The Spectrum, Structure and Interaction of Hadrons

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Jefferson Laboratory

- ***Goals***
- ***LQCD Project: Accomplishments and Opportunities***
  - ***Hadron Structure***
  - ***Spectroscopy***
  - ***Hadron-hadron interactions***
- ***Synergy with Experiment***
- ***Summary***

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?**

Hadronic and Nuclear Proposals

Class A	
Norman Christ	Simulations with Dynamical Domain Wall Fermions
Robert Edwards	Dynamical Anisotropic-Clover Lattice Production for Hadronic Physics
Robert Sugar	QCD with Three Flavors of Improved Staggered Quarks
Jozef Dudek	Spectral and Radiative Meson Physics of GlueX and CLEO-c
Keh-Fei Liu	Nucleon Form Factors and Hadron Spectroscopy
John Negele	Nucleon Structure in the Chiral Regime with Domain Wall Fermions
David Richards	Baryon Spectroscopy using Anisotropic Clover Lattices
Martin Savage	Lattice QCD for Nuclear Physics

Gauge generation (Norman Christ, Robert Edwards, Robert Sugar)

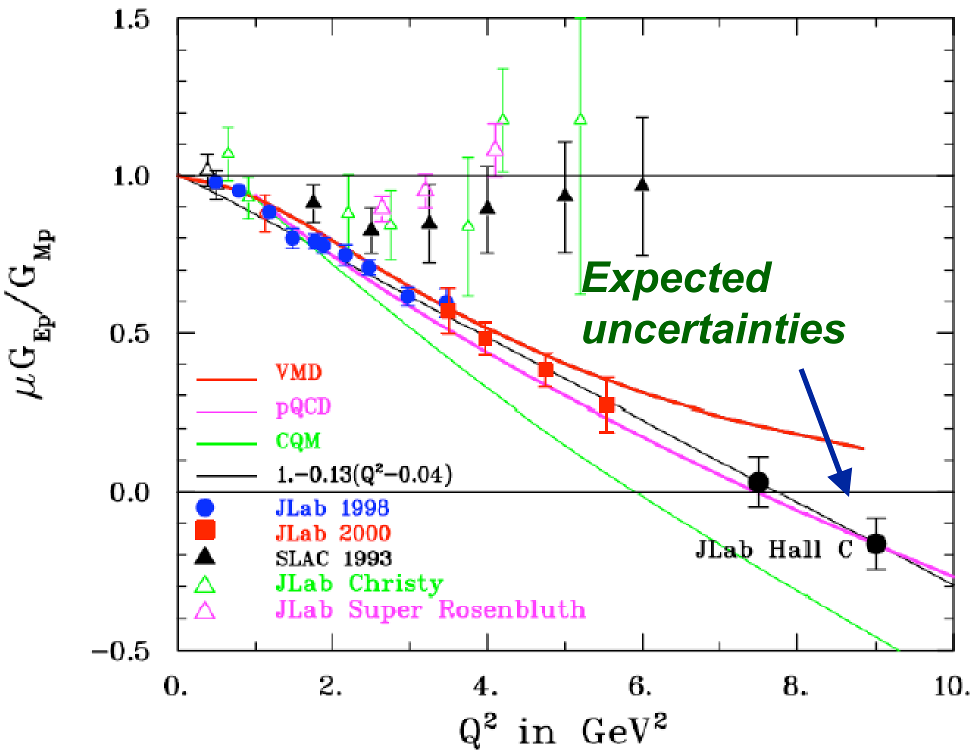
Class B	
Tom Blum	Electromagnetic Effects in Hadrons
Jimmy Juge	Simulating Two-Particle States on Dynamical, Anisotropic Lattices
Christopher Aubin	Delta Moments Using Background Field Techniques
Huey-Wen Lin	Study of Excited Form Factors Using Dynamical Anisotropic Lattice
Kostas Orginos	Octet Baryon Form Factors
James Osborn	Strange Quark Contribution to Nucleon Form Factors
Andre Walker-Loud	Hadronic Electromagnetic Properties
Walter Wilcox	External Field Simulations Using Dynamical Clover Fermions

Hadron Structure

- Hybrid calculation employing $N_f = 2 + 1$ MILC gauge configurations with *Asqtad* sea quarks, and valence quarks computed using Domain-Wall Fermions (DWF) enabling first investigations of hadron structure in approach to chiral regime.
- Menu of computations:
  - Nucleon's axial-vector charge
  - Isovector Form Factors
  - Moments of Generalized Parton Distributions:
    - Orbital angular momentum carried by quarks
    - Transverse structure of the nucleon
    - Complement experimental measurements of GPDs
- JLab, RHIC-spin

Proton EM Form-Factors - I

EM Form Factors describe the distribution of ***charge*** and ***current*** in the proton



C. Perdrisat (W&M) , JLab Users Group Meeting, June 2005

Important element of current and future program contributing to

HP 2010

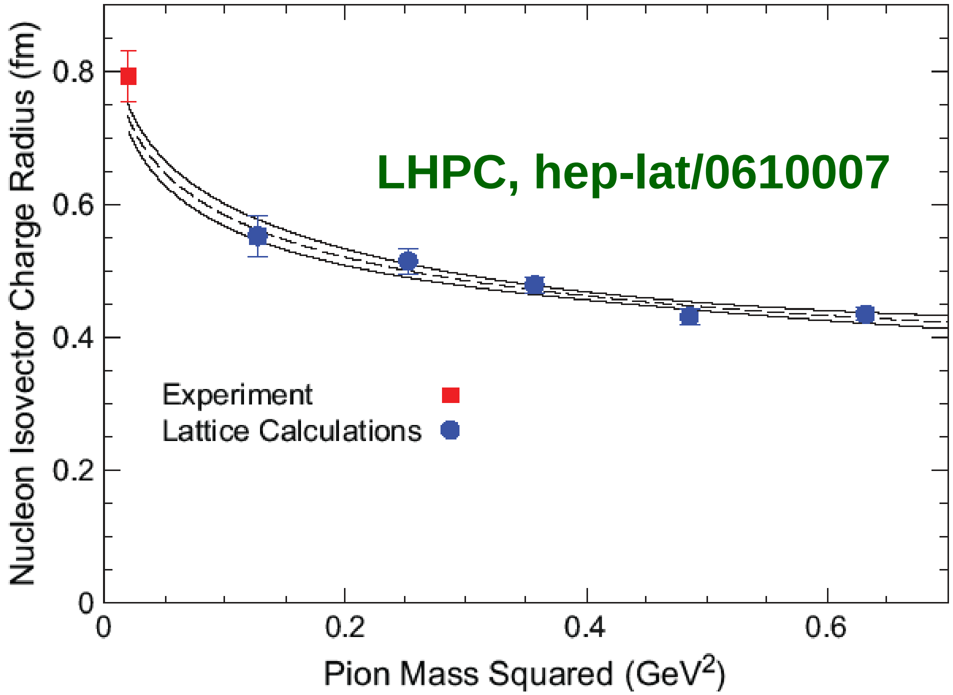
- **LT separation disagrees with polarization transfer**
- **New exp. at $Q^2 = 9\ GeV^2$**
- **Does lattice QCD predict the vanishing of $G_E^p(Q^2)$ around $Q^2 \sim 8\ GeV^2$?**

Proton EM Form Factors - II

- **Lattice QCD computes the *isovector* form factor**
- **Hence obtain Dirac charge radius assuming dipole form**
- **Chiral extrapolation to the physical pion mass**

$$\langle r^2 \rangle_{ch}^{u-d} = a_0 - 2\frac{(1+5g_A^2)}{(4\pi f_\pi)^2}\frac{1}{2}\log\left(\frac{m_\pi^2}{m_\pi^2+\Lambda^2}\right)$$

Leinweber, Thomas, Young, PRL86, 5011

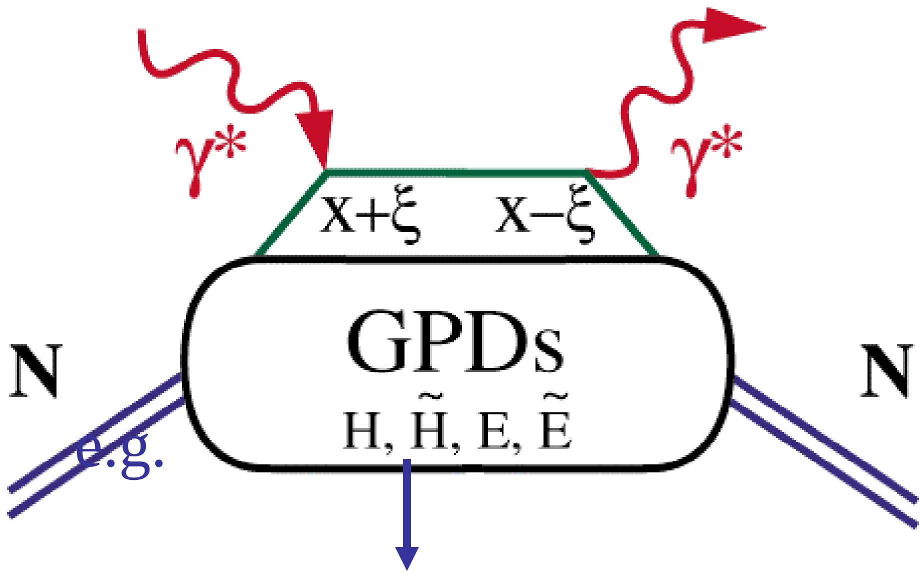


As the pion mass approaches the physical value, the size approaches the correct value

Generalized Parton Distributions (GPDs): New Insight into Hadron Structure

Measured in, e.g., Deeply Virtual Compton Scattering

HP 2008



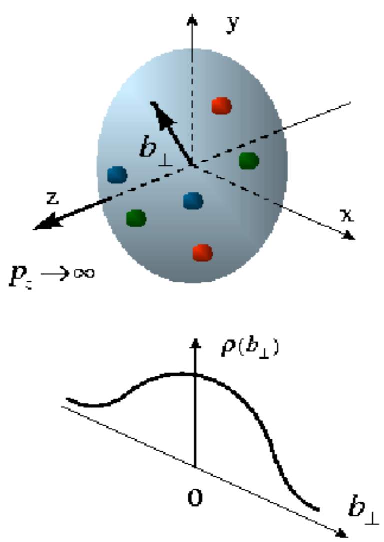
D. Muller *et al* (1994), X. Ji & A. Radyushkin (1996)

X. Ji, PRL 78, 610 (1997)

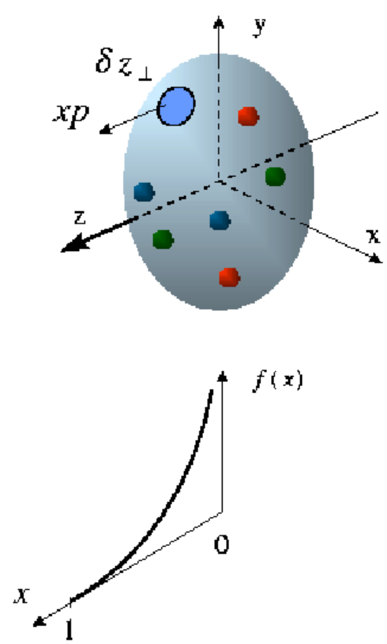
Quark angular momentum

$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx\,\left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

