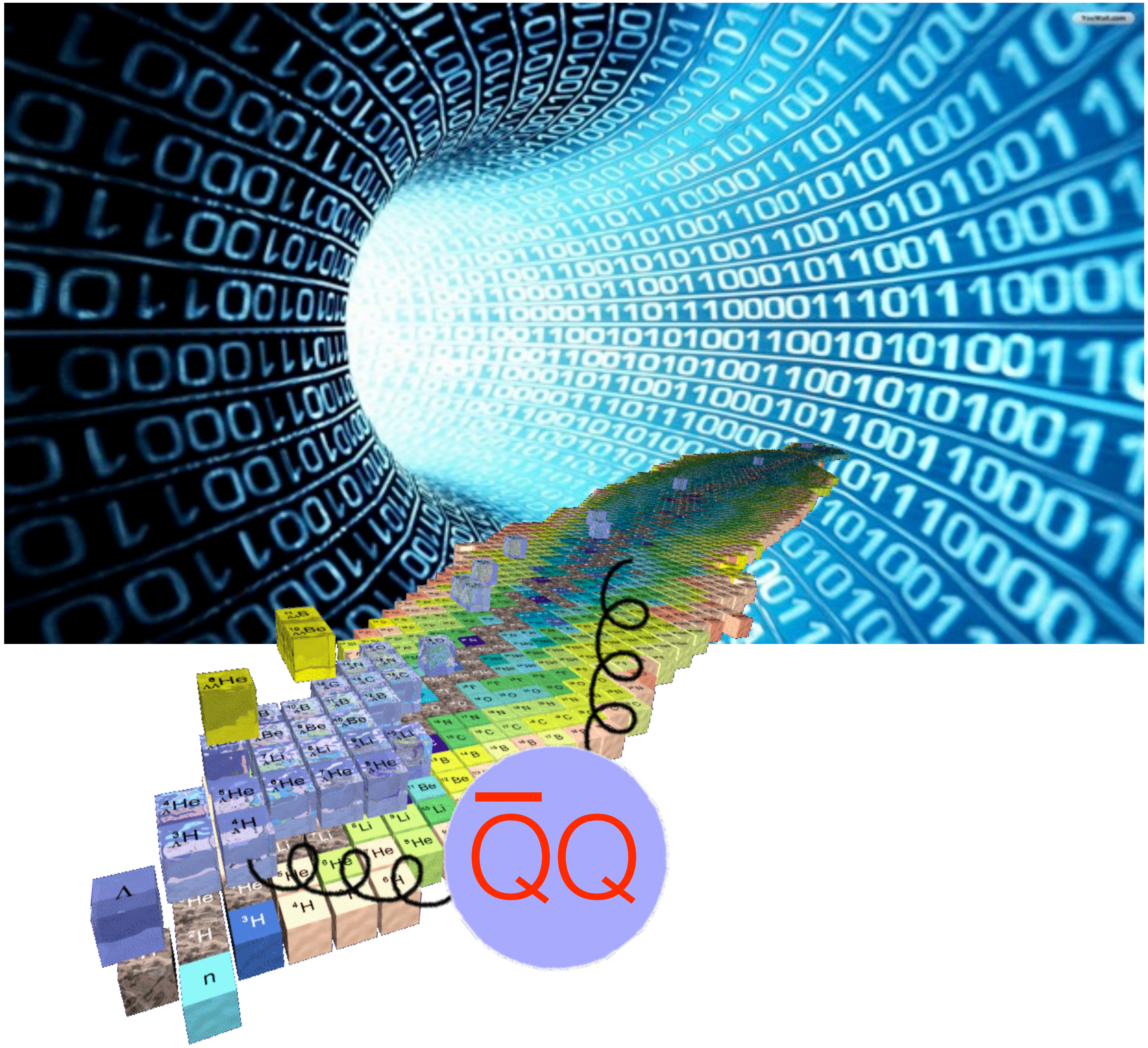


Quarkonium-Nucleus Interactions from Lattice QCD

(APS, Baltimore, April 2015)

Martin J Savage

INSTITUTE for NUCLEAR THEORY

Modeling Interactions with Nuclei

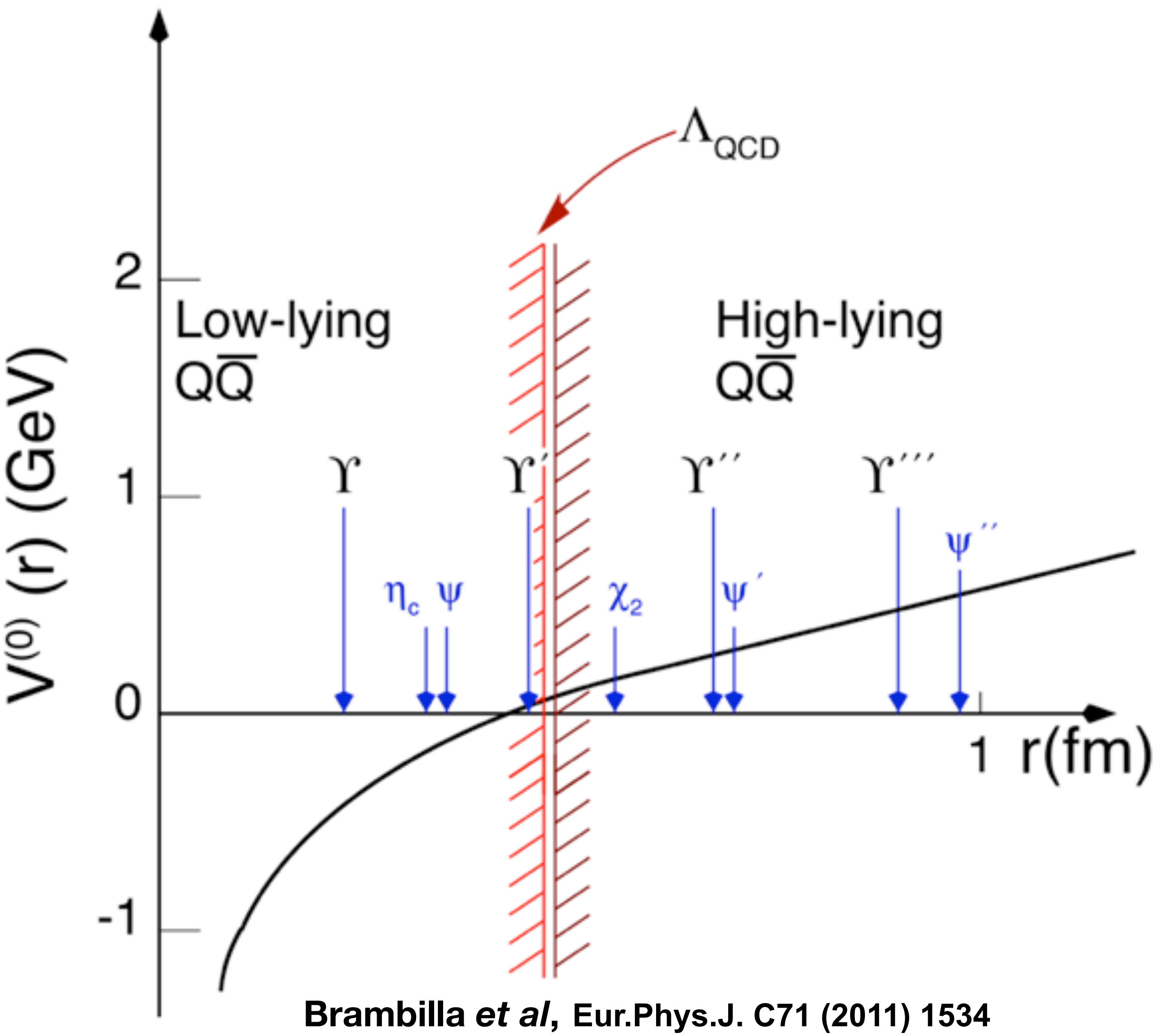
- Brodsky, Schmidt and deTeramond (1989)
  - multi-gluon exchange modeled by Pomerons
  - large binding energies, scaling with A

- Wasson (1991)
  - Saturation due to finite range interaction

Ref.	Binding Energy (MeV) ^{3}He η_c	^{4}He η_c	NM η_c	Binding Energy (MeV) ^{4}He J/ψ	NM J/ψ
[1]	19	140			
[2]	0.8	5	27		
[3]			10		10
[5]	*	*	9		
[6]					5
[7]				5	18
[8]				15.7	

[1] S. J. Brodsky, I. Schmidt, and G. de Teramond, Phys.Rev.Lett. **64**, 1011 (1990).
[2] D. Wasson, Phys.Rev.Lett. **67**, 2237 (1991).
[3] M. E. Luke, A. V. Manohar, and M. J. Savage, Phys.Lett. **B288**, 355 (1992), hep-ph/9204219.
[4] S. J. Brodsky and G. A. Miller, Phys.Lett. **B412**, 125 (1997), hep-ph/9707382.
[5] G. F. de Teramond, R. Espinoza, and M. Ortega-Rodriguez, Phys.Rev. **D58**, 034012 (1998), hep-ph/9708202.
[6] S. H. Lee and C. Ko, Phys.Rev. **C67**, 038202 (2003), nucl-th/0208003.
[7] K. Tsushima, D. Lu, G. Krein, and A. Thomas, Phys.Rev. **C83**, 065208 (2011), 1103.5516.
[8] A. Yokota, E. Hiyama, and M. Oka, PTEP **2013**, 113D01 (2013), 1308.6102.

Quarkonium Structure and Scales



Brambilla *et al*, Eur.Phys.J. C71 (2011) 1534

Small r → Coulomb

$V \sim \alpha_s(r)/r$

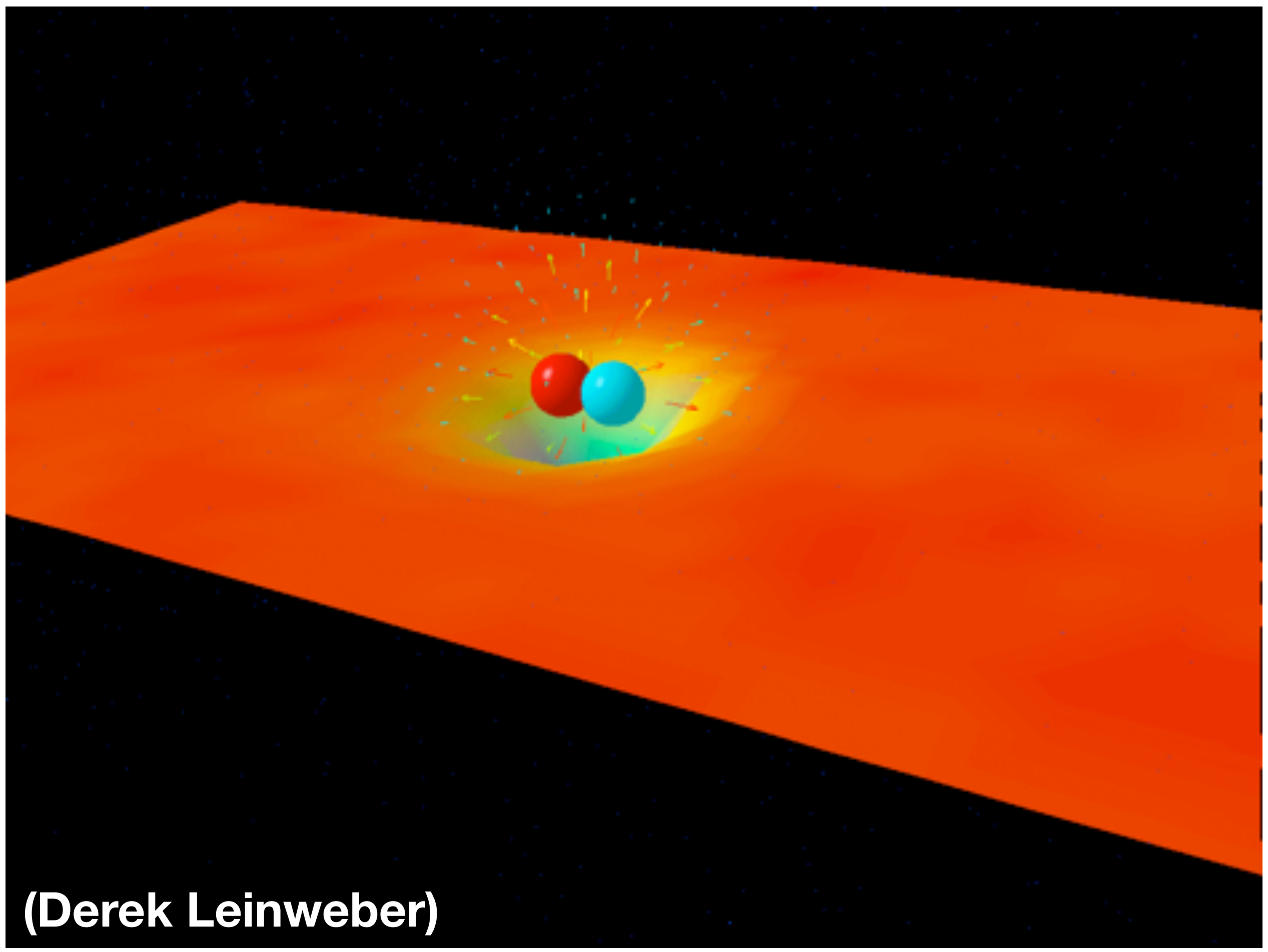
$r \sim 1/(\alpha_s(r)\, M_Q)$

$B \sim (\alpha_s(r))^2\, M_Q$

System Factorizes at small r

- color van der Waals

Quarkonium
Symmetries and Interactions



Gluon Energy Density

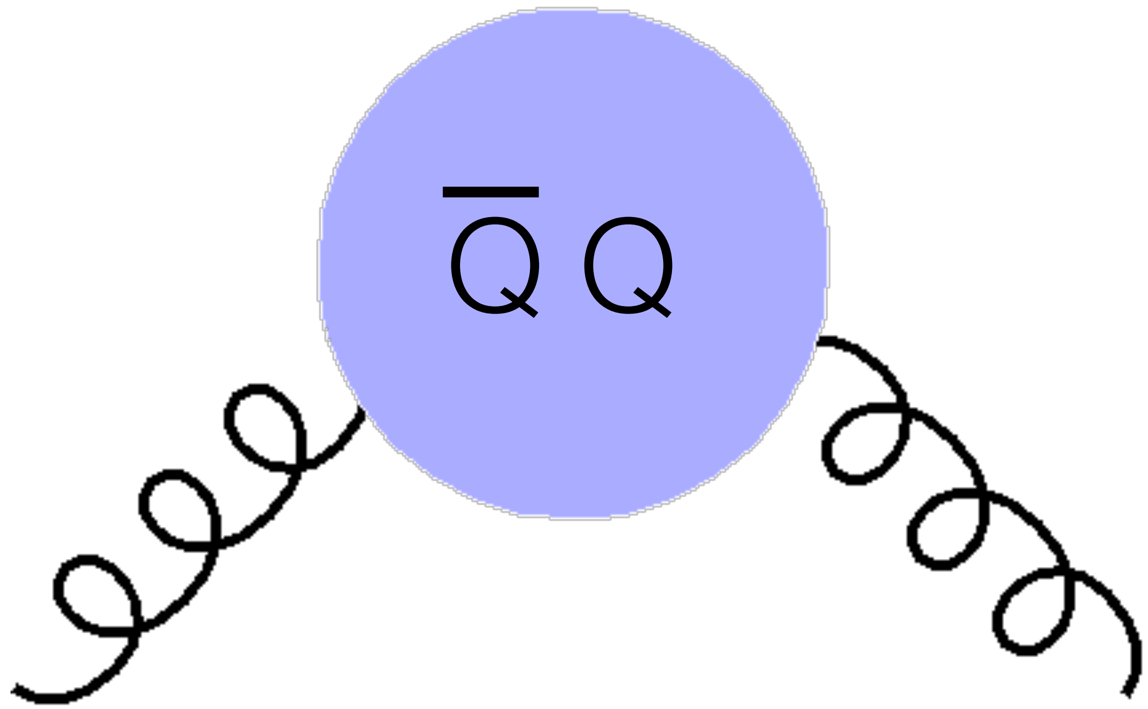
Heavy Quark Symmetry

ηc and J/ψ have same interactions in heavy-quark limit

Multipole expansion of the gluon interactions

Coefficients in Lagrangian Density ~ r^3 , ...

