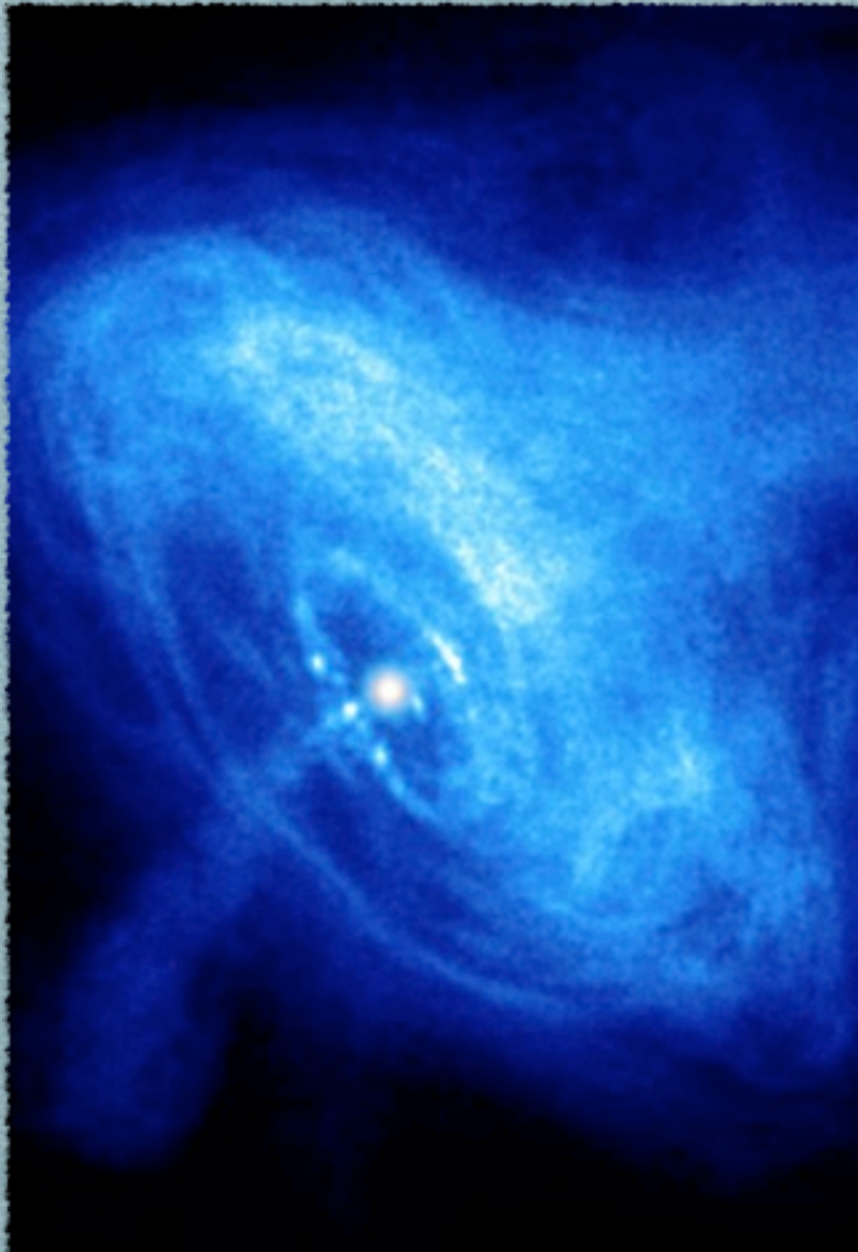
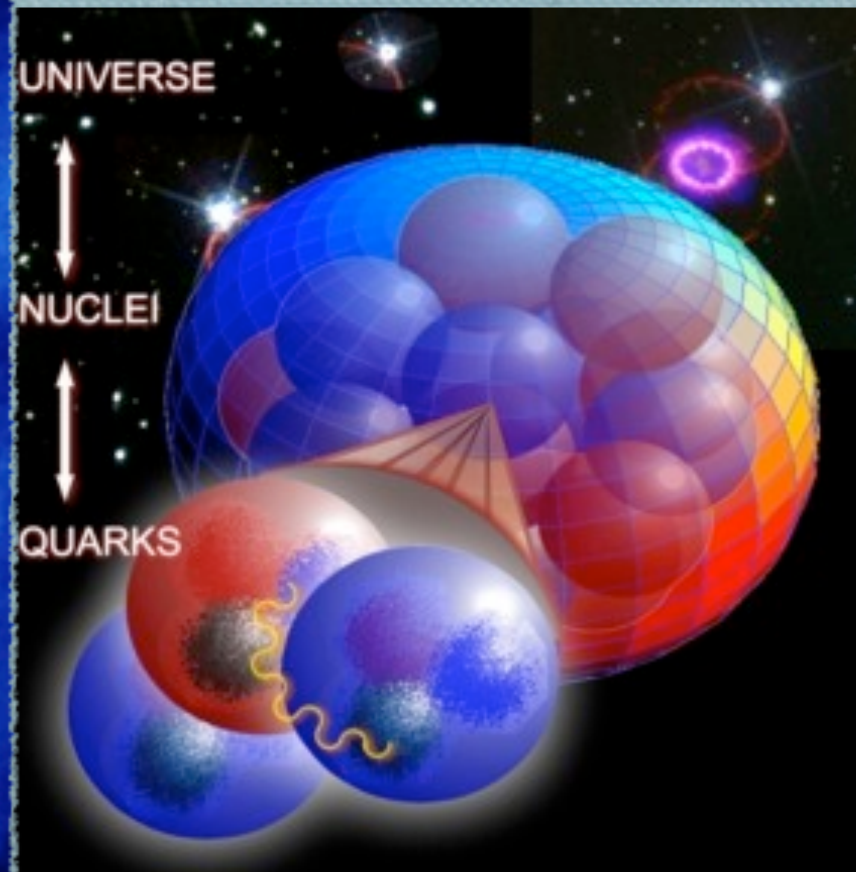
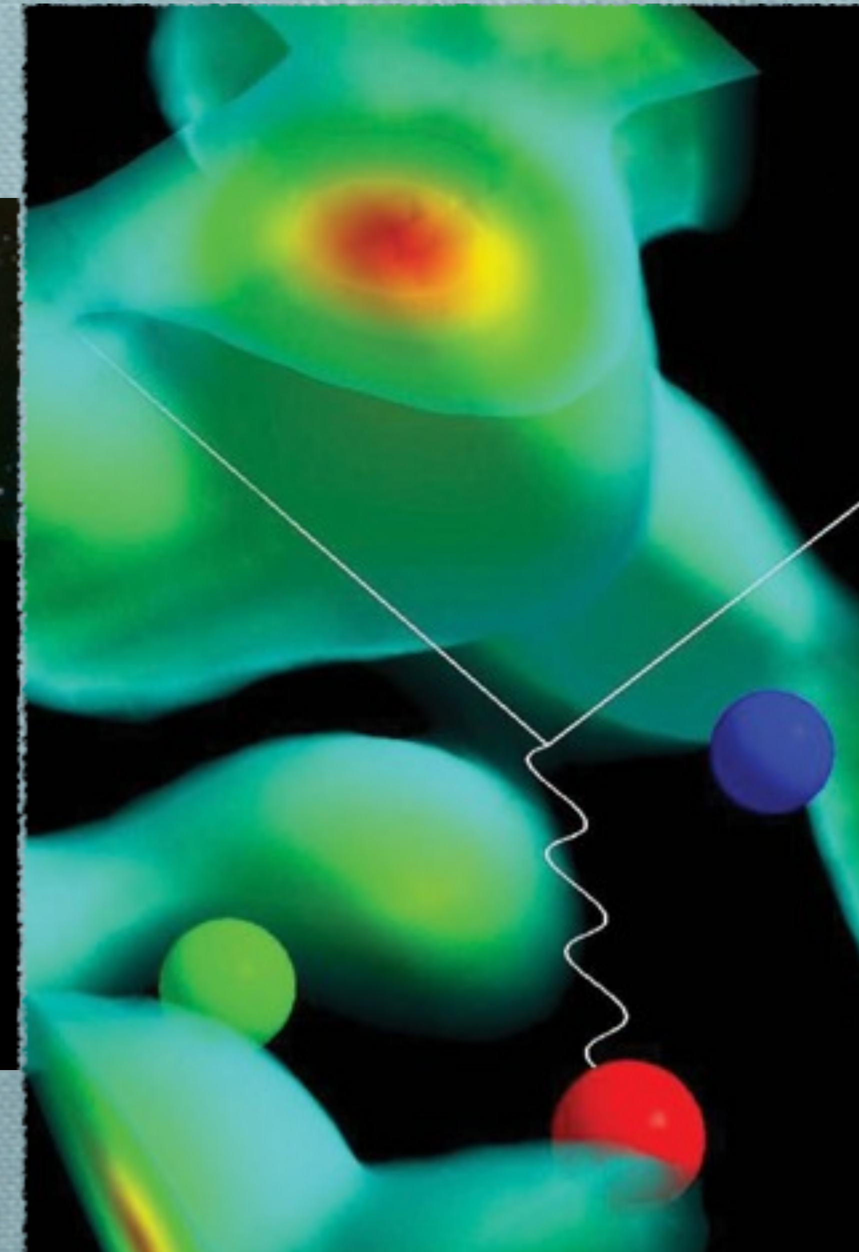