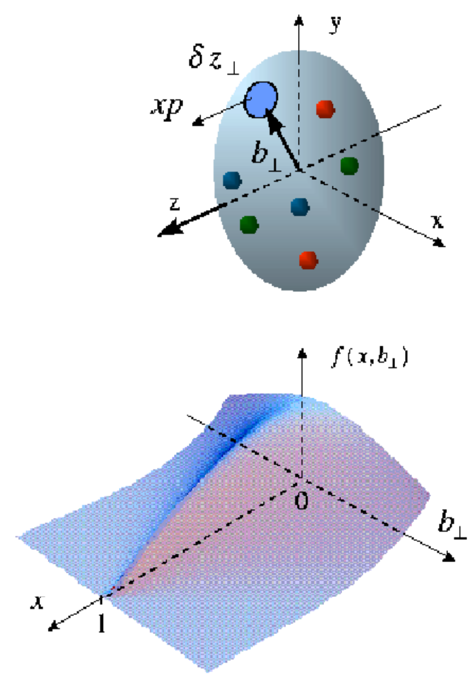
GPDs: Different Regimes in Different Experiments



Form Factors
transverse quark distribution in Coordinate space



Structure Functions
longitudinal quark distribution in momentum space



GPDs
Fully-correlated quark distribution in both coordinate and momentum space

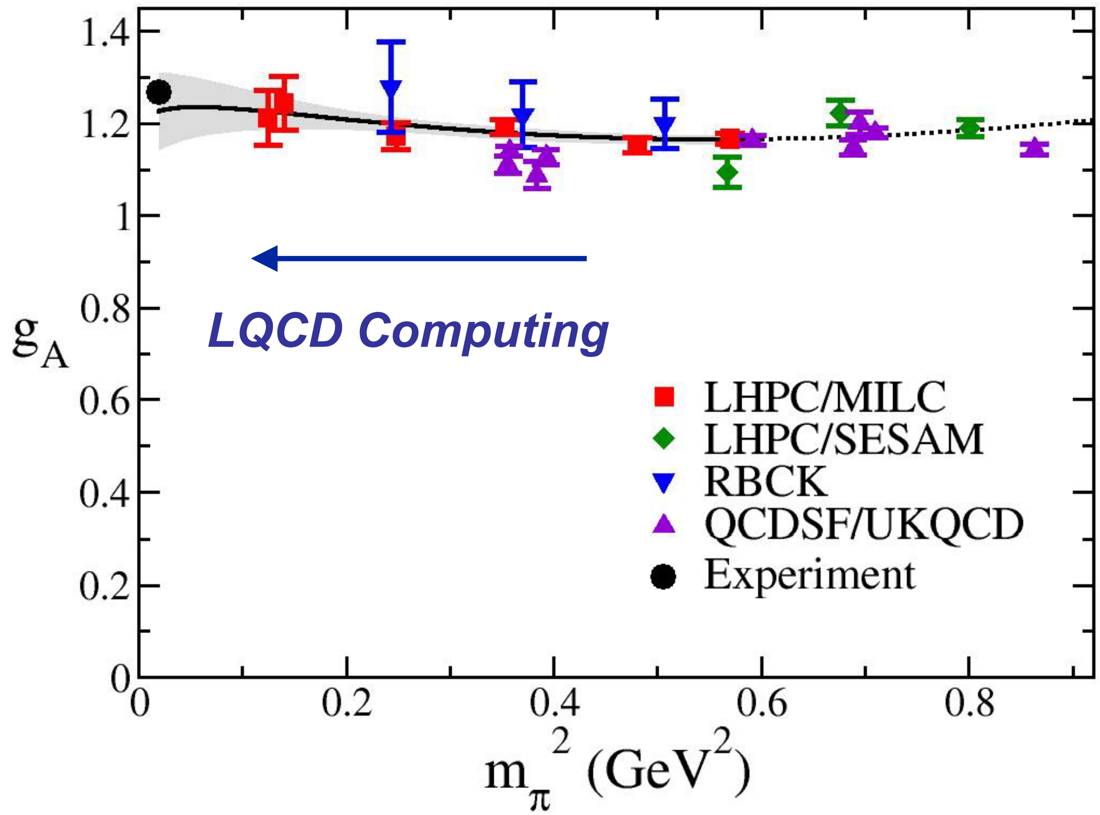
Nucleon Axial-Vector Charge

Nucleon's axial-vector charge g_A:

- ***Fundamental quantity determining neutron lifetime***
- ***Benchmark of lattice QCD***

- **Hybrid lattice QCD at m_π down to 350 MeV**
- **Finite-volume chiral-perturbation theory**

LHPC, PRL 96 (2006), 052001



Chiral Extrapolation - I

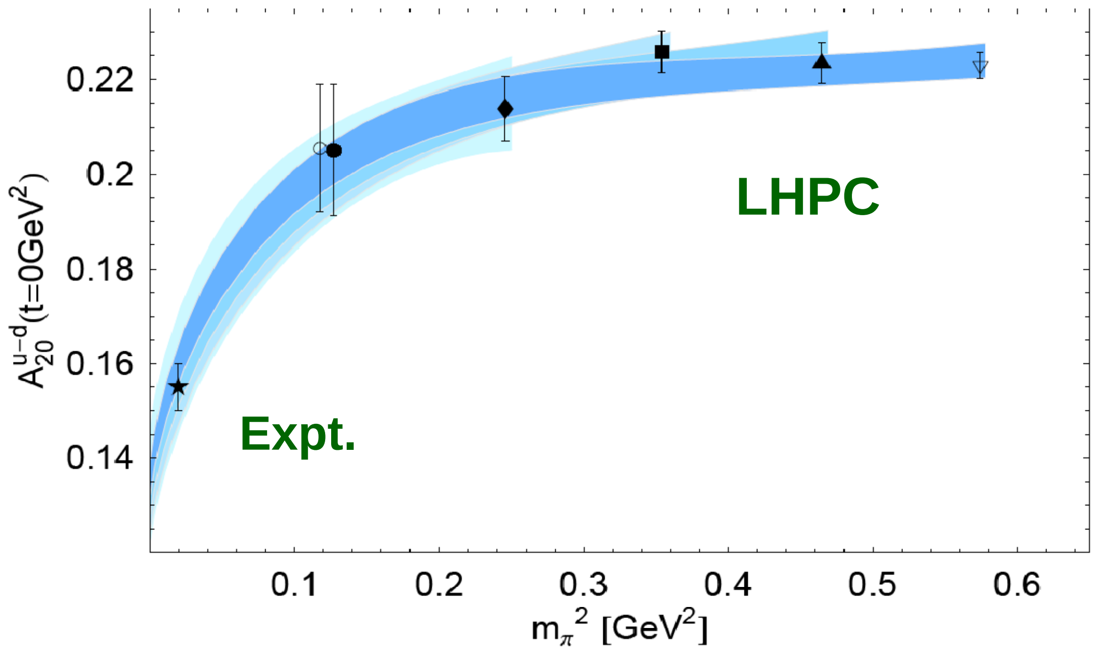
Isovector momentum fraction

$$\langle x \rangle_{u-d} = \langle x \rangle^0_{u-d} \left(1 - \frac{(3g_A+1)}{4\pi f_\pi^2} m_\pi^2 \ln m_\pi^2 \right) + \ldots$$

- **Dominates behavior at low mass**
- **g_A, f_π well-determined on lattice**

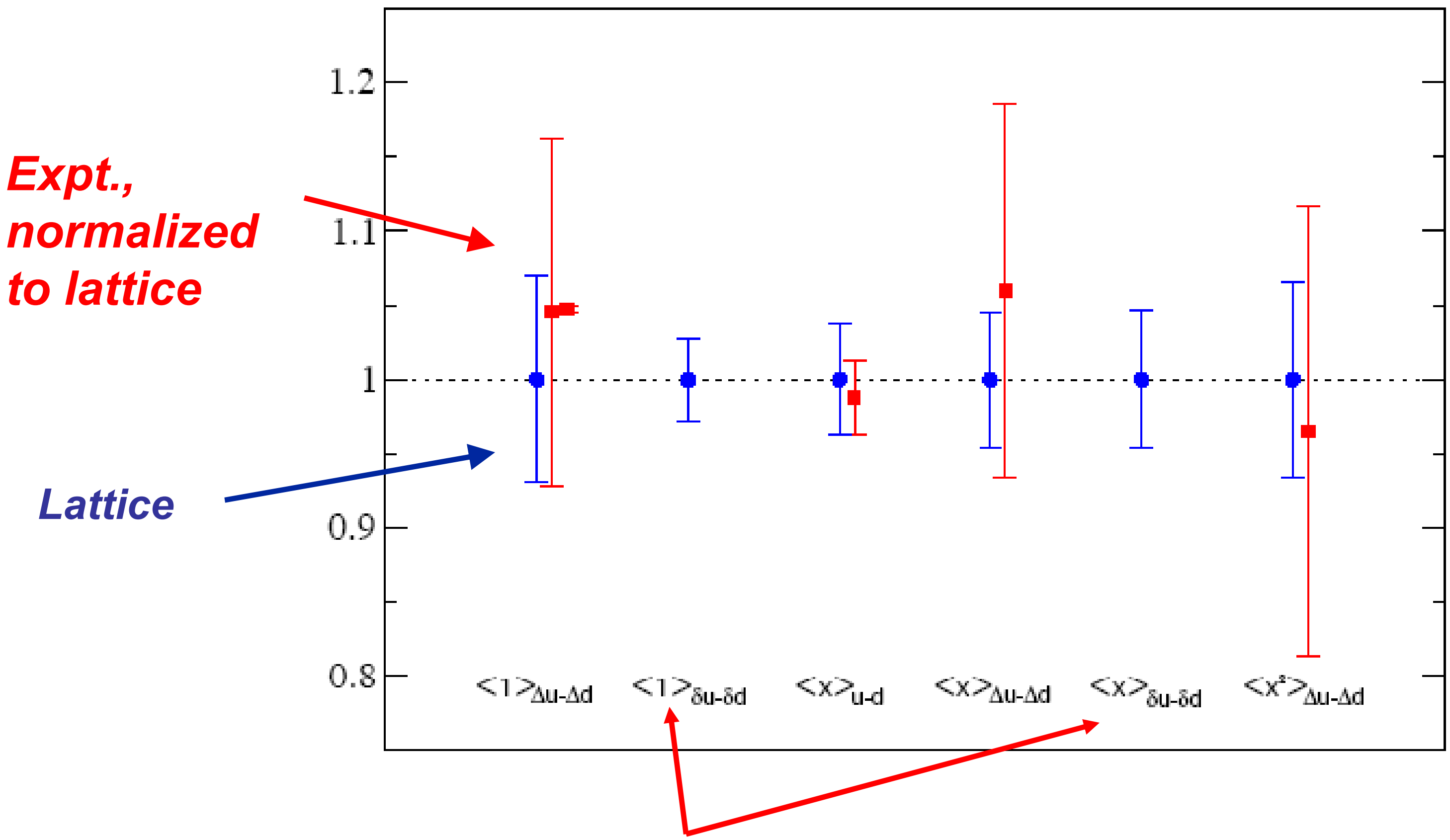
LHPC, Haegler et al., Phys. Rev. D 77, 094502 (2008)

