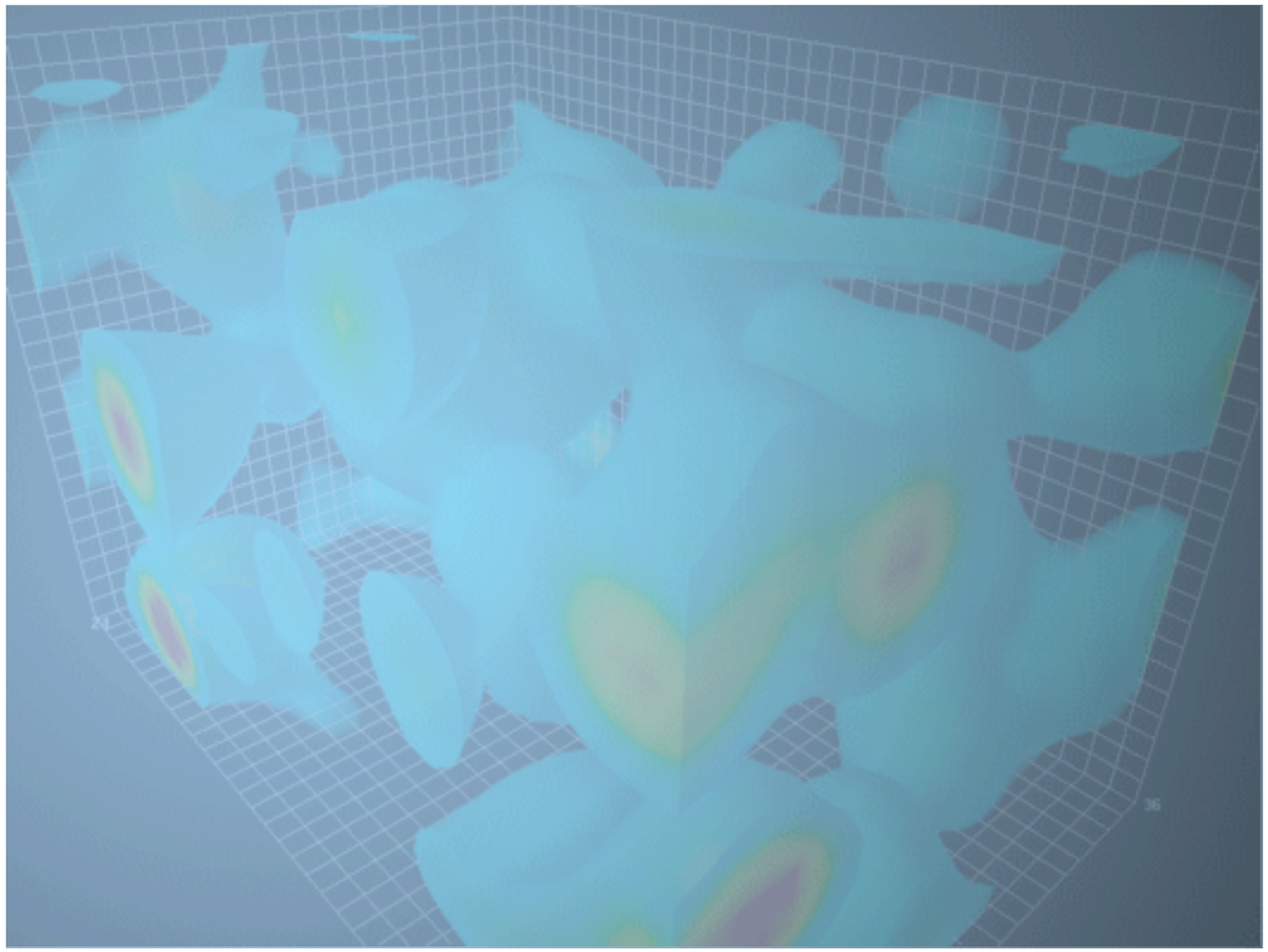


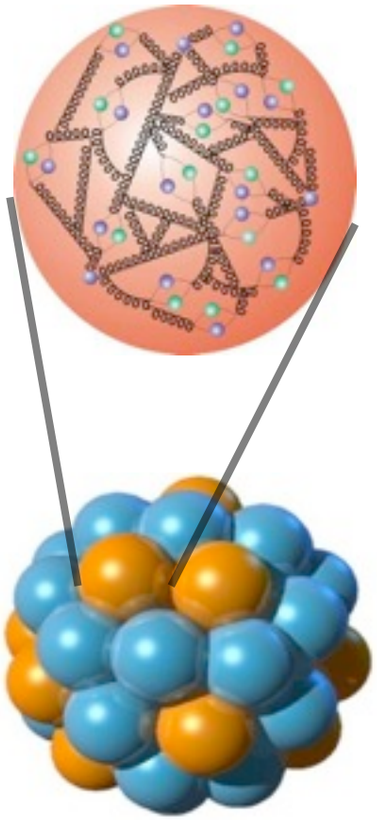
[INT Workshop (Briceno, Davoudi,Luu)]

Nuclear Reactions from Lattice QCD

Martin J. Savage
University of Washington
March 2013

Nuclear Physics from (Lattice) Quantum Chromodynamics

Proton



Quarks and Gluons

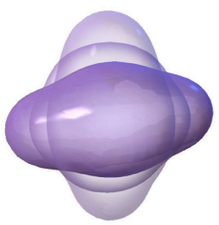
Nucleus

$$\Lambda_{\rm QCD}$$

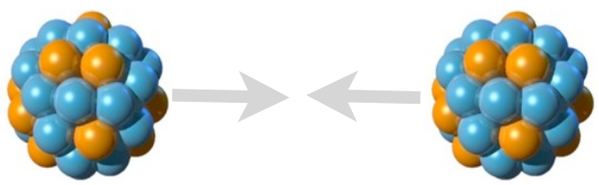
$$\frac{m_u}{\Lambda_{\rm QCD}} \quad \frac{m_d}{\Lambda_{\rm QCD}} \quad \frac{m_s}{\Lambda_{\rm QCD}}$$

$$\alpha_e$$

Fully Quantifiable Uncertainties



Vibrational and rotational excitations



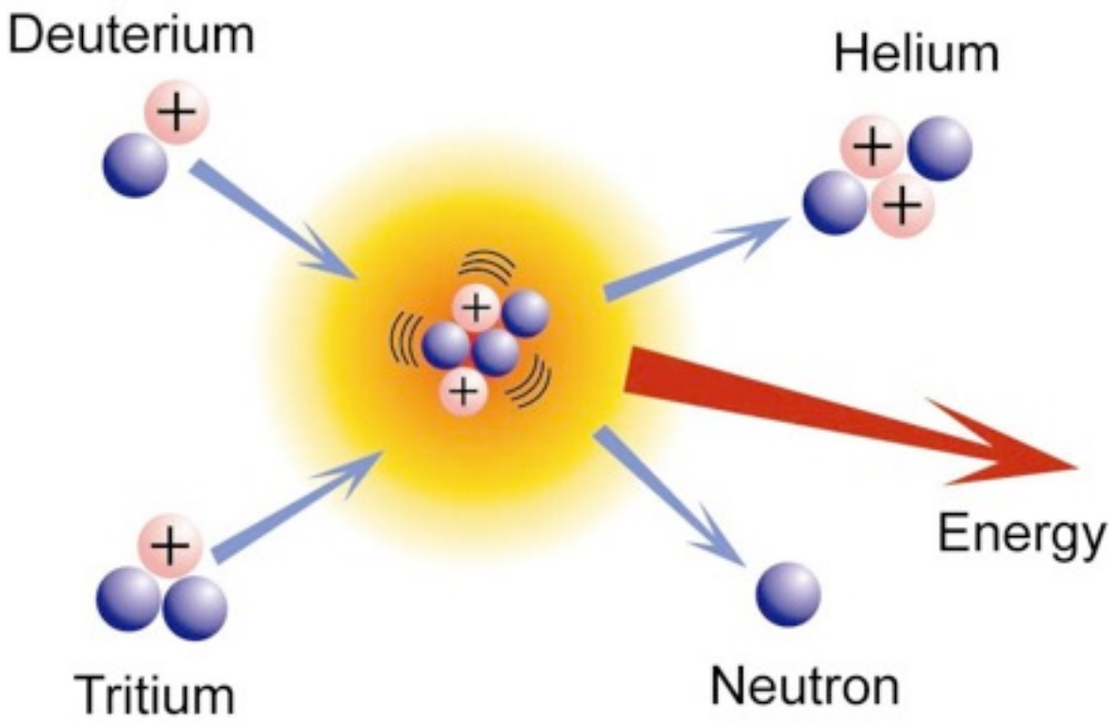
Nuclear Reactions

Computation

↓

L (IR) , a (UV)

Why must we think about Lattice QCD and Nuclear Reactions together?