Quarkonium
Symmetries and Interactions

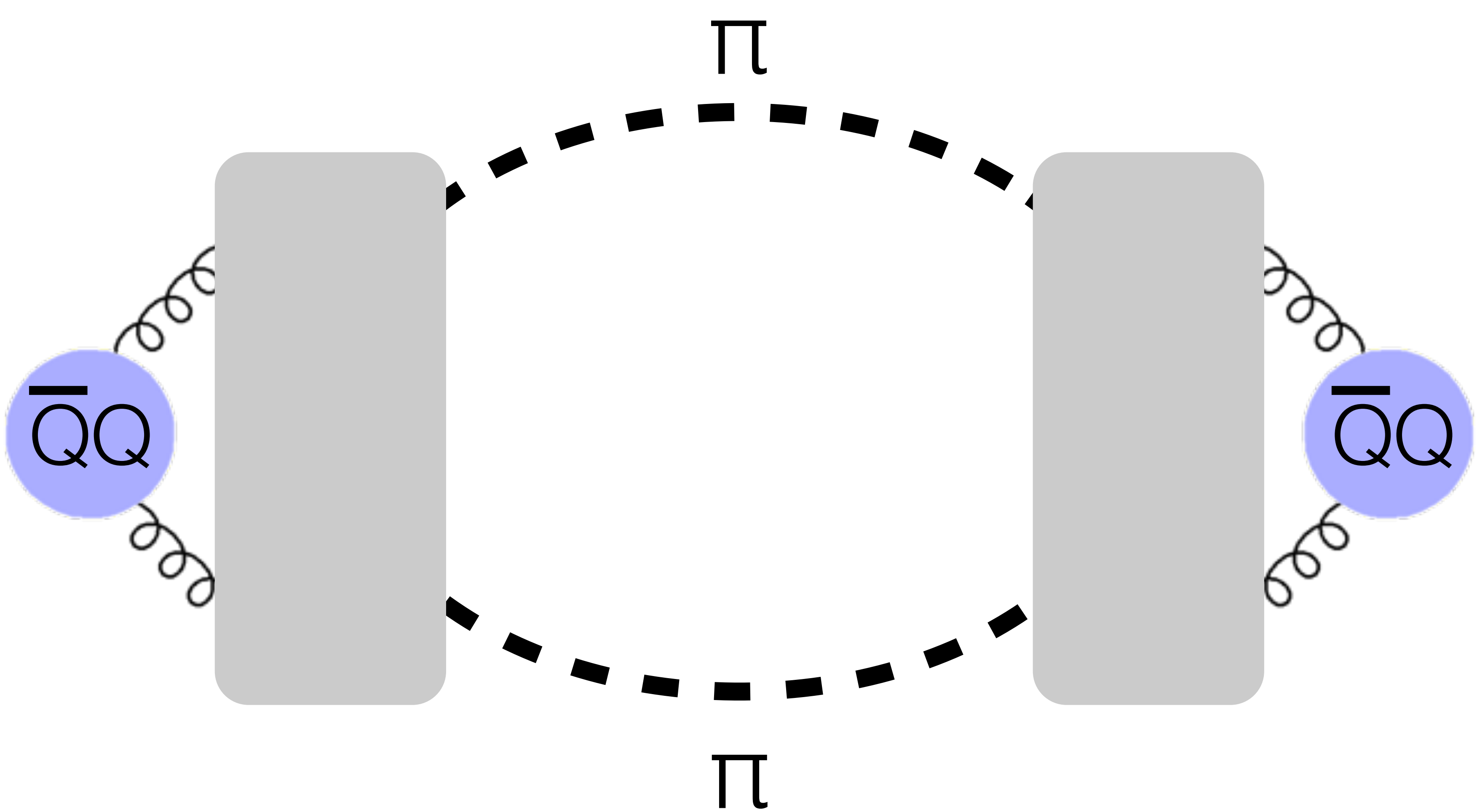


Only spin-0 and spin-2 , no spin-1 (requires 3 gluons)

$G_{\mu\nu} G^{\mu\nu}$, $G_{0\alpha} G_0{}^{\alpha}$ — O(1) (Luke, Manohar, MJS)

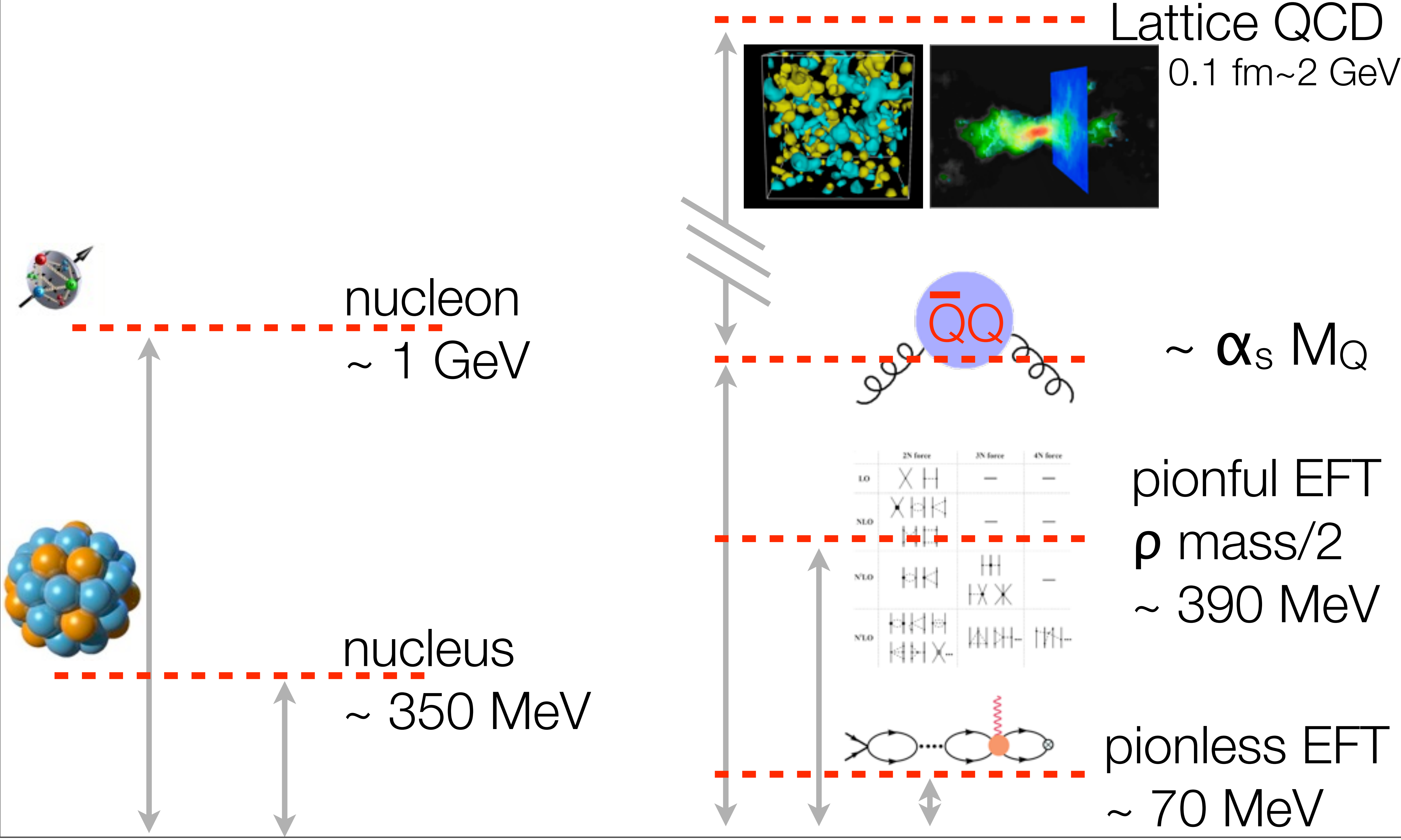
$G_{i\alpha} G_j{}^{\alpha}$ symmetrized, traceless — $O(1/M_Q)$

