Hadron Spectroscopy, Structure and Interactions

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Jefferson Lab

Annual Progress reviews of LQCD-ext and LQCD ARRA projects
FNAL
May 10-11, 2011

GOALS

- **Understanding structure, spectroscopy and interactions of hadrons from QCD is the central challenge of nuclear physics**
- **How are charge, current and spin distributed in the nucleon?**
- **What are the effective degrees of freedom describing the low-energy spectrum of the theory?**
- **How does the nucleon-nucleon and hadron-hadron interaction arise from QCD?**

Hadron Structure

NSAC Nuclear Physics Long Range Plan:

What is the internal landscape of the nucleons ?

- ***The distribution of quarks and gluons inside nucleons***
- ***The spin structure of protons and neutrons***
- ***Glue in the proton's spin***

NSAC Milestones in Hadronic Physics

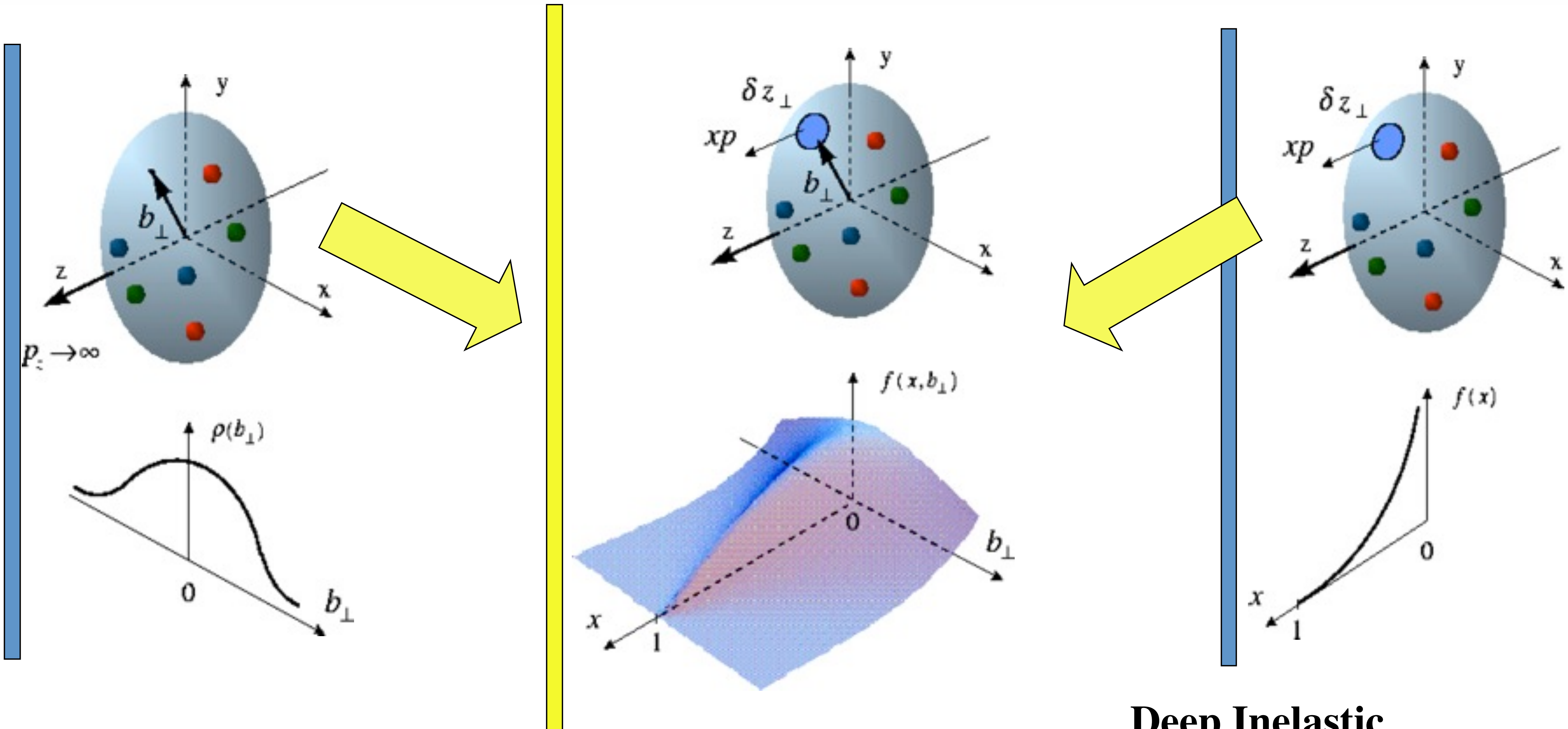
http://science.energy.gov/~/media/np/nsac/pdf/docs/perfmeasevalfinal.pdf

HP9 (2014) ***"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"***

Address key elements of DOEs experimental programs

- **quark distributions: HERMES, Fermilab, LHC**
- **form factors, GPDs: JLab**
- **contributions to the nucleon spin: JLab, RHIC-spin, future EIC**
- **Transverse-momentum-dependent distributions: JLab, RHIC-spin, future EIC**

Generalized Parton Distributions



Elastic Scattering
transverse quark
distribution in
Coordinate space
(charge and current densities)

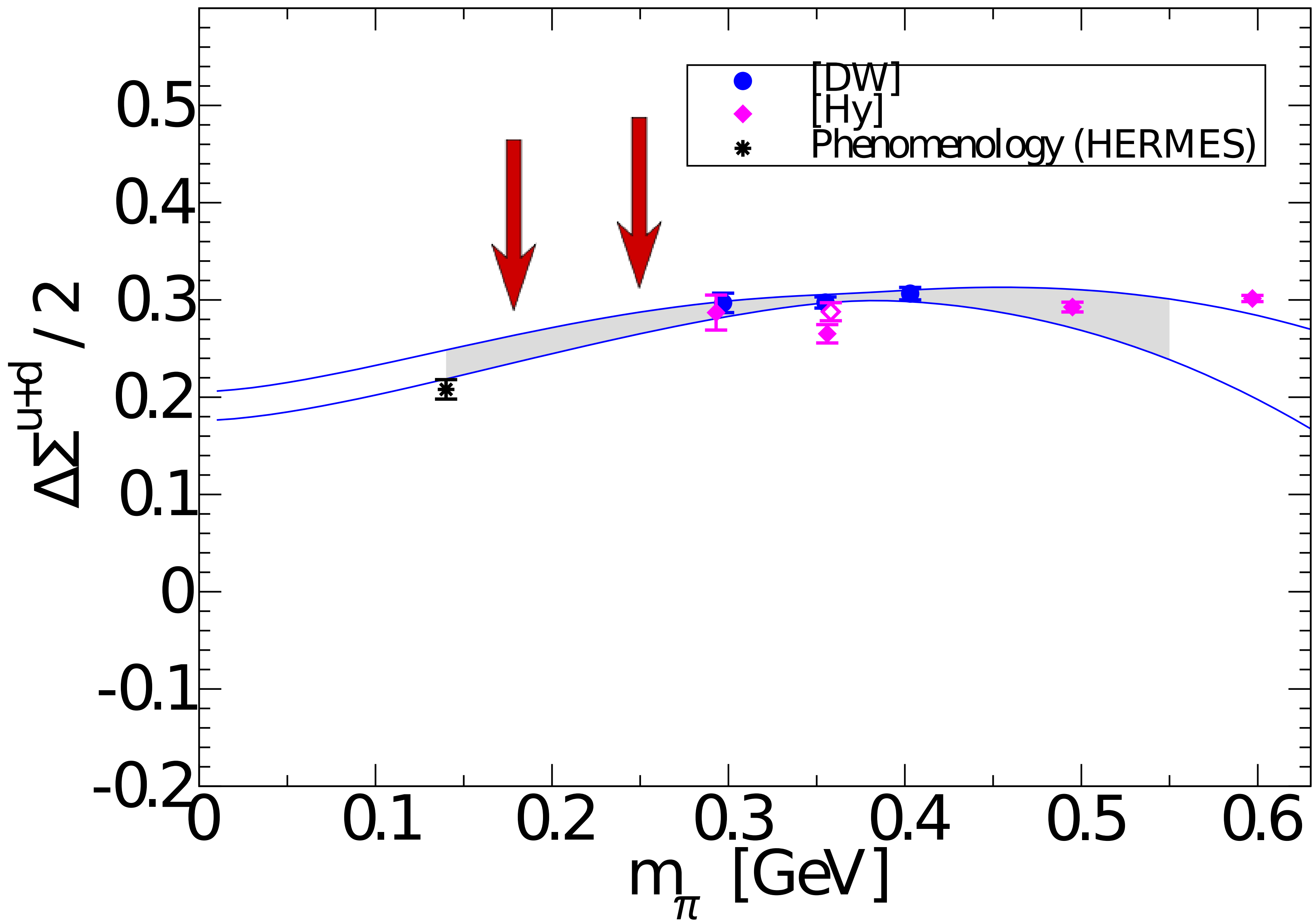
Deep Exclusive Scattering
fully-correlated quark
distribution in both coordinate
and momentum space
(Generalized Parton Distributions)

Deep Inelastic Scattering
longitudinal
quark distribution
in momentum space
(momentum and

X. Ji, D. Müller, A. Radyushkin (1994-1997)

Origin of the nucleon spin

quark spin: $\frac{1}{2}\Delta\Sigma = \frac{1}{2}\langle 1 \rangle_{\Delta u+\Delta d}$