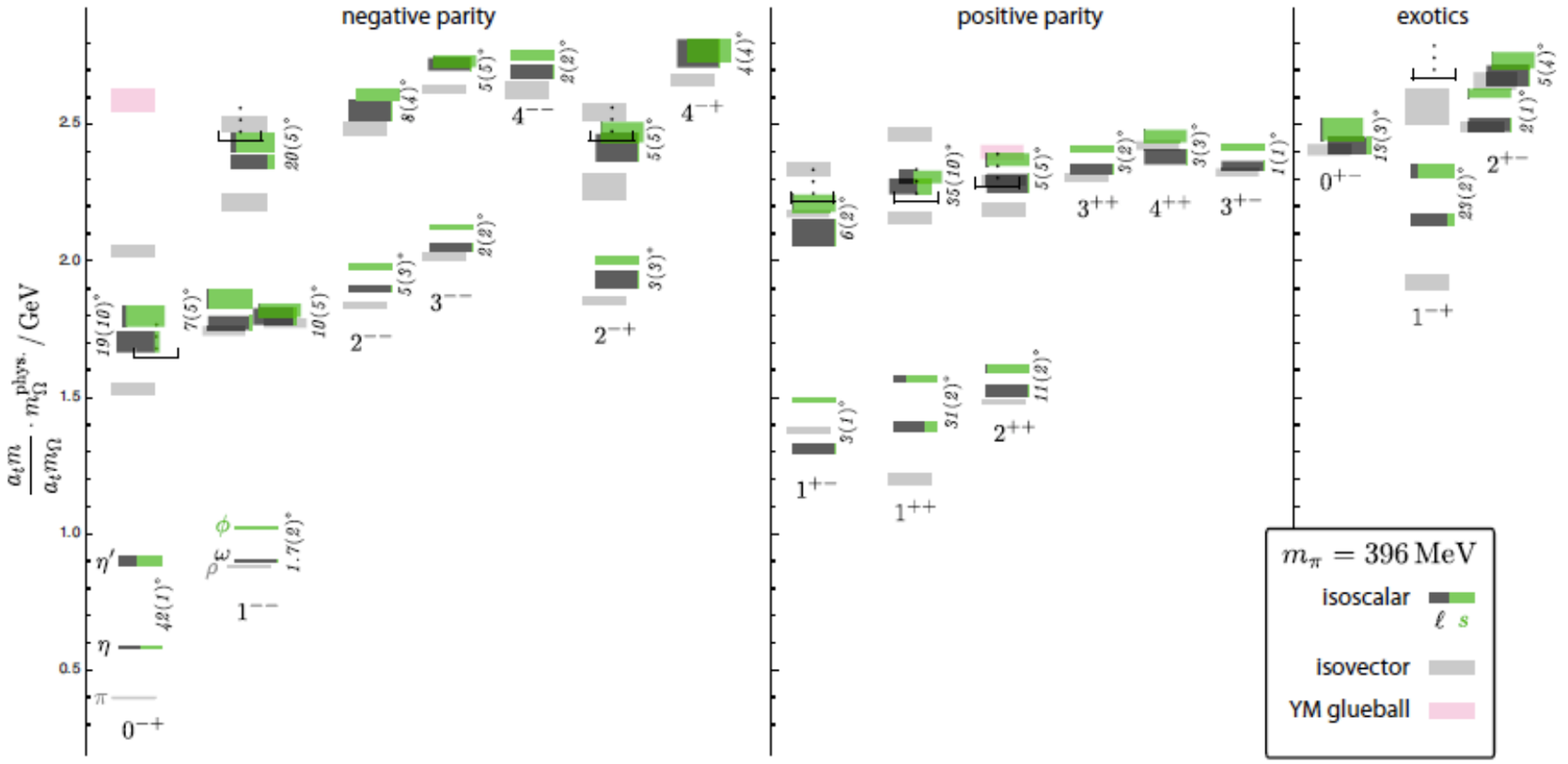


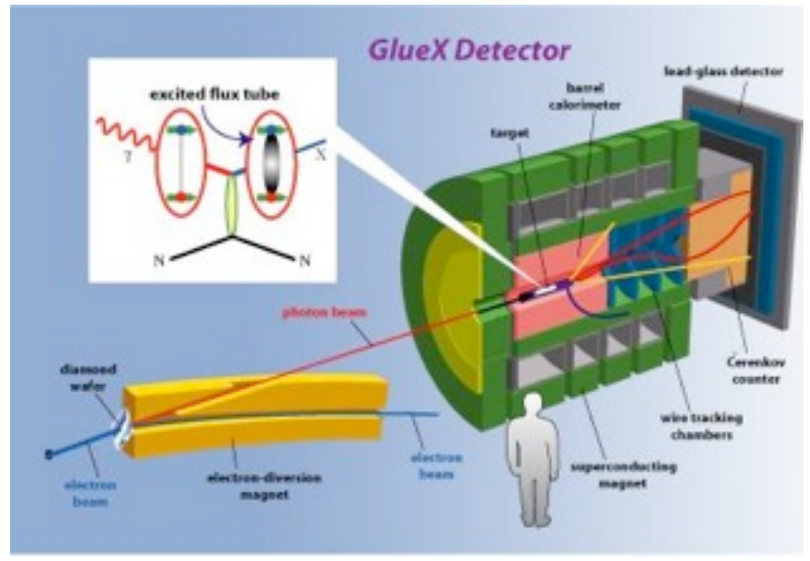
Don’t know the nuclear forces to sufficient precision from experiment for calculations in important systems.

Meson-exchange currents unrelated to scattering
(i.e. multi-nucleon-multi-gauge-field operators)