Leading Interactions

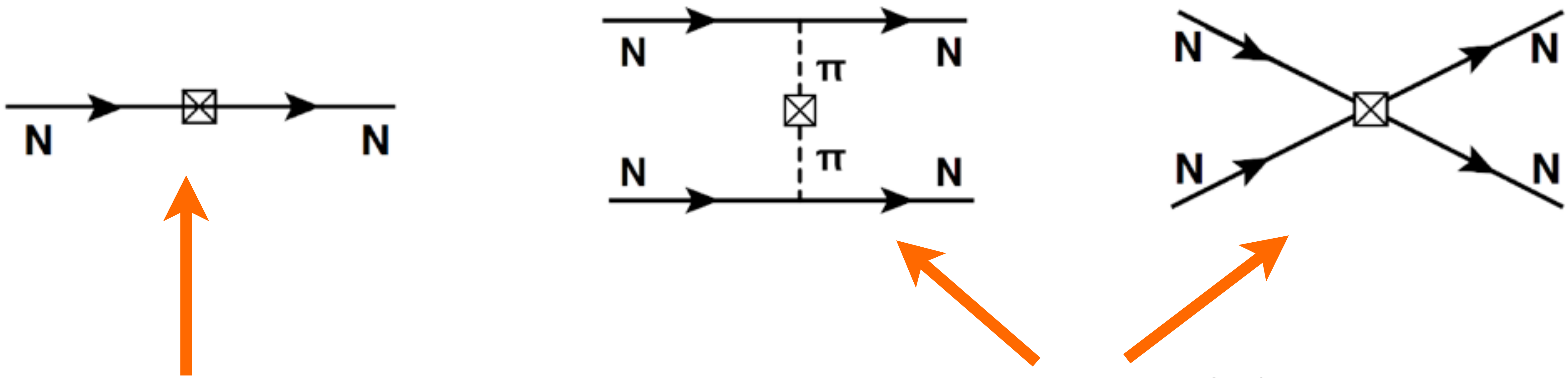


$$V \sim e^{-2mr} / r$$

Energy Scales



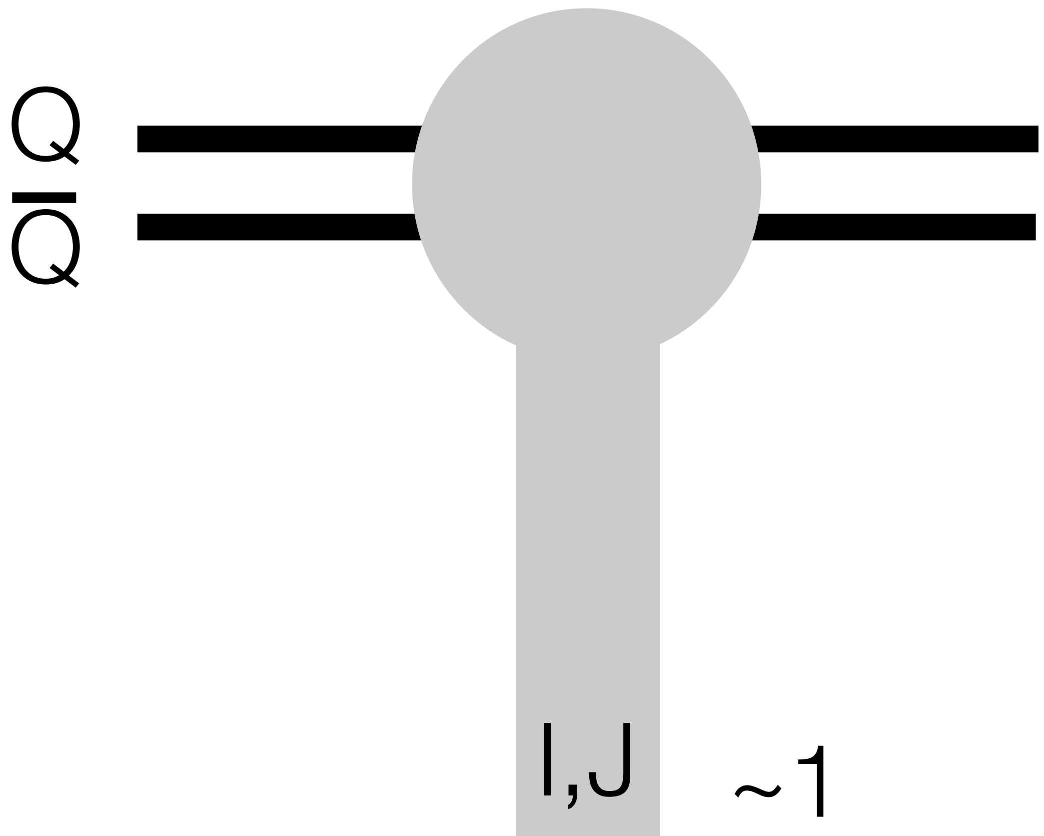
EFT Matching

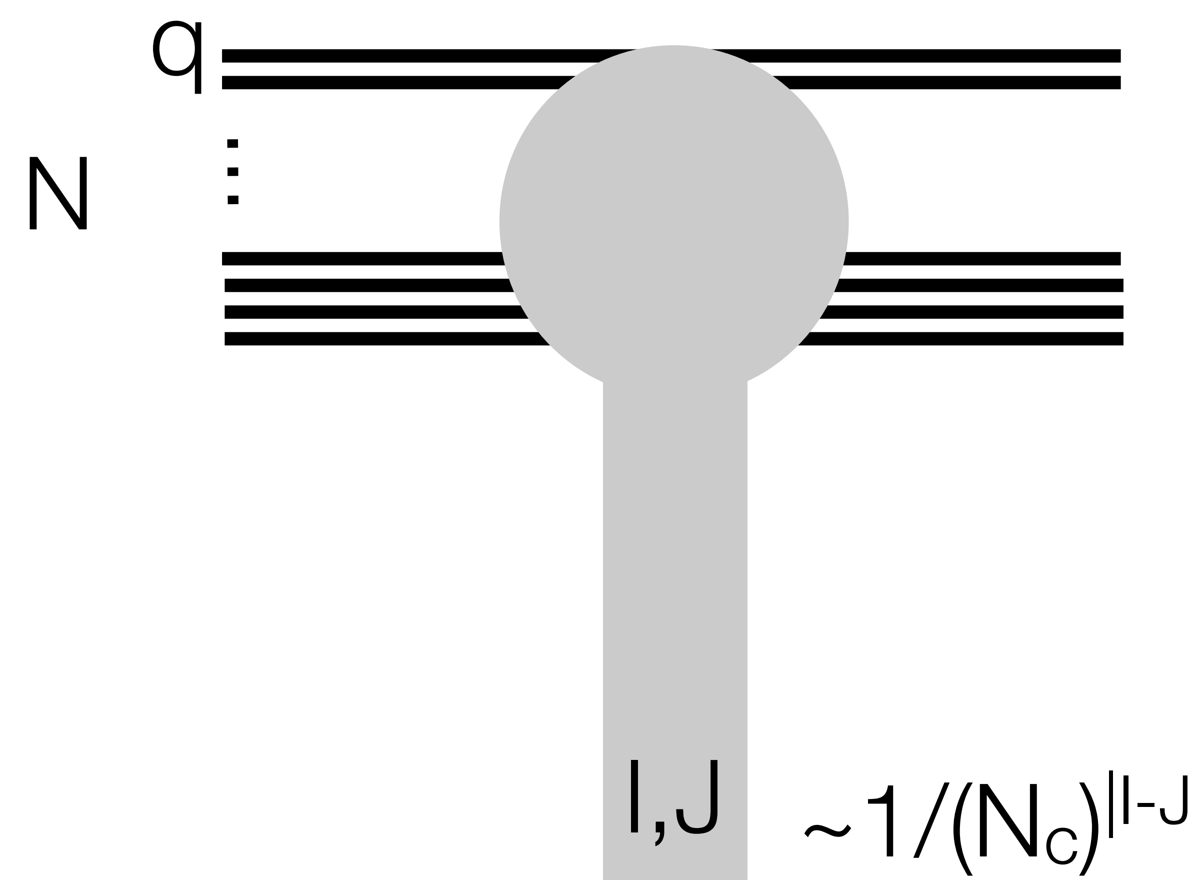


Single Nucleon

Required by QCD !
How big ??

Quarkonium
Symmetries and Interactions





Large-Nc Limit

η_c and J/ψ have spin-independent interactions up to $1/M_Q$

Nuclei have 1/Nc suppressions that depend on t-channel quantum numbers

J/ψ - deuteron Interactions

e.g., structures of the effective interactions

$\psi^{j\dagger}\ \psi_j\, d^{k\dagger}\ d_k$ $\quad J_t=0$

$O(1)$

$\epsilon^{ijk}\psi^{j\dagger}\ \psi_k\ \ \epsilon^{ilm} d^{l\dagger}\ d_m$ $\quad J_t=1$

$O(1/N_c,\ 1/M_Q\ ,\ g_s)$

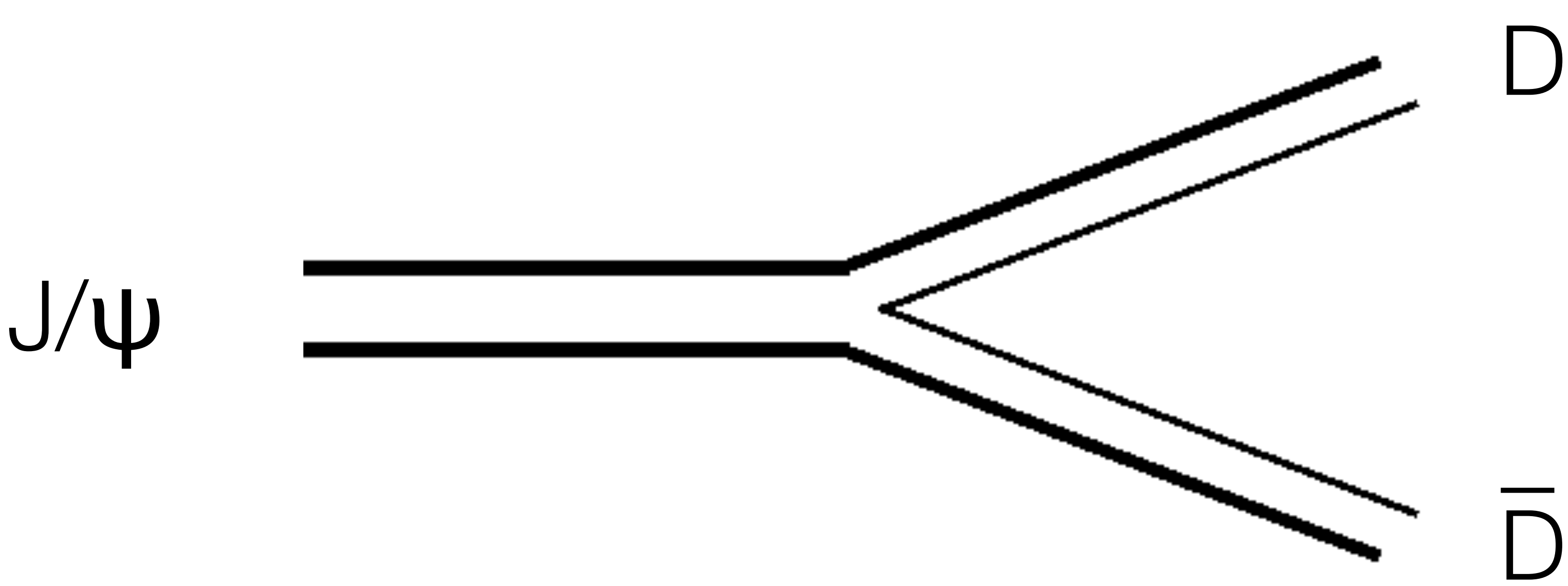
$(\psi^{\{i\dagger}\ \psi_{j\}}$ - $2/3\ \delta^{ij}$ traces$)\ (d^{\{i\dagger}\ d_{j\}}$ - $2/3\ \delta^{ij}$ traces$)$ $\quad J_t=2$

$O(1/N_c^2,\ 1/M_Q)$

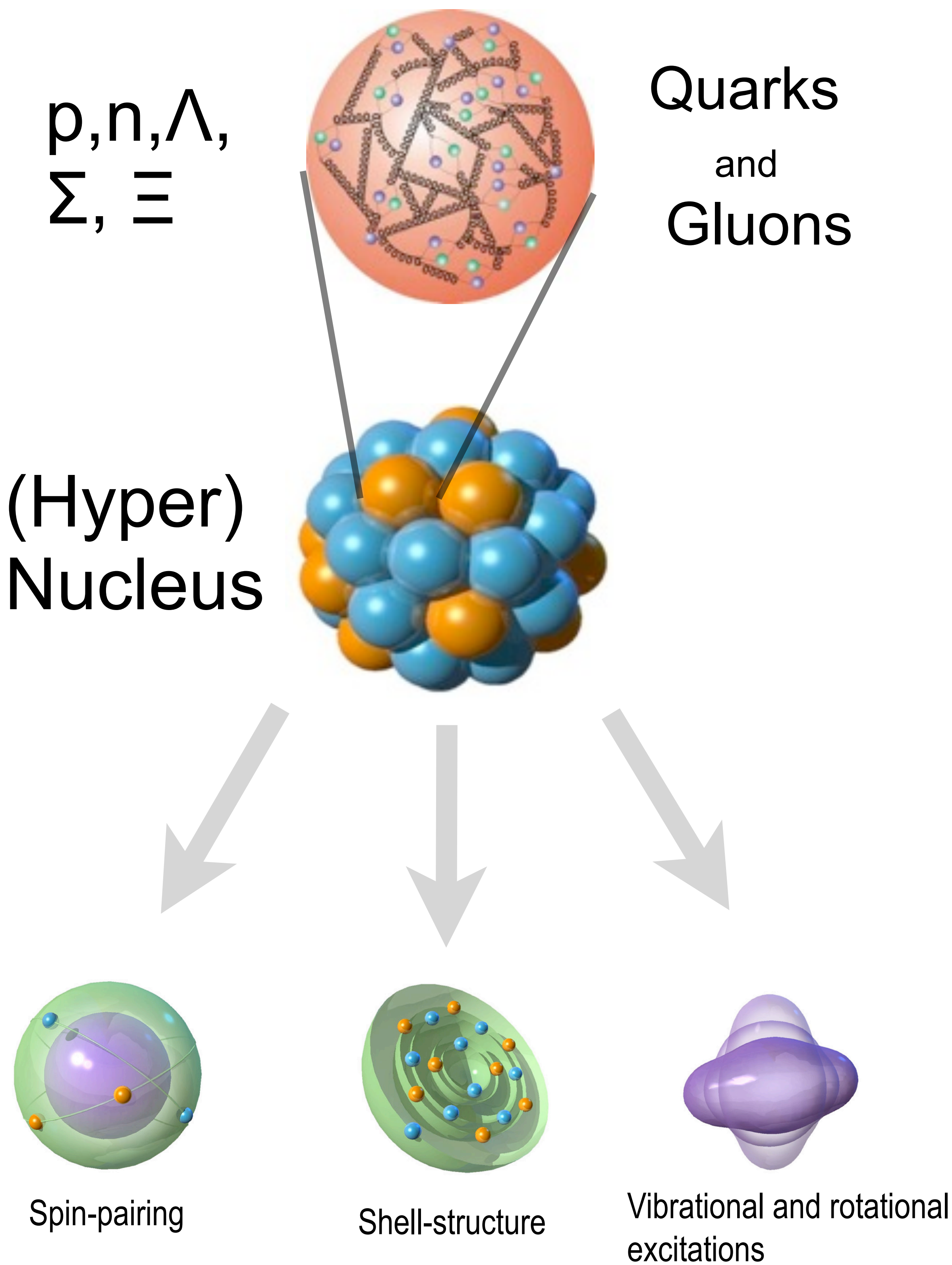
Chamonium Issues

- Is charmonium small enough ?
  - probably significant impact from charmed meson states

- Is strangeonium small enough ?
  - degenerate hadronic states, SU(3) symmetry



The Structure and Interactions of Matter from Quantum Chromodynamics



$$\Lambda_{QCD}$$

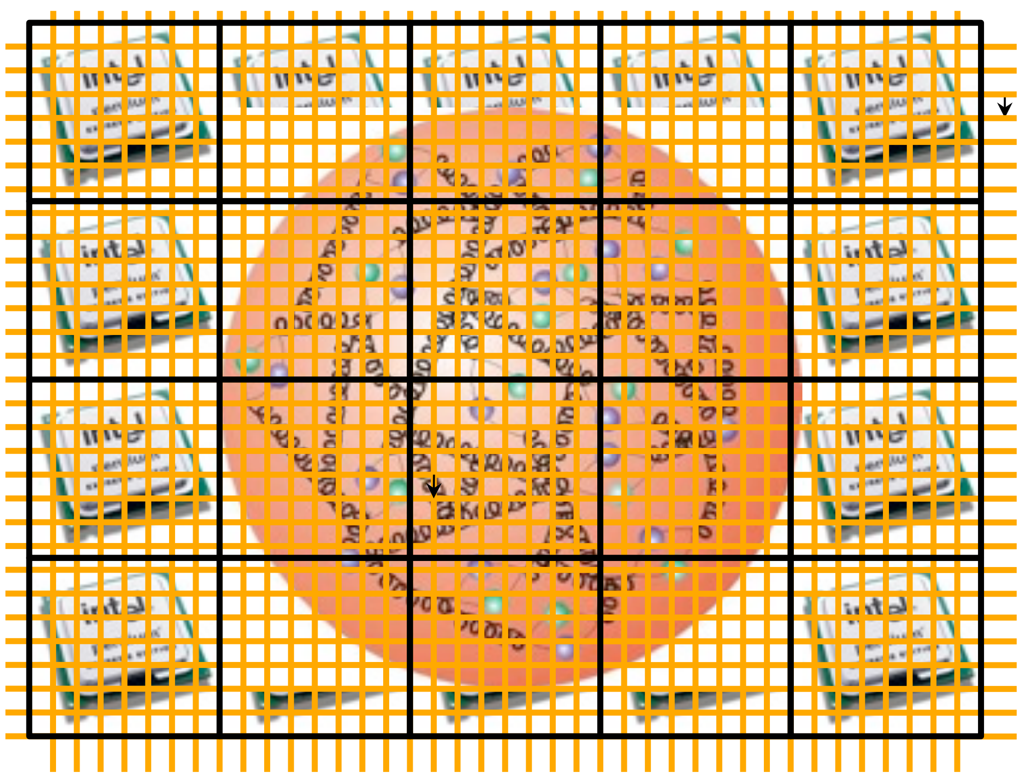
$$\frac{m_u}{\Lambda_{QCD}} \quad \frac{m_d}{\Lambda_{QCD}} \quad \frac{m_s}{\Lambda_{QCD}}$$

$$\alpha_e$$

Small number of input parameters responsible for all of strongly interacting matter

Lattice QCD

Using a Discretized Spacetime



Lattice Spacing :

$a << 1/\Lambda\chi$

(Nearly Continuum)

Lattice Volume :