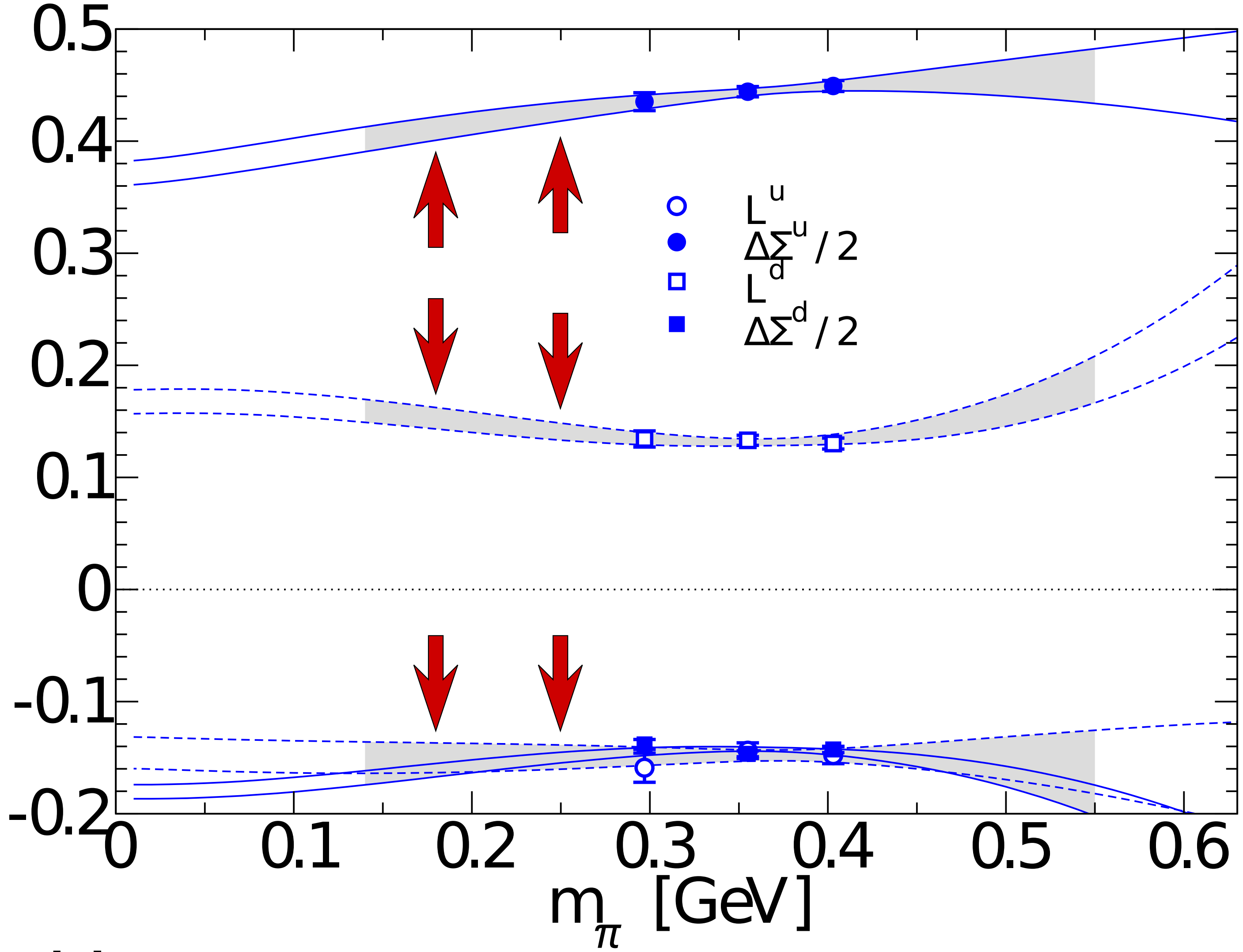
LHPC results

RBC/LHPC lattices + forward propagators

arrows: masses for current domain wall calculations
disconnected diagrams not yet included

Origin of the nucleon spin

Ji Sum Rule: $J_q = \frac{1}{2}[A_{20}^{u+d}(0) + B_{20}^{u+d}(0)] = \frac{1}{2}[\langle x \rangle_{u+d} + B_{20}^{u+d}(0)]$



LHPC

Surprises:

Total L negligible

Spin and L in opposite directions

51% of spin must be from glue

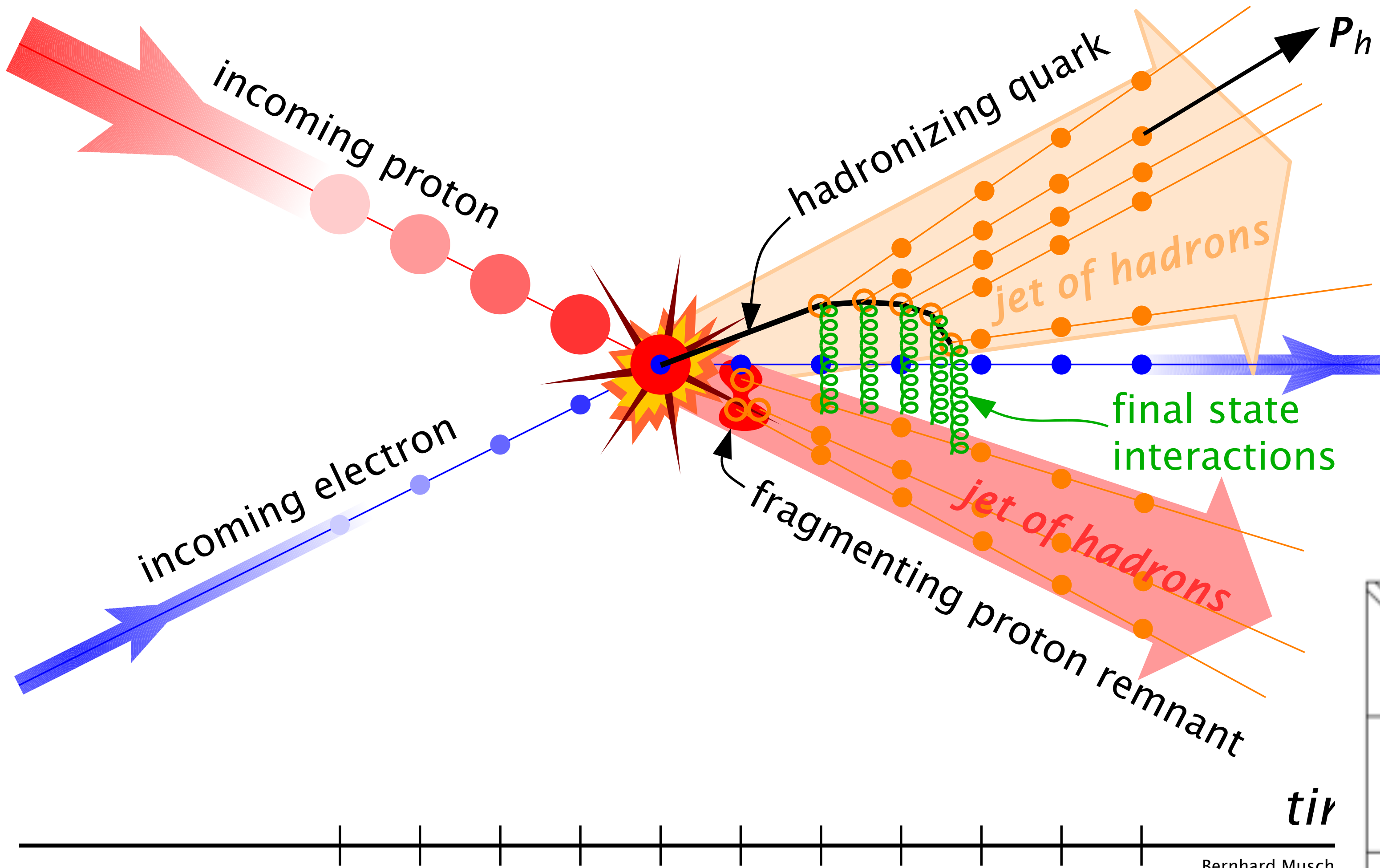
2011-2012 Plans

Hadron structure on $32^3 \times 64$ LHPC/RBC (UKQCD) lattices at $m_\pi = 180$ and 250 MeV

Transverse momentum distributions (TMDs)

from experiment, e.g., **SIDIS** (semi-inclusive deep inelastic scattering)

HERMES, COMPASS, JLab 6 GeV, JLab 12 GeV , ... , EIC



Cf: measured in Drell-Yan, eg at RHIC-spin

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

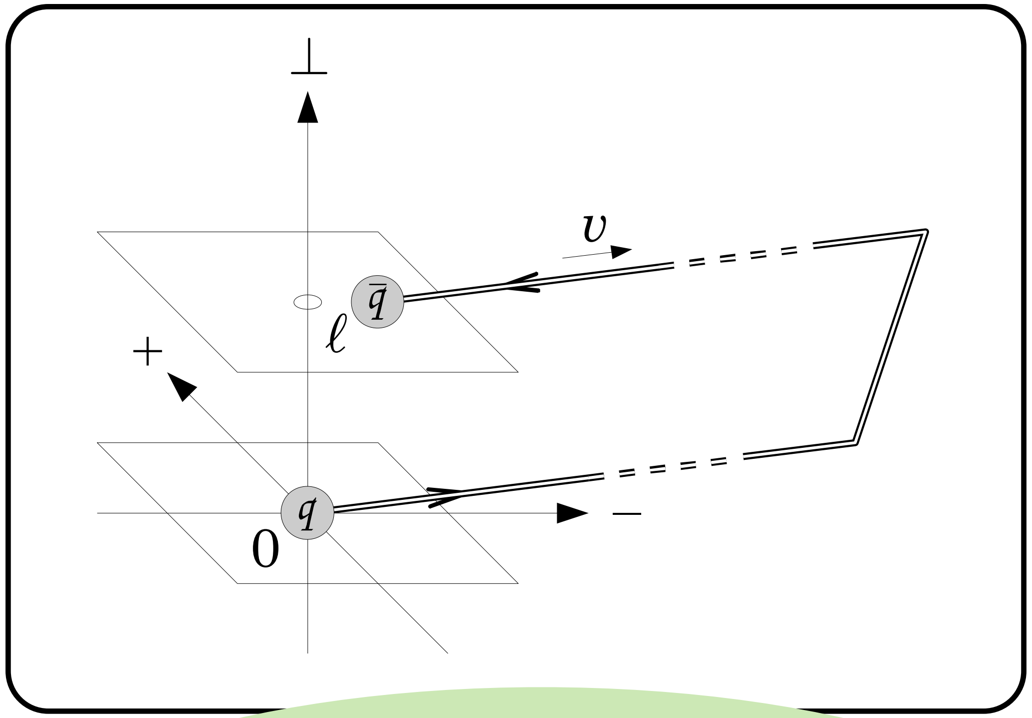
Boer-Mulders ($h_1^\perp$)

Sivers ($f_{1T}^\perp$) ← time-reversal odd

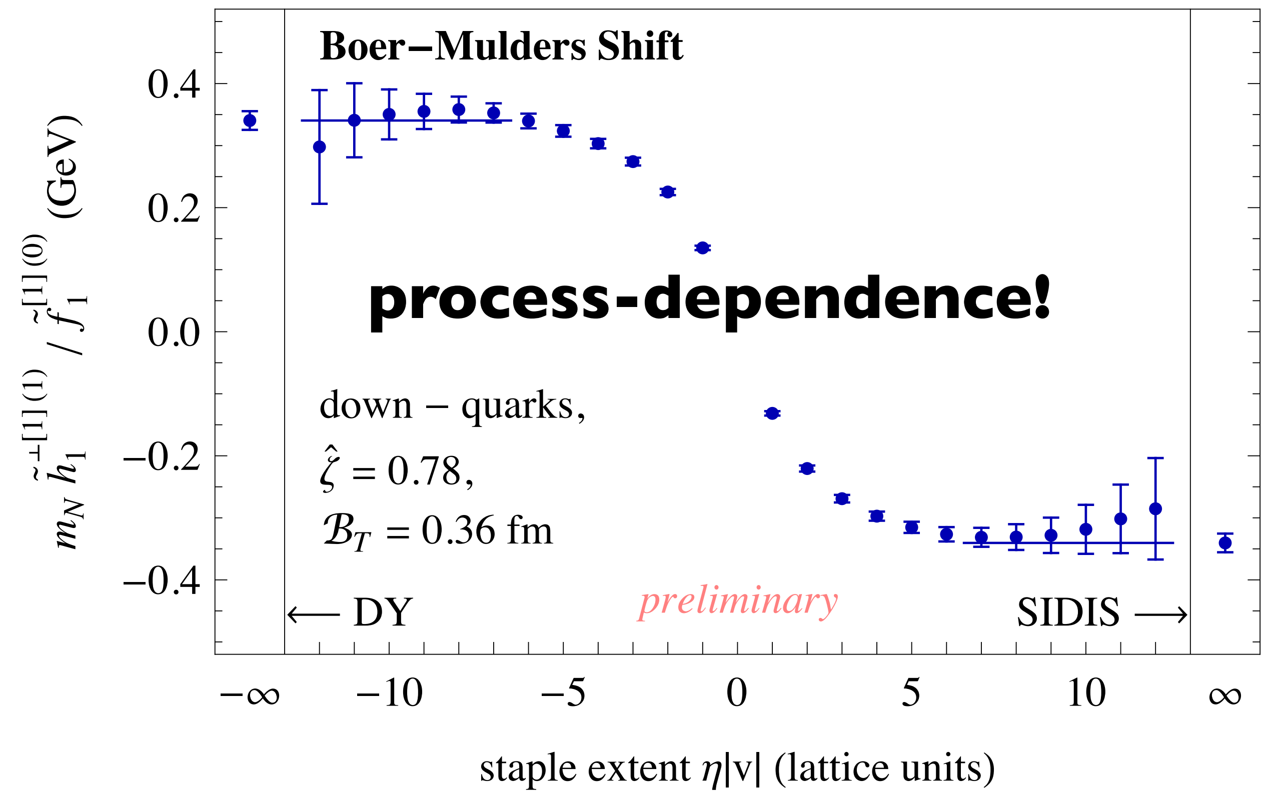
final state interactions!
explain large asymmetries otherwise forbidden!
signature of QCD!

