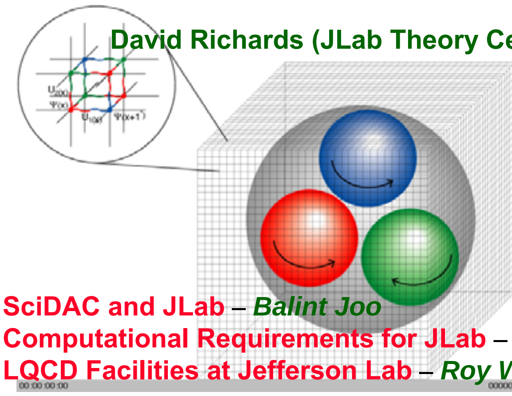
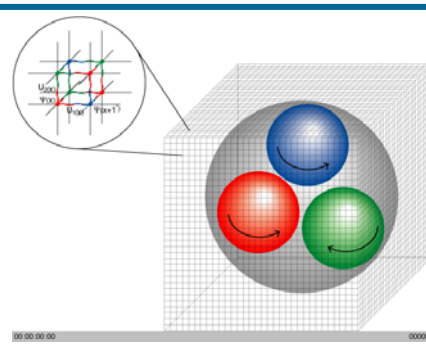
Overview of Lattice QCD at JLAB: Recent Achievements and Future Opportunities

David Richards (JLab Theory Center)



SciDAC and JLab – ***Balint Joo***
Computational Requirements for JLab – ***Robert Edwards***
LQCD Facilities at Jefferson Lab – ***Roy Whitney***

Lattice QCD



- **Lattice QCD enables us to undertake *ab initio computations of many of the low-energy properties of QCD***
- **Continuum Euclidean space time replaced by four-dimensional *lattice* – current typical sizes $28^3 \times 96$**
- **Computations dominated by *inversion of large, sparse matrices.***

$$3 \times 4 \times 28^3 \times 96$$

Color (3), spin (4), volume ($28^3 \times 96$)

Highly regular problem, with simple boundary conditions – *very efficient use of massively parallel computers using data-parallel programming.*

Lattice QCD at JLab

- **Lattice effort at JLab plays major role across spectrum of US and International lattice activities:**
  - **Theory research driven by physics goals of the laboratory - *Theory***
  - **Provision of resources to facilitate this research - *Facilities***
  - **Development of the software tools to exploit these resources – *SciDAC-I and SciDAC-II***

Theory Group: J. Dudek, R. Edwards, K. Orginos, D. Richards, A. Thomas, + PDF's (N. Mathur, R. Young) and students
HPC Group: J. Chen, Y. Chen, B. Joo, W. Watson

National Effort in hadronic physics coalesced around the Lattice Hadron Physics Collaboration (LHPC), *led by Jefferson Laboratory and MIT*.

JLab and National Effort

- **Jefferson Laboratory co-equal partner with BNL and FNAL in lattice QCD effort.**

FNAL
Weak matrix elements

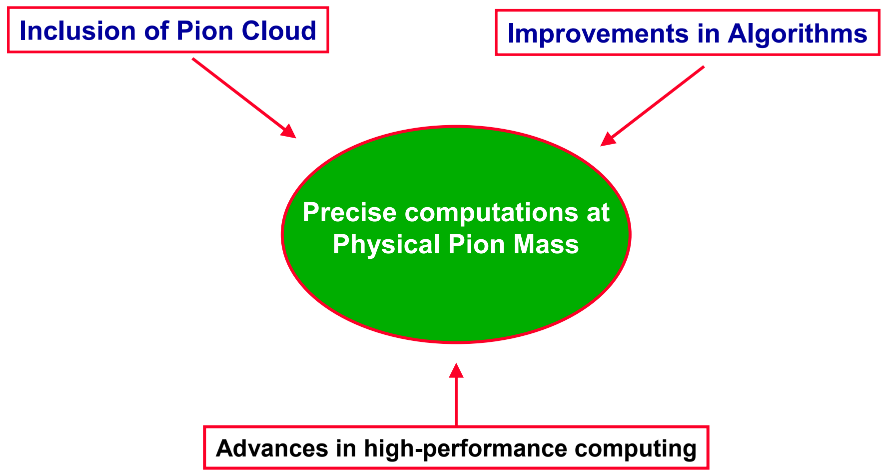
BNL
RHIC Physics

JLAB
Hadronic Physics

SciDAC – R&D Vehicle
• Cluster Prototyping – Balint Joo and Roy Whitney • **Software R&D** – Balint Joo