Neutron-rich, Hyperon systems for extreme enviroments

Excited Meson Spectrum
Exotics

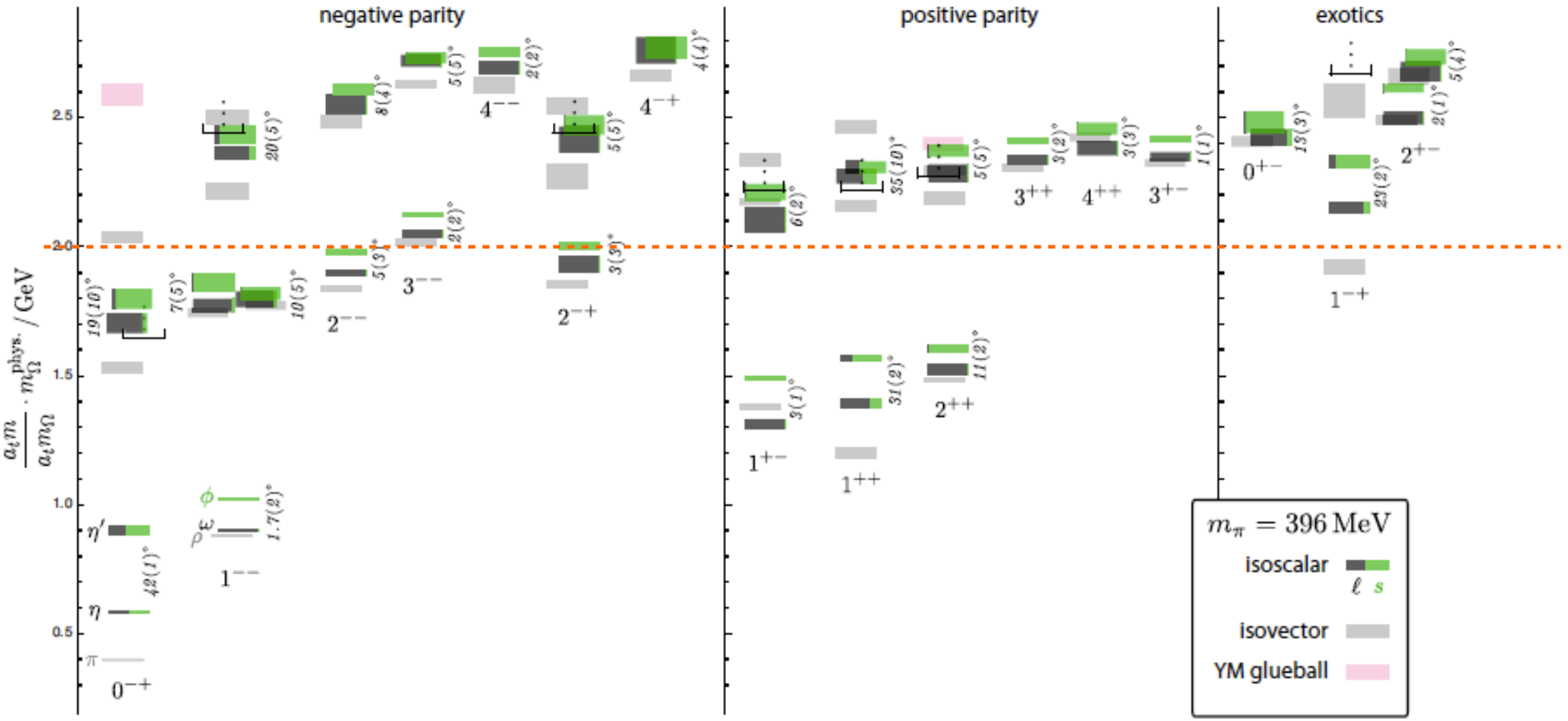




Dudek *et al* , arXiv:1102.4299

Lattice QCD will predict the exotic spectrum before or during the GlueX experiment (?)

Excited Meson Spectrum
Exotics

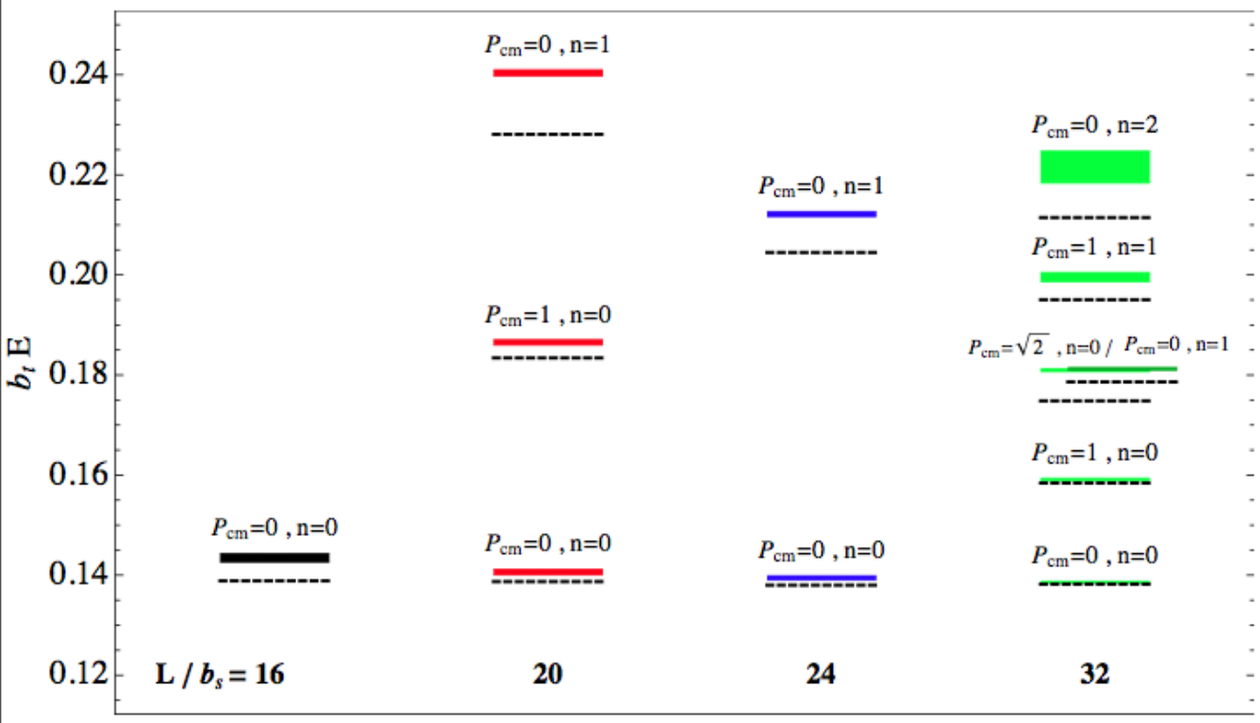


15 pions

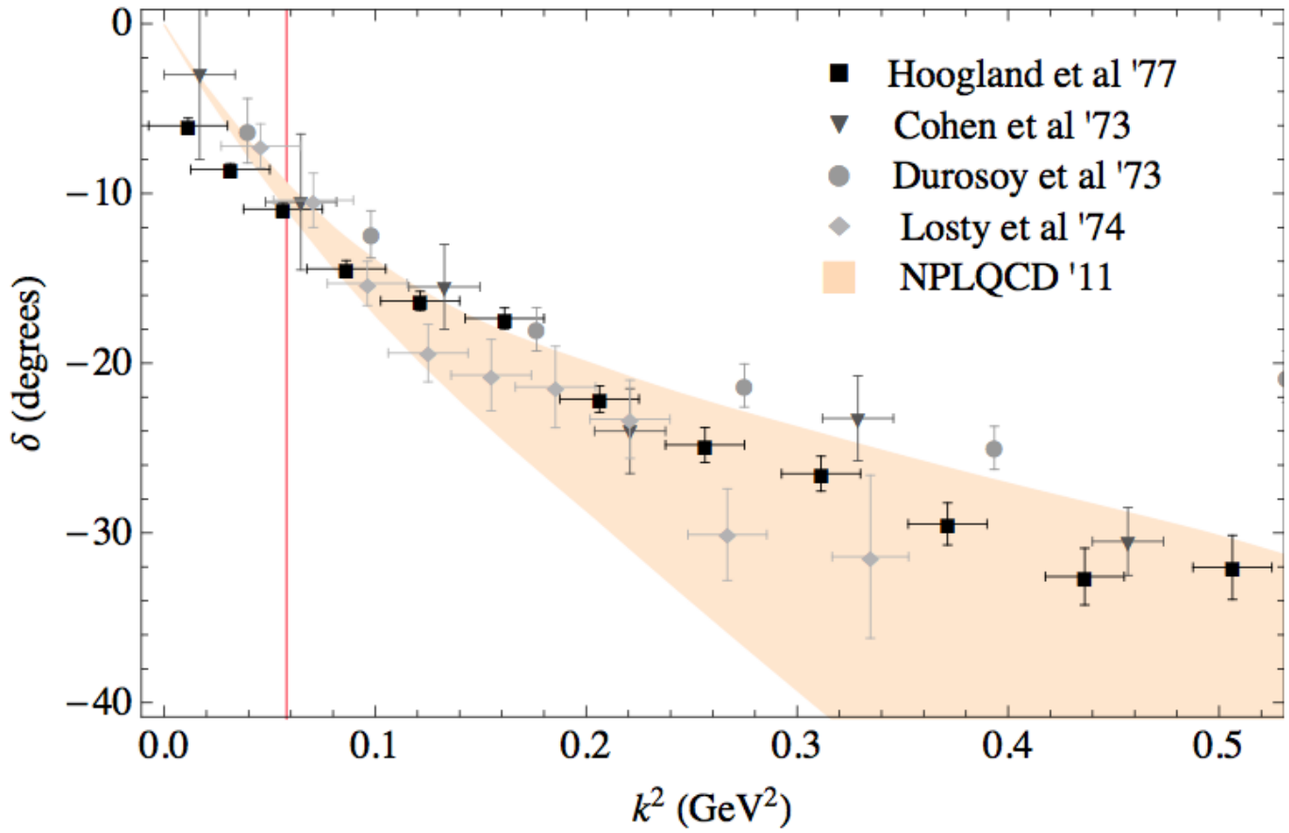
- NOT the Meson Spectrum but Energy Eigenstates in Lattice Volume
- Problem becomes more complicated as quark masses reduced