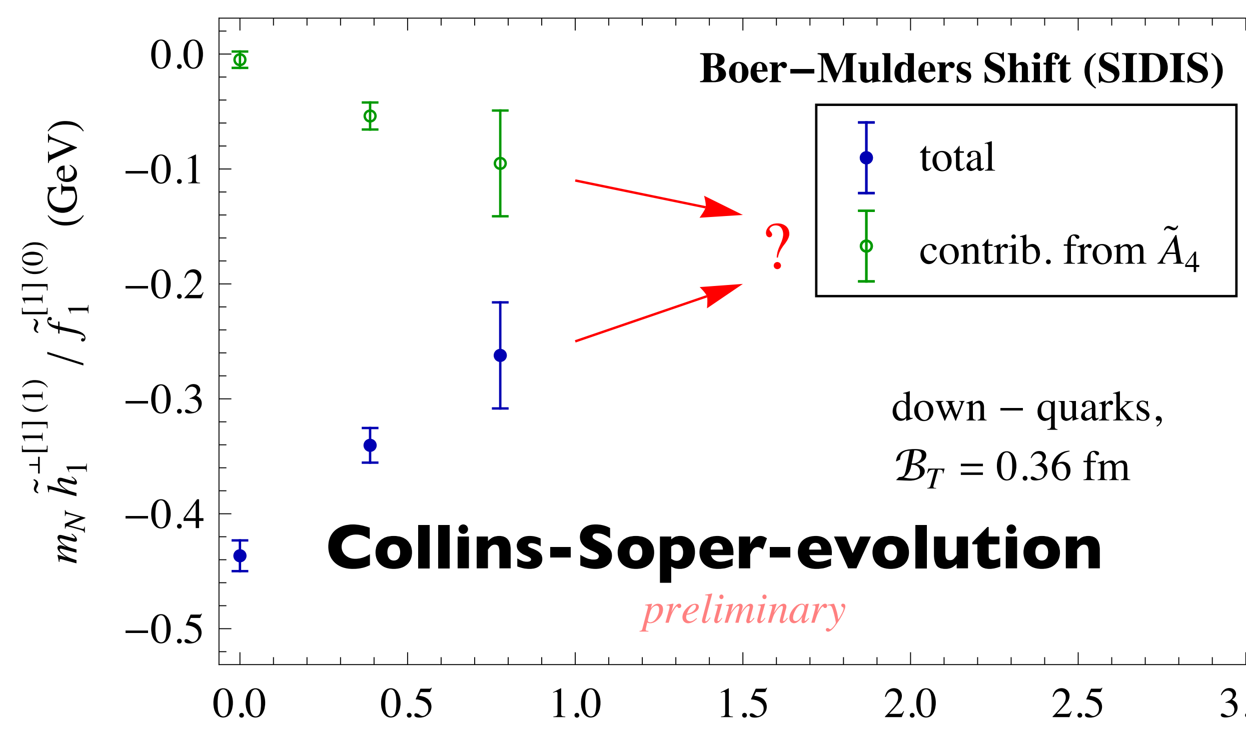
Transverse momentum distributions (TMDs)

Lattice QCD, including effect of final state interactions



new calculations with extended operator





preliminary results
m_π=500 MeV,
MILC lattices,
LHPC propagators

Boer-Mulders function :
odd signal (SIDIS vs. Drell-Yan)
still far from light cone
⇒ **Proposal to study pion TMDs**

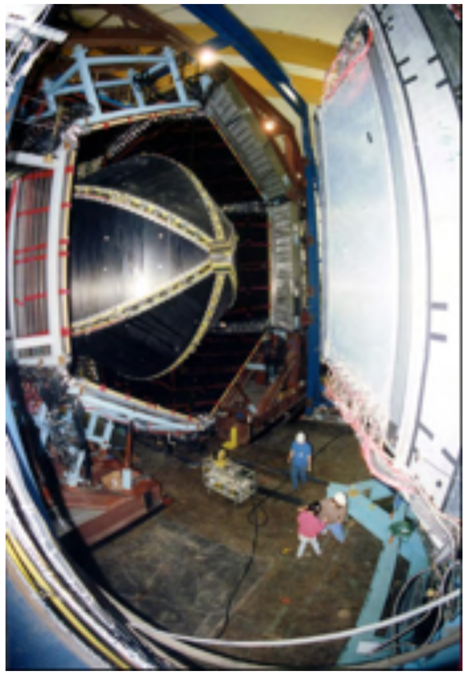
Hadron Structure in 2011-2012

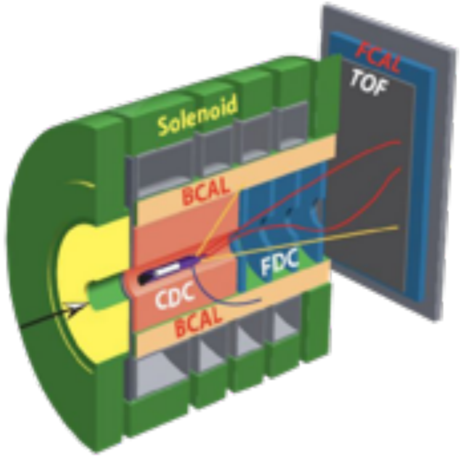
- Norman Christ *Simulations with Dynamical Domain-wall Fermions*
- Sergey Syritsyn *Nucleon Structure in the Chiral Regime with Domain Wall Fermions*
  - *Calculations close to the physical quark masses, with control over systematic effects*
- Bernhard Musch *The Boer-Mulders Function of the Pion*
- Dru Renner *Step-scaling methods for QCD form factors at large Q2*
- Keh-Fei Liu *Hadron Spectroscopy and Nucleon Form Factors*
- James Osborn *Disconnected contributions to nucleon form factors with chiral fermions*
- Michael Engelhardt *Spin polarizability of the neutron*

Flavor-singlet contributions to hadron structure

Excited-State Spectrum of QCD

- **Why is it important?**
  - *What are the key degrees of freedom describing the bound states?*
  - *What is the role of the gluon in the spectrum – search for exotics?*
  - *What is the origin of confinement, describing 99% of observed matter?*
  - *If QCD is correct and we understand it, expt. data must confront ab initio calculations*
- **NSAC Milestones in hadronic physics**
  - *"Complete the combined analysis of available data on single π, η, and K photo-production of nucleon resonances…" (HP3:2009)*
  - *"Measure the electromagnetic excitations of low-lying baryon states (<2 GeV) and their transition form factors…" (HP12)*
  - *"First results on the search for exotic mesons using photon beams will be completed" (HP15)*
- **Complementarity to 'Hot QCD' program**
  - **EOS close to phase transition and hadron gas model**
  - *"Workshop on Excited Hadronic States and the Deconfinement Transition", JLab, Feb 23-25, 2011 - expt + lattice + QCD-inspired models from both (cold + hot QCD!) communities*





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Excited states from LQCD

- Anisotropic lattices with N_f=2+1 dynamical fermions
  - Temporal lattice spacing $a_t < a_s$ (spatial lattice spacing)
  - High temporal resolution Resolve noisy & excited states
  - Major project within USQCD – Hadron Spectrum Collab.
- Extended operators
  - Subduction: sufficient derivatives: nonzero overlap at origin
- Variational method:
  - Distillation: matrix of correlators: *project onto excited states*

M. Peardon *et al.*, PRD80,054506 (2009)

$$C_M^{(2)}(t',t) = \mathrm{Tr}\left[\Phi^B(t')\,\tau(t',t)\,\Phi^A(t)\,\tau(t,t')\right]$$

$$\Phi^A_{\alpha\beta}(t) = V^\dagger(t)\,\left[\Gamma^A(t)\right]_{\alpha\beta}V(t)$$

Perambulators:
inversion of Dirac Matrix

$$\tau_{\alpha\beta}(t',t) = V^\dagger(t')M^{-1}_{\alpha\beta}(t',t)V(t),$$

New Science Reach with GPUs

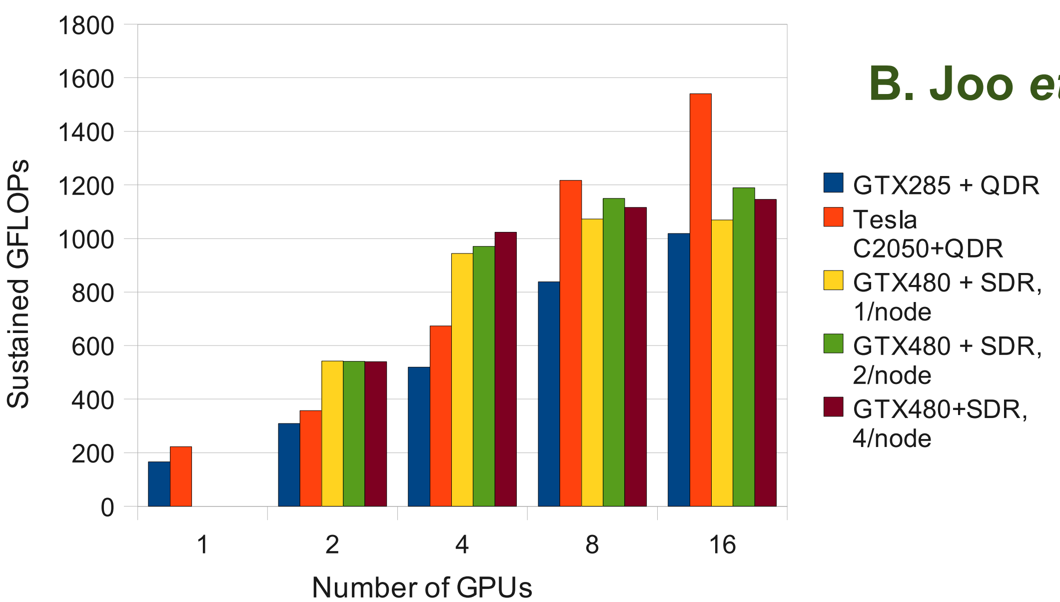
- Gauge generation: (next dataset)
  - INCITE: Crays BG/P-s, ~ 16K – 24K cores
  - Double precision
- Analysis (existing dataset): two-classes
  - Propagators (Dirac matrix inversions)
    - Few GPU level
    - Single + half precision
    - No memory error-correction
  - Contractions:
    - Clusters: few cores
    - Double precision + large memory footprint

