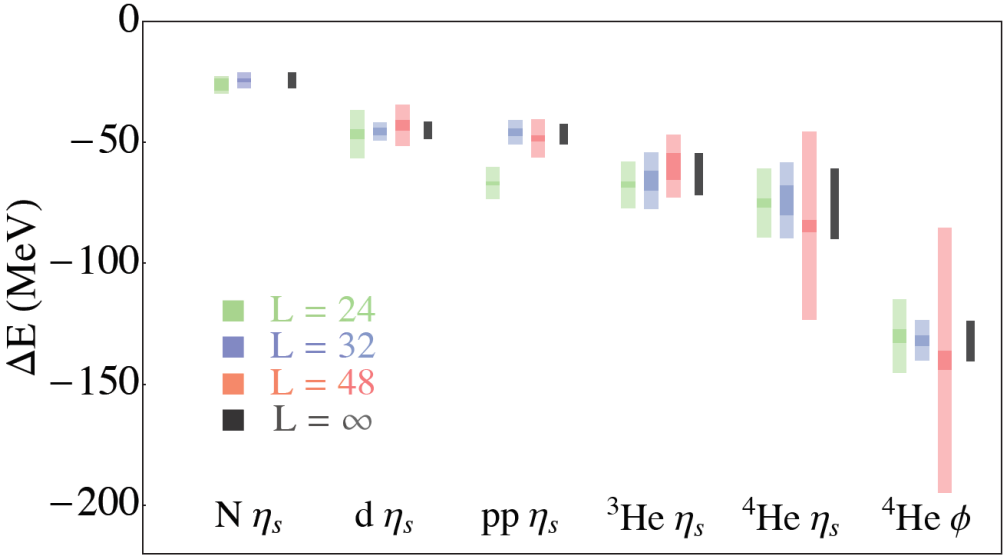
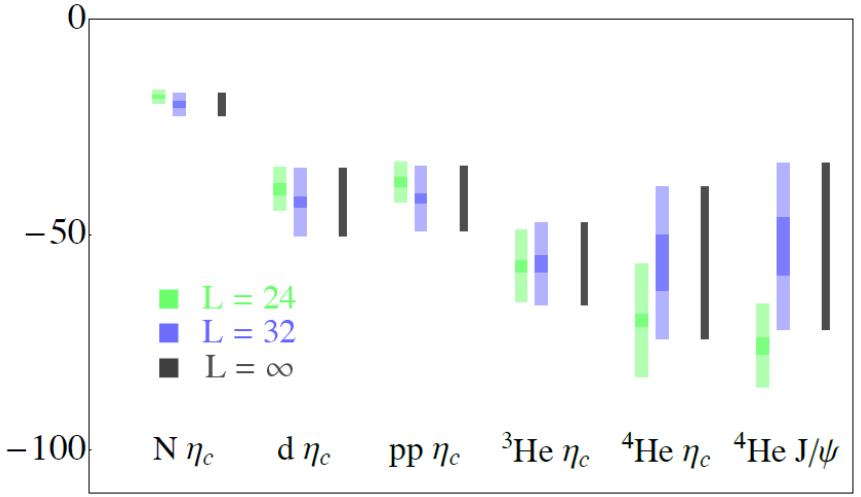
