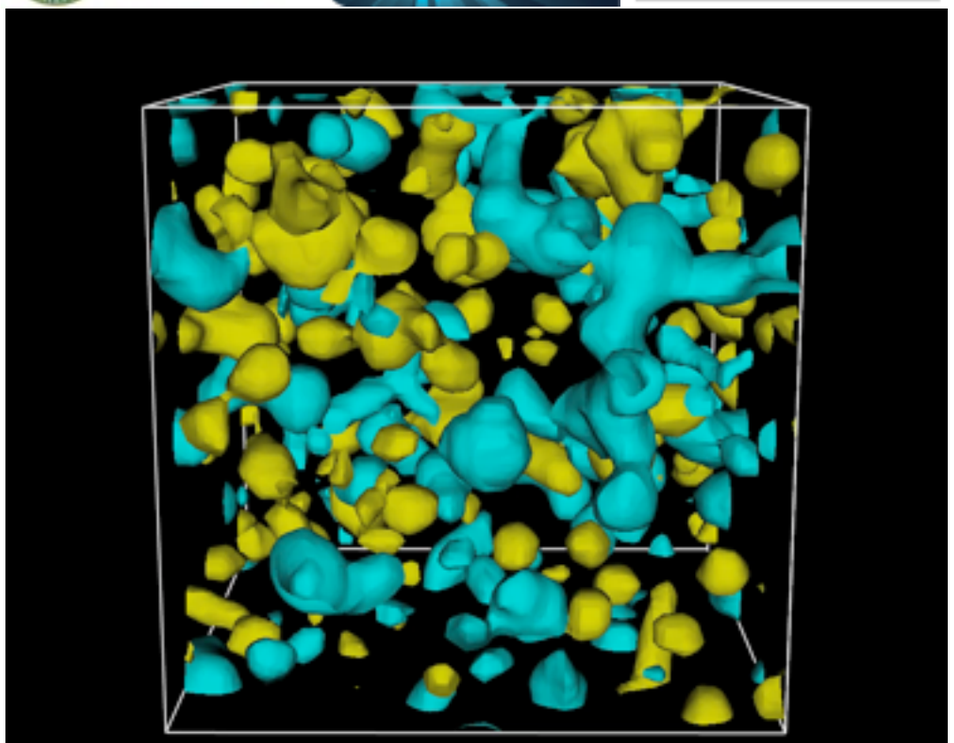


Science :	20 mins :	Martin Savage
Hardware :	15 mins :	Chip Watson
Code, Algorithms, Production :	35 mins :	Robert Edwards

Nuclear Physics from Lattice QCD

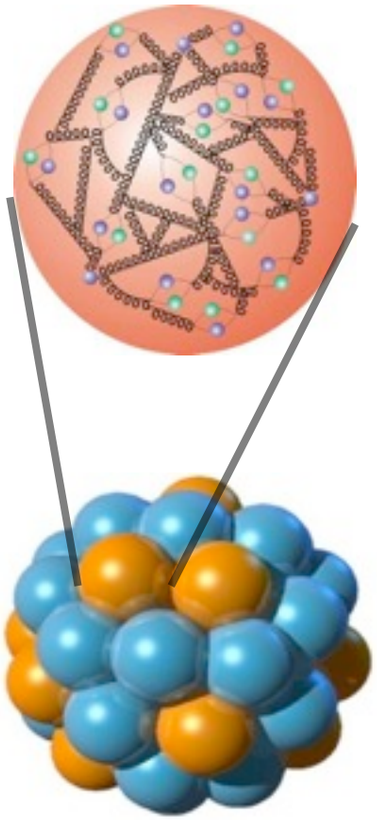
Resources at NERSC

Martin J. Savage, Robert Edwards
and Chip Watson

May 2011, Washington D.C.

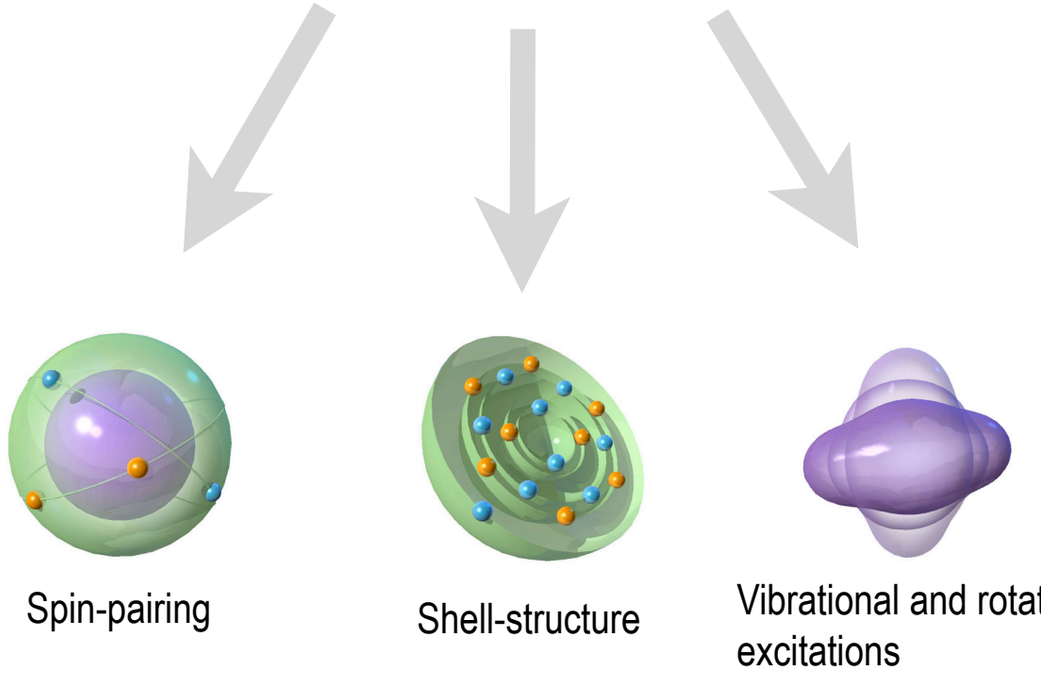
The Structure and Interactions of Matter from Quantum Chromodynamics

Proton



Quarks
and
Gluons

Nucleus



Spin-pairing

Shell-structure

Vibrational and rotational excitations

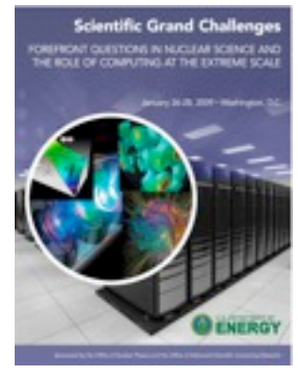
$$\Lambda_{\rm QCD}$$

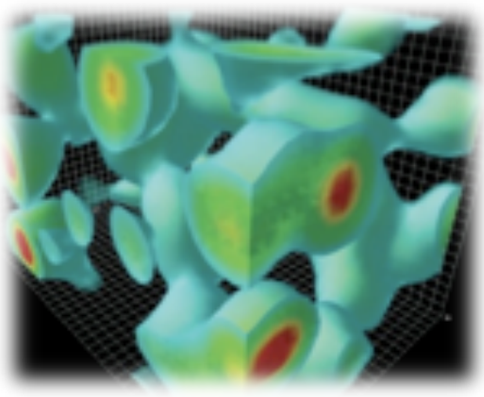
$$\frac{m_u}{\Lambda_{\rm QCD}} \qquad \frac{m_d}{\Lambda_{\rm QCD}} \qquad \frac{m_s}{\Lambda_{\rm QCD}}$$

$$\alpha_e$$

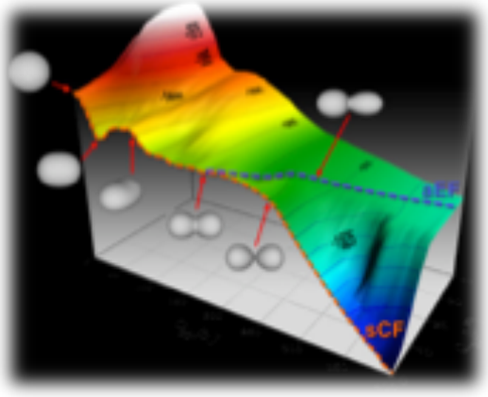
Small number of input parameters responsible for all of strongly interacting matter

Exa-Scale Computational Resources

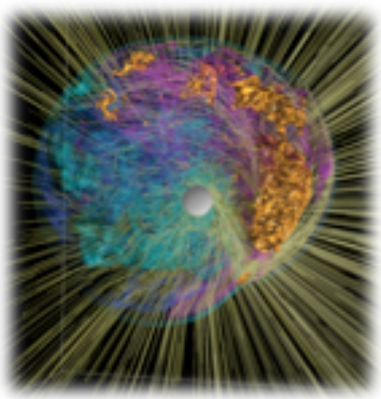




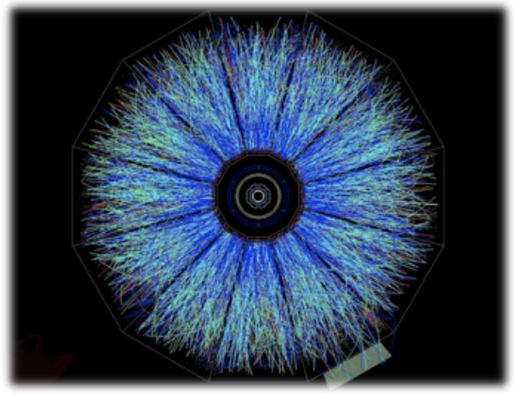
Cold QCD and Nuclear Forces



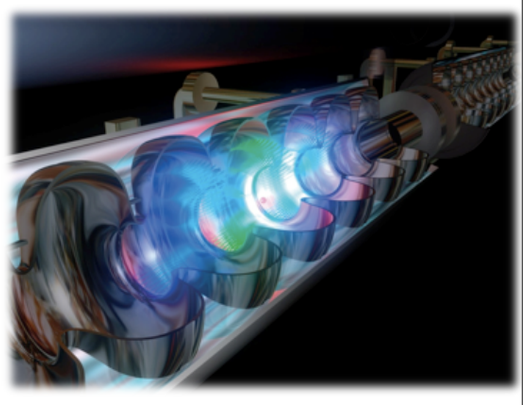
Nuclear Structure and Reactions



Nuclear Astrophysics



Hot and Dense QCD

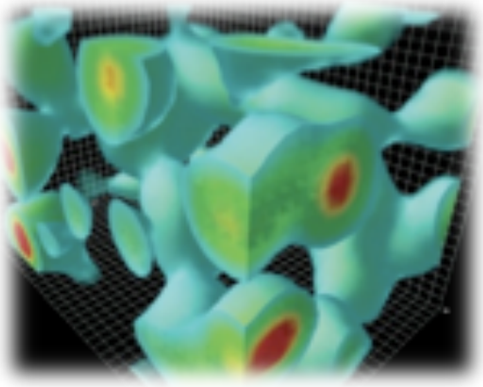


Accelerator Physics

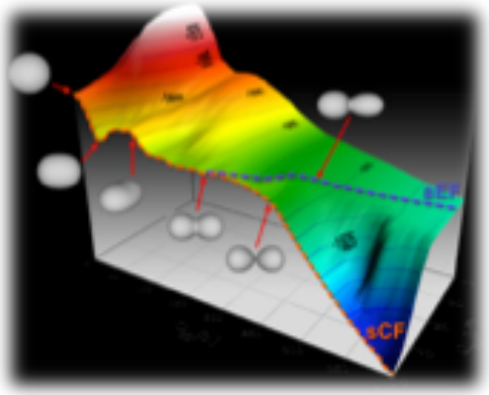
- **Predictive Capability for Nuclear Physics:** Calculations with **quantifiable uncertainties** of processes occurring in nuclei, and in dense and hot matter where experiments are not possible.