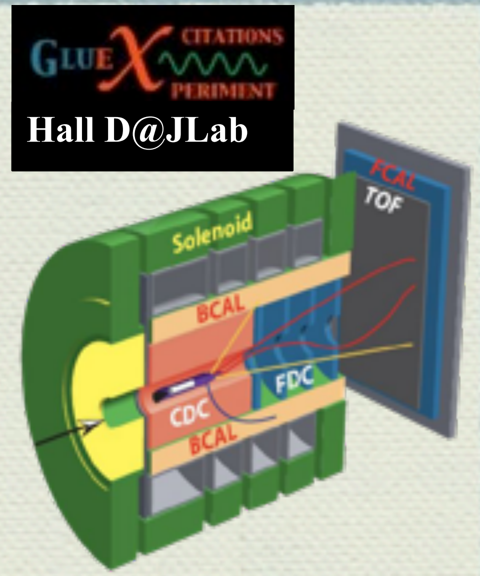
Jefferson Lab
Thomas Jefferson National Accelerator Facility

LQCD for Nuclear Physics

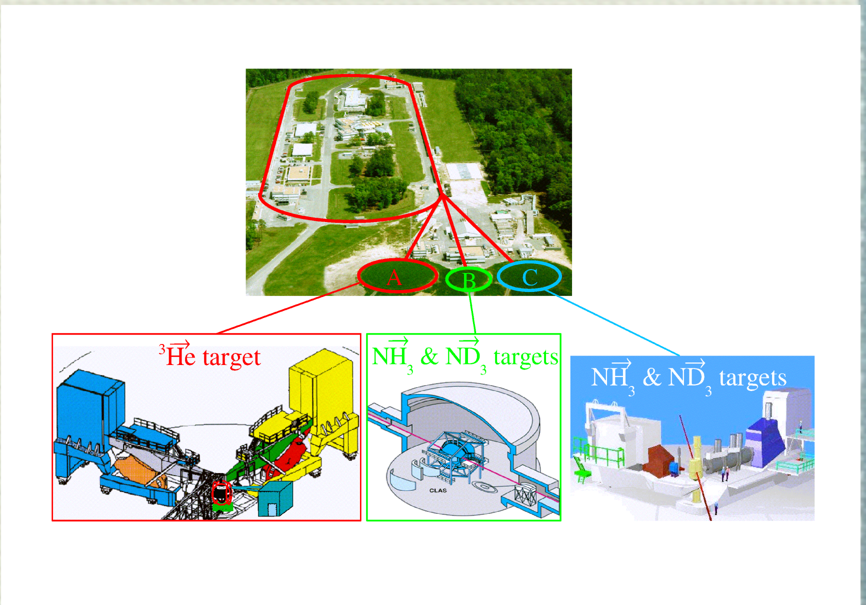
Kostas Orginos
The College of William and Mary / JLab

Goals

- Understanding the spectrum of hadrons
- Understanding the structure of hadrons
  - How charge and magnetic currents are distributed in the nucleon
- Understand how hadrons interact
  - The connection of nuclear physics to quarks and gluons
  - Properties of resonances



JLab @ 12 GeV



NSAC Performance Measures in Hadronic Physics

Year	#	Milestone
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
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.

Computational resources

Lattice QCD for Nuclear Physics

- Gauge field ensemble generation
  - Cray, BG/P, using 16-24K cores
  - require double precision
- Analysis
  - USQCD GPU clusters have played a central role
    - quark propagators -- single precision -- no error-correction memory
  - USQCD clusters are primarily used for analysis
- Contractions
  - Single core task -- double precision
  - Parallelization over Monte-Carlo ensemble
  - USQCD clusters have been a important tool

Ensembles+Analysis

Massive amount of resources needed:

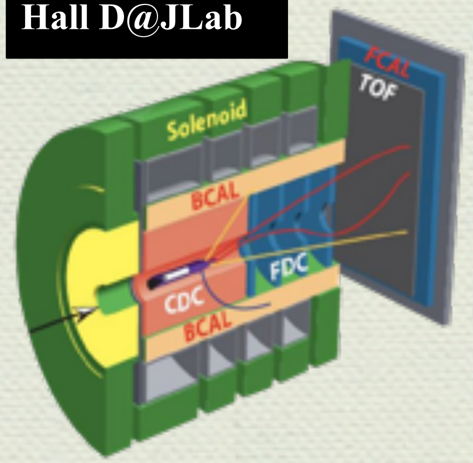
$\mathcal{O}$(100M) core-hours

Contractions

Small amount of resources needed:

$\mathcal{O}$(1M) core-hours

Spectroscopy



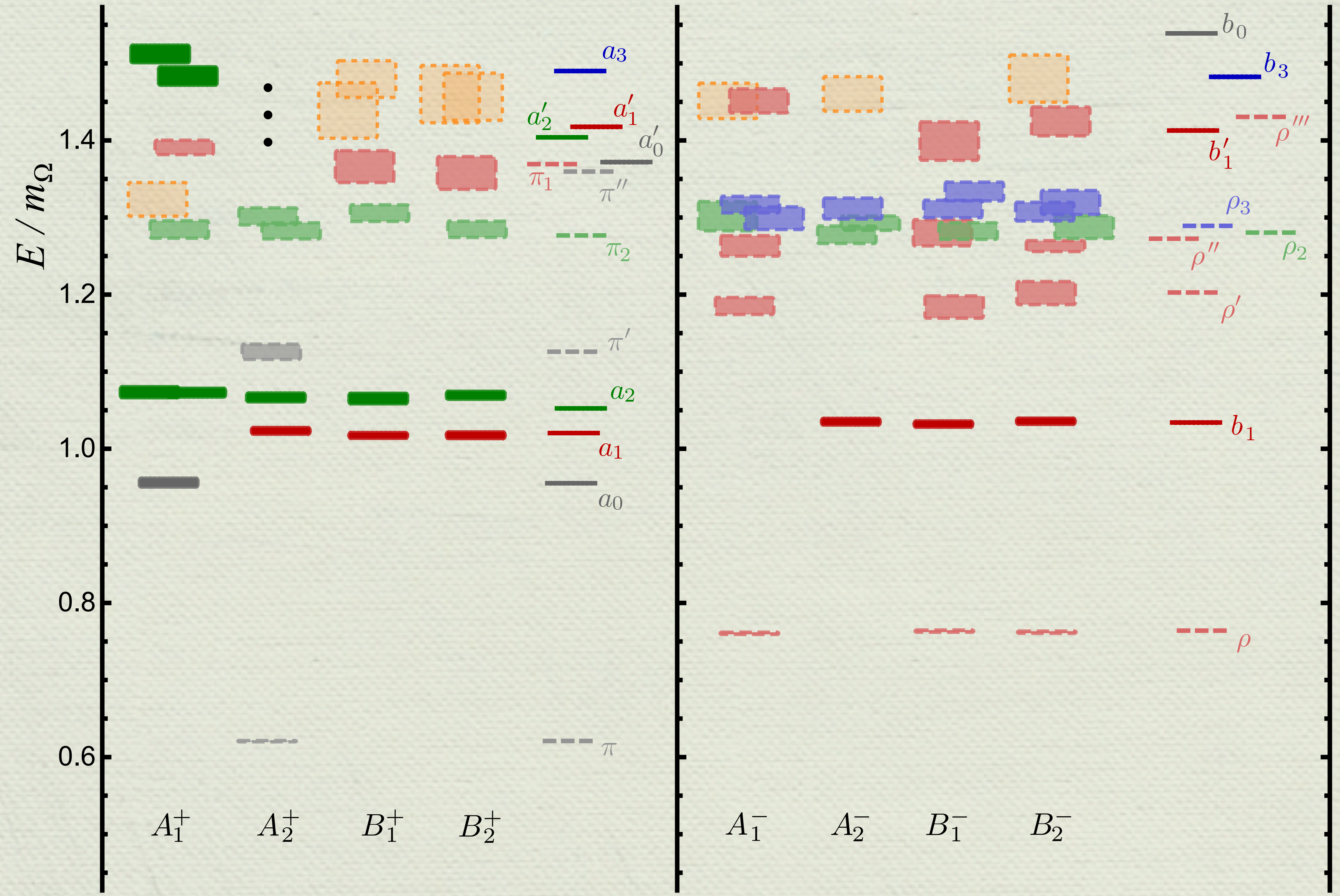
- Importance:
  - How bound states arise from QCD
  - Revealing the many body nature of hadronic states
  - Give insight to confinement mechanisms
  - Compare theoretical calculations and experimental observations

Accomplishments

- Helicity operators for mesons in flight
  - [C. Thomas et. al. arXiv: 1107.1930 Phys. Rev. D 85, 014507 (2012)]
- Hybrid Baryons in QCD
  - [C. Dudek and R. Edwards arXiv: 1201.2349]
- S and D wave phase shifts in I=2 π-π scattering
  - [J. Dudek et.al. arXiv: 1203.6041]
- Excited and charmonium spectrum
  - [L. Liu et.al. arXiv: 1204.5425]

