Looking for a Quarkonium-Nucleus Bound State on the Lattice

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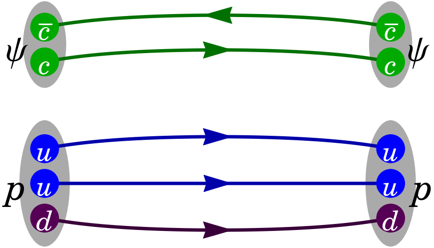
Lattice 2013
2013 August 02

Unique Probe of 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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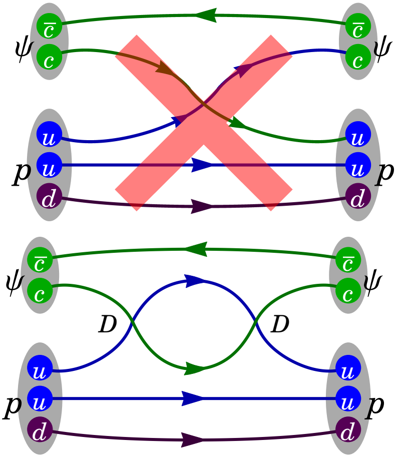

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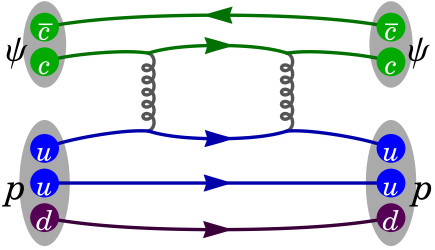
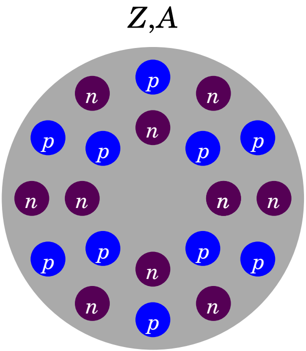


Model History

- 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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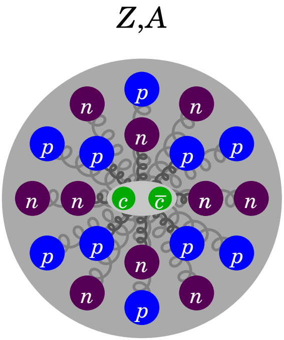

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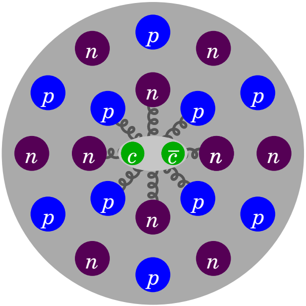
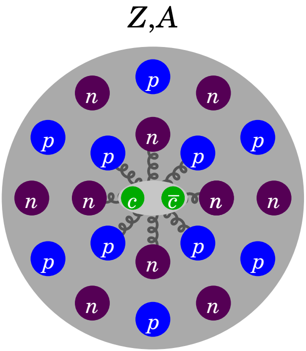
Z,A



Model History II

- 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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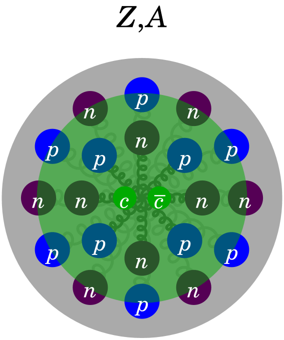

Model History III

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
  $\eta_c\,{}^6$Li: 0.1 MeV, $\eta_c\,{}^{208}$Pb: 9 MeV
- Lee and Ko [PRC67,038202 (2000)] look again at ψ' at saturation
  $J/\psi\,A$: 5 MeV, $\psi'(3686)\,A$: 130 MeV
- Thomas [PRC83,065208 (2011)] uses quark-meson coupling model
  $J/\psi\,\alpha$: 5 MeV, $J/\psi\,{}^{208}$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

NPLQCD Collaboration

NPLQCD

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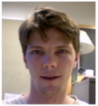
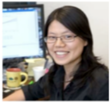
New Hampshire

Emmanuel Chang
Barcelona



William Detmold
Willam+Mary



Huey-Wen Lin
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Tom Luu
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Aaron Torok
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+

Jefferson Lab

... to make predictions for the structure and interactions of nuclei using lattice QCD.

USQCD US Lattice Quantum Chromodynamics

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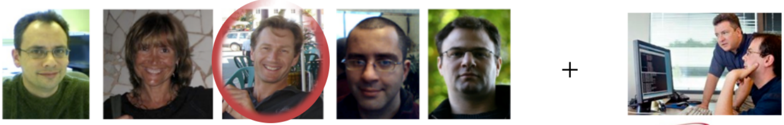

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USQCD — US Lattice Quantum Chromodynamics

The Trouble with Nucleons

Nucleons are more complicated than mesons because...