Exa-scale Computing is required to accomplish the objectives of the Nuclear Physics Research Program

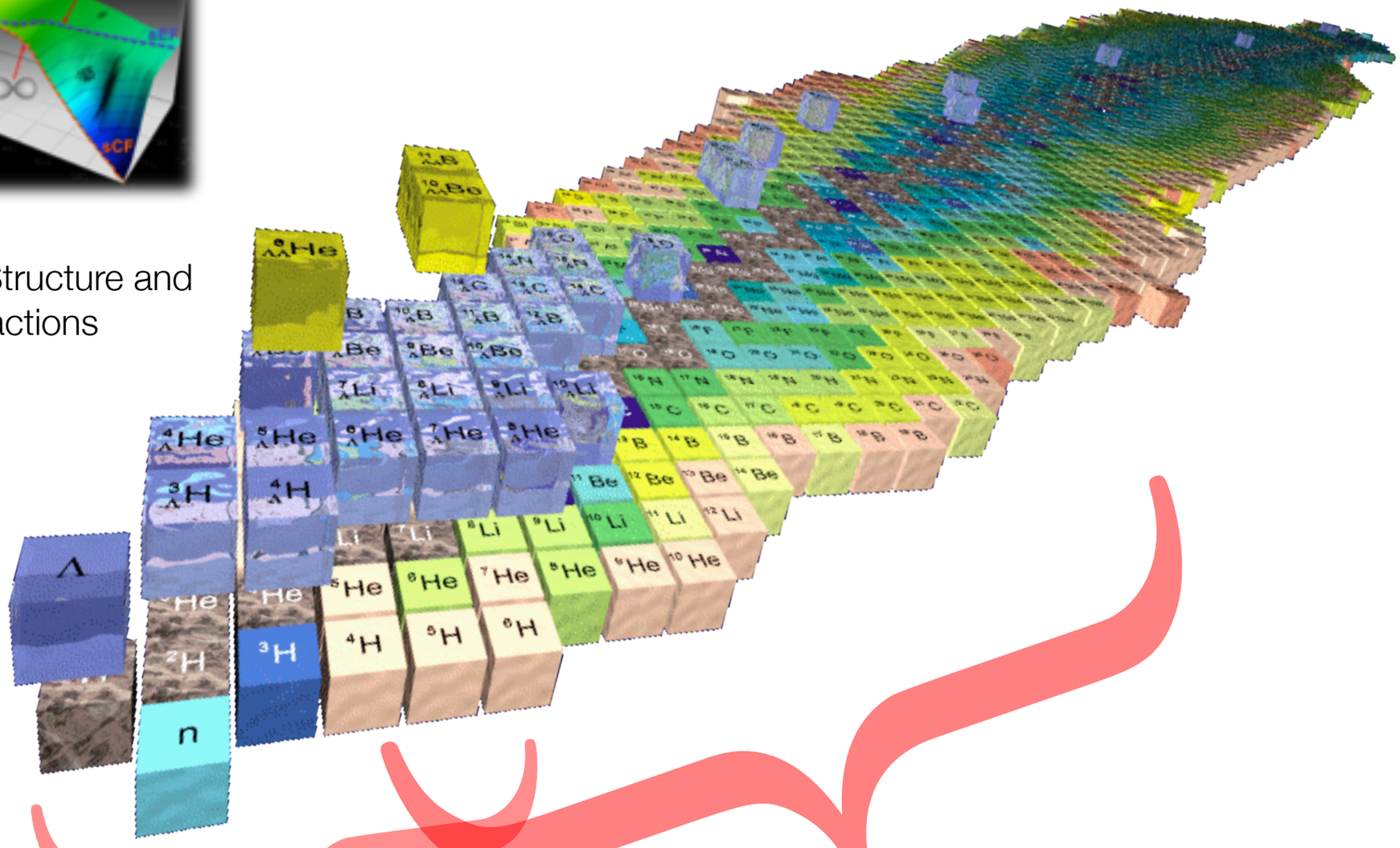
Lattice QCD is initiating a Partial Unification of Nuclear Physics



Cold QCD and
Nuclear Forces

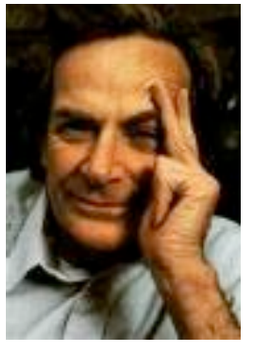


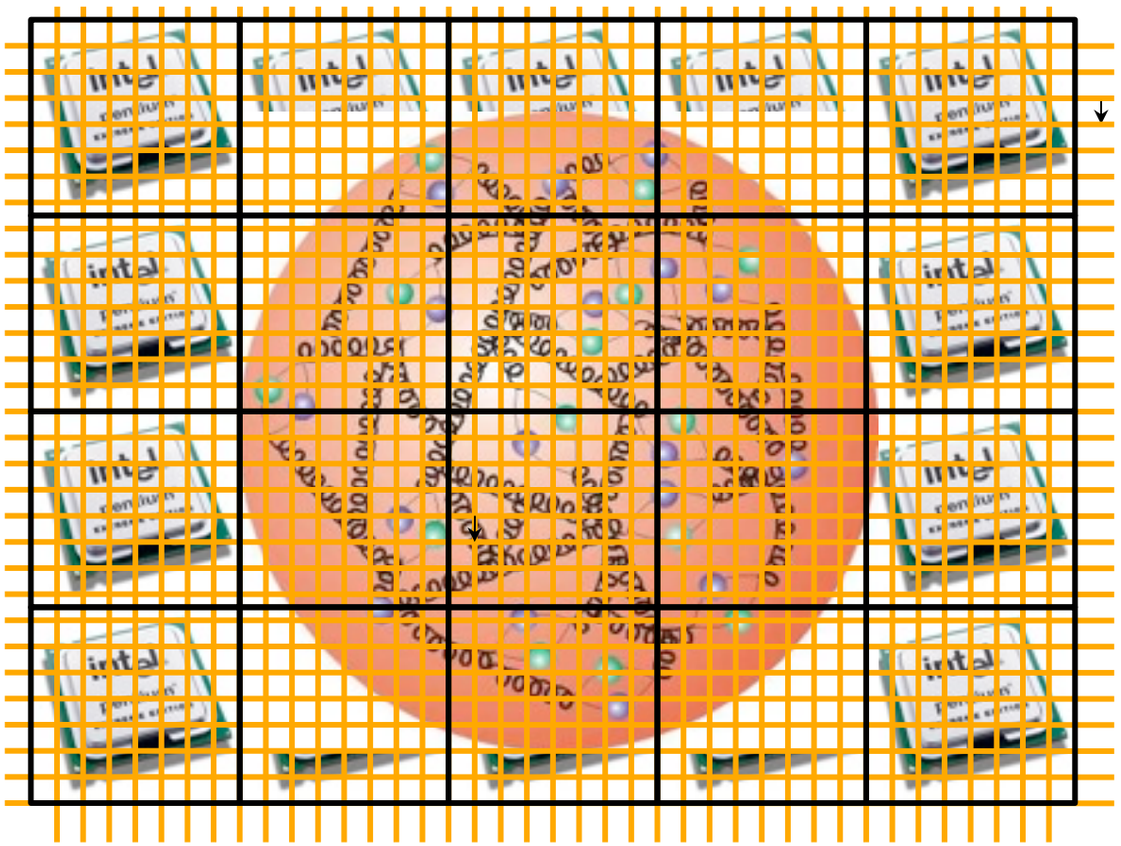
Nuclear Structure and
Reactions



Lattice QCD

Monte-Carlo Evaluation of QCD Path Integral





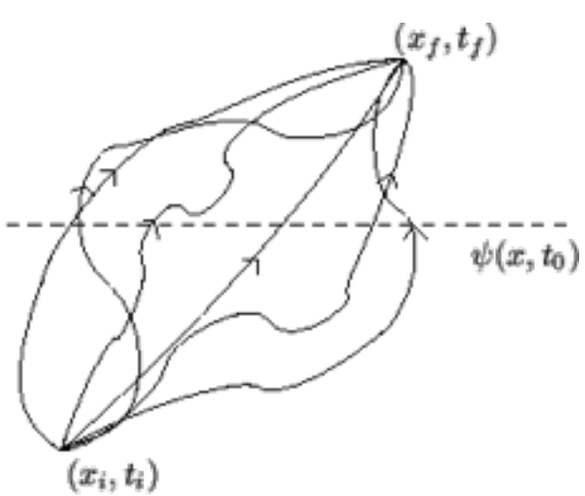
Lattice Spacing :

$a << 1/\Lambda\chi$

Lattice Volume :