Lattice QCD at JLab will have major impact on DOE's Nuclear Physics Program

Advances in Lattice QCD



Overview

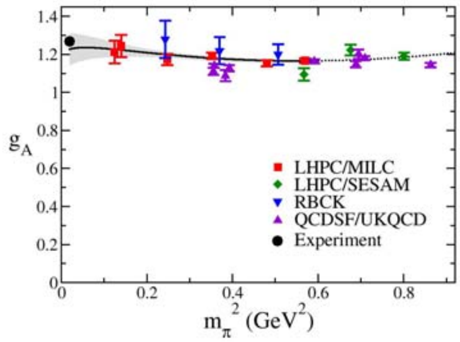
- Lattice QCD is addressing range of topics encompassing JLAB Physics Program at 6 GeV and at 12 GeV
  - Hadron Structure: Form Factors, Moments of GPD's, strange-quark contribution to EM form factors
  - Spectroscopy: excited baryon resonances, masses and photo-transitions of exotic mesons - GlueX
  - Origin of nuclear forces

Hadron Structure

- **Hybrid Computation of Hadron Structure using MILC asqtad lattices and domain-wall-fermion valence quarks**
- **Has enabled computations to be performed in full QCD at m_π approaching 350 MeV**

Nucleon's axial-vector charge g_A: benchmark of lattice QCD

LHPC (Edwards *et al.*), PRL 96 (2006) 052001



Hybrid approach: f_K/f_π

***Beane, Bedaque, Orginos, Savage*, hep-lat/0606023**

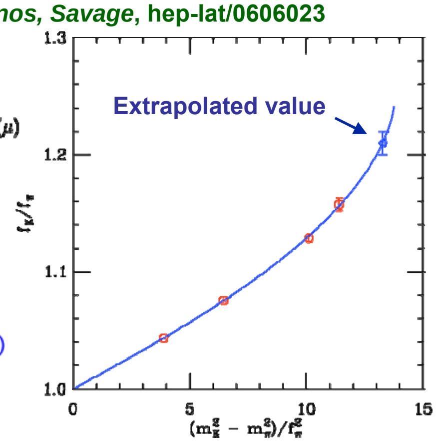
Gasser-Leutwyler:

$$\frac{f_K}{f_\pi} = 1 + \frac{5}{4} l_\pi(\mu) - \frac{1}{2} l_K(\mu) - \frac{3}{4} l_\eta(\mu) + \frac{8}{f^2}\left(m_K^2 - m_\pi^2\right) L_5(\mu)$$

$$l_i(\mu) = \frac{1}{16\pi^2}\frac{m_i^2}{f^2}\log\left(\frac{m_i^2}{\mu^2}\right)$$

$$\frac{f_K}{f_\pi} = 1.218(2)$$

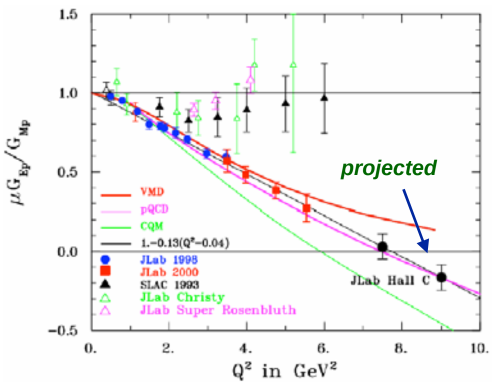
$$\left.\frac{f_K}{f_\pi}\right|_{\text{exp}} = 1.223(12)$$



Result comparable with MILC $\left.\frac{f_K}{f_\pi}\right|_{\text{MILC}} = 1.210(4)(13)$

