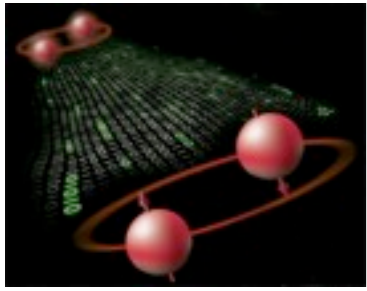


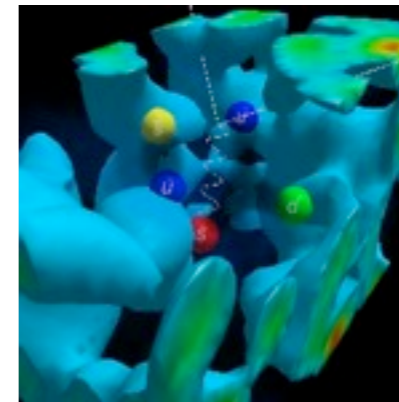
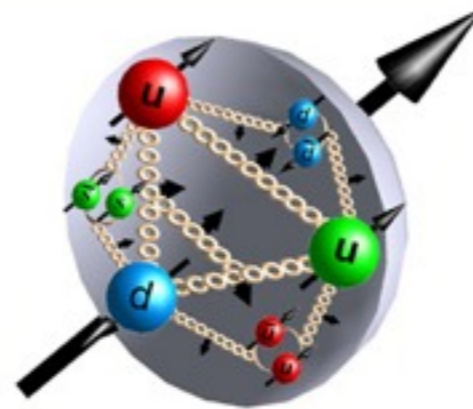
## Nuclear Physics in USQCD

Martin J. Savage  
University of Washington  
FermiLab , May 2012



# Cold Nuclear Physics Program

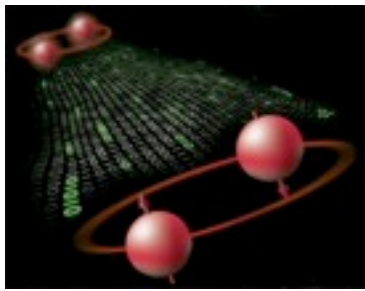
- Spectroscopy
- Nucleon Structure
- Nuclear Interactions



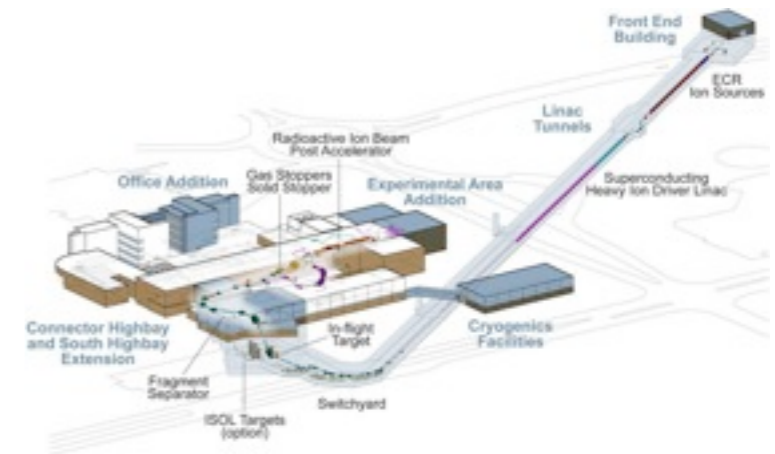
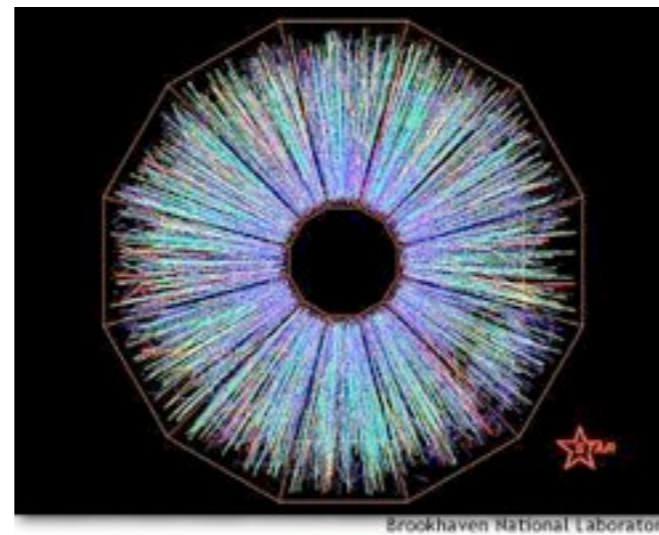
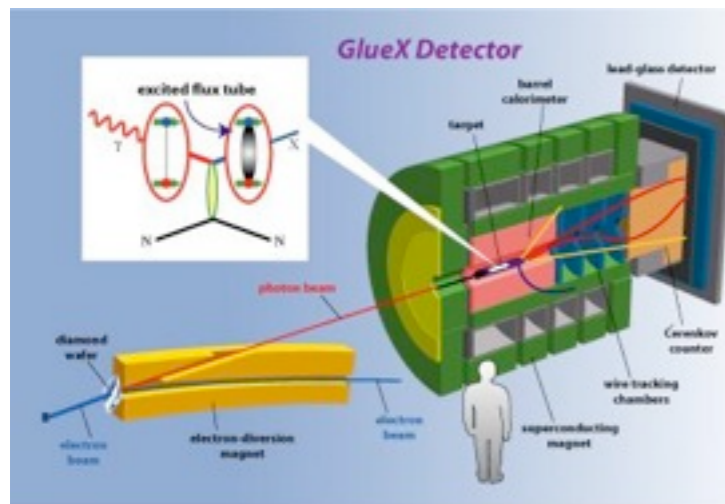
- NSAC Milestones