$m_\pi L >> 2\pi$

Effective Field Theory gives form of extrapolation $a = 0$ and $L = \infty$



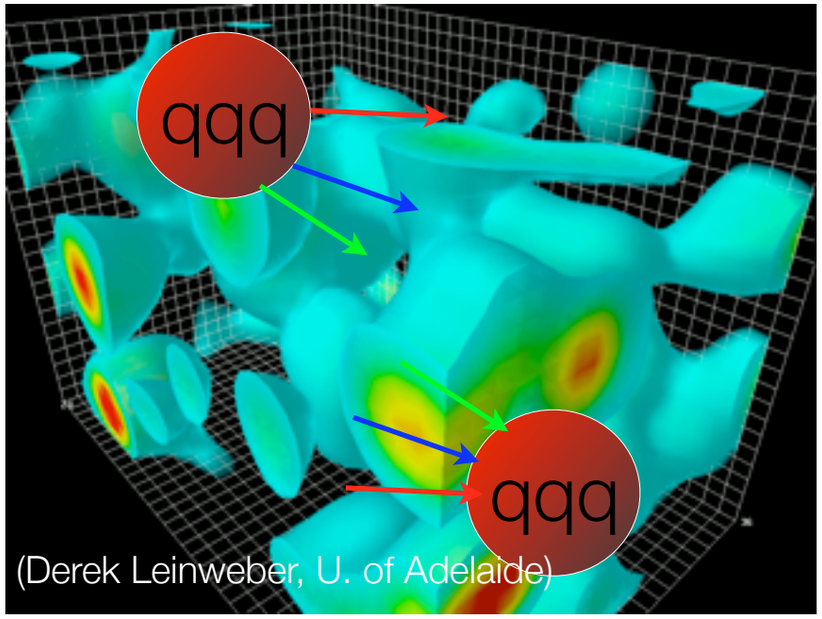
Propagators and Correlators

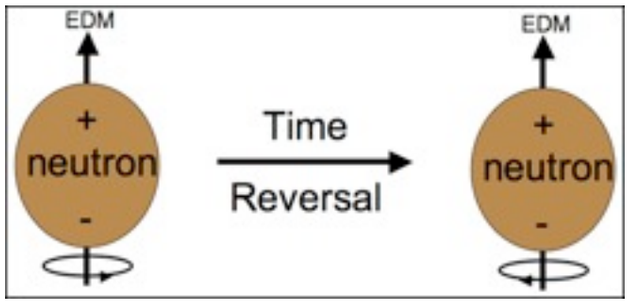
Gauge Configurations

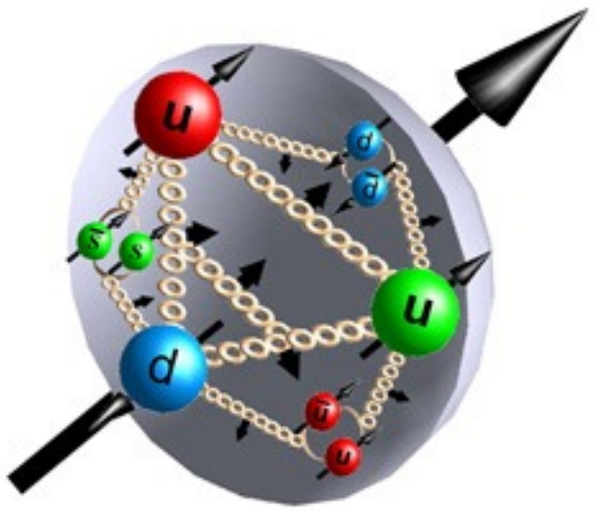
$$\langle \hat{\theta} \rangle \sim \int \mathcal{D}\mathcal{U}_\mu \; \hat{\theta}[\mathcal{U}_\mu] \; \det[\kappa[\mathcal{U}_\mu]] \; e^{-S_{YM}}$$

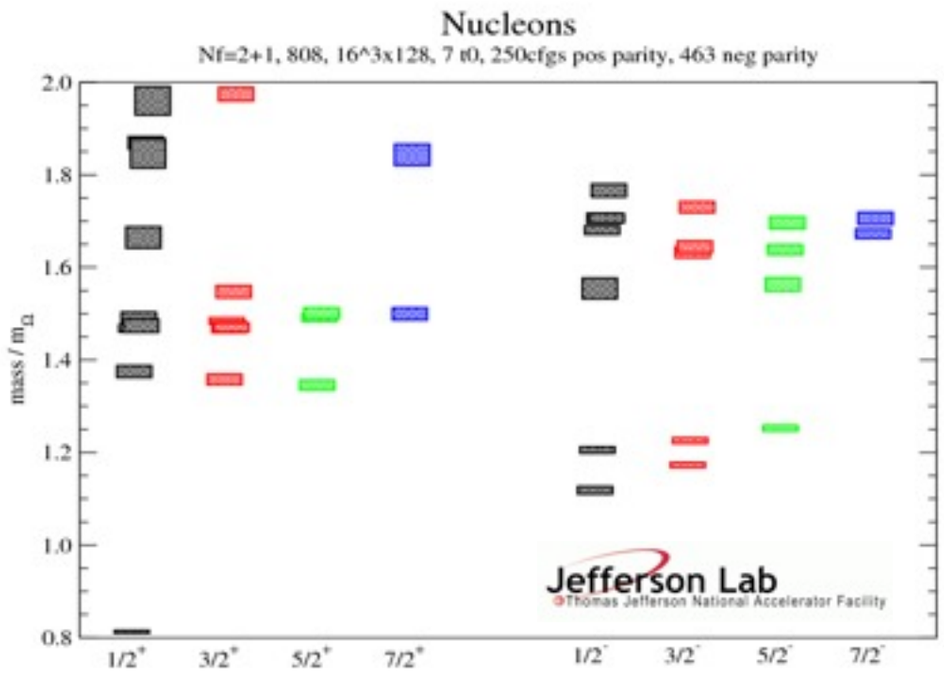
$$\rightarrow \frac{1}{N} \sum_{\text{gluon cfgs}}^{N} \hat{\theta}\,[\mathcal{U}_\mu]$$

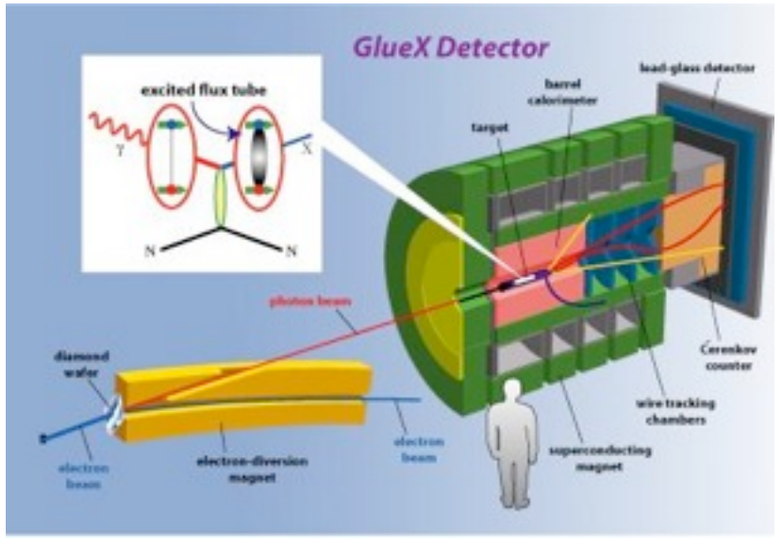
The Structure of Hadrons : Cold Lattice QCD





