First Principles Calculations of Nucleon and Pion Form Factors: Understanding the Building Blocks of Nuclear Matter from Lattice QCD

Lattice Hadron Physics Collaboration

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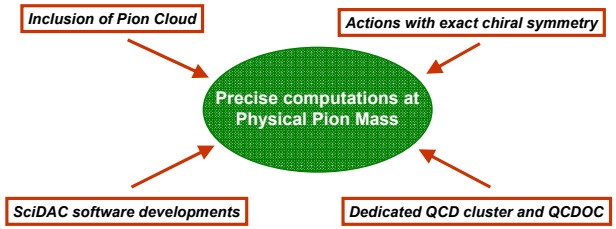
Hadronic Physics and Lattice QCD

Measurements from DOE-supported experiments such as those at Jefferson Laboratory, Bates and at BNL are providing information of an unprecedented quality regarding the quark and gluon structure of hadrons. *Lattice QCD is the essential complement to the current and anticipated 12 GeV Program at JLab, the current RHIC-Spin and a future electron-ion collider.*

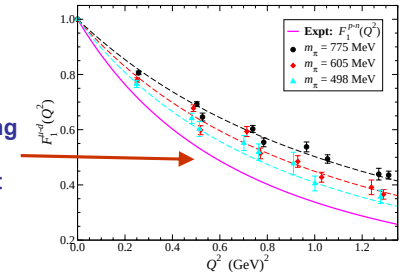


Nucleon Electromagnetic Form Factors

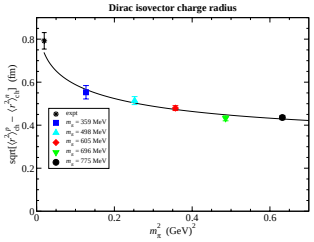
At low momentum transfer Q^2, the form factors $F_1(Q^2)$ and $F_2(Q^2)$ describe distribution of charge and current within nucleon. At high Q^2, they describe ability of system to receive high momentum while remaining in ground state. Lattice QCD can compute these form factors from first principles.

Size of nucleon: we are currently completing first full QCD calculations with light quarks of difference between proton and neutron form factors. The slope specifies *charge radius*.

Dipole form using charge radius from experiment



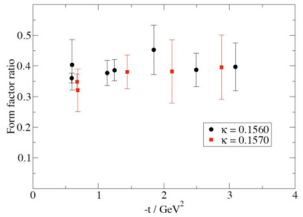
As the pion mass approaches the physical value, the size approaches the correct value.



Extrapolation form from Thomas *et al*, Phys. Rev. Lett. 86, 5011 (2001)

A striking JLab result was the observation that the ratio $Q^2 F_2 / \ln^2(Q^2/\Lambda^2) F_1$ is constant through 6 GeV^2.

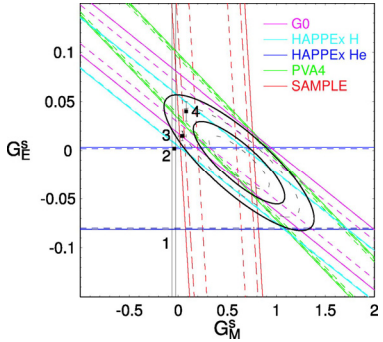
Lattice calculations with heavy quarks exhibit this behavior



A current SciDAC objective is to achieve quantitative agreement with experiment for physical light quarks.

Role of Strange Quarks

Seeking evidence of strange quarks within the nucleon explored at SAMPLE, HAPPEX and G-Zero.
Recent experimental evidence nucl-ex/0506021 suggests non-zero contribution from strange quarks to G^s_M and G^s_E



$G^s_E = -0.013 \pm 0.028$
$G^s_M = +0.62 \pm 0.31 \pm 0.62\ 2\sigma$

Contours
— 1σ, 2σ
— 68.3, 95.5% CL

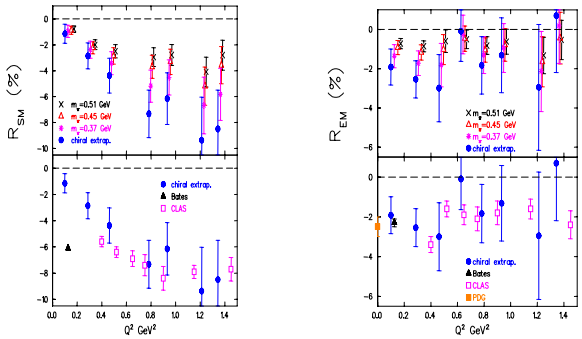
Previous lattice calculations in *quenched* QCD [3] and using amalgam of lattice and phenomenology [1].
Computation at light quark masses approved part of LHPC program at JLab QCD clusters and at BNL.

$\gamma N \rightarrow \Delta$ Transition Form Factor

Electric and Coulomb quadrupole transition form factors, G_E and G_C, are signatures of *deformation* in the nucleon or delta. Recent quenched QCD calculations yielded non-zero G_E and G_C form factors in qualitative agreement with experiments at JLab and Bates, and full QCD calculations with light quark masses are under way.

Alexandrou et al (2005)

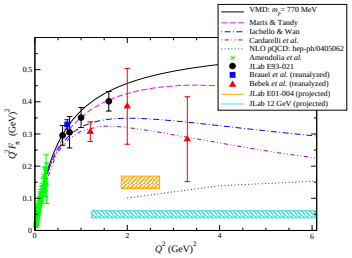
$R_{SM}=G_C/G_M$ $\qquad$ $R_{EM}=-G_E/G_M$



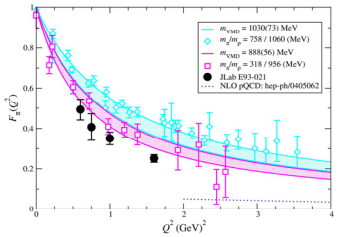
Pion Form Factor

Observe interplay between perturbative and non-perturbative aspects of QCD:

Current and Projected Experiments



Lattice computation at small m_π



$$F_\pi(Q^2) \approx \frac{1}{1 + Q^2/m^2_{VMD}}$$

$Q^2 \rightarrow \infty$, absolutely normalized