Lattice QCD : State of the Art
S-Wave Pion-Pion Scattering

Energy-Levels in Lattice Volume



χPT Extrapolation to Nature

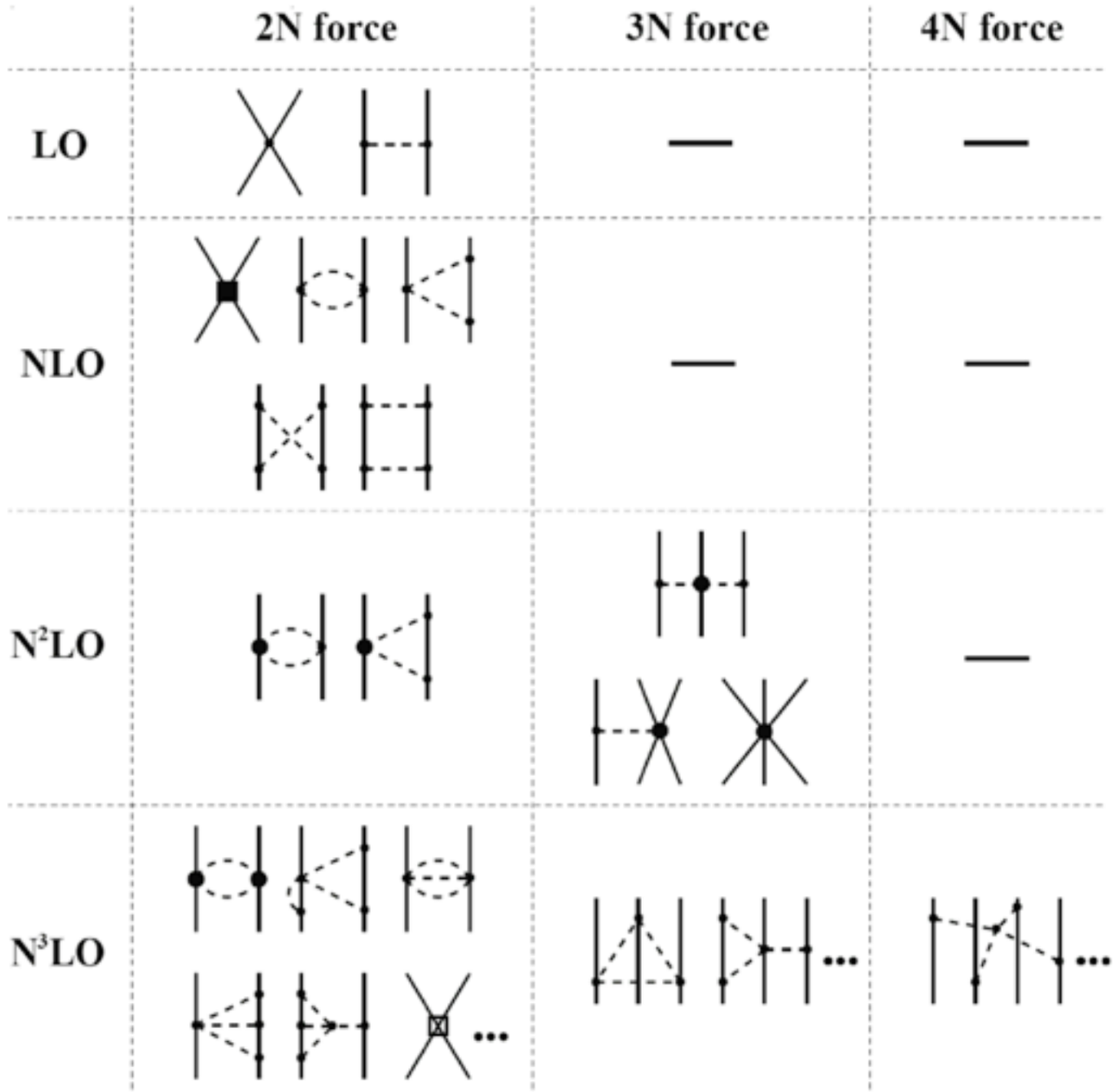


- Finite (small) numbers of energy levels determined
- Rigorously extract S-matrix element - single channel
- EFT allows for interpolation and extrapolation of LQCD calculations with additional quantifiable systematic uncertainties - optimal transcription of finite # of LQCD calcs

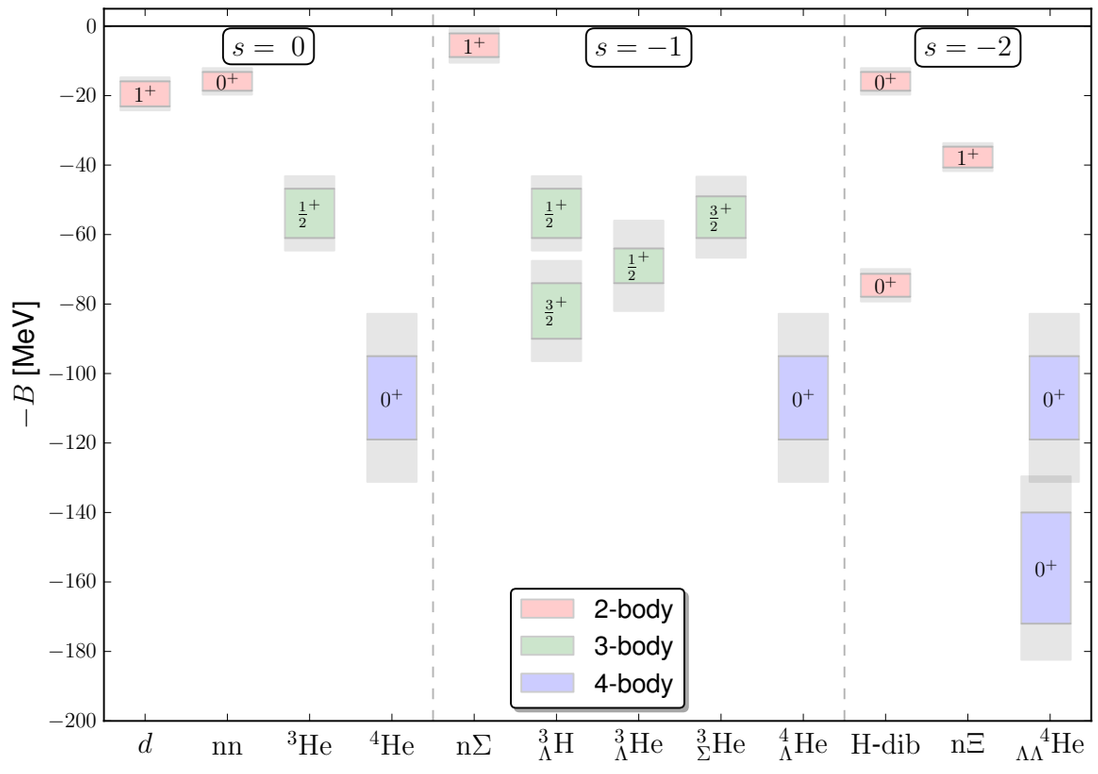
Organized Nuclear Forces
- Extending the Reach of LQCD