Helicity Operators

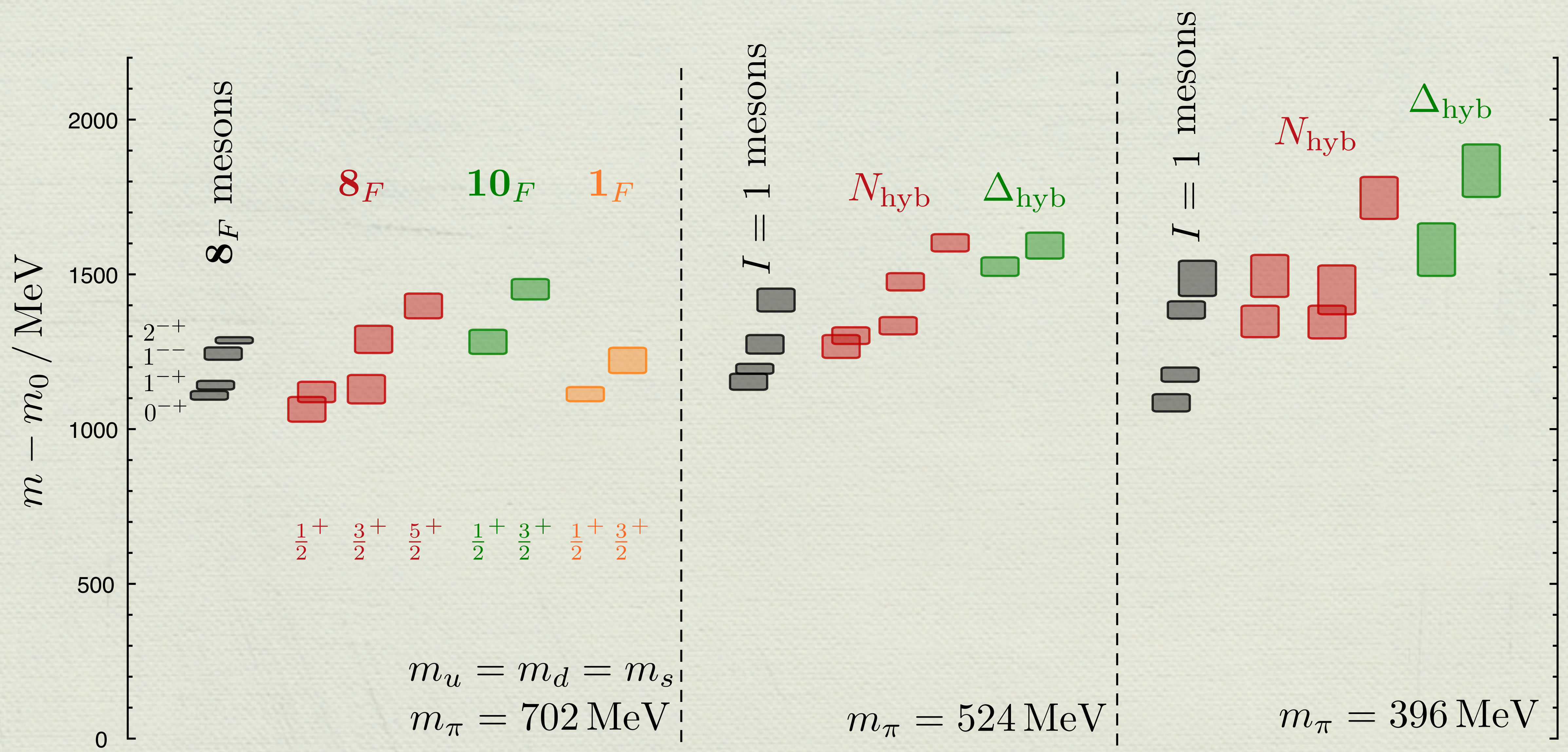
[C. Thomas et. al. arXiv: 1107.1930 Phys. Rev. D 85, 014507 (2012)]



Example of the non-zero momentum meson spectrum calculated from LQCD using the Helicity operators

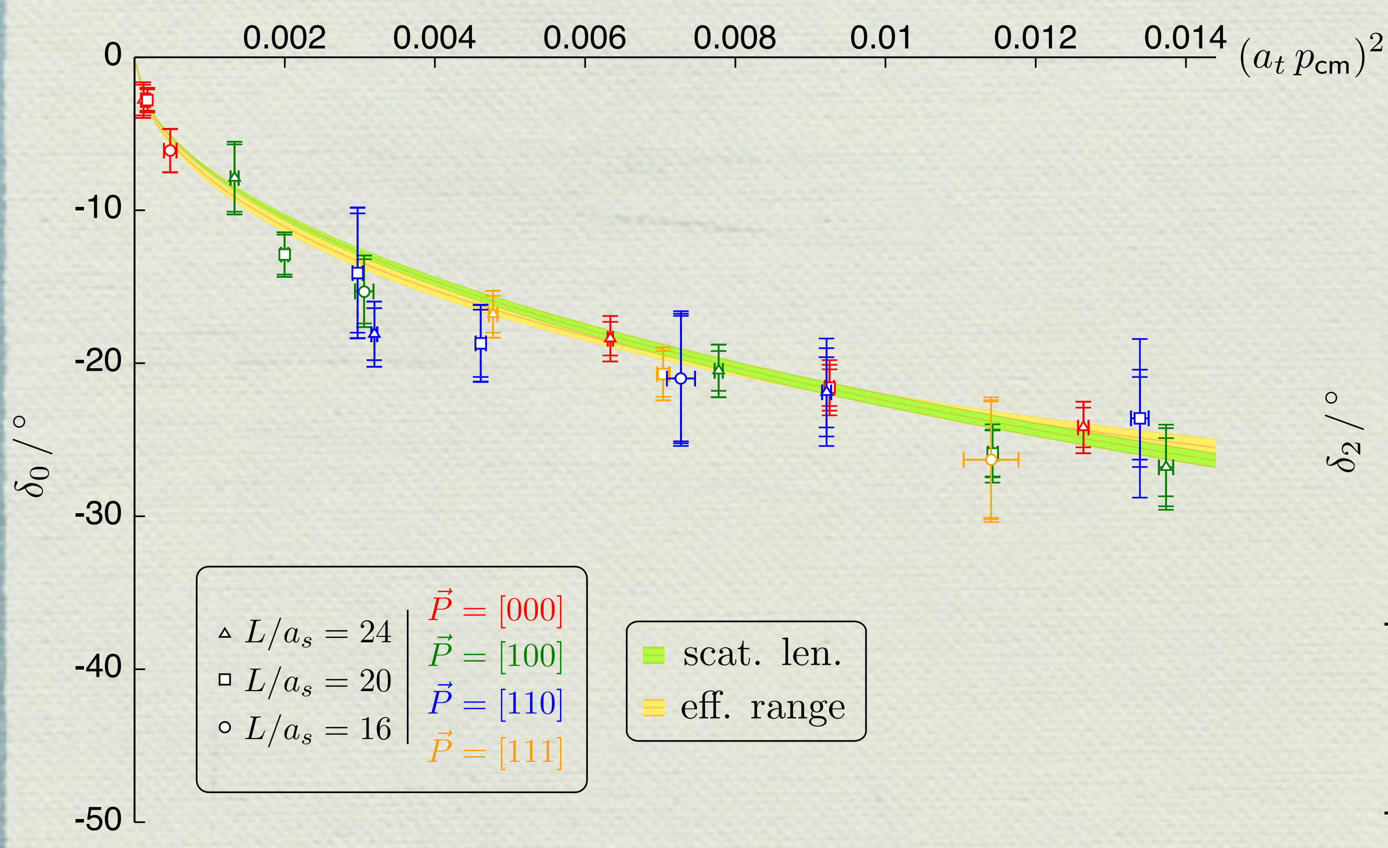
Hybrid Baryons

[C. Dudek and R. Edwards arXiv: 1201.2349]

