Overview of Jefferson Lab Physics Program

David Richards

1st June, 2008

HUGS

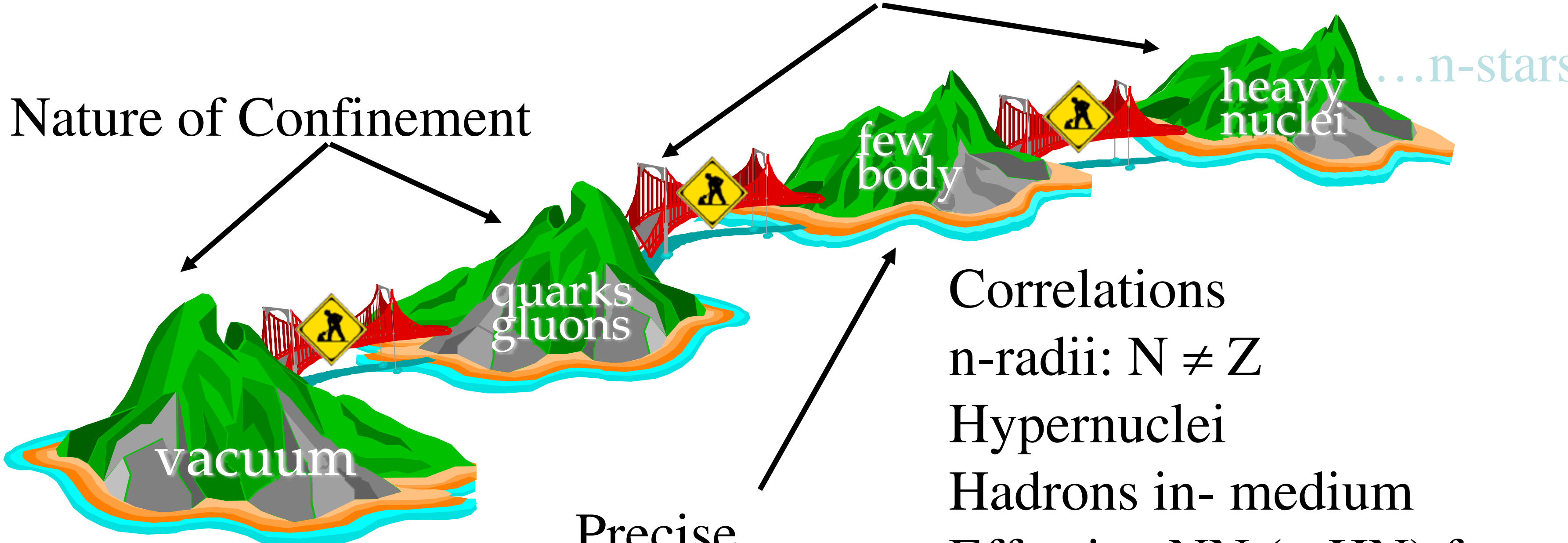
Why are we here?

- Describe how the fundamental building blocks of the nucleus, the protons and neutrons, are built from the primordial quarks and gluons - the fundamental fields of Quantum Chromodynamics (QCD).
- What are the effective degrees of freedom of QCD?
- Explain how the force that binds nucleons into nuclei arises from QCD
- Search for evidence of physics beyond the "Standard Model" of particle physics – complementary to the high-energy experiments at, say, the LHC
- We do this by Experiment, Theory, Computation and the confrontation of the three

JLab Central to Nuclear Science

Quark-Gluon Structure
Of Nucleons and Nuclei

Nature of Confinement



Correlations
n-radii: N ≠ Z
Hypernuclei
Hadrons in- medium
Effective NN (+ HN) force

Precise
few-nucleon
calculations

Exotic mesons
and baryons

Tony Thomas

JLab: 8 of 10 SC Milestones in Hadronic Physics

Year	Milestones:
2008 M1	Make measurements of spin carried by the glue in the proton with polarized proton-proton collisions at center of mass energy, $\sqrt{s_{NN}}$ = 200 GeV.
2008 M2	Extract accurate information on generalized parton distributions for parton momentum fractions, x, of 0.1 - 0.4 , and squared momentum change, –t, less than 0.5 GeV^2 in measurements of deeply virtual Compton scattering.
2009 M3	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 M4	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 M5	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 $^4He(\vec{e},e'\vec{p})^3H$ reaction.
2011 M6	Measure the l[illegible]ents of the unpolarized nucleon structure functions (both longitudinal and transverse) to 4 GeV[illegible]oton, and the neutron, and the deep inelastic scattering polarized structure functions g_1(x, Q^2) and g_2(x,[illegible]0.2-0.6, and 1 < Q^2 < 5 GeV^2 for both protons and neutrons.
2012 M7	Measure the electromagnetic excitati[illegible]lying baryon states (<2 GeV) and their transition form factors over the range Q^2 = 0.1 – 7 GeV^2 and measu[illegible]tro- and photo-production of final states with one and two pseudoscalar mesons.
2013 M8	Measure flavor-identified q and $\bar{q}$ contributions to the spin [illegible]on via the longitudinal-spin asymmetry of W production.
2014 M9	Perform lattice calculations in full QCD of nucleon form factors, low momen[illegible]eon structure functions and low moments of generalized parton distributions including flavor and spin dep[illegible]ndence.
2014 M10	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.

Note: M3, M7, M9 and M10 involve Theory in analysis

QCD

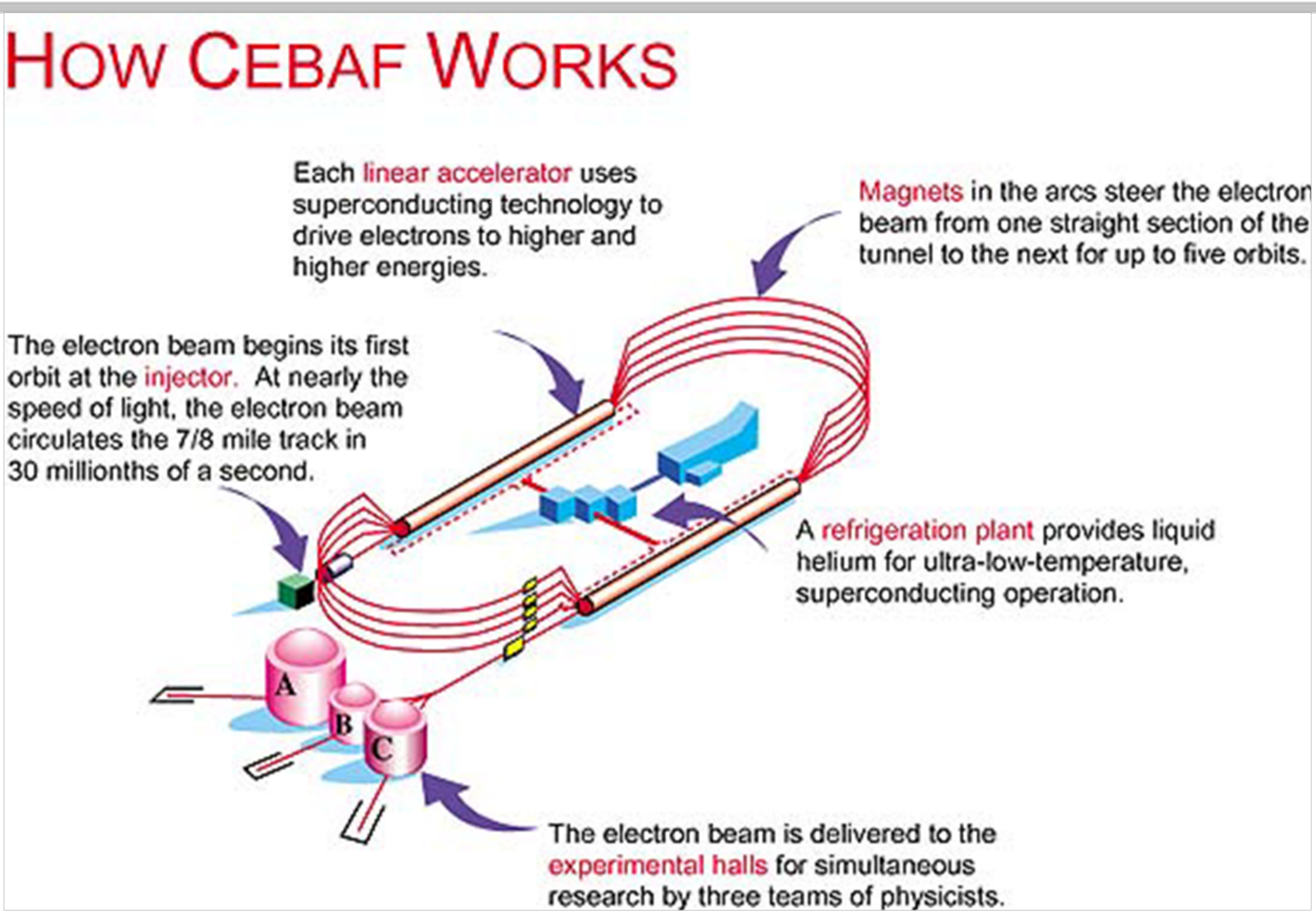
- QCD is the theory of the strong interaction – hadronic physics
- QCD is a *Gauge Theory*, characterised by local symmetry – c.f. QED

QED	QCD
Photon, γ	Gluons, G
Charged particles, e, μ, u, d,…	Quarks: u, d, s, c, b, t
Photon is *neutral*	Gluons carry *color charge* Theory is *non-Abelian*
$\alpha_e \simeq 1/137$	$\alpha_s \simeq O(1)$

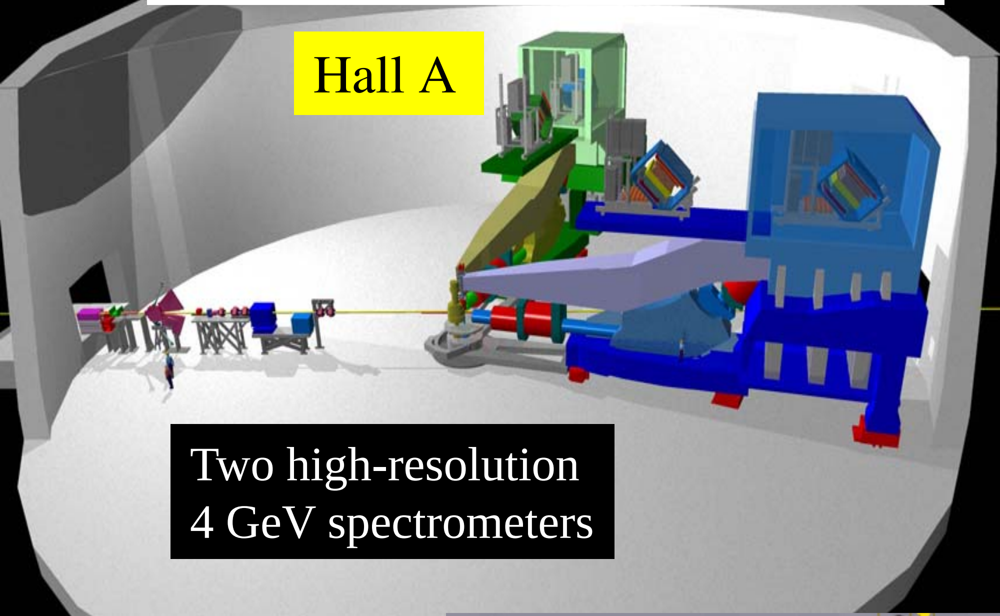
↓

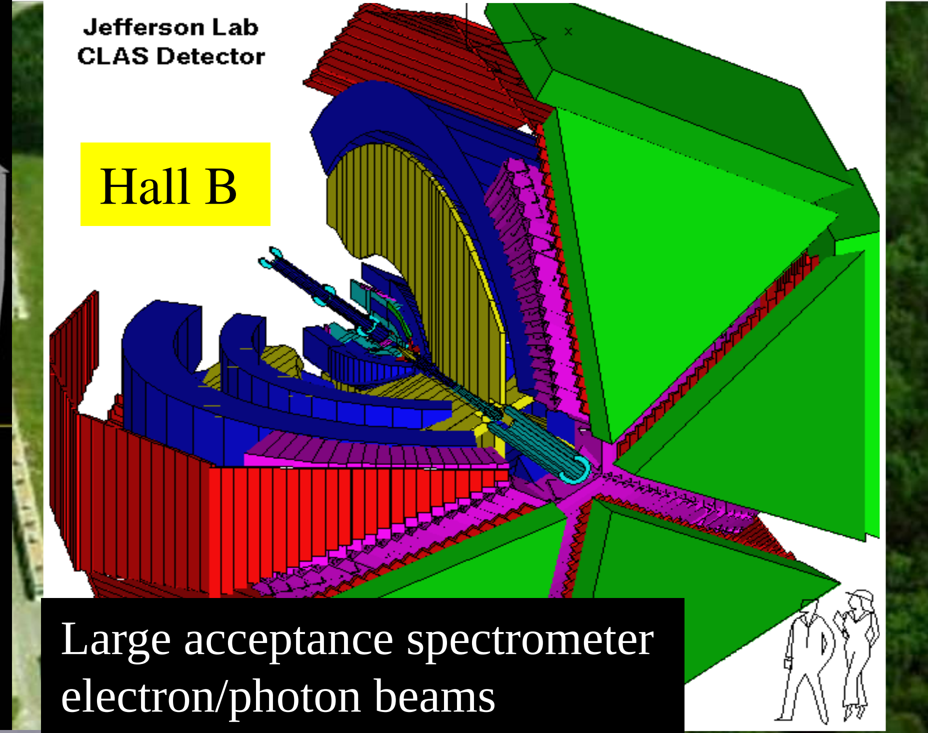
How do they give rise to protons, neutrons, nuclei?