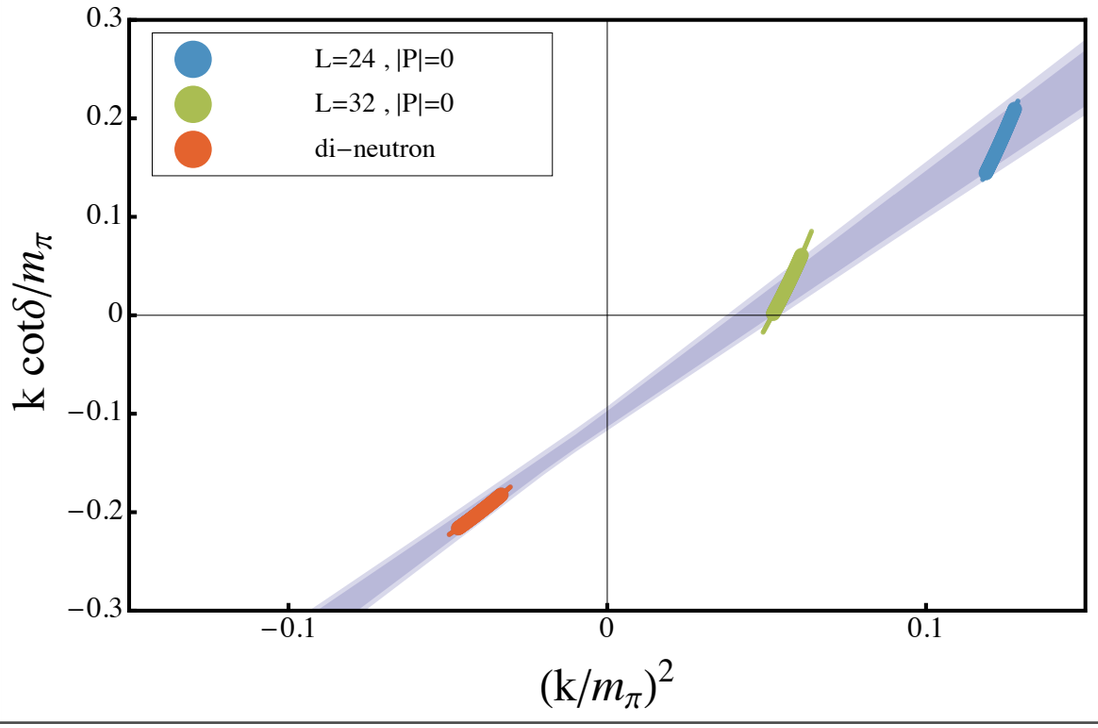
Effective Field Theory introduced by Weinberg in the early 1990's to systematize nuclear forces

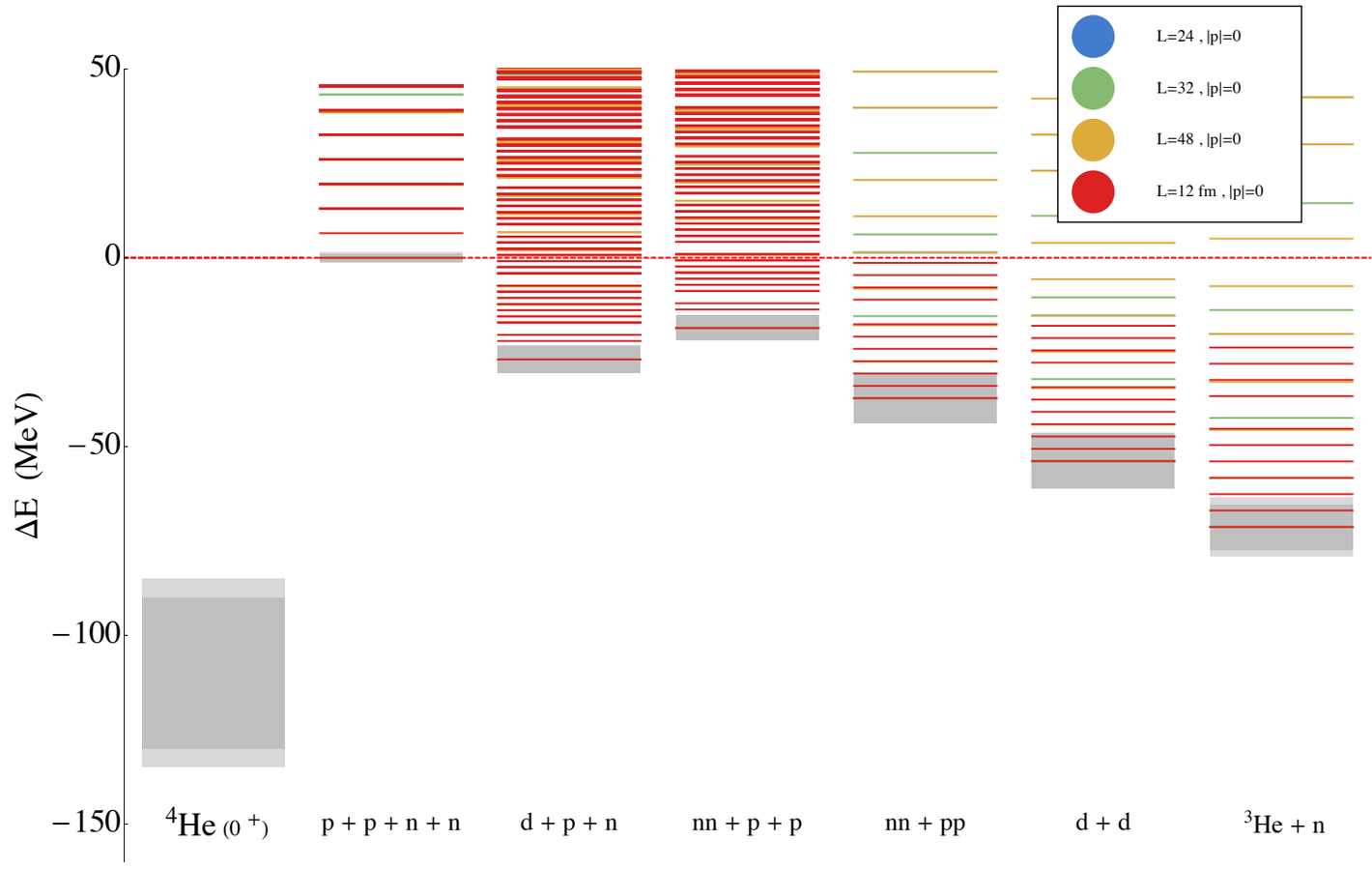
- Low-energy EFT of QCD
- Chiral symmetries of QCD
- Quark mass dependence
- Counterterms from expt or LQCD

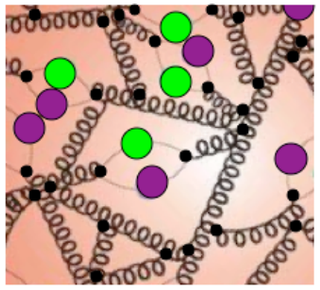
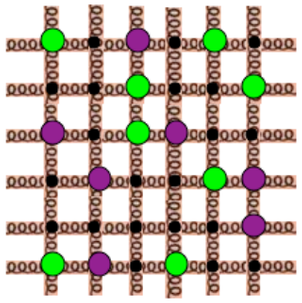


Light Nuclei and Hypernuclei
SU(3) limit, 800 MeV pions

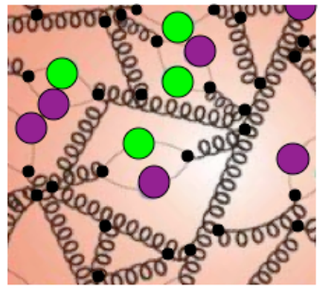
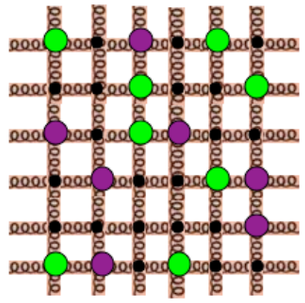