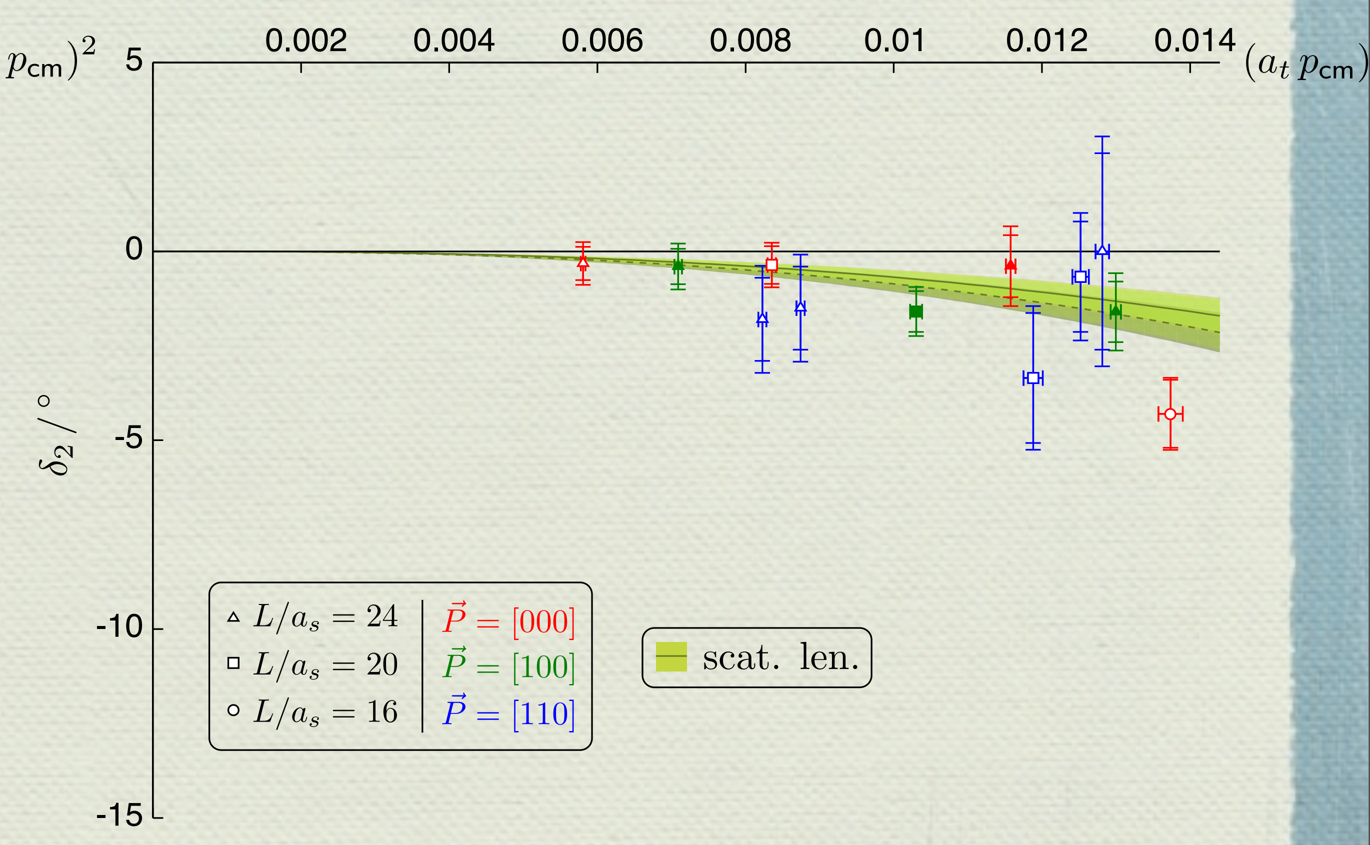


Phase shifts: π-π I=2

[J. Dudek et.al. arXiv: 1203.6041]



S-Wave



D-Wave

Future plans

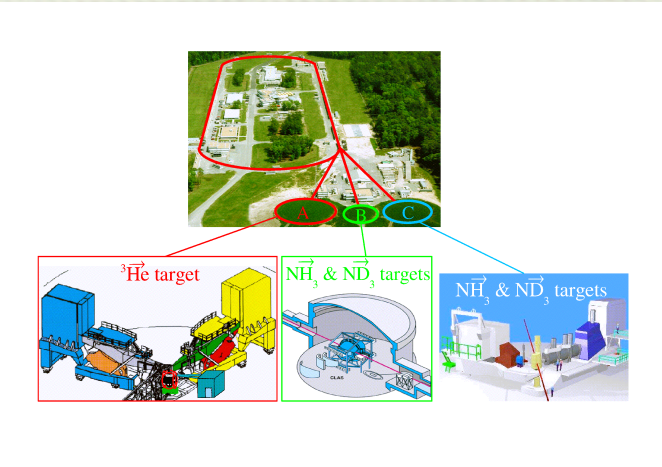
Hadron Spectrum Collaboration

- Application of a new method called LaPH (Morningstar et. al.)
  - Allows scaling to larger volumes
- Calculations on larger lattices closer to physical pion mass point (220MeV)
- Production of ensembles at 140MeV pion mass using INCITE time
- Introduce multi-particle interpolating fields to the operator basis
- Continue broad efforts on
  - Nucleon spectroscopy: (χQCD: K-F Liu)
  - Quarkonium physics: (MILC/Fermilab: DeTar)
  - Charmed and Bottom baryon spectrum (WMQCD: Meinel,Brown)
- Over the next 5 years calculations of the masses and widths of low lying resonances at physical pion masses (140 MeV) are expected

Hadron Structure

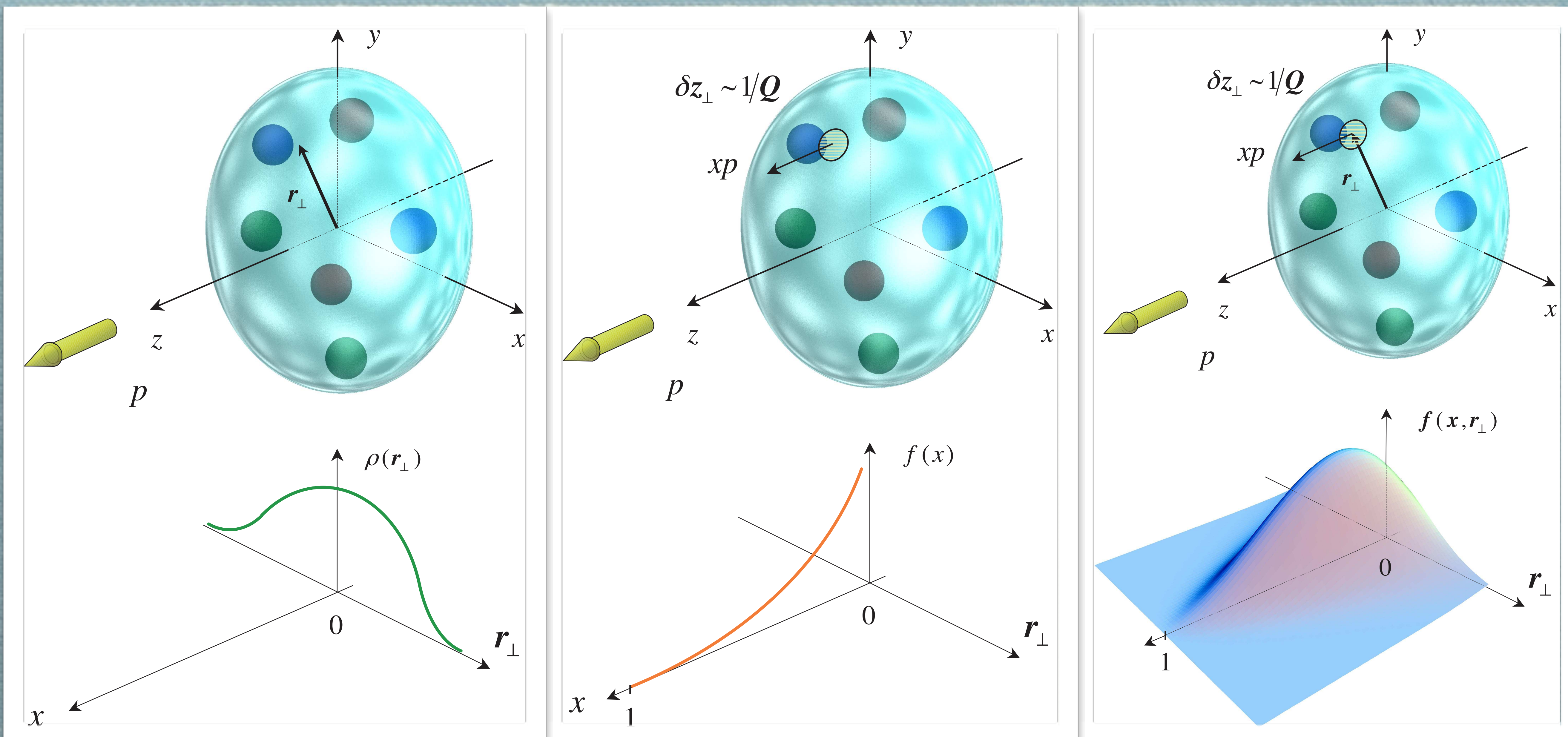
- Importance:
  - How are nucleons made up from the fundamental degrees of freedom (quarks and gluons)
  - Understand the charge and mangetization distributions in the nucleon
  - Complement key elements of DOEs experimental programs
    - quark distributions HERMES, Fermilab, LHC
    - form factors and GPDs: JLab
    - Contributions to the nucleon spin: JLab RHIC-spin, future EIC
    - Transverse momentum dependent distributions: JLab, RHIC-spin, Fermilab,future EIC