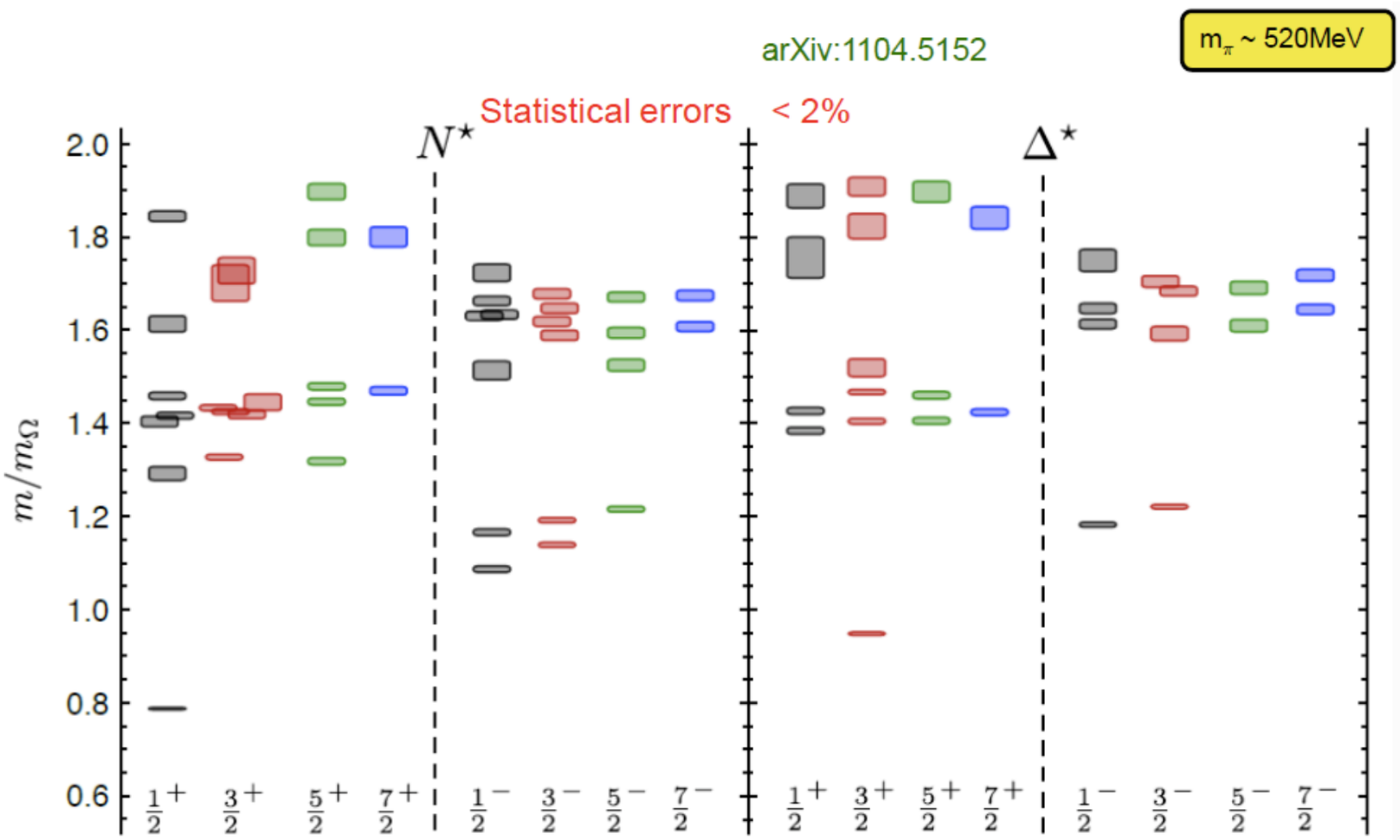






Excited Baryon Spectrum

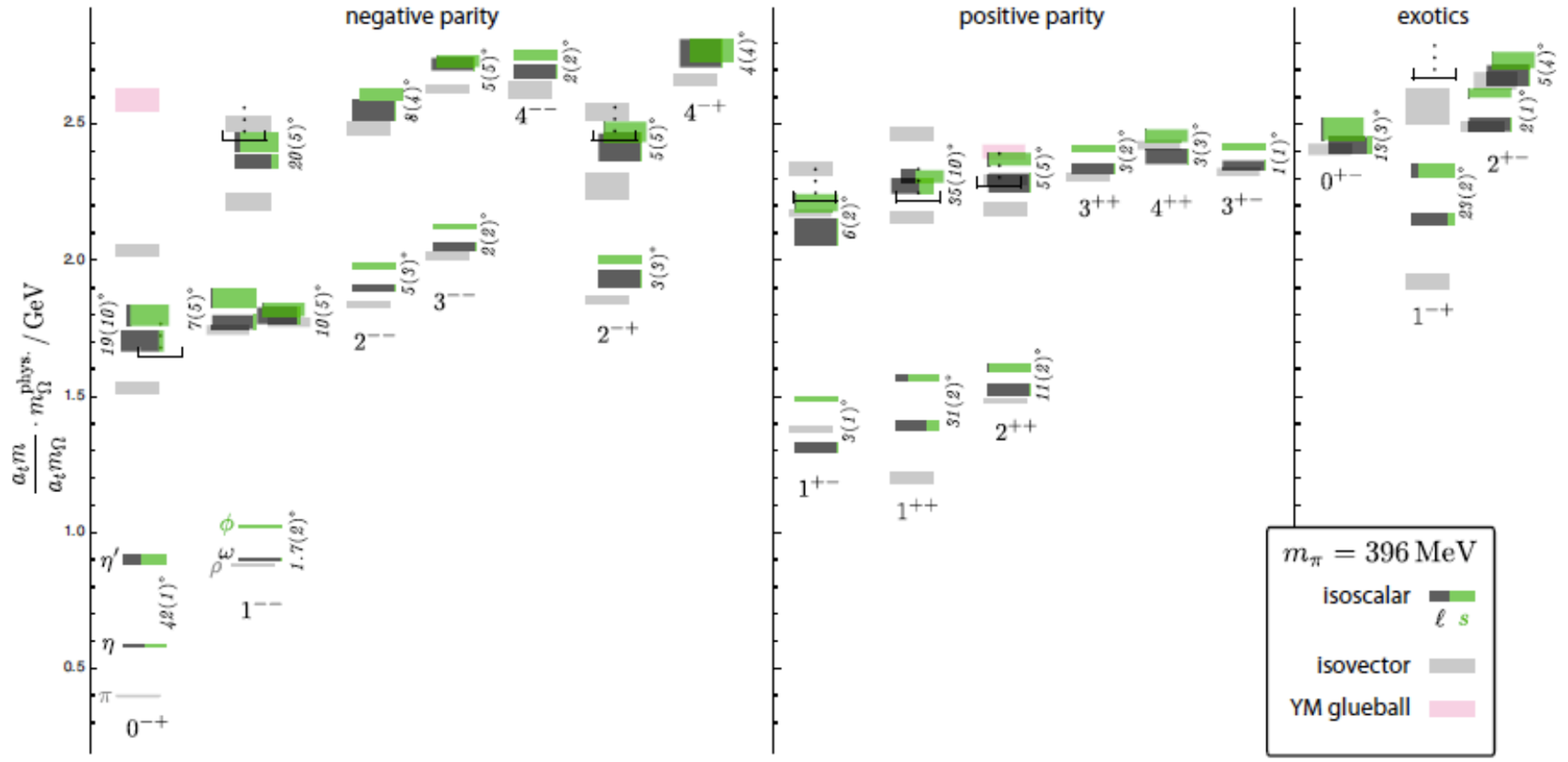
$m_\pi \sim 520$ MeV



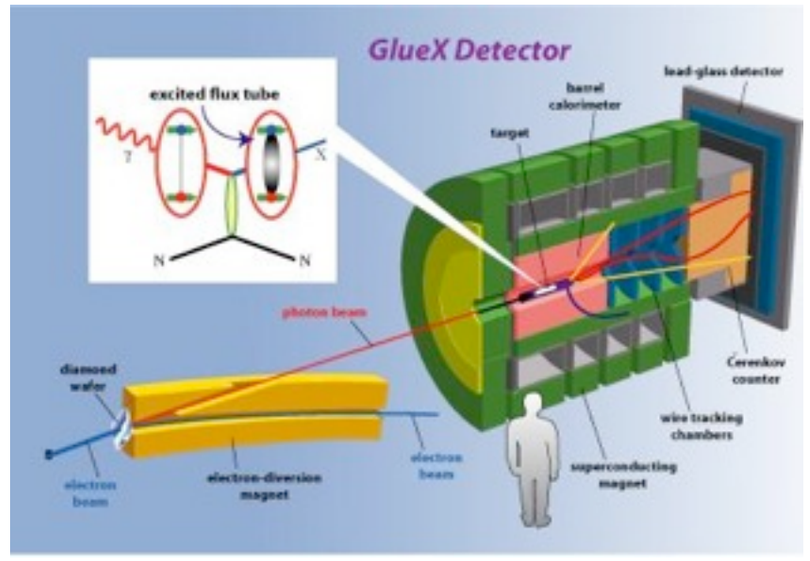
Edwards *et al*, arXiv:1104.5152

NSAC Milestone 2012 HP7: Measure the electromagnetic excitations of the low-lying baryon states and their transition form factors over a range Q2 = 0.1-7 GeV2 and measure the electro- and photo-production of final states with one and two pseudoscalar mesons

Excited Meson Spectrum
Exotics



Dudek *et al* , arXiv:1102.4299



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

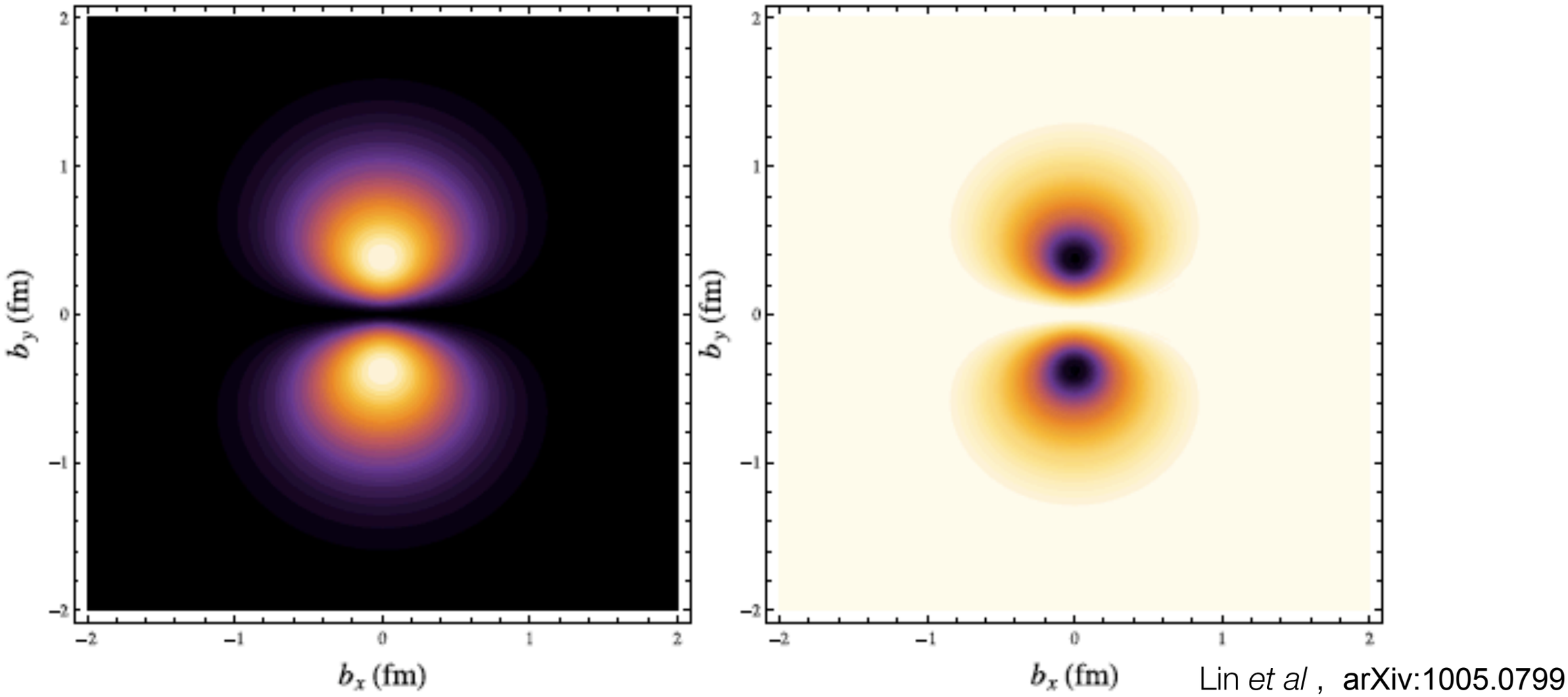
(with sufficient compute resources)

NSAC Milestone 2018 HP15: The first results on the search for exotic mesons using photon beams will be completed.