- Different mass scales in NP c/w HEP

- different production constraints - precision in baryon correlators is crucial
- different lattices - volumes, aniso ?, lattice spacing, pion masses
- different workflows
- “measurements” dominate production costs



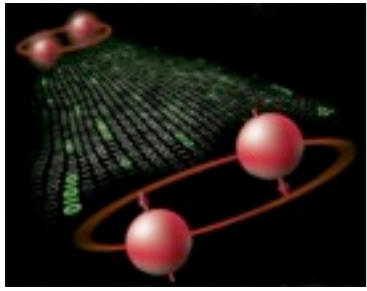
# NP Experimental Program



- JLab
- Spectroscopy
- Nucleon structure
- 12 GeV upgrade (future)
- Hall D - exotic spectroscopy

- Heavy-ion collisions
- RHIC, LHC
- exotic nuclei

- FRIB, FAIR (future)
- neutron rich nuclei
- refine nuclear forces



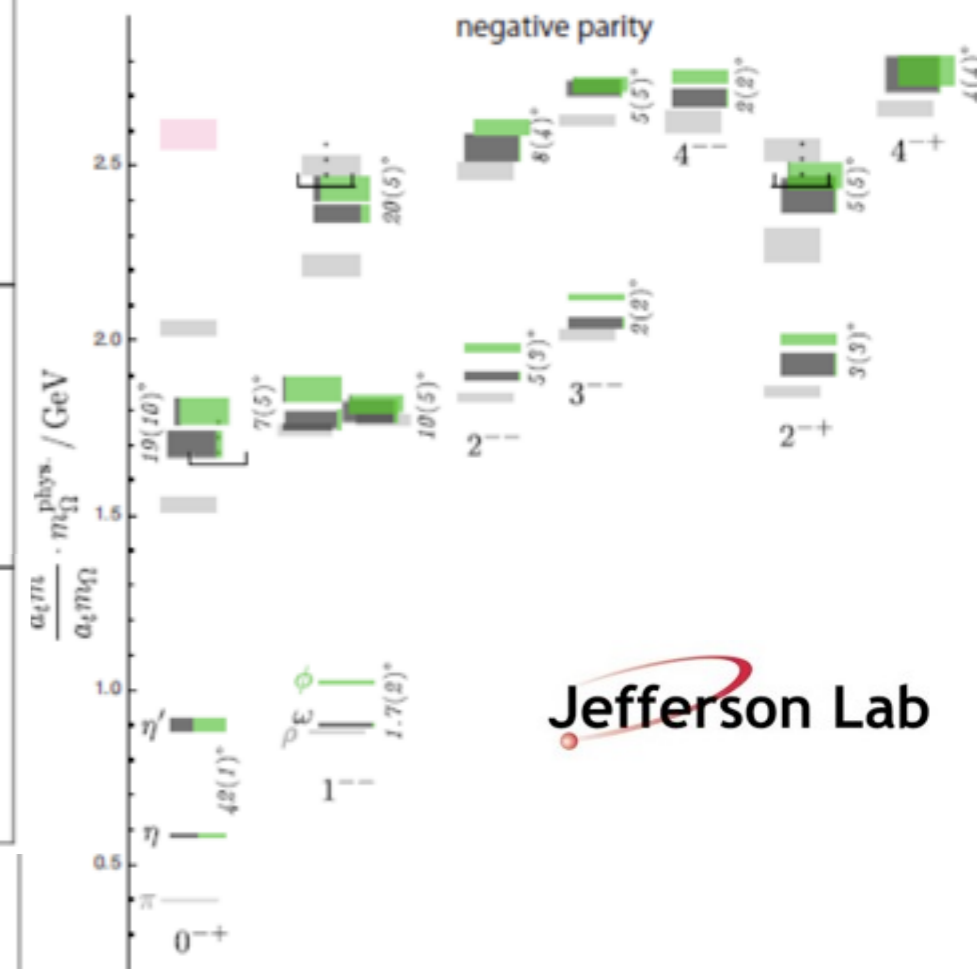
# Spectroscopy

2. Hadron states described with QCD over wide ranges of distance and energy; see Milestones HP5, HP6, HP7, HP10. No Milestone is yet past nor is any yet complete. HP6 was rated as 'exceeding' with the other three rated 'achieved'.