$\langle x \rangle_{u-d}$



Chiral Extrapolation - II

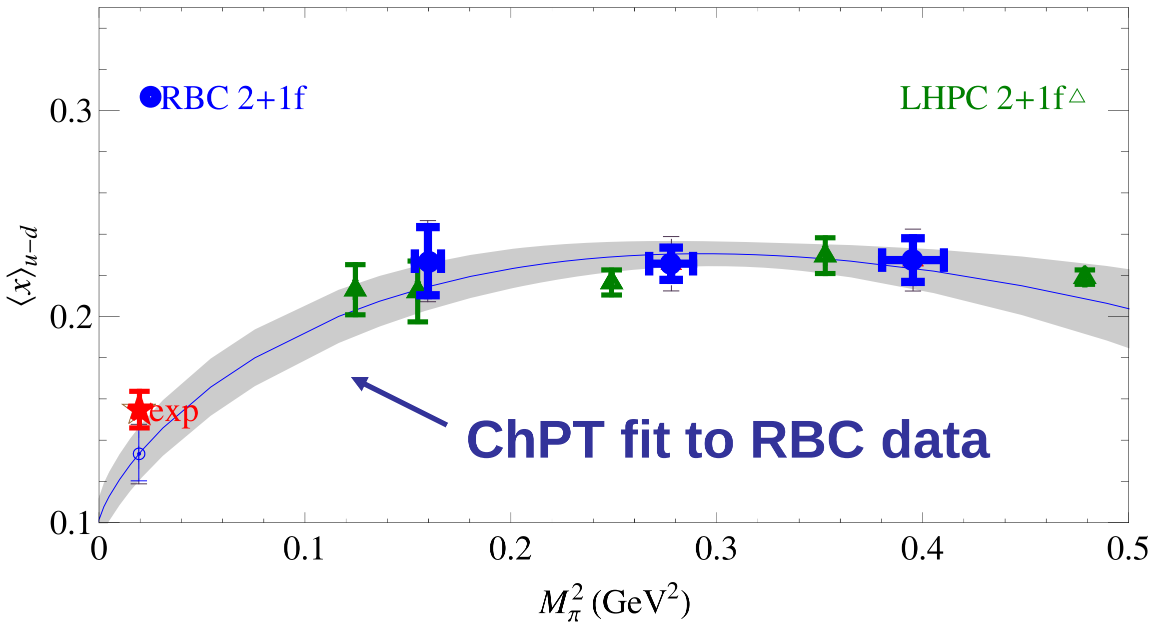
- **Gold plated observables for hadronic physics**



Predictions of tensor charge and moment *LHPC, hep-lat/0610007*

Momentum Fraction

- **Comparison among calculations of the momentum fraction**

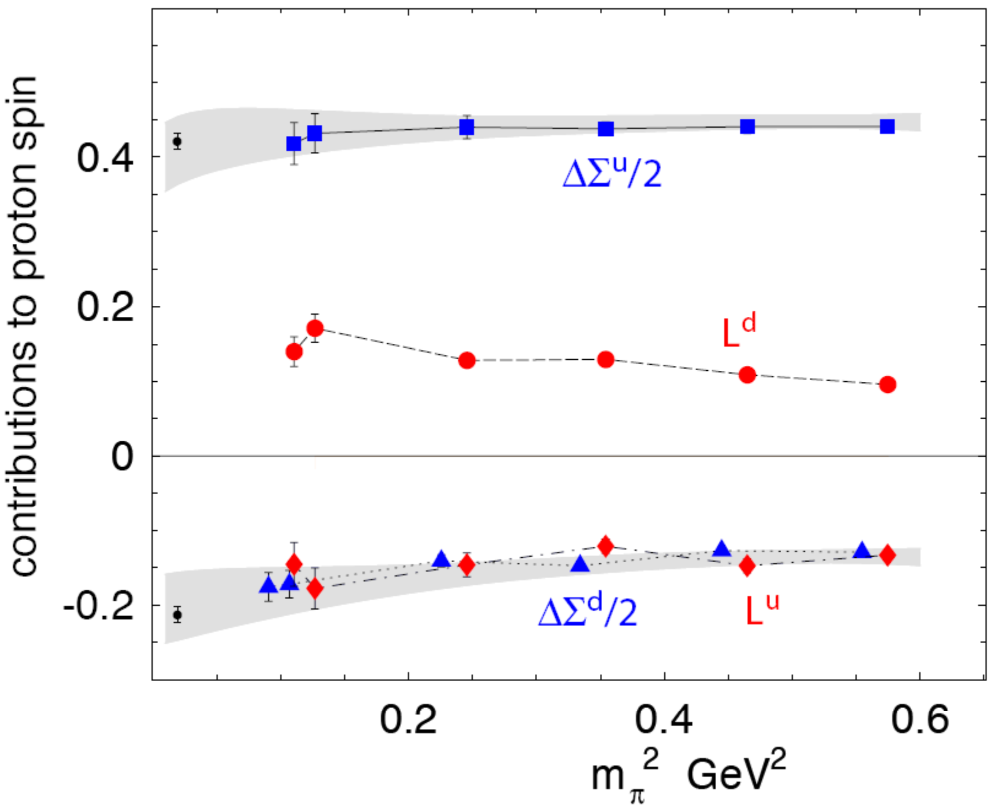


RBC, H-W Lin, arXiv:0707.3844

Origin of Nucleon Spin - I

How does the spin of the nucleon arise from quark spin, quark orbital angular momentum, and gluons?

Total Quark OAM negligible: that of individual flavors substantial.

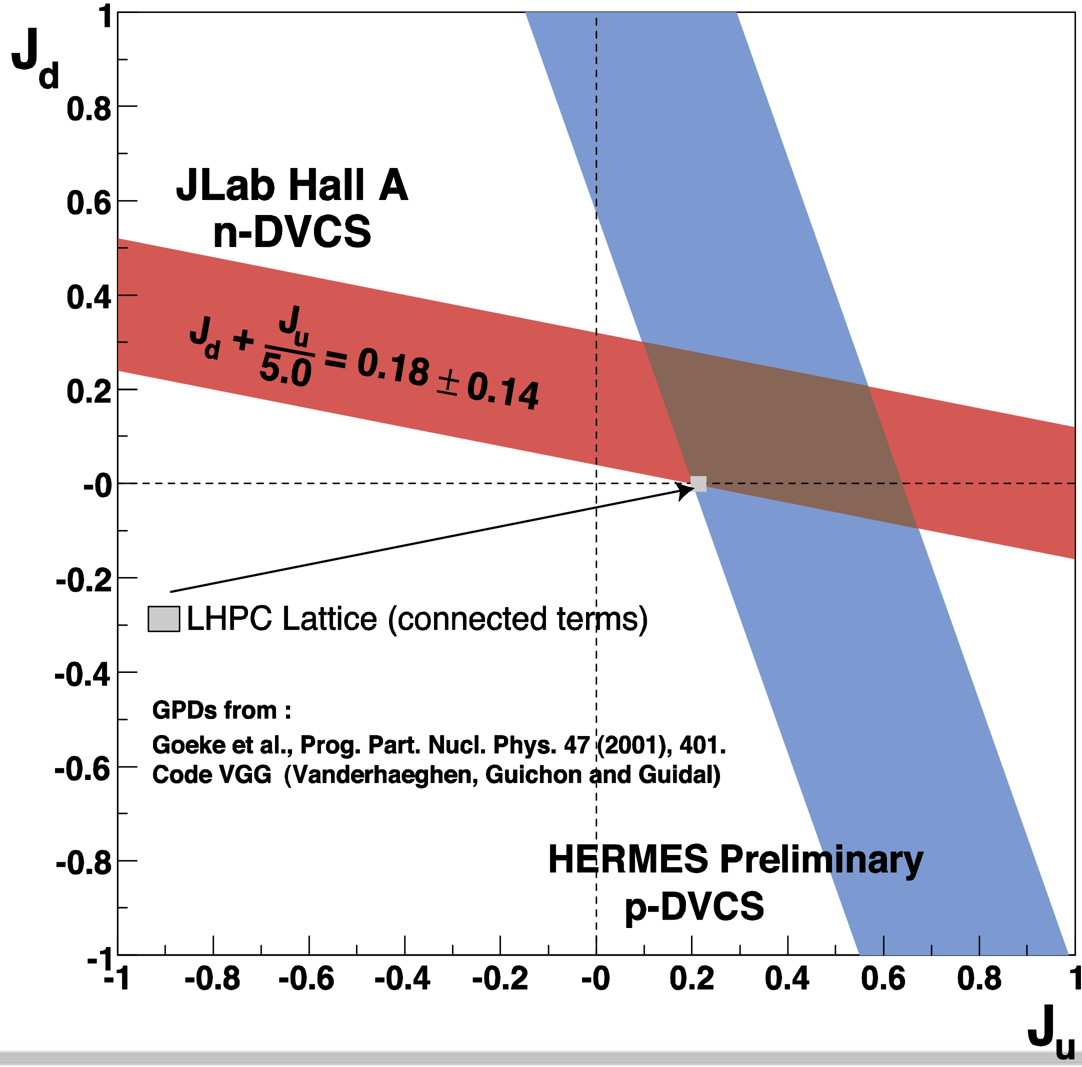


Ji's sum rule

LHPC, Haegler et al., Phys. Rev. D 77, 094502 (2008)

Sign subsequently confirmed by QCDSF

Origin of Nucleon Spin - II



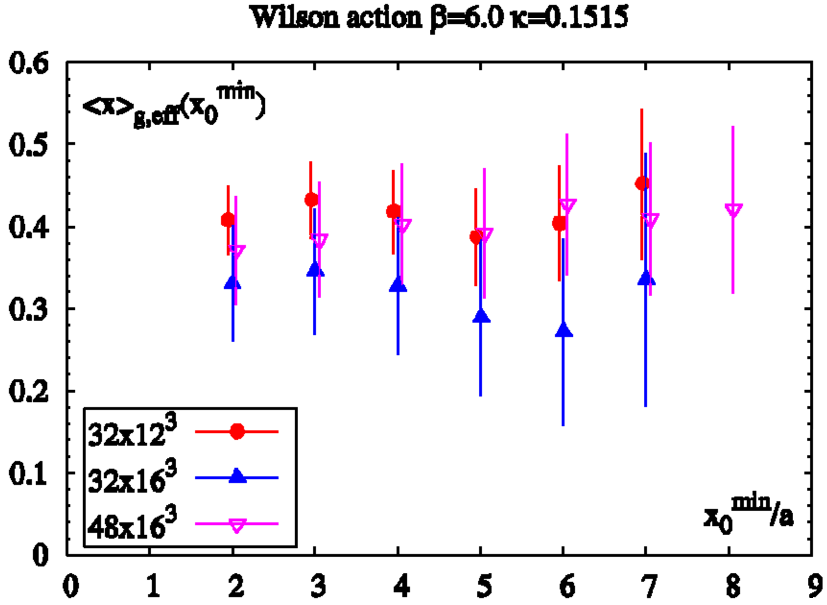
Lattice QCD + expt.