Nucleon Structure
Magnetization Density

Proton

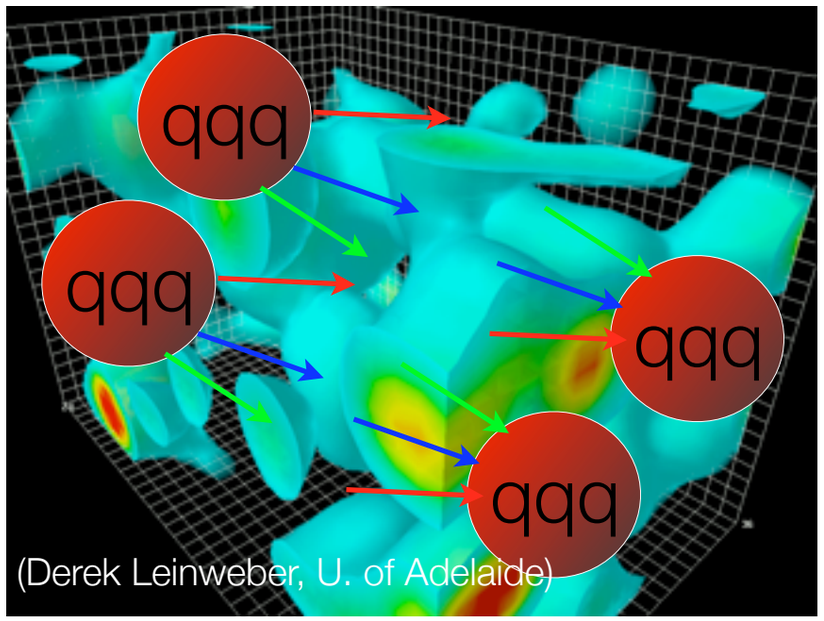
Neutron

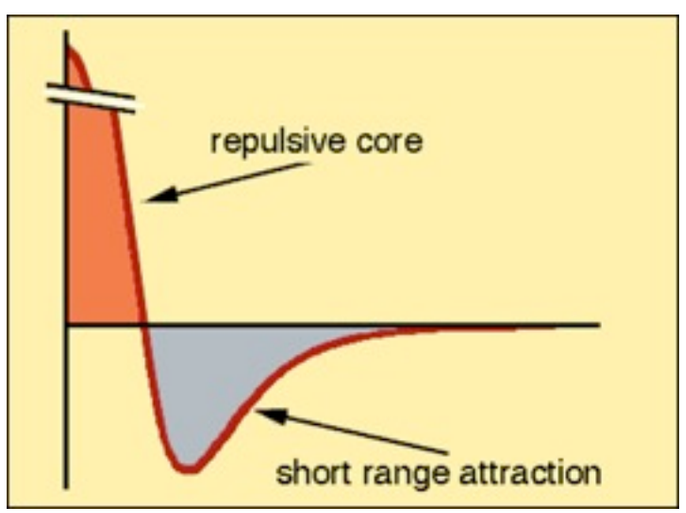


Lin *et al* , arXiv:1005.0799

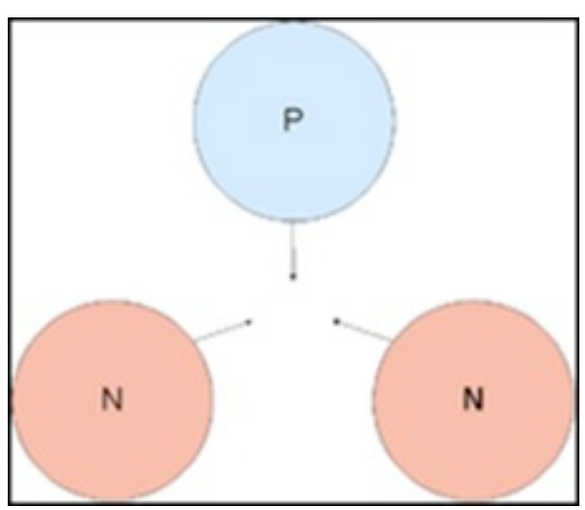
NSAC Milestone 2014 HP9: Perform lattice calculations in full QCD of nucleon form factors, low moments of nucleon structure functions and low moments of generalized parton distributions including flavor and spin dependence.