NSAC says :

|              |   |   |                   |
|--------------|---|---|-------------------|
| 2010<br>HP5  | Characterize high-momentum components induced by correlations in the few-body nuclear wave functions via (e,e'N) and (e,e'NN) knock-out processes in nuclei and compare free proton and bound proton properties via measurement of polarization transfer in the ${}^4\text{He}(\vec{e}, e\vec{p})$ reaction.  | No  | Expect to Achieve |
| 2011<br>HP6  | Measure the lowest moments of the unpolarized nucleon structure functions (both longitudinal and transverse) to $4 \text{ GeV}^2$ for the proton, and the neutron, and the deep inelastic scattering polarized structure functions $g_1(x, Q^2)$ and $g_2(x, Q^2)$ for $x=0.2-0.6$ , and $1 < Q^2 < 5 \text{ GeV}^2$ for both protons and neutrons. | No  | Expect to Exceed  |
| 2012<br>HP7  | Measure the electromagnetic excitations of low-lying baryon states ( $< 2 \text{ GeV}$ ) and their transition form factors over the range $Q^2 = 0.1 - 7 \text{ GeV}^2$ and measure the electro- and photo-production of final states with one and two pseudoscalar mesons.   | No  | Expect to Achieve |
| 2014<br>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 origin of the nucleon-nucleon interaction.   | No  | Expect to Achieve |
| 2018         | HP15 (new)  | The first results on the search for exotic mesons using photon beams will be completed. |                   |

Jefferson Lab  
 $\chi$ QCD Collaboration

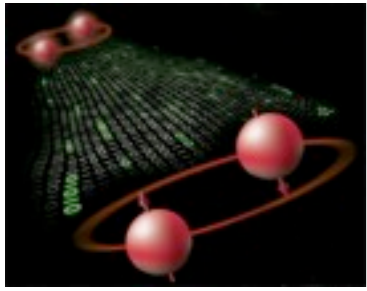




# Spectroscopy

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- Establish the ground and excited states of single hadrons
- Resolve multiple, rapidly decaying states
  - fine lattice spacing in time direction
  - extensive source constructions
- Excited states in lattice volume are scattering states
  - need multiple volumes, boosted CoM to map out phase-shifts to extract poles and widths
  - becomes more extensive at lighter quark masses



# Spectroscopy

- DeTar *et al* : **Quarkonium Physics in Full QCD**
  - 1.9 M ANL/reg + 2.5 M ANL/zero
  - charmonium spectroscopy - HISQ
- Edwards *et al* : **Dynamical Anisotropic Clover Lattice Production**
  - 22.5 M (ORNL) + 0.050 M (B)
  - configuration generation - clover , one lattice spacing
- Liu *et al* : **Nucleon Form Factors and Hadron Spectroscopy**
  - 28.9 M (FNAL)
  - N formfactors, spectroscopy, q+g L+J, sbar - overlap/DW
- Richards *et al* : **Excited Meson and Baryon States using Anisotropic Clover Lattices**
  - 39.6 M JLab + 2.67 M GPU
  - spectroscopy - clover

