QCD spectra and structure of nuclei

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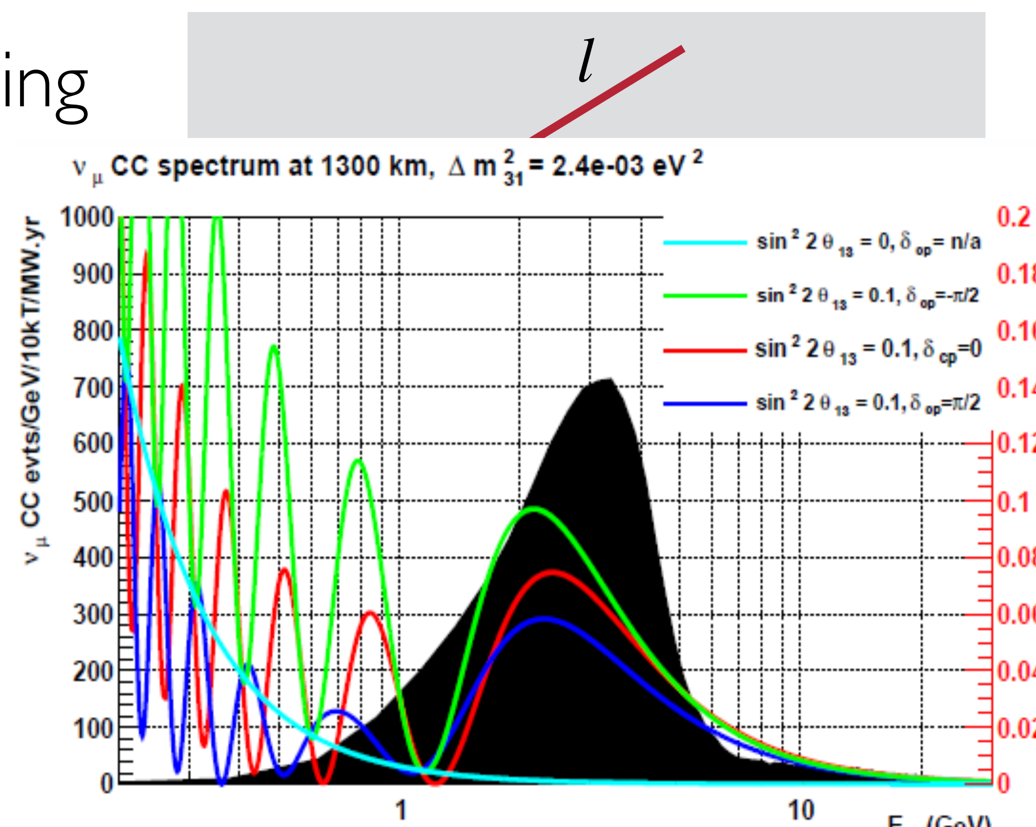
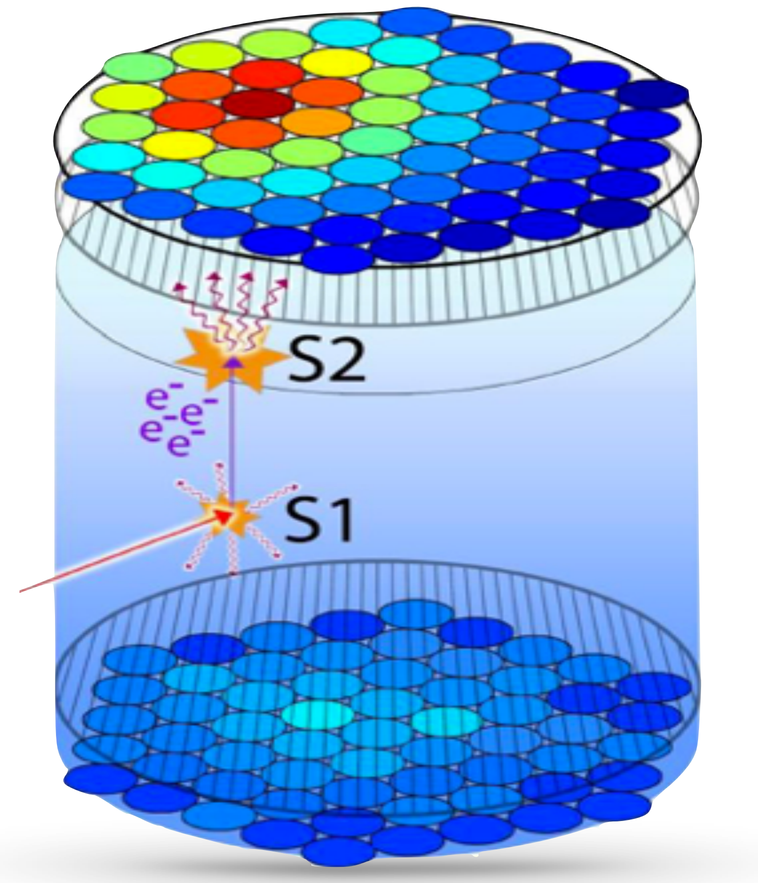
- Many nuclear physics and nuclear astrophysics reasons to study nuclei!!
- Particle physics is at an interesting juncture: over the next decade(s) many experiments address the intensity frontier
  - Targets are nuclei (C, Fe, Si, Ar, Ge, Xe, Pb, CH_x, H_2O)
- Extraction of neutrino mass hierarchy and mixing parameters at LBNF requires knowing energies/fluxes to high accuracy
  - Nuclear axial & transition form factors
  - Nuclear structure in neutrino DIS
  - ~10% effects on oscillation parameters
    [C Mariani, INT workshop 2013]



[U Mosel FSNu town meeting]

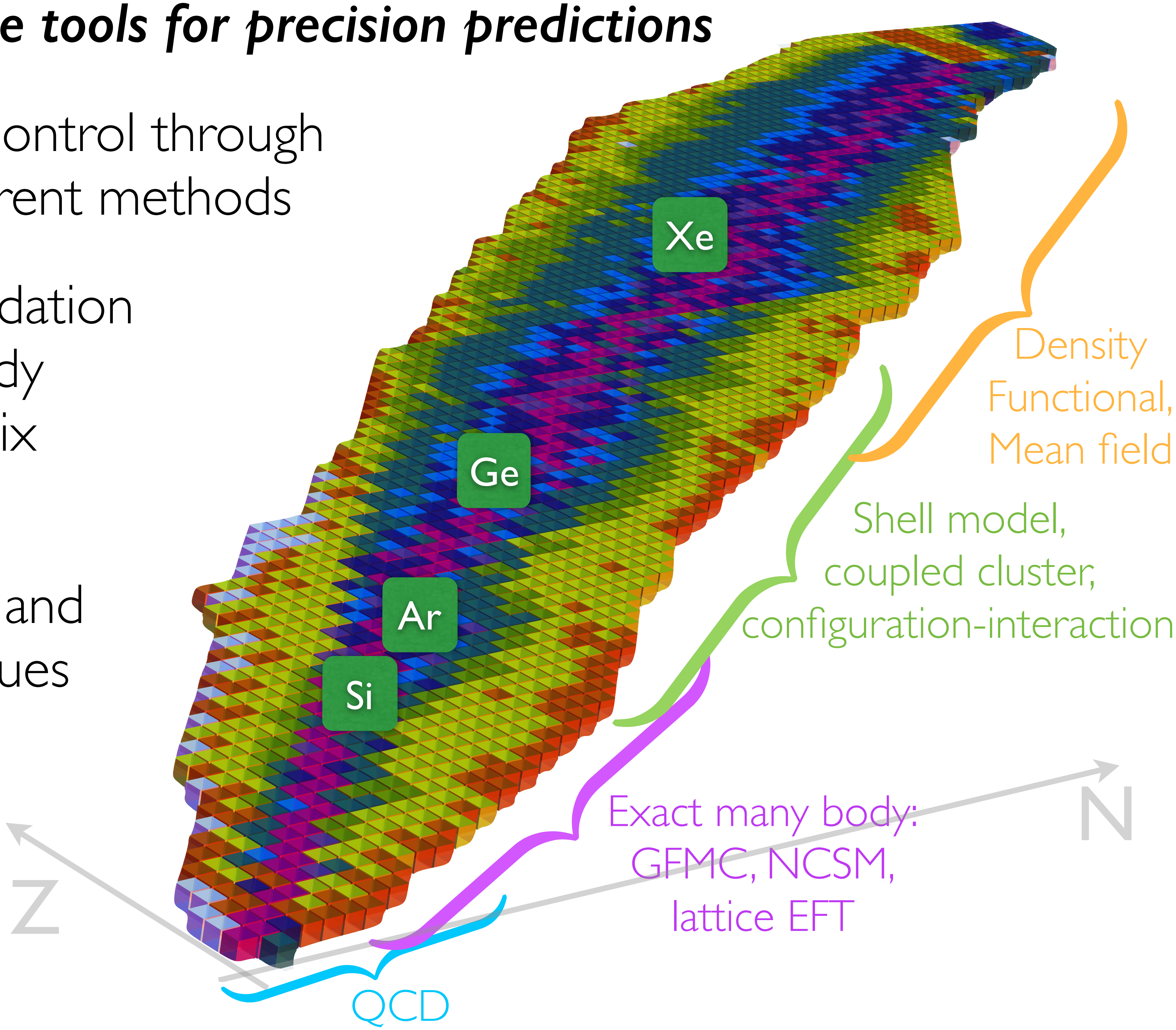


http://www.hep.ucl.ac.uk/darkMatter/

- Laboratory searches for new physics
  - Dark matter detection: nuclear recoils as signal
    Nuclear matrix elements of exchange current
  - μ2e conversion expt: similar requirements
  - If(when) we detect dark matter or μ→e, we <u>will need</u> precise nuclear matrix elements to learn what it is
- *Nuclear physics is the new flavour physics!*

Precision nuclear physics

- ***Our job to develop the tools for precision predictions***
- Establish quantitative control through linkages between different methods
  - QCD forms a foundation determines few body interactions & matrix elements
  - Match existing EFT and many body techniques onto QCD

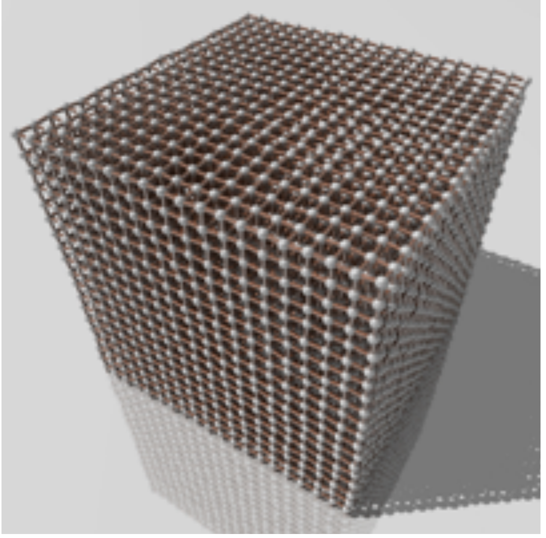


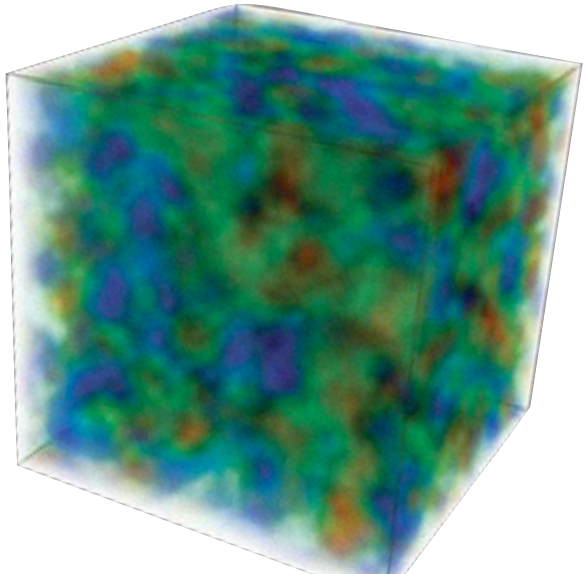
Quantum Chromodynamics

- Lattice QCD: tool to deal with quarks and gluons
  - Formulate problem as functional integral over quark and gluon d.o.f. on R_4

$$\langle \mathcal{O} \rangle = \int dA_\mu dq d\bar{q}\, \mathcal{O}[q, \bar{q}, A] e^{-S_{QCD}[q, \bar{q}, A]}$$