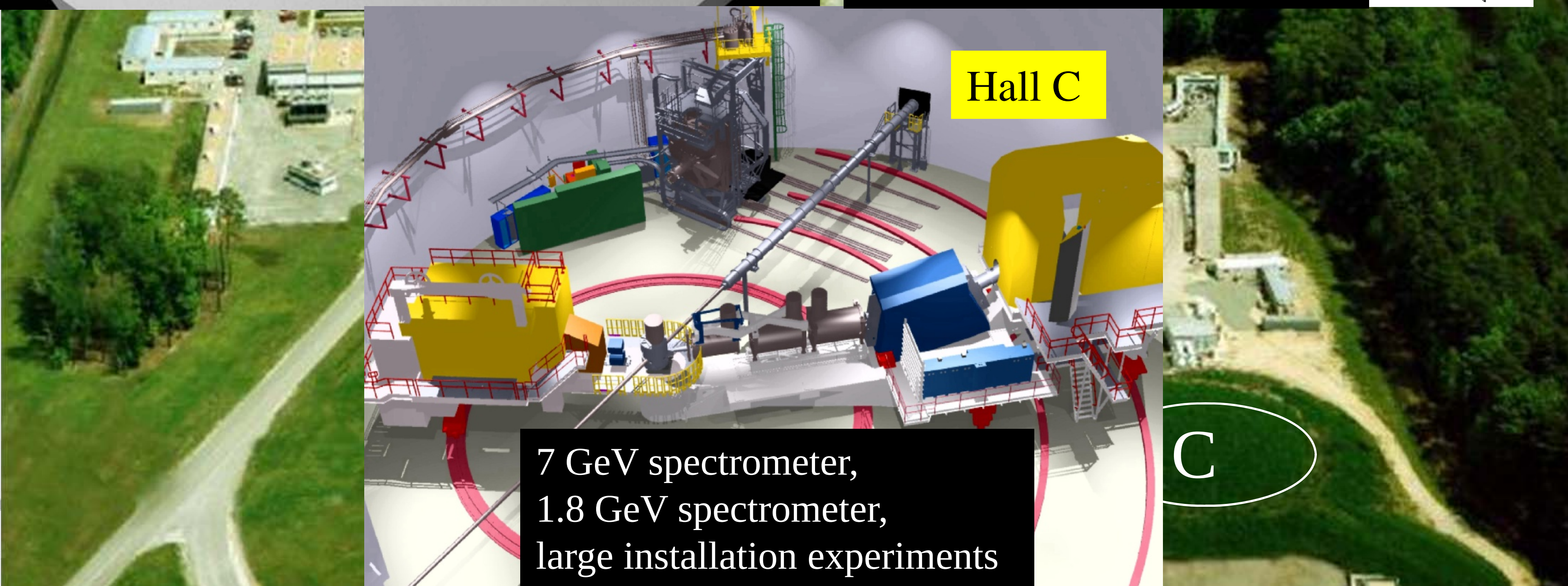
Jefferson Laboratory – 6 GeV



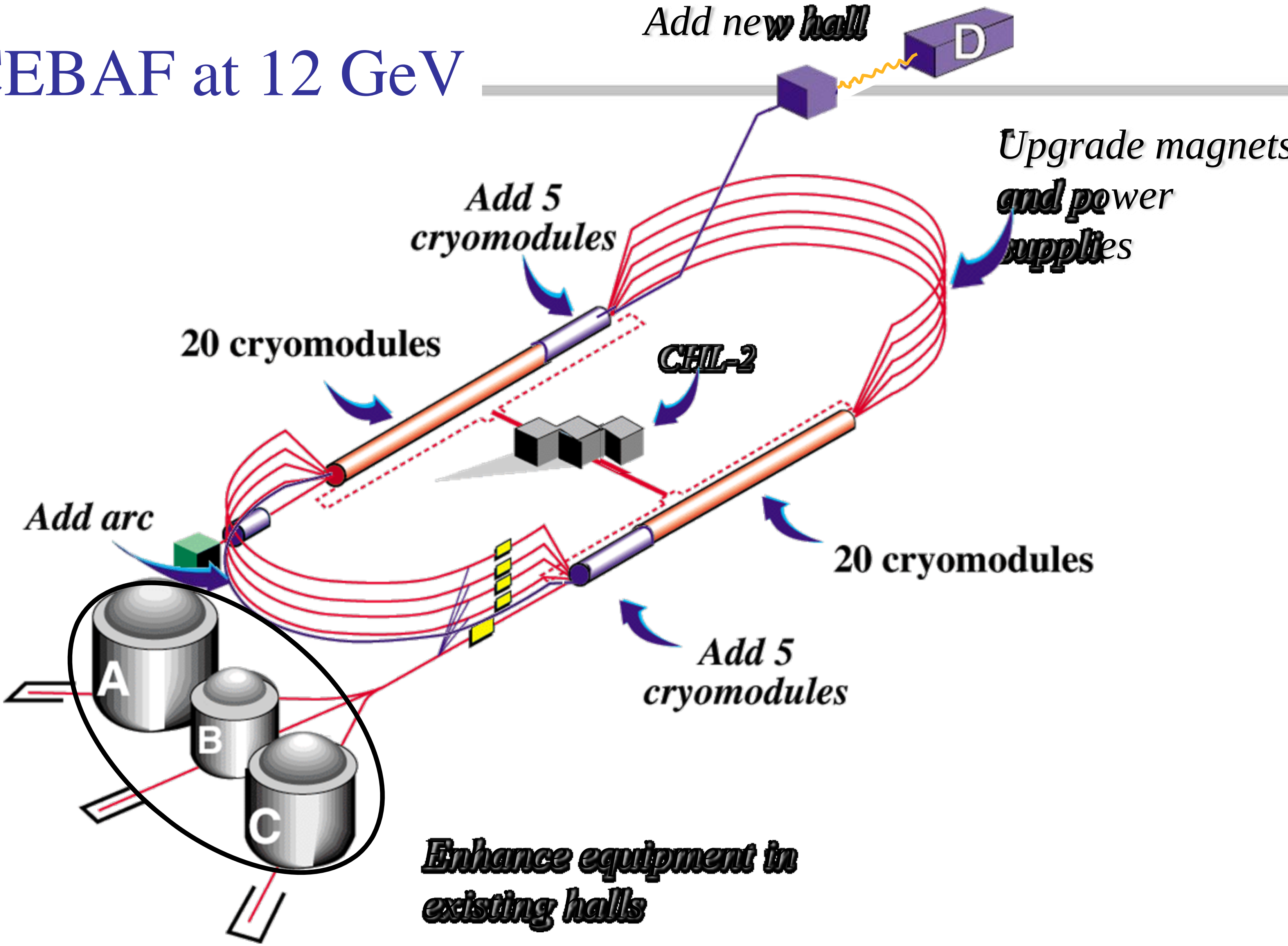
Jefferson Lab Today







CEBAF at 12 GeV

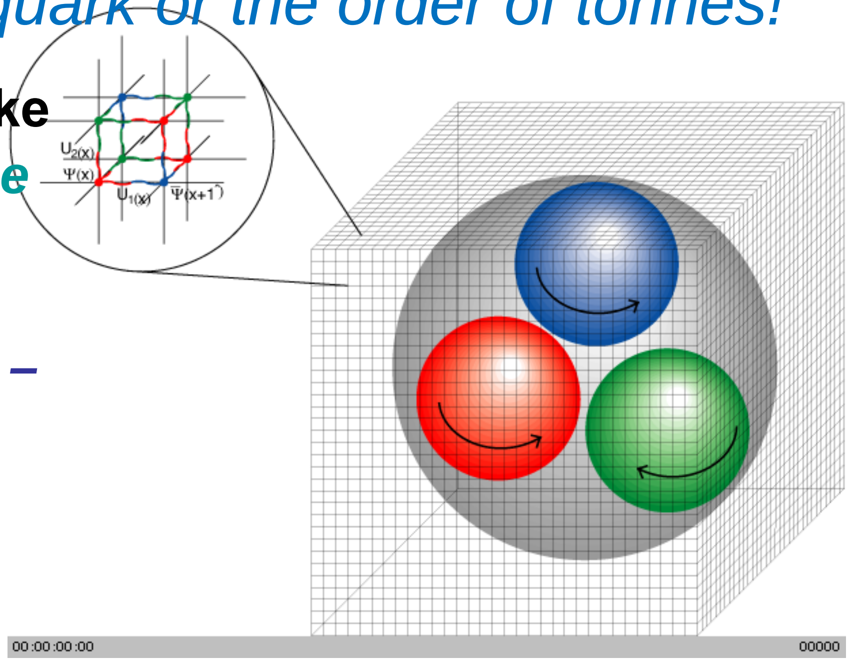


Experimental Program

- EM Form Factors of Proton
- Pion Form Factor
- Generalized Parton Distributions
- Baryon Spectroscopy
- The search for Hybrids

Lattice QCD

At *short distance* QCD is asymptotically free (2004 Nobel Prize!). At *long distances* coupling becomes stronger – *force between quark and anti-quark or the order of tonnes!*

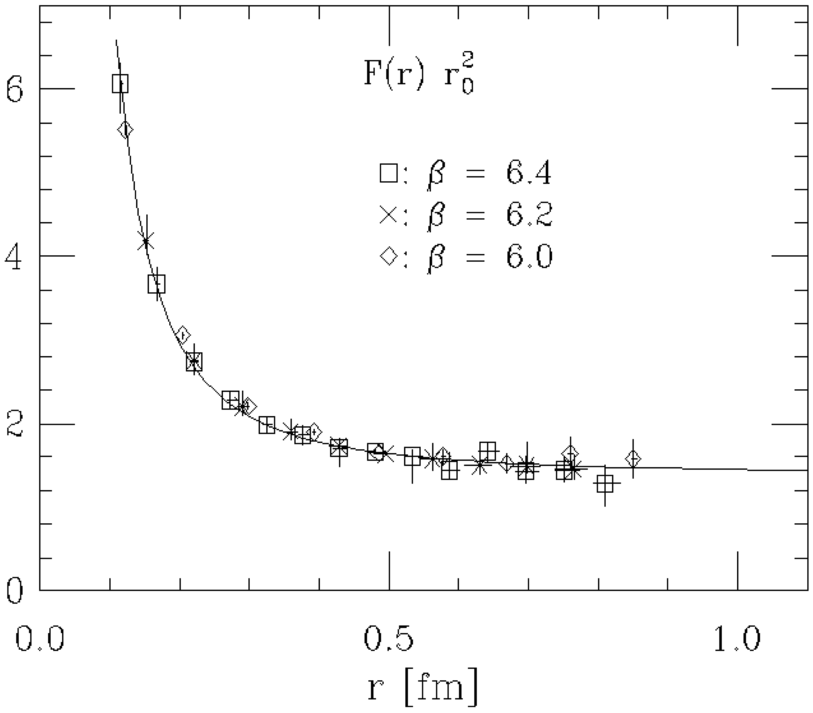


- **Lattice QCD enables us to undertake *ab initio computations of many of the low-energy properties of QCD***
- **Continuum Euclidean space time replaced by four-dimensional *lattice* – current typical sizes $28^3 \times 96$**
- **Computations dominated by *inversion of large, sparse matrices.***