$m_\pi L >> 2\pi$

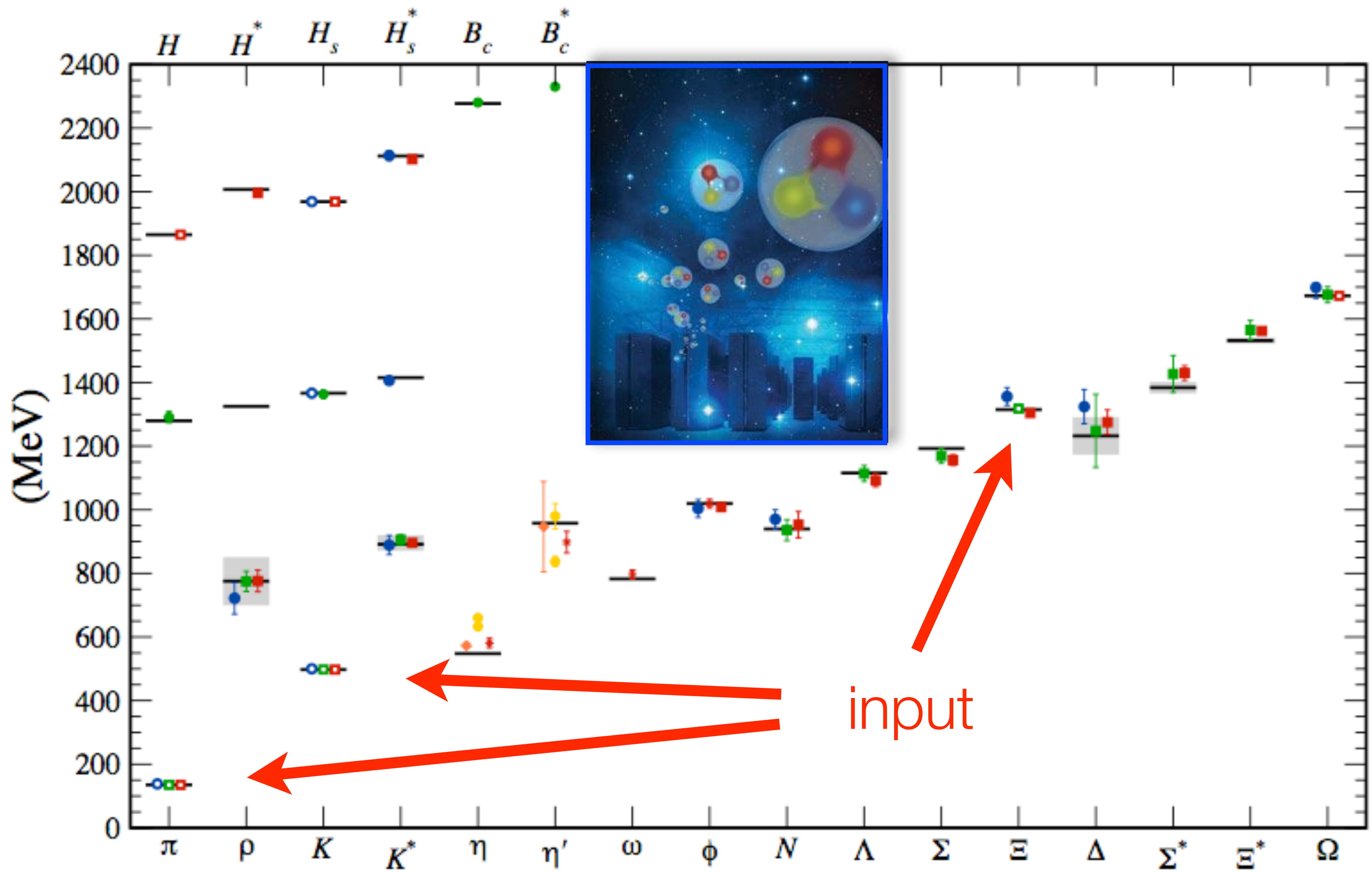
(Nearly Infinite Volume)

Extrapolation to $a = 0$ and $L = \infty$

Systematically remove non-QCD parts of calculation

$$\langle\hat{\theta}\rangle \sim \int \mathcal{D}\mathcal{U}_\mu \; \hat{\theta}[\mathcal{U}_\mu] \; \det[\kappa[\mathcal{U}_\mu]] \; e^{-S_{YM}} \;\; \rightarrow \frac{1}{N} \sum_{\text{gluon cfgs}}^{N} \hat{\theta}\,[\mathcal{U}_\mu]$$

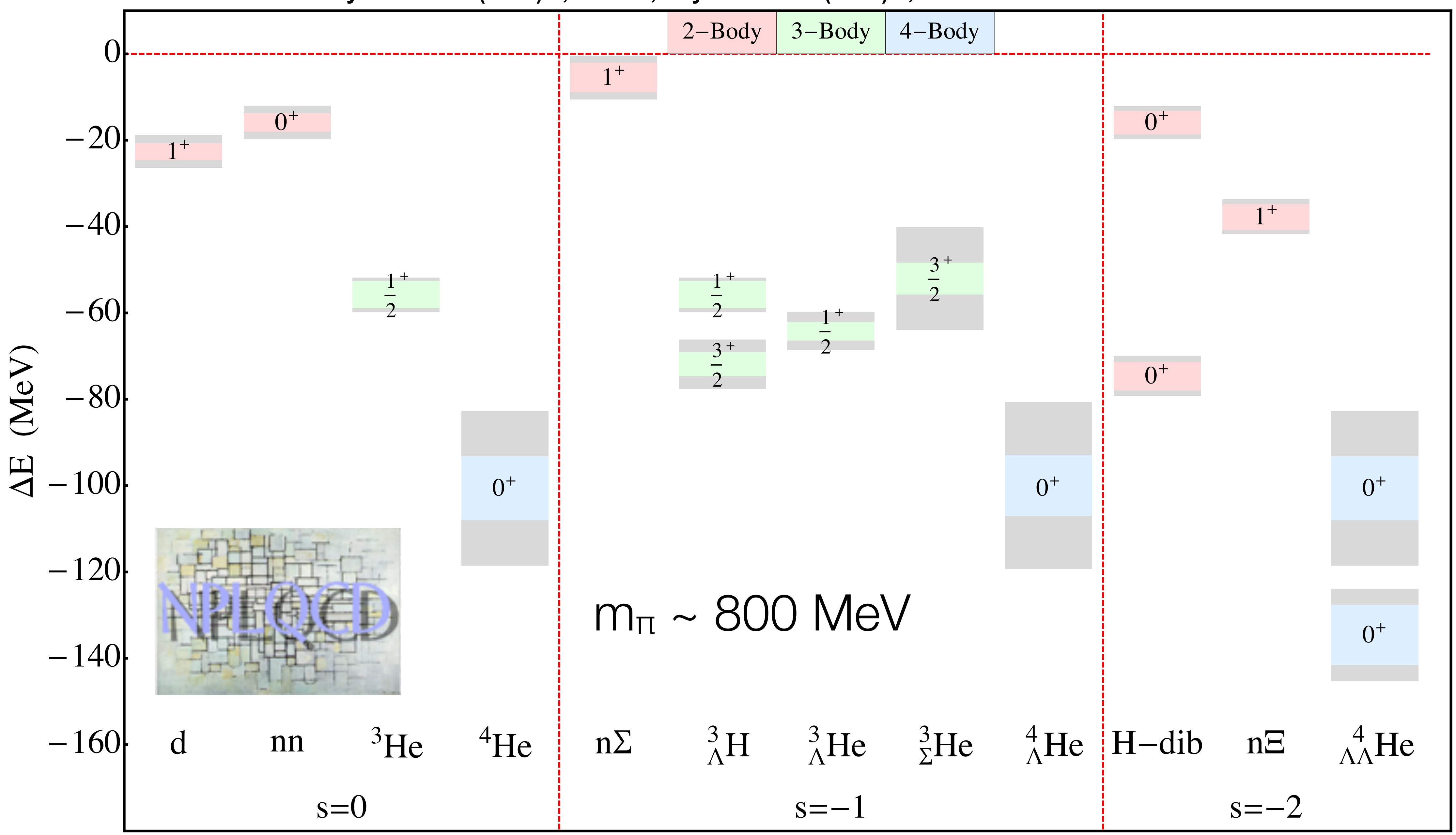
Hadron Masses



(Kronfeld)

(Hyper)Nuclei from QCD

Beane, Chang, Cohen, Detmold, Lin, Luu, Orginos, Parreno, MJS, Walker-Loud, Phys.Rev. D87 (2013) 3, 034506, Phys.Rev. C88 (2013) 2, 024003

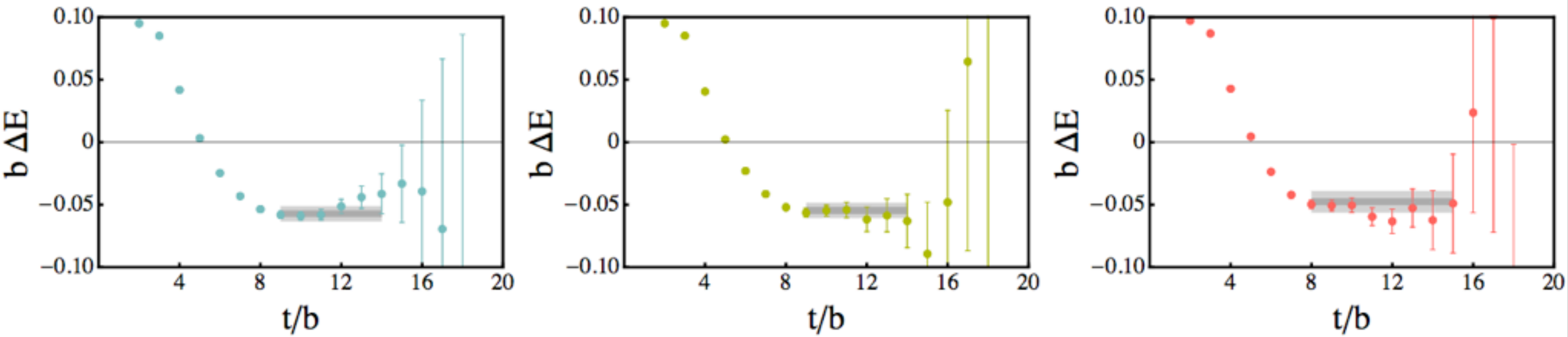


Extensive study of s-shell nuclei and hypernuclei, and baryon-baryon interactions at SU(3) symmetric point

(Hyper)Nuclei from QCD

Beane, Chang, Cohen, Detmold, Lin, Luu, Orginos, Parreno, MJS, Walker-Loud,
Phys.Rev. D87 (2013) 3, 034506, Phys.Rev. C88 (2013) 2, 024003

e.g. 3-body correlator - $n\Lambda\Lambda$, ${}^{3}_{\Lambda}H$



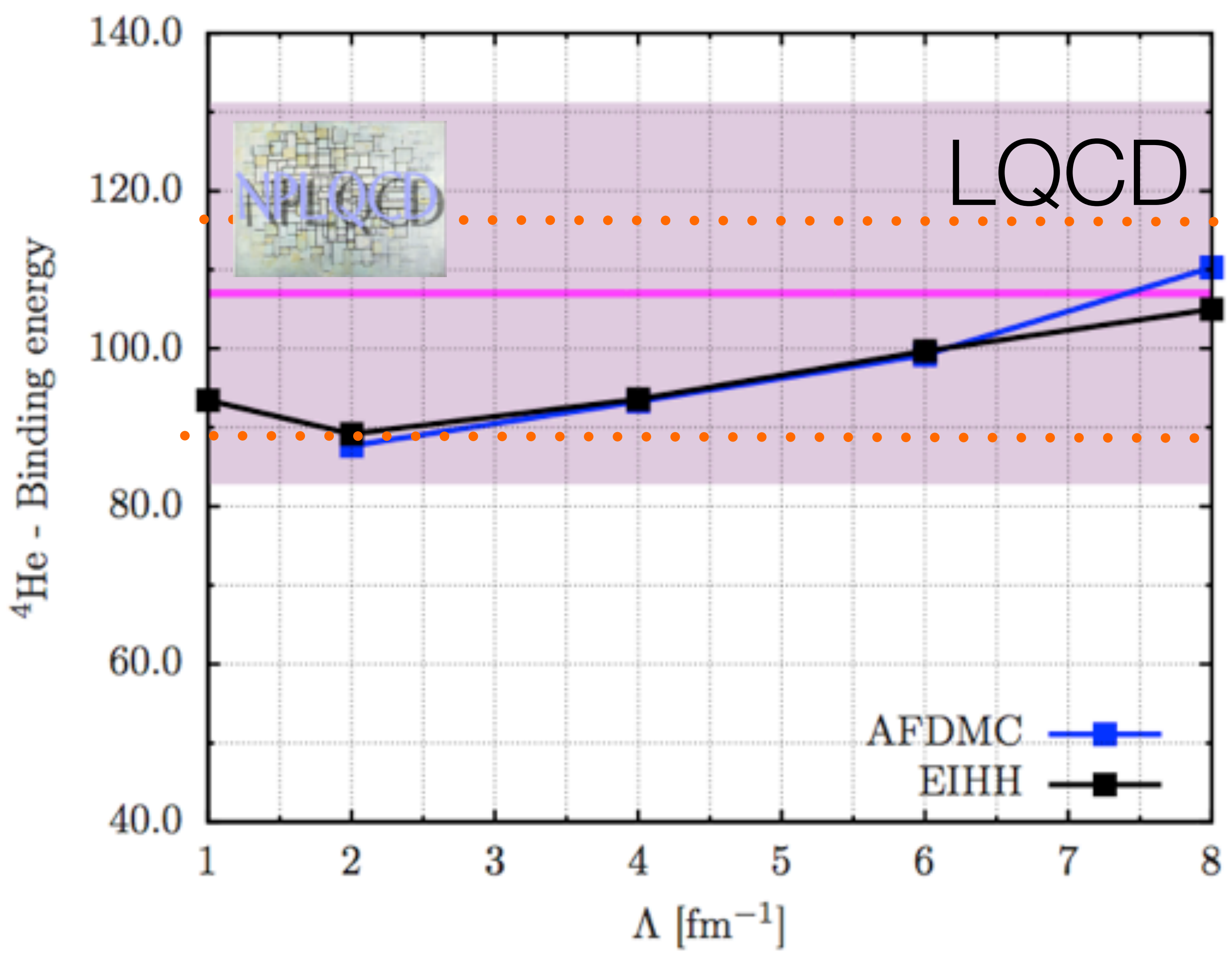
LQCD to Pionless EFT to Nuclei

LQCD Nuclei for 800 MeV pions

- Fit 2-body and 3-body LQCD bindings
- Predict 4-body, c/w LQCD prediction

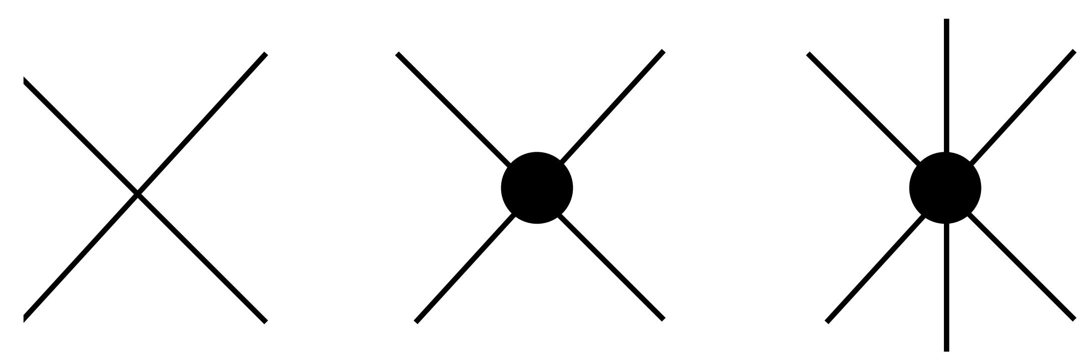
Barnea, Conressi, Gazit, Pederiva and van Kolck