} ~ 10 Tflops **Capability**

} ~ 10 Tflops **Capacity**

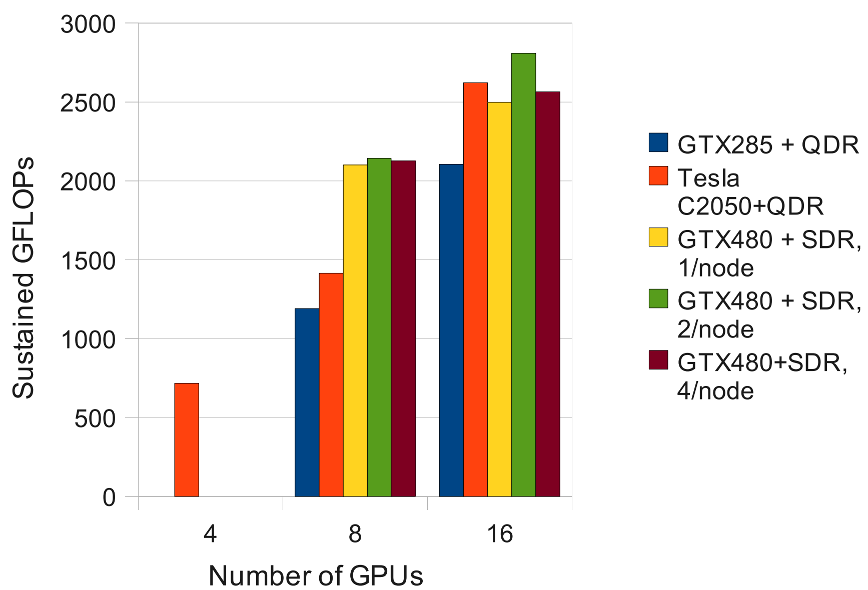
~ 1 Tflops

2010-2011 lattices: $24^3 \times 128$

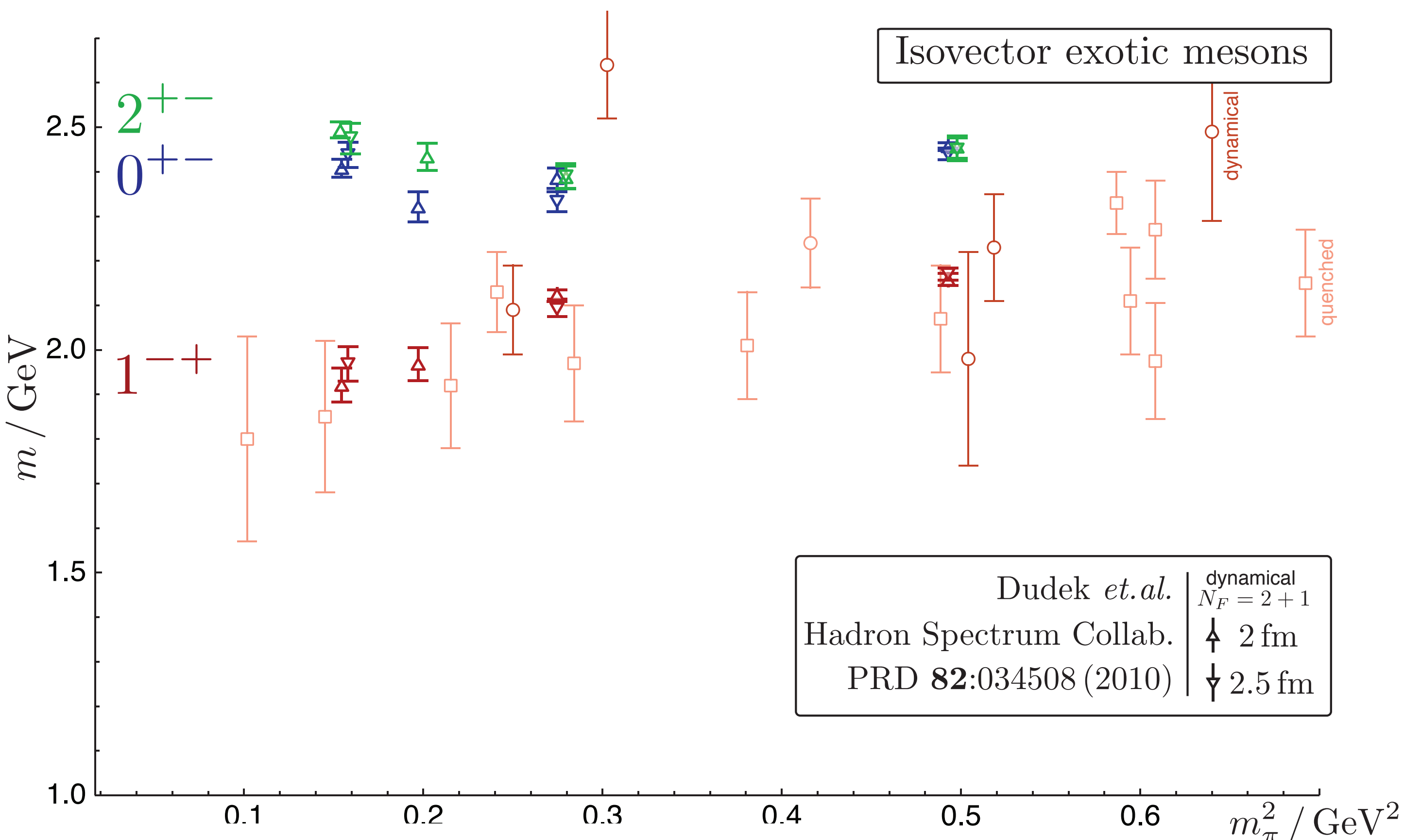


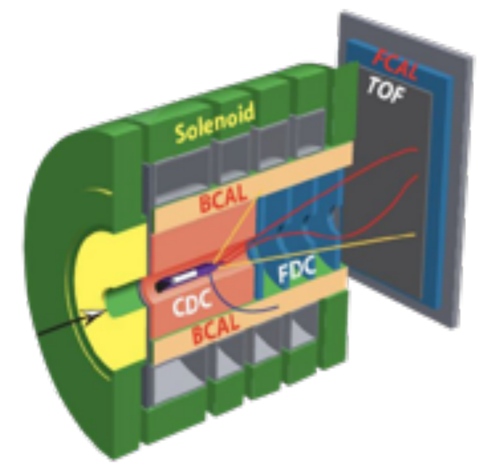
B. Joo *et al*, SciDAC 2010

2011-2012 lattices: $32^3 \times 256$



Isovector Meson Spectrum





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USQCD calculation vs. world "lightest" exotic 1^{-+}

J. Dudek, 2011 Early Career Research Award, *Meson Spectroscopy from QCD*

Department of Energy

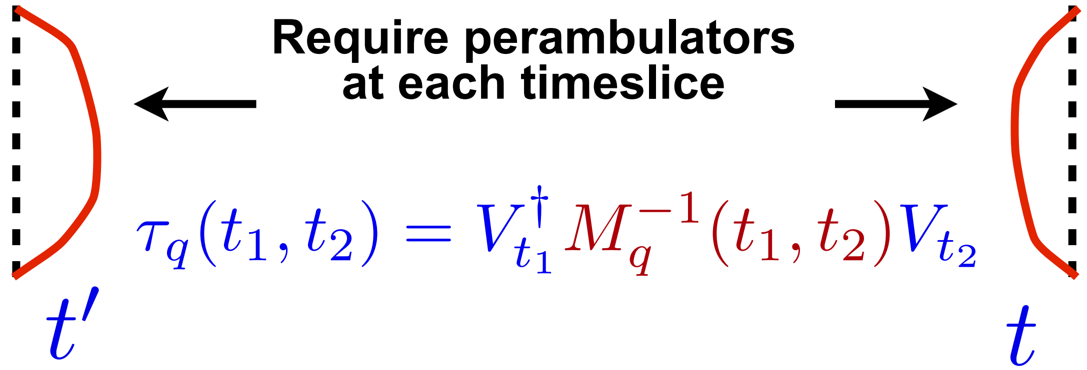
FY 2012 Congressional Budget Request

Selected FY 2010 Accomplishments

- LQCD calculations continue to bring exciting physics results and computational advances. The Hadron Spectrum Collaboration provided new physics insight into how quarks are bound in mesons and hadrons through the calculation of the masses of states with exotic quantum numbers from dynamic LQCD. The quantum numbers of exotic meson states cannot be constructed from the conventional excitations of a bound quark-anti-quark pair, and the existence of these states may signal the explicit influence of the gluons that bind quarks together.

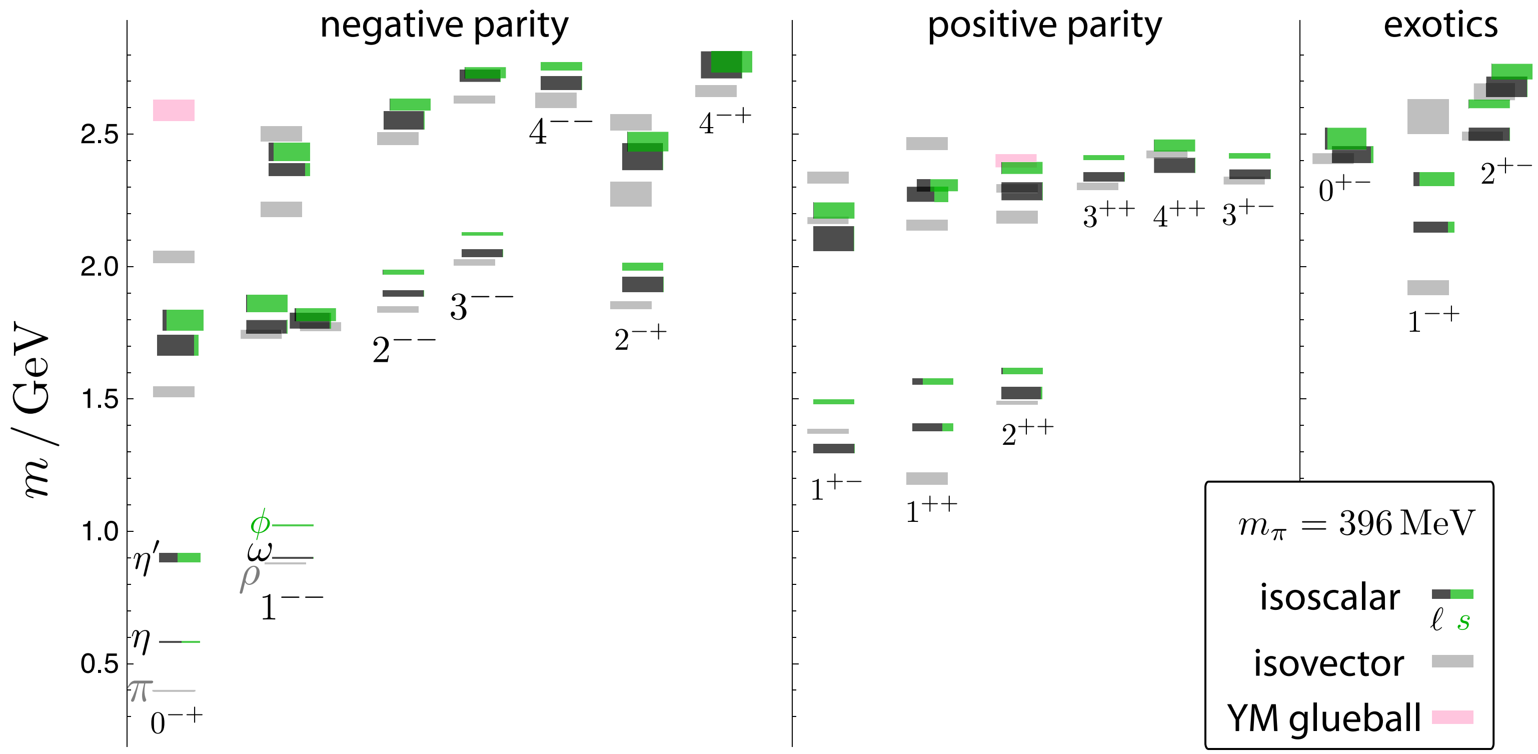
Isoscalar Meson Spectrum

Isoscalar requires disconnected contributions



Dominated by quark-propagator inversions - ENABLED BY GPU

J. Dudek *et al.*, arXiv:1102.4299



- **Spin-identified single-particle spectrum: states of spin as high as four**
- **Hidden flavor mixing angles extracted - except 0^{-+}, 1^{++} near ideal mixing**
- ***First determination of exotic isoscalar states: comparable in mass to isovector***