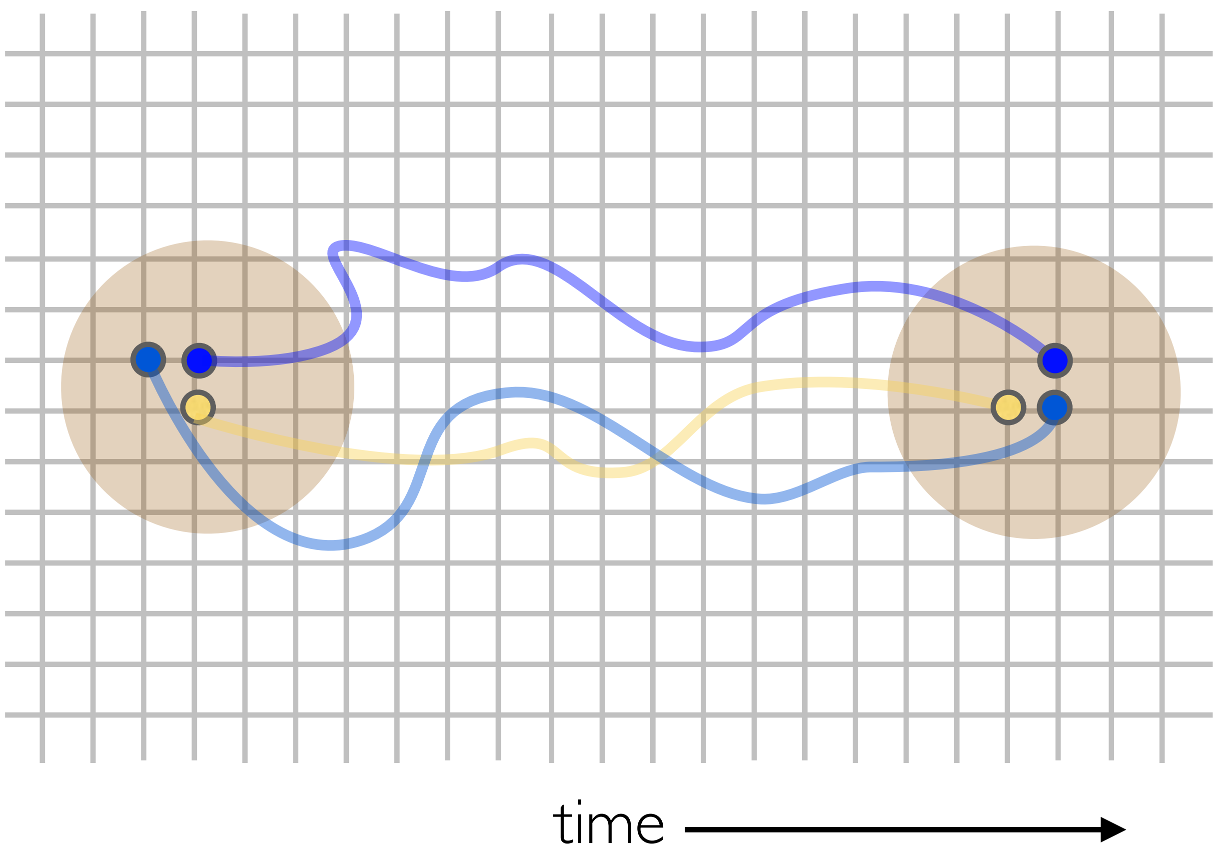
  - Discretise and compactify system
    - Finite but large number of d.o.f (10^{10})
  - Integrate via importance sampling (average over important configurations)
  - Undo the harm done in previous steps





Spectroscopy

- How do we measure the proton mass?
- Create three quarks at a source: and annihilate the three quarks at sink far from source
- QCD adds all the quark anti-quark pairs and gluons automatically: only eigenstates with correct q#'s propagate



Spectroscopy

- Correlation decays exponentially with distance

$$C(t) = \sum_n Z_n \exp(-E_n t)$$

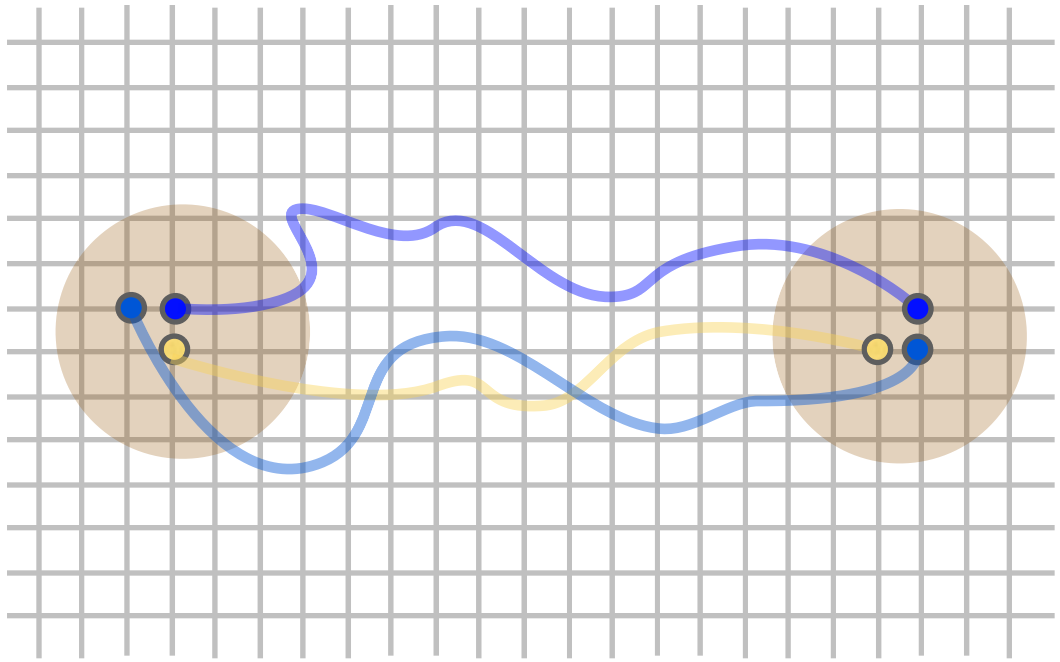
n ← all eigenstates with q#'s of proton

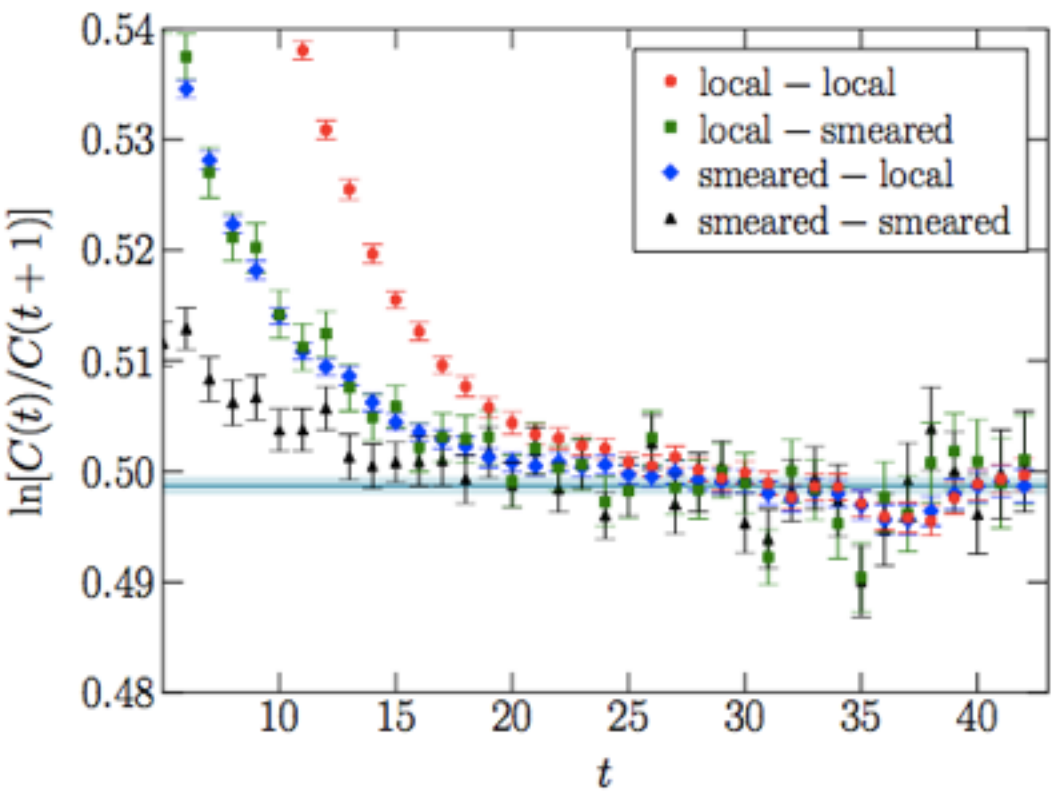
at late times

$$\rightarrow Z_0 \exp(-E_0 t)$$

- Ground state mass revealed through "effective mass plot"

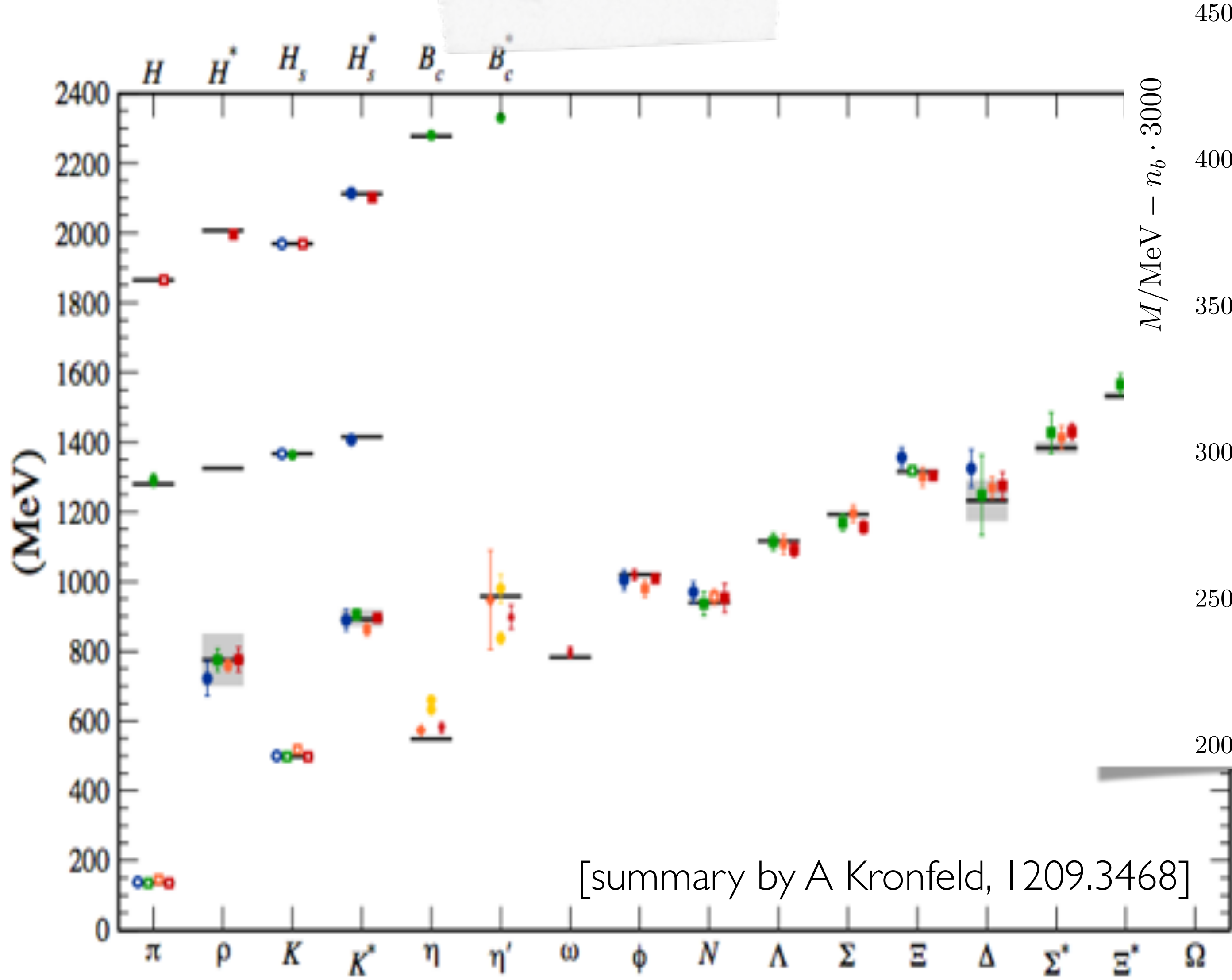
$$M(t) = \ln\left[\frac{C(t)}{C(t+1)}\right] \xrightarrow{t\to\infty} E_0$$