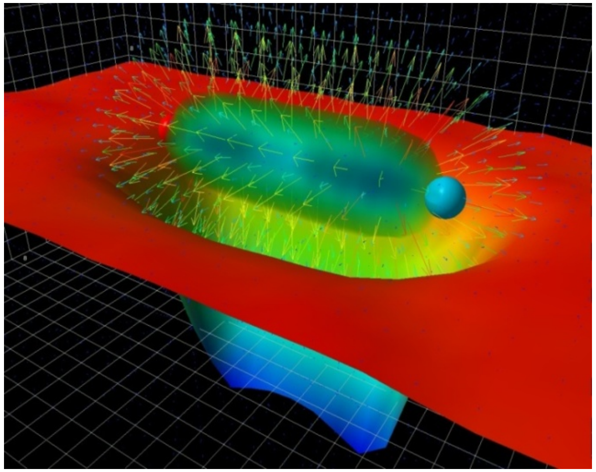
Highly regular problem, with simple boundary conditions – *very efficient use of massively parallel computers using data-parallel programming.*

Confinement

Why do we never see a free quark? One of the early successes of lattice QCD was the demonstration of *confinement – the constant force between color-non-singlet objects at large distances.*



10 Tonnes



Force between heavy quark-antiquark pair constant *UKQCD (1994)*

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

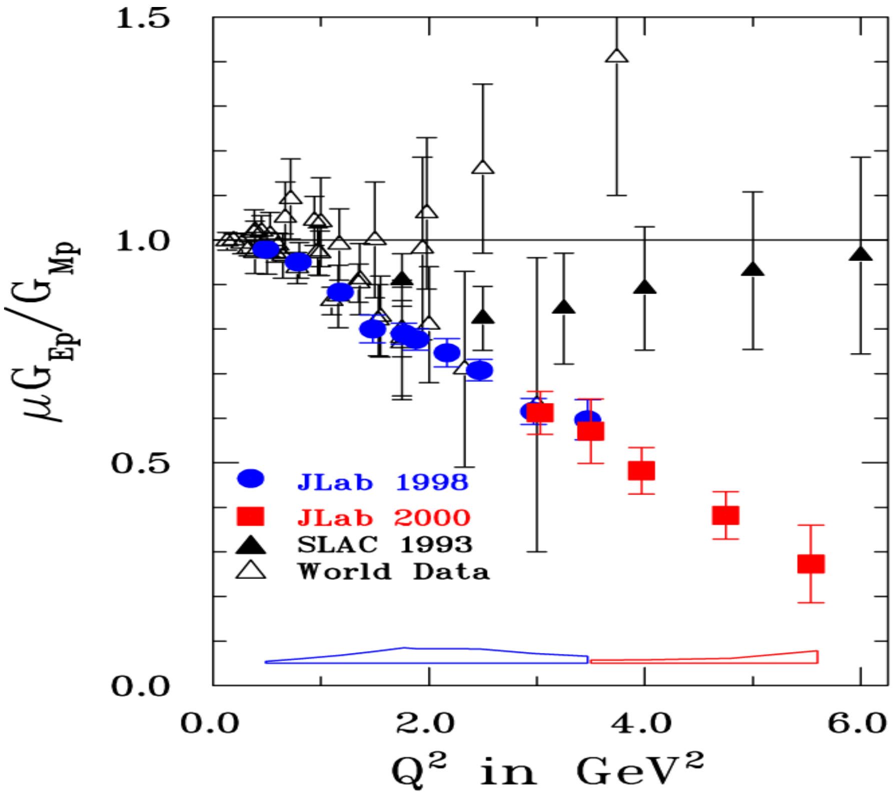
SciDAC – R&D Vehicle

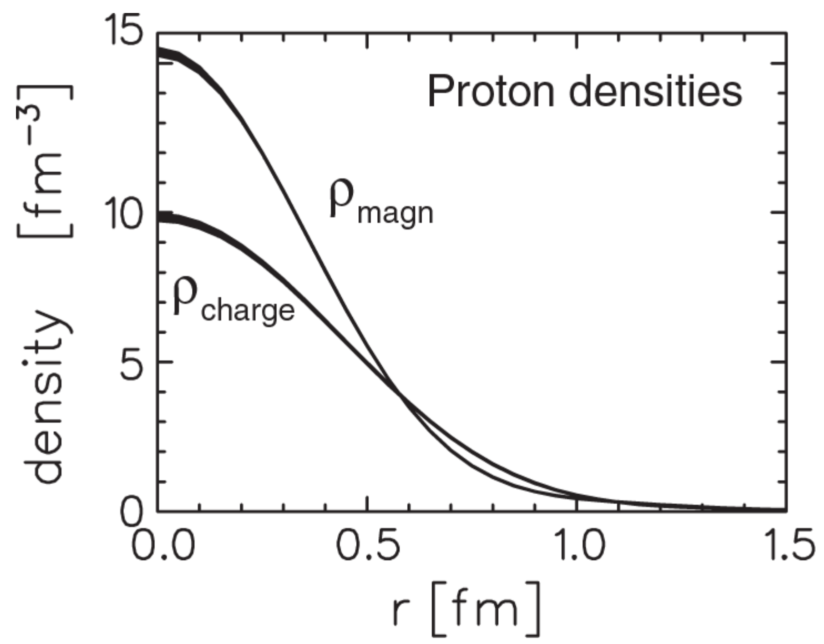
Lattice QCD at JLab will have major impact on DOE's Nuclear Physics Program

Hadron Structure

Electric and Magnetic Form Factor

- Electric and Magnetic Form Factors encapsulate distribution of charge and current within a nucleon → fundamental measure of nucleon structure
- Core of Jefferson Laboratory Experimental Program