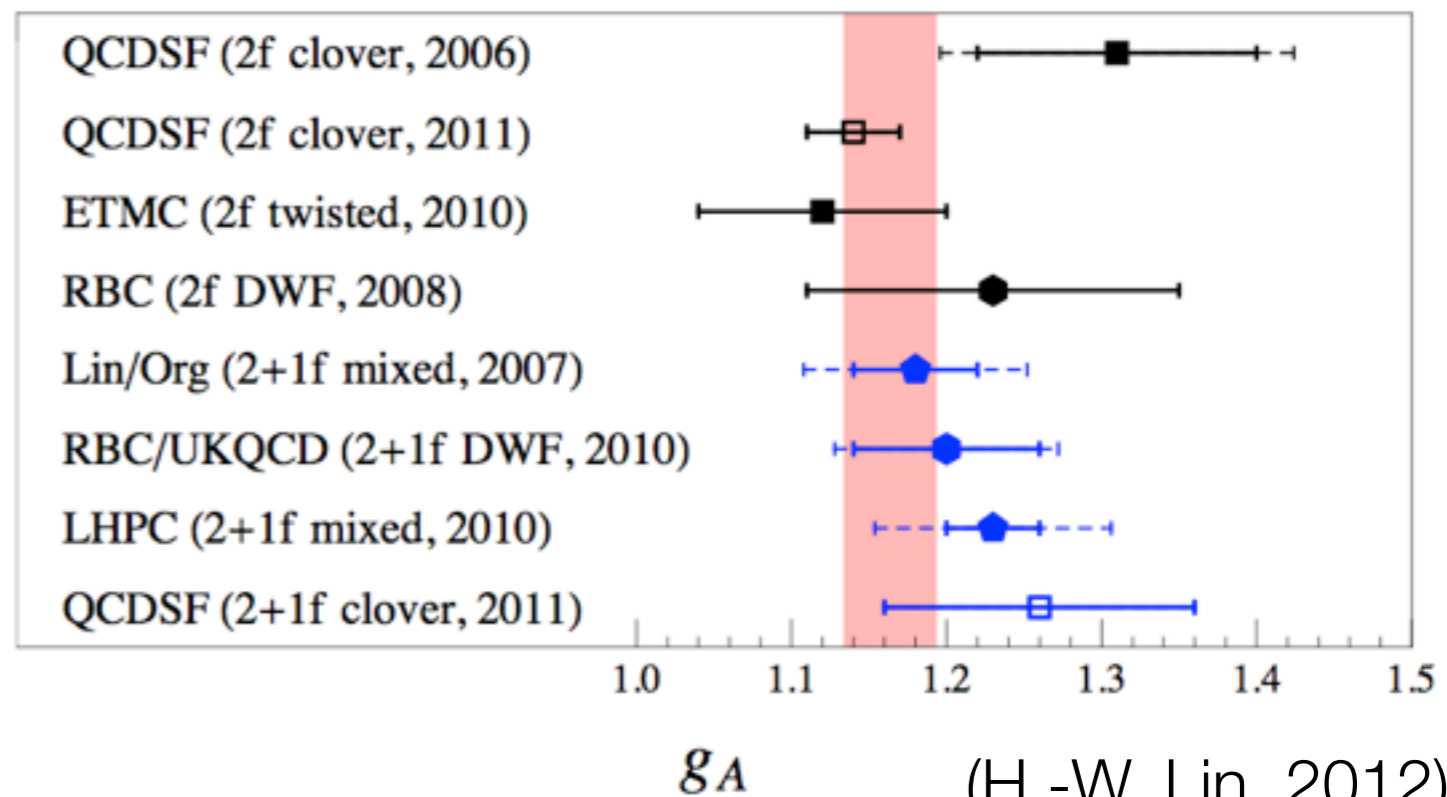
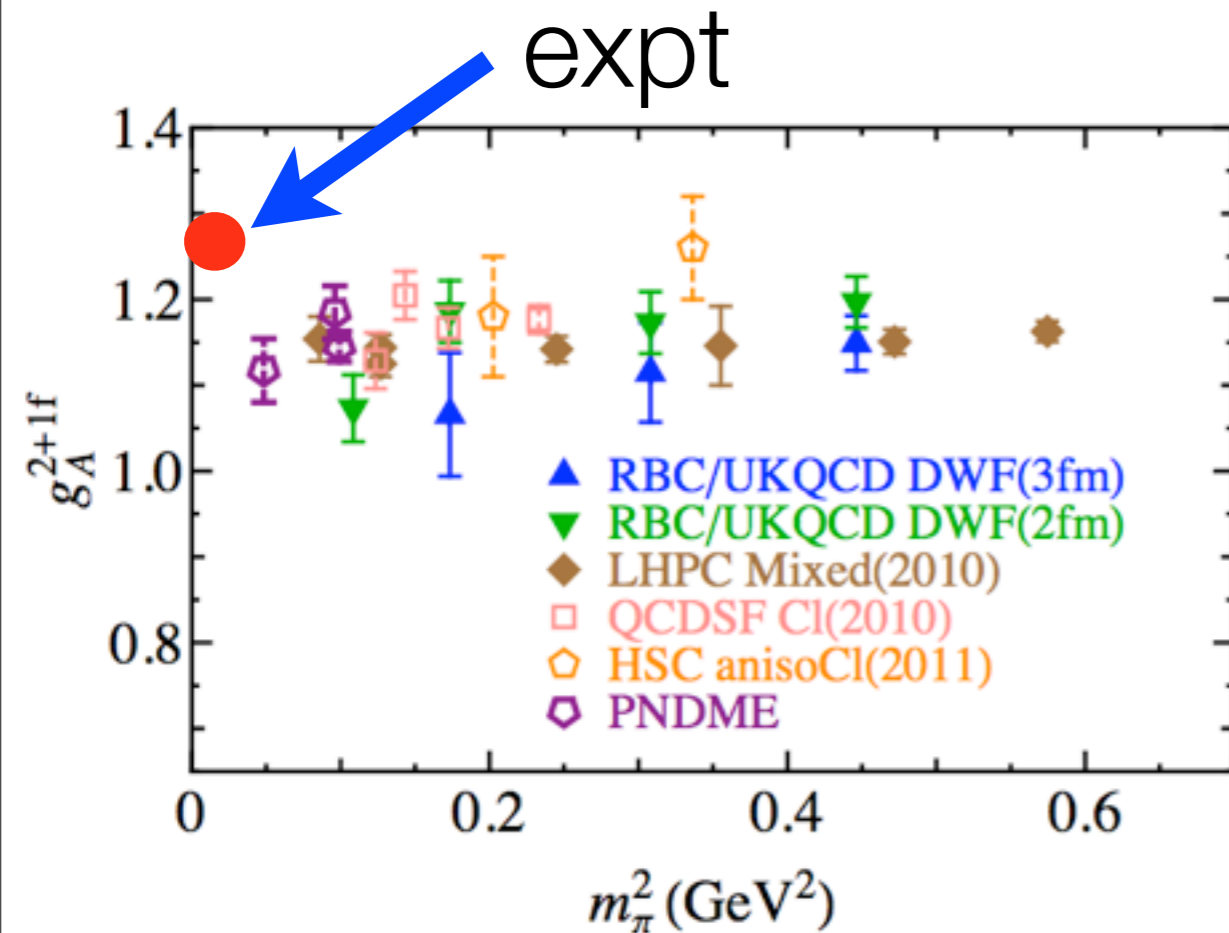
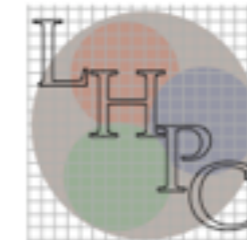