Need much higher precision to see effects of Mixed χPT Baer et.al.'05

Proton Electromagnetic Form-Factors - I



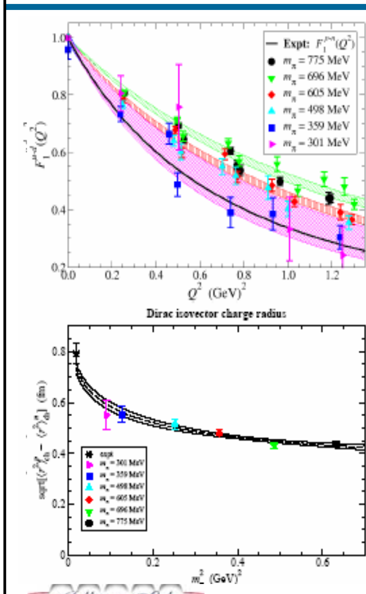
C. Perdrisat (W&M) , JLab Users Group Meeting, June 2005

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



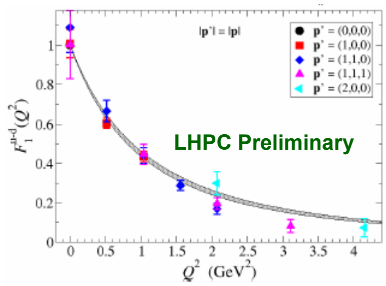
- **Lattice QCD computes the *isovector* form factor**
- **Hence obtain** Dirac charge radius $\langle r^2 \rangle^{u-d}_{ch}$ **assuming dipole form**
- **Chiral extrap. Using LNA and LA terms and finite-range regulator.**

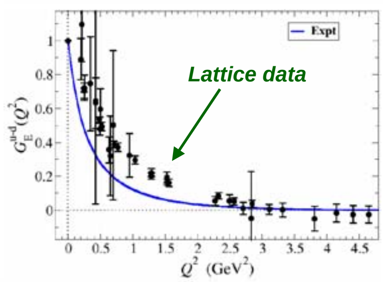
Leinweber, Thomas, Young, PRL86, 5011

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

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

Isovector Form Factor at Higher Q^2





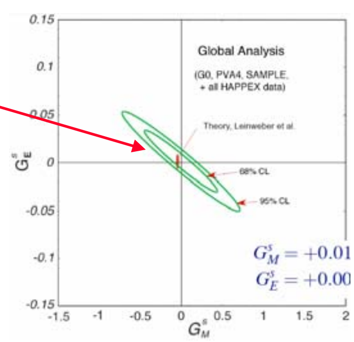
- Preliminary calculation with $m_\pi \simeq$ 600 MeV enabling us to reach $Q^2 \simeq 4$ GeV^2
- Fits of experimental data suggest G_E^{u-d} vanishes at $Q^2 \sim 4$ GeV^2
- Tantalising suggestion of such behavior in lattice data.

Form factor at $Q^2 > 10$ GeV^2, at pion masses down to 254 MeV in Asqtad/DWF Computation.

Strange Quark Form Factors

Strange-quark contribution to EM form factors – HAPPEX and G0.

Amalgam of Lattice QCD and Phenomenology by Leinweber *et al.*

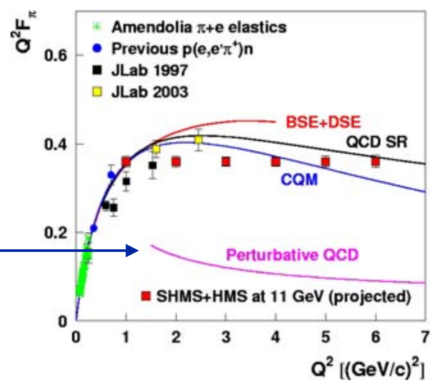


Ab initio computations of strange-quark contribution, at $Q^2 = 0$ and Q^2 away from 0.

Pion Form Factor –I

- Laboratory for observing interplay between perturbative and non-perturbative aspects of QCD
  - Asymptotic normalization determined

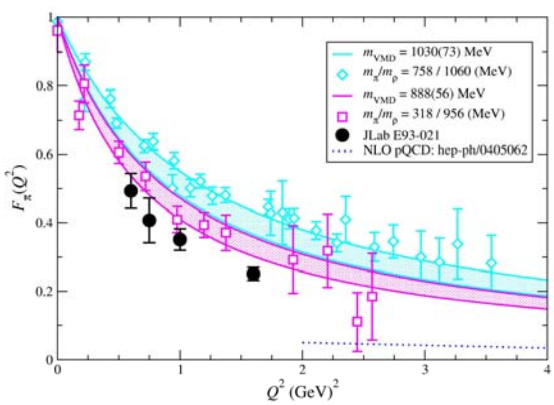
$$F_\pi(Q^2) = \frac{8\pi\alpha_s(Q^2)f_\pi^2}{Q^2} \quad \text{as} \quad Q^2 \to \infty.$$