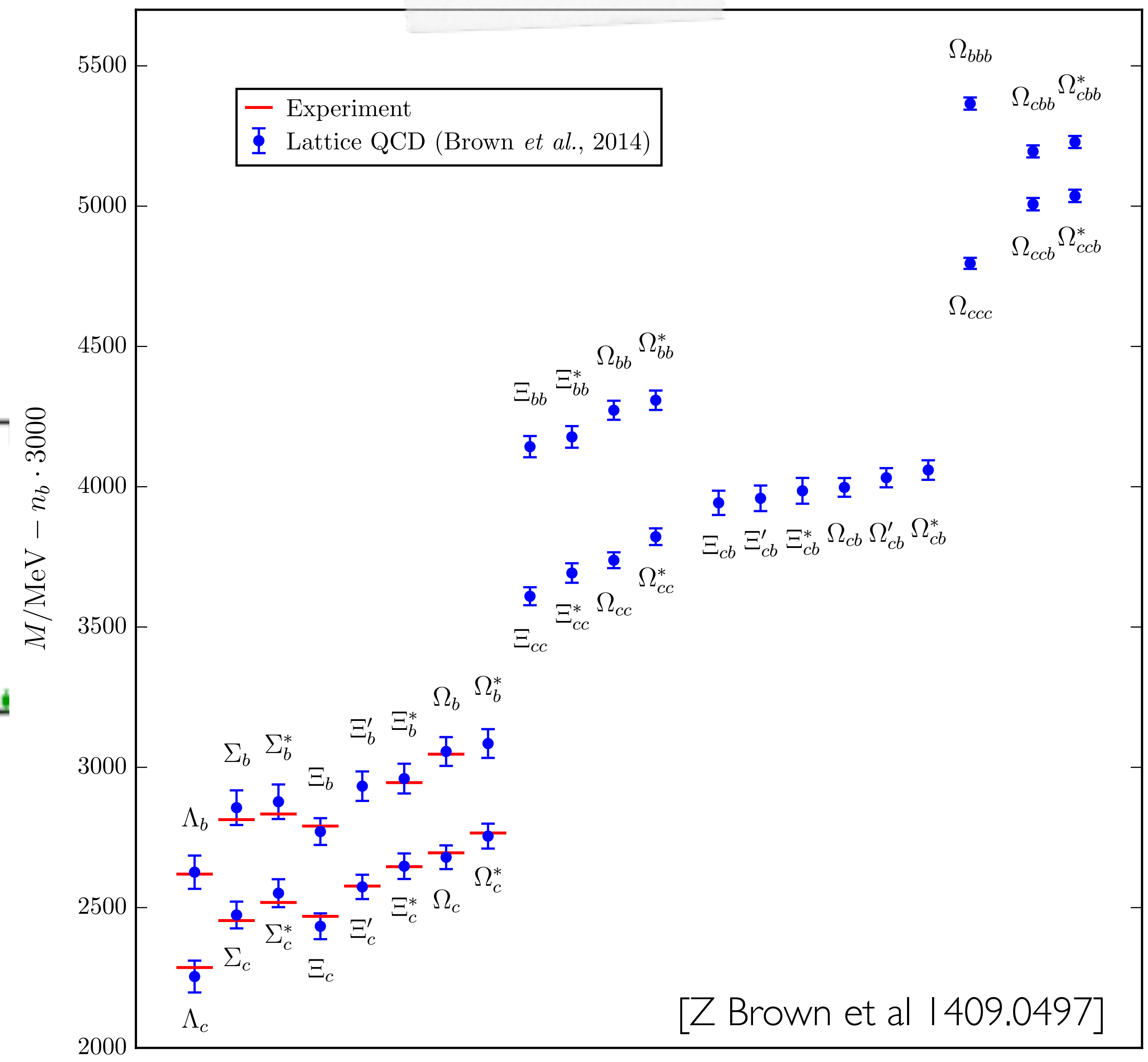




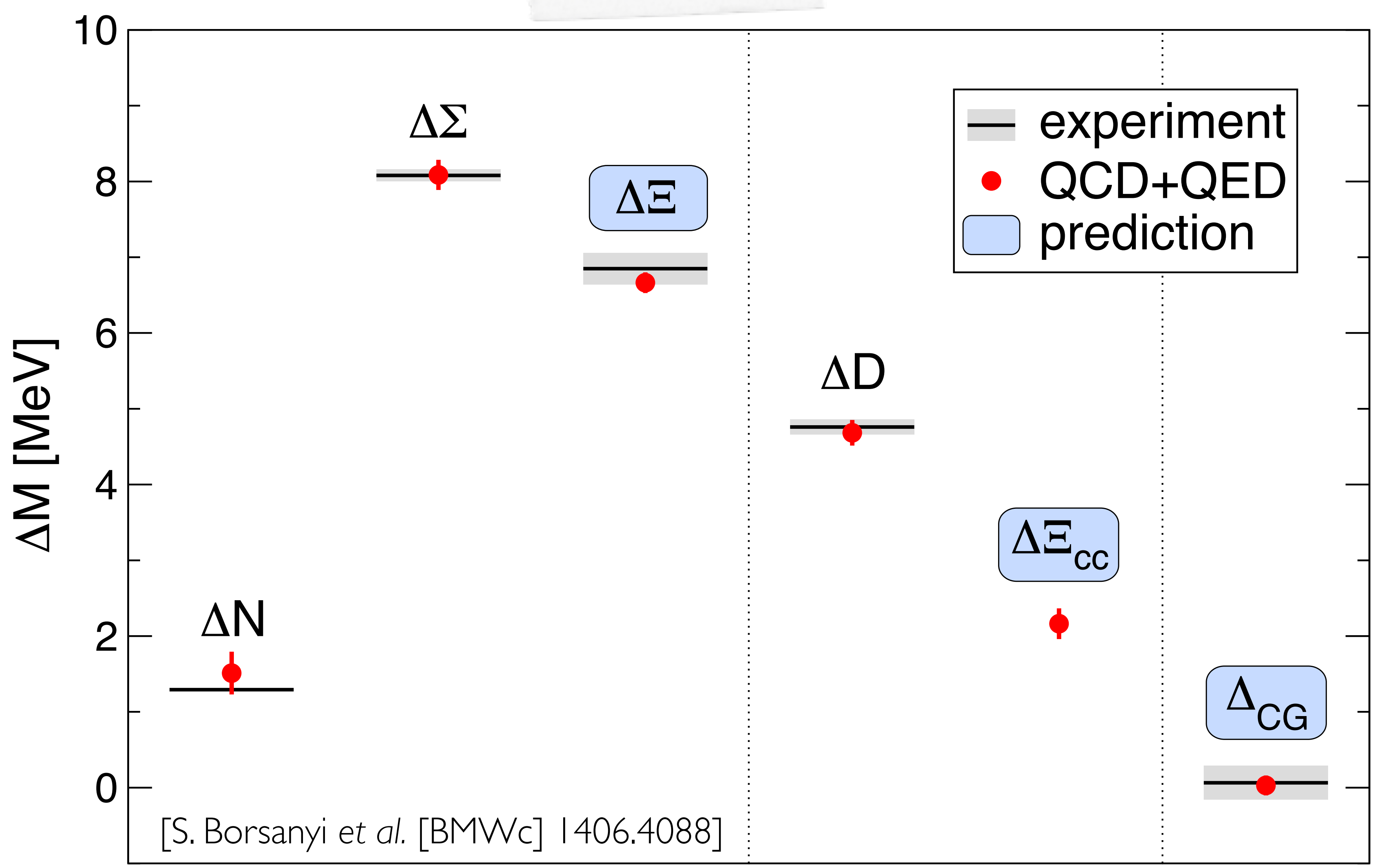
QCD spectrum

- After 30 years of developments
- 😍 Ground state hadron spectrum reproduced and predicted



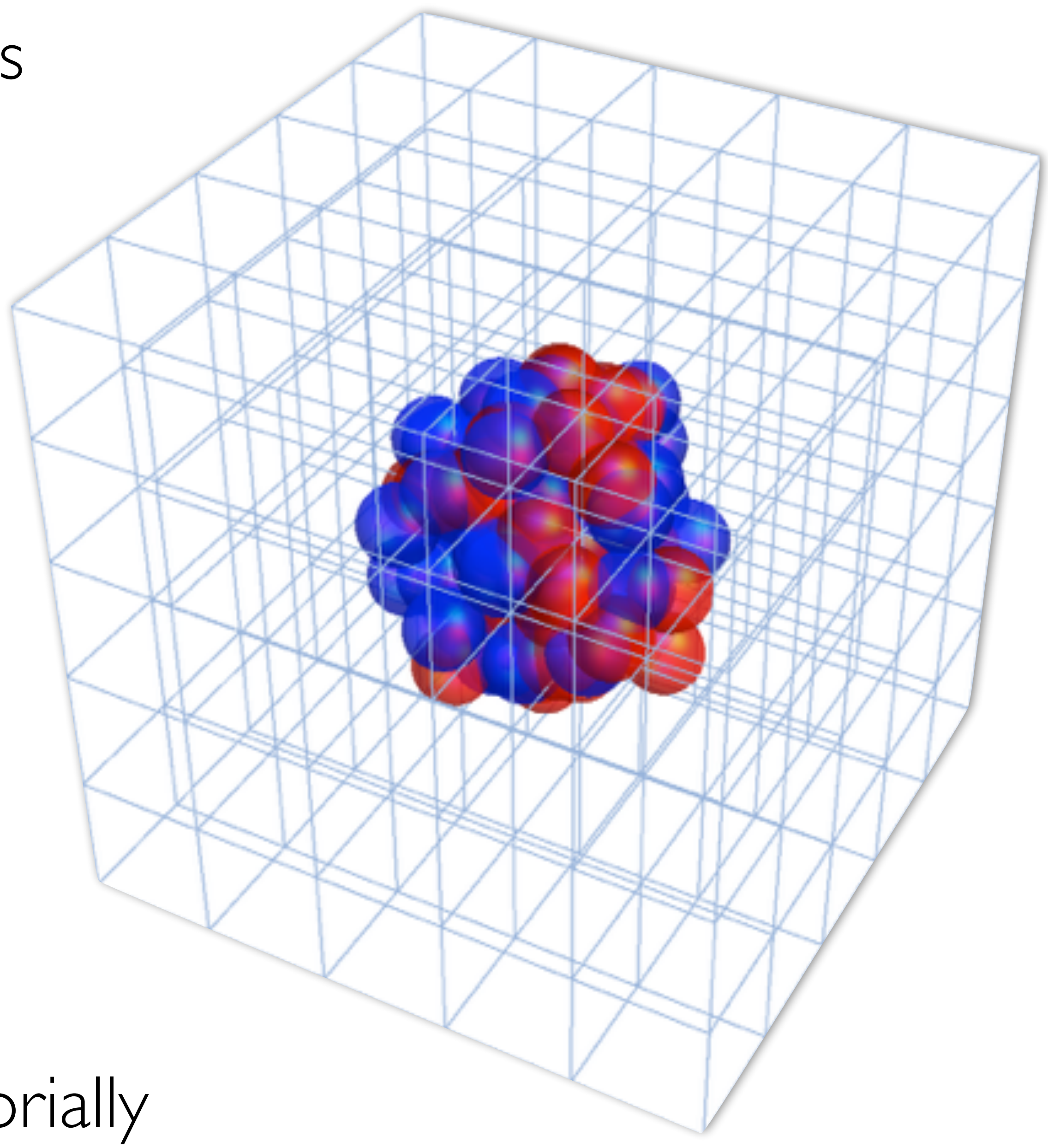


😍 Precise isospin mass splittings in QCD+QED

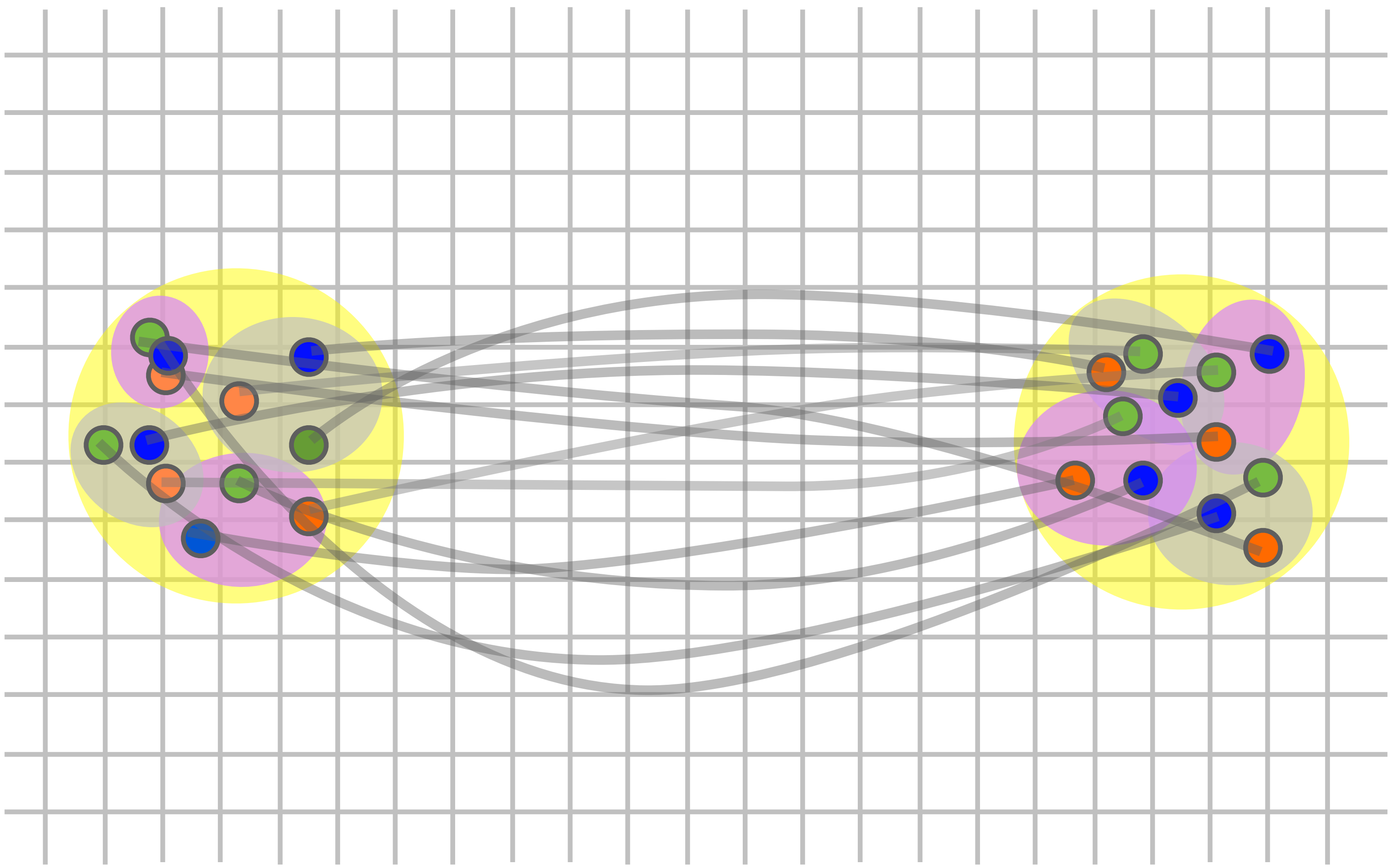


Nuclear Spectra

- QCD (+EW) describes nuclear physics
  - Can compute the mass of lead nucleus ... in principle
- In practice: a hard problem
- At least two exponentially difficult challenges
  - Noise: probabilistic method so statistical uncertainty grows exponentially with A
  - Contraction complexity grows factorially