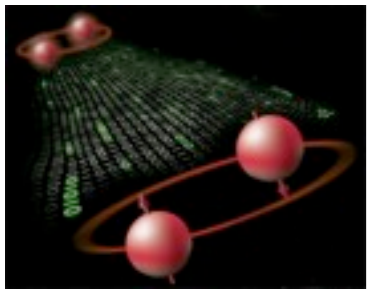
# Nucleon Structure

|           |   |    |                   |
|-----------|---|----|-------------------|
| 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.  | No | Expect to Exceed  |
| 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 origin of the nucleon-nucleon interaction. | No | Expect to Achieve |



$\chi$ QCD Collaboration





# Nucleon Structure

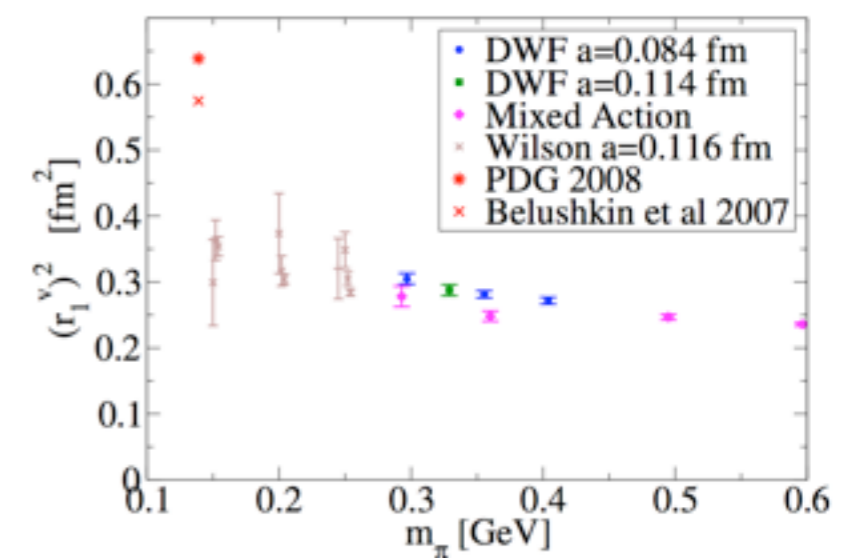
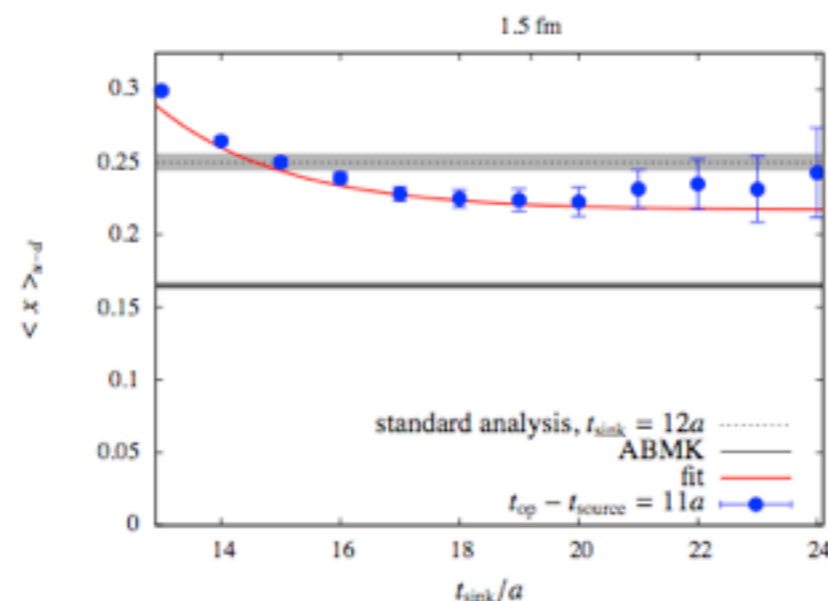
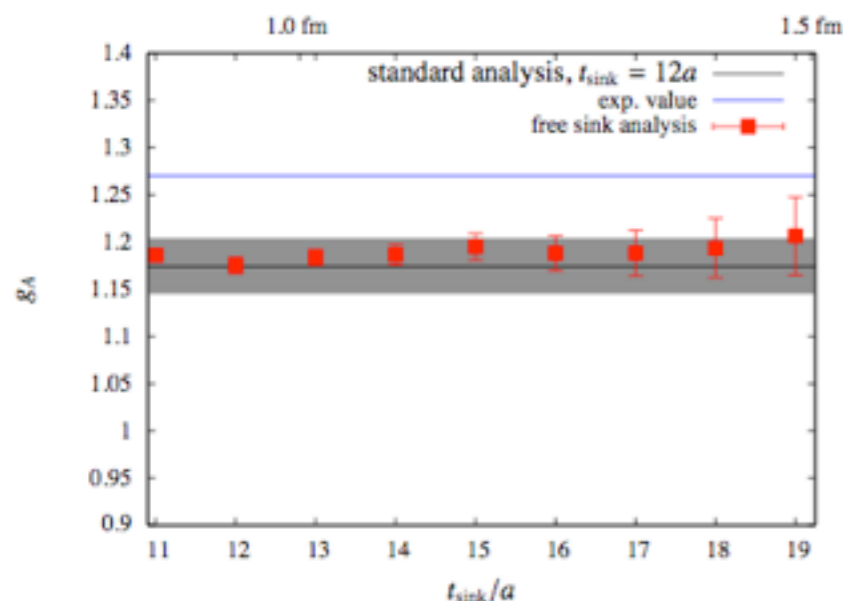
## Matrix elements in the nucleon and octet baryons