Momentum-dependent I = 2 ππ Phase Shift

Dudek *et al.*, Phys Rev D83, 071504 (2011)

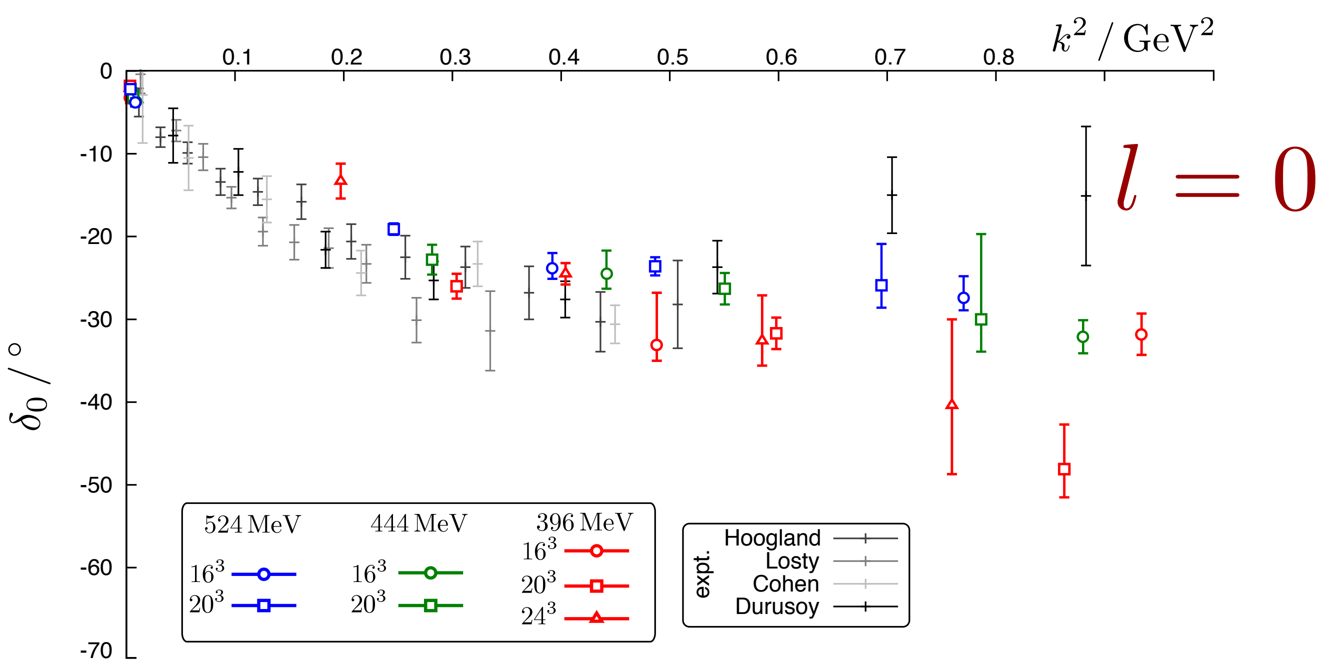
Luescher: energy levels at finite volume ↔ phase shift at corresponding *k*

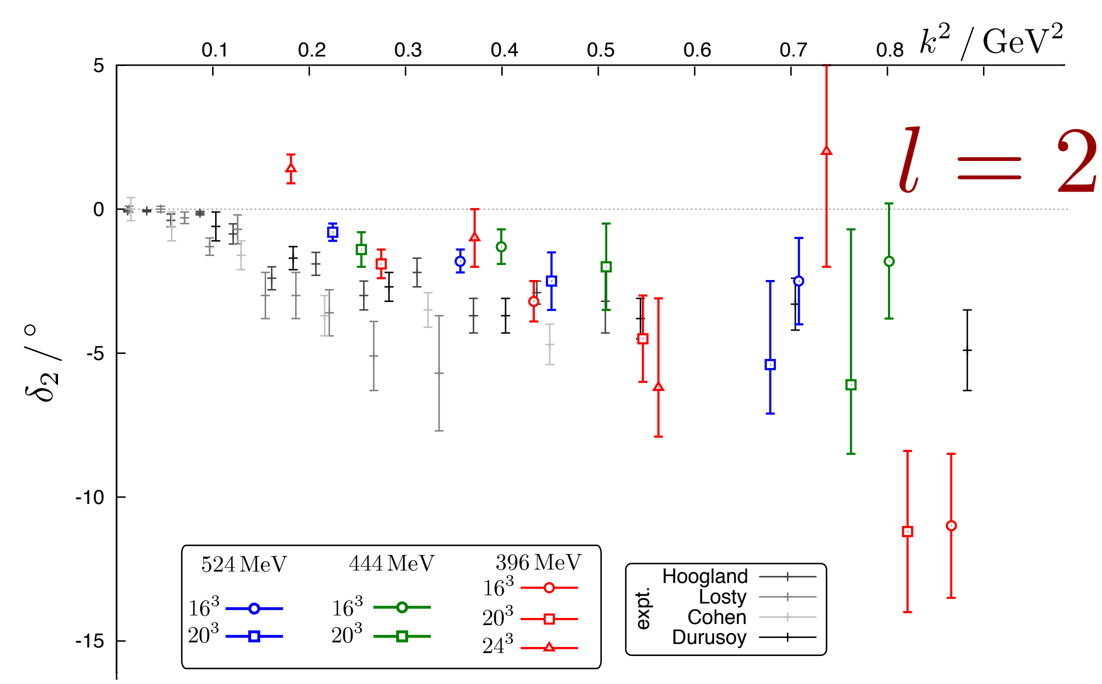
$$\det\left[e^{2i\boldsymbol{\delta}(k)} - \mathbf{U}_\Gamma\left(k\frac{L}{2\pi}\right)\right] = 0$$

Matrix in l ↗   ↖ **lattice irrep**

Operator basis $\mathcal{O}^{\Gamma,\gamma}_{\pi\pi}(|\vec{p}|) = \sum_m \mathcal{S}^{\ell,m}_{\Gamma,\gamma} \sum_{\hat{p}} Y^m_\ell(\hat{p})\, \mathcal{O}_\pi(\vec{p})\mathcal{O}_\pi(-\vec{p})$

Total momentum zero - pion momentum ±*p*



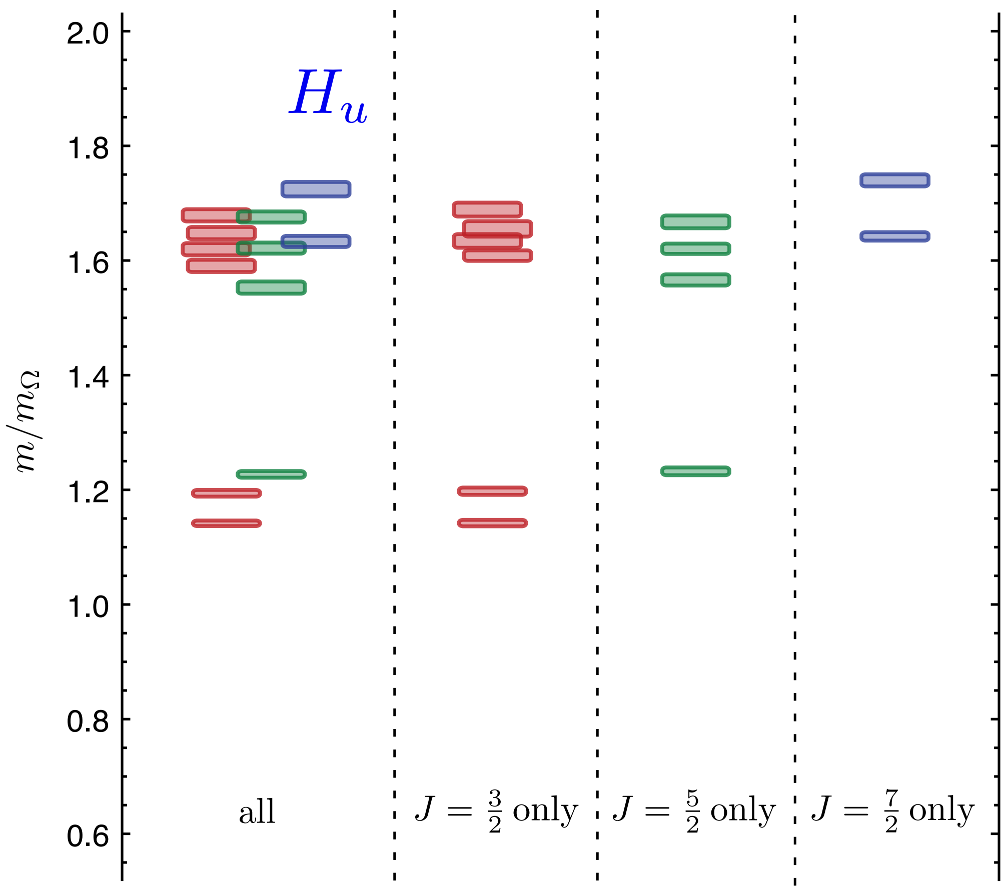


Excited Baryon Spectrum - I

- **Major challenge: identifying continuum spins of single-particle states in lattice QCD**
- **Construct basis of 3-quark interpolating operators in the continuum:**

$$\left(N_{\mathsf{M}} \otimes \left(\tfrac{3}{2}^{-}\right)^{1}_{\mathsf{M}} \otimes D^{[2]}_{L=2,\mathsf{S}}\right)^{J=\frac{7}{2}}$$

- **Subduce to lattice irreps:** $\mathcal{O}^{[J]}_{n\Lambda,r} = \sum_{M} \mathcal{S}^{J,M}_{n\Lambda,r}\mathcal{O}^{[J,M]} : \Lambda = G_{1g/u}, H_{g/u}, G_{2g/u}$