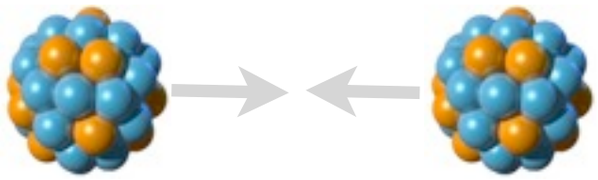


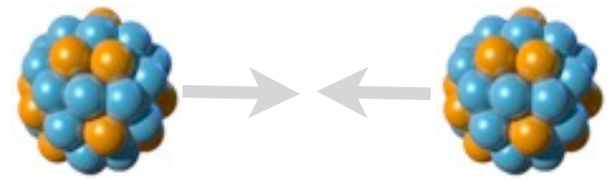
Lattice QCD

- Contractions no longer an issue
  - multibaryon systems now doable
- Physical pion mass calculations (for the lucky!)
- Electromagnetism is important for Nuclei
  - Coulomb can be included externally in many systems
- 3,4-neutron interactions are important output
  - NN = verification and mq-dep of forces (inelastic)



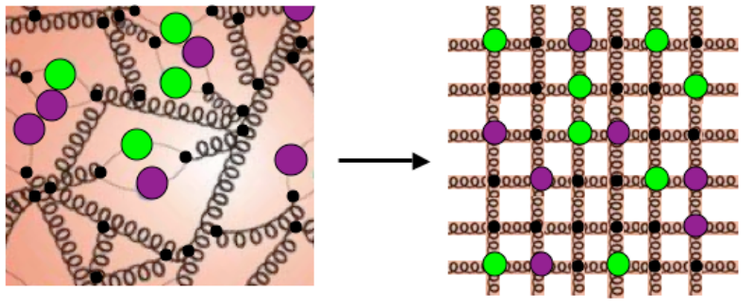
Nuclear Reactions and Calculations



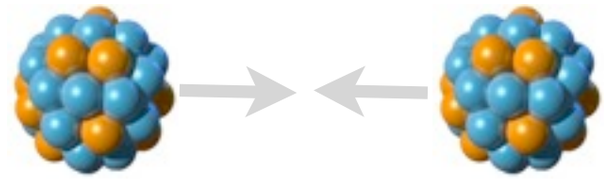
- Chiral Forces are being used at increasing orders of precision - NCSM, Lattice-EFT, RG-improvement

- Numerical challenges to do full implementation
  - Soft interactions don't work beyond light nuclei, A>~8
    - no surprise - relevent momentum scales should be dynamical

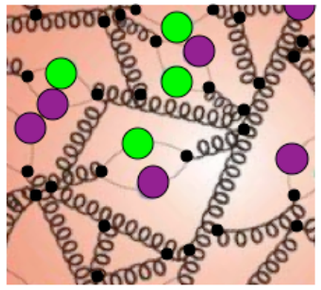
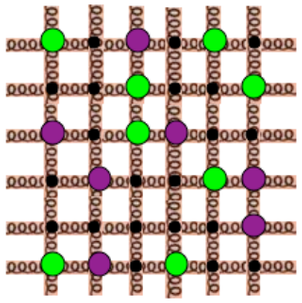
- Is LQCD needed ? - YES
  - refine nuclear forces, 3-body,
  - multi-neutron systems/forces poorly constrained by expt
  - hypernuclei and their reactions



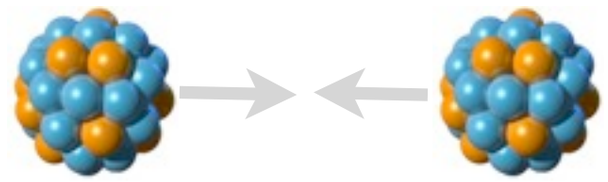
Lattice QCD and Nuclear Reactions



- Can we get S-matrix elements directly?
  - 2-body - yep! = Luscher + other recent developments
  - progress in NN, including boosted systems
  - progress in 3-body direction
- Chiral interactions, nuclear many-body theory greatly extend the reach of (L)QCD
  - crucial for QCD in NP
  - c_i - currently contribute large uncertainties
  - gravitational wave predictions !
- 3-body coupled channels - focus for the last year or so
  - recovered threshold
  - quantification of exponential contributions
- Fundamental interactions, $\beta\beta$-decay, Dark Matter

Lattice QCD and Nuclear Reactions (EFT)



- EFT usually good place to start to establish more general S-matrix relations

- EFT out to N^3LO, EM operators, observables with cancellations (light nuclei) from LQCD

- Electromagnetic EFT-LQCD matching

Plan for Next 2 Years (1)

- d+t = α+n
  - NCSMC and chiral+3N within reach (resonance in α+n)
  - isolate systematics sources - separate from many-body
  - LQCD = need p-shell calculations - more complex that what has been done so far - but doable.
- ^{7}Be(p,γ)^{8}B using EFT
- More precise LEFT - Hoyle state systematics, m_q-dependences
- Formal developments in A=3,4,+.. systems
  - higher partial waves, mixing, boosted systems

Plan for Next 2 Years (2)

- LQCD calcs at lower pion masses
  - precision multi-A m_π~400 MeV, maybe lower ?
  - NN scattering, bound state(s)
  - Nuclei, multi-n systems, 3-neutrons
  - YN and hypernuclei
- Double-beta decay matrix elements, electroweak matrix elements