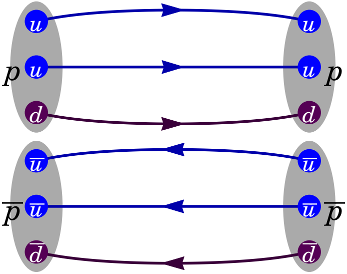
- Noise
  Signal diminishes at large t relative to noise
- Excited-state contamination
  Nearby excited state Roper $N(1440)$
- Hard to extrapolate in pion mass
  Δ resonance nearby; multiple expansions, poor convergence
- Requires large volume and high statistics
  Ensembles are not always generated with nuclear physics in mind
- Quark contractions
  Naively scale like $N_u!N_d!N_s!$
  Blocking and recursion: [PRD87,114512 (2013)]

Signal-to-Noise Ratio

Why is noise such a problem for nucleons?

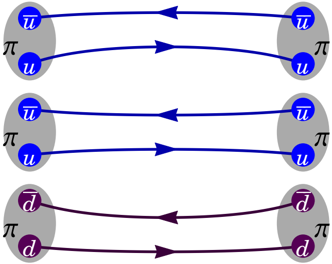
Recall that variance is $\sigma_O^2 = \langle O^2 \rangle - \langle O \rangle^2$.
For a nucleon correlator, our operator is $O \propto qqq(t)\,\bar{q}\bar{q}\bar{q}(0)$

What you want



$$S/N \sim e^{-M_N t}/e^{-2M_N t/2} \sim \text{const}$$

What you get



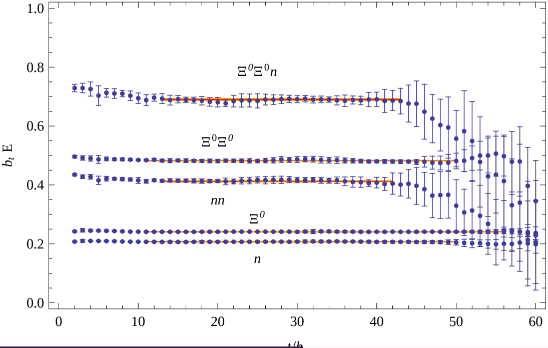
$$\sim e^{-M_N t}/e^{-3M_\pi t/2} \sim e^{-(M_N - \frac{3}{2}M_\pi)t}$$

The Golden Window

Things don't always have to go wrong

Although the exponential behavior is known, the coefficients are not. Suppose there is suppression of the overlap of the $\langle N^\dagger N \rangle$ onto the 3π state.

$$\sigma^2 = Z_0 e^{-2AM_N t} + \frac{A^2}{(M_\pi L)^3} Z_1 e^{-(2(A-1)M_N + 3M_\pi)t} + \ldots$$



For $Z_n \ll Z_{n+1}$,
$t_{\text{gold}} \sim \frac{2}{2M_N - 3M_\pi} \ln\left(\frac{(M_\pi L)^3}{A^2}\right)$

Momentum-projected operators cover full volume; pions only form if N and $N^\dagger$ coincide spatially.

[PRD80,074501 (2009)]

SU(3)-Symmetric QCD

- 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)

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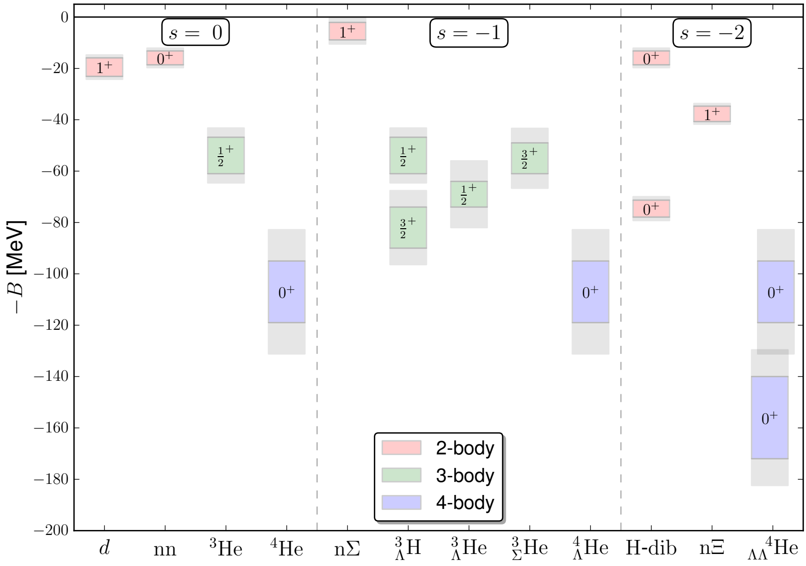