- Currently confusing - presently not extrapolating reliably to reproduce nature
- Systematics from excited states likely underestimated
- high statistics studies are required

## Form factors

## What are current lattice values for each ? Phenomenology?

- how many calculations of  $\langle N | s \bar{s} | N \rangle$  are needed ?
- how much improvement will be provided by any given calculation ? (needs to be in proposals)

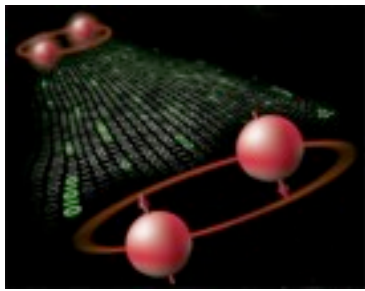






# Nucleon Structure

- Edwards *et al* : **Dynamical Anisotropic Clover Lattice Production**
  - 22.5 M (ORNL) + 0.050 M (B)
  - configuration generation - clover
- Liu *et al* : **Nucleon Form Factors and Hadron Spectroscopy**
  - 28.9 M (FNAL)
  - N formfactors, spectroscopy,  $q+g$  L+J, sbar - overlap/DW
- Negele *et al* : **Precision Calculations to Extract Nucleon Ground State Structure in the Chiral Regime**
  - 41.8 M (FNAL) + 1.641 M (GPU)
  - Nucleon ME's with isotropic clover, N-pi srcs, disconnected's
- Orginos *et al* : **Isotropic Clover Fermions**
  - 32.5 M (FNAL + ANL/zero)
  - isotropic clover lattice generation



# Nucleon Structure

- Alexandru *et al* : Sea quark effects in hadron electric polarizability
  - 0.093 (GPU)
  - reweighting sea quarks with electric charges,  $nf=2$  isotropic clover
- Engelhardt : Electric spin polarizability of the neutron
  - 2.45 M (FNAL) , quenched
- Engelhardt *et al*: Nucleon TMD PDF's with DW fermions on fine lattices
  - 2.42 M (JLab)
- Osborn *et al*: Disconnected contributions to Nucleon form factors with chiral fermions
  - 0.090 M (GPU)
- Renner *et al* : Step-scaling methods for operator mixing
  - 2.16 M (Cluster) , extraction of higher moments of PDF's ?

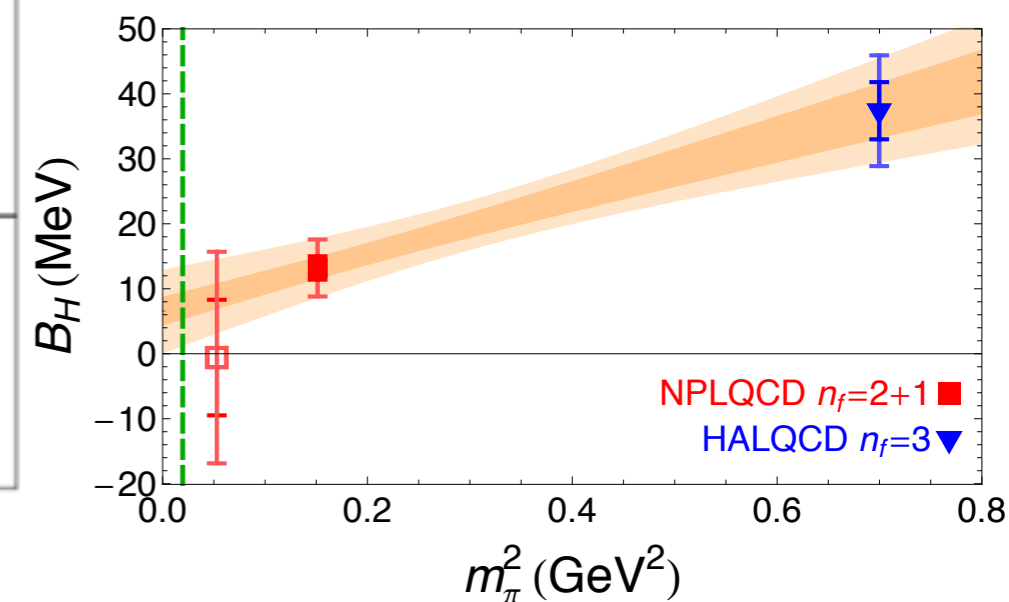


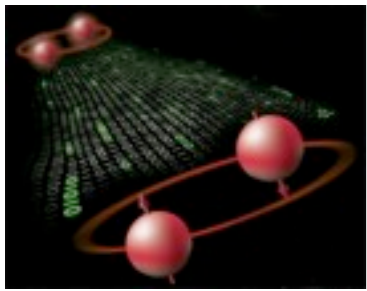
# Nuclear Interactions

3. The nucleon-nucleon interaction mechanisms determined from QCD; see Milestones HP3, HP7, HP9, HP10. No Milestone is yet past nor is any yet complete. HP9 was rated 'exceeding' and HP7 and HP10 were rated as 'achieved'.