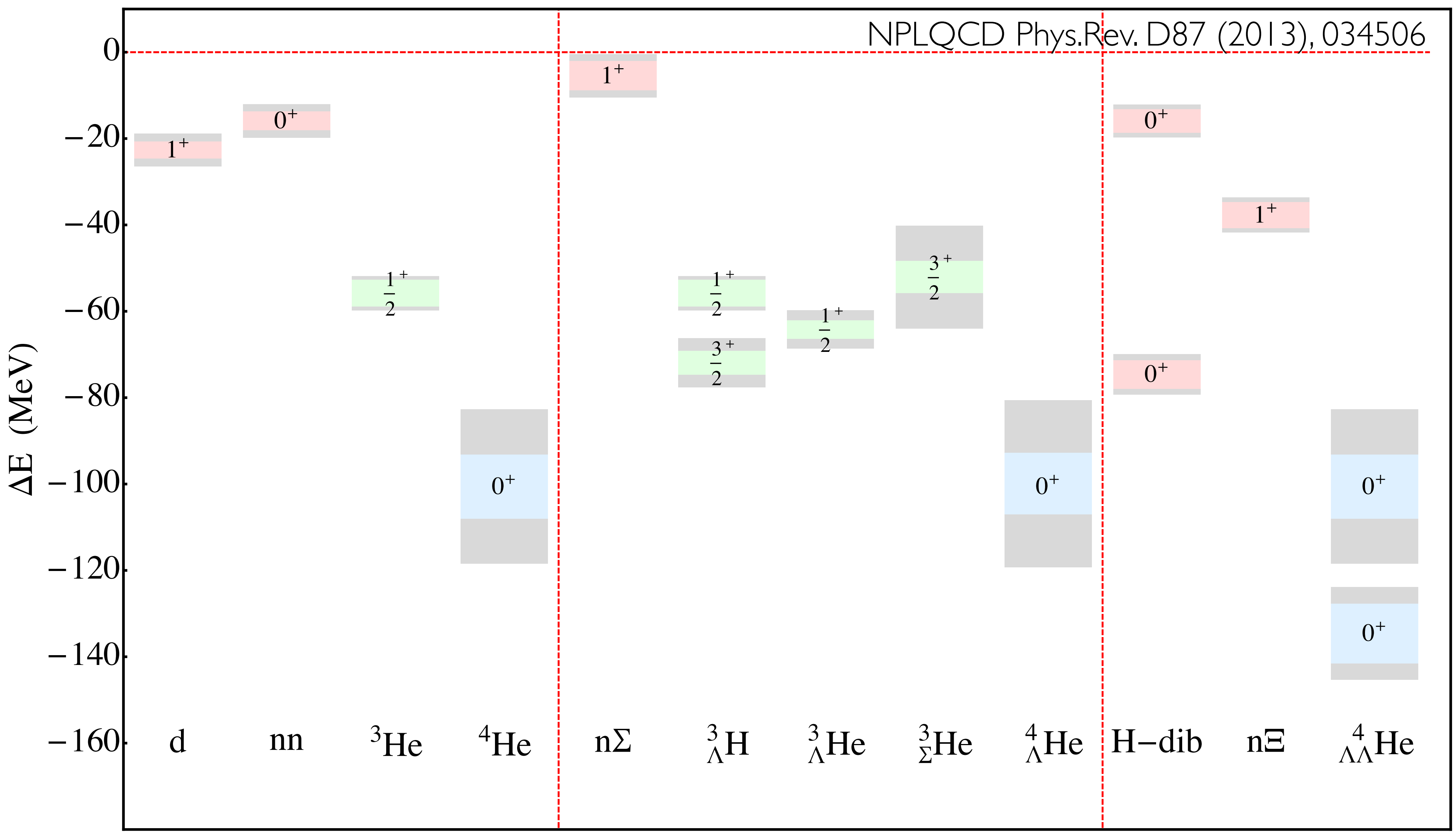
- Quarks need to be tied together in all possible ways
  - $N_{\text{contractions}} = N_u! N_d! N_s!$



- Managed using algorithmic trickery [WD & Savage, WD & Orginos; Doi & Endres]
  - Study up to N=72 pion systems, A=5 nuclei

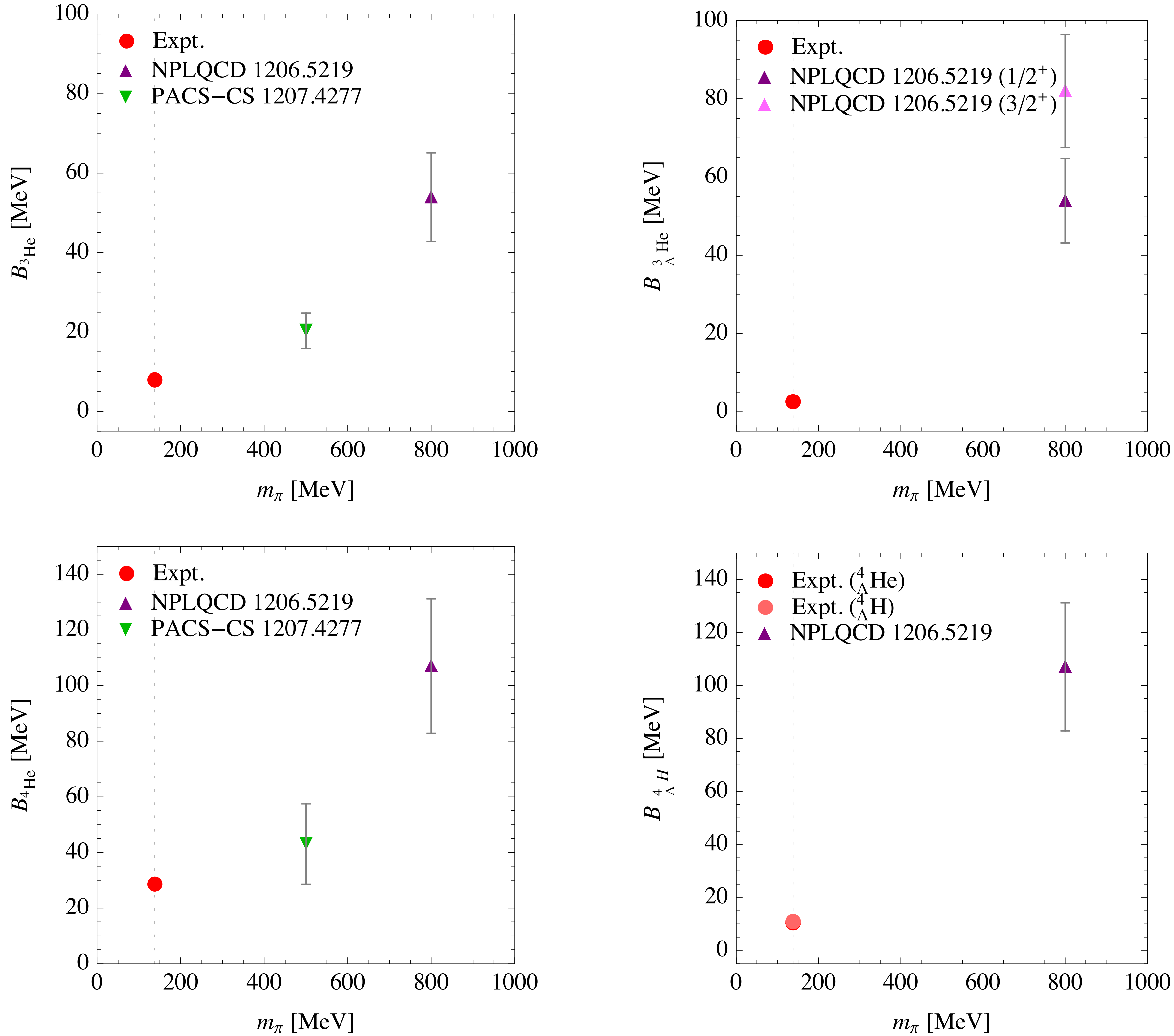
Light nuclei

- Light hypernuclear spectrum @ 800 MeV



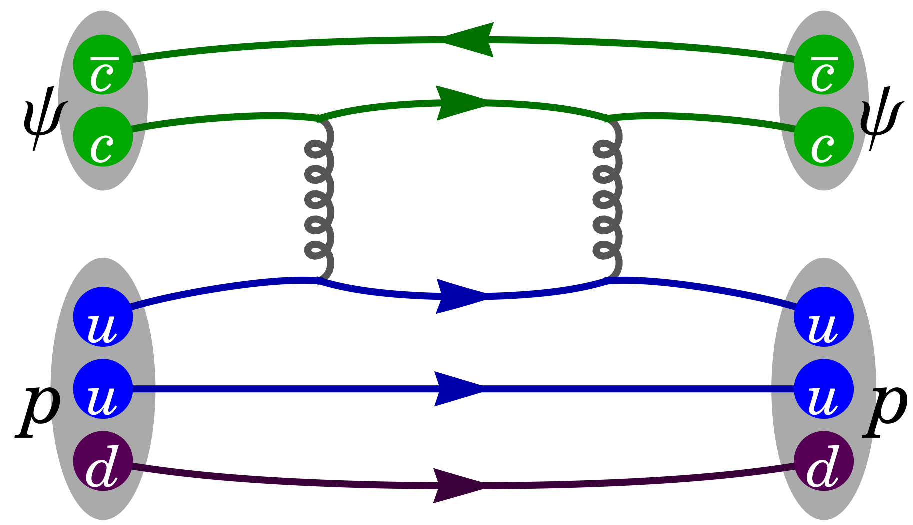
see also talks of Yamazaki, Hatsuda (Monday), Ikeda (Tuesday)

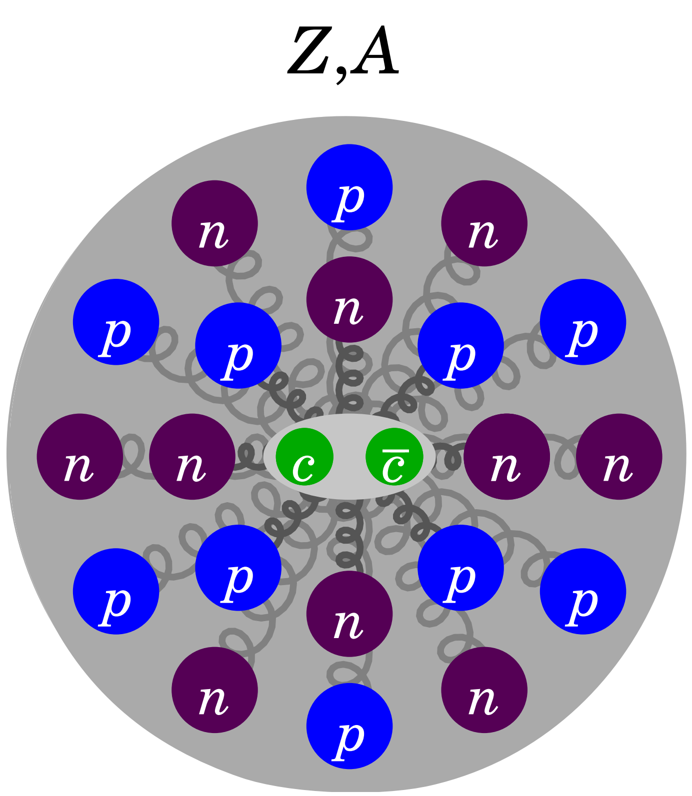
QCD Nuclei (s=0,-1)