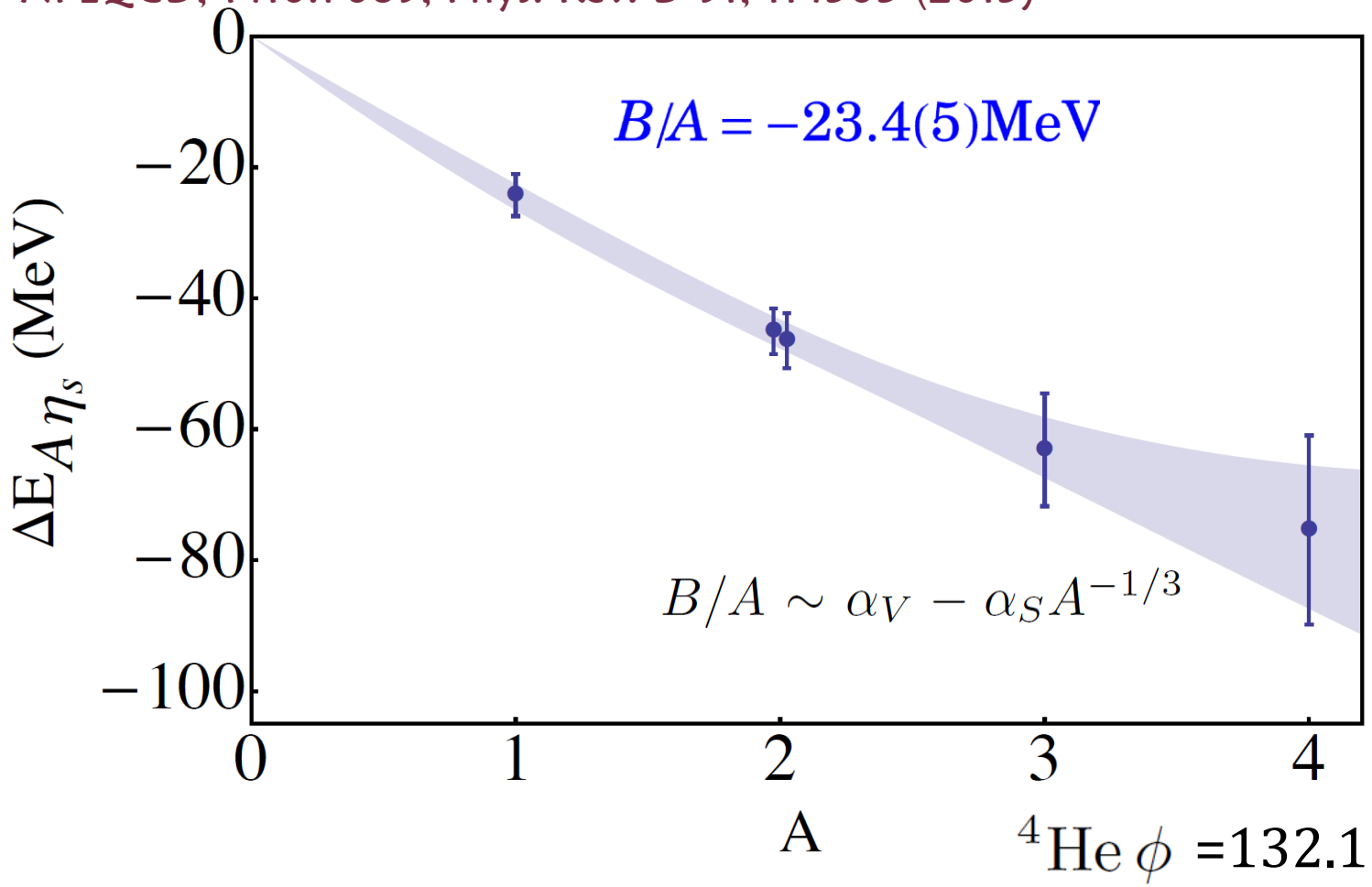