Discovering origin of nucleon spin

LHPC, Haegler et al., Phys. Rev. D 77, 094502 (2008)

Gluon Momentum Fraction in Pion

- Notoriously difficult, but essential
- Improved operator $E^2 - B^2$: 40x increase in signal
- Normalize operator by ratio of entropy at finite T
- Mixing with quarks: perturbative correction



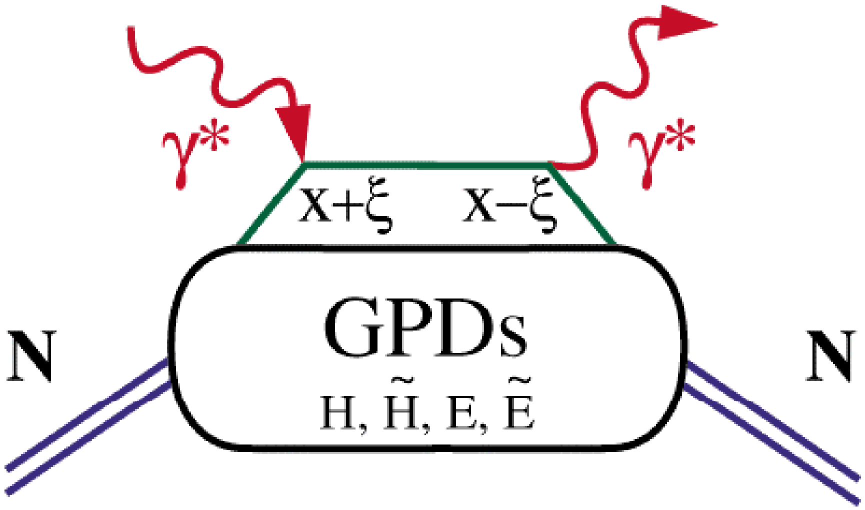
H. Meyer, J. Negele, arXiv:0710.0019

$$\langle x \rangle_{\text{glue}}(\mu = 2\ \text{GeV}) = 0.37 \pm 8 \pm 12$$

RHIC-spin

Momentum sum rule: $\langle x \rangle_{\text{glue}} + \langle x \rangle_{\text{quarks}} = 0.99 \pm 8 \pm 12$

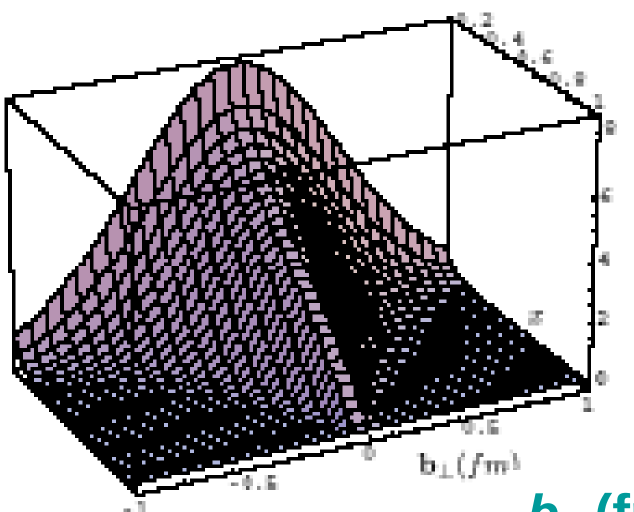
Transverse Distribution - I



HP 2008

- **Lattice QCD can compute moments of GPDs and PDFs, and their Q^2-dependence**

$$A^q_{n0}(-\vec{\Delta}_\perp^2) = \int d^2b_\perp \, e^{i\vec{\Delta}_\perp\cdot\vec{b}_\perp} \int_{-1}^{1} dx \, x^{n-1} \, q(x,\vec{b}_\perp)$$



x

b_T (fm)

Compare to phenomenological models

Decrease slope : decreasing transverse size as $x \to 1$

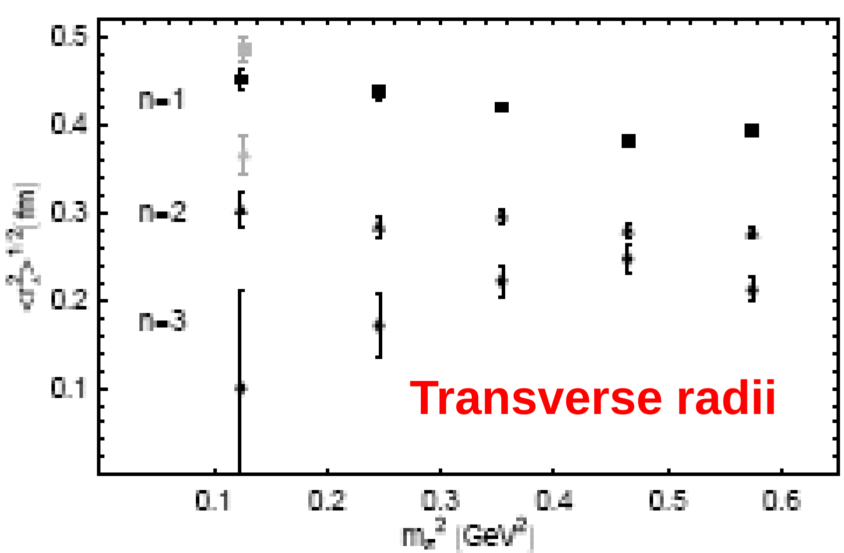
Burkardt

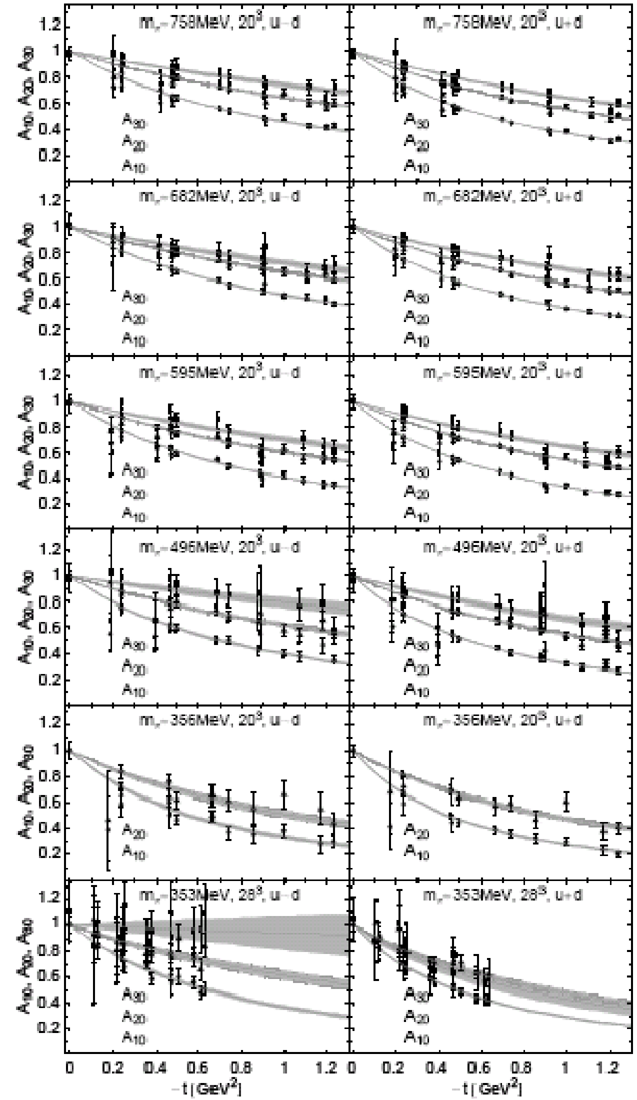
Transverse Distribution - II

Lattice results reveal narrowing of transverse size with increasing x

LHPC, Haegler et al., Phys. Rev. D 77, 094502 (2008)

Flattening of GFFs with increasing n

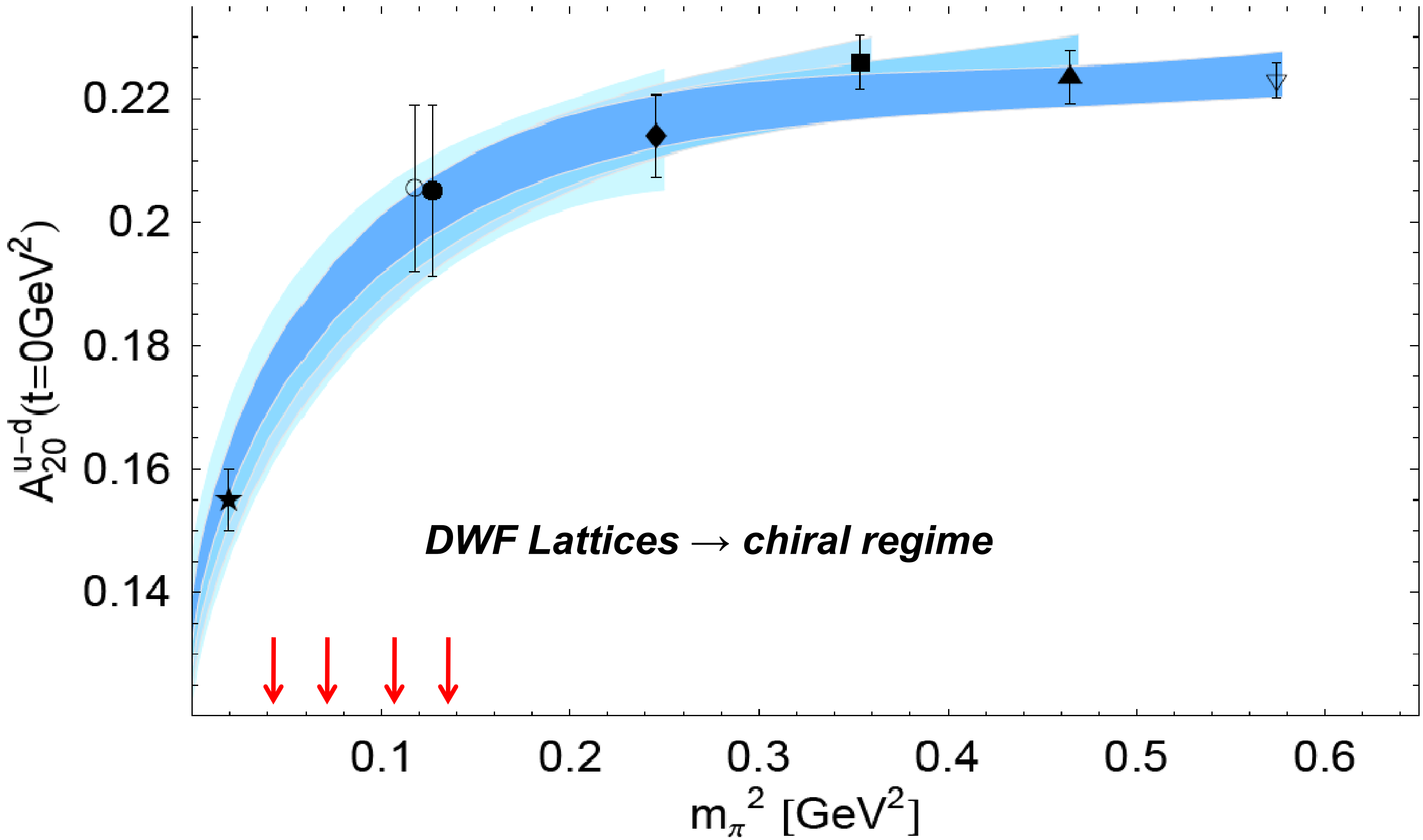




Hadron Structure – Opportunities

- **Accomplishments**
  - **Hybrid Asqtad/DWF approach enabling first entre into chiral regime**
  - **Higher-precision computations of range of benchmark quantities, eg g_A,,charge radius, $\langle x \rangle$, form factors,...**
  - **Insight into hadron structure: spin and orbital angular momentum carried by quarks, transverse size of nucleon, pion form factor,…**
- **Through *LQCD-I***
  - **Dramatic algorithmic improvements (RHMC) enabling completely chiral $N_f = 2 + 1$ DWF gauge configurations**
  - **Joint RBC/LHPC proposal to generate DWF configurations and propagators at $a = 0.086$:**
  - **Physics thrusts:**
    - ***Increased precision for nucleon structure, including form factors, structure functions, GPDs,…***
    - ***Exploratory calculations of new observables: disconnected diagrams, gluon contributions…***
    - ***Properties of octet baryons…***

Hadron Structure – Opportunities



Hadron Spectroscopy

- **Spectroscopy is classic tool for gleaning information about structure of theory**
- **Both experimental and *ab initio* N* and Exotic-meson programs aim at *discovering effective degrees of freedom of QCD*, and resolving competing low-energy models**
  - **HP2009 and HP2012 milestones**
  - **Excited Baryon Analysis Center (EBAC) at Jefferson Lab**

- **Spectroscopy of Exotic Mesons flagship component of CEBAF@12GeV**

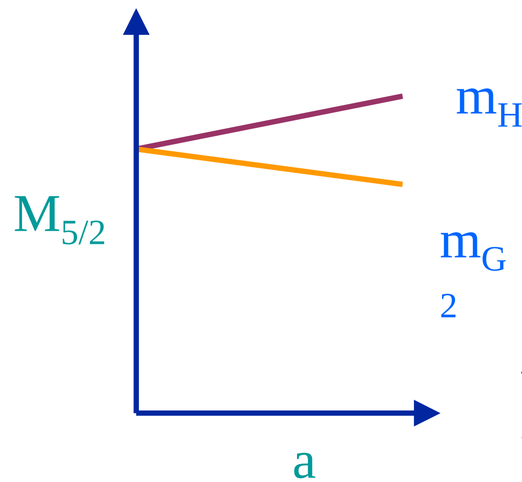
"Calculate the masses of strongly interacting particles and obtain a qualitative understanding….."