JLab @ 12 GeV



GPDs

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



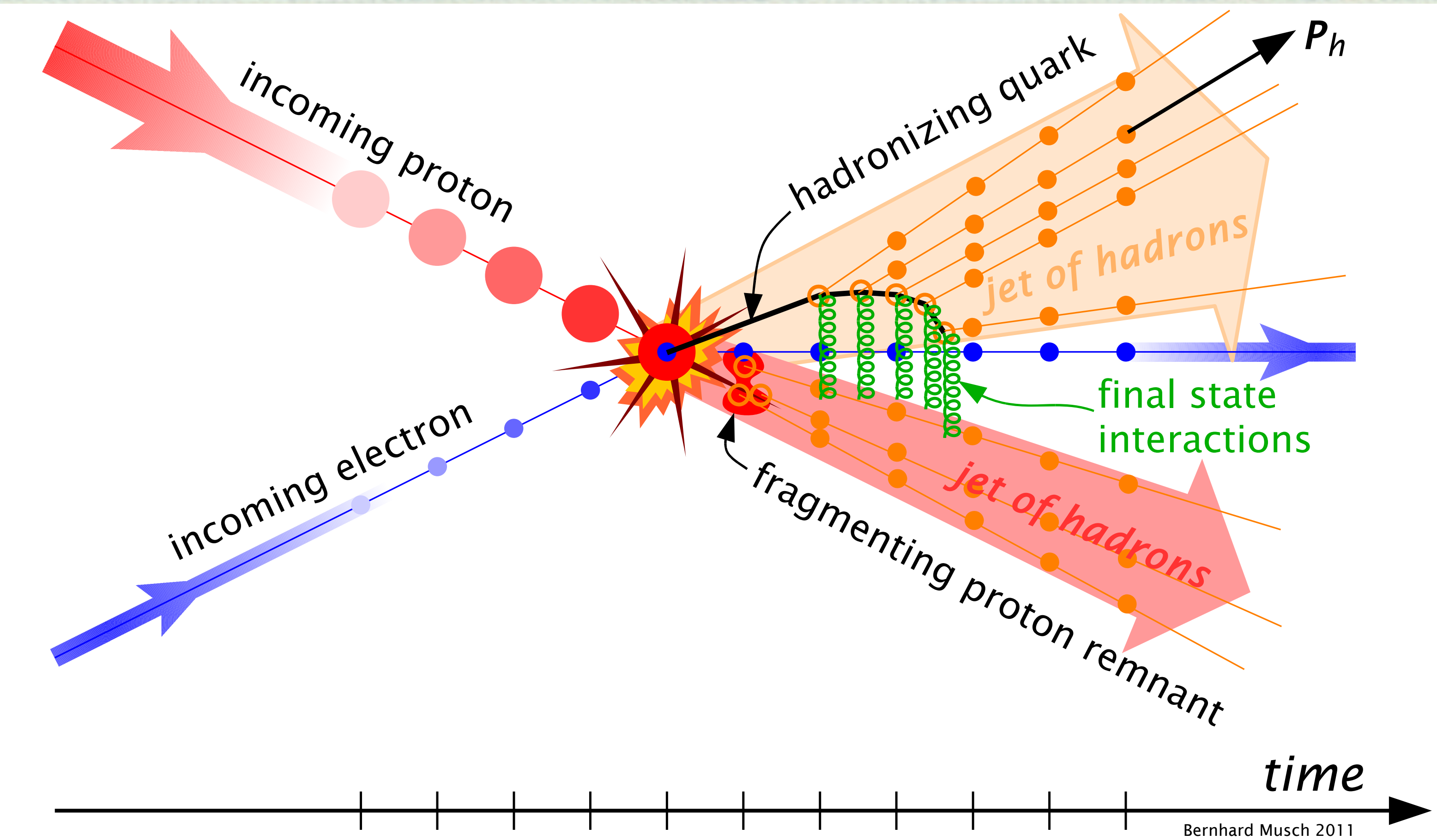
Form Factors

Parton Distribution functions

Generalized Parton Distribution functions

TMDs (Transverse momentum distributions)

from experiment e.g. SIDIS (semi-inclusive deep inelastic scattering)
Drell-Yan



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

Sivers ← time-reversal odd

Final state interactions
explain large asymmetries
Signature of QCD

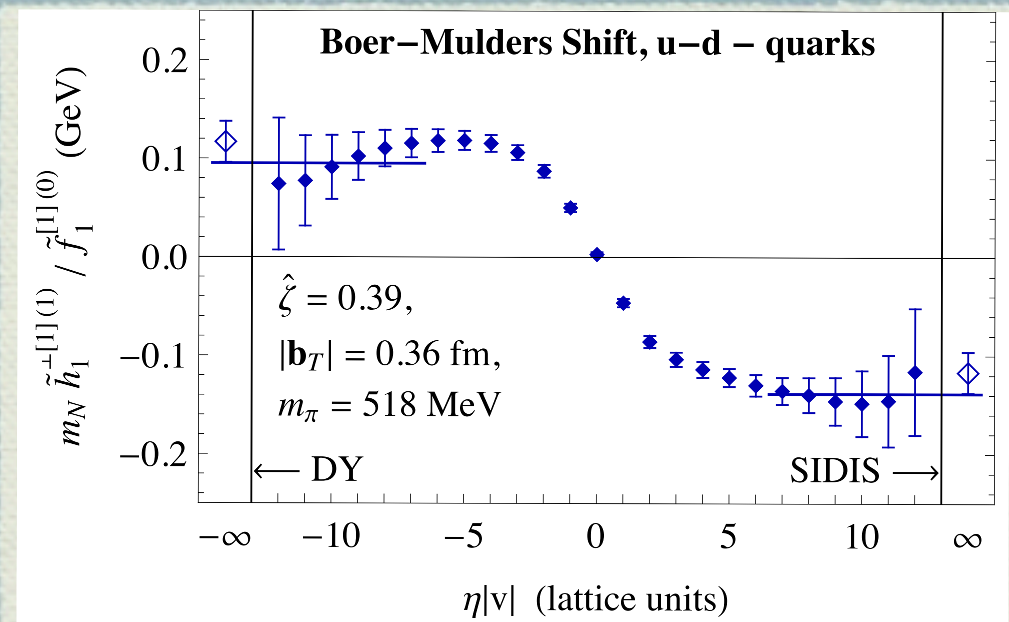
form experiment:
HERMES COMPASS,
JLab 6 GeV, JLab 12 GeV,
...,
EIC

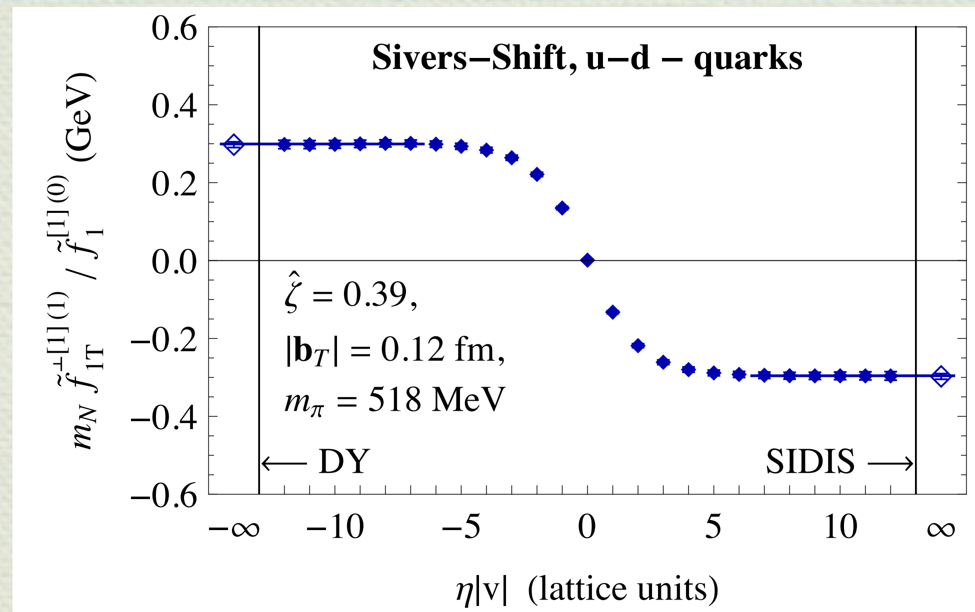
Accomplishments

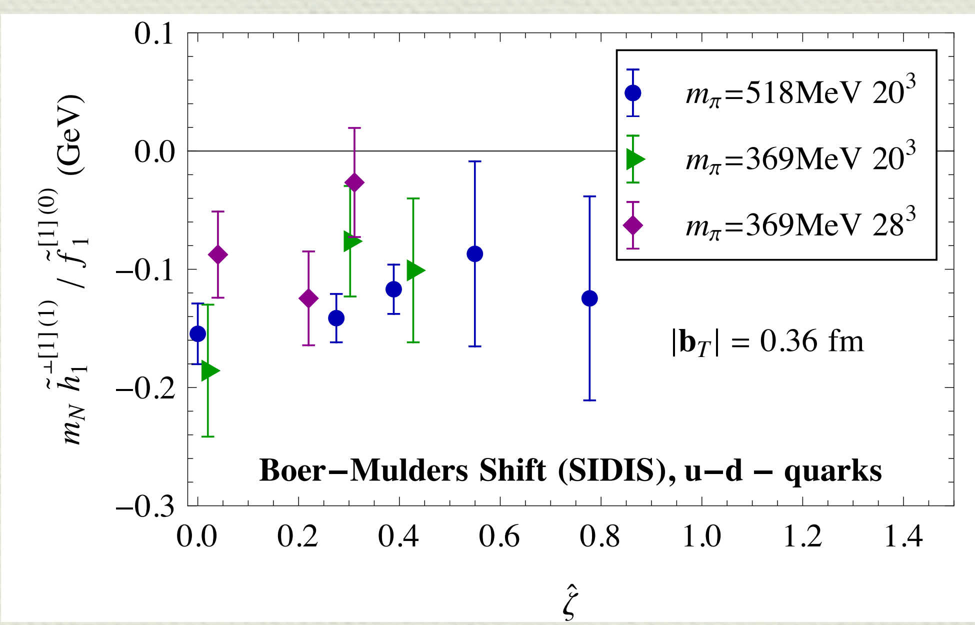
- Excited state contamination in nucleon structure
  - [J. Green et. al. arXiv:1111.0255 PoS(Lattice 2011) 157]
- Quark contributions to nucleon momentum and spin from DWF calculations
  - [S. Syritsyn et. al. arXiv:1111.0718 PoS(Lattice 2011)]
- Sivers and Boer-Mulders observables from Lattice QCD
  - [B. Munch et. al. arXiv:1111.4249]
- The strangeness and charmness of the nucleon from overlap fermions
  - [M. Gong et.al. arXiv: 1204.0685]
- Quark and glue momenta and angular momenta in the proton
  - [K-F. Liu et. al. arXiv:1203.6388 PoS(Lattice 2011)]