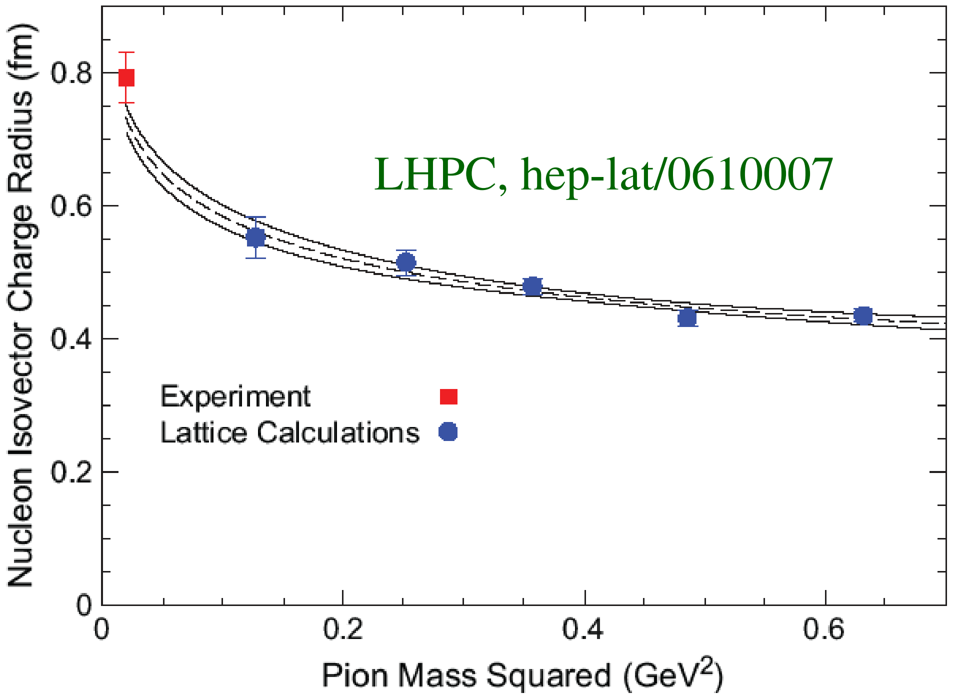


Proton EM Form Factors - II

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

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

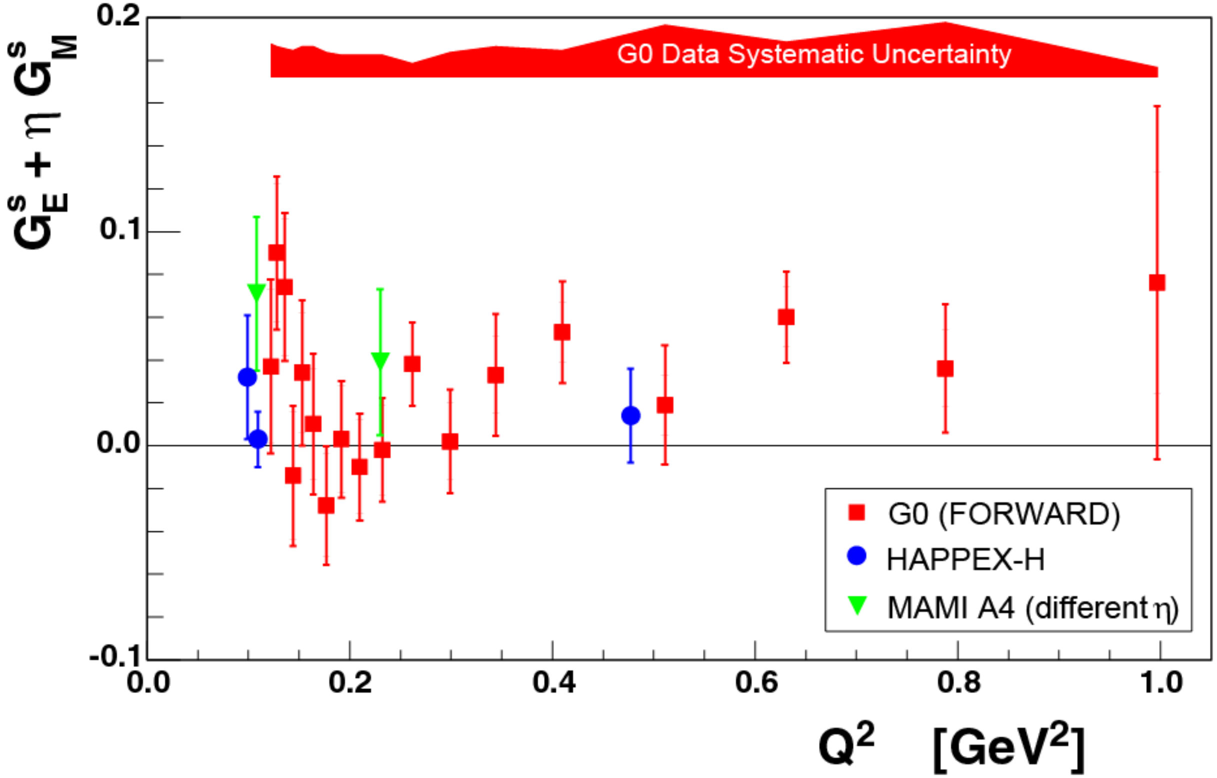
Leinweber, Thomas, Young, PRL86, 5011



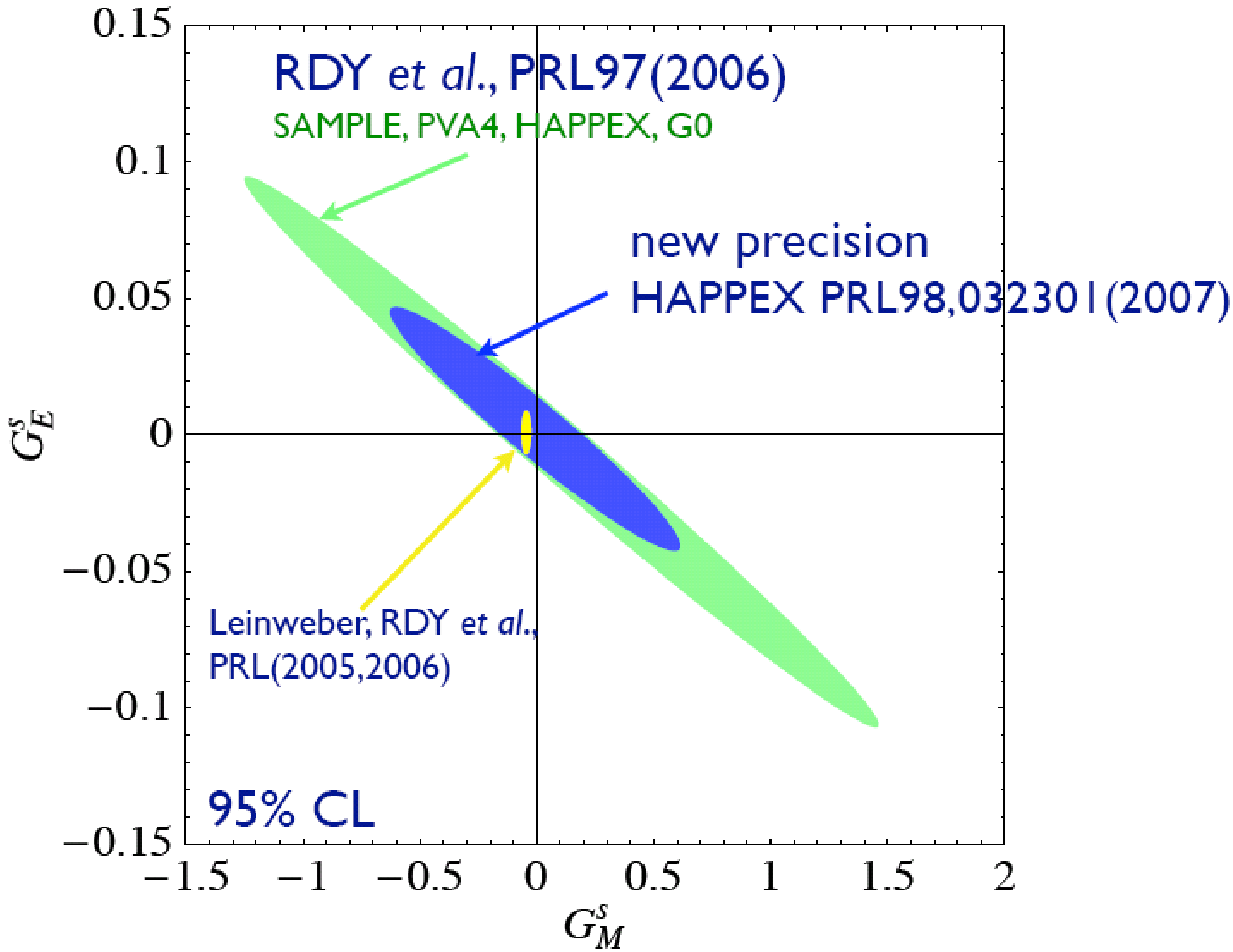
As the pion mass approaches the physical value, the size approaches the correct value

What is role of heavier quarks?

- *Can we measure the contribution of the heavier (s,c,t,b) quarks to hadron structure?*
- *Yes, in Parity-Violating Electron Scattering (PVES)*



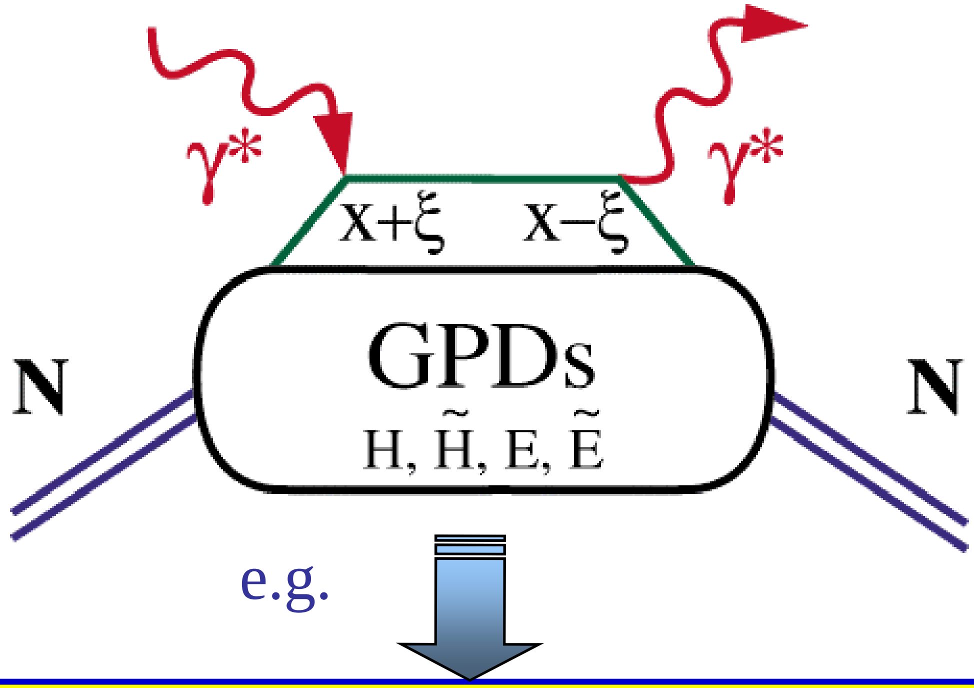
Strange-quark form factors



Generalized Parton Distributions (GPDs)

Measured in eg Deeply Virtual Compton Scattering

HP 2008



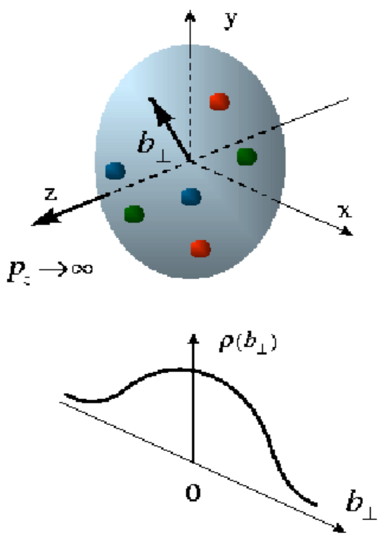
D. Muller (93). X. Ji & A. Radyushkin (1996)

Quark angular momentum (Ji's sum rule)

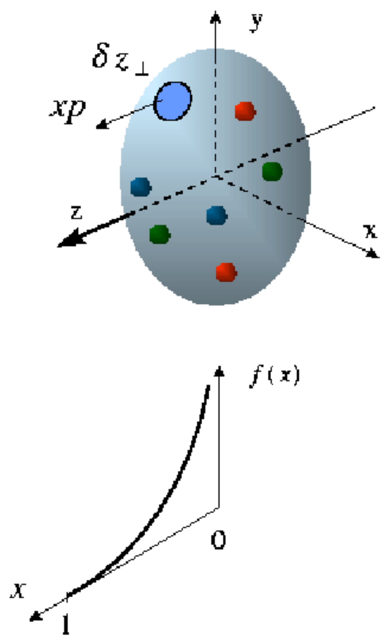
$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x dx \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

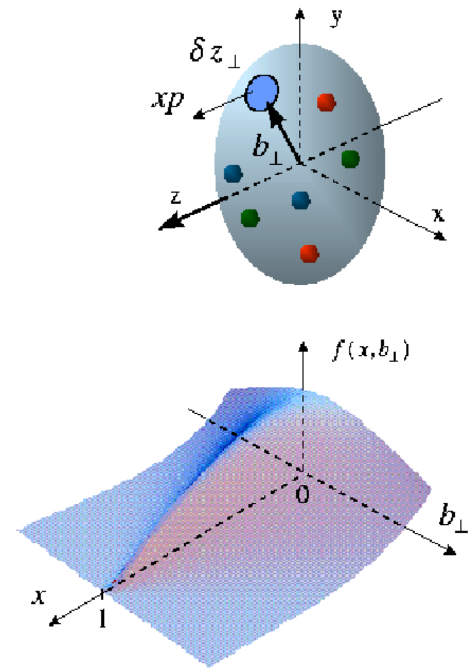
GPDs: Different Regimes in Different Experiments



Form Factors
transverse quark distribution in Coordinate space



Structure Functions
longitudinal quark distribution in momentum space

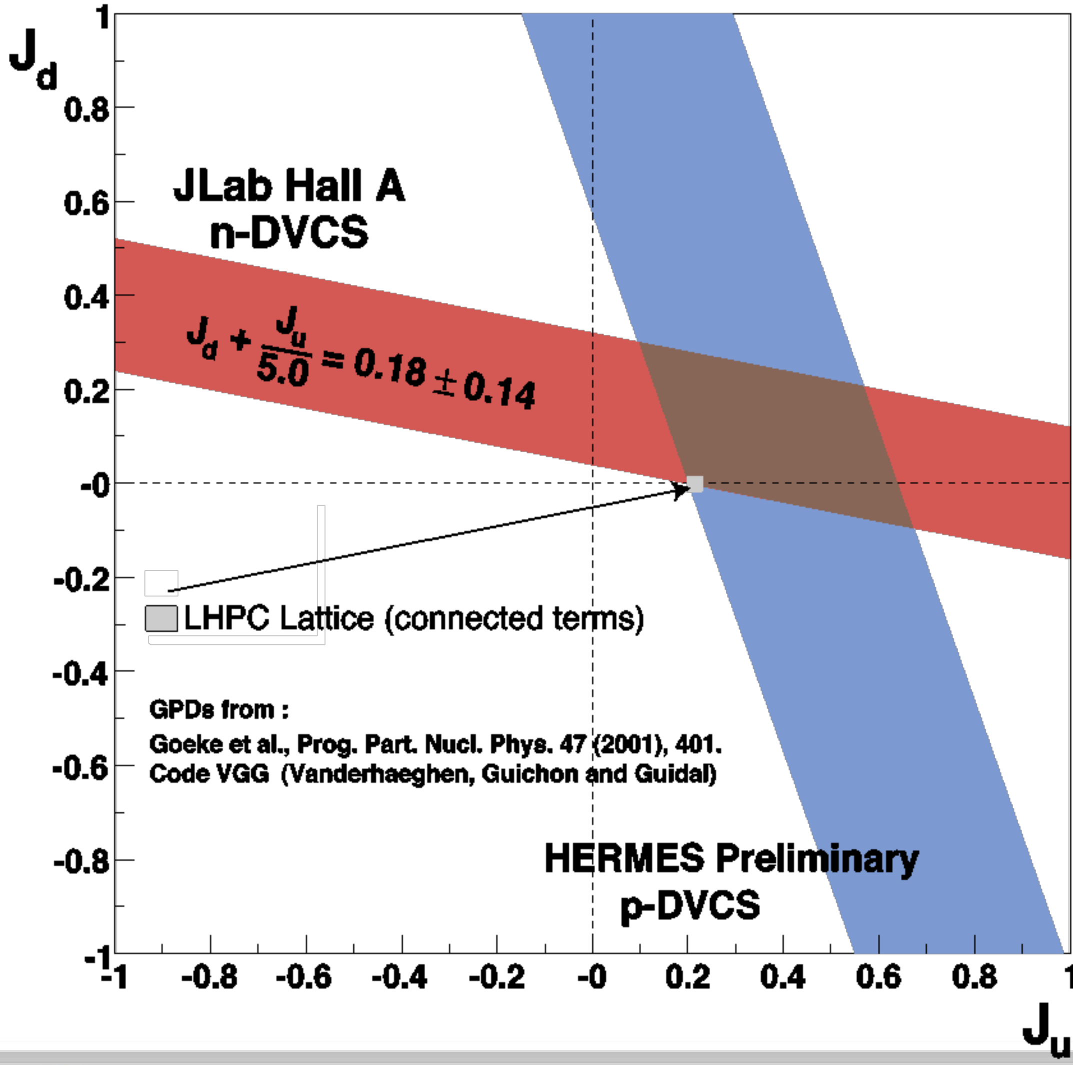


GPDs
Fully-correlated quark distribution in both coordinate and momentum space

Origin of Nucleon Spin

- How is the spin of the proton distibuted between valence quarks, sea quarks and antiquarks, gluons and orbital angular momentum
- Spin carried by quarks long measured in Deep Inelastic Scattering (DIS)
- GPDs allow us to measure (by experiment) or calculate (lattice QCD or QCD-inspired models)