Lattice "PWA"

- **Do not have full rotational symmetry: J, $J_z \rightarrow \Lambda, \lambda$**
- **States at rest classified according to cubic symmetry**

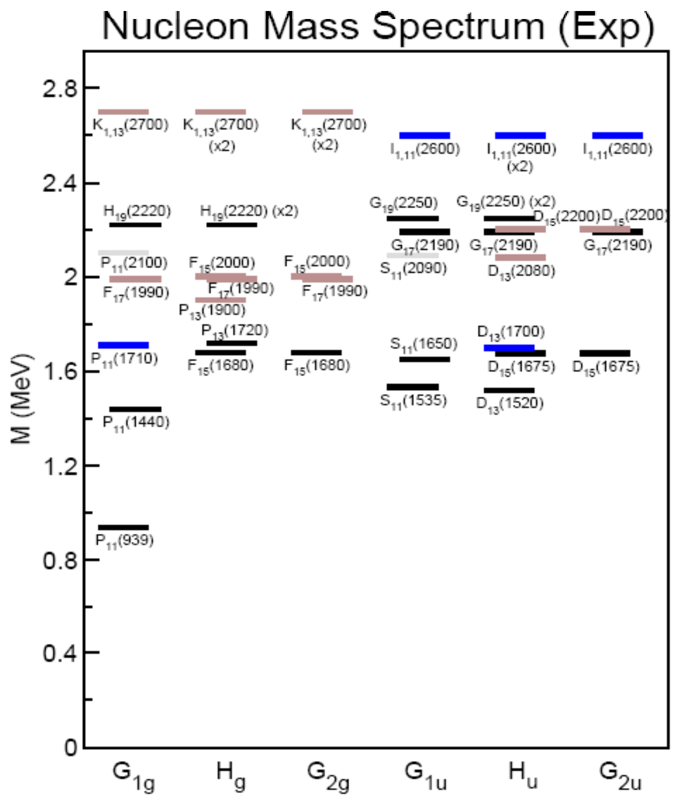
J	$n^J_{G_1}$	$n^J_{G_2}$	n^J_H
$\frac{1}{2}$	1	0	0
$\frac{3}{2}$	0	0	1
$\frac{5}{2}$	0	1	1
$\frac{7}{2}$	1	1	1
$\frac{9}{2}$	1	0	2
$\frac{11}{2}$	1	1	2
$\frac{13}{2}$	1	2	2
$\frac{15}{2}$	1	1	3
$\frac{17}{2}$	2	1	3

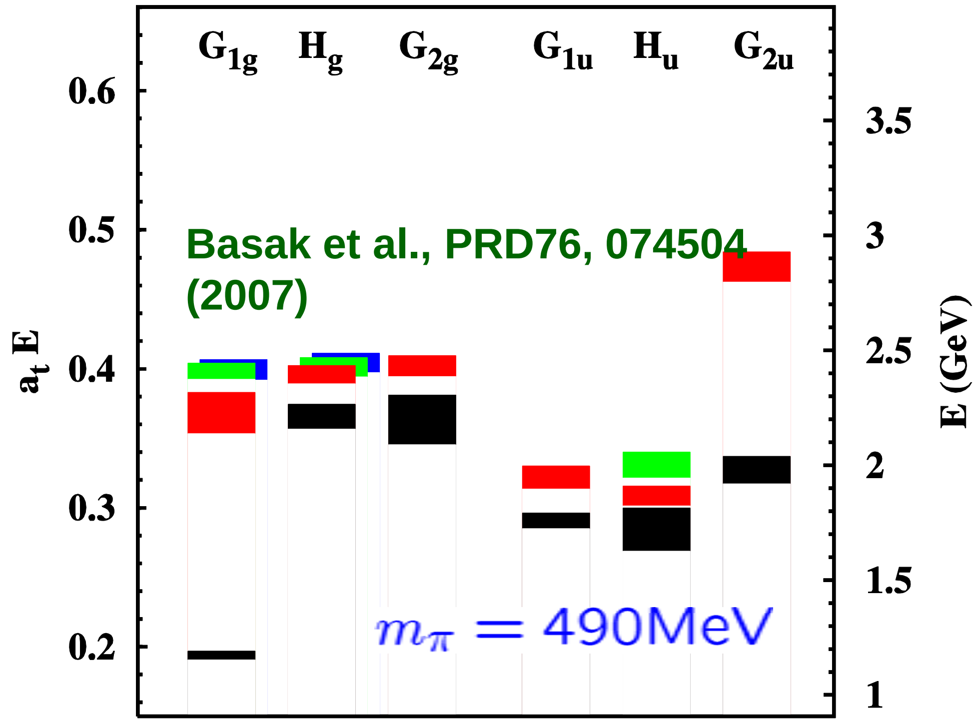
Spins identified from degeneracies in continuum limit – *or by using continuum behavior of operators*



S. Basak *et al.*, *PRD72:074501,2005* *PRD72:094506,2005*

Quenched Demonstration

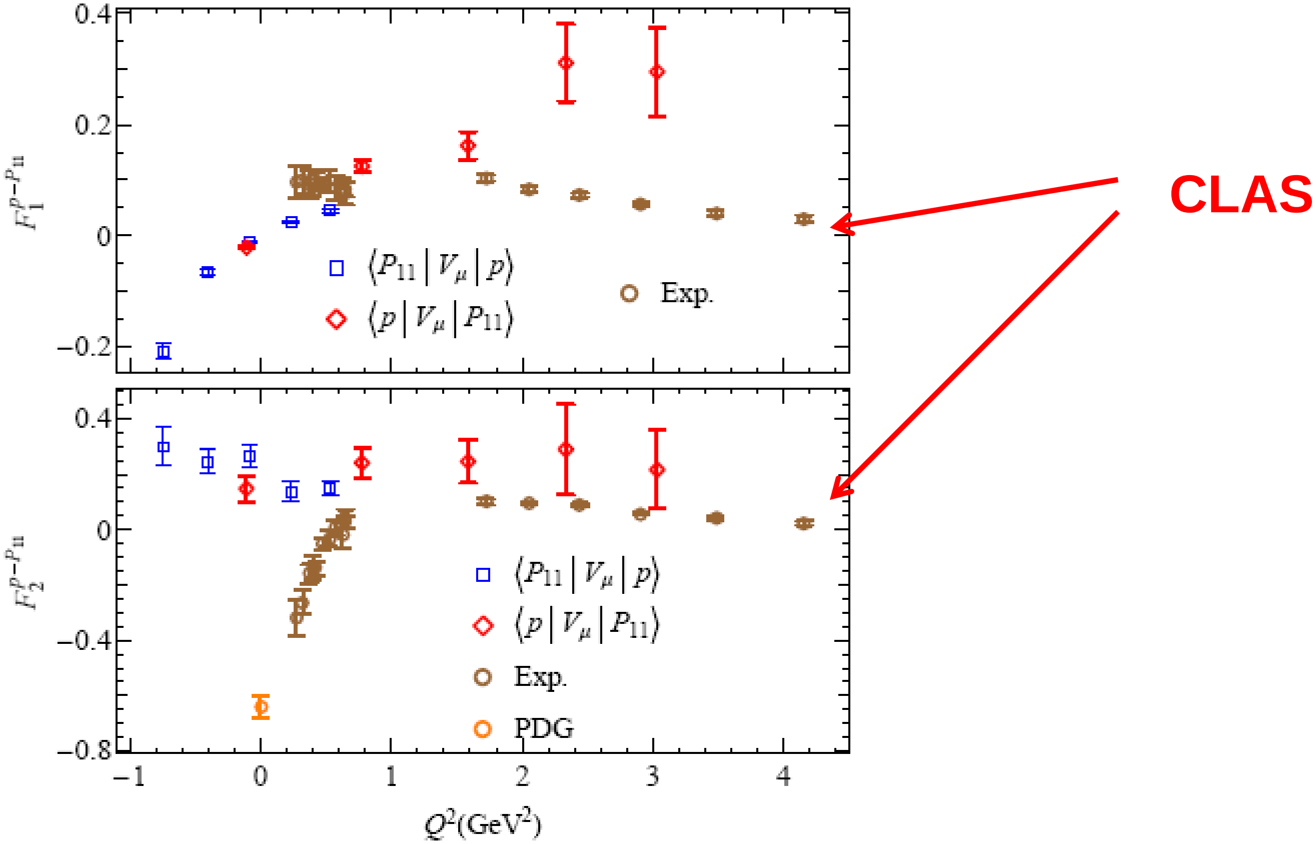




- **Demonstration of our ability to extract nucleon resonance spectrum**
- **Hints of patterns seen in experimental spectrum**
- **Methodology central to remainder of project**
- ***Calculation of transition form factor to Roper - Cohen et al., arXiv:0803:3020***

Nucleon-Roper Transition

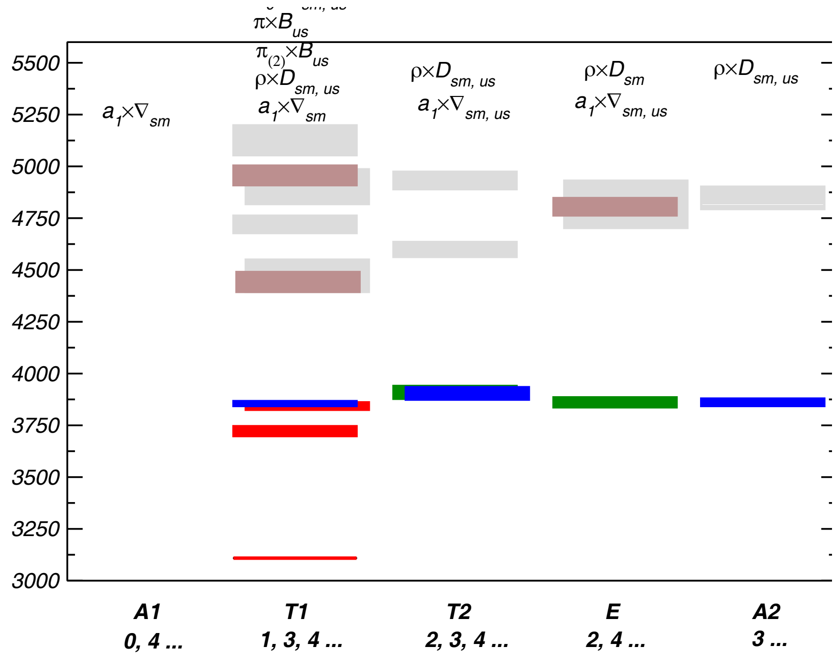
- First measurement of nucleon-Roper transition form factor
- *Quenched calculation, at high pion mass*
- Measurements by CLAS at JLab