Nuclear Forces and Multi-Hadron Systems



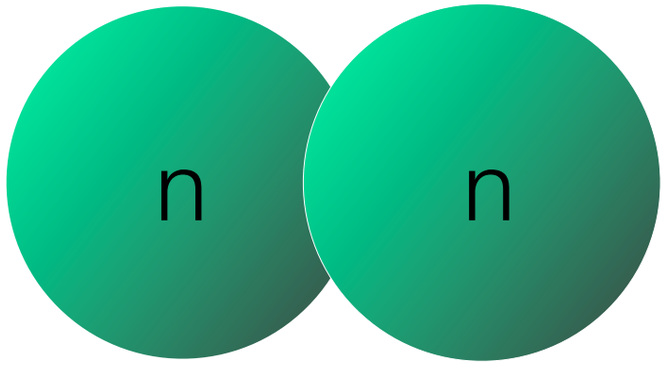


χ-symmetry

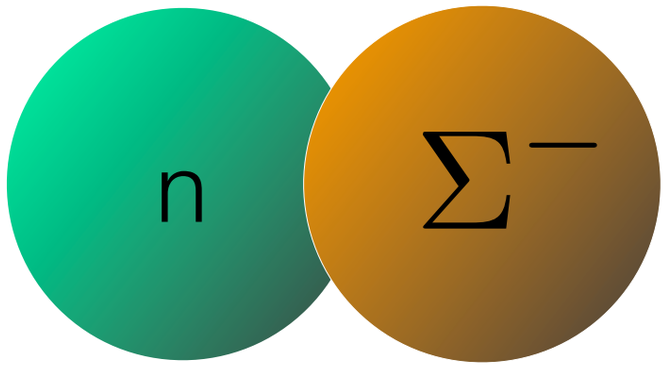


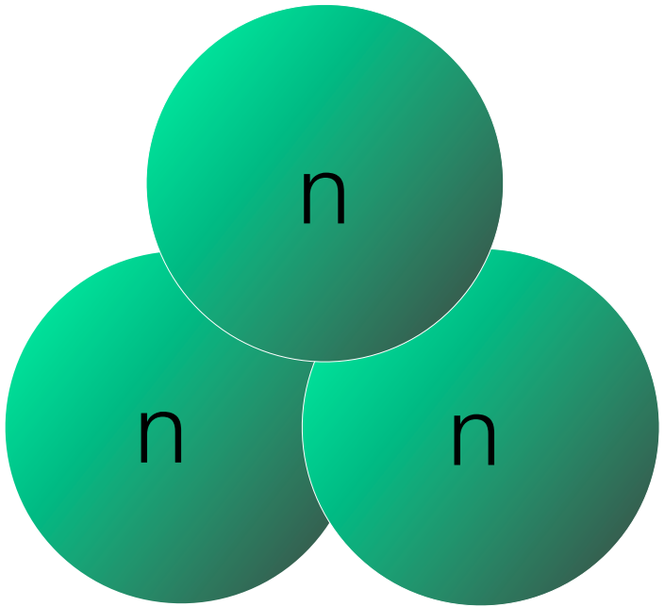
χ-symmetry

Hadronic Interactions

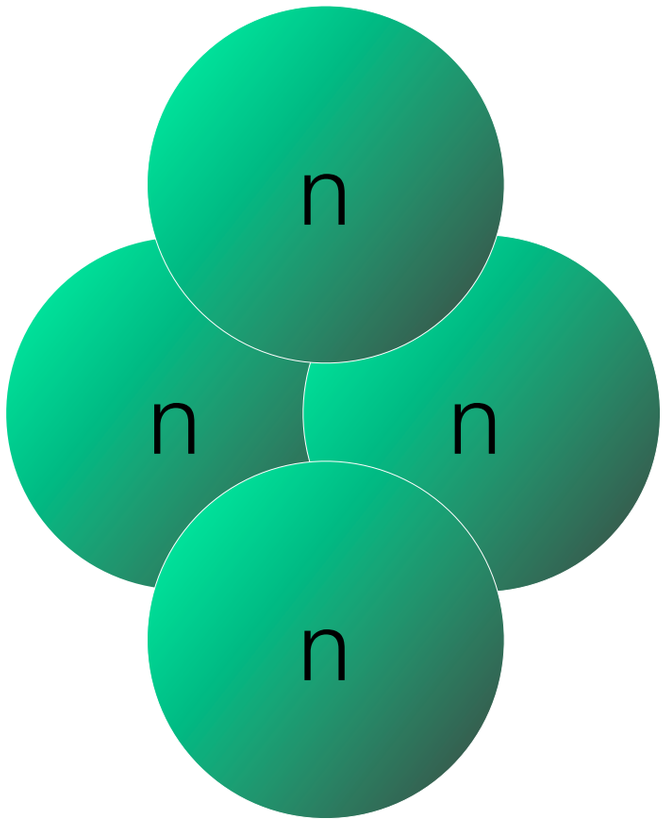


NN-interaction verification

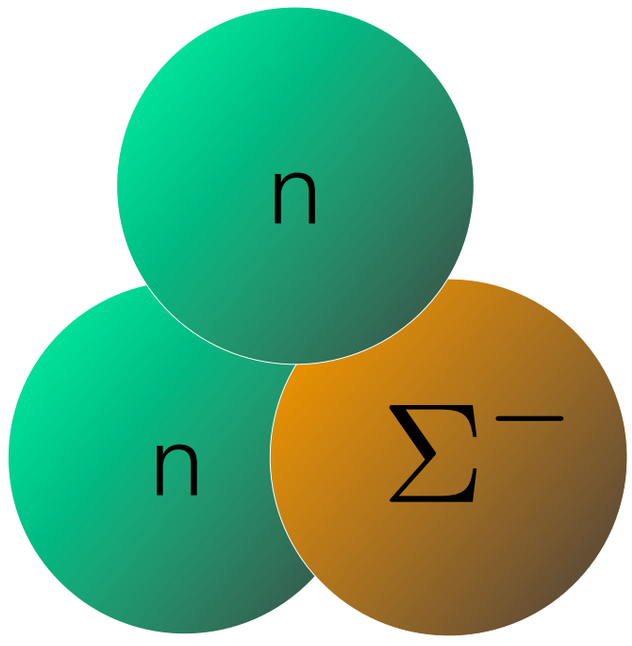




NNN

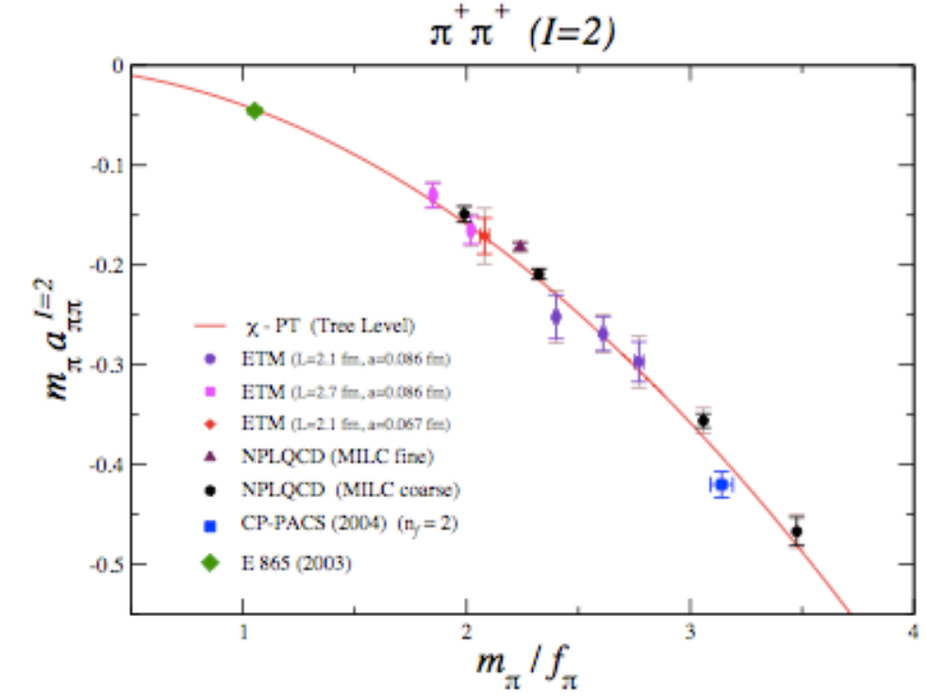


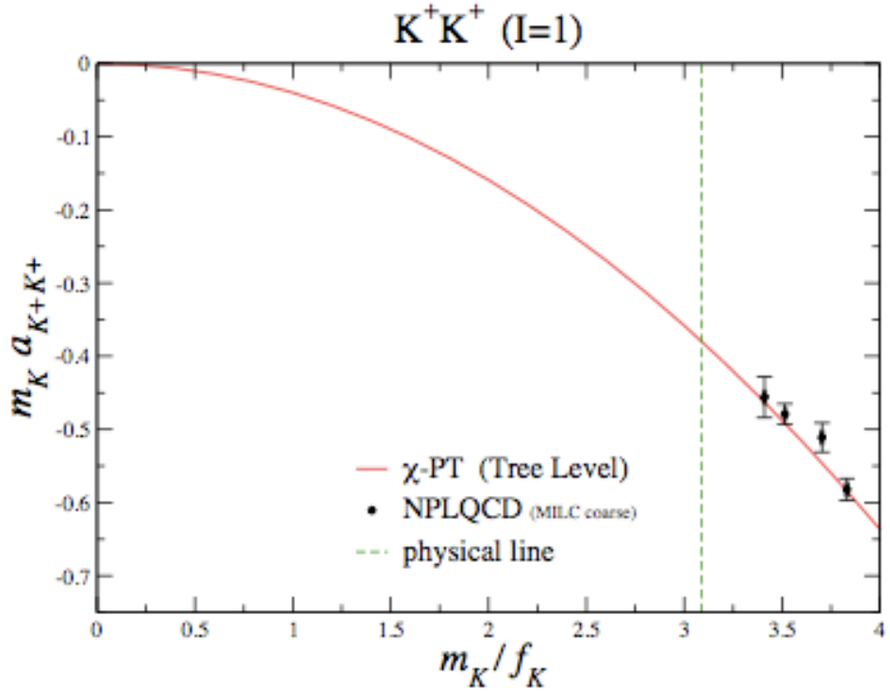
NNNN

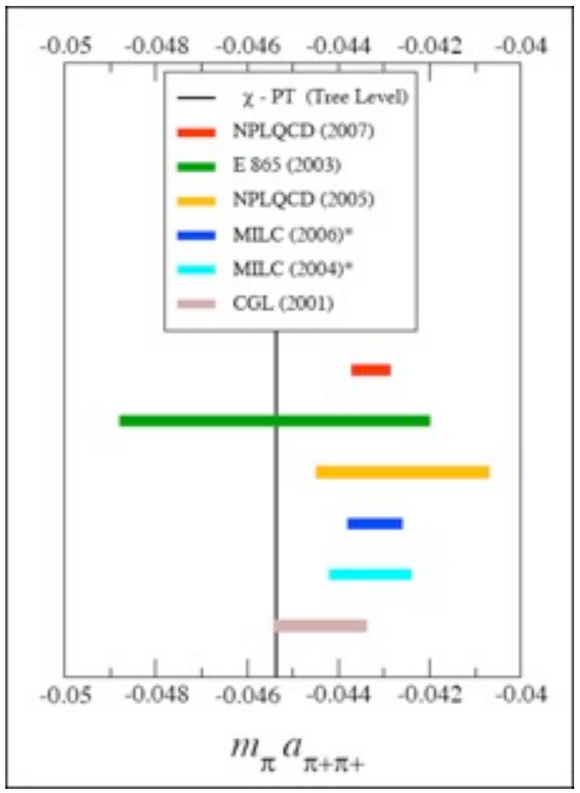


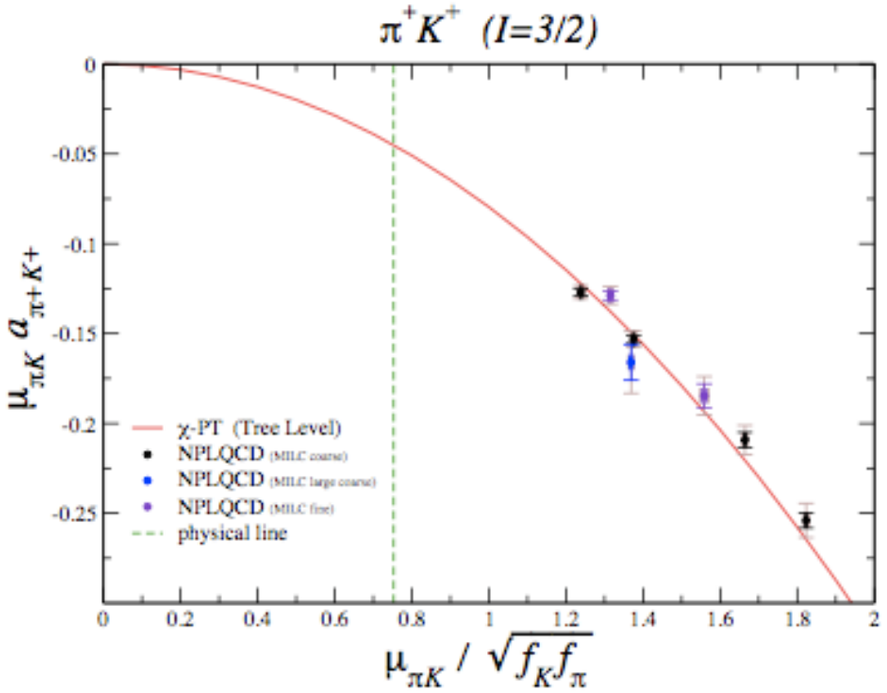
YNN

Lattice QCD and the Simplest Hadronic Interactions







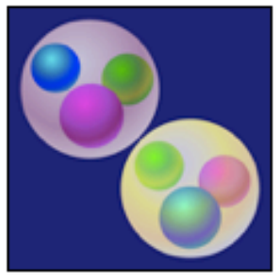


H-Dibaryon
An Exotic Nucleus

Jefferson Lab

sics » Synopses » Binding baryons on the lattice

Binding baryons on the lattice



Credit: Alan Stonebraker

Evidence for a Bound *H* Dibaryon from Lattice QCD

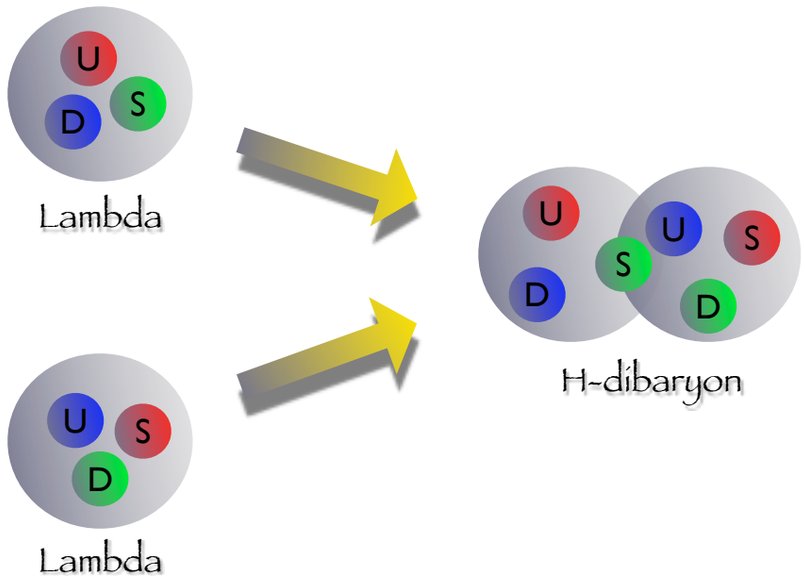
S. R. Beane, E. Chang, W. Detmold, B. Joo, H. W. Lin, T. C. Luu, K. Orginos, A. Parreño, M. J. Savage, A. Torok, and A. Walker-Loud (NPLQCD Collaboration)