  - Small Q^2, vector-meson dominance provides faithful description

$$F_\pi(Q^2) \approx \frac{1}{1+Q^2/m_{VMD}^2} \quad \text{for} \quad Q^2 \ll m_{VMD}^2.$$

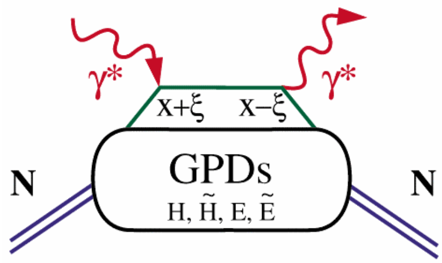
Pion Form Factor –II



LHPC, Bonnet *et al*
PRD72, 054506

- Pion Form factor over Q^2 commensurate with experiment
- Pion GPDs and transition form factors

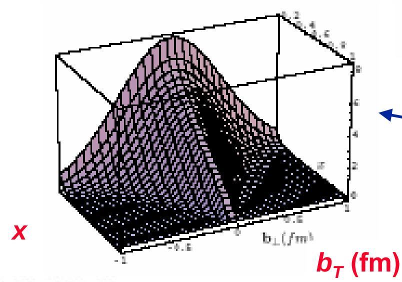
Moments of PDFs and GPDs – I



HP 2008

- **Lattice QCD can compute moments of GPDs and PDFs, and the *t*-dependence**

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



Compare to phenomenological models

Decrease slope : decreasing transverse size as x → 1

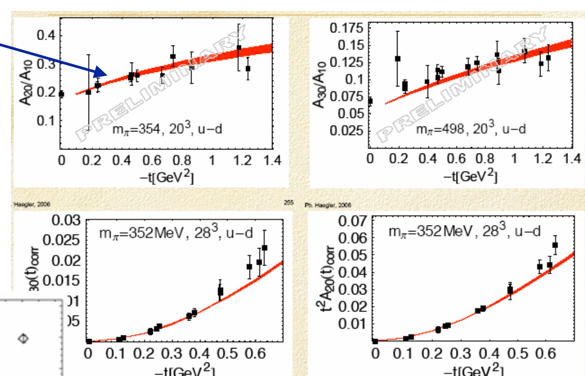
Burkardt

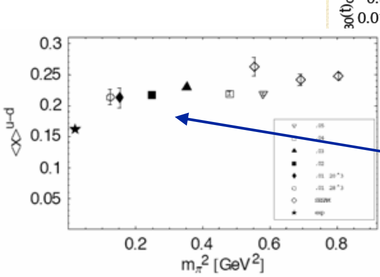
Moments of PDFs and GPDs - II

Diehl et al, EPJC 39 (2005)

LHPC, Haegler *et al.*

HP 2014



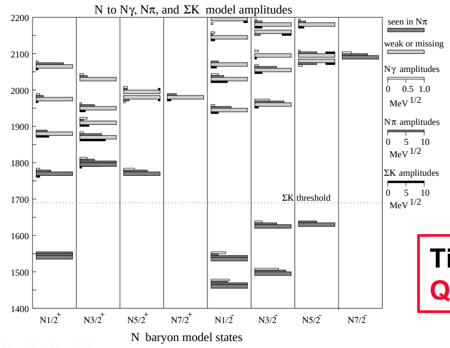


Importance of light pion masses

Systematic errors on lowest moments < 5% in fully-consistent DWF computation

Spectroscopy - I

- Classic tool for gleaning information about *degrees of freedom of QCD*
- Experimental and *ab initio* N* and Hybrid programs aim at discovering effective degrees of freedom of QCD, and resolving competing low-energy models:

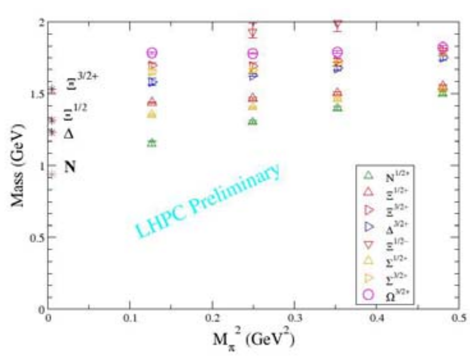


Capstick and Roberts, PRD58 (1998) 074011

Timely opportunity for lattice QCD in concert with EBAC

Spectroscopy - II

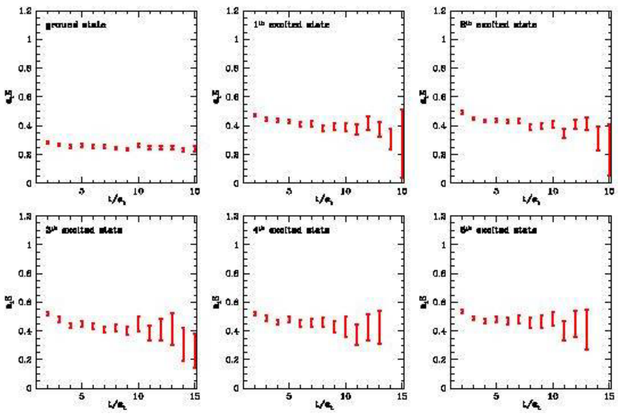
- Important progress at constructing baryon interpolating operators – LHPC, PRD72, 072501, PRD72, 094506
- First application to computation of lowest lying resonances in hybrid asqtad/DWF calculation
- Exciting opportunities for *Cascade program* – narrow states/reliable lattice calculations



HP2009

Spectroscopy - III

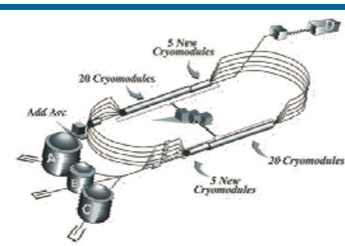
Application of Variational Method in trial calculation allows extraction of up to eight excited states

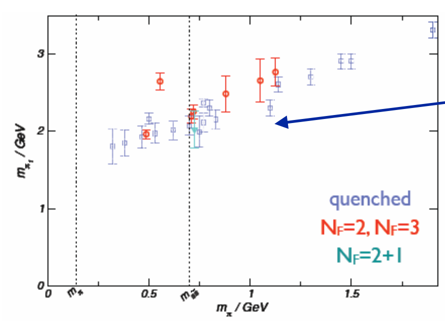


USQCD Scientific Program Committee award of 0.55 Tflop-year for generation and analysis of anisotropic lattices with full QCD using "clover" action for resonance spectroscopy – ***Robert Edwards***

Hybrids and GlueX - I

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

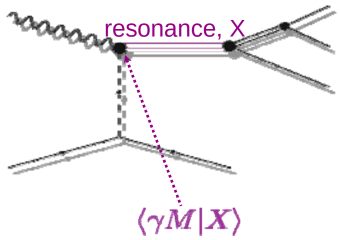


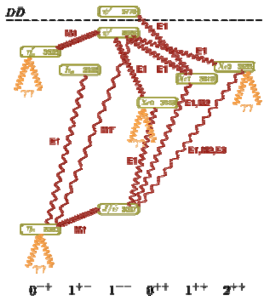


- **Only a handful of studies of hybrid mesons at light masses – mostly of 1^{-+} exotic**
- **Variational method to enable comprehensive computation low-lying meson spectrum**

Hybrids and GlueX - II

- An important realization of JLab Theorists was that lattice QCD enabled calculation of photocouplings
- Guide experimental program as to expected photoproduction rates.