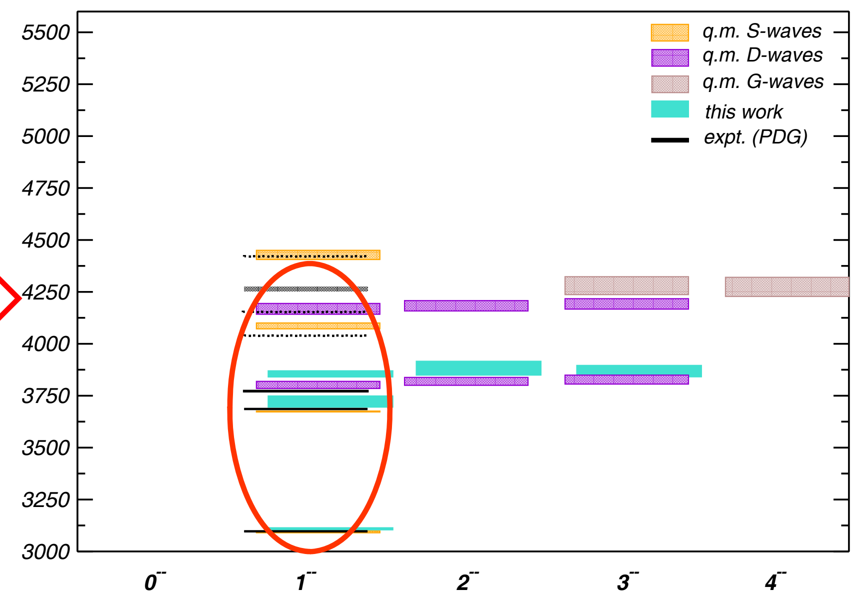


Meson Spectroscopy

- ***Mesons admit exotics – J^{PC} not accessible in NR quark model***
- ***Reveal gluon/flux-tube degrees of freedom***

$J^{PC} = J^{--}$, charmonium



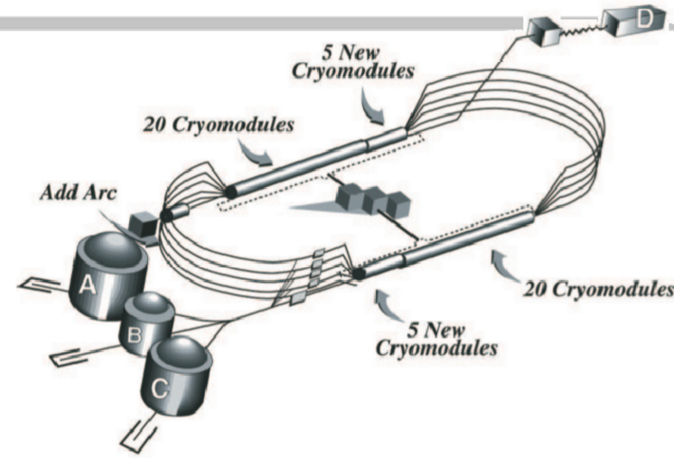


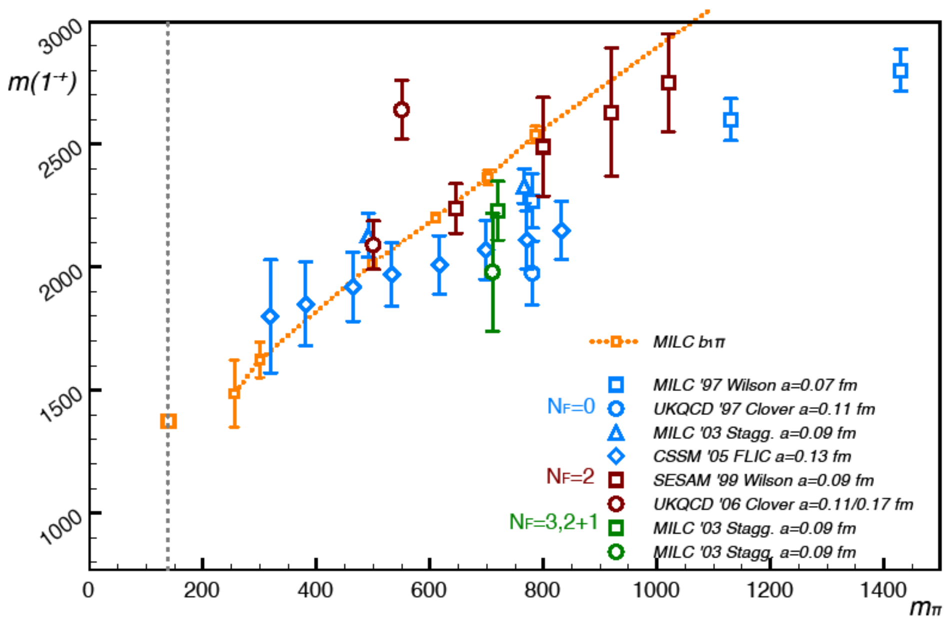
Resolve higher states

Dudek, Edwards, Mathur, DGR,
PRD77, 034501 (2008)

Lattice QCD: Hybrids and GlueX - I

- **GlueX aims to photoproduce hybrid mesons in Hall D.**
- **Lattice QCD has a crucial role in both predicting the spectrum and in computing the production rates**





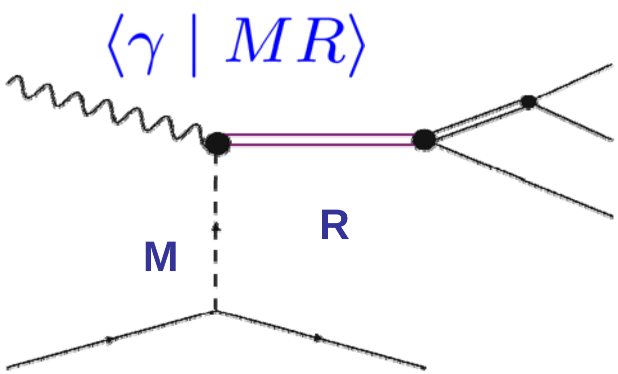
• Only a handful of studies of hybrid mesons at light masses – mostly of 1^{-+} exotic

Central goal through LQCD-I

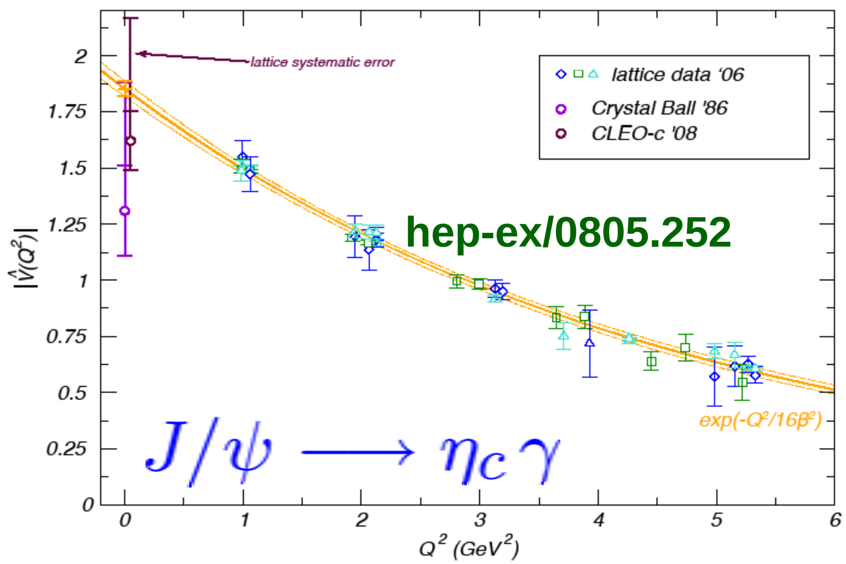
Lattice QCD: Hybrids and GlueX - II

- **Lattice can compute photocouplings.**
- **Initial computations in charmonium**

Dudek, Edwards, Richards, PRD73, 074507



cc $\to \gamma\gamma$: Dudek, Edwards, PRL97, 172001 (2006)



Experimental analysis driven by lattice calculations

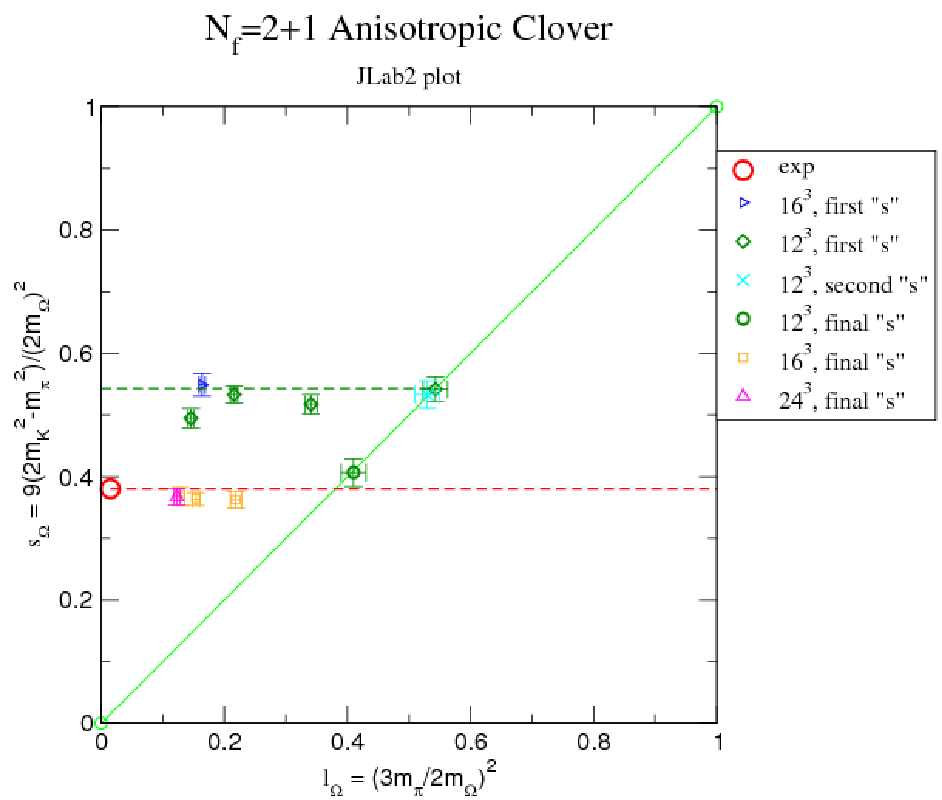
Anisotropic lattice Generation

- **Analysis of spectrum on two-flavor anisotropic Wilson lattices underway**
- **Non-perturbative determination of parameters of three-flavor anisotropic-clover action completed.**

***R.G. Edwards, B. Joo, H-W Lin*, arXiv:0803.3960**

INCITE 2007, 2008

- **Improved prescription for setting of strange-quark mass and lattice spacing**