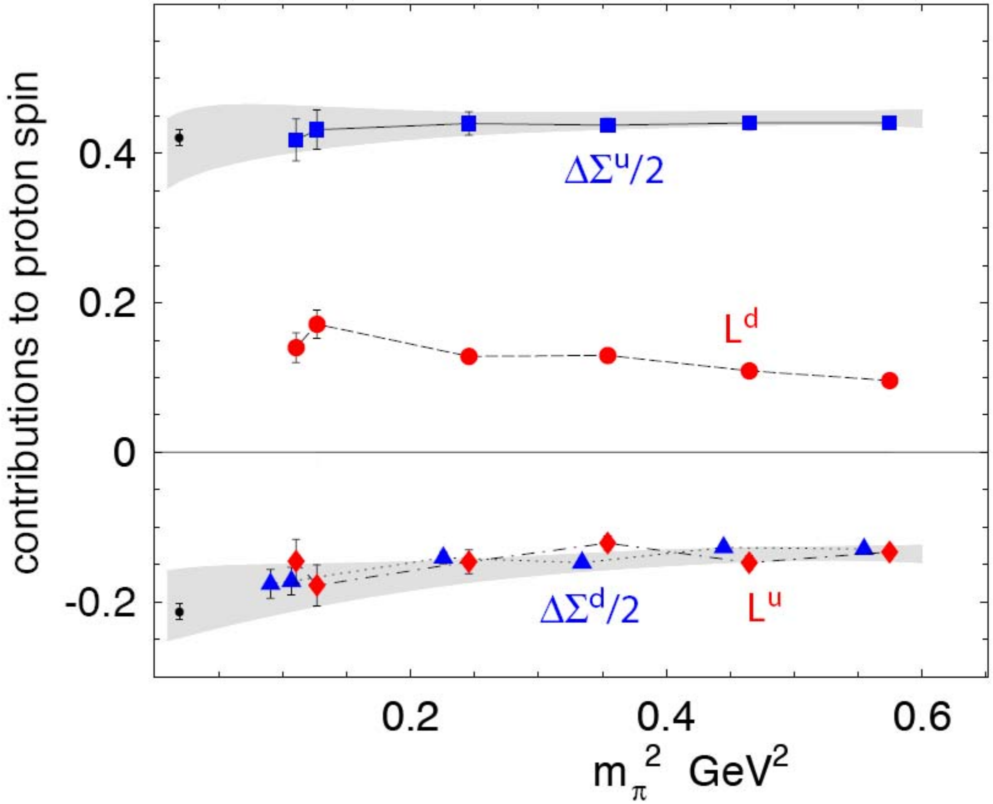
Origin of Nucleon Spin



- Jlab measurement of DVCS on Neutron
- Hermes Measurement of DVCS on Proton

Origin of Nucleon Spin - II

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

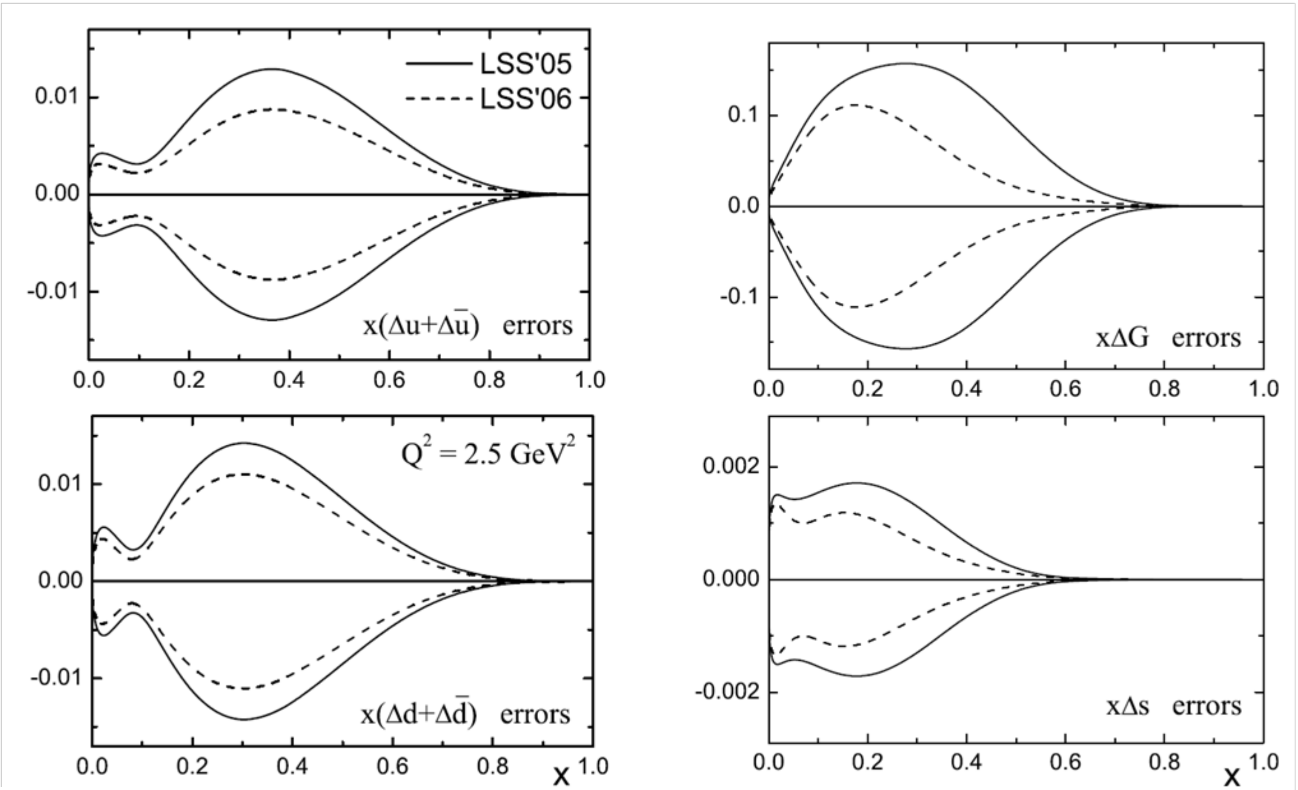


Total Quark OAM negligible: that of individual flavors substantial.

Impact of CLAS Precision Data on Parton Distribution Functions

CLAS precision data more than doubled the data points in the DIS region from 30 years of high energy polarized structure function measurements.

The much improved control of higher twist (HT) effects achieved with these data allows to use them in global fits of the world data to extract PDFs.



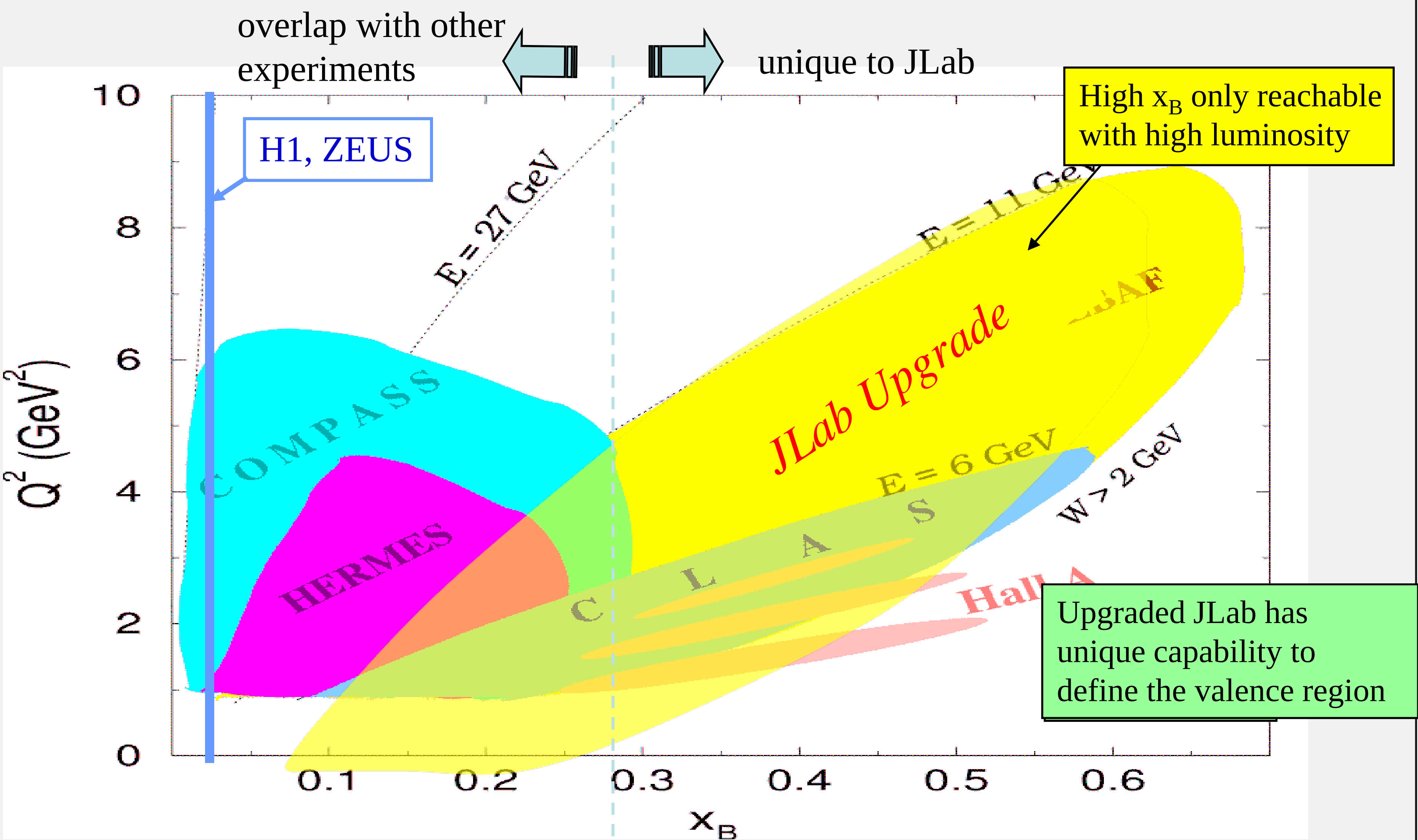
At moderate x_B=0.4, the relative uncertainty of $x\Delta G$ is reduced by a factor 3 and of Δs-$\Delta\bar{s}$ by a factor 2.

Conclude
$|\Delta G| < 0.3$
at $Q^2 = 1\ GeV^2$

The dashed lines include the CLAS data in the analysis (LSS'06).

E. Leader, A. Sidorov, D. Stamenov, Phys.Rev.D75:074027,2007.

Kinematics Coverage of the 12 GeV Upgrade



Spectroscopy

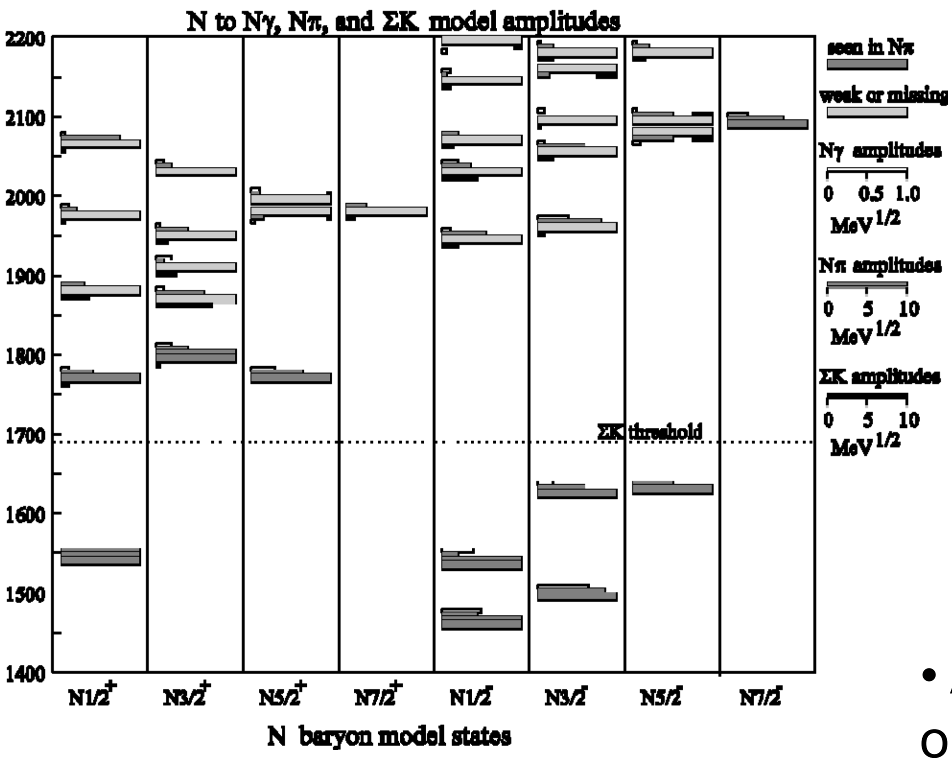
QCD is a complicated many-body theory
What are the effective low-energy degrees of freedom?