arXiv:1311.4966



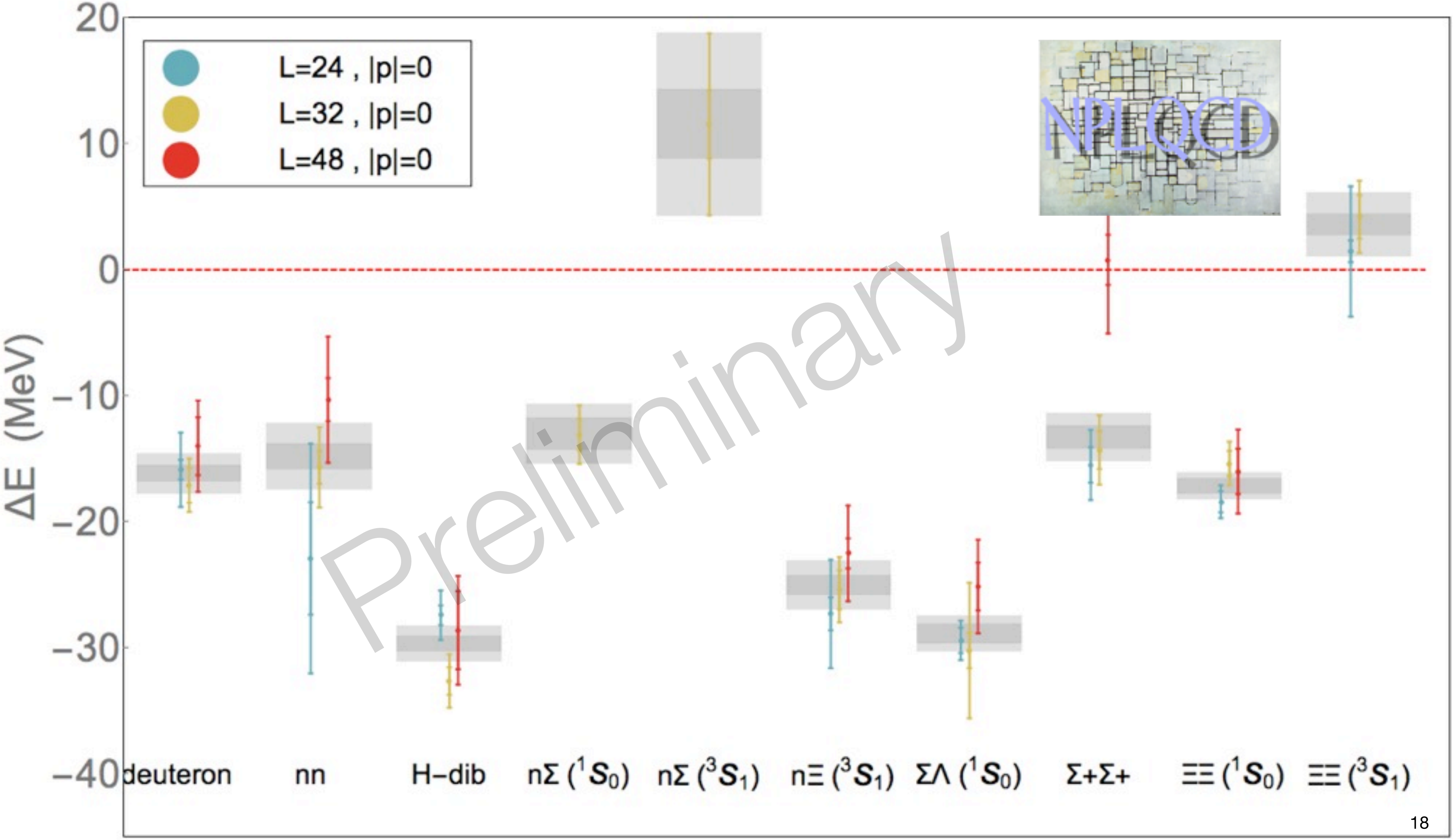
pionless EFT valid for nuclei

``First Contact``

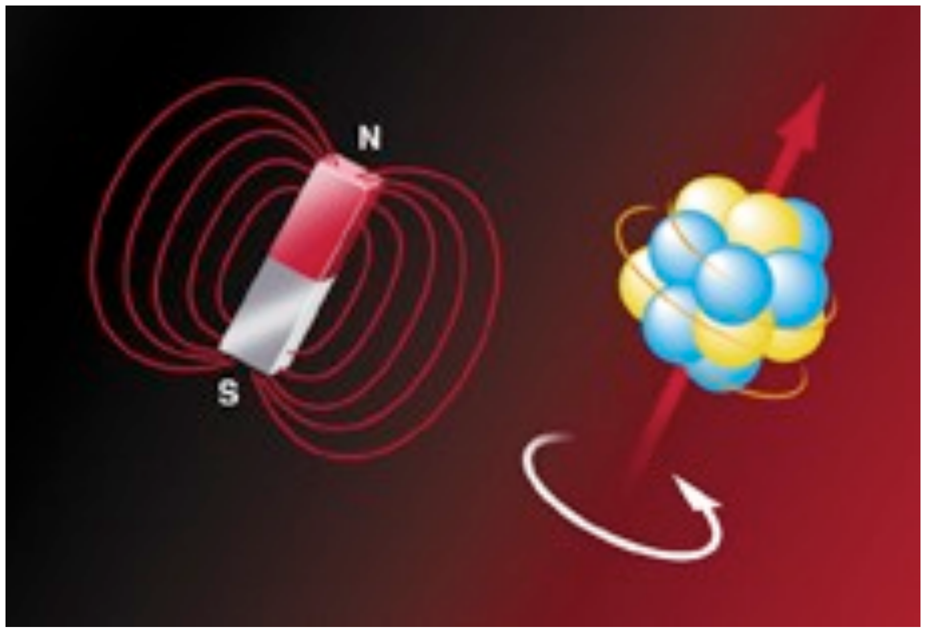


(Hyper)Nuclei from QCD

m_π ~ 430 MeV

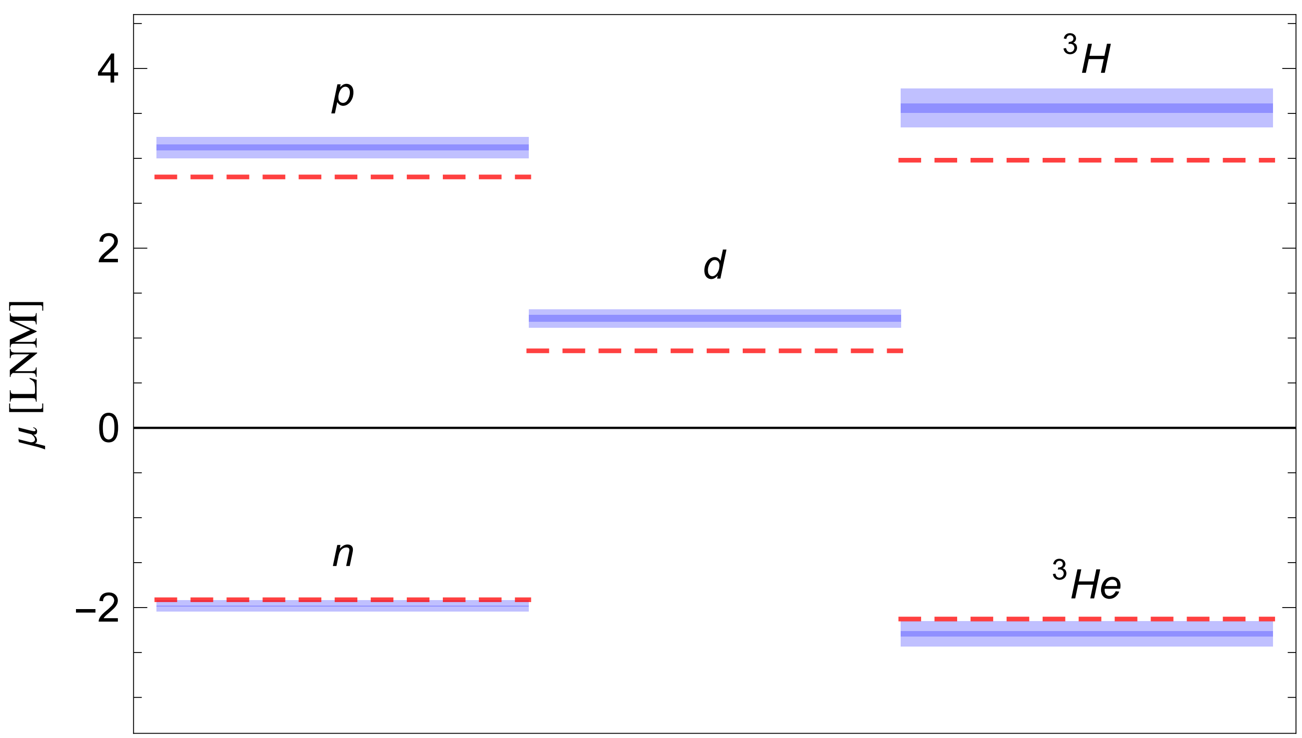


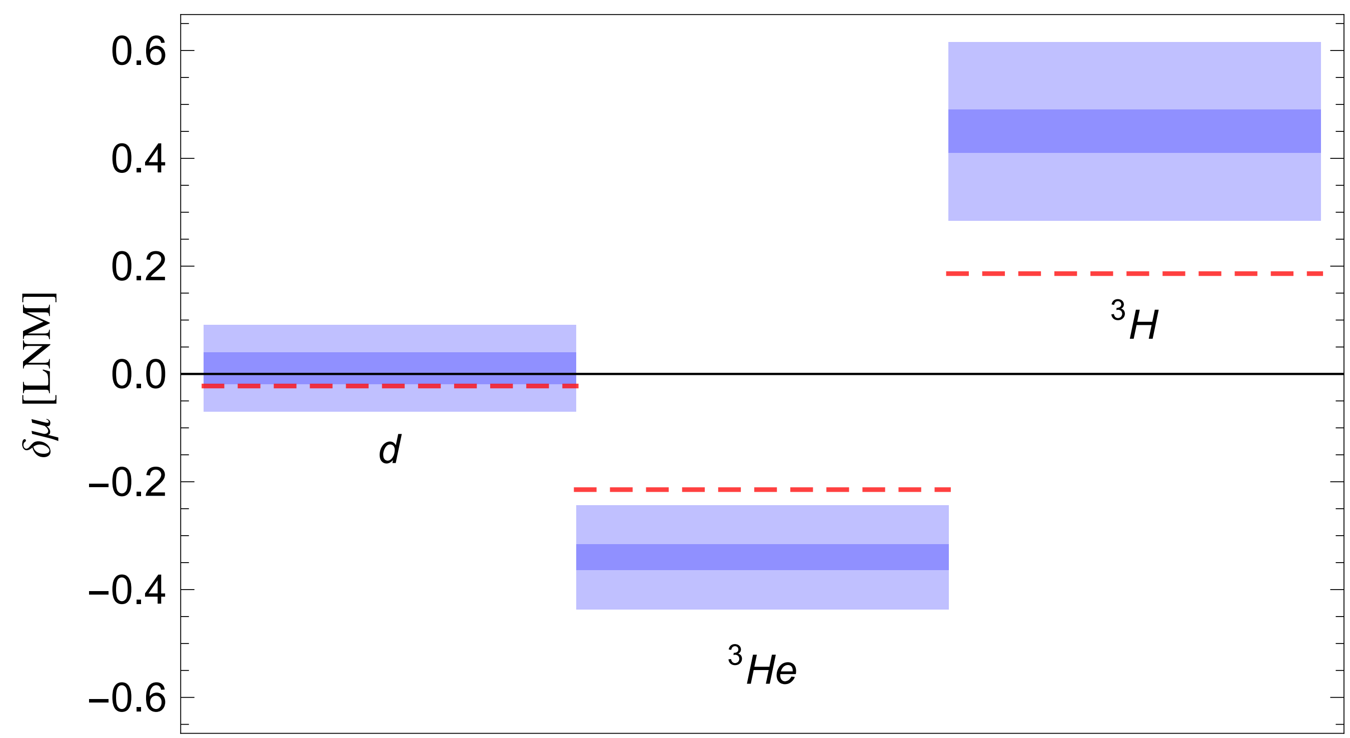
The Structure of Nuclei : Magnetic Moments