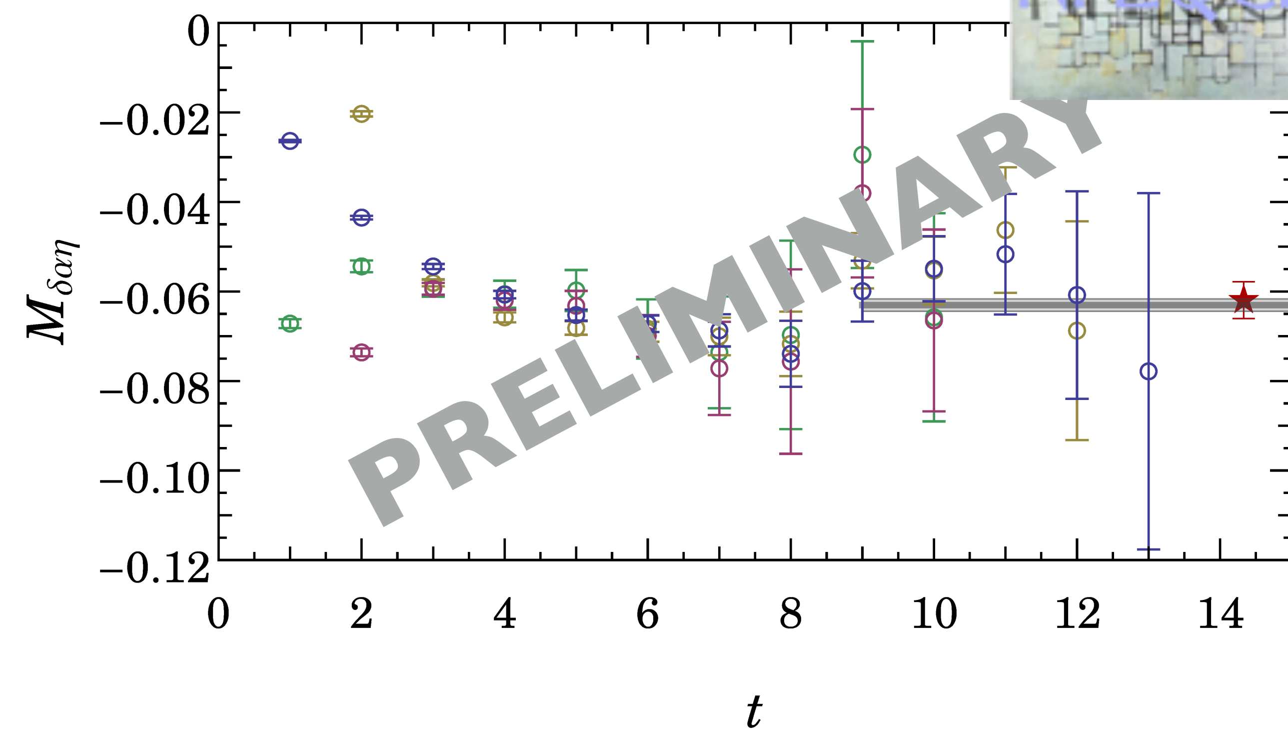
Onium-nucleus binding

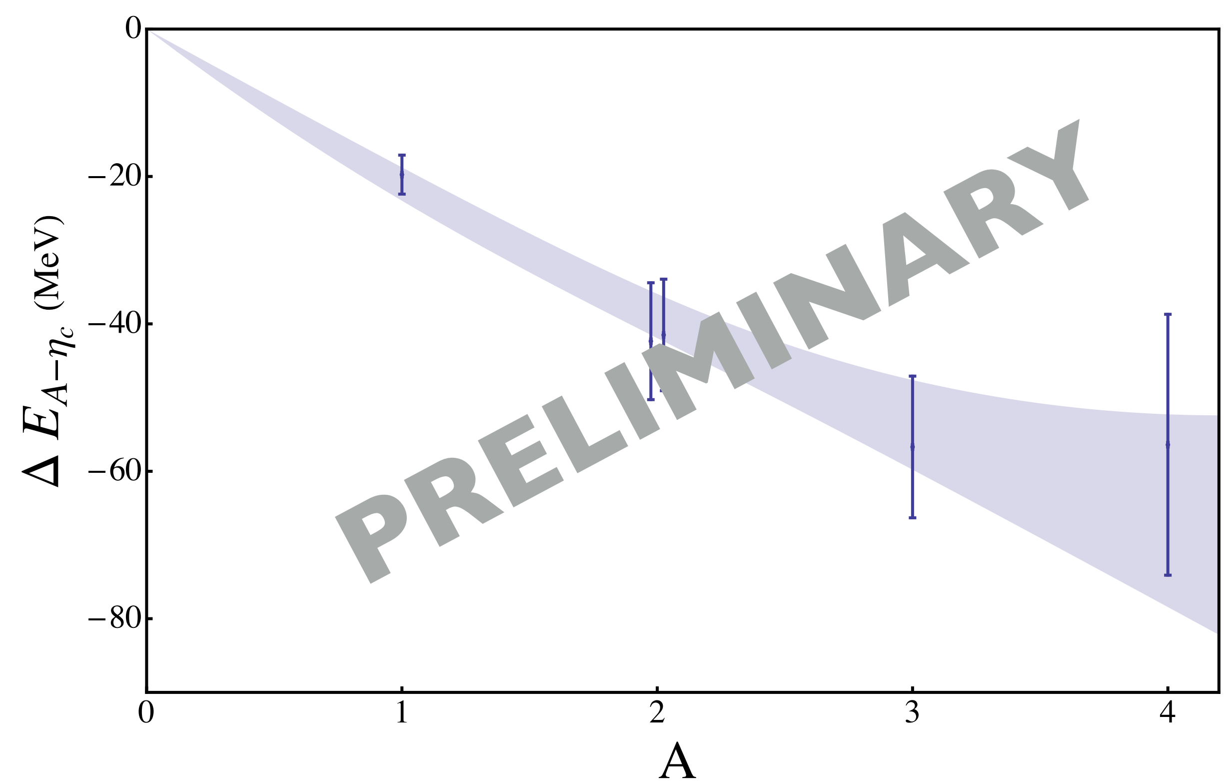
- Quarkonium interactions with light quark systems via colour van der Waals
- Colour stark effect: onium induces dipoles in nucleons that attract
  - Brodsky et al. [PRL64,1011 (1990)] suggested large binding: ^{9}Be–η_c ~ 400 MeV
  - Nuclei not point-like: gluons screened Typical model estimates now: J/Ψ–A ~ 10 MeV
- Eta-mesic nuclei possibly seen at COSY
- ATHENNA experiment at JLab12GeV looking for charmonium nuclei





- NPLQCD 1410.XXXX
- Straightforward LQCD calculation
- Study at m_π~800 MeV using strangonium and charmonium
- Energy shift from $M_\eta+M_A$
- Multiple volumes to extract infinite volume binding energy
- Binding energy vs A
    - Very strong binding!

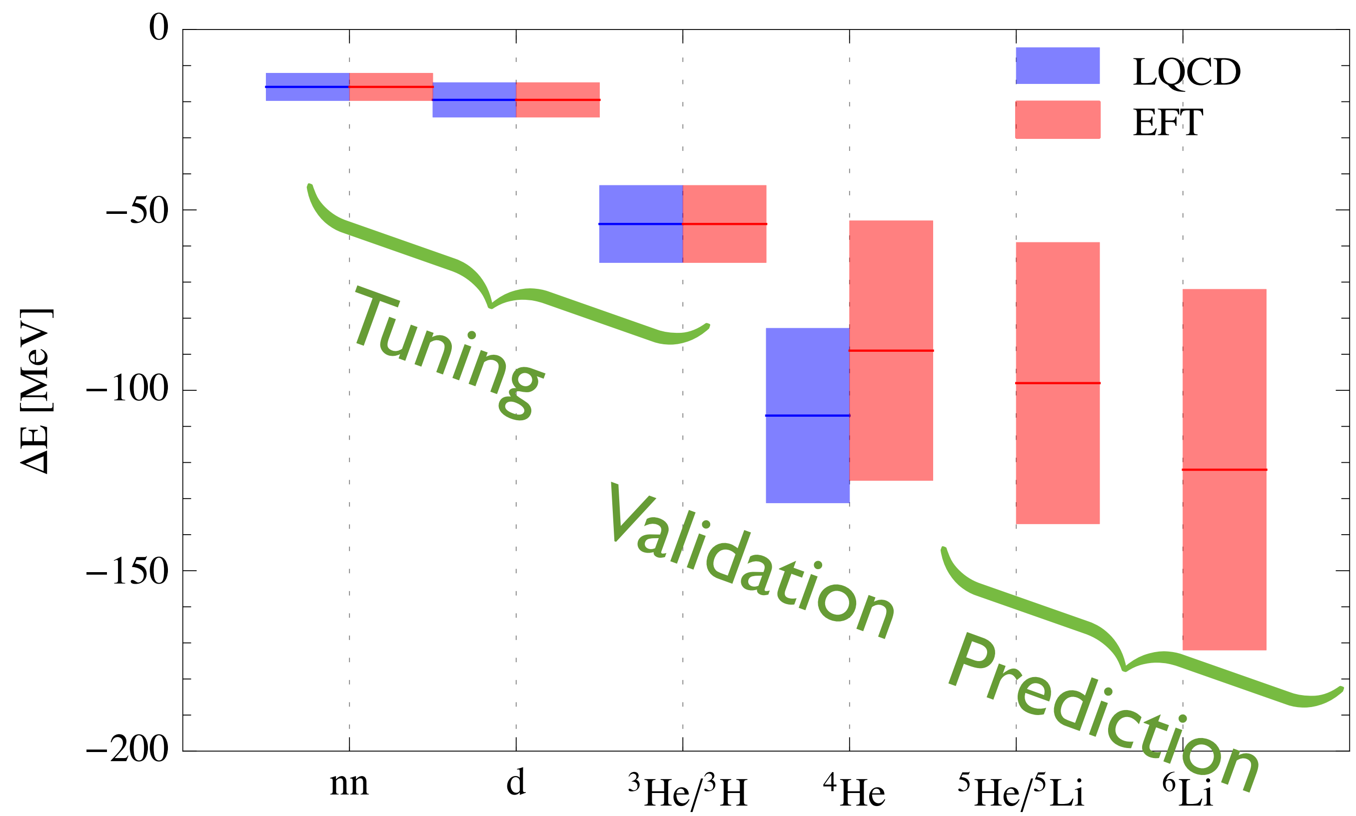




Heavy quark universe

[Barnea, et al. 1311.4966]

- LQCD and nuclear EFT are now coming together
- For heavy quarks, even spectroscopy requires QCD matching:



In a world @ m_π = 800 MeV

- Equally important for matrix elements

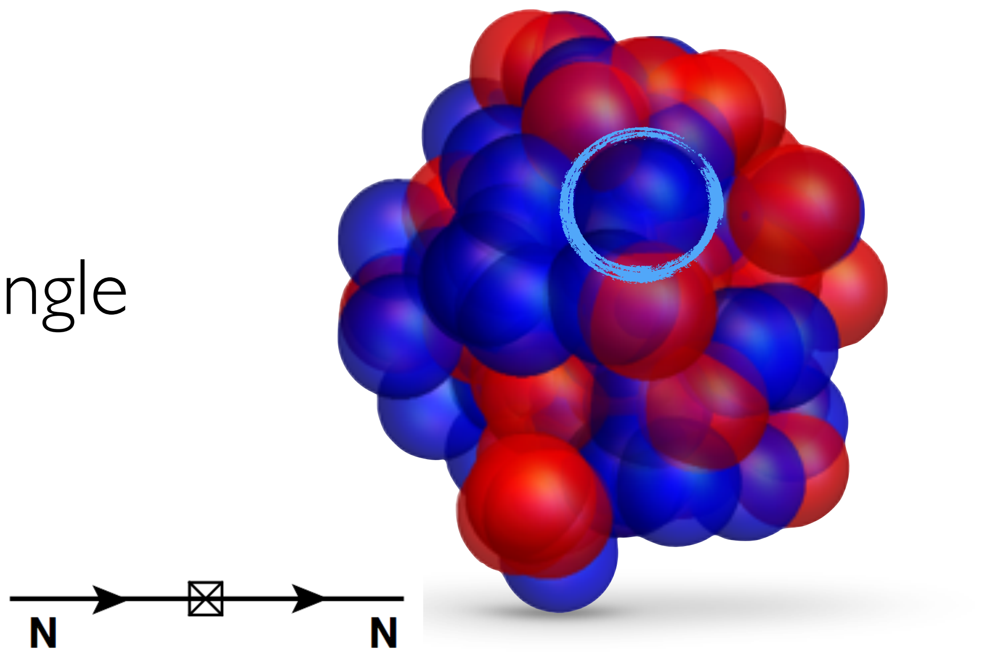
Nuclear Structure

External currents and nuclei

- Current-nucleus interaction
  - Born approximation – interacts with a single nucleon

$$\sigma \sim |A \, \langle N|J|N\rangle|^2$$

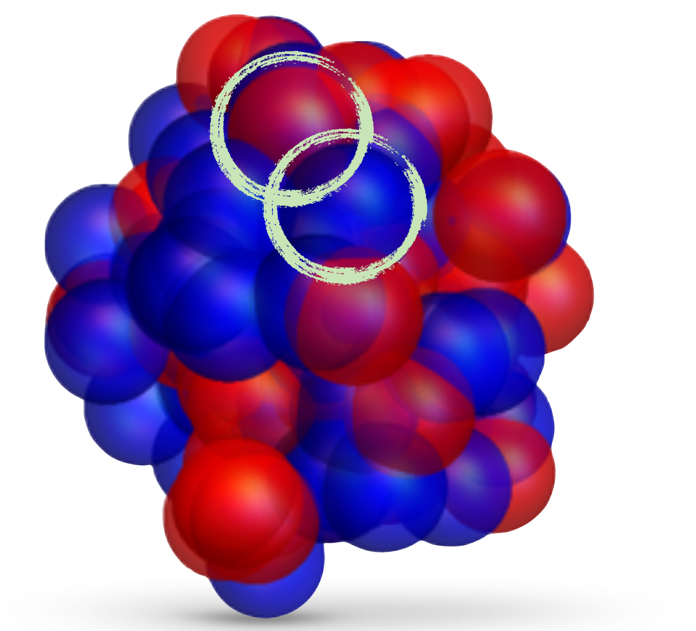
known from expt/LQCD



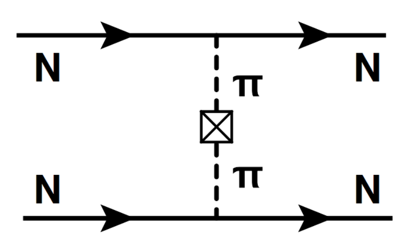
  - Interact non-trivially with multiple nucleons

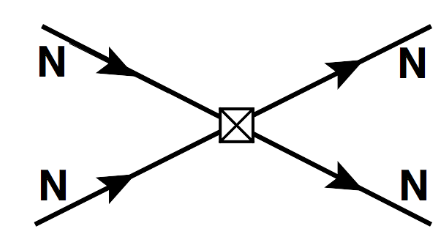
$$\sigma \sim |A \, \langle N|J|N\rangle + \alpha \, \langle NN|J|NN\rangle + \ldots|^2$$

poorly known!