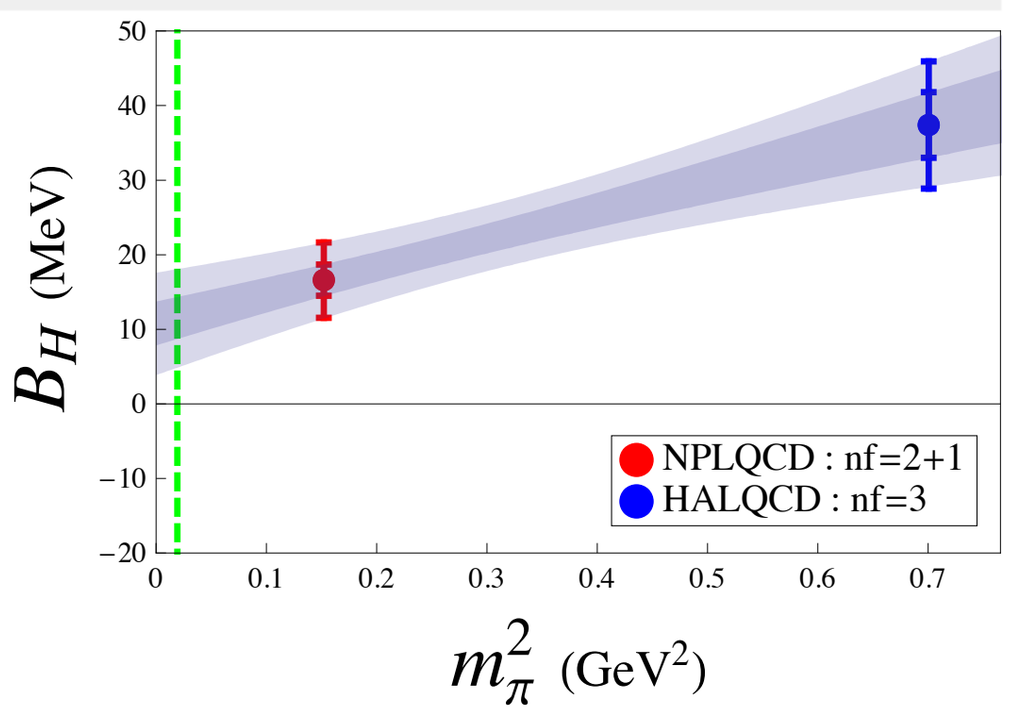
Phys. Rev. Lett. **106**, 162001 (Published April 20, 2011)

Bound *H* Dibaryon in Flavor SU(3) Limit of Lattice QCD

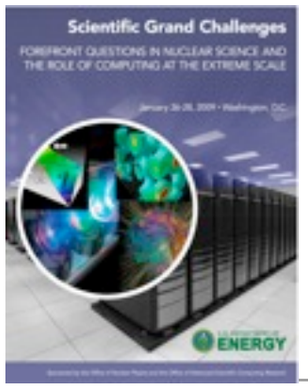
Takashi Inoue, Noriyoshi Ishii, Sinya Aoki, Takumi Doi, Tetsuo Hatsuda, Yoichi Ikeda, Keiko Murano, Hidekatsu Nemura, and Kenji Sasaki (HAL QCD Collaboration)

Phys. Rev. Lett. **106**, 162002 (Published April 20, 2011)

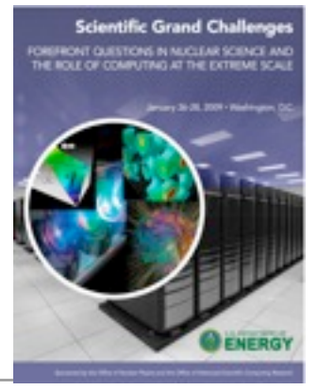




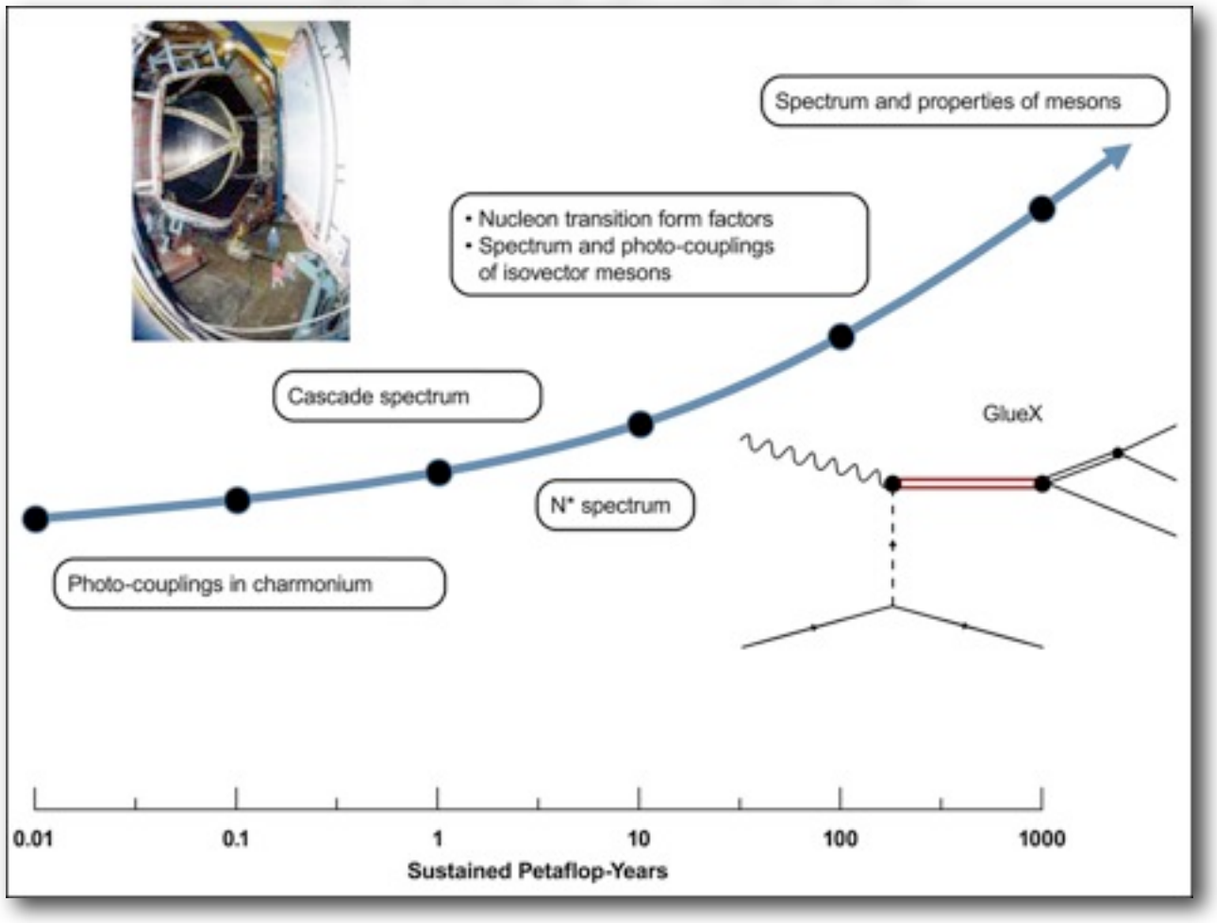
NSAC Milestone 2014 HP10: Carry out *ab initio* microscopic studies of the structure and dynamics of light nuclei based on two-nucleon and many-nucleon forces and lattice QCD calculations of hadron interaction mechanisms relevant to the origins of the nucleon-nucleon interaction