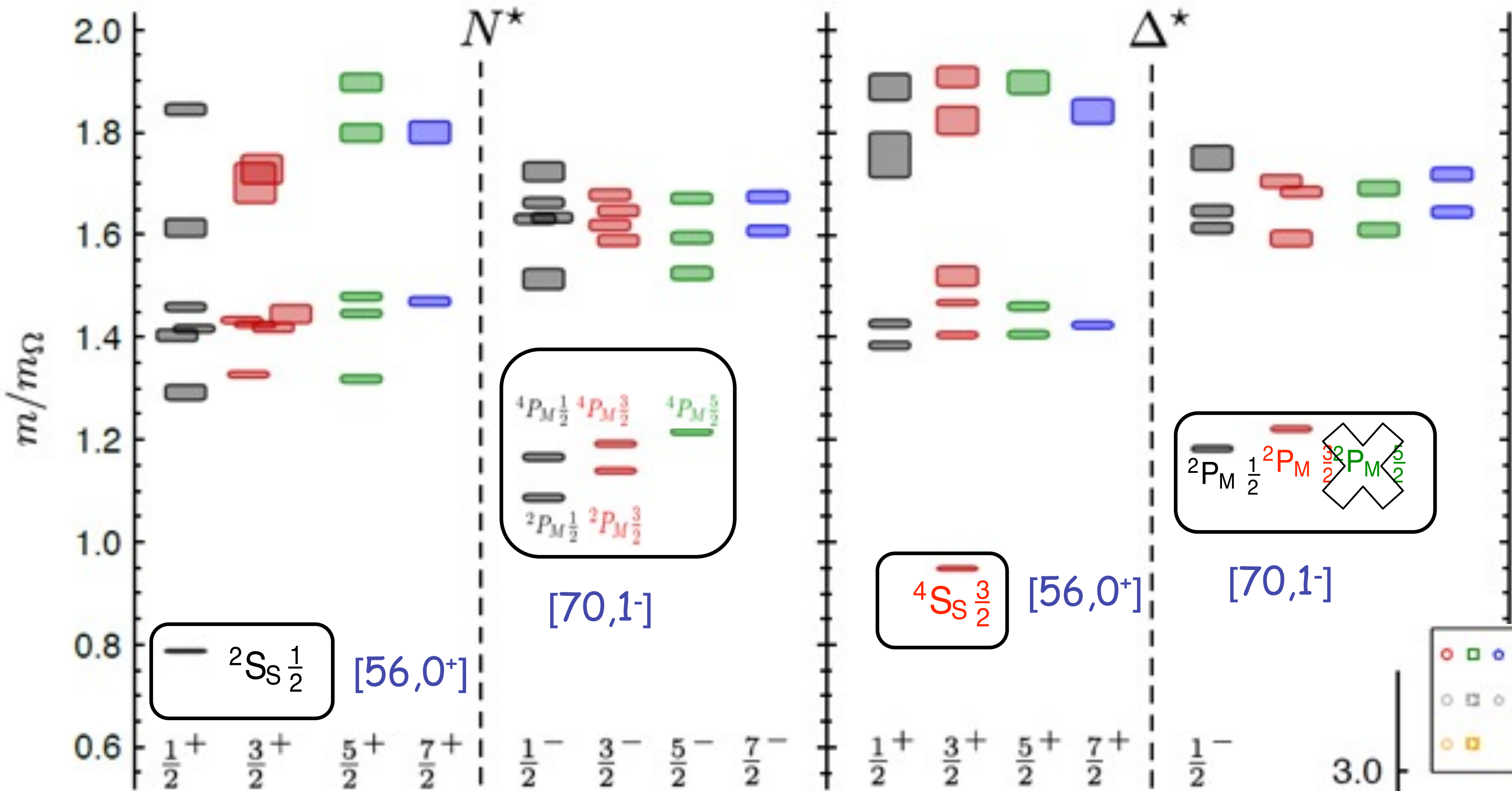
Continuum antecedents

R.G.Edwards et al., arXiv:1104.5152

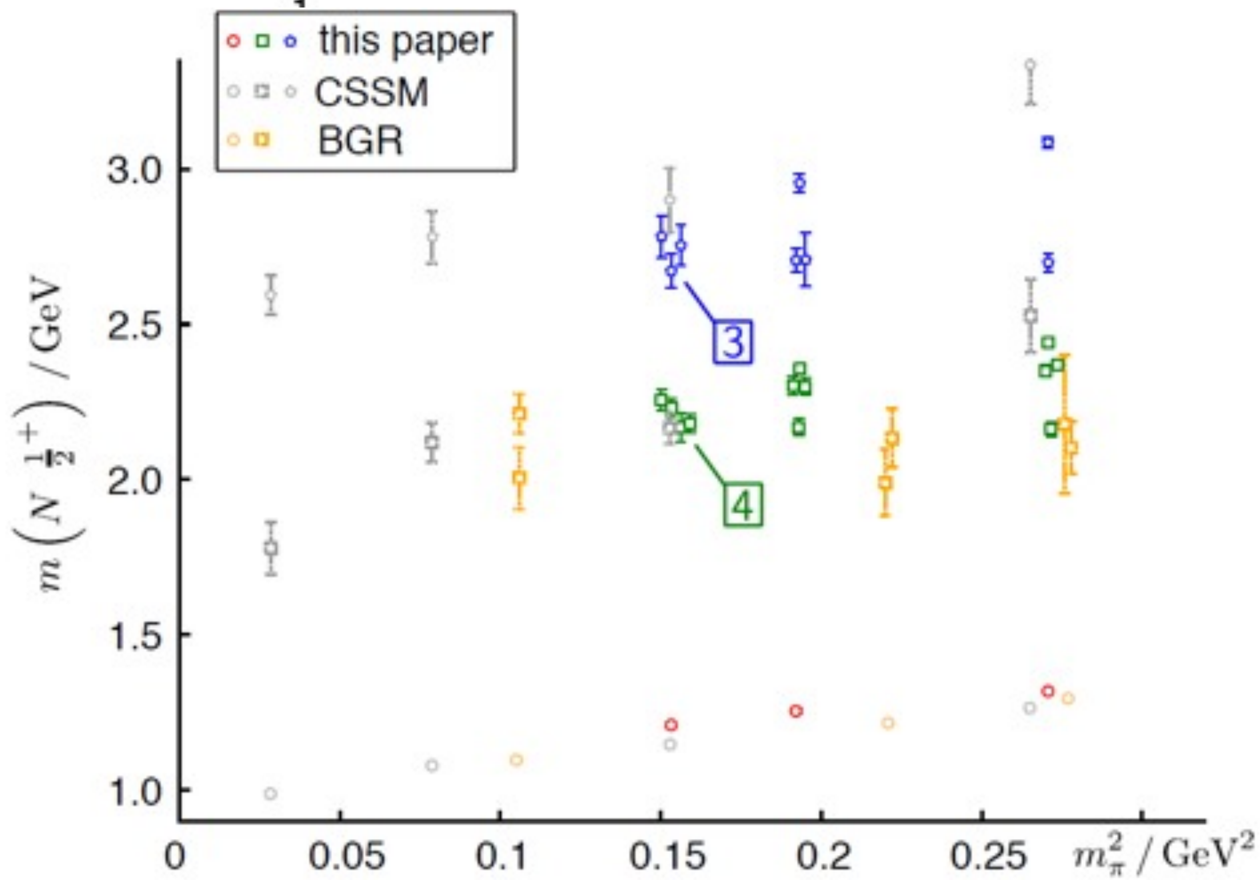
$16^3 \times 128$ lattices $m_\pi = 524, 444$ and 396 MeV

Observe remarkable realization of rotational symmetry at hadronic scale: *reliably determine spins up to 7/2, for the first time in a lattice calculation*

Excited Baryon Spectrum - II



- **Broad features of SU(6)xO(3) symmetry**
- **Counting of states consistent with NR quark model**
- **Inconsistent with quark-diquark picture or parity doubling**



N $^{1/2+}$ sector: need for complete basis to faithfully extract states

Polarizabilities using Lattice QCD

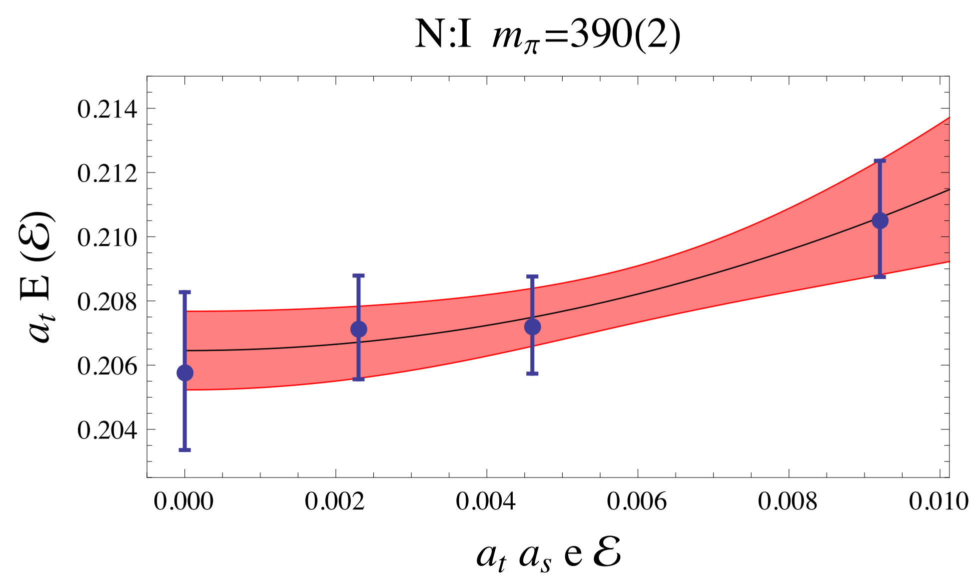
Response of hadron to background EM field

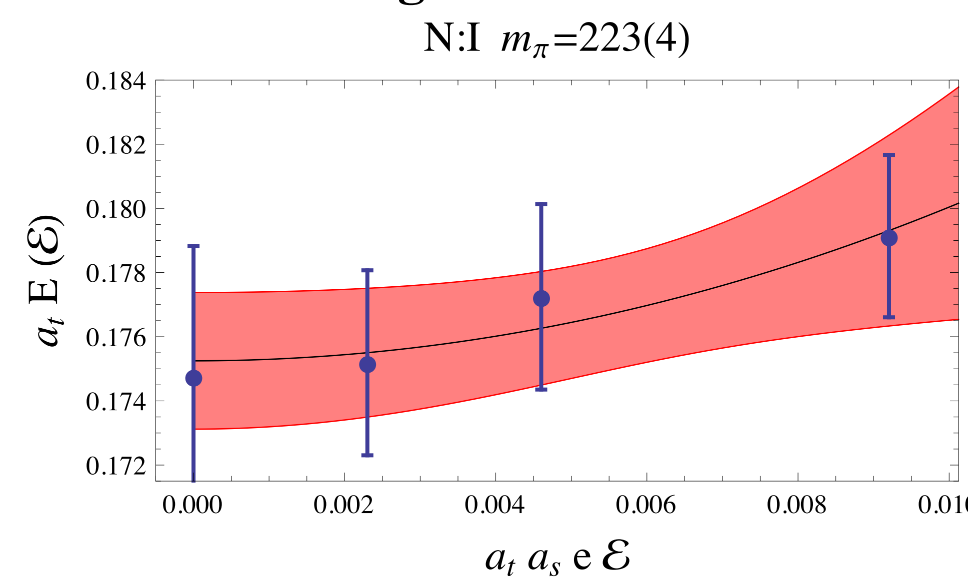
Calculation dominated by inversion of Dirac matrix in background field - *enabled by GPU*