- Second term may be significant
  - Eg.: important for scalar DM interactions [Prezeau *et al* PRL 2003]
  - Would lead to significant uncertainty



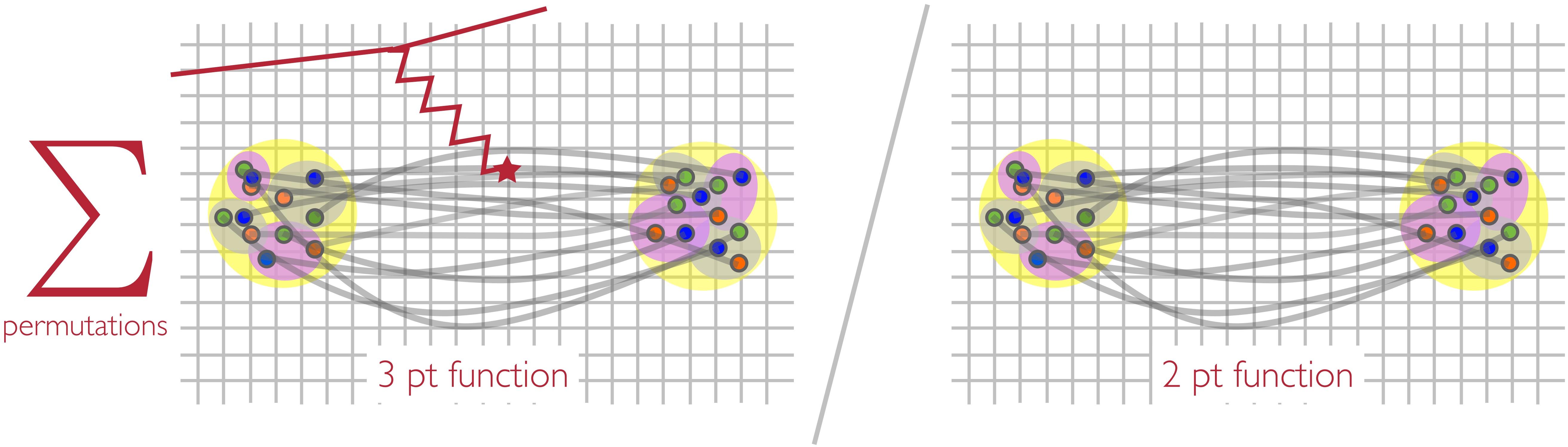


External currents and nuclei

- Power counting of nuclear effective field theory:
  - 1-body currents are dominant
  - 2-body currents are sub-leading *but non-negligible*
    Higher-body currents are even less important
- Determine one body contributions from single nucleon
- Determine few-body contributions from A=2,3,4...
- Match EFT and many body methods to LQCD to make predictions for larger nuclei

Nuclear matrix elements

- For deeply bound nuclei, use the techniques as for single hadron matrix elements

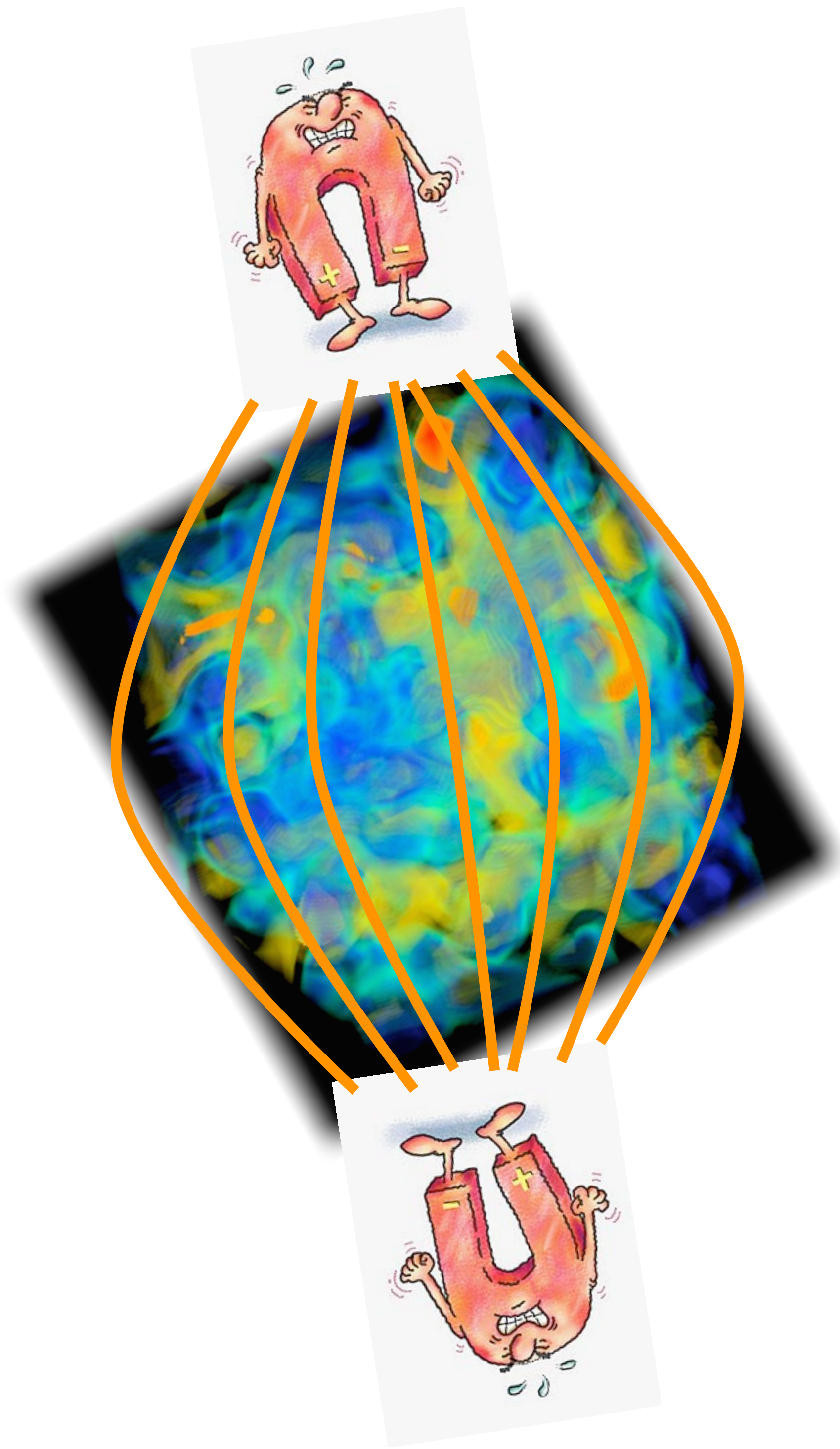


- At large time separations gives matrix element of current
- For near threshold states, need to be careful with volume effects
- Calculations of matrix elements of currents in light nuclei just beginning for A<5

- Hadron/nuclear two-point functions in presence of fixed eternal fields are modified
- Eg: fixed B field

$$E(\mathbf{B}) = M + \frac{|Q\,e\,\mathbf{B}|}{2M} - \boldsymbol{\mu}\cdot\mathbf{B} - 2\pi\beta_{M0}\,|\mathbf{B}|^2 - 2\pi\beta_{M2}T_{ij}B_iB_j + \ldots$$

- QCD calculations with multiple fields enable extraction of coefficients of response
  - Eg: magnetic moments, polarisabilities, …
  - Not restricted to simple EM fields (axial, twist-2,…)



Magnetic moments of nuclei

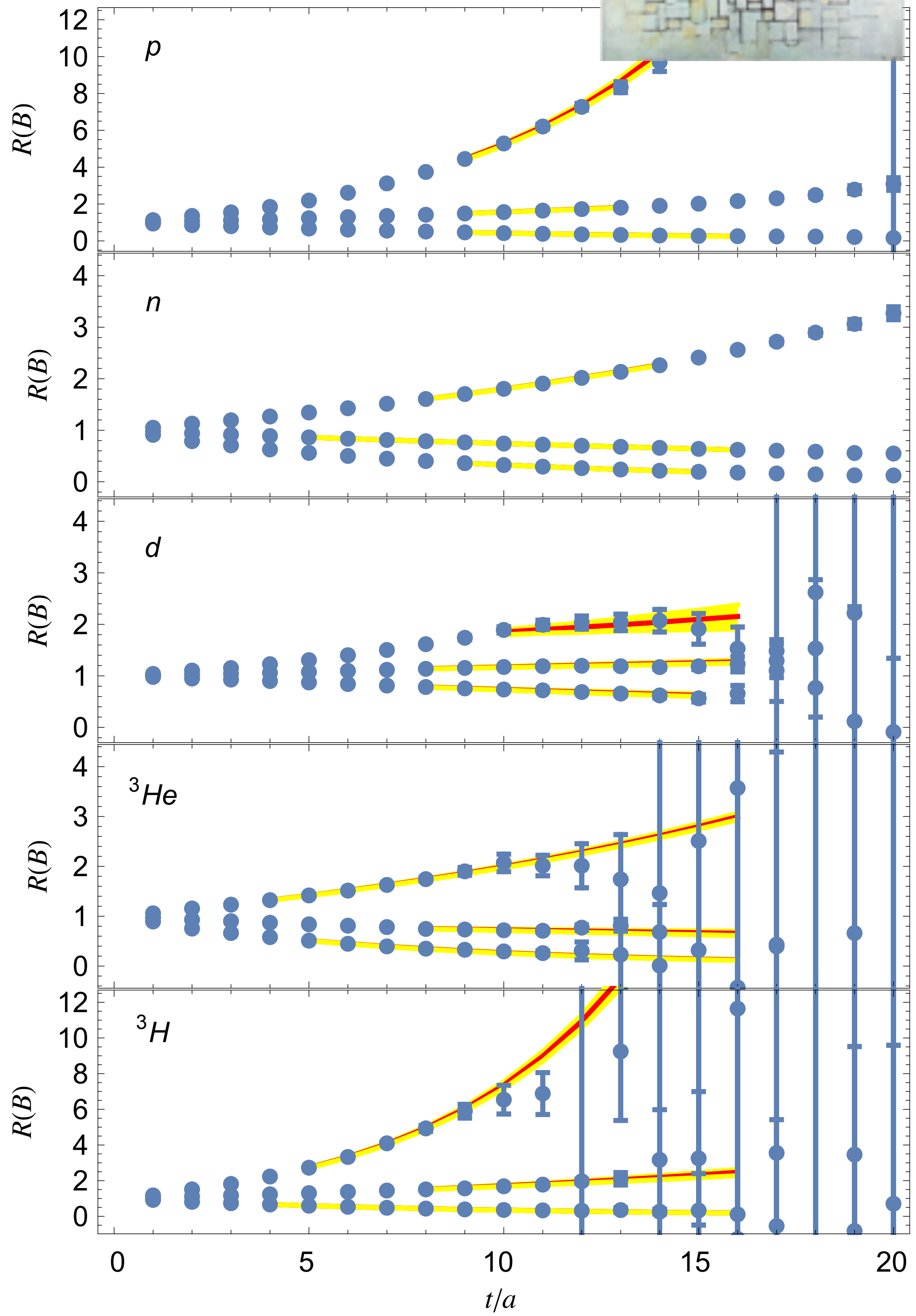
- Magnetic moments from spin splittings

$$\delta E^{(B)} \equiv E^{(B)}_{+j} - E^{(B)}_{-j} = -2\mu|\mathbf{B}| + \gamma|\mathbf{B}|^3 + \ldots$$

- Extract splittings from ratios of correlation functions

$$R(B) = \frac{C^{(B)}_j(t)\ C^{(0)}_{-j}(t)}{C^{(B)}_{-j}(t)\ C^{(0)}_j(t)} \stackrel{t\to\infty}{\longrightarrow} Ze^{-\delta E^{(B)}t}$$