Beane, Chang, Cohen, Detmold, Lin, Luu, Orginos, Parreno, MJS, Tiburzi, Phys.Rev. Lett. 113 (2014) 25, 252001

m_π ~ 800 MeV Vs Nature



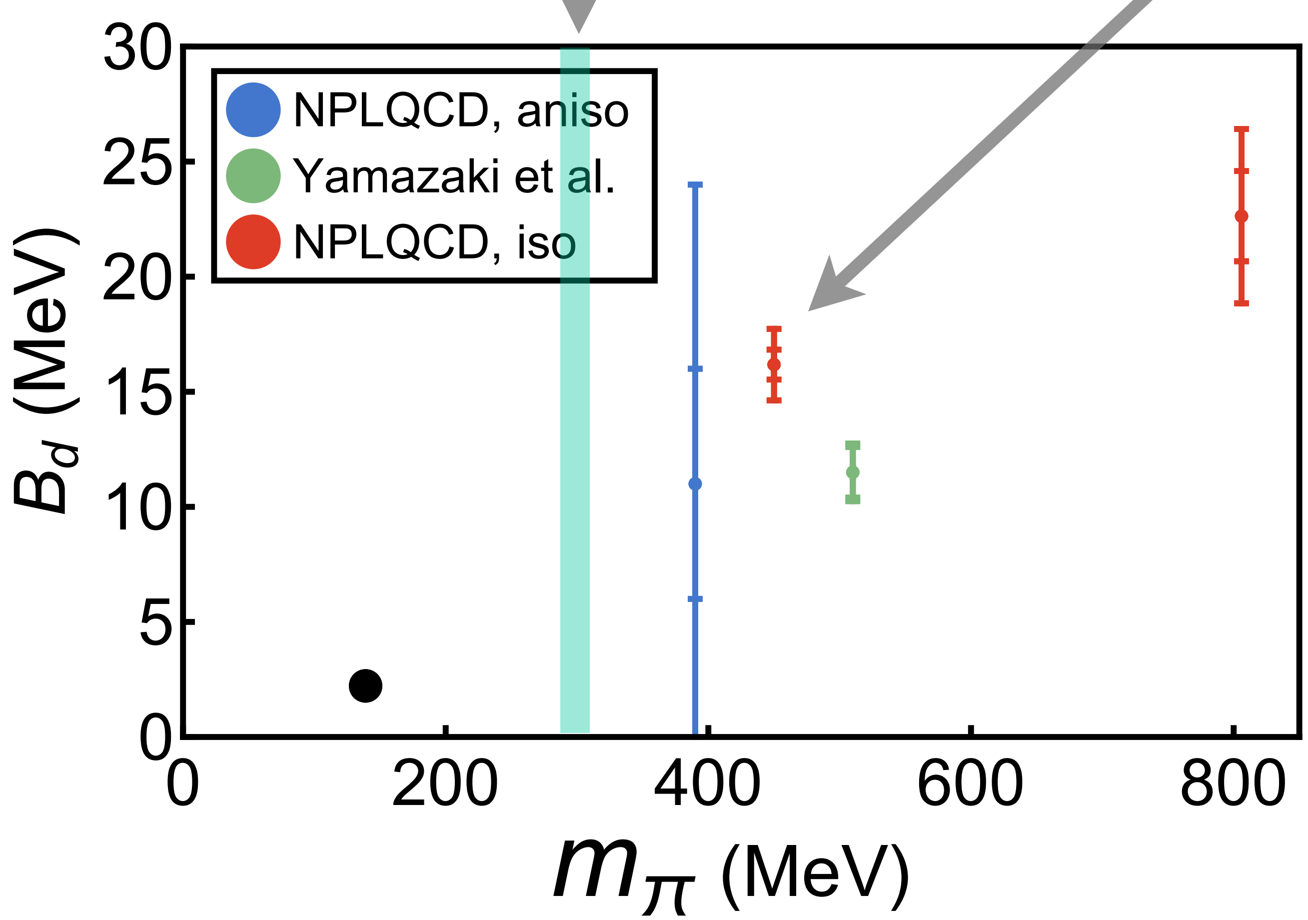


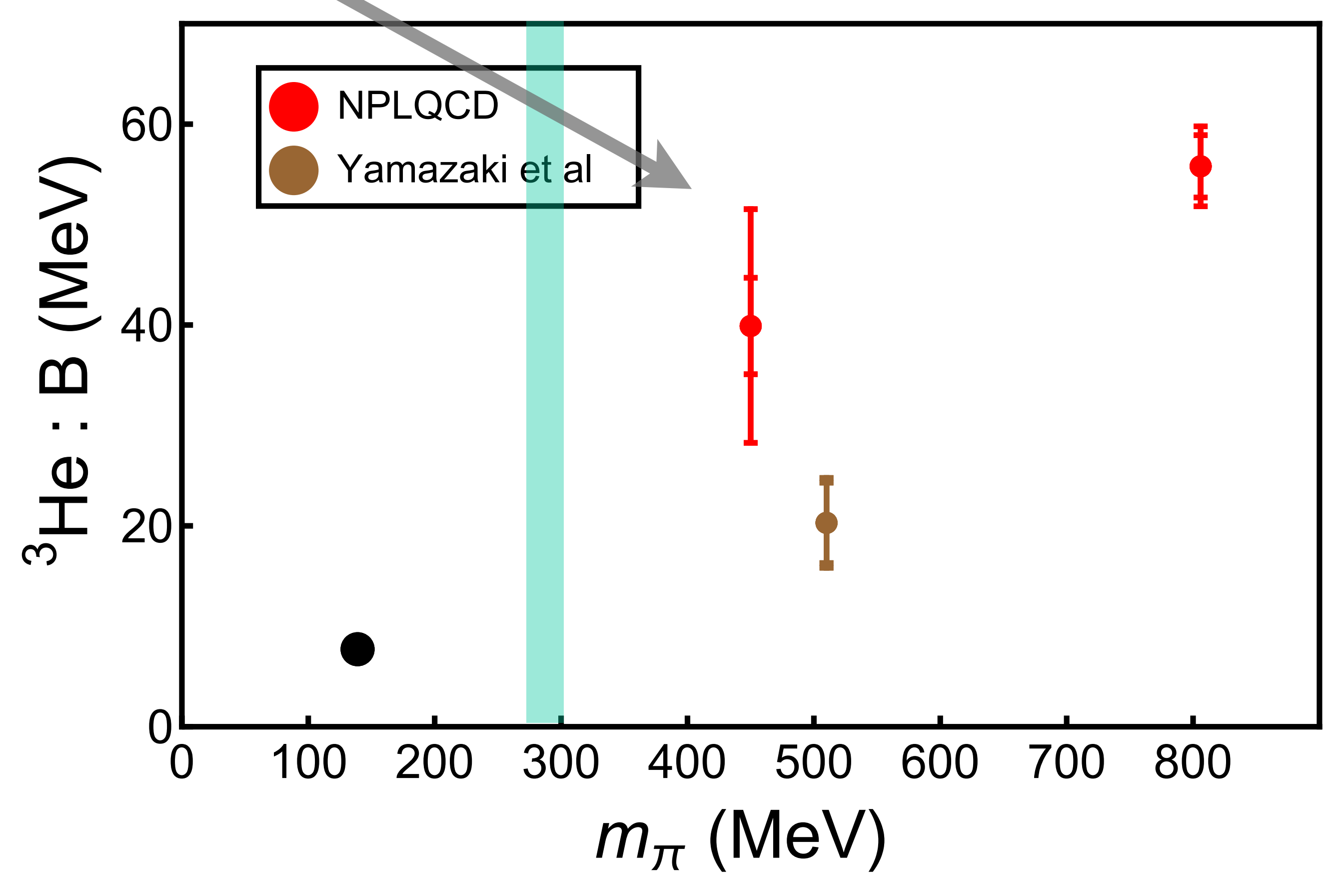
Nuclei are collections of nucleons
- shell model phenomenology!