Spectroscopy – Opportunities

- **Accomplishments**
  - Development of methodology to extract the resonance spectrum for states containing quarks
  - Demonstration of ability to extract many energy levels in N* and hybrid resonance spectrum
  - Pioneering calculations of photo-transition amplitudes in charmonium, important for CLEO-c, and of 2γ width
  - Transition form factor to Roper resonsonance in quenched QCD
- **Through *LQCD-I***
  - Anisotropic $N_f = 2$ Wilson and $N_f = 2 + 1$ Clover gauge configurations designed for spectroscopy: 2007 INCITE, 2008 INCITE, LQCD
  - Investigate new methods of computing hadron correlation functions: all-to-all propagators and eigenvector methods – ***multi-particle states***
  - Physics goals
    - Low-lying baryon spectrum for states composed of u/d and s quarks, with scattering states delineated
    - Low-lying exotic meson spectrum; first calculation of photo-couplings involving conventional and exotic mesons

Spectroscopy - Opportunities

L_s(fm)	1.92fm	2.4fm	2.9fm	3.8fm
m_π(MeV)	$16^3 \times 128$	$20^3 \times 128$	$24^3 \times 128$	$32^3 \times 128$
875	10k, JLab[0.20M](8.4)			
580	20k, JLab[0.48M](5.6)			
400		20k, JLab[1.35M](4.8)		
315		30k, JLab[2.35M](3.8)	30k, ORNL[4.66M](4.5)	30k, X[13.7M](6.0)
250			30k, TACC[5.44M](3.6)	30k, ?[16.0M](4.8)

Review Recommendations 2007

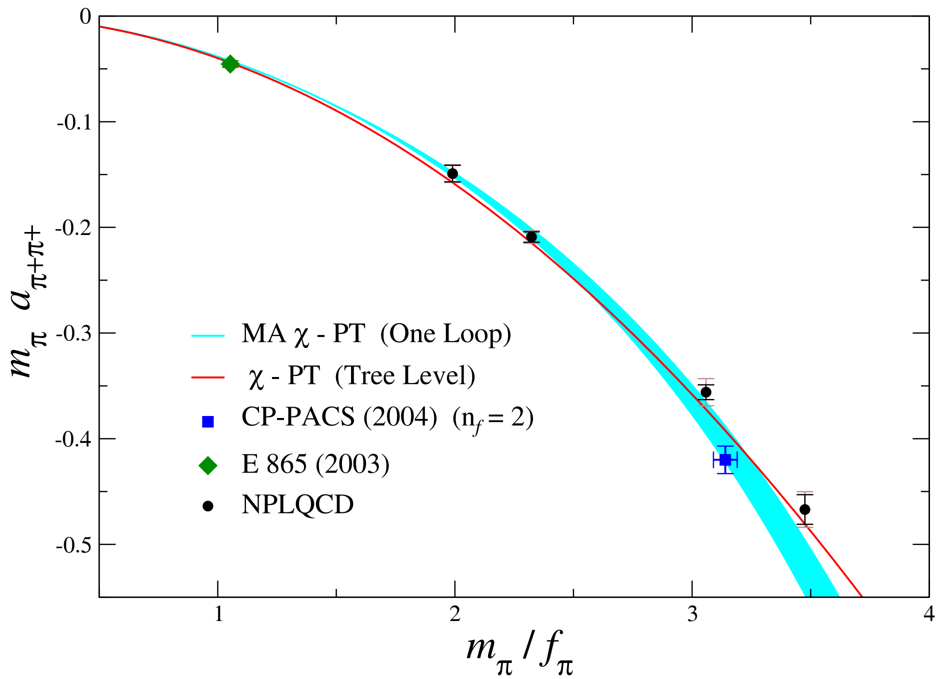
"With respect to baryon spectroscopy, interesting results have been obtained on the resonance spectrum in the quenched approximation at a rather large pion mass. However, many of the resonances in this approximation may be stable, and it is not clear why the analysis applied there will carry over to the unquenched case with light quark masses. The analysis tools developed so far are certainly essential, but may have to be augmented with other tools, such as using volume dependence."

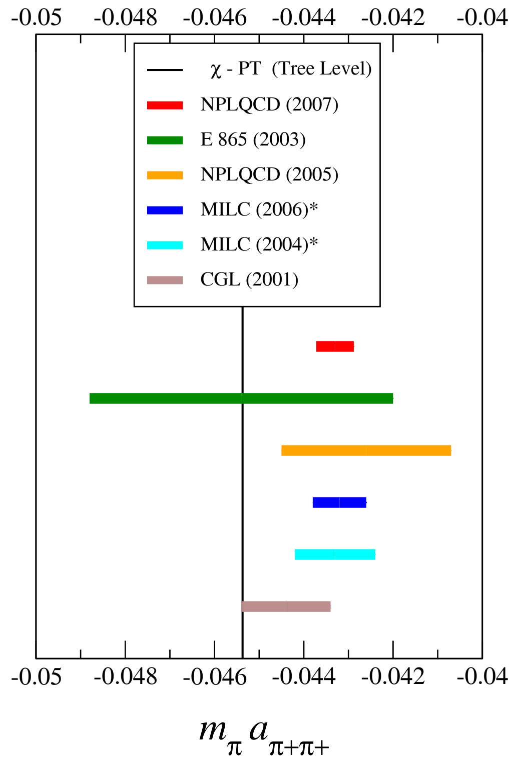
Hadron-Hadron Interactions

- **Grand Challenge to rigorously compute properties and interactions of nuclei**
- **HP2014:** ***Ab intio microscopic calculations of light nuclei…. …based on two-nucleon, three-nucleon forces and lattice QCD…***
- **Hyperon-nucleon interaction, with dearth of experimental data, provide opportunity for lattice QCD to provide astrophysical insight: input to nuclear EOS in neutron stars**

Meson-Meson Interaction - I

- **NPLQCD calculation using DWF valence quarks on $N_f = 2 + 1$ MILC configurations**
- **Amalgam of ChPT + lattice QCD at m_π down to 290 MeV**