Hadron Spectroscopy

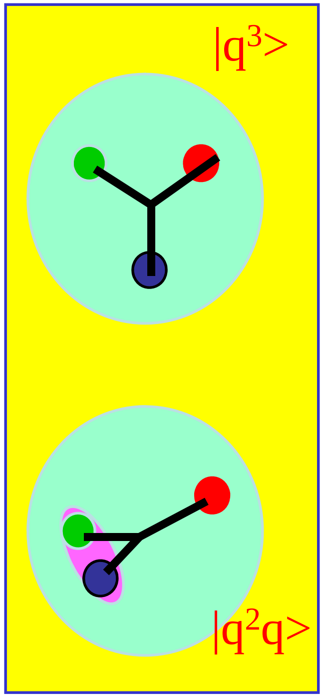
- **Spectroscopy is classic tool for gleaning information about structure of theory**
- **Both experimental and *ab initio* N* and Exotic-meson programs aim at *discovering effective degrees of freedom of QCD*, and resolving competing low-energy models**
  - **HP2009 and HP2012 milestones**
  - **Excited 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….."

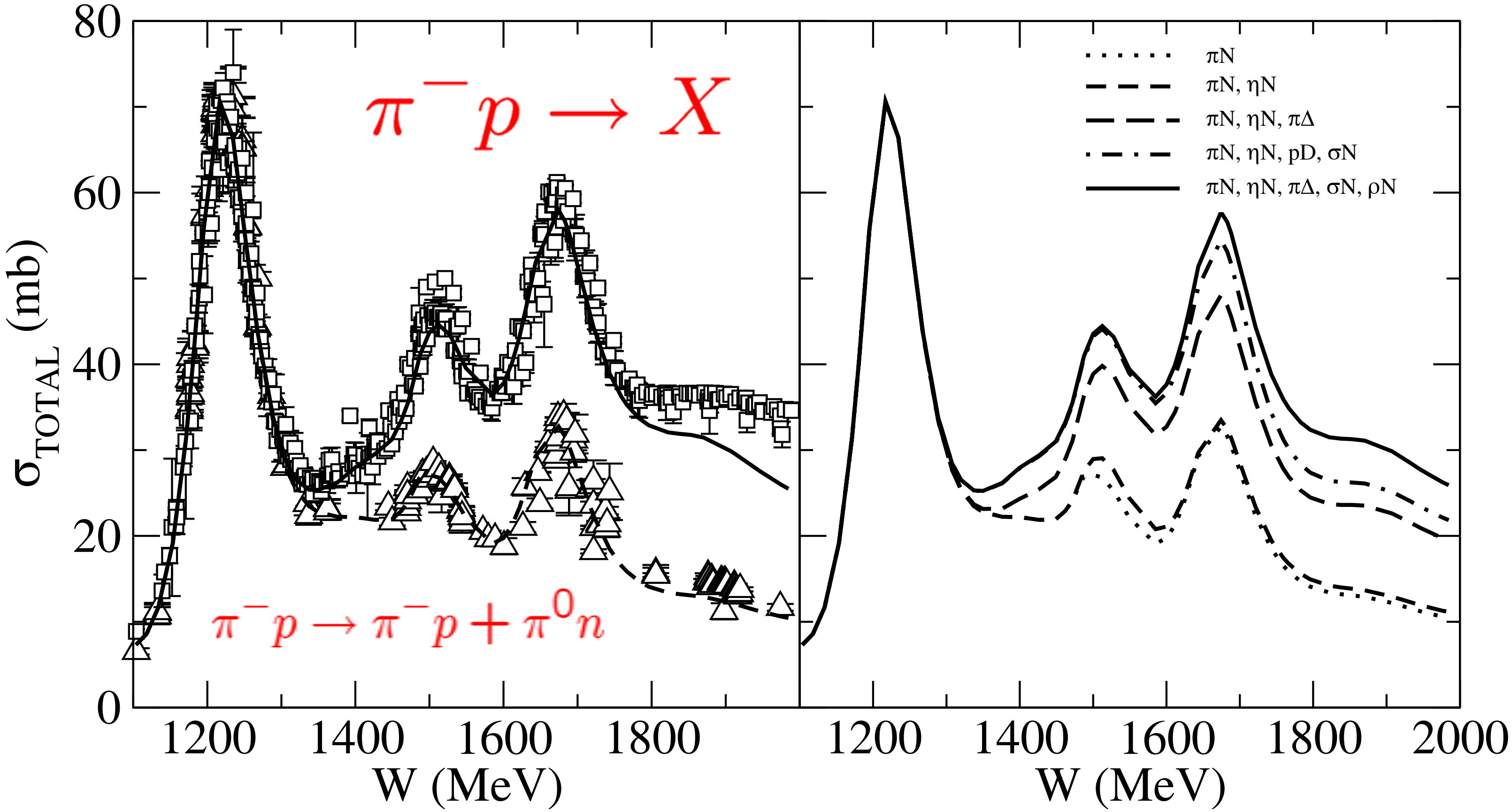
N* Spectroscopy - I



Capstick and Roberts, PRD58 (1998) 074011

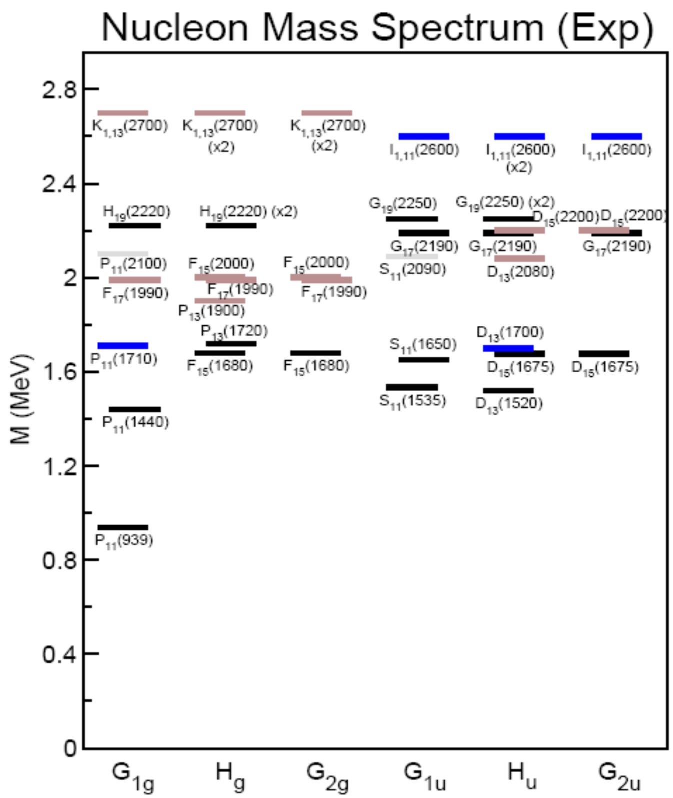


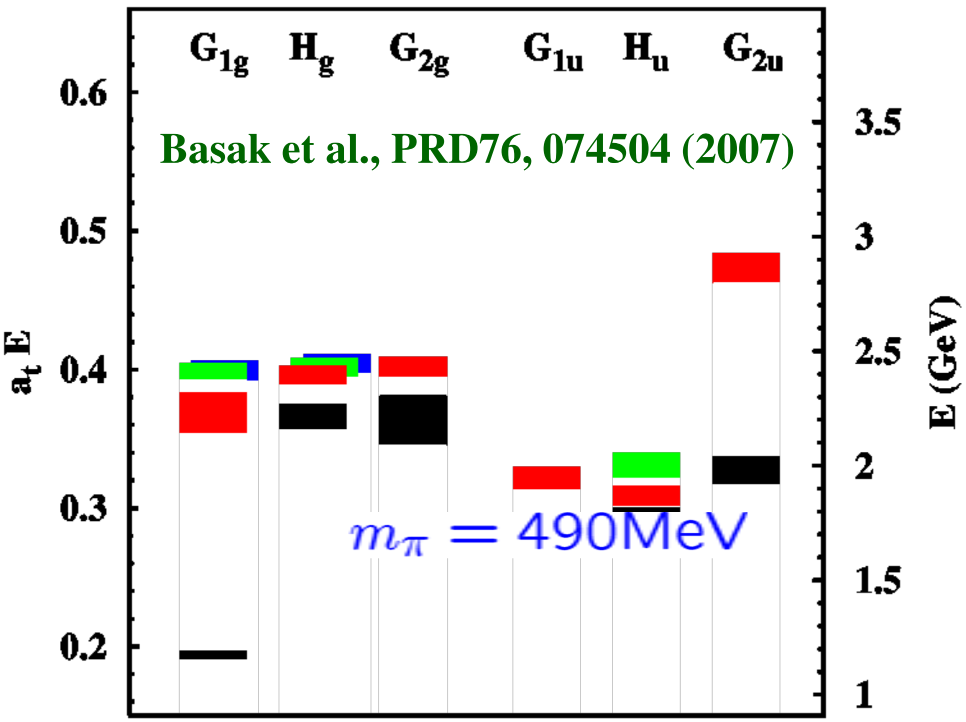
- Are states Missing, because our pictures are not expressed in correct degrees of freedom?
- Do they just not couple to probes?



Excited Baryon Analysis Center

Lattice QCD

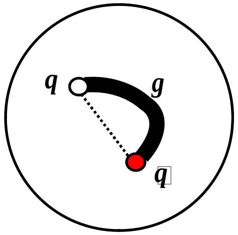




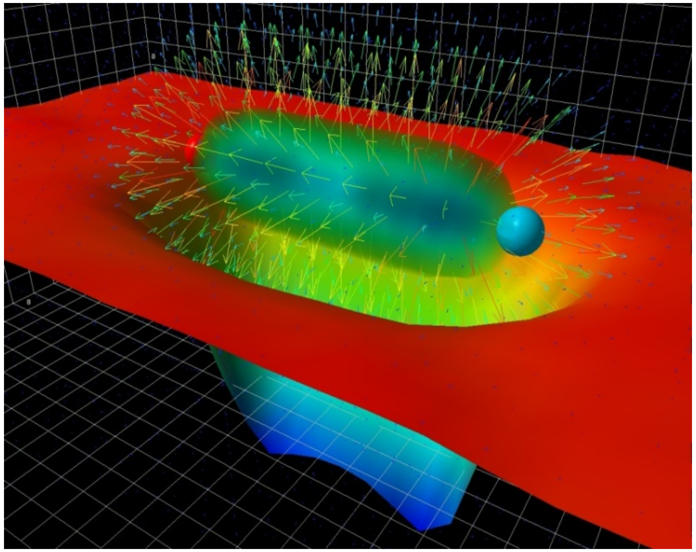
Lattice "Symmetries"