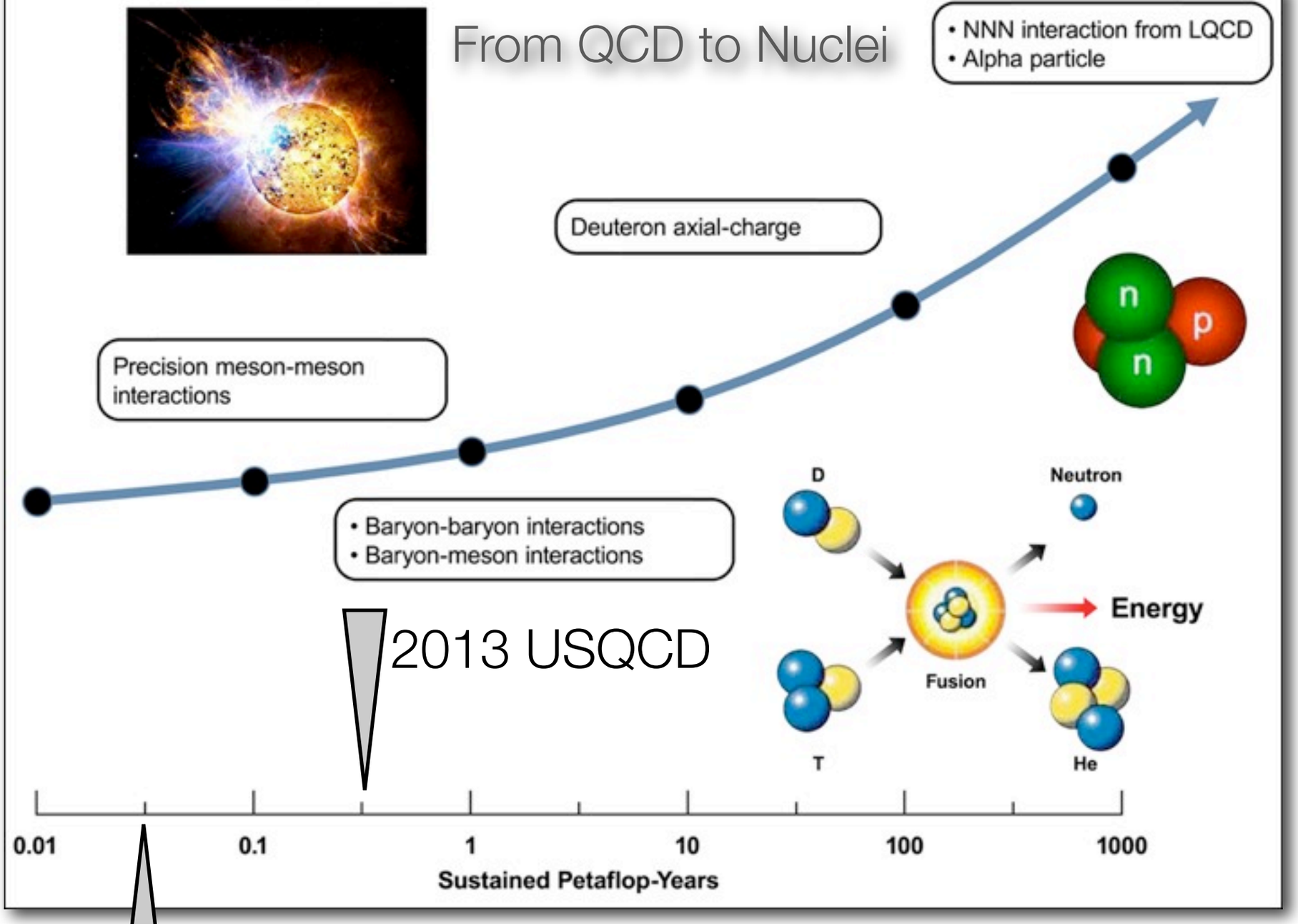
Plan for Next 5 Years

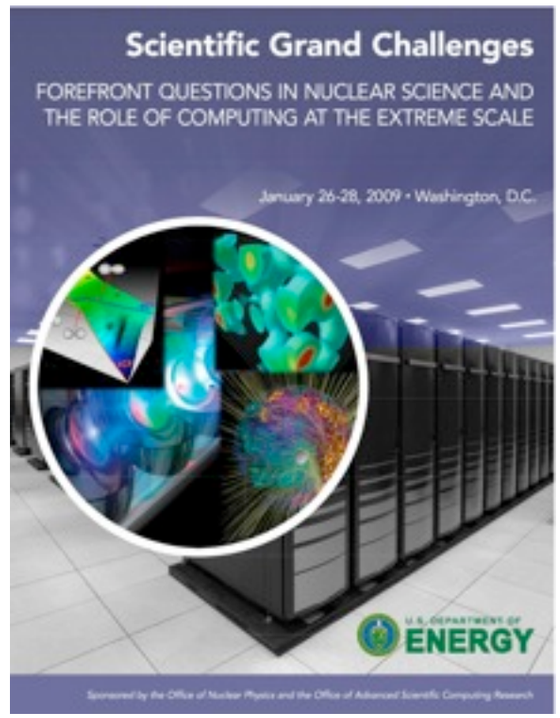
- NCSM - α-clustering included
  - algorithms and not hardware
- LQCD calculations at lower pion masses
  - multi-A calcs at m_π~140 MeV
- Extractions of 3-body and 4-body interactions
- Formal developments continue
- Systematic matching between LQCD and Many-Body theory

Plan für die nächsten 10 Jahre

- Multi-A calcs at m_π~140 MeV
  - including isospin breaking + EM
- Precision extraction of 3-body and 4-body interactions
- Do it all !!