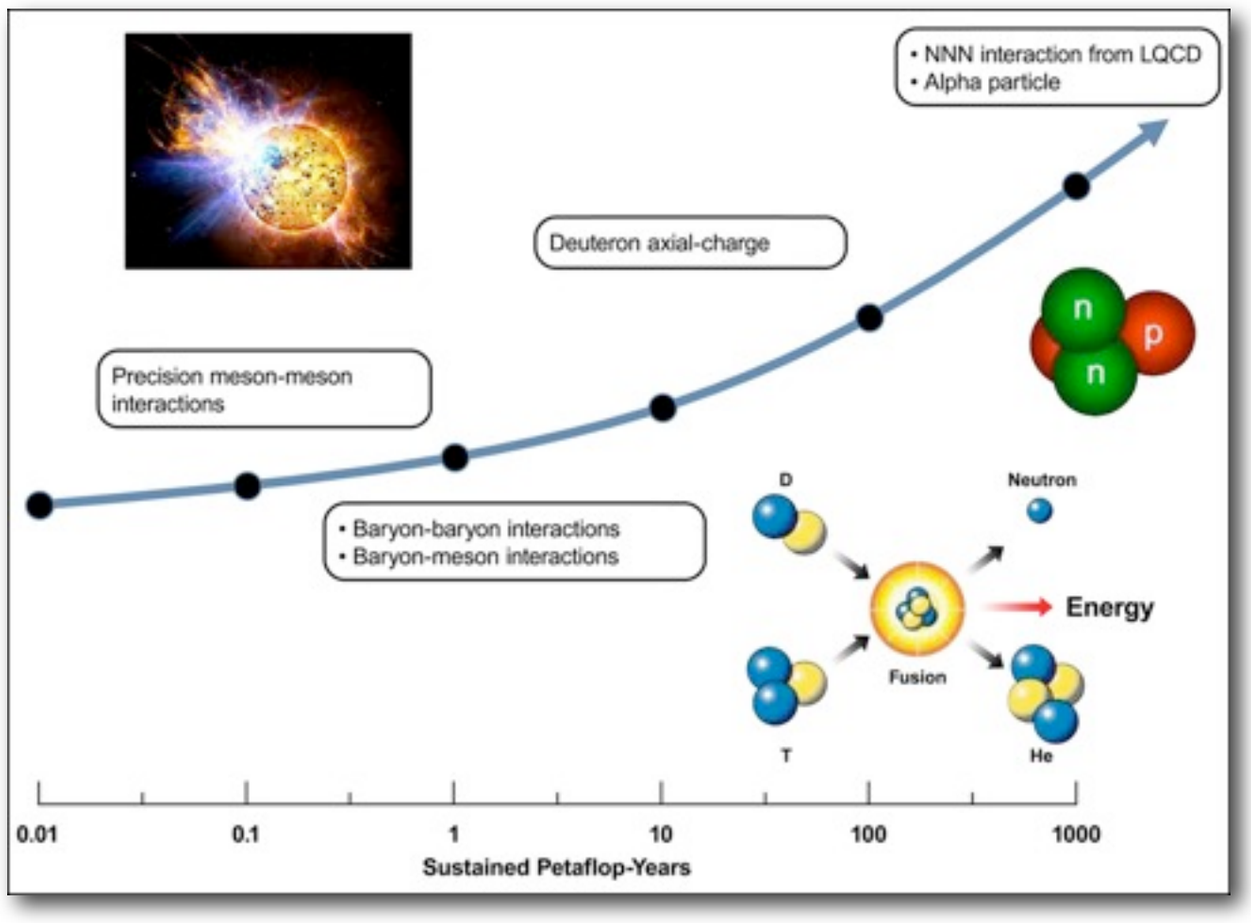
Computational Requirements



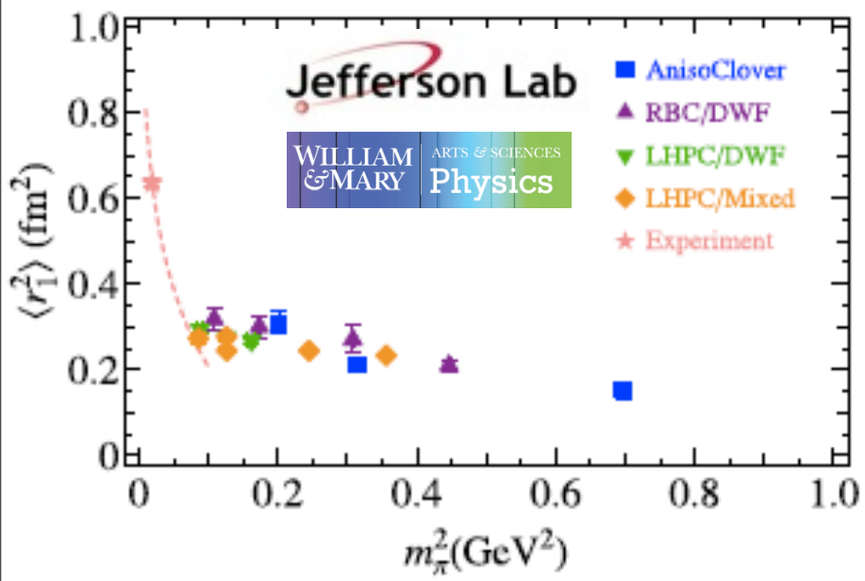
The Spectrum and Structure of hadrons

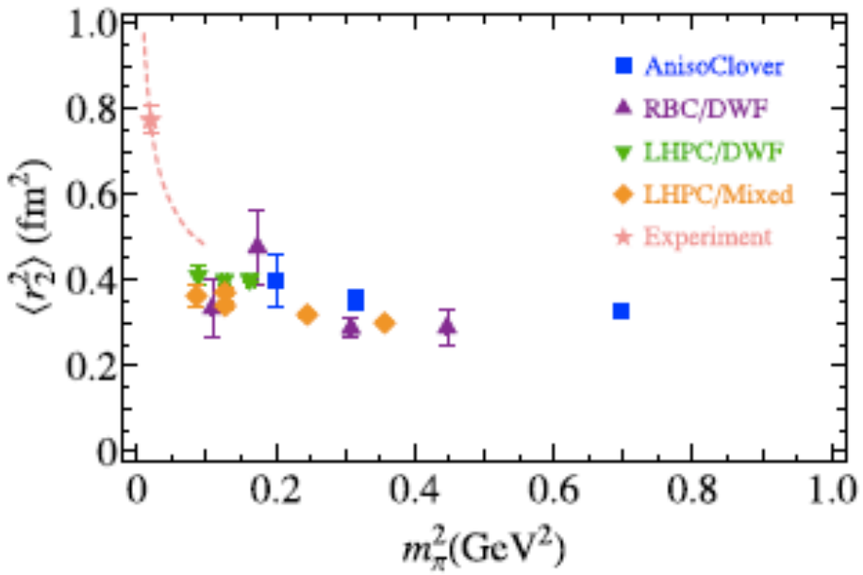


From QCD to Nuclei

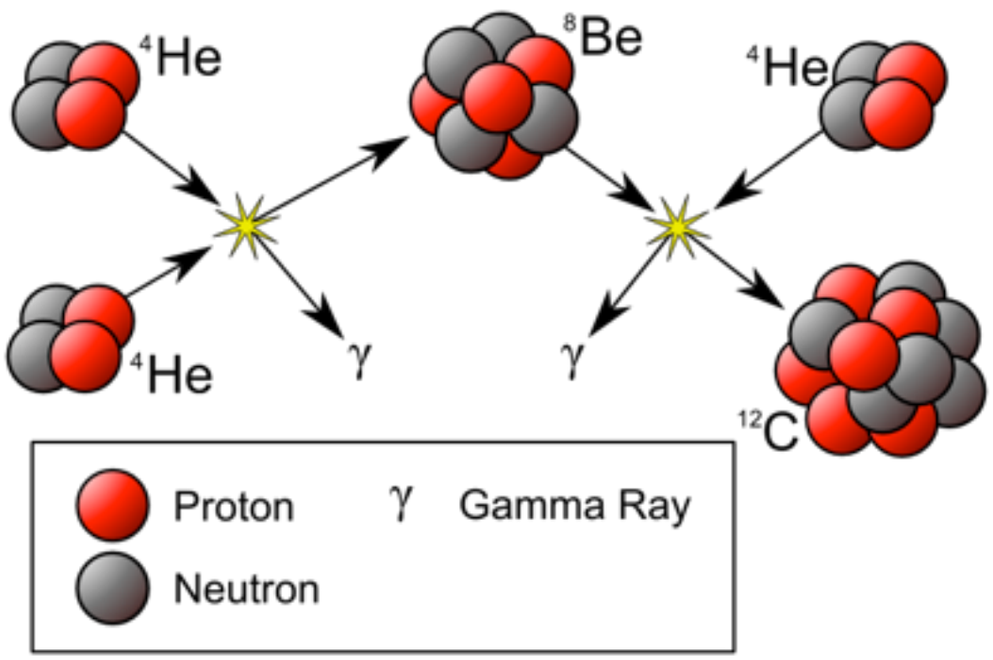


Nuclear Physics at the Physical Pion Mass





Chiral Behavior
-QCD symmetries



Nuclear Physics is Fine-Tuned
-QCD input parameters
-Our universe is special ?

Presentations by
Chip Watson and Robert Edwards

Summary of NERSC Resources 2011-2014 for Lattice QCD for Nuclear Physics (I)

- Field has evolved forward rapidly during 2006-2011

- More than 10^9 core-hours per year (average) during 2011-2014 to accomplish relevant near-term NSAC milestones
  - physical pion mass (elimination of a major systematic)
  - structure of matter
  - nuclear forces and the interactions of hadrons
  - all codes, algorithms, formalism in place for peta-scale resources

- Code evolution to exa-scale

- GPU hardware and software deployed

Summary of NERSC Resources 2011-2014 for Lattice QCD for Nuclear Physics (II)

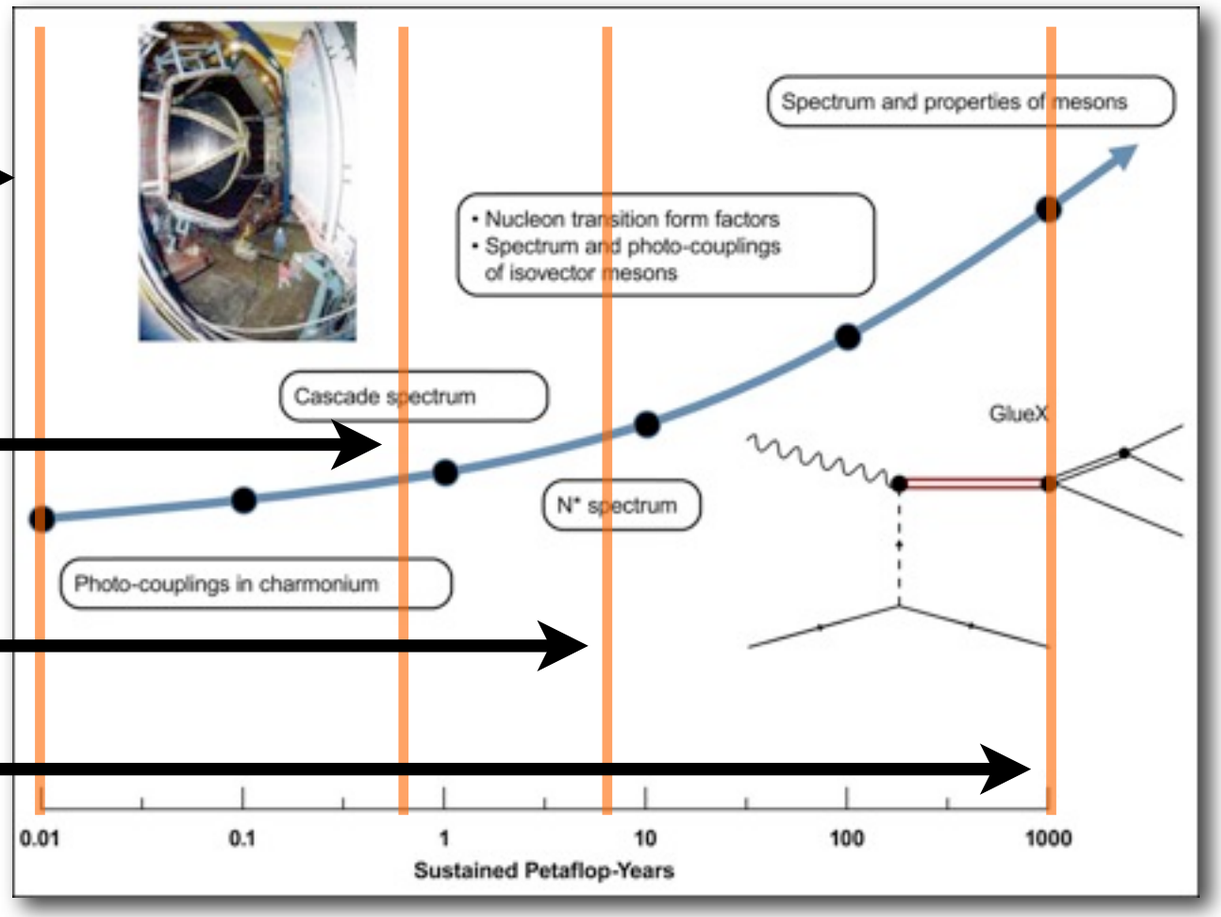
- 2010 - 2011 : ~16 x 10^6 core-hrs charged and 70 x 10^6 core-hrs USED
- x 50 : 3.5 x 10^9 core-hrs
- Transformational for NP : > 5 Pflops sustained~ 50x 10^9 core-hrs

NERSC Nuclear Physics 2010-2011

x 50

5 Pflop-yrs

Exascale in 2018 ?



Nuclear Physics ``opens up'' to Lattice QCD around the Peta-Scale

END