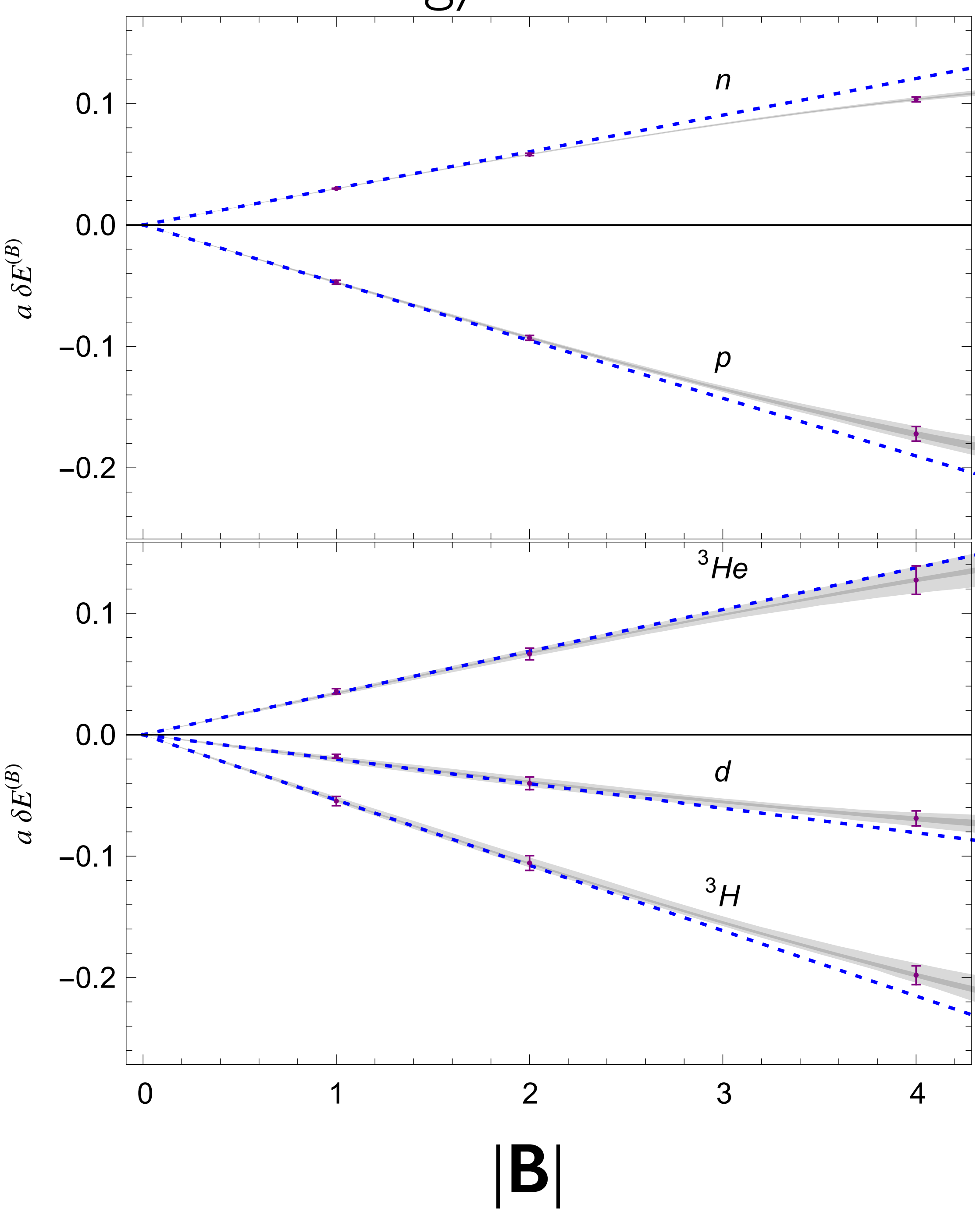
- Careful to be in single exponential region of each correlator

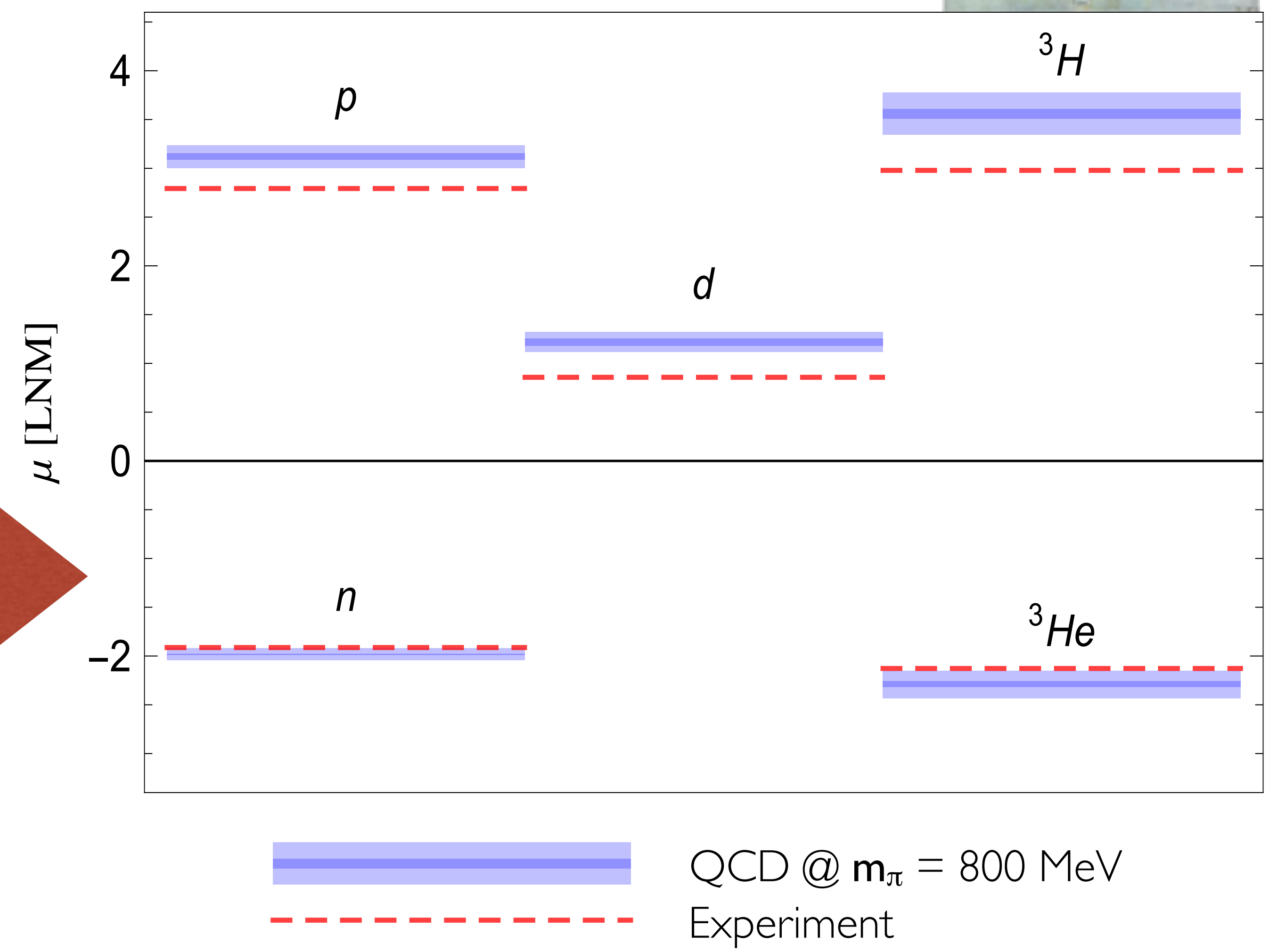


[NPLQCD 1409.3556]

Magnetic moments of nuclei

Energy shift vs B





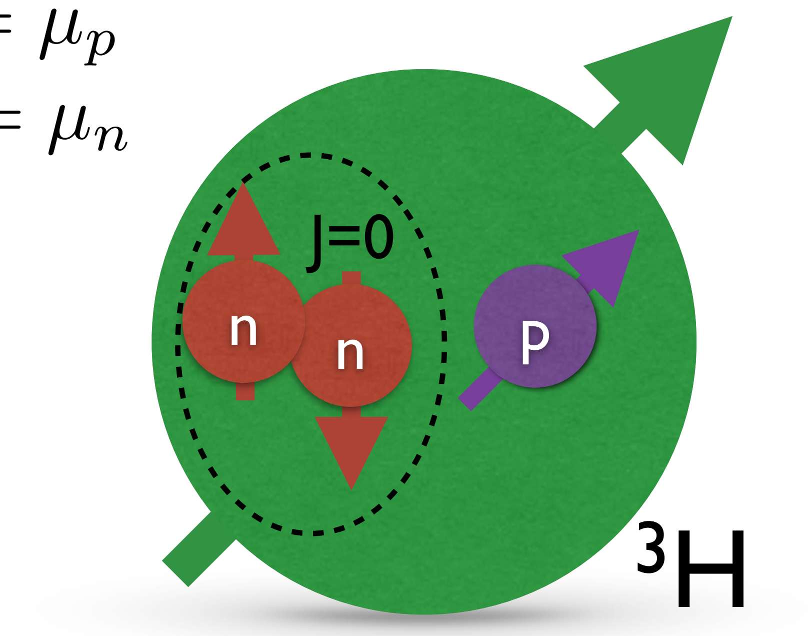
	n	p	d	3	3
μ	-1.98(1)(2)	3.21(3)(6)	1.22(4)(9)	-2.29(3)(12)	3.56(5)(18)

In units of appropriate nuclear magnetons (heavy M_N)

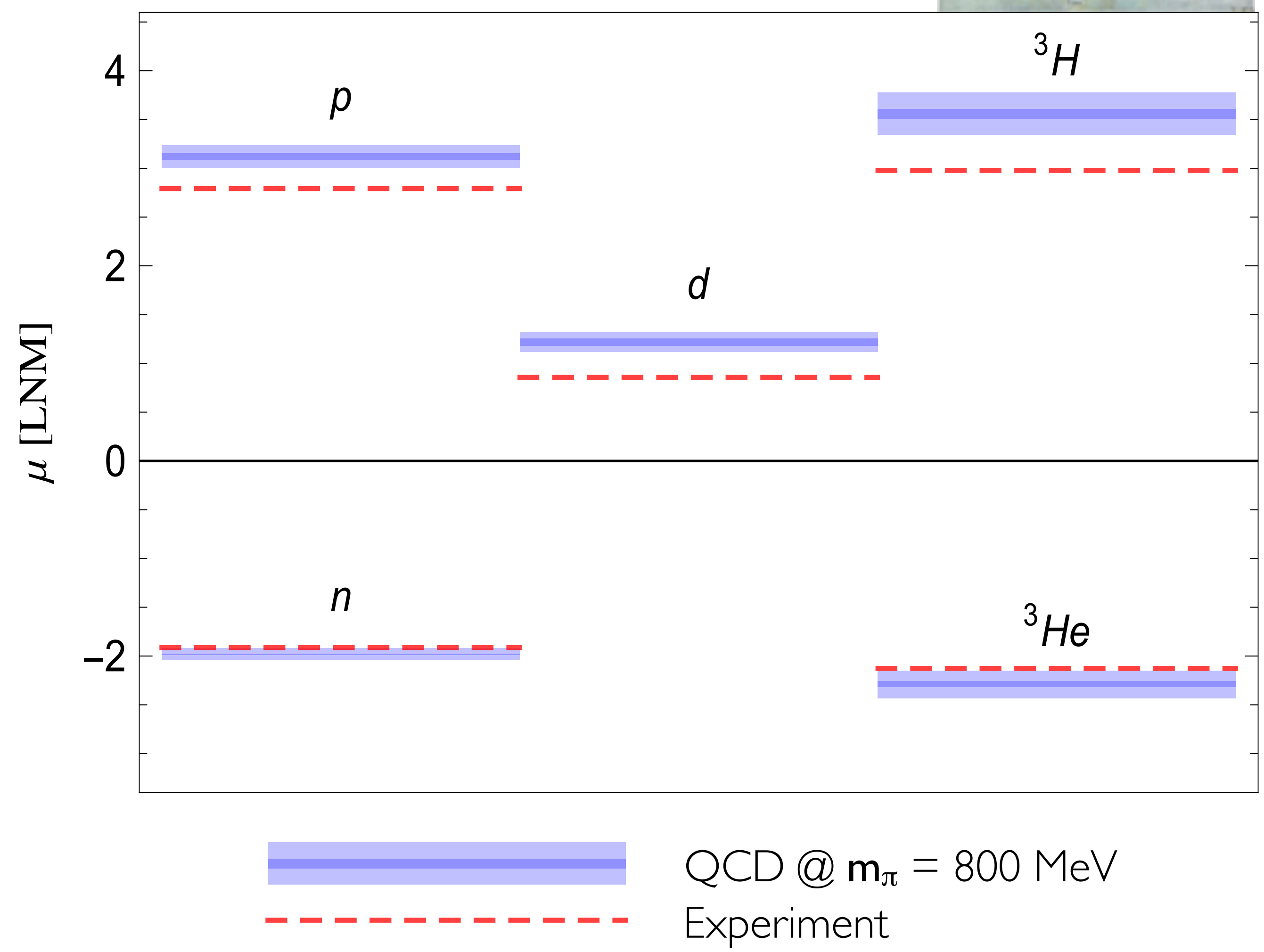
[NPLQCD 1409.3556]

- Numerical values are surprisingly interesting
- Shell model expectations

$$\mu_d = \mu_p + \mu_n$$
$$\mu_{^3\mathrm{H}} = \mu_p$$
$$\mu_{^3\mathrm{He}} = \mu_n$$



- Lattice results appear to suggest heavy quark nuclei are shell-model like!