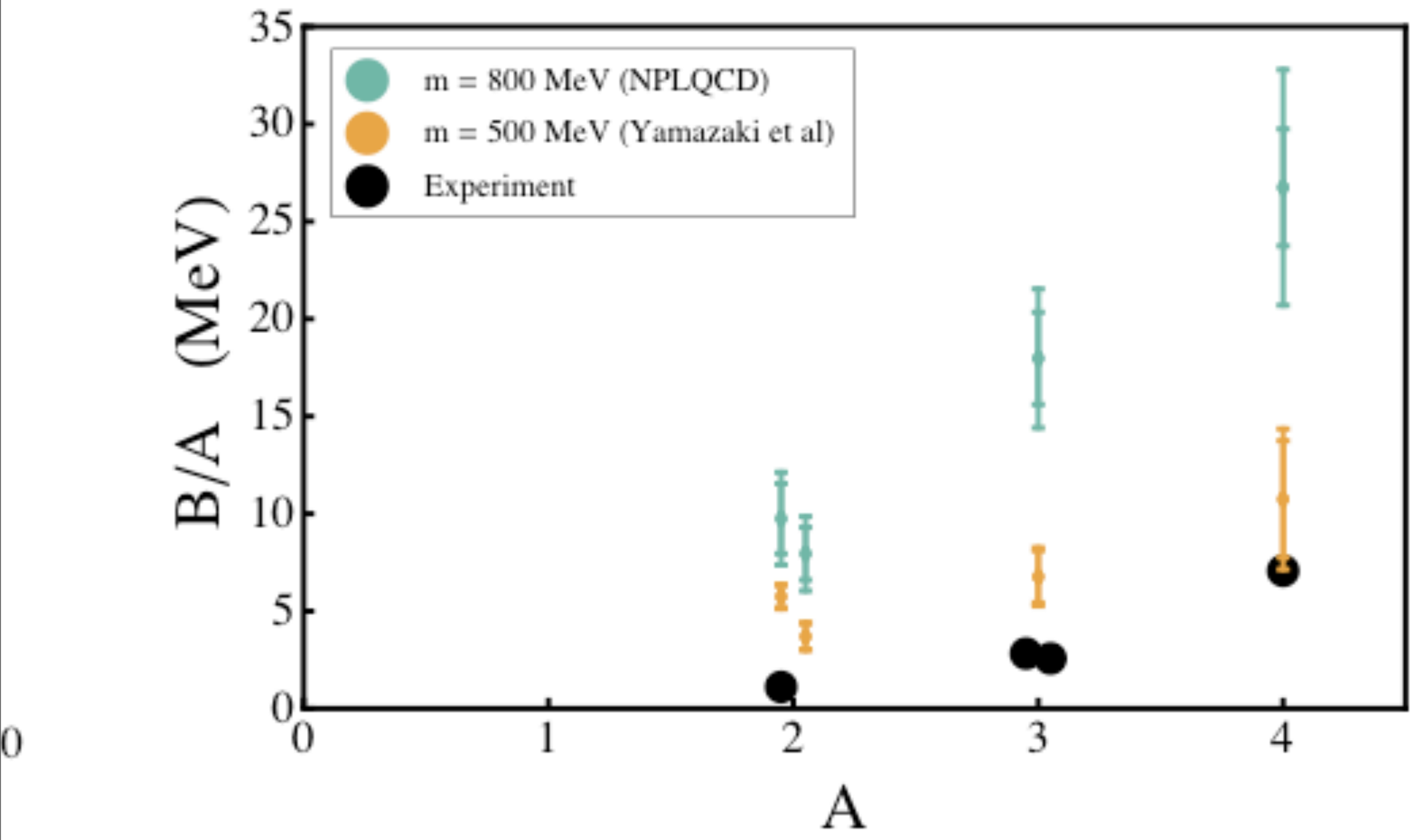
LQCD Computational Resources





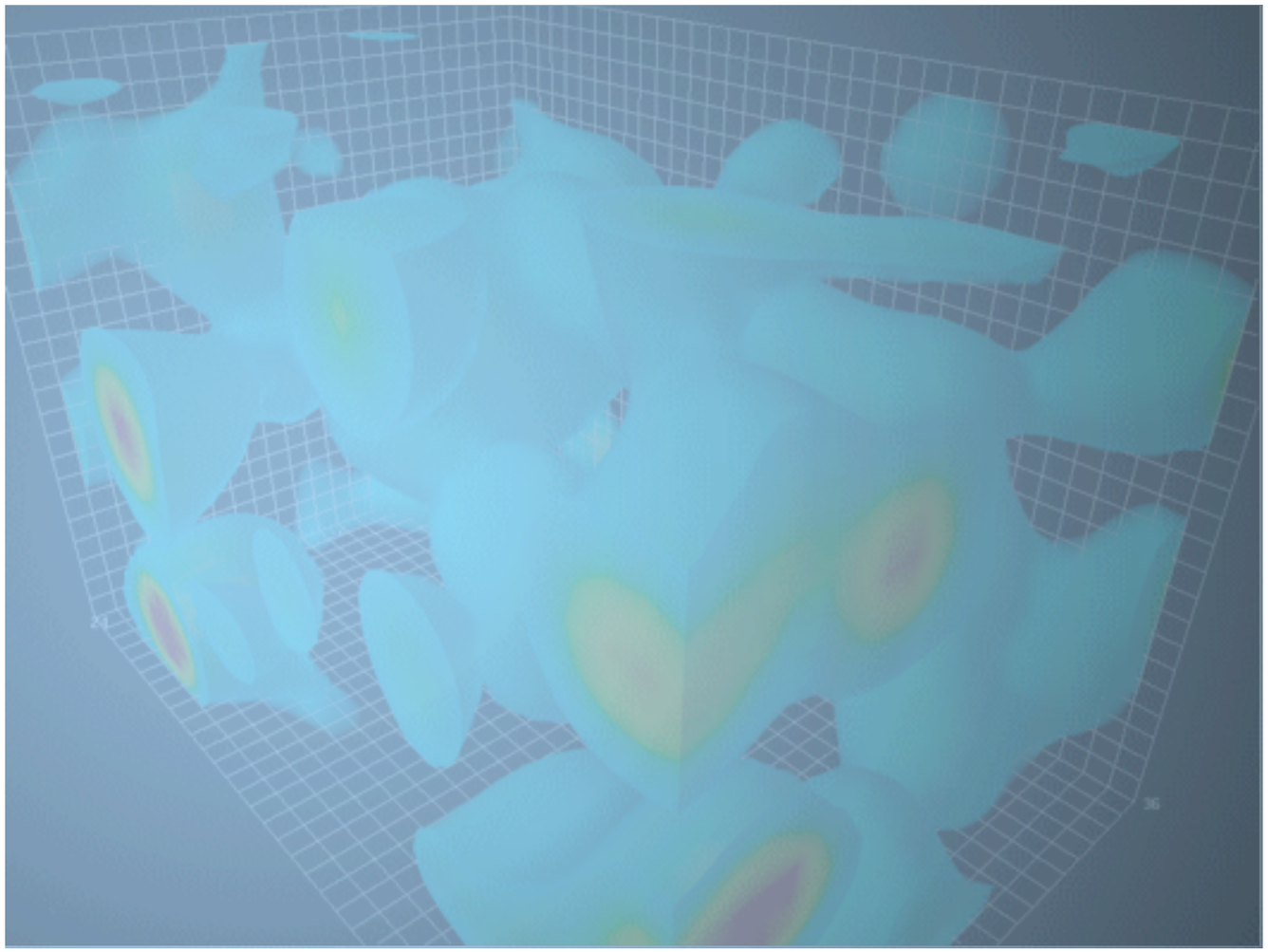
Electromagnetism
Isospin Breaking
The Real Deal !

The Future Starts Today !



The First Workshop on :

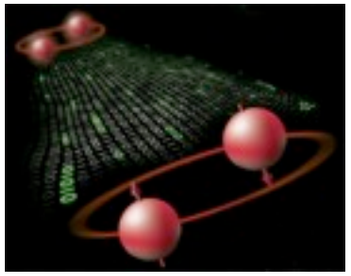
Nuclear Reactions from Lattice QCD



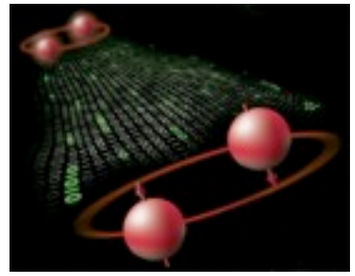
- Crucial research direction for connecting LQCD and NP
- Progress is being made
- Much yet to accomplish
  - future directions outlined

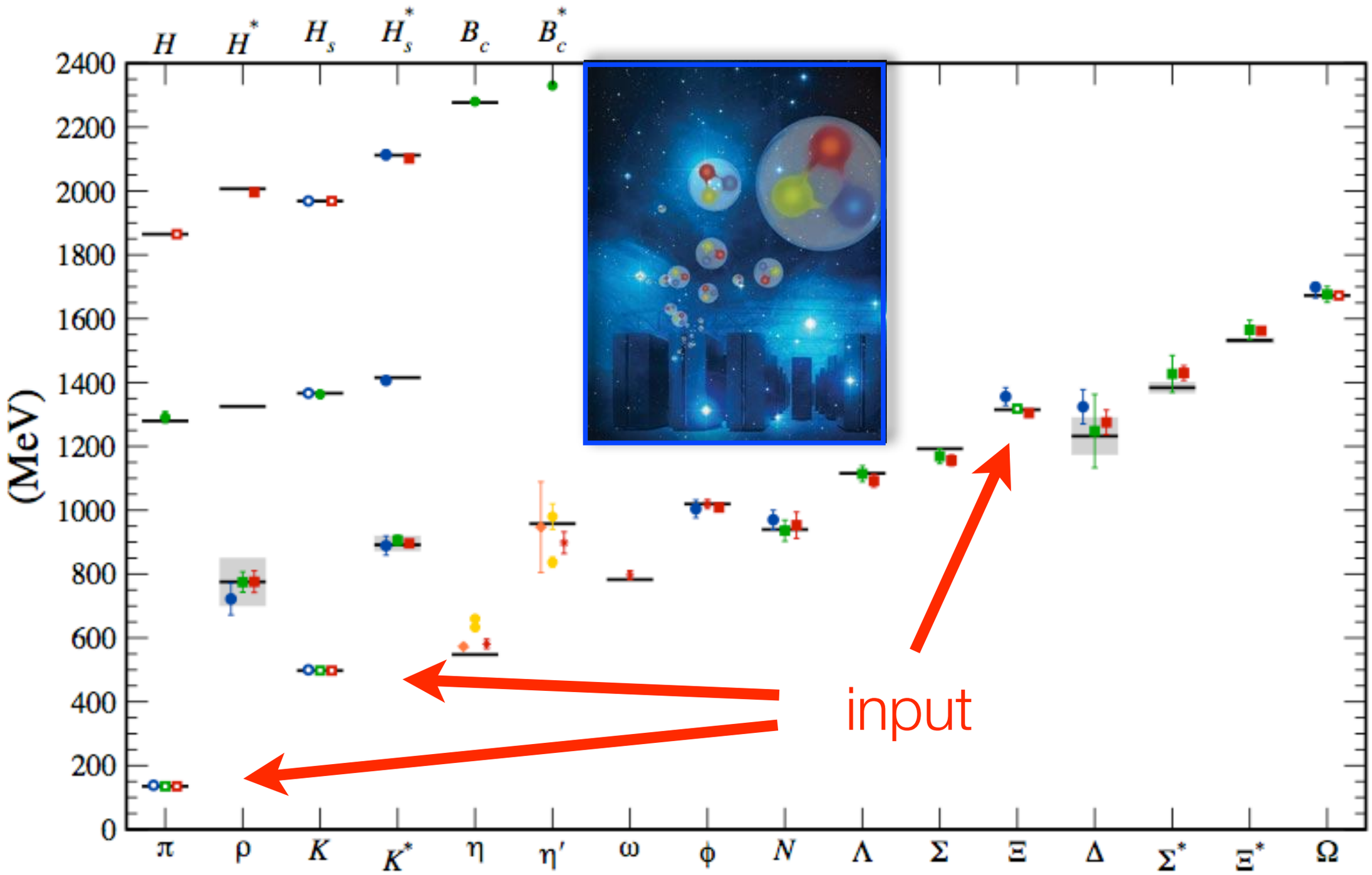
Thanks to :
- Raul Briceno, Zohreh Davoudi and Tom Luu - Great job!
- INT (and NAC), David Kaplan
- Participants !

END



Masses





(Kronfeld)