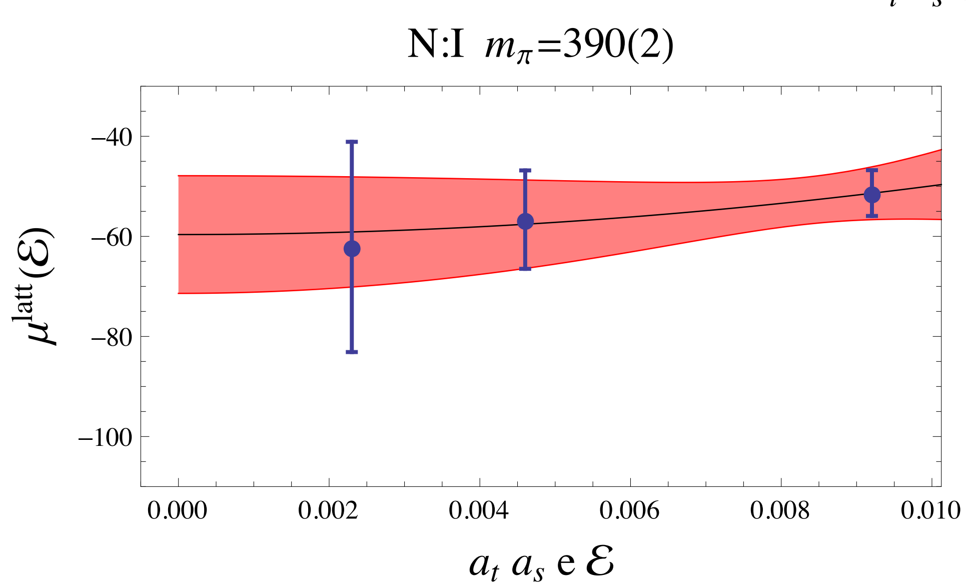
$32^3 \times 256$ anisotropic clover

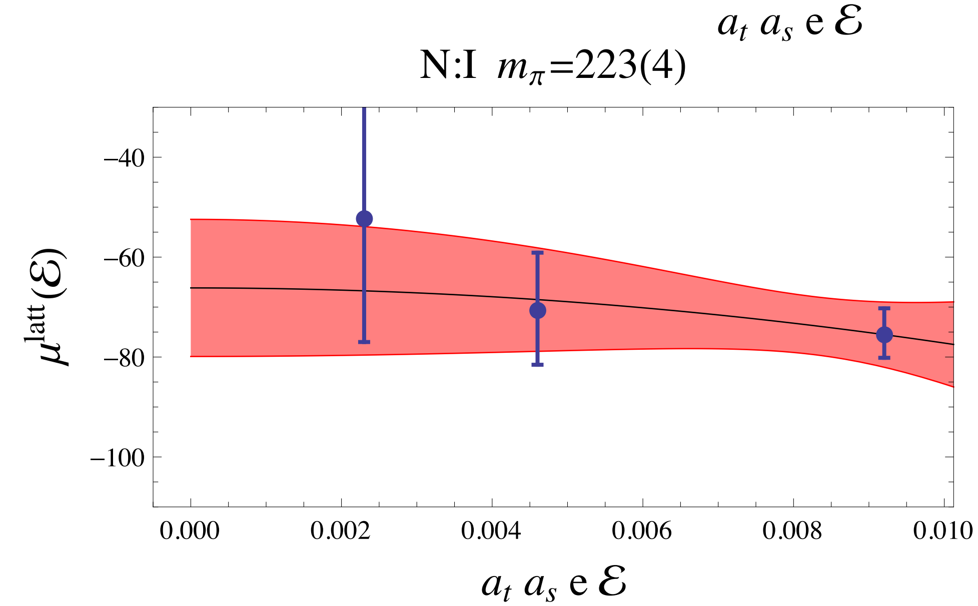
Electro**M**agnetic **C**ollaboration

Neutron polarizability









Spectroscopy in 2011-2012

Spectroscopy on anisotropic clover lattices

Edwards, Richards

- Distillation - method of computing correlation functions for both single and multi-particle operators - *single-hadron spin-identified spectrum*
- GPUs: *efficient computational engine for Dirac matrix inversions*
- Demonstration of Luscher method: *energy dependent phase shifts in non-resonant channel*

Spectroscopy, including multi-particle contributions, on $32^3 \times 256$ lattices at $m_\pi = 230$ and 380 MeV

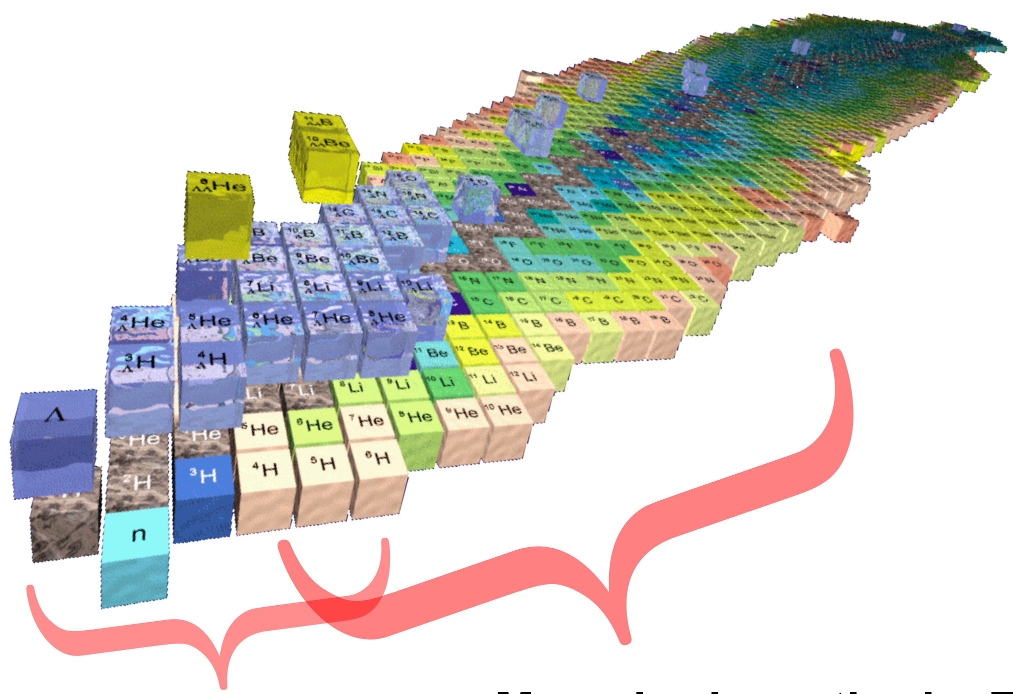
Momentum-dependent phase shifts in both non-resonant and resonant channels - fit to Breit-Wigner parameters

Broad activity in Spectroscopy

- Brian Tiburzi *Hadronic electromagnetic properties*
- Andrei Alexandru *Hadron electric polarizability in the chiral limit*
- Keh-Fei Liu *Hadron Spectroscopy and Nucleon Form Factors*
- Carleton DeTar *Quarkonium Physics in Full QCD*

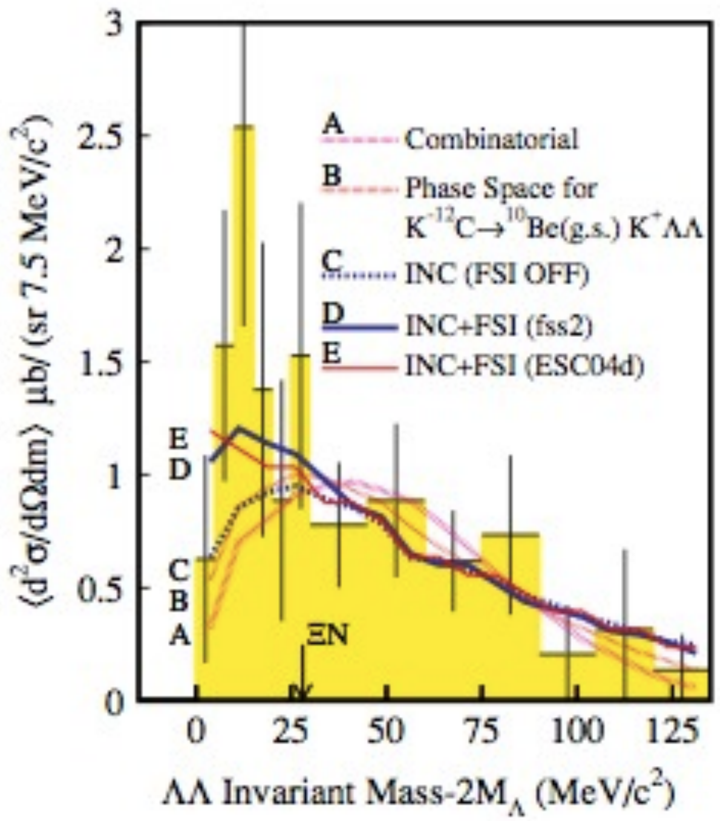
Hadron-Hadron Interactions

- **Grand Challenge to rigorously compute properties and interactions of nuclei**
- **HP10 (2014): "*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.*"**
- **Hyperon-nucleon interaction, with dearth of experimental data, provide opportunity for lattice QCD to provide astrophysical insight: input to nuclear EOS in neutron stars**



H-Dibaryon - I

- Bound state of two (strange) baryons uuddss, originally proposed by Jaffe (1977)



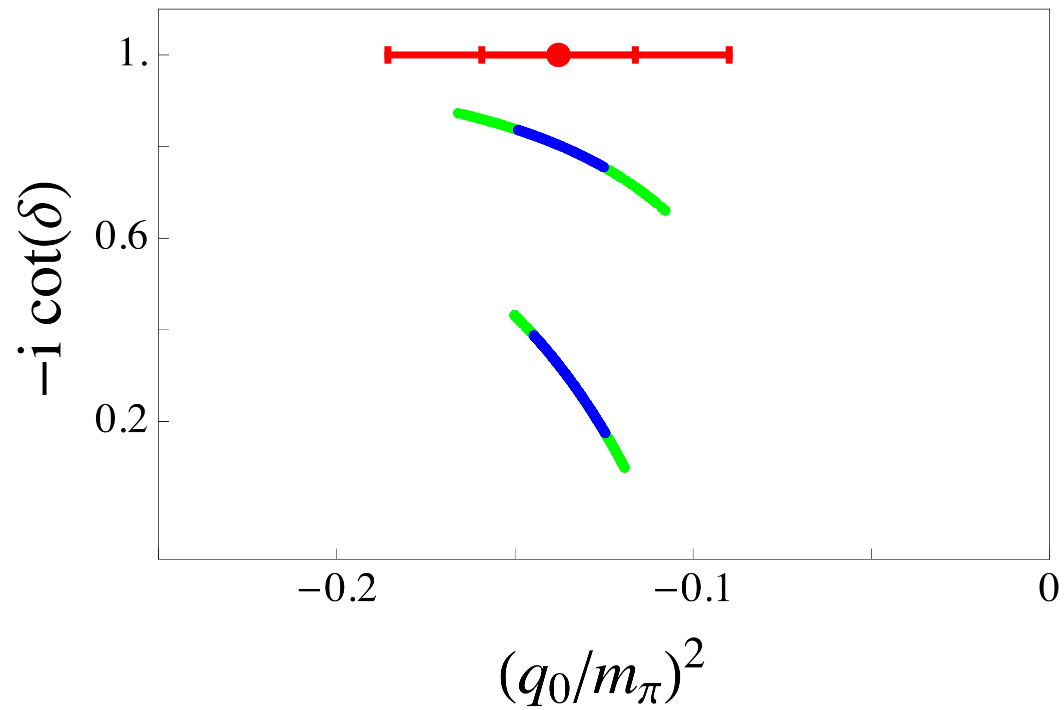
KEK-ps (2007) ($K^- \, {}^{12}C \rightarrow K^+ \Lambda\Lambda X$)
Enhancement seen just above ΛΛ threshold