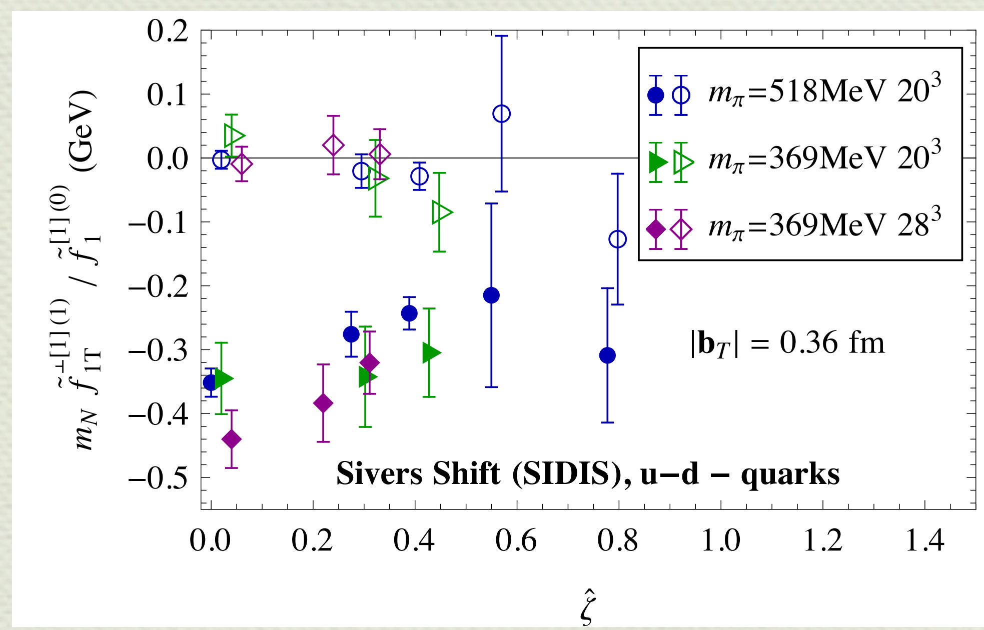
TMDs: Lattice QCD

[B. Munch et. al. arXiv:1111.4249]



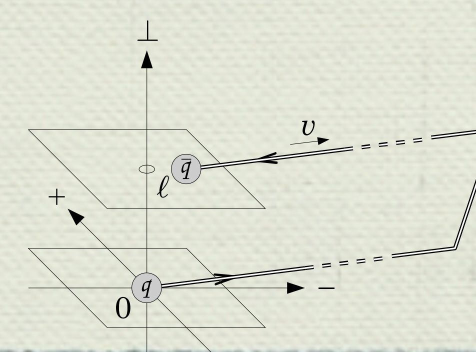






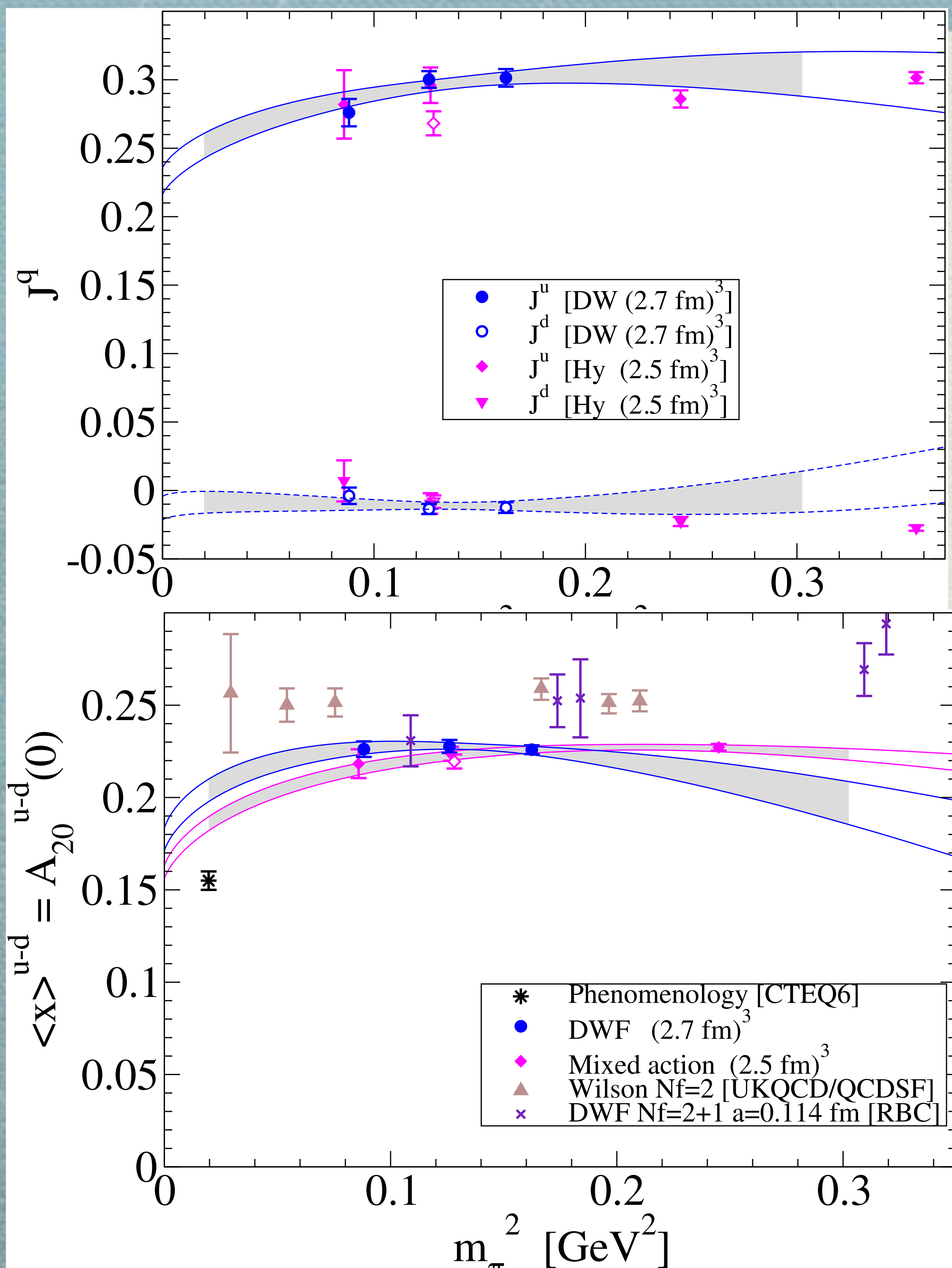
MILC:
gauge fields
2+1 flavors
asqtad fermions

LHPC:
domain wall
fermion propagators
m_π ~ 500, 350MeV



GPDs: Lattice QCD

[S. Syritsyn et. al. arXiv:1111.0718 PoS(Lattice 2011)]



Angular momentum

RBC/UKQCD:

gauge fields

2+1 flavors

domain wall fermions

MILC:

gauge fields

2+1 flavors

asqtad fermions

Momentum faction

Puzzle:

Why the difference from experiment?

- Excited state contamination in nucleon structure
  - [J. Green et. al. arXiv:1111.0255 PoS(Lattice 2011) 157]

Future plans

- LHPC (J. Negele): Study the systematics of extracting moments of GPDs from the lattice using the isotropic clover Wilson fermion ensembles
- JLAB(Orginos): Generate isotropic clover Wilson fermion ensembles suitable for hadron structure calculations (request INCITE resources)
- 5 year plan:
  - Understand systematic errors and reliably compute experimentally measured nucleon matrix elements such as the nucleon axial charge and the momentum fraction
  - Compute moments of GPDs and TMDs
    - Synergy of LQCD with experiment in determining GPDs

Hadron Interactions

Goals:

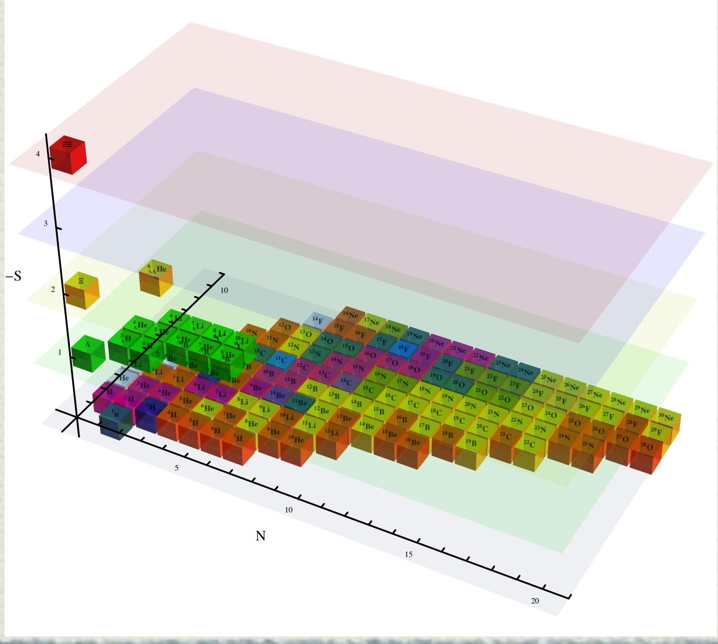
- Challenge: Compute properties of nuclei from QCD
  - Spectrum and structure
- Confirm well know experimental observation for light nuclei
- Explore the largely unknown territory of hyper-nuclear physics
- Provide input for the equation of state for nuclear matter in neutron stars
- Go beyond the few baryon systems to understand properties of multi-baryon systems

Jefferson Lab

FAIR

J-PARC

KEK
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION



Accomplishments

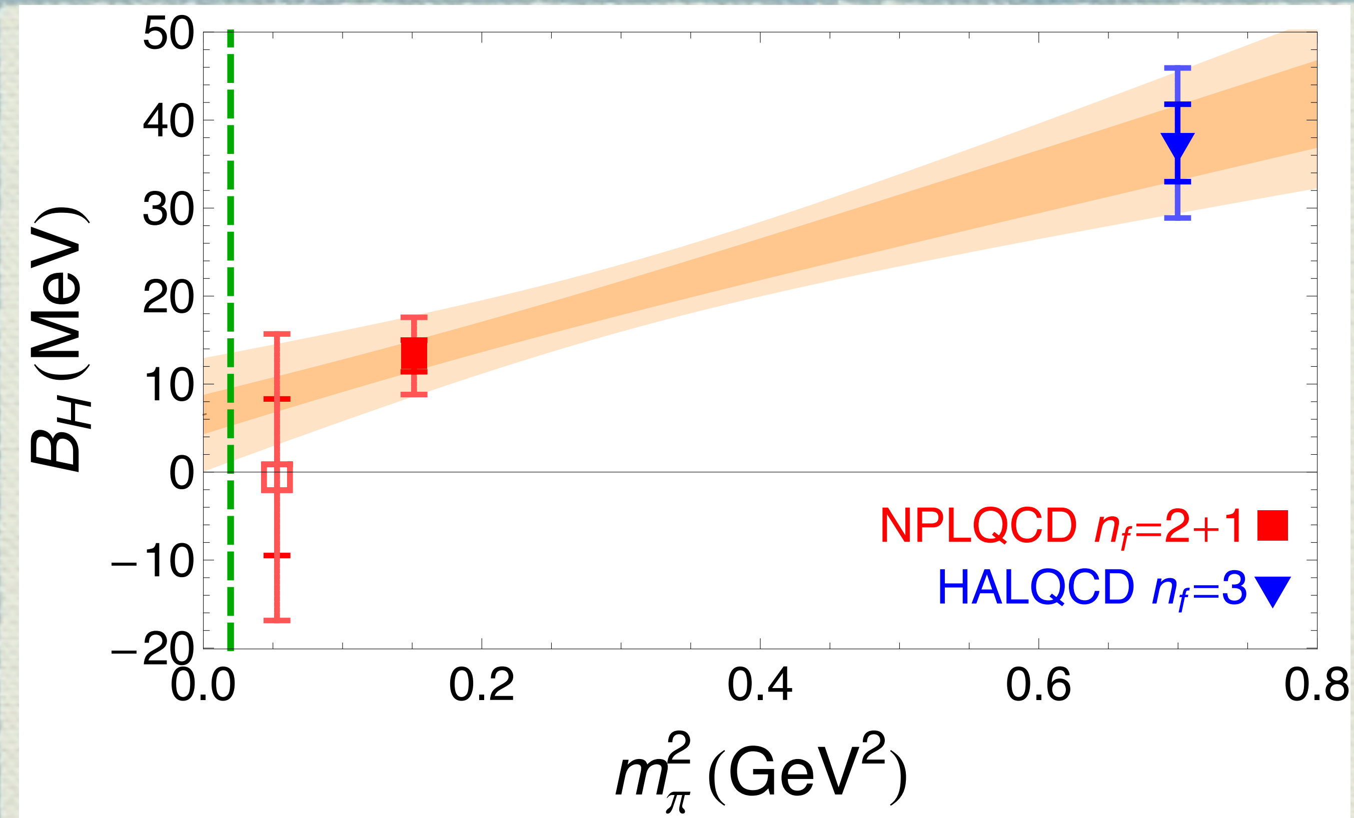
- Present Constraints on the H-dibaryon at the Physical Point from Lattice QCD
  - [S. Beane et.al. arXiv:1103.2821 Mod. Phys. Lett. A26: 2587, 2011]
- High Statistics Analysis using Anisotropic Clover Lattices: (IV) Volume Dependence of Light Hadron Masses
  - [S. Beane et.al. arXiv:1104.4101 Phys.Rev.D84:039903,2011]
- The I=2 pipi S-wave Scattering Phase Shift from Lattice QCD
  - [S. Beane et.al. arXiv:1107.5023 submitted to Phys.Rev.D]
- The Deuteron and Exotic Two-Body Bound States from Lattice QCD
  - [S. Beane et.al. arXiv:1108.2889 submitted to Phys.Rev.D]
- Hyperon-Nucleon Interactions and the Composition of Dense Nuclear Matter from Quantum Chromodynamics
  - [S. Beane et.al. arXiv:1204.3606 submitted to Phys. Rev. Lett.]

H-dibaryon

S=-2, B=2, $J^p=0^+$

NPLQCD

[S. Beane et.al. arXiv:1103.2821 Mod. Phys. Lett. A26: 2587, 2011]



gauge fields 2+1 flavors (JLab)
anisotropic clover
m_π~ 220MeV, 390MeV

- Perturbative color-spin interactions are attractive for (uuddss)
- Experimental searches
  - BNL-RHIC Excludes the region [-95, 0] MeV
    - A. L. Trattner, PhD Thesis, LBL, UMI-32-54109 (2006).
  - KEK Resonance near threshold
    - C. J. Yoon et al., Phys. Rev. C 75, 022201 (2007).
- Several LQCD calculations have looked for the H-dibaryon

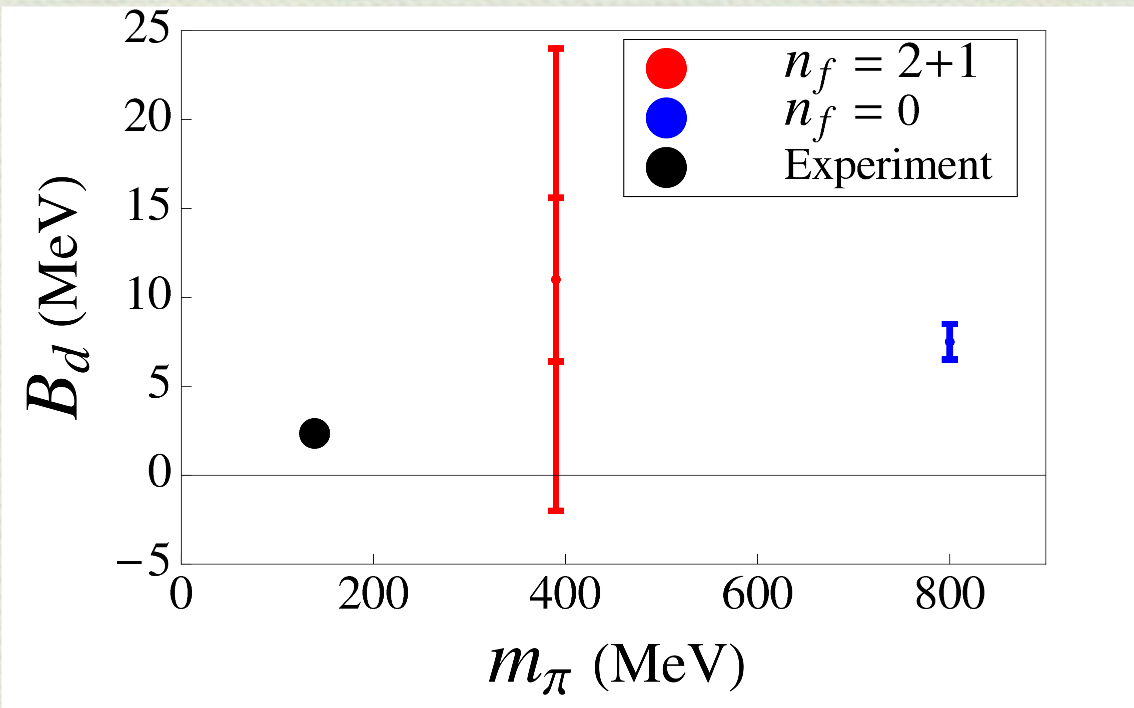
H-dibaryon:
Is bound at heavy quark masses. May be unbound at the physical point