Light Nuclei : Compilation

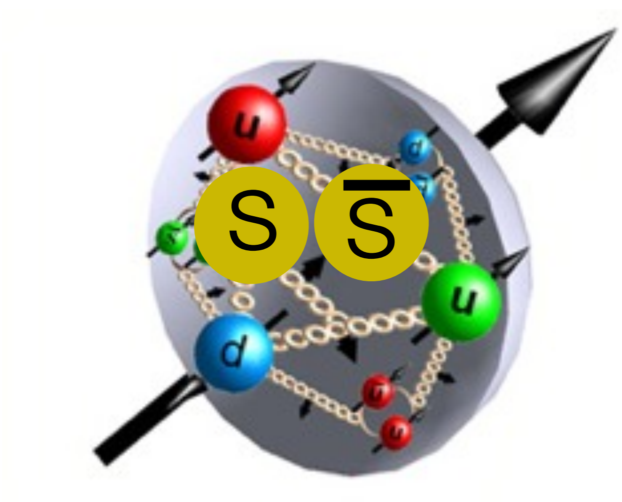
current production

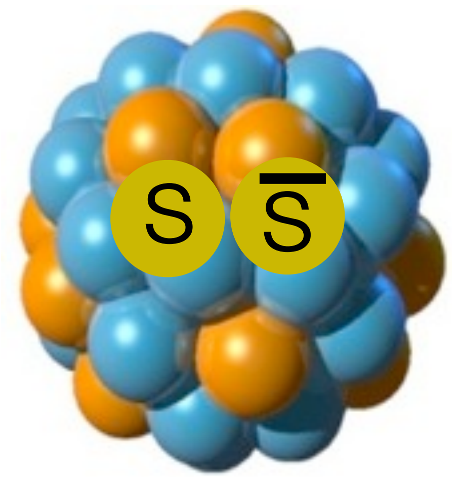
preliminary

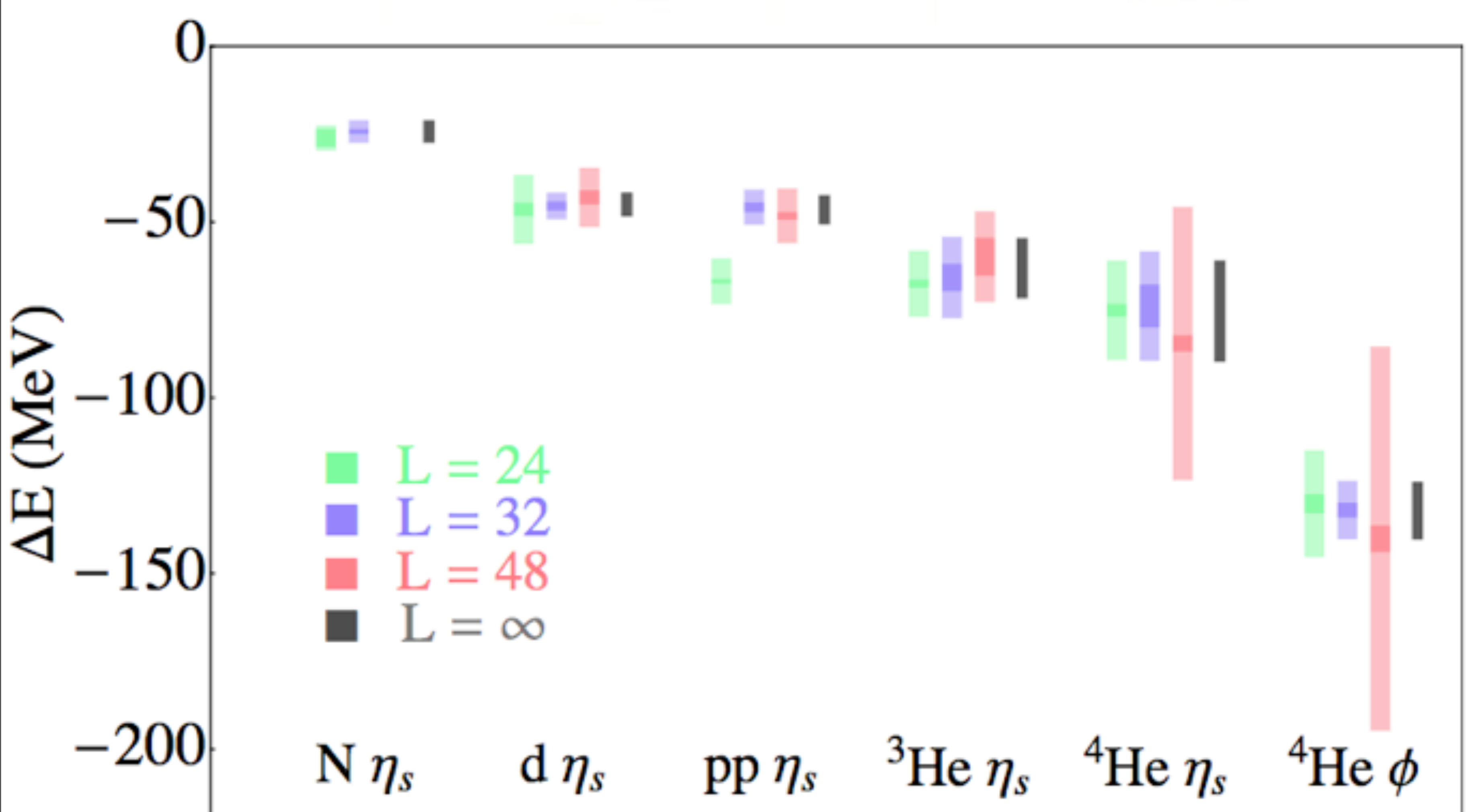




Strangeonium-Nuclei
$m_\pi \sim 800$ MeV





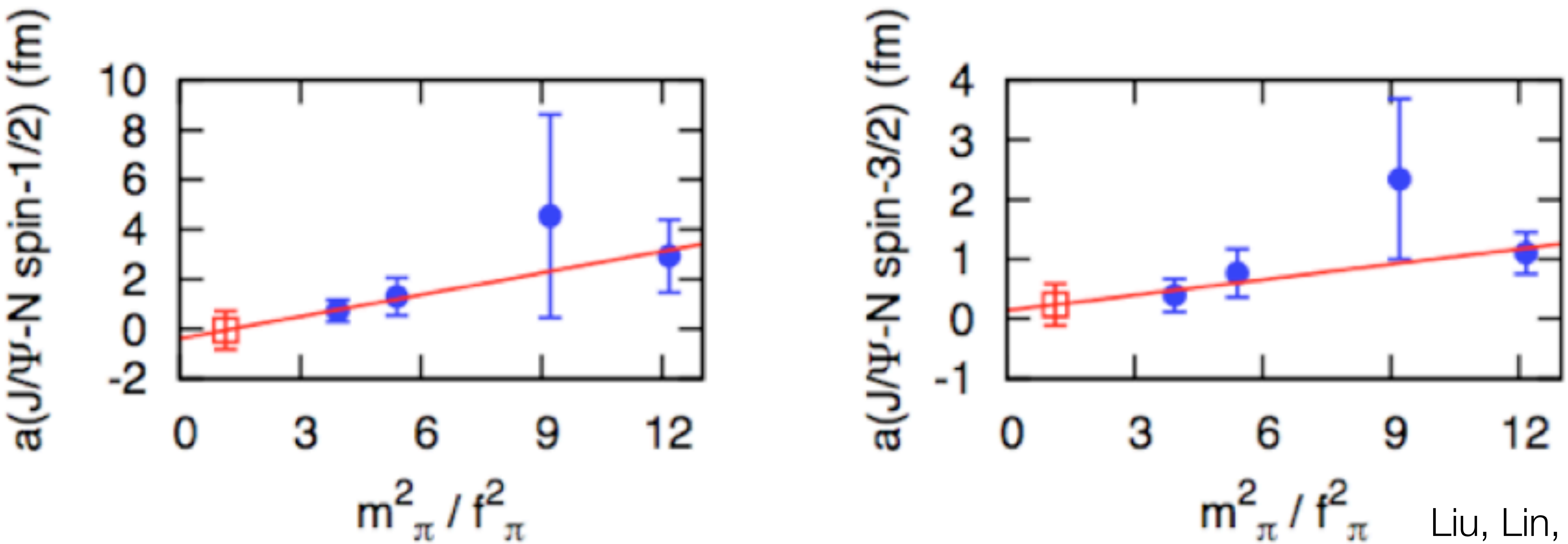


- coupled-channels
- challenging

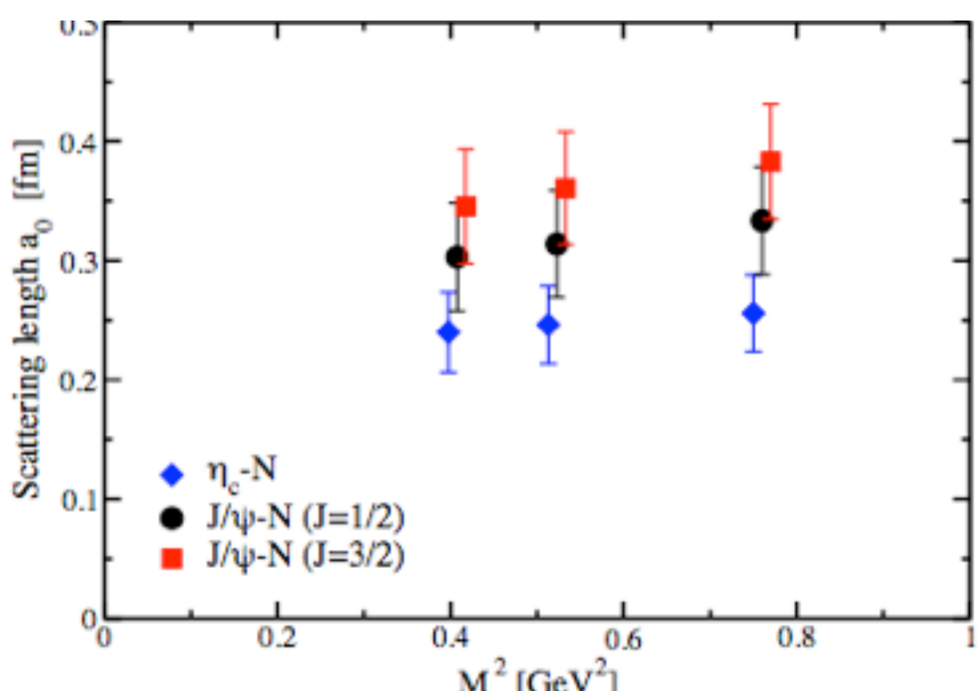
(Beane, Chang, Cohen, Detmold, Lin, Orginos, Parreno, MJS , arXiv:1410.7069)

Charmonium-Nucleon

Previous Calculations



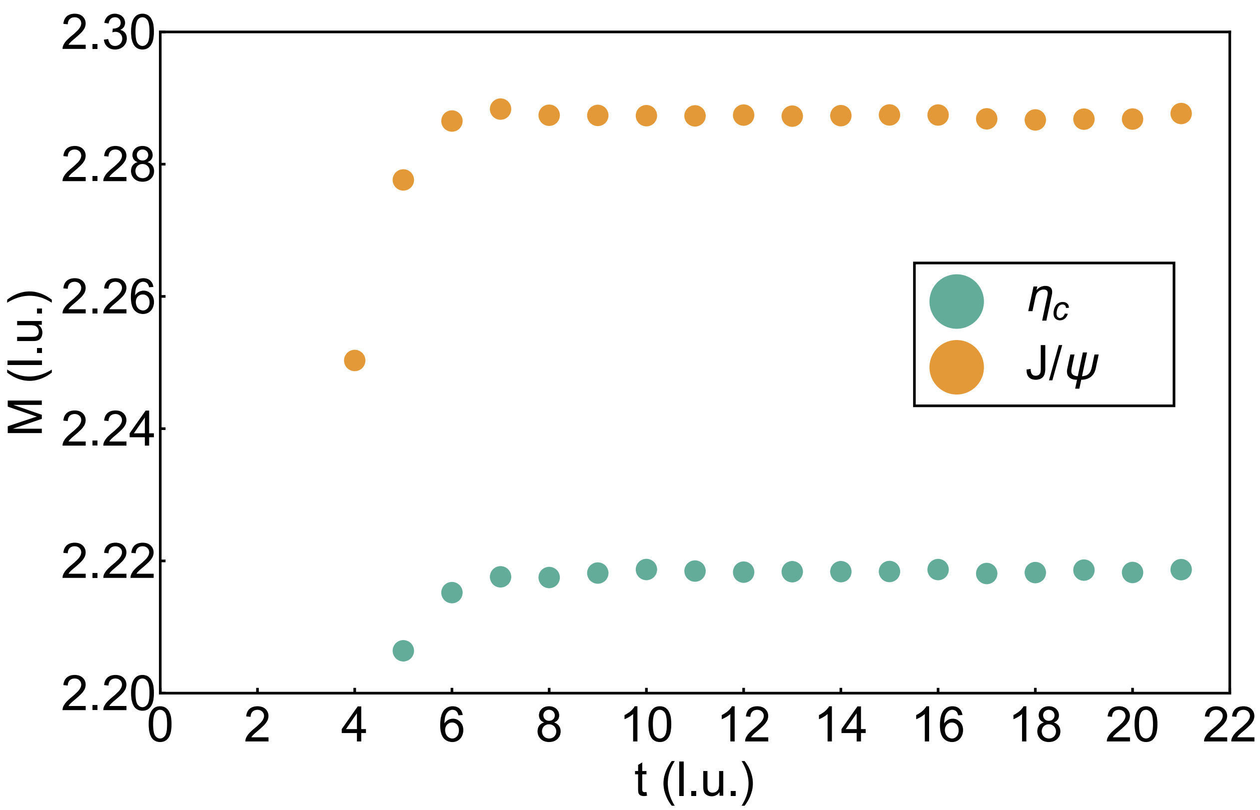
Liu, Lin, Orginos, (2008)



Kawanai, Sasaki, (2010)

Charmonium-Nuclei
m_π ~ 800 MeV

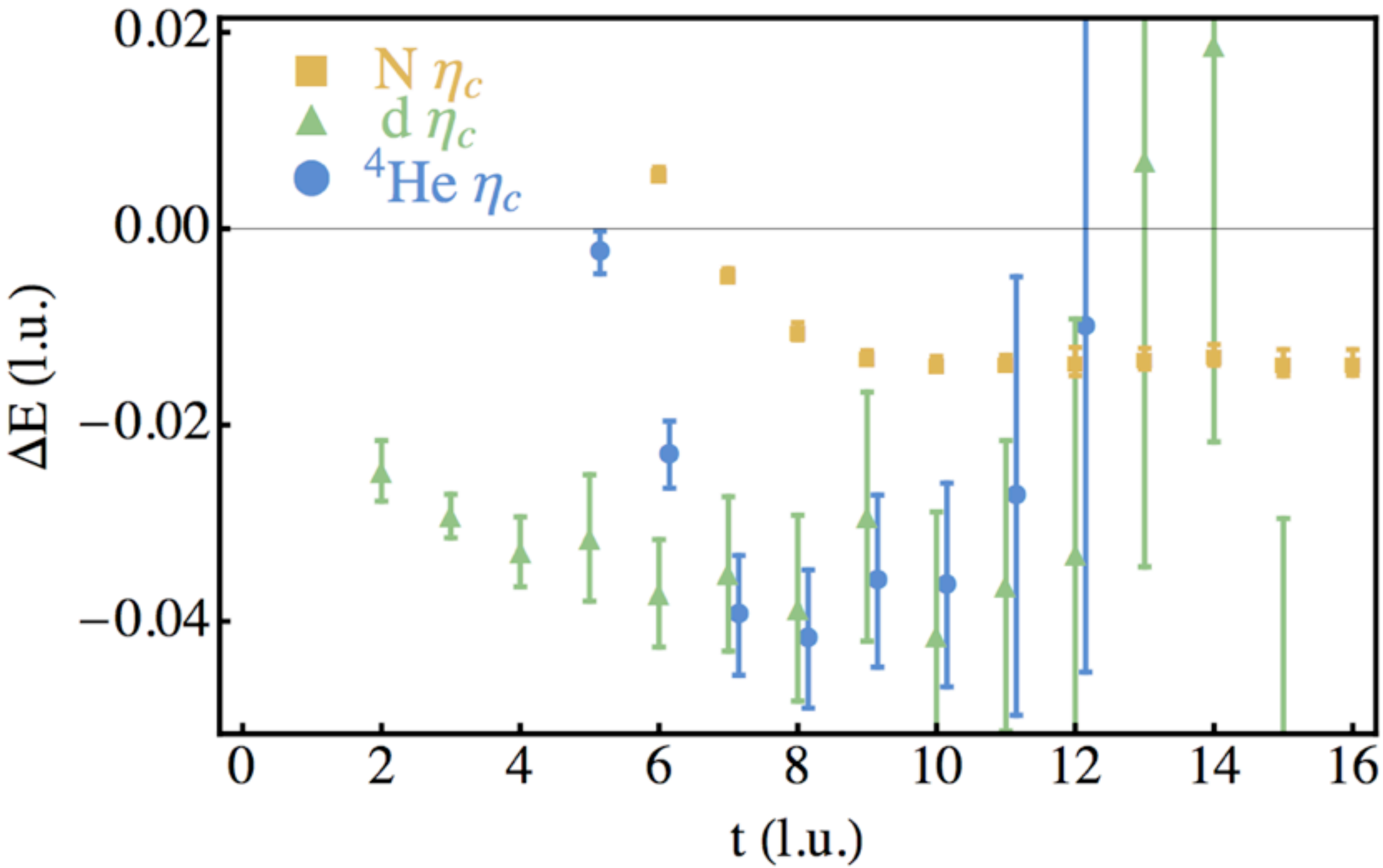
$$S_Q = \sum_{x,x'} \overline{Q}_x \left(m_0 + \gamma_0 D_0 - \frac{a}{2} D_0^2 + \nu \left(\gamma_i D_i - \frac{a}{2} D_i^2 \right) - \frac{a}{4} c_B \sigma_{ij} G_{ij} - \frac{a}{2} c_E \sigma_{0i} G_{0i} \right)_{xx'} Q_{x'} ,$$



- tune to dispersion relations
- postmultiply nuclear correlators
  - src point by src point
  - shift in time to align plateaus

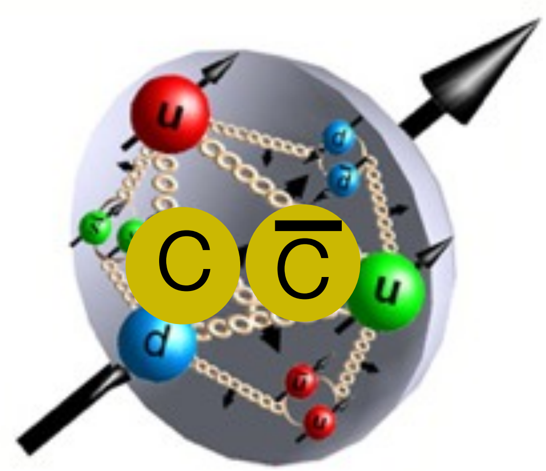
(Beane, Chang, Cohen, Detmold, Lin, Orginos, Parreno, MJS , arXiv:1410.7069)