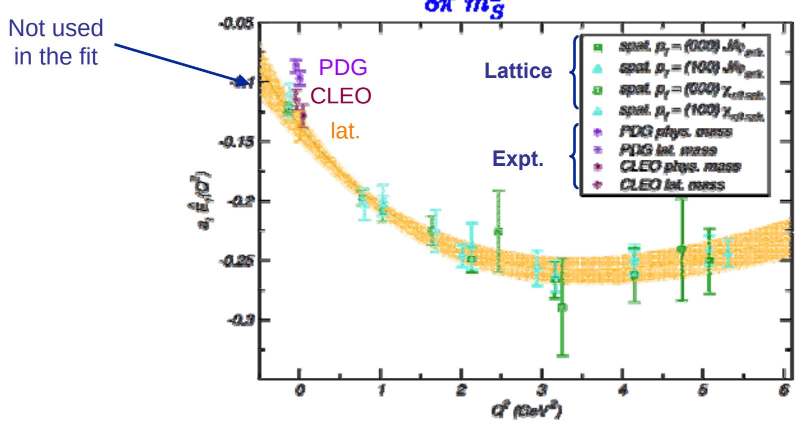
- Initial exploration in Charmonium
  - Good experimental data
  - Allow comparison with QCD-inspired models
  - *Lattice computations pioneered at JLab*

Photocouplings - I

Dudek, Edwards, Richards, PRD73, 074507

- Recent study of transitions between conventional mesons, e.g. S → γ V

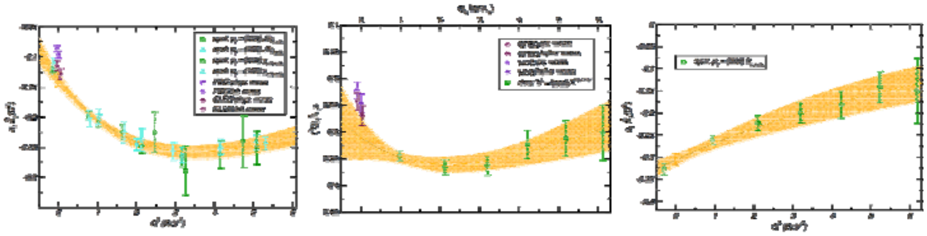
$$\Gamma(\chi_{c0} \to J/\psi\,\gamma) = \frac{1}{8\pi}\frac{|\vec{q}\,|}{m_S^2}\,2\,(2e_c)^2\,|\,E_1(0)\,|^2$$



Photocouplings - II

Q²-dependence inspired by NR potential model with rel. corrections:

$$E_1(Q^2) = E_1(0)\left(1 + \frac{Q^2}{\rho^2}\right) e^{-\frac{Q^2}{16\beta^2}}$$

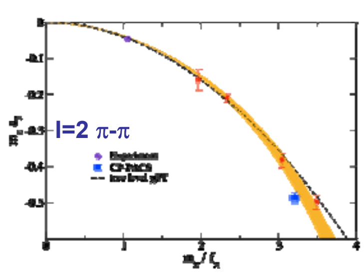


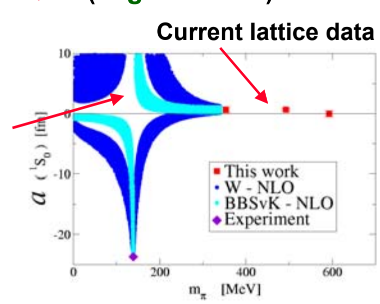
$\chi_{c0} \to J/\psi\gamma_{E1}$	$\chi_{c1} \to J/\psi\gamma_{E1}$	$h_c \to \eta_c\gamma_{E1}$
$\beta = 542(35)$ MeV	$\beta = 555(113)$ MeV	$\beta = 689(133)$ MeV
$\rho = 1.08(13)$ GeV	$\rho = 1.65(59)$ GeV	$\rho \to \infty$

First computation of exotic meson resonance spectrum, and of 1^{-+} photocouplings, at pion masses down to 220 MeV

Origins of Nuclear Forces

- Lattice QCD beginning to address nature of origins of nuclear forces
- First dynamical calculation of scattering lengths in $^1S_0$ channel and $^3S_1$ - $^3D_1$ coupled channels by NPLQCD (Orginos et al.).





Computations closer to physical pion mass will enable *ab initio* predictions of scattering lengths

Summary

- Emerging computational resources allowing exploitation of theoretical advances
- Schedule of computations that will have a *major impact* on the JLab Physics Program at both 6 and 12 GeV.
  - Precise computations of low moments of nucleon PDF's and GPD's, pion form factor, transition form factors – *understanding of structure of hadrons..*
  - Hybrid spectrum, photocouplings, decay, *crucial for GlueX*
  - First steps at understanding nuclear forces