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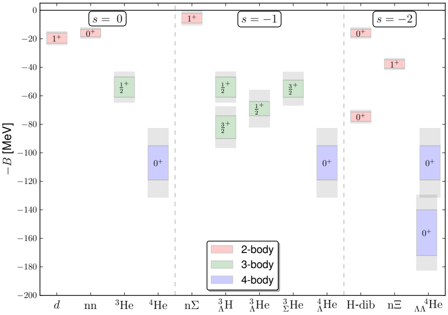

- H-dibaryon deeply bound: $B_H = 74.6(3.3)(3.3)(0.8)$ MeV
- Deuteron clearly bound: $B_d = 19.5(3.1)(0.2)$ MeV more bound than quenched
- Small d-nn splitting other splittings larger
- α also more bound than 0f $B_\alpha = 107(12)(21)(1)$ MeV

Gluonic-Interaction Data

How can we leverage this dataset?

- Many correlators for nuclei, hypernuclei, strange and light mesons
- Ideal for gluonic interactions
- First, apply method to strange quarkonia: η_s, ϕ

- No free quark lines $\Longrightarrow$ no quark exchange
- No spin degrees of freedom $\Longrightarrow$ limited to η or α

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  - Very high statistics:
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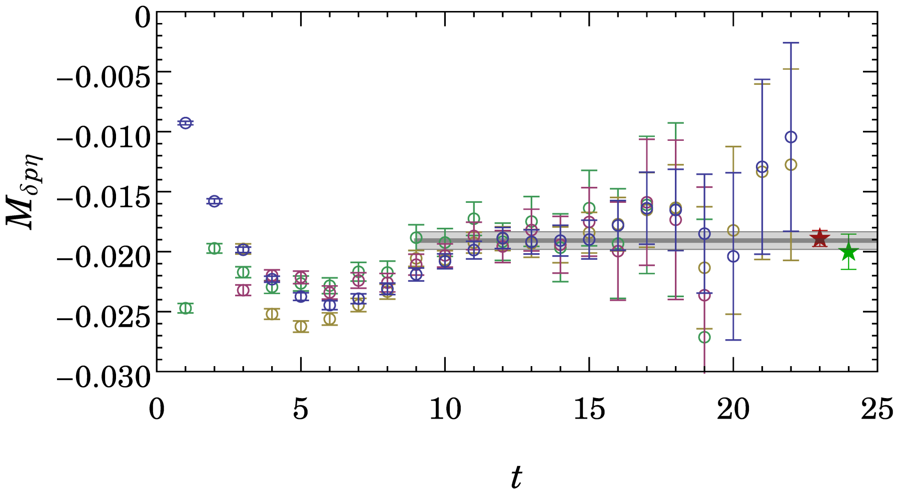
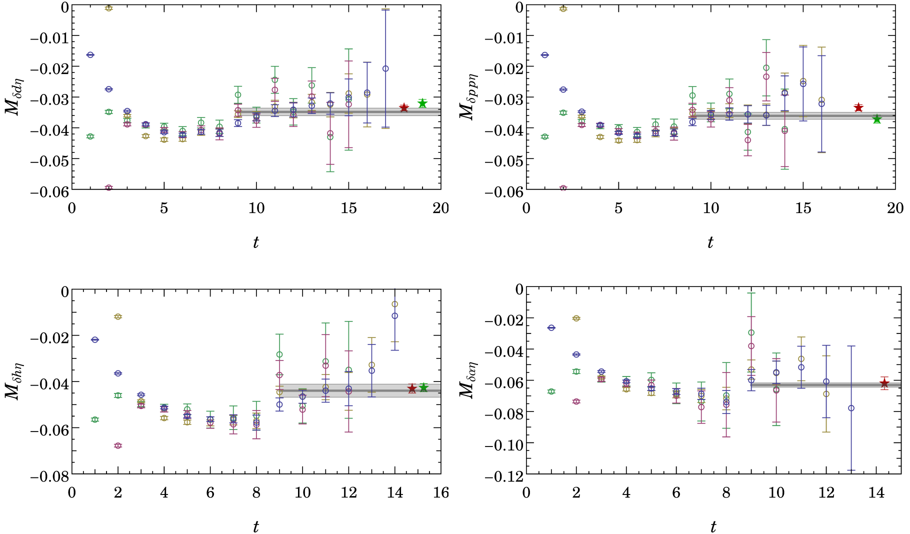
- Several sources and smearings available for each correlator
- Extract binding energies using three methods:
  - One-state fit to ratio of correlators (gray bar)
    time-extent of bar **does not indicate fit range**
  - Splitting between energies extracted from one-state fits (red)
  - Splitting between energies extracted from two-state fits (green)