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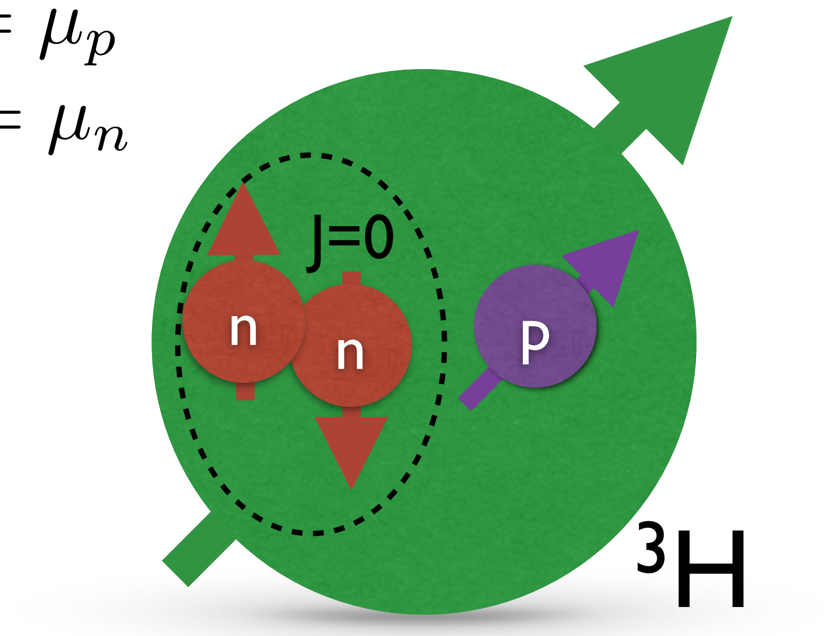

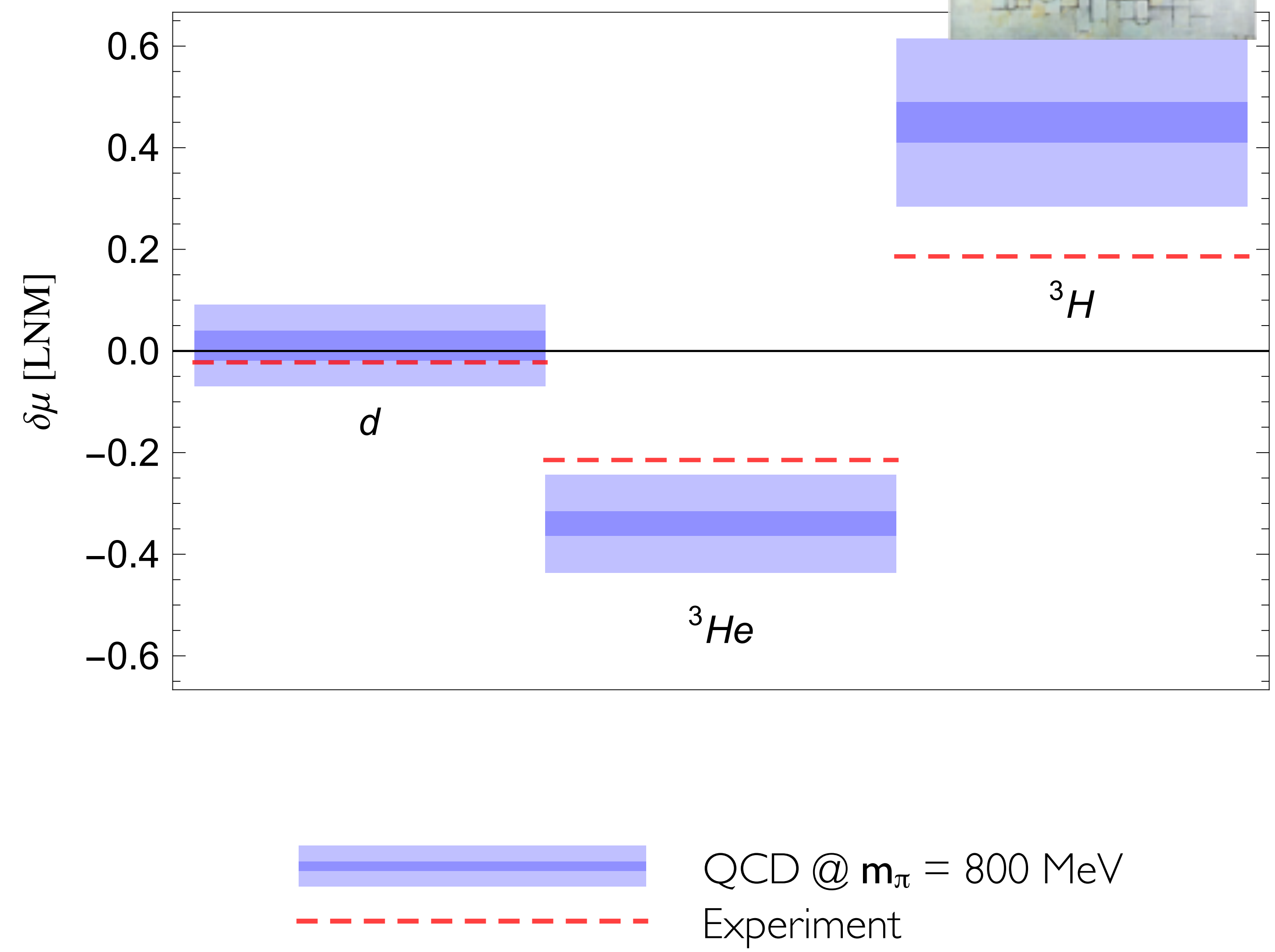

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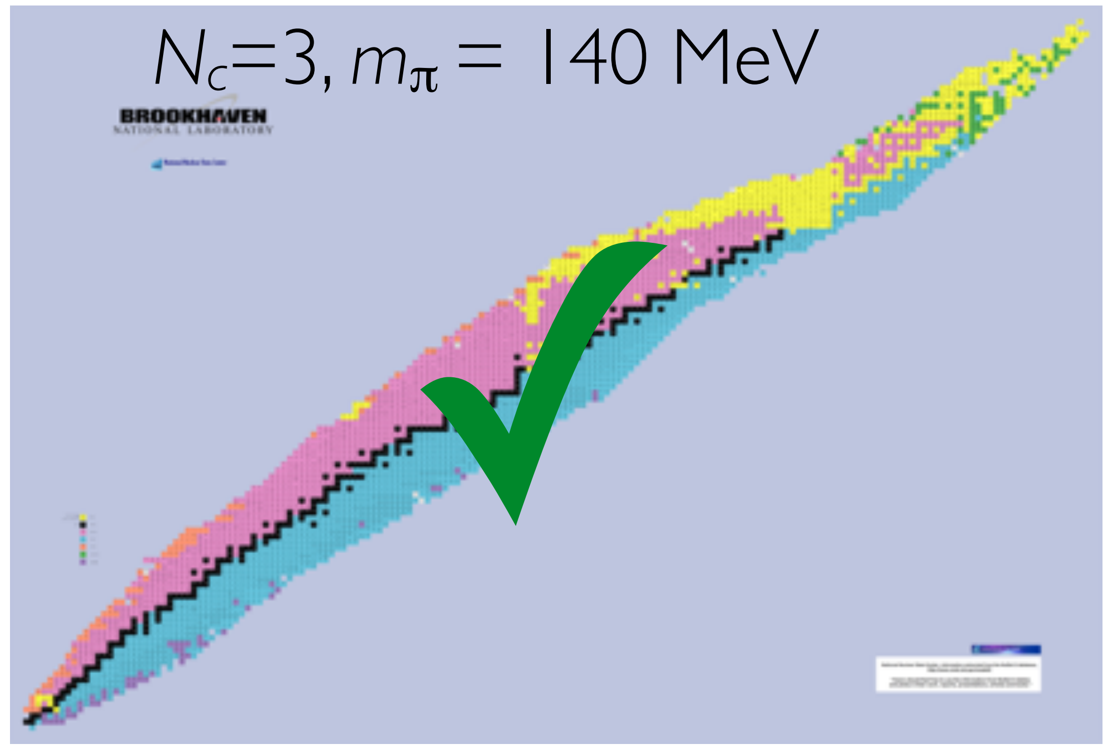
	d	3	3
δμ	0.01(3)(7)	-0.34(2)(9)	0.45(4)(16)

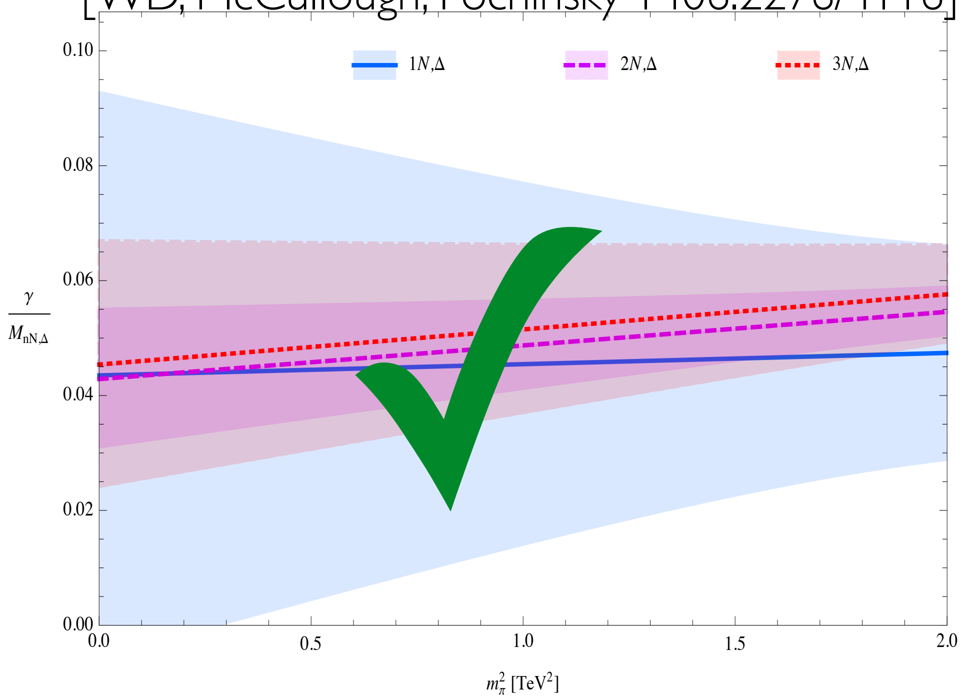
Difference from NSM expectation

[NPLQCD 1409.3556]

The ubiquity of nuclei?

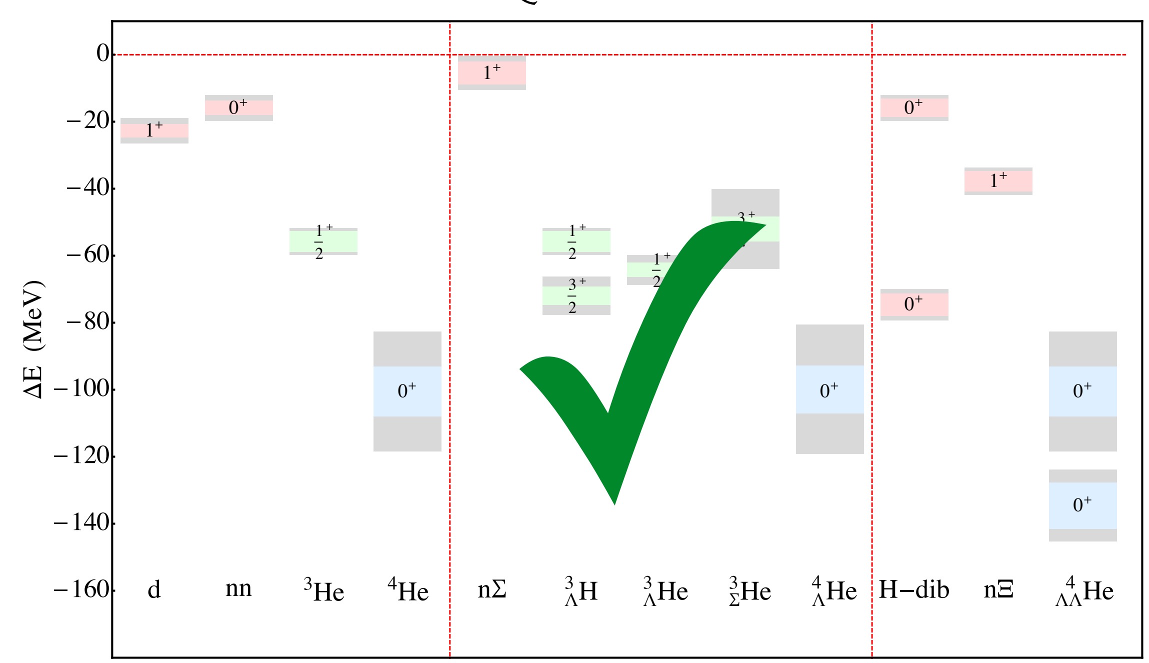


[WD, McCullough, Pochinsky 1406.2276/4116]



N_c=2, m_π = 1 TeV

NPLQCD collaboration



N_c=3, m_π = 400–800 MeV

QCD for nuclei

- Nuclei are under serious study directly from QCD
  - Spectroscopy of light nuclei and exotic nuclei (strange, charmed, …)
  - Nuclear properties/matrix elements
- Prospect of a quantitative connection to QCD makes this a very exciting time for nuclear physics
  - Critical role in current and upcoming particle physics experimental program
- Learn many interesting things about nuclear physics along the way

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