Lattice-QCD Results

η_s-Nucleus Binding vs A

NPLQCD, 1410.7069, Phys. Rev. D 91, 114503 (2015)

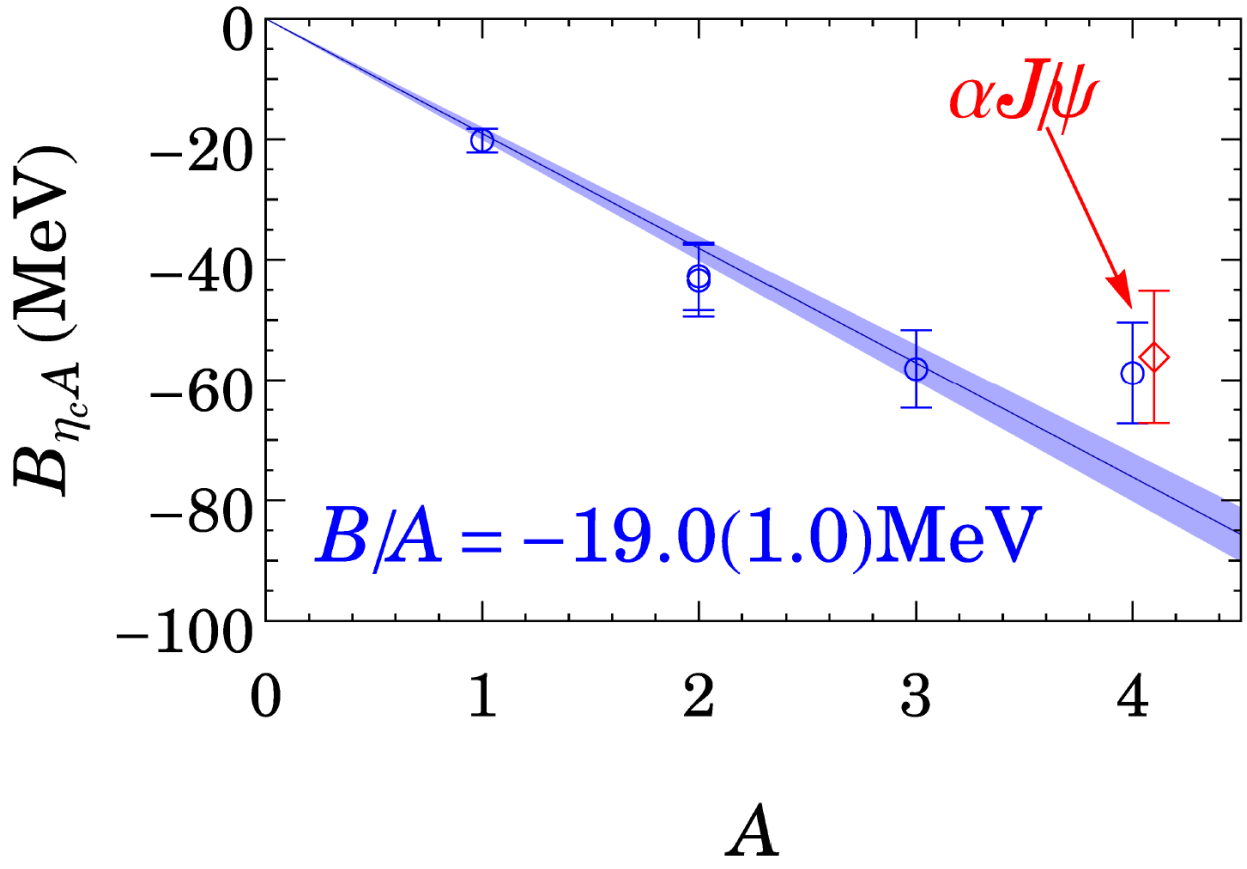


$^4\text{He}\,\phi$ =132.1(8.1) MeV

Lattice-QCD Results

Charmonium-Nucleus Binding

NPLQCD, 1410.7069, Phys. Rev. D 91, 114503 (2015)



$$B^{\text{NM}}_{\text{phys}} \lesssim 40 \text{ MeV}$$

Summary and Outlook

Progress So Far

- Now possible to explore gluonic nuclear interactions up to $A = 4$
- η_s has an attractive interaction for all $A \leq 4$
- Multiple volumes show consistent bound state
- Energy shift linear in A with slope $B_{\eta_s A} = 23.4(5)$ MeV$/A$
- ϕ-α has a deeply bound state with $B_{\phi\alpha} = 134(14)$ MeV
- Good signal in charmonium, most bindings close to strange

Future Directions

- Study coupled channels (e.g. $N\phi$-ΛK^*)
- Examine boosted systems
- Excited states?
- Move toward lighter pions