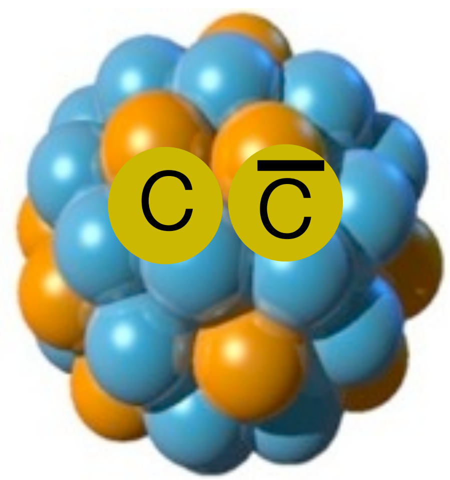
Charmonium-Nuclei
$m_\pi \sim 800$ MeV



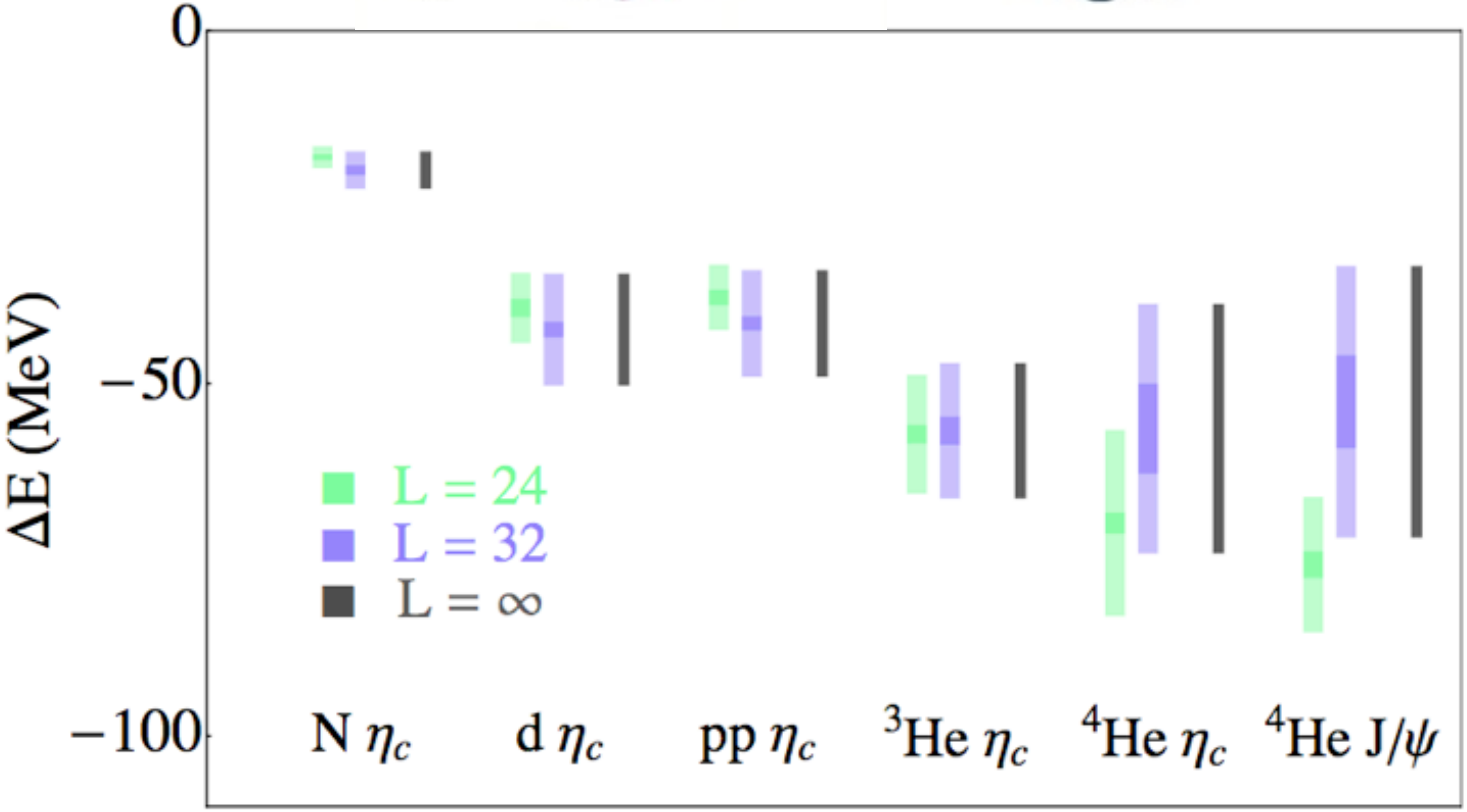
$32^3 \times 32^3 \times 32^3 \times 64$

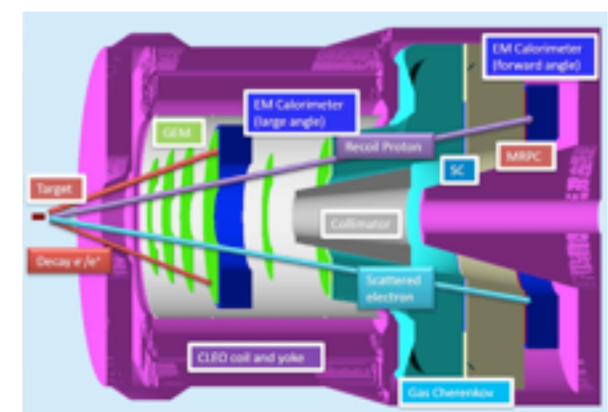
Charmonium-Nuclei
$m_\pi \sim 800$ MeV





NPLQCD



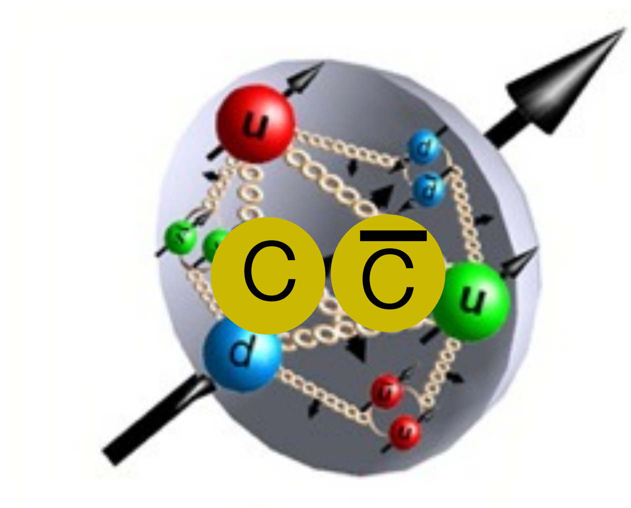


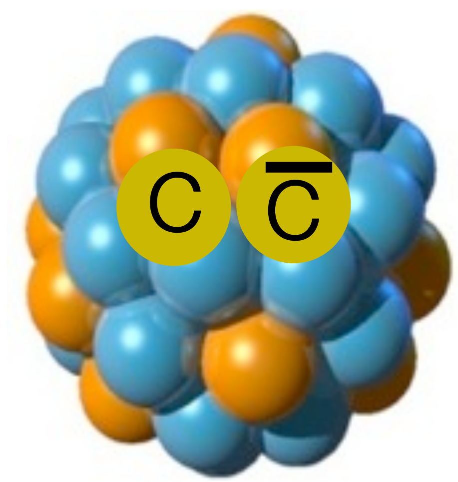
Athenna

Jefferson Lab
EXPLORING THE NATURE OF MATTER

(Beane, Chang, Cohen, Detmold, Lin, Orginos, Parreno, MJS , arXiv:1410.7069)

Charmonium-Nuclei
Extrapolation to Nature

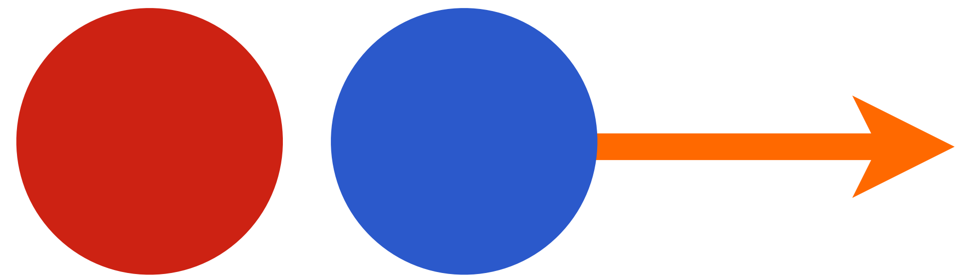


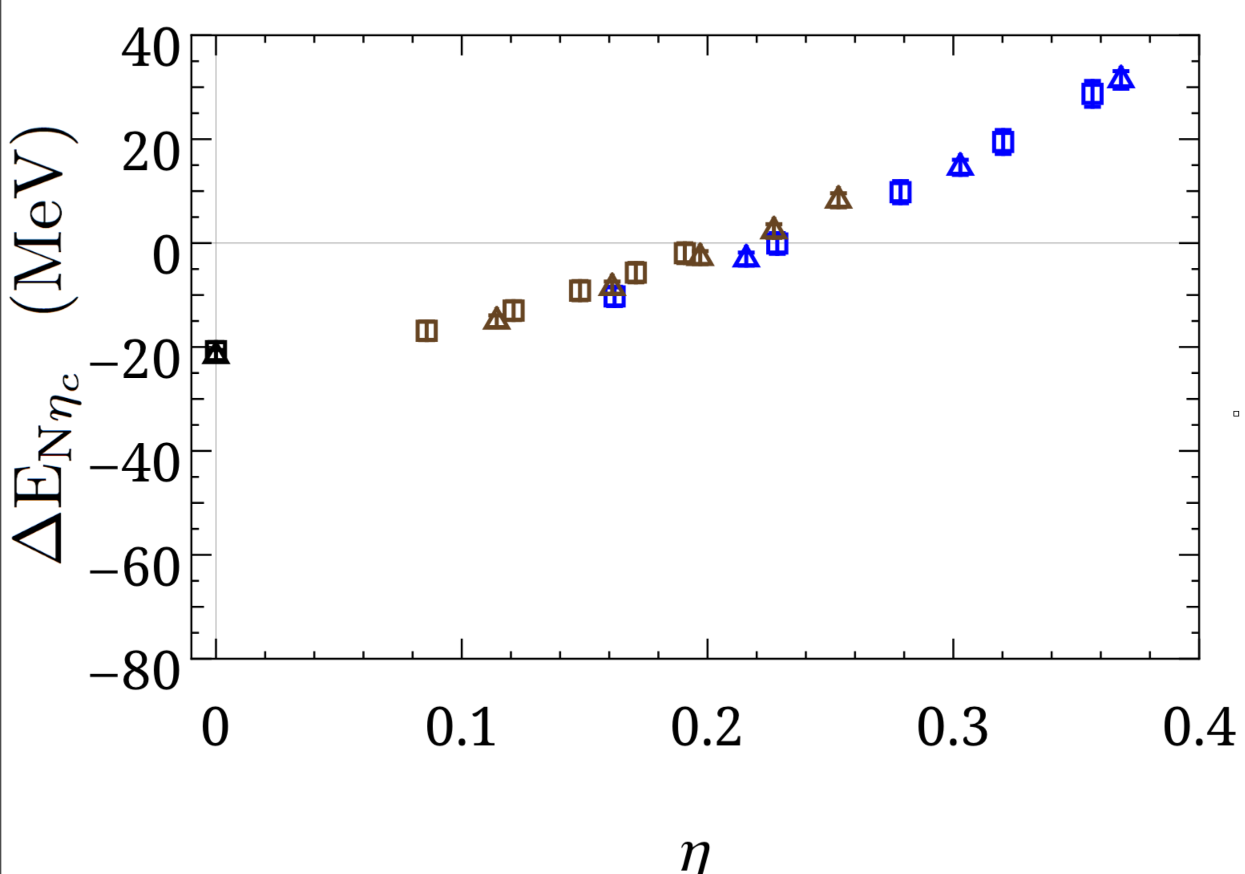


- Leading Gluonic Matrix Element ~ M_N
  - B~60 MeV @ m_π = 800 MeV extrapolates to B~40 MeV @ m_π = 140 MeV
- Calculations at lighter masses underway

Charmonium-Nuclei
Boosted Systems and Sources

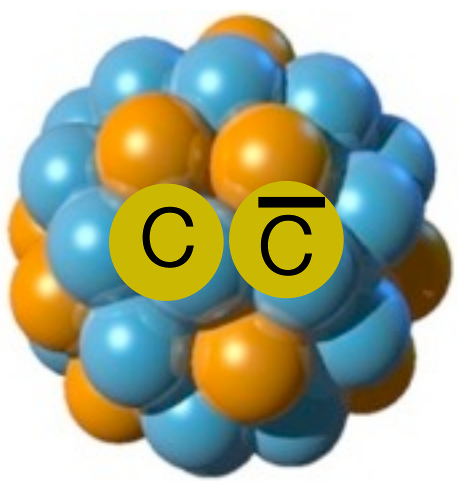
Boosted src structure
- one hadron is boosted

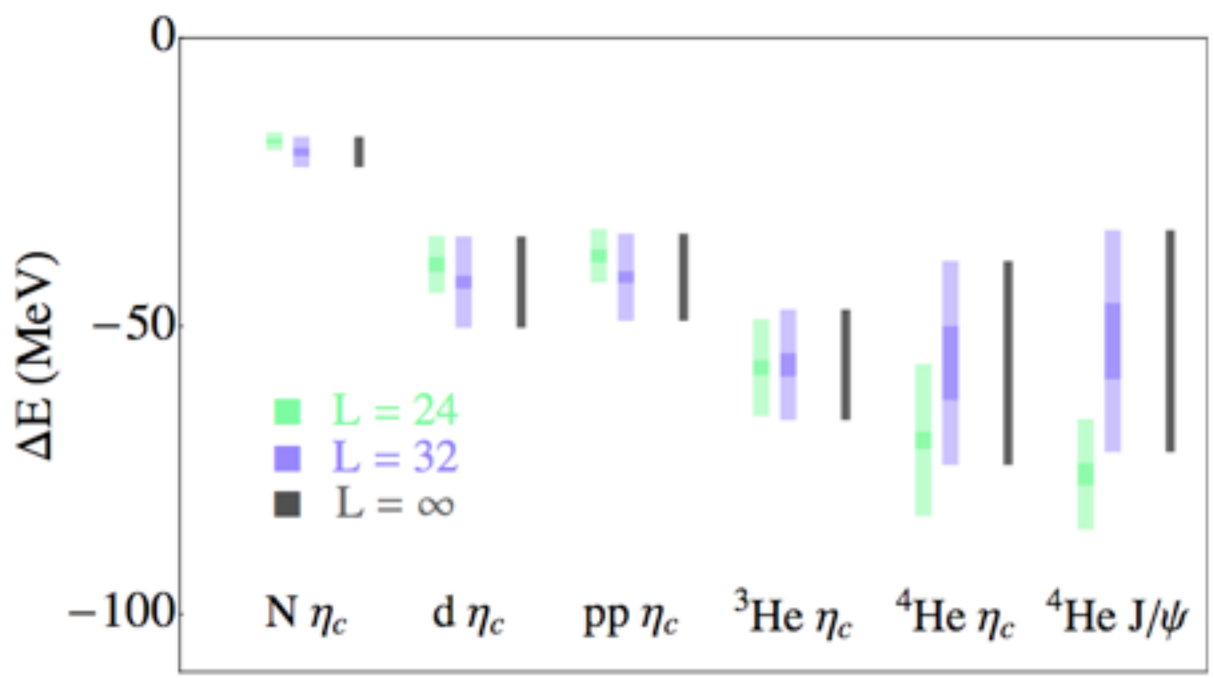


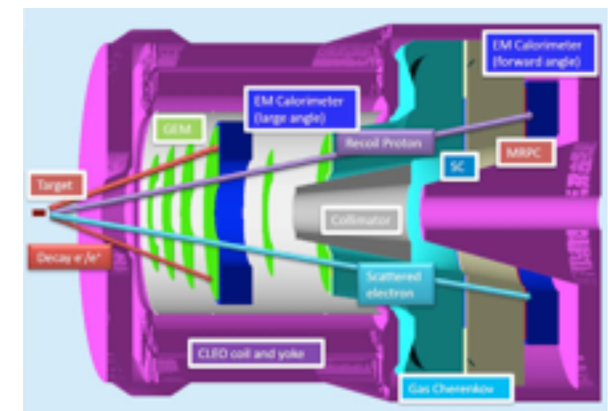


- Spectrum
  - BS suppressed at higher relative P
  - Continuum is independent of relative P
  - Continuum contamination unresolved !

Summary







First calculations from Lattice QCD - multi-volume but one lattice spacing

Binding consistent with realistic hadronic models

Next generation LQCD will be higher precision and closer to physical quark masses

[Aside : Gluonic operators impact Techni-baryon Dark Matter signals]

END