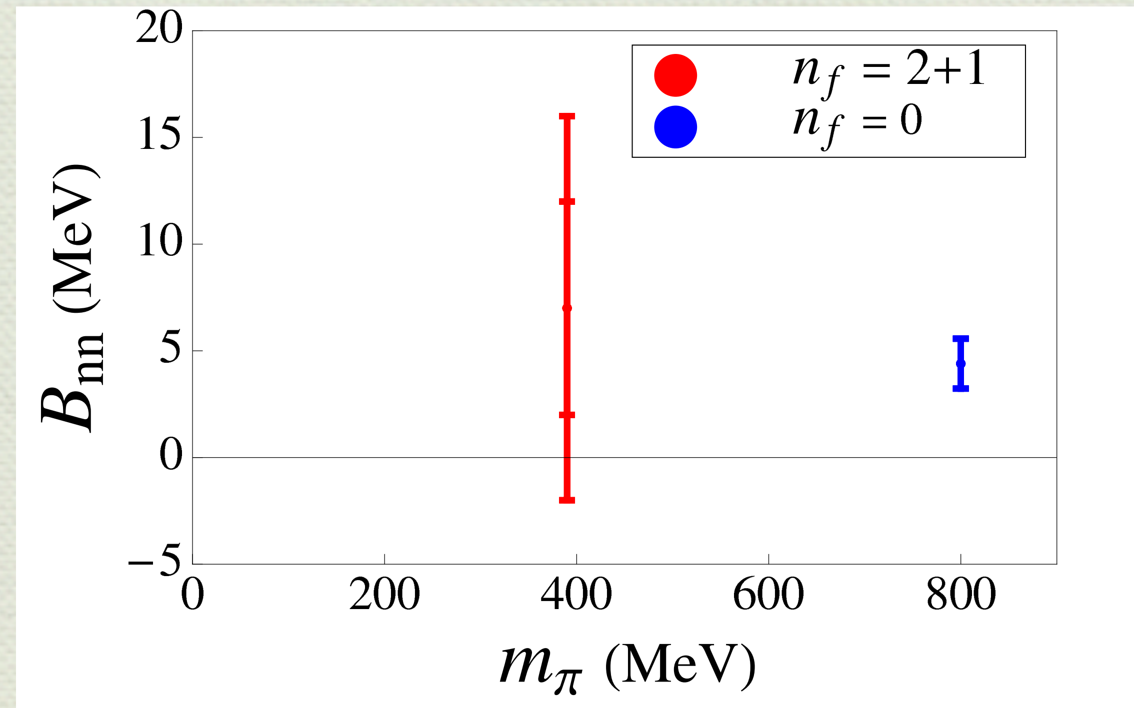
Immediate future: Perform computations close to the physical pion mass point

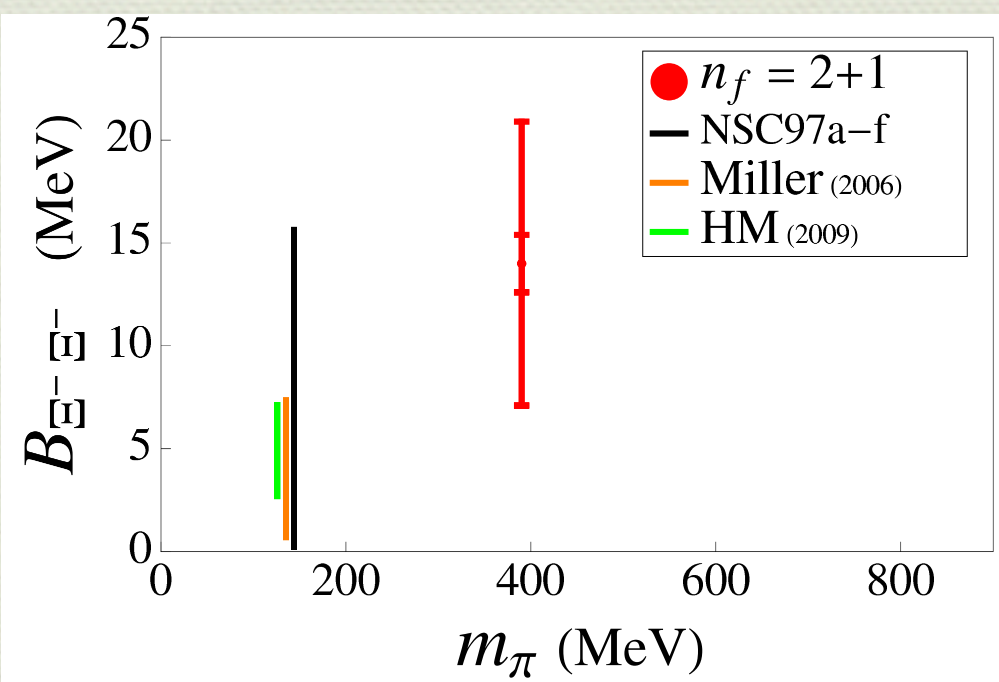
Two baryon bound states

NPLQCD

[S. Beane et.al. arXiv:1108.2889 submitted to Phys.Rev.D]







V. G. J. Stoks and T. A. Rijken
Phys. Rev. C 59, 3009 (1999)
[arXiv:nucl-th/9901028

G. A. Miller,
arXiv:nucl-th/0607006

J. Haidenbauer, Ulf-G. Meisner
Phys.Lett.B684,275-280(2010)
arXiv:0907.1395

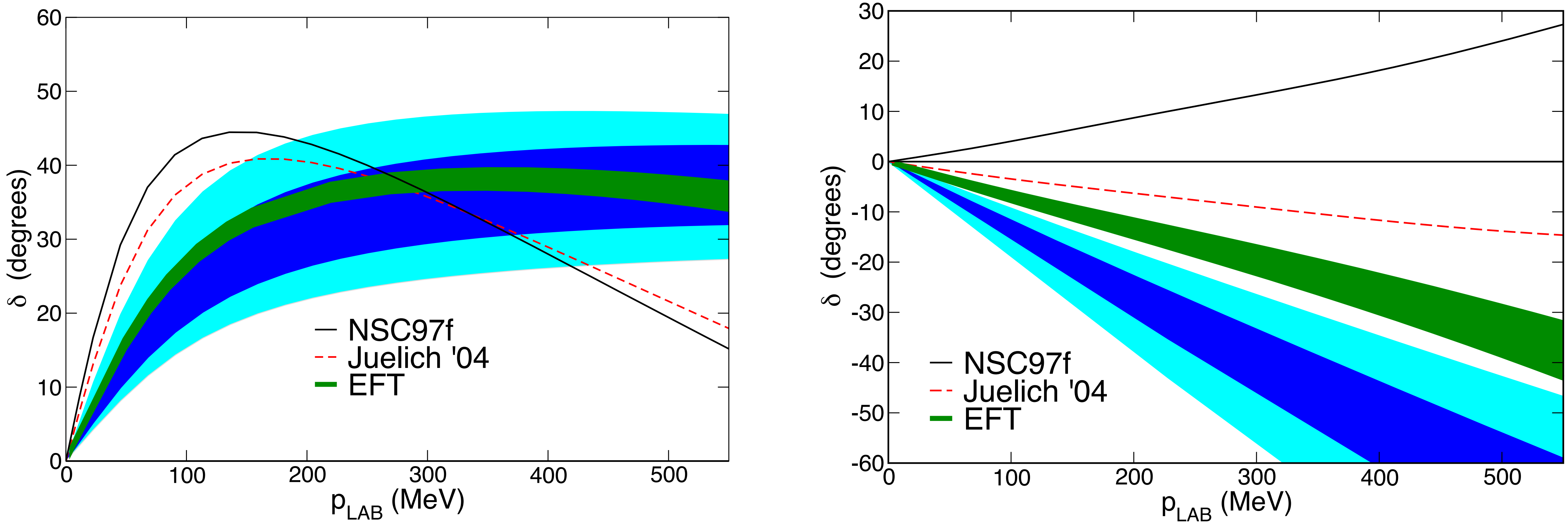
n_f=0:
Yamazaki, Kuramashi, Ukawa
Phys.Rev. D84 (2011) 054506
arXiv: 1105.1418

gauge fields 2+1 flavors (JLab)
anisotropic clover m_π~ 390MeV

Hyperon-Nucleon

NPLQCD

[S. Beane et.al. arXiv:1204.3606 submitted to Phys. Rev. Lett.]



n-Σ spin singlet

n-Σ spin triplet

gauge fields 2+1 flavors (JLab)

anisotropic clover

m_π~ 390MeV

Future plans

- Generate isotropic clover Wilson fermion ensembles (Orginos)
  - Emphasis on large volumes (~6^3fm)
  - large ensembles
  - To be used for hadron structure and spectroscopy
- Use isotropic ensembles at the SU(3) flavor symmetric point and at m_π 400MeV (Detmold)
  - High statistics
  - Operator basis optimized for contraction speed and overlap with ground states
  - focus on multi-nucleon states

NPLQCD

- Five year program:
  - Control systematics of the calculations of properties of two baryon systems
  - Develop the methods that will allow reliable computations of properties of multi-baryon systems

Summary

- Past year:
  - Significant progress has been made
  - USQCD facilities have played an important role in enabling science
- Calculations are maturing and can produce results of phenomenological importance
- Challenges still remain
  - Require theoretical developments and continued support to computing facilities in order to be addressed
- Expect significant progress in the near future

Calculations complement the experimental program and address the NSCA Milestones