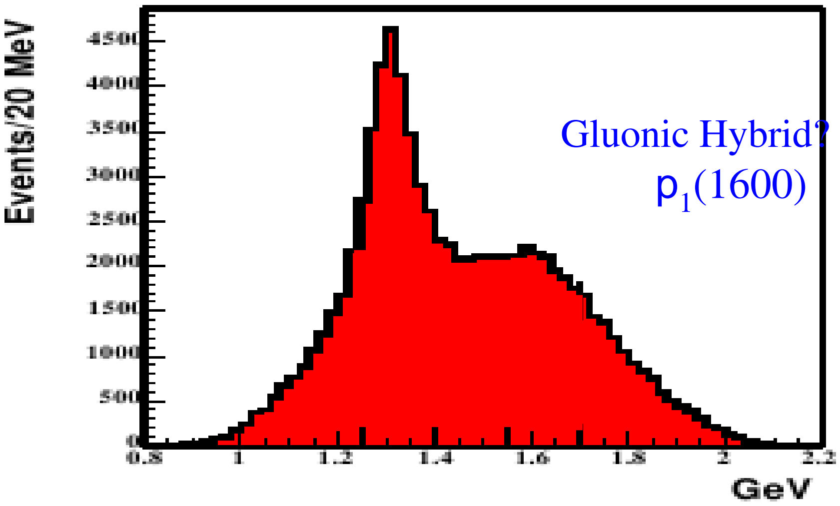
Exotics – I

- Exotic Mesons are those whose values of J^{PC} are in accessible to quark model
  - **Multi-quark states:** $q\bar{q}q\bar{q}$
  - **Hybrids with *excitations of the flux-tube***



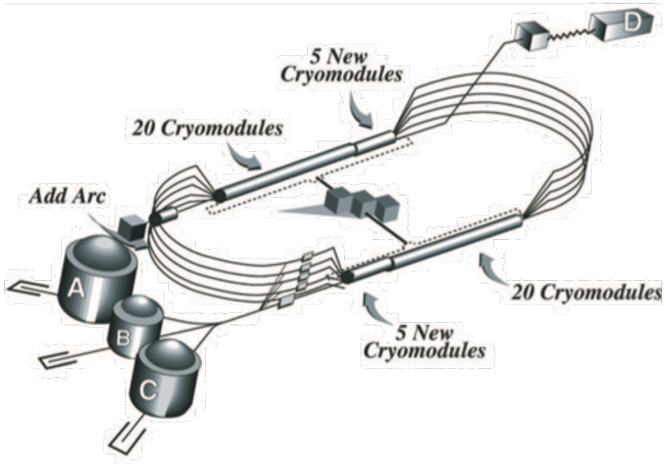
- Study of hybrids: revealing gluonic and flux-tube degrees of freedom of QCD.



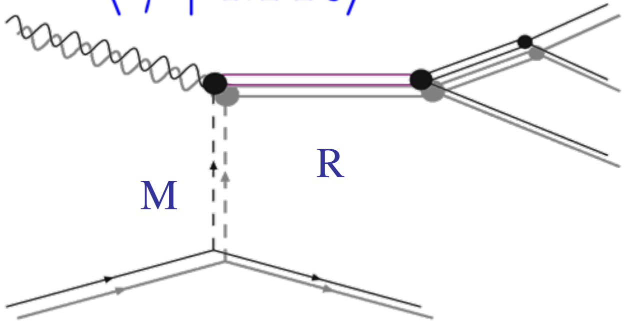


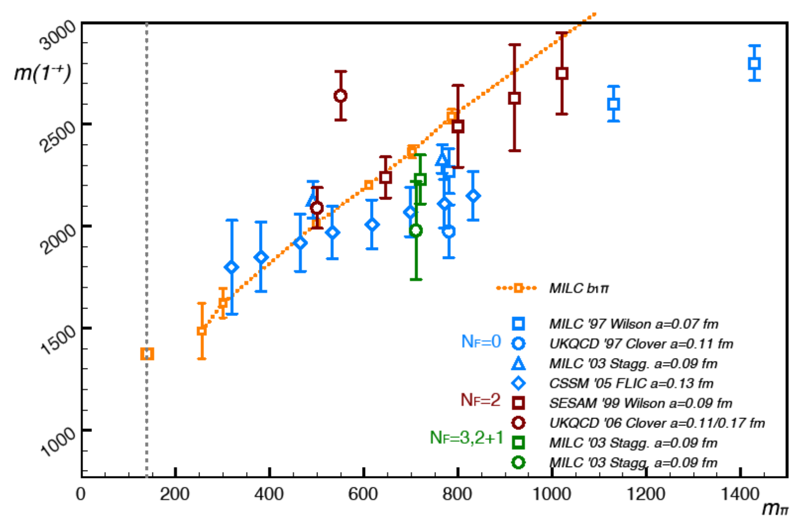
Lattice QCD: Hybrids and GlueX - I

- **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**



$\langle \gamma \mid M R \rangle$





Important goal for LQCD

Few-Body Physics

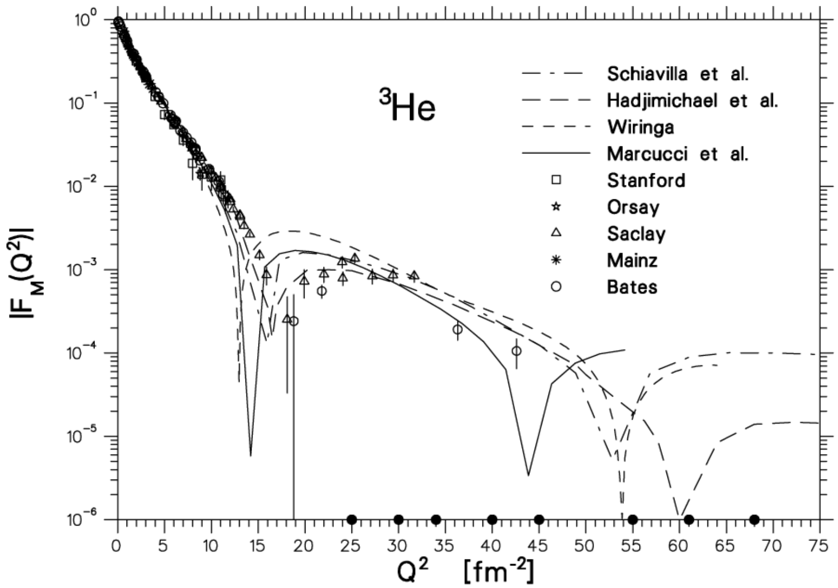
- Build an effective description of the interaction between nucleons
- Show how that description arises from QCD, via effective theory, Lattice QCD,

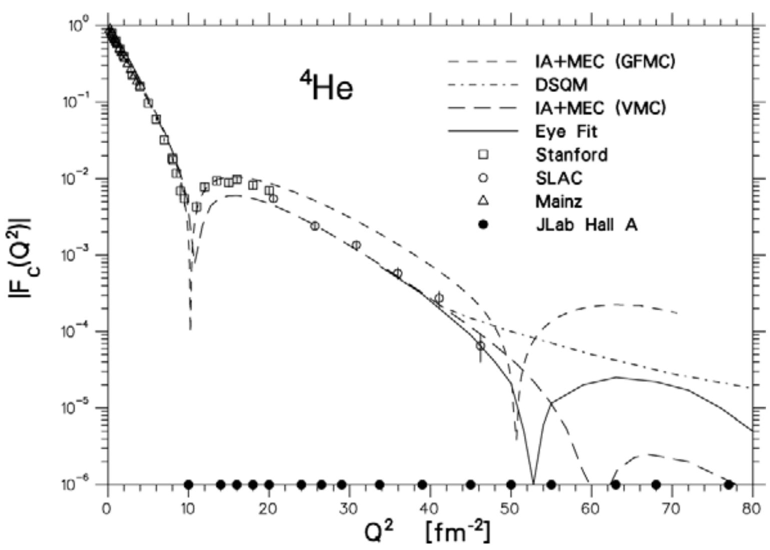
Elastic Scattering off ^3He and ^4He

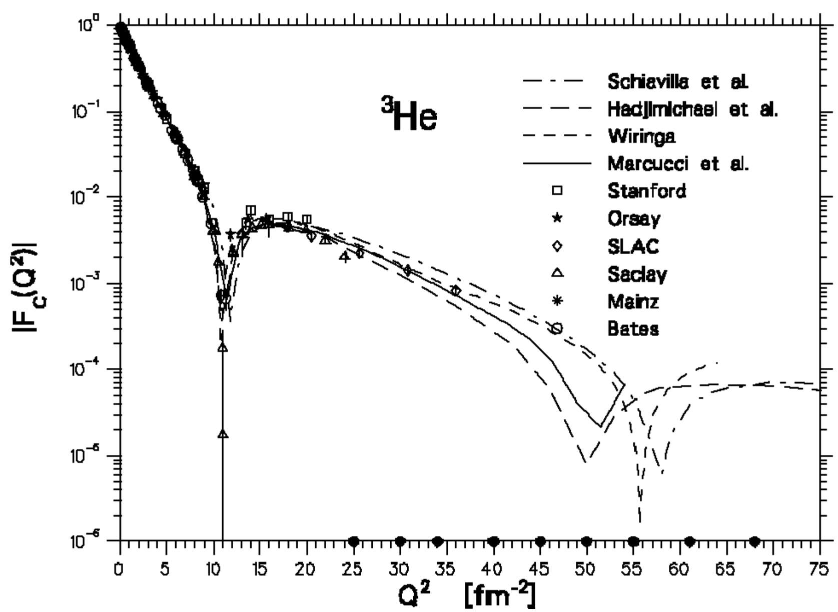
Hall A E04-018

FY07 Data

- Measurement of the form factors of ^3He and ^4He up to the largest Q^2 possible (~3 GeV^2).
- Data precision/range is pivotal for the establishment of a standard hadronic (nucleon-meson) model for the description of the few-body nuclear systems, severely constraining impulse approximation, meson exchange currents, nucleon-nucleon potential etc.