NSAC says :

|              |  |    |                             |
|--------------|--|----|-----------------------------|
| 2009<br>HP3  | Complete the combined analysis of available data on single $\pi$ , $\eta$ , and $K$ photo-production of nucleon resonances and incorporate the analysis of two-pion final states into the coupled-channel analysis of resonances.                                    | No | Expect to Not Achieve Fully |
| 2012<br>HP7  | Measure the electromagnetic excitations of low-lying baryon states ( $<2$ GeV) and their transition form factors over the range $Q^2 = 0.1 - 7$ GeV <sup>2</sup> and measure the electro- and photo-production of final states with one and two pseudoscalar mesons. | No | Expect to Achieve           |
| 2014<br>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.   | No | Expect to Exceed            |
| 2014<br>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 origin of the nucleon-nucleon interaction.          | No | Expect to Achieve           |





# Nuclear Interactions

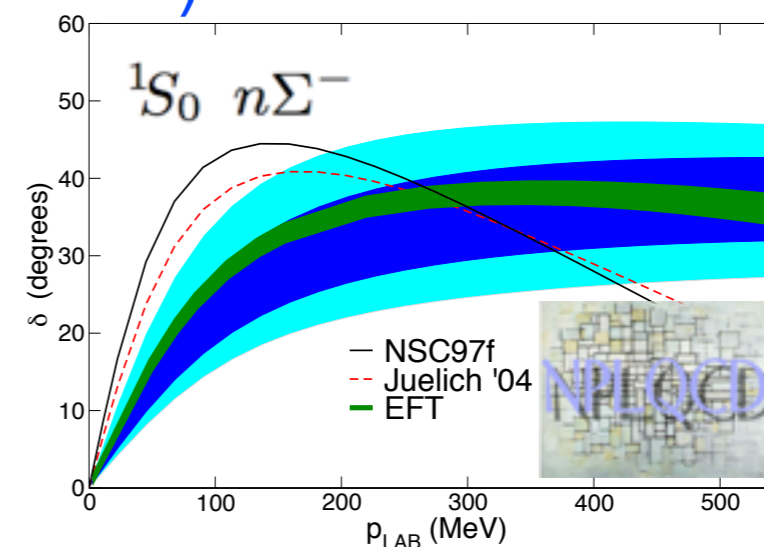
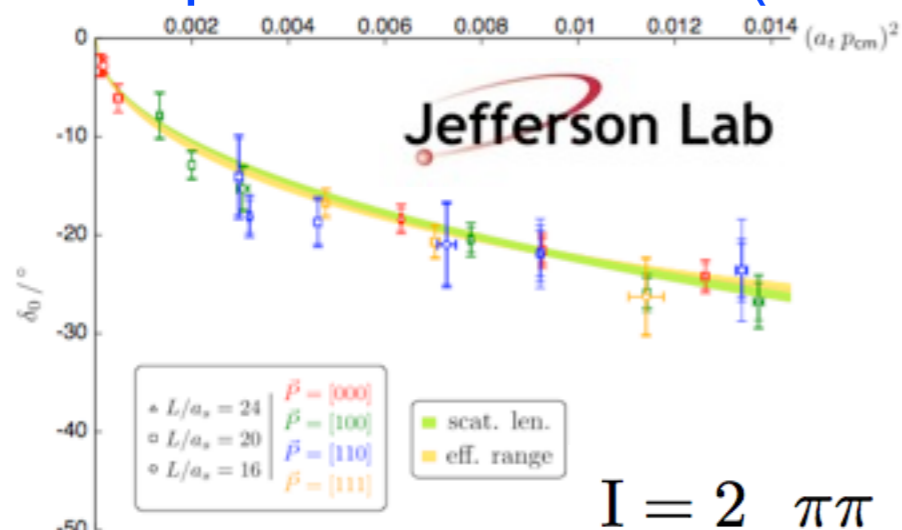
## ● Scattering parameters and phase-shifts

- pi+pi+ s-wave and first d-wave (2011)
- multiple states in lattice volume
- crucial to resonance program
- multi-baryons near non-trivial fixed-point at physical parameters - unitarity, scale-invariance

## ● Bound States

- H-dibaryon, Xi0Xi0, with pion masses ~ 400 MeV, anisotropic clover
- less binding at lighter pion mass - difficult to extract

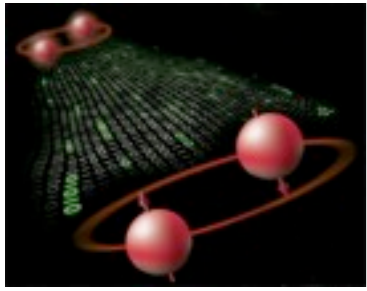
## ● Frontier is multi-hadron systems and precision meson-meson phase-shifts (disconnecteds?)