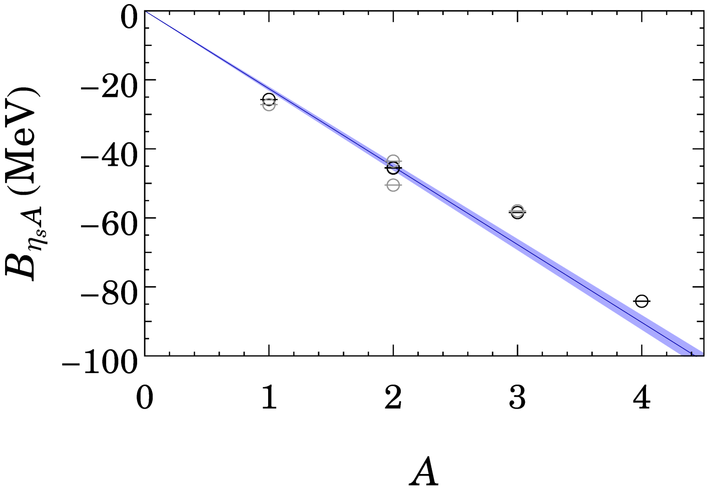
η_s-N Binding Effective Mass



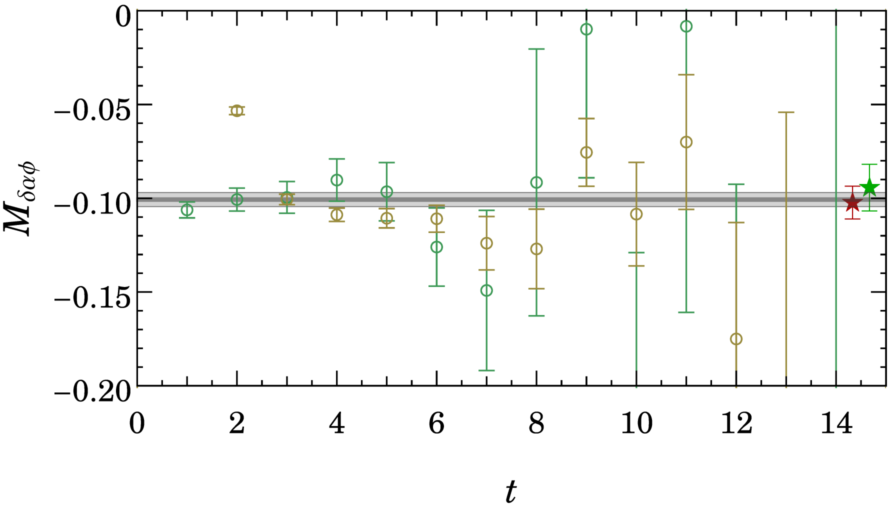
η_s-A Binding Effective Masses



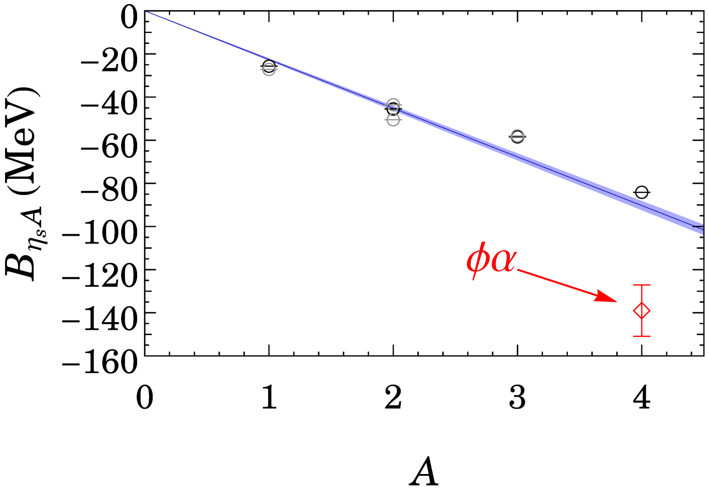
η_s-Nucleus Binding vs A



ϕ-α Binding Effective Mass



ϕ-α Binding



Conclusions

Summary

- Now possible to explore gluonic nuclear interactions up to $A = 4$
- η_s has an attractive interaction for all $A \leq 4$
- Energy shift linear in A with slope $B_{\eta_s A} = 22.6(5)$ MeV$/A$
- ϕ-α has a clear bound state with $B_{\phi\alpha} = 139(12)$ MeV

Future Directions

- Study coupled channels (e.g. $N\phi$-ΛK^*)
- Examine boosted systems and multiple volumes
  to clarify bound-state identification versus attractive scattering
- Charmonium bindings (in progress)
- Excited states?