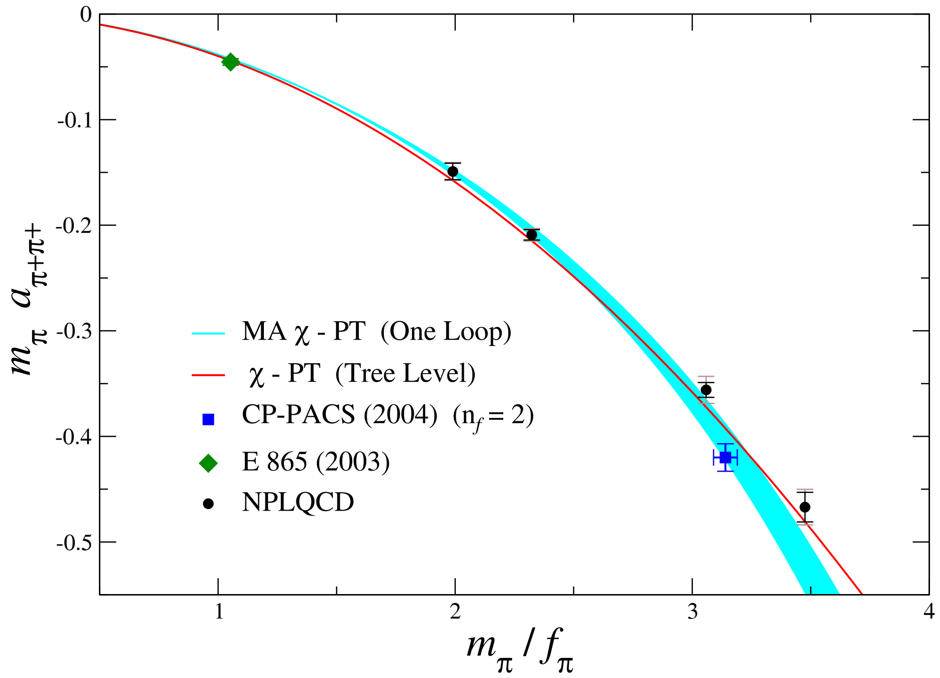


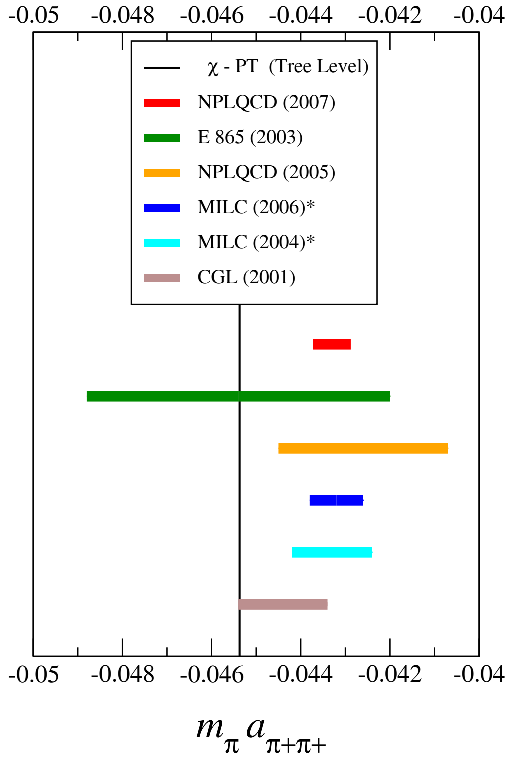


Few-body System in Lattice QCD

* Currently, can investigate **Meson-Meson** system in lattice QCD

$$I = 2\pi - \pi \text{ Scattering Length}$$

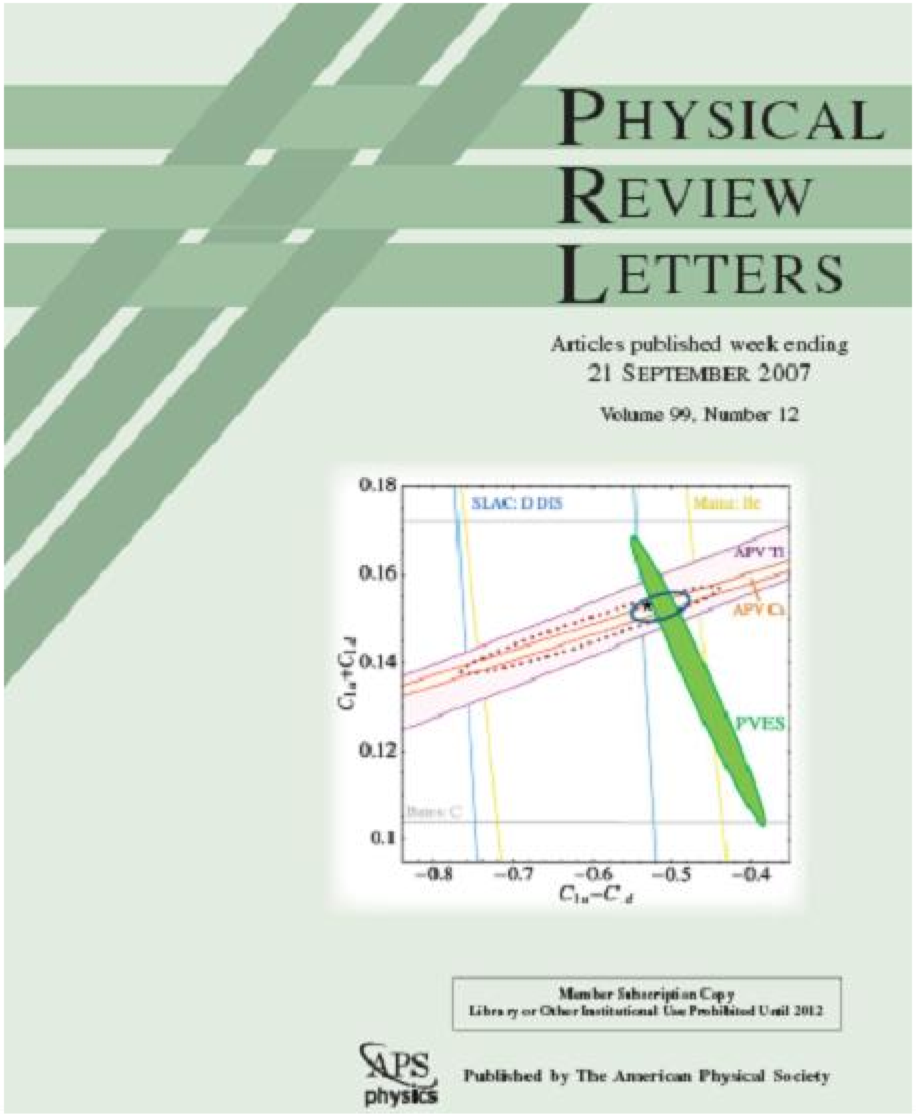




NPLQCD, arXiv:0706.3026

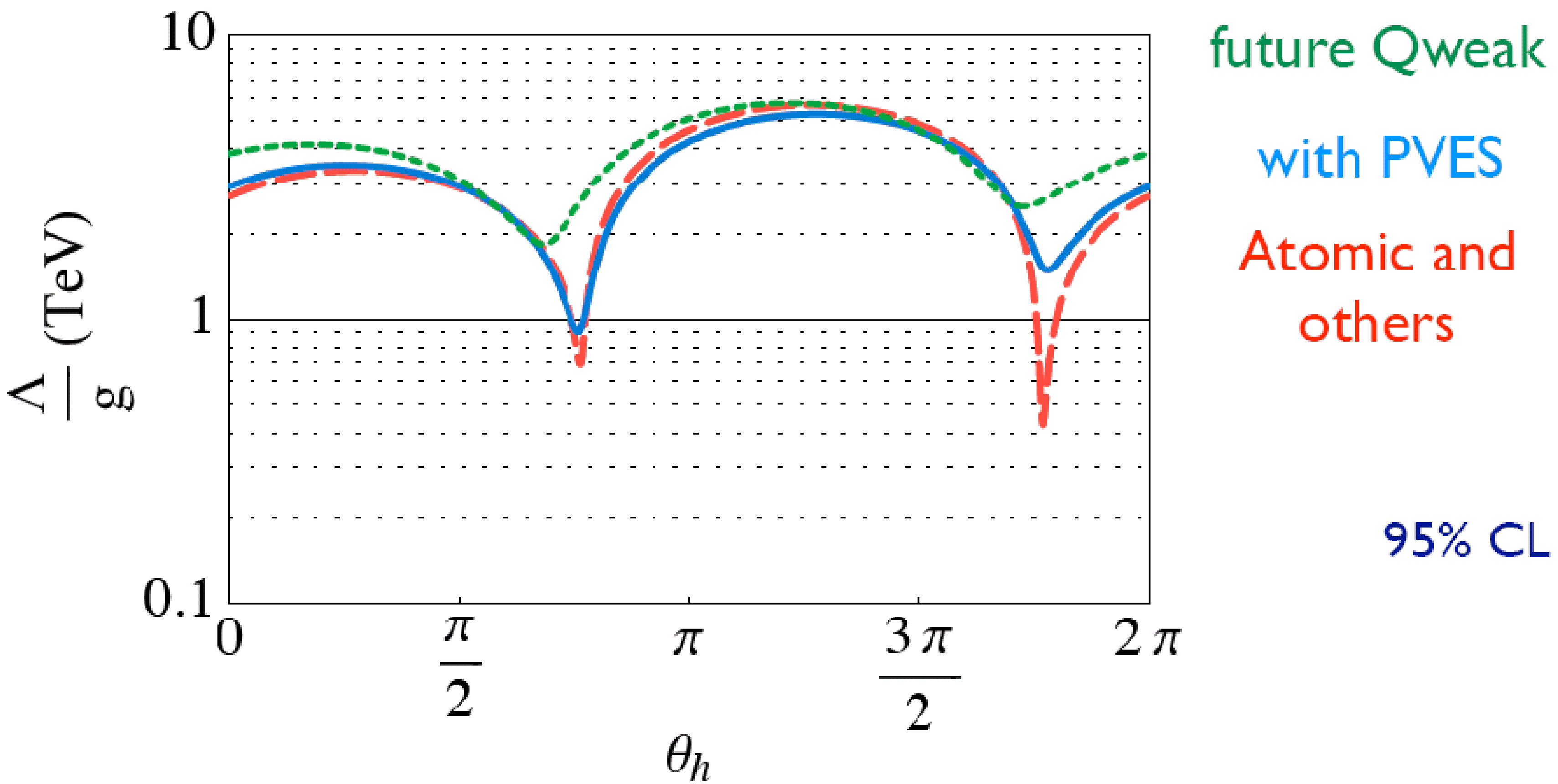
Standard Model and Beyond

PVES - I



- Can Jefferson Lab help in the search for new physics beyond the *Standard Model* of particle and nuclear physics?
- Yes – precise measurements of low energy constants

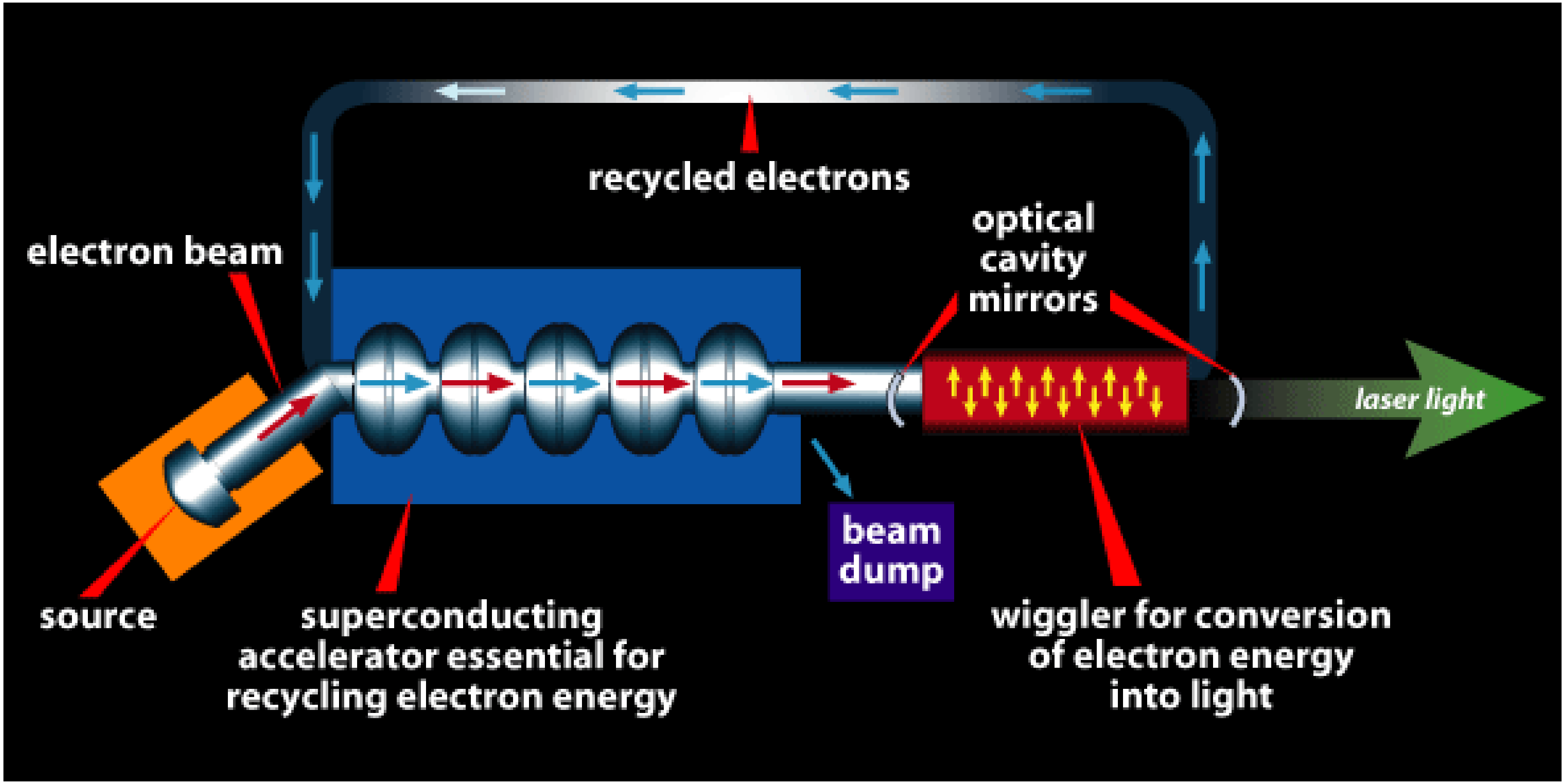
PVES - II



Young, Carlini, Thomas, Roche, hep-ph/0704.2618

QWEAK will constrain new physics to beyond 2 TeV

Jefferson Lab's Energy Recovered Linac / FEL



Search for Axions

Summary

- Exciting physics program at 6 GeV aimed at gleaning an understanding of the structure of nucleons are nuclei in terms of the fundamental quarks and gluons of QCD
- On track for the 12 GeV Upgrade, with next milestone (CD-3) later this year
- ***Great opportunities for the next generation of Experimentalists, Theorists and amalgams of the two***