# Nuclear Interactions

- Detmold et al : **Lattice QCD study of Multi-Baryon Systems**
  - 51 M (Cluster) + 0.8 M (GPU) + 0.050 (BG/Q)
  - Isotropic Clover , SU(3) symmetric point ,  $A < 7$
- Orginos *et al* : **Isotropic Clover Fermions**
  - 32.5 M (FNAL + ANL/zero)
  - isotropic clover lattice generation
- Richards *et al* : **Excited Meson and Baryon States using Anisotropic Clover Lattices**
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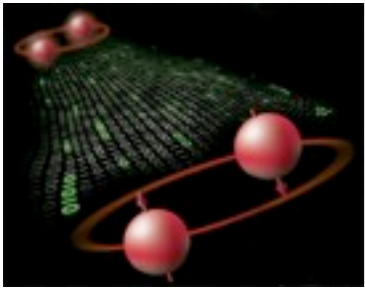
## Summary

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- Good proposals focused on the NP mission
- Systematics need to be re-assessed for some quantities
- Isotropic and anisotropic cfg's are both required at present
- Measurements dominate resource requirements
- USQCD averaged numbers are required for some quantities, e.g.  $\langle N | \bar{s} s | N \rangle$



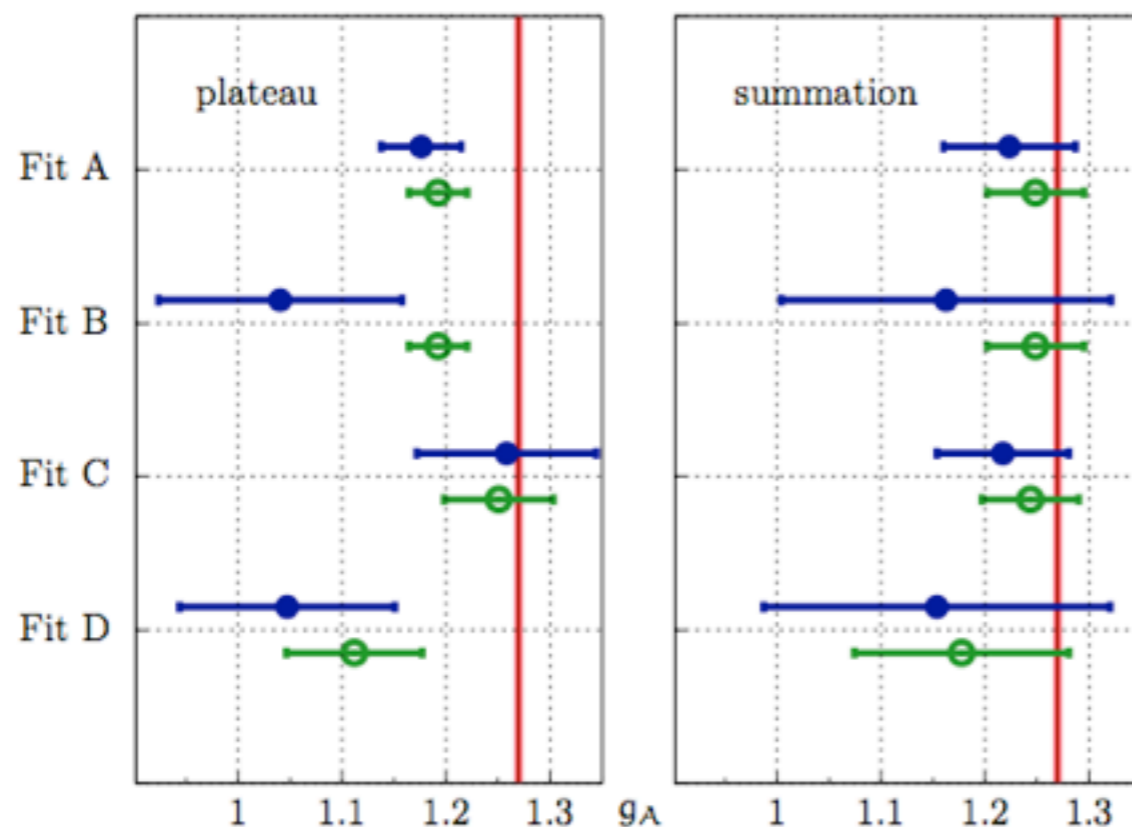
End



# Nucleon Structure

## ● Matrix elements in the nucleon and octet baryons

- Currently confusing - presently not extrapolating reliably to reproduce nature
- Systematics from excited states likely underestimated
- high statistics studies are required



Capitani *et al* ,  
*1205.0180 hep-lat*

**Figure 4:** Results for  $g_A$  at the physical pion mass for the plateau and summation methods. Solid points refer to a pion mass cut at  $m_\pi < 540$  MeV, while open symbols are used to denote results from fits across the entire pion mass range. Fits A, B and D were applied to the volume-corrected data (see text). The vertical lines represent the experimental value.