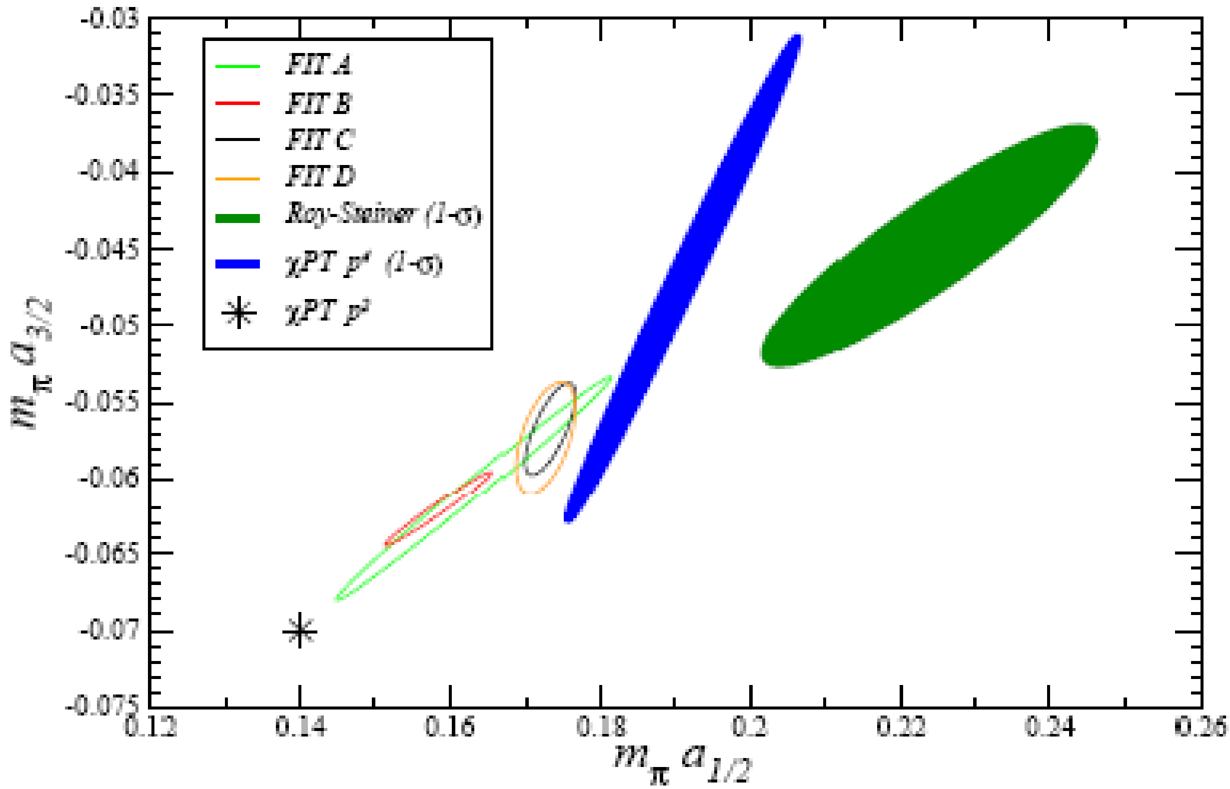


NPLQCD, arXiv:0706.3026

→ ***High-precision computation***

Meson-Meson Interactions - II

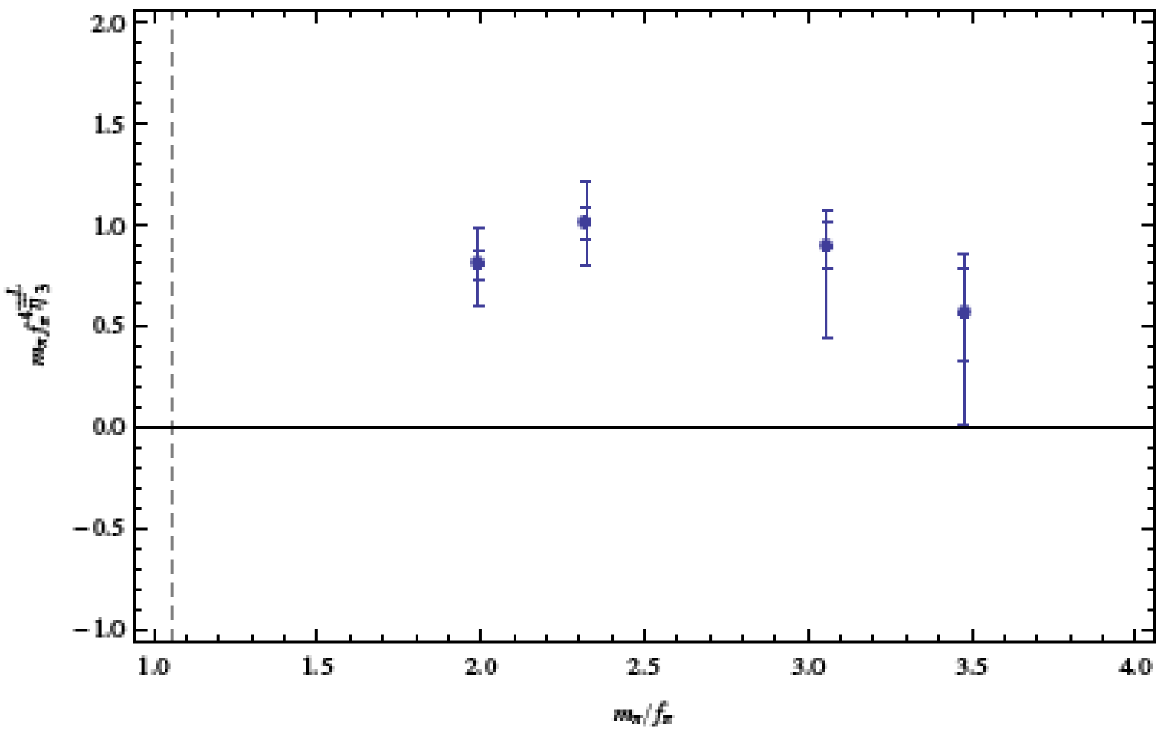
NPLQCD, Phys.Rev. D74 (2006) 114503



NPLQCD: Predictions for K π scattering lengths for both I = 3/2 and I = 1/2

Meson-Meson Interaction - III

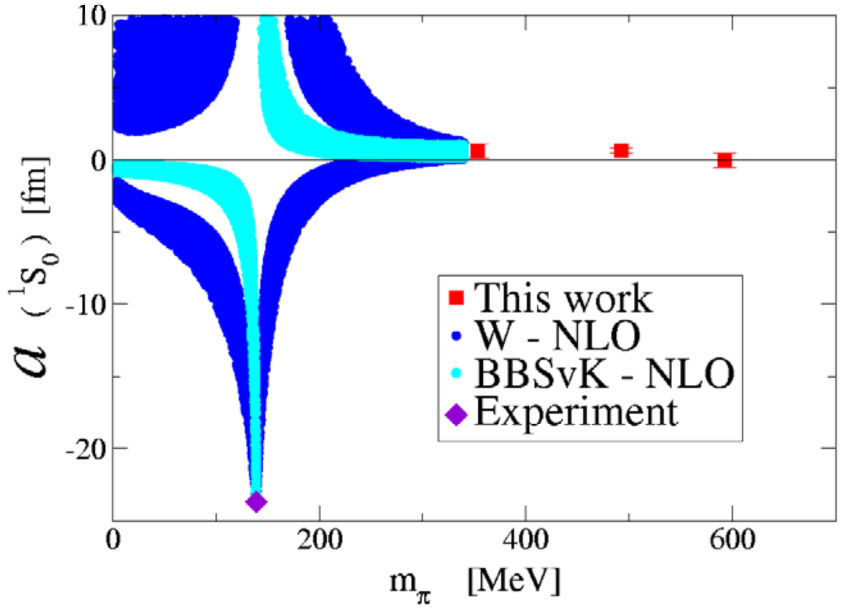
- **Formalism extended to multi-pions in box**
- **Computation of $\pi\ \pi$ scattering lengths in agreement with two-pion case**
- ***Unambiguous demonstration of low-energy three-body force***

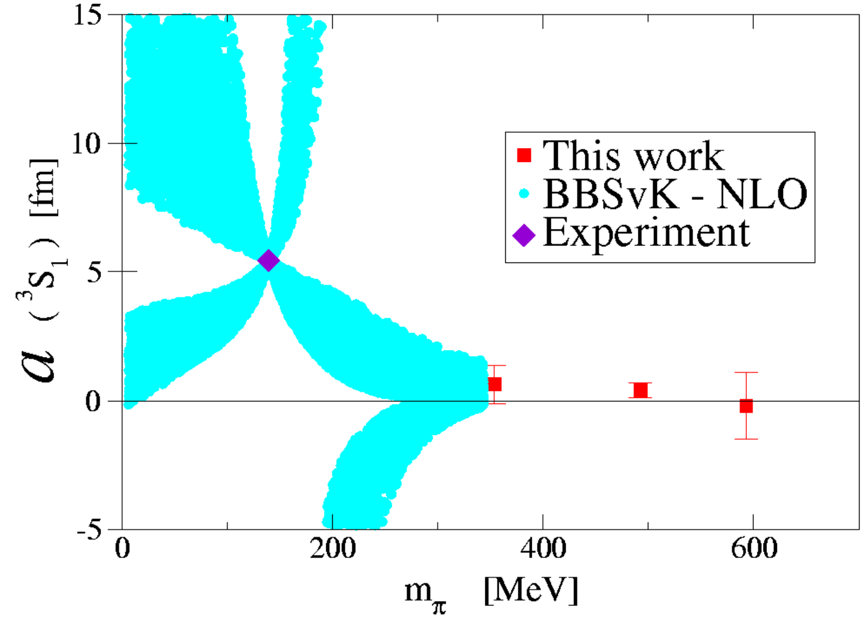


NPLQCD, arXiv:0803.2728

NN Scattering

NPLQCD: S. Beane, P. Bedaque, K. Orginos, M. Savage ; PRL97, 012001 (2006))





Calculations at lower m_π to constrain scattering length at physical quark masses

$^1S_0$: pp , pn , nn

$^3S_1$-$^3D_1$: pn : deuteron

Interactions - Opportunities

- **Accomplishments**
  - **Realization that lattice QCD could provide rigorous results for nuclear physics in near future**
  - **Computation of meson-meson scattering lengths using DWF on N_f=2+1 MILC configurations**
  - **First computation of K π scattering lengths in both isospin channels using lattice QCD + ChPT**
  - **First studies of NN scattering in dynamical lattice QCD**
  - **Unamiguous presence of three-body force in pion system**
- **Through *LQCD-I***
  - **DWF valence quarks on fine Asqtad lattices: *approach to the continuum limit***
  - **High-precision studies of meson-meson systems**
  - **Meson-baryon and octet baryon-baryon interactions**

Synergy with Experiment - I

- **Lattice QCD effort well integrated with experimental program**
- **Workshops focused on complementarity of lattice QCD and experiment:**
  - **Workshop on Synergy between Experiment and Lattice QCD in Exploring Hadron Structure, INT, April 24-25, 2006**
  - **Experiment and Lattice QCD: Revealing Hadron Structure and Interactions, Jlab, Nov. 21-22, 2008**
- **Topical hadronic-physics workshops with important lattice involvement:**
  - **Cascade Physics: a New Window on Baryon Spectroscopy, Jlab, Dec. 1-3, 2005**
  - **Photon-hadron physics with the GlueX detector at Jefferson Lab, Mar. 6-8, 2008**
  - **The 4th Electron Ion Collider Workshop, Hampton University, May 19-23, 2008**

Synergy with Experiment - II

Workshop on
SYNERGY BETWEEN EXPERIMENT AND LATTICE QCD IN
EXPLORING HADRON STRUCTURE
Institute for Nuclear Theory
University of Washington
April 24 and 25, 2006

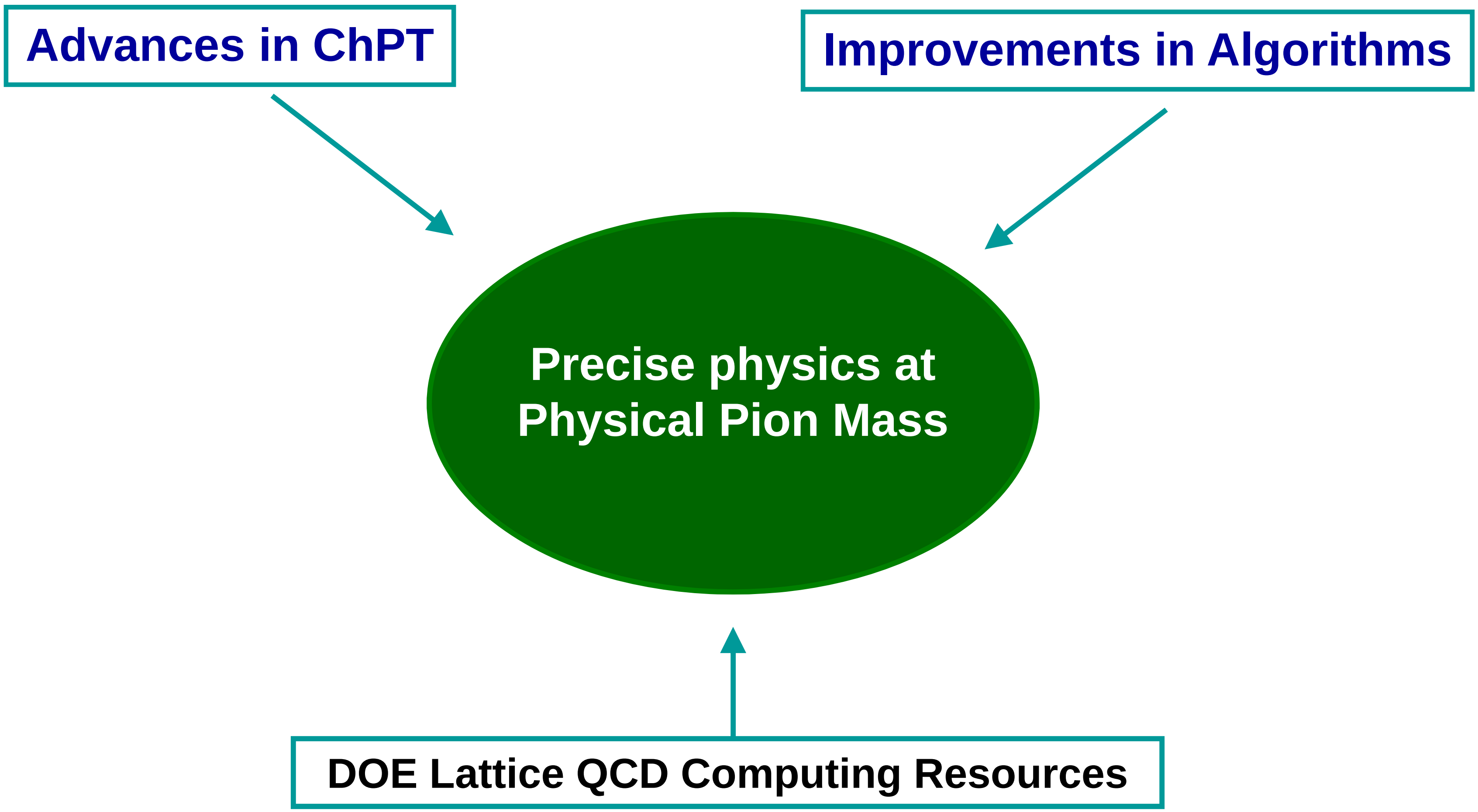
Jointly sponsored by the Institute for Nuclear Theory and Jefferson Laboratory

The purpose of this workshop is to survey contemporary experimental results revealing the quark and gluon structure of nucleons and other hadrons, and to explore the synergy of these and future experiments with first-principle calculations using lattice QCD. The workshop is planed around a limited number of pedagogical talks by experimentalists spanning the range of contemporary experiments, with the opportunity for extensive informal discussion.

The preliminary program of experimental talks includes:

- Electormagnetic Form Factors - John Arrington
- Deeply Virtual Compton Scattering - Latifa Elouadrhiri *
- Transition Form Factors - Volker Burkert
- Strangeness in the Nucleon - Doug Beck
- Nucleon Polarizability - Zein-Eddine Meziani
- RHIC Spin experiments Bernd Surrow
- HERMES experiments - Naomi Makins

Summary


Advances in ChPT
Improvements in Algorithms
Precise physics at
Physical Pion Mass
DOE Lattice QCD Computing Resources

Summary - II

- Lattice QCD calculations essential to our understanding of hadronic physics, and to achieving the DOE nuclear-physics goals
- Dramatic algorithmic improvements are enabling us both to measure previously studied quantities to greater precision, and to exploit new opportunities
- Physics measurements, rather than gauge configuration generation, an increasingly computationally demanding part of the effort
- Increasing recognition of lattice QCD as essential tool for hadronic physics among both theory and experimental communities