NPLQCD, anisotropic clover lattices

N_f=2+1, a_s=0.12 fm, m_π=390 MeV, L=2.0, 2.5, 3.0, 3.9 fm

Extrapolation to infinite volume

$$E \sim -B \; + \; c_1 \, \frac{e^{-\gamma L}}{L} \; + \; ....$$



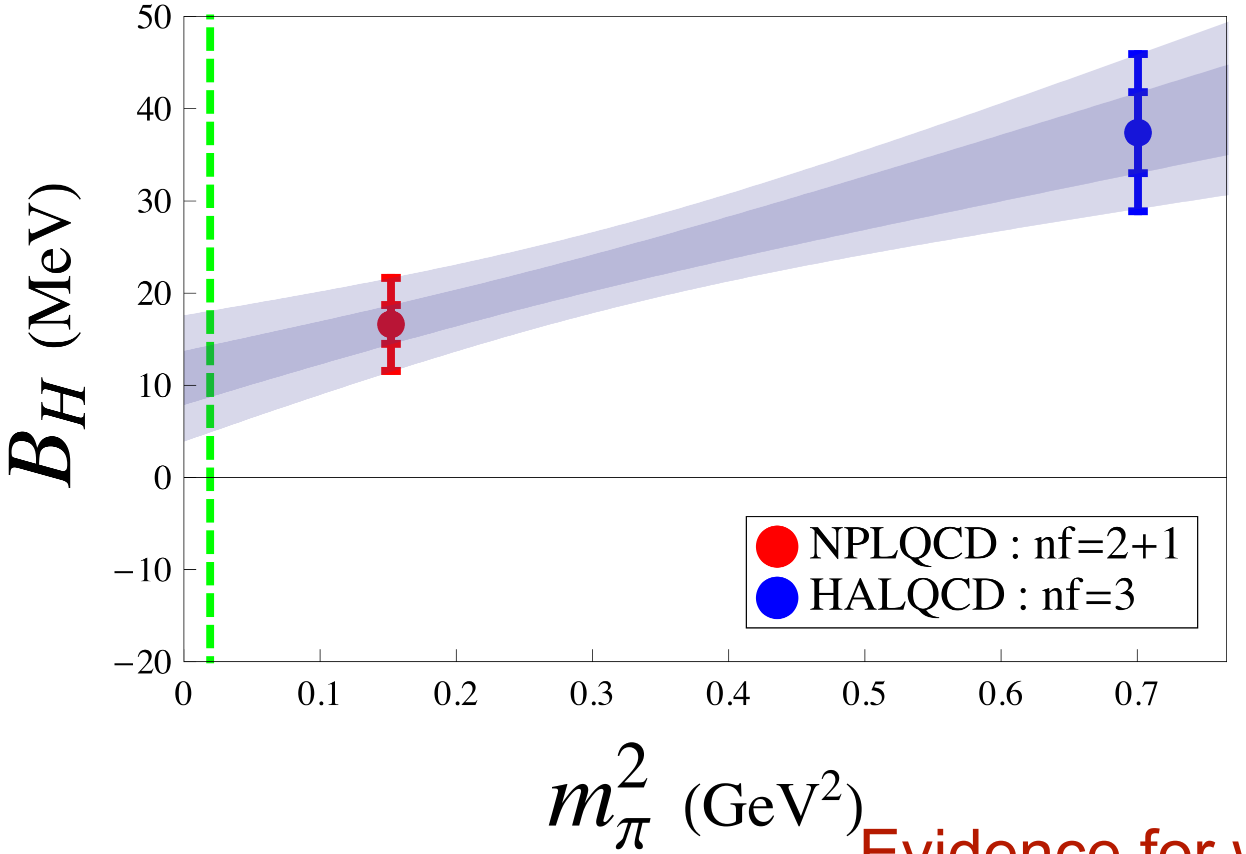
$$B \;=\; 16.6 \pm 2.1 \pm 4.6 \text{ MeV}$$

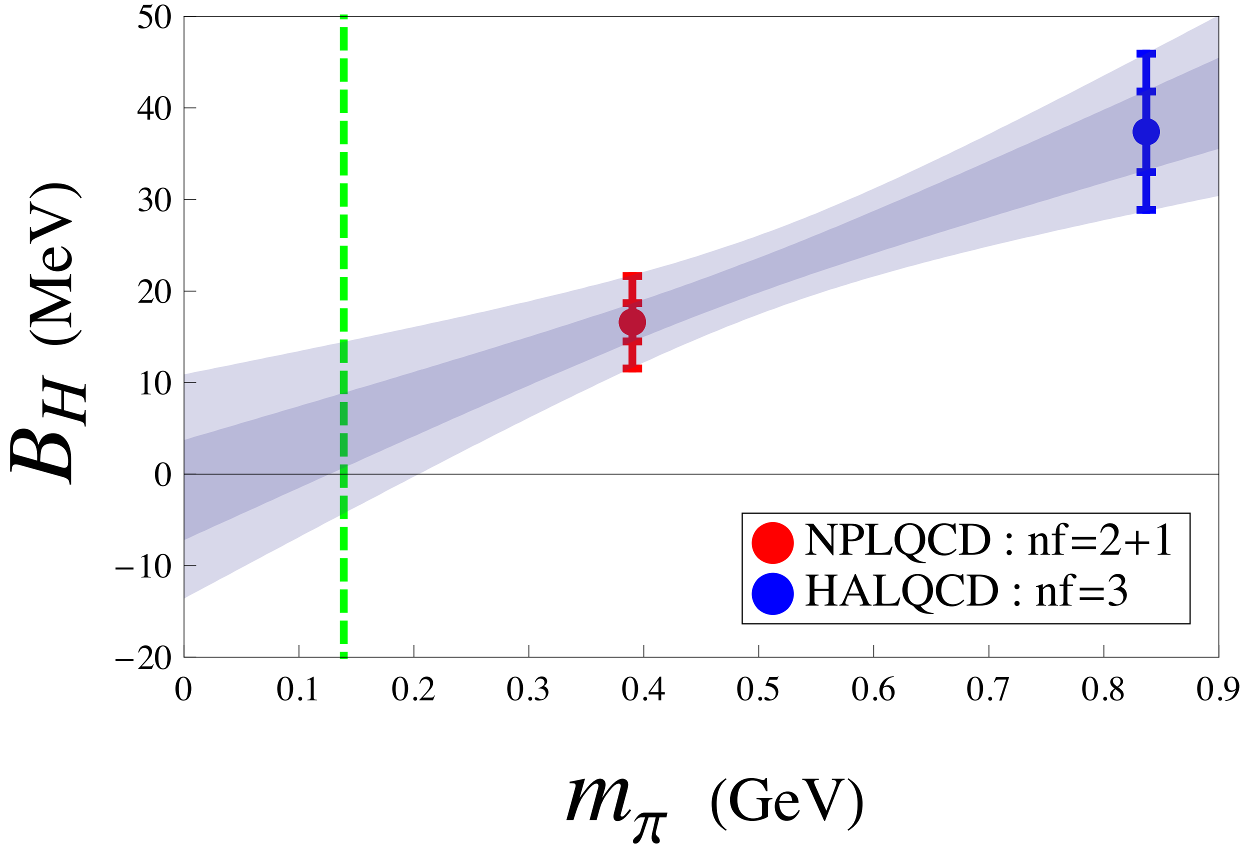
H-Dibaryon...

Physical Review Letters – 22 April 2011.
Volume 106, Issue 16

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)
Published 20 April 2011 (4 pages), 162001.

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)
Published 20 April 2011 (4 pages), 162002.





Evidence for weakly bound or just unbound dibaryon

Hadron Interactions in 2011-2012

Explore anisotropic clover lattices at 32^3 x 256 and 40^3 x 256

- H-dibaryon binding
  - refine chiral extrapolation
  - YN and YY interactions
    - - other possible bound-states
- NN scattering lengths and Deuteron
  - 230 MeV -- entering regime where can connect with experiment
- Meson-meson interactions

- **In the near term, QCD calculations of light nuclei will become precise**
  - **Hyper-nuclear realm: golden opportunity for predictions**
- **Longer term: address nuclear properties/matrix elements**

Summary

- Past year has seen range of high-impact calculations:
  - GPDs and TMDs
  - Isoscalar meson spectroscopy, spin-identified baryon spectrum, phase shift in non-resonant channel
  - Electromagnetic polarizabilities
  - Binding in H-dibaryon system
- GPUs have enabled otherwise intractable calculations
- Range of new calculations in nuclear physics proposed for 2011-2012
- Low-energy tests of Standard Model/Fundamental Symmetries
  - Saul Cohen Radiative Decays of Neutral Mesons
  - Huey-Wen Lin *Probing TeV Physics through Neutron-Decay Matrix Elements*
  - Christopher Aubin *Hadronic contributions to the muon g–2 using Asqtad staggered fermions*
  - Taku Izubuchi *Applications of QCD+QED simulations: Isospin breaking in the hadron spectrum and Hadronic contributions to the muon anomalous magnetic moment*

Calculations directly impact the Experimental program: *NSAC Milestones*

NSAC Performance Measures in Hadronic Physics

Year	#	Milestone
2009	HP3	Complete the combined analysis of available data on single π, η and K photo-production of nucleon resonances and incorporate the analysis of two-pion final states into the coupled-channel analysis of resonances.
2010	HP4	Determine the four electromagnetic form factors of the nucleons to a momentum-transfer squared, Q^2, of 3.5 GeV^2 and separate the electroweak form factors into contributions from the u, d and s-quarks for $Q^2 < 1$ GeV^2 .
2010	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 ^4He (*e,e'p*) reaction.
2011	HP6	Measure the lowest moments of the unpolarized nucleon structure functions (both longitudinal and transverse) to 4 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 $1 < Q^2 < 5$ GeV^2 for both protons and neutrons.
2012	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^2 and measure the electro- and photo-production of final states with one and two pseudoscalar mesons.
2012	HP11	Measure the helicity-dependent and target-polarization-dependent cross-section differences for Deeply Virtual Compton Scattering (DVCS) off the proton and the neutron in order to extract accurate information on generalized parton distributions for parton momentum fractions, x, of 0.1 – 0.4, and squared momentum transfer, t, less than 0.5 GeV^2 .
2013	HP8	Measure flavor-identified q and q contributions to the spin of the proton via the longitudinal-spin asymmetry of W production.
2013	HP12	Utilize polarized proton collisions at center of mass energies of 200 and 500 GeV, in combination with global QCD analyses, to determine if gluons have appreciable polarization over any range of momentum fraction between 1 and 30% of the momentum of a polarized proton.
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.
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.
2015	HP13	Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering **TMDs**
2018	HP14	Extract accurate information on spin-dependent and spin-averaged valence quark distributions to momentum fractions x above 60% of the full nucleon momentum
2018	HP15	The first results on the search for exotic mesons using photon beams will be completed.